

New results from T2K experiment

Ken Sakashita for T2K collaboration
2011/June/15, KEK Physics Seminar

T2K Collaboration



International collaboration
(~500 members, 59 institutes, 12 countries)

T2K (Tokai-to-Kamioka) experiment



T2K Main Goals:

- ★ Discovery of $\nu_{\mu} \rightarrow \nu_e$ oscillation (ν_e appearance)
- ★ Precision measurement of ν_{μ} disappearance

Overview of this talk

1. Introduction of T2K experiment
2. Search for ν_e appearance with 1.43×10^{20} protons on target (p.o.t.)
(Previous results w/ 0.32×10^{20} p.o.t.)
 - Analysis overview
 - ν_e selection criteria
 - The expected number of events at Far detector
 - Systematic uncertainty
 - Observation at Far detector & Results
3. Conclusion

Reference: arXiv:1106.1238 for the T2K experimental setup

Physics Motivation of ν_e appearance

★ discovery of $\nu_\mu \rightarrow \nu_e$

Direct detection of neutrino flavor mixing in “appearance” mode

Determine θ_{13}

The last mixing angle θ_{13} can be determined by $\nu_\mu \rightarrow \nu_e$

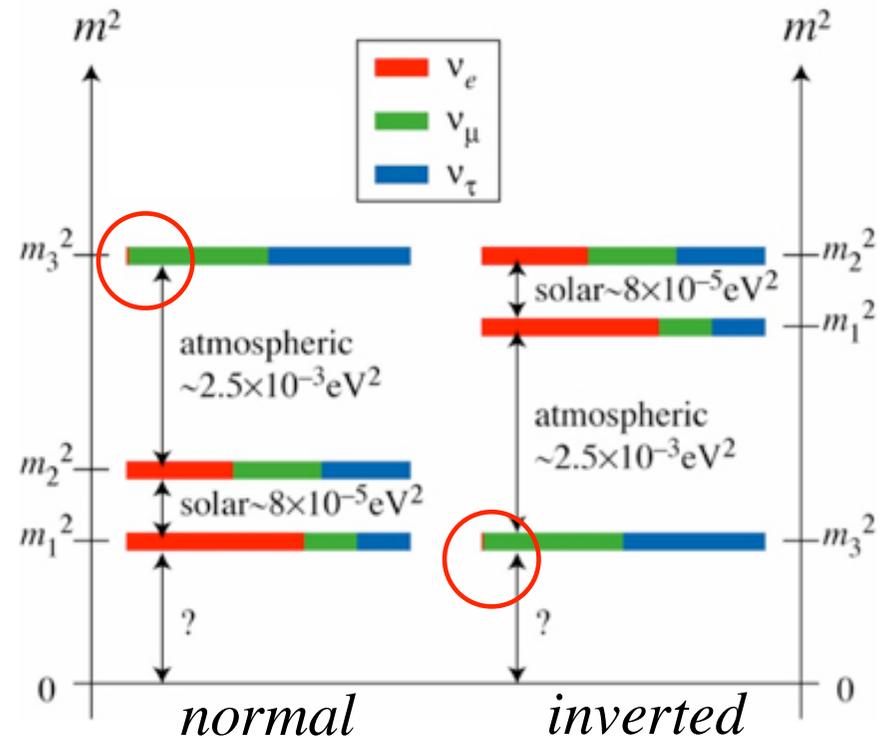
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2(\Delta m_{31}^2 L/4E) + \dots$$

($\Delta m_{23}^2 \sim \Delta m_{31}^2$)

Open a possibility to measure CP violation in lepton sector

CPV term in $P(\nu_\mu \rightarrow \nu_e) \propto \sin\theta_{12} \sin\theta_{13} \sin\theta_{23} \sin\delta$

Neutrino mass & three flavor mixing



Mixing angle: $\theta_{12}, \theta_{23}, \theta_{13}$

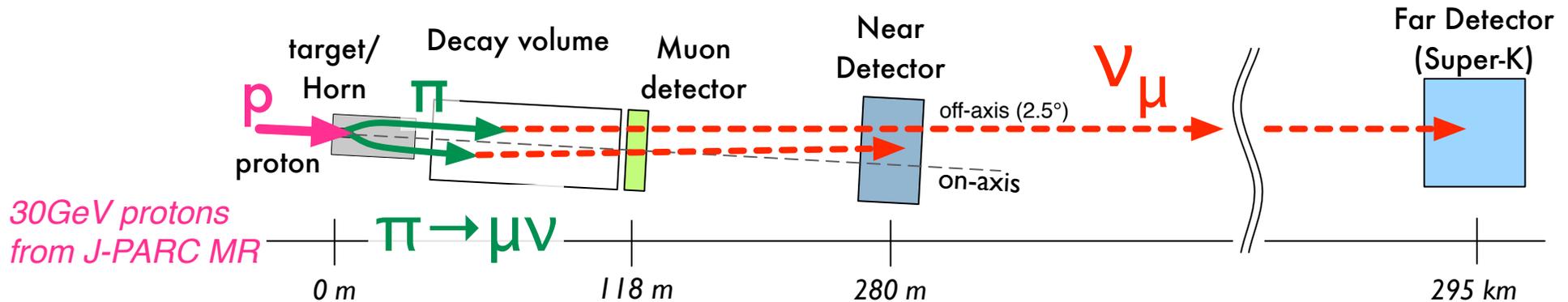
$$\theta_{12} = 34^\circ \pm 3^\circ \quad \theta_{23} = 45^\circ \pm 5^\circ$$

Last unknown mixing angle θ_{13}

$$\sin^2 2\theta_{13} < 0.15 \quad \text{at 90\% C.L.}$$

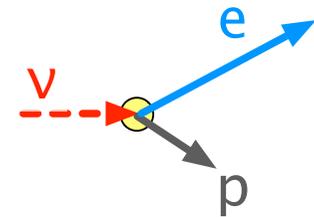
CHOOZ (reactor exp.) and MINOS (accelerator exp.)

Design Principle of T2K



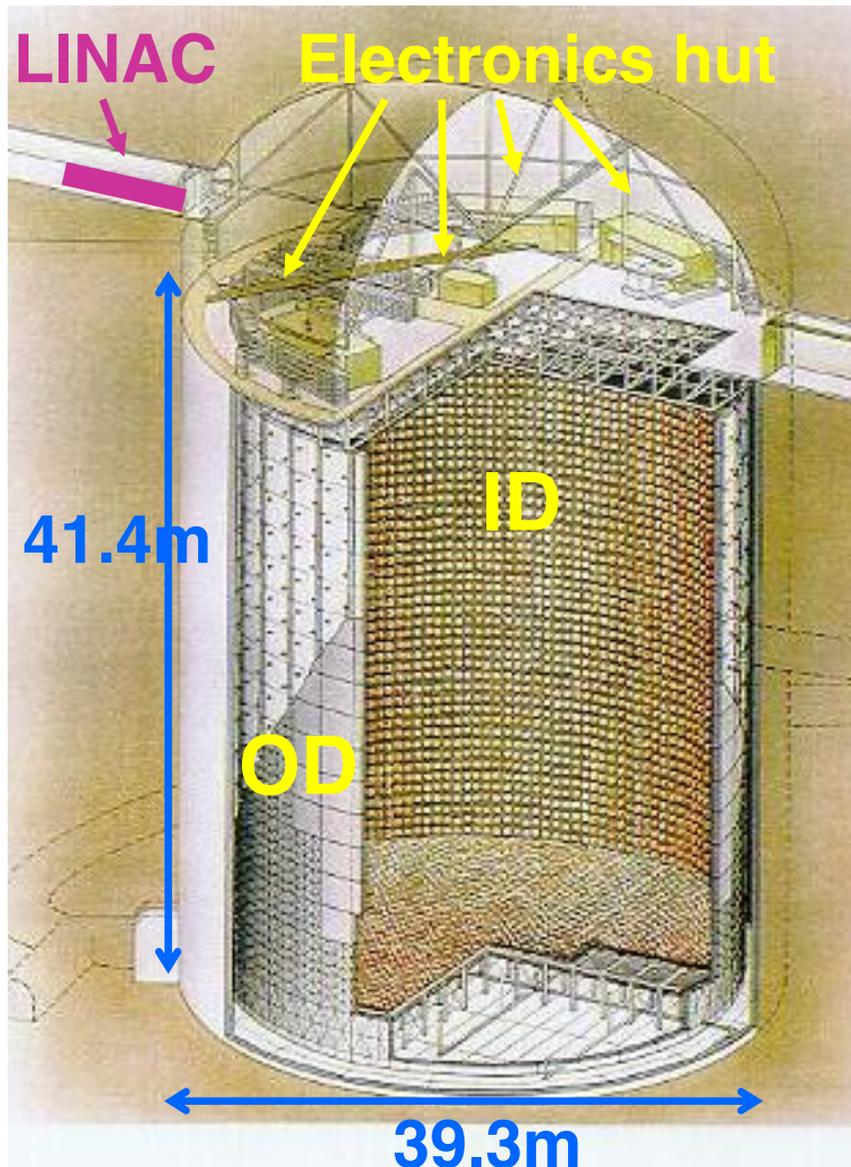
☑ Super-Kamiokande(SK) as far neutrino detector

- Excellent performance for single particle event
 - $\nu_e + n \rightarrow e + p$ (T2K ν_e signal)
 - This event is dominant at sub GeV beam
- Need to reduce high energy tail (reduce background)
- Need high intensity

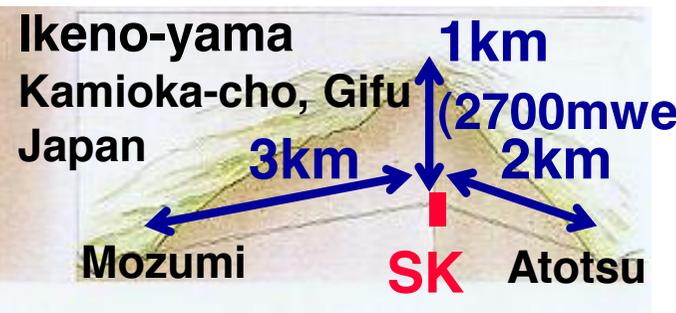


→ Off-axis beam (The first operational long-baseline off-axis ν beam)

Far detector (Super-K)

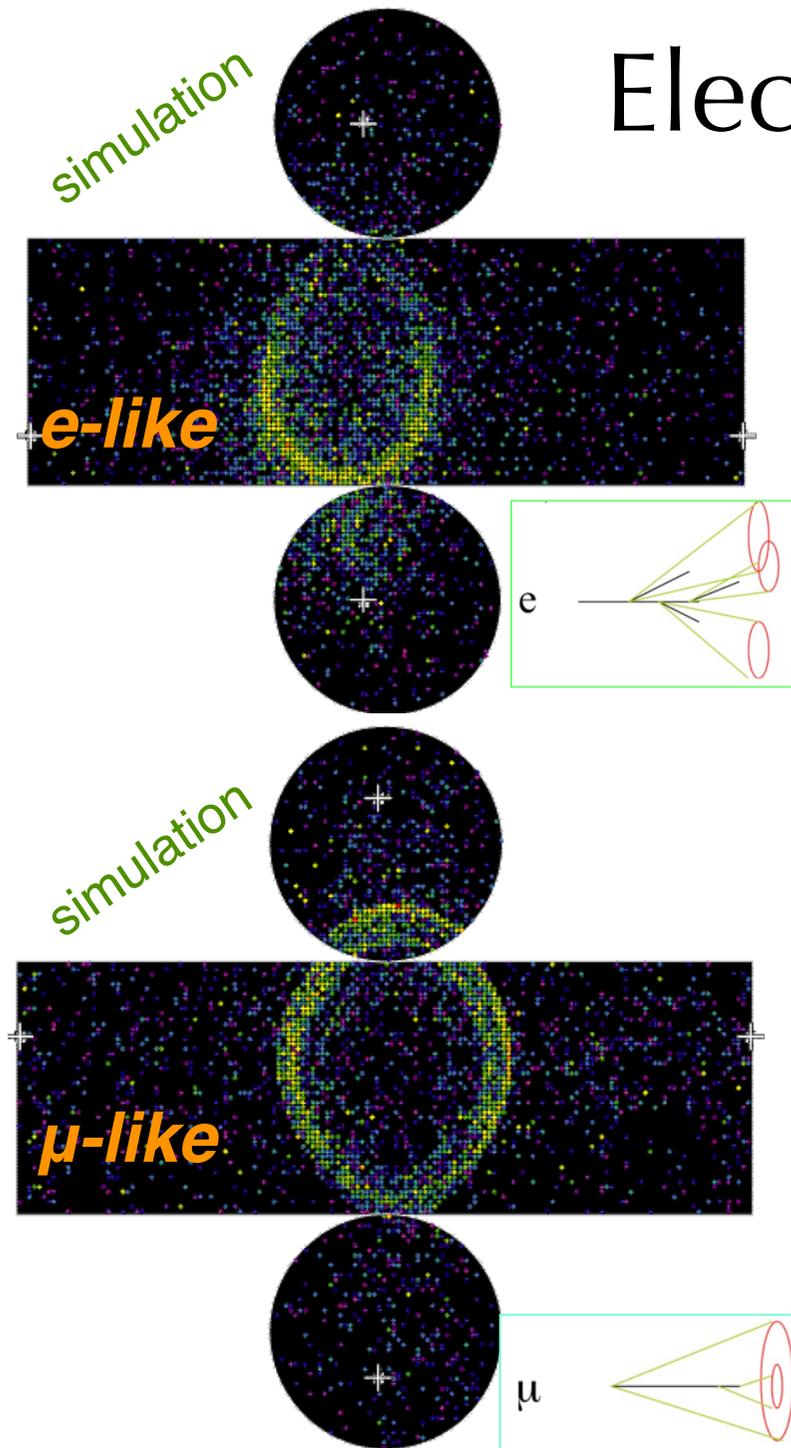


- Stable operation since April 1996
 - Water Cherenkov detector w/ fiducial volume 22.5kton
 - Dead-time less DAQ system (2008~)
 - Detector performance is well-matched at sub GeV
 - Excellent performance for single particle event
 - Good e-like(shower ring) / μ -like separation
- (next page)*

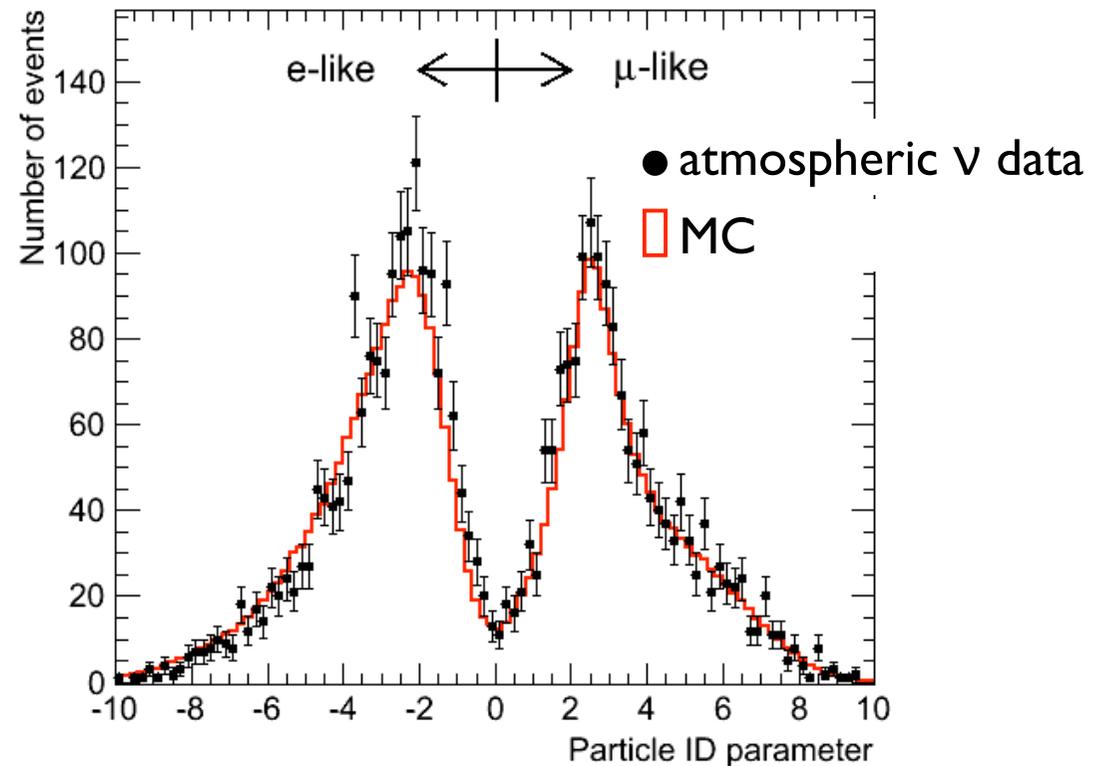


~11000 x 20inch PMTs (inner detector, ID)

Electron-like and muon-like event at SK

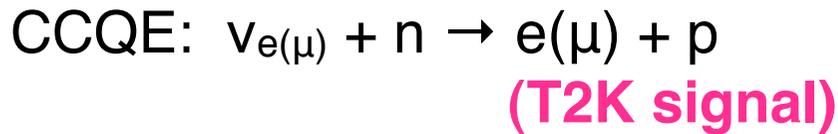
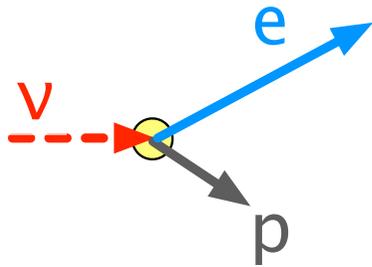


Particle identification using ring shape & opening angle

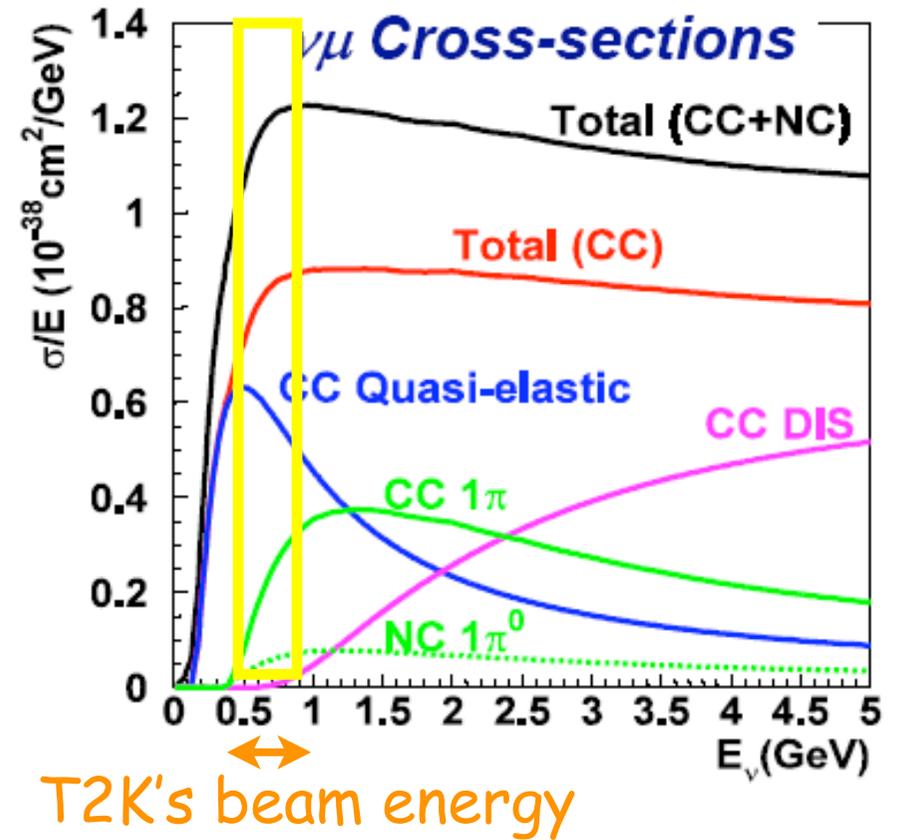


Probability that μ is mis-identified as electron is $\sim 1\%$

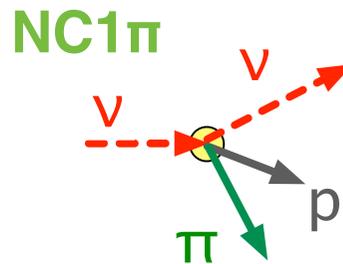
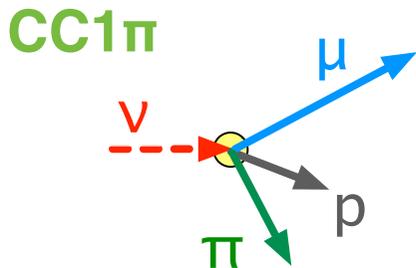
Charged Current Quasi-elastic (CCQE) interactions dominate at sub GeV



