NEW RESULTS FROM T2K EXPERIMENT

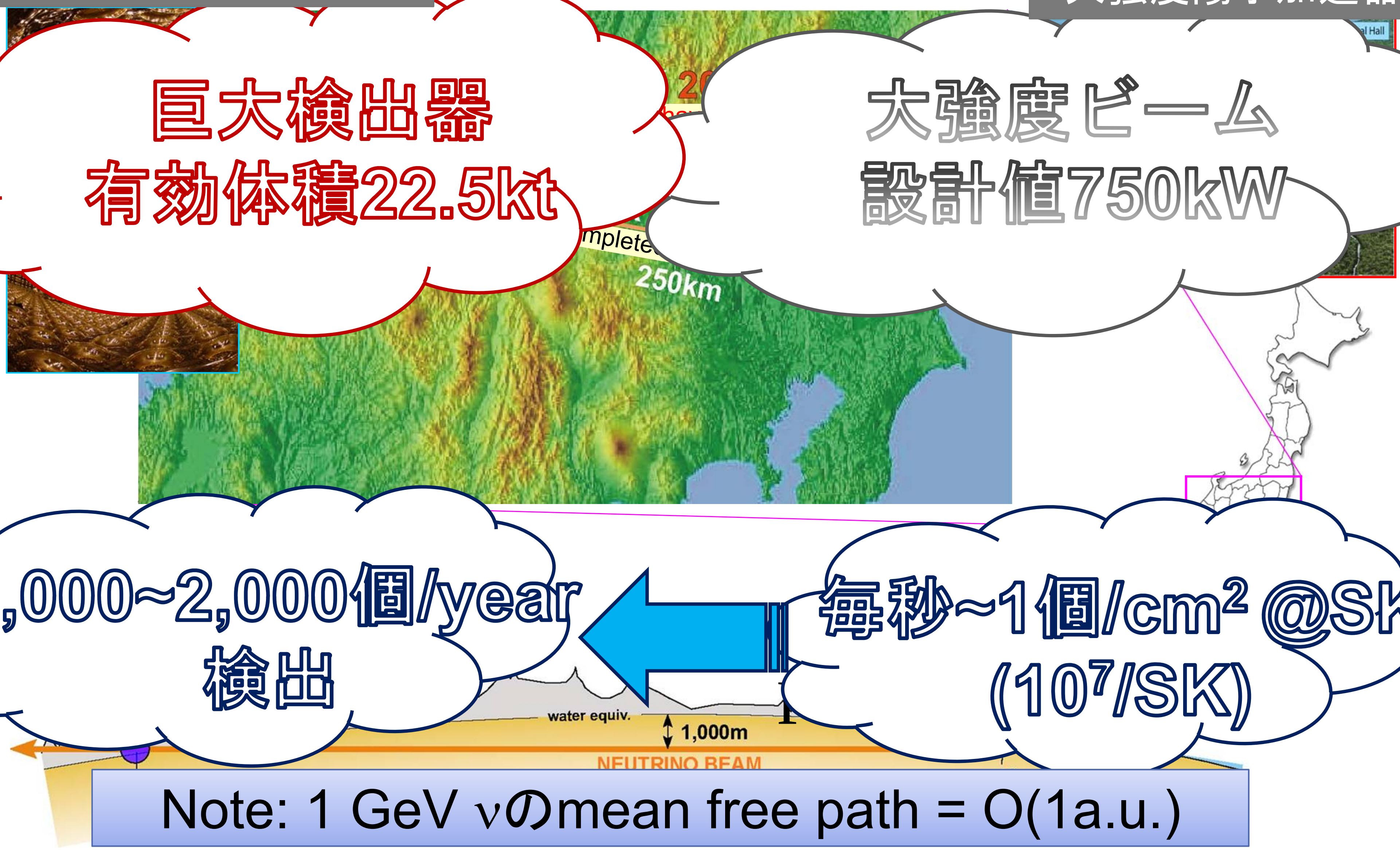
Atsuko K. Ichikawa for T2K collaboration

2011/June/15, 京大談話会

T2K 東海 TO 神岡 長基線ニュートリノ振動実験

水チェレンコフ検出器

大強度陽子加速器



巨大検出器
有効体積22.5kt

大強度ビーム
設計値750kW

1,000~2,000個/year
検出

毎秒~1個/cm^2 @SK
(10^7/SK)

Note: 1 GeV νのmean free path = O(1a.u.)

T2K COLLABORATION

International collaboration

(~500 members, 59 institutes, 12 countries)

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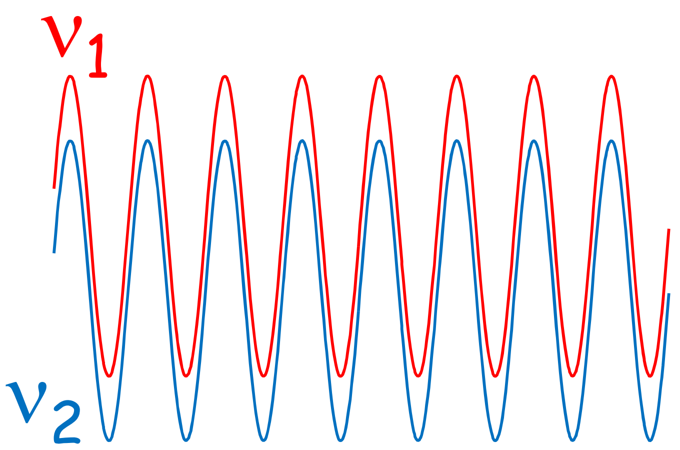
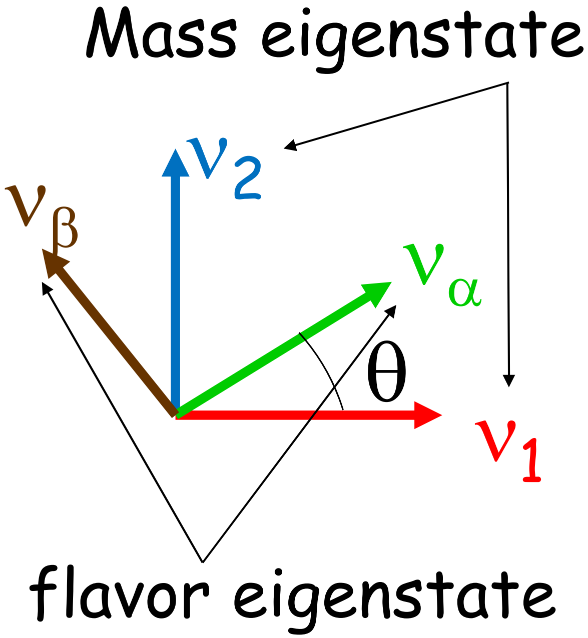
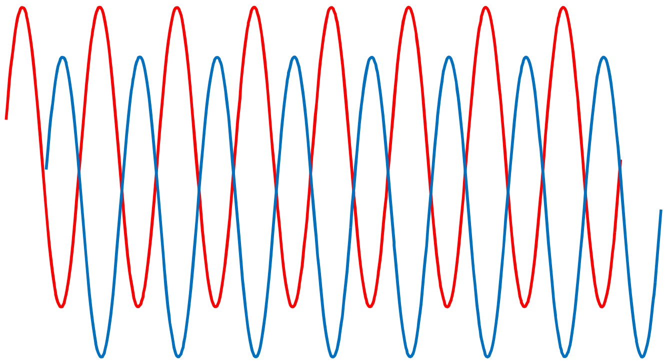
   with data upto 11th March
   (1.43×10^{20} protons on target)
3. Conclusion and Prospect

ニュートリノ振動とは？





Trabeling distance L

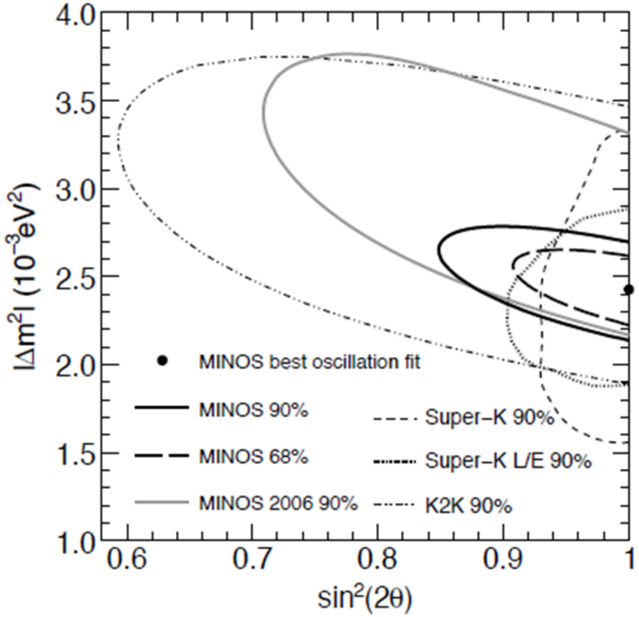


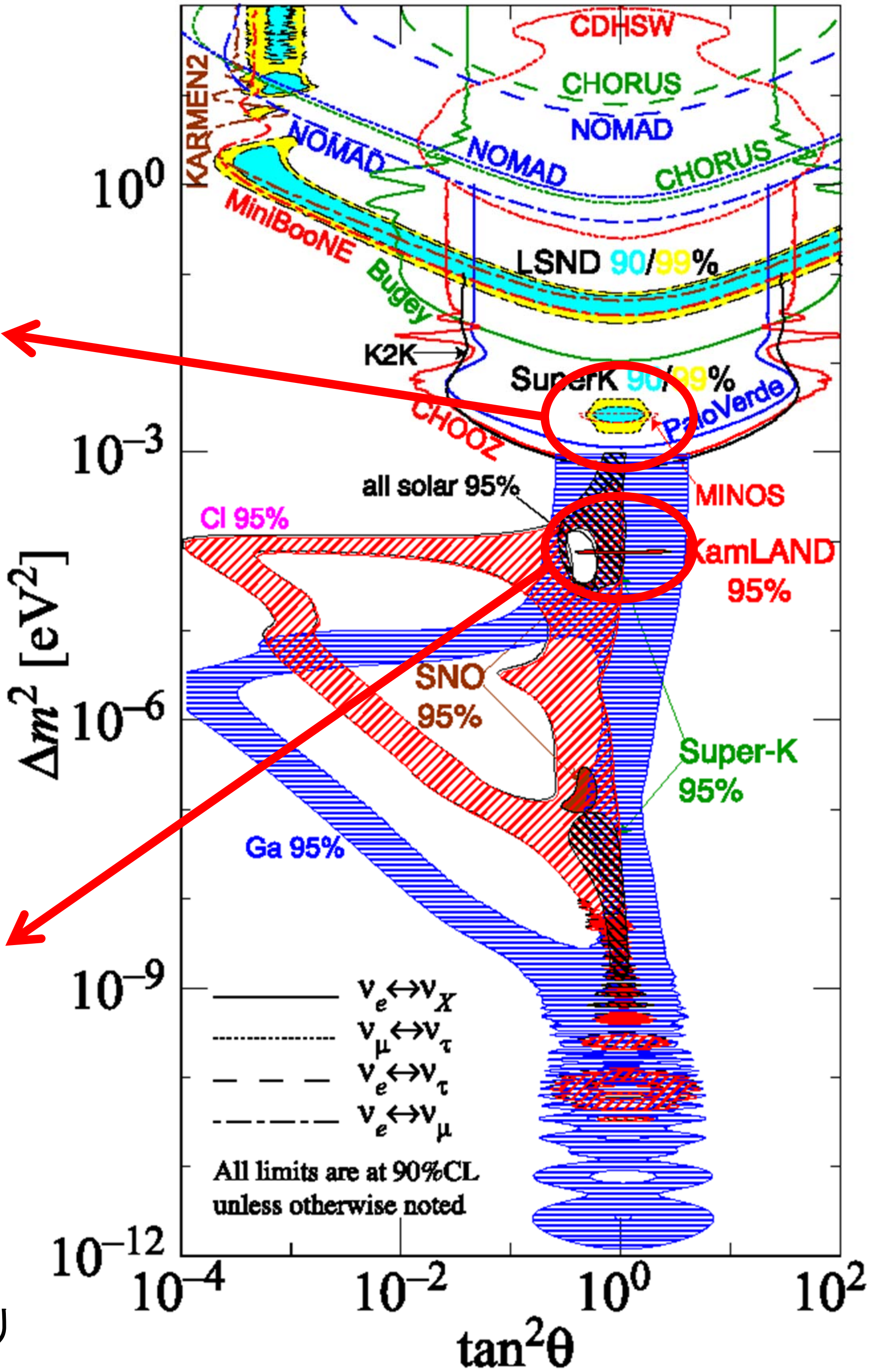
$|\nu_\alpha\rangle = |\nu_1\rangle\cos\theta + |\nu_2\rangle\sin\theta$, $\alpha = e, \mu, \tau$

$$|\nu_1\rangle e^{-i\frac{m_1^2}{2E}L}\cos\theta + |\nu_2\rangle e^{-i\frac{m_2^2}{2E}L}\sin\theta$$

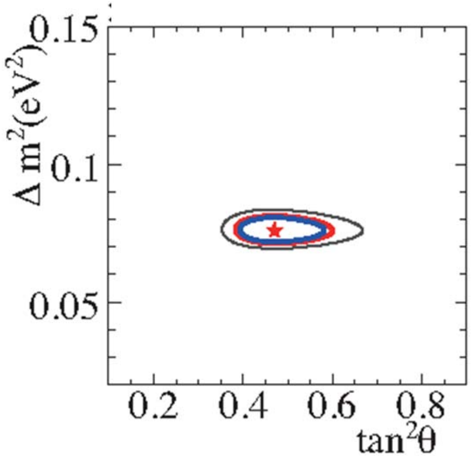
$$P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | \nu_\alpha \rangle\right|^2 = \sin^2 2\theta \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

太陽ニュートリノと大気ニュートリノ





太陽ニュートリノ
　　Super-K, SNO,
　　KamLAND(原子炉ν),
　　Bolexino,……
大気ニュートリノ
　　Super-K, K2K(加速器ν),
　　MINOS(加速器ν)



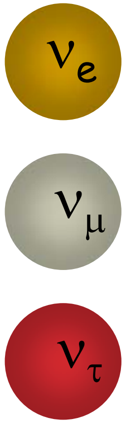
2010 PDGより

THREE FLAVOR MIXING IN LEPTON SECTOR

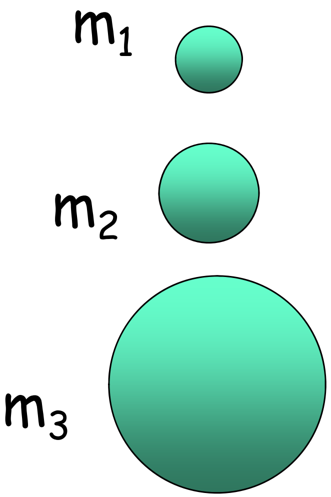
ニュートリノには、3世代あるので、3世代で混合を考えるべき

Weak eigenstates

mass eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U}_{\mathrm{MNS}} \mathrm{V}_{\mathrm{M}}^{\mathrm{CP}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



太陽ニュートリノ

$$\mathrm{U}_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & \boxed{+s_{23}} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & \boxed{+s_{13}e^{-i\delta}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & \boxed{+s_{12}} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

大気ニュートリノ

θ_{12}, θ_{23}, θ_{13}

+ δ (+2 Majorana phase)

Δm_{12}, Δm_{23}, Δm_{13}

わかっていること

$\theta_{12} = 34° \pm 1°$

$\theta_{23} = 45° \pm 8° \quad (90\%\mathrm{CL})$

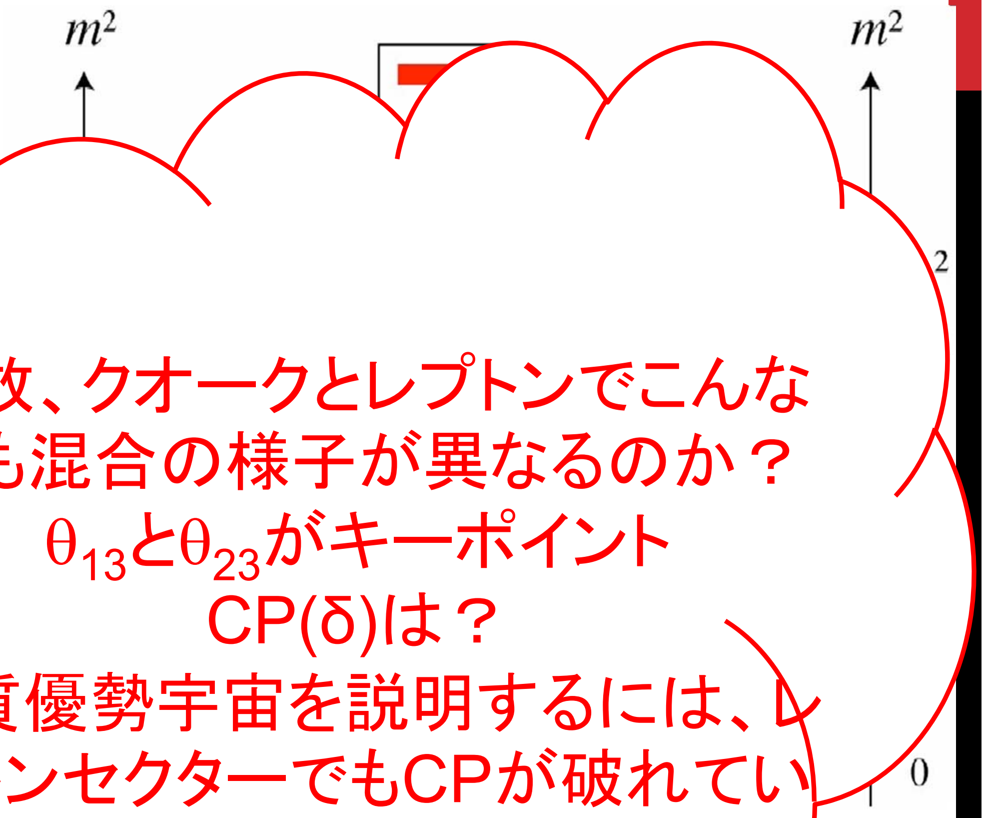
$\theta_{13} \leq 12° \quad (90\%CL)$

$$U_{MNS} \approx \begin{pmatrix} 0.8 & 0.55 & \boxed{<0.21} \\ -0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

δ=?

$$U_{CKM} \approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

δ~60°



何故、クオークとレプトンでこんなにも混合の様子が異なるのか？

θ_{13}とθ_{23}がキーポイント

CP(δ)は？

物質優勢宇宙を説明するには、レプトンセクターでもCPが破れていることが望ましい。

$\nu_\mu \to \nu_e$ APPEARANCE

Leading term at around atm. osciilation maximum

$$P(\nu_\mu \to \nu_e) = \boxed{4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\frac{\Delta m_{31}^2 L}{4E} \times \Big(1}+\frac{2a}{\Delta m_{31}^2}(1-2S_{13}^2)\Big)$$

$$+8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\frac{\Delta m_{32}^2 L}{4E}\sin\frac{\Delta m_{31}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$

$$-\boxed{8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\frac{\Delta m_{32}^2 L}{4E}\sin\frac{\Delta m_{31}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}}$$

$$+4S_{12}^2 C_{13}^2\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\}\sin^2\frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2\cos\frac{\Delta m_{32}^2 L}{4E}\sin\frac{\Delta m_{31}^2 L}{4E}\frac{aL}{4E}(1-2S_{13}^2)$$

θ_{13}

CPC

CPV

Solar

Matter effect (small in T2K)

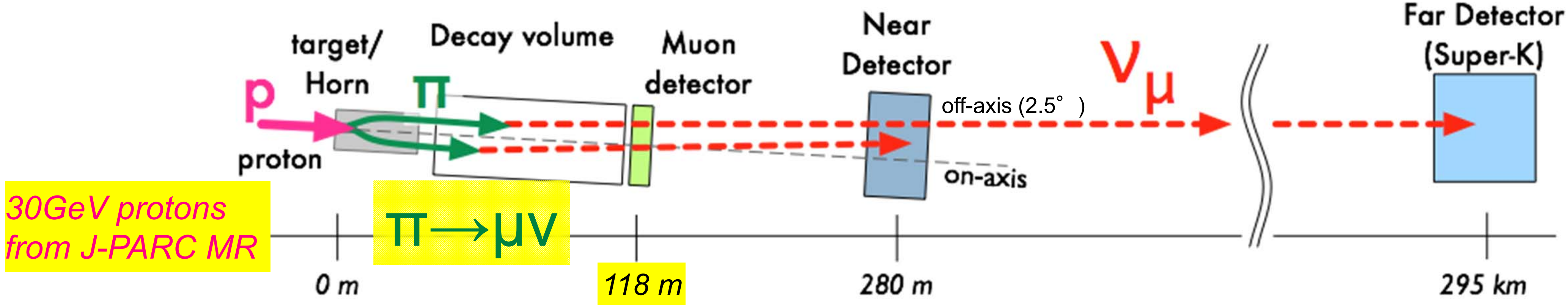
CP violating term introduced by interference btw. θ_{13} and θ_{12}

$a \to -a$, $\delta \to -\delta$ for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

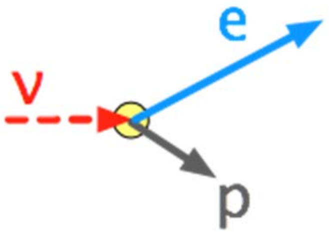
$$a = 7.56\times10^{-5}[\mathrm{eV}^2]\cdot\left(\frac{\rho}{[\mathrm{g/cm^3}]}\right)\cdot\left(\frac{E}{[\mathrm{GeV}]}\right)$$

