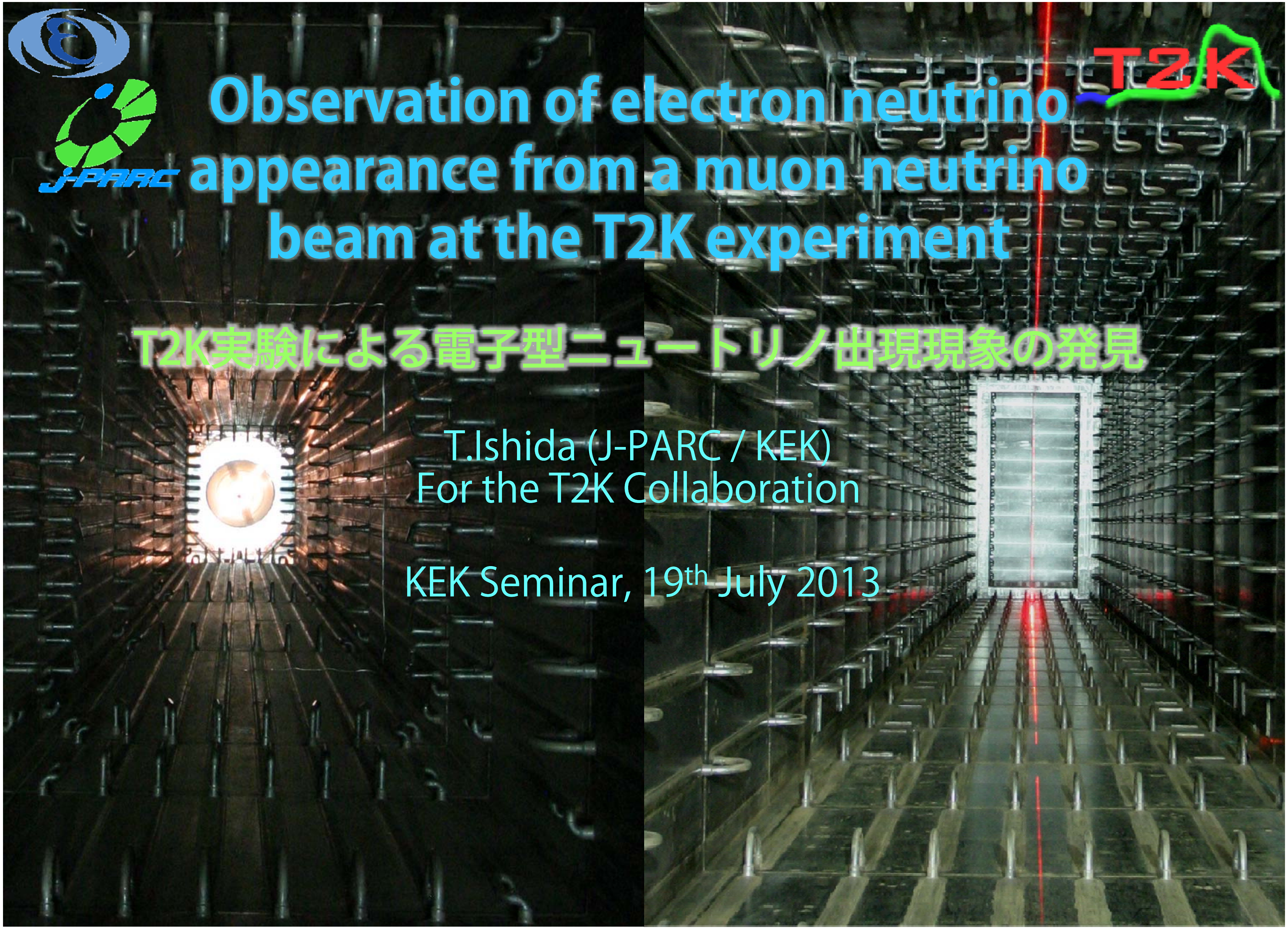


Observation of electron neutrino appearance from a muon neutrino beam at the T2K experiment

T2K実験による電子型ニュートリノ出現現象の発見

T.Ishida (J-PARC / KEK)
For the T2K Collaboration

KEK Seminar, 19th July 2013

The T2K Collaboration

~500 members, 59 Institutes, 11 countries

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

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

Germany
Aachen U.

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

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

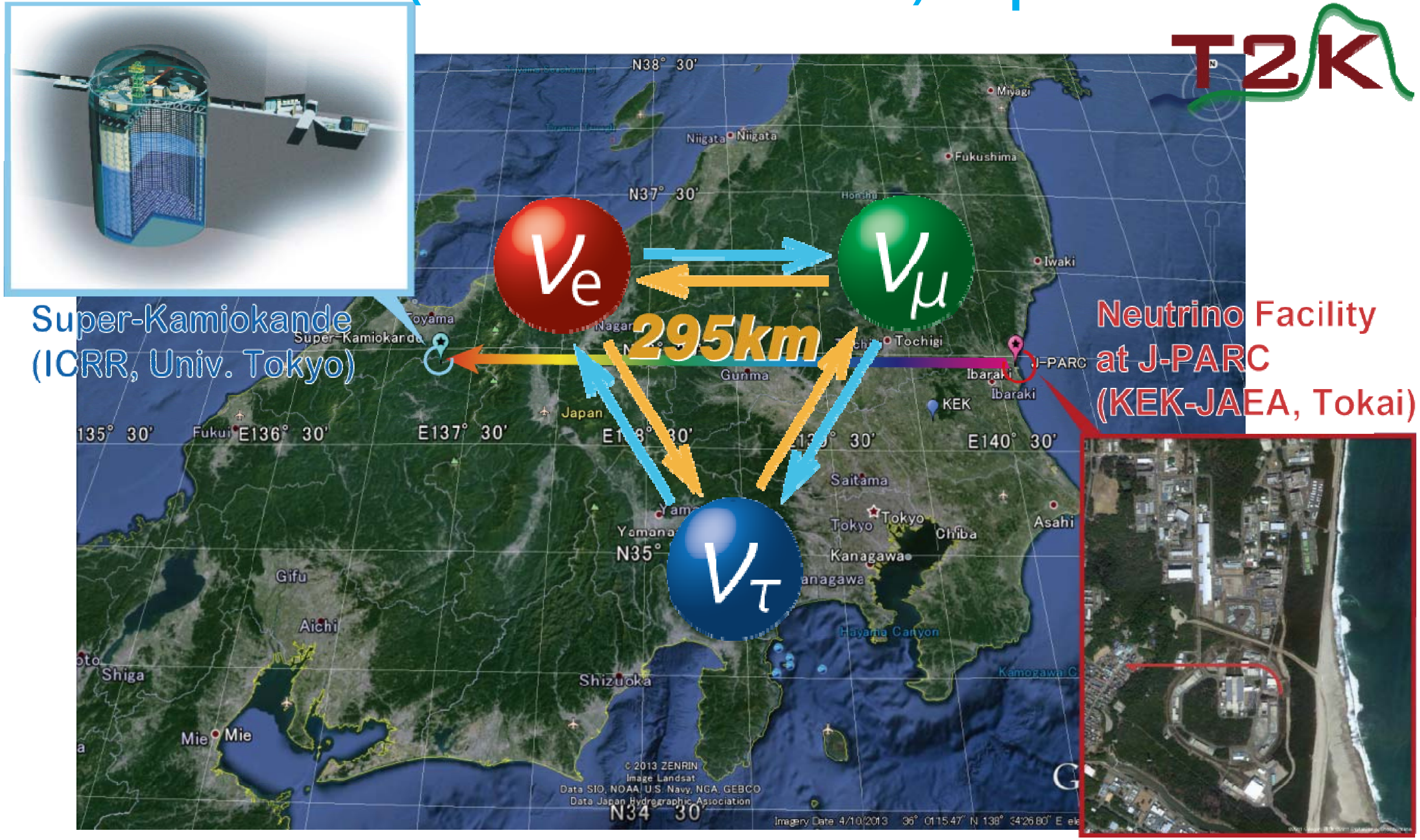
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Outline of this talk

- Physics motivation
- The T2K experiment
- Observation of ν_e appearance
- Summary and prospect

The T2K (Tokai-to-Kamioka) experiment

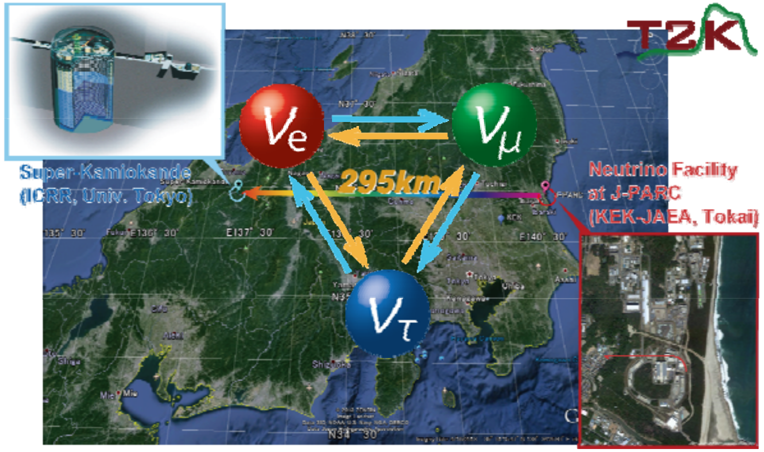


Primary Goals

- Discovery of $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance)
- Precision measurement on $\nu_\mu \rightarrow \nu_{\tau(x)}$ oscillation (ν_μ disappearance)

Physics motivation

- **Discovery of $\nu_\mu \to \nu_e$**
  - Direct detection of neutrino flavor mixing in "appearance" mode
  - ν_μ to ν_e plays an important role to study CP violation and mass hierarchy

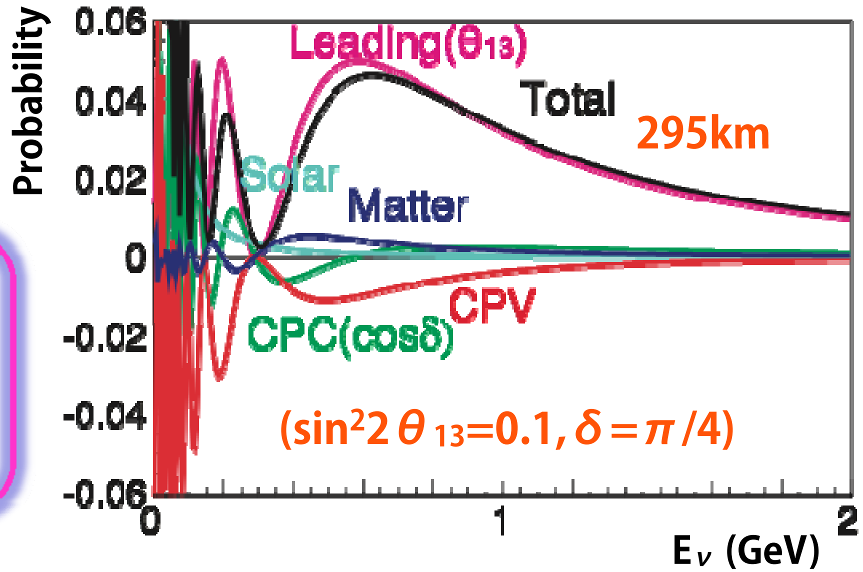


$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E)$$

$$+ (\text{CPV term}) + (\text{matter term}) \ldots$$

CPV $\propto$

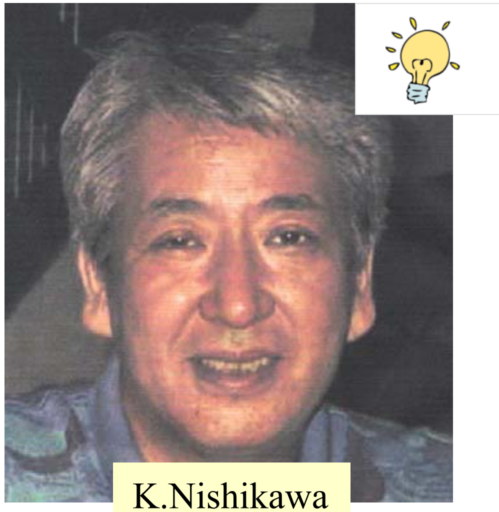
$$\sin\theta_{12} \times \sin\theta_{13} \times \sin\theta_{23} \times \sin\delta$$



History

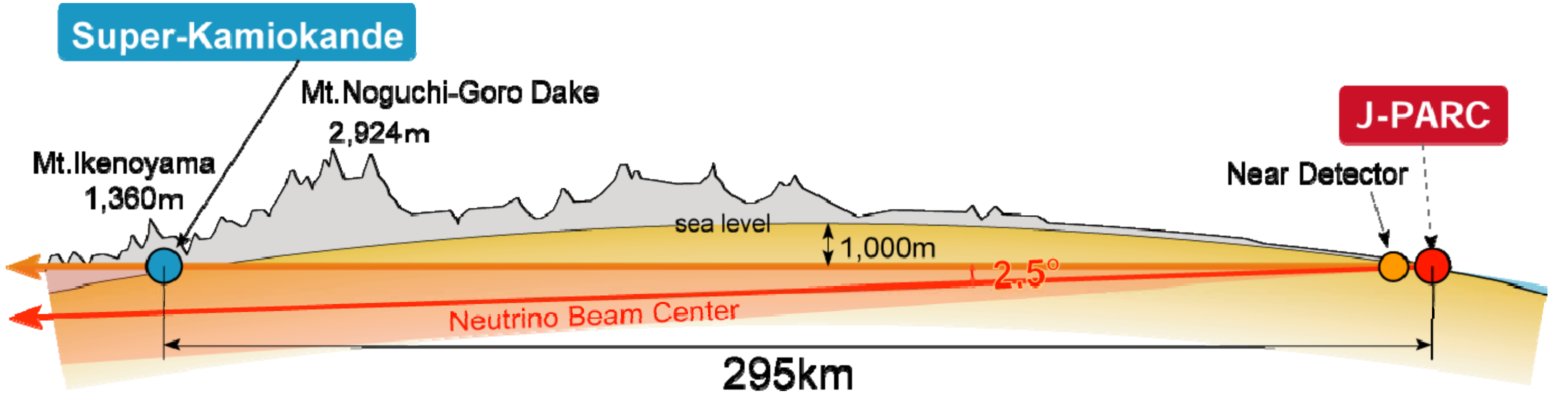
- 1999: Nishikawa & Totsuka proposed to measure ν_e appearance
- Feb. 2000: LoI
- April 2004:
  - Officially approved by Japanese Government and 5yr construction started
  - T2K international collaboration officially formed
- April 23, 2009:
  - First neutrino beam production and commissioning started
- **January 2010:**
  - **Data accumulation for oscillation search started!**
  - Mar.11,2011 - shutdown due to earthquake damage
- June 2011: First 2.5σ indication of ν_e appearance
  - Dec. 2011: Accelerator resumed operation
  - Mar.2012: T2K resumed data taking
- June/July 2012: 3.1σ evidence of ν_e appearance results

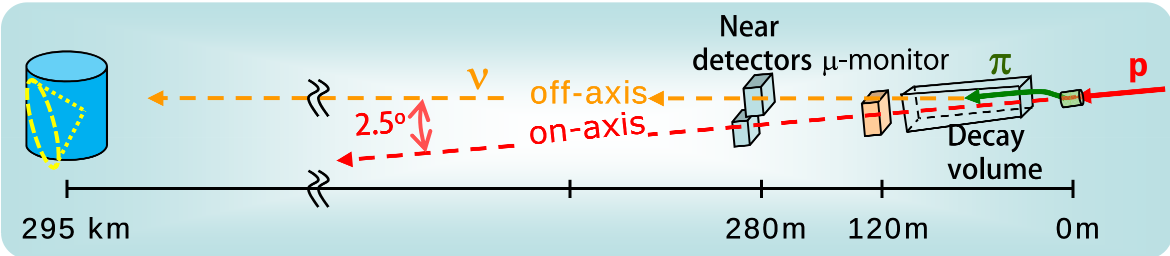
Y.Totsuka (1942~2008)

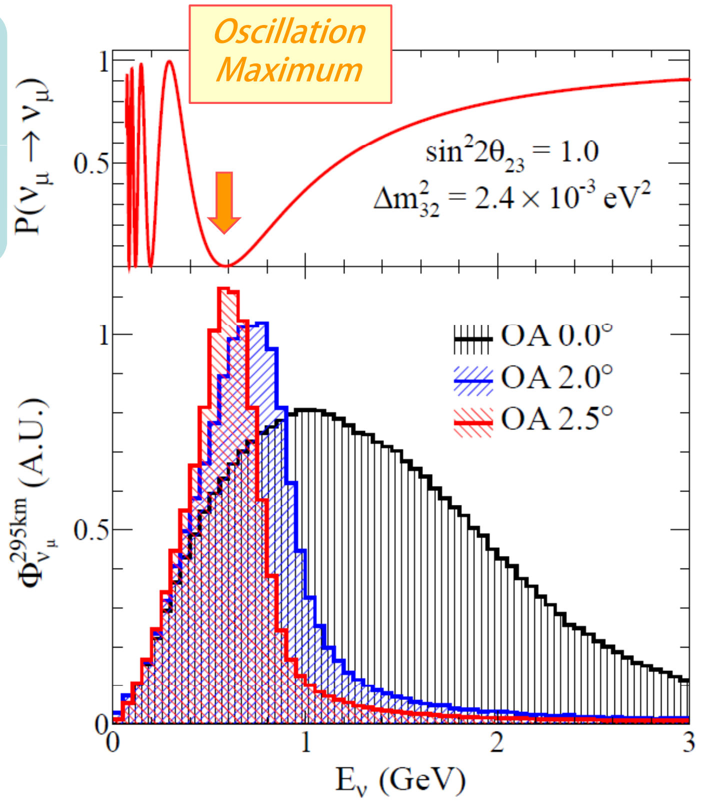


K.Nishikawa

The T2K experiment (Overview)

