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 x 10^{20} protons on target (p.o.t.)

(Previous results w/ 0.32 x 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 $\nu_\mu \rightarrow \nu_e$

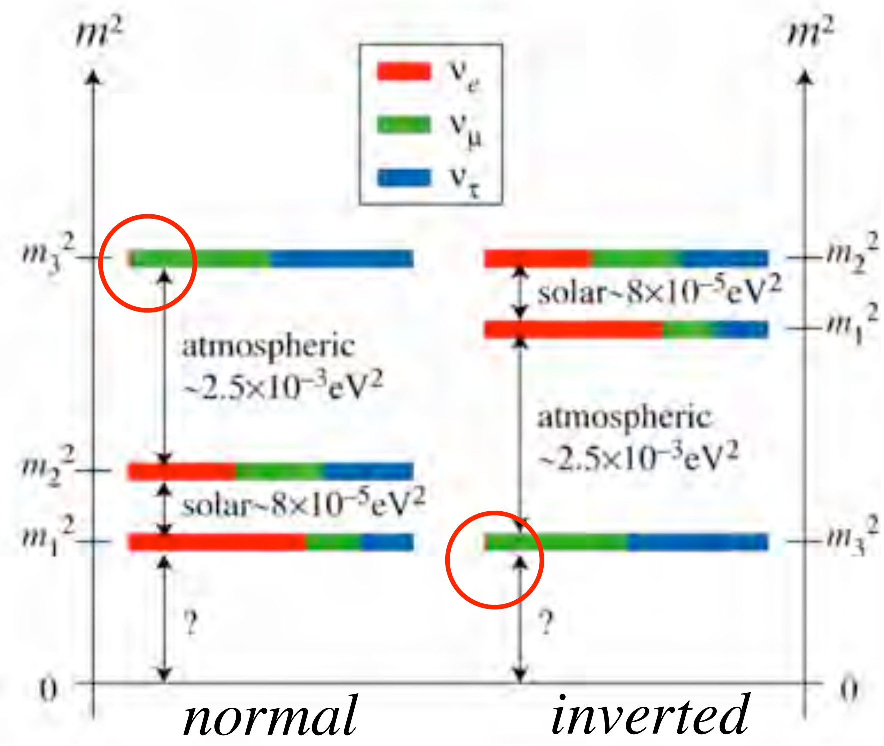
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E) + \ldots$$

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

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: θ_{12}, θ_{23}, θ_{13}

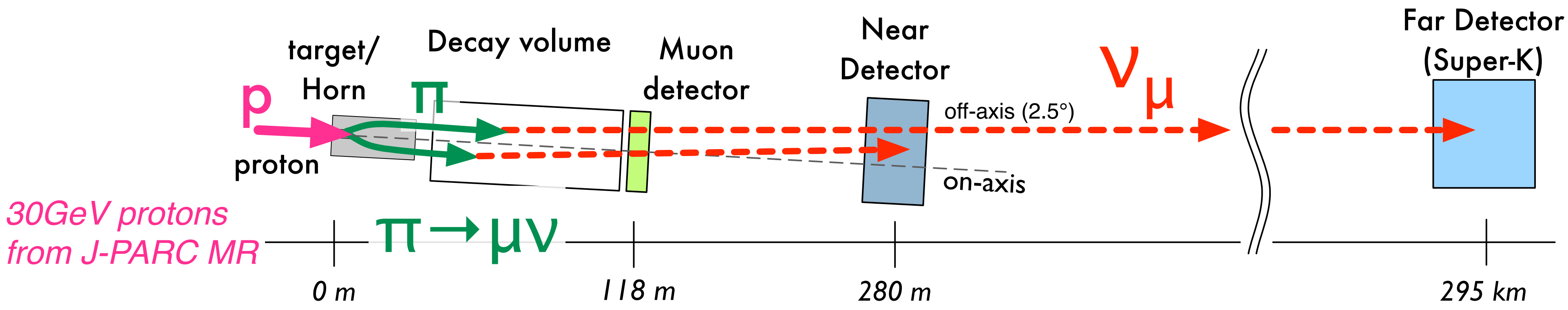
$\theta_{12} = 34° \pm 3°$ $\theta_{23} = 45° \pm 5°$

Last unknown mixing angle θ_{13}

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

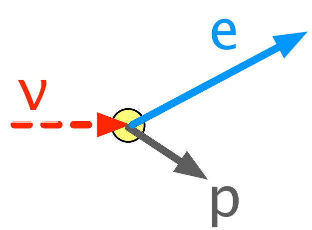
CHOOZ (reactor exp.) and MINOS (accelerator exp.)

Design Principle of T2K



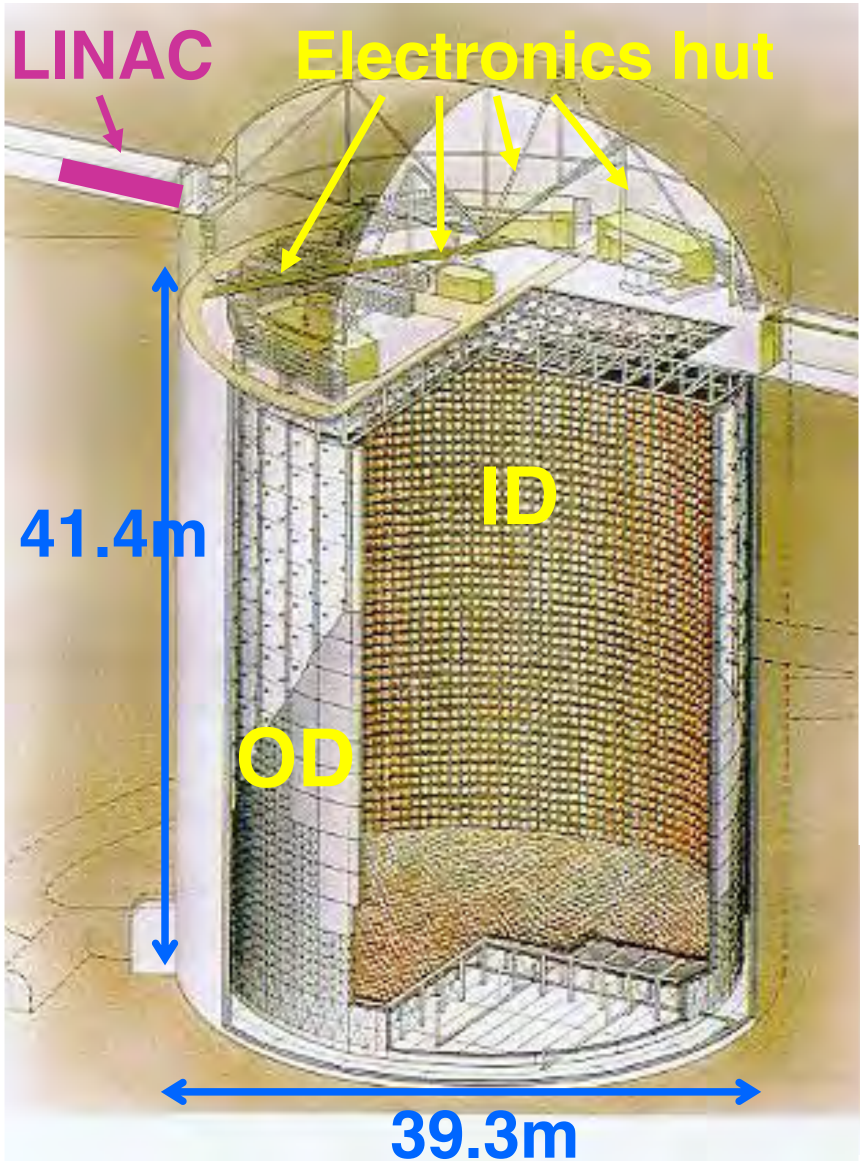
☑ Super-Kamiokande(SK) as far neutrino detector

- 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



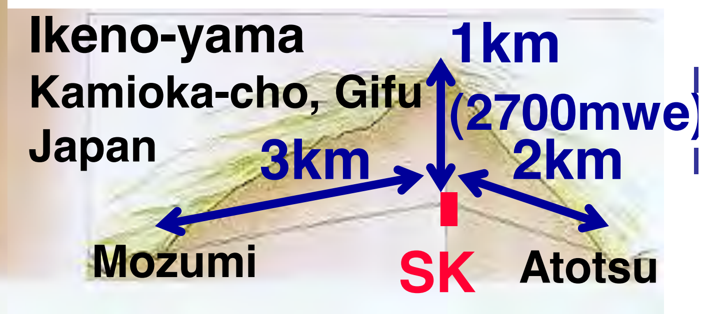
→ *Off-axis beam (The first operational long-baseline off-axis ν beam)*

Far detector (Super-K)

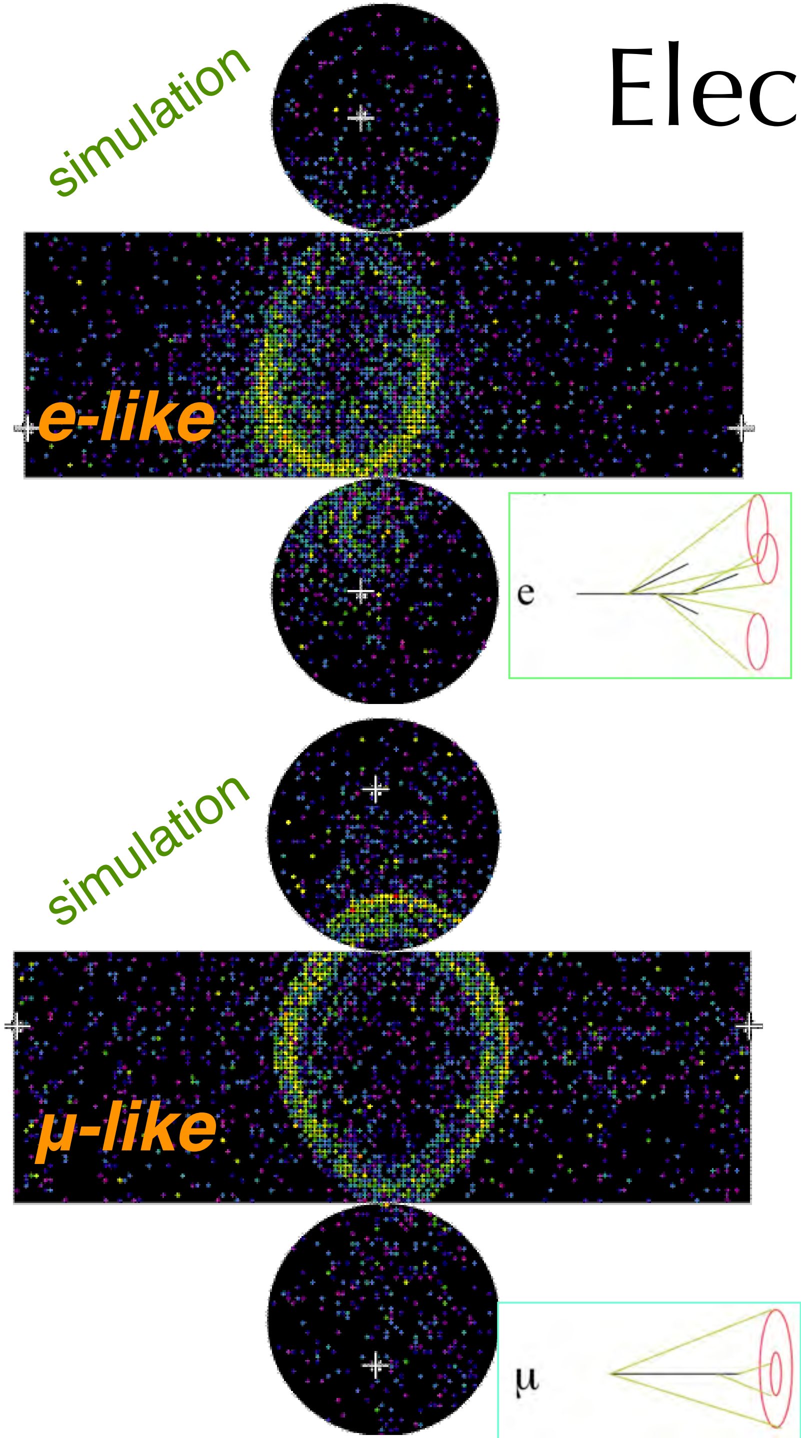


~11000 x 20inch PMTs (inner detector, ID)

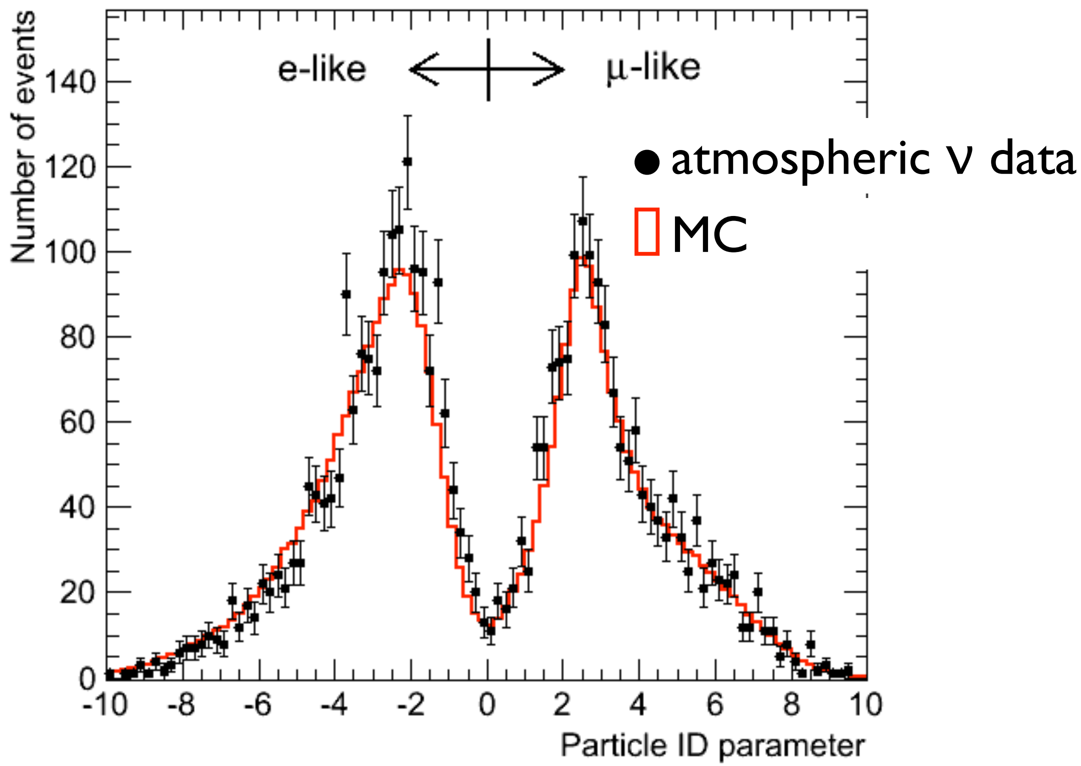
- Stable operation since April 1996
- Water Cherenkov detector w/ fiducial volume 22.5kton
- Dead-time less DAQ system (2008~)
- Detector performance is well-matched at sub GeV
  - Excellent performance for single particle event
  - Good e-like(shower ring) / μ-like separation *(next page)*



Electron-like and muon-like event at SK

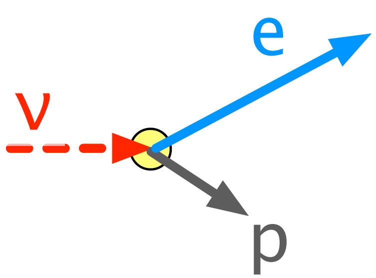


Particle identification using ring shape & opening angle

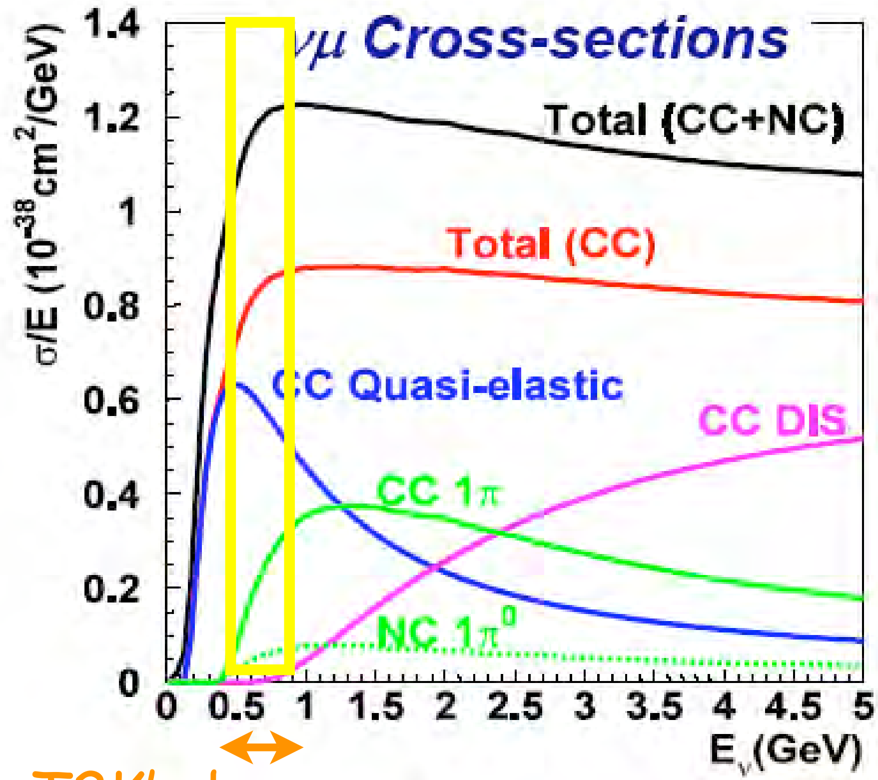


Probability that μ is mis-identified as electron is ~1%

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



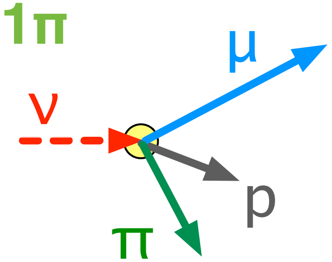
CCQE: $\nu_{e(\mu)} + n \rightarrow e(\mu) + p$
(T2K signal)

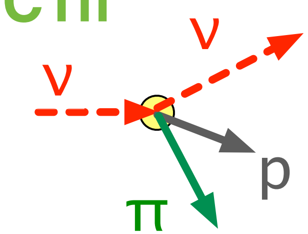


T2K's beam energy

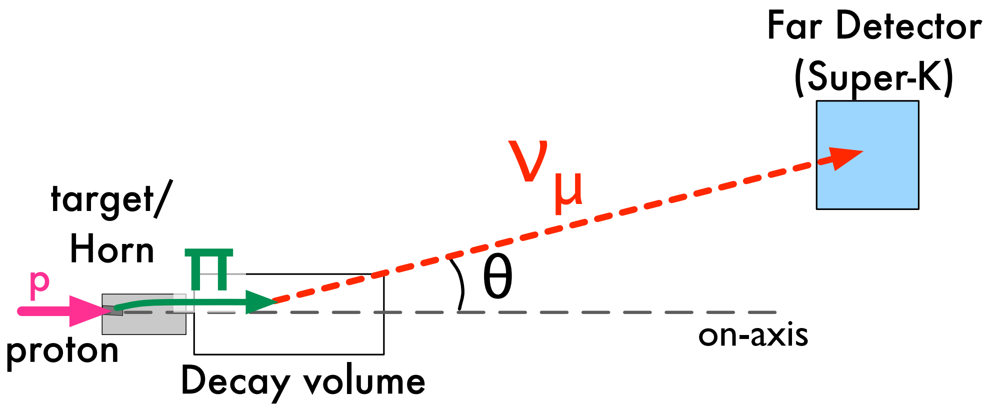
ν interactions at high energy cause background events in T2K
(e.g. $NC1\pi^0$ is one of ν_e background)