L=295km, $\langle E_\nu \rangle$ ~0.6GeV

DESIGN PRINCIPLE OF T2K

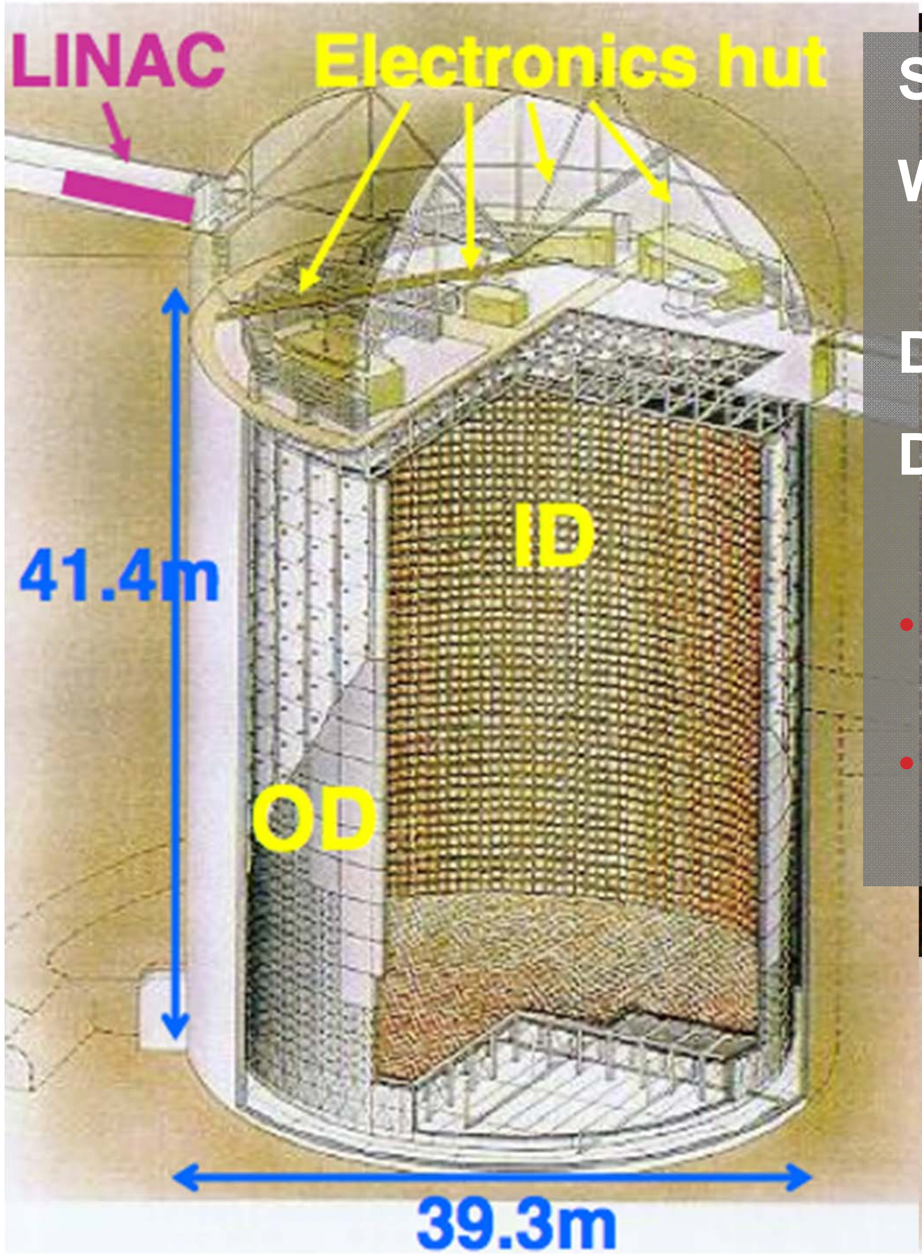


- ☑ **High Intensity ν_μ beam from J-PARC**
- ☑ **Super-Kamiokande(SK) as a far neutrino detector**
  - 22.5kt fiducial volume mass
  - Excellent performance for single particle event
    - $\nu_e + n \rightarrow e + p$ (T2K ν_e signal)



- ☑ **Less high energy tail by off-axis beam method**
  - First application at long baseline experiment

FAR DETECTOR (SUPER-K)



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

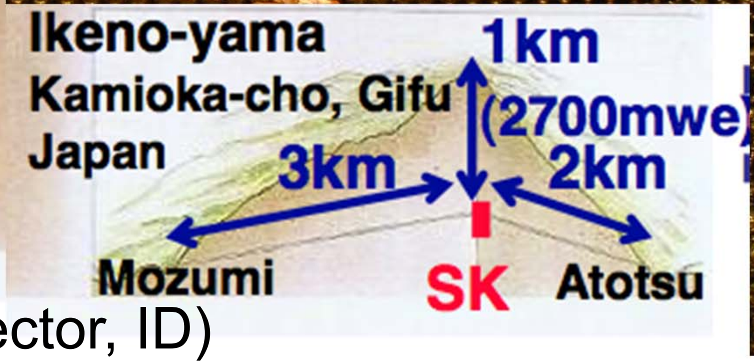
Stable operation since April 1996

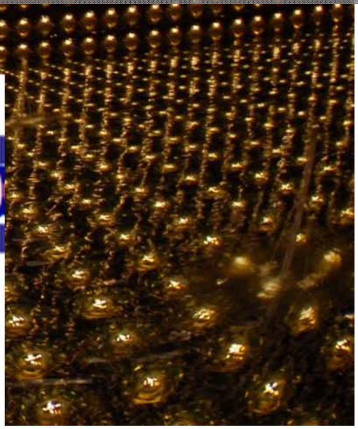
Water Cherenkov detector w/ fiducial volume 22.5kton

Dead-time less DAQ system (2008~)

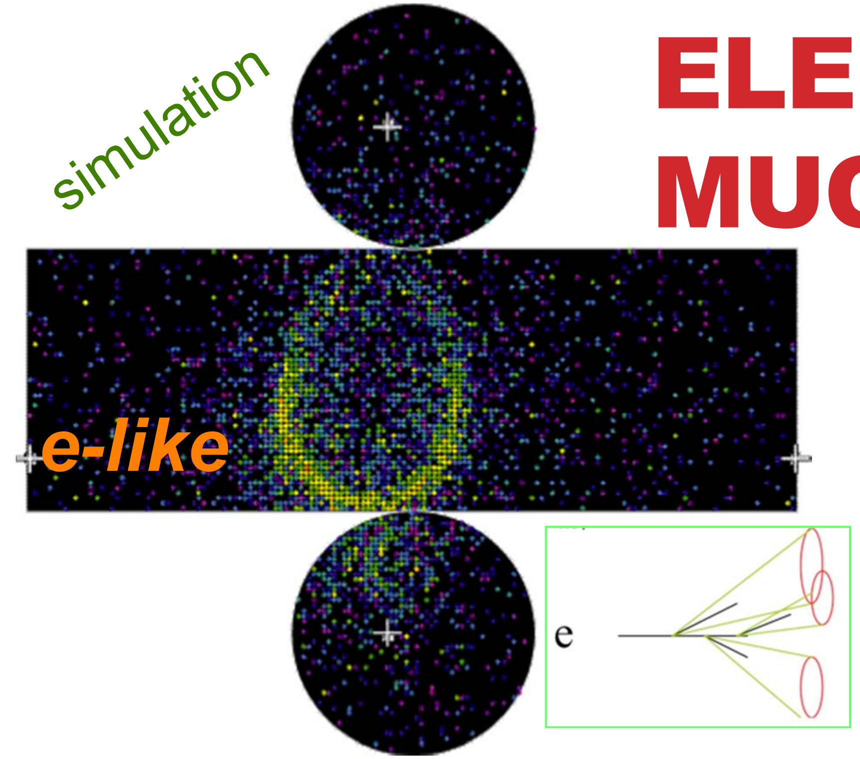
Detector performance is well-matched at sub GeV

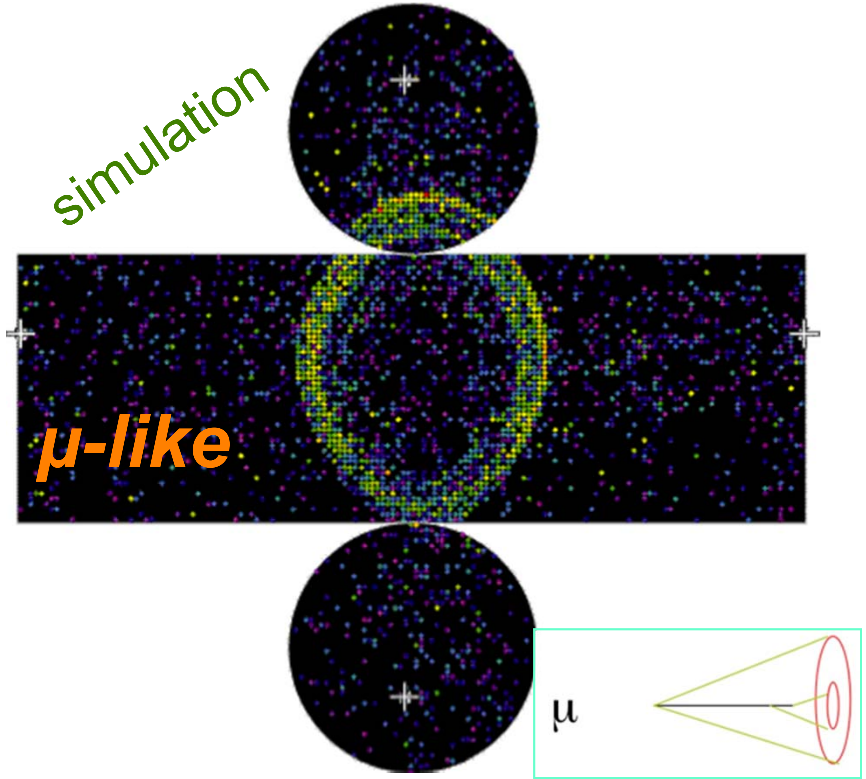
- Excellent performance for single particle event
- Good e-like(shower ring) / μ-like separation *(next page)*



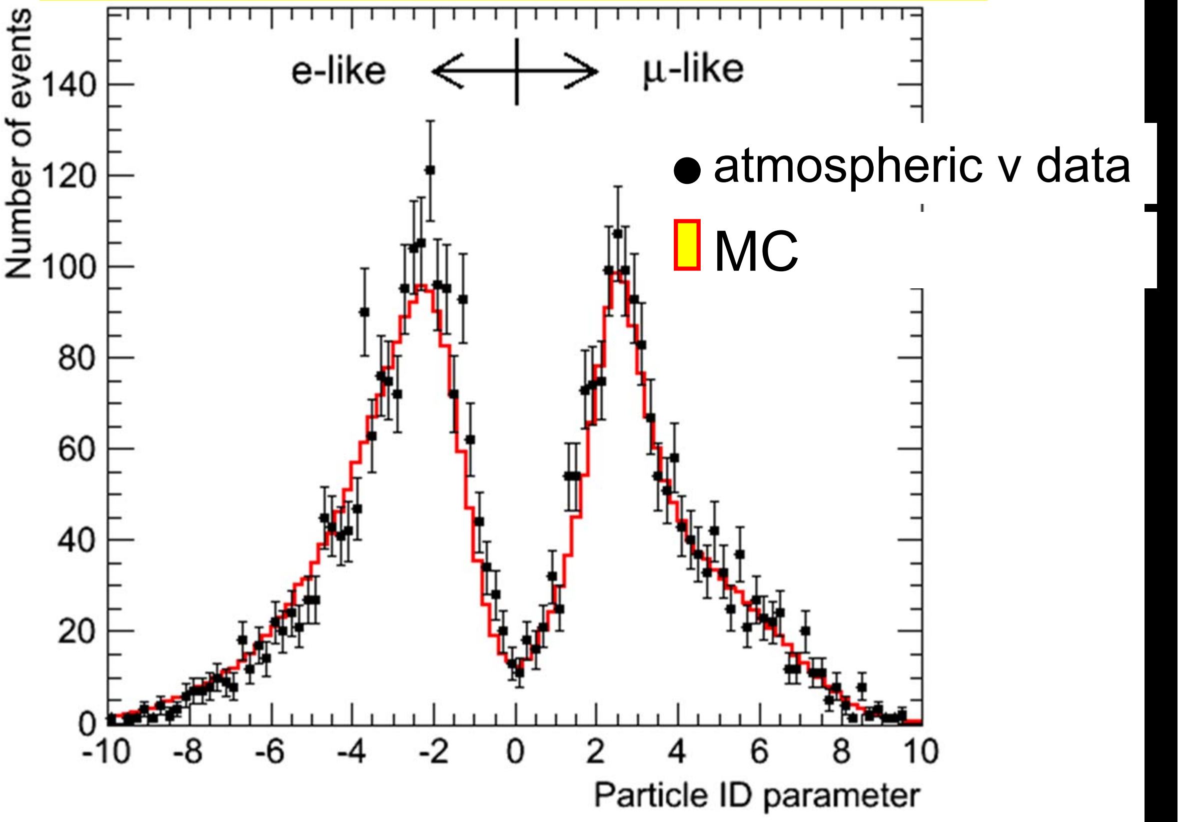


ELECTRON-LIKE AND MUON-LIKE EVENT AT SK



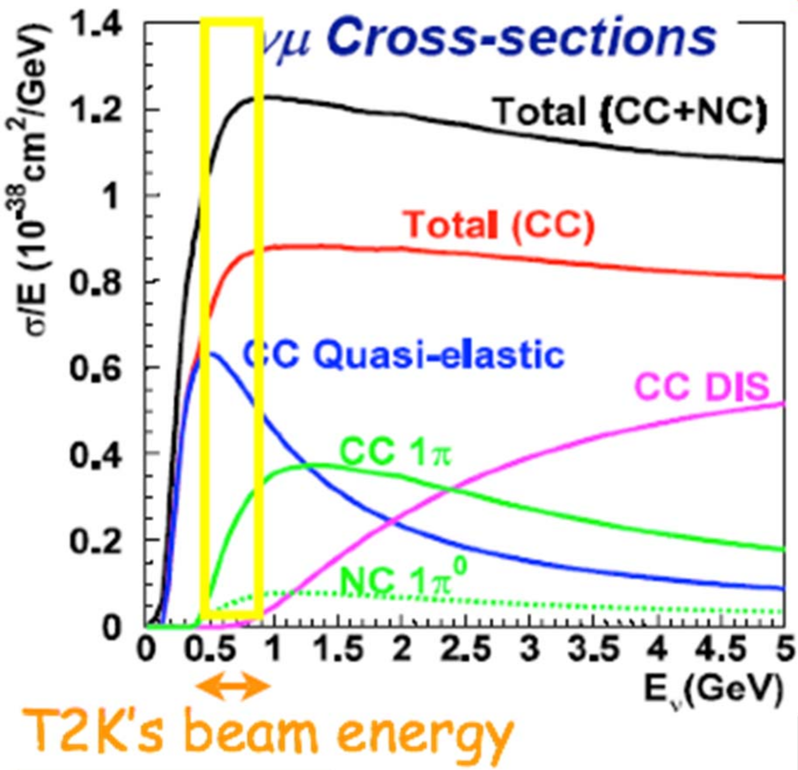


Particle identification using ring shape & opening angle



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

T2K SIGNAL & BACKGROUND FOR ν_e APPEARANCE



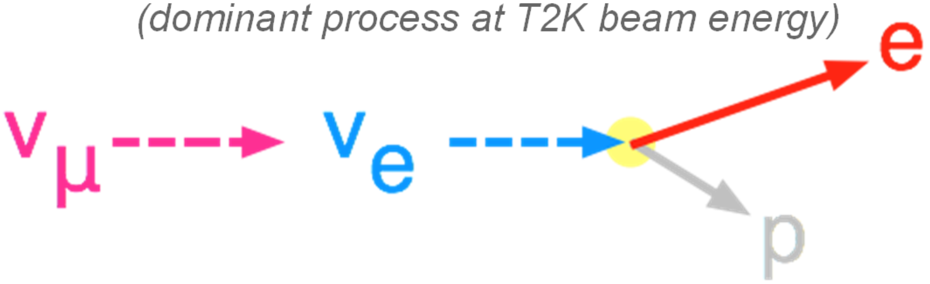
Signal = single electron event

oscillated ν_e

Charged Current Quasi-elastic interaction :

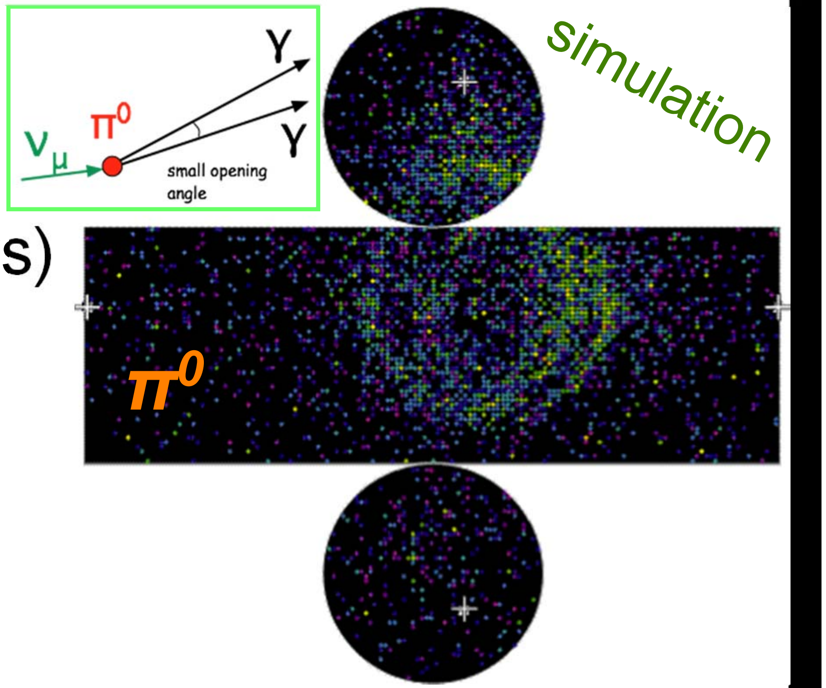
CCQE : $\nu_e + n \rightarrow e + p$

(dominant process at T2K beam energy)

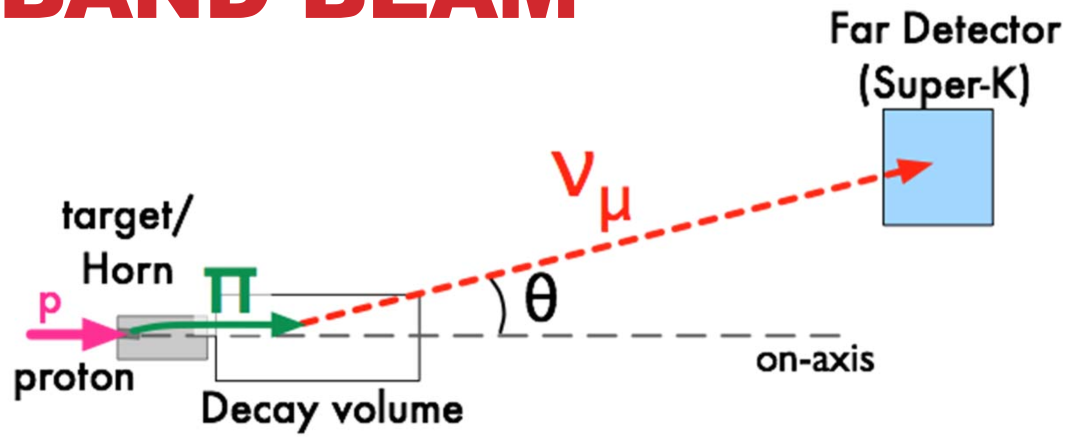


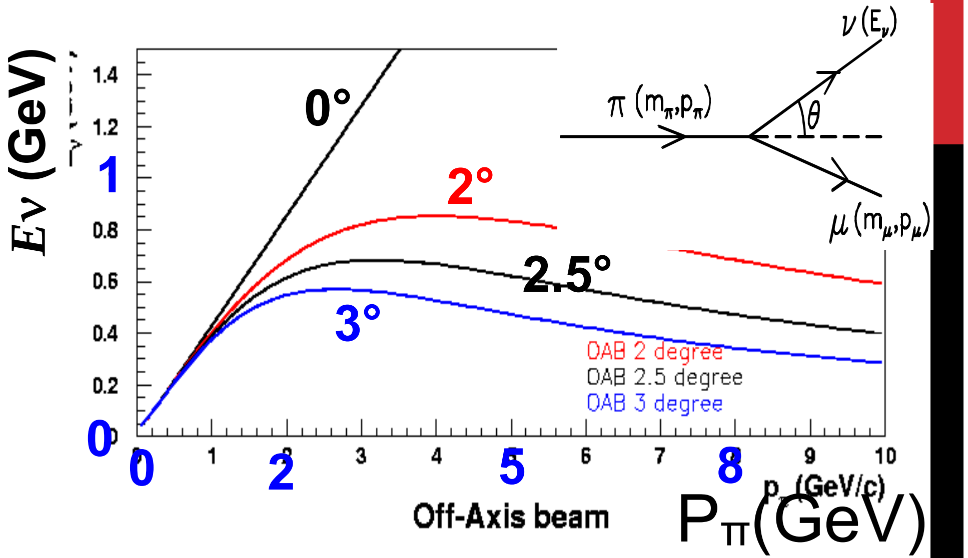
Background

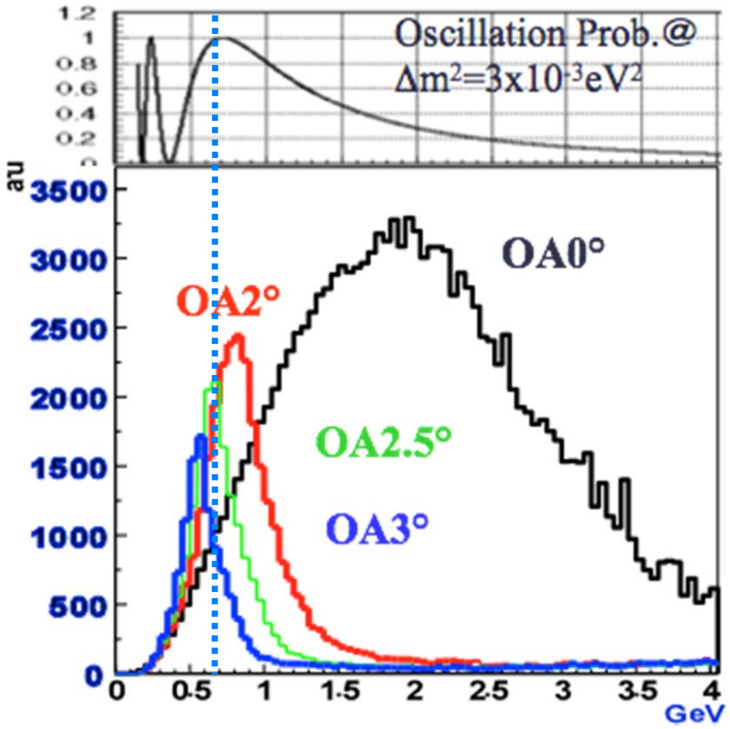
- intrinsic ν_e in the beam (from μ, K decays)
  - <0.5% at energy peak
- π^0 from Neutral Current interaction



