T2K Experiment

- Neutrino beam commissioning -

Ken Sakashita(KEK) for T2K collaboration
Feb/22/2010, 「フレーバーの物理の新展開」研究会2010

1. Introduction of T2K experiment
    - Motivation, Features and Sensitivity
2. Beam Commissioning [Apr ’09 ~]
    - **T2K ν beam-line operation started**
3. Status of hadron production measurement
4. Future prospects
5. Summary

Motivation

$U_{e3} = s_{13}e^{-i\delta}$

NEUTRINOS

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & \boxed{?} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Next step in ν Oscillation Experiment

- **discover a finite θ_{13}** *T2K: ν_e appearance*

→ **important role for future neutrino experiments**

  - **CPV in lepton sector**

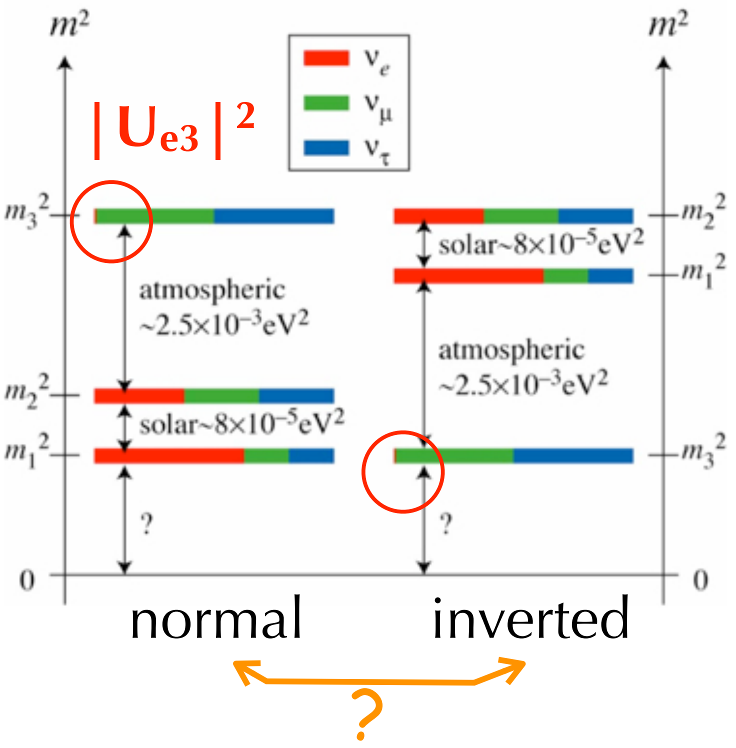
    → hint on Baryon# asymmetry of Universe

  - mass hierarchy

- **precise measurement**

Is θ_{23} maximal ?

