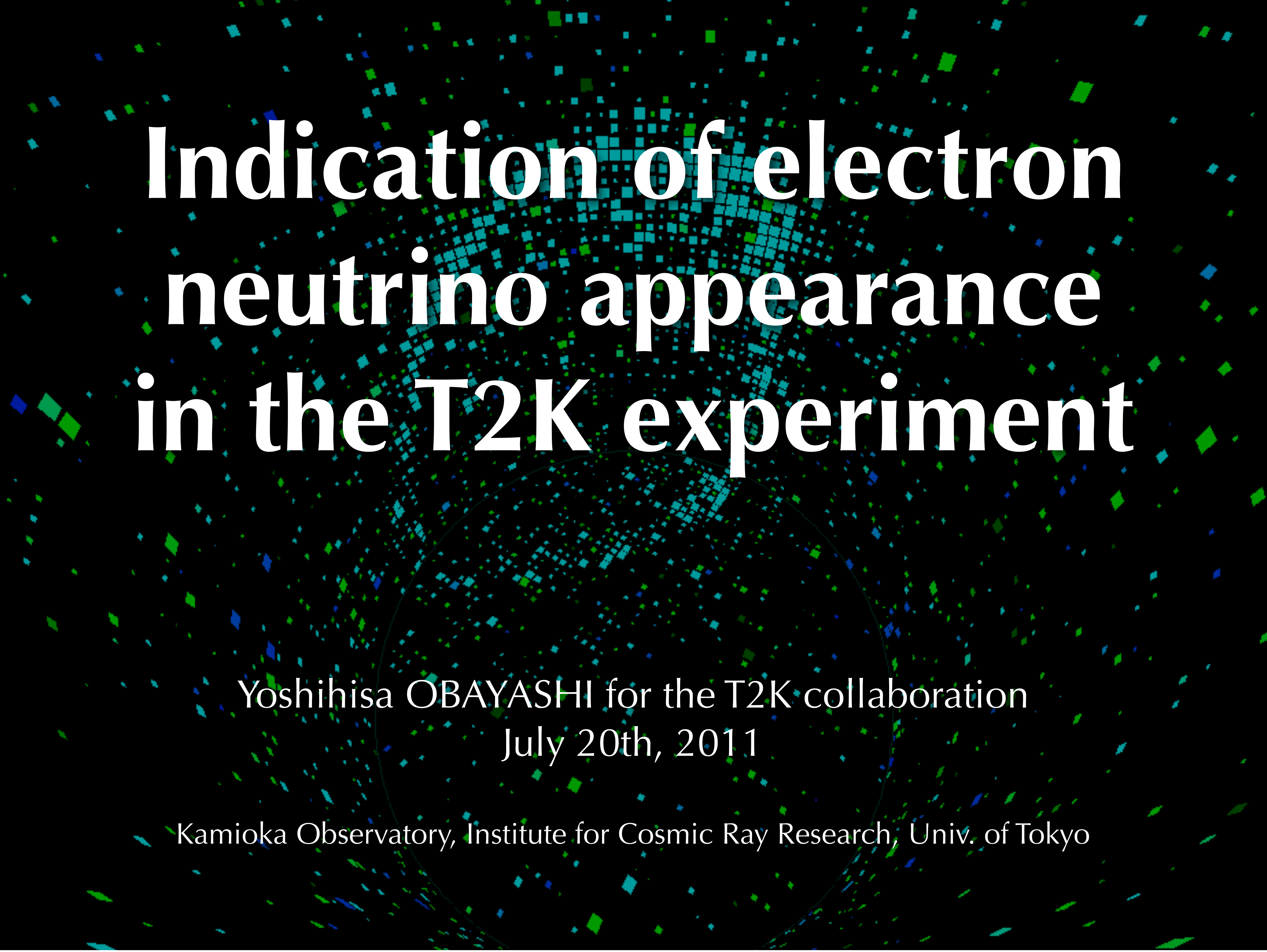

Indication of electron neutrino appearance in the T2K experiment

Yoshihisa OBAYASHI for the T2K collaboration

July 20th, 2011

Kamioka Observatory, Institute for Cosmic Ray Research, Univ. of Tokyo

PRL 107, 041801 (2011) PHYSICAL REVIEW LETTERS week ending 22 JULY 2011

Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam

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Neutrino Oscillation

Flavor Eigenstate (ν_e,ν_μ,ν_τ) ≠ Mass Eigenstate (ν_1,ν_2,ν_3)

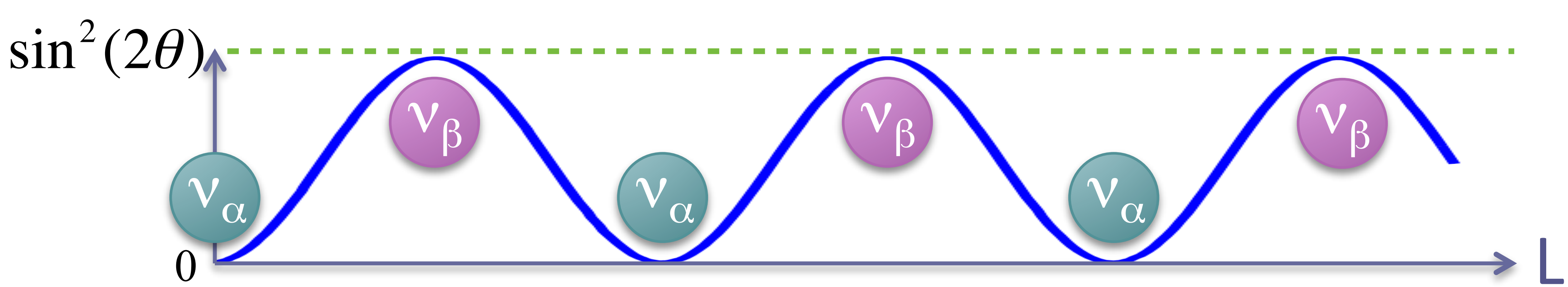
$$\begin{pmatrix}\nu_\alpha \\ \nu_\beta\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_i \\ \nu_j\end{pmatrix}$$

α,β = Flavor states
i,j = Mass states

Probability that ν_α observed as ν_β after traveling L:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2(eV^2)L(km)}{E_\nu(GeV)}\right)$$

$\Delta m^2 = |m_i^2 - m_j^2|$



Three Flavour Oscillation

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

U_{PMNS}=

$$\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Oscillation between three neutrino flavors are represented by three mixing angle (θ_{12},θ_{23},θ_{13}), two mass differences (Δm^2_{12}, Δm^2_{23}) and CP phase δ.

Current Status of Experimental Knowledge

$\theta_{12} = 34° \pm 3°$

$\Delta m_{12}^2 \sim 8 \times 10^{-5} eV^2$

solar ν, reactor ν

$\theta_{23} = 45° \pm 5°$

$\Delta m_{23}^2 \sim 2.5 \times 10^{-3} eV^2$

atmospheric ν, accelerator ν

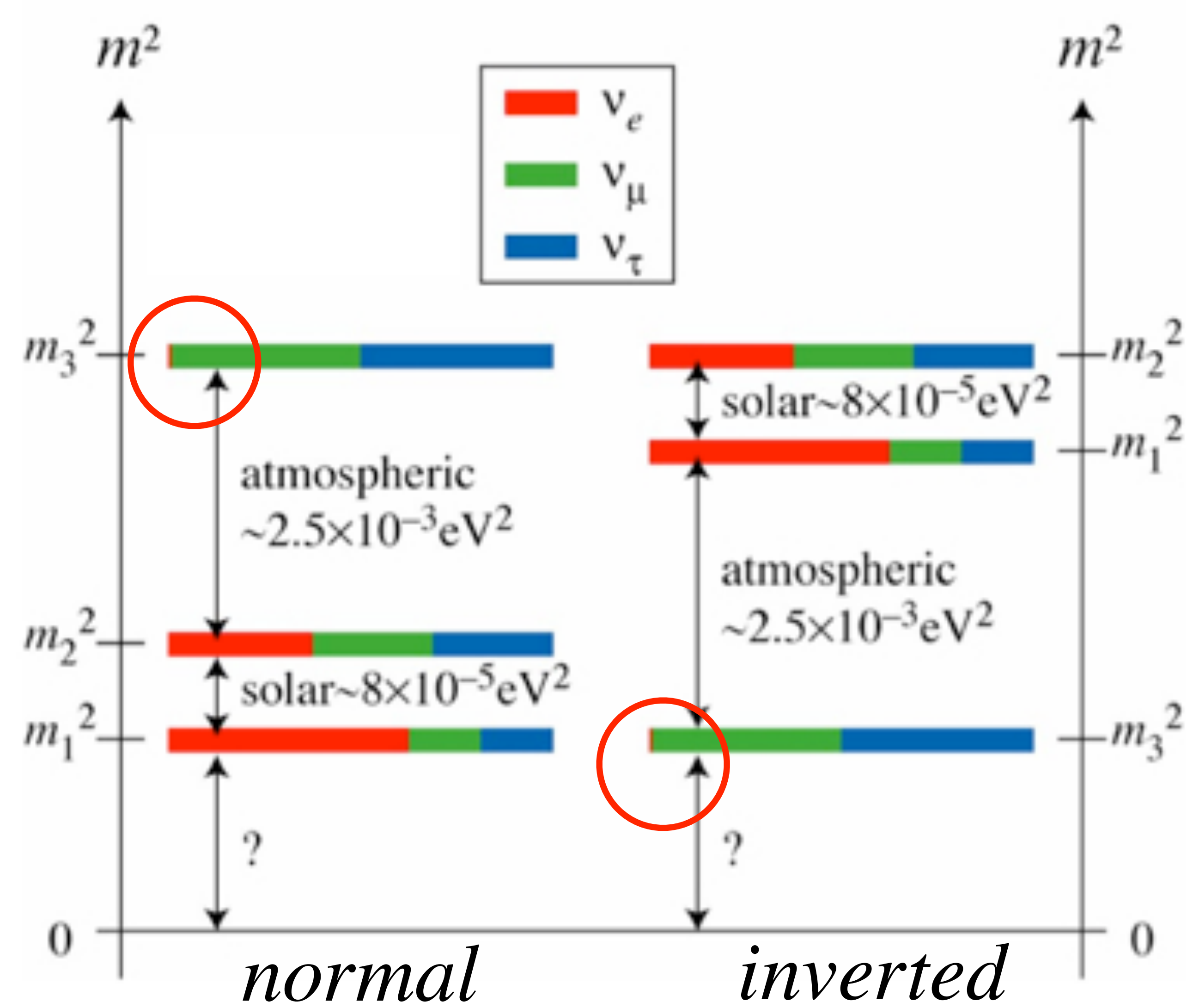
$\theta_{13} < 11°$

reactor ν, accelerator ν

Last Unknown mixing angle θ_{13}

$\sin^2(2\theta_{13}) < 0.15$ @90%CL

by CHOOZ, MINOS



Mass Hierarchy (m_3 >? <? m_1,m_2),

CP phase δ:

UNKNOWN.

Physics Motivation of ν_e appearance

★ **discovery of $\nu_\mu \to \nu_e$**

Direct detection of neutrino flavor mixing in "appearance" mode then **Determine θ_{13}**

$P(\nu_\mu \to \nu_e)$ =

$$\sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(1.27\Delta m^2_{31} L/E) + \ldots$$

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

Cf: In Reactor experiment,
$P(\nu_e \to \nu_x)$ =

$$\sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E) + \ldots$$

Open a possibility to measure CP violation in lepton sector in future

CP odd term in $P(\nu_\mu \to \nu_e)$ $\propto$

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

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

T2K Collaboration

International collaboration

(~500 members, 59 institutes, 12 countries)

Transparencies of JHF HEP wor...

http://www.icepp.s.u-tokyo.ac.jp/~mihara/hecsec

JHF high energy physics workshop

date ; 7-Jan-2000 / place ; Seminar Hall @ KEK

はじめに (駒宮幸男 @ 東京大学) **Session I ; Kaon Physics** (chair : 山中)

Introduction (山中 卓 @ 大阪大学) (gziped transparency , 638kbyte)

K+ -> pi + nu nu-bar , T violation in Kmu3 decay

(小松原 健 @ KEK田無) (gziped transparency , 1401kbyte)

(新川 孝男 @ KEK) (gziped transparency , 1276kbyte)

KL -> pi0 nu nu-bar TOF method (笹尾 登 @ 京都大学) (gziped transparency , 1130kbyte)

KL -> pi0 nu nu-bar @ low energy (稲垣 隆雄 @ KEK) (gziped transparency , 1389kbyte)

KL -> pi0 nu nu-bar @ high energy (山中 卓 @ 大阪大学) (gziped transparency , 1482kbyte)

CPT experiment at JHF (青木 正治 @ KEK) (gziped transparency , 1482kbyte)

まとめ (山中 卓 @ 大阪大学) (gziped transparency , 453kbyte)

全体での議論

Session II ; Lepton Flavour Violation (chair : 森)

JHF Project の進行状況 (永宮 正治 @ JHF 推進室) (gziped transparency , 951kbyte)

50GeV PS における大強度 muon beam (久野 良孝 @ KEK) (gziped transparency , 11225kbyte)

LFV 実験 (森 俊則 @ ICEPP) (gziped transparency , 1353kbyte)

全体での議論

Session III ; Neutrino Physics (chair : 野崎)

Future Prospect (久野 良孝 @ KEK) (gziped transparency , 2949kbyte)

JHF での ニュートリノ振動実験

Introduction (西川 公一郎 @ 京都大学) (gziped transparency , 420kbyte)

Summary of SK and K2K (伊藤 好孝 @ ICRR) (gziped transparency , 1895kbyte)

Beam at JHF (小林 隆 @ KEK) (gziped transparency , 2059kbyte)

nu_mu disappearance 実験 (中家 剛 @ 京都大学) (gziped transparency , 1161kbyte)

nu_e appearance 実験 (大林 由尚 @ ICRR) (gziped transparency , 1262kbyte)

Sterile in long baseline (早戸 良成 @ KEK) (gziped transparency , 624kbyte)

Medium baseline (小林 隆 @ KEK) (gziped transparency , 1993kbyte)

まとめ (西川 公一郎 @ 京都大学) (gziped transparency , 73kbyte)

海外でのニュートリノ振動実験 (小松 雅宏 @ 名古屋大学) (gziped transparency , 2368kbyte)

全体での議論

If you have any opinion , send an email to us !

Hajime Nishiguchi, *Osamu Jinnouchi*

24-Jan-2000

Letter of Intent: A Long Baseline Neutrino Oscillation Experiment using the JHF 50 GeV Proton-Synchrotron and the Super-Kamiokande Detector

February 3, 2000

—**V1.0**—

JHF Neutrino Working Group

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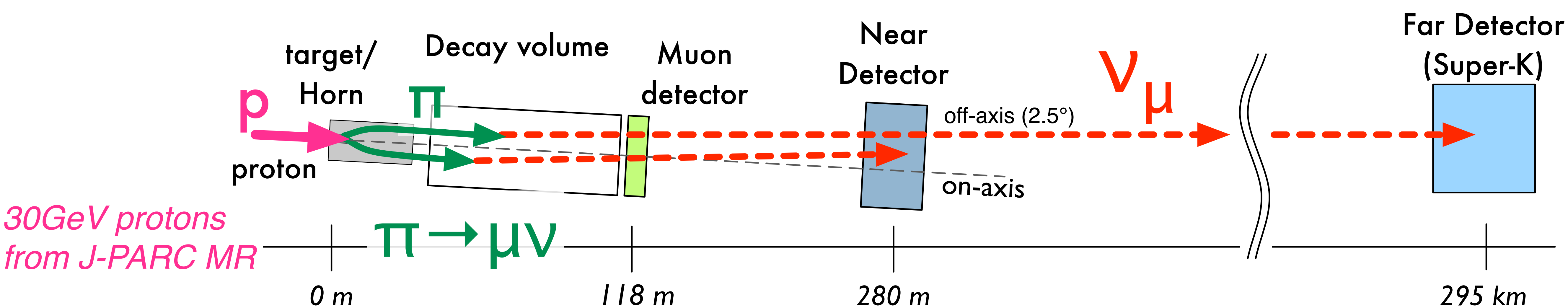
[4] Organizer: nishikaw@neutrino.kek.jp

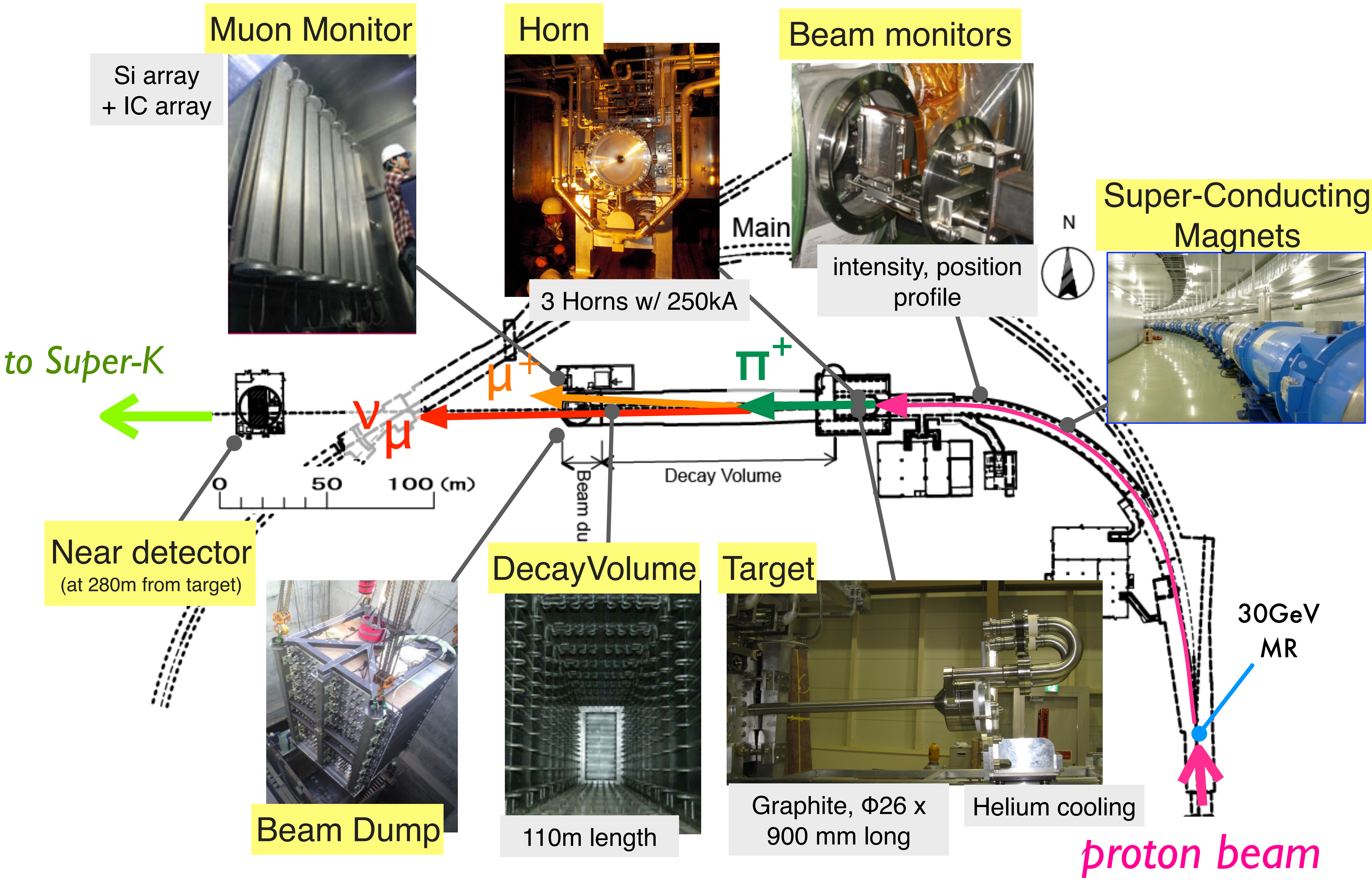
Overview of this talk

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

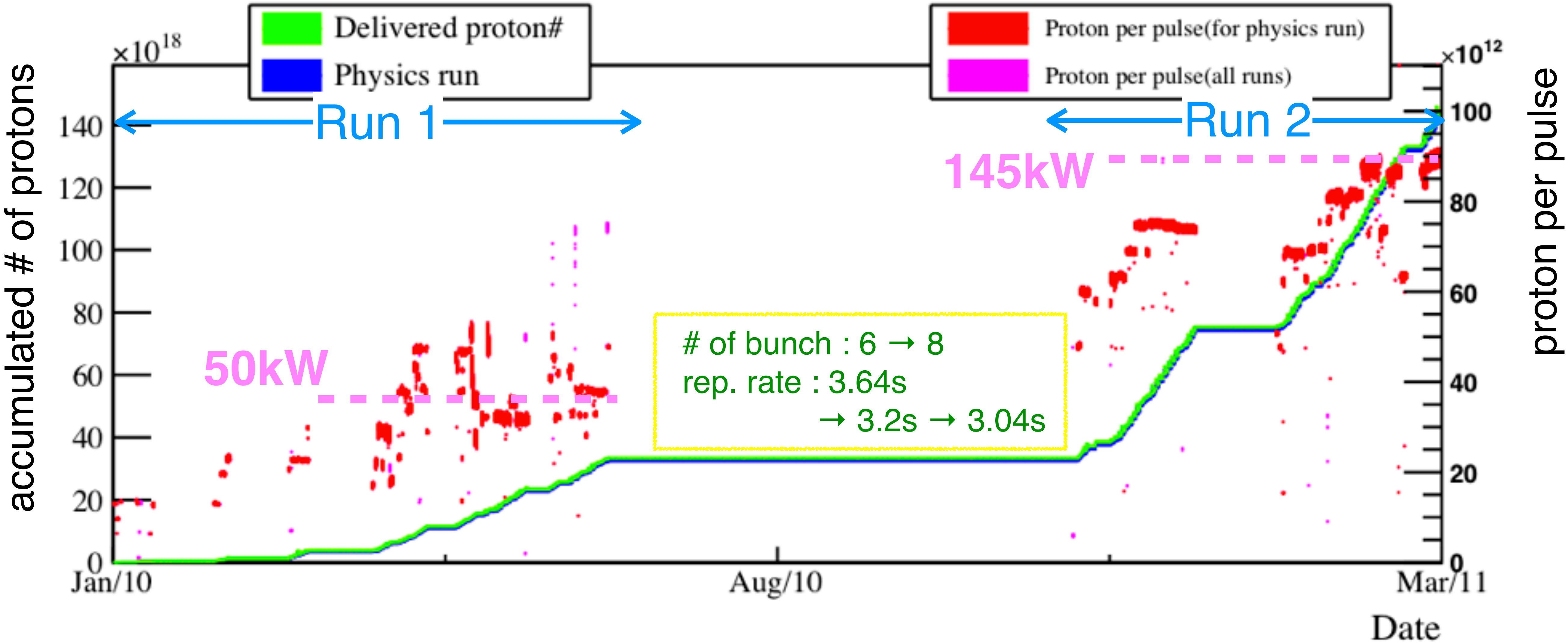
Experimental Setup



J-PARC Neutrino beam facility



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)

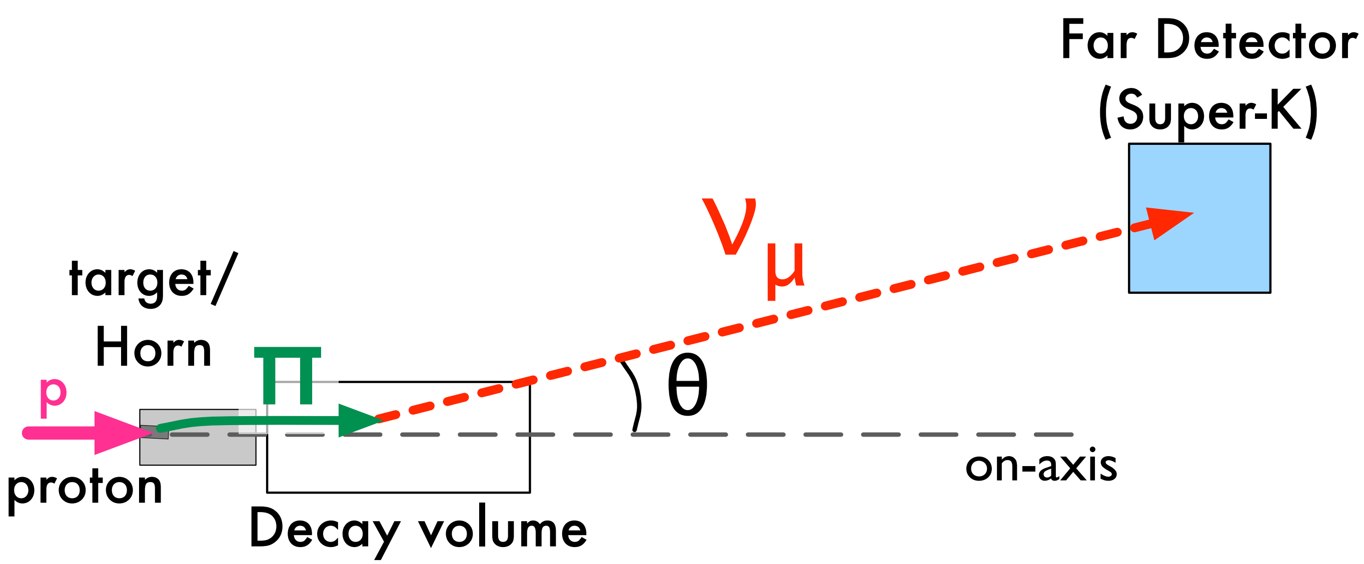
- 11.08 x 10^{19} p.o.t. for analysis
- ~145kW beam operation

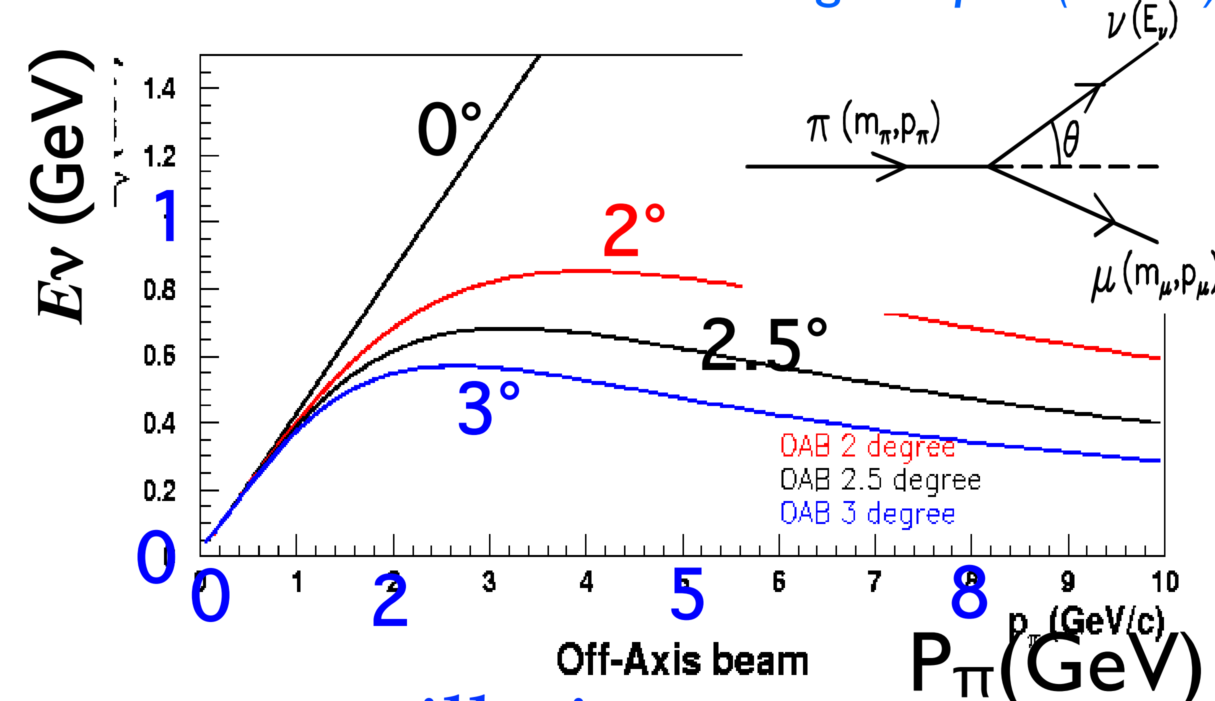
Total # of protons used for this analysis is 1.43 x 10^{20} pot

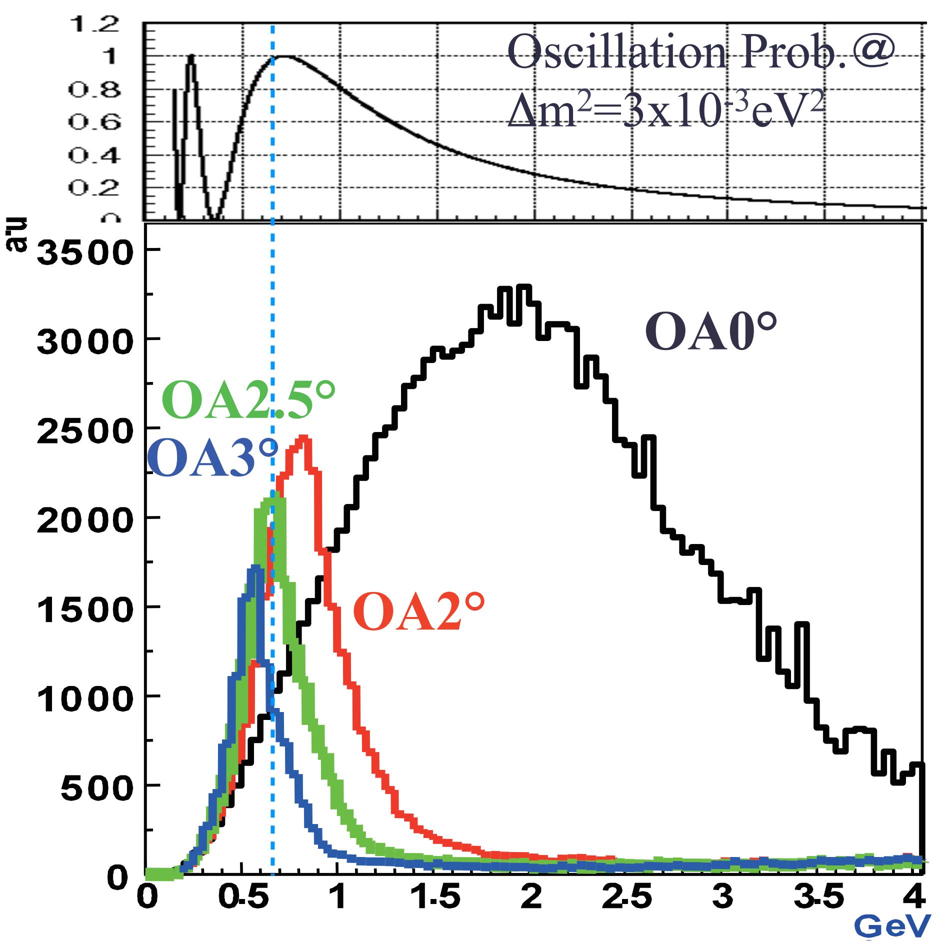
2% of T2K's final goal and x 5 exposure of the previous report

Off-axis beam : intense & narrow-band beam

BNL E889 Design Report(1995)







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 ν_e component (0.5%@peak)