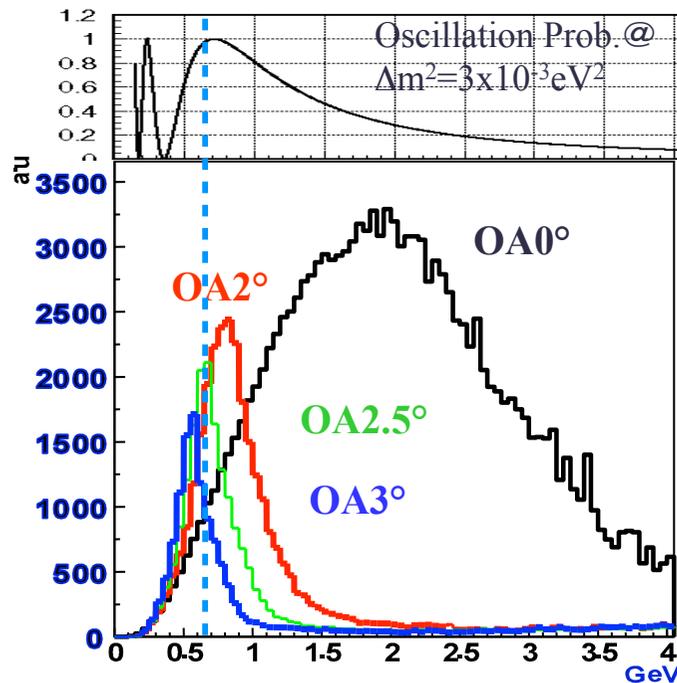
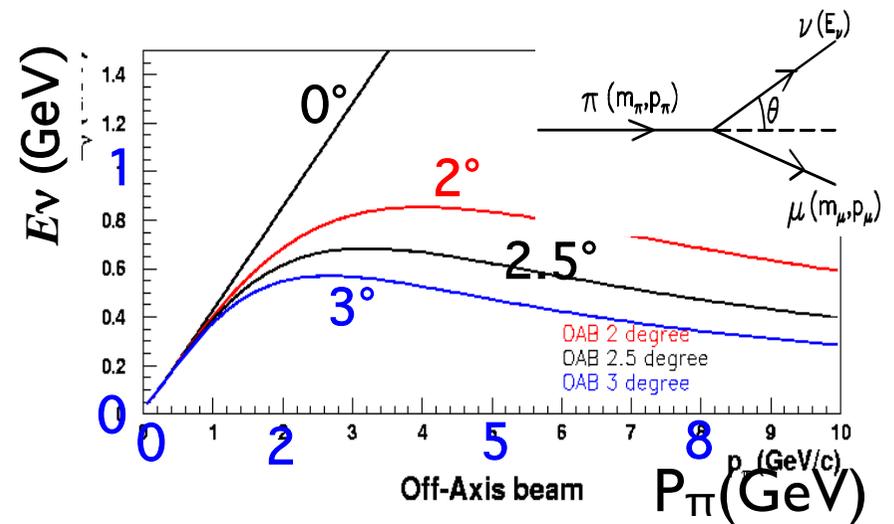
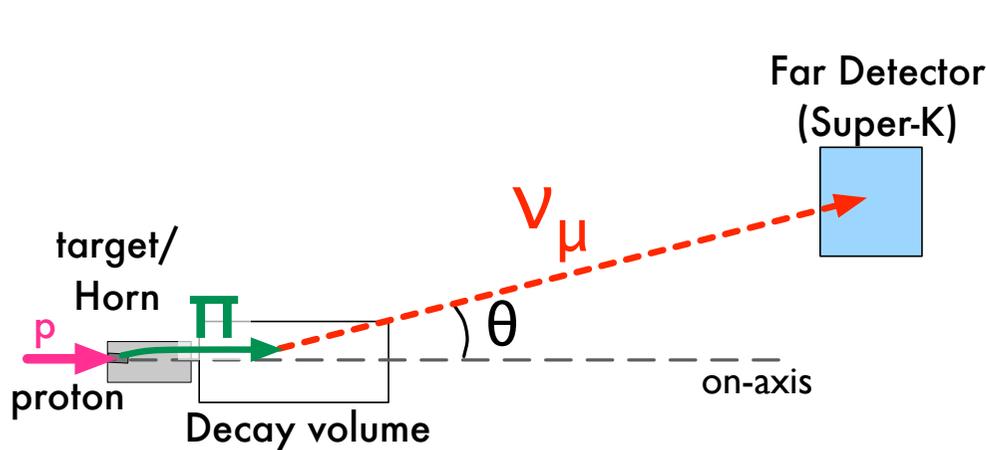
ν interactions at high energy cause background events in T2K
 (e.g. $NC1\pi^0$ is one of ν_e background)



→ **need to reduce high energy ν**



Off-axis beam : intense & narrow-band beam



Beam energy at oscillation max.

$$E_\nu \sim 0.6 \text{ GeV}$$

(based on Δm^2_{23} & $L=295\text{km}$)

→ T2K off-axis angle is 2.5°

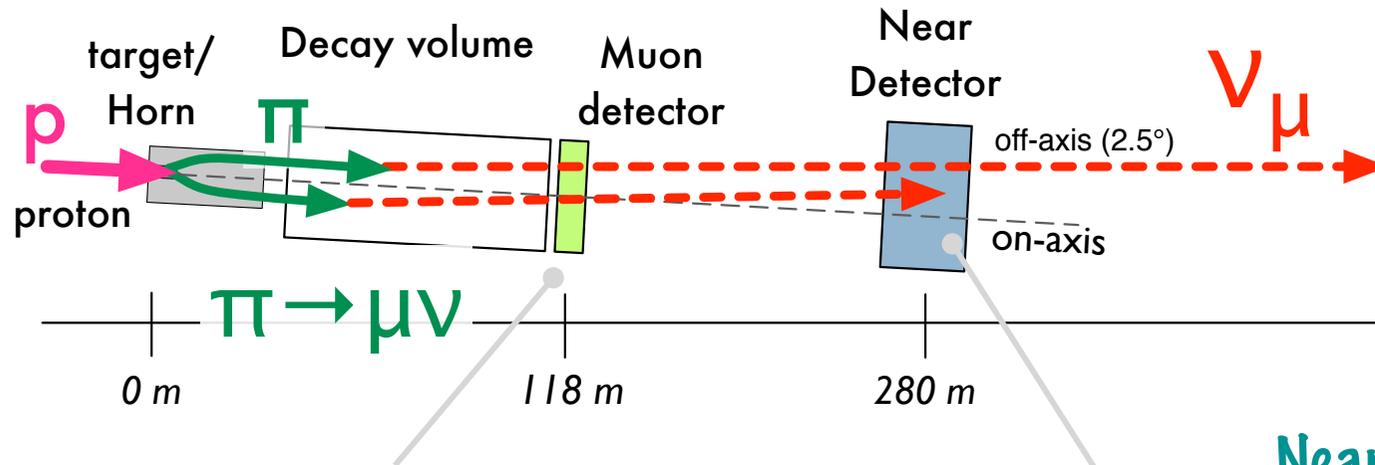
(maximize physics sensitivity)

Small high energy tail

→ small background

Important to keep beam direction stable
(Keep the peak energy stable)

Monitor beam direction and intensity



- **Muon monitor**

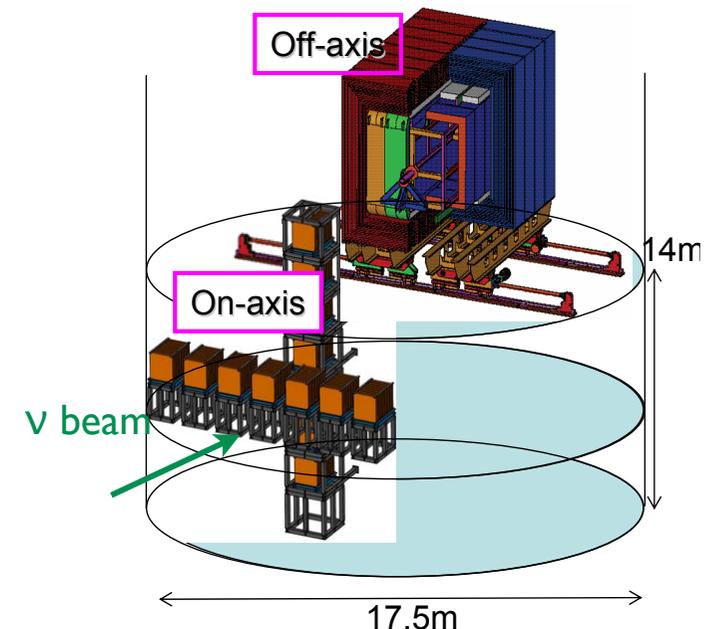
- monitor spill-by-spill

- **On-axis INGRID**

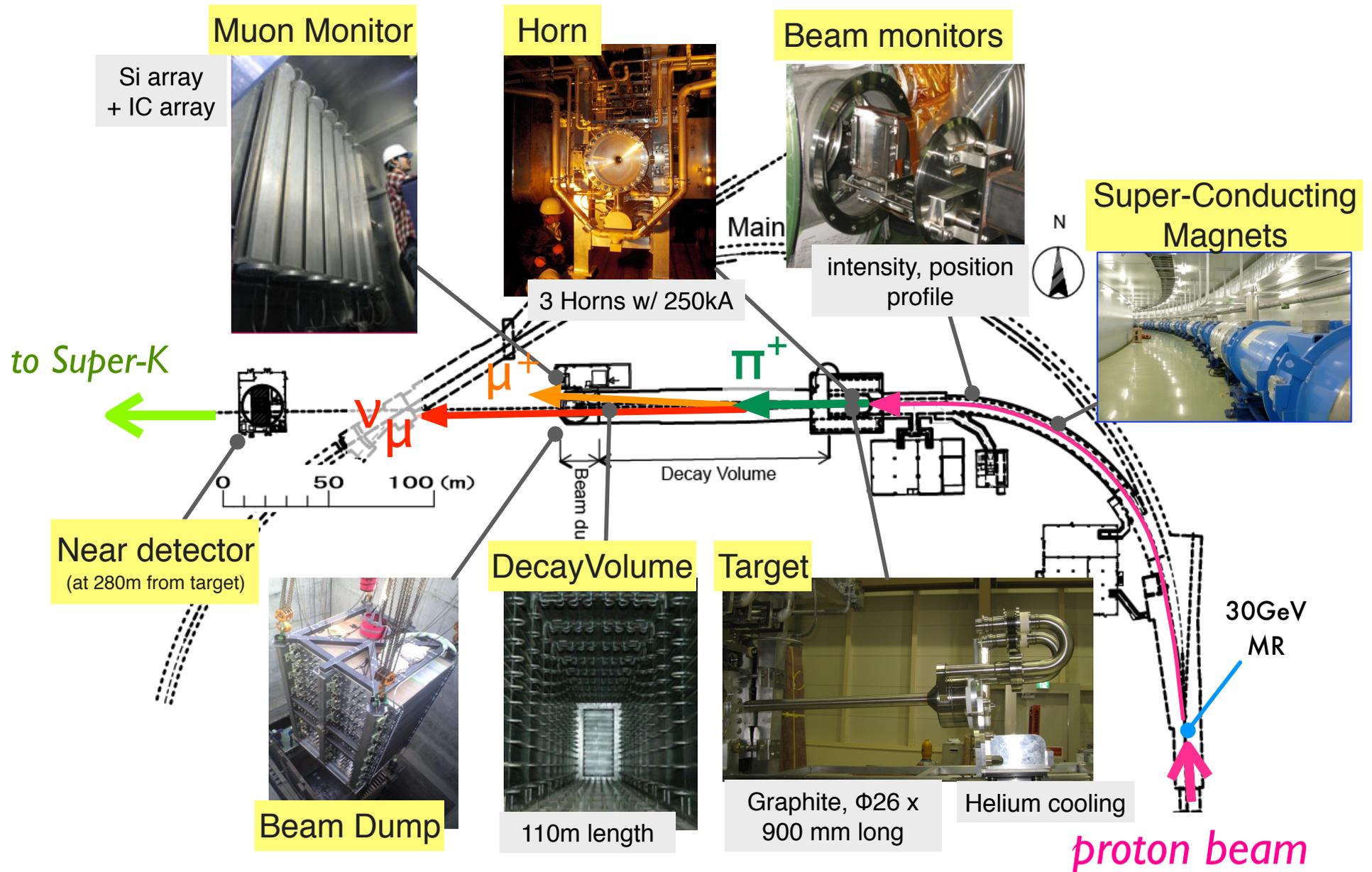
- monitor actual ν beam day-by-day
- detector coverage is 10m x 10m

*Stability of beam direction should be < 1 mrad
(to keep the peak energy at SK stable $\delta E < 2\%$)*

Near Detectors



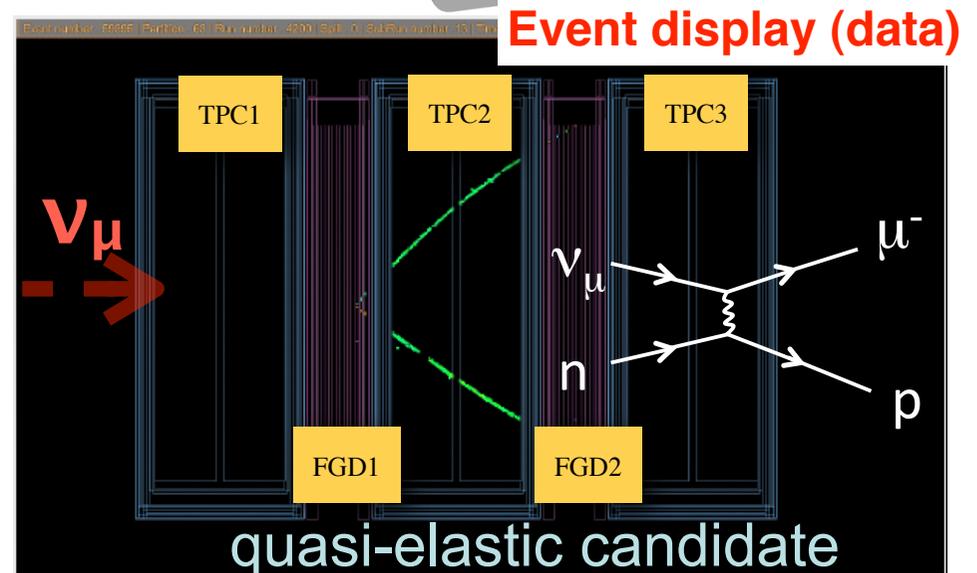
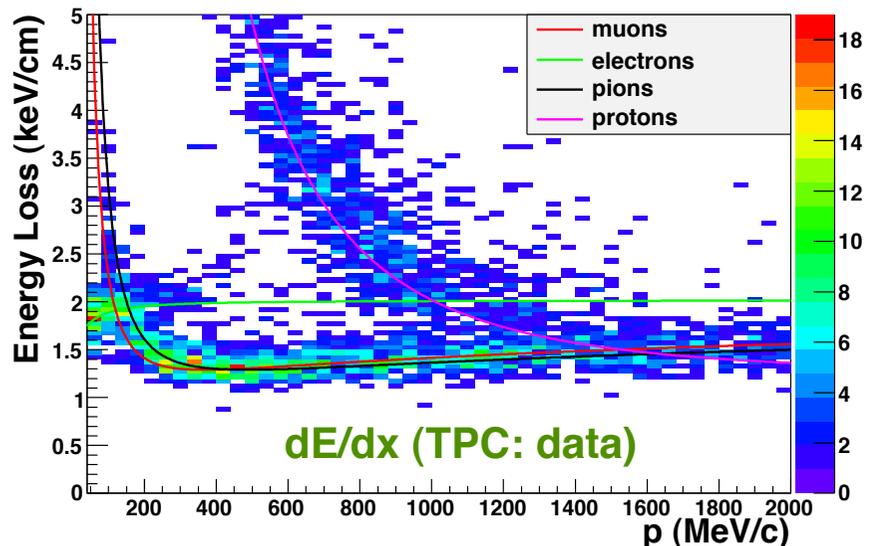
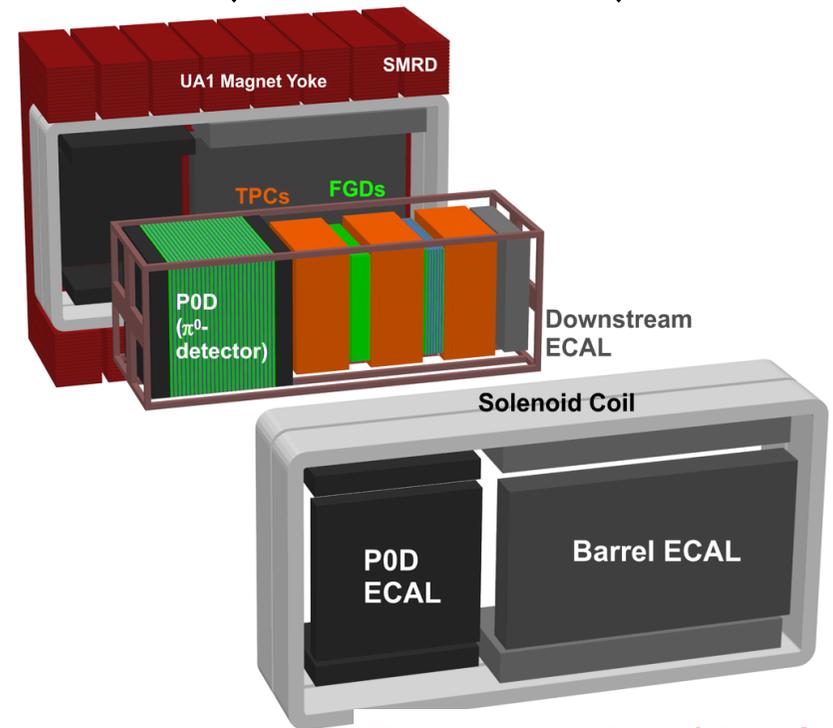
J-PARC Neutrino beam facility



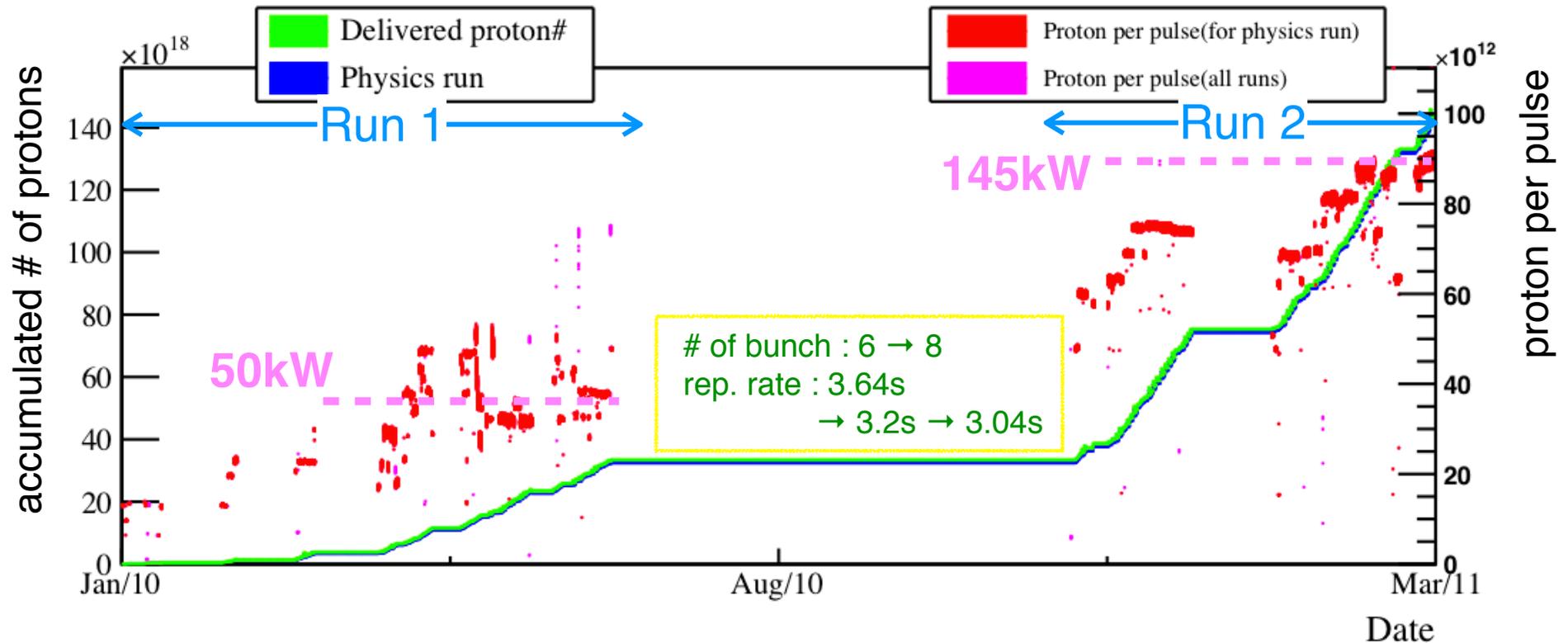
Off-axis Near Detector (ND280)

ν_μ CC events rate measurement in present analysis

- 0.2 T UA1 magnet
- Fine Grained Detector (FGD)
 - scintillator bars target (water target in FGD2)
 - 1.6ton fiducial mass for analysis
- Time Projection Chambers (TPC)
 - better than 10% dE/dx resolution
 - 10% momentum resolution at 1 GeV/c



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

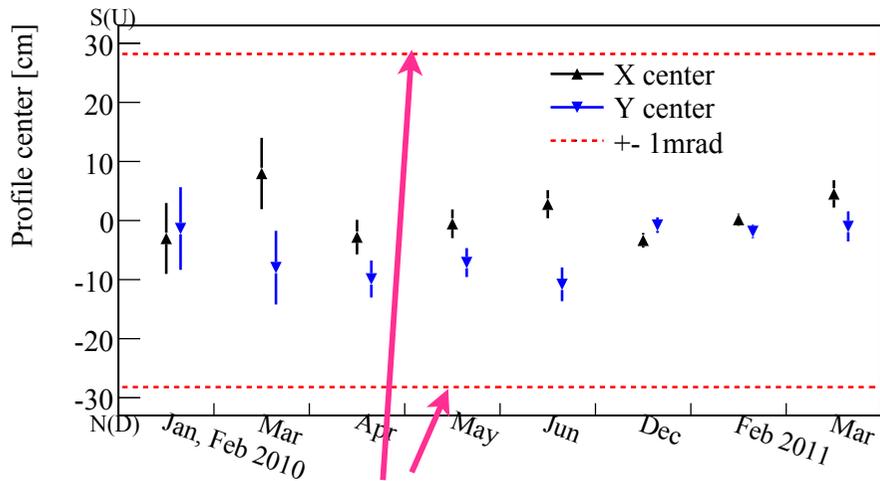
Run 2 (Nov. '10 - Mar. '11)