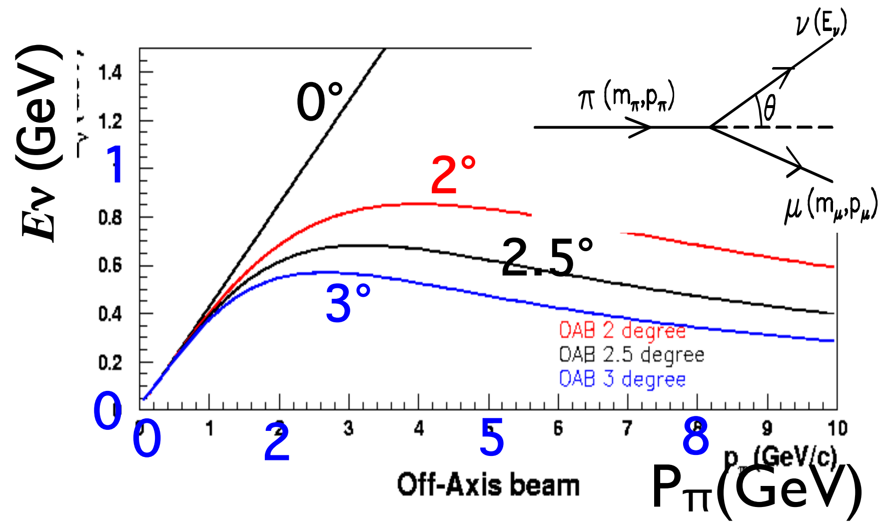
→ ***need to reduce high energy ν***

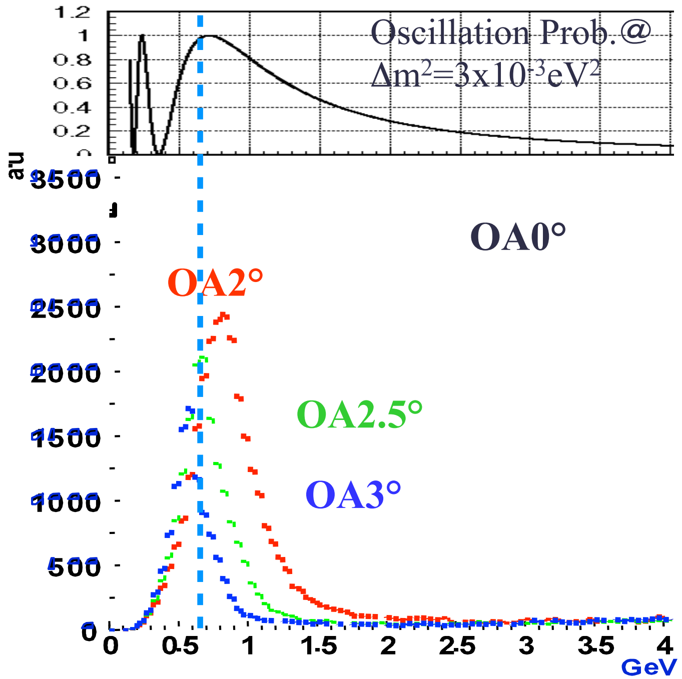




Off-axis beam : intense & narrow-band beam







Beam energy at oscillation max.

E_ν ~ 0.6 GeV (based on Δm^2_{23} & L=295km)

→ T2K off-axis angle is 2.5°

(maximize physics sensitivity)

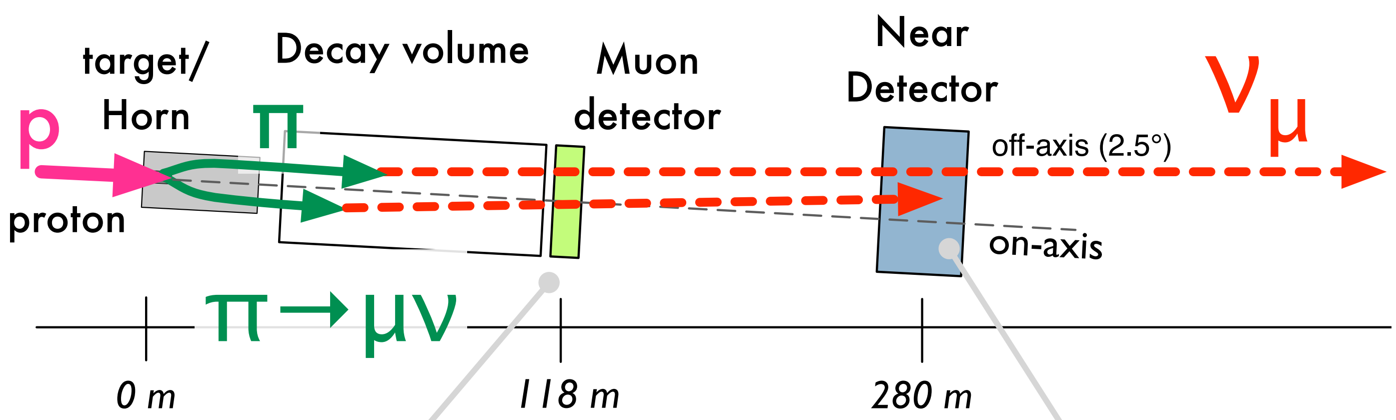
Small high energy tail

→ small background

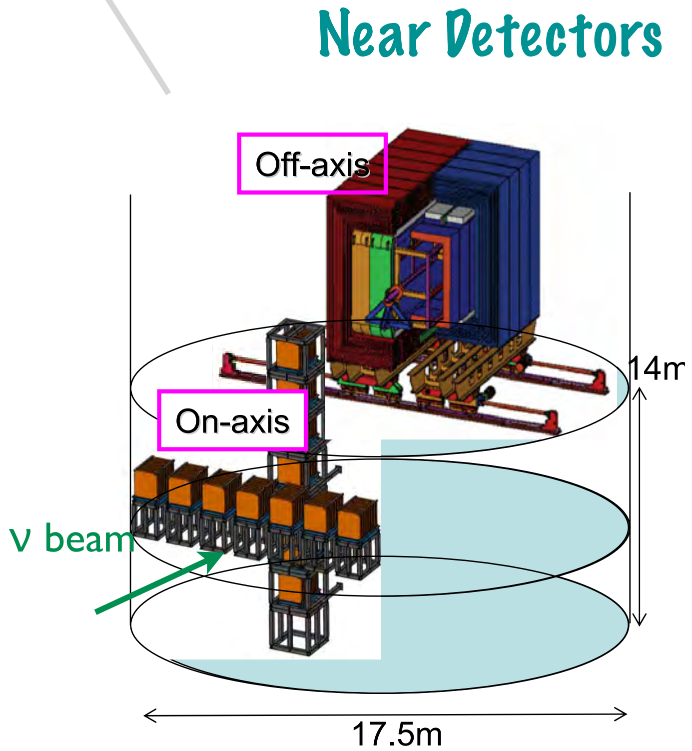
Important to keep beam direction stable

(Keep the peak energy stable)

Monitor beam direction and intensity

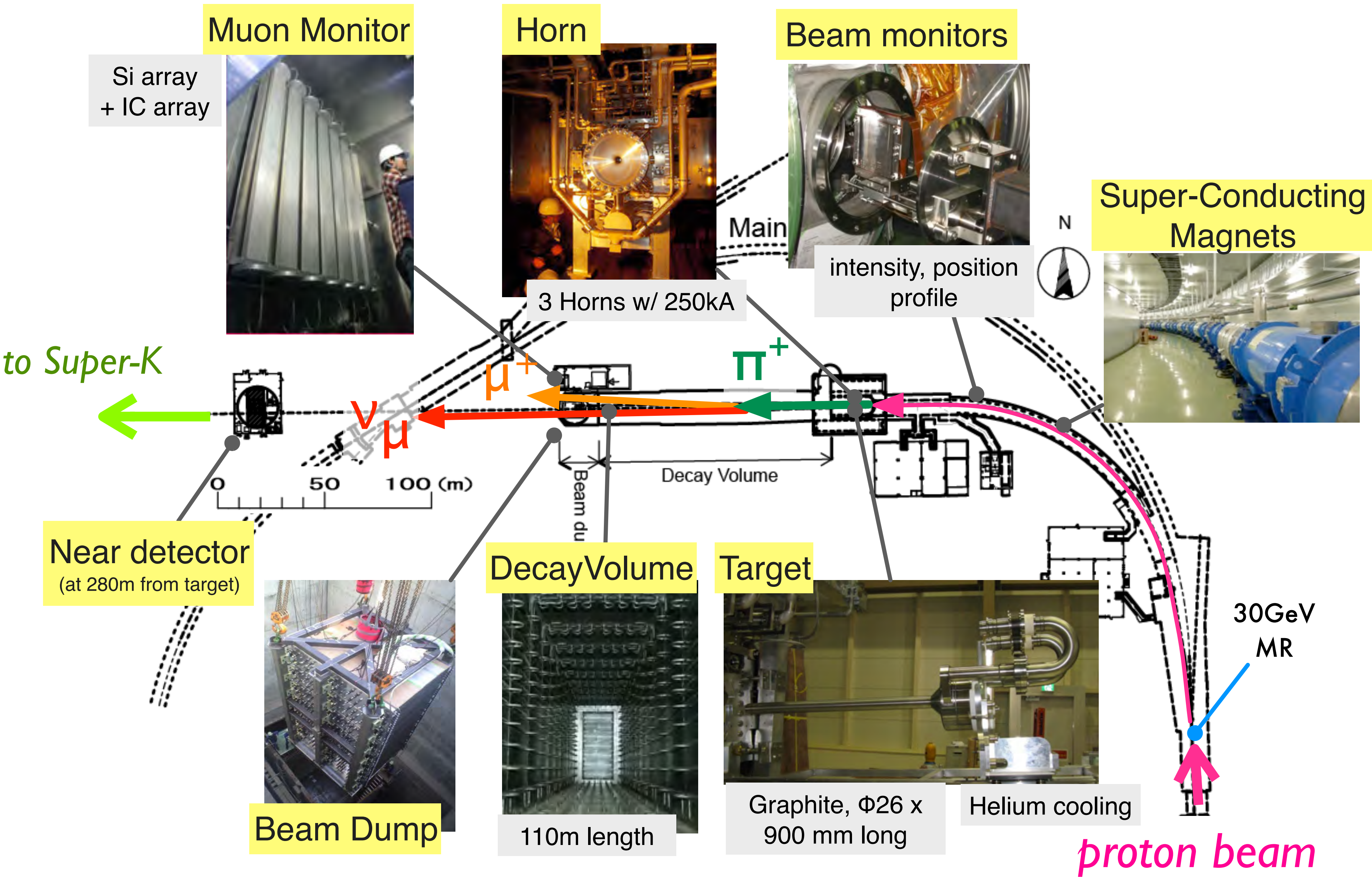


- **Muon monitor**
  - monitor spill-by-spill
- **On-axis INGRID**
  - monitor actual ν beam day-by-day
  - detector coverage is 10m x 10m



Stability of beam direction should be <1mrad
(to keep the peak energy at SK stable δE<2%)

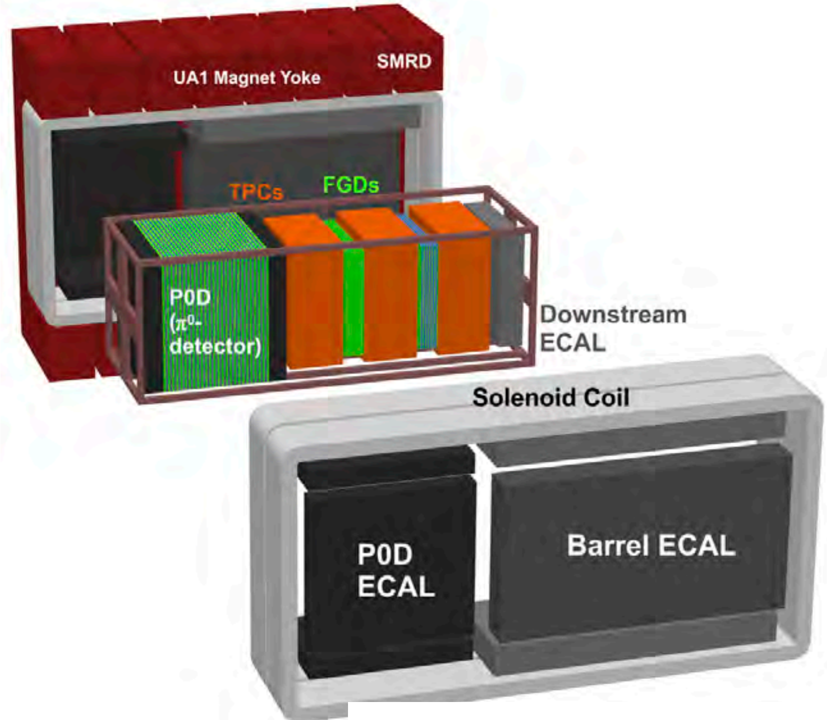
J-PARC Neutrino beam facility

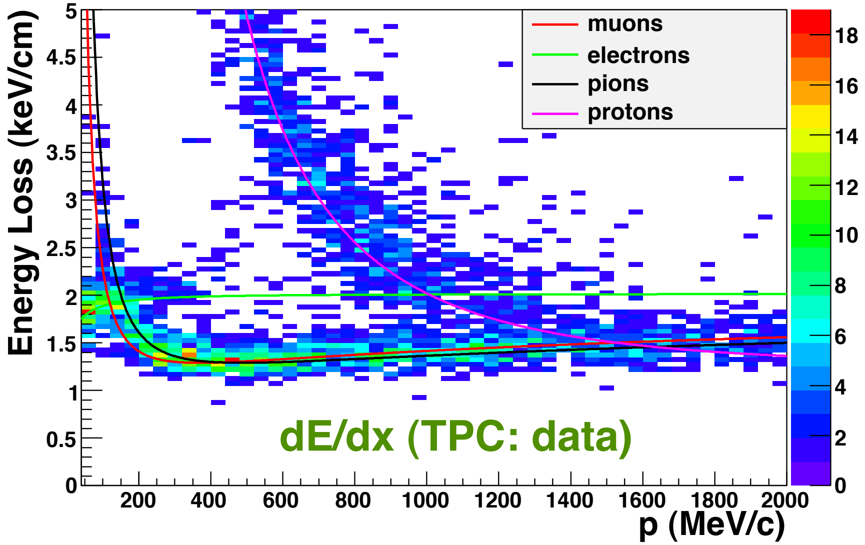


Off-axis Near Detector (ND280)

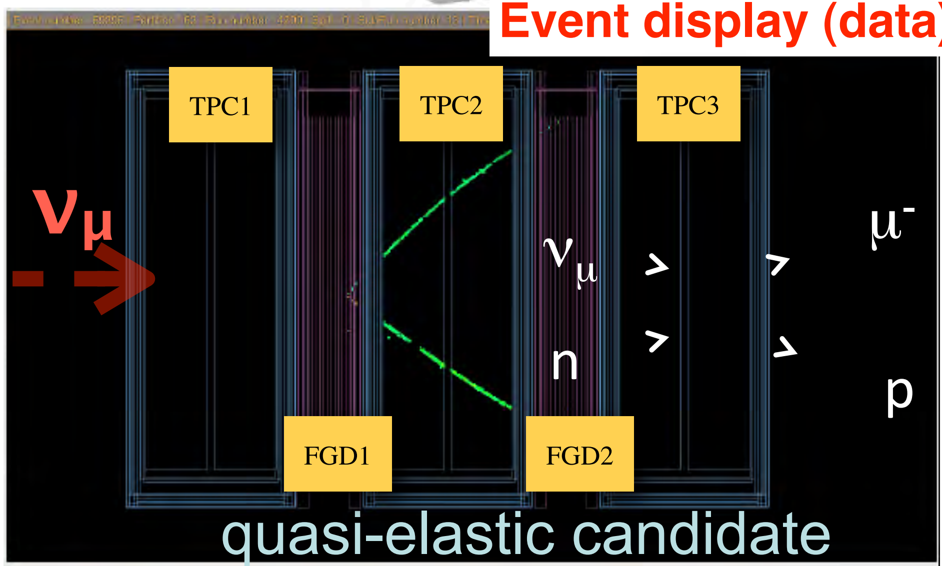
ν_μ CC events rate measurement in present analysis

- 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 1GeV/c

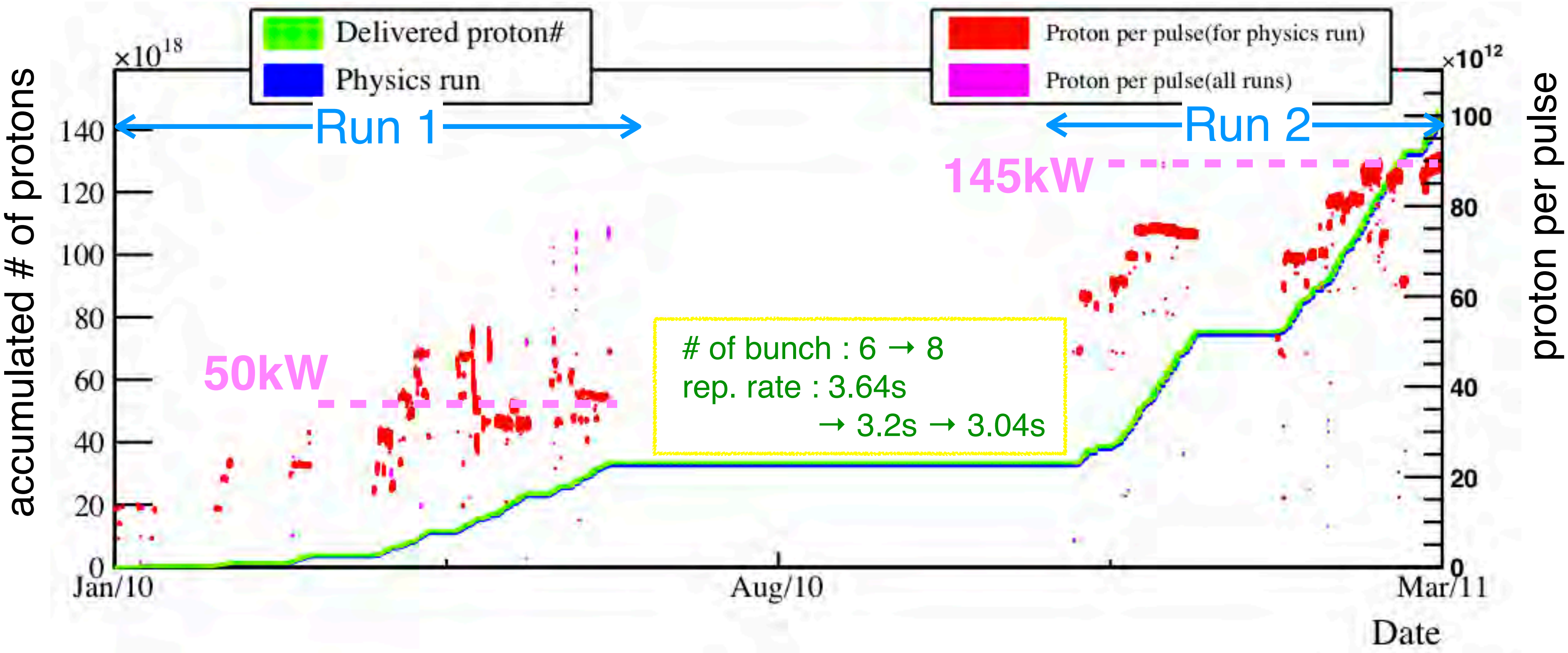




Event display (data)