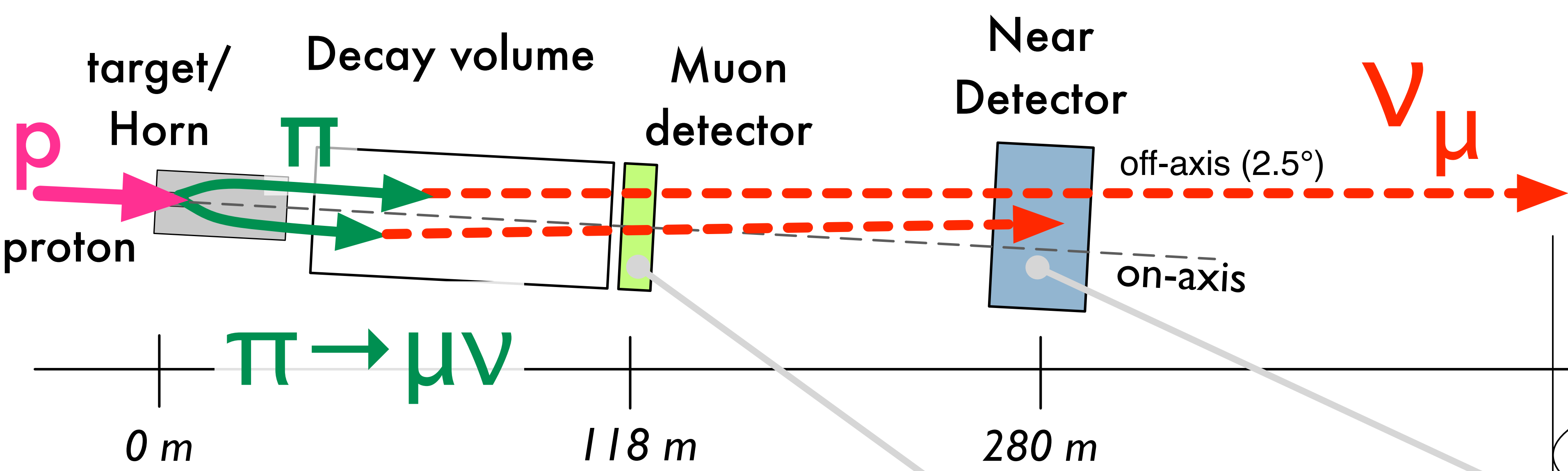
Small high energy tail

→ small background

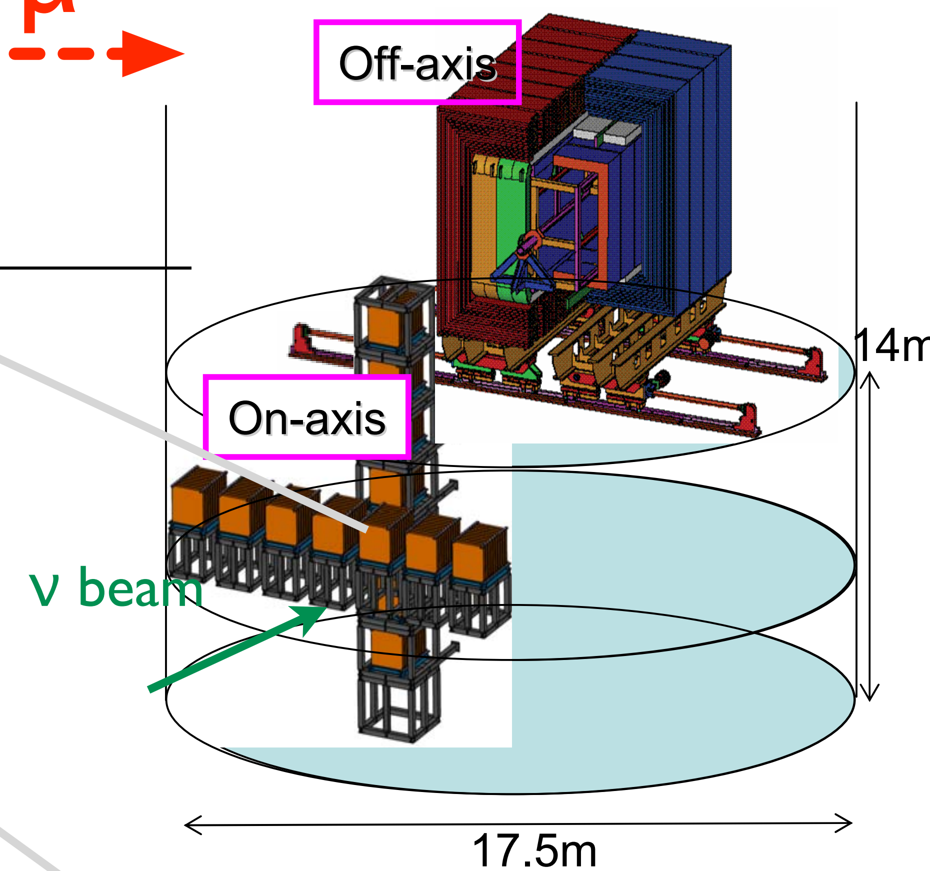
Accurate and stable beam pointing is important

(Keep the peak energy stable)

Monitor beam direction and intensity



Near Detectors



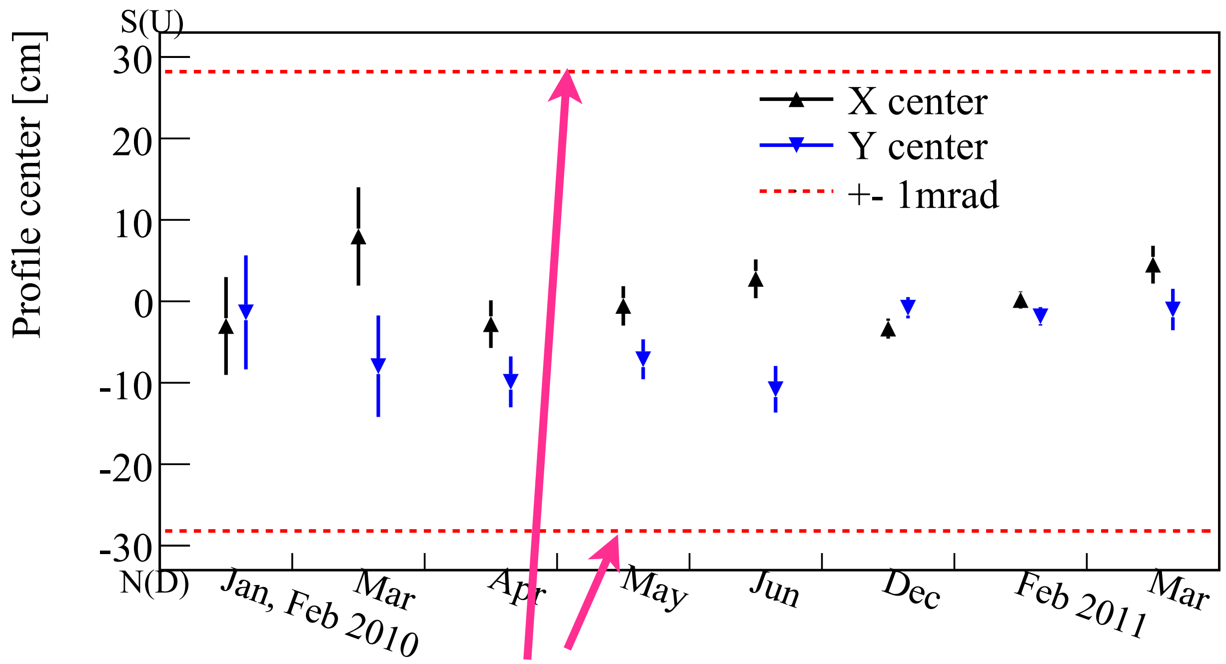
Stability of beam direction should be <1mrad
(to keep the peak energy at SK stable δE<2%)

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

ν beam stability

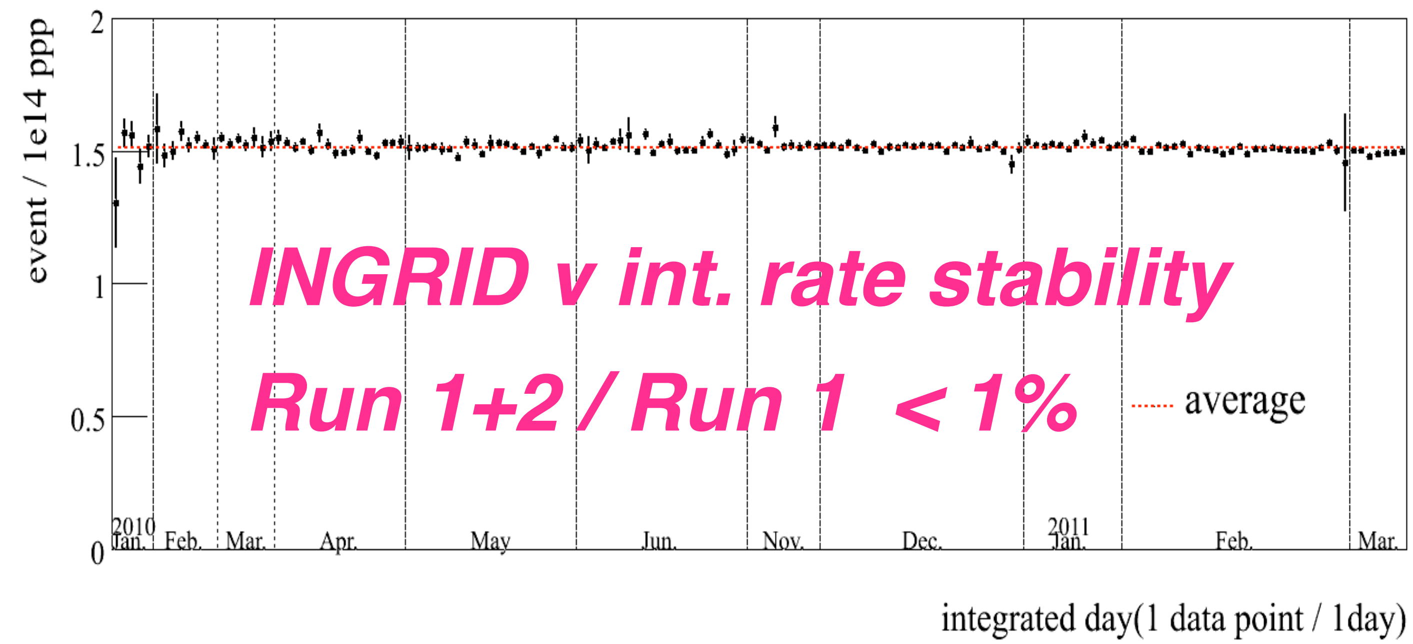
Stability of beam direction should be <1mrad
(to keep the peak energy at SK stable δE<2%)

Stability of ν beam direction (INGRID)



ν beam dir. stability < 1mrad

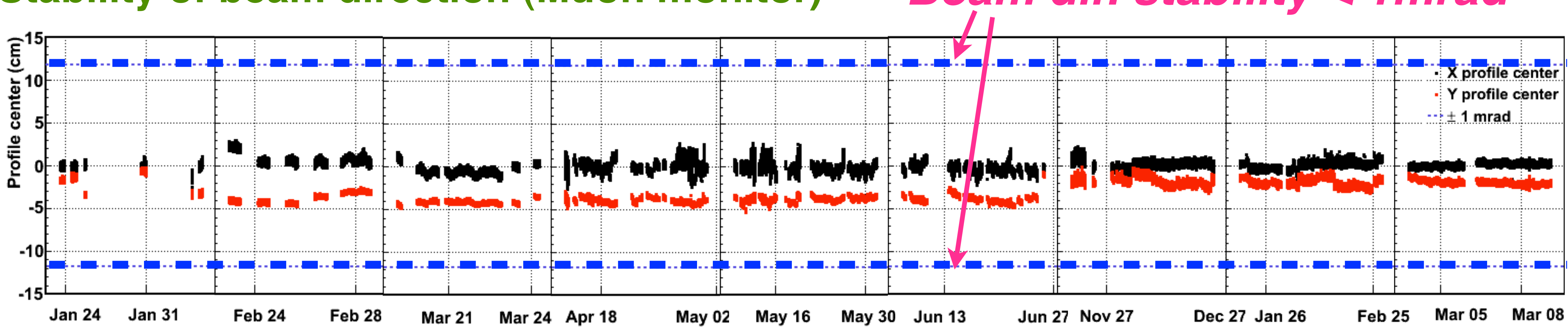
Stability of ν interaction rate normalized by # of protons (INGRID)



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

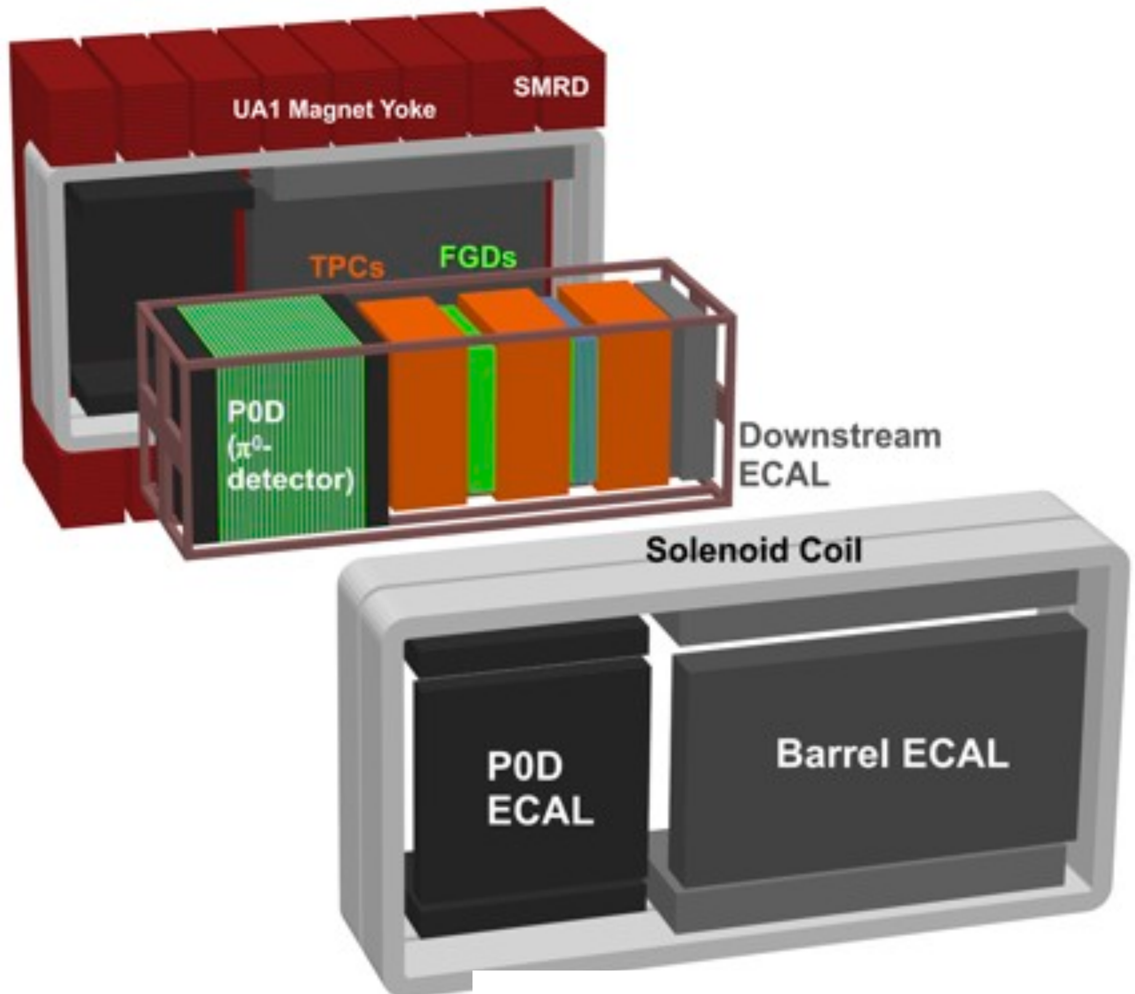
Stability of beam direction (Muon monitor)

Beam dir. stability < 1mrad

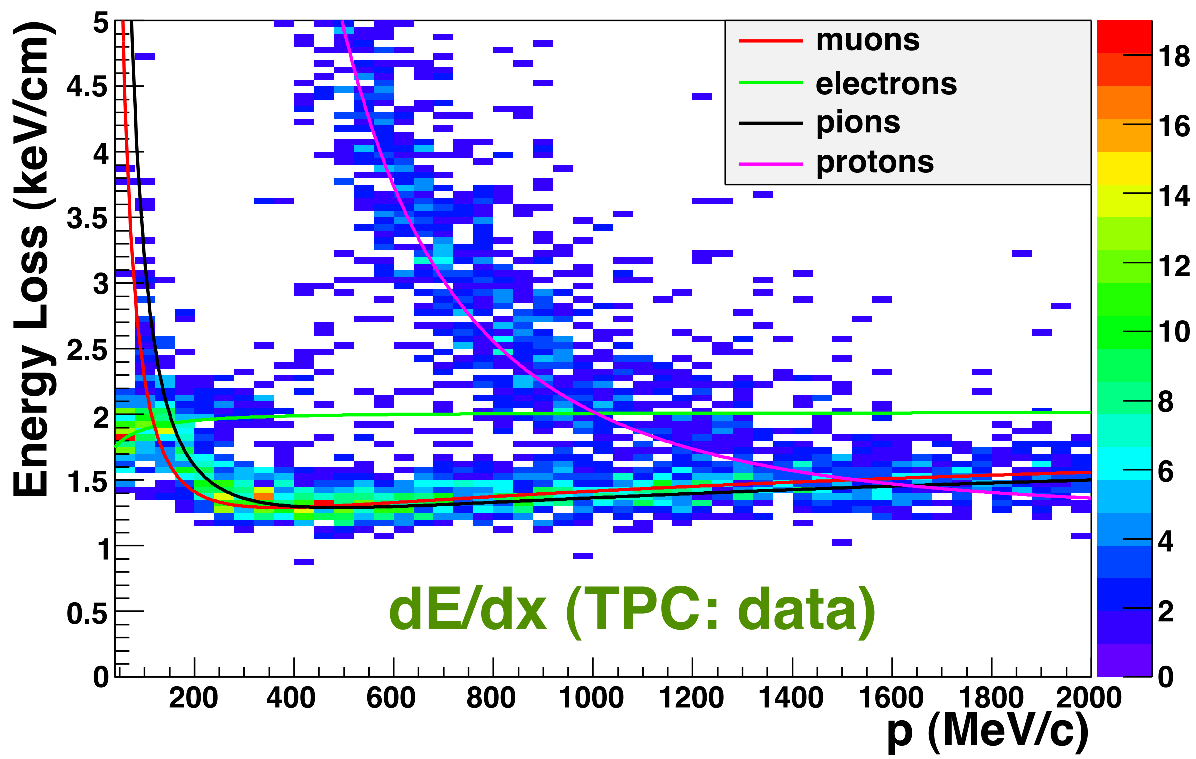


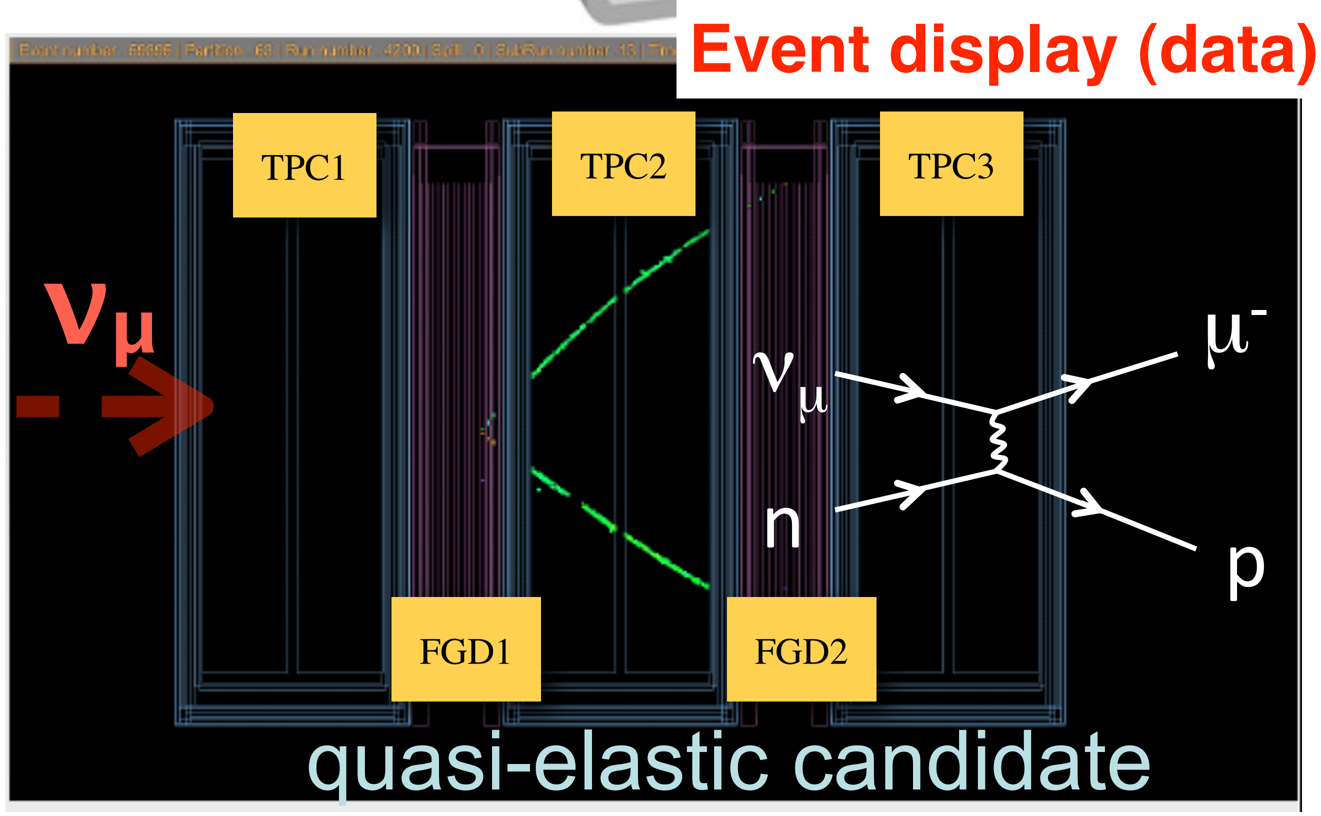
Off-axis Near Detector (ND280)

- 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

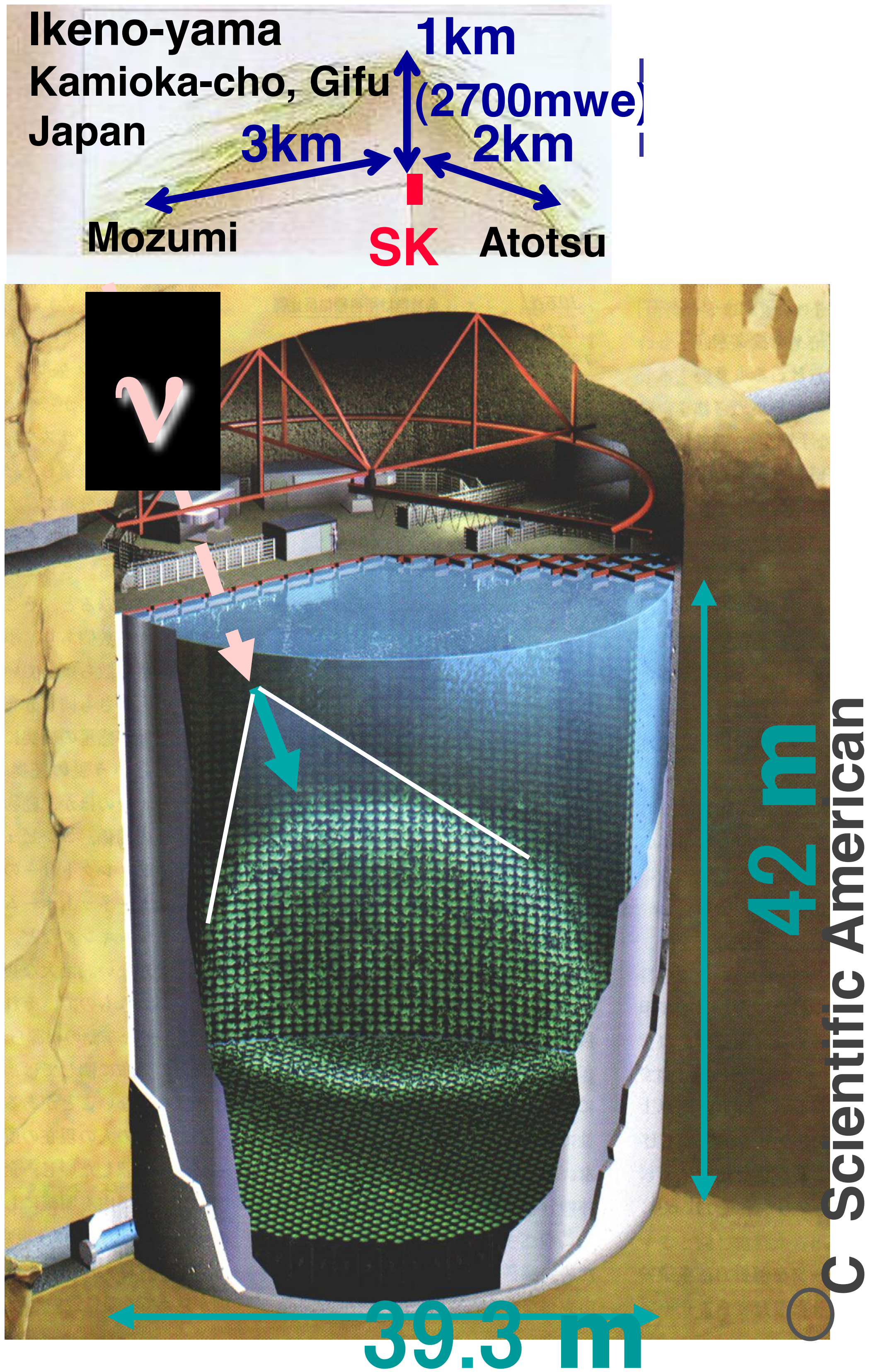


ν_μ CC events rate measurement in present analysis





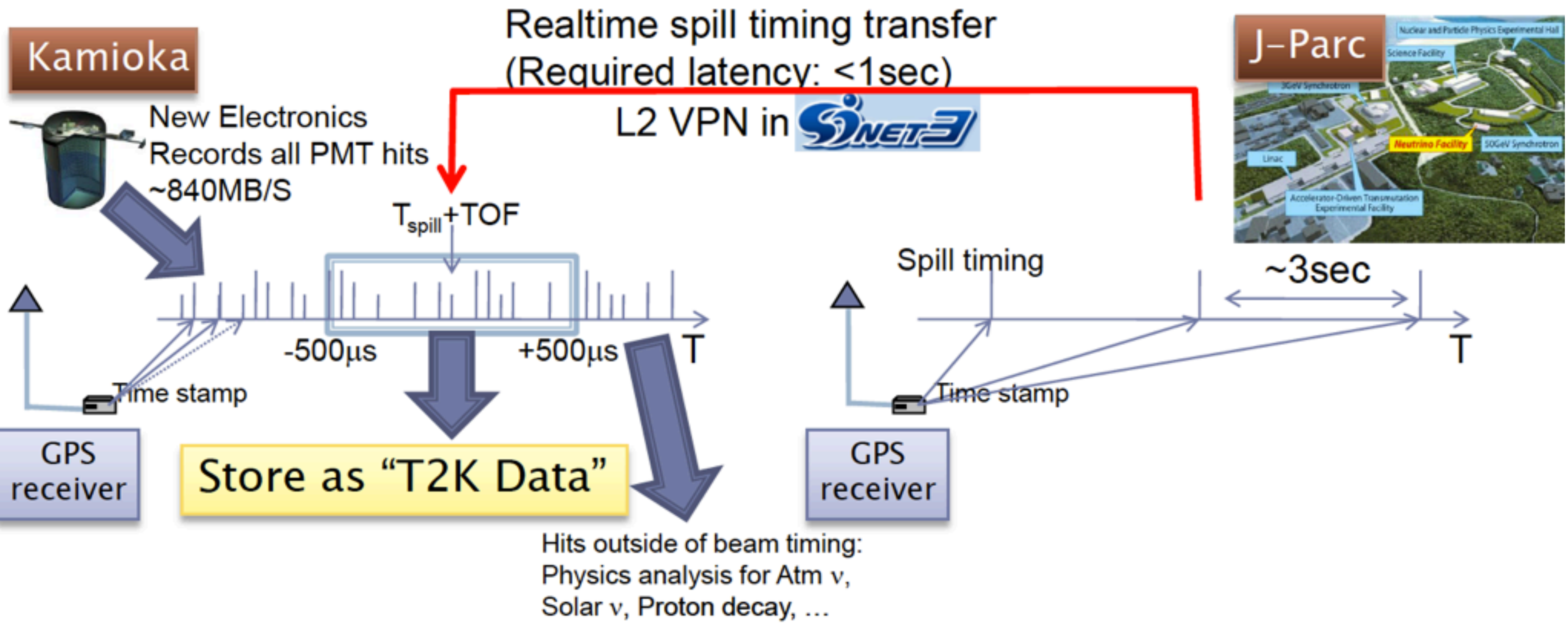
Far detector (Super-K)



- Water Cherenkov detector w/ fiducial volume 22.5kton (Total 50kton)
- Phase IV w/ Dead-time less DAQ system since September 2008
- T2K event trigger by accelerator beam timing
- atmospheric ν samples as control samples to study detector performance.