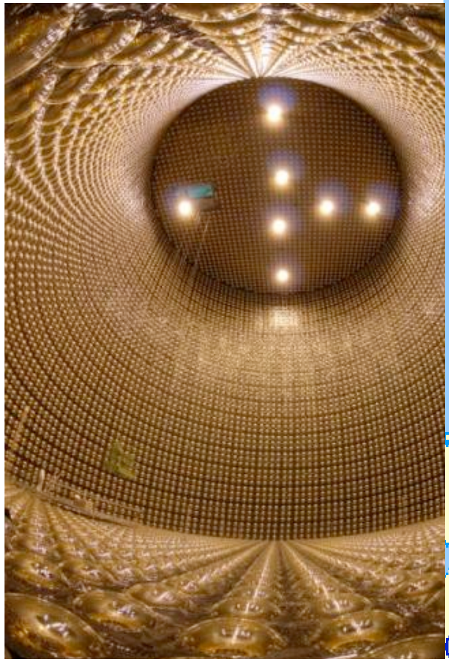
T2K: ν_μ disappearance



0νββ decay exp.	Dirac or Majorana
Tritium β decay exp.	absolute mass scale

T2K Experiment

Super-Kamiokande



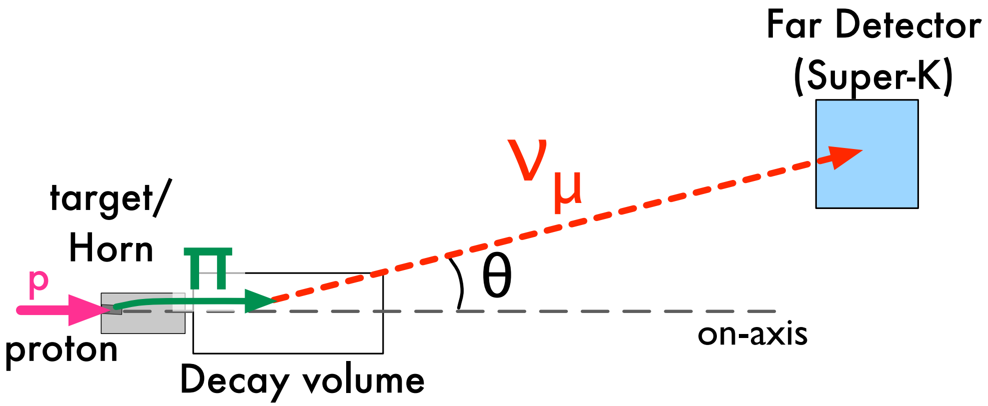
Long base-line ν oscillation experiment

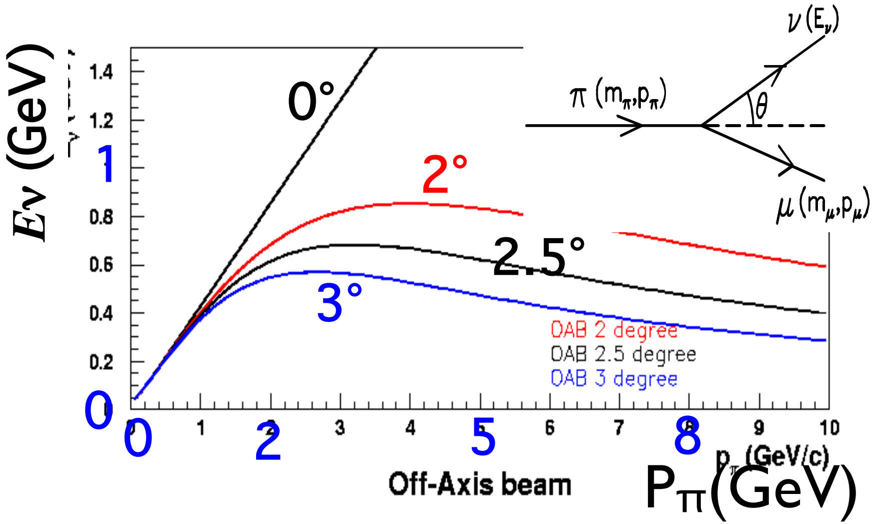
New accelerator(~MW),
ν beam-line & detector

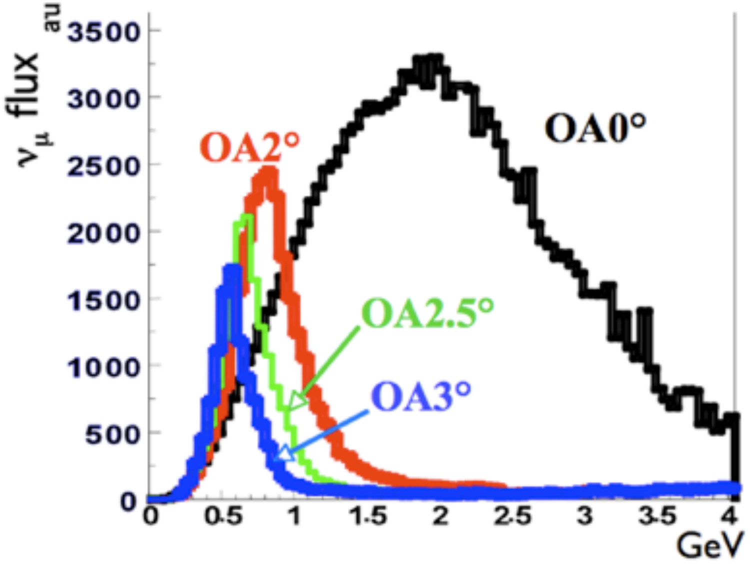
T2K features to enhance the sensitivity

- **Super-Kamiokande(SK) as main neutrino detector**
- **Intense narrow band ν_μ beam from J-PARC** → Off-axis method
- **Neutrino energy reconstruction** :
  CCQE interactions dominate at T2K beam energy

Off-axis beam : intense & narrow-band beam







the beam energy depends on the off-axis angle (beam direction)

set off-axis angle to 2.5°

→ **beam energy at oscillation max.**

(current Δm^2_{23} & L=295km)