- 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

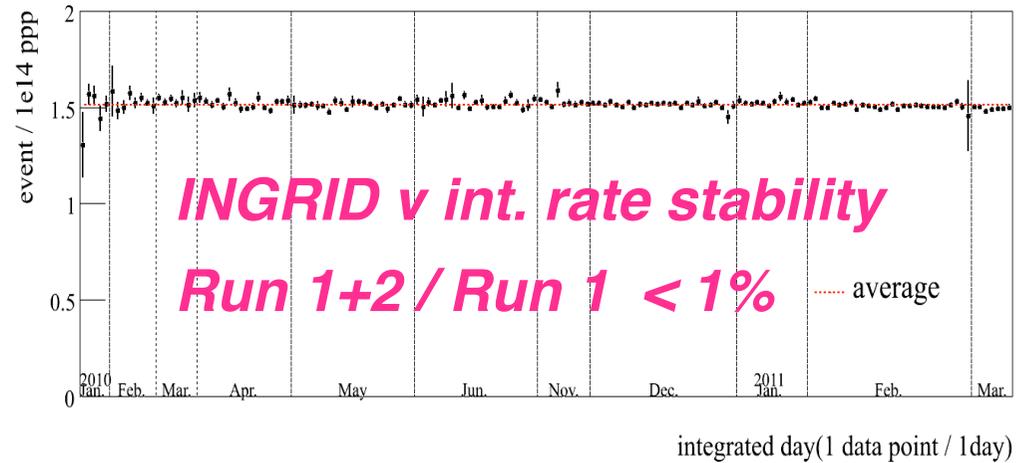
ν beam stability

Stability of ν beam direction (INGRID)



ν beam dir. stability < 1mrad

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

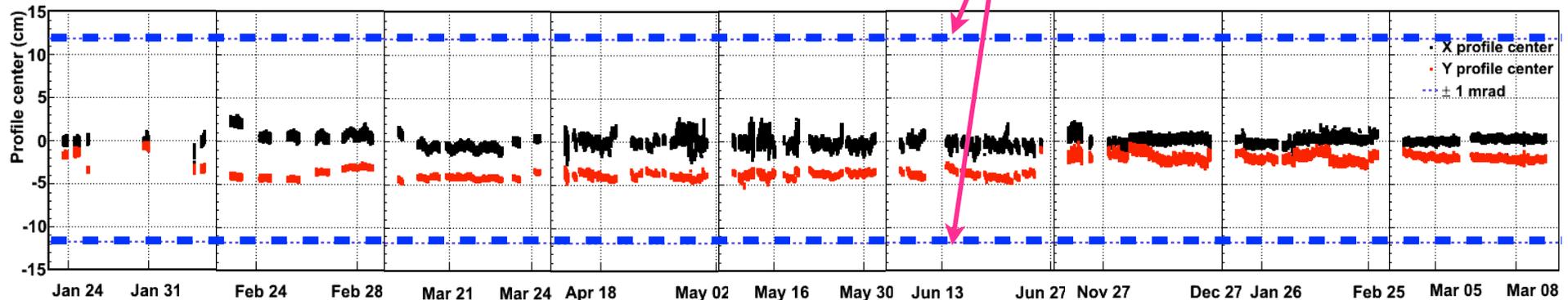


*INGRID ν int. rate stability
Run 1+2 / Run 1 < 1%*

integrated day(1 data point / 1day)

Stability of beam direction (Muon monitor)

Beam dir. stability < 1mrad



Search for ν_e appearance

Analysis overview

1. Apply ν_e selection criteria to the events at far detector (SK)
2. Compare the observed number of events and the expected number of events (for $\sin^2 2\theta_{13}=0$)
→ **search for ν_e appearance**

Contents in this section

- ✿ ν_e selection criteria
- ✿ The expected number of events at Far detector
using **Hadron (pion) production measurement** &
ND event rate measurement
- ✿ Systematic uncertainty
- ✿ Observation at Far detector & Results

❖ ν_e selection criteria

❖ The expected number of events at Far detector

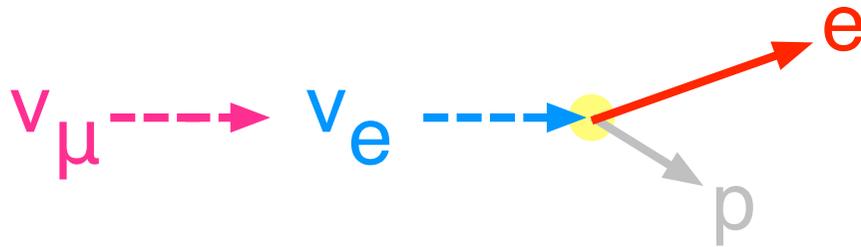
❖ Systematic uncertainty

❖ Observation at Far detector & Results

T2K Signal & Background for ν_e appearance

- Signal = **single electron event**

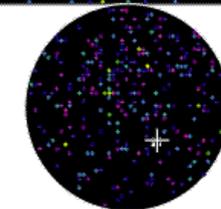
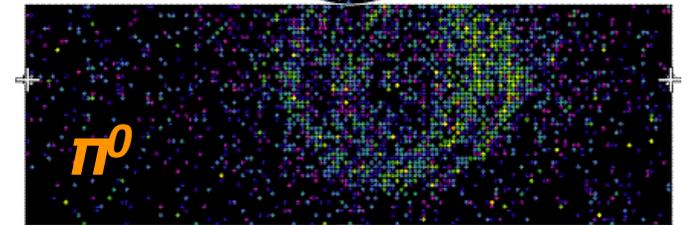
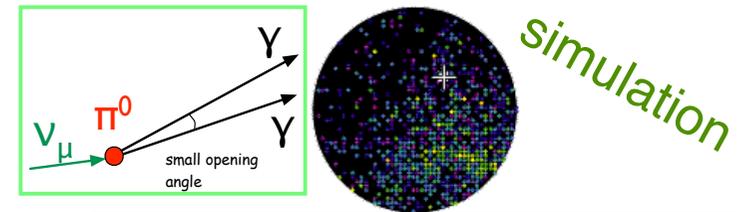
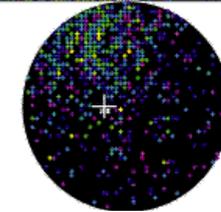
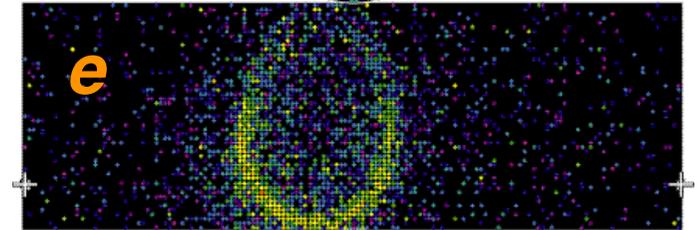
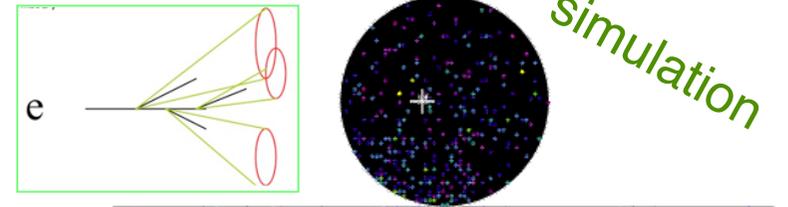
- oscillated ν_e interaction :



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



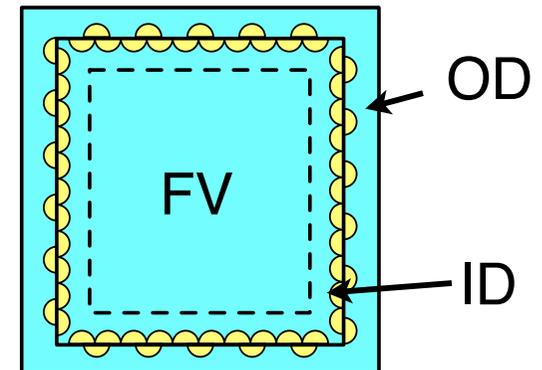
ν_e selection at far detector (SK)

The selection criteria were optimized for initial running condition

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

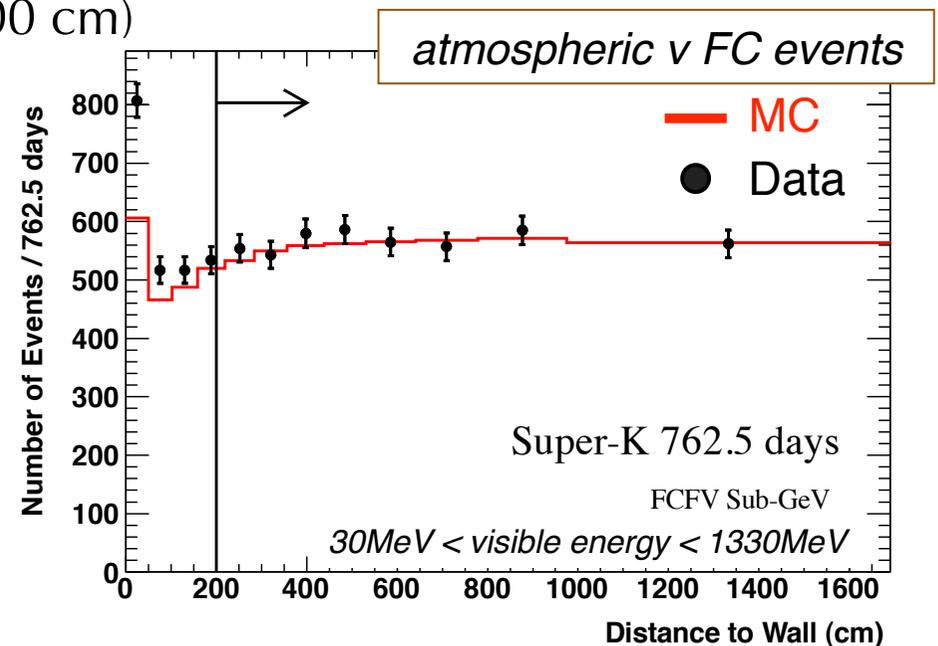
7 selection cuts

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

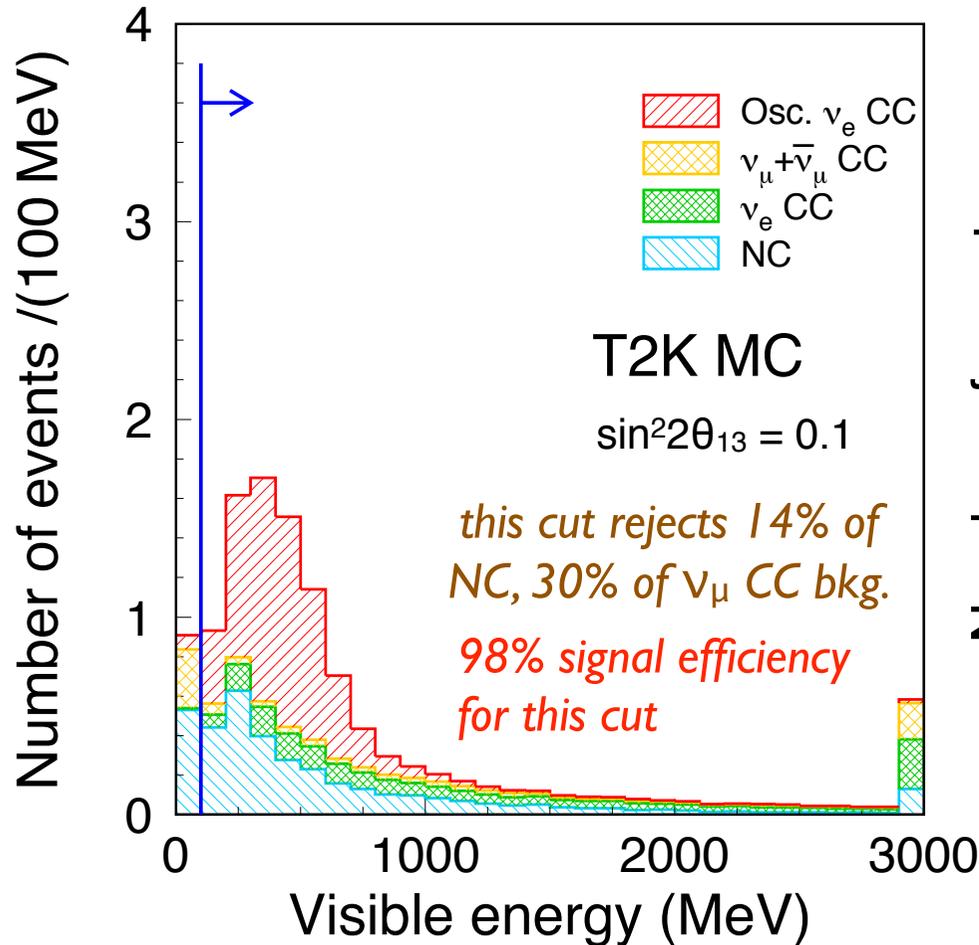
3. Single electron
(# of ring is one & e-like)



4. Visible energy > 100 MeV

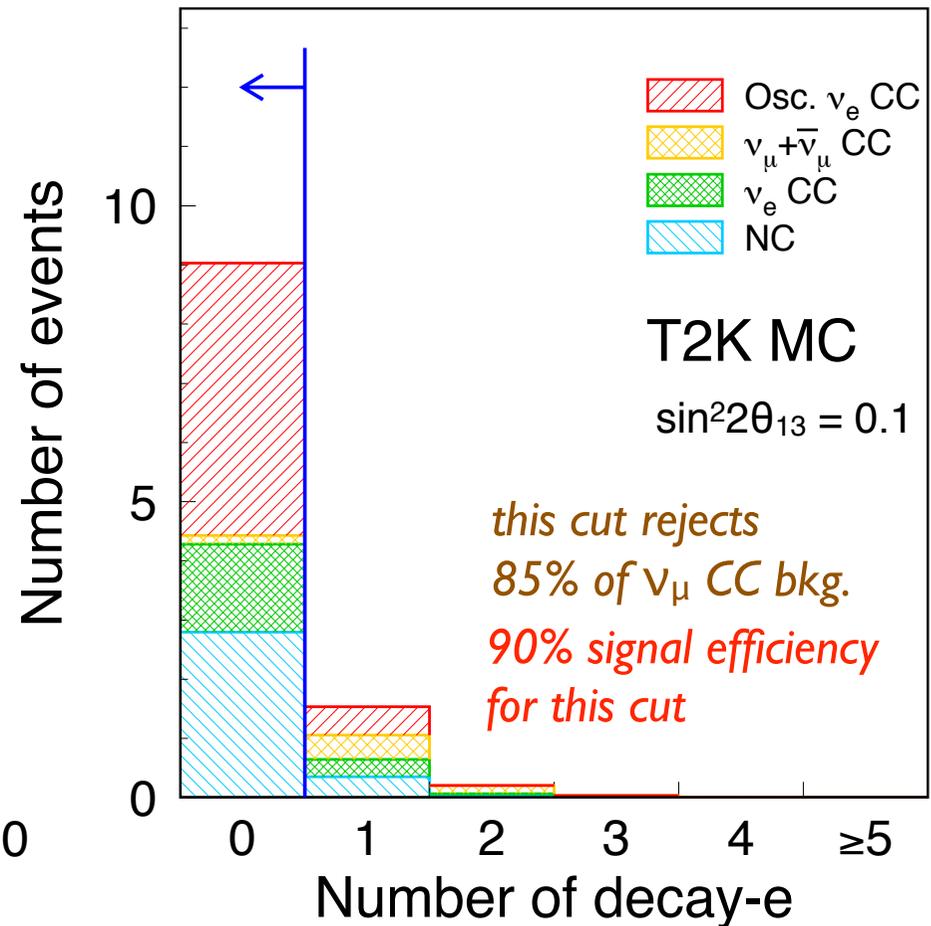
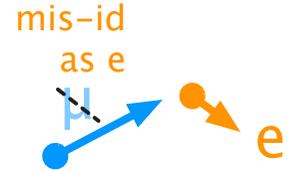
(visible energy =
electron energy deposited in ID)

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



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

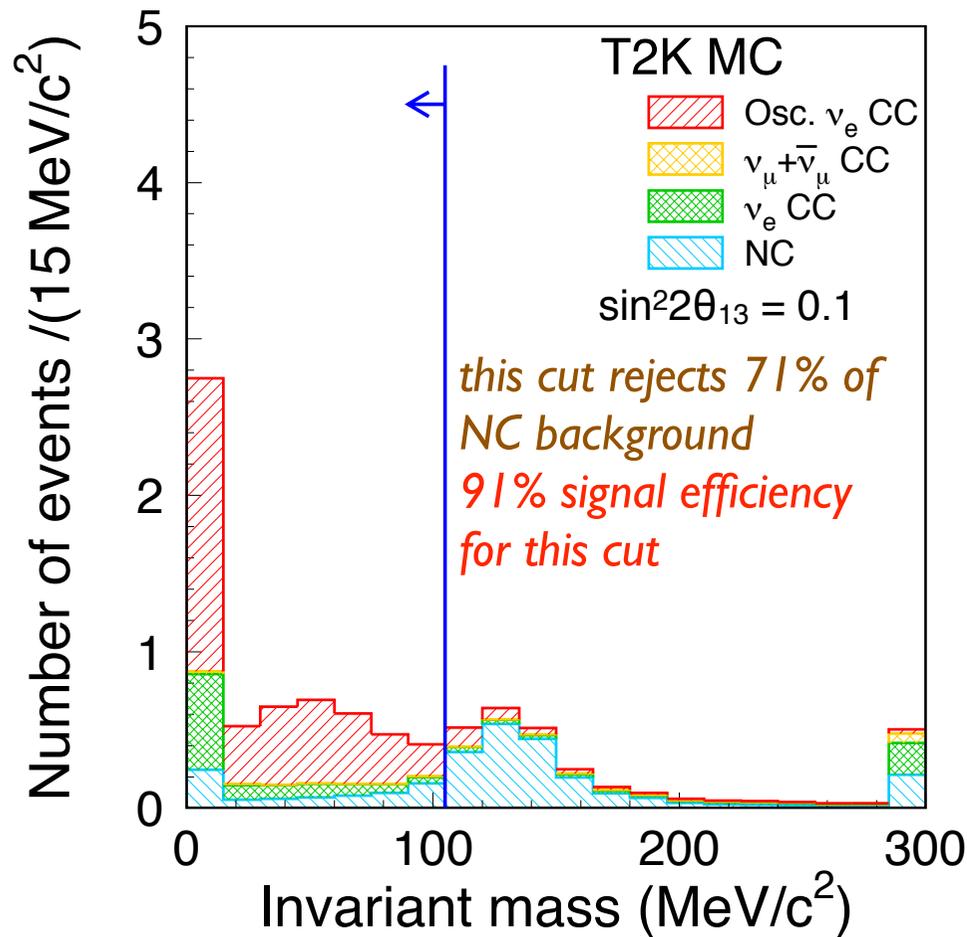
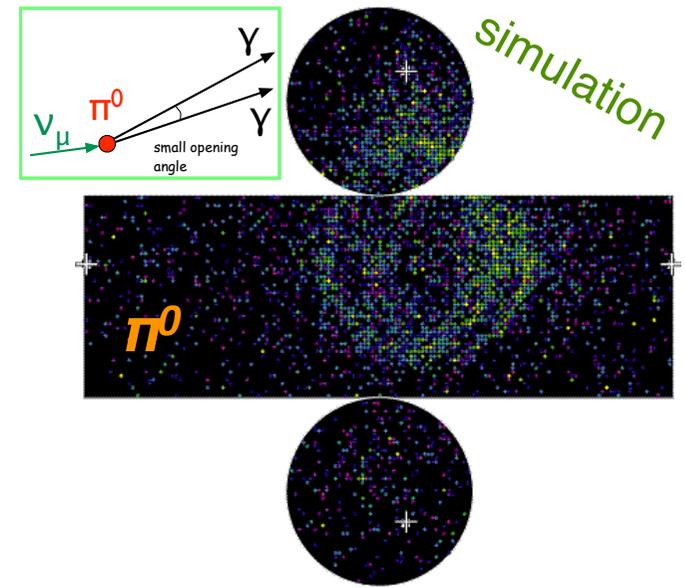
* Reject events with muons or pions which are invisible or mis-identified as electron (ν_μ events or CC non-QE events)