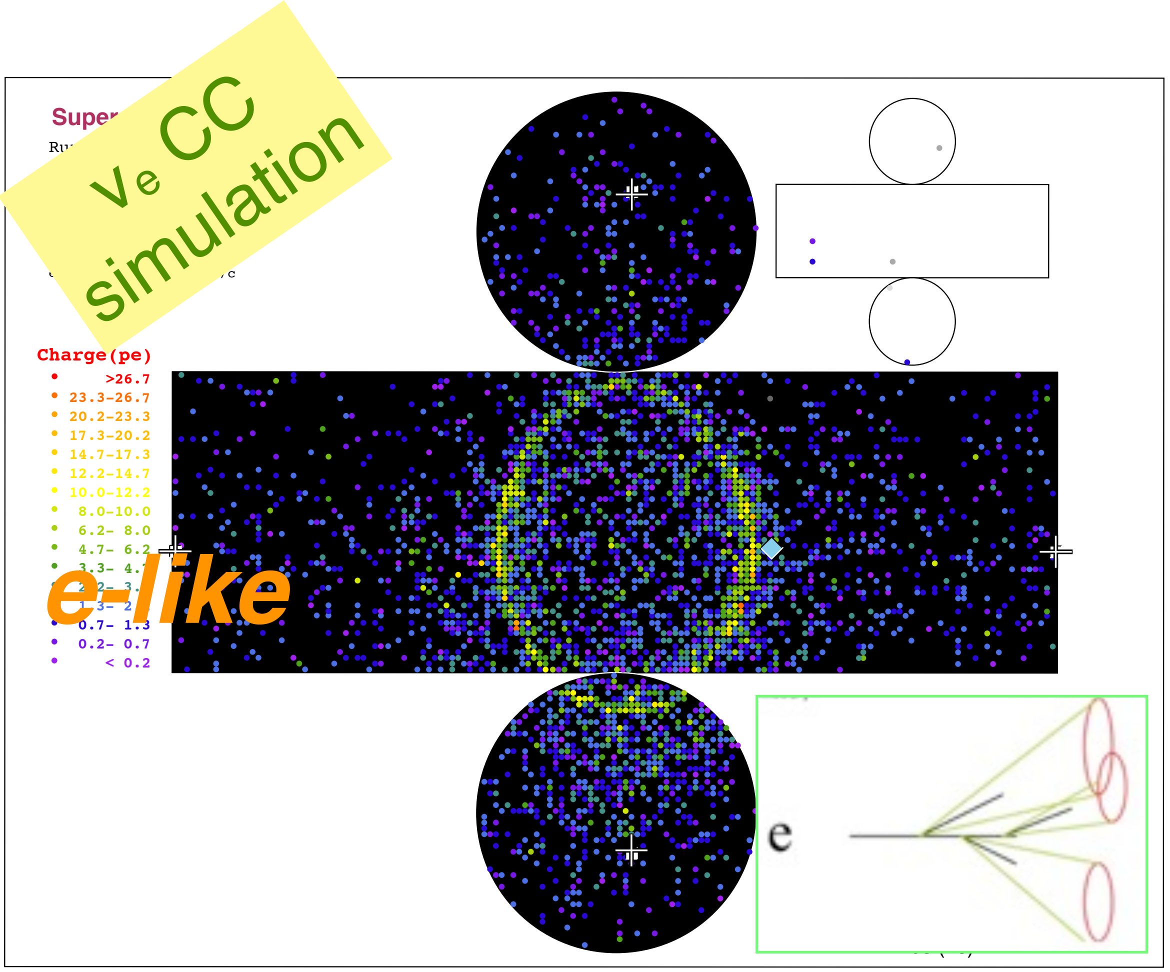
11,129 x 20inch PMTs (inner detector, ID)

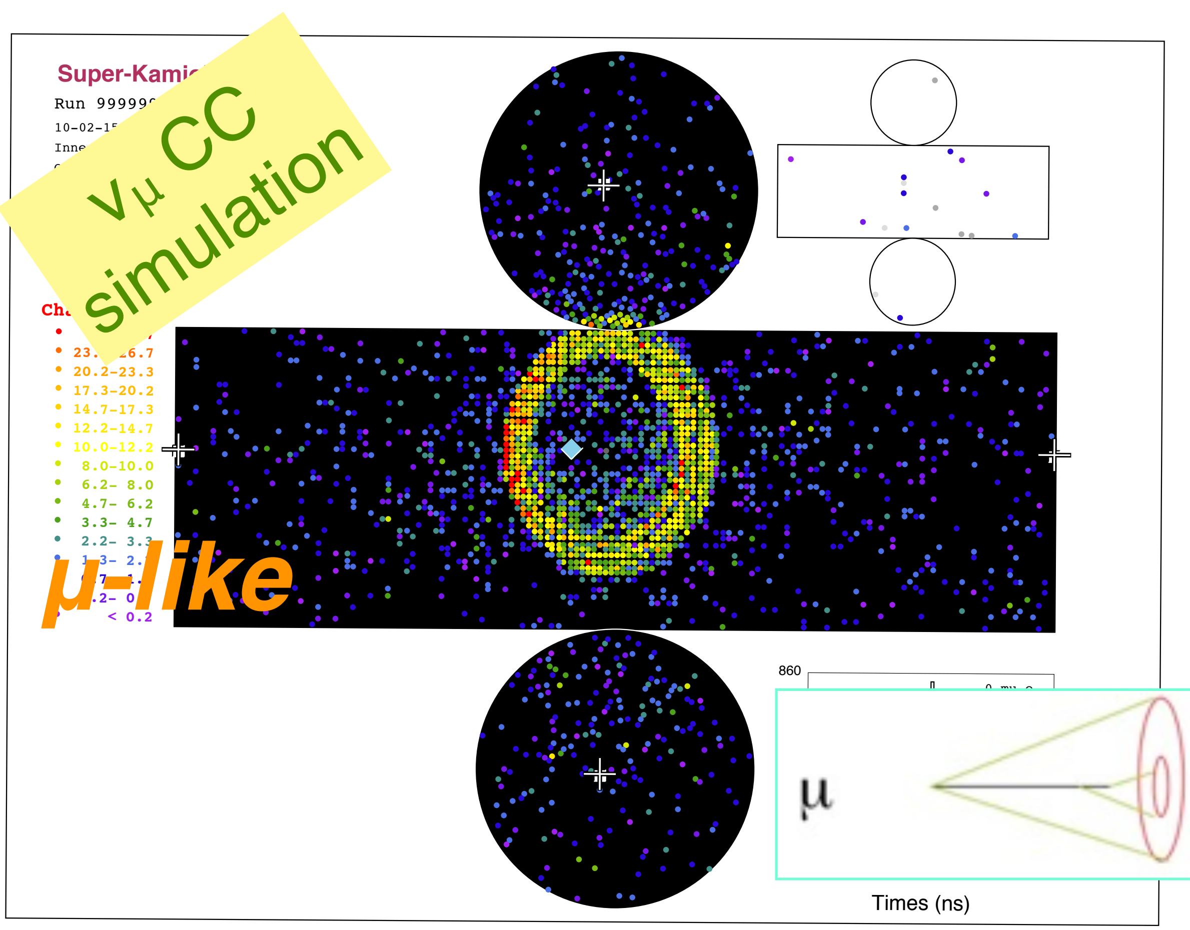
GPS Timing Synchronization and Beam Event Selection



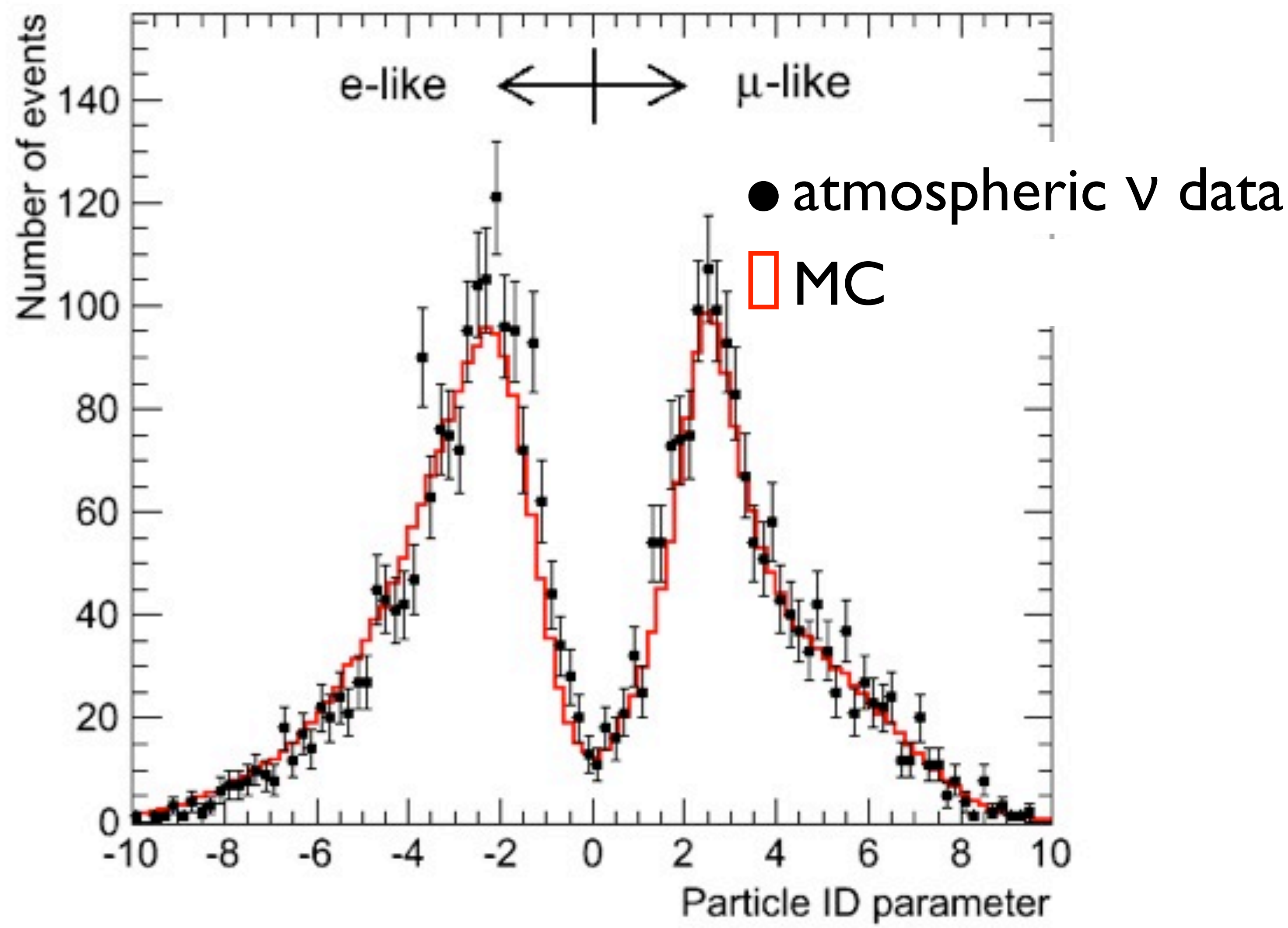
- "REALTIME" beam event selection has been applied.
- GPS Timing Accuracy < 150ns

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%

Search for ν_e appearance

Analysis overview

1. Apply ν_e selection criteria to the events at far detector (SK)
2. Compare # of observed events and # of expected events
   → search for ν_e appearance

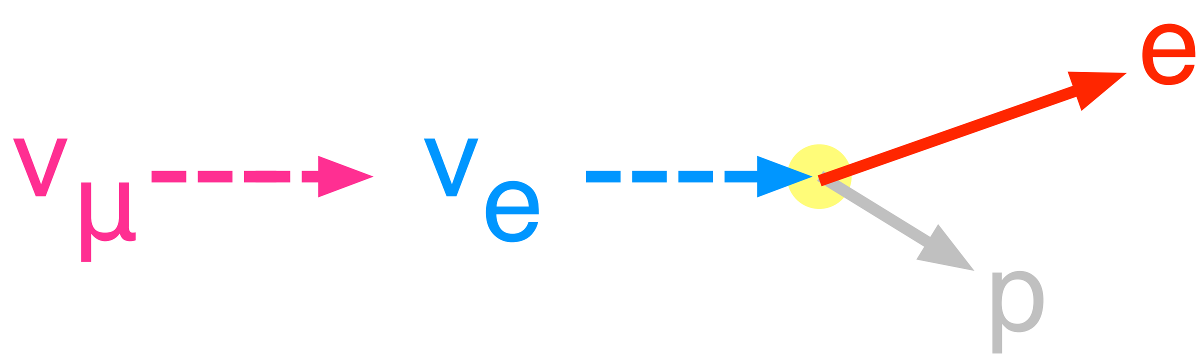
Contents in this section

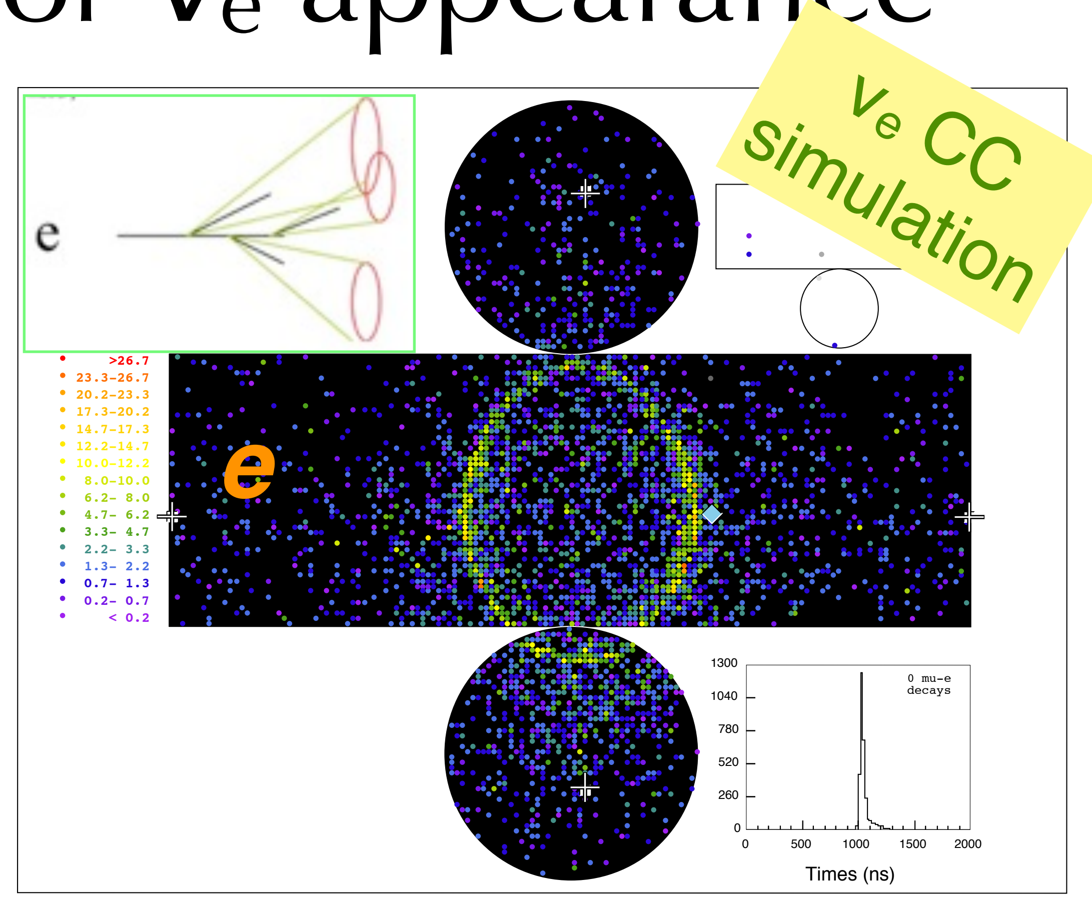
- ν_e selection
- The expected number of events at Far detector
- Systematic uncertainty
- Results

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

T2K Signal & Background for ν_e appearance

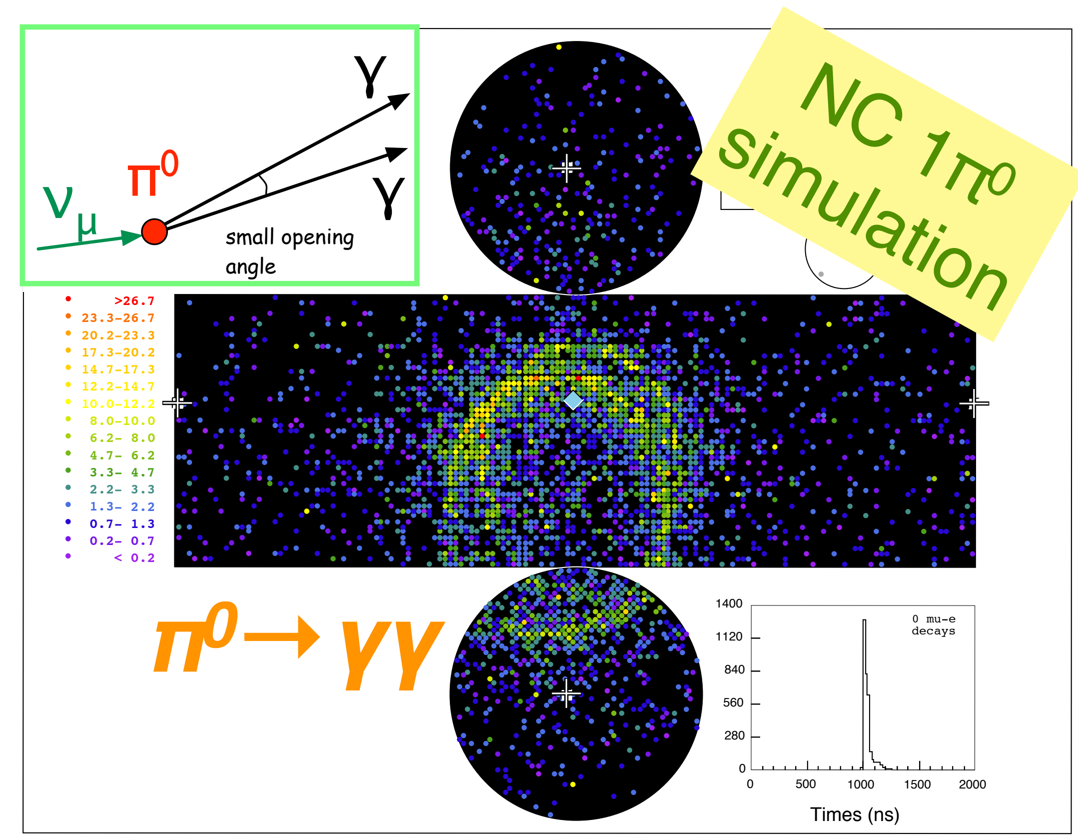
- Signal = **single electron event**
  - oscillated ν_e interaction :





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

(dominant process at T2K beam energy)



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

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

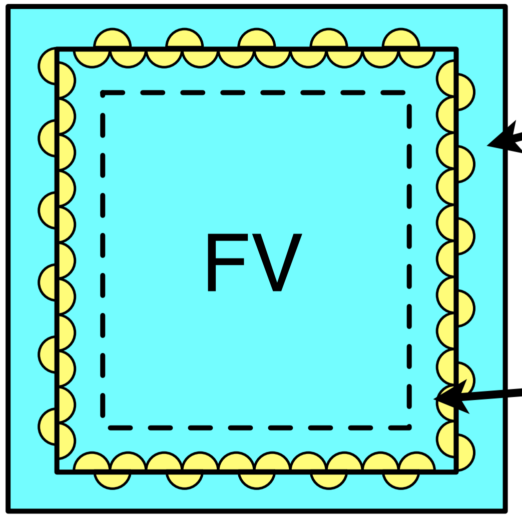
7 selection cuts

1. T2K beam timing & Fully contained (FC)
   (synchronized the beam timing, no activities in the OD)
2. In fiducial volume (FV)
   (distance btw recon. vertex and wall > 200 cm)
3. Single electron
   (# of ring is one & e-like)
4. Visible energy > 100 MeV

5. No decay electron observed
   (no delayed electron signal)
6. Reconstructed invariant mass (M_{inv}) < 105 MeV/c^2

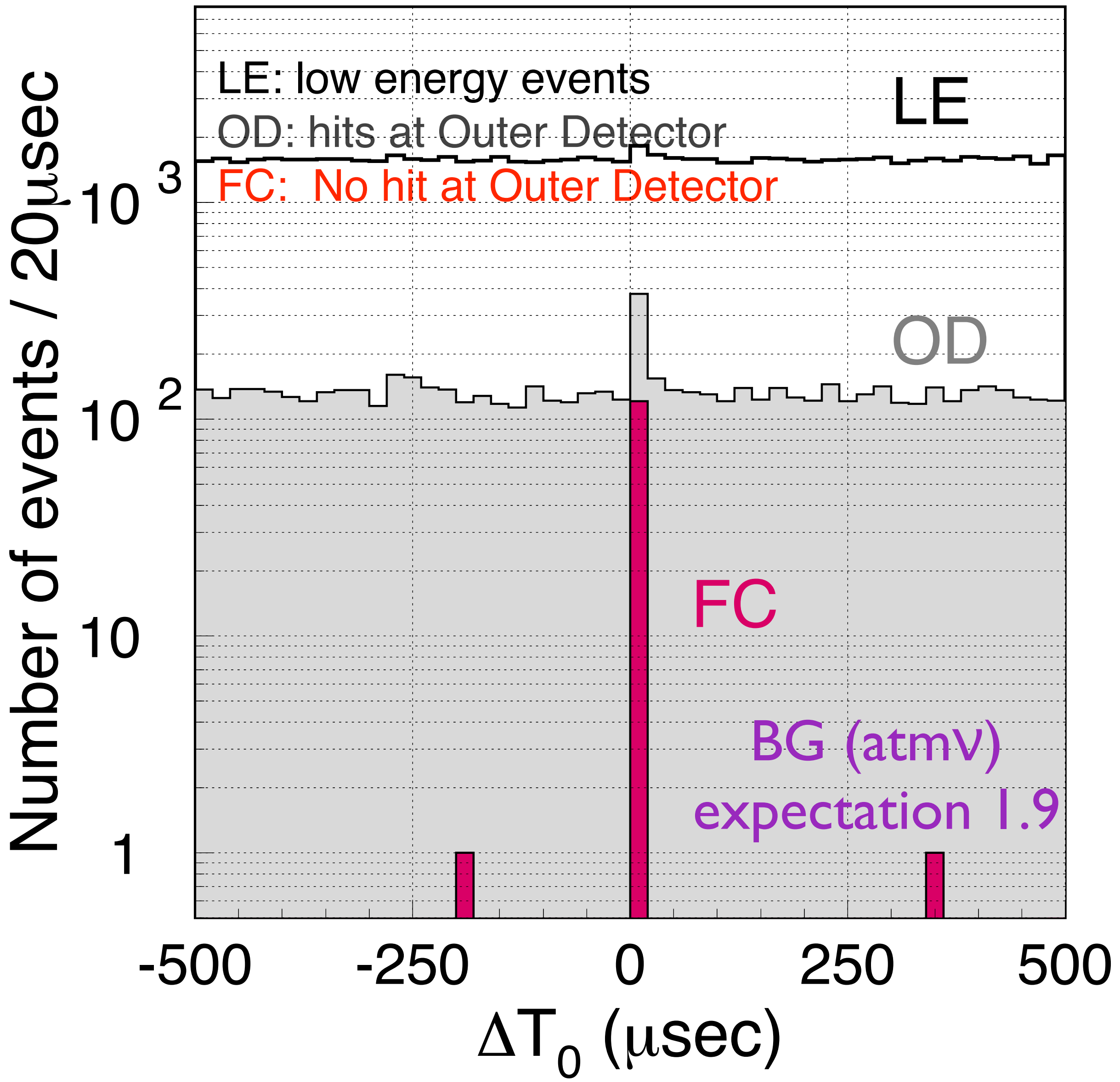
7. Reconstructed neutrino energy (E_{rec}) < 1250 MeV

1.Beam timing and FC cut

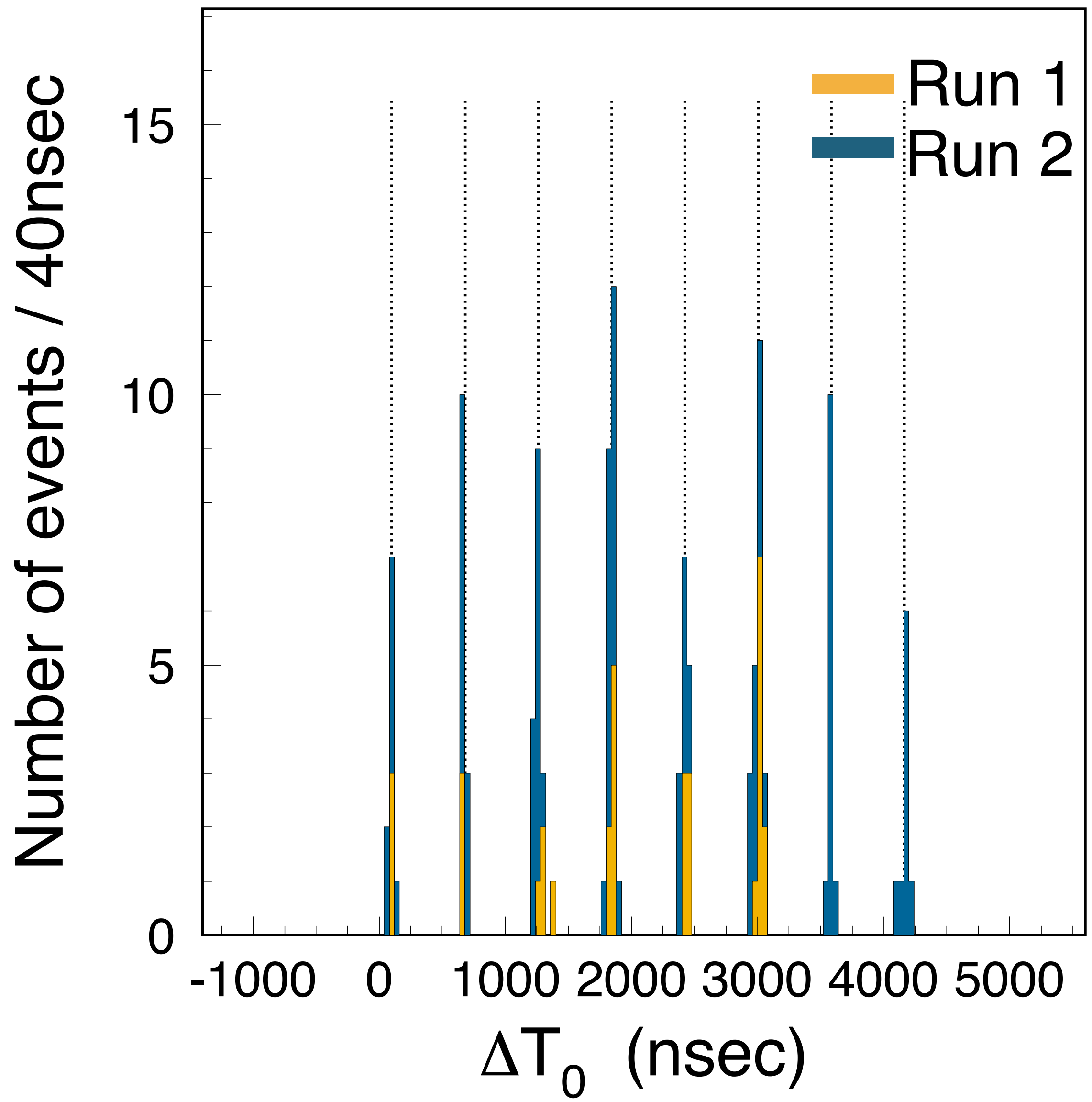


- Events in the T2K beam timing synchronized by GPS

relative event timing to the spill timing



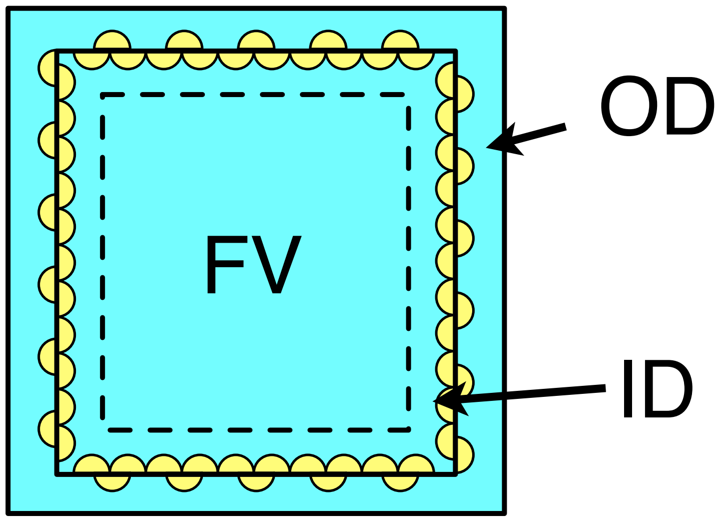
Clear beam structure !