OFF-AXIS BEAM : INTENSE & NARROW-BAND BEAM







Pseud monochromatic beam utilizing pion decay kinematics
T2K off-axis angle is 2.5°
peak energy at oscillation max.
(~0.6GeV at L=295km)
less high energy tail
↓
maximize physics sensitivity

OFF-AXIS NEAR DETECTOR (ND280)

ν_μ CC events rate measurement in present analysis

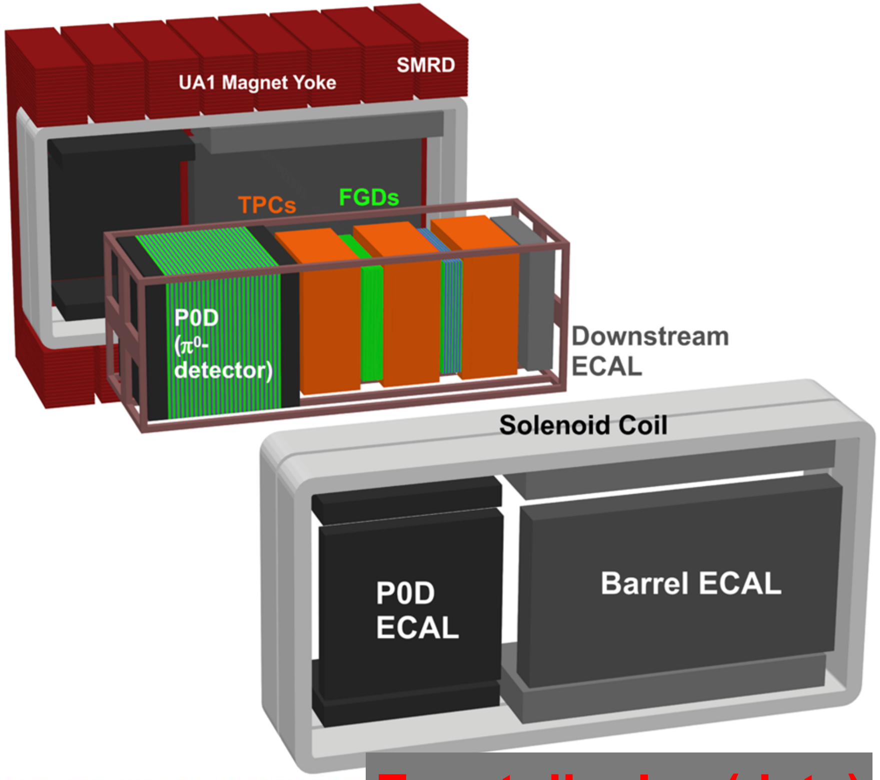
0.2 T UA1 magnet

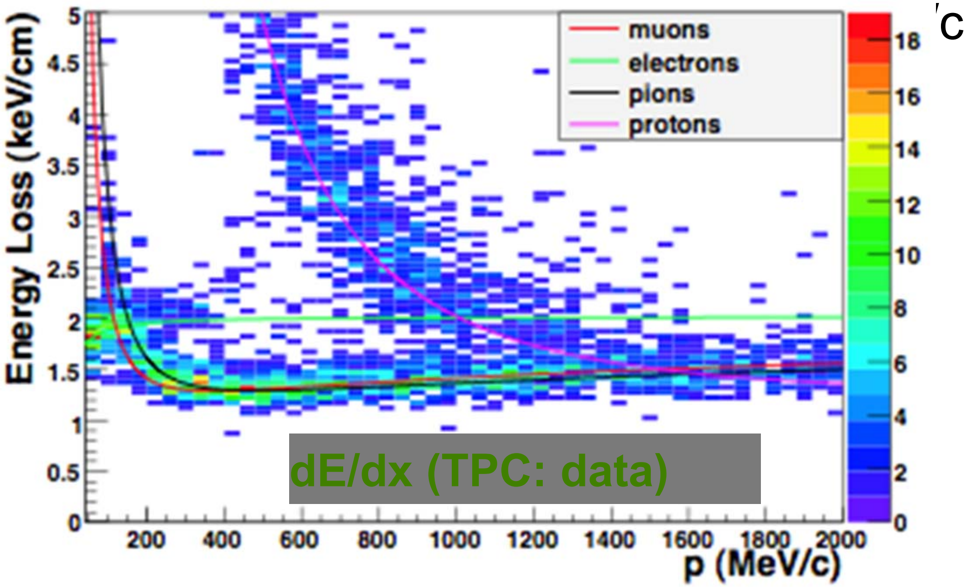
Fine Grained Detector (FGD)

- scintillator bars target (water target in FGD2)
- 1.6ton fiducial mass for analysis

Time Projection Chambers (TPC)

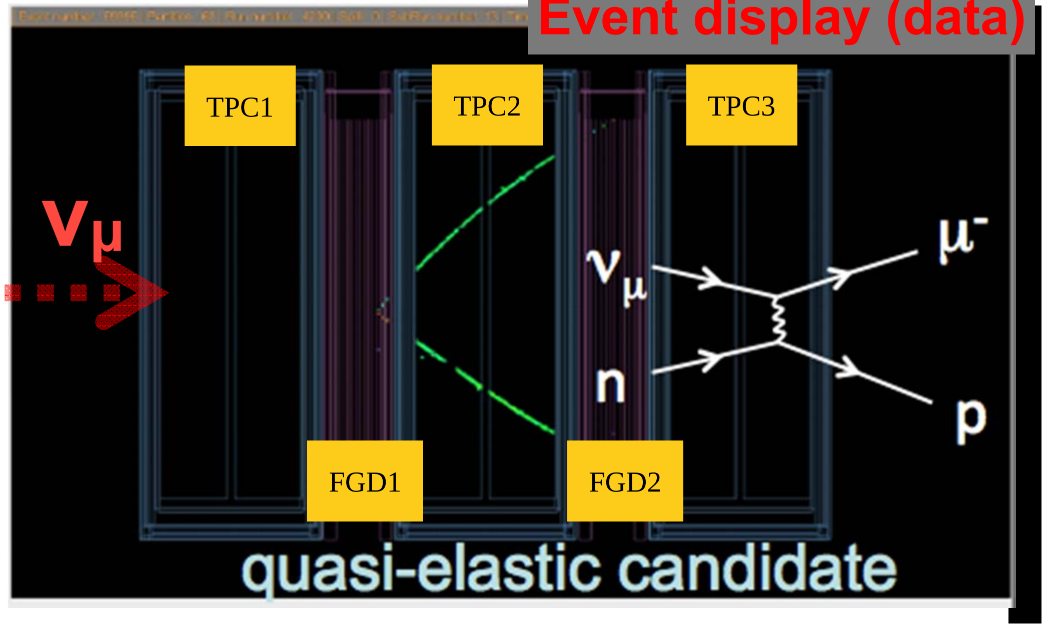
- better than 10% dE/dx resolution





dE/dx (TPC: data)

Event display (data)



quasi-elastic candidate

HISTORY

- 1990年代東大原子核研究所大型ハドロン計画（JHF）
- 1999 原研の中性子科学研究計画との統合計画（J-PARC）
- 2001.4 J-PARC本予算スタート6年で（νは2期）
- 2003.8 文科省ニュートリノ予算を財務省へ
- 2003.10 総合科学技術会議ニュートリノをCランクに格付け
- 2003.11 プロジェクト再検討
- 2003.12 財務省ニュートリノプロジェクト認める

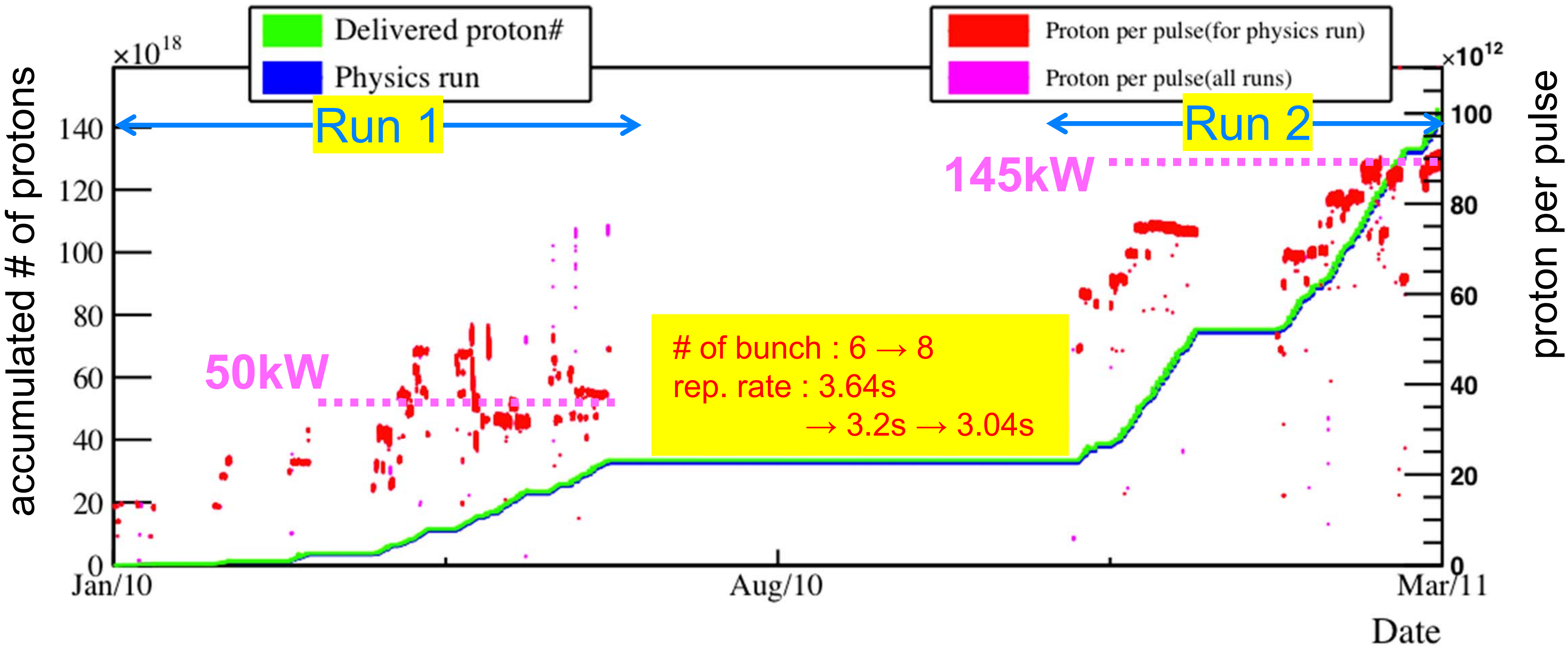
-- 建設 -- 建設 -- 建設 -- 建設 -- 建設 -- 建設 -- 建設 -- 建設 -- 建設 --

- 2009.4 ニュートリノ施設のコミッショニング開始(数ショット)
- 2009.11 J-PARCで最初のニュートリノ観測
- 2010.1 物理データ取得開始 (<20kW)

-- 強度化 -- 強度化 -- 強度化 -- 強度化 -- 強度化 -- 強度化 -- 強度化 --

- 2010.2 Super-Kで最初のJ-PARCニュートリノを観測 (~30kW)
- 2011.3.10 ~145kW

TOTAL # OF PROTONS USED FOR ANALYSIS



# of bunch : 6 → 8
rep. rate : 3.64s
→ 3.2s → 3.04s

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)

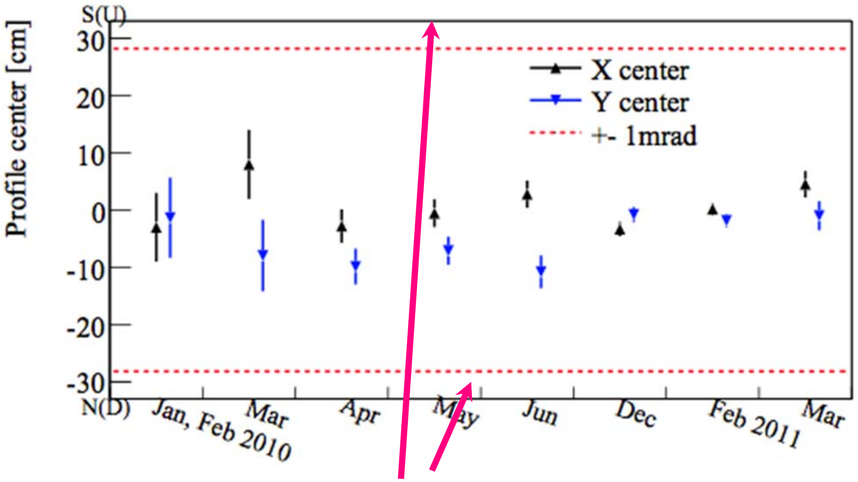
- 11.08 x 10^{19} p.o.t. for analysis
- ~145kW beam operation

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

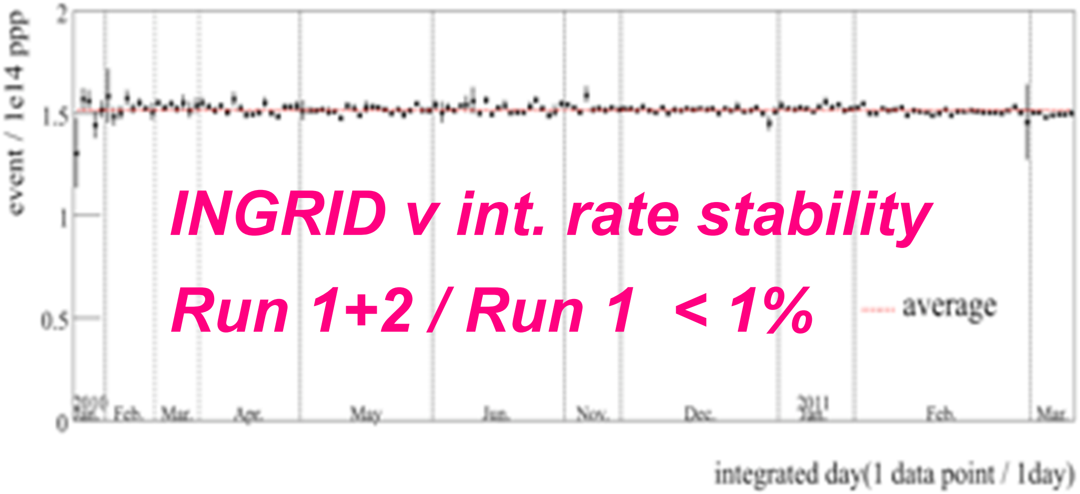
ν BEAM STABILITY

Stability of ν beam direction (INGRID)



ν beam dir. stability < 1mrad

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

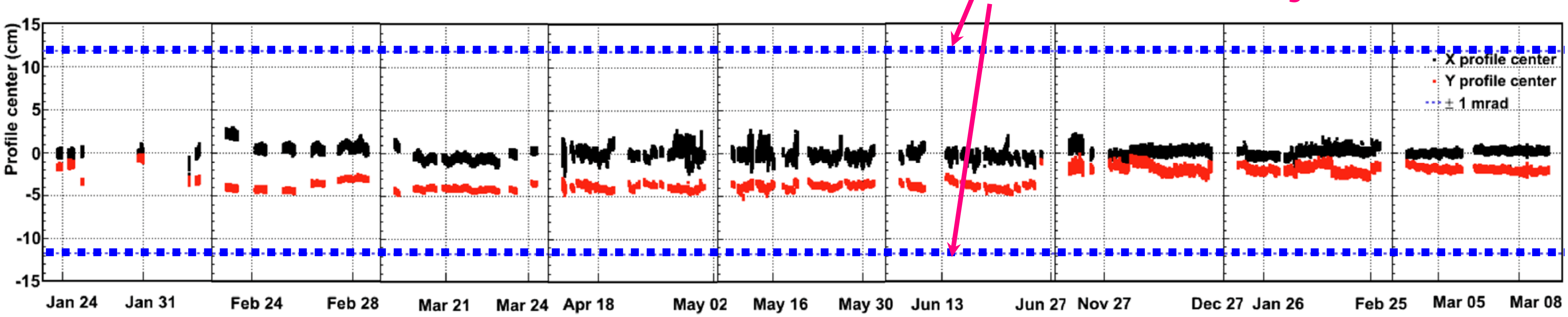


INGRID ν int. rate stability

Run 1+2 / Run 1 < 1%

Stability of beam direction (Muon monitor)

Beam dir. stability < 1mrad



DOCUMENT 3/11

加速器メンテナンスのためビームは停止中

15:00より Run1の結果をKEKにて発表予定

京都では、物二教室発表会開催中

14:46　最初の地震　→　最大震度 6強

- 東海にいたT2K関係者の多くが、(TV会議で)セミナーに出席しようと敷地内を移動中
- 京大の高エネグループ院生 5名を含む

地震直後に携帯で京都と連絡

- 人の被害はない模様
- その後、数日間は連絡を取れなくなる

2011.3.24.

3月24日のリニアック地下部

3月17日に1センチでの水であったのが、3月24日には10センチに。
約100トンの水。3月25日より自家発電機で排水を開始。

2011.3.17.