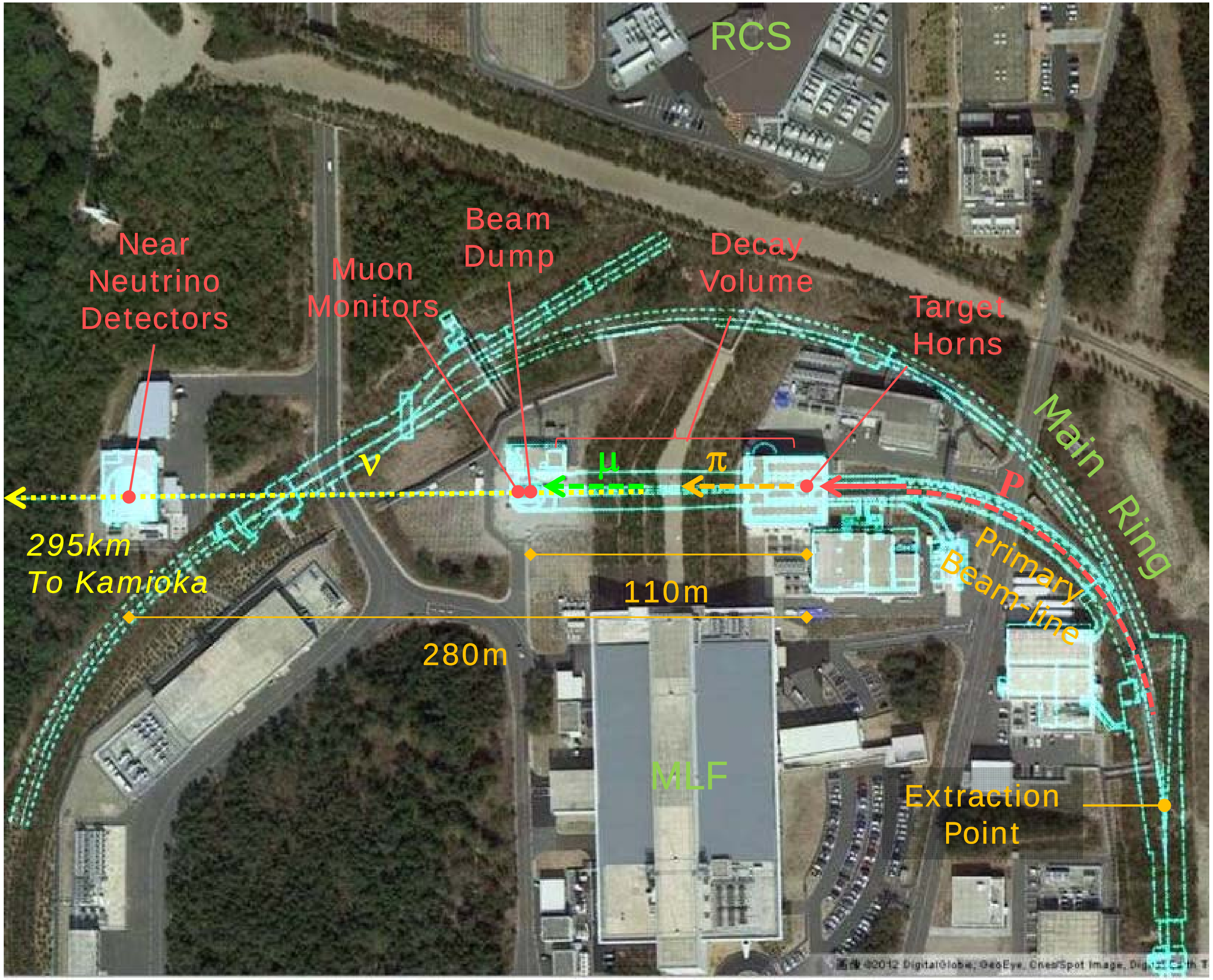




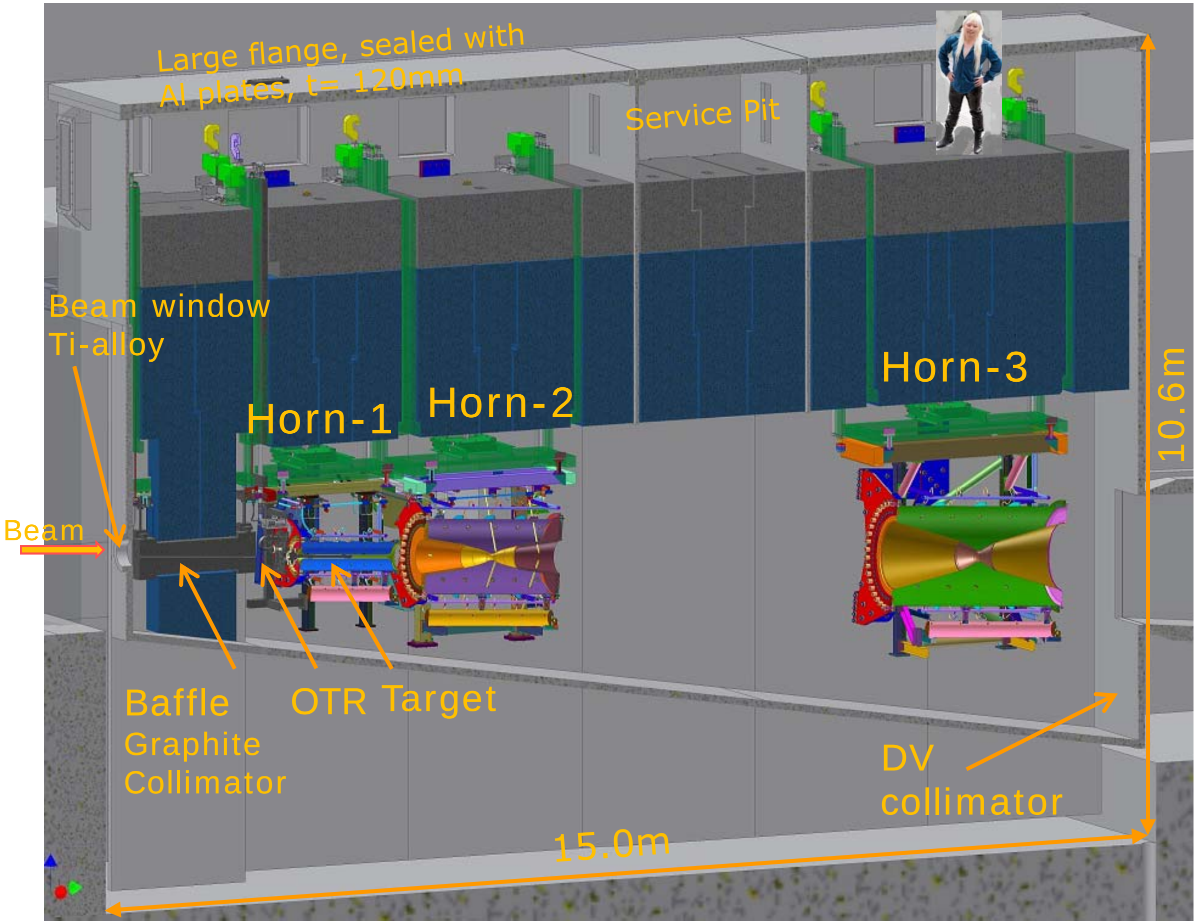


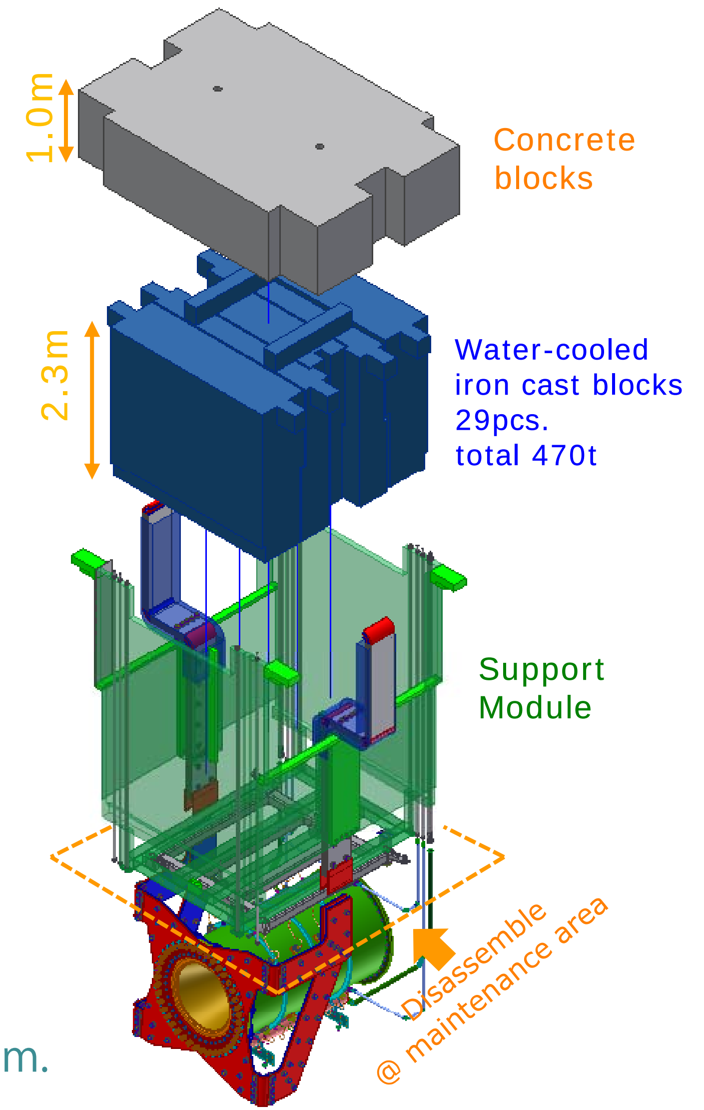
- Conventional "horn-magnet-focused" ν beam
  - 30GeV Protons on a graphite target: daughter $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- First application of Off-Axis(OA) beam:
  - Beam is 2.50° off-axis with respect to the far detector direction
  - Low-energy narrow-band beam, peak at oscillation maximum
  - Small high-energy tail: reduce background events in T2K
- Near neutrino detectors @ 280m from target
  - On-Axis (INGRID) detector / Off-Axis (ND280) detector
- Far detector: Super-Kamiokande @ 295km from J-PARC

Neutrino experimental facility at J-PARC



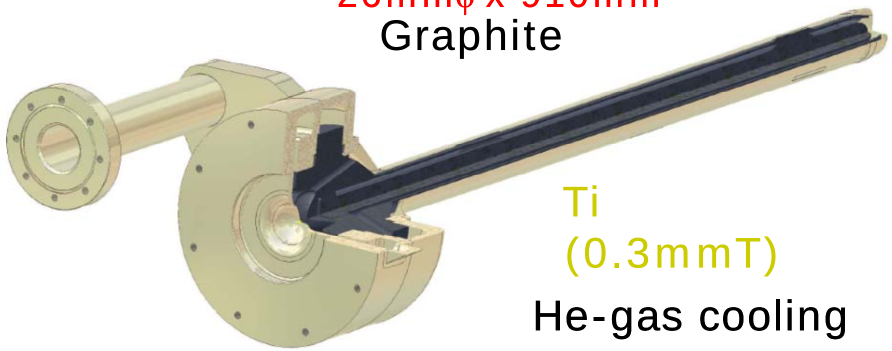
Target Station (TS)

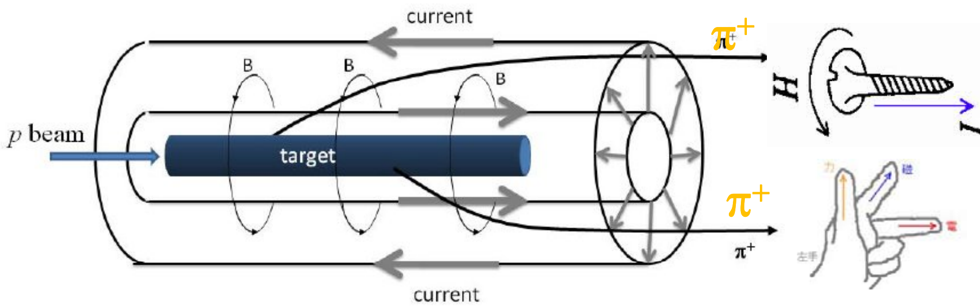


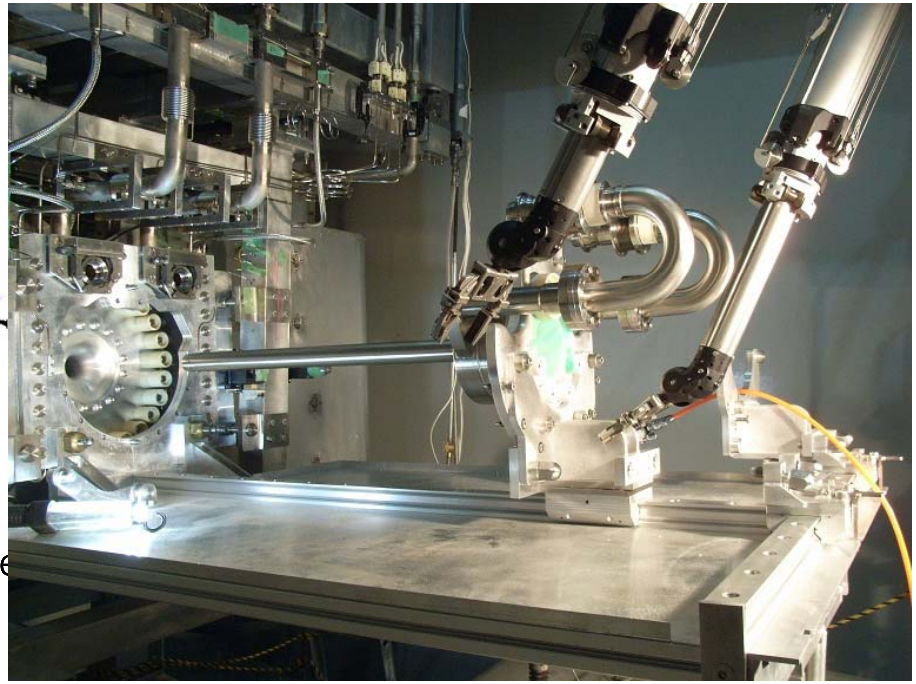


- 3 horns / a baffle are supported from the wall of vessel by support modules.
- Apparatus on the beam-line are highly irradiated after beam. Remote maintenance is key issue.

Electromagnetic Horns and Target



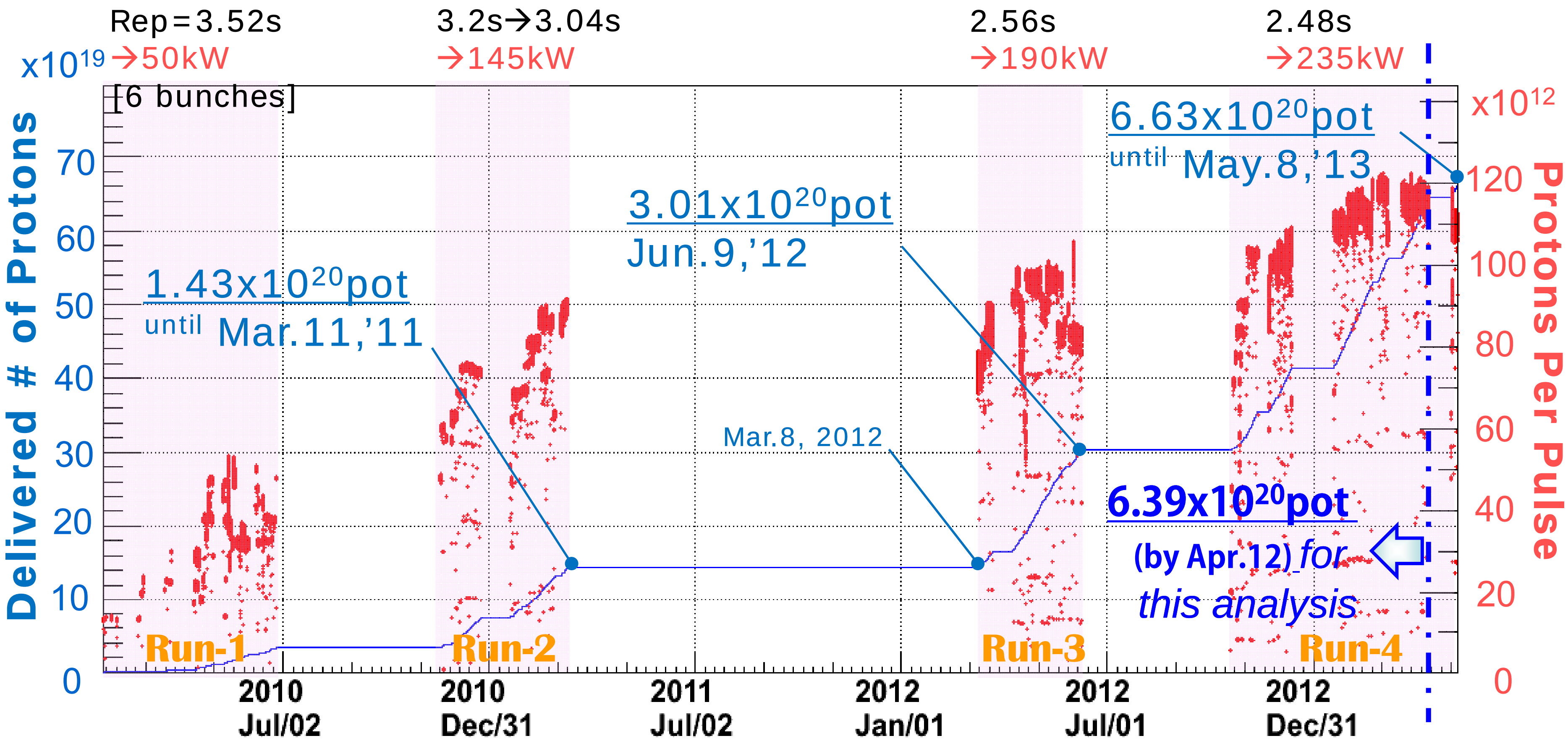




- By applying a 250kA pulsed current synchronized to the spill timing, a toroidal magnetic field of 1.6 Tesla is generated
- Current stability ~2%, Alignment : 0.3mm(x), 1mm(y,z)

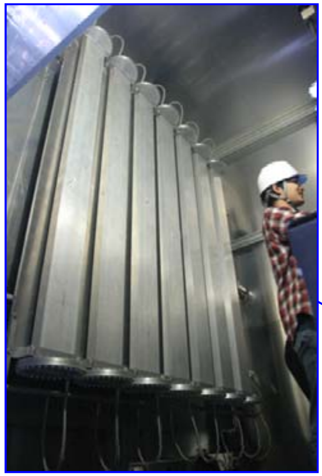
- Remote maintenance

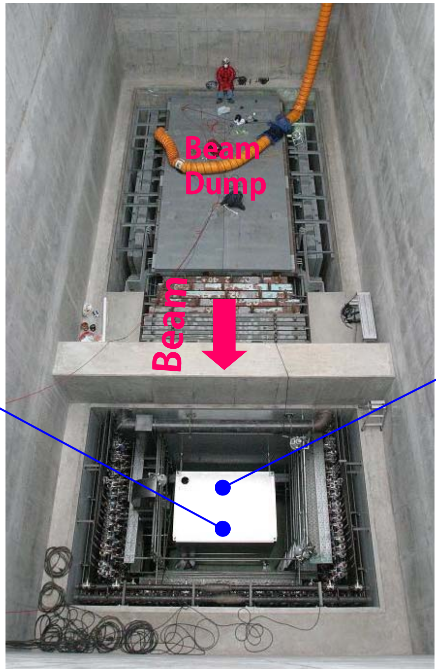
Delivered POT to neutrino facility



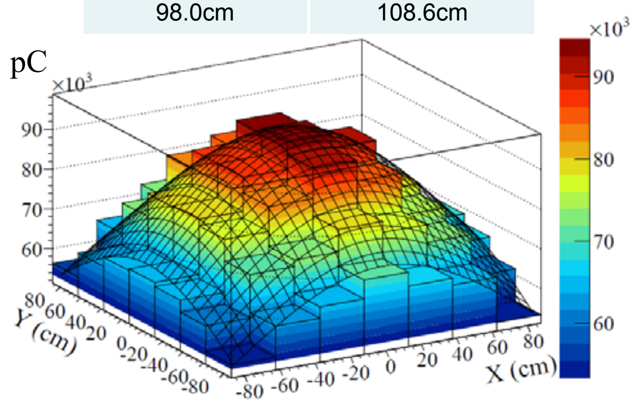
- Stable operation at ~220kW achieved.
  - >1.2x10[14]ppp (1.5x10[13]x8b) is the *world record* of extracted protons per pulse for synchrotrons.
- Data for today's talk: *6.39x10[20]pot* (by Apr.12). 6.63x10[20] by May.8.
  - Statistics has been *doubled* successfully compared to the previous analysis (3.01x10[20]pot)

Muon monitors



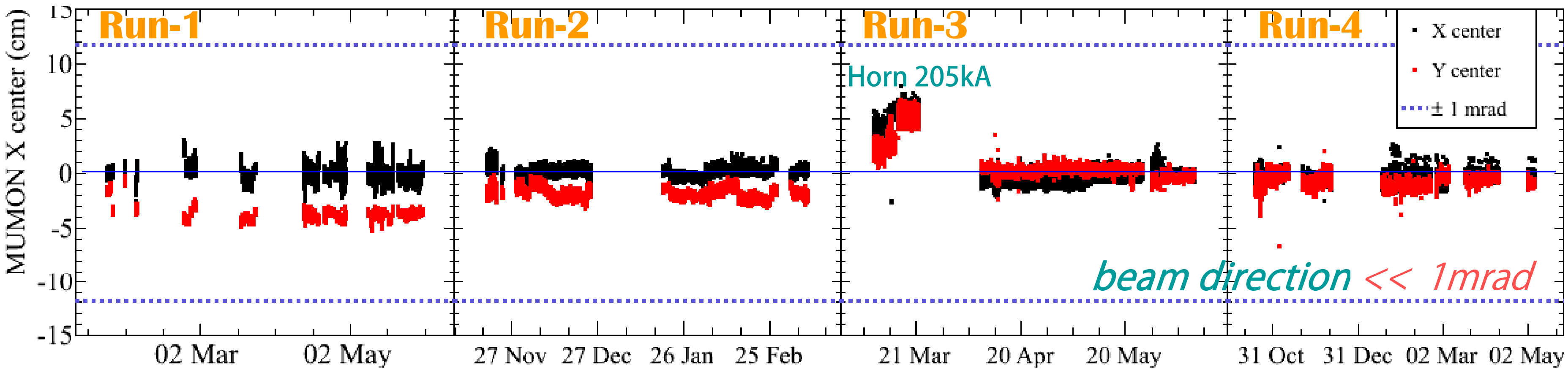


X-CENTER	Y-CENTER
-0.123cm	-0.838cm
X-sigma	Y-sigma
98.0cm	108.6cm

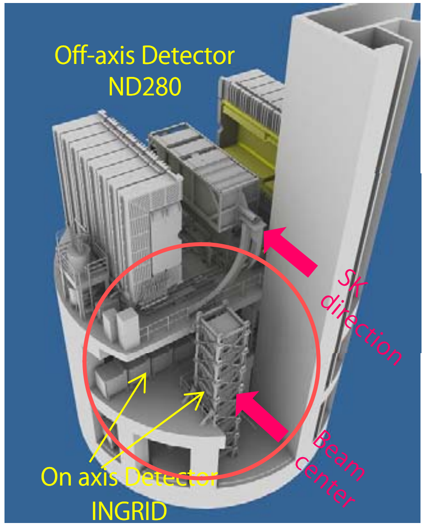


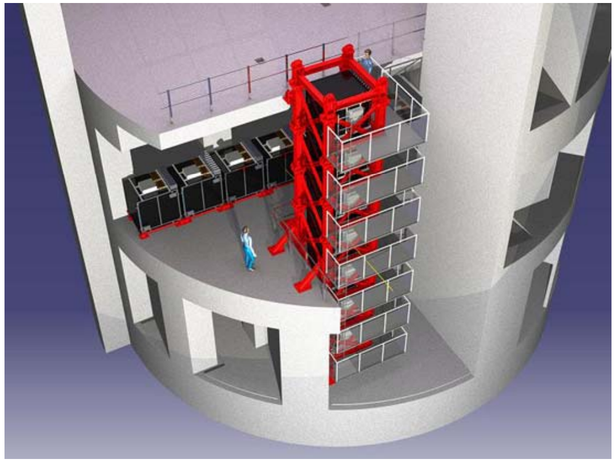
Total charge = 32.2 nC /1e12ppp

- Shot-by-shot monitoring for the beam center
- 1 mrad shift of direction= ~2% shift of peak energy