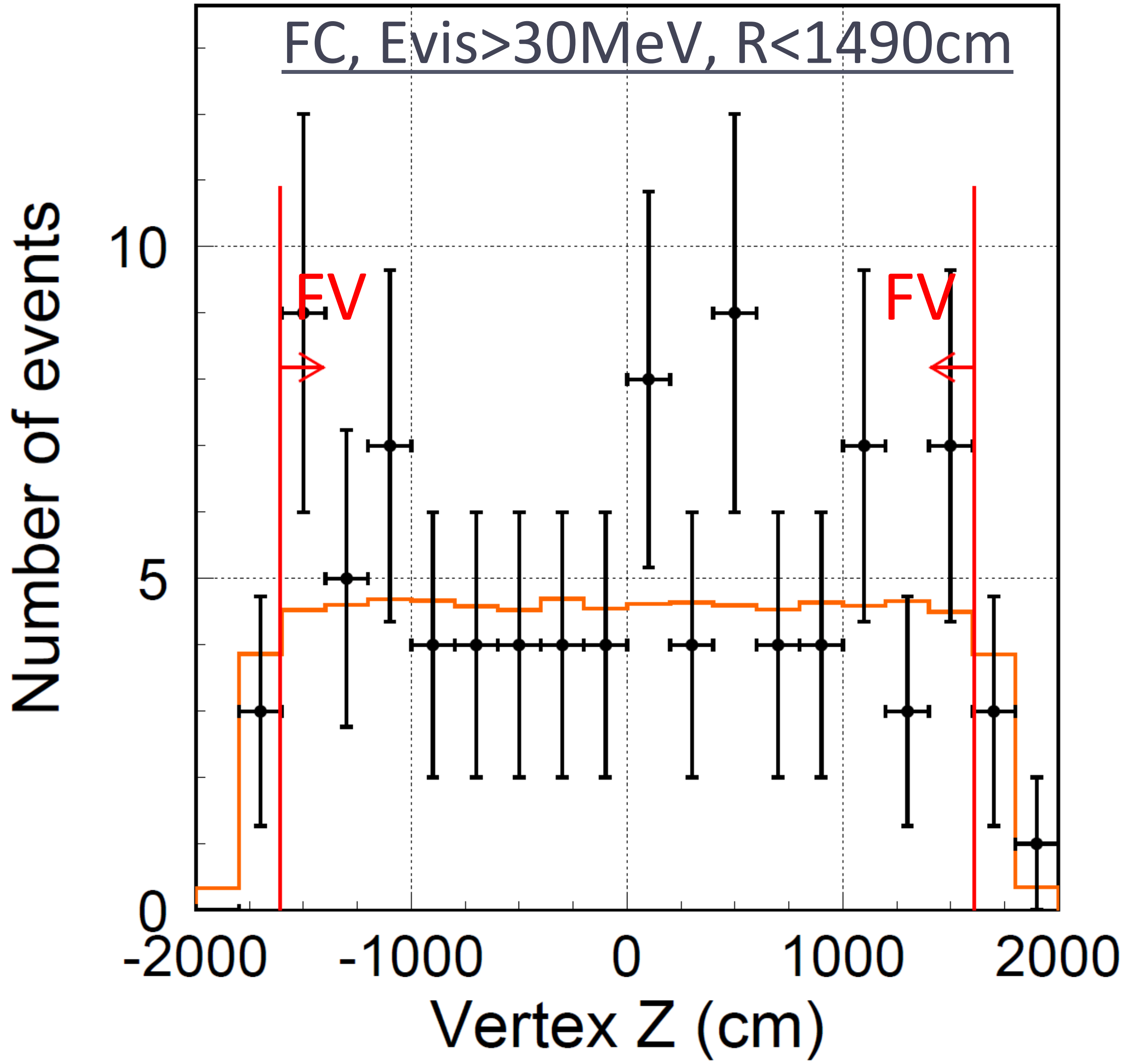


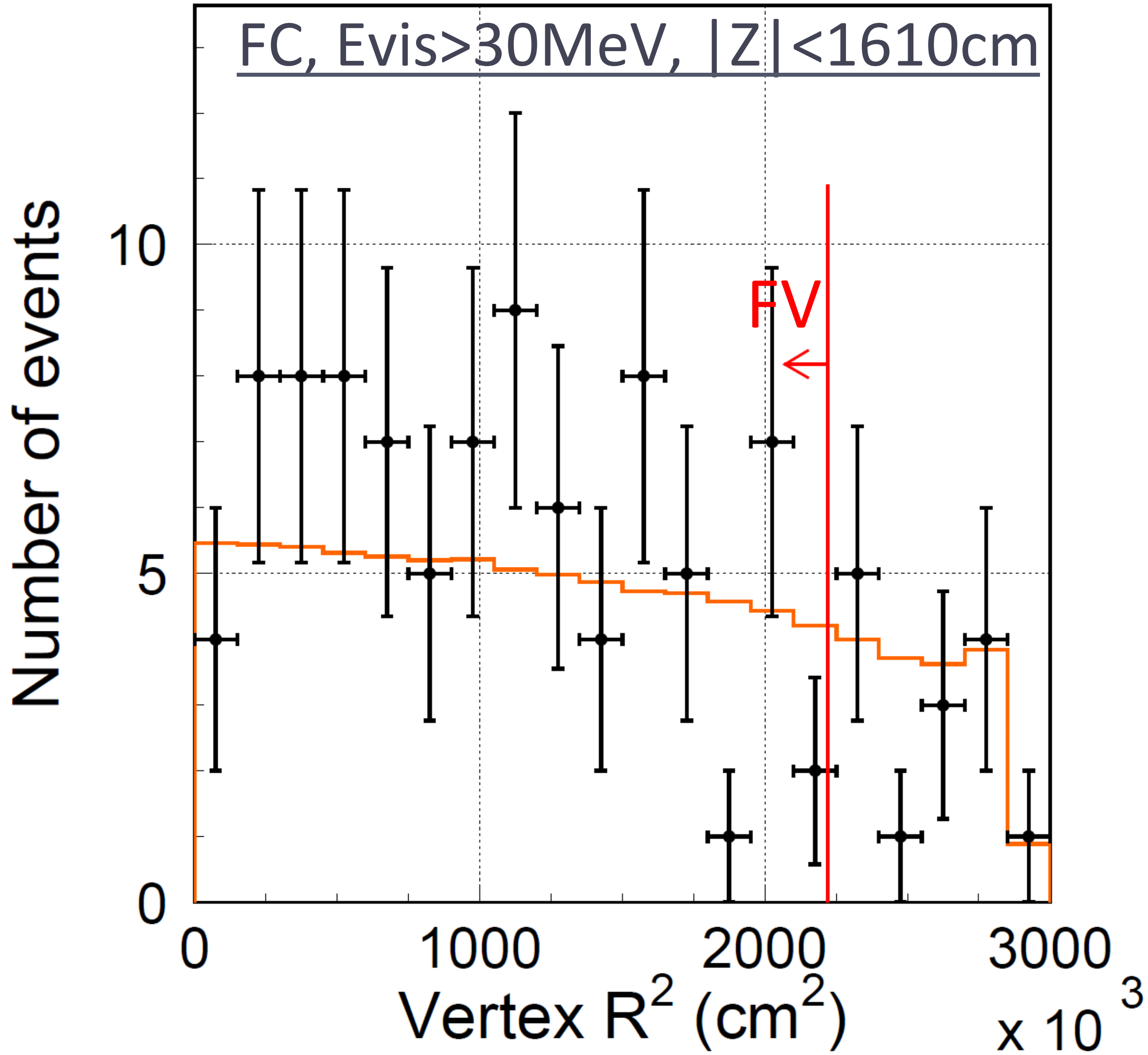
$\Delta T_0 = T_{GPS}@SK - T_{GPS}@J\text{-}PARC - TOF(\sim 985\mu sec)$

2. Fiducial volume cut

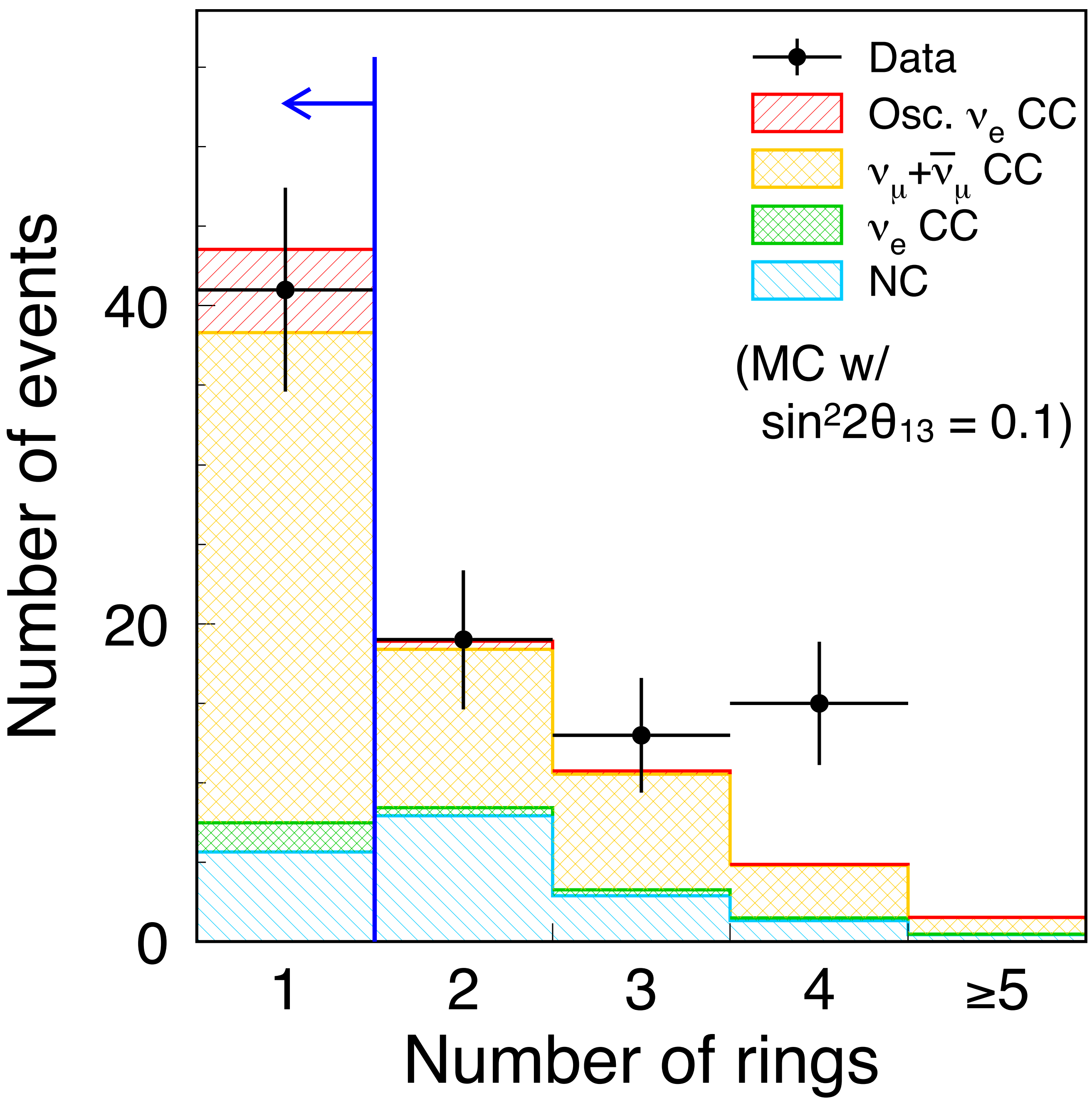
(distance between recon. vertex and wall > 200cm)

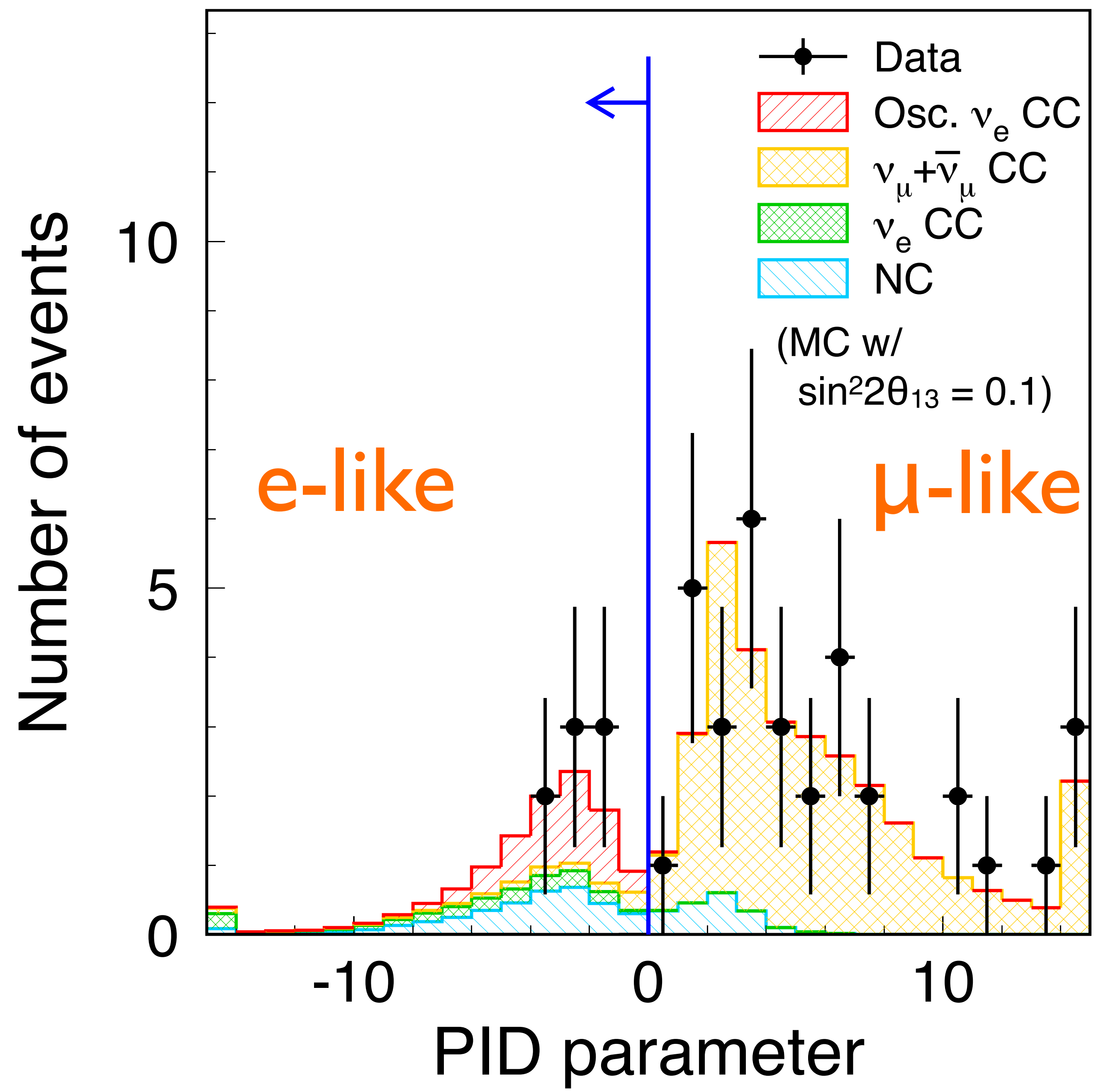






3. Single electron cut (# of ring is one & e-like)

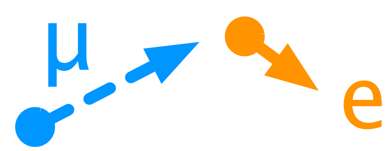


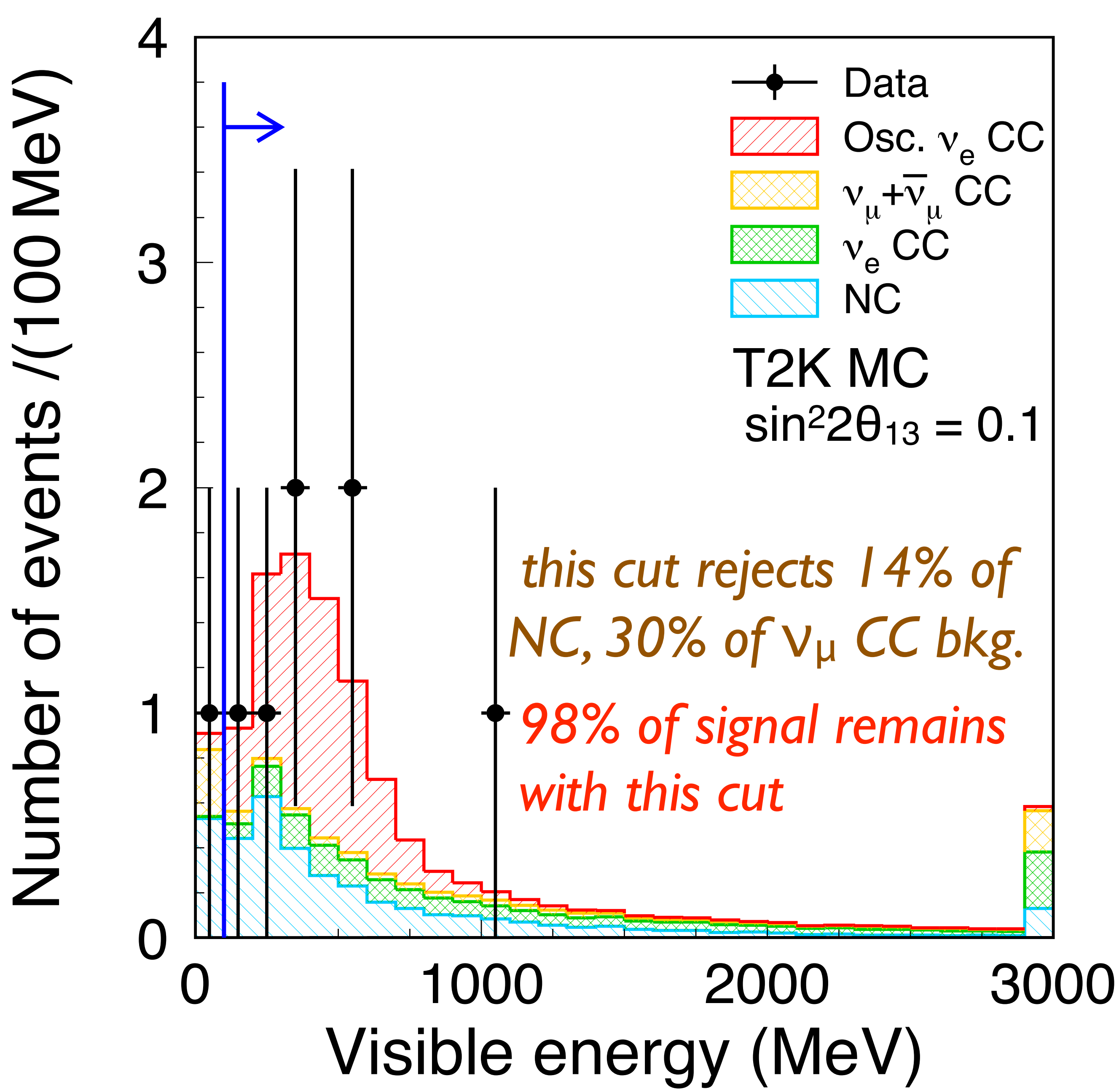


4. Visible energy > 100 MeV

(visible energy = electron-equivalent energy deposited in ID)

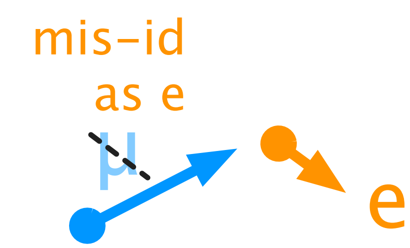
* Reject low energy events, such as NC background and decay electrons from invisible muon decays

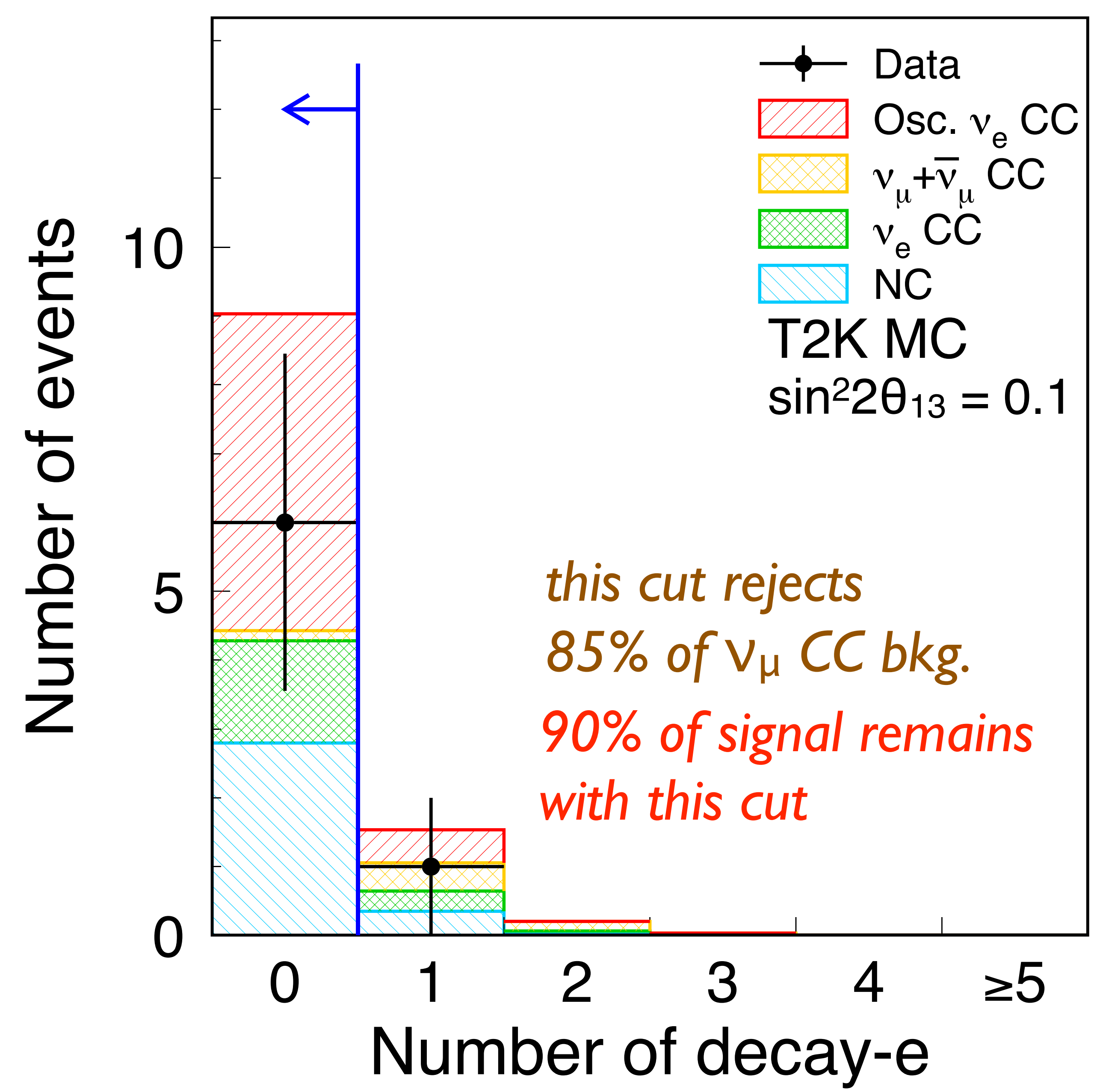




5. No decay electron observed (no delayed electron signal)

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

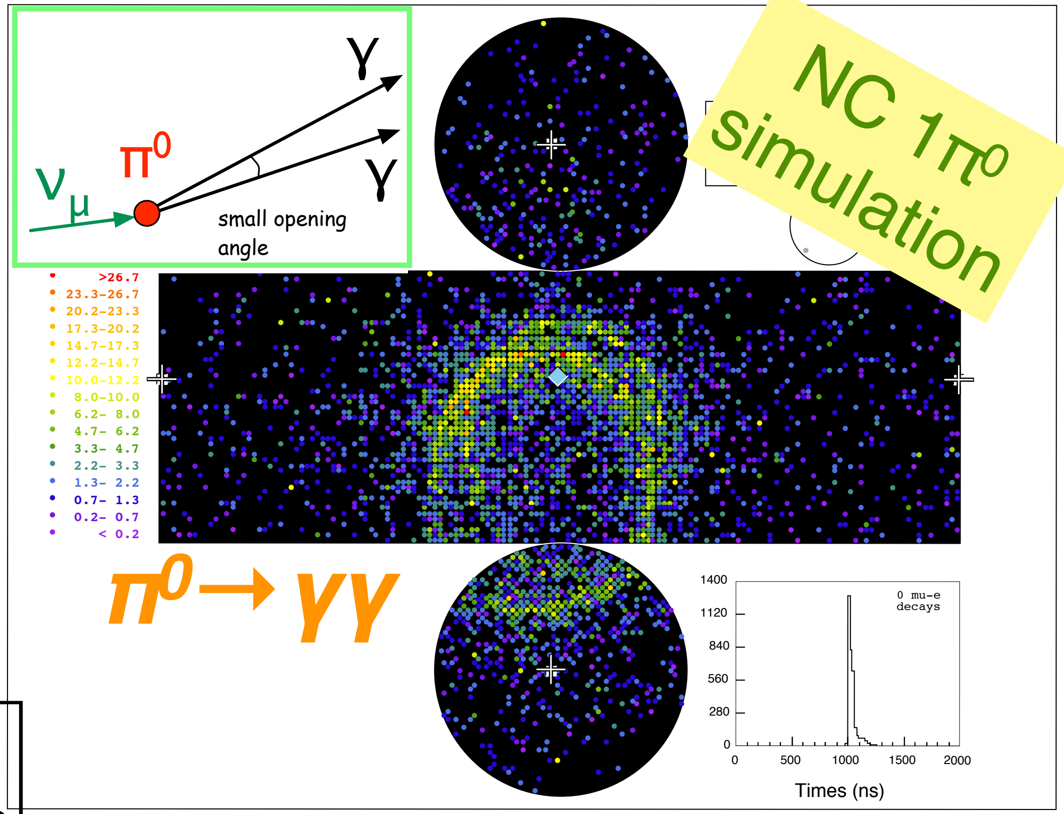


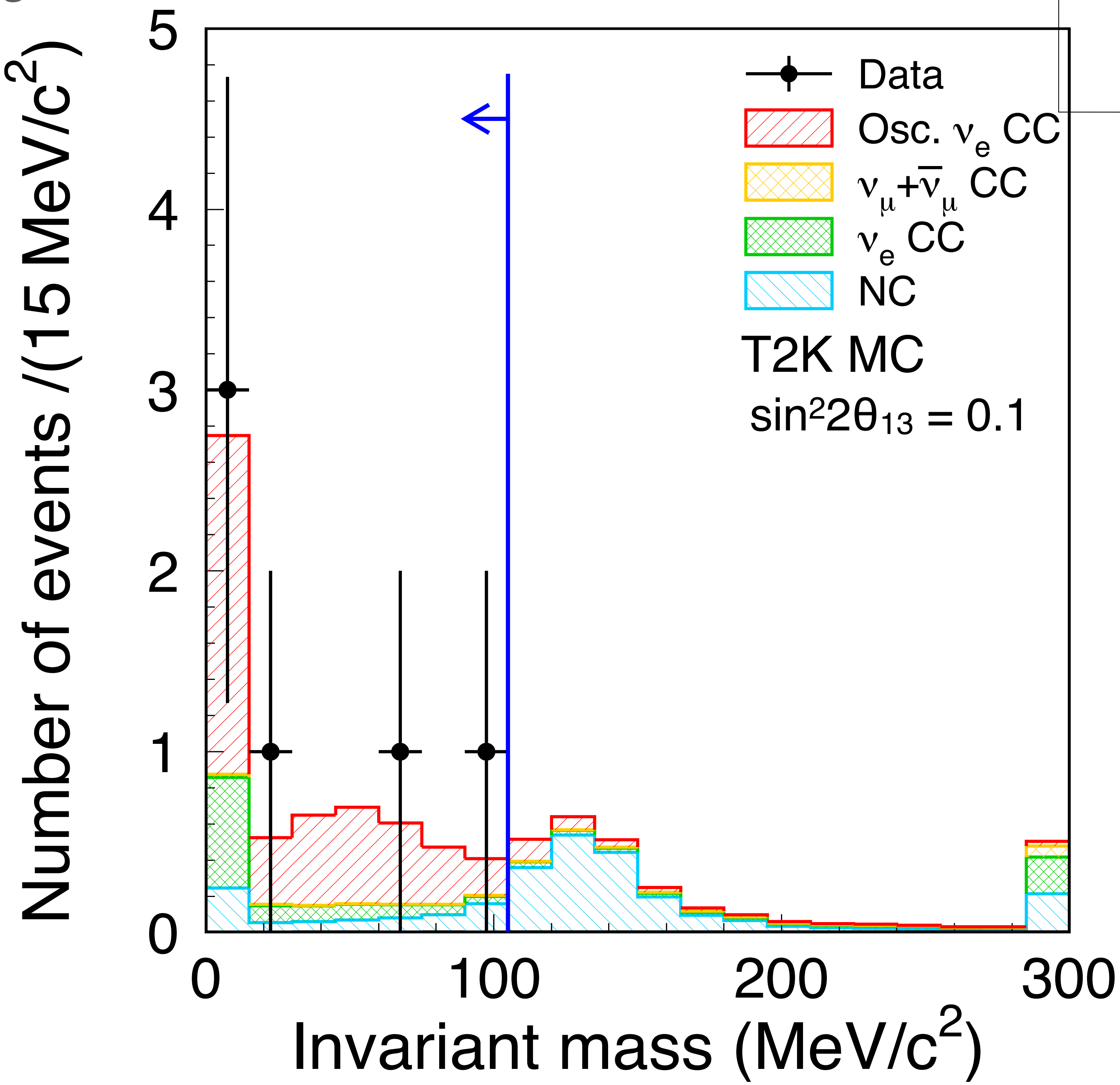


6. Reconstructed invariant mass (M_{inv}) < 105 MeV/c^2

* Suppress NC π^0 background

Forced to find 2nd ring by using expected light pattern under the 2 e-like rings assumption, and then reconstruct invariant mass of these 2 e-like rings



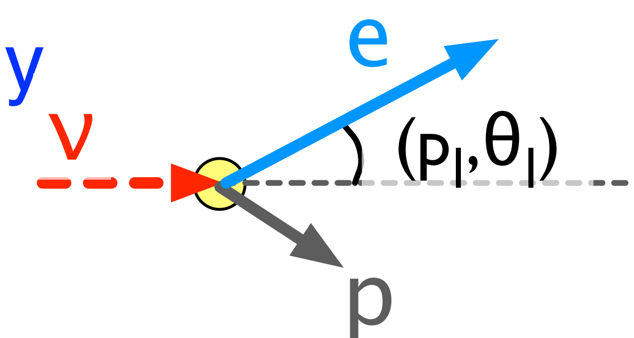


this cut rejects 71% of NC background

91% of signal remains with this cut

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

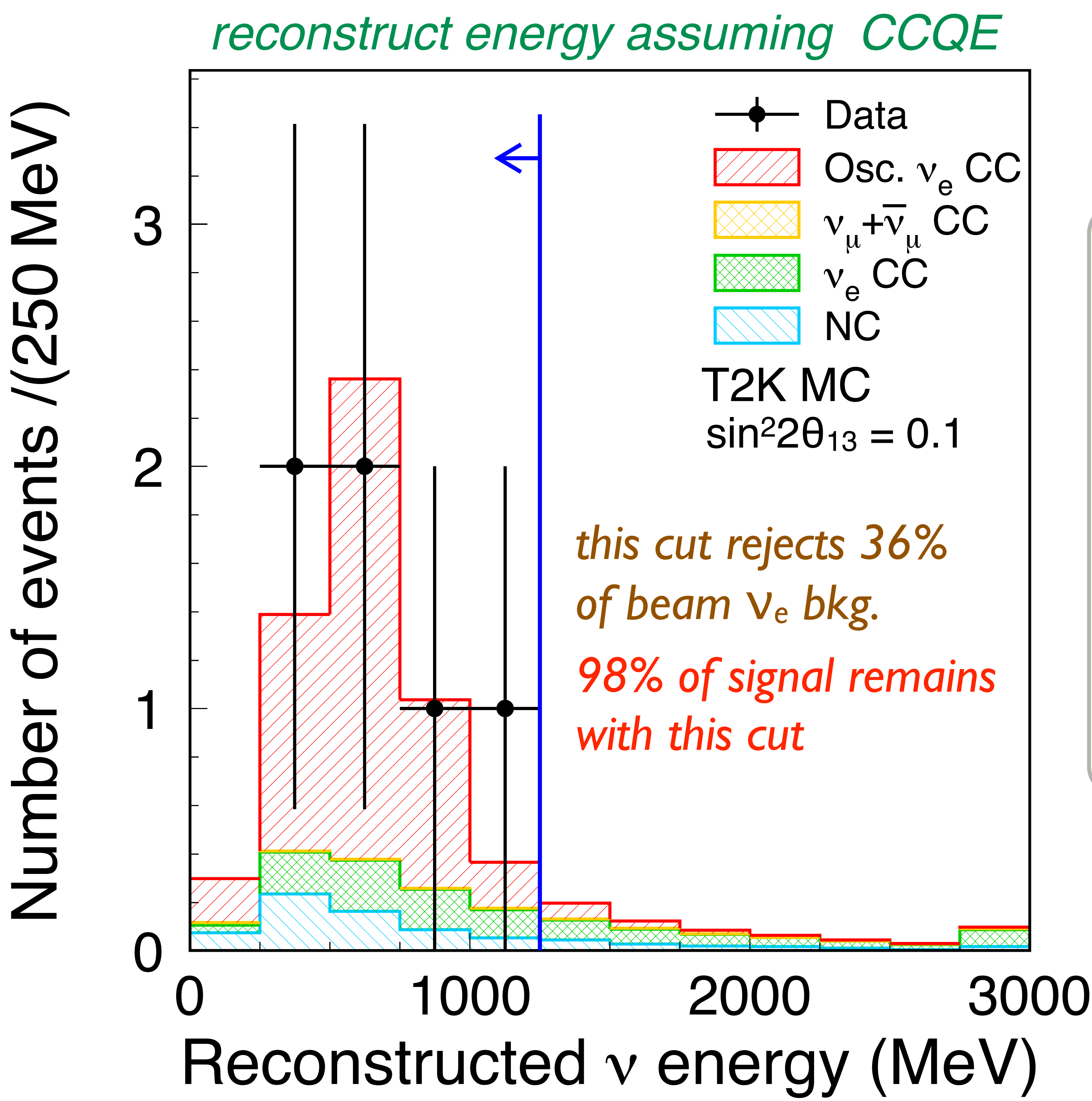
* Reject intrinsic beam ν_e backgrounds at high energy
* Signal ($\nu_\mu \rightarrow \nu_e$) has a sharp peak at E_ν~600MeV



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

(with additional correction for nuclear potential)

reconstruct energy assuming CCQE



After all the selection criteria

background rejection :