Total # of protons used for analysis



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

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

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

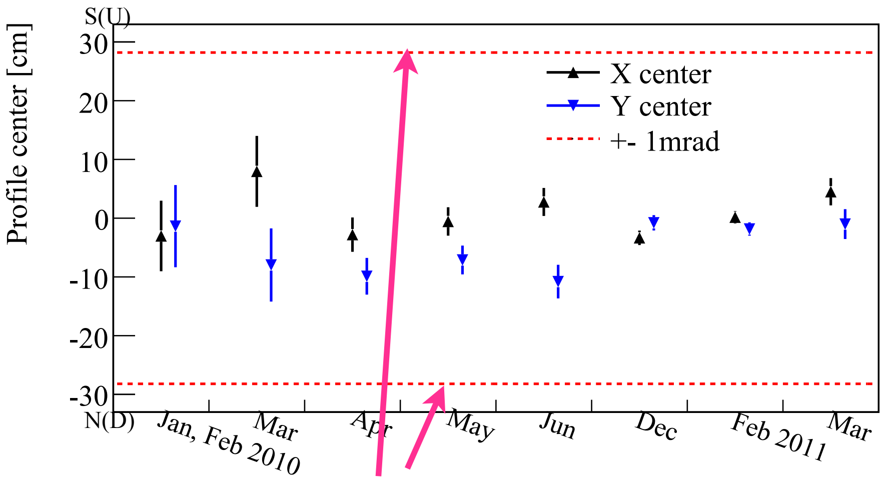
- 11.08 x 10^{19} p.o.t. for analysis
- ~145kW beam operation

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

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

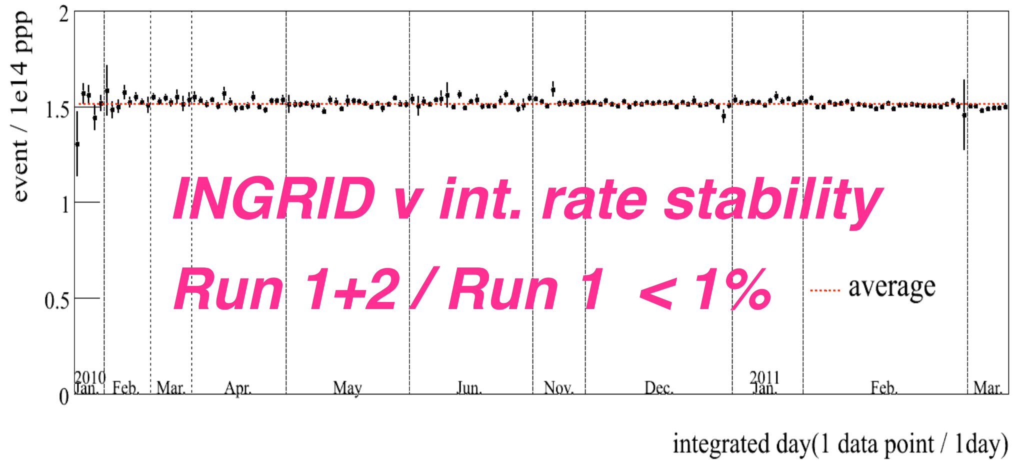
ν beam stability

Stability of ν beam direction (INGRID)



ν beam dir. stability < 1mrad

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

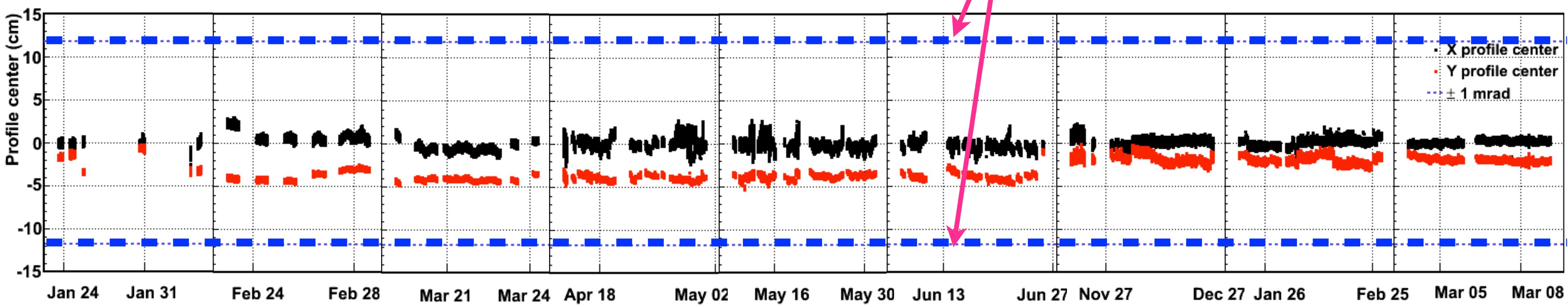


INGRID ν int. rate stability

Run 1+2 / Run 1 < 1%

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**

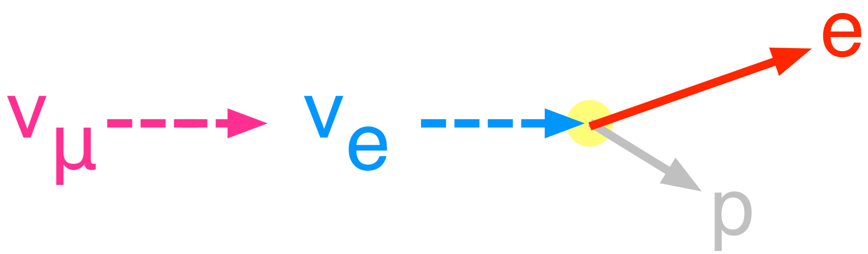
Contents in this section

- 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

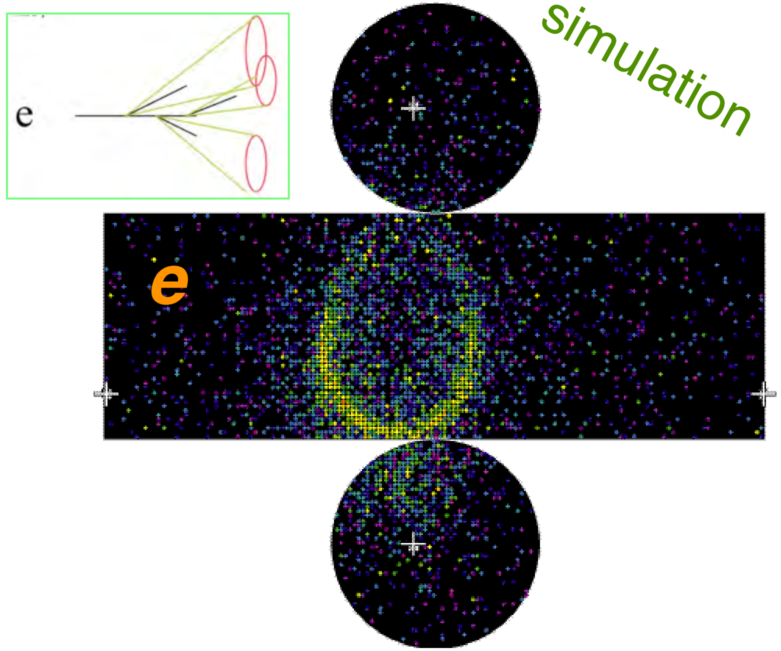
T2K Signal & Background for ν_e appearance

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

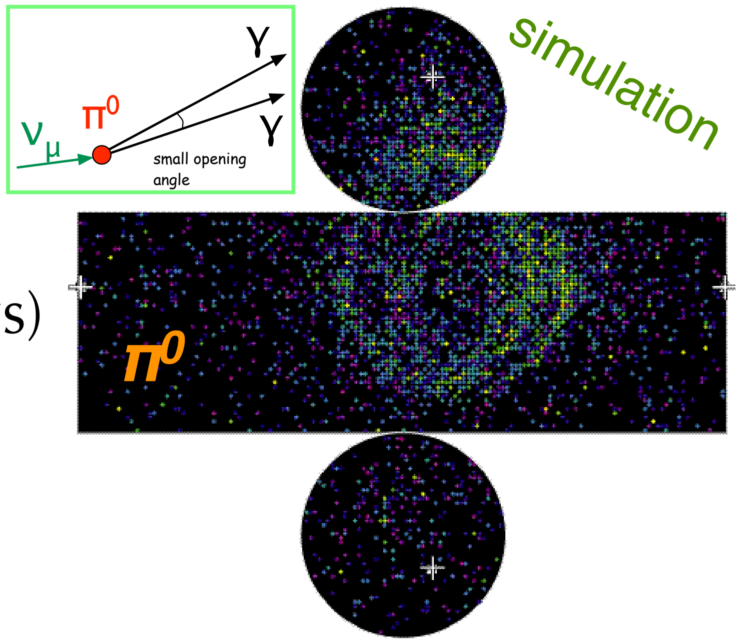


CCQE : $\nu_e + n \to$ **e** $+ p$

(dominant process at T2K beam energy)



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



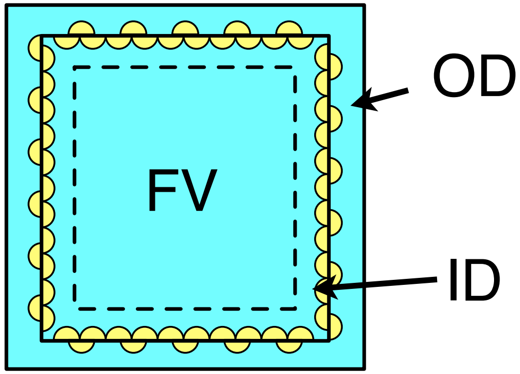
ν_e selection at far detector (SK)

The selection criteria were optimized for initial running condition

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

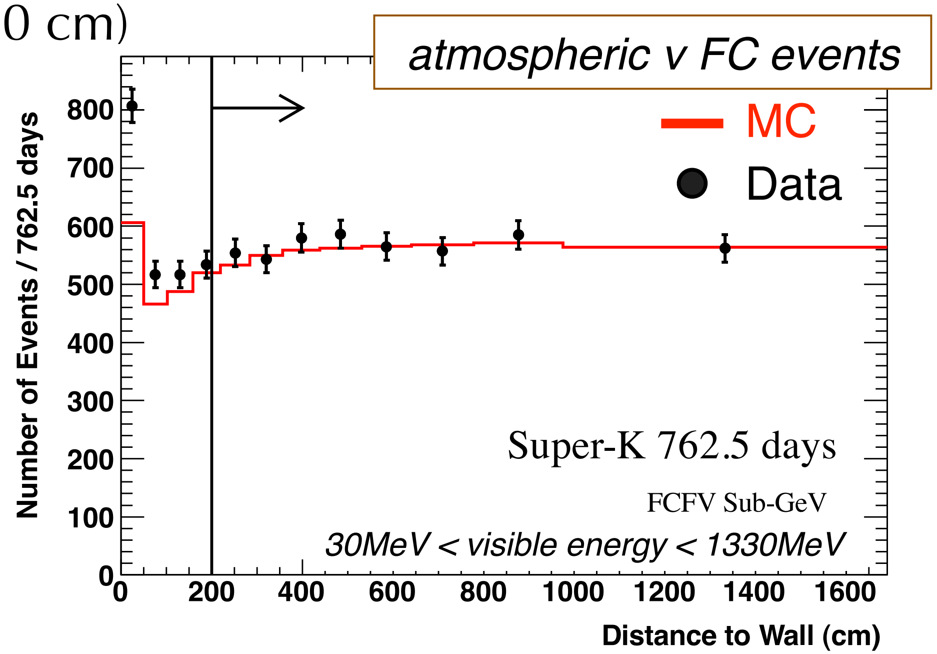
7 selection cuts

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

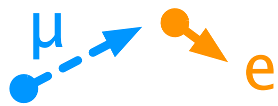


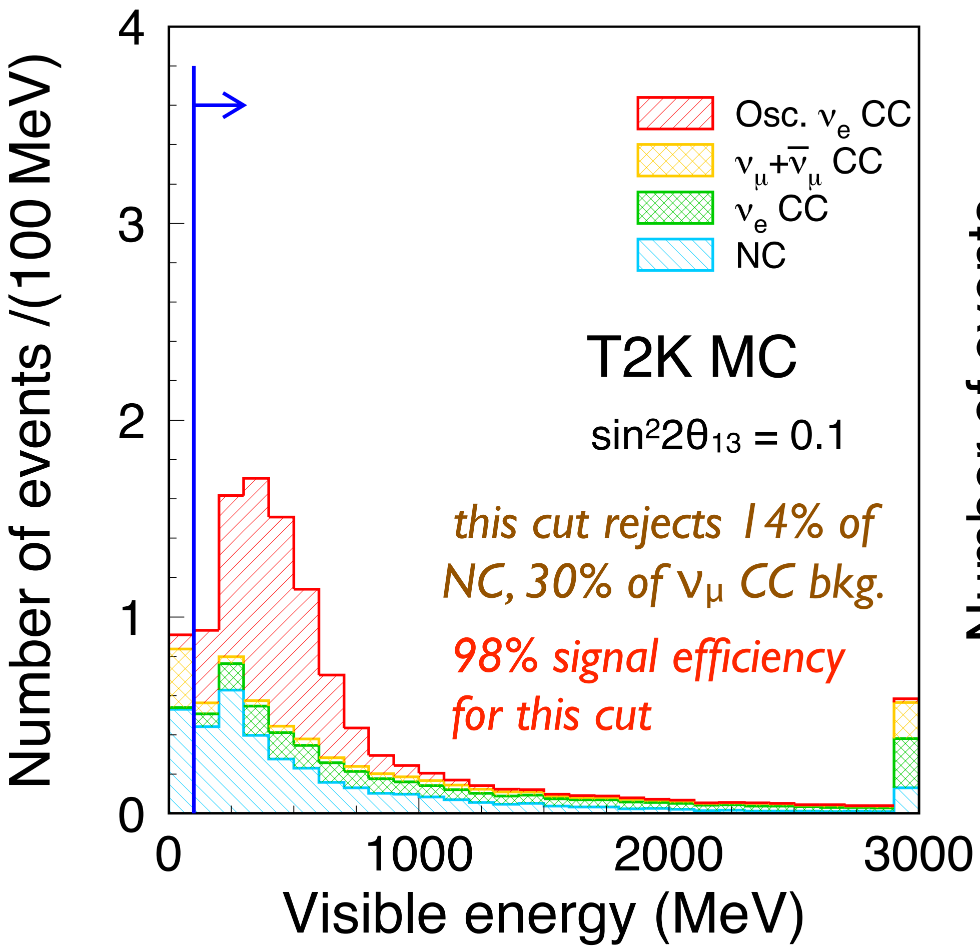
3. Single electron
   (# of ring is one & e-like)

4. Visible energy > 100 MeV

(visible energy = electron energy deposited in ID)

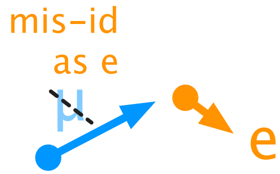
* Reject low energy events, such as NC background and decay electrons produced by invisible muons