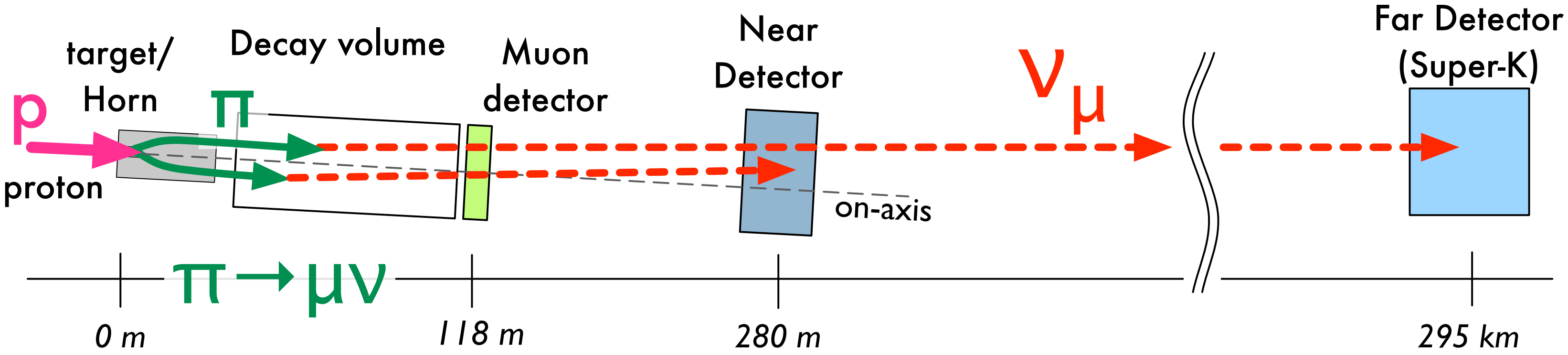
- ~1.2k CC int./year for SK
- small high Eν tail (narrow-band)

→ **small # of bkg. for CCQE**

Important to keep the beam direction stable

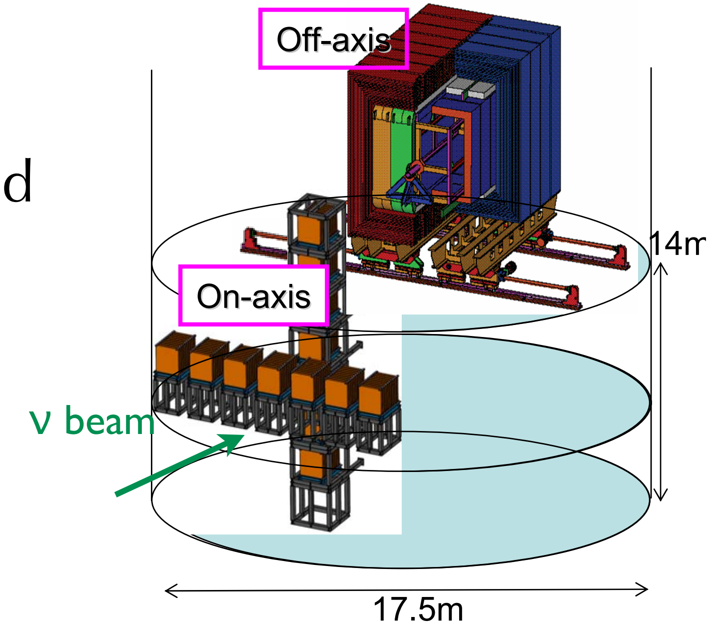
(monitoring & controlling the beam)

Experimental Setup



- Muon monitor & on-axis neutrino detector
  - monitor direction of μ and ν_μ beam
    - ✓ uncertainty of beam direction to be < 1mrad
- off-axis neutrino detector
  - measure E_ν distribution, flux, flavor contents
- Far neutrino detector (Super-Kamiokande)
  - measure ν beam composition after 295 km