>99% for ν_μ CC,

77 % for beam ν_e CC,

99 % for NC

$\nu\mu \rightarrow \nu e$ CC signal eff. : 66 %

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

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

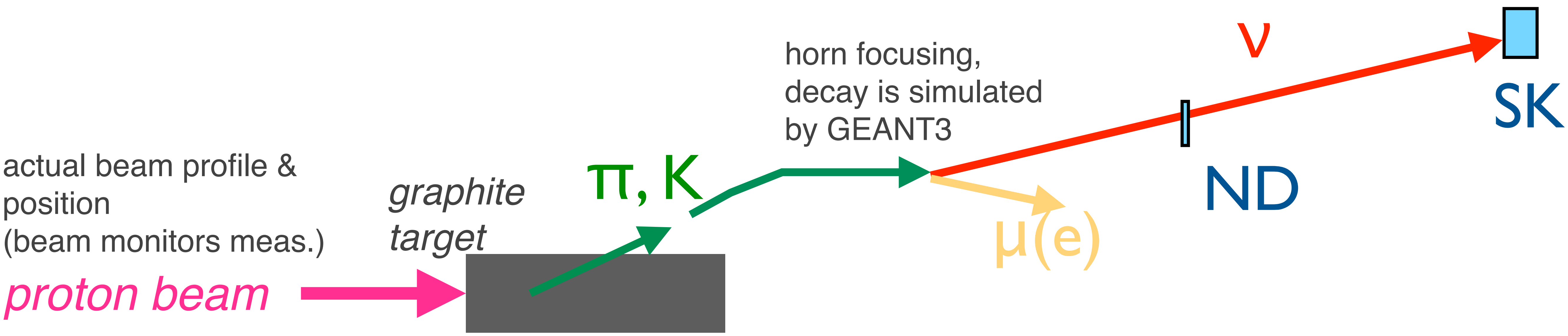
(flux) *x (osc. prob.) x (x-section) x (efficiency) x (det. mass)*

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

Neutrino flux prediction

T2K Neutrino beam simulation based on Hadron production measurements

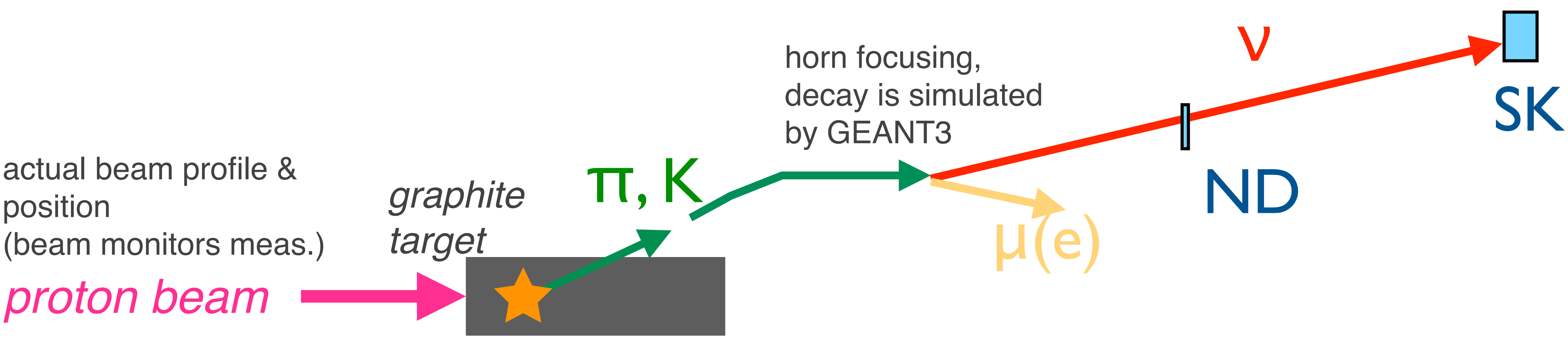
$$\frac{\int \Phi^{SK}_{\nu_\mu}(E_\nu) \cdot P_{\nu_\mu \to \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\ dE_\nu}$$



Neutrino flux prediction

T2K Neutrino beam simulation based on Hadron production measurements

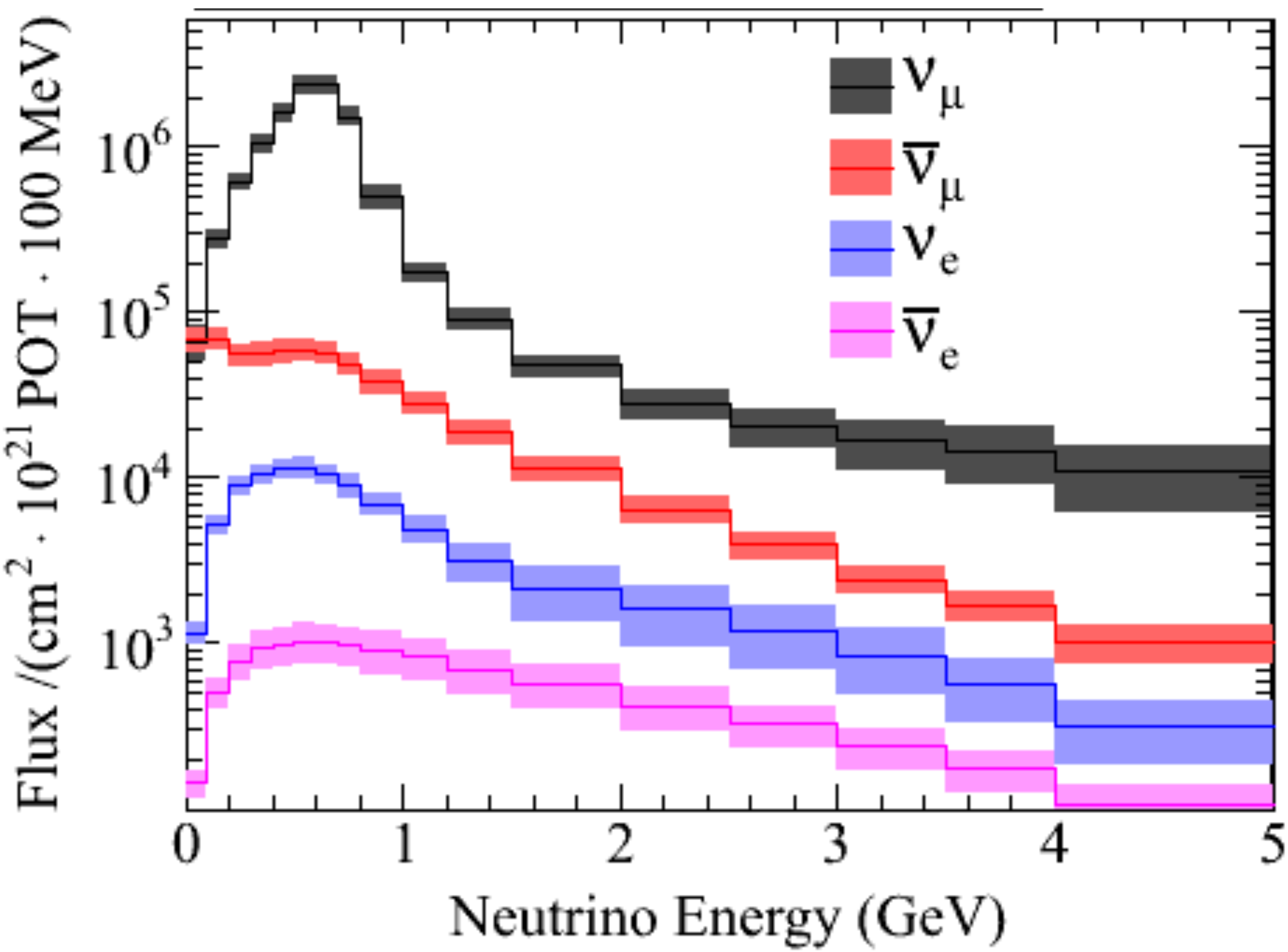
$$\frac{\int \Phi^{SK}_{\nu_\mu}(E_\nu) \cdot P_{\nu_\mu \rightarrow \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu) \; dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu) \; dE_\nu}$$



Hadron production in 30GeV proton + C

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

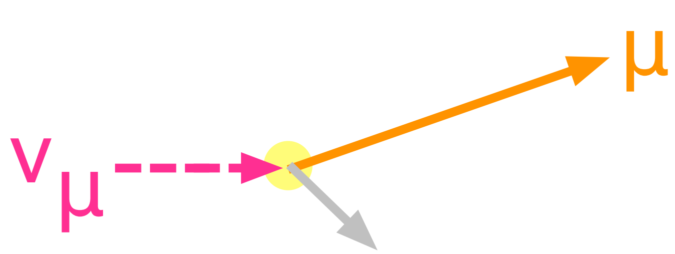
Predicted Neutrino Flux at SK



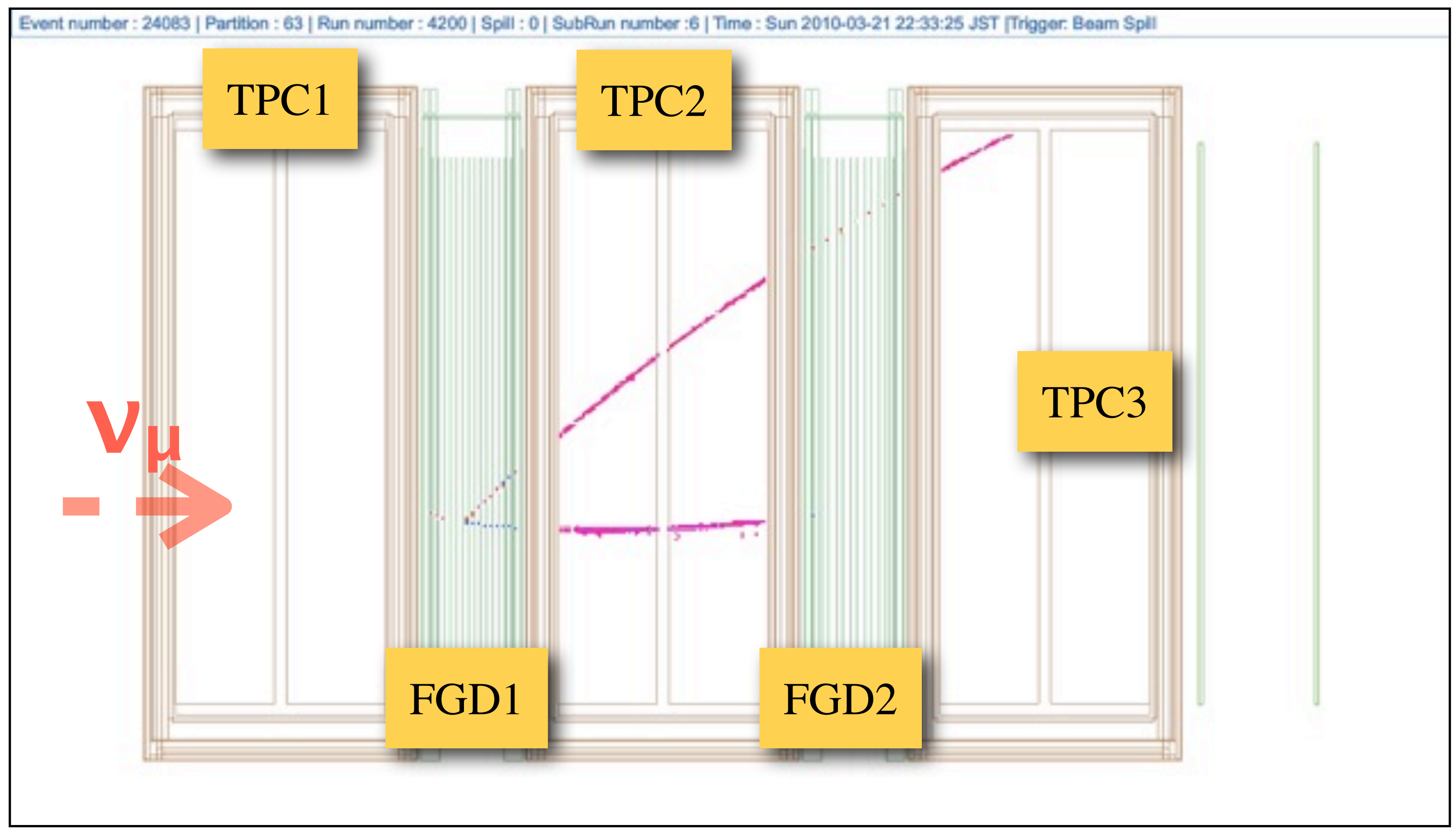
ν_μ interaction rates at near detector

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

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

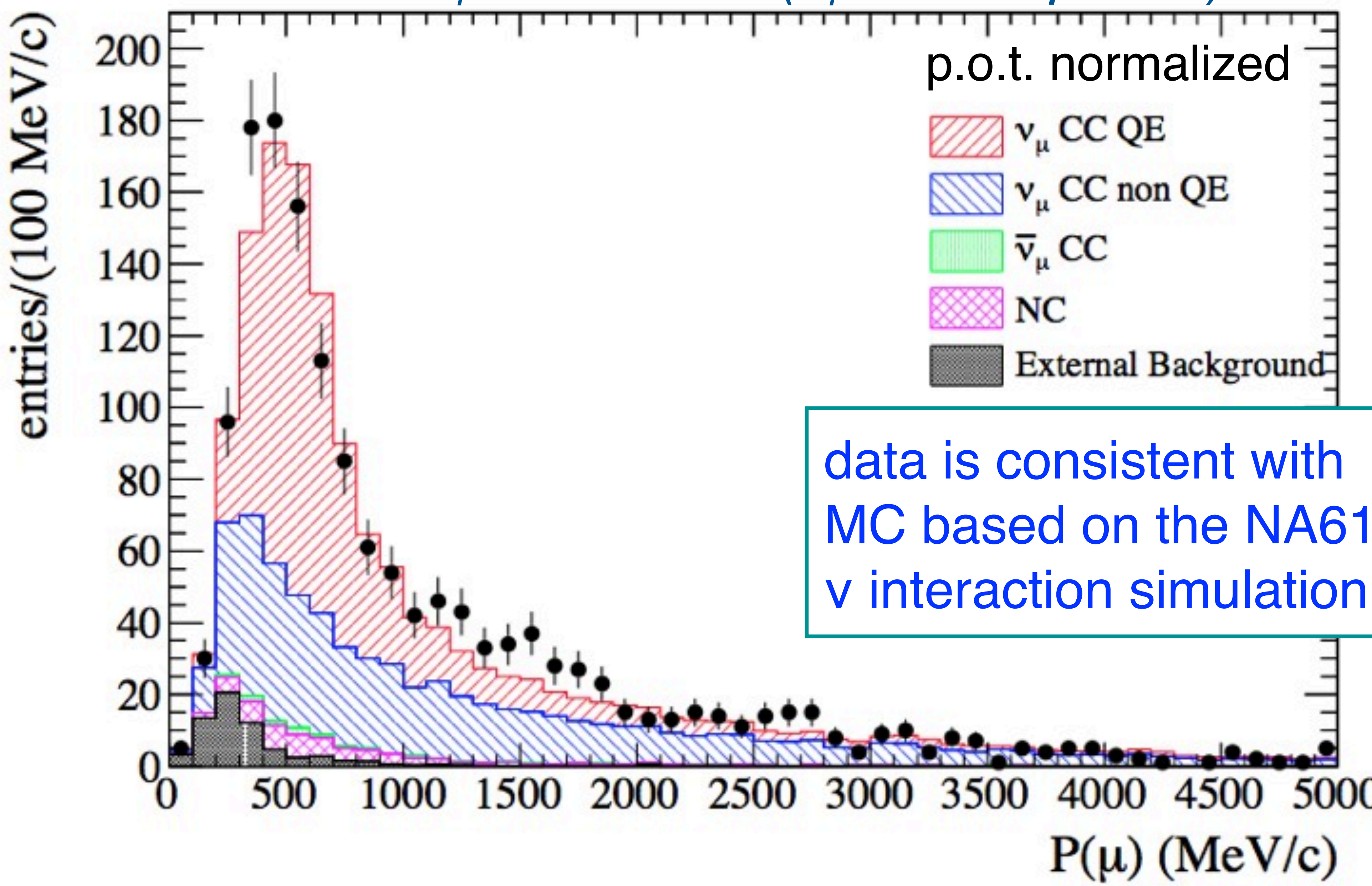


Event display (data)



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

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

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

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.

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

	beam ν_μ CC	beam ν_e CC	NC	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	Total
The expected # of events at SK	**0.03**	**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 $\sin^2 2\theta_{13}=0$

➡ *$N^{exp}_{SK}=1.5\pm 0.3$ events*

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

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

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

error source	syst. error
(1) ν flux	$\pm 8.5\%$
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Total	$^{+22.8}_{-22.7}\%$

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

$N^{exp}_{SK}=1.5\pm0.3$ events

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

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

Neutrino flux uncertainty

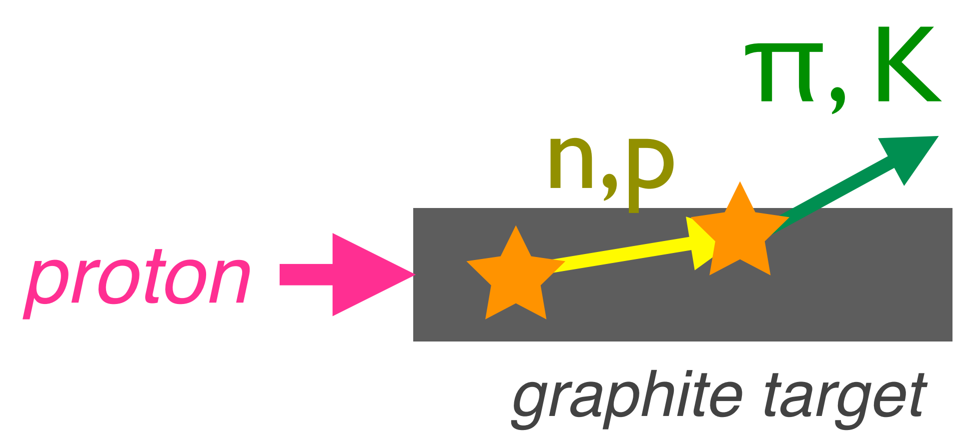
error source
(1) ν flux
(2) ν cross section
(3) Near detector
(4) Far detector
(5) Near det. statistics

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

Uncertainties in hadron production and interaction are dominant sources

Error source

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



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

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

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

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

Hadron production & interaction

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

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

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

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

Hadron production & interaction

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

Error cancellation works for some beam uncertainties

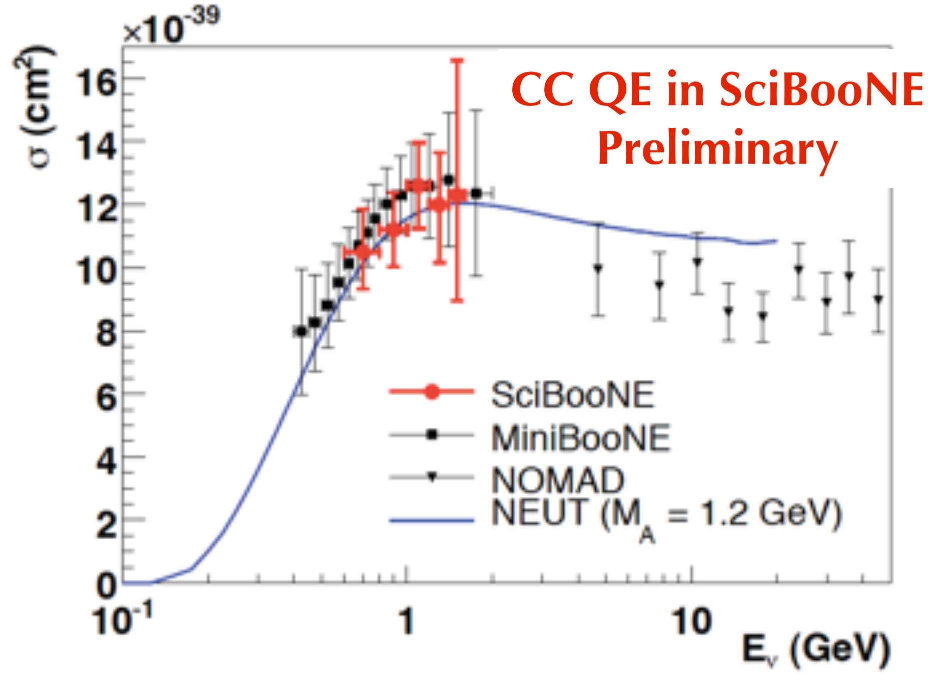
ν int. cross section uncertainty

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

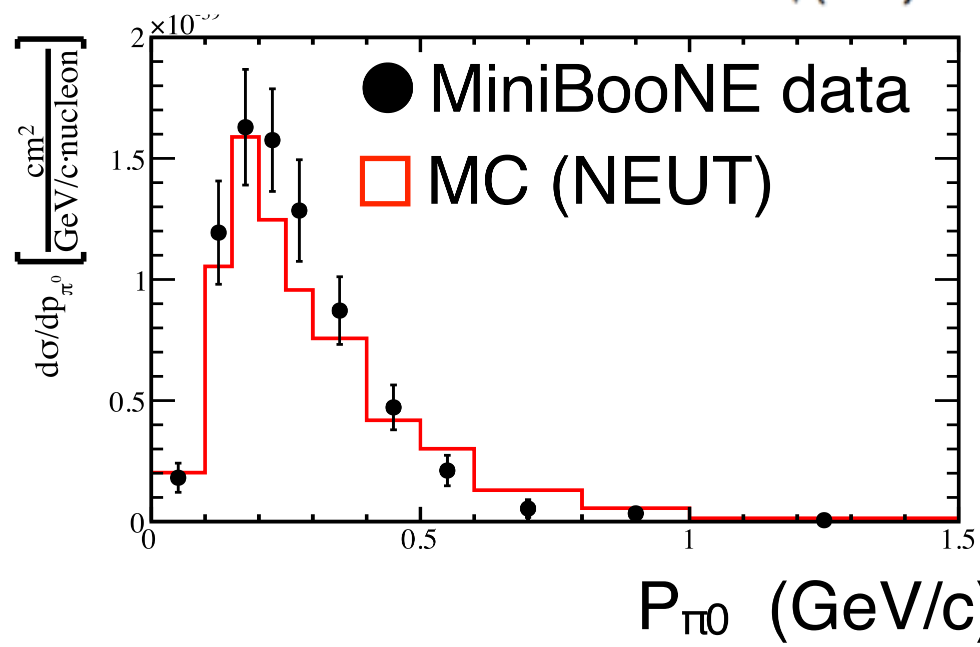
$$\frac{\int \Phi^{SK}_{\nu_\mu(\nu_e)}(E_\nu)\cdot P_{osc.}(E_\nu)\cdot \sigma(E_\nu)\cdot \epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu)\cdot \sigma(E_\nu)\cdot \epsilon_{ND}(E_\nu)\ dE_\nu}$$

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



Cross section uncertainty relative to the CCQE total x-section

Process	Systematic error (comment)
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 $\sigma(\nu_e)/\sigma(\nu_\mu) = \pm 6\%$

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

Main ν interaction in each event

NC background : $NC1\pi^0$
Beam ν_e background : ν_e CCQE
Signal : ν_e CCQE
ND CC event : CCQE(50%)
CC1π(23%)

Error source

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 syst. is **14%** ($\sin^2 2\theta_{13}=0$)

Far detector uncertainty

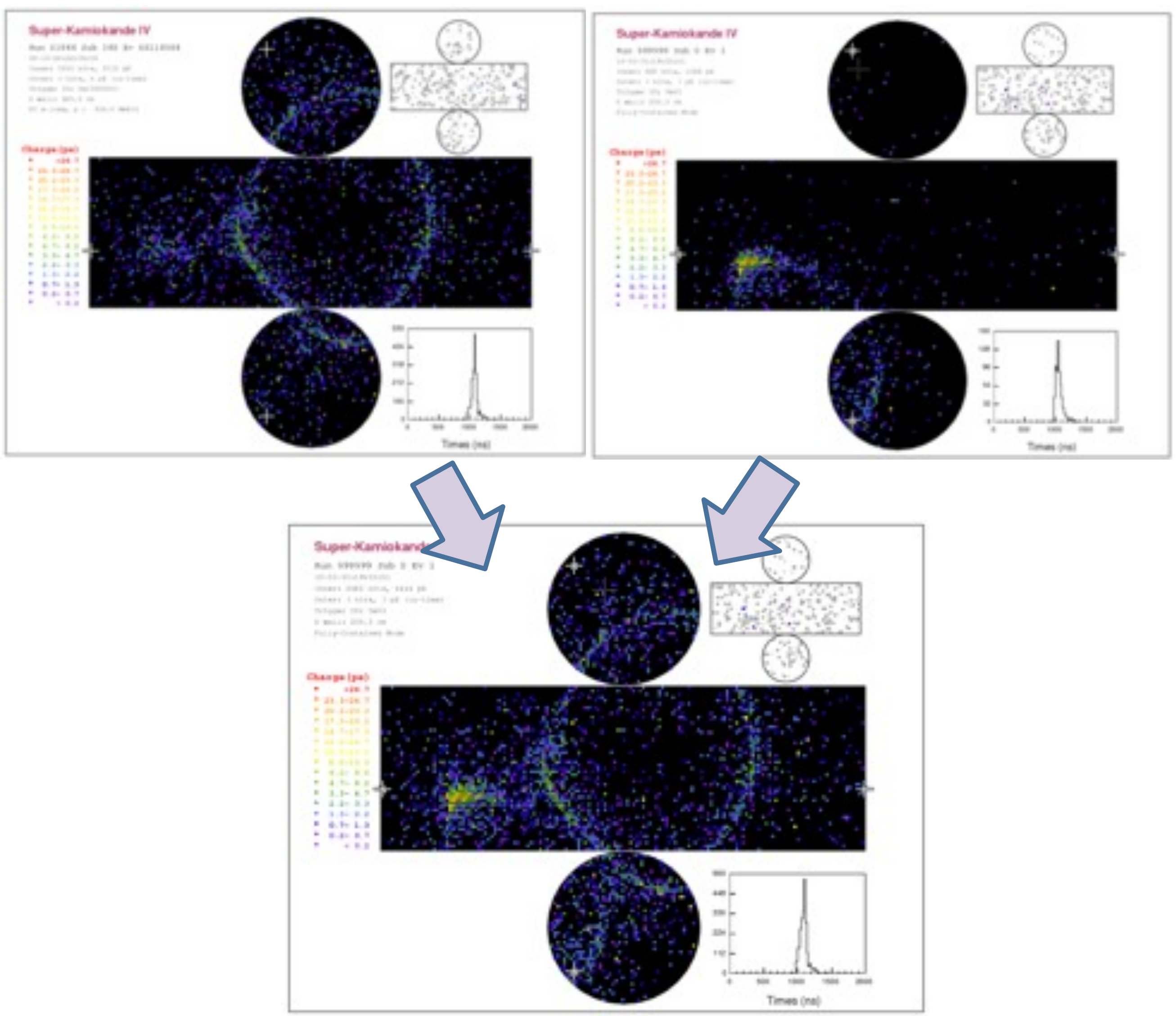
error source
(1) ν flux
(2) ν cross section
(3) Near detector
(4) Far detector
(5) Near det. statistics

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

- Uncertainty due to the SK detector systematics
- Evaluate using various control sample

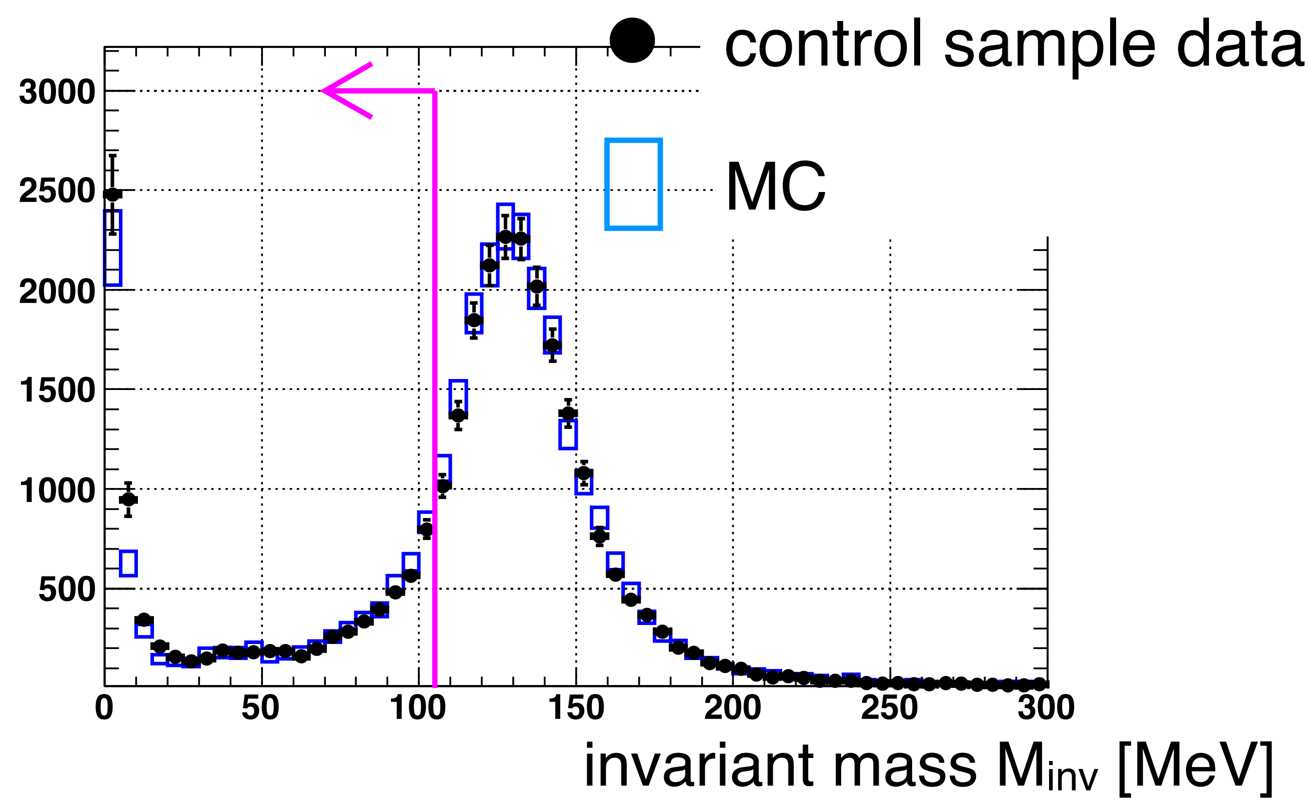
Uncertainty of NC π^0 rejection

Topological control sample of π^0 made by combining 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