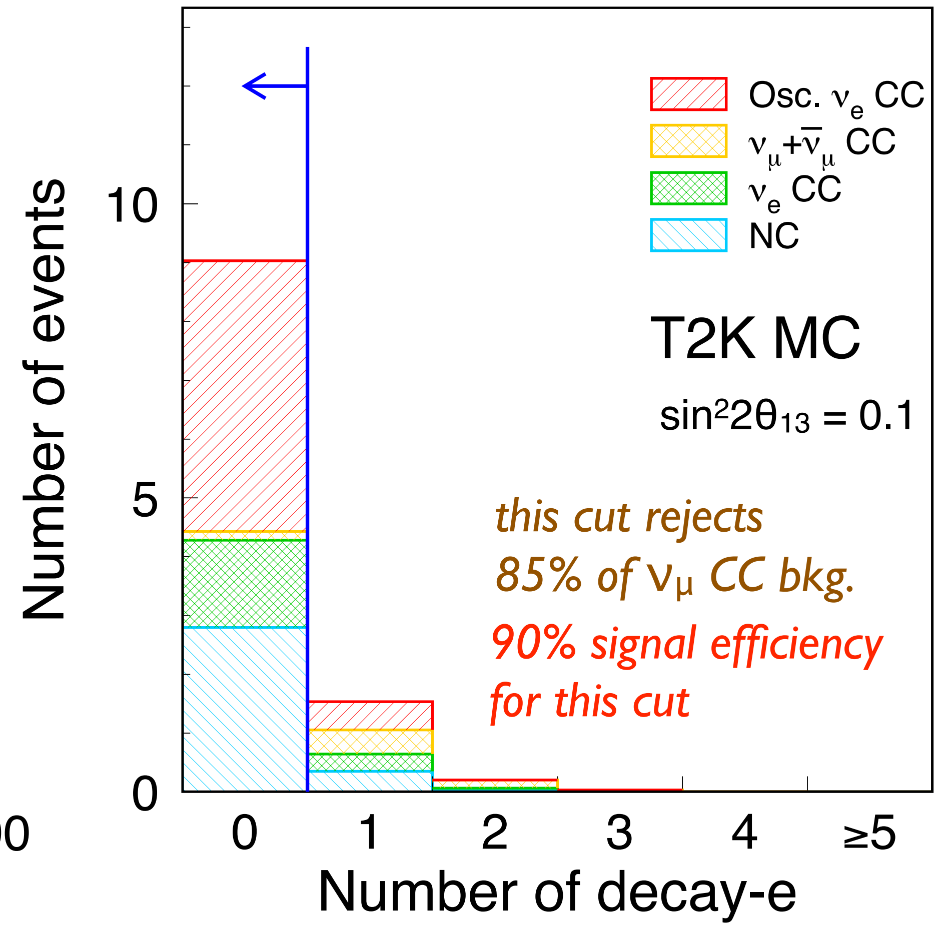




5. No decay electron observed (no delayed electron signal)

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

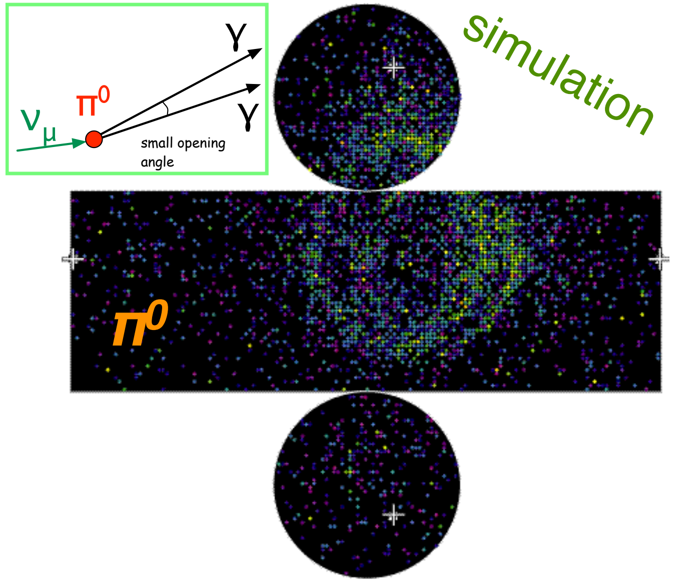


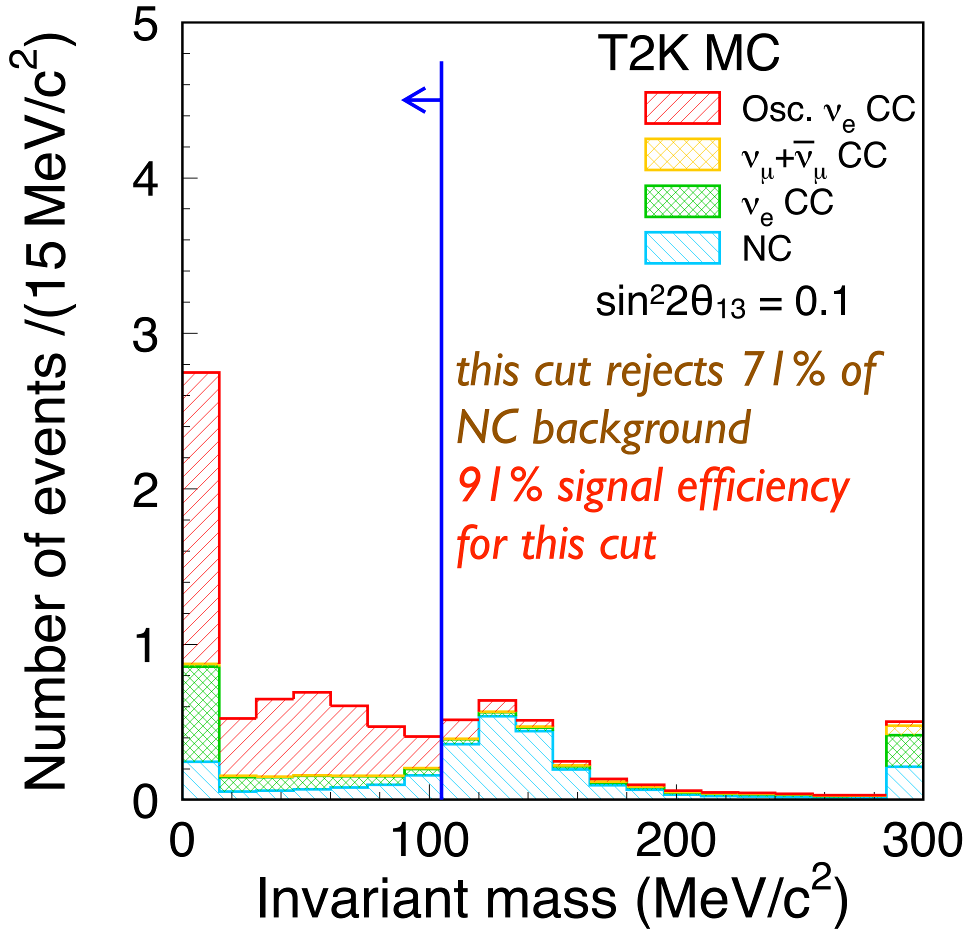


6. Reconstructed
invariant mass (M_{inv}) < 105 MeV/c^2

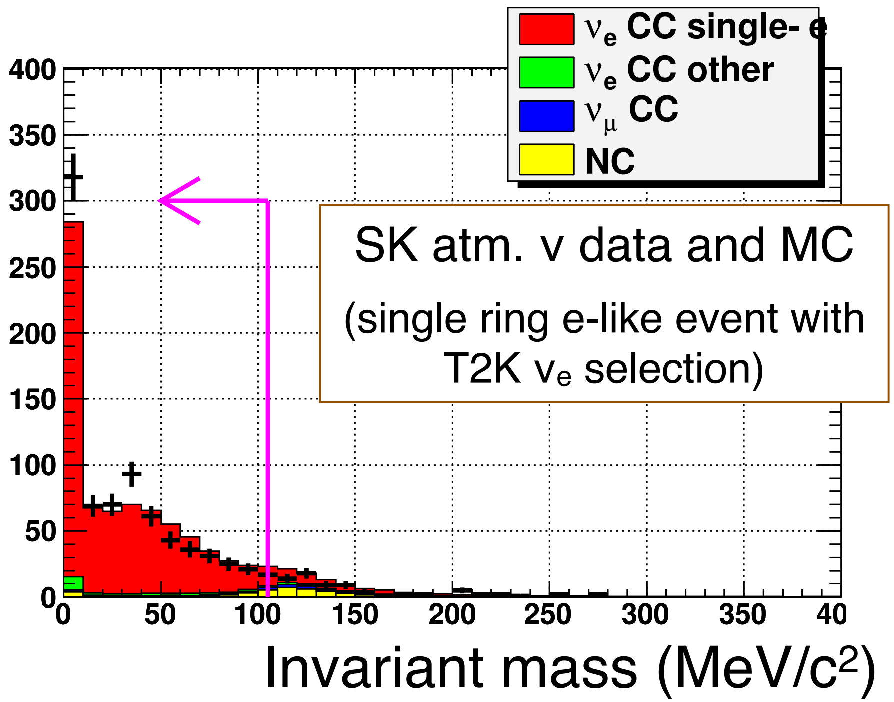
* Suppress NC π^0 background

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





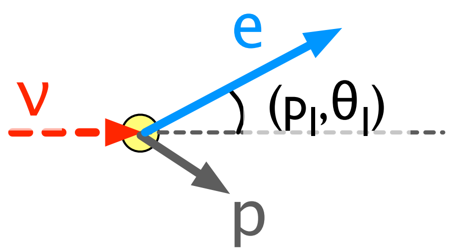
demonstrate to reconstruct invariant mass using atmospheric ν data



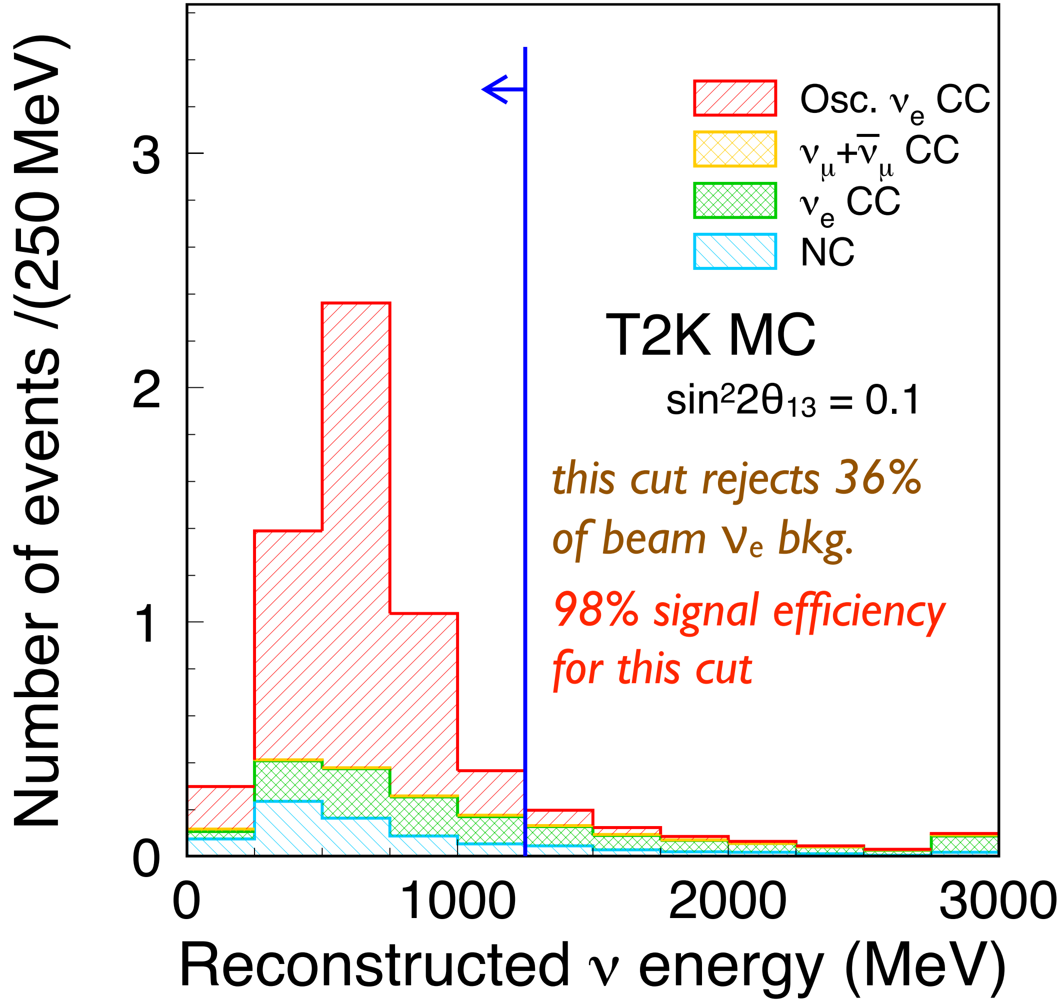
7. Reconstructed energy (E_{rec}) < 1250 MeV

* Reject intrinsic beam ν_e backgrounds at high energy

* Signal ($\nu_\mu \rightarrow \nu_e$) has a sharp peak at E~600MeV



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 x 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)

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

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)

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

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)

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

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

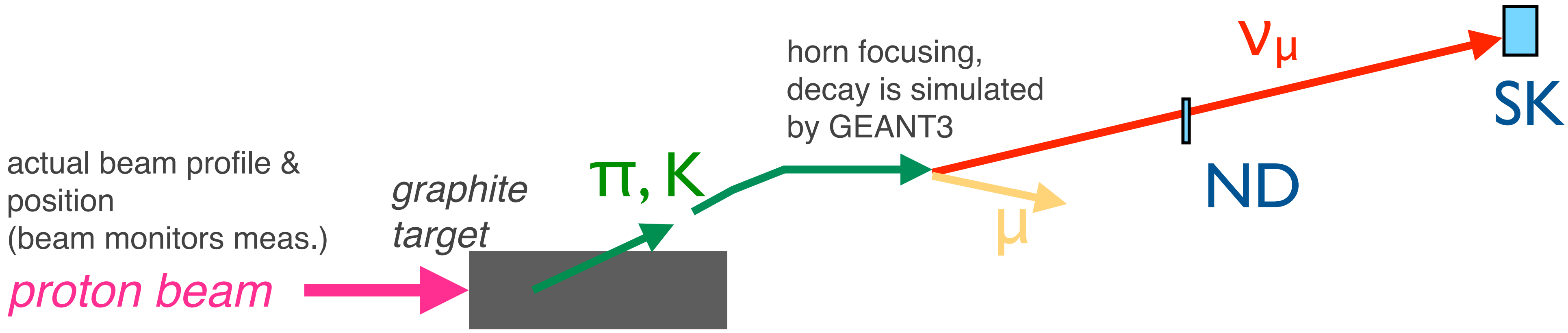
(flux) *x (osc. prob.) x (x-section) x (efficiency) x (det. mass)*

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

Neutrino flux prediction

T2K Neutrino beam simulation based on Hadron production measurements

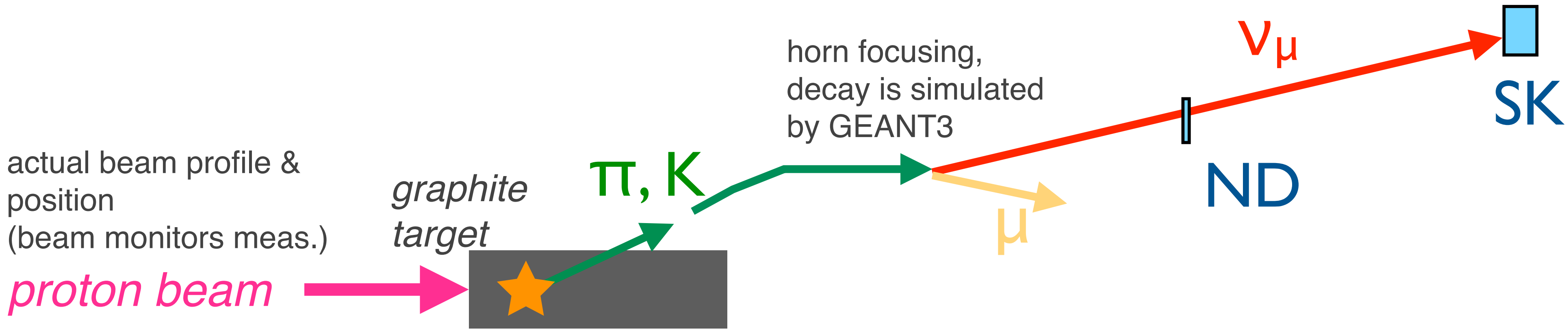
$$\frac{\int \Phi^{\mathrm{SK}}_{\nu_\mu}(E_\nu) \cdot P_{\nu_\mu \to \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{\mathrm{ND}}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\ dE_\nu}$$



Neutrino flux prediction

T2K Neutrino beam simulation based on Hadron production measurements

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



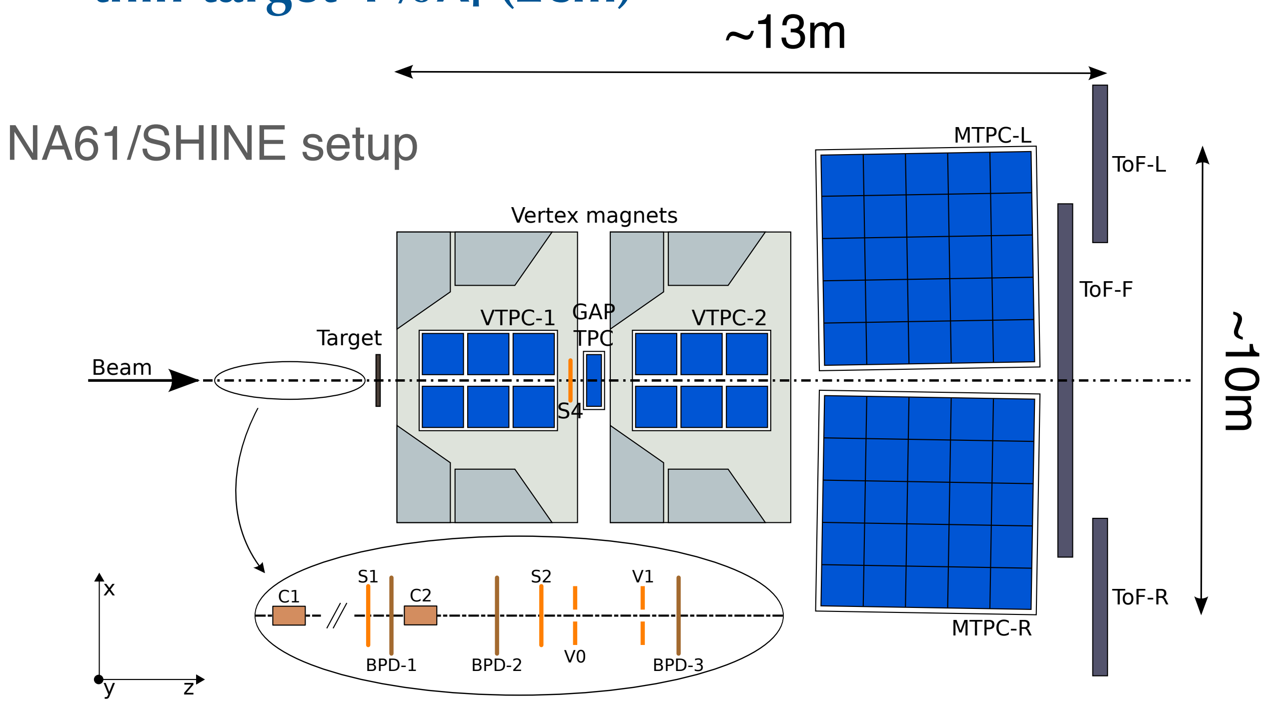
Hadron production in 30GeV proton + C

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

CERN NA61/SHINE measurement

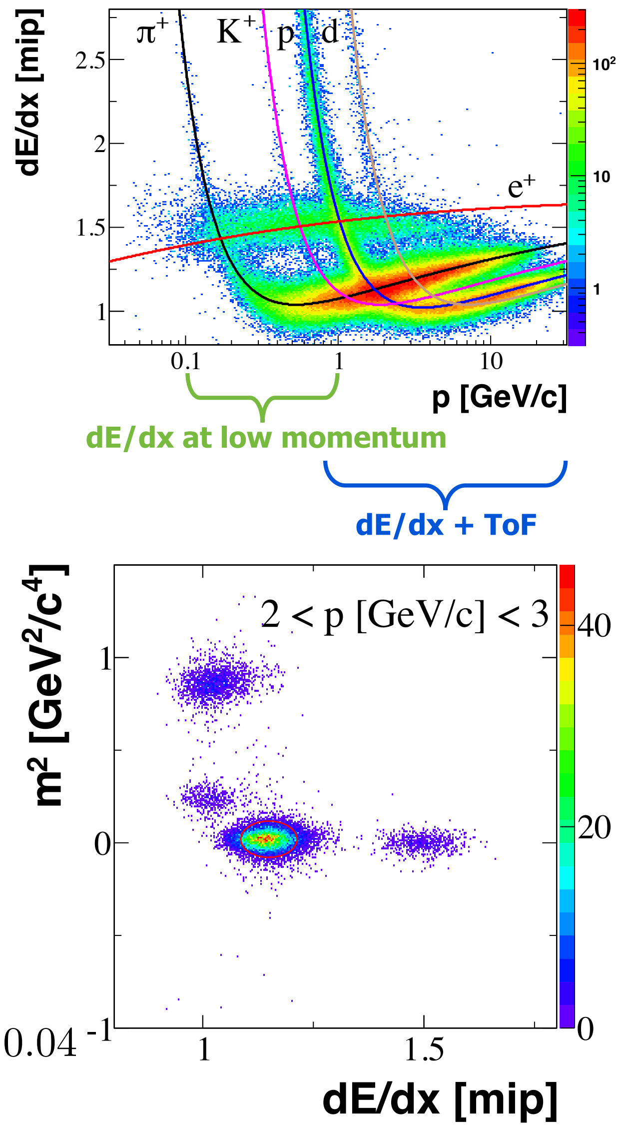
Measure hadron(π, K) yield distribution in 30 GeV p + C inelastic interaction

- thin target 4%λ_I (2cm)



Large acceptance spectrometer + TOF

π+ production: Two analysis for different momentum region



detector performance

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

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

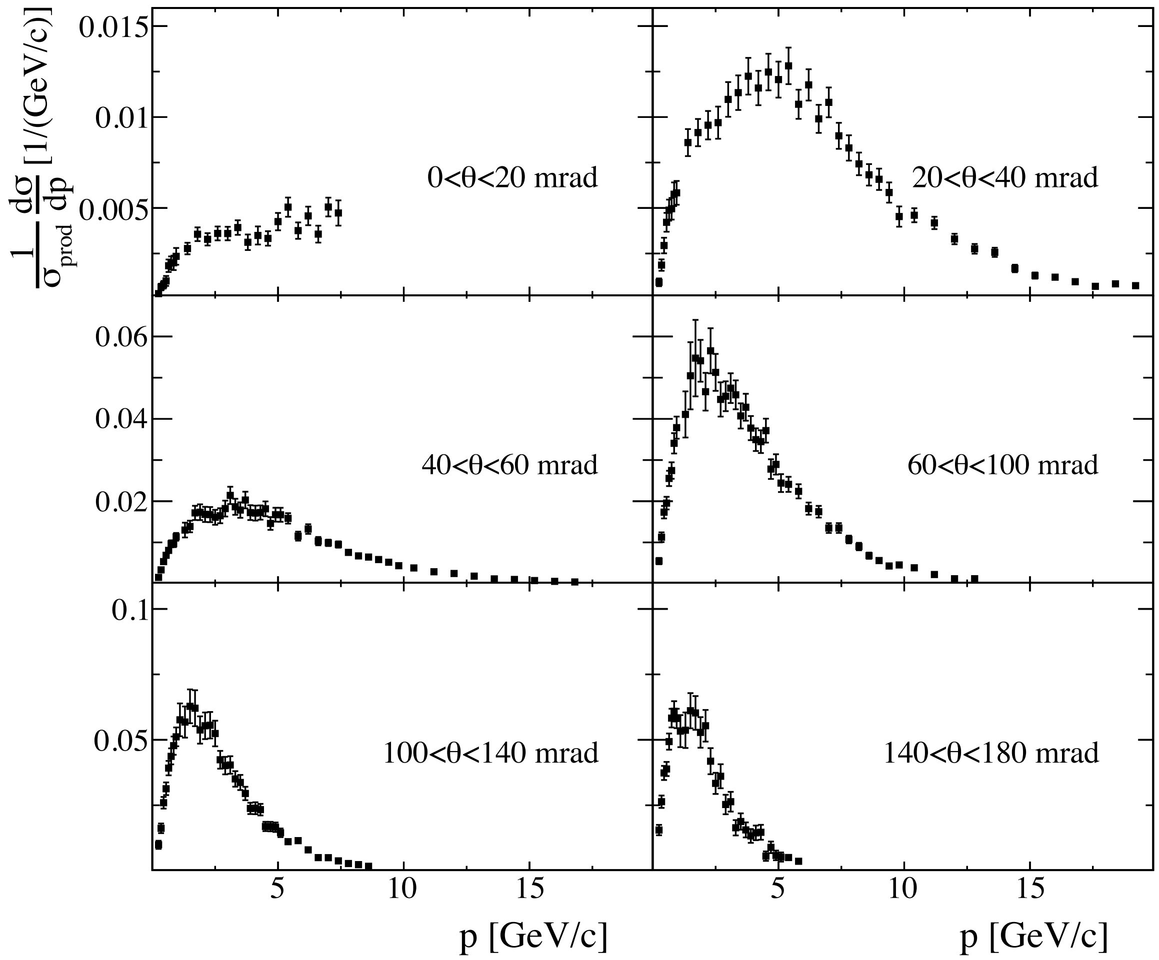
$\sigma(\mathrm{TOF\text{-}F}) \approx 115$ ps