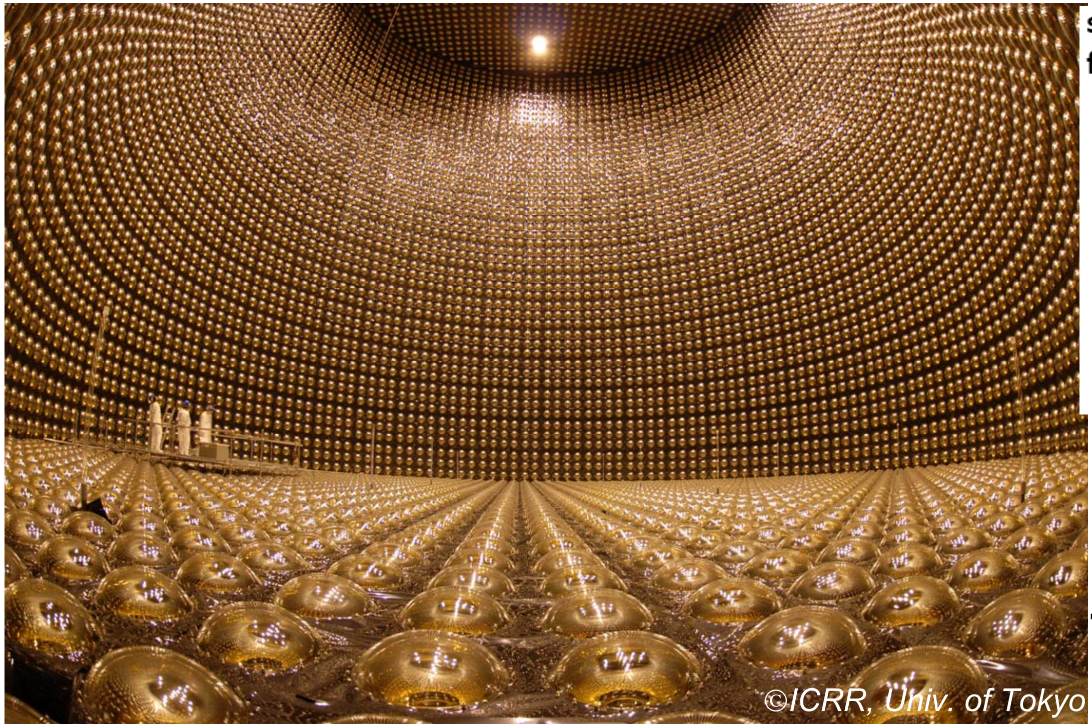
Near Detectors



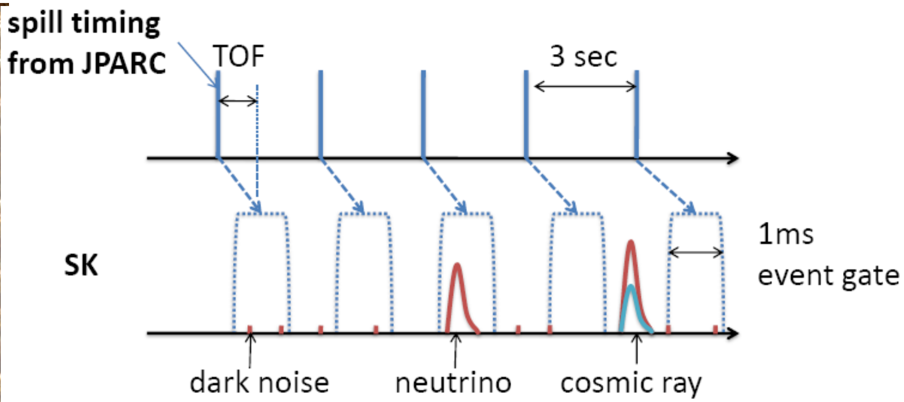
Super Kamiokande (far detector)

- 50 kton water Cherenkov detector (fiducial volume: 22.5 kton)
  - good e-like(shower ring) / μ-like separation, δE_{scale} ~ 2%
- New electronics & DAQ was installed in summer 2008 & stably running
- realtime transfer of T2K beam spill (GPS) information

→ trigger of T2K event



©ICRR, Univ. of Tokyo



T2K trigger = spill timing ± 500μsec

~11000 x 20inch PMTs
(inner detector)