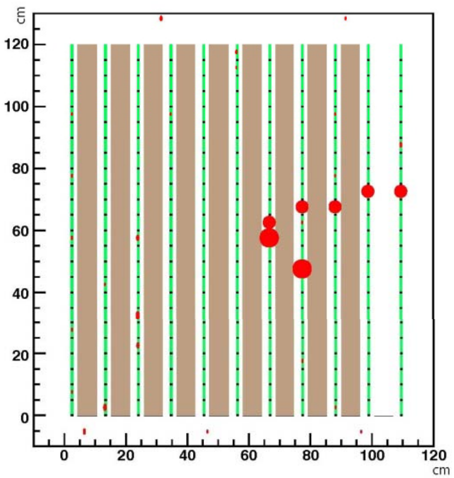


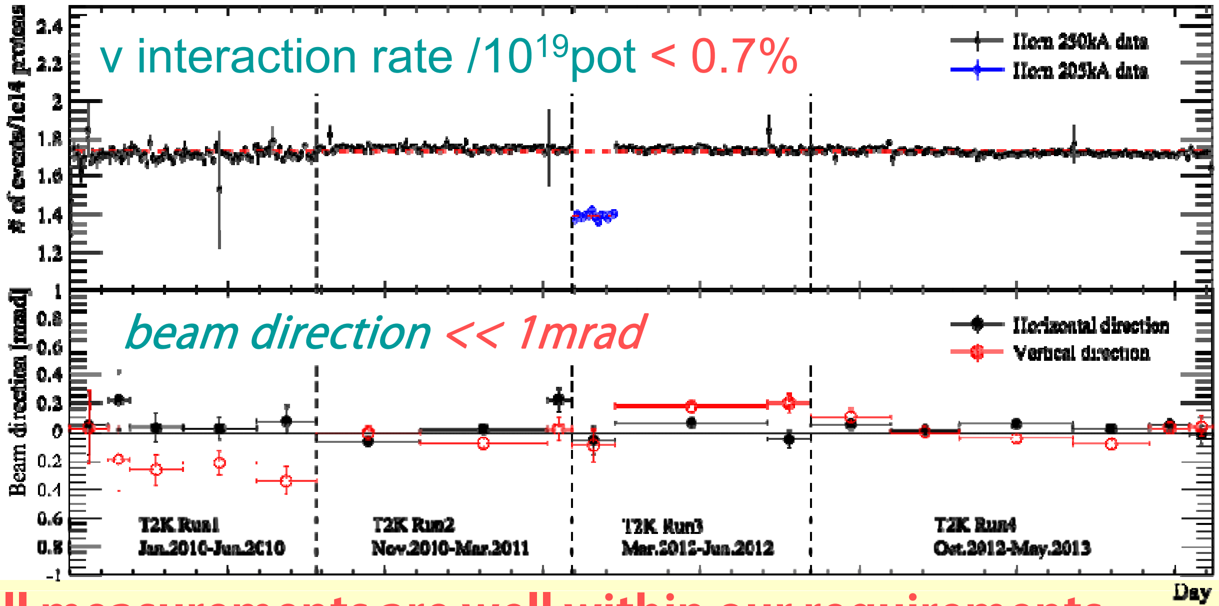
On-Axis near detector (INGRID)





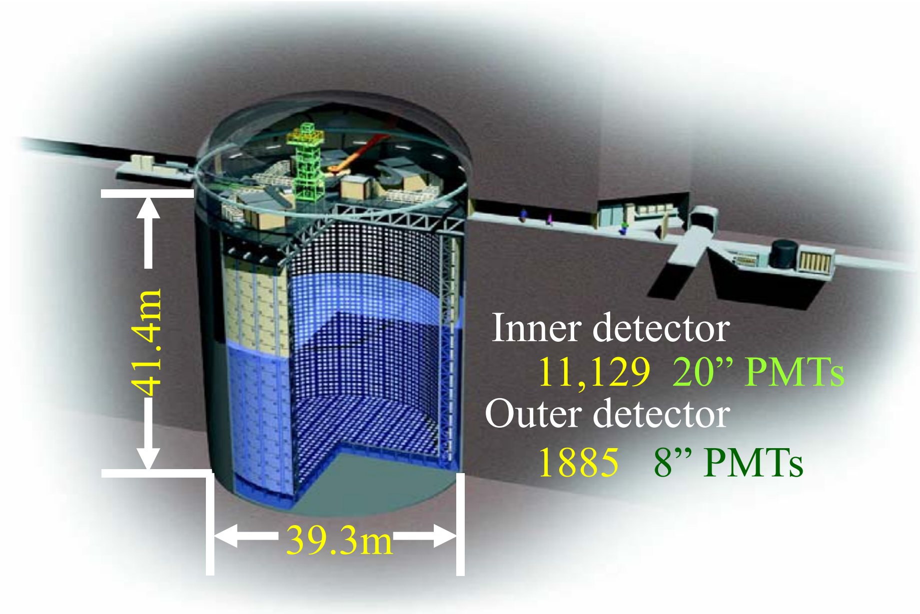
Side view





- **Beam is being stable, all measurements are well within our requirements.**

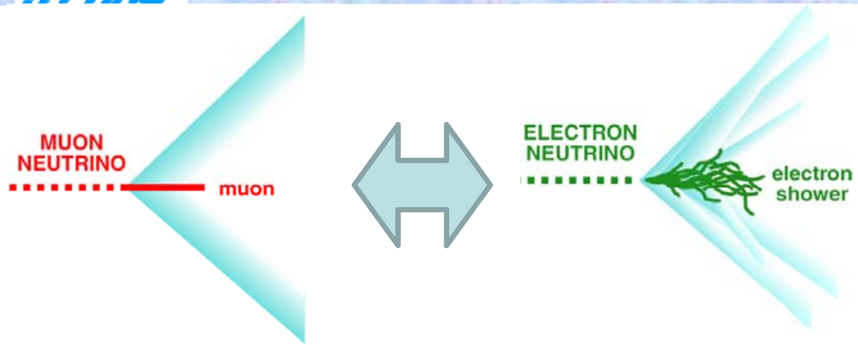
Far detector : Super-Kamiokande (SK)



50,000t水チェレンコフ測定器
1991年から5年で建設
1996年4月から稼働

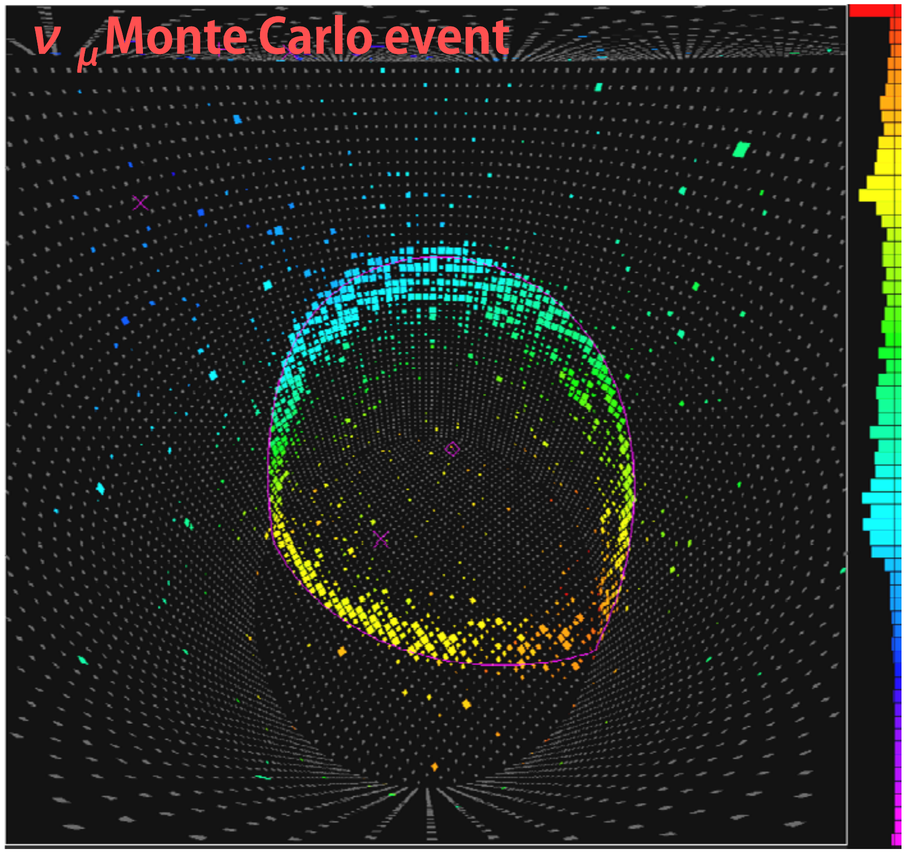
防爆ケースに入った
20インチ光電子増倍管

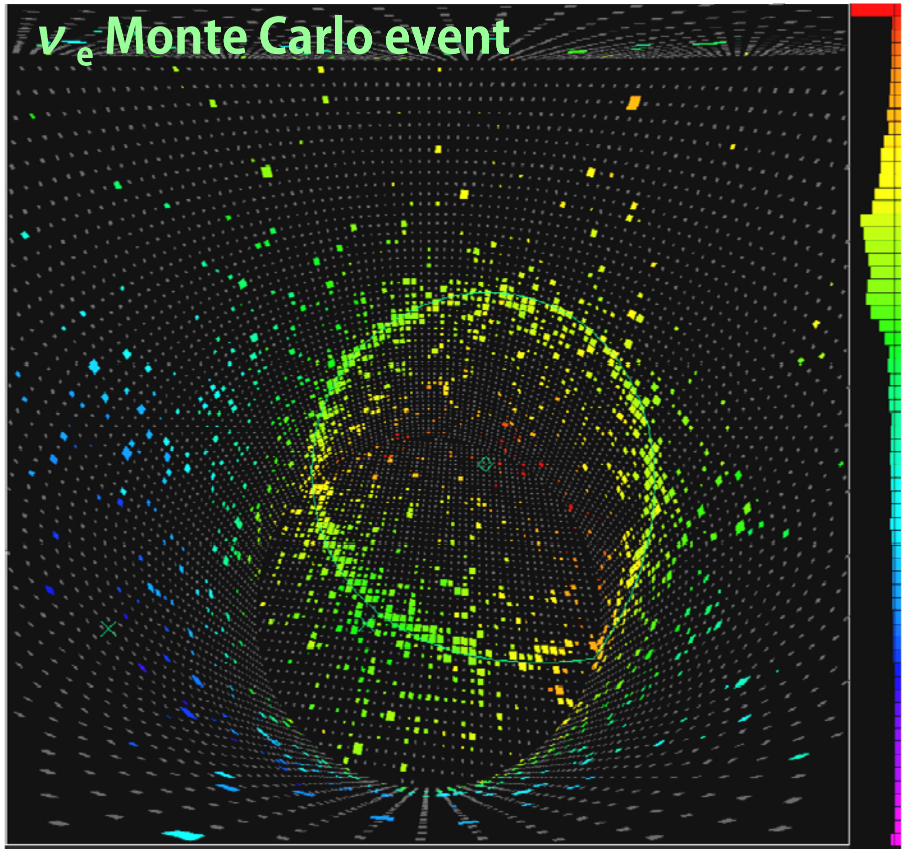
Particle identification



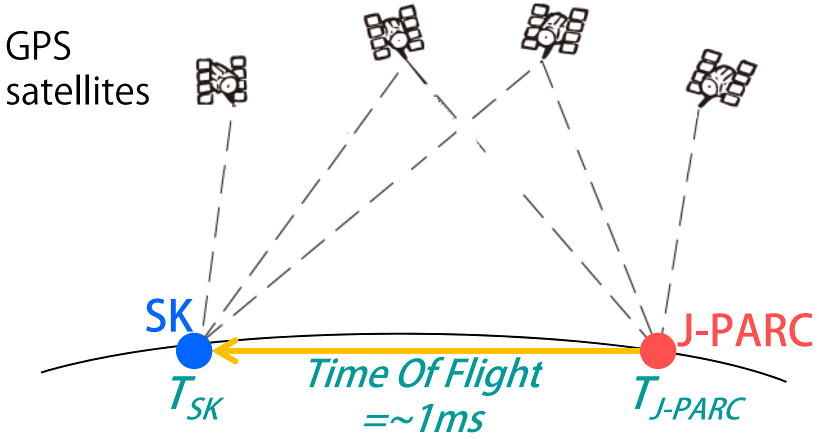
- 電子は電磁シャワーをおこすので、ミューオンに比べてぼやけたリングになる
- 間違う確率：
  ＜1GeV：0.6%、数GeV：≲2%

（KEKのビームテストで検証済）

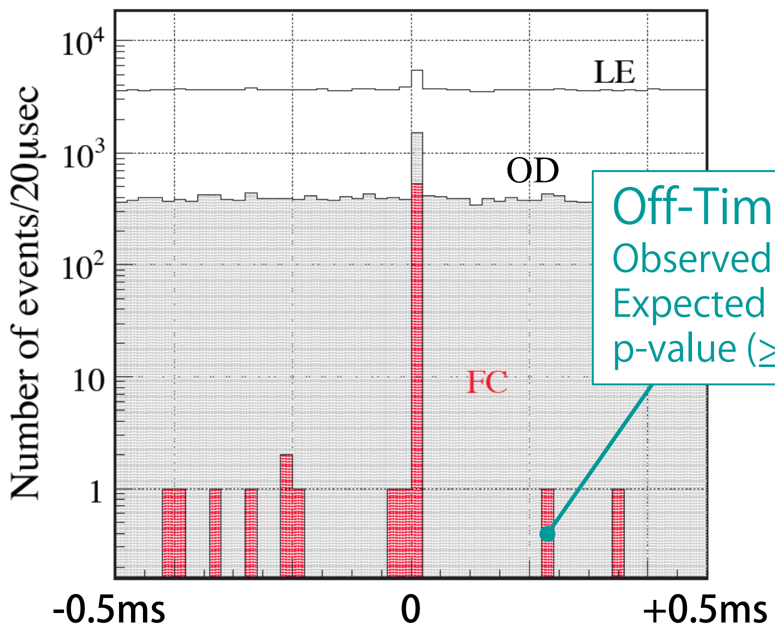




Event selection



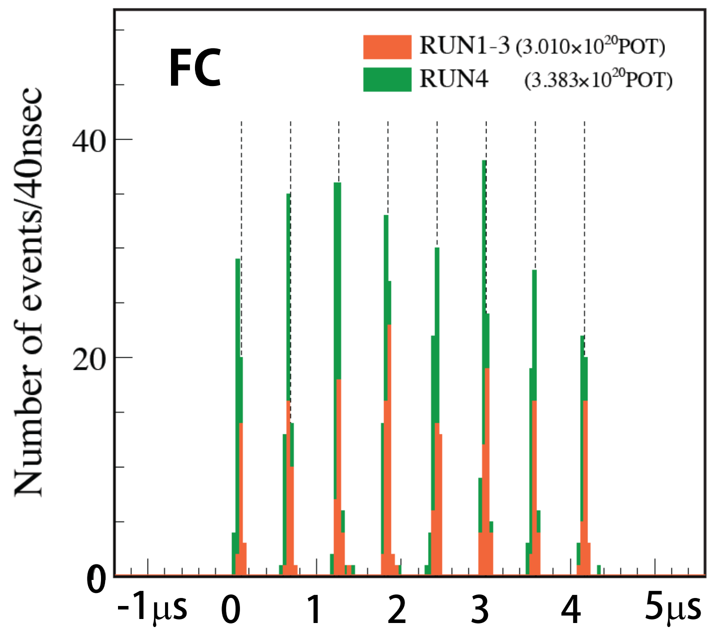
$\Delta T_0 = T_{SK} - T_{J\text{-}PARC} - TOF$



Off-Timing FC
- Observed : 11
- Expected BG: 5.8
- p-value (≥11) : 3.5%

- On-Timing Fully-Contained(FC) events in the inner detector
  - Observed : 532
  - in Fiducial Volume(FV): 363
  - Expected BG: 0.07 [FCFV 0.008]

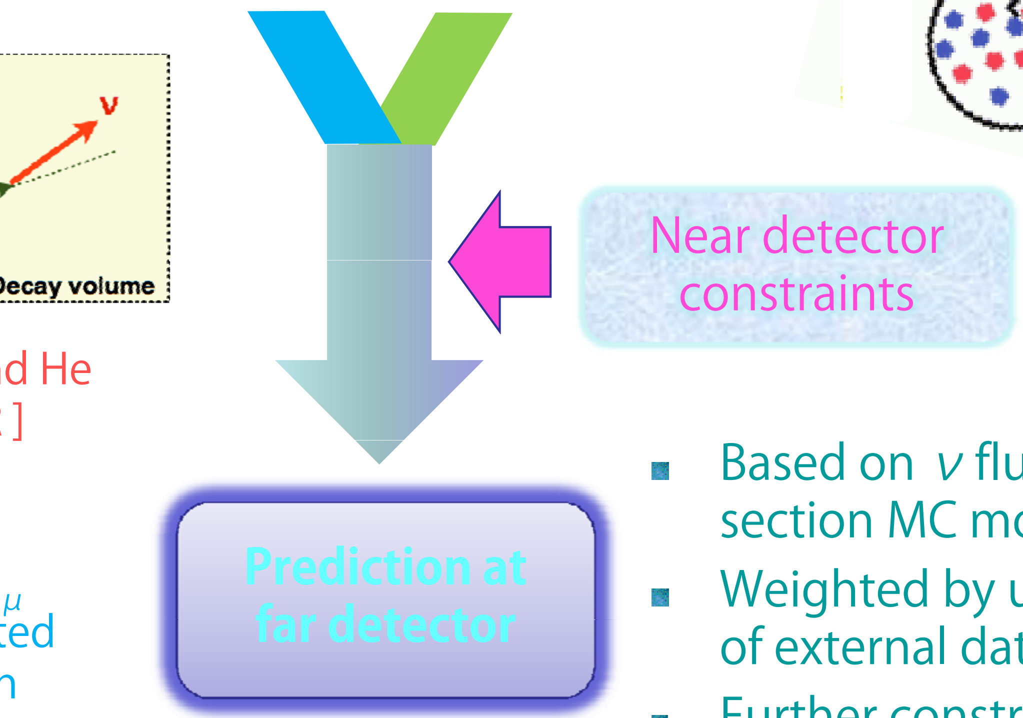
Clear 8-bunch structure at J-PARC MR can be seen at Super-K

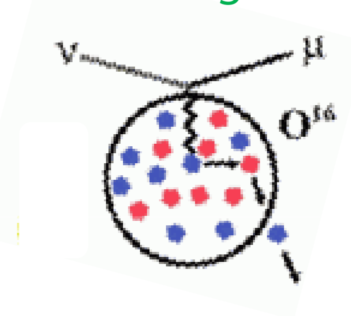


Method of Monte-Carlo prediction

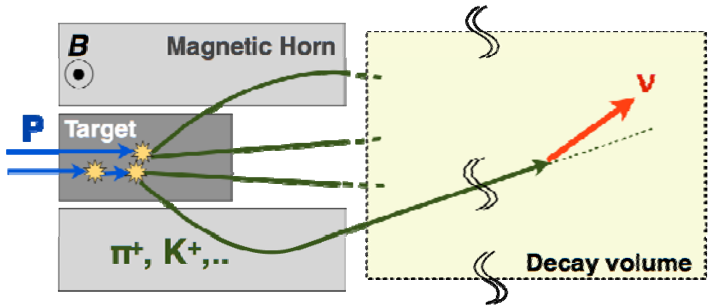
A. Interaction of primary beam in the target [FLUKA2008.3d]
← π / K production
(Mainly CERN NA61)