ニュートリノビームダンプ周辺

南側 (ビーム上流から下流を見る)

DOCUMENT 3/11

東海地区は、電気、ガス、水が止まる。余震がひどい

- 交通手段も麻痺 (高速道路、鉄道ともに止まる。一般道も信号がつかない。ガソリンが手に入らない）
- 院生は、コンビニエンスストアで、食糧を調達

3/14 KEKがバスを手配し、ユーザーをすべて東海から引き上げる

- 院生は無事、帰京

研究所はしばらく閉鎖

その後、空間放射線レベルが上がる。東海での上昇は、最大3~4μSv/h。すぐに下がる。

１週間後から徐々にInspection start

(3/24 市川、車で帰宅。ガソリン、納豆が手に入らない）

4月に入ってから、高速道路、鉄道も復旧。徐々にユーザーも来訪可に。

損害は大きいが、修復可能！

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

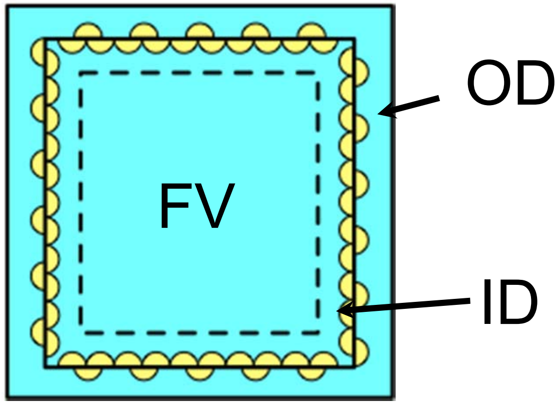
ν_e SELECTION AT FAR DETECTOR (SK)

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)

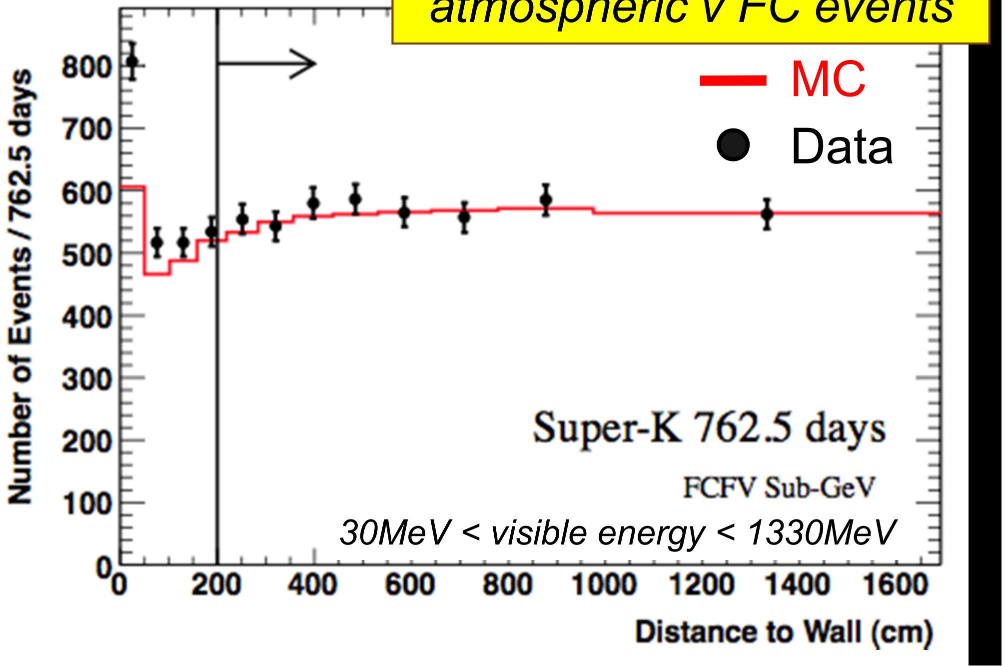
* Events too close to the wall are difficult to accurately reconstruct vertex

* Reject events which are originated outside the ID

* Define FV 22.5kton

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

atmospheric ν FC events

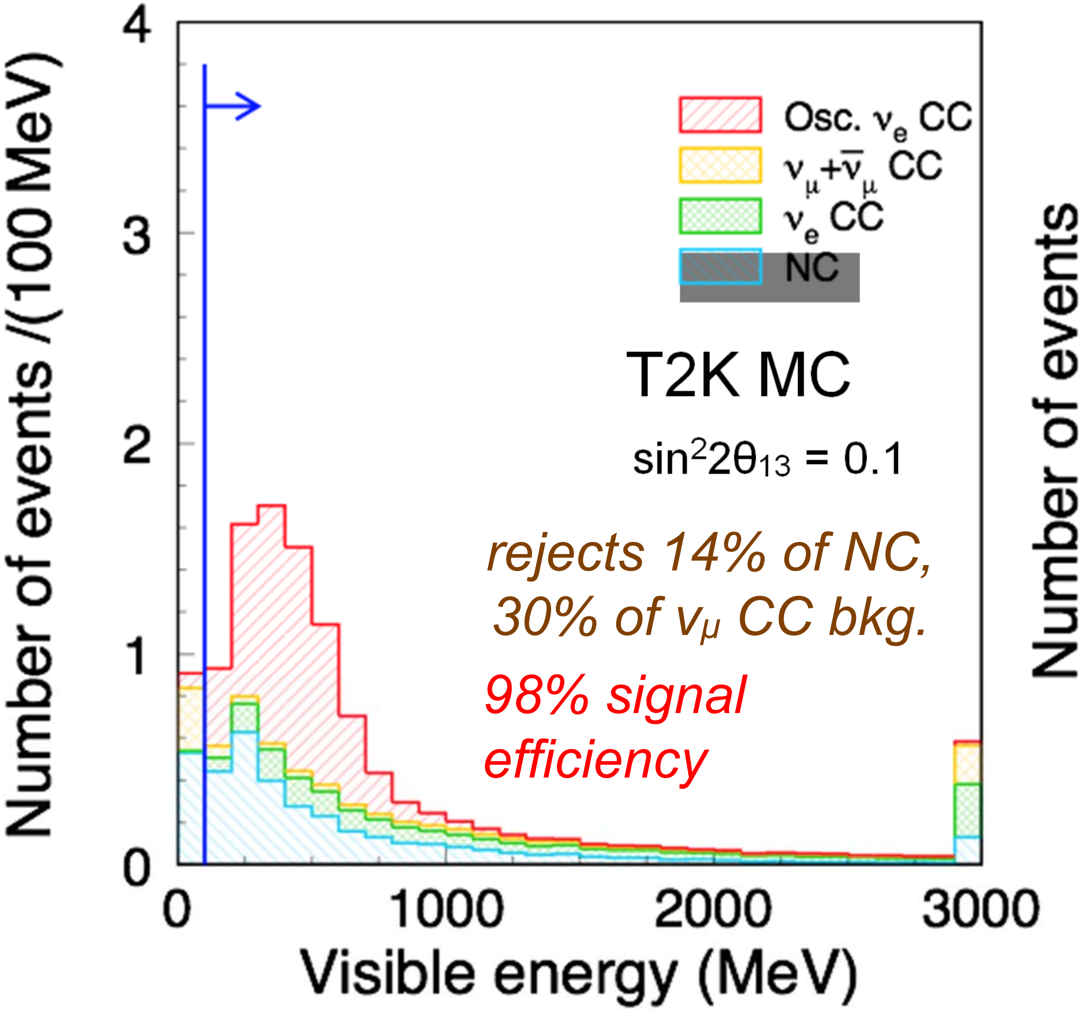


30MeV < visible energy < 1330MeV

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

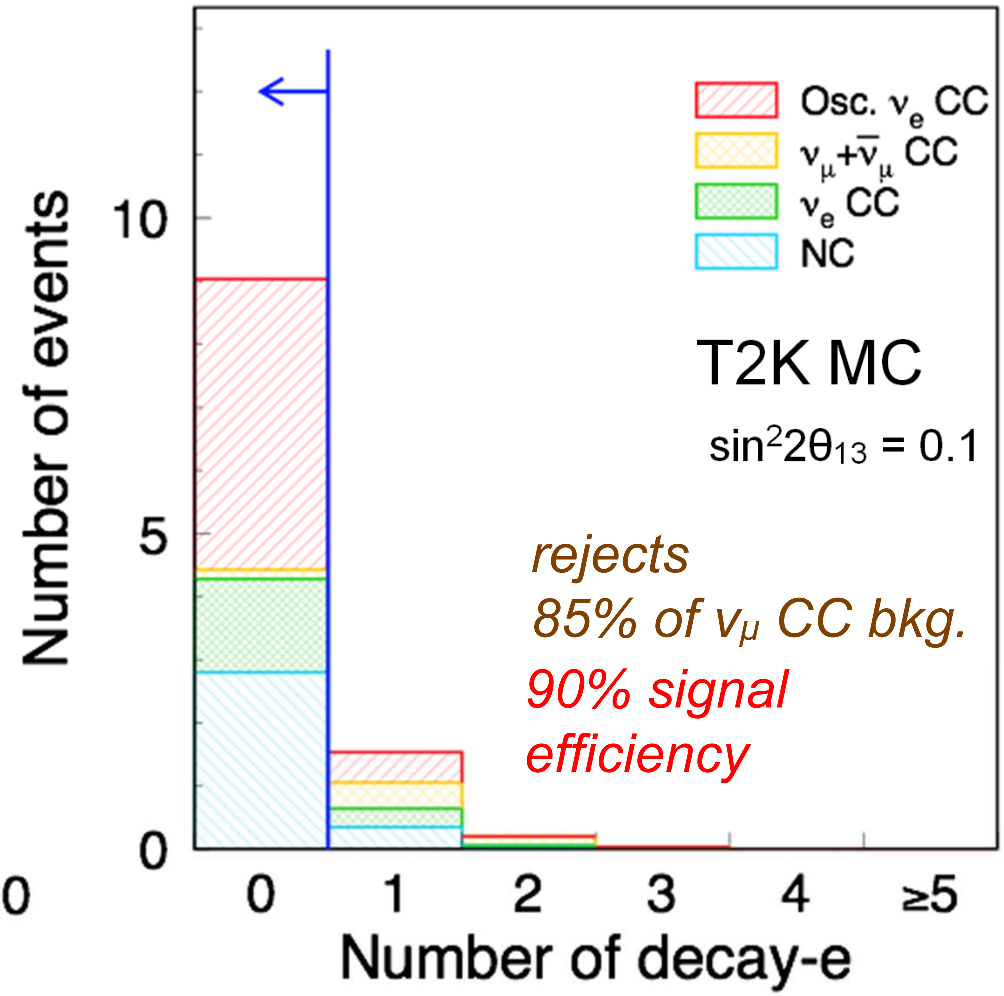


rejects 14% of NC,
30% of ν_μ CC bkg.

98% signal
efficiency

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)



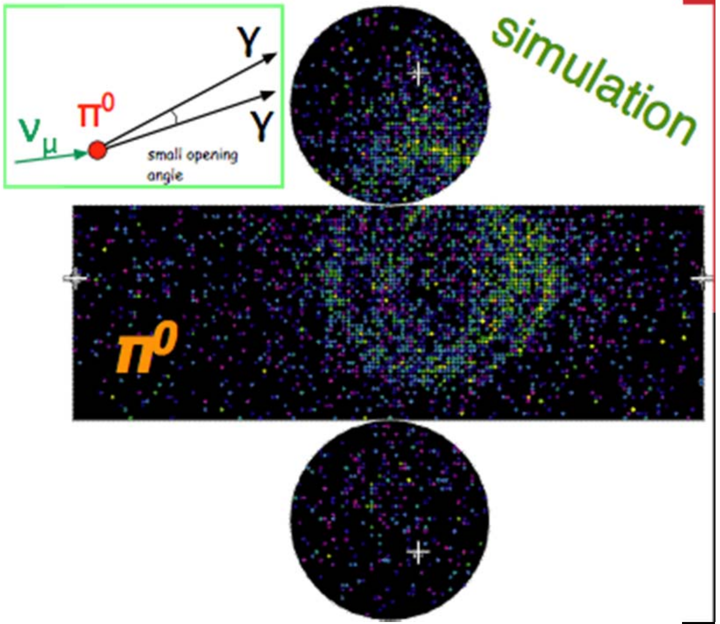
rejects
85% of ν_μ CC bkg.

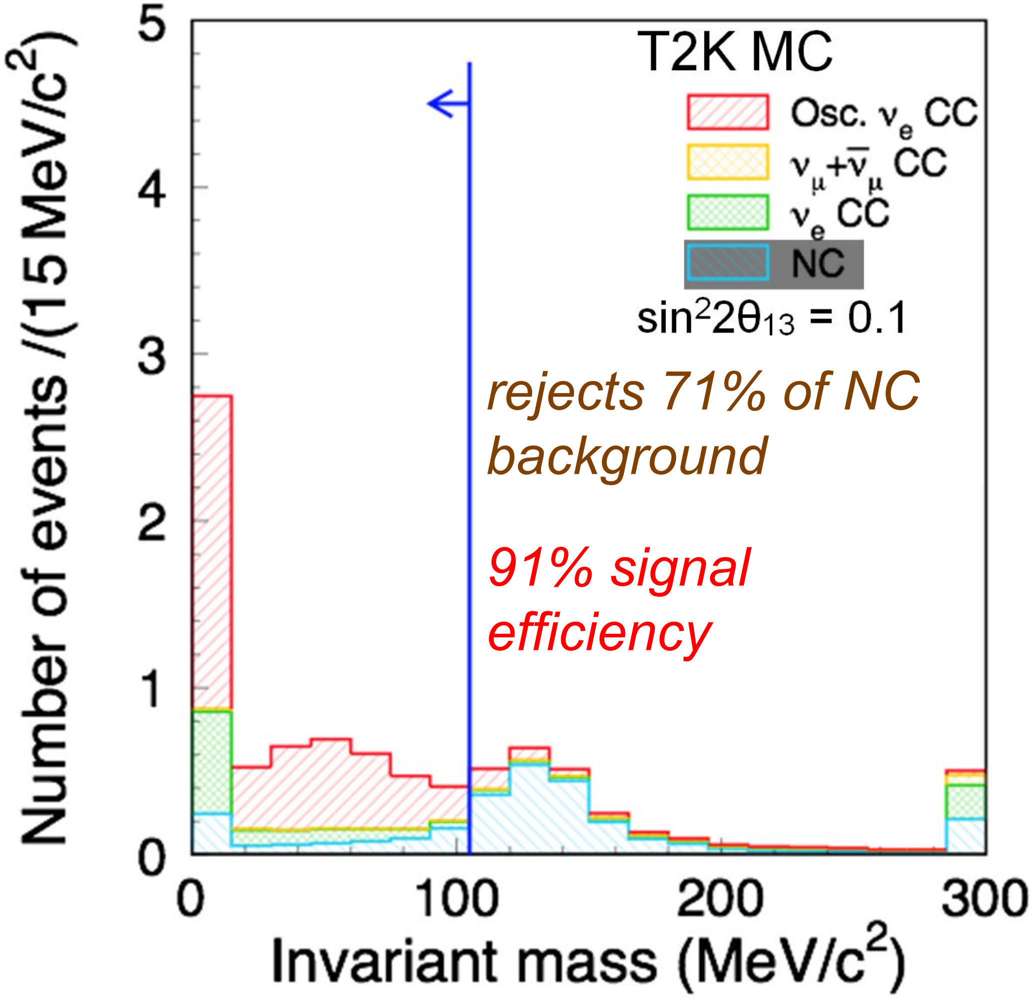
90% signal
efficiency

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

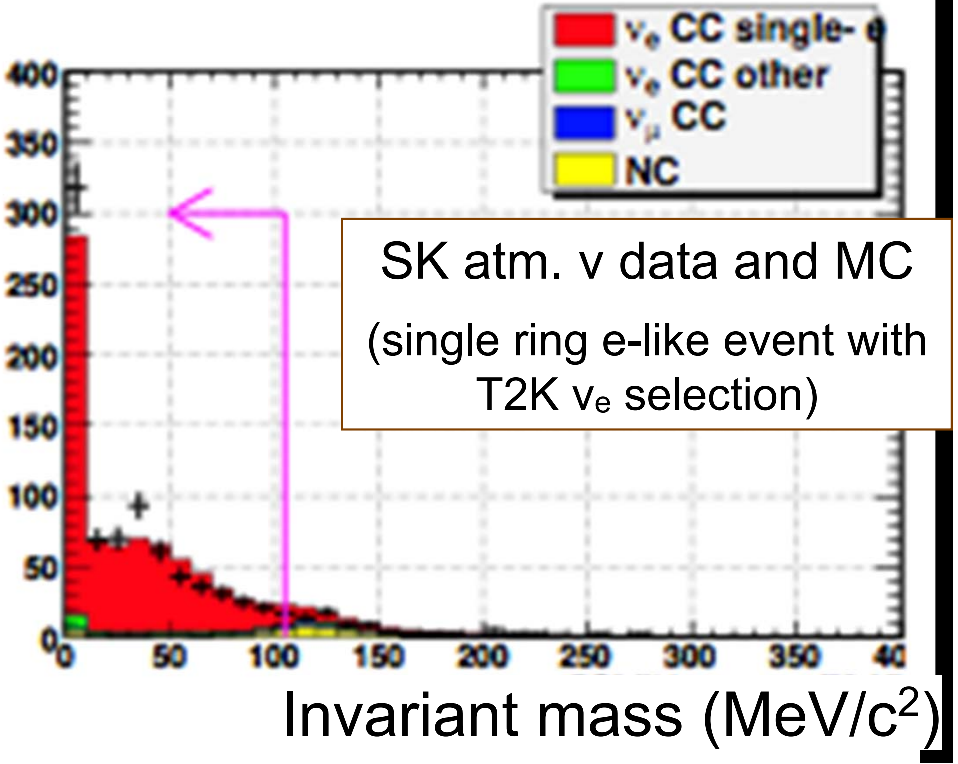




rejects 71% of NC background

91% signal efficiency

demonstrate to reconstruct invariant mass using atmospheric ν data

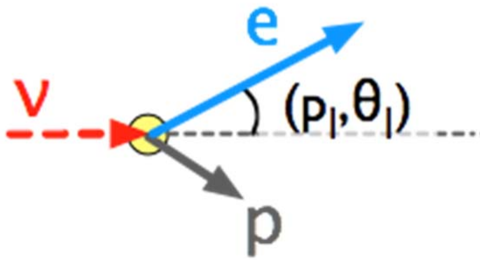


SK atm. ν data and MC

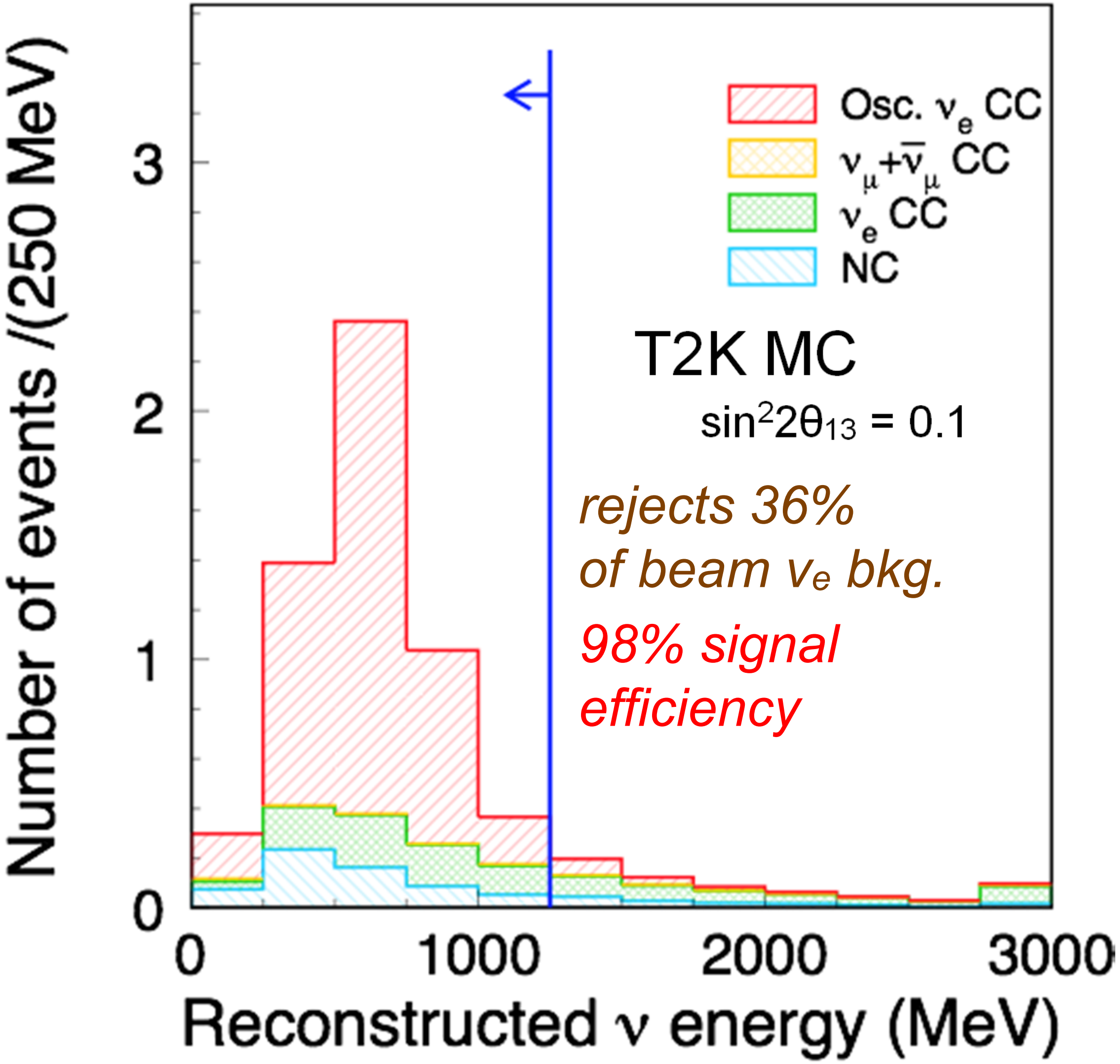
(single ring e-like event with T2K ν_e selection)

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



T2K MC

$\sin^2 2\theta_{13} = 0.1$

rejects 36% of beam ν_e bkg.