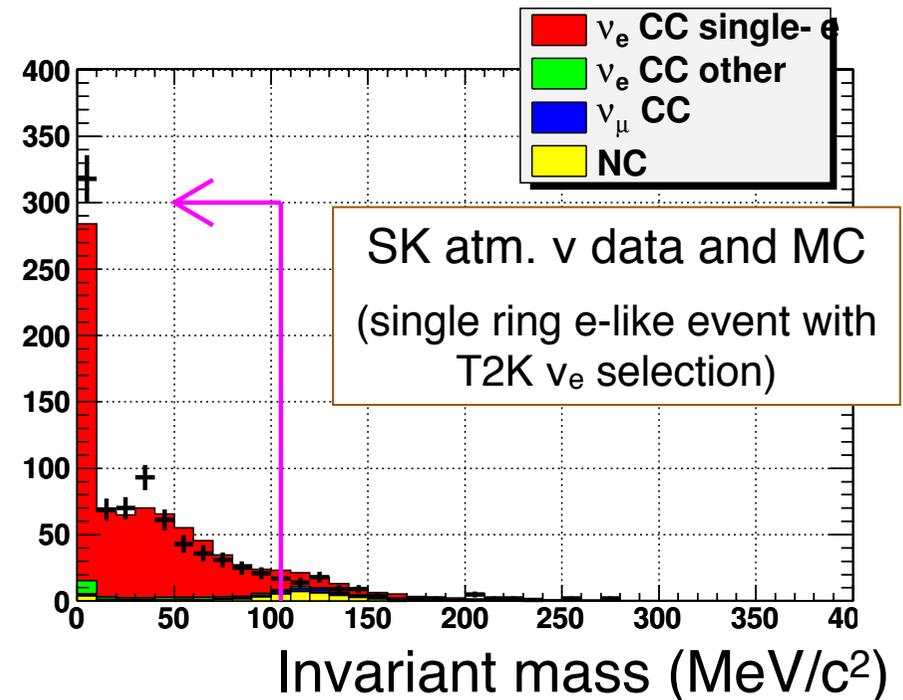
6. Reconstructed invariant mass (M_{inv}) $< 105 \text{ MeV}/c^2$

* 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

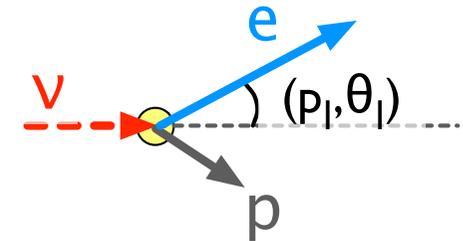


demonstrate to reconstruct invariant mass using atmospheric ν data

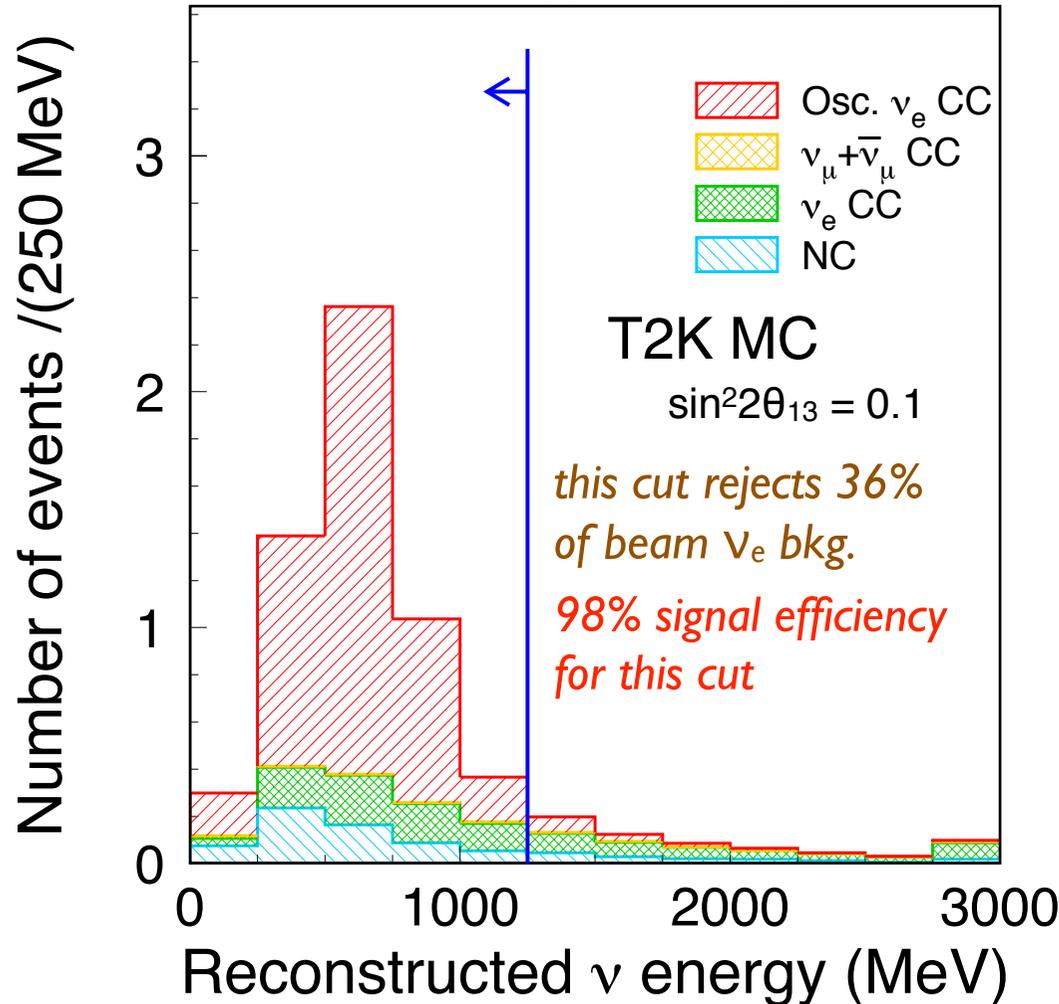


7. Reconstructed energy (E_{rec}) < 1250 MeV

- * Reject intrinsic beam ν_e backgrounds at high energy
- * Signal ($\nu_\mu \rightarrow \nu_e$) has a sharp peak at $E \sim 600$ MeV



reconstruct energy assuming CCQE



$$E_{rec} = \frac{m_n E_l - m_l^2/2 - (m_n^2 - m_p^2)/2}{m_n - E_l + p_l \cos \theta_l}$$

(with correcting nuclear potential)

After all the selection criteria
background rejection :
77 % for beam ν_e ,
99 % for NC
signal efficiency : 66 %
for the number of events in FV

- ❖ ν_e selection criteria
- ❖ **The expected number of events at Far detector
with 1.43×10^{20} p.o.t.**
- ❖ Systematic uncertainty
- ❖ Observation at Far detector & Results

Expected # of events at Far detector

The number of signal and background events are derived by the # of observed ν_μ event rate at near detector ($R^{\mu, Data}_{ND}$) and the ratio of the expected events at the far detectors and the expected event rate at the near detector (F/N ratio)

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

Expected # of events at Far detector

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ND ν_μ event rate
measurement

Expected # of events at Far detector

The number of signal and background events are derived by the # of observed ν_μ event rate at near detector ($R^{\mu, Data}_{ND}$) and the ratio of the expected events at the far detectors and the expected event rate at the near detector (F/N ratio)

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

ND ν_μ event rate measurement

F/N ratio is estimated by using MC which is based on measurements

Expected # of events at Far detector

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

ND ν_μ event rate

Measurement of the number of inclusive ν_μ charged-current events in ND per p.o.t. using data collected in Run 1 (2.88×10^{19} p.o.t.)

Stability of the beam event rate is confirmed by INGRID measurement

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

F/N ratio for ν_e signal event

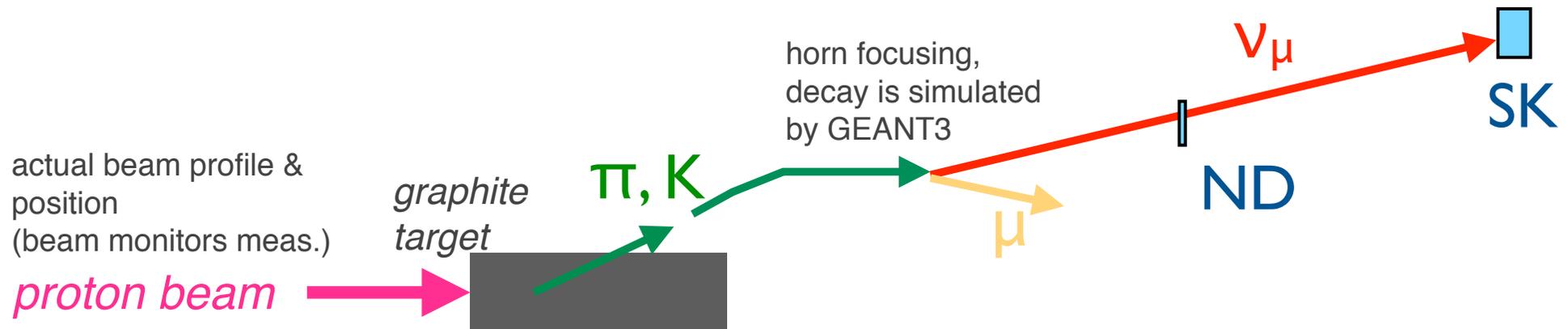
(flux) x (osc. prob.) x (x-section) x (efficiency) x (det. mass)

$$\frac{N_{SK}^{MC} \nu_e sig.}{R_{ND}^{\mu, MC}} = \frac{\int \Phi_{\nu_\mu}^{SK}(E_\nu) \cdot P_{\nu_\mu \rightarrow \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu) dE_\nu}{\int \Phi_{\nu_\mu}^{ND}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu) dE_\nu} \cdot \frac{M^{SK}}{M^{ND}} \cdot POT^{SK}$$

Neutrino flux prediction

T2K Neutrino beam simulation based on Hadron production measurements

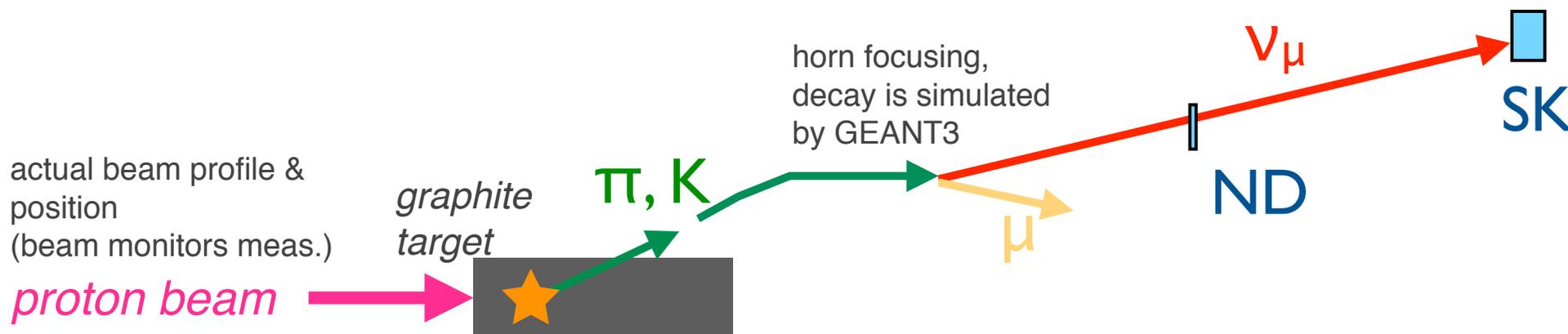
$$\frac{\int \Phi_{\nu\mu}^{\text{SK}}(E_\nu) \cdot P_{\nu\mu \rightarrow \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{\text{SK}}(E_\nu) dE_\nu}{\int \Phi_{\nu\mu}^{\text{ND}}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{\text{ND}}(E_\nu) dE_\nu}$$



Neutrino flux prediction

T2K Neutrino beam simulation based on Hadron production measurements

$$\frac{\int \Phi_{\nu\mu}^{\text{SK}}(E_\nu) \cdot P_{\nu\mu \rightarrow \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{\text{SK}}(E_\nu) dE_\nu}{\int \Phi_{\nu\mu}^{\text{ND}}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{\text{ND}}(E_\nu) dE_\nu}$$



Hadron production in 30GeV proton + C

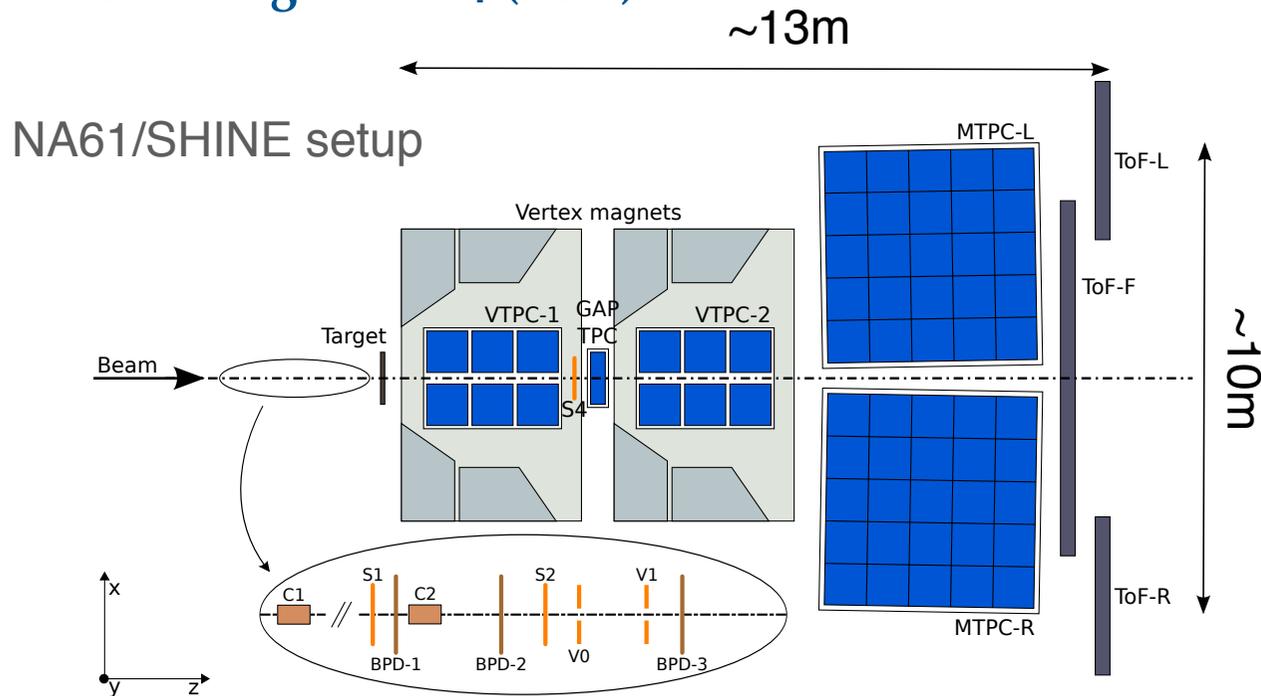
- **Use CERN NA61/SHINE pion measurement (large acceptance: >95% coverage of ν parent pions)**
- *Kaon, pion outside NA61 acceptance, other interaction in the target were based on FLUKA simulation*
- *Secondary interaction x-sections outside the target were based on experimental data*

CERN NA61/SHINE measurement

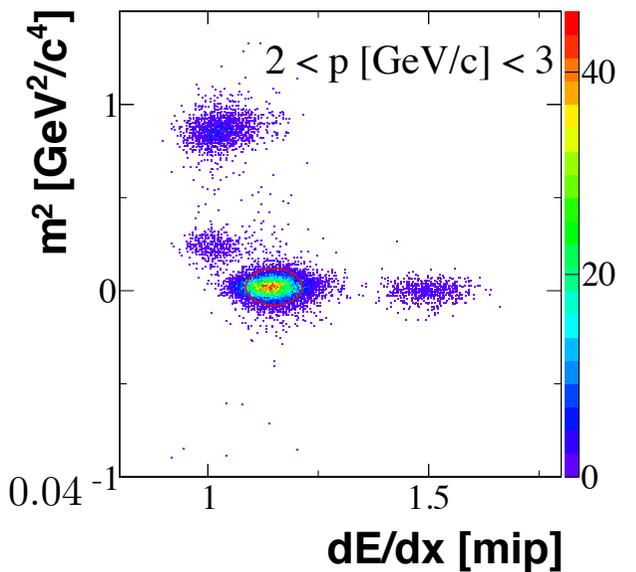
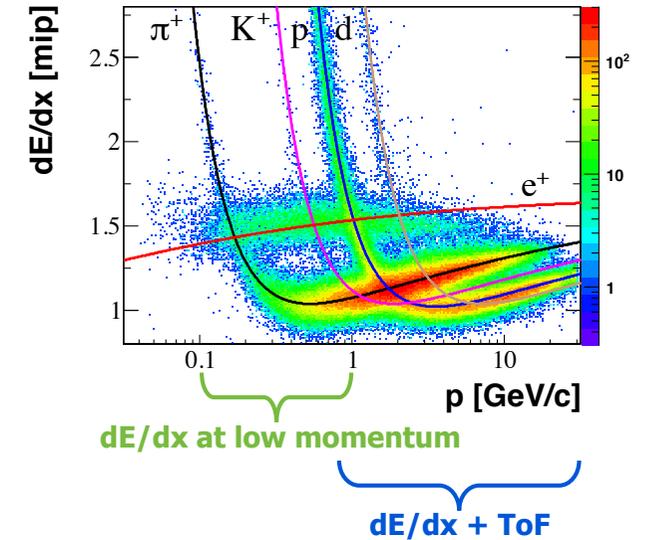
Measure hadron(π , K) yield distribution in 30 GeV p + C inelastic interaction

- thin target $4\% \lambda_I$ (2cm)

π^+ production: Two analysis for different momentum region



Large acceptance spectrometer + TOF



detector performance

$$\sigma(p)/p^2 \approx 2 \times 10^{-3}, 7 \times 10^{-3}, 3 \times 10^{-2} (\text{GeV}/c)^{-1} \quad \sigma(dE/dx)/\langle dE/dx \rangle \approx 0.04$$

for $p > 5, p = 2, p = 1$ GeV/c

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

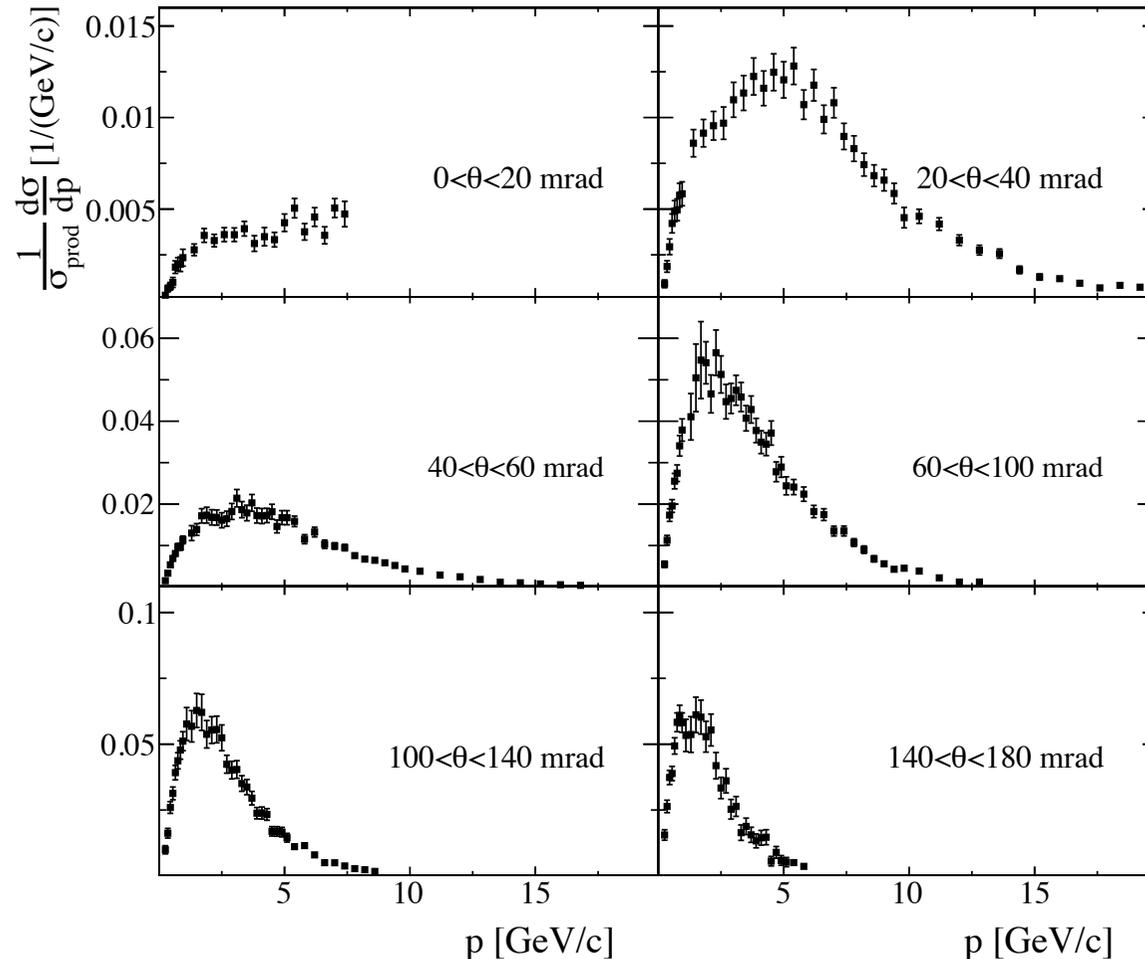
Results of pion production from thin target (2007 data)