Sensitivity

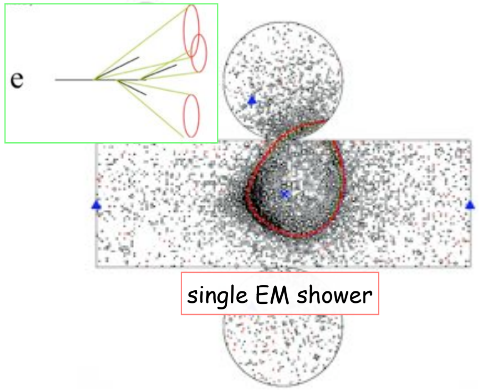
ν_e appearance

signal

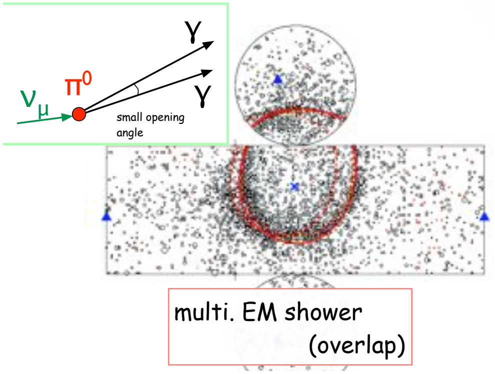
beam ν_e background

π^0 background

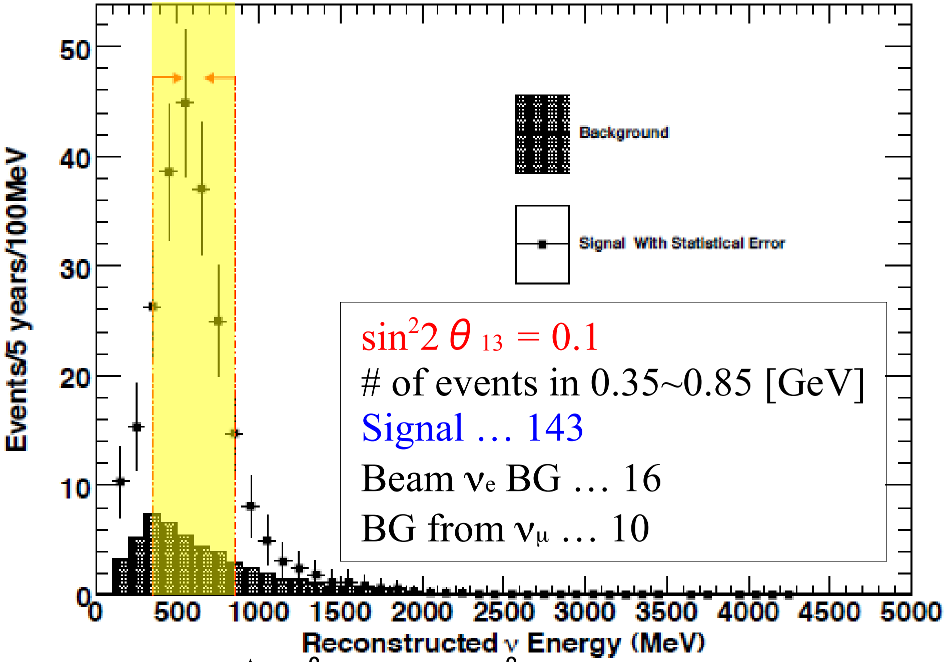
@ 8 x 10^{21} protons(30GeV)
on target



single EM shower



multi. EM shower
(overlap)