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



→ Input to T2K neutrino beam simulation

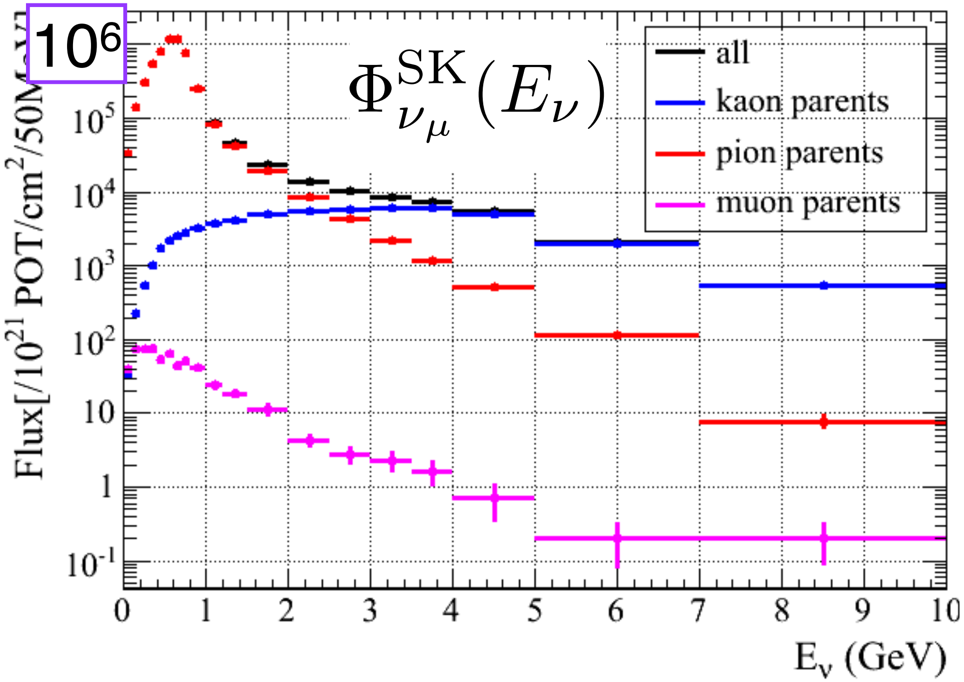
Systematic uncertainty was evaluated in each (p,θ) bin

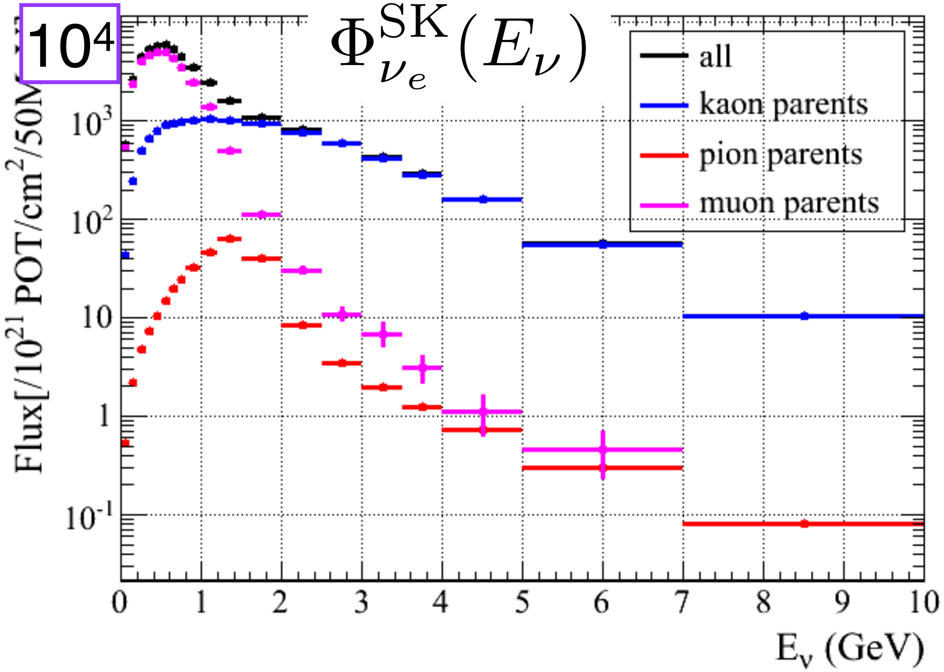
typically 5-10%

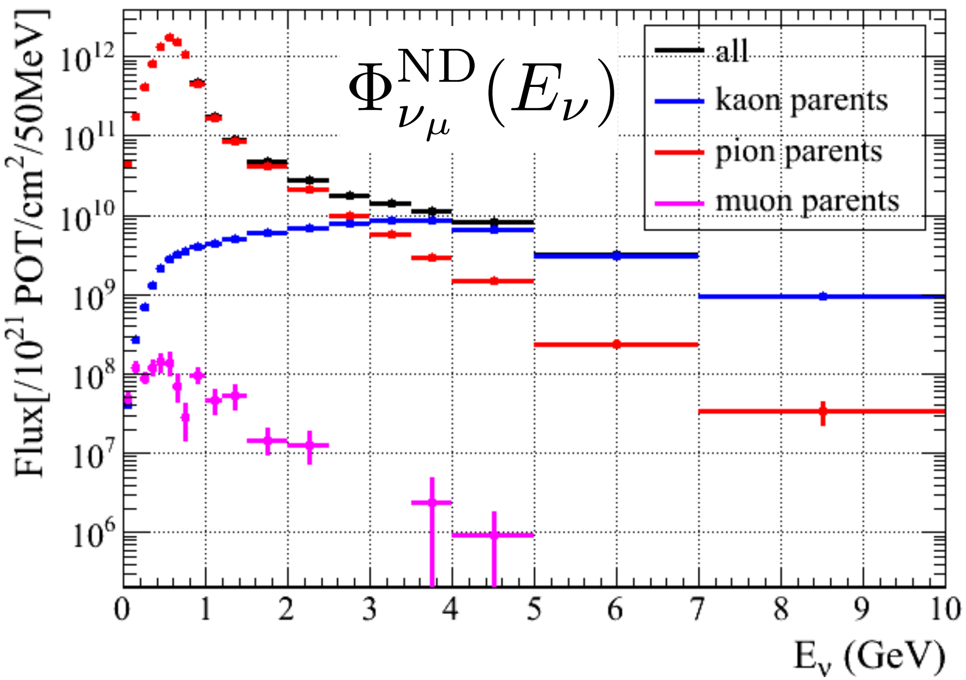
The normalization uncertainty is 2.3% on the overall (p,θ)

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

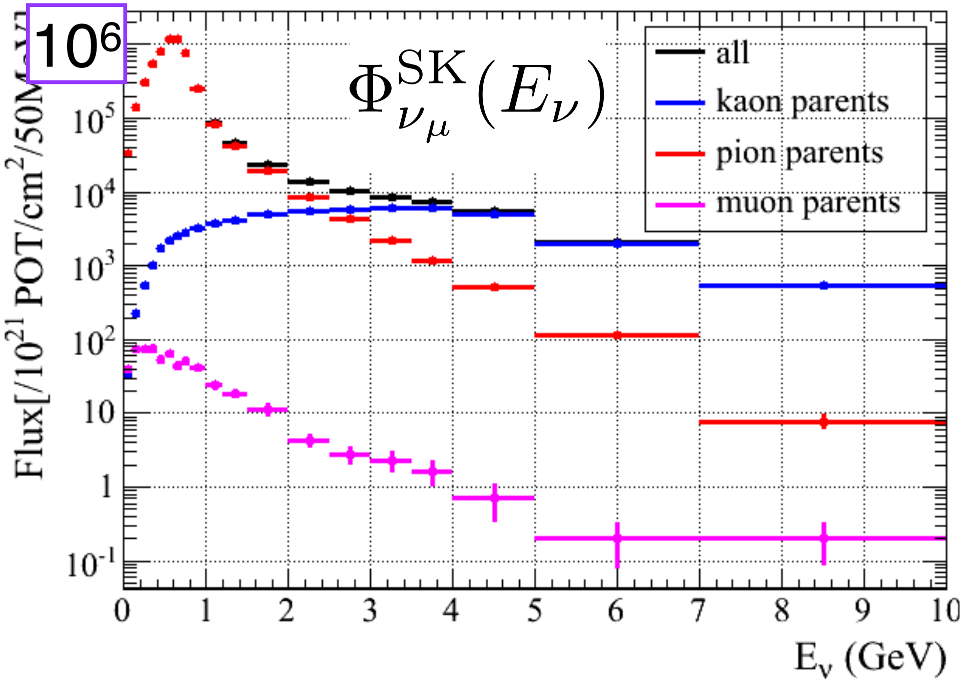
Predicted neutrino flux (center value)

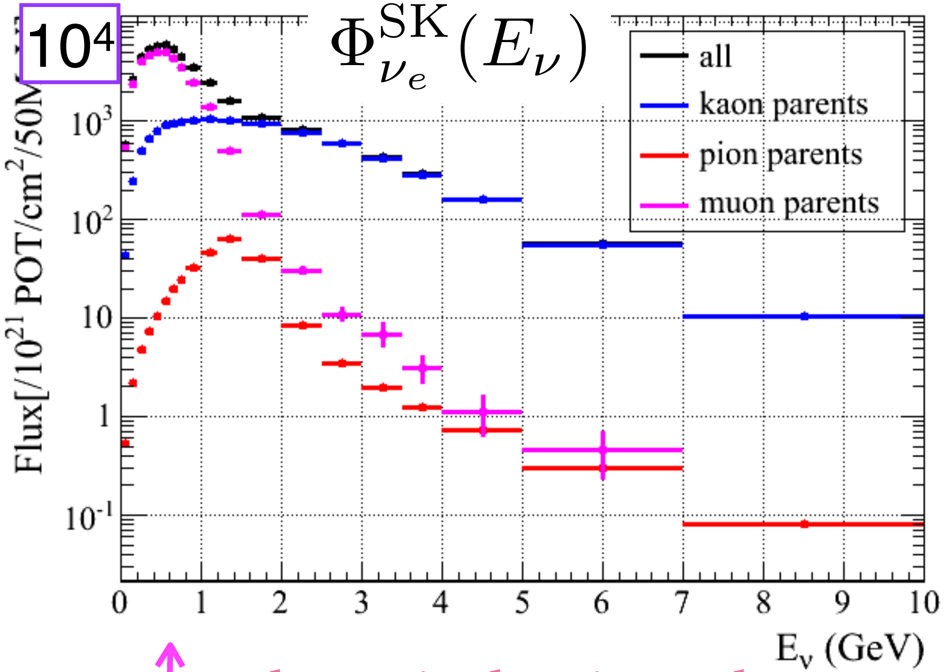






Predicted neutrino flux (center value)

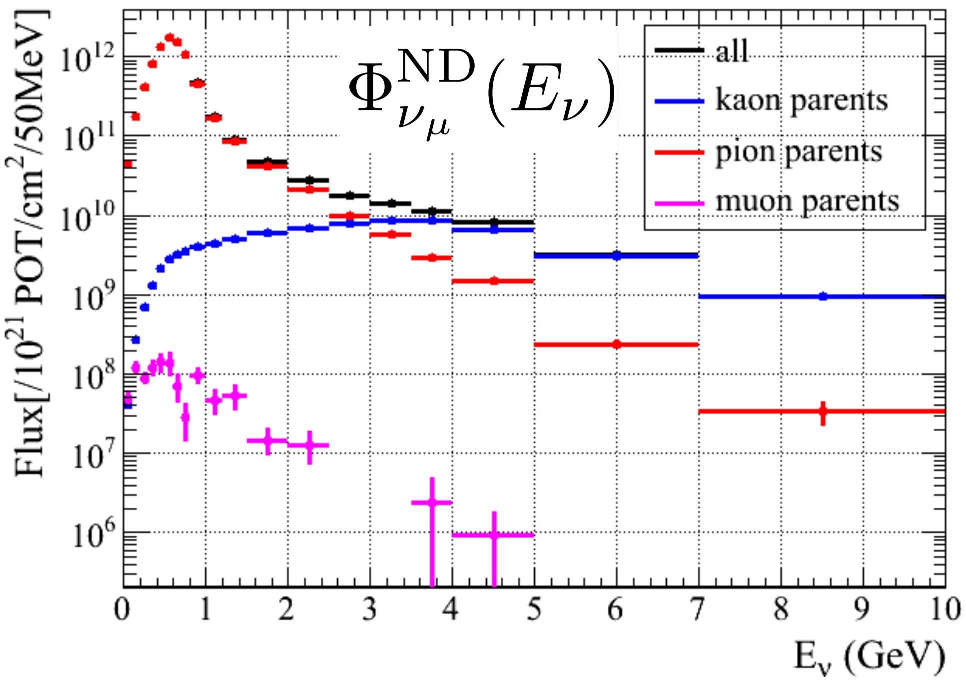




μ decay is dominated at low energy

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

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

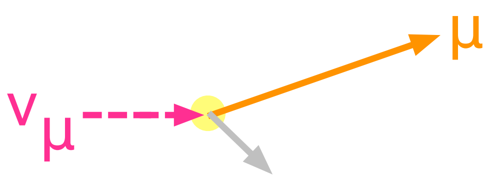


NA61 pion measurement predicts the beam ν_e from pion origin

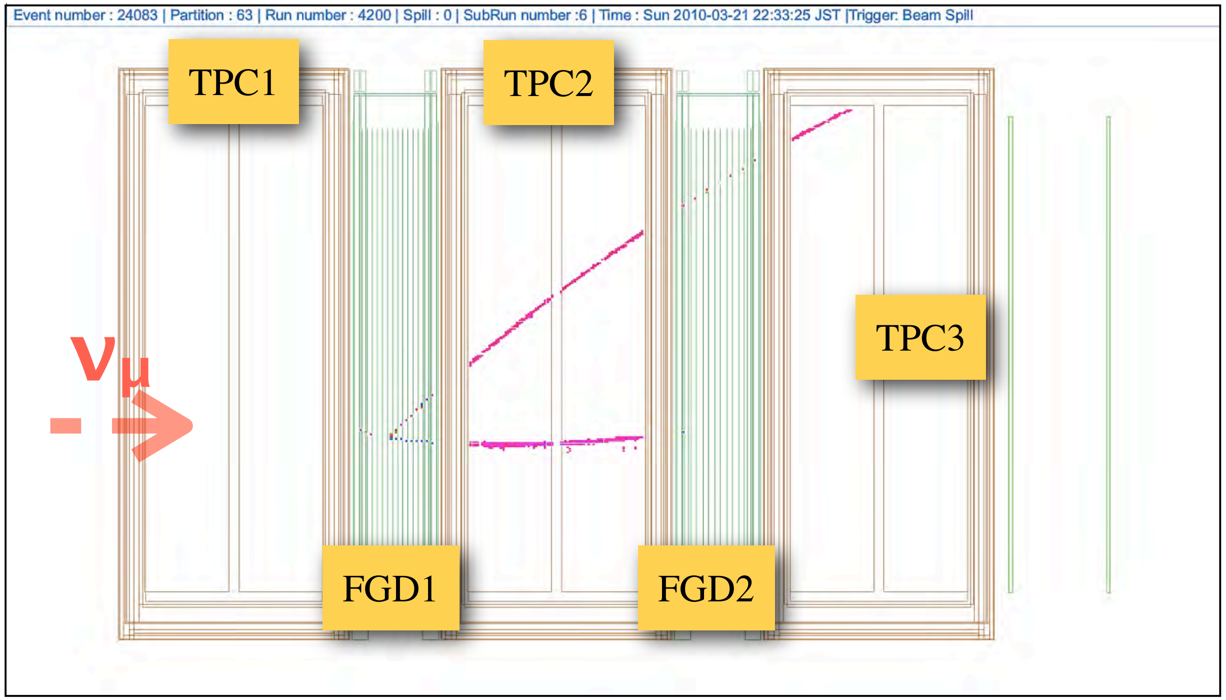
ν_μ interaction rates at near detector

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

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

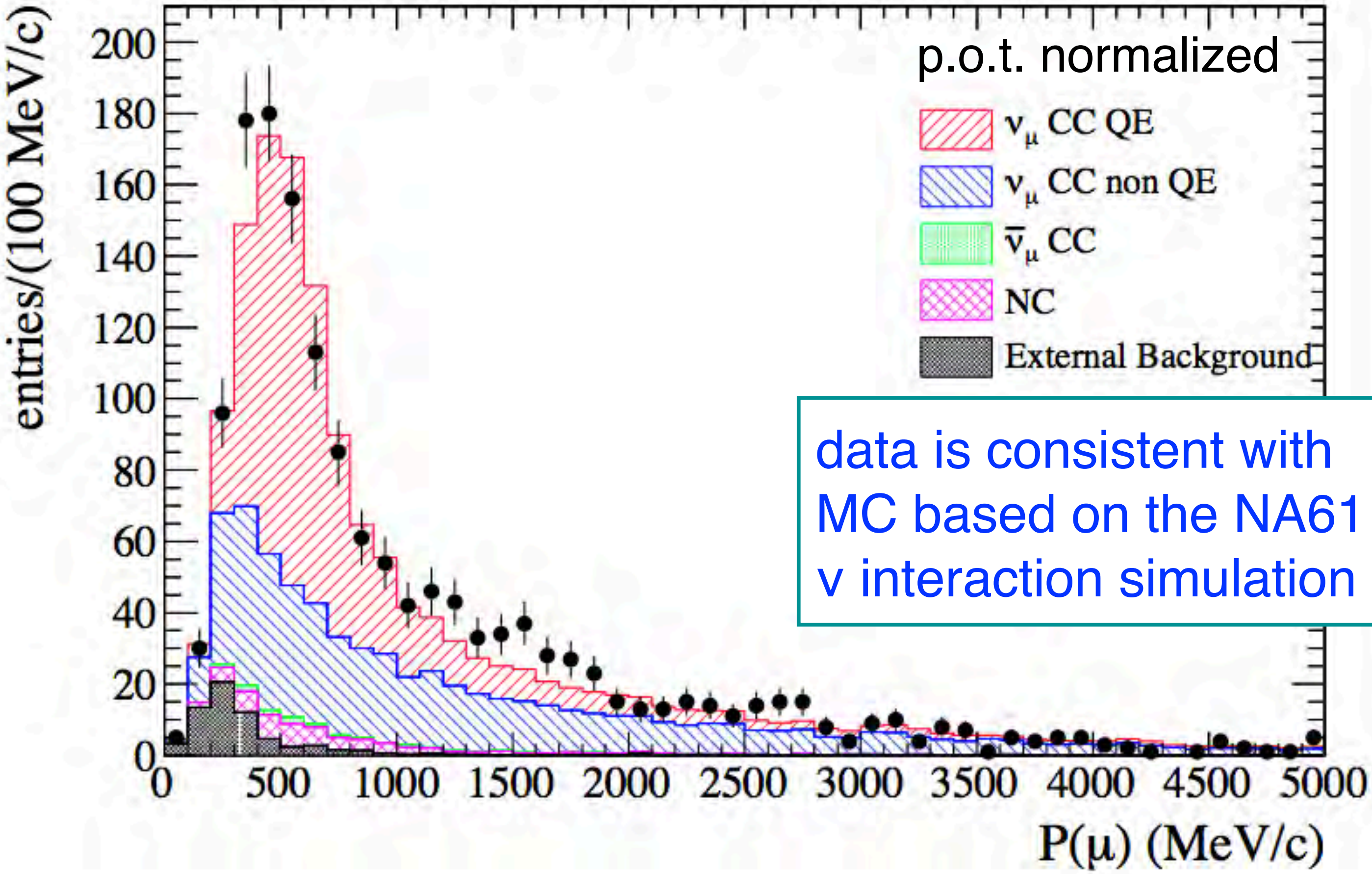


Event display (data)