Neutrino-Nucleus interactions in a few GeV region [NEUT]





M_A
p_F
E_b
…



B. Tracking inside horns and He vessel [GEANT3+GCALOR]

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

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

$K^+ \rightarrow \mu^+ \nu_\mu$

$K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$

$K^+ \rightarrow \pi^0 e^+ \nu_e$

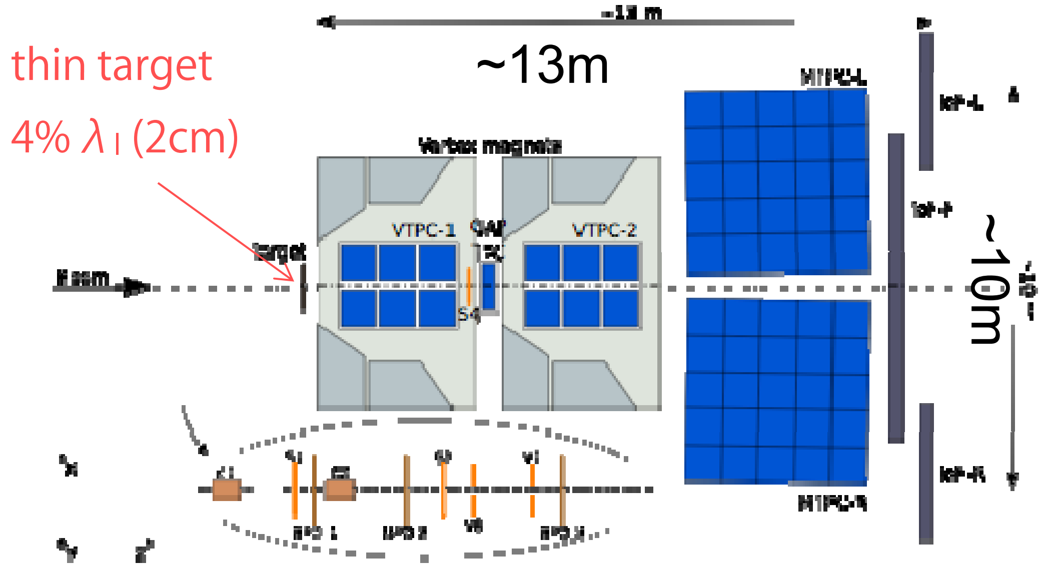
ν_e / ν_μ correlated through parent hadrons

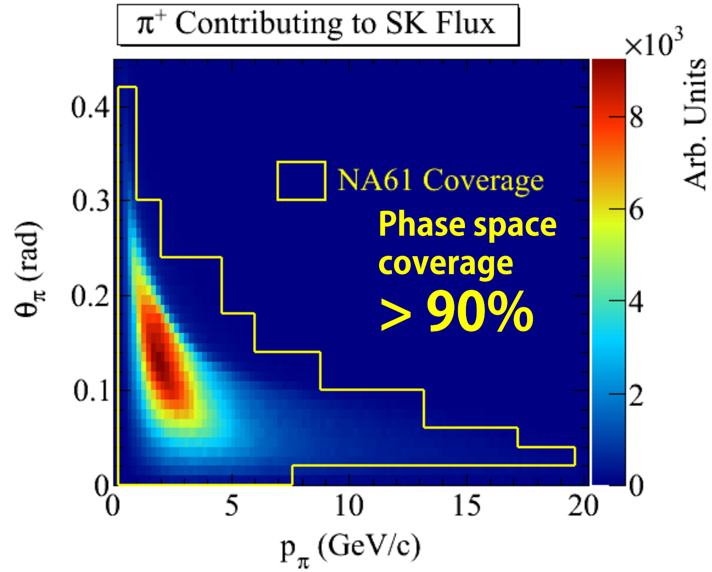
Evaluate Neutrino flux and neutrino interaction model based on experimental data as much as possible

- Based on ν flux ⓧ cross section MC models.
- Weighted by using as many of external data as input.
- Further constrain these predictions by the near detector measurements.

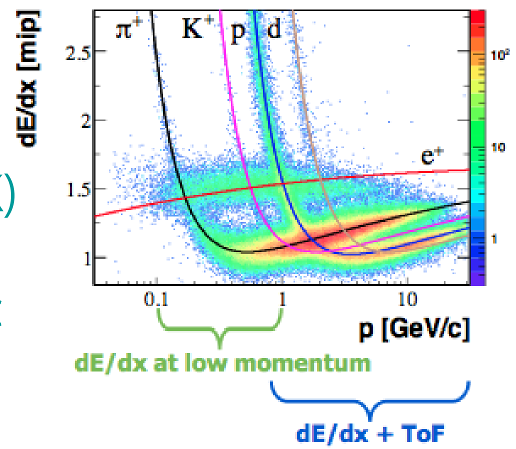
Hadron production measurements

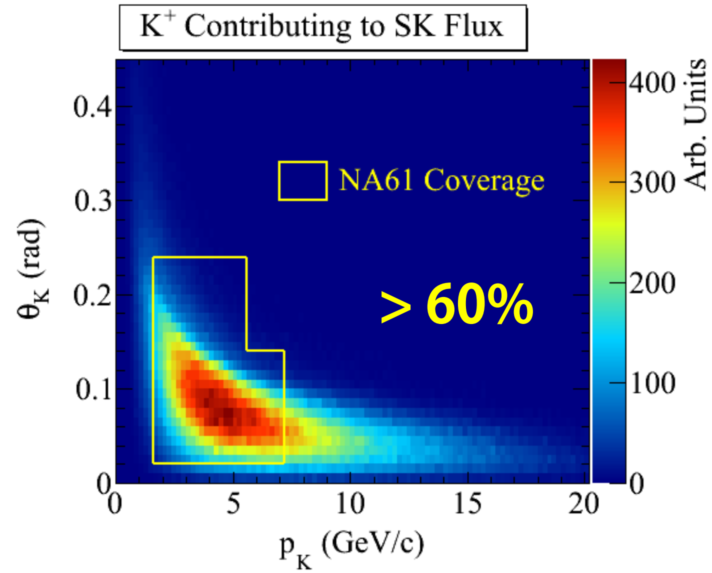
CERN NA61/SHINE experiment



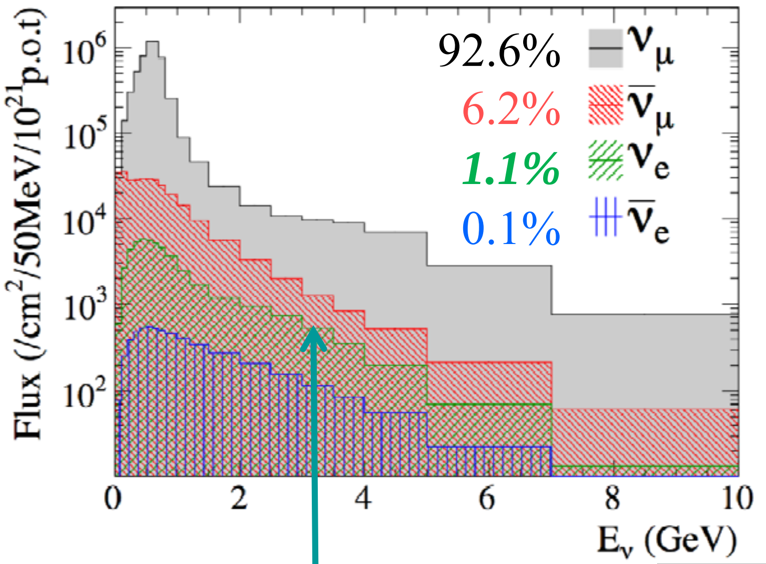


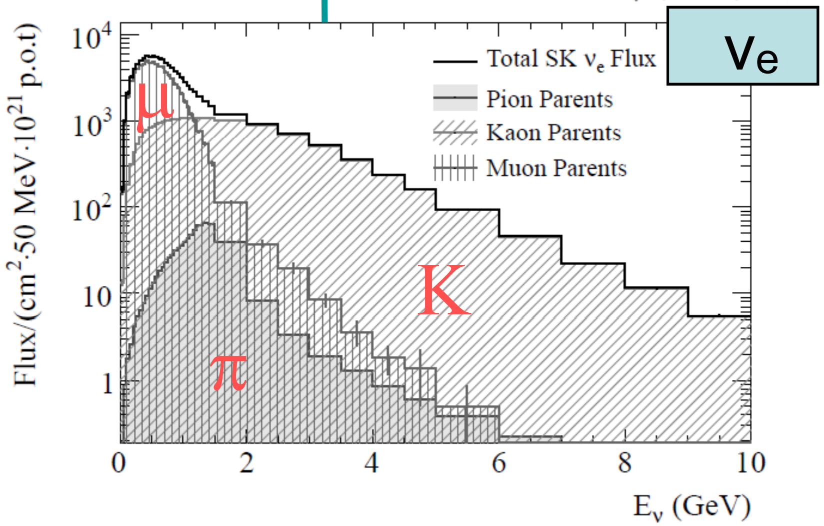
- Large acceptance spectrometer + TOF
- Measure hadron(π, K) yield distribution in 30 GeV p + C inelastic interaction



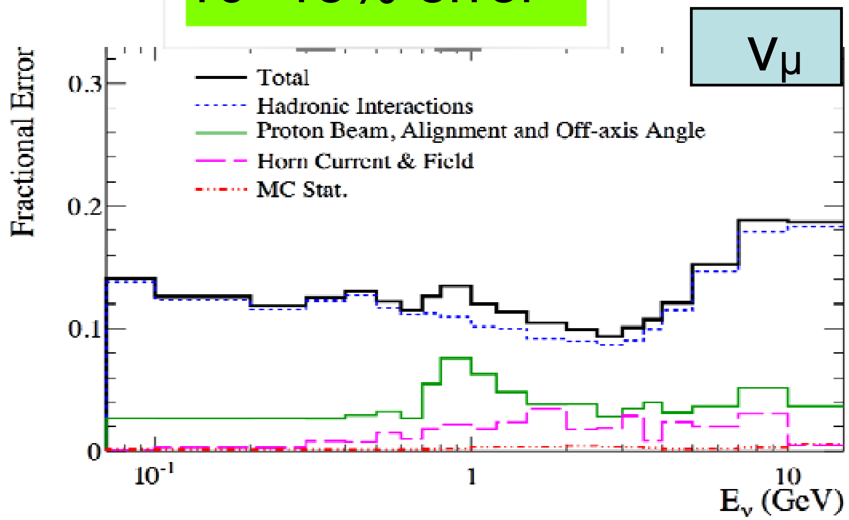


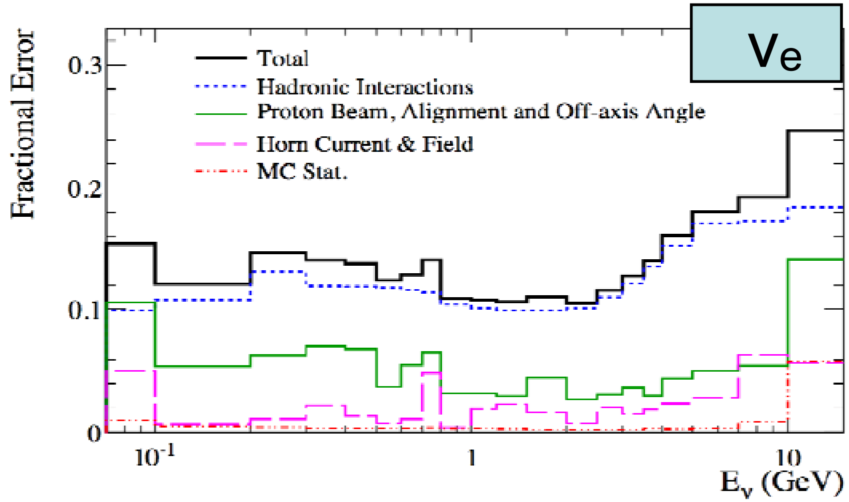
T2K beam flux prediction





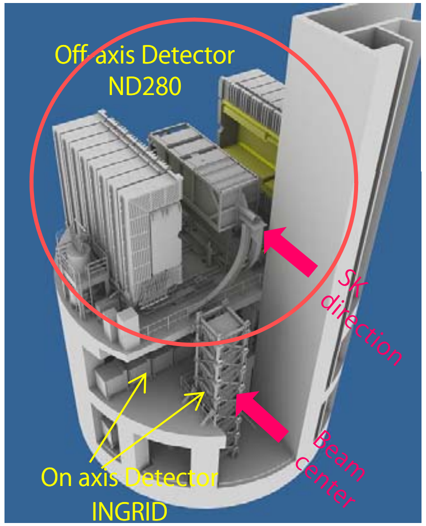
10~15% error

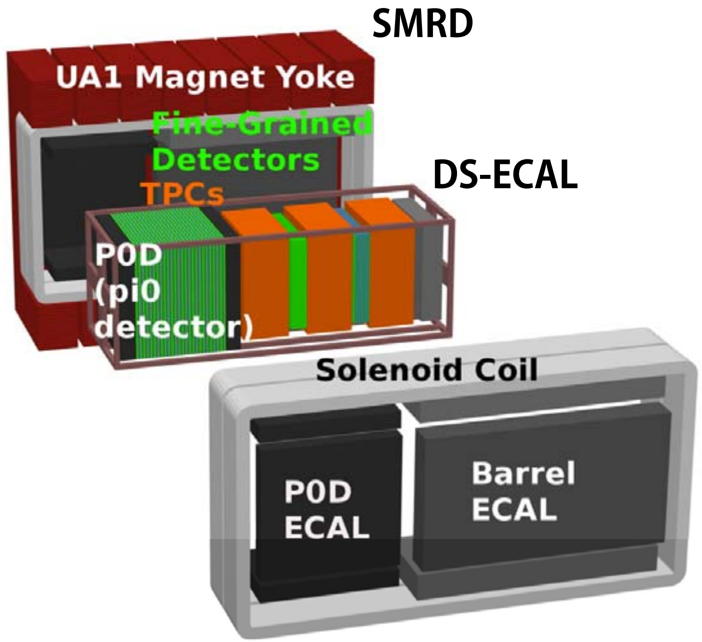




- ν_e component in T2K beam: ***~1.1%*** (Intrinsic BG for ν_e appearance search)

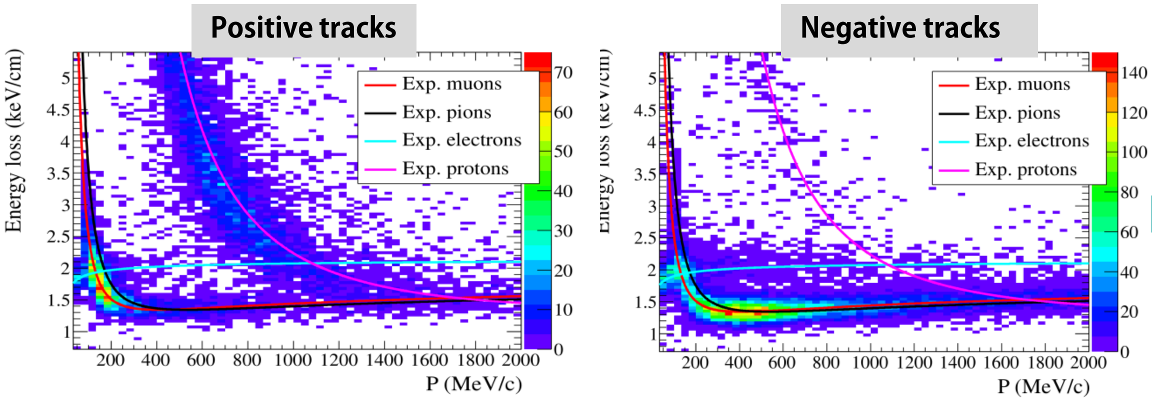
Off-axis near detector (ND280)





- Flux normalization/spectrum reconstruction
- Neutrino-nucleus interaction cross-sections

TPC PID



Inside of UA1 magnet (0.2T)

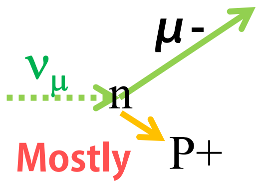
- 2 fine-grained detectors (FGD)
- 3 gas TPCs
- π^0 detector (P0D)
- electromagnetic calorimeter (ECAL)

Instrumented magnet yoke

- Side Muon Range Detector (SMRD)

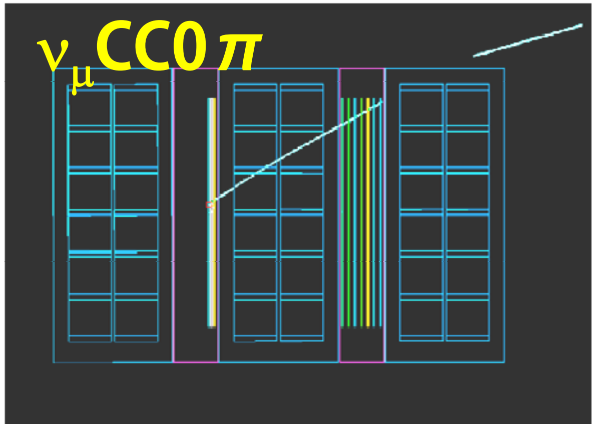
Typical tracker events

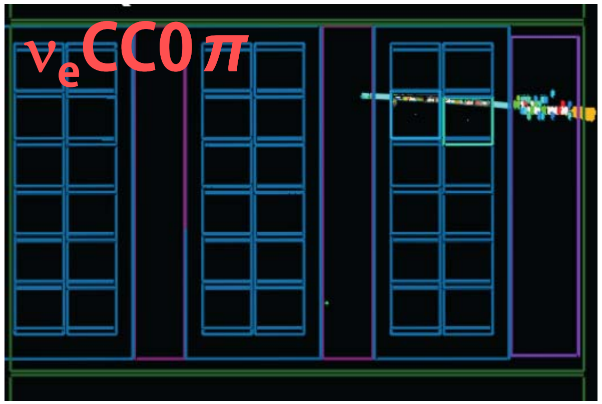
- ν_μCC-nonQE samples are separated into two categories

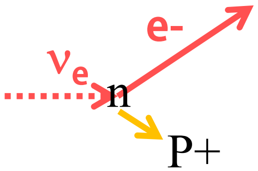


Mostly from Charged Current Quasi-Elastic

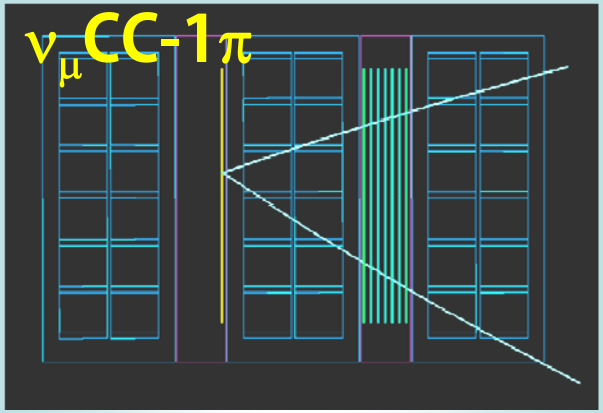
荷電
準弾性
散乱

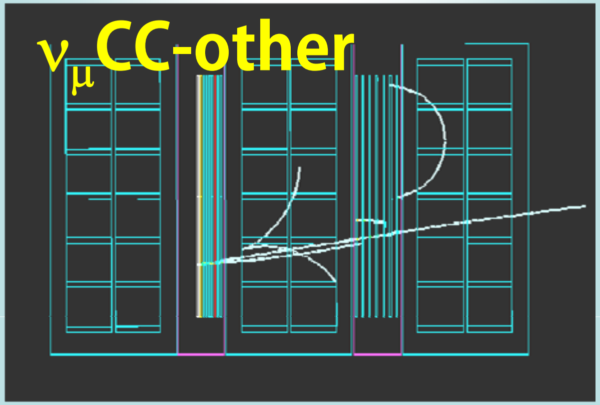




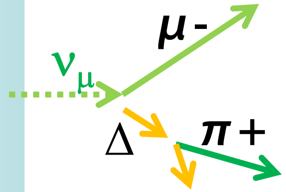


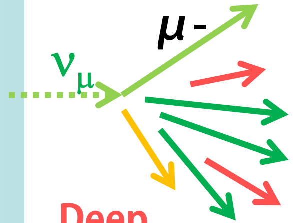
CC-nonQE in 2012 Release





Δ共鳴
Δ-resonance production





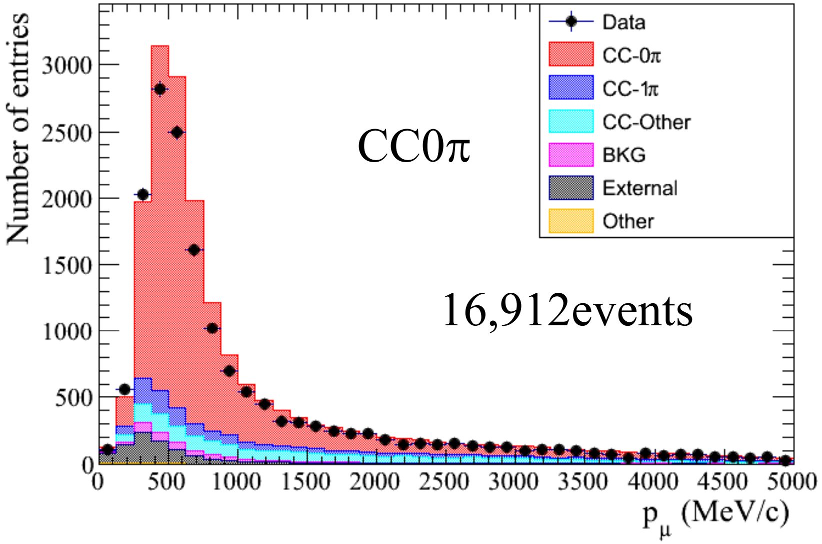
Deep Inelastic Scattering

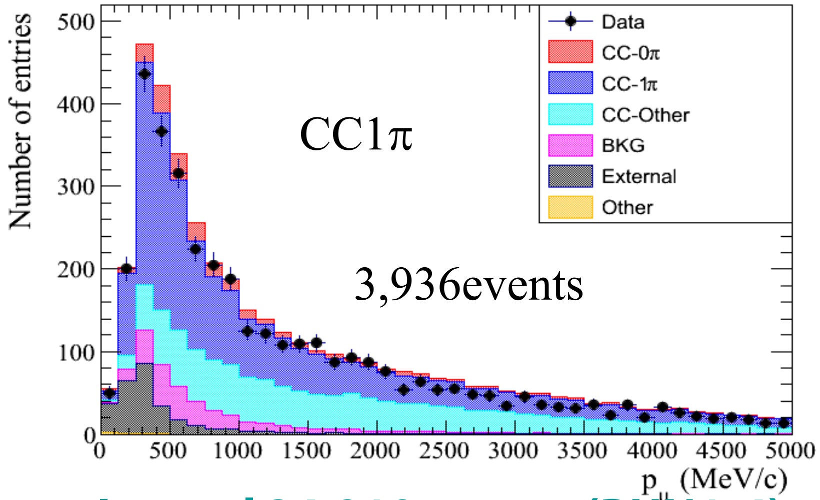
深非弾性
散乱

※ non-QE events are now characterized by the presence of a pion candidate (including michel electrons) or electromagnetic objects.