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

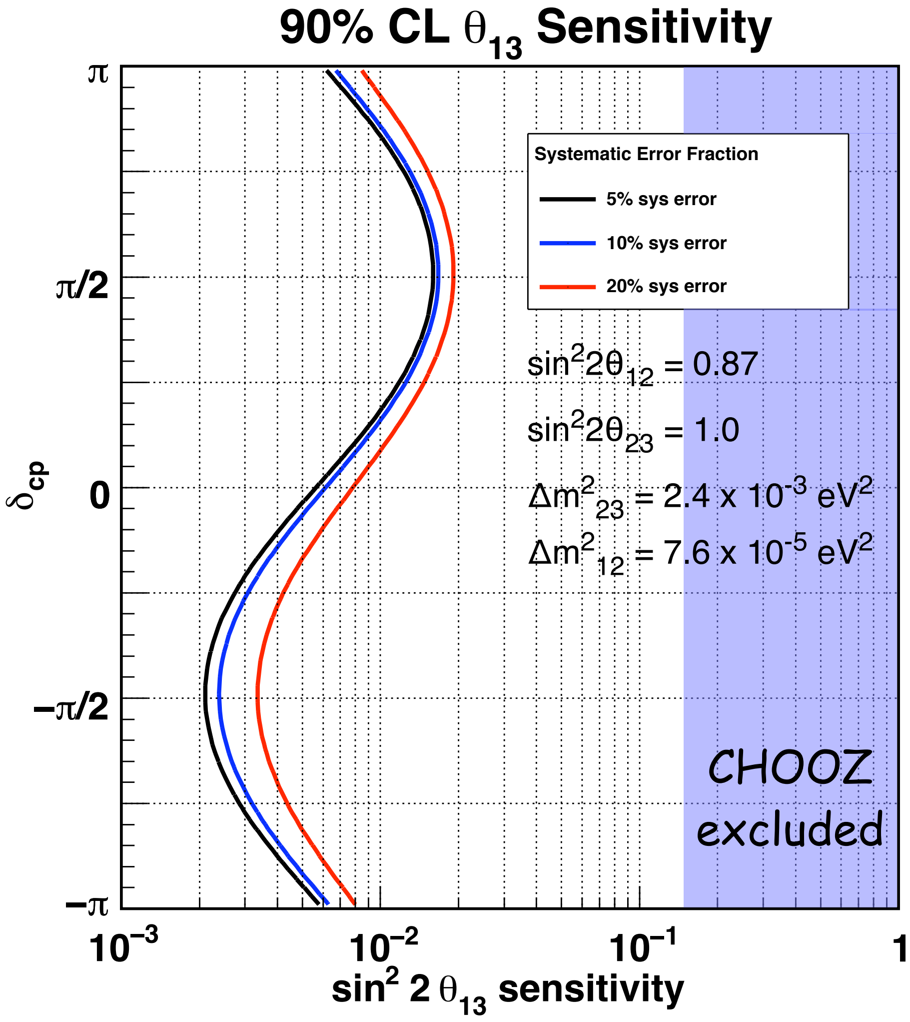
\# of events in 0.35~0.85 [GeV]

Signal … 143

Beam ν_e BG … 16

BG from ν_μ … 10

$\Delta m^2 = 2.4 \times 10^{-3}$, 10% sys. error



$\sin^2 2\theta_{12} = 0.87$

$\sin^2 2\theta_{23} = 1.0$

$\Delta m^2_{23} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$

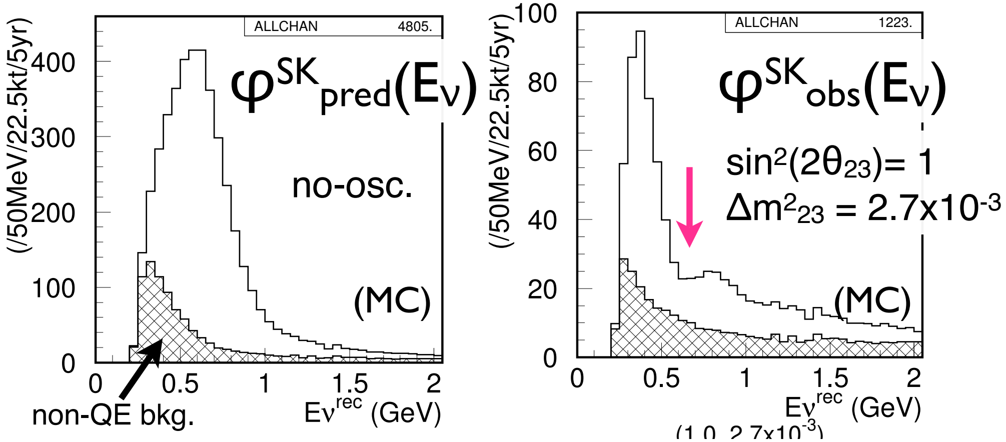
$\Delta m^2_{12} = 7.6 \times 10^{-5}\ \mathrm{eV}^2$