98% signal efficiency

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

(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

Normalization by Near detector
both for signal and background

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

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 ← systematic error cancelation

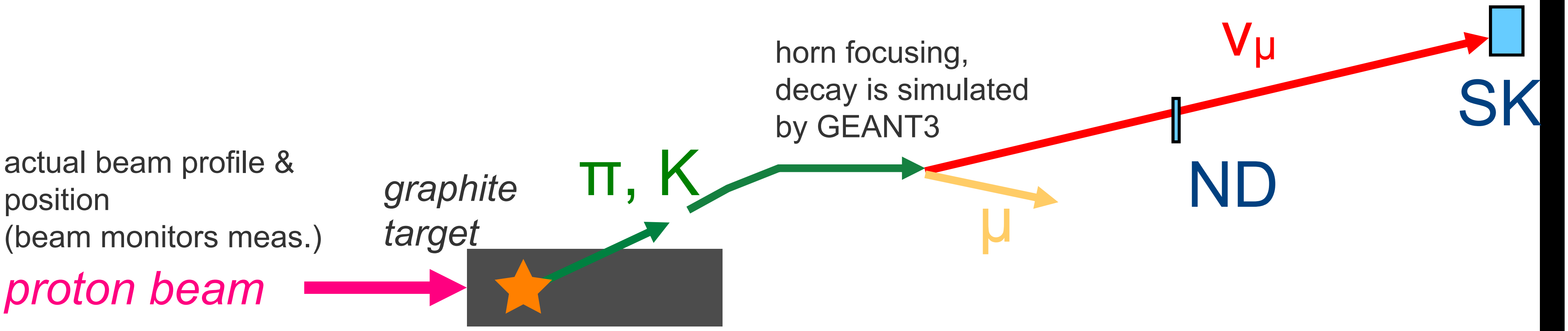
(flux) *x (osc. prob.) x (x-section) x (efficiency) x (det. mass)*

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

NEUTRINO FLUX PREDICTION

T2K Neutrino beam simulation based on Hadron production measurements

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



actual beam profile & position (beam monitors meas.)

proton beam

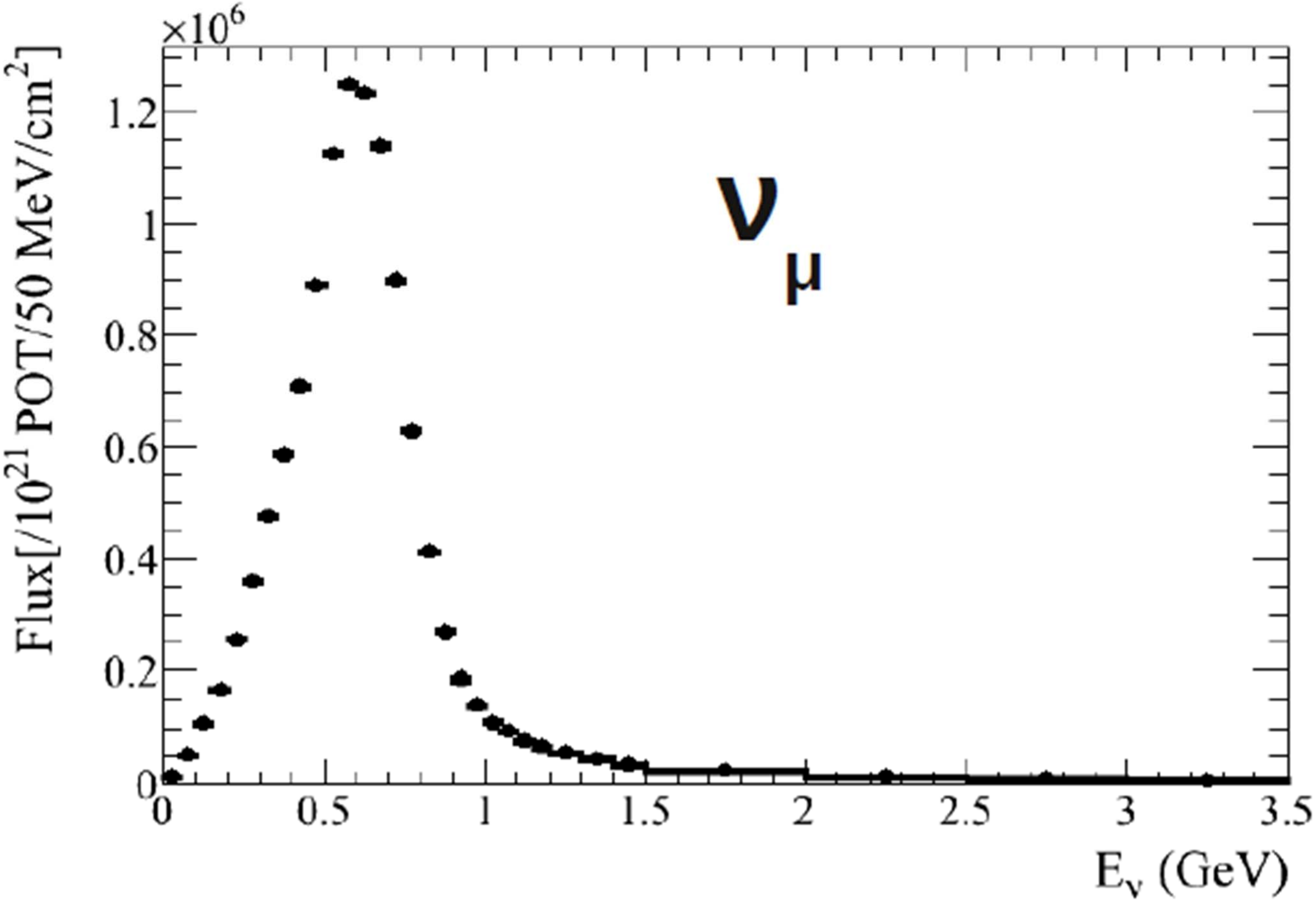
graphite target

horn focusing, decay is simulated by GEANT3

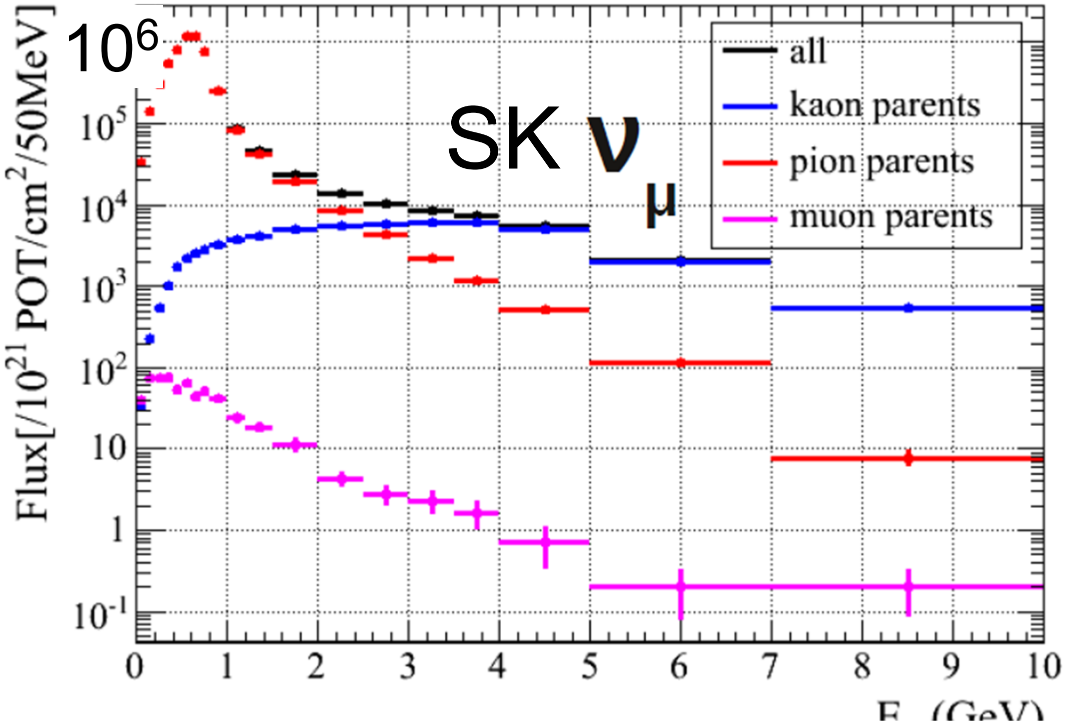
Hadron production in 30GeV proton + C

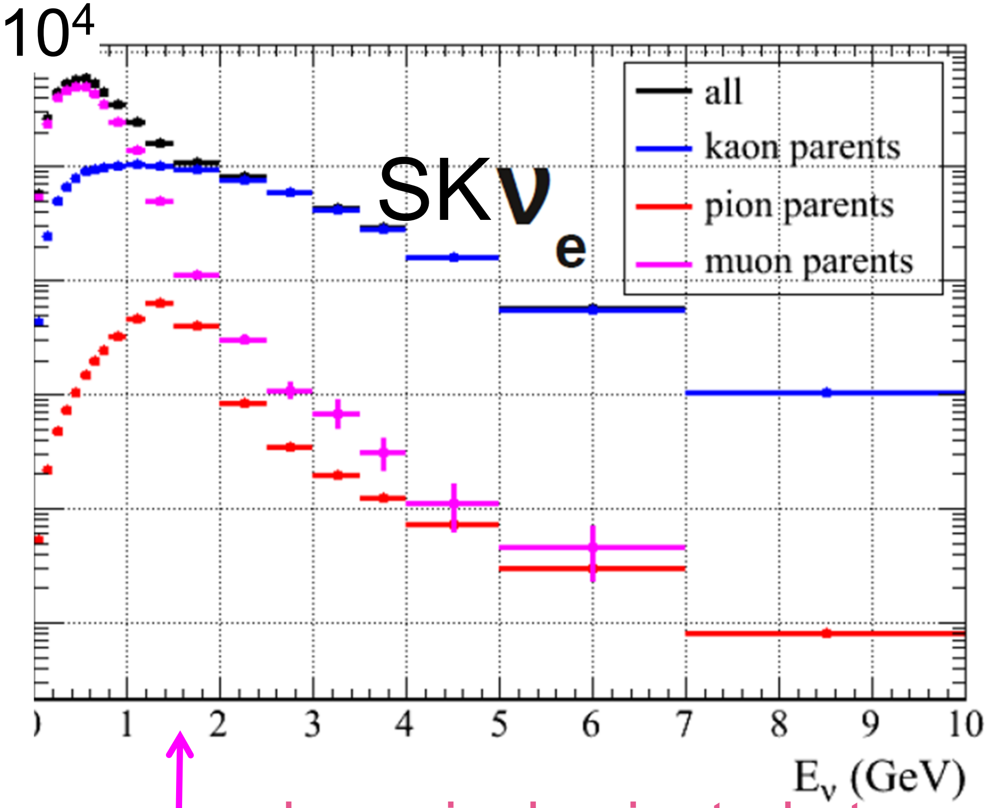
- ***Use CERN NA61/SHINE pion measurement***
  (large acceptance: >95% coverage of ν parent pions)
  5~10% systematic error
- *Kaon, pion outside NA61 acceptance, other interaction in the target were based on FLUKA simulation*
- *Secondary interaction x-sections outside the target were based on experimental data*

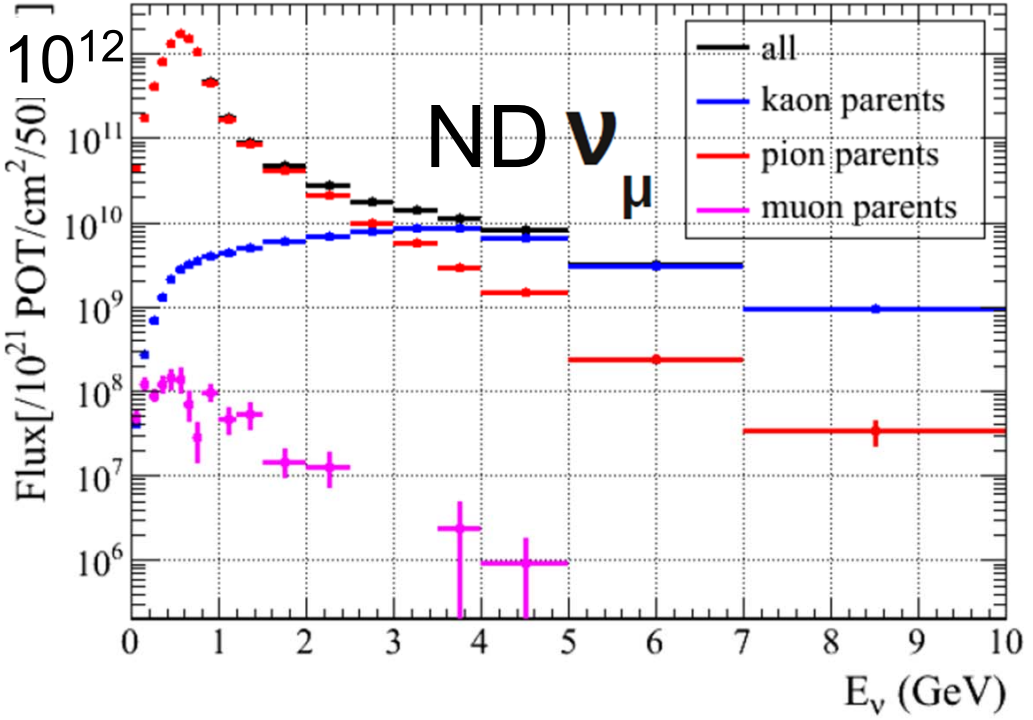
Predicted neutrino flux



Predicted neutrino flux







μ decay is dominated at low energy

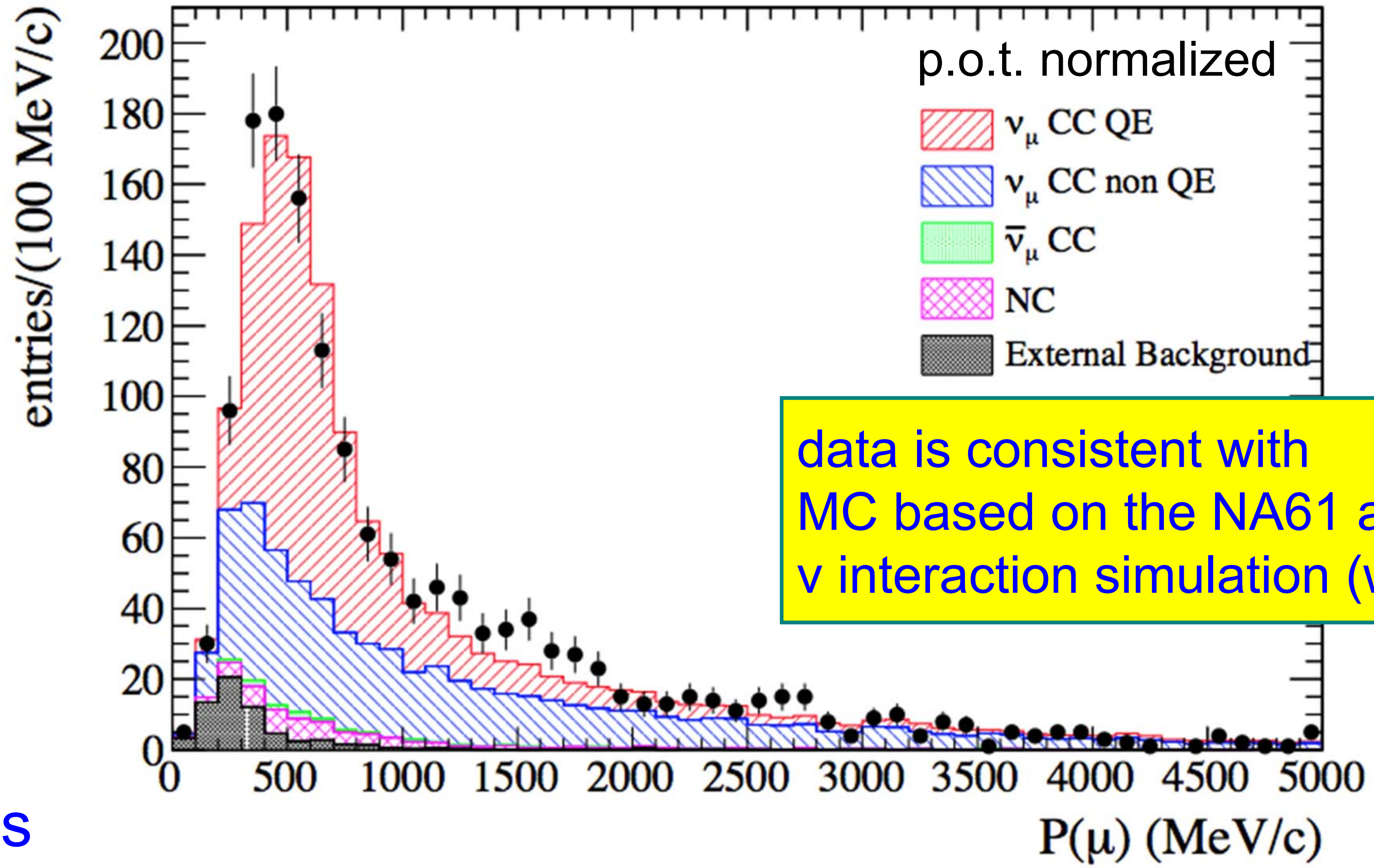
$$\pi^+ \rightarrow \mu^+\nu_\mu$$

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

NA61 pion measurement predicts the beam ν_e from pion origin

ν_μ INTERACTION RATES AT NEAR DETECTOR

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 x 10^{20} p.o.t.

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

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

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

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

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

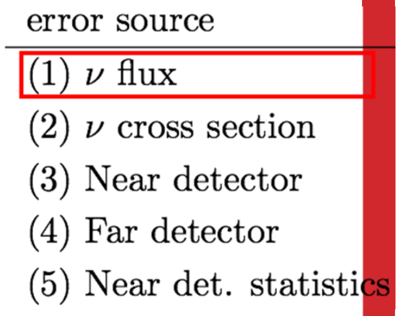
SYSTEMATIC UNCERTAINTY ON N^{EXP}_{SK}

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

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

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

NEUTRINO FLUX UNCERTAINTY



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

Uncertainties in hadron production and interaction are dominant sources

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

Error source

Pion production

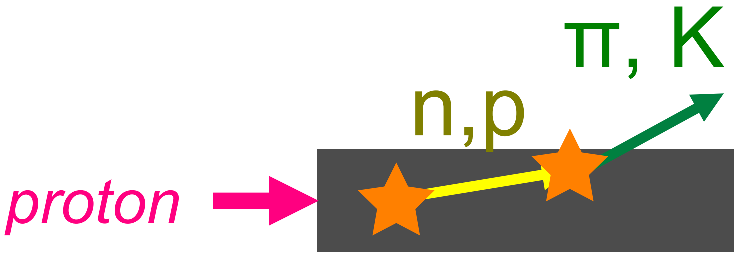
- NA61 systematic uncertainty in each pion’s (p,θ) bin

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



graphite target

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}
Pion production	5.7%	6.2%
Kaon production	10.0%	11.1%
Nucleon production	5.9%	6.6%
Production x-section	7.7%	6.9%
Proton beam position/profile	2.2%	0.0%
Beam direction measurement	2.7%	2.0%
Target alignment	0.3%	0.0%
Horn alignment	0.6%	0.5%
Horn abs. current	0.5%	0.7%
Total	15.4%	16.1%

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

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

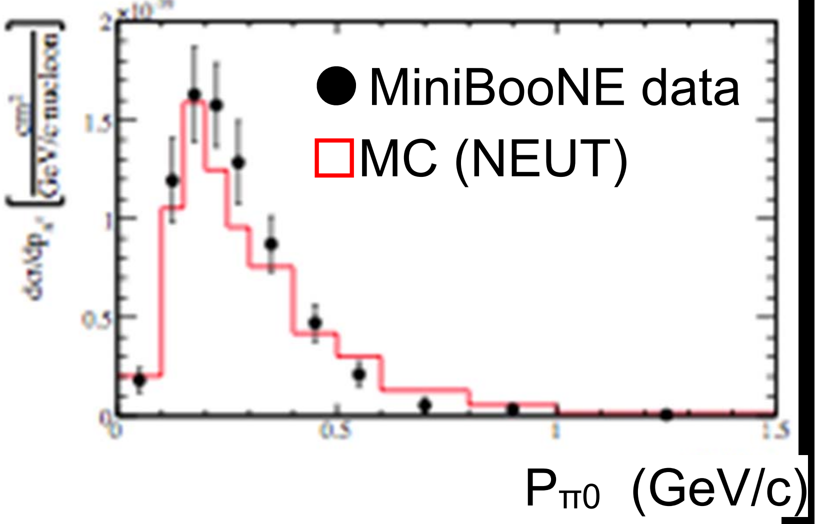
Main ν interaction in each event category

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

Cross section uncertainty
relative to the CCQE total x-section

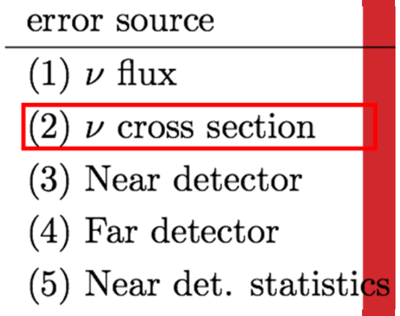
Process	
CCQE	energy dependent (∼ ±7% at 500 MeV)
CC 1π	30% ($E_\nu < 2$ GeV) – 20% ($E_\nu > 2$ GeV)
CC coherent π^0	100% (upper limit from [30])
CC other	30% ($E_\nu < 2$ GeV) – 25% ($E_\nu > 2$ GeV)
NC 1π^0	30% ($E_\nu < 1$ GeV) – 20% ($E_\nu > 1$ GeV)
NC coherent π	30%
NC other π	30%
FSI	energy dependent (∼ ±10% at 500 MeV)

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

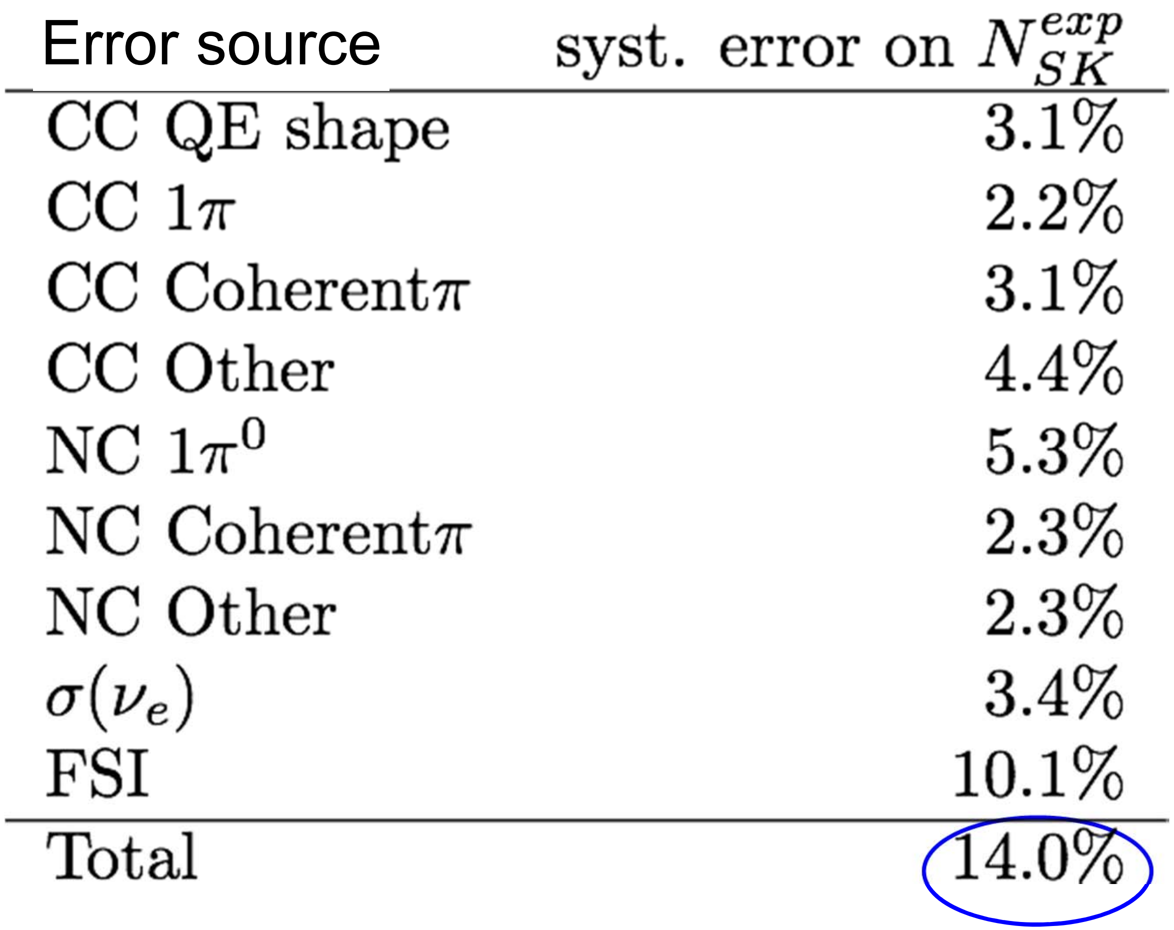


Uncertainty of $\sigma(\nu_e)/\sigma(\nu_\mu)$ = ±6%

ν INT. CROSS SECTION UNCERTAINTY ON N^{EXP}_{SK} FOR $SIN^2 2\theta_{13}$=0



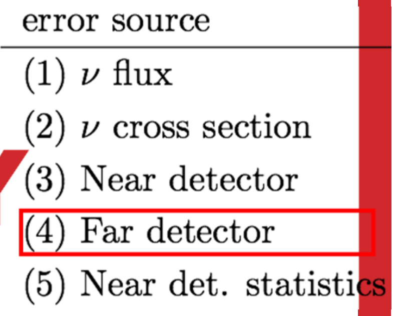
error source
(1) ν flux
(2) ν cross section
(3) Near detector
(4) Far detector
(5) Near det. statistics