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

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



data is consistent with MC based on the NA61 and ν interaction simulation (w/o tuning)

Results

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

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

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

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

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

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

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

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

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

↑

# of NC background is calculated by

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

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

for sin²2θ₁₃=0

➡ *$N^{exp}{}_{SK}$=1.5±0.3 events*

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

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

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

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

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

→ *N^{exp}_{SK}=1.5±0.3 events*

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

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

Neutrino flux uncertainty

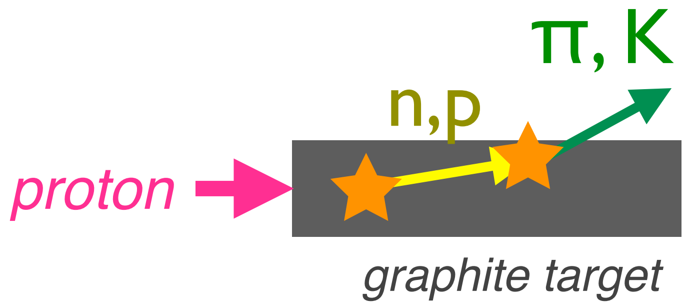
error source
(1) ν flux
(2) ν cross section
(3) Near detector
(4) Far detector
(5) Near det. statistics

Uncertainties in hadron production and interaction are dominant sources

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

Error source

- Pion production
  - NA61 systematic uncertainty in each pion's (p,θ) bin
- Kaon production
  - Used model (FLUKA) is compared with the data(Eichten et. al.) in each kaon's (p,θ) bin
- Secondary nucleon production
  - Used model (FLUKA) is compared with the experimental data
- Secondary interaction cross section
  - Used model (FLUKA and GCALOR) is compared with the experimental data of interaction x-section (π, K and nucleon)



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

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

Error source	$\frac{N^{MC}_{SK}}{R^{\mu,\,MC}_{ND}}$	
Pion production	2.5%	Hadron production & interaction
Kaon production	7.6%	
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^{exp}_{SK} due to the beam flux uncertainty is **8.5%**

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

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

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%
Kaon production	10.0%	11.1%	7.6%
Nucleon production	5.9%	6.6%	1.4%
Production x-section	7.7%	6.9%	0.7%
Proton beam position/profile	2.2%	0.0%	2.2%
Beam direction measurement	2.7%	2.0%	0.7%
Target alignment	0.3%	0.0%	0.2%
Horn alignment	0.6%	0.5%	0.1%
Horn abs. current	0.5%	0.7%	0.3%
Total	15.4%	16.1%	8.5%

Hadron production & interaction

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

Error cancellation works for some beam uncertainties

ν int. cross section uncertainty

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

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

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

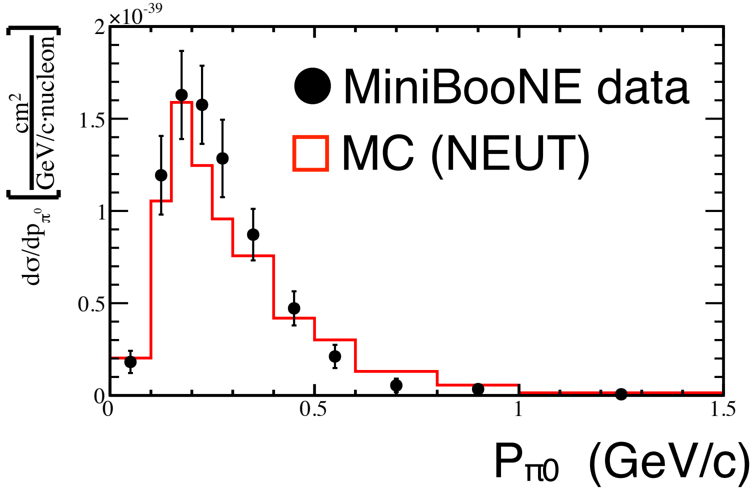
Main ν interaction in each event category

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

Process	Cross section uncertainty relative to the CCQE total x-section
CCQE	energy dependent ($\sim \pm 7\%$ at 500 MeV)
CC 1π	30% ($E_\nu < 2$ GeV) – 20% ($E_\nu > 2$ GeV)
CC coherent π^0	100% (upper limit from [30])
CC other	30% ($E_\nu < 2$ GeV) – 25% ($E_\nu > 2$ GeV)
NC $1\pi^0$	30% ($E_\nu < 1$ GeV) – 20% ($E_\nu > 1$ GeV)
NC coherent π	30%
NC other π	30%
Final State Int.	energy dependent ($\sim \pm 10\%$ at 500 MeV)

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

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



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

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

Error source	syst. error on N_{SK}^{exp}
CC QE shape	3.1%
CC 1π	2.2%
CC Coherentπ	3.1%
CC Other	4.4%
NC $1\pi^0$	5.3%
NC Coherentπ	2.3%
NC Other	2.3%
$\sigma(\nu_e)$	3.4%
FSI	10.1%
Total	14.0%

Uncertainty in pion's final state interaction is dominant

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

Far detector uncertainty

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

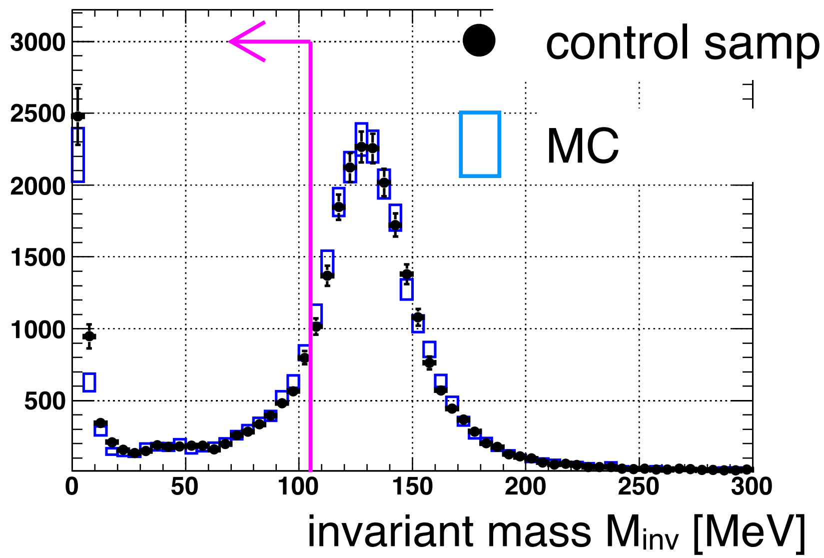
- Uncertainty due to the SK detector uncertainty
- Evaluation using control sample

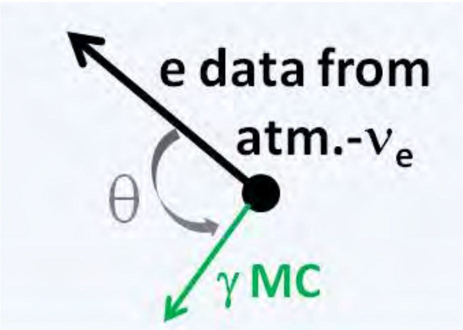
$$\frac{\int \Phi^{SK}_{\nu_\mu(\nu_e)}(E_\nu)\cdot P_{osc.}(E_\nu)\cdot\sigma(E_\nu)\cdot\epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu)\cdot\sigma(E_\nu)\cdot\epsilon_{ND}(E_\nu)\ dE_\nu}$$

One of big error sources:

detection efficiency of NC $1\pi^0$ 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	$\frac{\delta N^{MC}_{SK\ \nu_e\ sig.}}{N^{MC}_{SK\ \nu_e\ sig.}}$	$\frac{\delta N^{MC}_{SK\ bkg.\ tot.}}{N^{MC}_{SK\ bkg.\ tot.}}$
π^0 rejection	-	3.6%
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass cut	5.1%	8.7%
Fiducial volume cut etc.	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay electron finding	0.1%	0.3%
Muon PID	-	1.0%
Total	**7.6%**	**15%**

Evaluated by atmospheric ν_e enriched data

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

Total Systematic uncertainties

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

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

$N^{exp}_{SK\ tot.} = 1.5 \pm 0.3$ 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	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

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

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

(due to small Far det. uncertainty for signal)

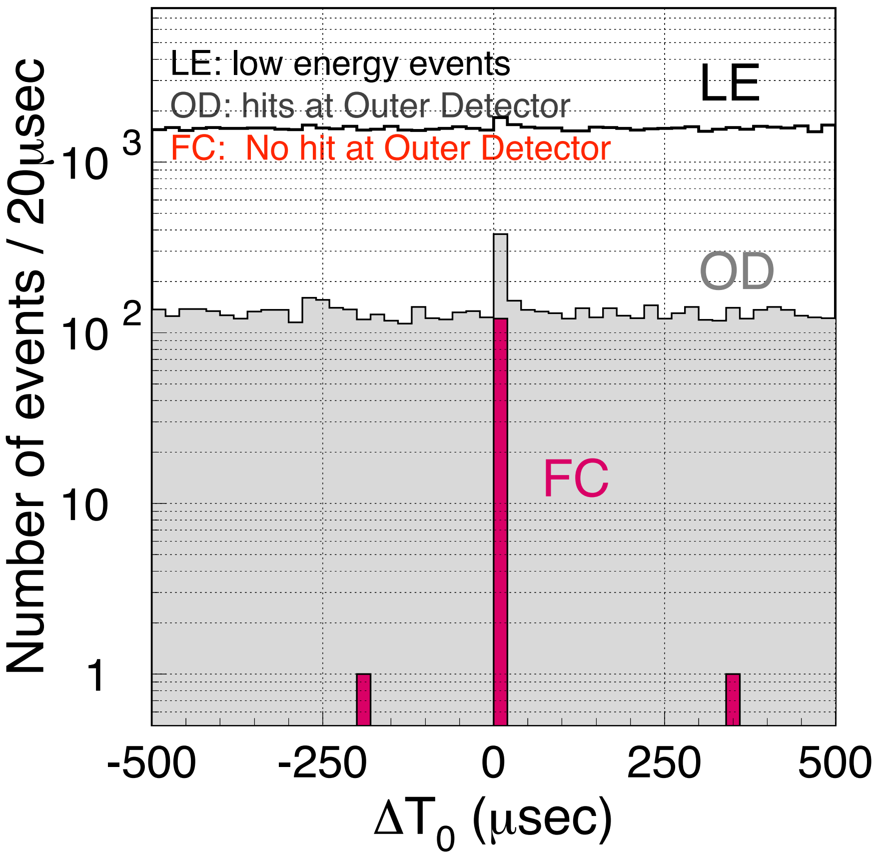
$N^{exp}_{SK\ tot.} = 1.5 \pm 0.3$ events for $\sin^2 2\theta_{13}=0$ (w/ 1.43×10^{20} p.o.t.)

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

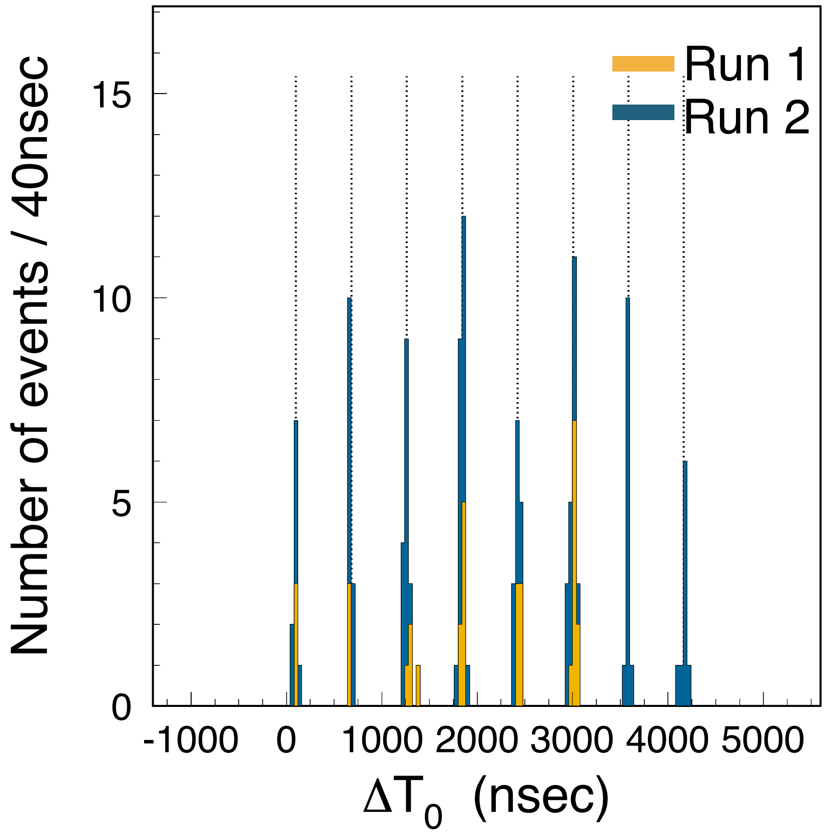
SK events in beam timing

- Events in the T2K beam timing synchronized by GPS

relative event timing to the spill timing



Clear beam structure !



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

Number of T2K events at far detector

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

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

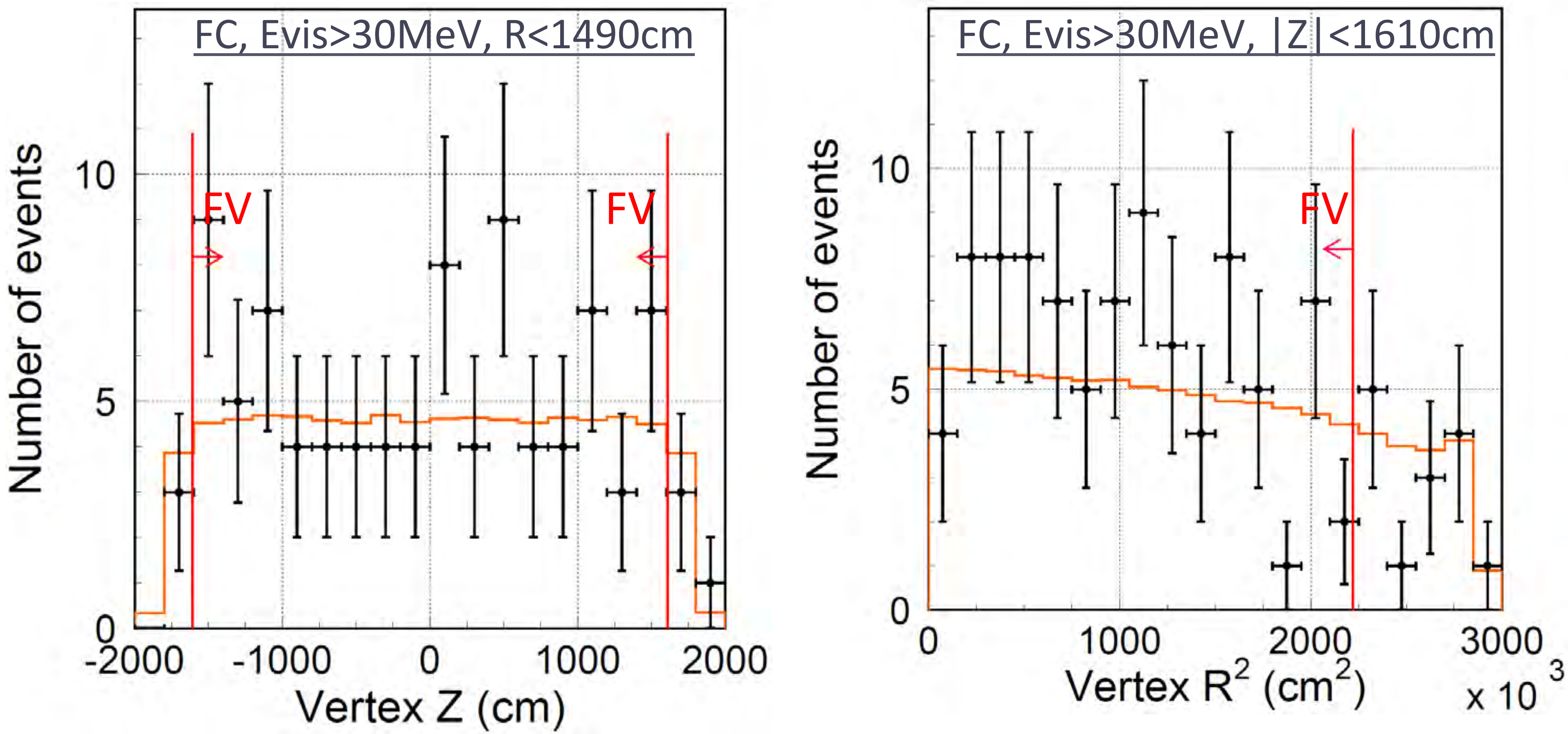
The accidental contamination from atmospheric ν background is estimated using the sideband events to be 0.023

Apply ν_e event selection

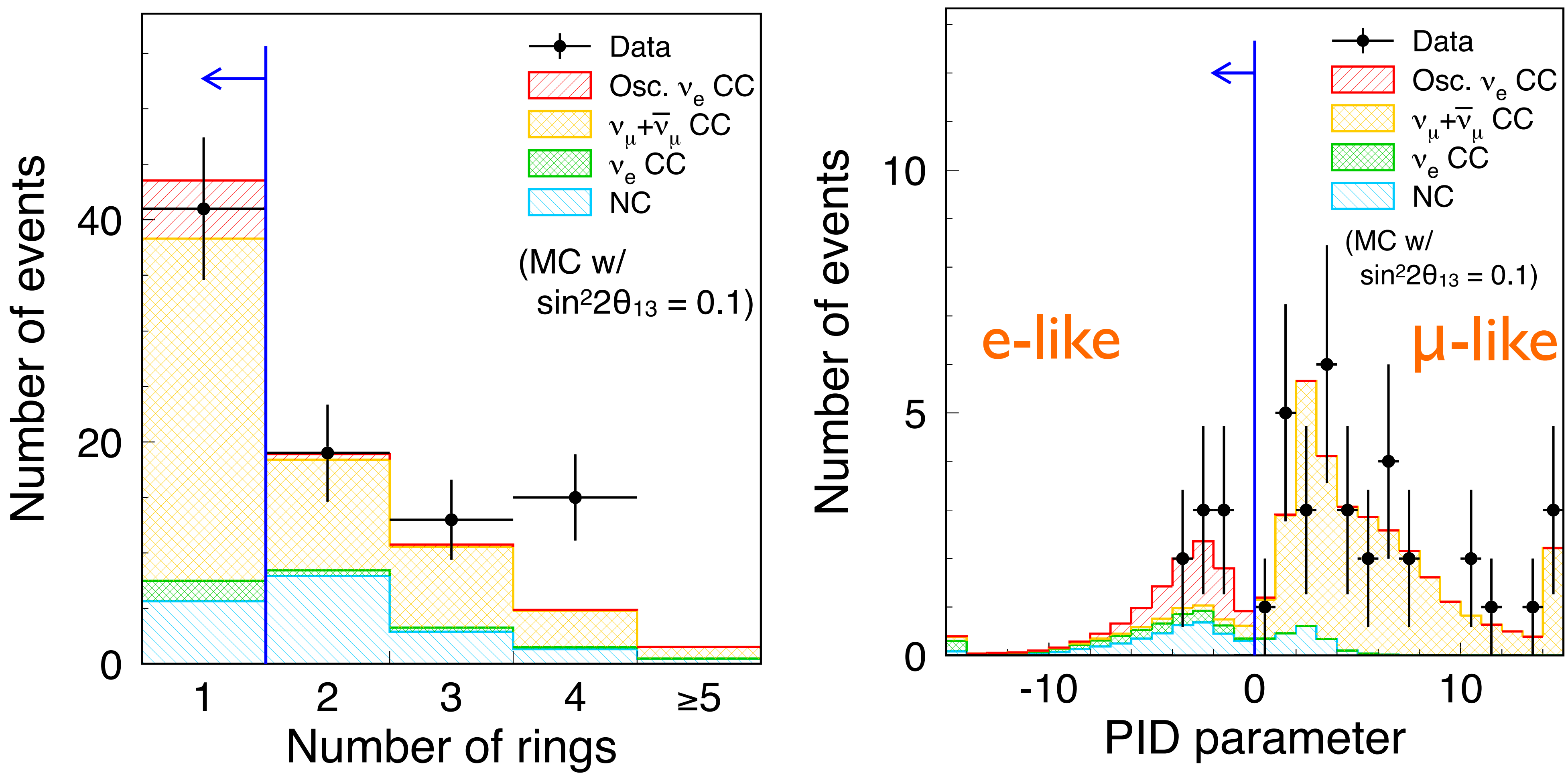
defined before the data collection
6 selection cuts in addition FC cut