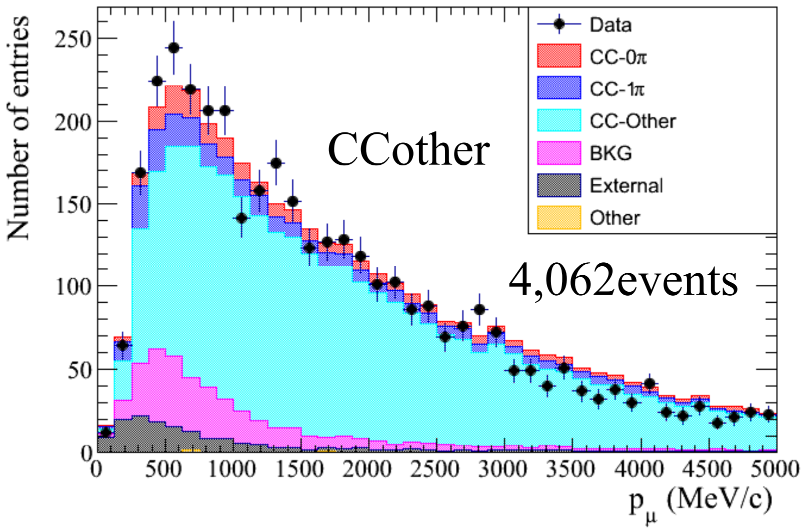
※ In the old 2012 analysis, nonQE was characterized by events with a second TPC/FGD track, so it could include true CCQE where the proton penetrated to the TPC.

Muon momentum distributions





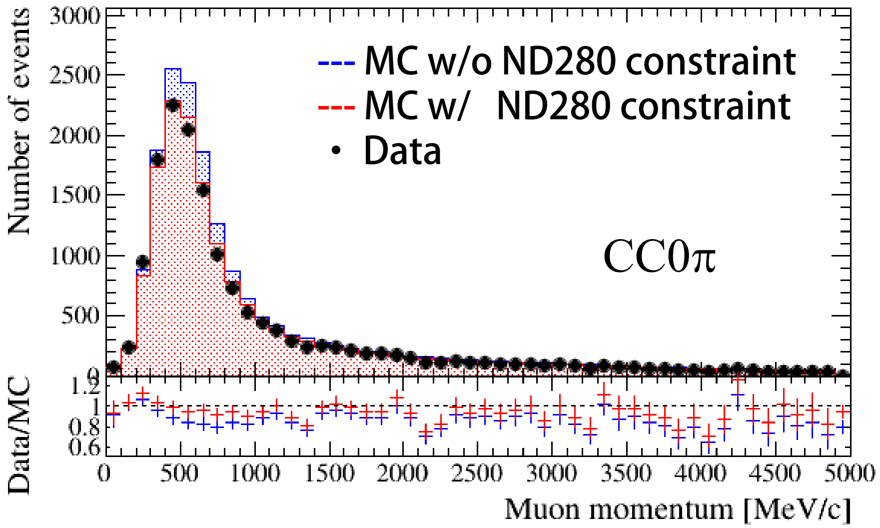
In total 24,910 events (RUN1-4)

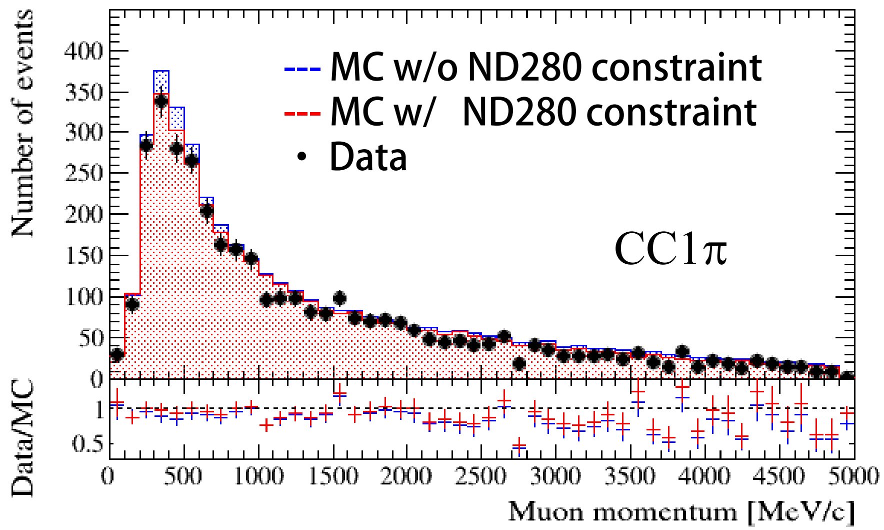


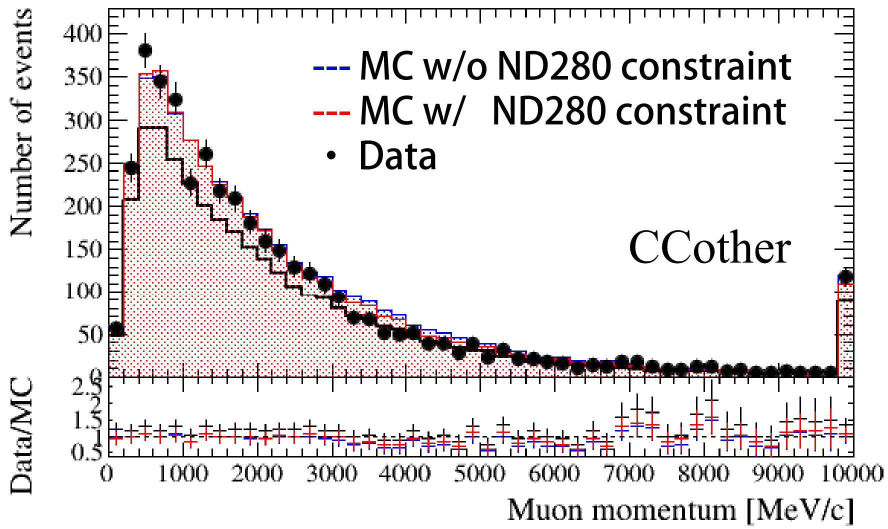
	CC0π purities	CC1π purities	CCother purities
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-nu)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

- **MC w/o ND280 constraint**
- Constrain (p_μ, θ_μ) distributions for each category
- Finer binning adopted compared to 2012 analysis

Muon momentum (w/ ND280 constraint)







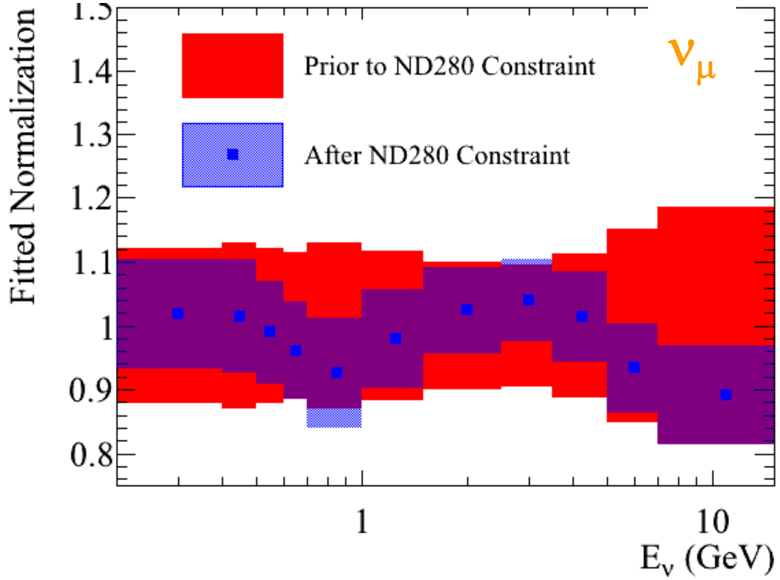
Parameter	w/o ND280 constraint	With ND280 constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.223 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.963 ± 0.063
CCQE Norm.*	1.00 ± 0.11	0.961 ± 0.076
CC1π Norm.**	1.15 ± 0.32	1.22 ± 0.16

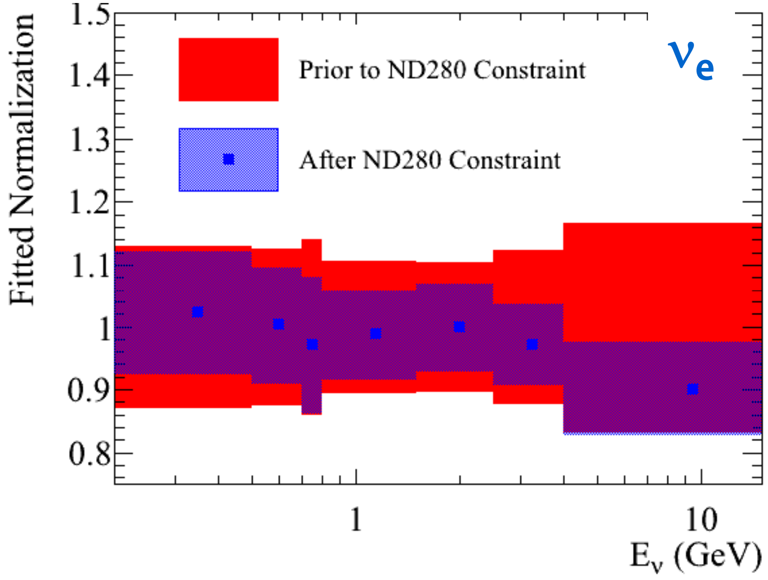
*For E_ν<1.5 GeV **For E_ν<2.5 GeV

- Significant changes to M_A^{RES} and CC1π normalization parameters

Flux & cross section model parameters

Extrapolated to the far detector





Predicted number of events and systematic uncertainties

Predicted # of events w/ 6.4×10^{20} POT

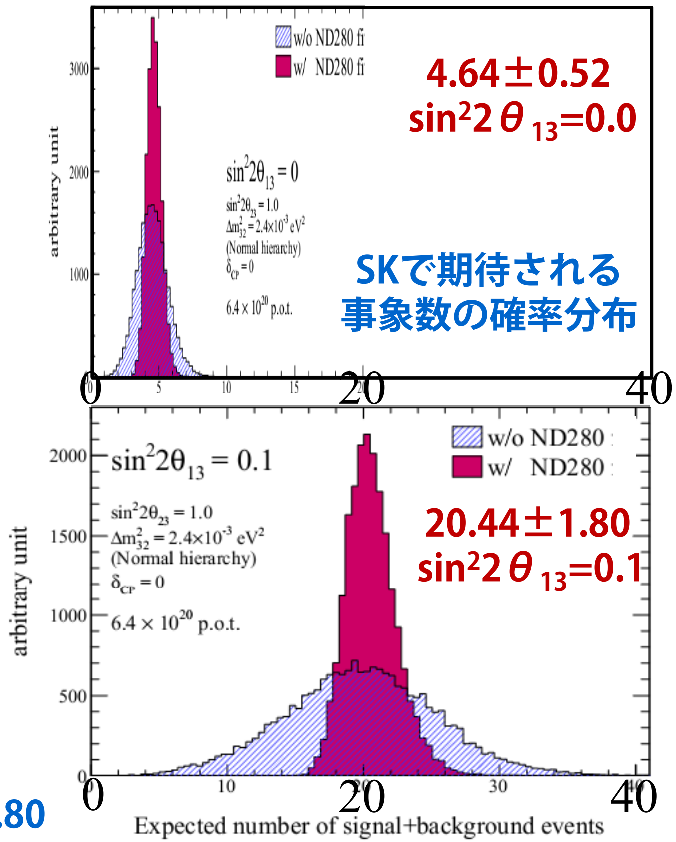
Event category	$\sin^2 2\theta_{13}$=0.0	$\sin^2 2\theta_{13}$=0.1
ν_e signal	0.38	16.42
ν_e background	3.17	2.93
ν_μ background (mainly NCπ^0)	0.89	0.89
$\bar{\nu}_\mu + \bar{\nu}_e$ background	0.20	0.19
Total	4.64	20.44
(Total (w/ 2012 flux & cross section parameters))	(5.15)	(21.77)

Systematic uncertainties

Error source	$\sin^2 2\theta_{13}$=0.0	$\sin^2 2\theta_{13}$=0.1
Beam flux + ν int. w/ND constraint	4.9 %	3.0 %
ν int. (from other exp.)	6.7 %	7.5 %
Far detector (+FSI+SI+PN)	7.3 %	3.5 %
Total	11.1 %	8.8 %
(Total (2012))	(13.0 %)	(9.9 %)

SKでの期待値誤差：4.64×0.111=±0.52　　20.44×0.088=±1.80

The predicted number of events distribution



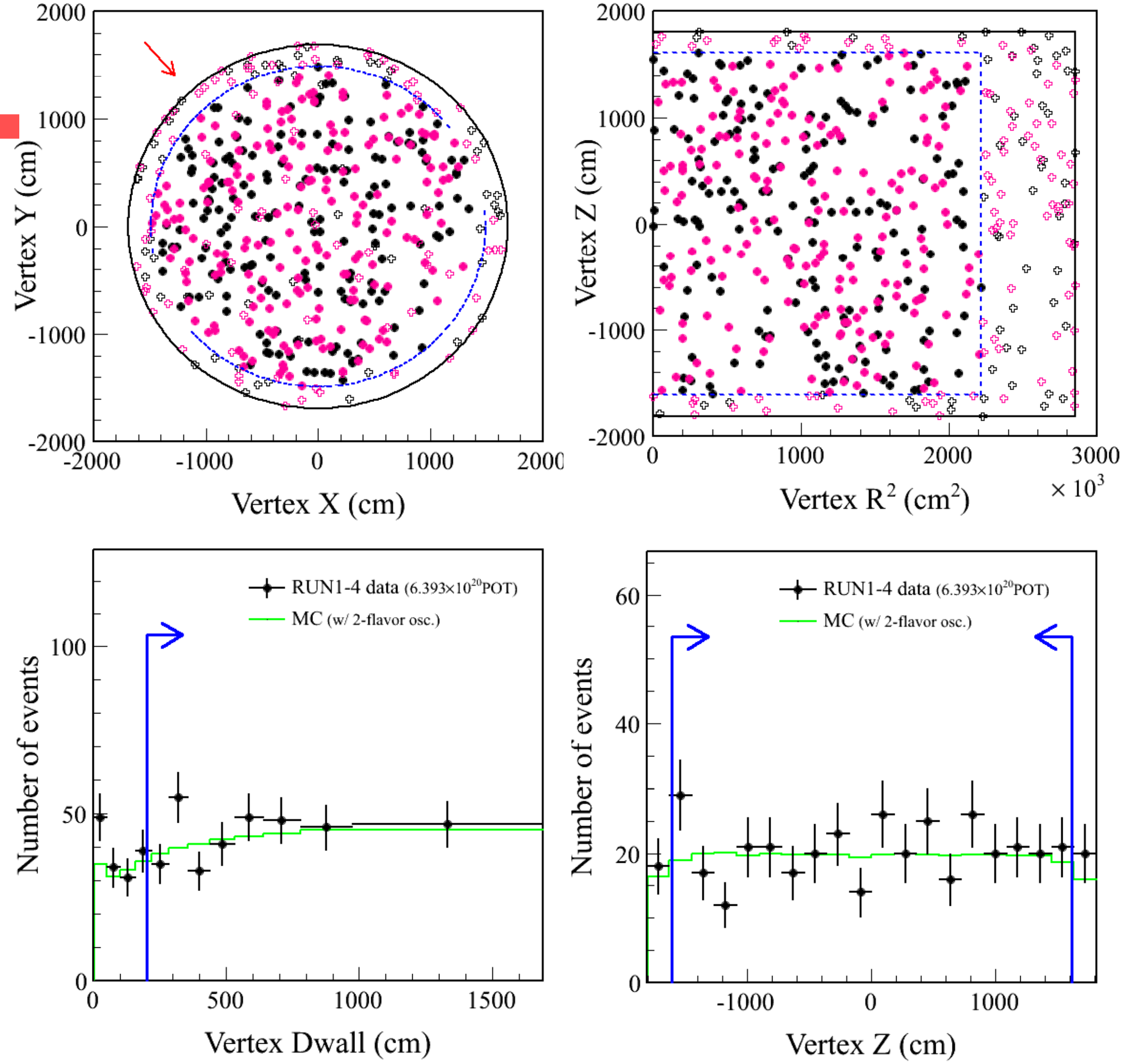
- Systematic uncertainties are reduced from 2012, due to improvements for near detector analysis：new selection (CCQE/1pi/other), improved reconstruction, finer binning
- Current analysis with ND constraint predicts consistent number of events compared to 2012 within its systematic uncertainties

ν_e candidate event selection

SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. Event's invariant mass not consistent with π^0 mass
7. Reconstructed ν energy E_ν^{rec} <1,250MeV

(1)



ν_e candidate event selection

SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
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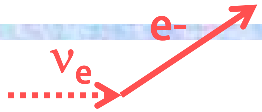
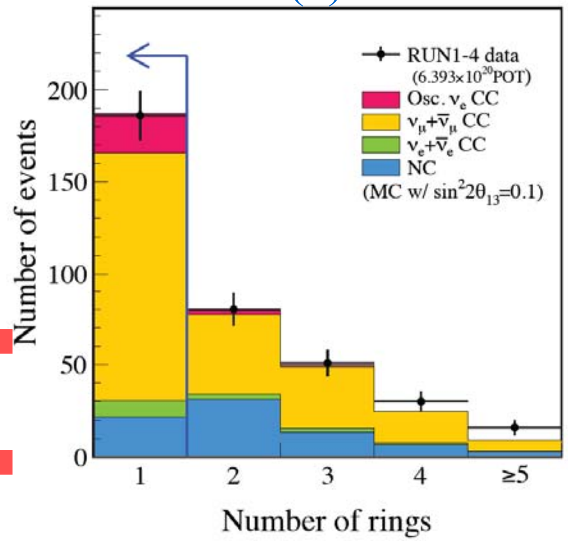
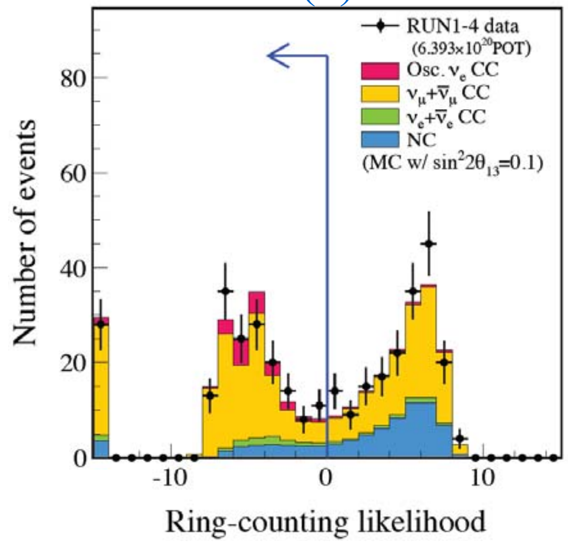
7. Reconstructed ν energy E_ν^{rec} <1,250MeV