Error source	syst. error on N_{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)



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

FAR DETECTOR UNCERTAINTY

Uncertainty due to the SK detector uncertainty

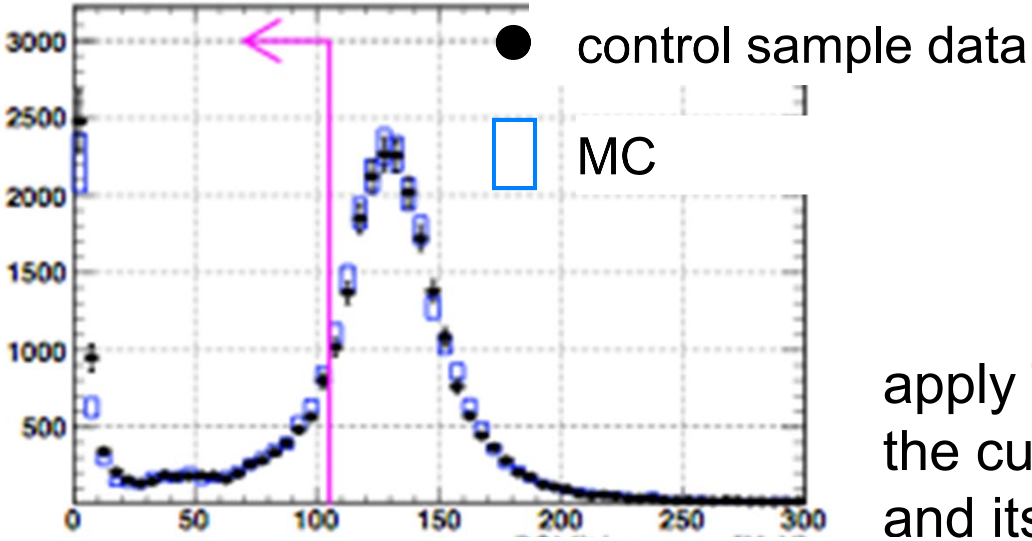
Evaluation using control sample

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

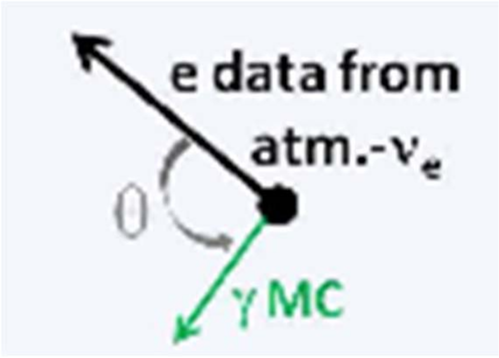
One of big error sources:

detection efficiency of NC 1π^0 background

control sample with one data electron + one simulated γ



invariant mass M$_{inv}$ [MeV]



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

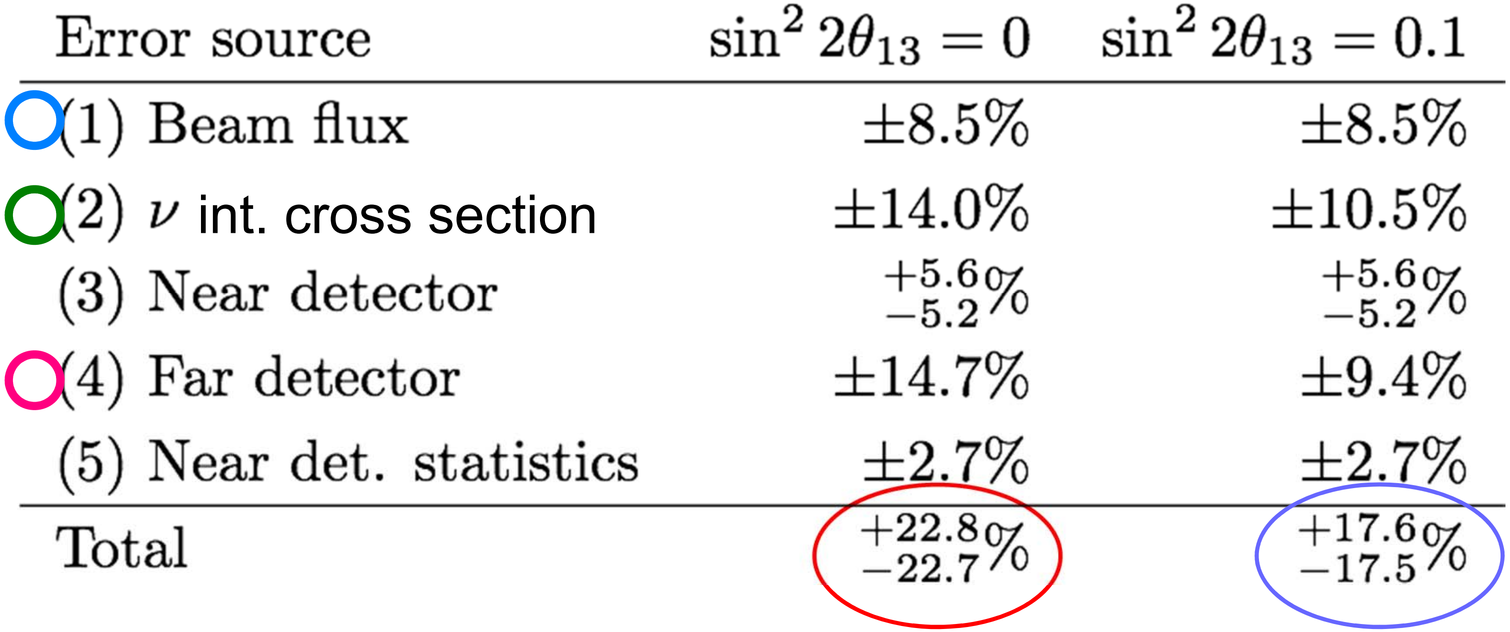
Error source	$\frac{\delta N^{MC}_{SK\ \nu_e\ sig.}}{N^{MC}_{SK\ \nu_e\ sig.}}$	$\frac{\delta N^{MC}_{SK\ bkg.\ tot.}}{N^{MC}_{SK\ bkg.\ tot.}}$
π^0 rejection	-	3.6%
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass cut	5.1%	8.7%
Fiducial volume cut etc.	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay 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 $\sin^2 2\theta_{13}=0$ 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 $\sin^2 2\theta_{13}=0$

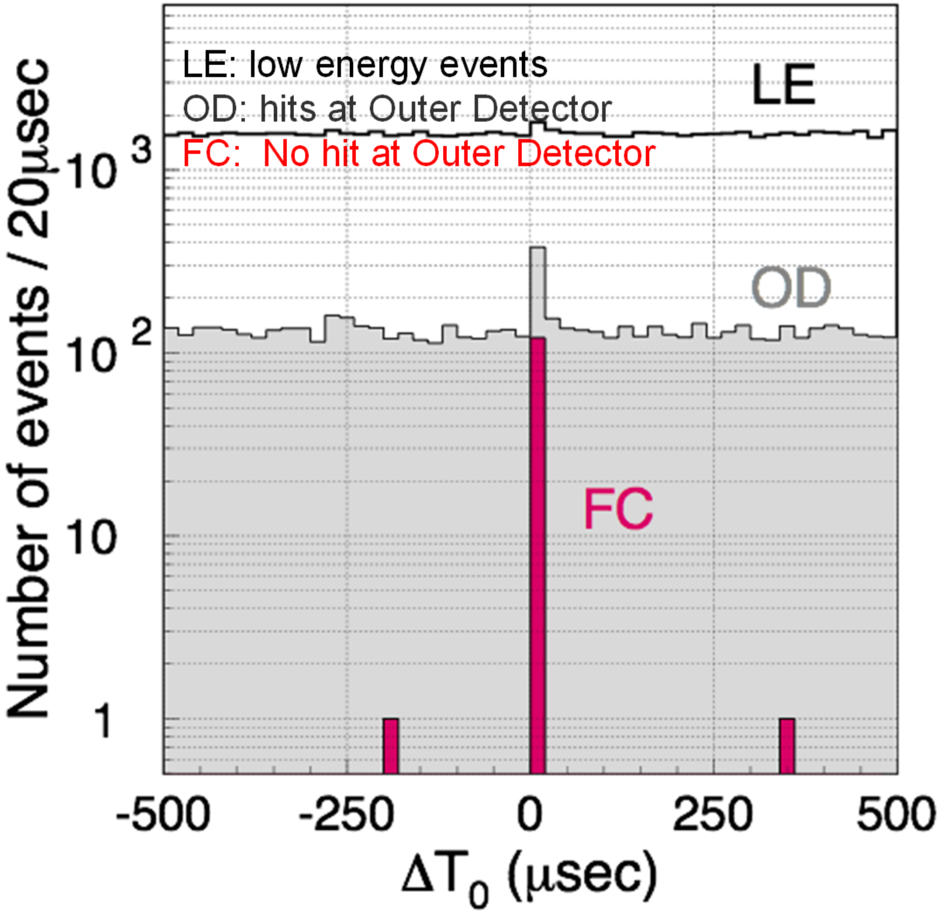
(w/ 1.43×10^{20} p.o.t.)

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

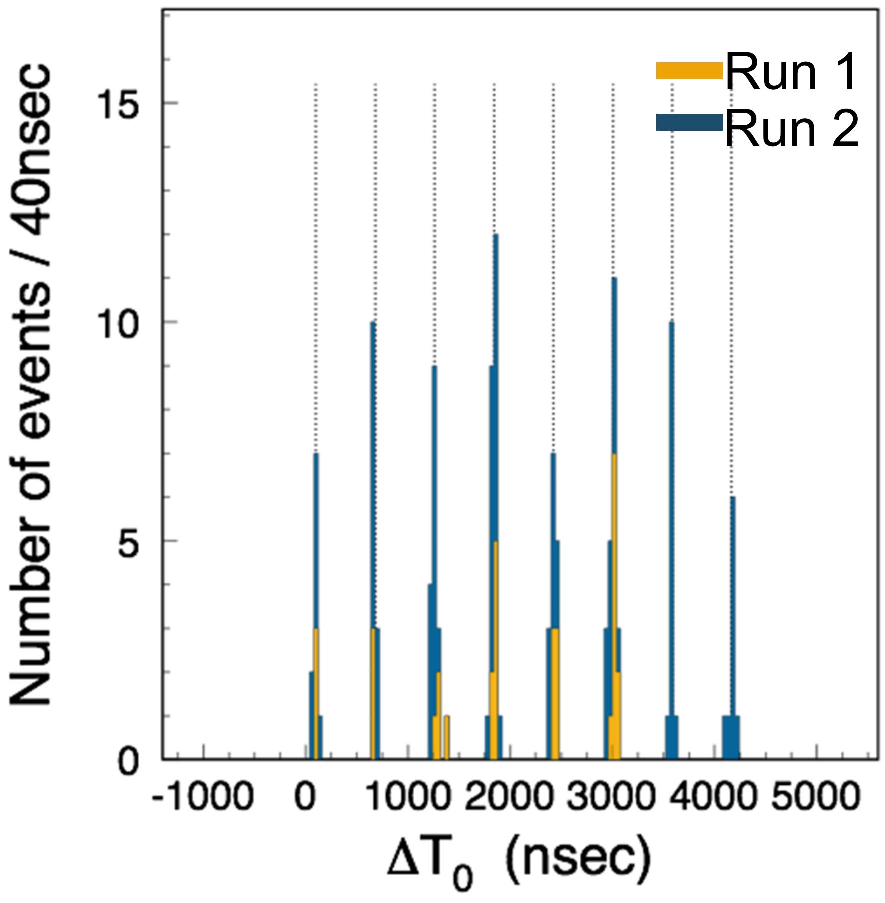
SK EVENTS IN BEAM TIMING

Events in the T2K beam timing synchronized by GPS

relative event timing to the spill timing

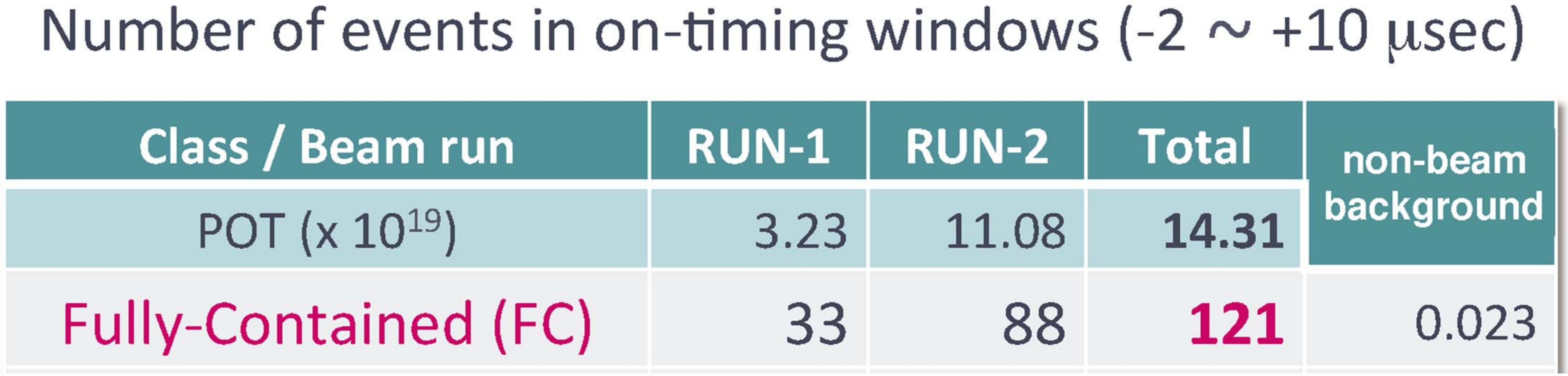


Clear beam structure !



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

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

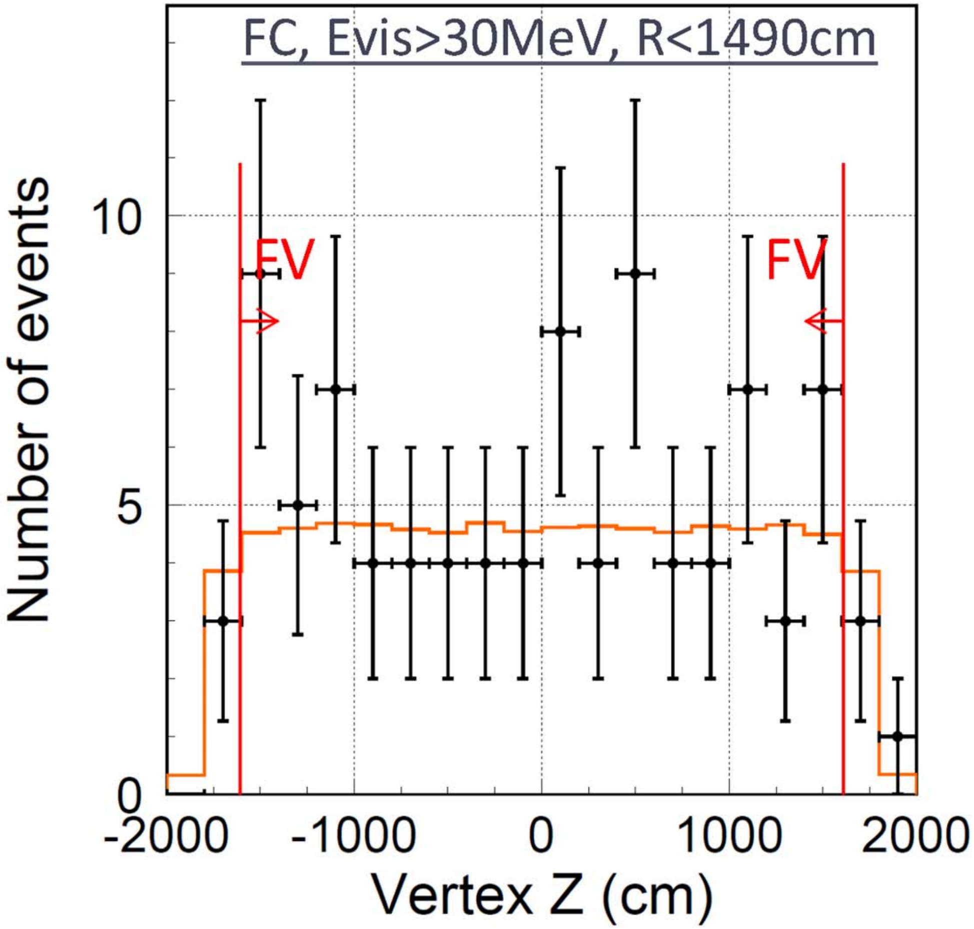
The accidental contamination from atmospheric ν background is estimated using the sideband events to be 0.023