Fiducial volume cut

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

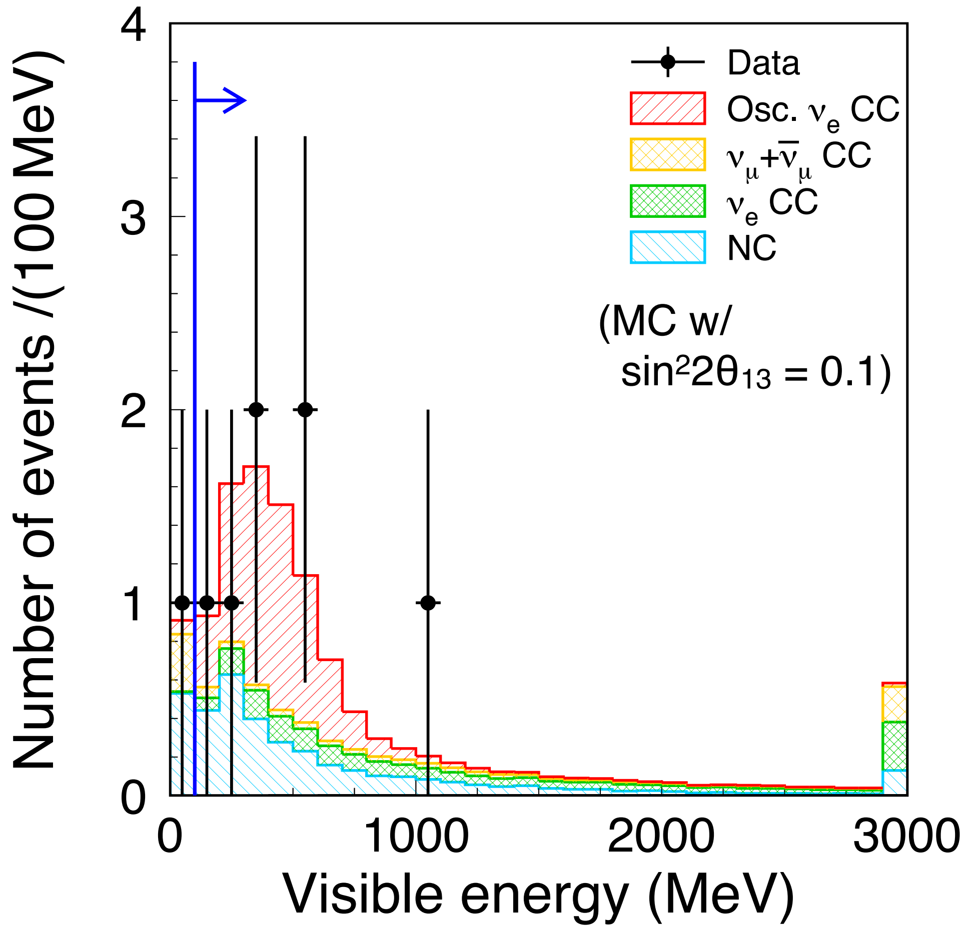


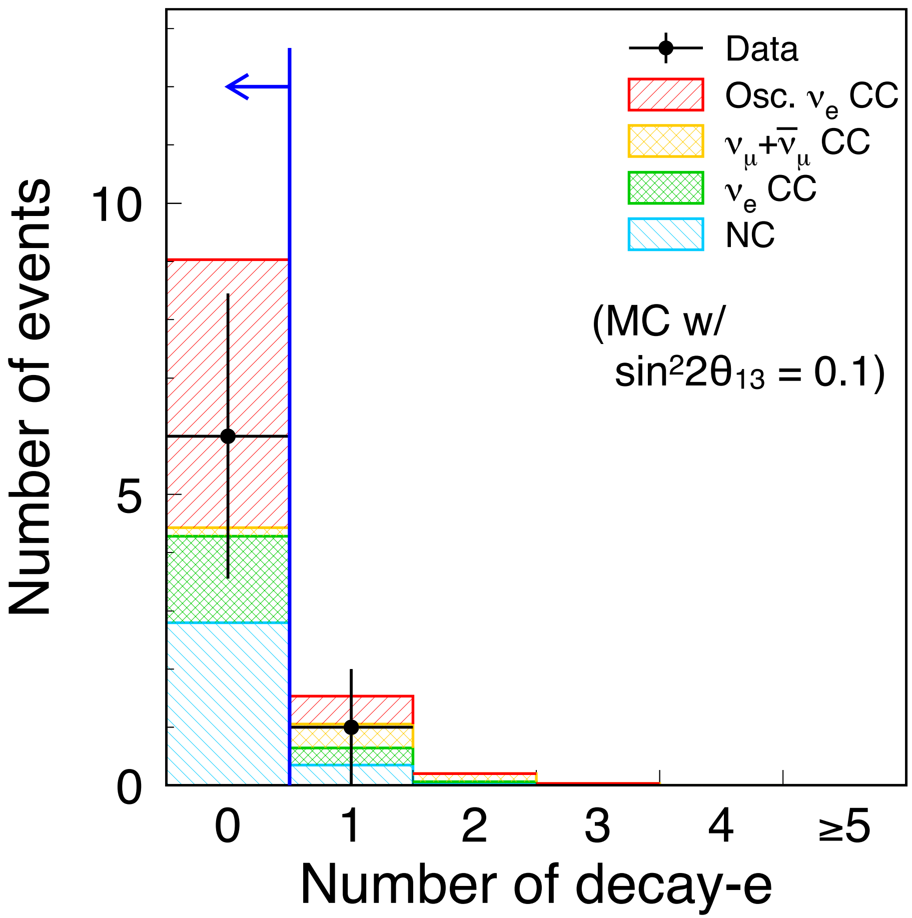
Single electron cut (# of ring is one & e-like)



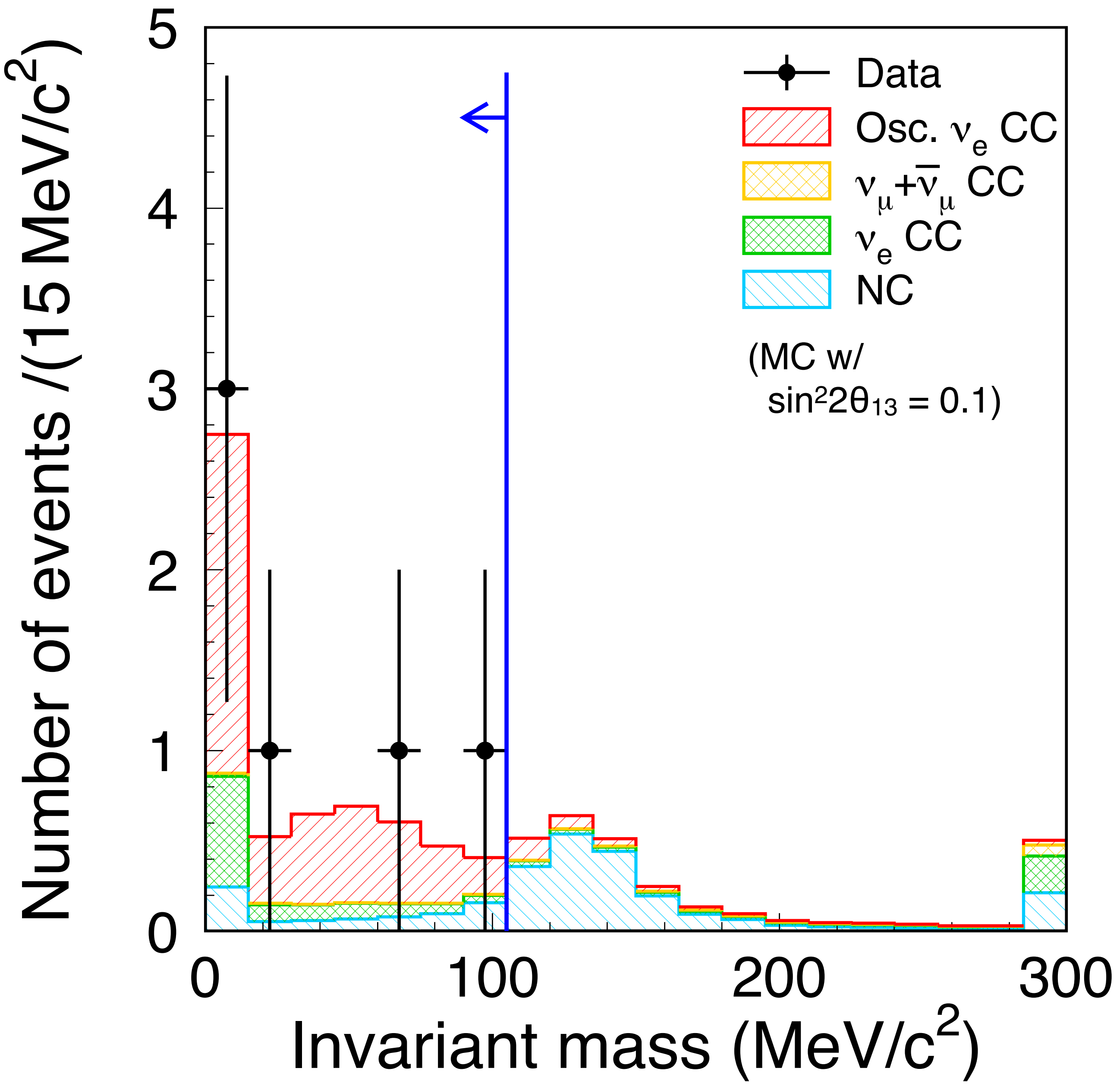
Visible energy > 100 MeV

No decay electron

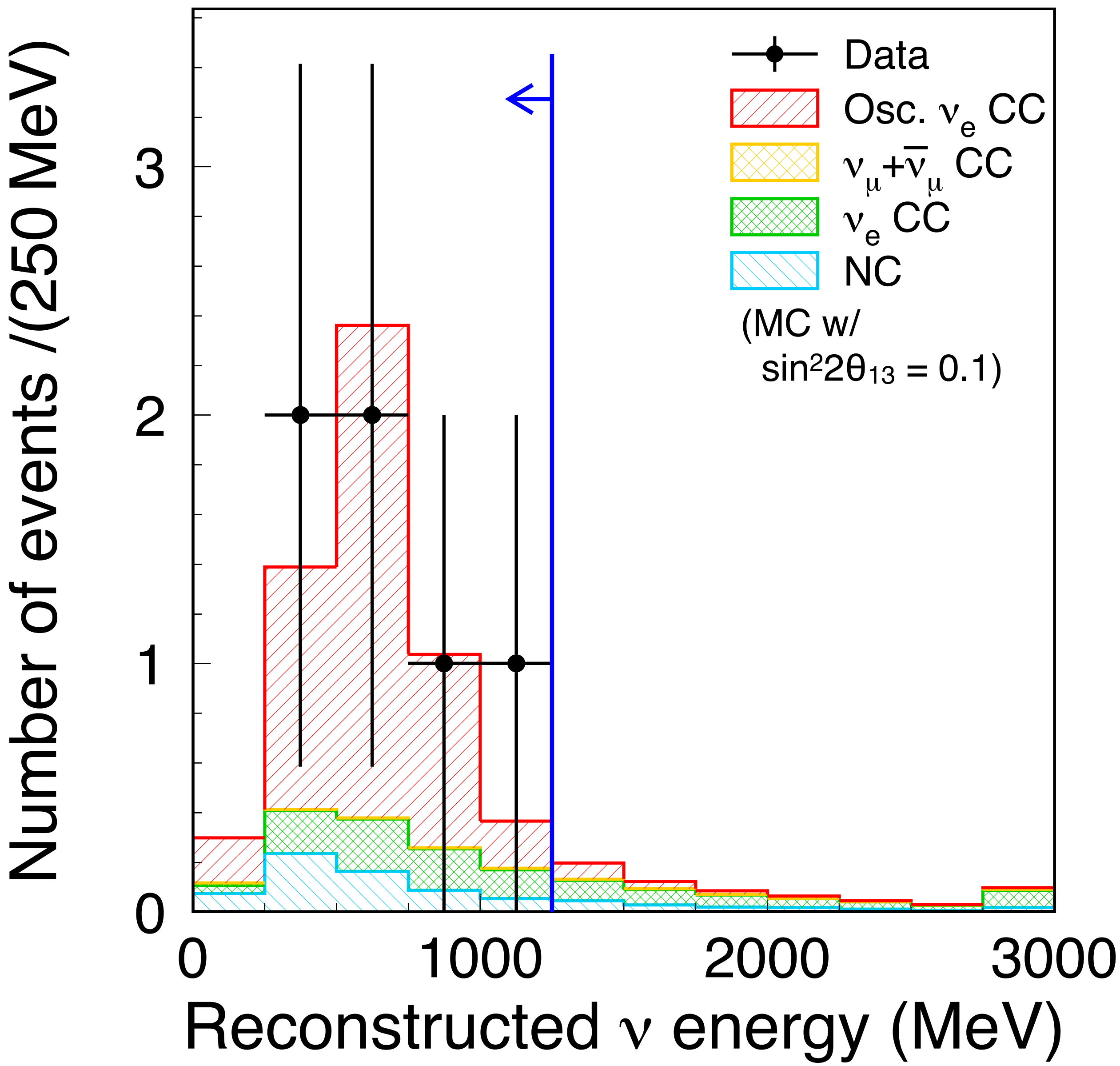




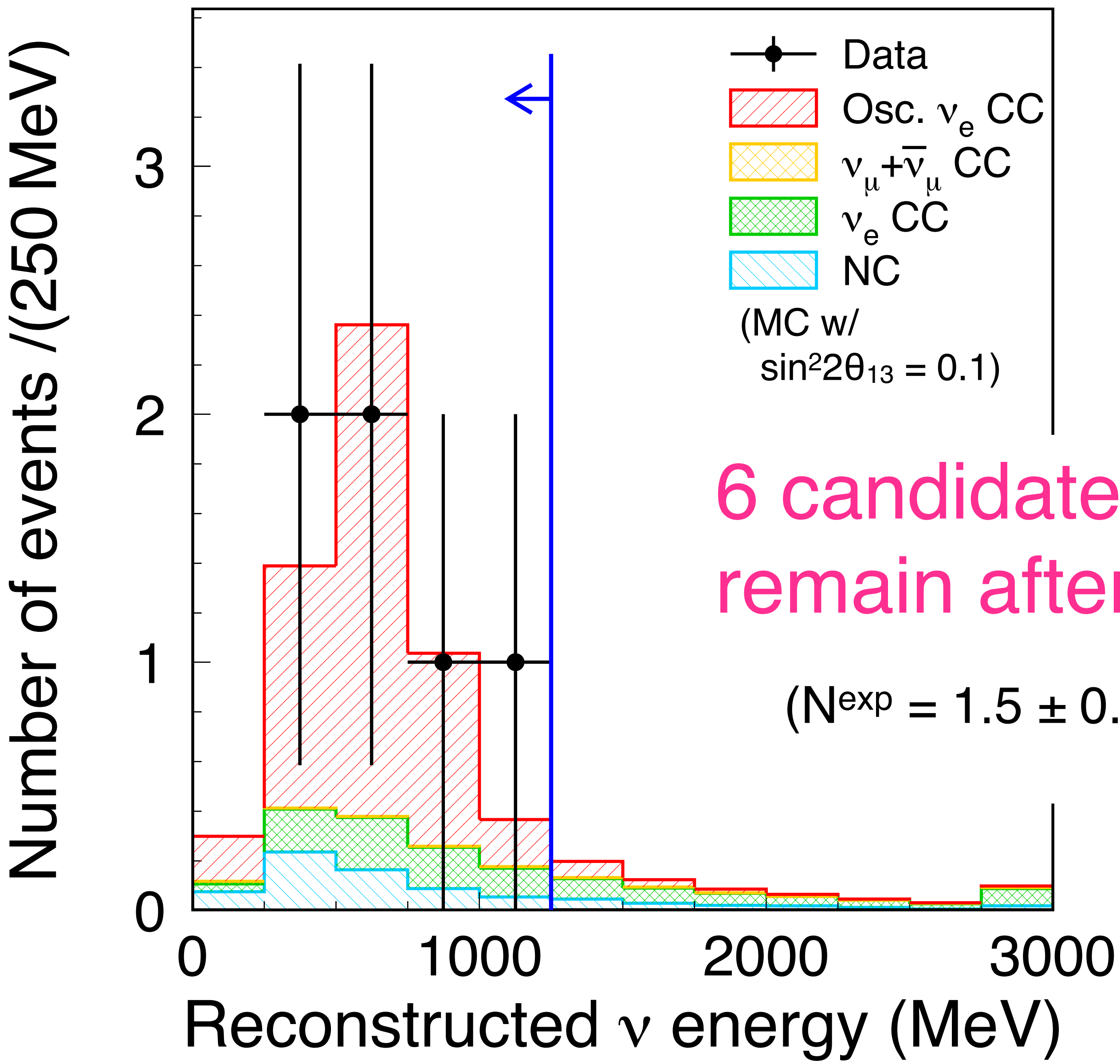
Invariant mass cut ($M_{inv} < 105$ MeV/c^2)