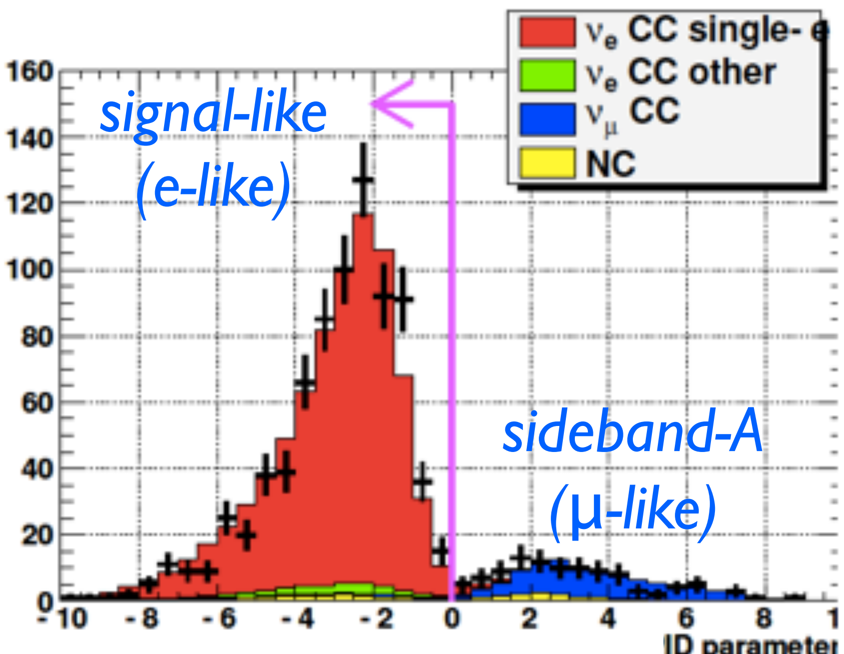
π^0 efficiency=6.8±0.7(syst.)%

Uncertainty of ν_e CCQE selection efficiency

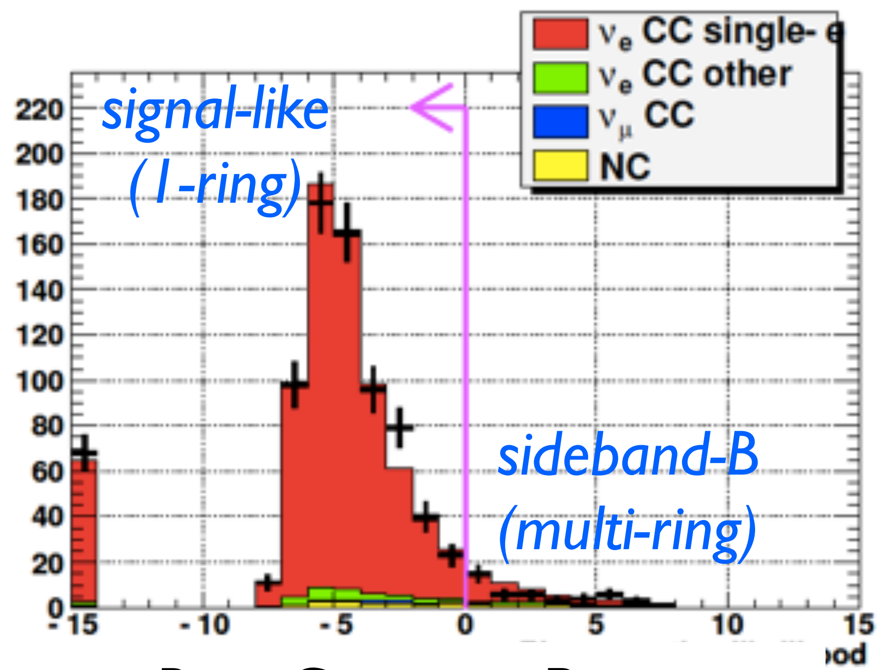
detection efficiency of ν_e CC (for dominant BG and signal)

atmospheric ν sample

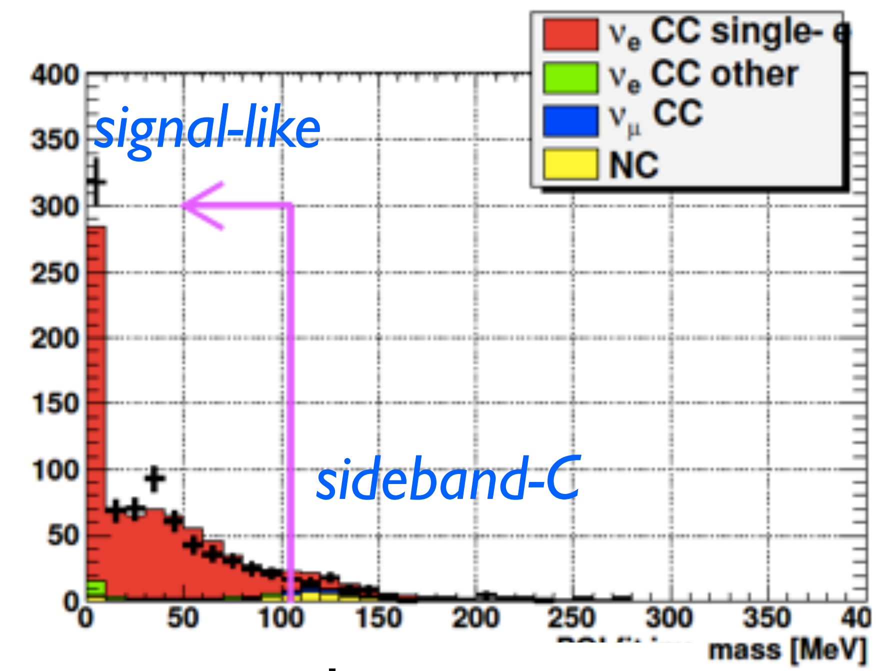
subsample which satisfies all T2K νe selection criteria (signal-like) and sidebands



PID parameter



Ring Counting Parameter



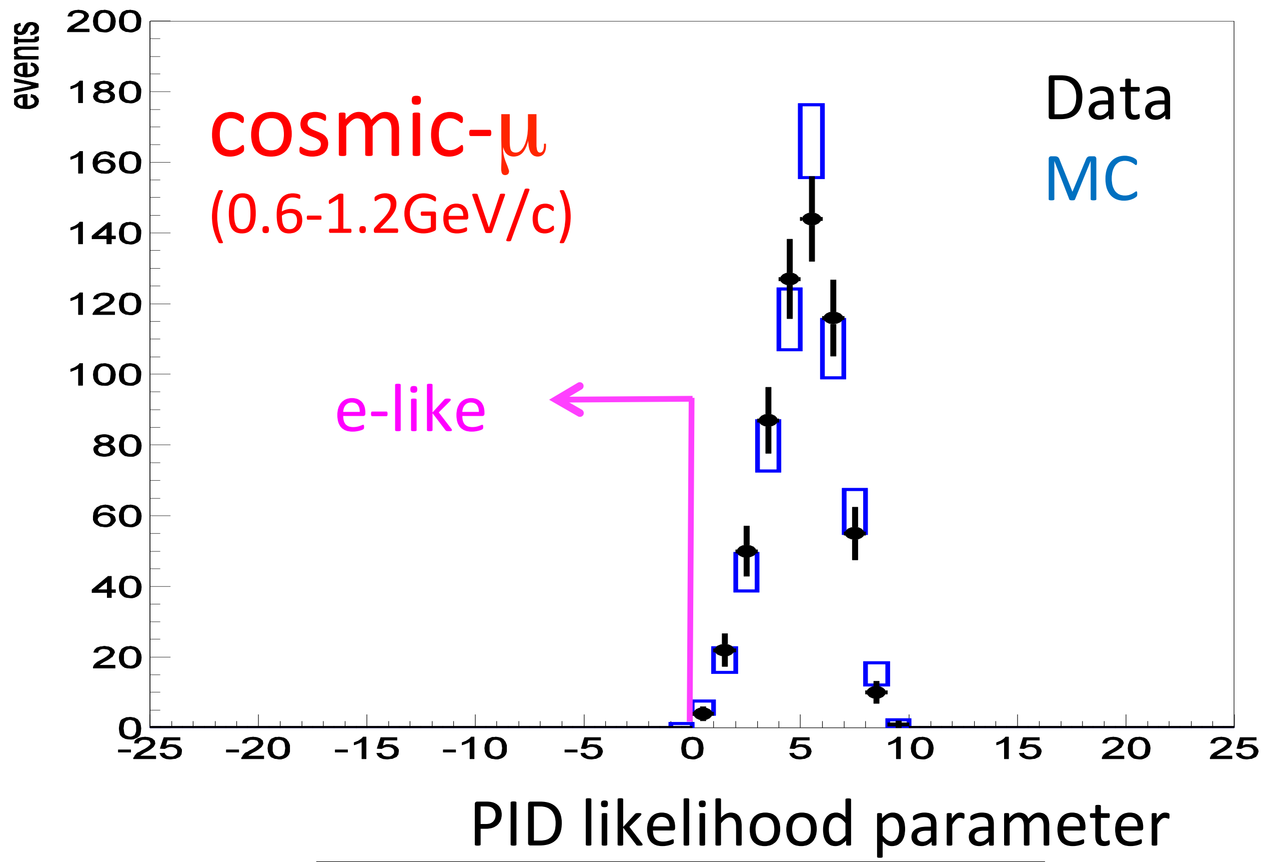
Invariant mass

From comparisons btw the atmν data and MC, we constrain selection efficiency of each cuts.

	Efficiency [%] (T2K beam ν_e)	Efficiency [%] (T2K signal ν_e)
Ring-counting	96.8 ± 1.9(syst.)	96.6 ± 1.6(syst.)
PID	98.9 ± 1.1(syst.)	98.8 ± 1.4(syst.)
POLfit mass	90.1 ± 6.1(syst.)	90.7 ± 4.1(syst.)

Particle ID uncertainty study

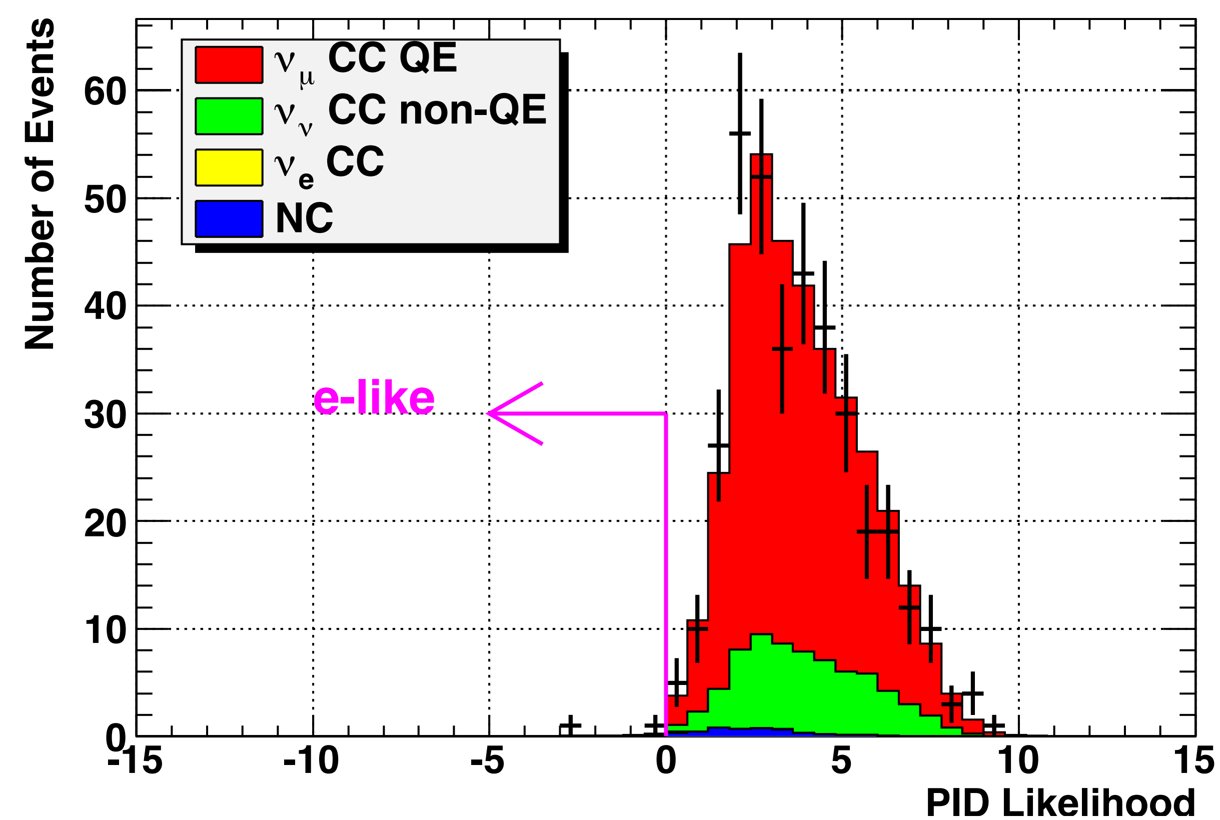
Cosmic ray μ sample



mis-PID:
Data: 0.00±0.16(stat.)%
MC : 0.10±0.10(stat.)%

atmospheric ν sample

μ control sample selected by decay electrons



mis-PID:
Data: 0.54±0.39(stat.)%
MC : 0.20%

The mis-ID fraction and the likelihood are well reproduced.
→PID uncertainty < 1%

Summary of Far detector systematics 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%**

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

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

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

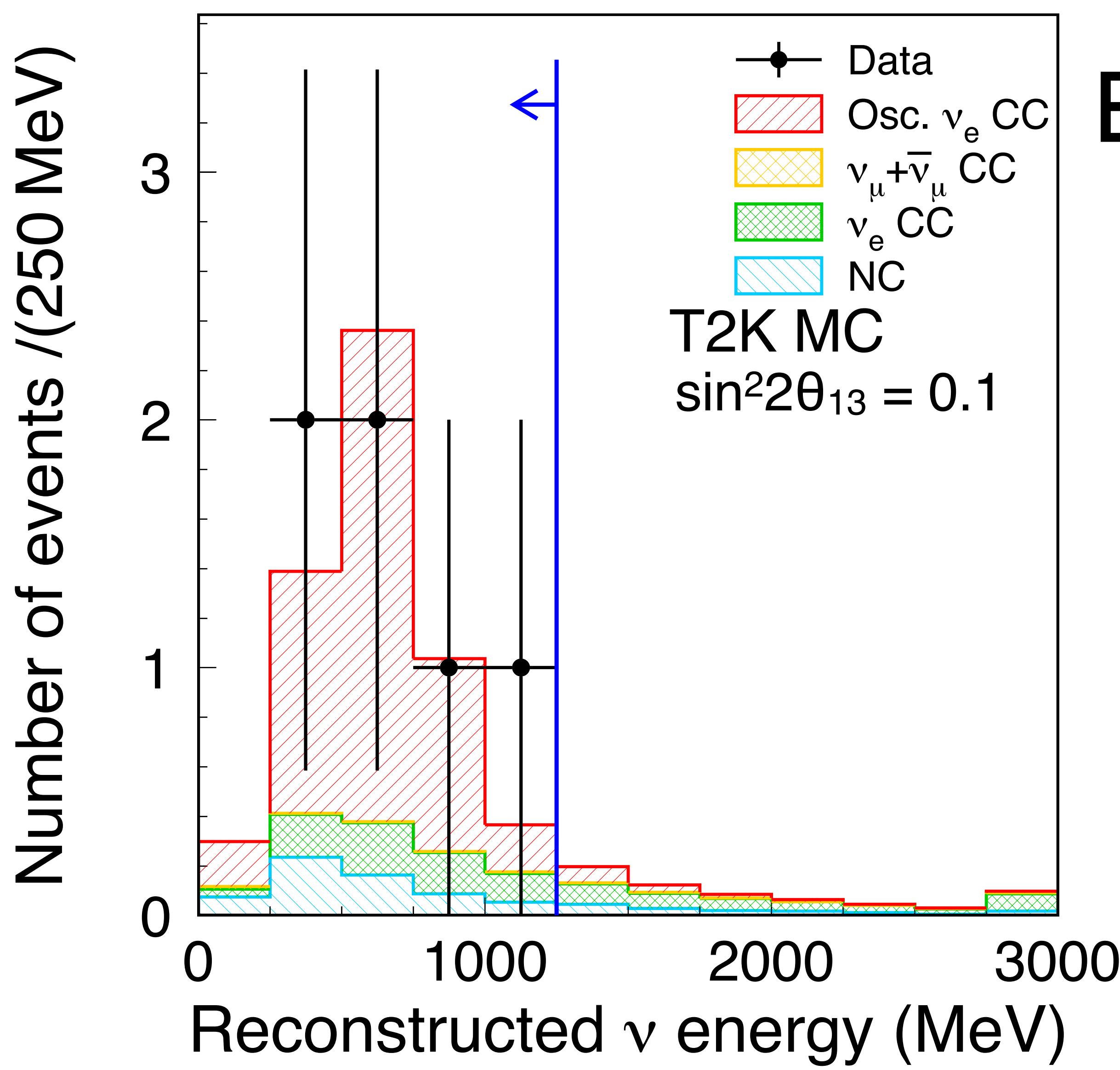
$\sin^2 2\theta_{13}$=0.1:
#sig = 4.1 #bkg = 1.3

(due to small Far det. uncertainty for signal)

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

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

	beam ν_μ CC	beam ν_e CC	NC	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	Total
The expected # of events at SK	**0.03**	**0.8**	**0.6**	**0.1**	**1.5**



Expected # of events @ θ_{13}=0

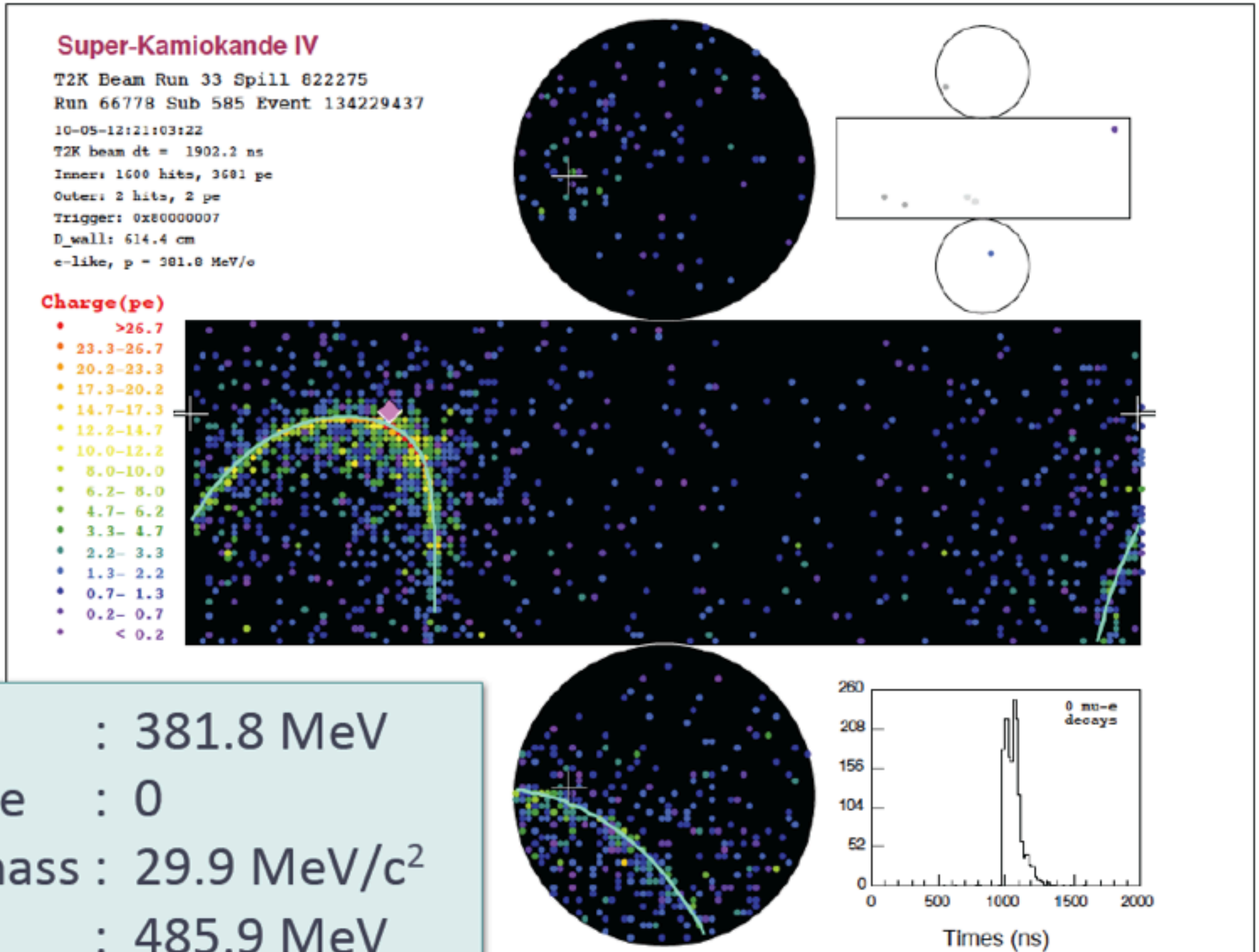
N_{sk}^{exp}=1.5±0.3

Observed # of events

N_{sk}^{obs}= 6

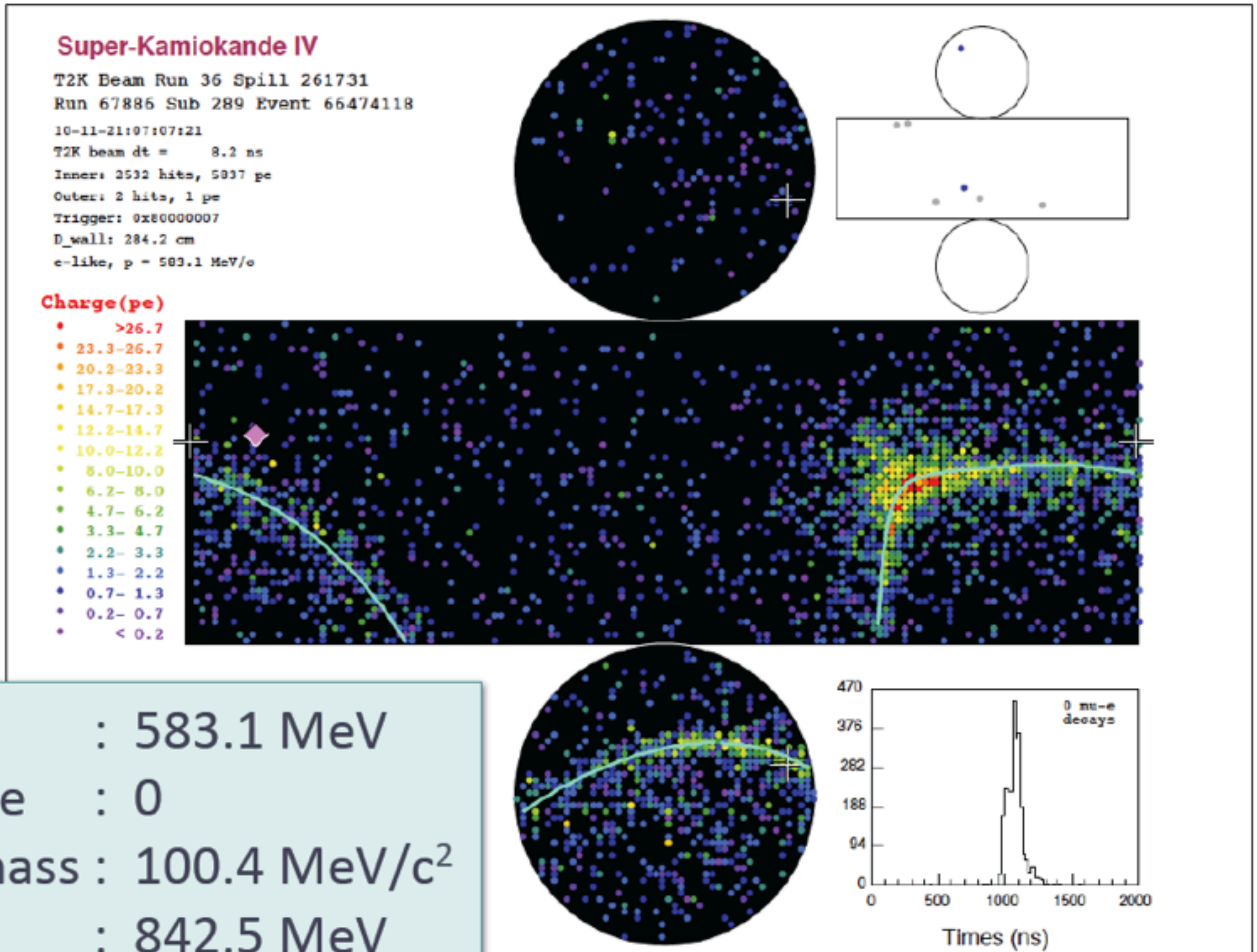
ν_e candidate events

ν_e event #1



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

ν_e event #2



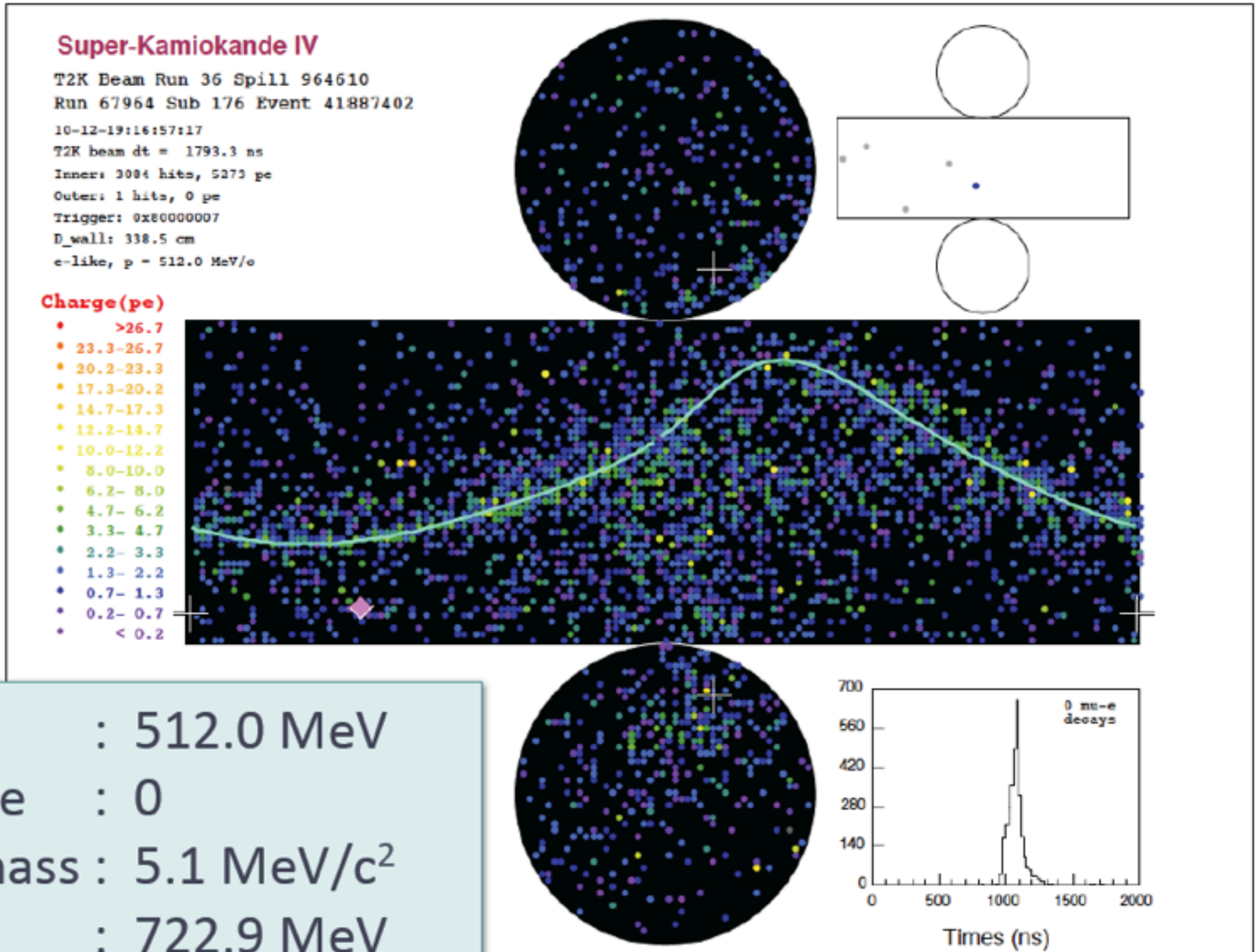
Evis : 583.1 MeV

Ndecay-e : 0

POLfit mass : 100.4 MeV/c^2

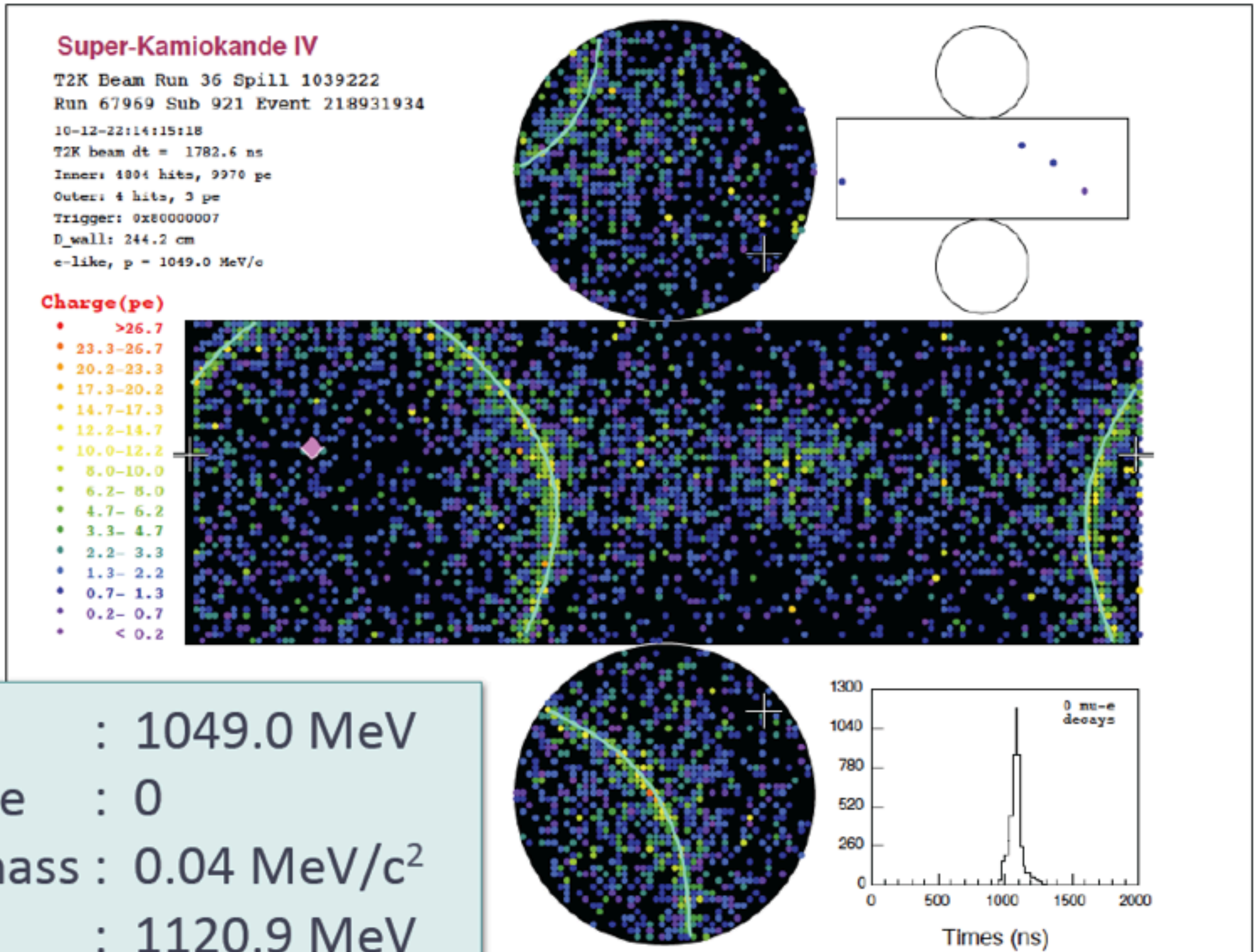
E_ν^{rec} : 842.5 MeV

ν_e event #3



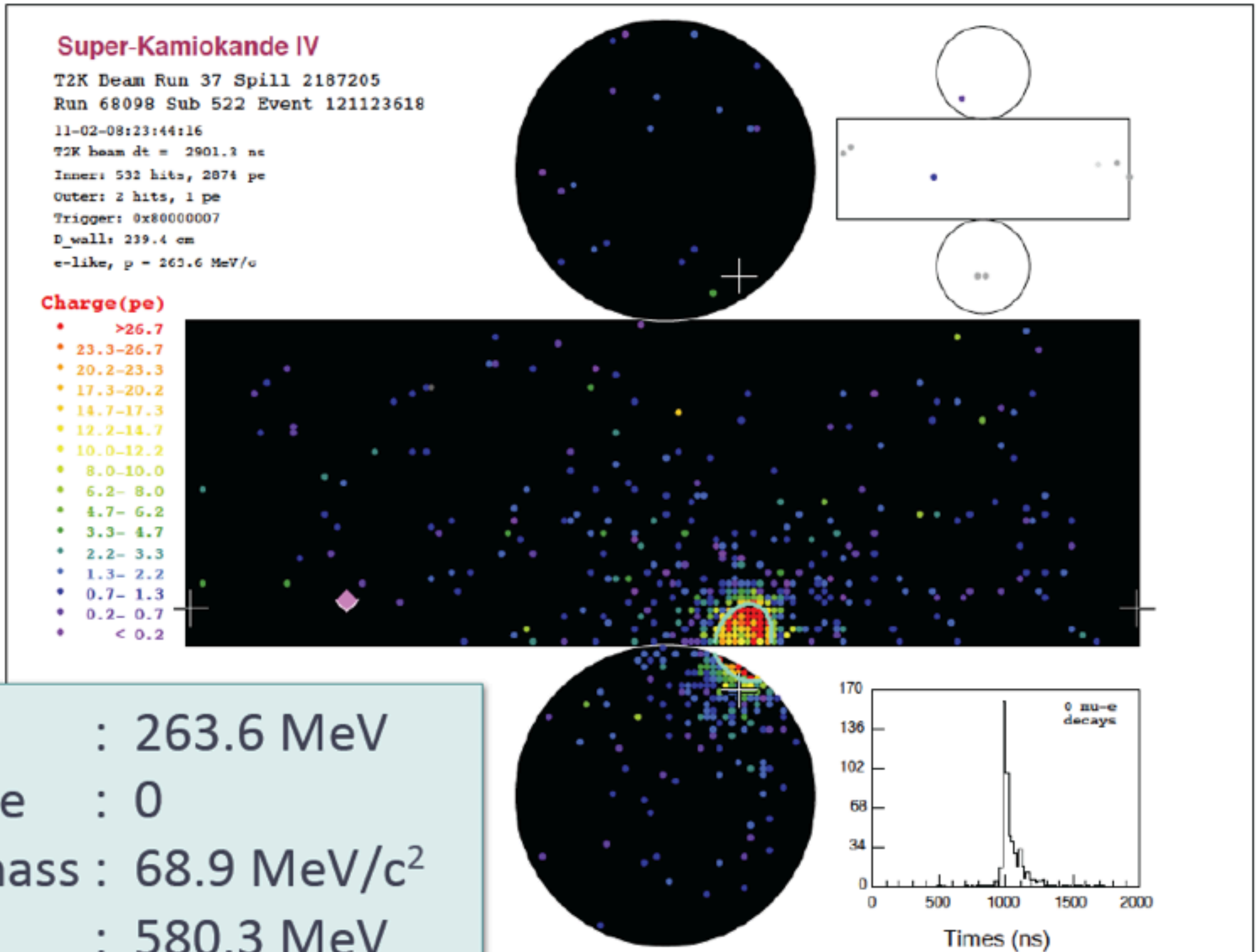
Evis	:	512.0 MeV
Ndecay-e	:	0
POLfit mass	:	5.1 MeV/c^2
E_ν^{rec}	:	722.9 MeV