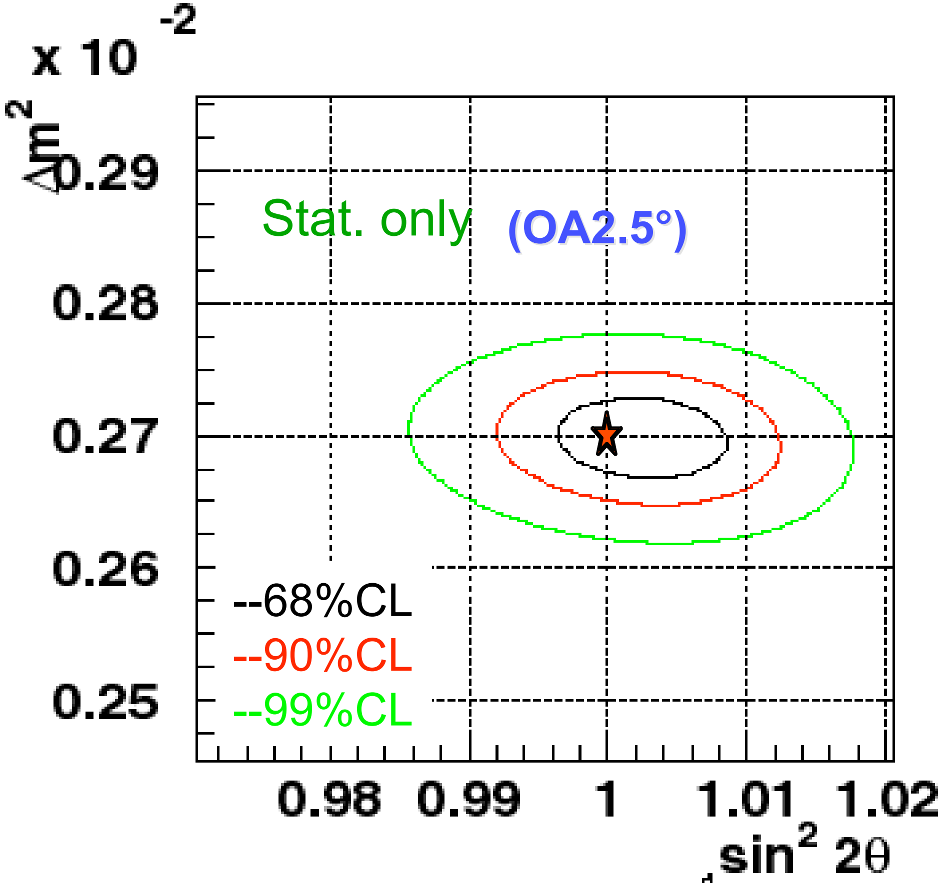
x10 improvement from CHOOZ limit

Sensitivity

ν_μ disappearance

@ 8 x 10^{21} protons(30GeV)
on target





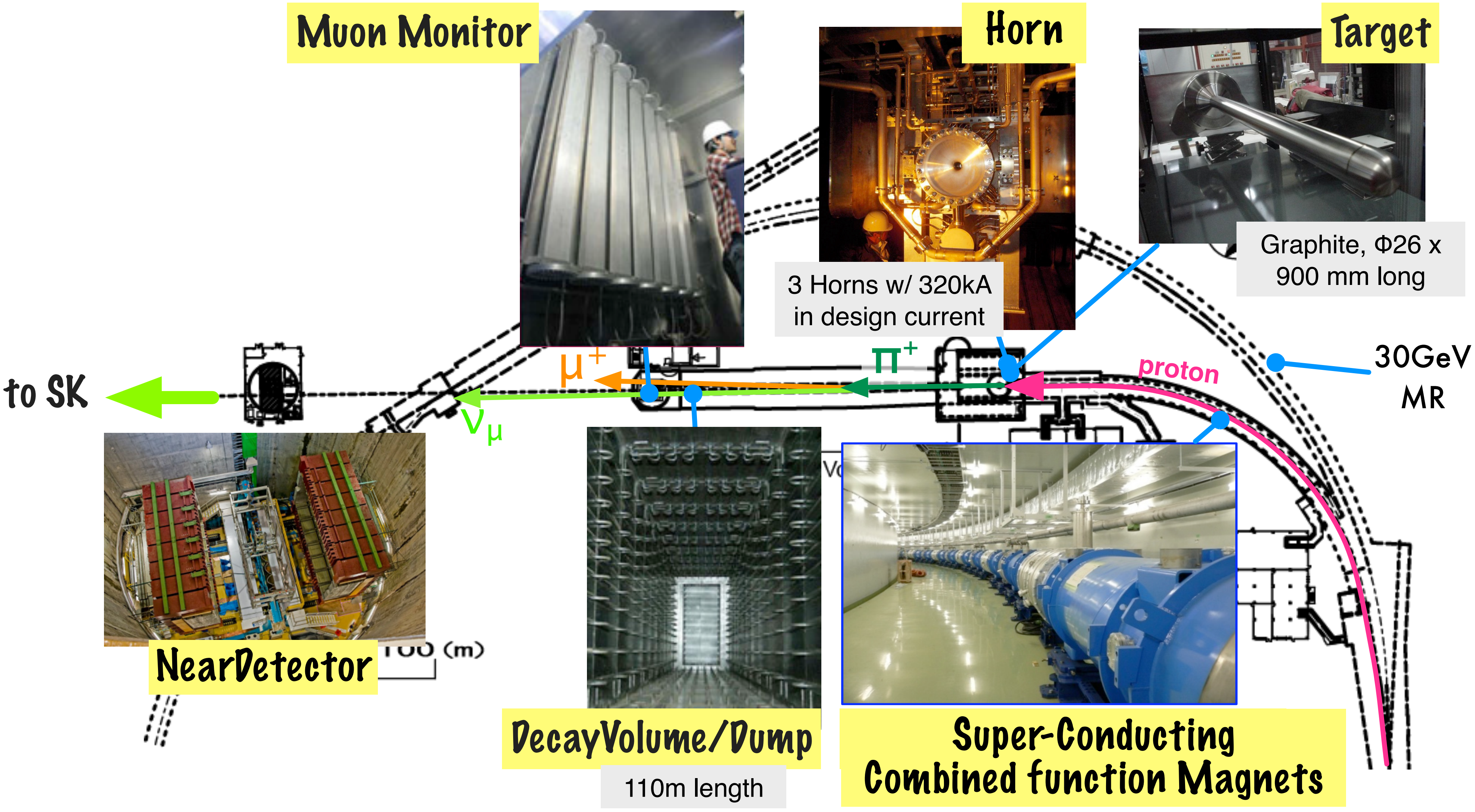
$\delta(\sin^2 2\theta_{23}) \sim 1\%$

$\delta(\Delta m^2_{23}) < 1 \times 10^{-4}\ \mathrm{eV}^2$

T2K beam-line

T2K Neutrino Beam-line

construction was almost completed in April/2009 [2004-2009, 5years]



Muon Monitor

Horn