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

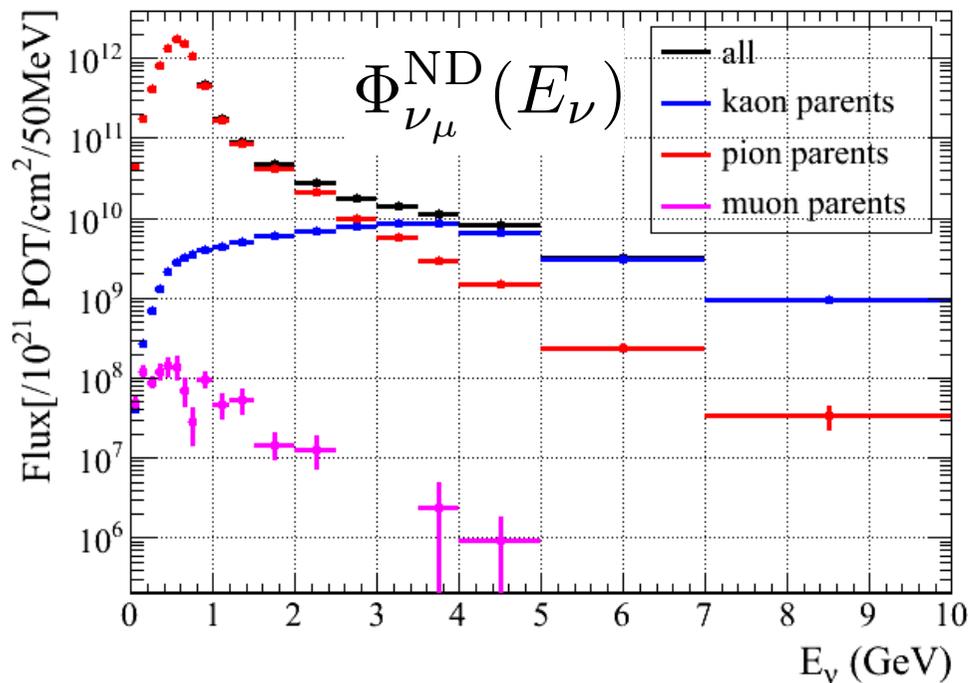
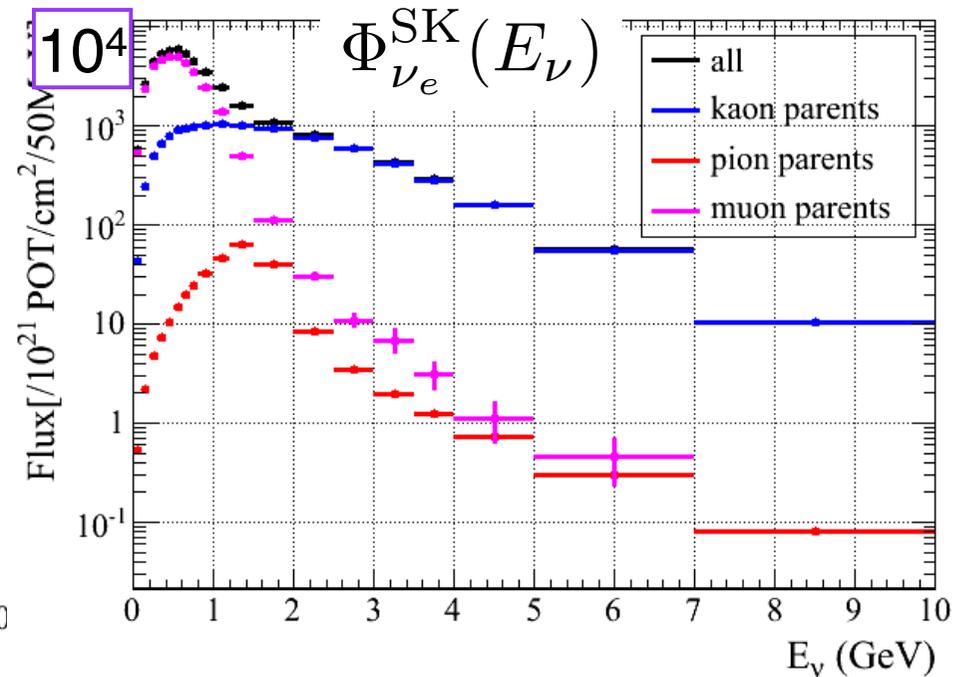
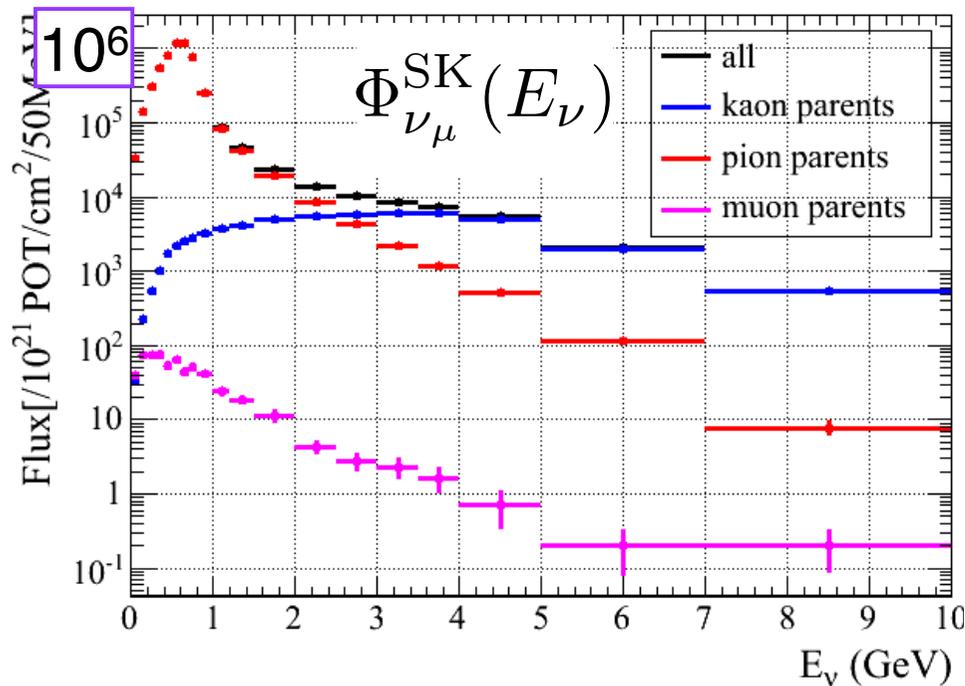
typically 5-10%

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

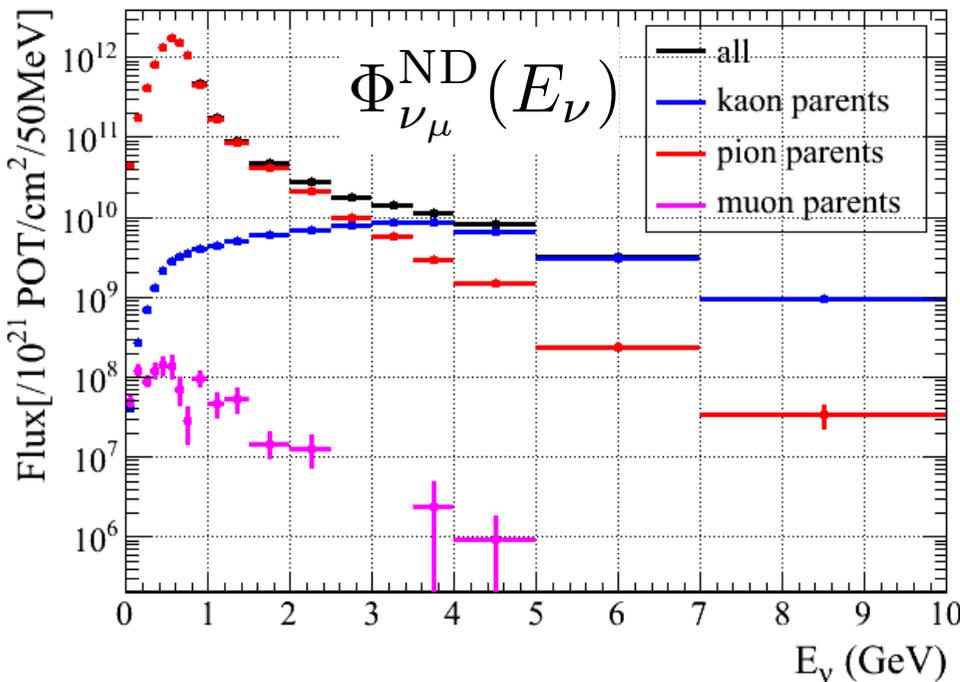
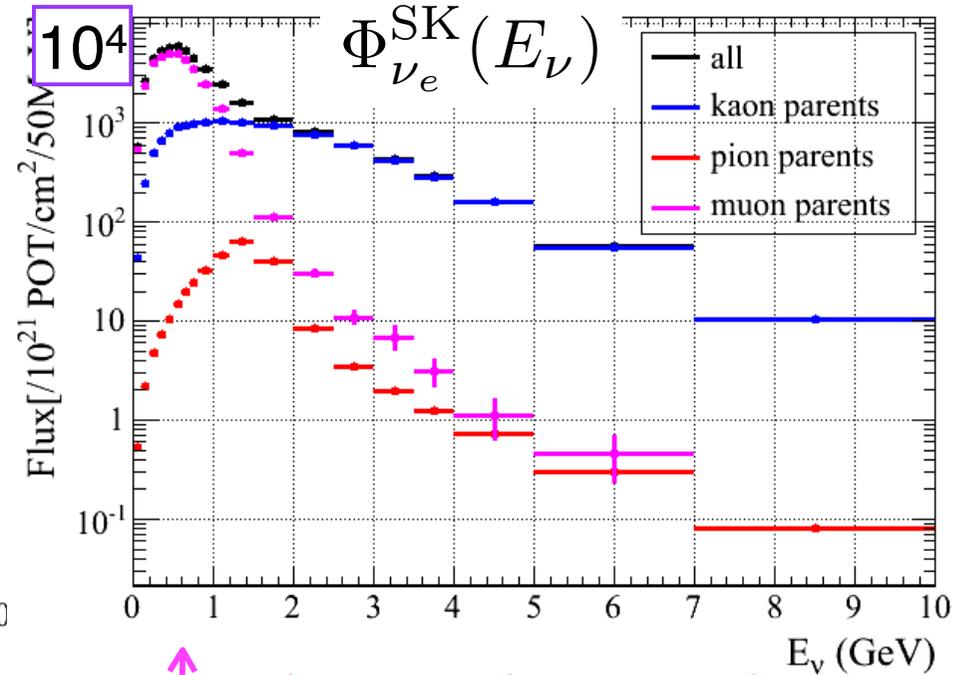
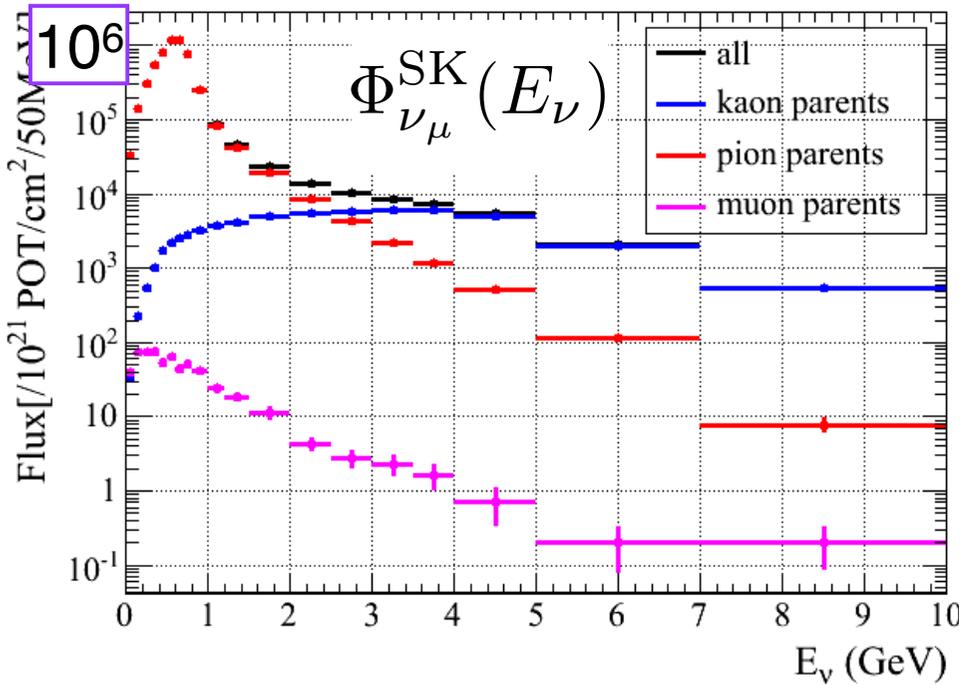
→ Propagate the systematic
uncertainty in each (p, θ) bin
into the expected number of
events in T2K

→ Input to T2K neutrino beam simulation

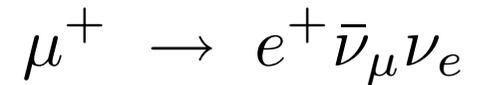
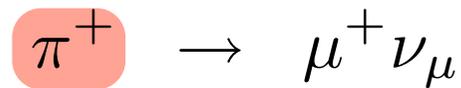
Predicted neutrino flux (center value)



Predicted neutrino flux (center value)



↑ μ decay is dominated at low energy



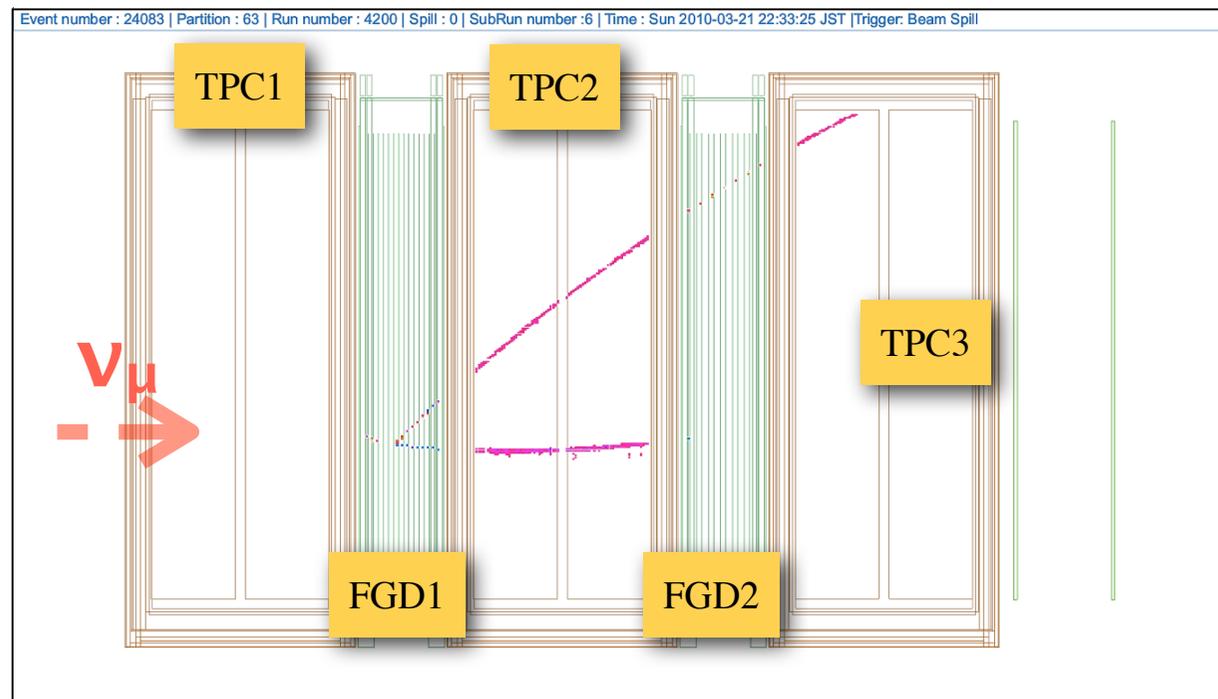
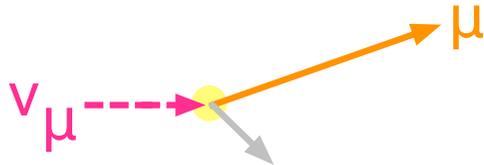
NA61 pion measurement predicts the beam ν_e from pion origin

ν_μ interaction rates at near detector

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

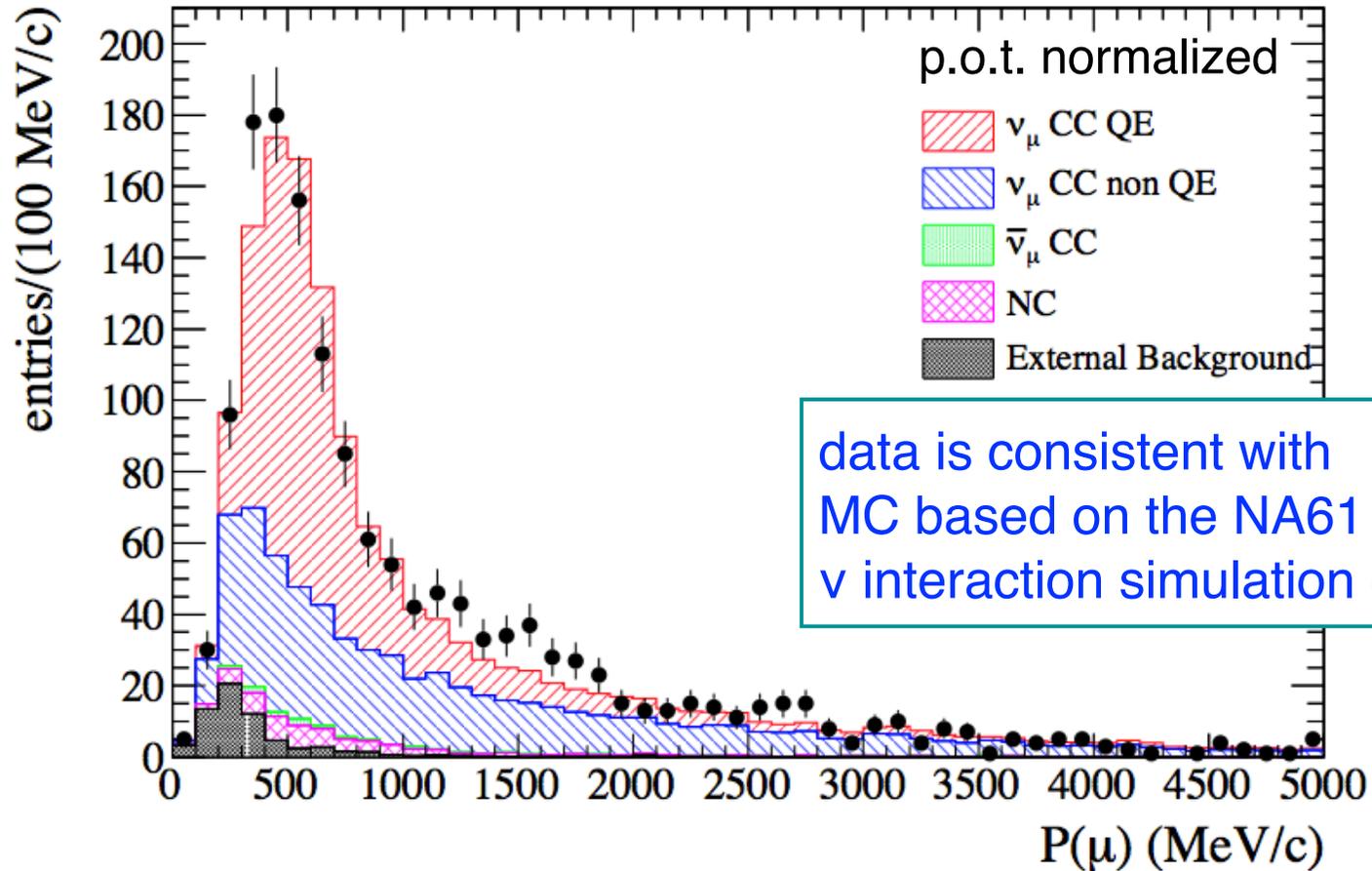
Event display (data)

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



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

ND Measurement of muon momentum in inclusive ν_μ CC events ($\nu_\mu + N \rightarrow \mu^+ + X$)



Results

$$R_{ND}^{\mu, Data} = 1529 \text{ events} / 2.9 \times 10^{19} \text{ p.o.t.}$$

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

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

$$N_{SK \text{ beam } \nu_e \text{ bkg.}}^{exp} = R_{ND}^{\mu, Data} \times \frac{N_{SK \text{ beam } \nu_e \text{ bkg.}}^{MC}}{R_{ND}^{\mu, MC}}$$

$$\frac{N_{SK \text{ beam } \nu_e \text{ bkg.}}^{MC}}{R_{ND}^{\mu, MC}} = \frac{\int \Phi_{\nu_e}^{SK}(E_\nu) \cdot P_{\nu_e \rightarrow \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu) dE_\nu}{\int \Phi_{\nu_\mu}^{ND}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu) dE_\nu} \cdot \frac{M^{SK}}{M^{ND}} \cdot POT^{SK}$$

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

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

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

	Beam ν_e background	NC background	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	Total
<i>The expected # of events at SK</i>	0.8	0.6	0.1	1.5



of NC background is calculated by

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

- ❖ ν_e selection criteria
- ❖ The expected number of events at Far detector
- ❖ **Systematic uncertainty**
- ❖ Observation at Far detector & Results

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

error source	syst. error	<i>for $\sin^2 2\theta_{13}=0$</i>
(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%	

$$N^{exp}_{SK} = R_{ND}^{\mu, Data} \times \frac{N^{MC}_{SK}}{R_{ND}^{\mu, MC}} \rightarrow N^{exp}_{SK} = 1.5 \pm 0.3 \text{ events}$$