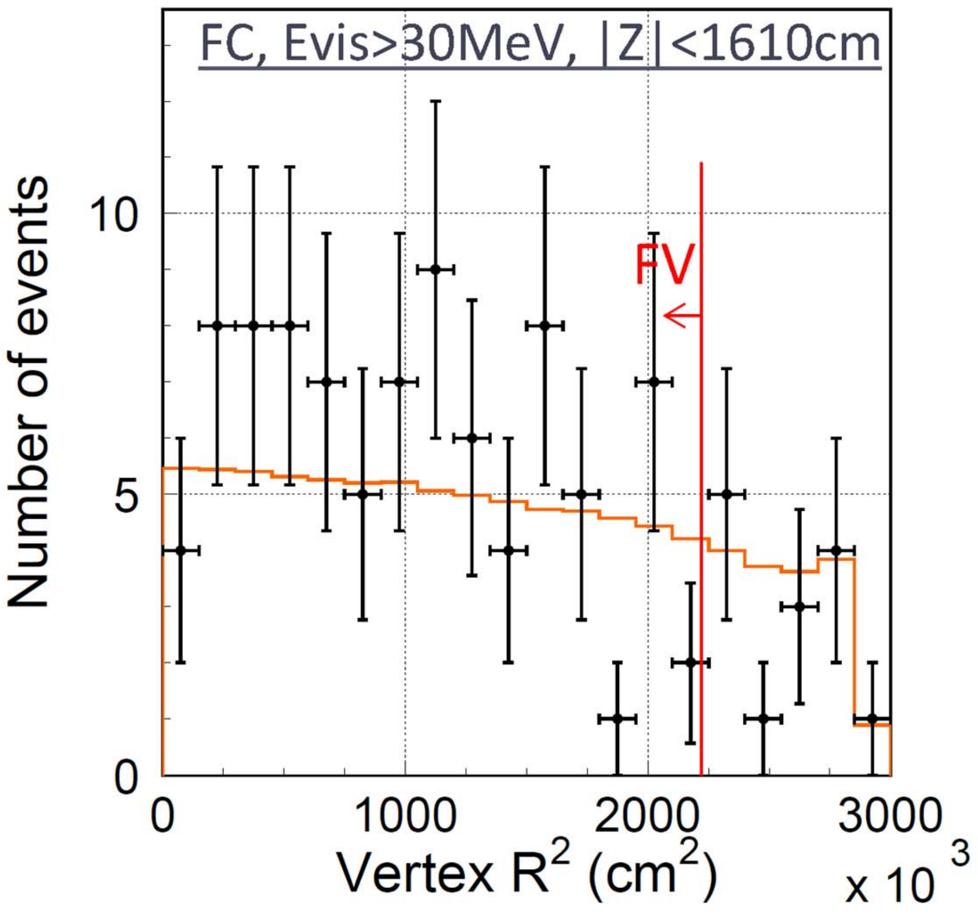
APPLY ν_e EVENT SELECTION

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

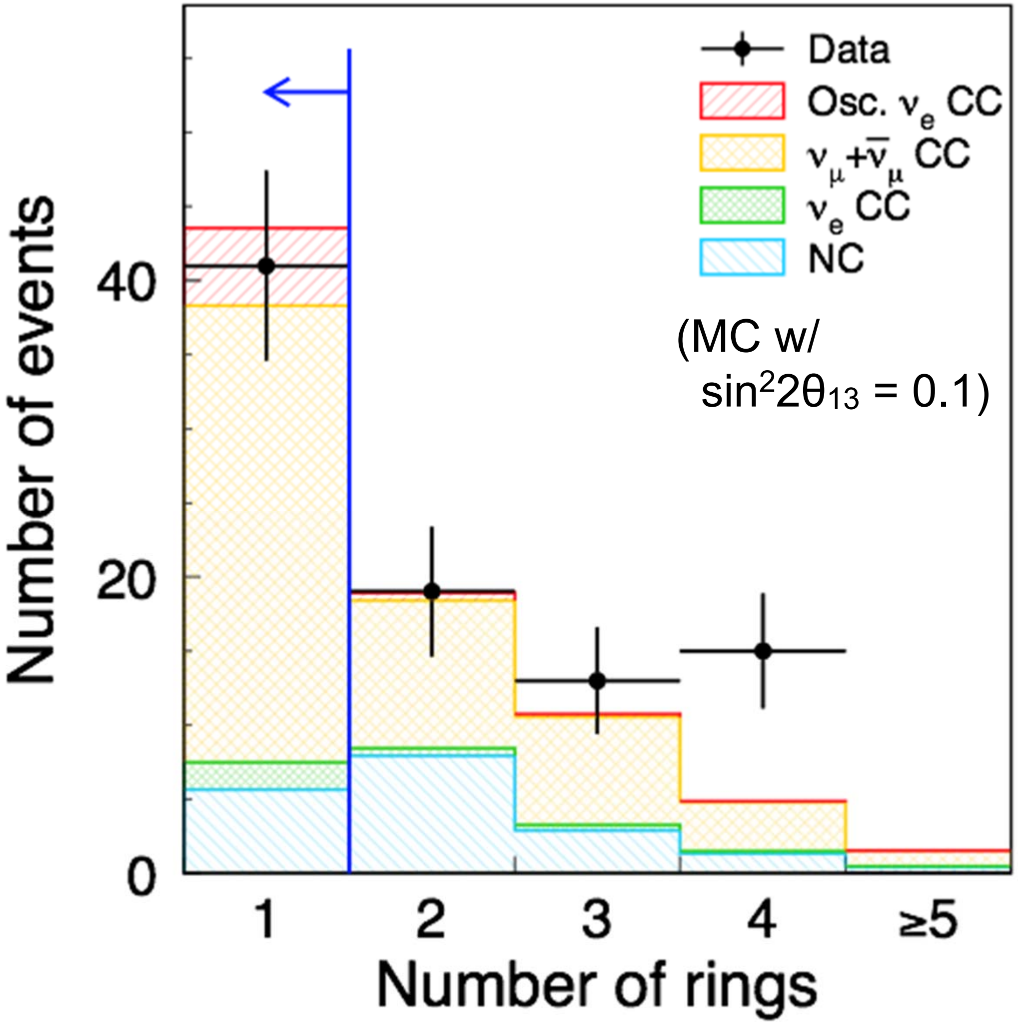
Fiducial volume cut

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

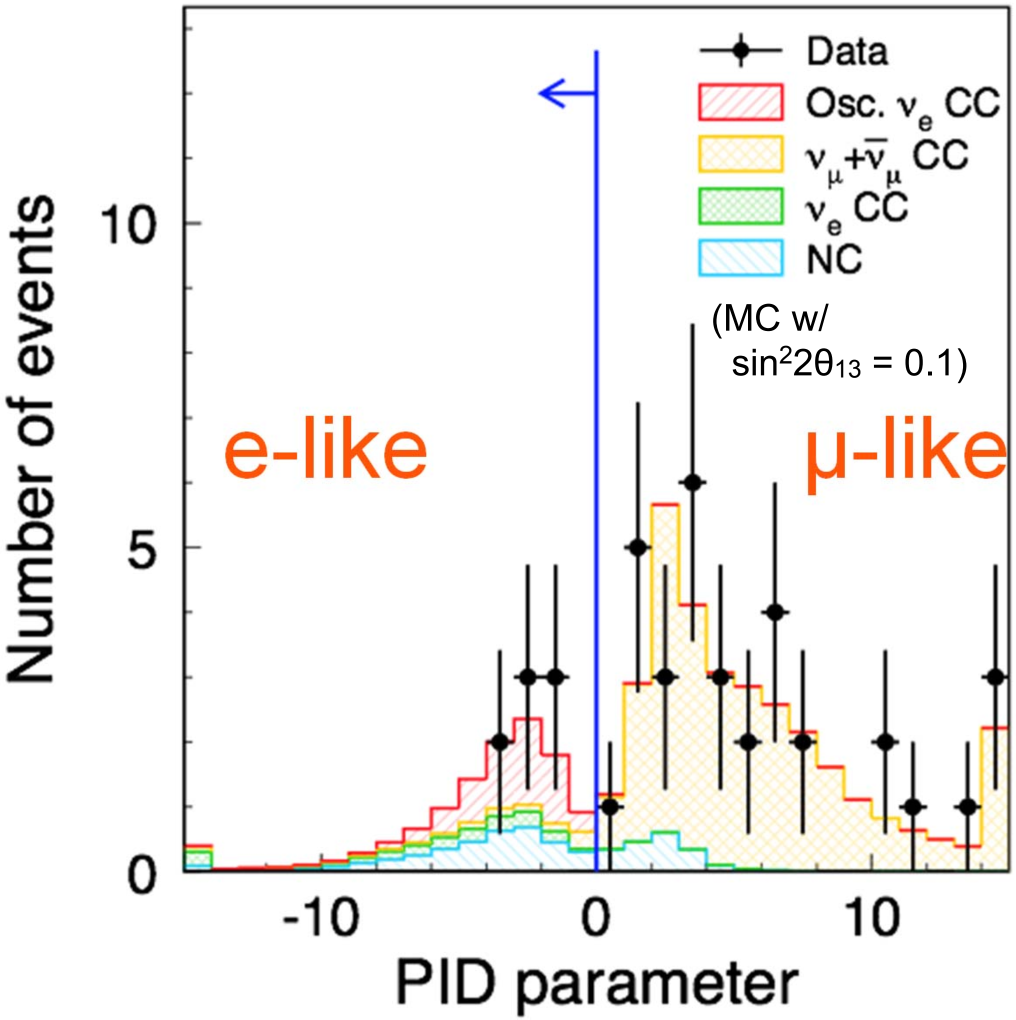




Single electron cut (# of ring is one & e-like)



(MC w/ $\sin^2 2\theta_{13} = 0.1$)

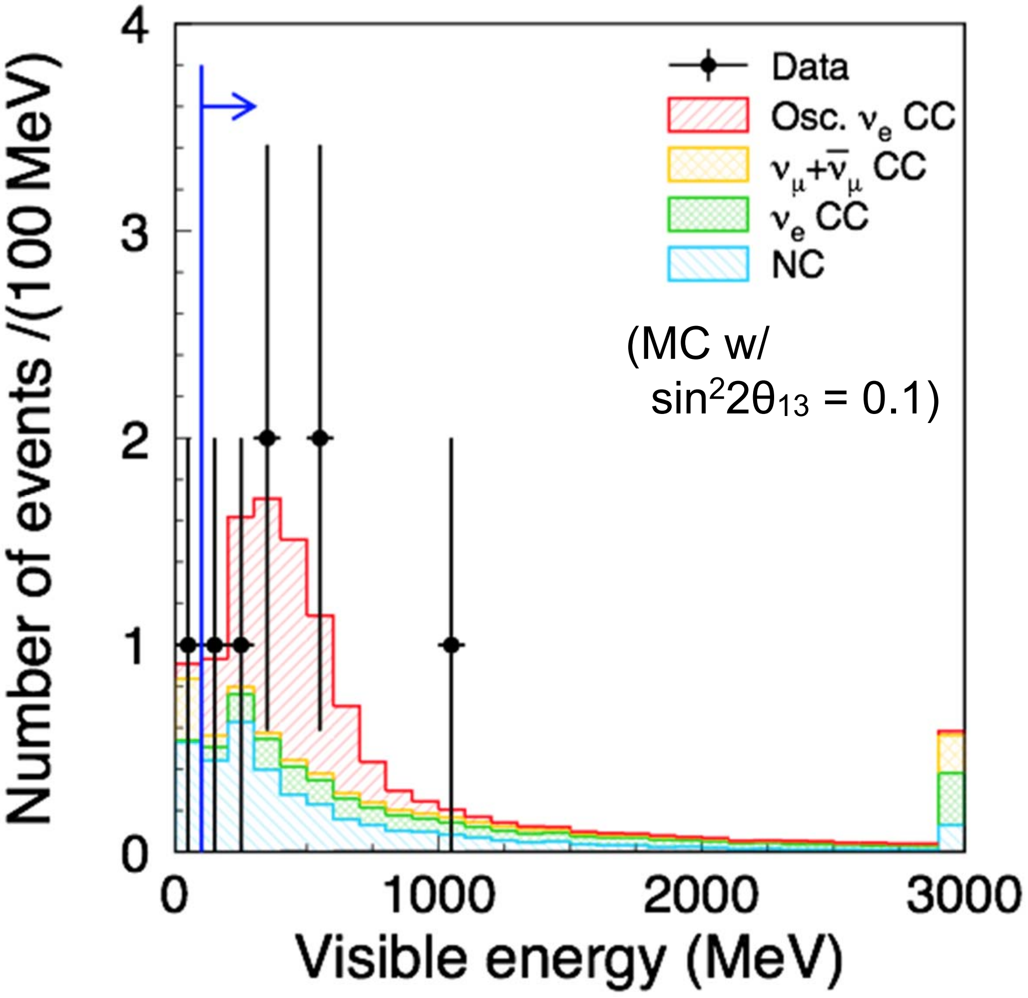


(MC w/ $\sin^2 2\theta_{13} = 0.1$)

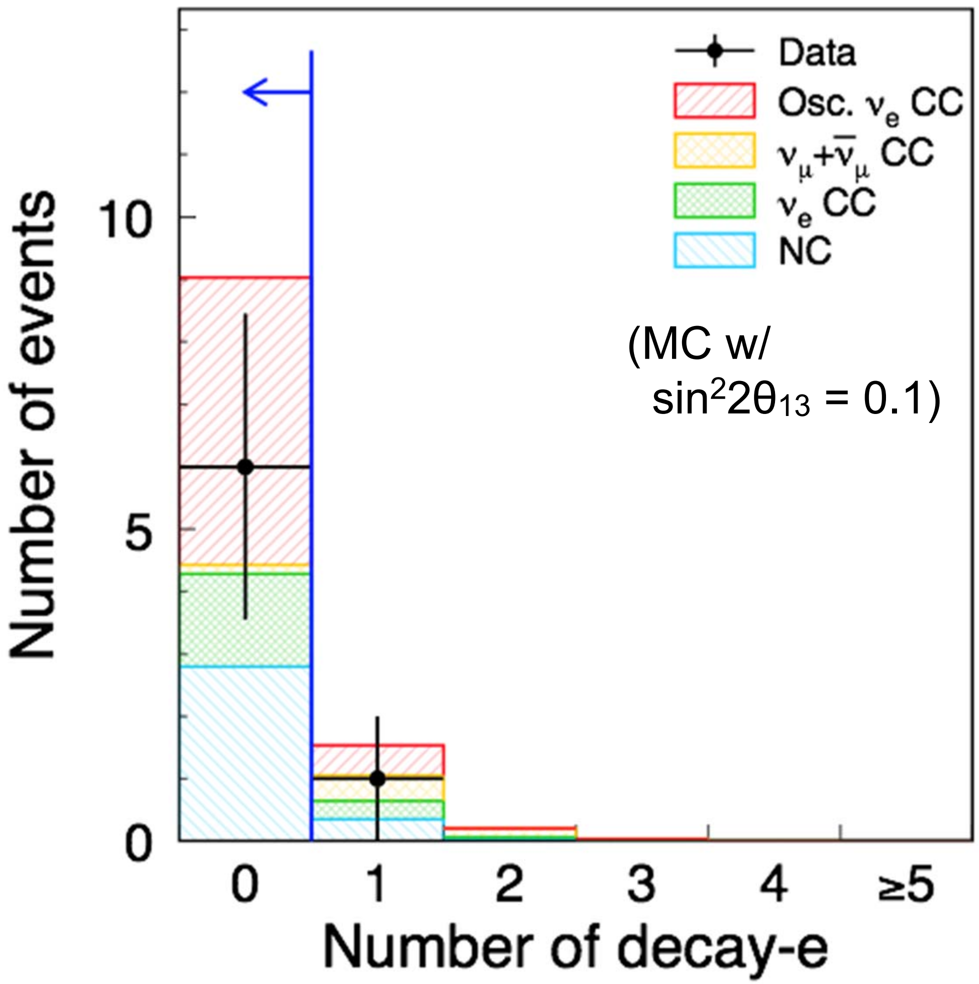
e-like

μ-like

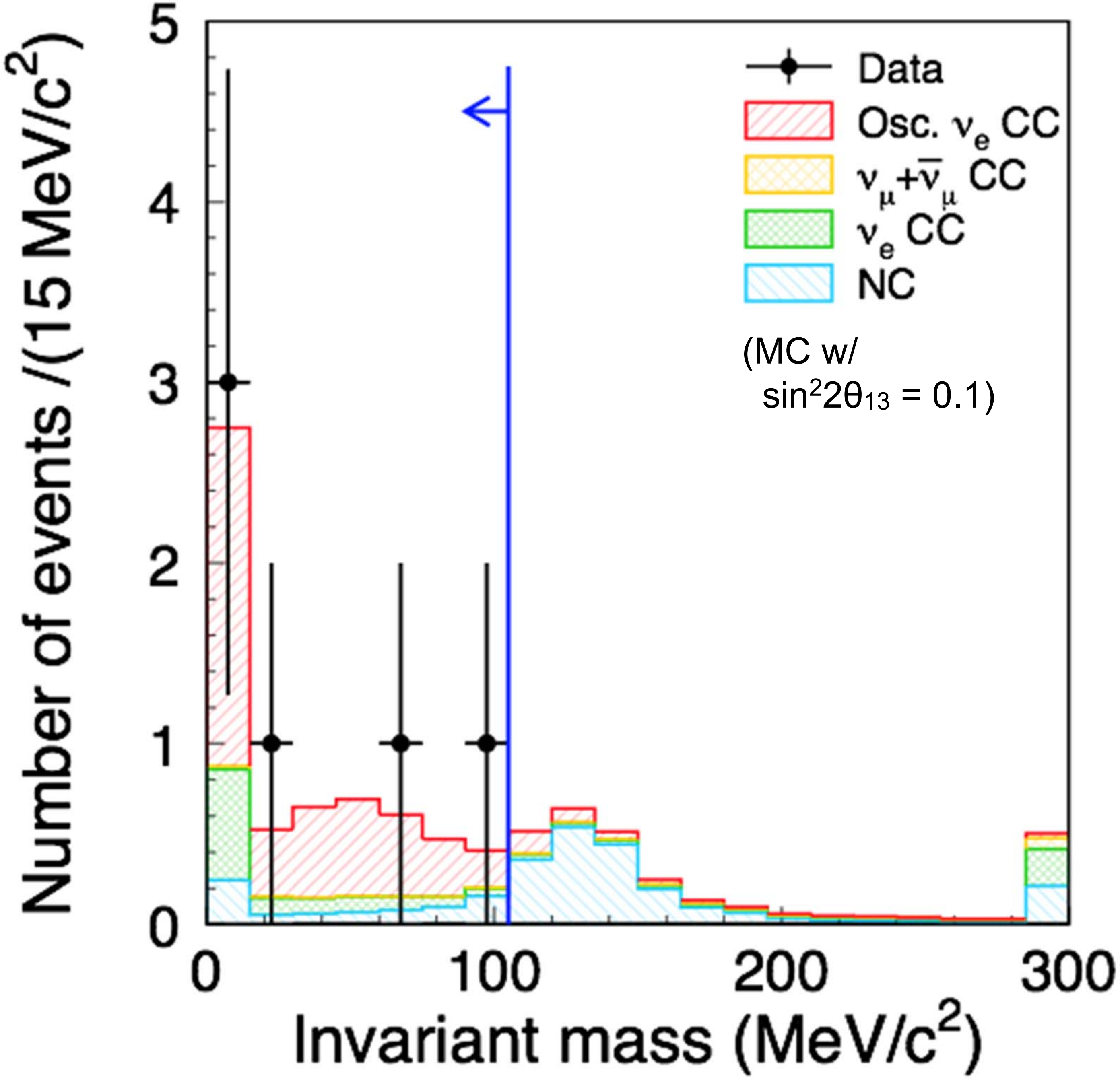
Visible energy > 100 MeV


(MC w/ $\sin^2 2\theta_{13} = 0.1$)

No decay electron


(MC w/ $\sin^2 2\theta_{13} = 0.1$)

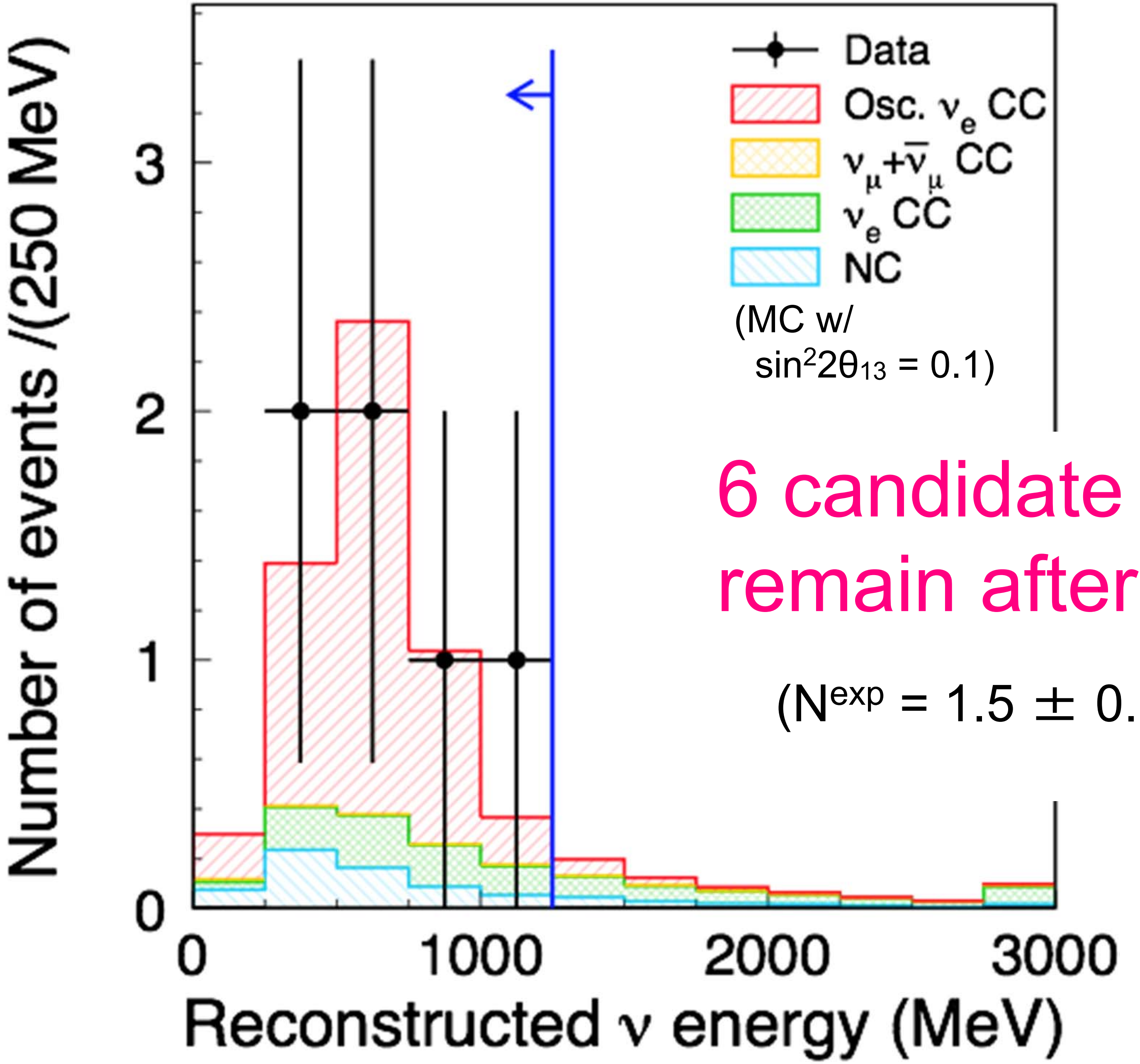
Invariant mass cut ($M_{inv} < 105$ MeV/c^2)



(MC w/
$\sin^2 2\theta_{13} = 0.1$)

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

Final cut

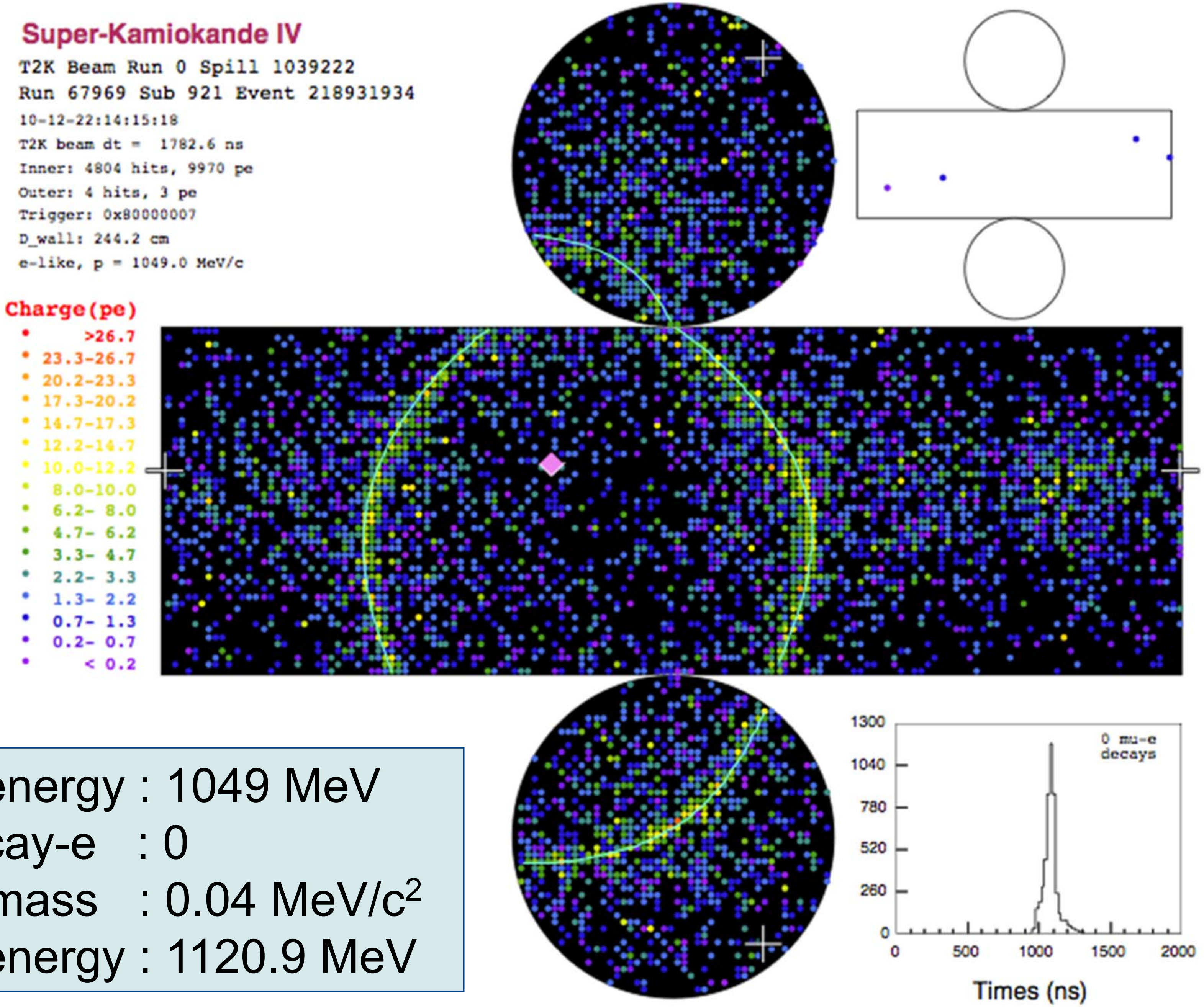


(MC w/ $\sin^2 2\theta_{13} = 0.1$)

6 candidate events remain after all cuts !!