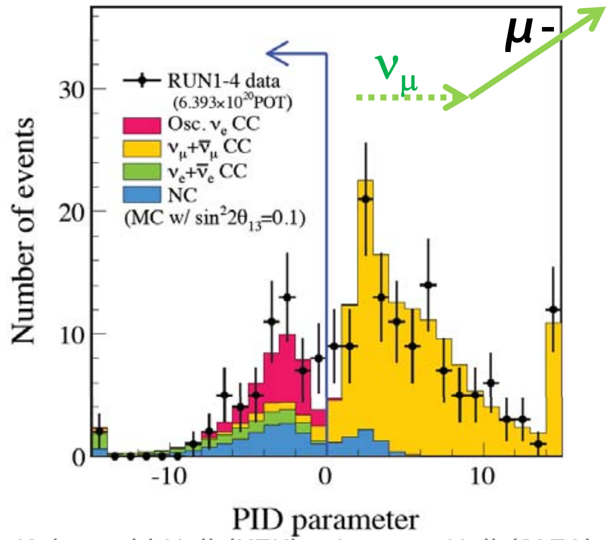
(2)



(2)



(3)



Assumed Parameter Values

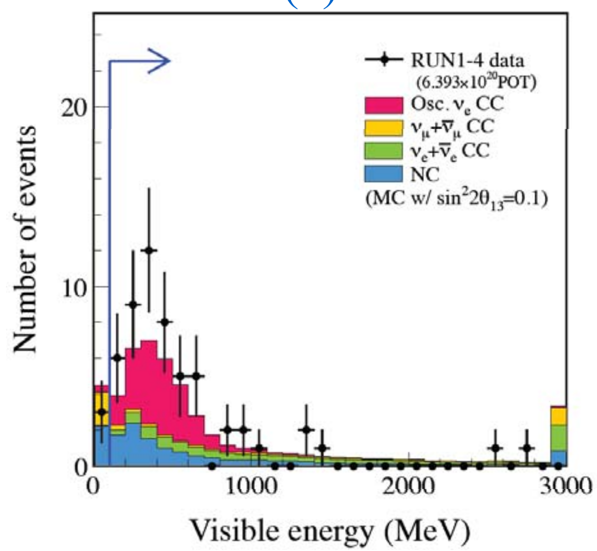
Parameter	Value
Δm^2_{21}	7.6×10^{-5}eV^2
Δm^2_{32}	2.4×10^{-3}eV^2
$\sin^2 2\theta_{12}$	0.8495
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{13}$	0.1
δ_{CP}	0
Mass hierarchy	Normal
ν travel length	295 km
Earth density	2.6g/cm^3

ν_e candidate event selection

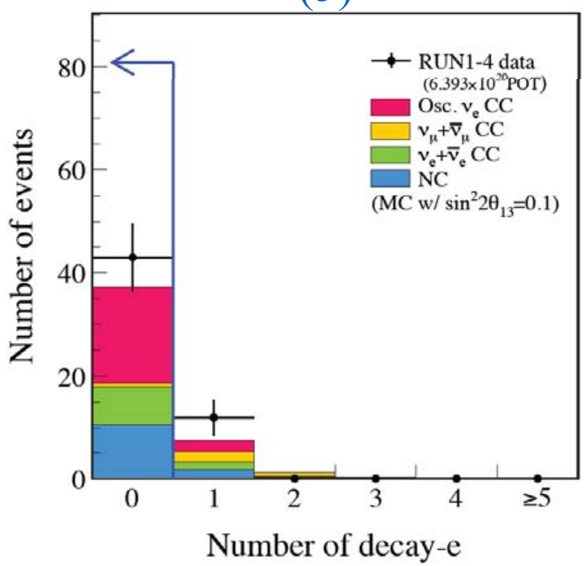
SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. Event's invariant mass not consistent with π^0 mass
7. Reconstructed ν energy E_ν^{rec} <1,250MeV

(4)



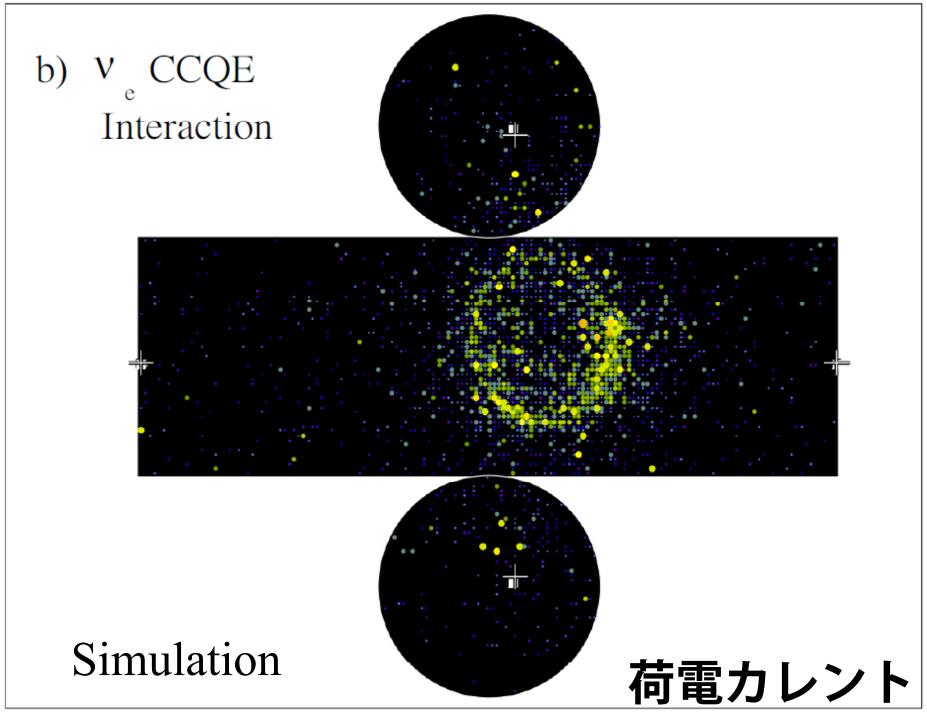
(5)



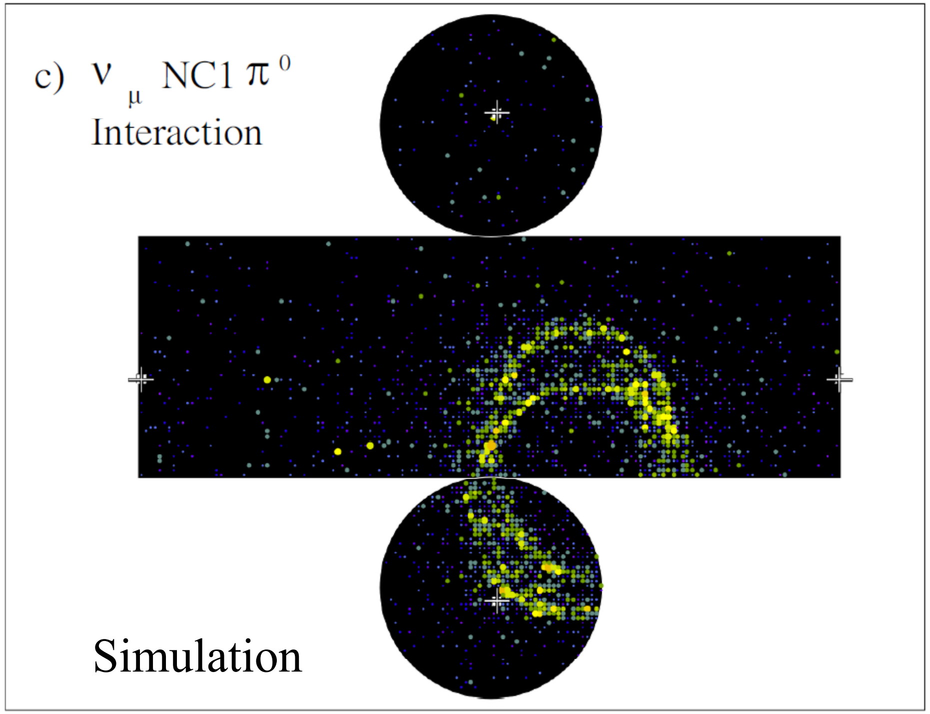
NC ?

中性カレントπ^0生成事象

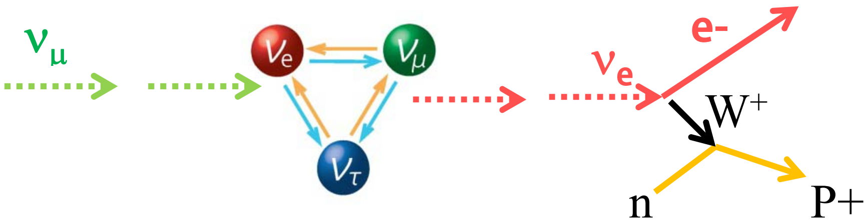
シグナル（いるもの）

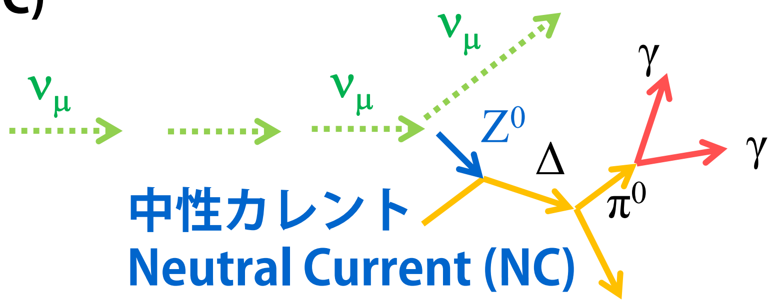


バックグラウンド（いらないもの）



荷電カレント
Charged Current (CC)





中性カレント
Neutral Current (NC)

- 電子型ニュートリノ出現事象の主要なバックグラウンド

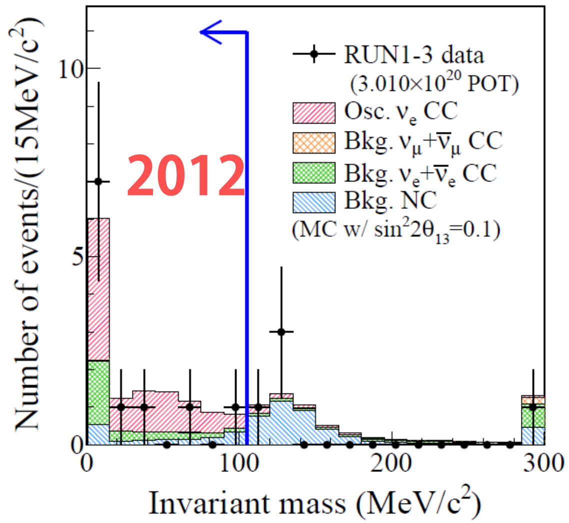
NC π^0 background reduction (2012)

SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. Event's invariant mass not consistent with π^0 mass
7. Reconstructed ν energy E_ν^{rec} <1,250MeV

$$\nu + N \rightarrow \nu + \Delta$$
$$\Delta \rightarrow N' + \pi^0$$
$$\pi^0 \rightarrow \gamma + \gamma$$

(6)



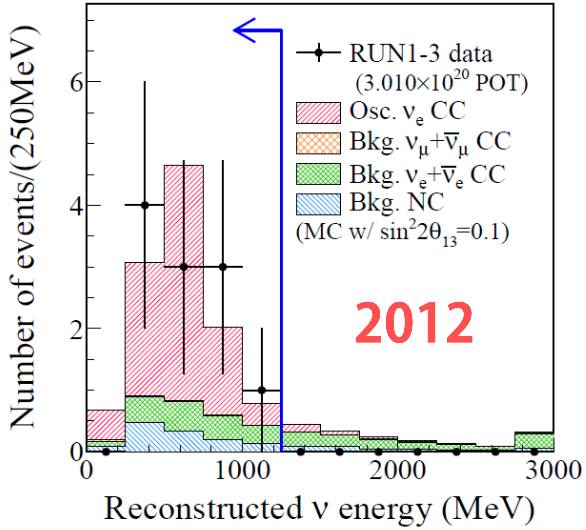
Until 2012 analysis we used a special fitter which reconstruct each event with a two photon ring hypothesis, searching for the direction and energy of second ring which maximizes the likelihood.

Selected ν_e candidates (2012)

SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. Event's invariant mass not consistent with π^0 mass
7. Reconstructed ν energy E_ν^{rec} <1,250MeV

(7)



RUN1-3 data
(3.010×10^{20} POT)

Data	11
MC Total※	11.2
CC ν_μ	0.06
CC ν_e	1.8
NC	1.2
CC $\nu_\mu \rightarrow \nu_e$	8.2

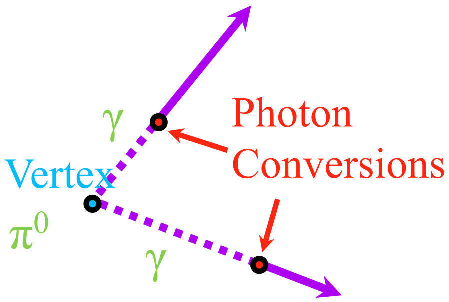
※3.3±0.4sys($\sin^2 2\theta_{13}$=0)
→ p=0.0009(*3.1σ*)

統計のいたずらで
この測定結果が得られる確率が0.1パーセント
EVIDENCE OF ν_e APPEARANCE
電子ニュートリノ出現現象の『兆候をとらえた』
でも、3σでは
『発見した』とは言えない。
（確率が0.1パーセントもある！）

NC π^0 background reduction (this analysis: new π^0 fitter)

SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. Event's invariant mass not consistent with π^0 mass → **new 2D cut**
7. Reconstructed ν energy E_ν^{rec} <1,250MeV

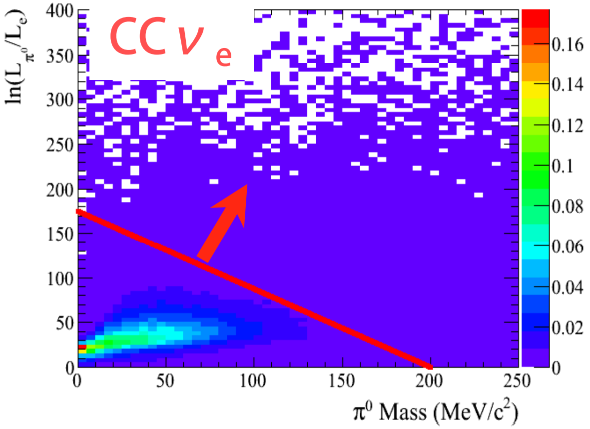


Assumes two electron rings produced at a common vertex [12 parameters]

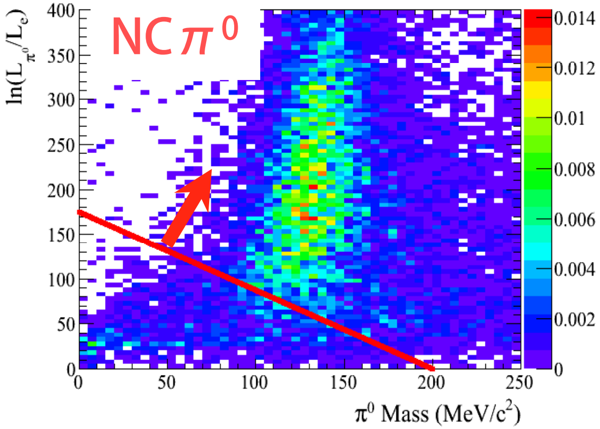
- Vertex(X,Y,Z,T)
- Directions(θ_1, φ_1, θ_2, φ_2)
- Momenta (p_1, p_2)
- Conversion lengths (c_1, c_2)

* Start from result of the single-track electron fit.

2D cut : π^0 mass and the likelihood ratio $\ln(L_{\pi^0}/L_e)$



Efficiency: -2%

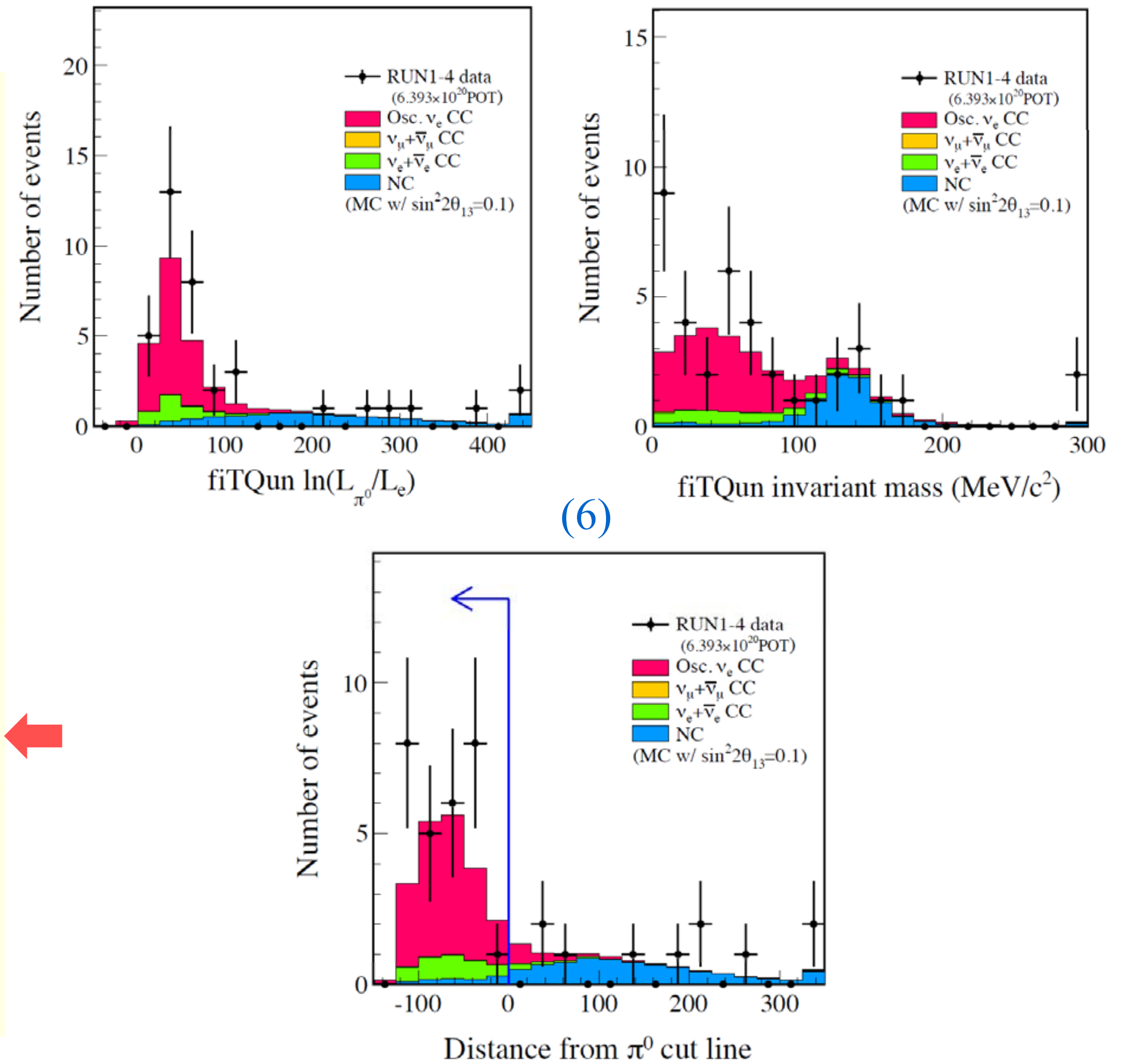


BG reduction: ~70%

NCπ^0 background reduction

SELECTION CRITERIA

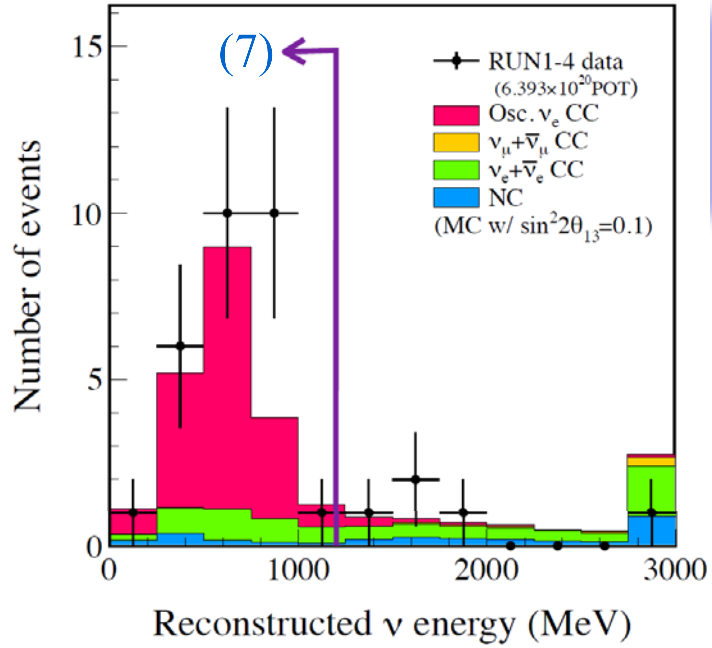
1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. 2D cut : π^0 mass and the likelihood ratio $\ln(L_{\pi^0}/L_e)$
7. Reconstructed ν energy E_ν^{rec} <1,250MeV



Selected ν_e candidate events

SELECTION CRITERIA

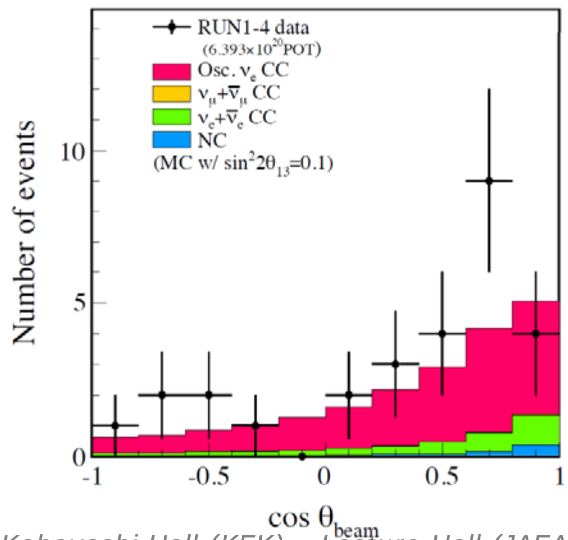
1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. 2D cut : π^0 mass and the likelihood ratio $\ln(L_{\pi 0}/L_e)$
7. Reconstructed ν energy E_ν^{rec} <1,250MeV



ν_e candidate = 28 events

Expected
20.44±1.80
for $\sin^2 2\theta_{13}$=0.1

4.64±0.52
for $\sin^2 2\theta_{13}$=0.0



- The new NC π^0 fitter removes all FV events rejected by 2012 analysis.
- Additionally, 3 more events removed.
- 31 → 28 events remain.