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

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

error source	syst. error	
○(1) ν flux	$\pm 8.5\%$	<i>for $\sin^2 2\theta_{13}=0$</i>
○(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%	

$$N^{exp}_{SK} = R_{ND}^{\mu, Data} \times \frac{N^{MC}_{SK}}{R_{ND}^{\mu, MC}} \quad \rightarrow \quad N^{exp}_{SK} = 1.5 \pm 0.3 \text{ events}$$

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

Neutrino flux uncertainty

error source

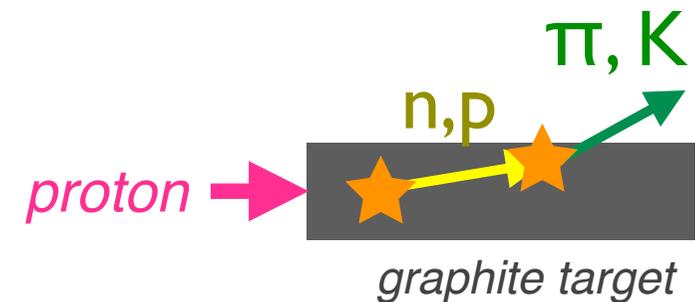
- (1) ν flux
- (2) ν cross section
- (3) Near detector
- (4) Far detector
- (5) Near det. statistics

Uncertainties in hadron production and interaction are dominant sources

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

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 $N^{\text{exp}}_{\text{SK}}$ for $\sin^2 2\theta_{13}=0$

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

Error source	$\frac{N^{\text{MC}}_{\text{SK}}}{R^{\mu, \text{MC}}_{\text{ND}}}$	
Pion production	2.5%	
Kaon production	7.6%	<i>Hadron production & interaction</i>
Nucleon production	1.4%	
Production x-section	0.7%	
Proton beam position/profile	2.2%	
Beam direction measurement	0.7%	
Target alignment	0.2%	
Horn alignment	0.1%	
Horn abs. current	0.3%	
Total	8.5%	

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

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

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

Error source	$R^{\mu, \text{MC}}_{\text{ND}}$	$N^{\text{MC}}_{\text{SK}}$	$\frac{N^{\text{MC}}_{\text{SK}}}{R^{\mu, \text{MC}}_{\text{ND}}}$	
Pion production	5.7%	6.2%	2.5%	<i>Hadron production & interaction</i>
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%	

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

Error cancellation works for some beam uncertainties

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

Main ν interaction in each event category

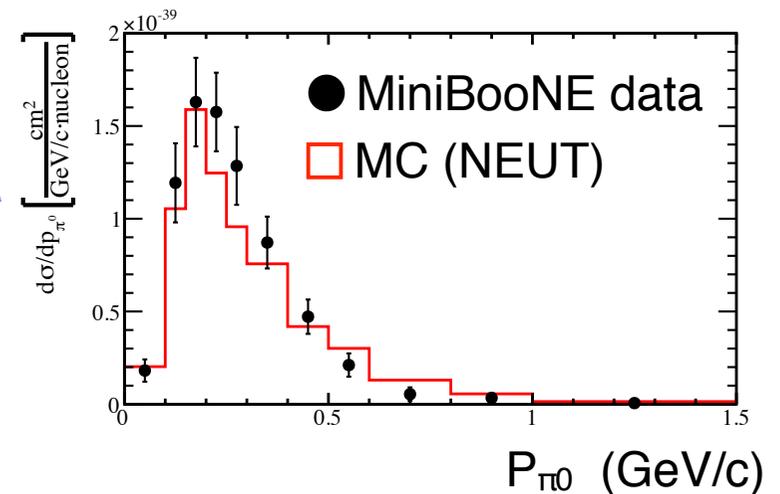
NC background : NC1 π^0
 Beam ν_e background : ν_e CCQE
 Signal : ν_e CCQE
 ND CC event : CCQE(50%)
 CC1 π (23%)

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

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

Process	Cross section uncertainty relative to the CCQE total x-section
CCQE	energy dependent ($\sim \pm 7\%$ at 500 MeV)
CC 1 π	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 π^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 $\sigma(\nu_e) / \sigma(\nu_\mu) = \pm 6\%$



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

error source

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

Error source	syst. error on N^{exp}_{SK}
CC QE shape	3.1%
CC 1π	2.2%
CC Coherent π	3.1%
CC Other	4.4%
NC $1\pi^0$	5.3%
NC Coherent π	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

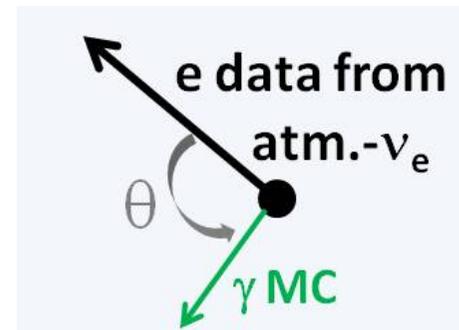
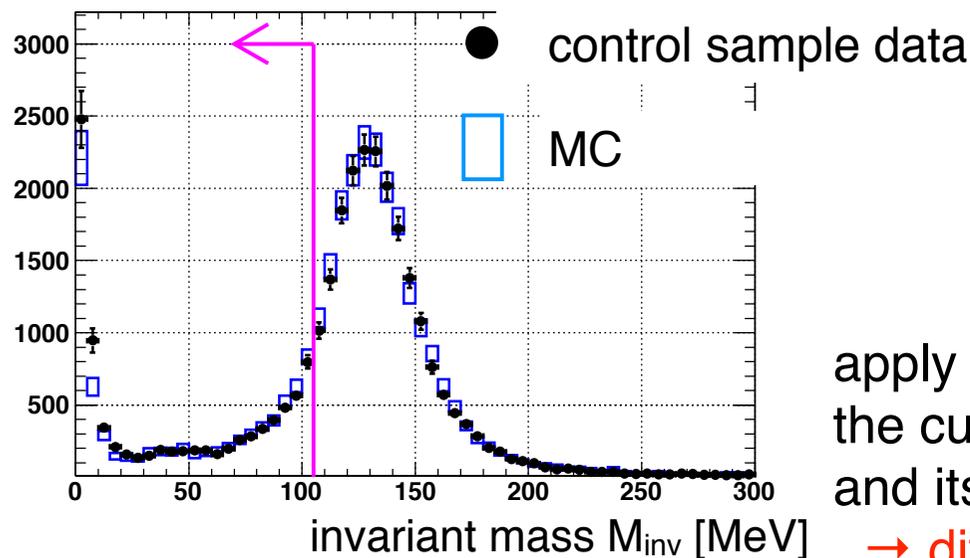
- Uncertainty due to the SK detector uncertainty
- Evaluation using control sample

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

One of big error sources:

detection efficiency of NC $1\pi^0$ 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	$\frac{\delta N_{SK \nu_e sig.}^{MC}}{N_{SK \nu_e sig.}^{MC}}$	$\frac{\delta N_{SK bkg. tot.}^{MC}}{N_{SK bkg. tot.}^{MC}}$	
π^0 rejection	-	3.6%	Evaluated by atmospheric ν_e enriched data
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%	

→ The total uncertainty on $N_{SK tot.}^{MC}$ 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 $N^{\text{exp}}_{SK \text{ total}}$ for $\sin^2 2\theta_{13}=0$

Error source	$\sin^2 2\theta_{13} = 0$
○(1) Beam 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%

cf.

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

#sig = 0.1 #bkg = 1.4

$N^{\text{exp}}_{SK \text{ tot.}} = 1.5 \pm 0.3$ events for $\sin^2 2\theta_{13}=0$ (w/ 1.43×10^{20} p.o.t.)

Total Systematic uncertainties

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

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$	cf.
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$	$\sin^2 2\theta_{13}=0:$ #sig = 0.1 #bkg = 1.4
(2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$	
(3) Near detector	$+5.6\%$ -5.2%	$+5.6\%$ -5.2%	$\sin^2 2\theta_{13}=0.1:$ #sig = 4.1 #bkg = 1.3
(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)

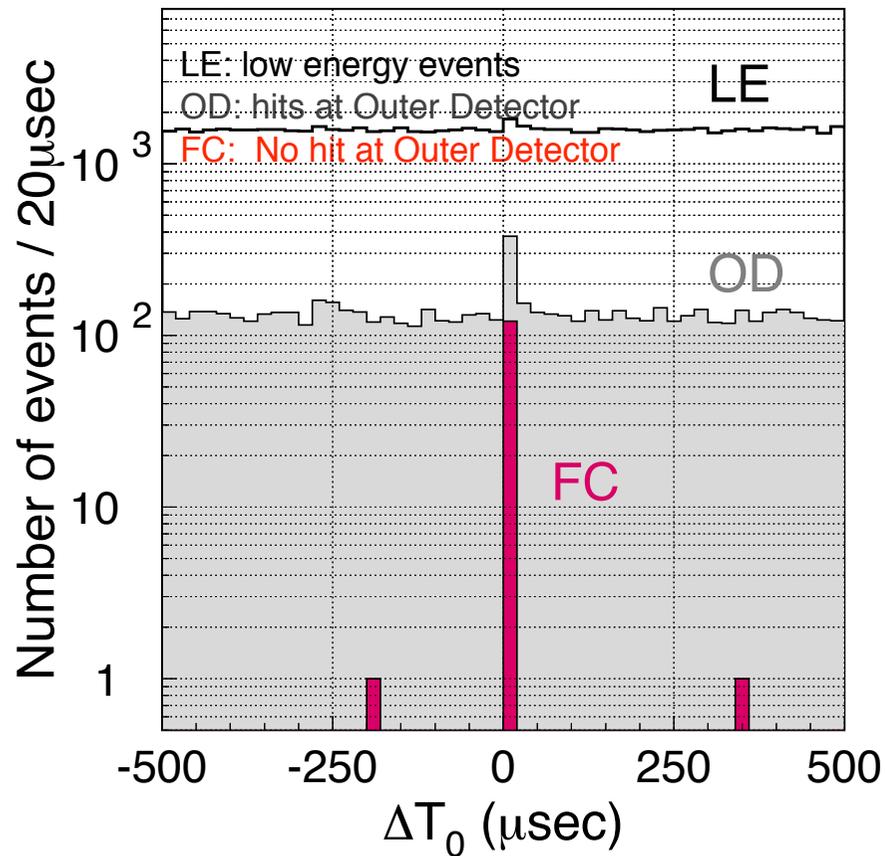
$N^{exp}_{SK\ tot.} = 1.5 \pm 0.3$ events for $\sin^2 2\theta_{13}=0$ (w/ 1.43×10^{20} p.o.t.)

- ✿ ν_e selection criteria
- ✿ The expected number of events at Far detector
- ✿ Systematic uncertainty
- ✿ **Observation at Far detector & Results**

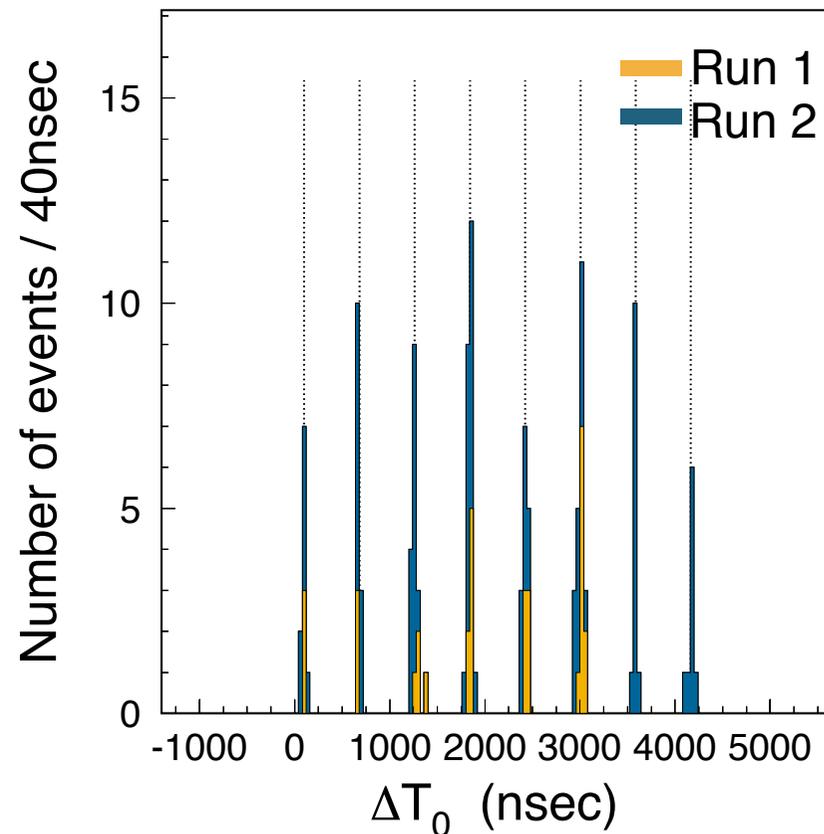
SK events in beam timing

- Events in the T2K beam timing synchronized by GPS

relative event timing to the spill timing



Clear beam structure !



$$\Delta T_0 = T_{\text{GPS}@\text{SK}} - T_{\text{GPS}@\text{J-PARC}} - \text{TOF}(\sim 985 \mu\text{sec})$$

Number of T2K events at far detector

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

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

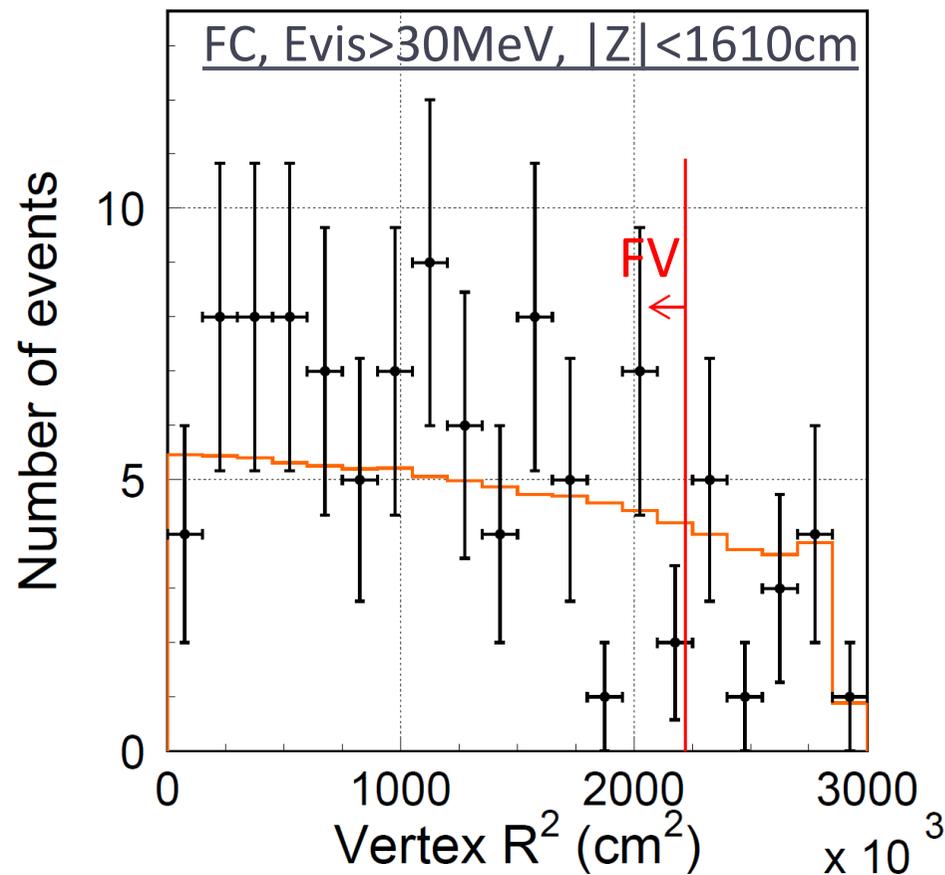
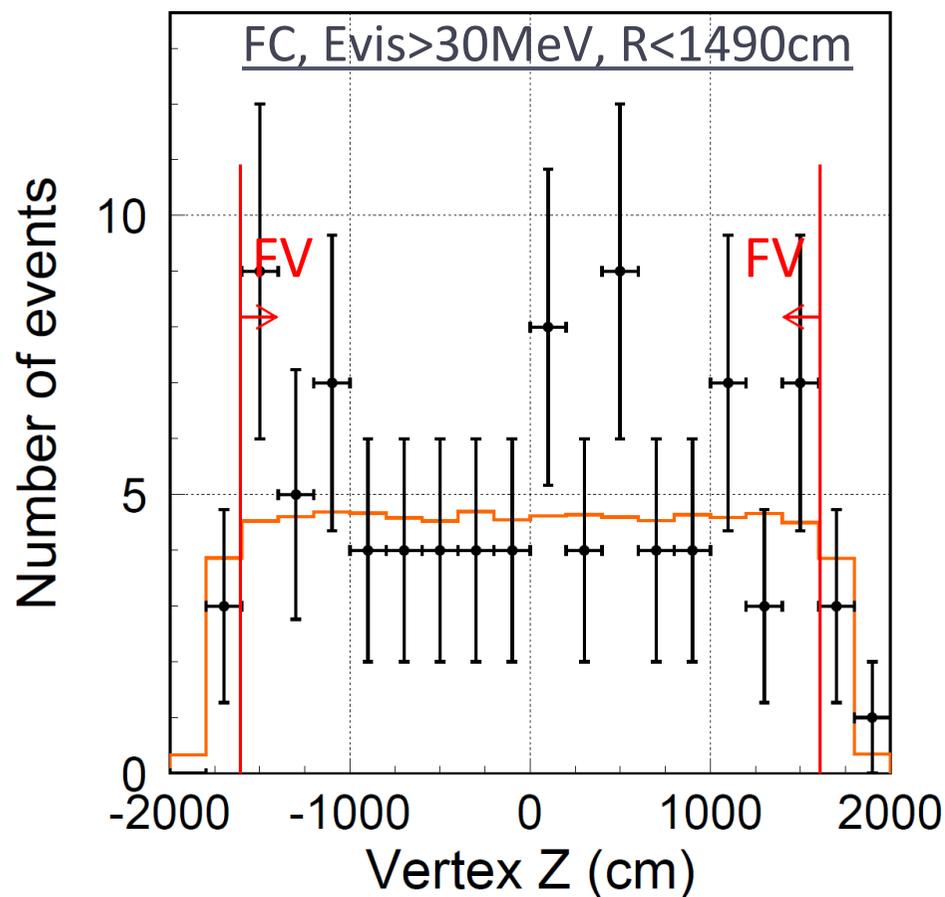
The accidental contamination from atmospheric ν background is estimated using the sideband events to be 0.023

Apply ν_e event selection

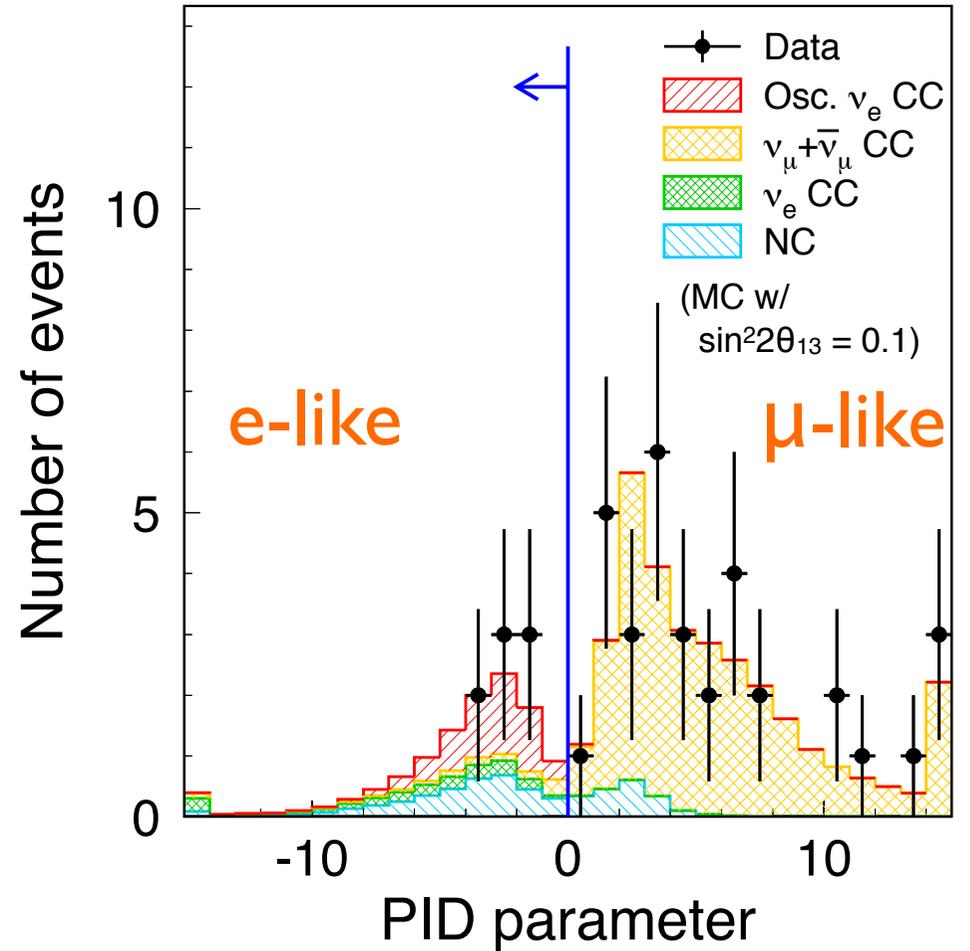
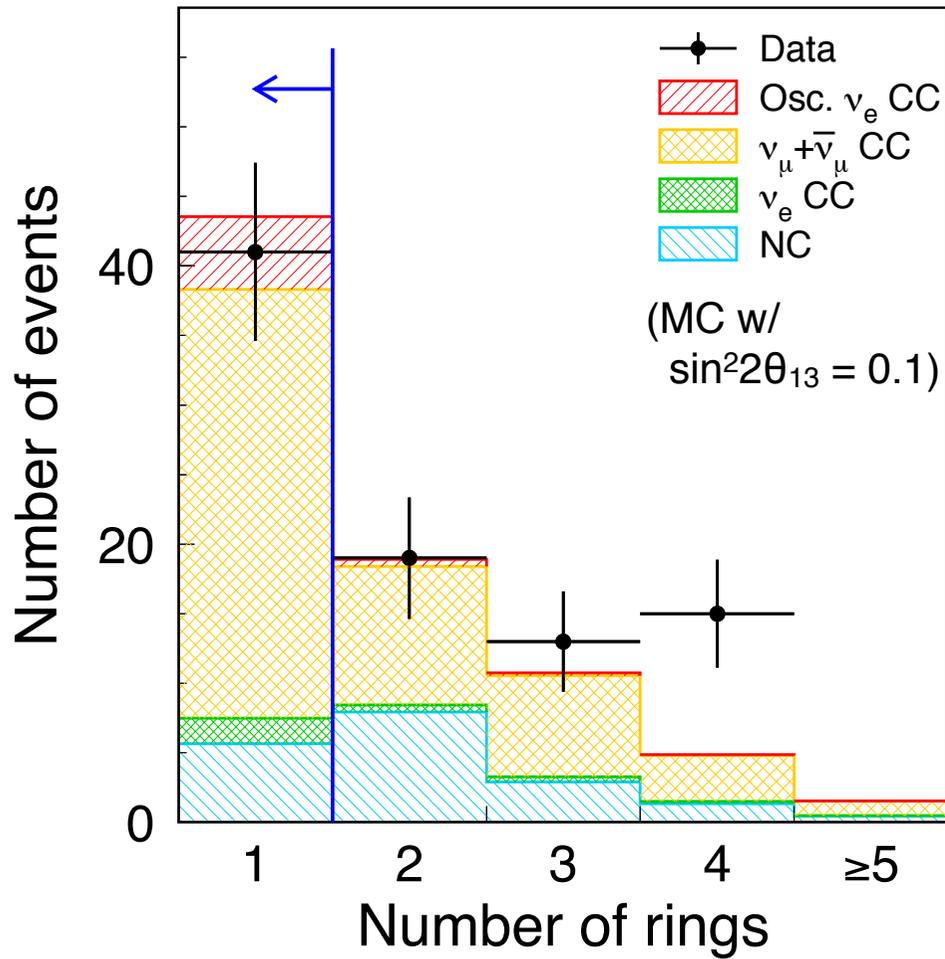
defined before the data collection
6 selection cuts in addition FC cut