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

A ν_e CANDIDATE EVENT



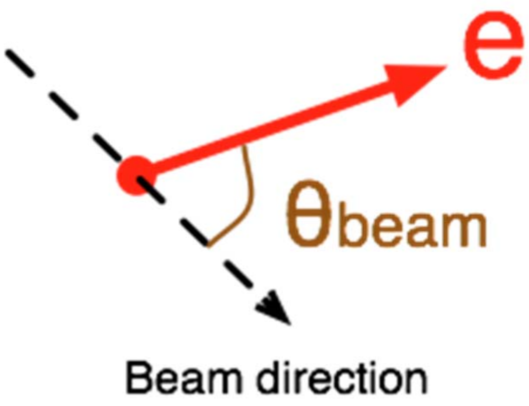
Super-Kamiokande IV

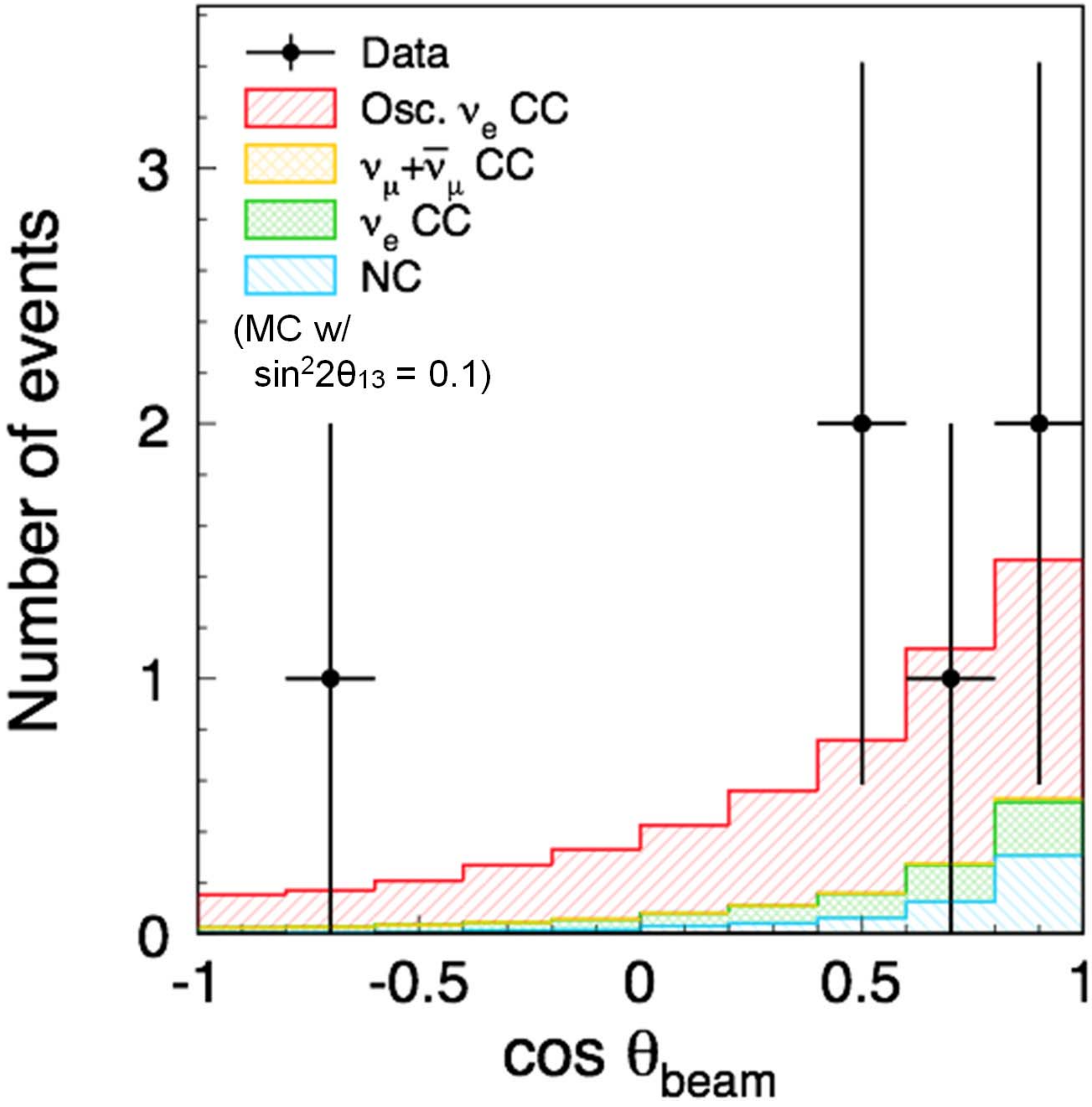
```
T2K Beam Run 0 Spill 1039222
Run 67969 Sub 921 Event 218931934
10-12-22:14:15:18
T2K beam dt =  1782.6 ns
Inner: 4804 hits, 9970 pe
Outer: 4 hits, 3 pe
Trigger: 0x80000007
D_wall: 244.2 cm
e-like, p = 1049.0 MeV/c
```

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

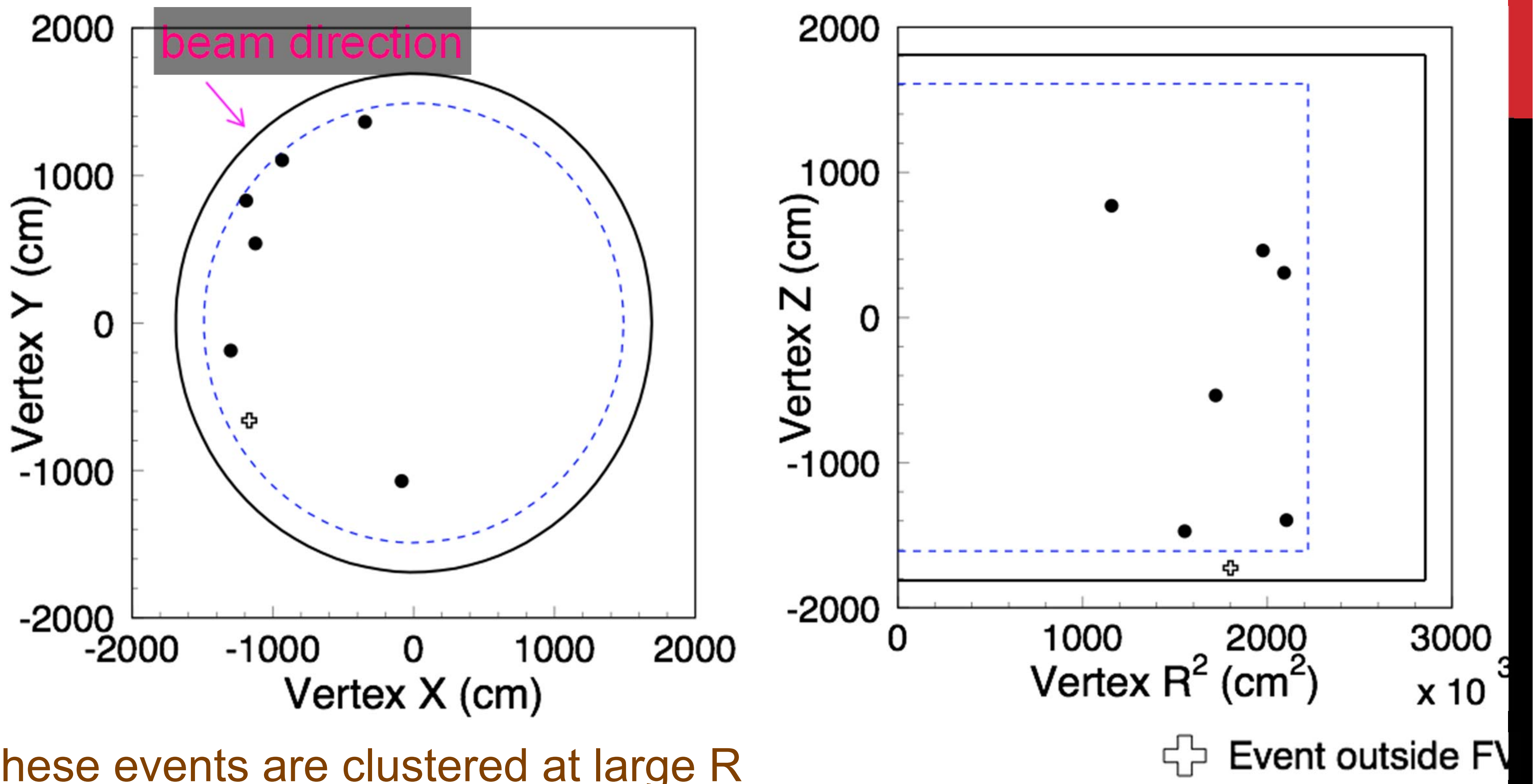
FURTHER CHECK

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 contaminatio

* 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**

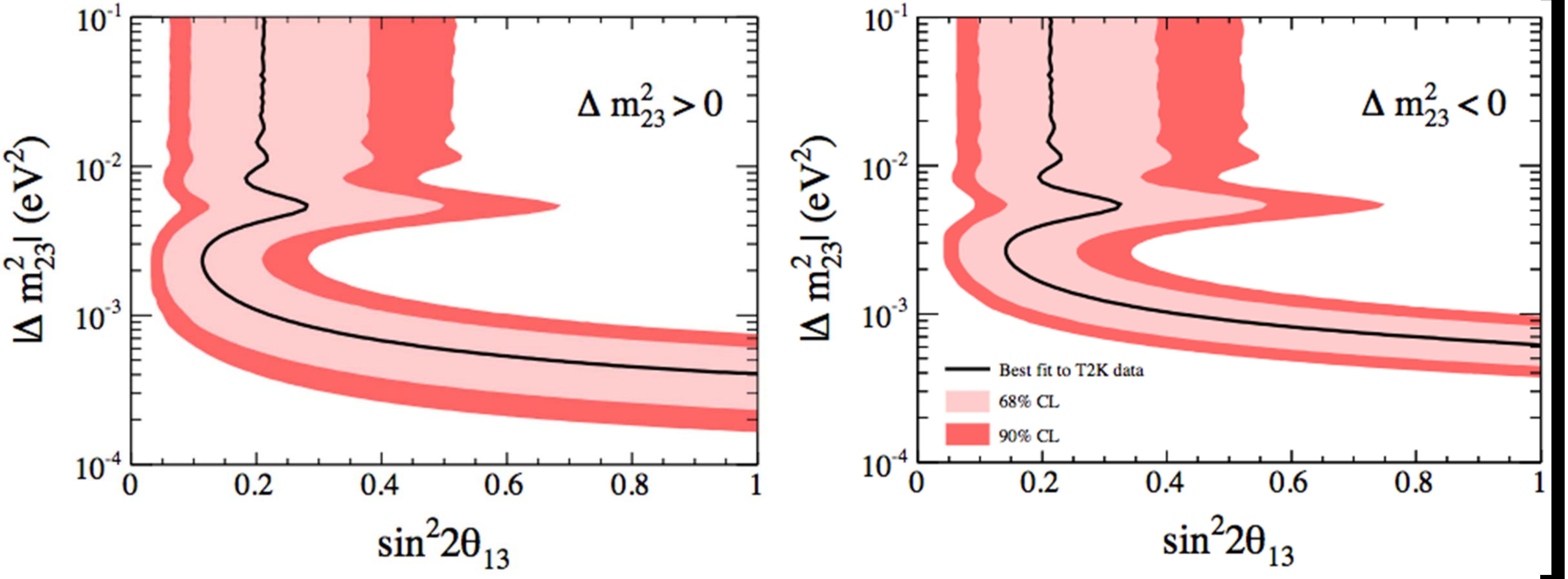
The expected number of events is **1.5 ± 0.3**

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}2θ$_{13}$ AS A FUNCTION OF ΔM$^2_{23}$

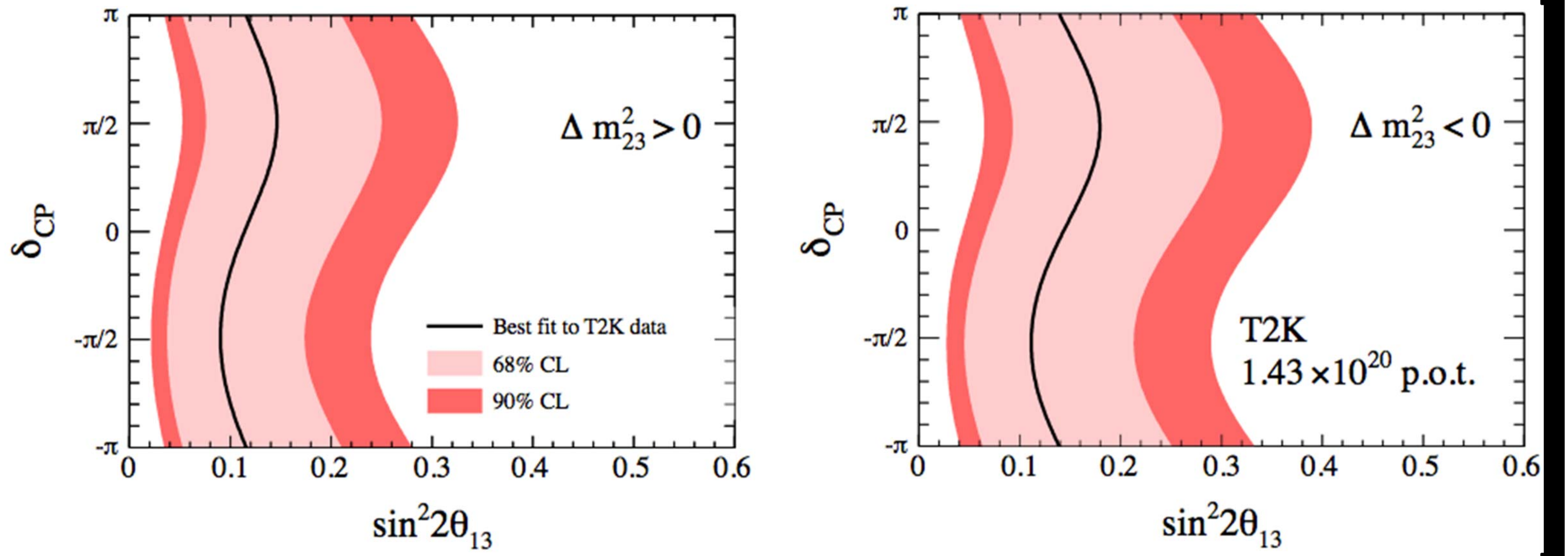
(assuming $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)



Feldman-Cousins method was used

ALLOWED REGION OF $\sin^2 2\theta_{13}$ AS A FUNCTION OF δ_{CP}

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



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

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

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

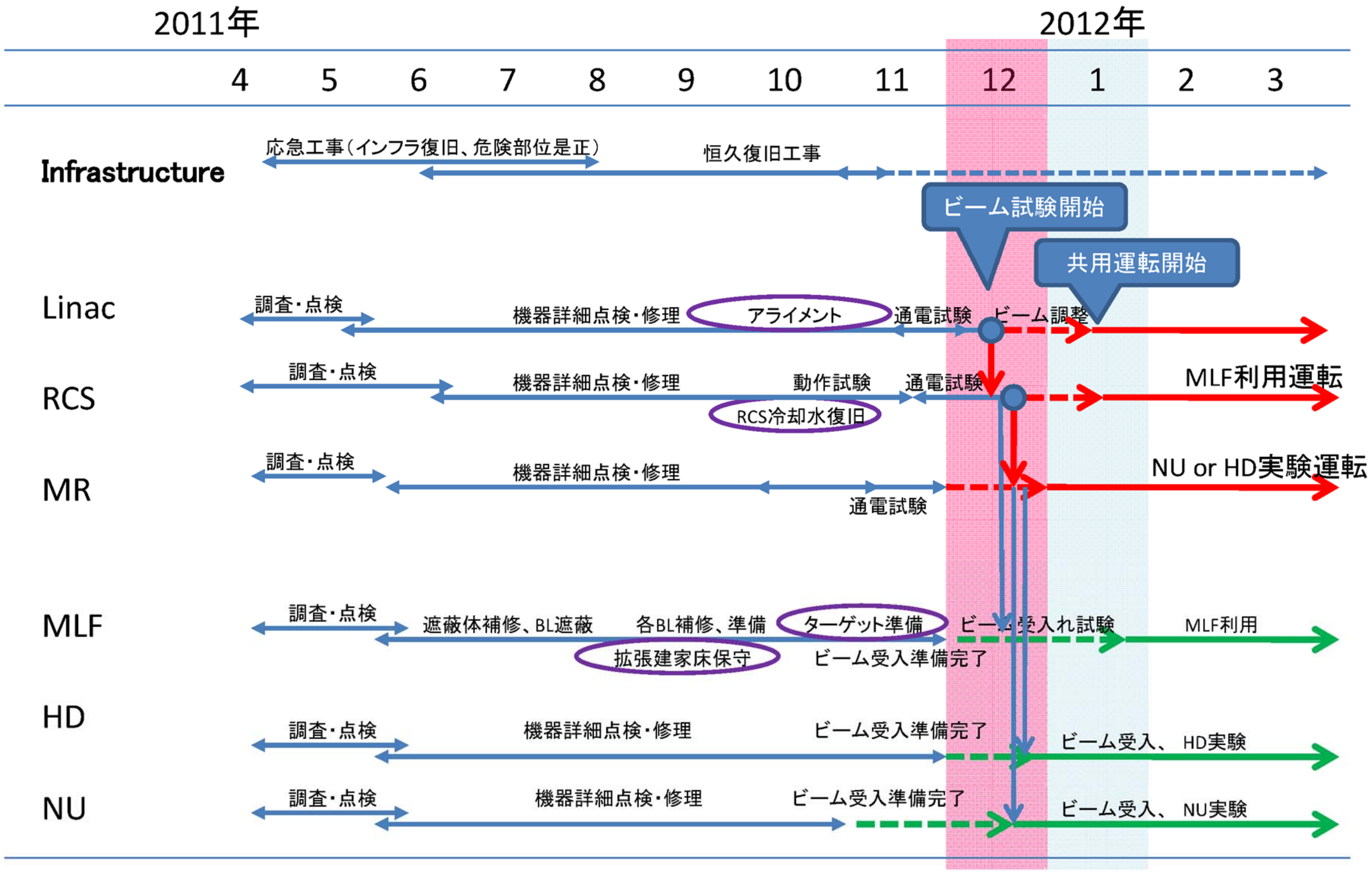
$0.04 < \sin^2 2\theta_{13} < 0.34$

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

T2K NEXT STEPS

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

J-PARC復旧スケジュール （@2011.5.20）



CONCLUSION

We reported new results on $\nu_\mu \rightarrow \nu_e$ oscillation analysis based on 1.43 x 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 x 10^{20} p.o.t. data will be reported this summer