ν_e event #4



Evis	:	1049.0 MeV
Ndecay-e	:	0
POLfit mass	:	0.04 MeV/c^2
E_ν^{rec}	:	1120.9 MeV

ν_e event #5



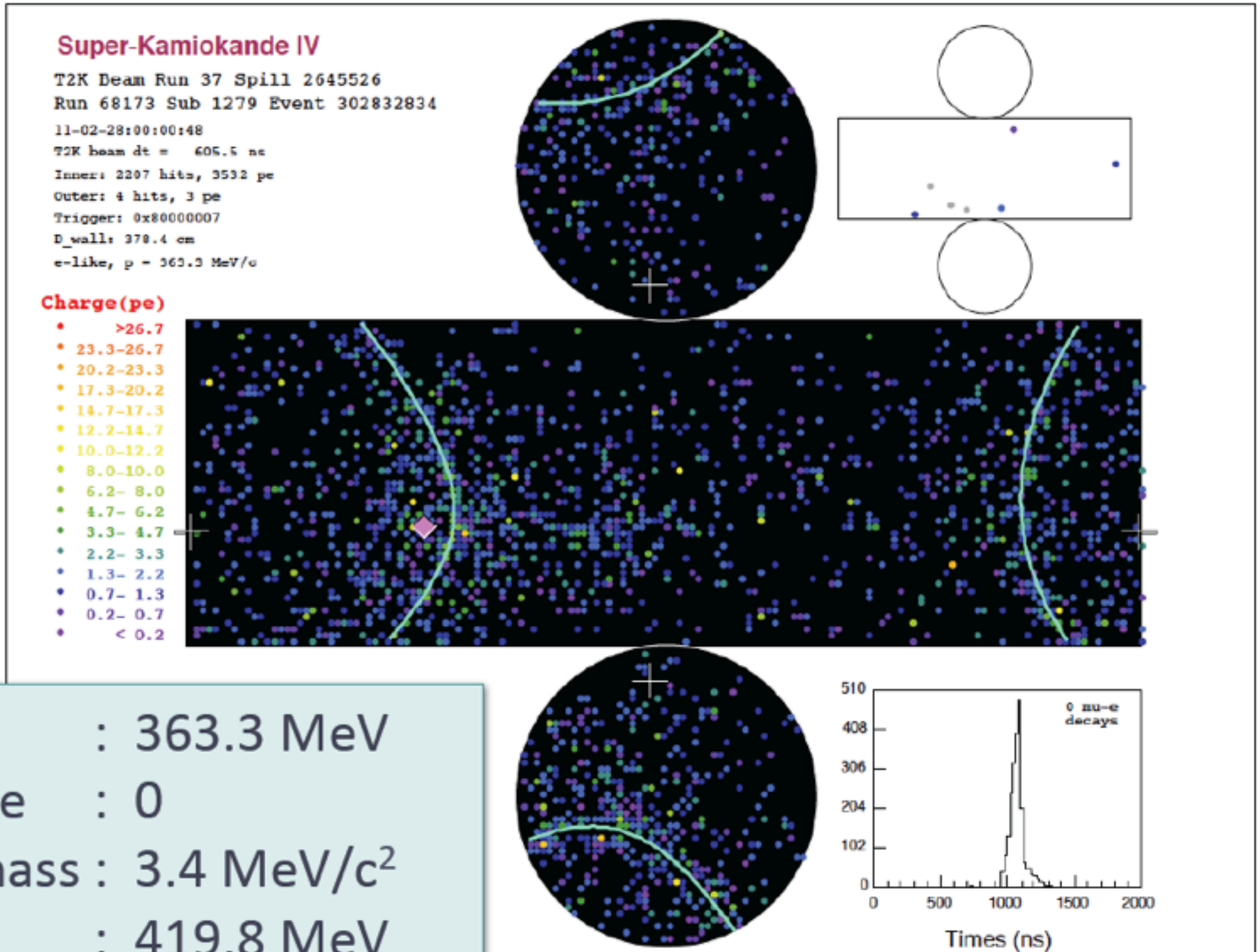
Evis : 263.6 MeV

Ndecay-e : 0

POLfit mass : 68.9 MeV/c^2

E_ν^{rec} : 580.3 MeV

ν_e event #6



Evis : 363.3 MeV

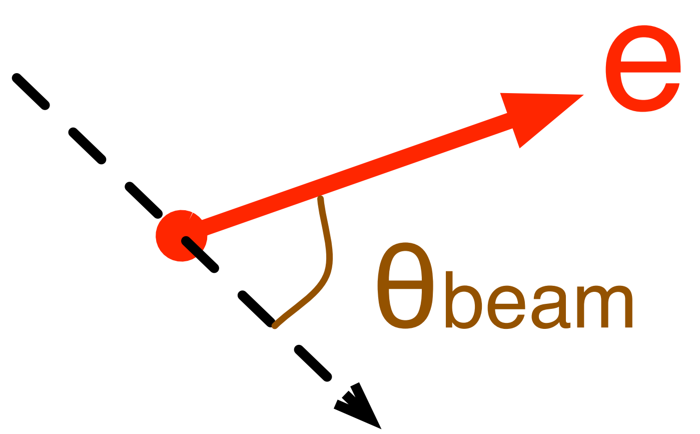
Ndecay-e : 0

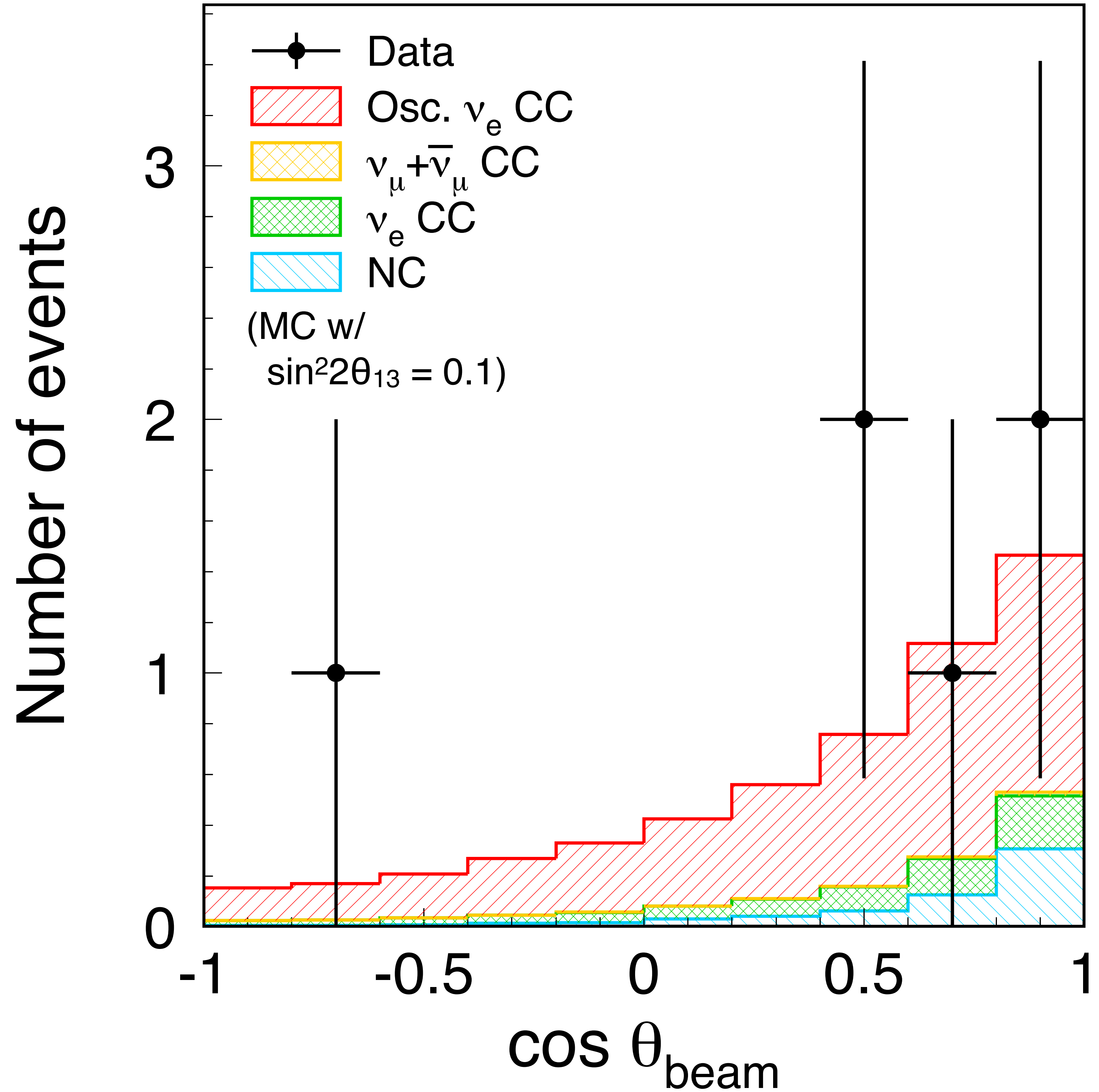
POLfit mass : 3.4 MeV/c^2

E_ν^{rec} : 419.8 MeV

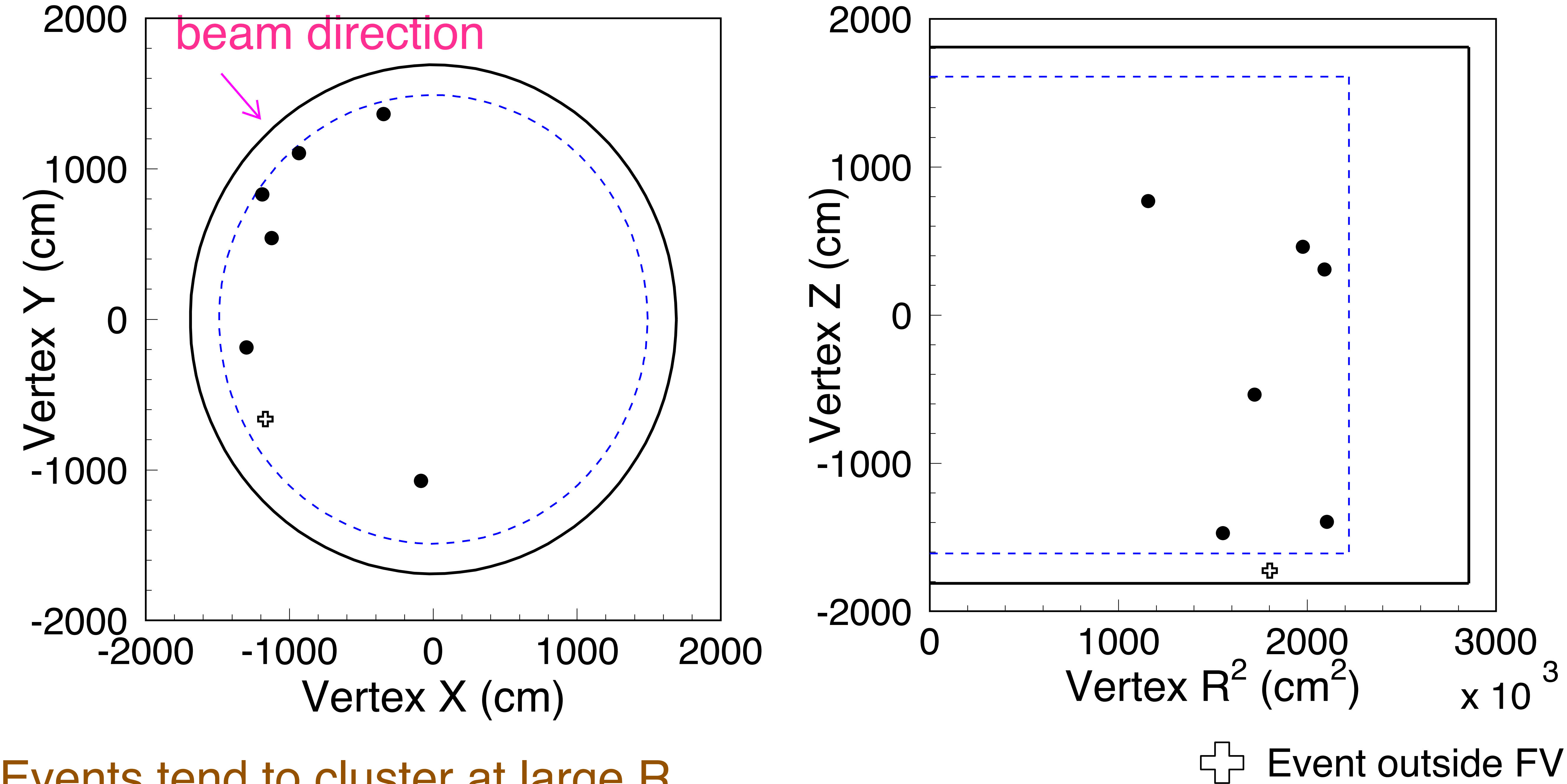
Further check

Check several distribution of ν_e candidate events





Vertex distribution of ν_e candidate events



Events tend to cluster at large R

→ Perform several checks. for example

* Check distribution of events outside FV → no indication of BG contamination
* Check distribution of OD events → no indication of BG contamination
* A K.S. test on the R^2 distribution yields a p-value of 0.03

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

The observed number of events is **6**

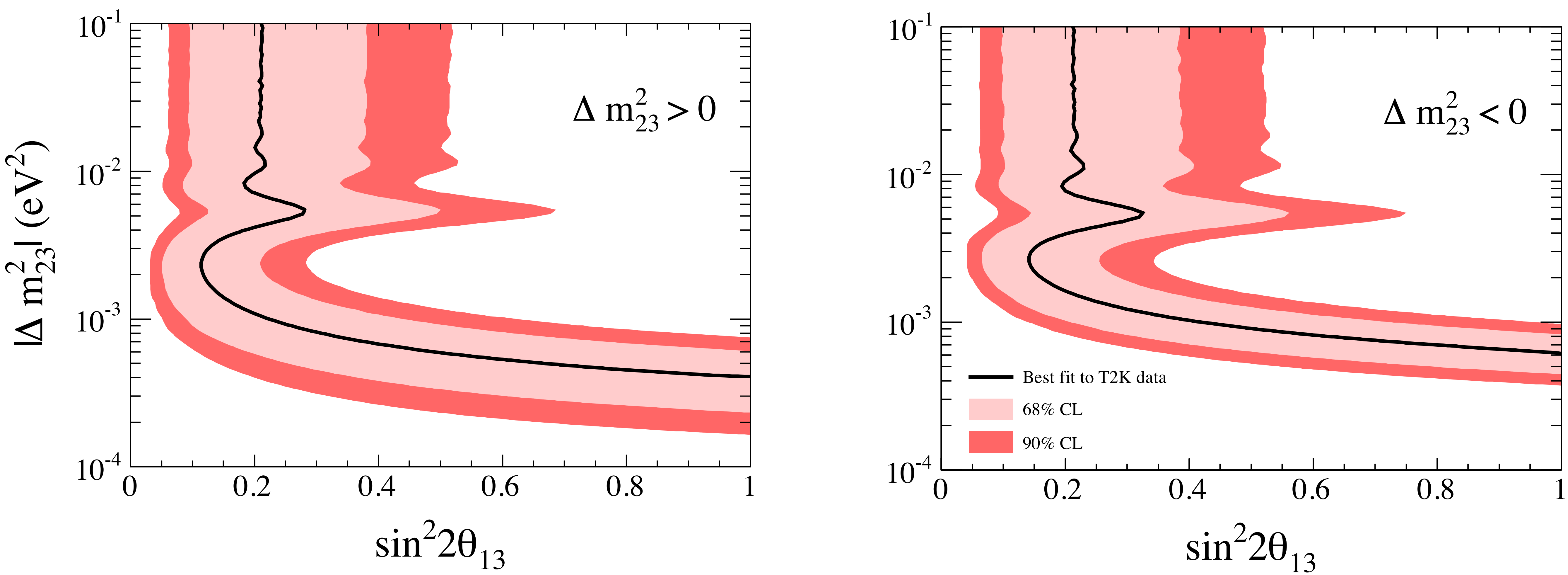
The expected number of events is **1.5 ± 0.3**

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

→ Probability to observe 6 or more events is 0.7%, assuming $\theta_{13}=0$, corresponding to 2.5σ significance.

Allowed region of $\sin^2 2\theta_{13}$ for each Δm^2_{23}

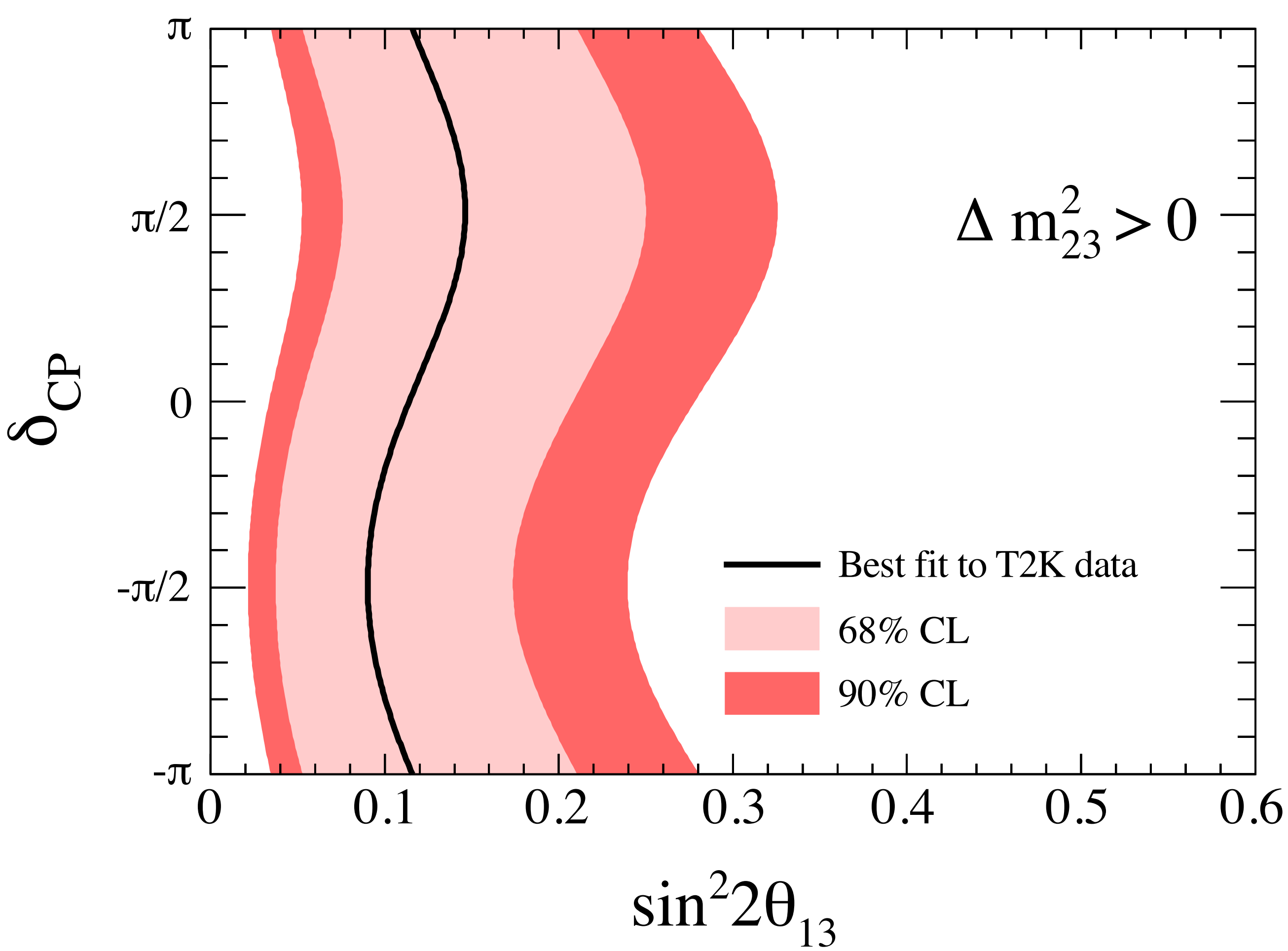
(assuming $\delta_{CP}=0, \sin^2 2\theta_{23}=1.0$)

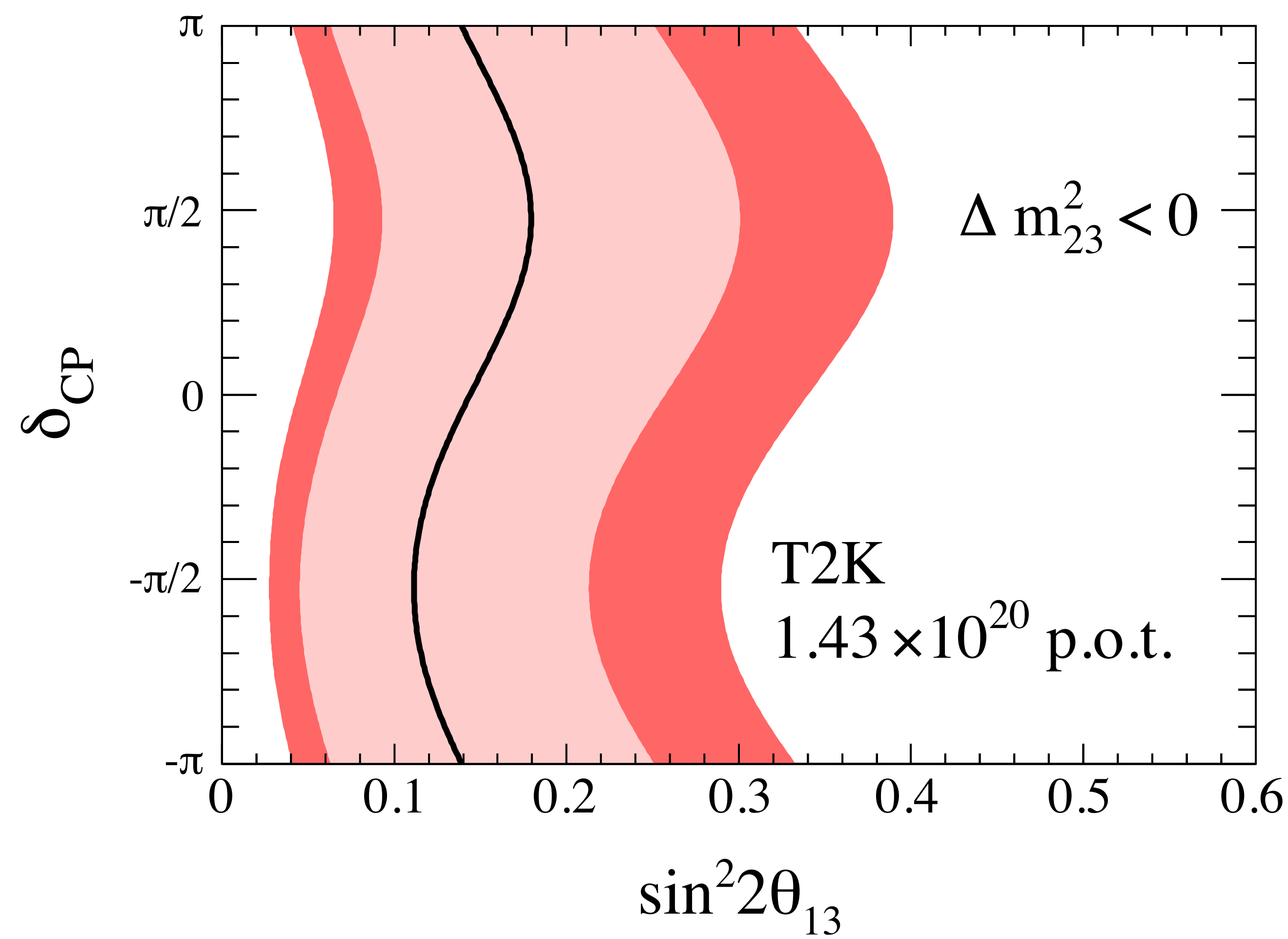


Feldman-Cousins method was used

Allowed region of $\sin^2 2\theta_{13}$ for each δ_{CP}

(assuming Δm^2_{23}=2.4 x 10^{-3} eV^2)



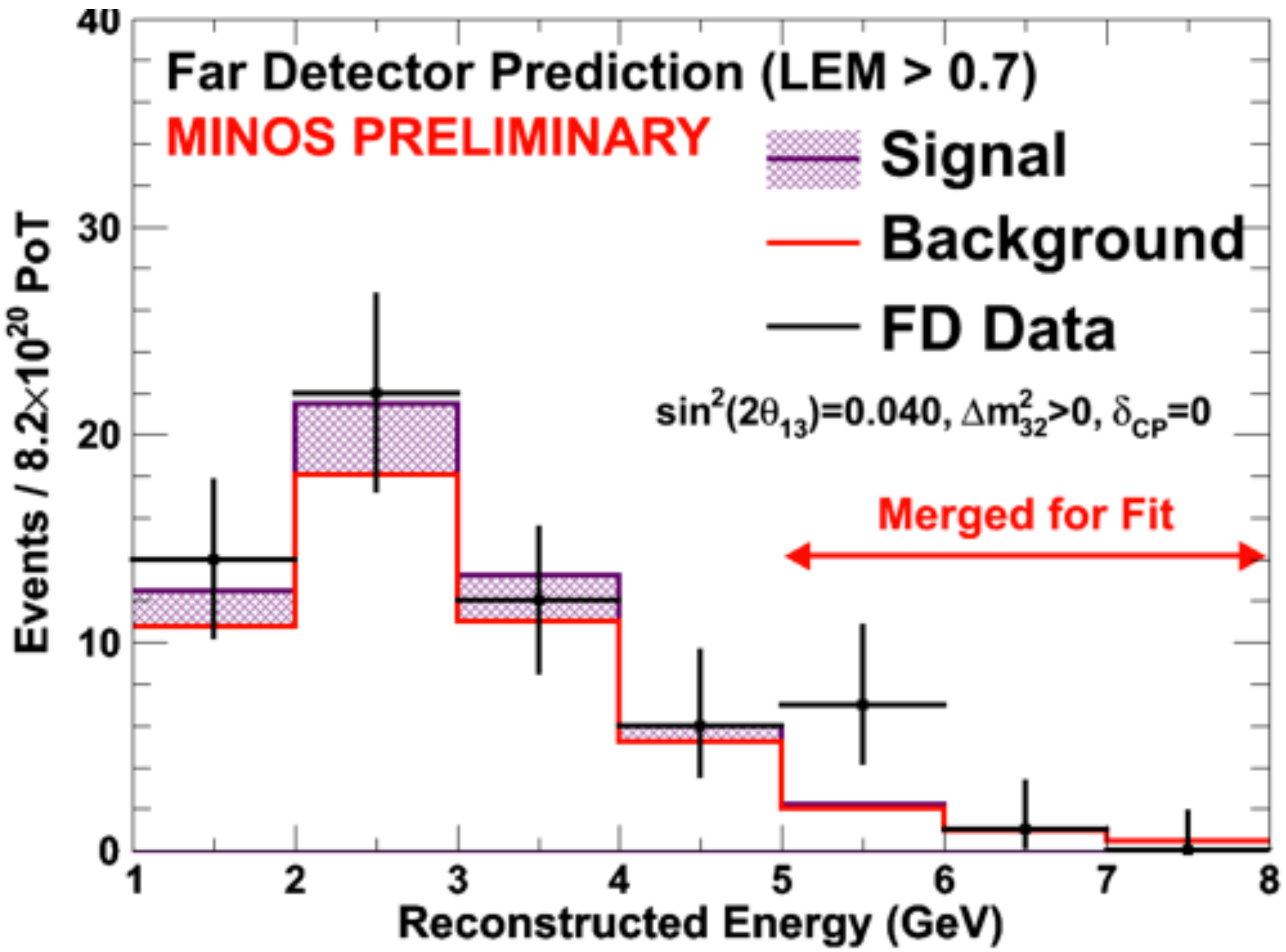


90% C.L. interval (assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, δ_{CP}=0)

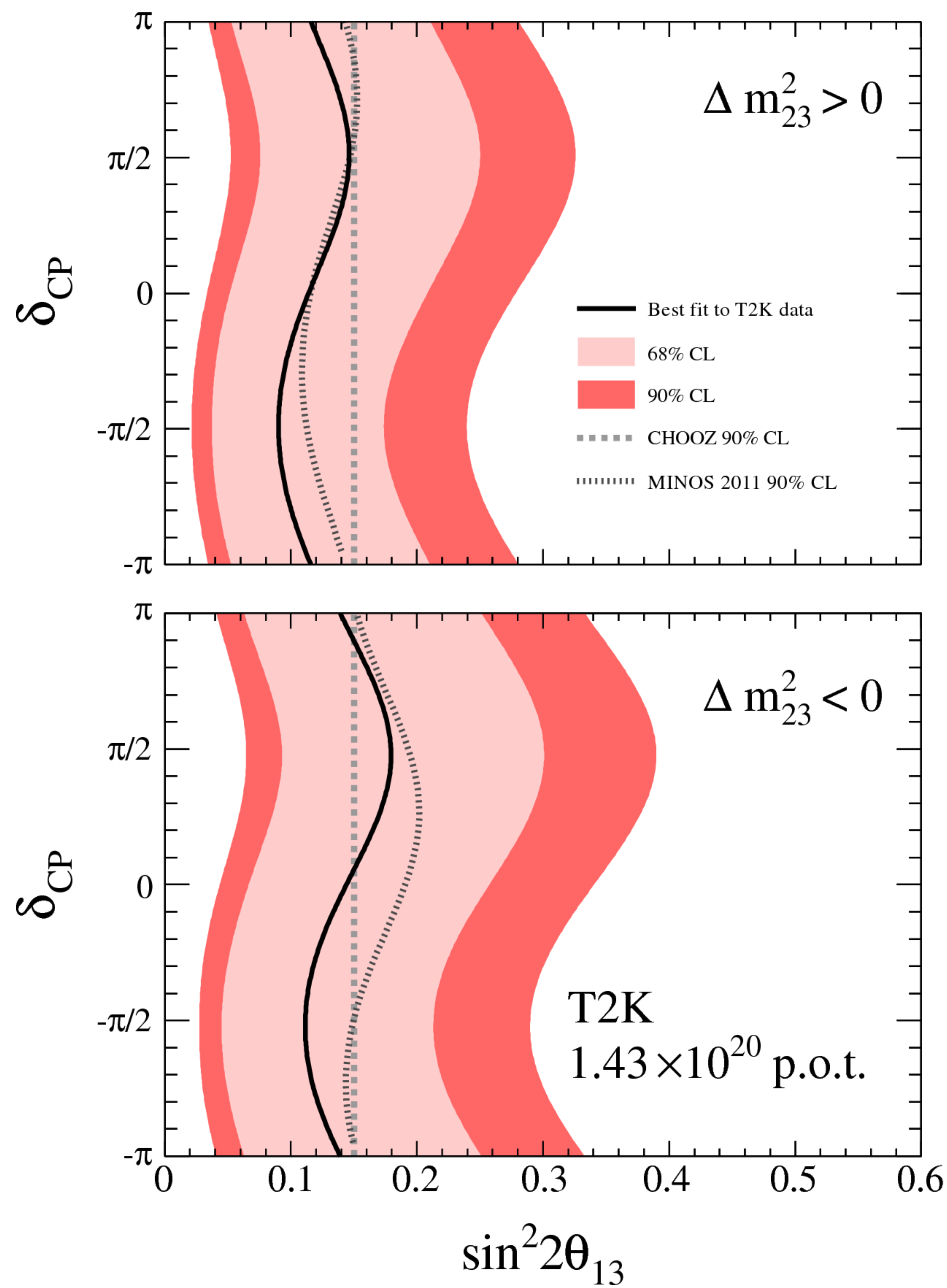
$0.03 < \sin^2 2\theta_{13} < 0.28$

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

Comparison with MINOS



In signal-enhanced region(LEM>0.7):
Expected background ($\theta_{13}=0$):
49.5 +- 2.8 (syst) +- 7.0 (stat)
Observed data:
62



T2K Next steps

Aim to establish ν_e appearance and to determine the angle θ_{13}

This result is obtained by only 2% exposure of T2K's goal.