Typical event displays (RUN-4)

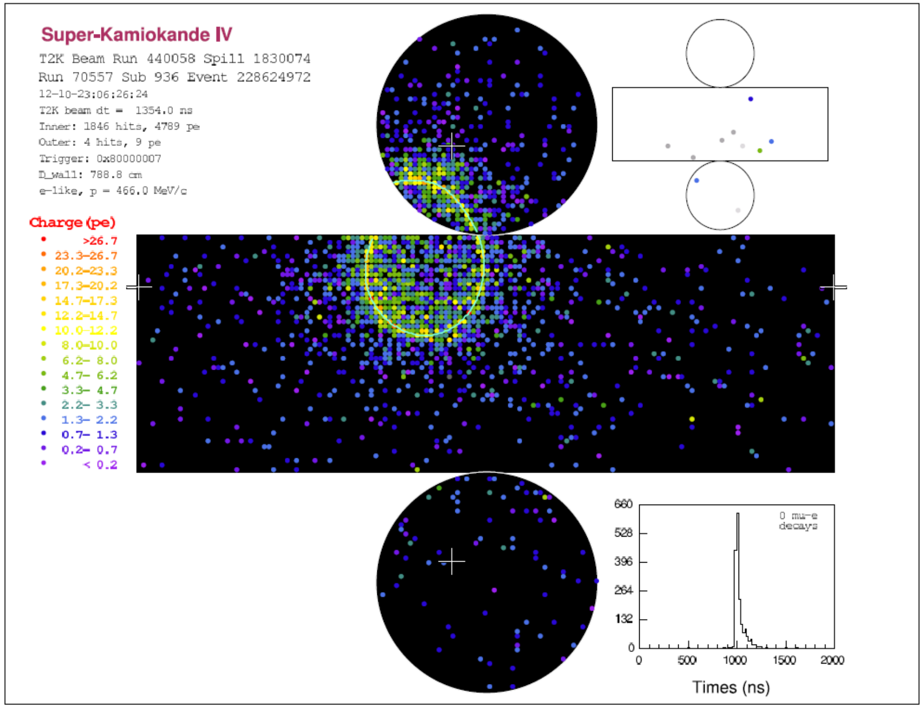


Figure 12: ν_e candidate event #12

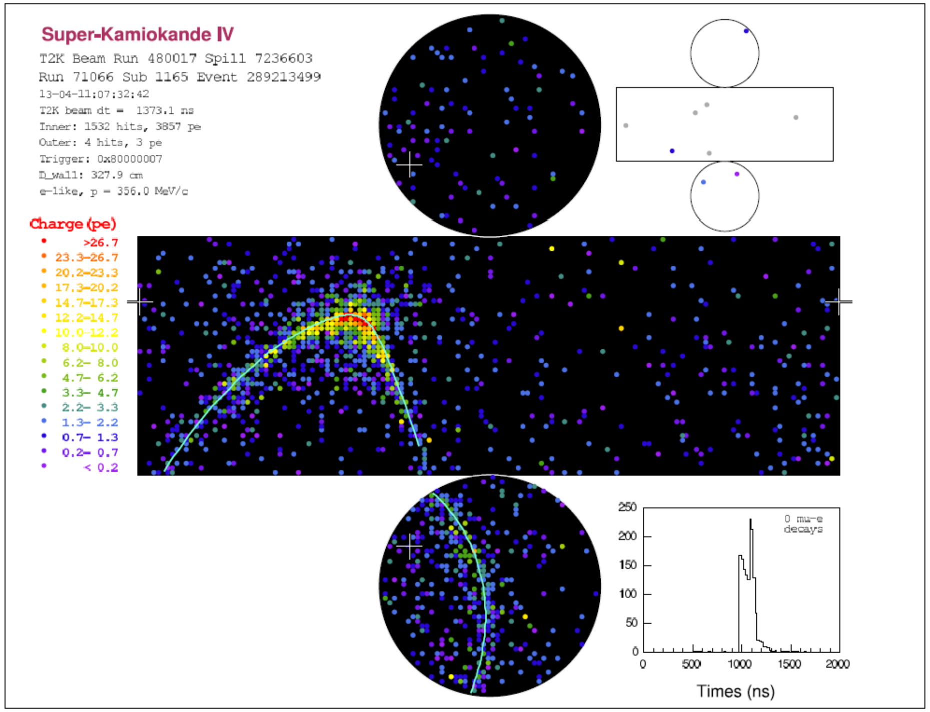
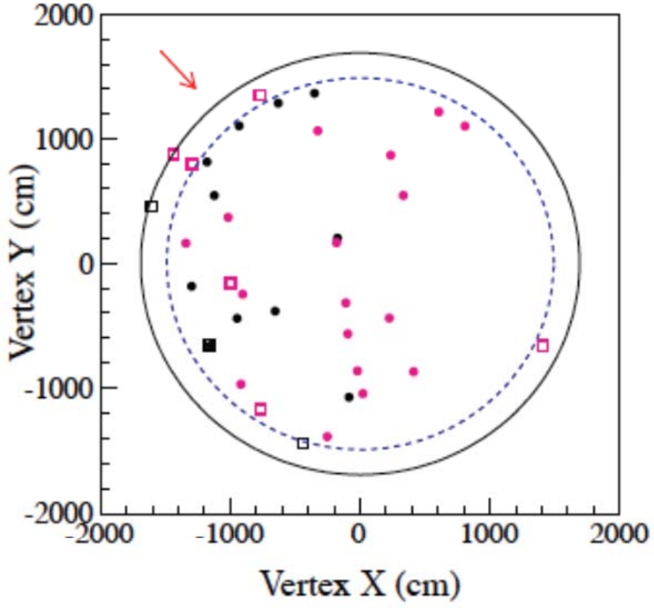
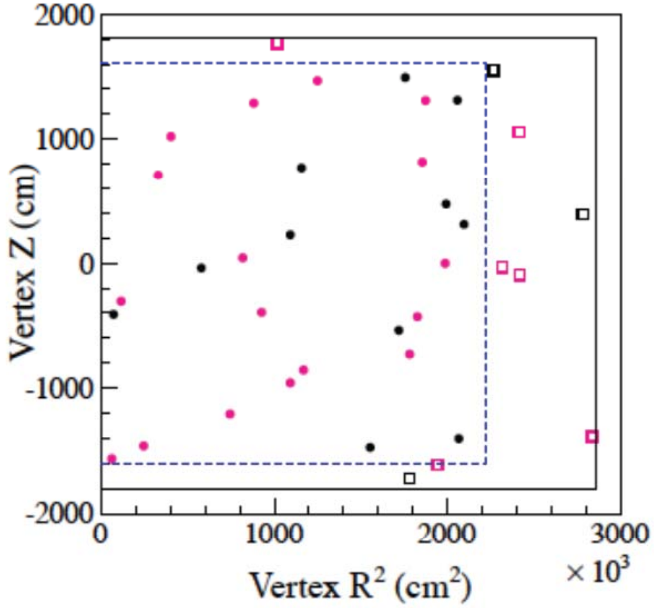


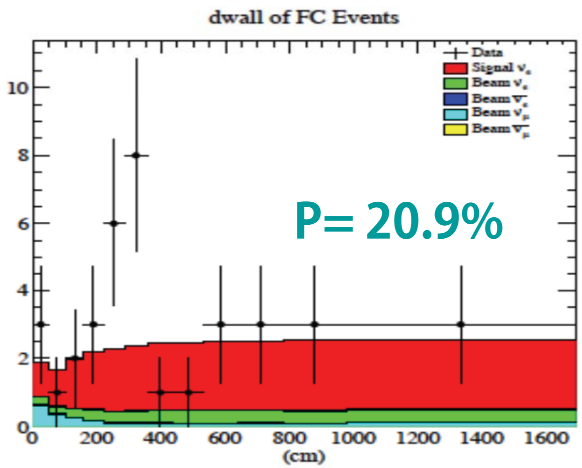
Figure 31: ν_e candidate event #31

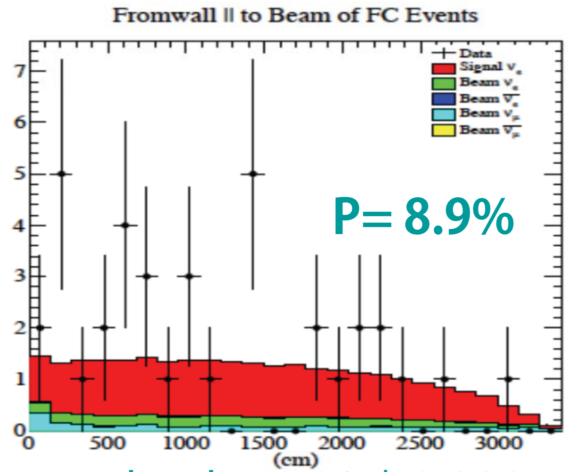
- 1st and last candidate events in Run-4

Vertex distributions









- BG enterng from OD interactions: estimated to be 0.03±0.009 events:
  - O(0.1%) of FCFV νe candidates

Candidate event summary

Data	28	
MC	$\sin^2 2\theta_{13}=0$	$\sin^2 2\theta_{13}=0.1$
Osci. $\nu_\mu \to \nu_e$	0.38	16.42
ν_e BG (Beam)	3.17	2.93
ν_μ BG (NC π^0 etc)	0.89	0.89
$\bar{\nu}_e + \bar{\nu}_\mu$ BG	0.20	0.19
MC Total	4.64	20.44
Sys.Err(%)	(11.1%)	(8.8%)
Sys.Err(#)	±0.52	±1.80
Sys.Err(%)-2012	(13.0%)	(9.9%)

Assumed Parameter Values

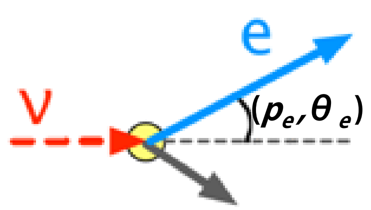
Parameter	Value
Δm^2_{21}	$7.6 \times 10^{-5}\mathrm{eV}^2$
Δm^2_{32}	$2.4 \times 10^{-3}\mathrm{eV}^2$
$\sin^2 2\theta_{12}$	0.8495※
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{13}$	0.1 (or 0)
δ_{CP}	0
Mass hierarchy	Normal
ν travel length	295 km
Earth density	$2.6\mathrm{g/cm}^3$

※ 0.8704 in 2012 analysis

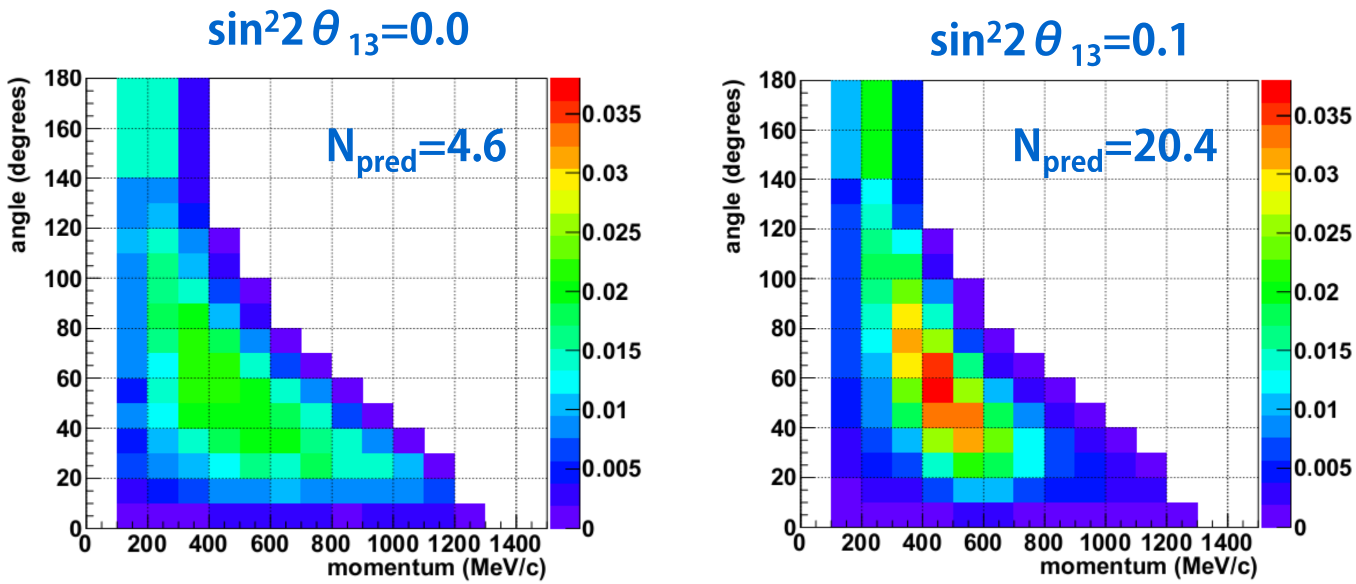
- N_{exp}=20.4 at $\sin^2 2\theta_{13}=0.1$, while we observe 28 events
- ν_μ background significantly reduced by using new NCπ^0 fitter
  - ~2.3 events expected with old (m_{π^0}-only) reduction
- Systematic uncertainties are reduced from 2012 release, mainly thanks to improvements for the near detector analysis

Determination of neutrino oscillation parameters

- An extended maximum likelihood fit as in 2012 analysis
  - Scan over $\sin^2 2\theta_{13}$ to find its best-fit value, where a likelihood ($\mathcal{L}$) becomes maximum.
  - $\mathcal{L}$ is calculated by comparing the total number of observed events (N_{obs}) and electron momentum-angle (p_e, θ_e) of each event with MC predictions.
  - We fix other oscillation parameters as shown in the previous page.



(p_e, θ_e) Probability Density Function (PDF)



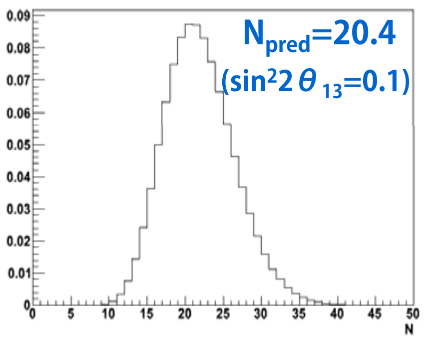
Definition of the Likelihood

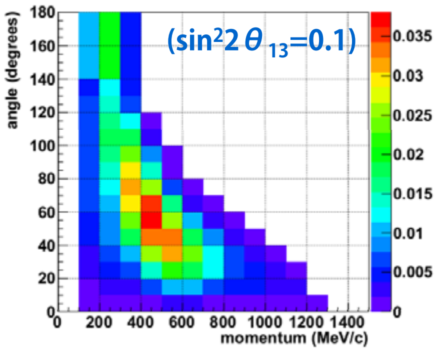
$$\mathcal{L} = \mathcal{L}_{norm} \times \mathcal{L}_{shape} \times \mathcal{L}_{syst}$$

$$Poisson(N_{obs})_{\text{mean=Npred}}$$

$$\prod_{i=1}^{N_{obs}} \phi(p_i, \theta_i)$$

constraint term for the nuisance parameters





Bayesian marginalization

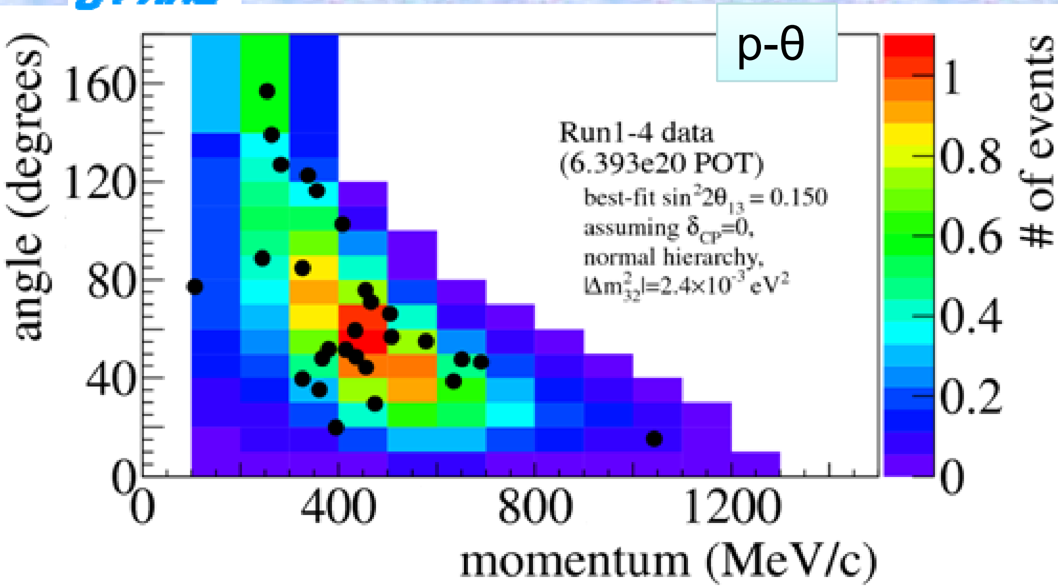
$$\mathcal{L}'(\vec{o}) = \int \mathcal{L}_{norm}(\vec{o}, \vec{f}) \times \mathcal{L}_{shape}(\vec{o}, \vec{f}) \times \mathcal{L}_{syst}(\vec{f}) d\vec{f}$$