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



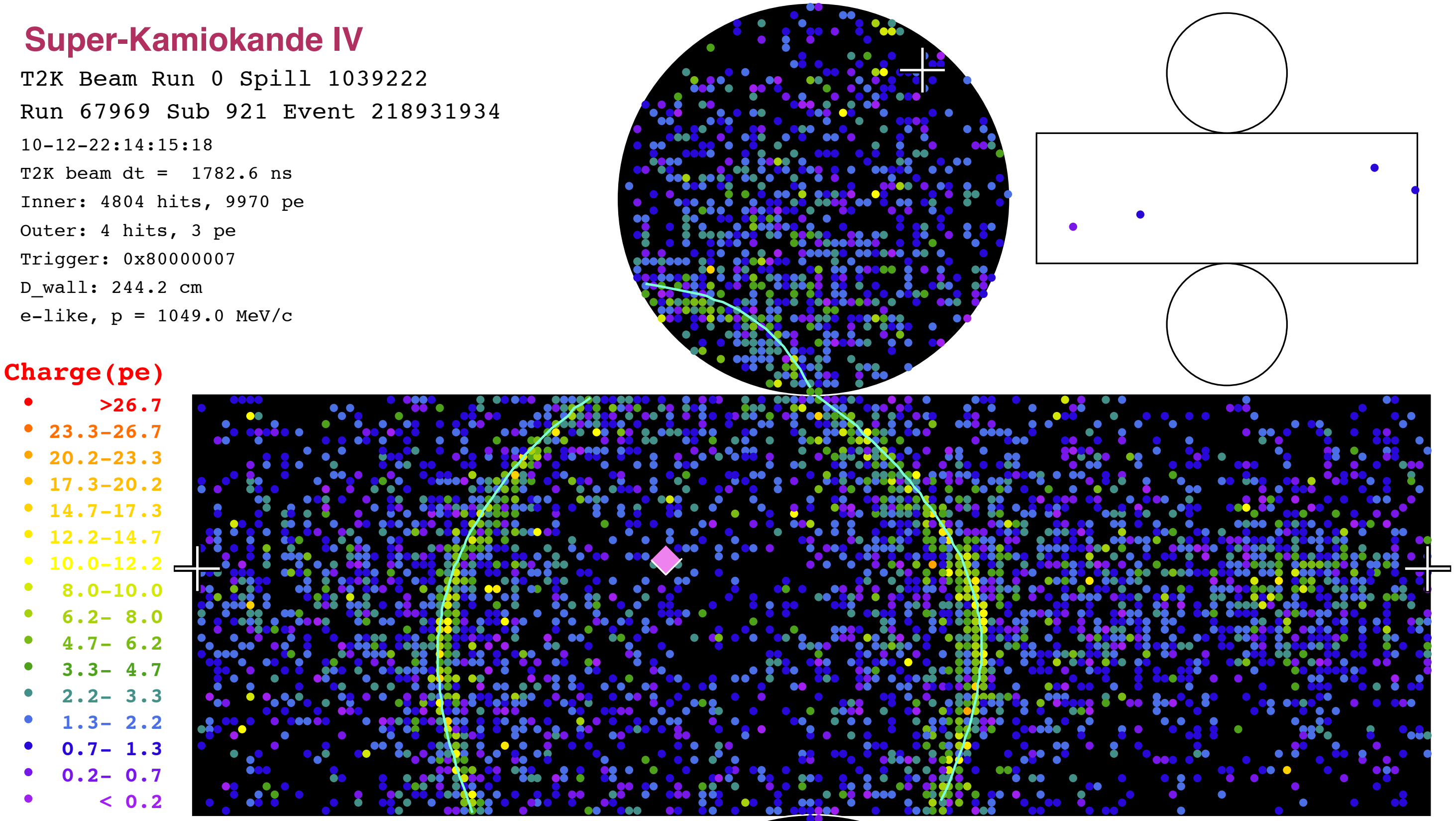
Reconstructed ν energy cut (E_{rec} < 1250 MeV) : *Final cut*

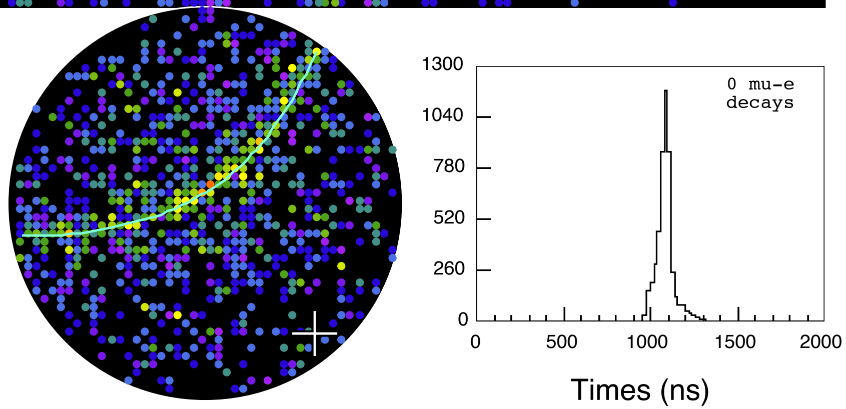


6 candidate events remain after all cuts !!

(N^{exp} = 1.5 ± 0.3 at $\sin^2 2\theta_{13}$=0)

ν_e candidate event

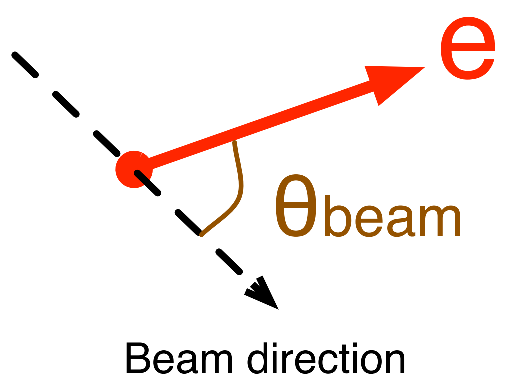


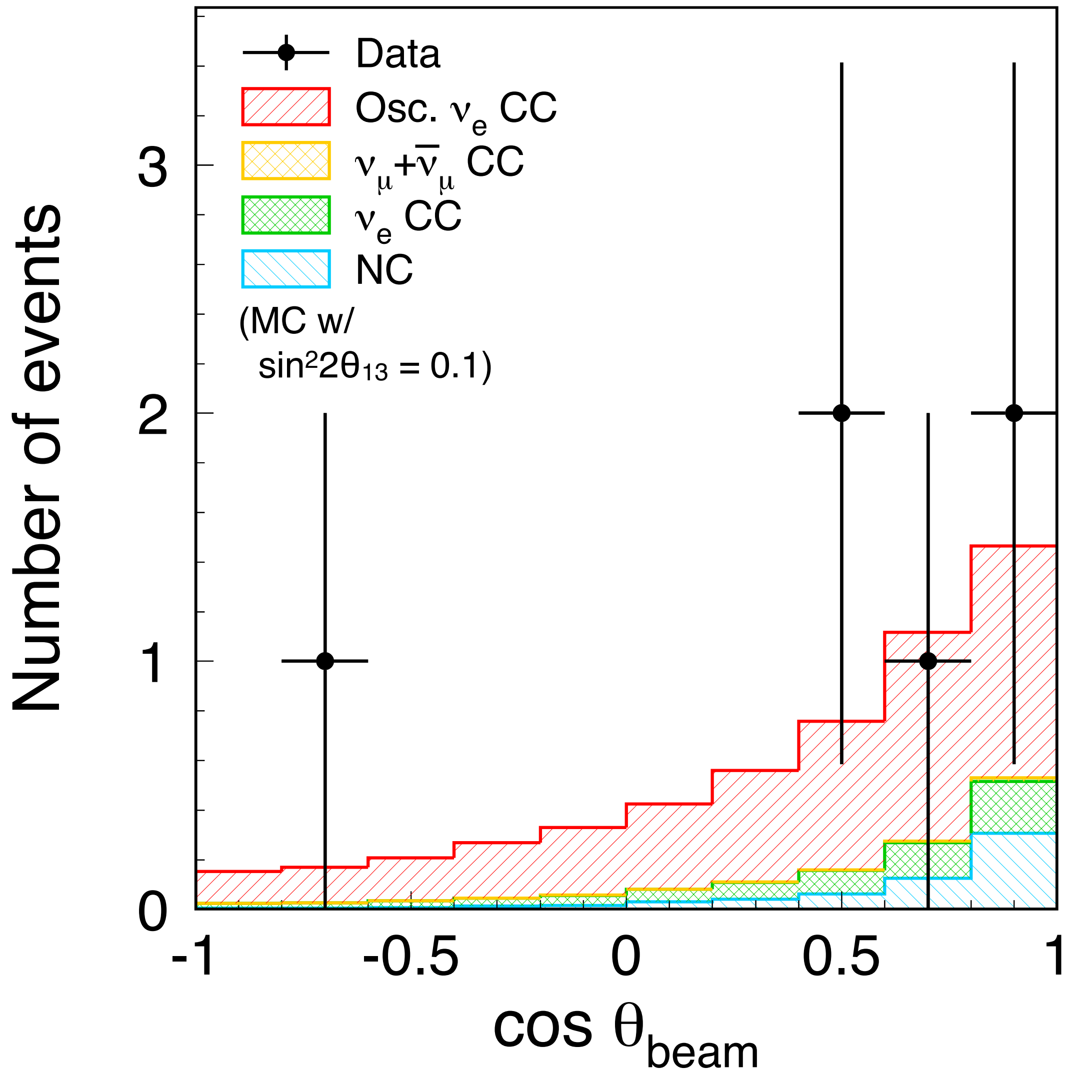


visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c²
recon. energy : 1120.9 MeV

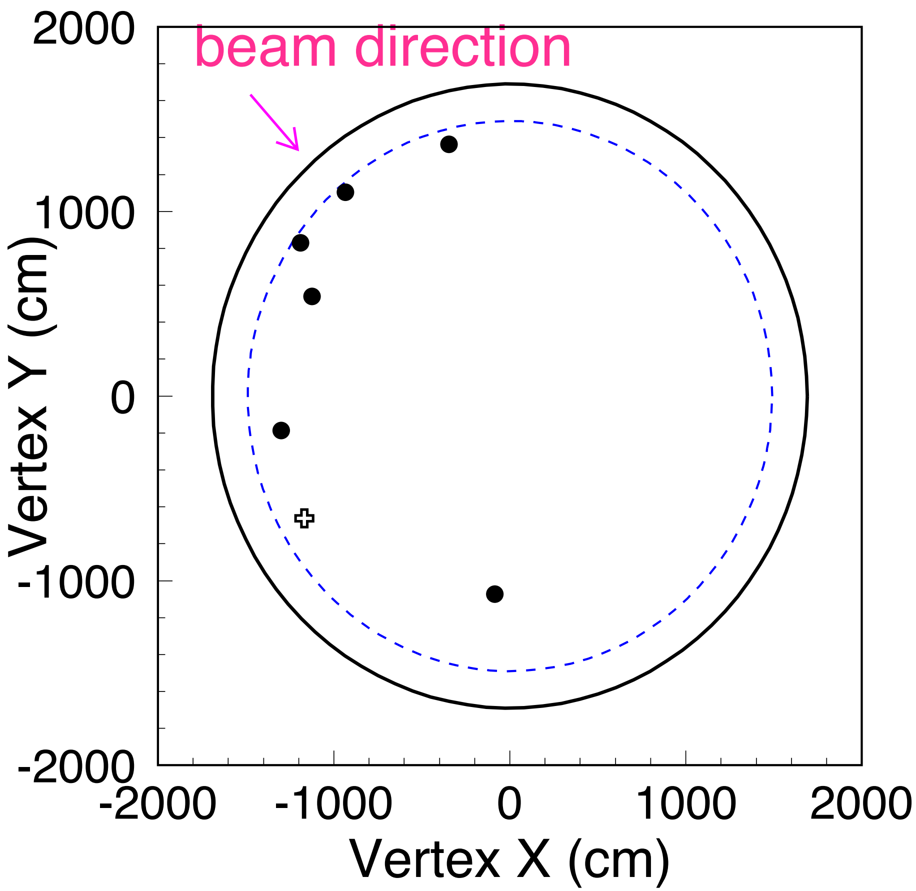
Further check

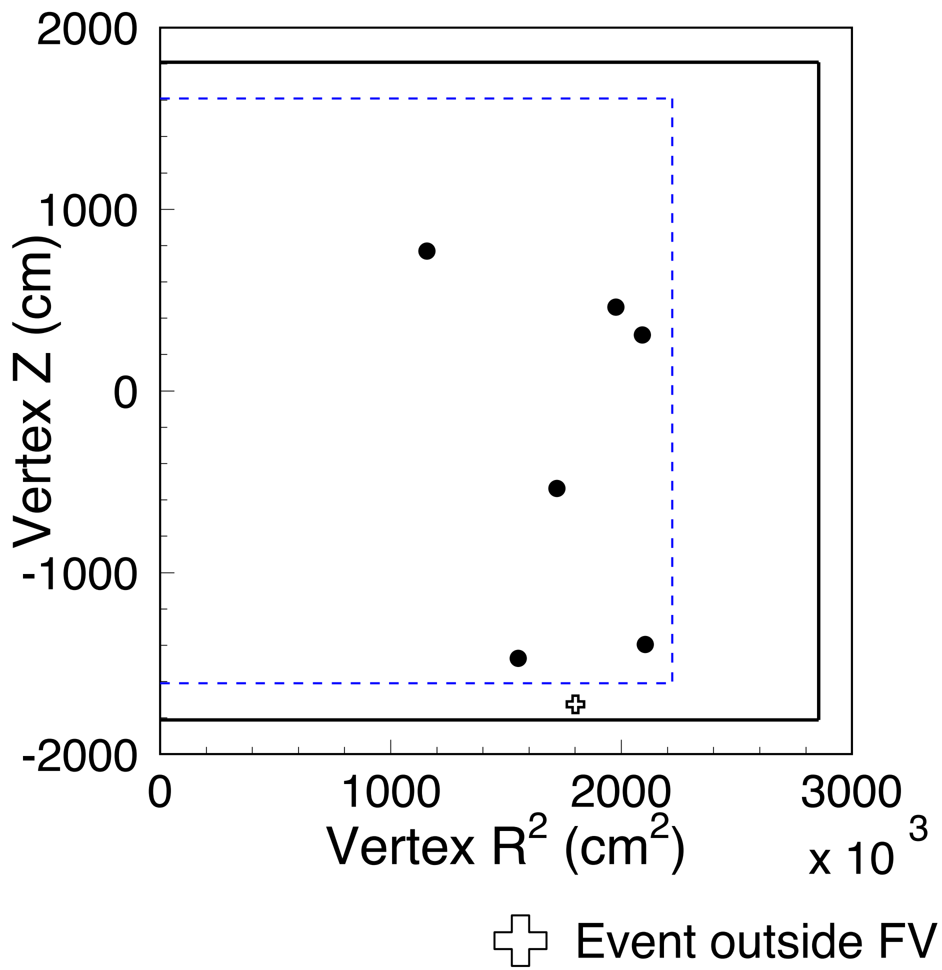
Check several distribution of ν_e candidate events





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 R^2 distribution yields a p-value of 0.03

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

The observed number of events is **6**

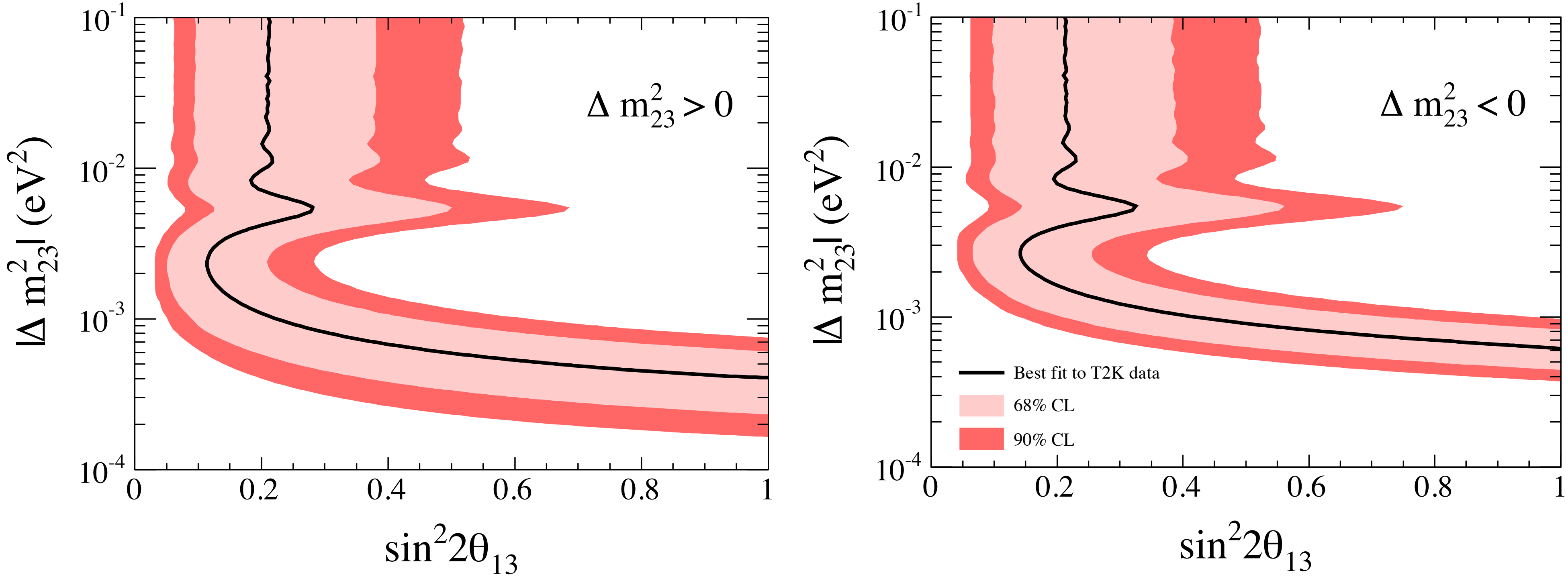
The expected number of events is **1.5 ± 0.3**

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}

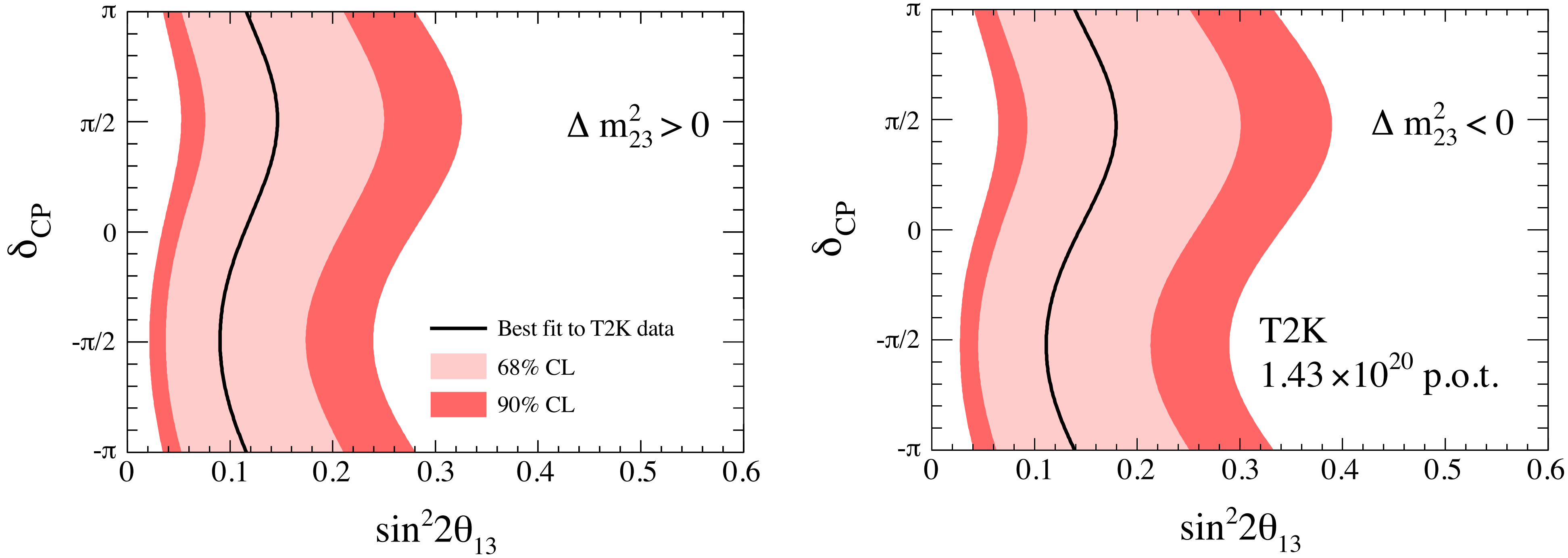
(assuming $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)



Feldman-Cousins method was used

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

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



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

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

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 $\nu_\mu \to \nu_e$ 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 $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

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