- Plan for re-starting experiment in this calendar year
  - Recovery works in progress
- Analysis improvement
  - New analysis methods using ν_e signal shape (e.g. recon. energy) are under developing
  - Improve uncertainties in the Super-K for subdominant BG sources, *i*.e. $\pi^{\pm}$, $\pi^{\pm}\pi^{0}$, $\mu\pi^{0}$ etc.

Conclusion

- We reported new results from $\nu_\mu \rightarrow \nu_e$ oscillation analysis based on 1.43 x 10^{20} p.o.t. (2010 Jan. - 2011 Mar.)
  - Observe 6 candidate events
  - # of expected events = 1.5 ± 0.3(syst.) ($\sin^2 2\theta_{13} = 0$)
  - Under null θ_{13} hypothesis, prob. of observing 6 or more 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 Δm^2_{23}=2.4 x 10^{-3} eV^2, δ_{CP}=0, $\sin^2 2\theta_{23}$=1.0)

Indication of $\nu_\mu \rightarrow \nu_e$ appearance

This result was published as Phys. Rev. Lett. 107, 041801 (2011)

Reference: arXiv:1106.1238 for the T2K experimental setup.

- Plan for improve the measurement after recovery of the experiment in this calendar year
- ν_μ disappearance result with 1.43 x 10^{20} p.o.t. data will be reported this summer

Backup

Toward full picture of neutrino masses and mixings

atmospheric ν

Discovery of (θ_{23}, Δm^2_{23})

solar, reactor ν

→ (θ_{12}, Δm^2_{12})

→ θ_{13} in a few year?

If θ_{13} is really large ($\sin^2 2\theta_{13} \sim 0.1$) as indicated by T2K, we have to think very seriously how to explore last ν's parameter in the MNS matrix:

$$\delta_{CP}$$

CP odd term in $P(\nu_\mu \rightarrow \nu_e)$

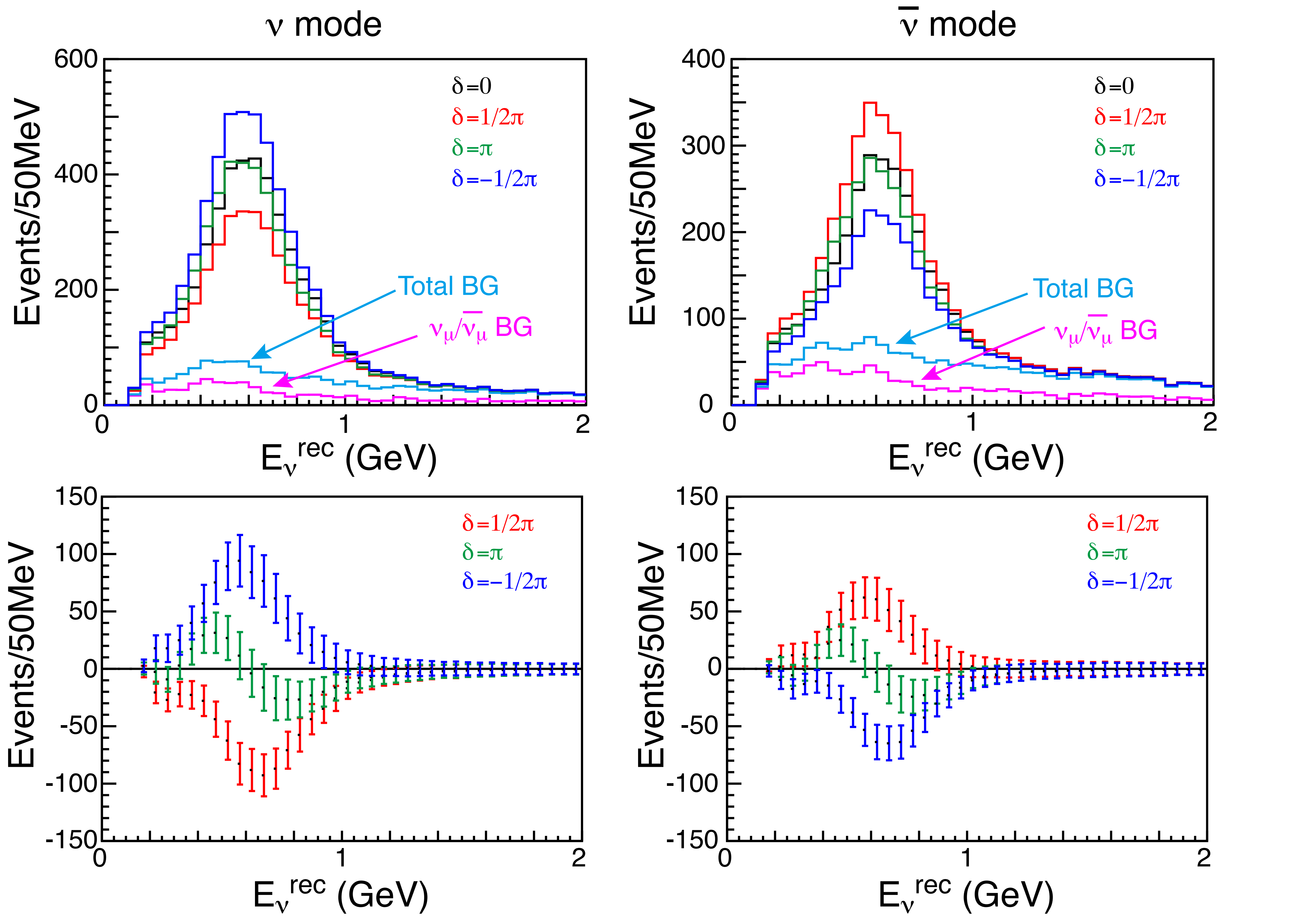
$\propto \sin\theta_{12}\mathbf{\sin\theta_{13}}\sin\theta_{23}\mathbf{\sin\delta}$


Photo-Detectors
Height 54m
Hyper-K
Super-K
x20 Larger Target
~0.6GeV νμ
295km
Quest for CP Violation
in lepton sector.
Higher Intensity
JPARC
© 2010 ZENRIN
Data © 2010 MIRC/JHA
© 2010 Cnes/Spot Image
© 2010 Mapabc.com
©2009 Google
36°24'46.66" N 139°18'01.27" E 標高 214 メートル
高度 188.55 キロメートル

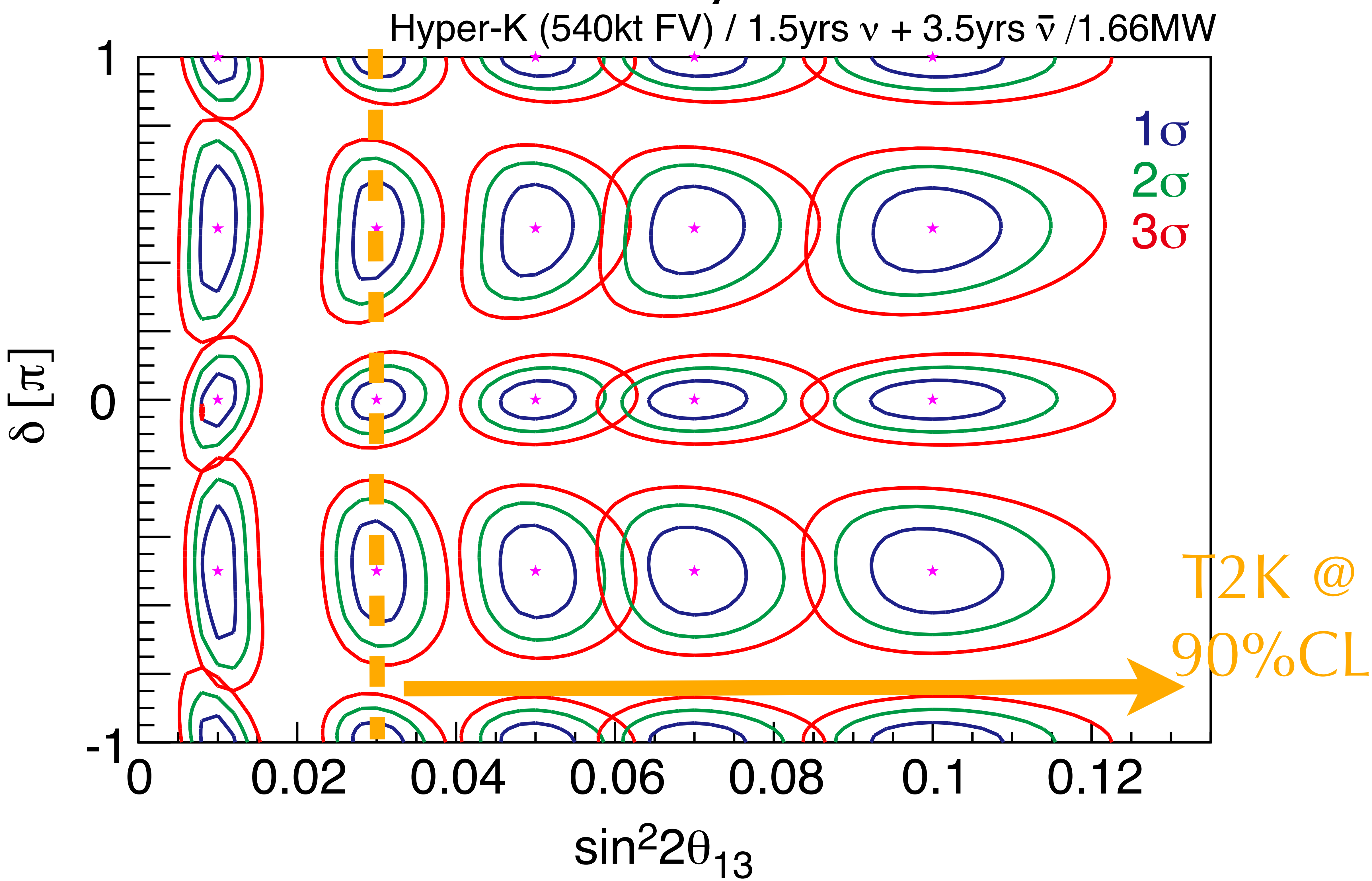
Compare electron appearance (number and spectrum) in ν and anti-ν beam

ν_e candidates

diff. from δ=0 case



Sensitivity on δ_{CP}

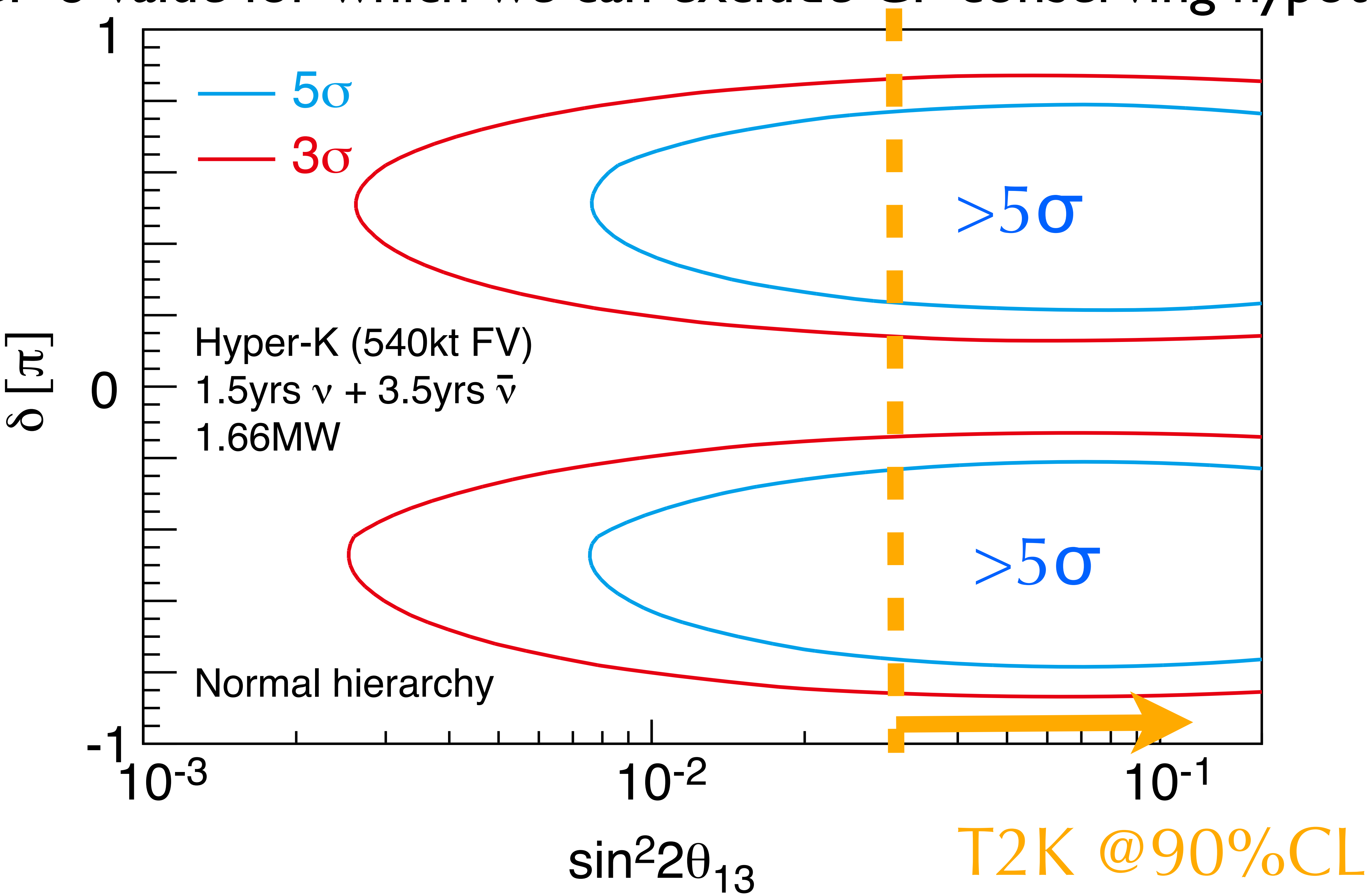


5 years (1.1yrs ν beam and 3.9yrs anti-ν beam)

assuming 5% uncertainties for signal, ν_μ BG, ν_e BG, and ν_e/anti-ν_e.

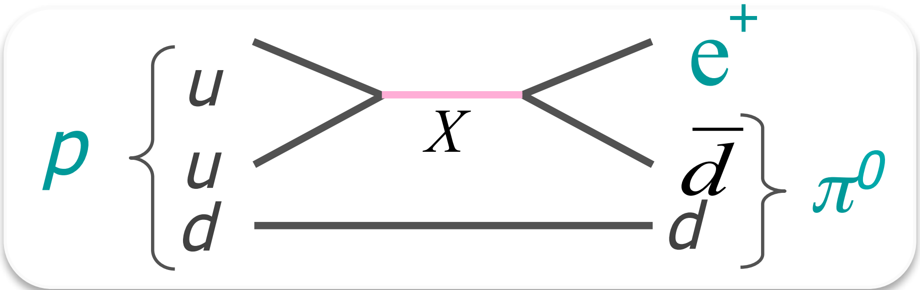
CPV discovery potential

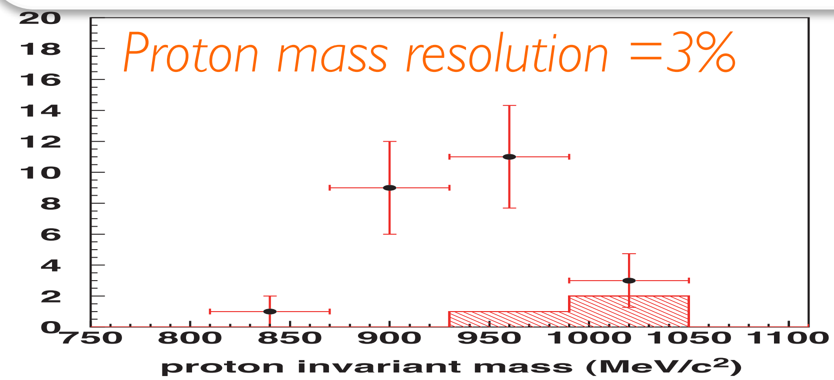
CP δ value for which we can exclude CP conserving hypothesis.



Proton Decay

- explore quark/lepton unification -





$p \rightarrow e^+\pi^0$

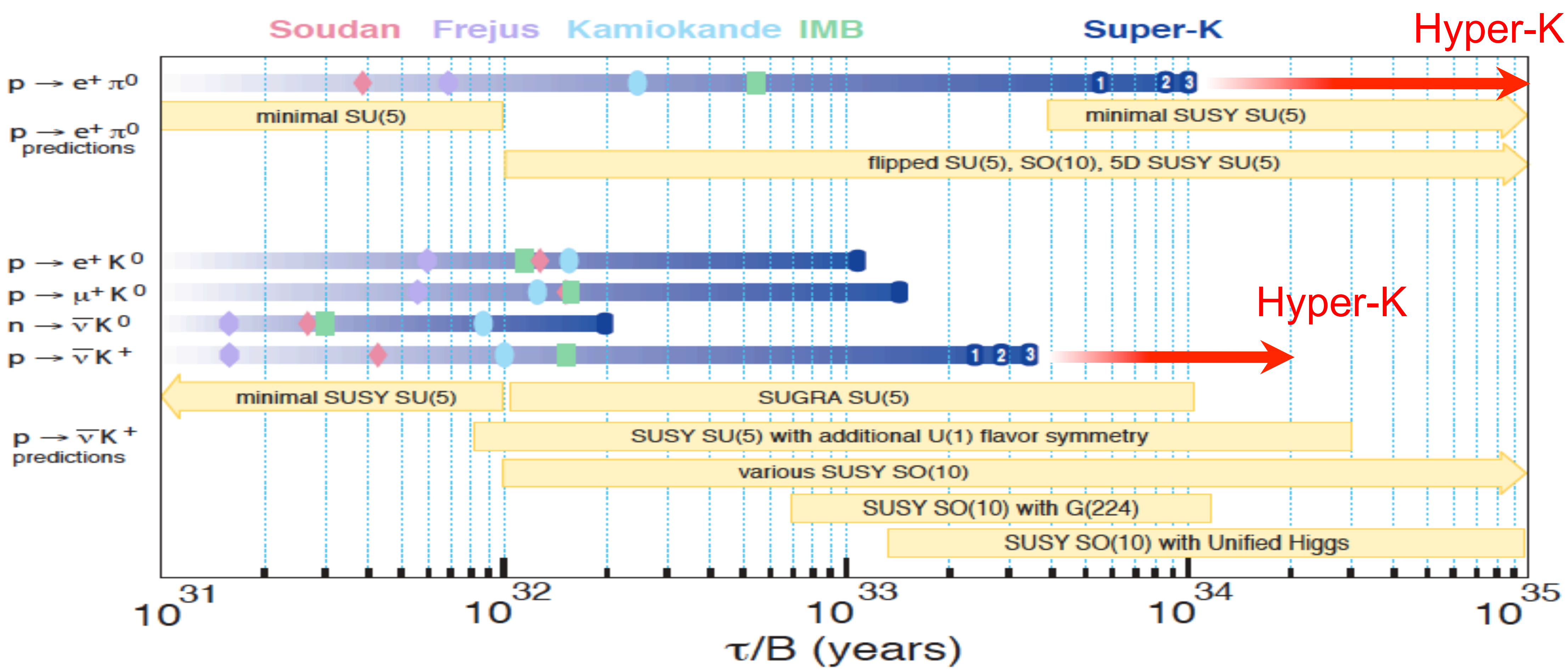
- 1.0×10^{34} years (Super-K I+II+II @ 90% C.L.)

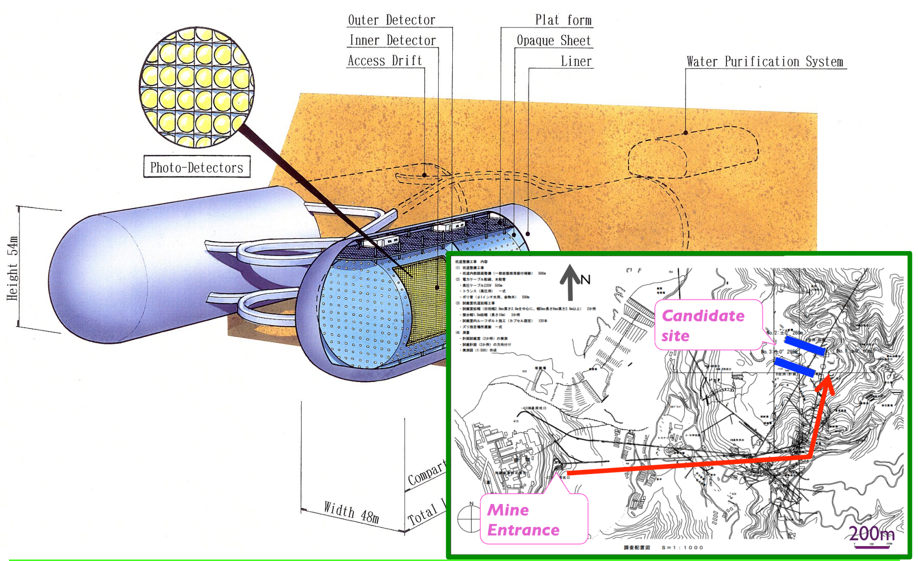
  → 1×10^{35} years (0.54Mton x 10yrs @ 90% CL)

$p \rightarrow \nu K^+$

- 3.3×10^{33} years (Super-K I+II+III @ 90%C.L.)

  → 2×10^{34} years (0.54 Mton x 10yrs @ 90% CL)



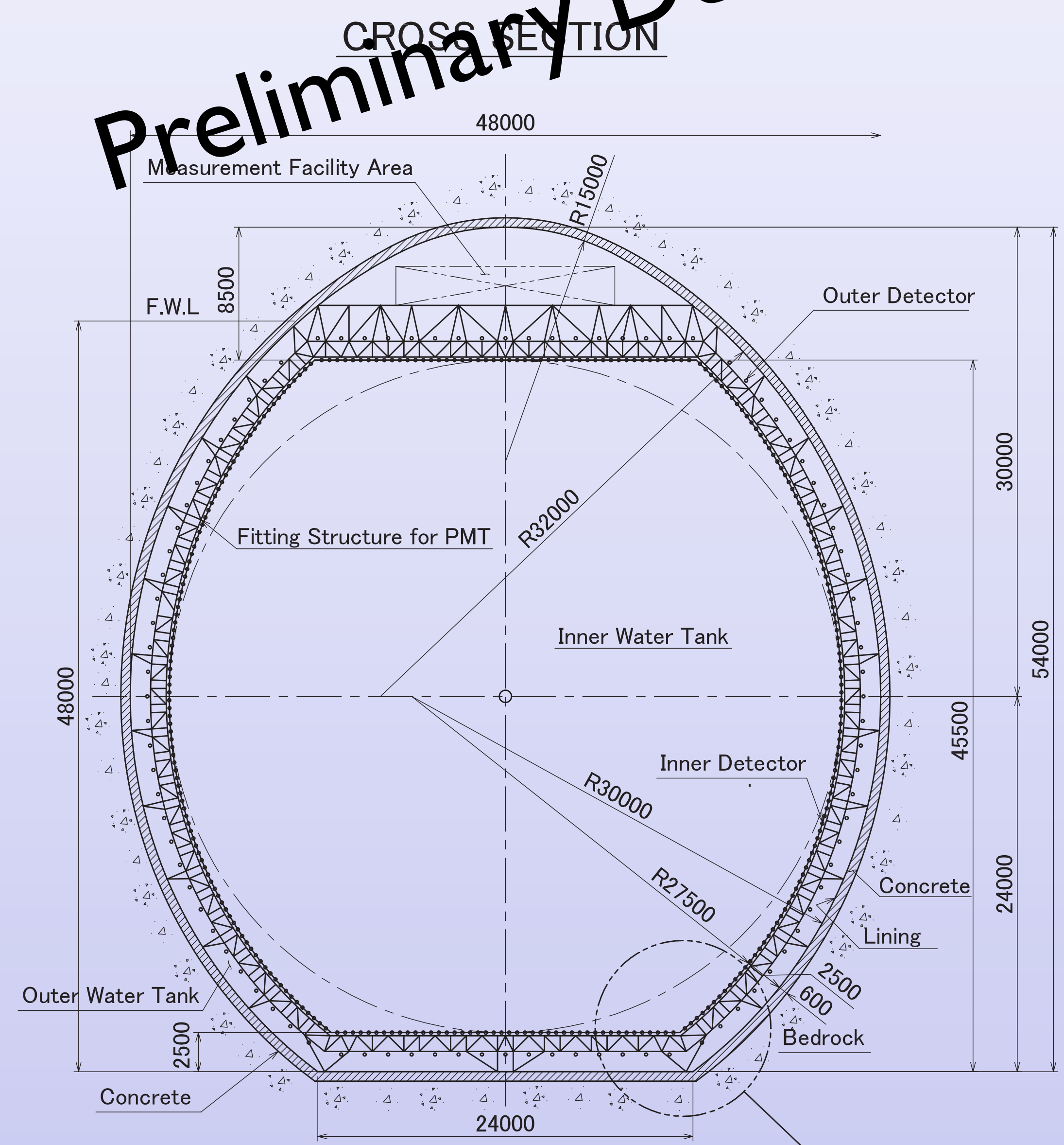


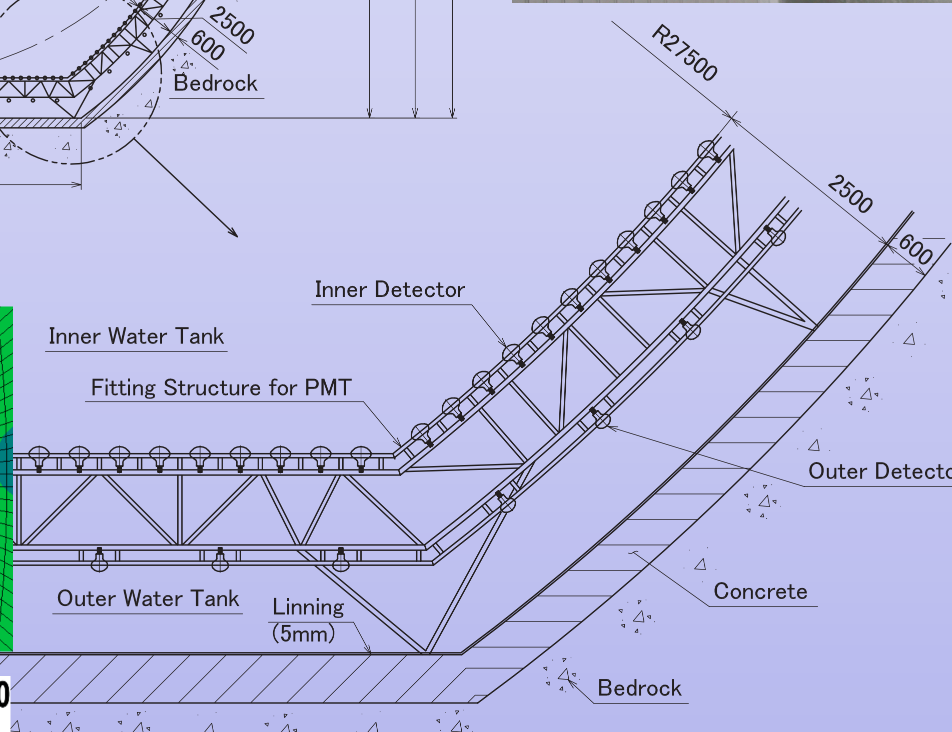
Hyper-K Base-Design

- 1Mton total volume, twin cavity
- 0.54Mton fiducial volume
- Inner (D43m x L250m) x 2
- Outer Detector >2m
- Photo coverage 20% (1/2 x SK)

- Base-design to be optimized
- Geological survey of the site is going on
- Qualitative studies on physics potential

Preliminary Design





20" PMT w/ cover

FEM analysis (Factor of safety)