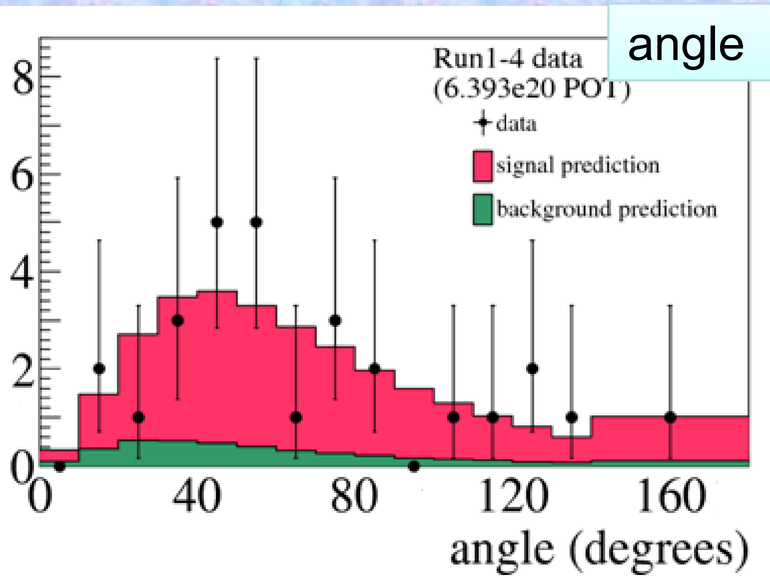
$\vec{f}$: systematic parameters

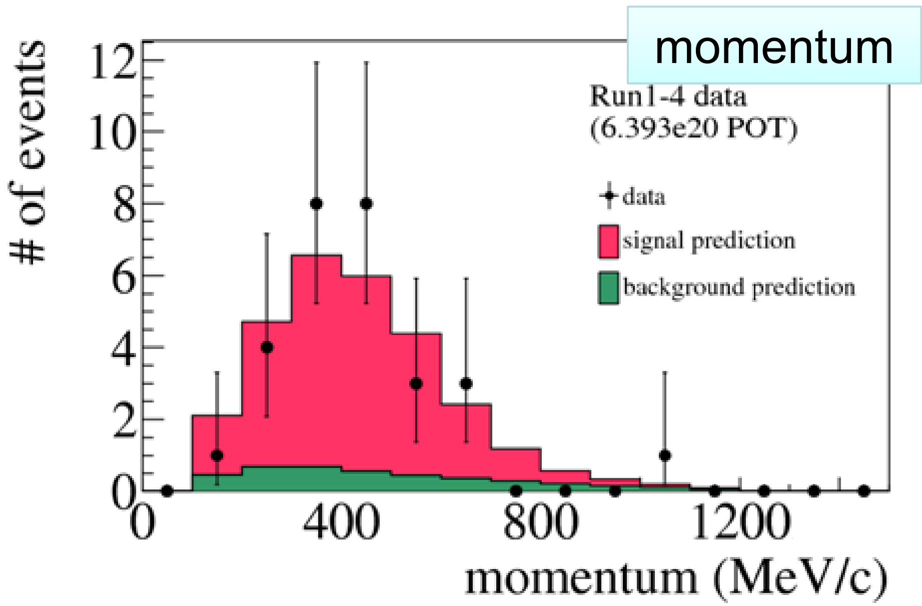
$\vec{o}$: oscillation parameters

- $\mathcal{L}_{norm}$: Poisson probability with mean = N_{pred} to have $N=N_{obs}$ events.
- $\mathcal{L}_{shape}$: Product of the probabilities that each event has a particular value of (p_e, θ_e).
  - φ: predicted Probability Density Function(PDF) .
- $\mathcal{L}_{syst}$: A multivariate normal distribution of systematic parameters defined by the parameters' prior values and covariance matrix.
- We use a Bayesian marginalization technique in order to incorporate the systematic uncertainties, by integrating over all systematic parameters.

Results







- Best fit w/ 68% C.L. error:

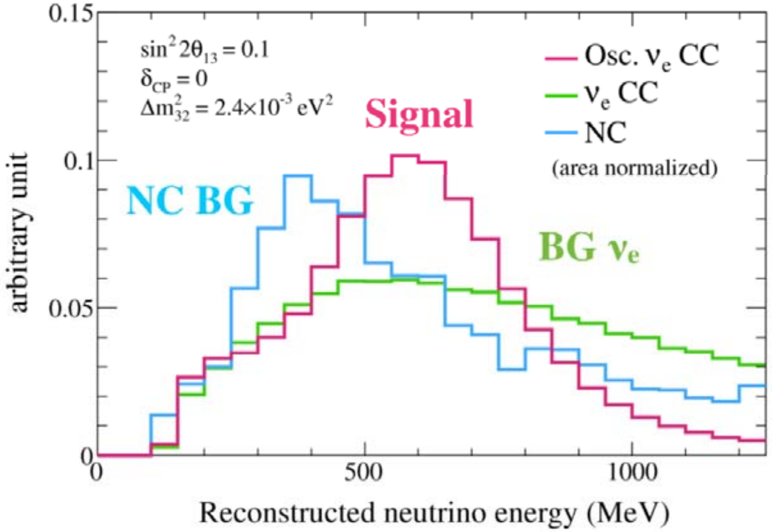
$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

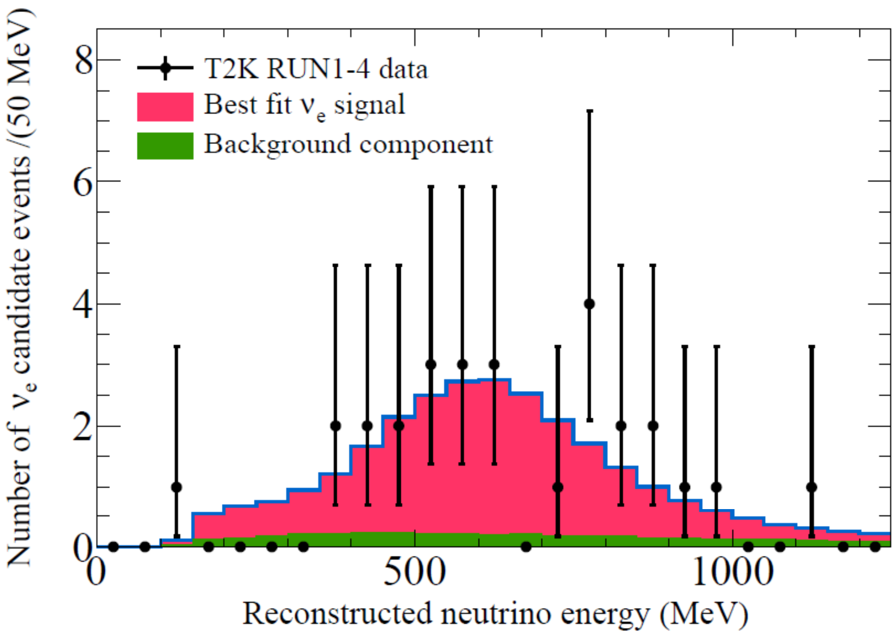
- 90% allowed region:

$$0.097 < \sin^2 2\theta_{13} < 0.218$$

Assuming
- $\delta_{CP}=0$
- normal hierarchy
- $|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2
- $\sin^2 2\theta_{23}=1$

Alternative (rate + E_ν shape) analysis





- Fit data to the reconstructed energy distribution

$$E^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

- best fit w/ 68% C.L. error:

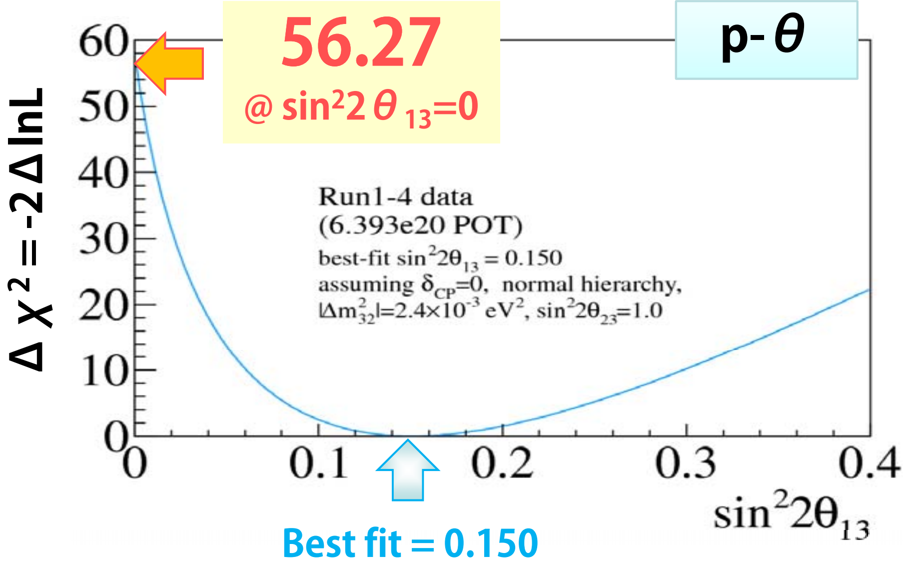
$$\sin^2 2\theta_{13} = 0.152^{+0.041}_{-0.034}$$

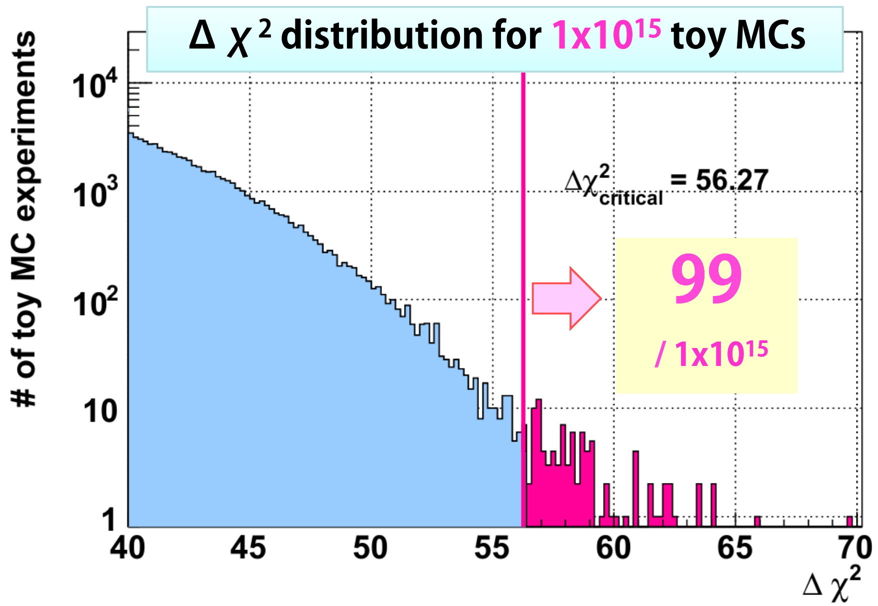
assuming
$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2
$\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$,
Normal hierarchy

- Very consistent to p-θ analysis

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

Significance to exclude $\sin^2 2\theta_{13}$=0.0





- The significance with a simple calculation ($\sqrt{\Delta\chi^2}$)

$\sqrt{-2\Delta \ln L}=\sqrt{56.27}$

=7.5σ

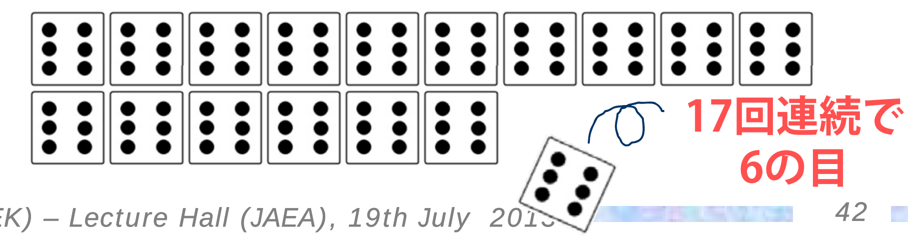
Our official value for the significance

$\sin^2 2\theta_{13}$=0.であるにもかかわらず、28事象測定されてしまう確立（p-value）

（シミュレーションによる模擬実験を多数回行って検証）

p-value = 9.9×10^{-14} (=7.4σ)

約10兆分の1



δ_{CP} vs. $\sin^2 2\theta_{13}$ contours

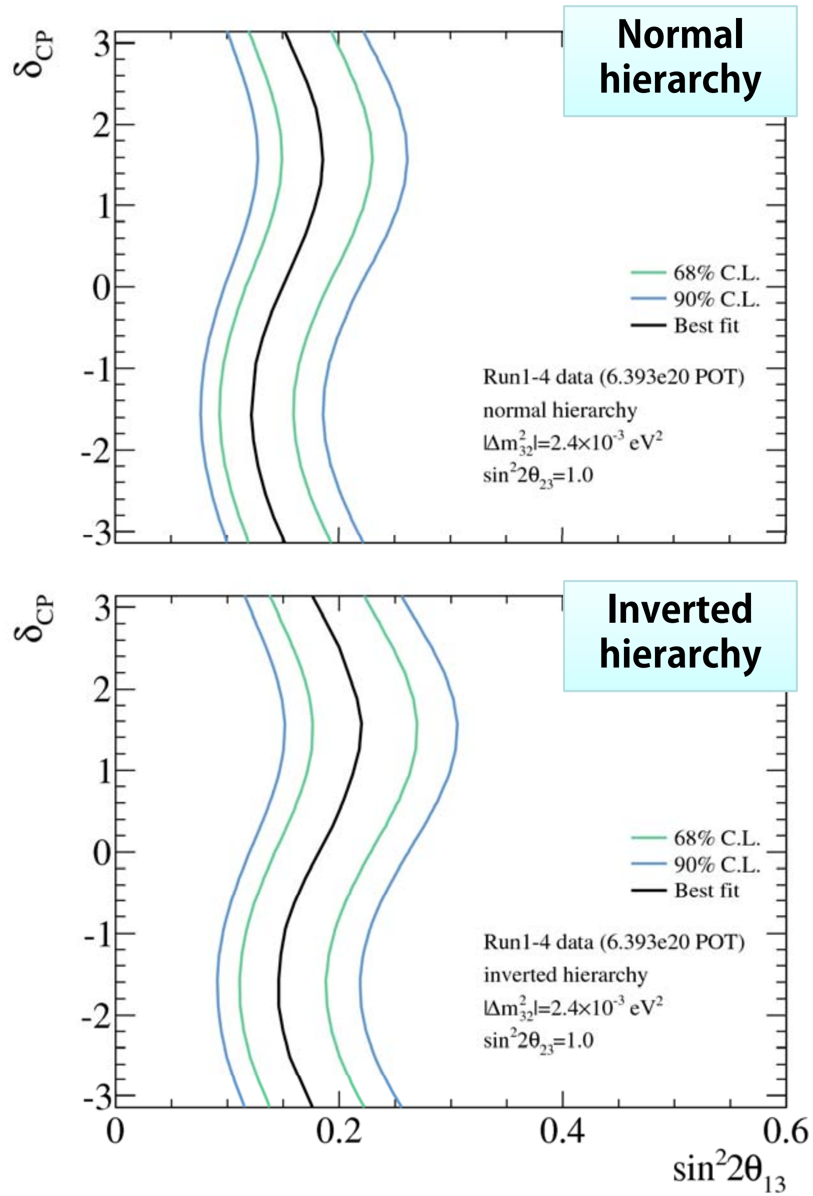
- Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}
- Best fit w/ 68% C.L. error @ $\delta_{CP}=0$
  - normal hierarchy

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

  - inverted hierarchy:

$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

Assuming
$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2
$\sin^2 2\theta_{23}=1.0$

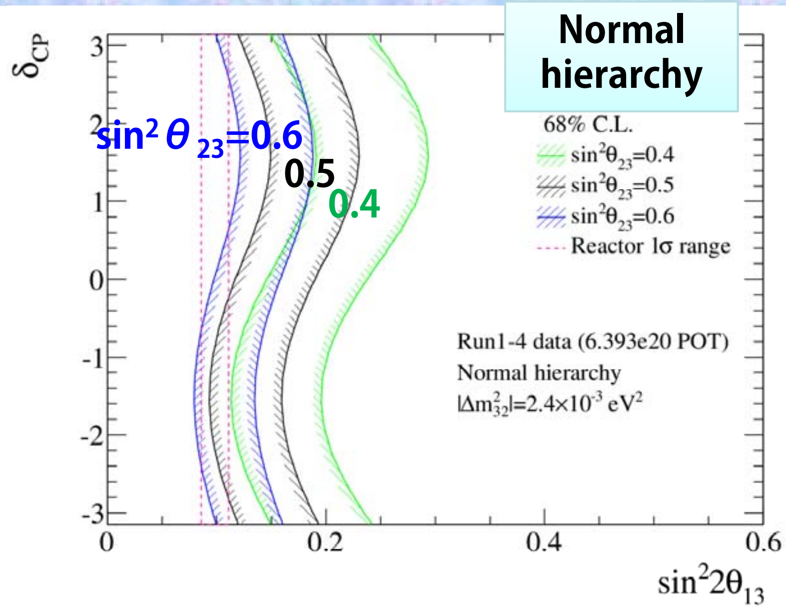


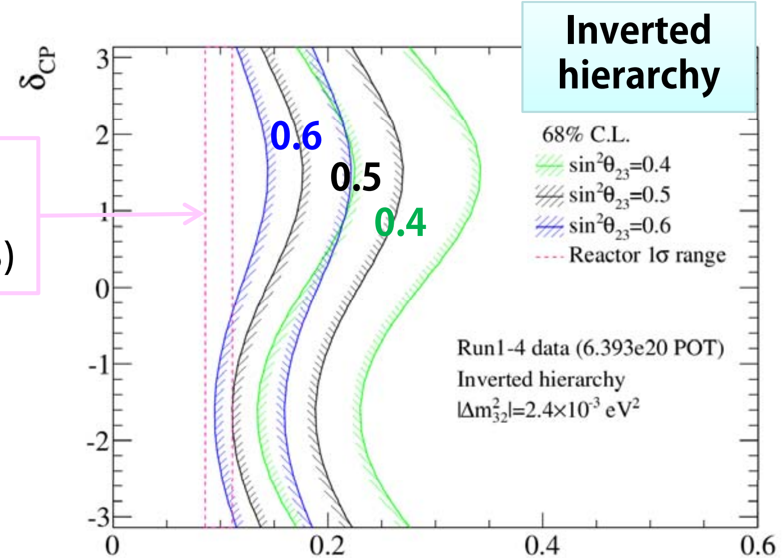
Cf. $\sin^2 2\theta_{13}$: 0.098±0.013 (PDG2012)

δ_{CP} vs. $\sin^2 2\theta_{13}$ for different $\sin^2\theta_{23}$

$$P_{\nu_\mu \to \nu_e} \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E_\nu}$$

- Oscillation probability is largely dependent on $\sin^2\theta_{23}$ (octant)
  - PDG2012: $\sin^2(2\theta_{23}) > 0.95$
    - $\sin^2\theta_{23} = 0.50 \pm 0.11$
    - $\theta_{23} = 45 \pm 6.5°$
  - To reduce error on $\sin^2\theta_{23}$ is critical for further improvements





PDG2012 reactor average value (0.098±0.013)

T2K's ν_μ disappearance study will play a leading role.

NOTE: These are 1D contours for various values of δ_{CP}, NOT 2D contours $\sin^2 2\theta_{13}$

Message from T2K International Collaboration to J-PARC/JAEA/KEK Members

- This timely discovery was made possible by the unyielding and tireless effort by the J-PARC/JAEA/KEK staff members and management to deliver high quality beam to T2K.

- We should all remember that after the devastating March 2011 earthquake in eastern Japan, which caused severe damage to the accelerator complex and facilities at J-PARC, the beam commissioning was resumed within the calendar year, and physics data taking was also resumed within 1 year. It was not possible without all of your strong supports.

- We are excited to continue producing beautiful physics results, so let's continue to work together.

Summary and prospect

- We report a new result on ν_e appearance analysis based on 6.39×10^{20} protons on target.
  - 28 candidate events are observed, while expectation w/o ν_μ to ν_e oscillation is to be $4.6 \pm 0.5_{sys}$
  - An extended likelihood analysis over number of observed events and the momentum of electrons gives $\Delta \chi^2 = 56.3$ for $\sin^2 2\theta_{13} = 0.0$, thus the significance to exclude $\sin^2 2\theta_{13} = 0.0$ is calculated to be **7.5σ**
  - Note the results are dependent on assumptions on other neutrino oscillation parameters, such as $\sin^2 \theta_{23}$ and δ_{CP} .

WE HAVE SUCCESSFULLY OBSERVED THE ν_e APPEARANCE
which is one of the critical milestones for the further progress on the neutrino physics research.

Summary and prospect

- 6.39 x 10^{20} protons on target is only ~8% exposure of T2K's design goal.
  - The ν_e appearance study is still dominated by statistics.
  - We definitely need more data to proceed.
- T2K will continue to play an essential role to resolve the entire picture of neutrino mass and mixing.
  - Further studies on ν_μ disappearance studies : $\Delta^2 m_{32}$, $\sin^2\theta_{23}$, resolving octant degeneracy (θ_{23}<45° or >45°)
  - ν_μ disappearance studies will contribute to the improvement on the ν_e appearance studies.
  - Combined 3-flavor analysis on ν_e appearance and ν_μ disappearance
  - Data taking with anti-neutrino beam.
  - First exploration onto CP-violationg phase, δ_{CP}