Fiducial volume cut

(distance between recon. vertex and wall $> 200\text{cm}$)

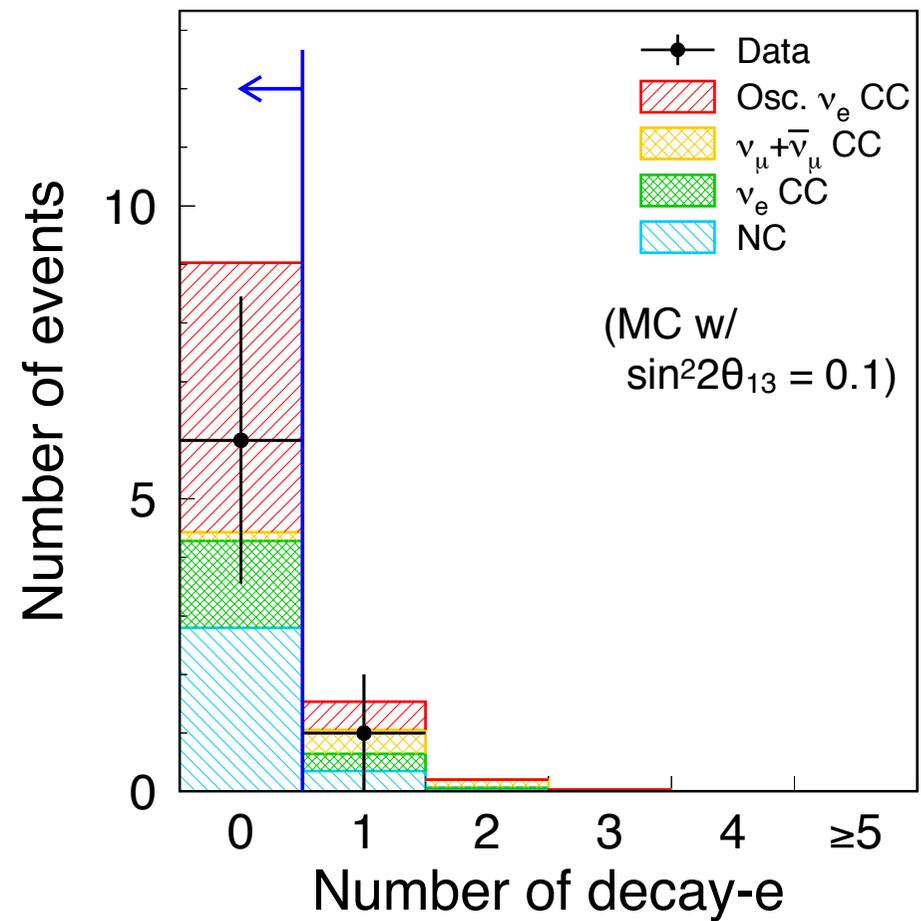
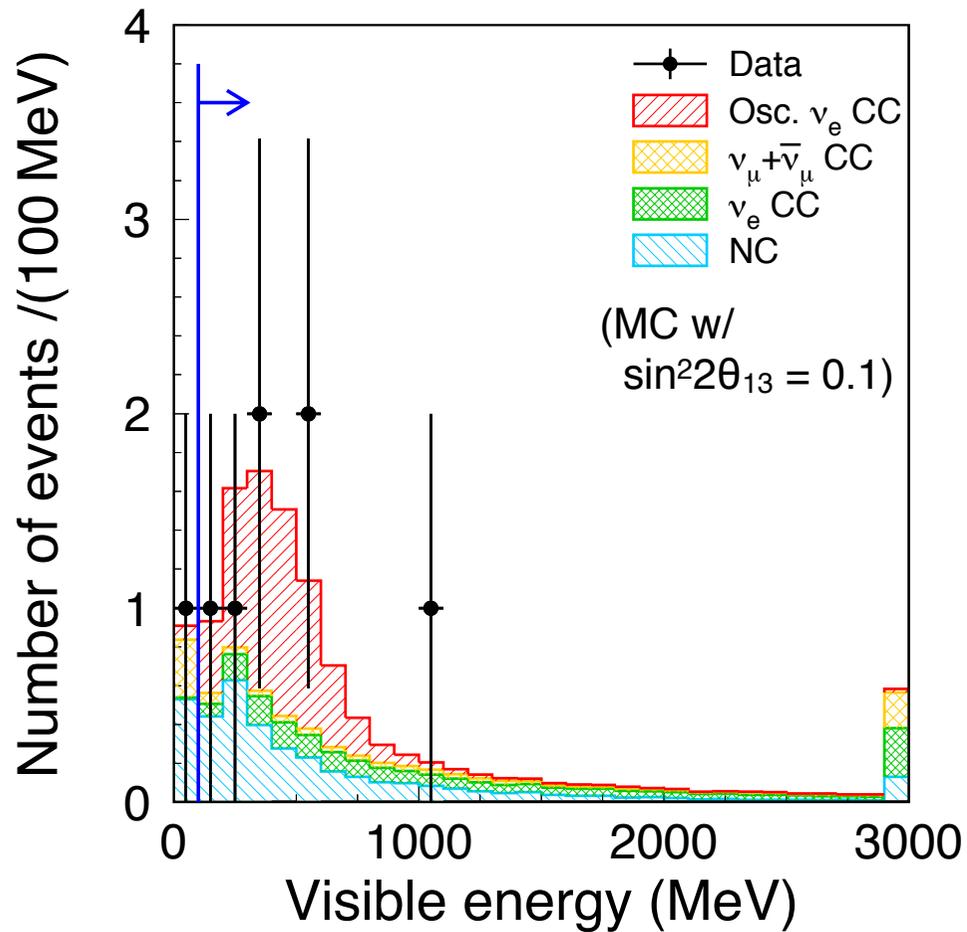


Single electron cut (# of ring is one & e-like)

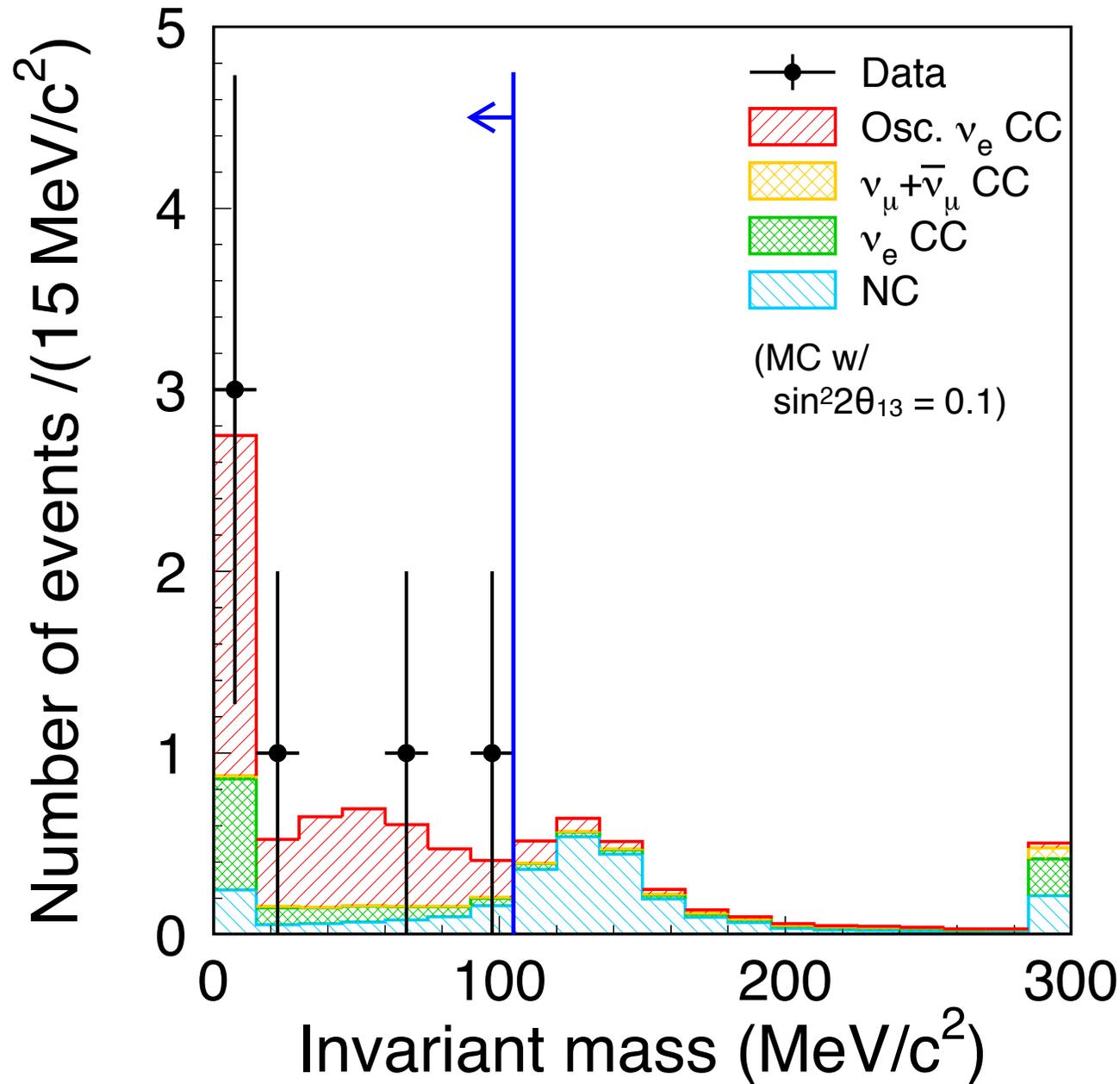


Visible energy > 100 MeV

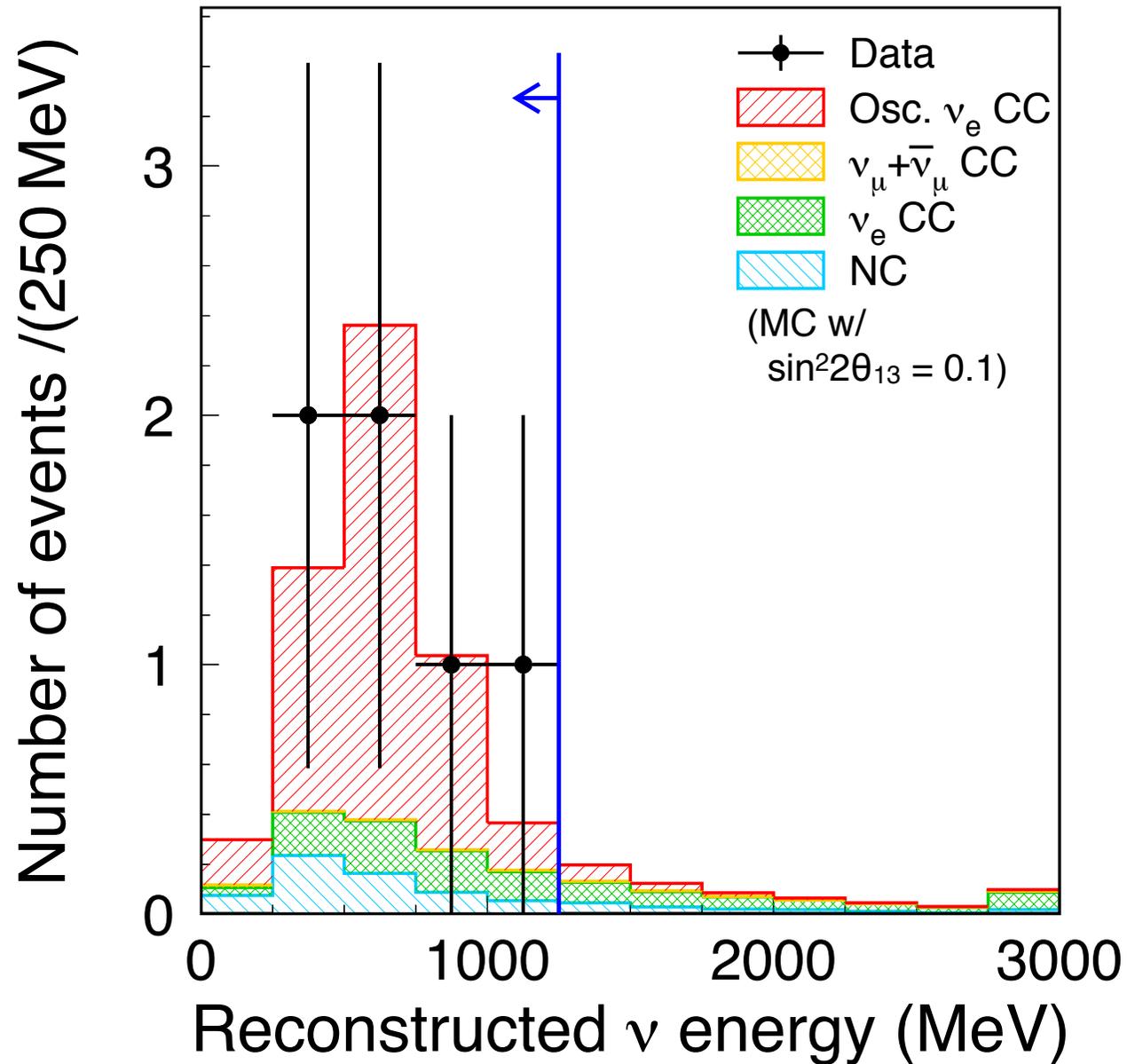
No decay electron



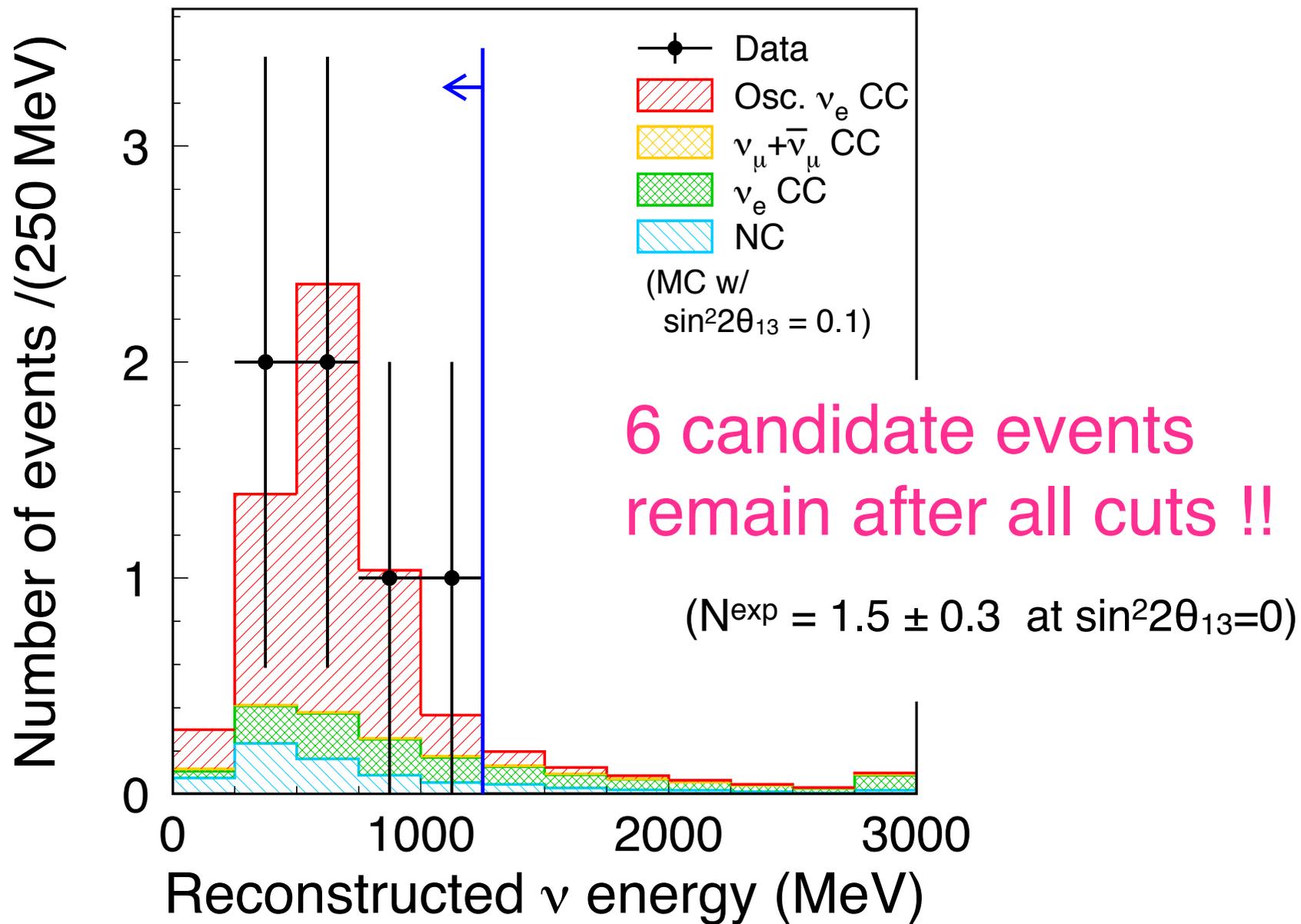
Invariant mass cut ($M_{inv} < 105 \text{ MeV}/c^2$)



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



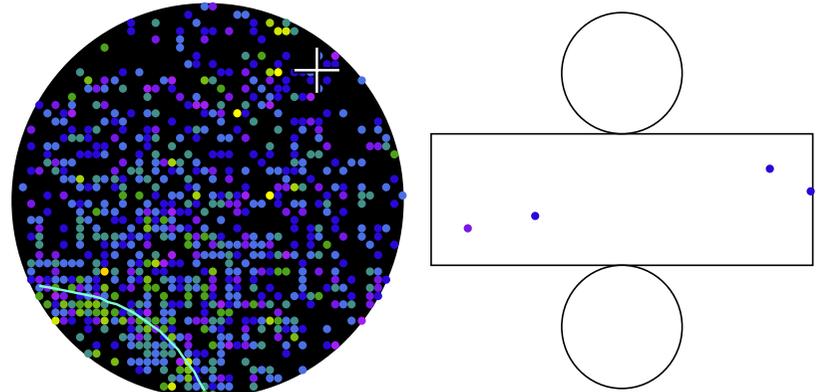
Reconstructed ν energy cut ($E_{\text{rec}} < 1250 \text{ MeV}$) : *Final cut*



ν_e candidate event

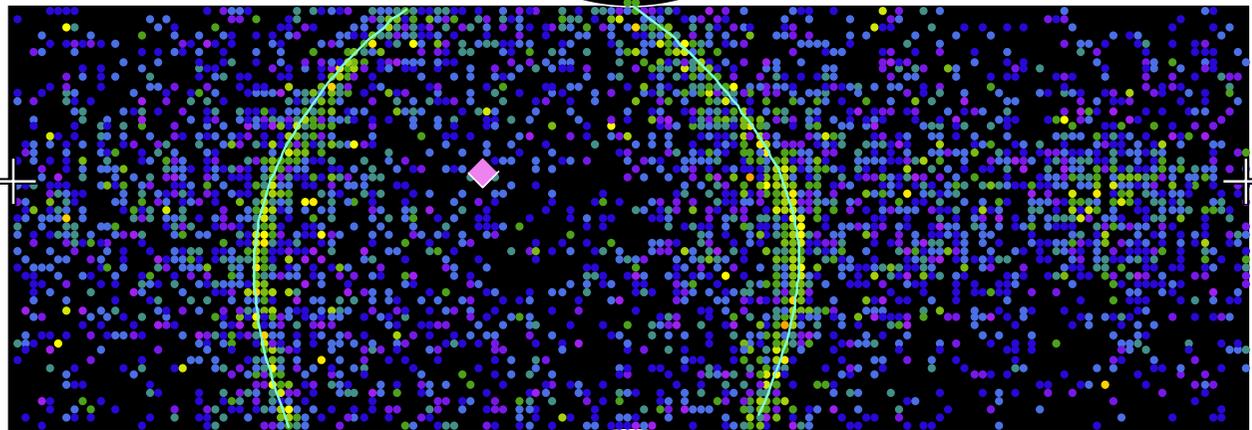
Super-Kamiokande IV

T2K Beam Run 0 Spill 1039222
Run 67969 Sub 921 Event 218931934
10-12-22:14:15:18
T2K beam dt = 1782.6 ns
Inner: 4804 hits, 9970 pe
Outer: 4 hits, 3 pe
Trigger: 0x80000007
D_wall: 244.2 cm
e-like, p = 1049.0 MeV/c

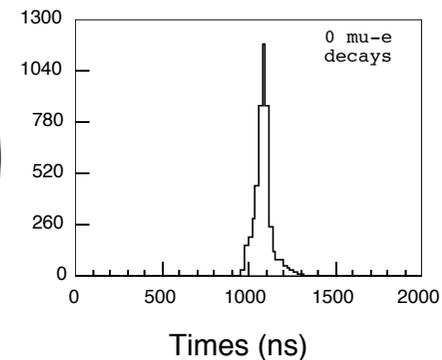
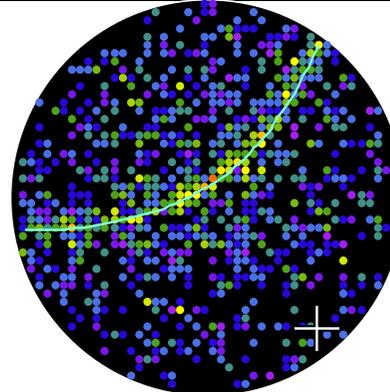


Charge (pe)

- >26.7
- 23.3-26.7
- 20.2-23.3
- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 8.0-10.0
- 6.2- 8.0
- 4.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2

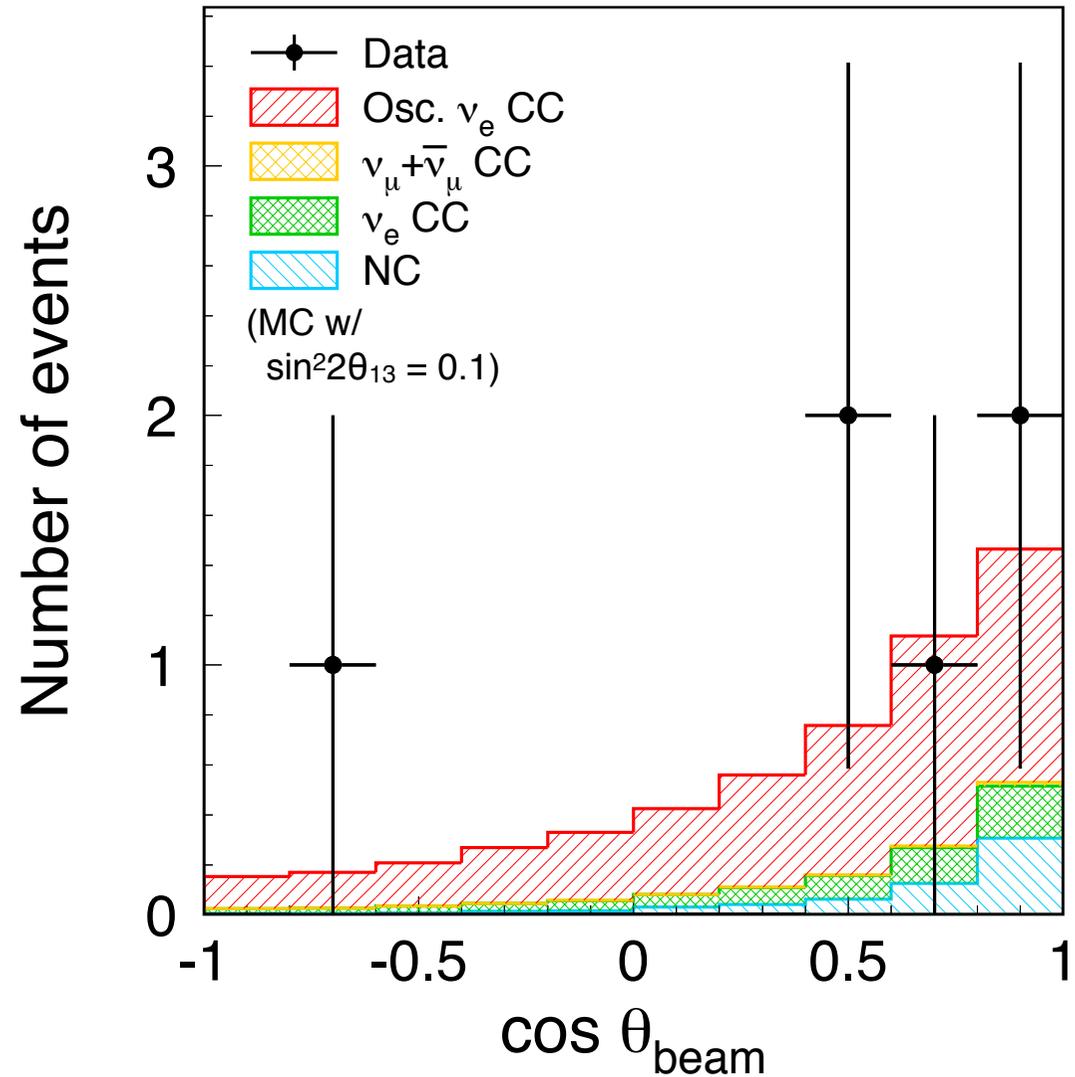
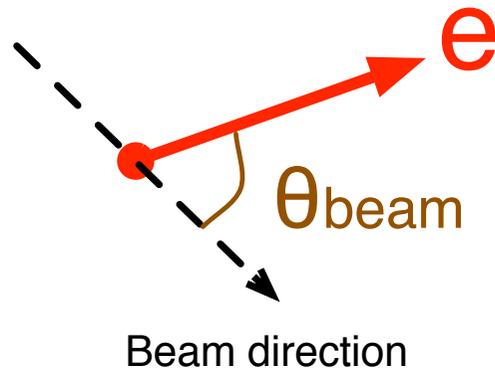


visible energy : 1049 MeV
of decay-e : 0
2 γ Inv. mass : 0.04 MeV/c²
recon. energy : 1120.9 MeV

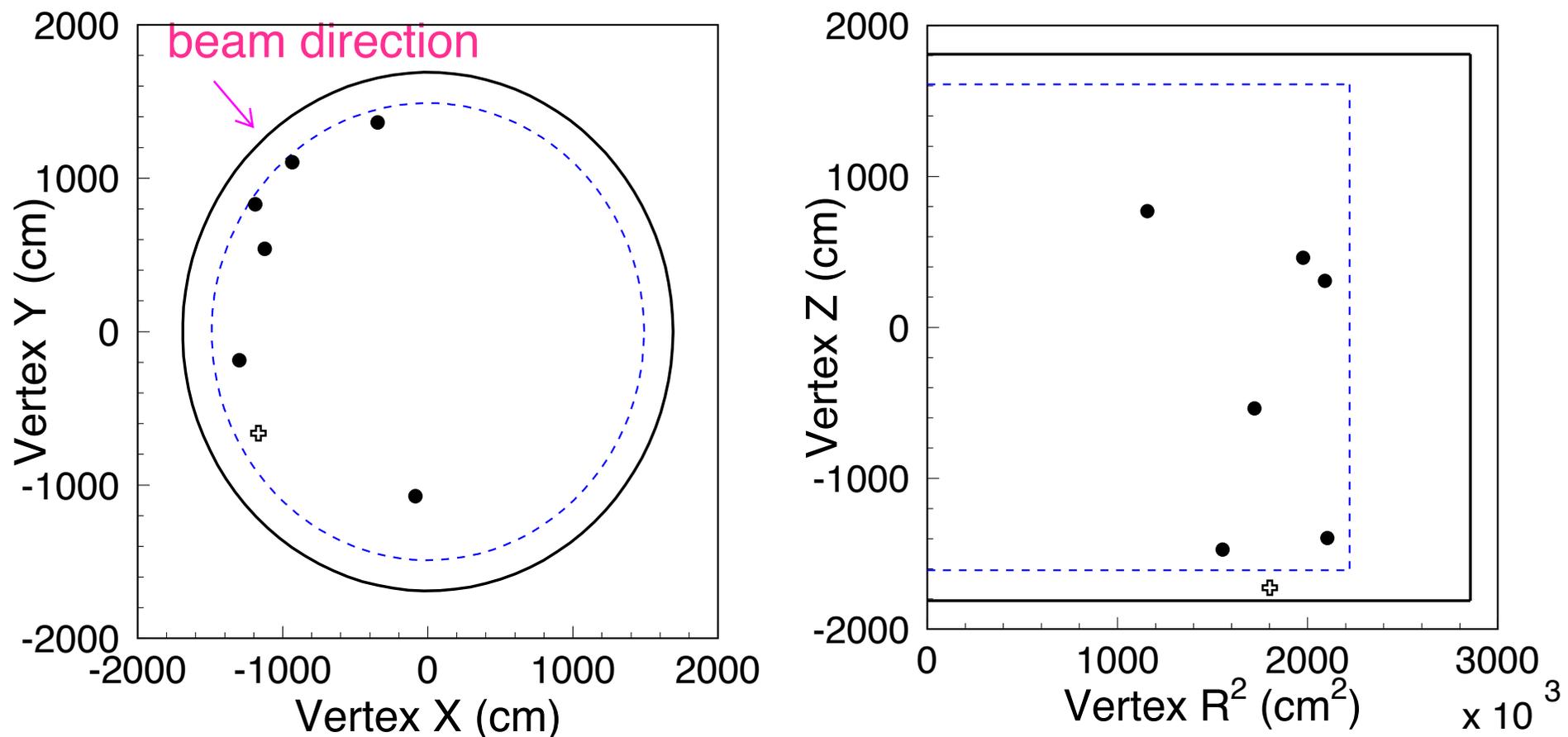


Further check

Check several distribution of ν_e candidate events



Vertex distribution of ν_e candidate events



These events are clustered 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 R² distribution yields a p-value of 0.03

⊕ Event outside FV

Results for ν_e appearance search with 1.43×10^{20} p.o.t.

The observed number of events is **6**

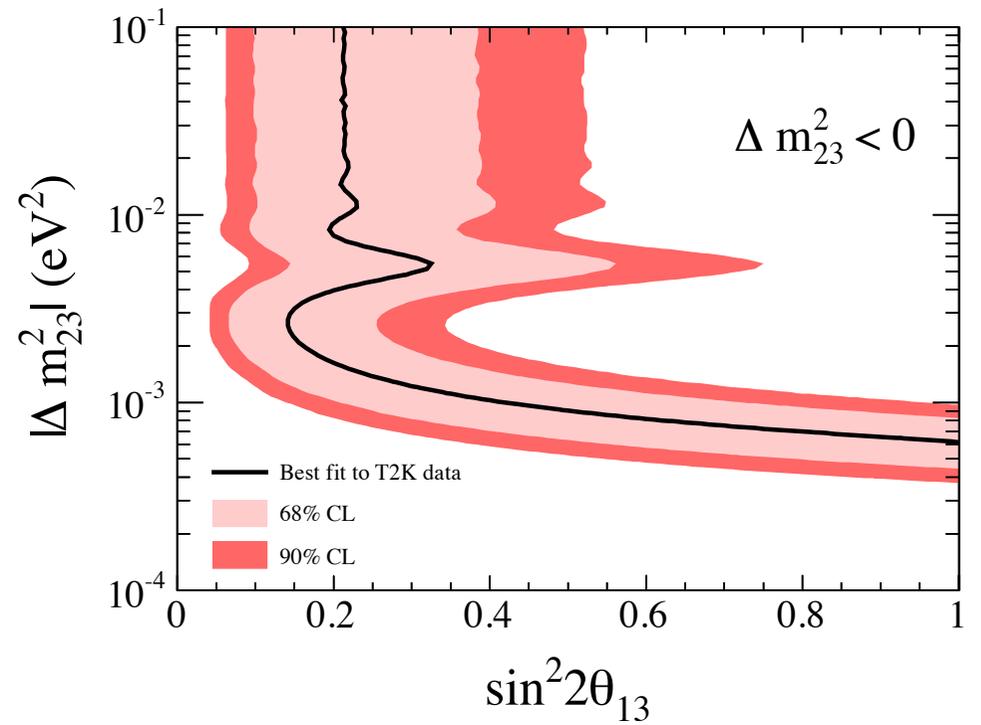
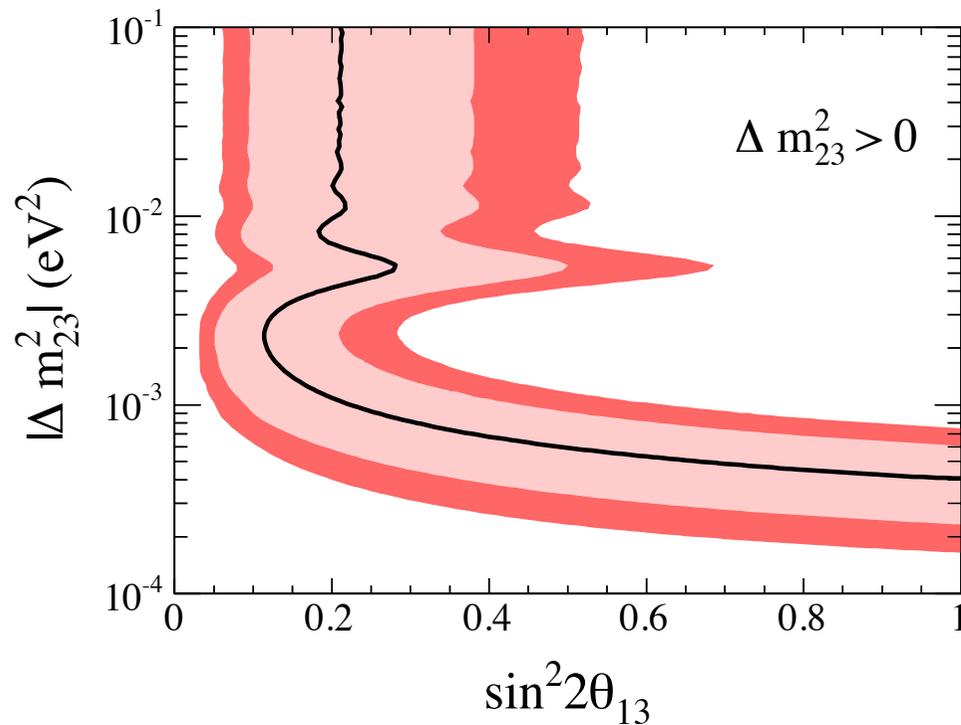
The expected number of events is **1.5 ± 0.3**

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

Under the $\theta_{13}=0$ hypothesis, the probability to observe six or more candidate events is 0.007 (equivalent to 2.5σ significance)

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

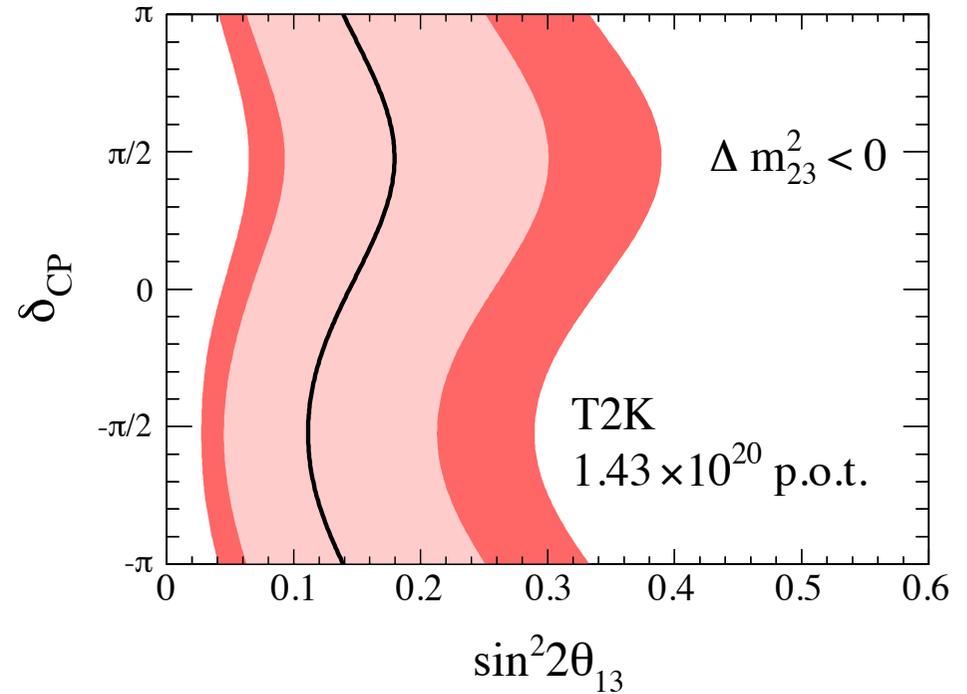
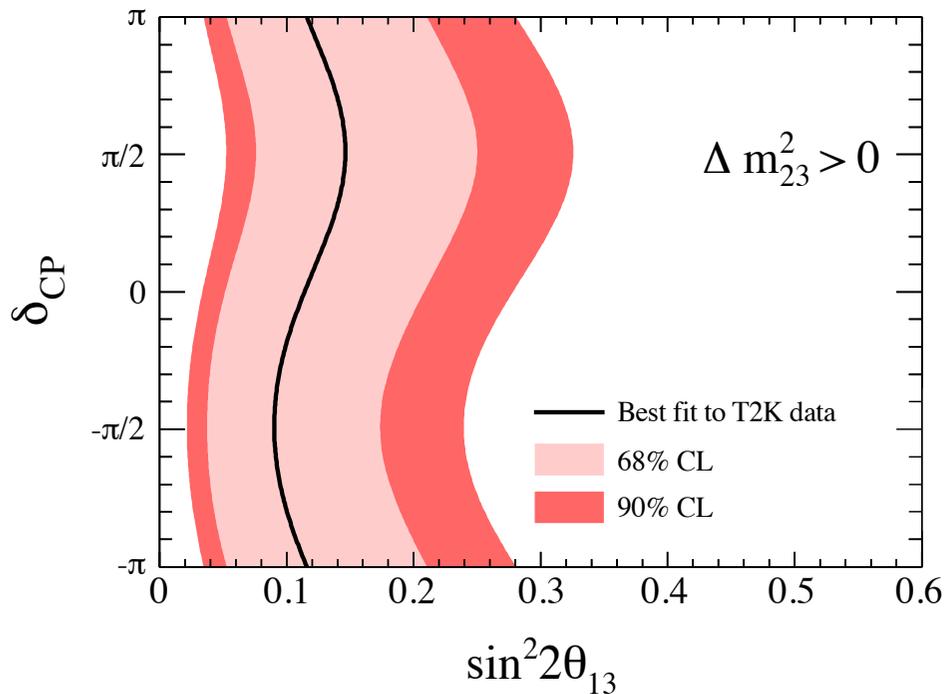
(assuming $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)



Feldman-Cousins method was used

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

(assuming $\Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{23} = 1$)



90% C.L. interval & Best fit point (assuming $\Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{23} = 1$, $\delta_{CP} = 0$)

$$0.03 < \sin^2 2\theta_{13} < 0.28$$

$$\sin^2 2\theta_{13} = 0.11$$

$$0.04 < \sin^2 2\theta_{13} < 0.34$$

$$\sin^2 2\theta_{13} = 0.14$$

T2K Next steps

Aim for firmly establishing ν_e appearance and better determining the angle θ_{13}

- Resume experiment
 - Recovery works in progress
 - We will resume J-PARC activity including accelerator complex and neutrino facility by December, 2011
 - Neutrino facility will be ready by November
- Analysis improvement
 - New analysis methods using ν_e signal shape (e.g. recon. energy) are under development

Conclusion

- We reported new results on $\nu_\mu \rightarrow \nu_e$ oscillation analysis based on 1.43×10^{20} p.o.t. (2% exposure of T2K's goal)
 - The expected number of events is 1.5 ± 0.3 ($\sin^2 2\theta_{13} = 0$)
 - 6 candidate events are observed
 - Under $\theta_{13}=0$ hypothesis, the probability to observe 6 or more candidate events is 0.007 (equivalent to 2.5σ significance)
 - 0.03 (0.04) $< \sin^2 2\theta_{13} < 0.28$ (0.34) at 90% C.L. for normal (inverted) hierarchy (assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV², $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

Indication of ν_e appearance

submitted to PRL

- Resume experiment as soon as possible and improve analysis method to conclude ν_e appearance phenomenon
- ν_μ disappearance result with 1.43×10^{20} p.o.t. data will be reported this summer