3 Horns w/ 320kA in design current

Target

Graphite, Φ26 x 900 mm long

30GeV MR

to SK

NearDetector

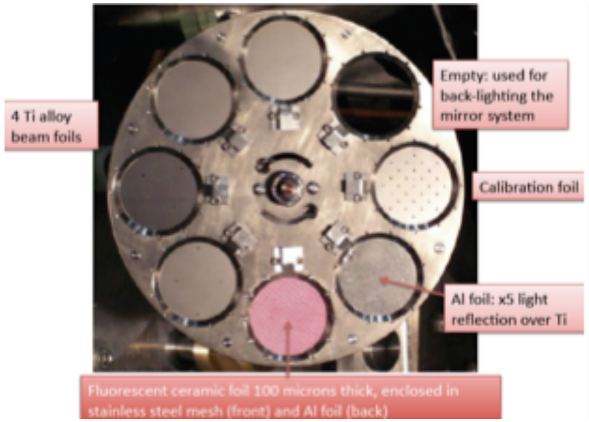
DecayVolume/Dump

110m length

Super-Conducting Combined function Magnets

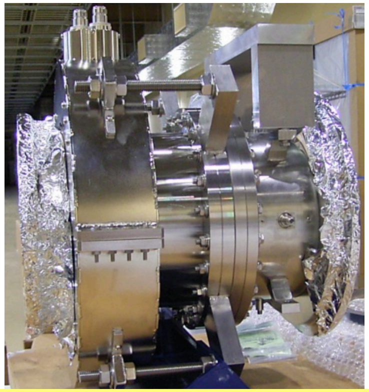
Proton beam monitor

ターゲット直前の
ビームプロファイル



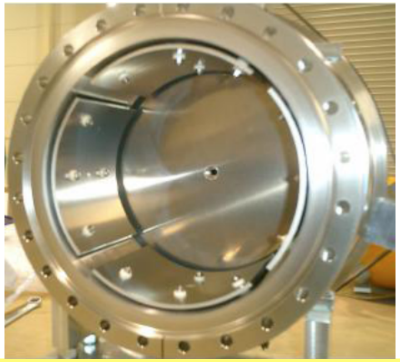
Optical Transition Radiation (OTR)

ビーム強度



Current Transfomer (CT)

ビーム位置

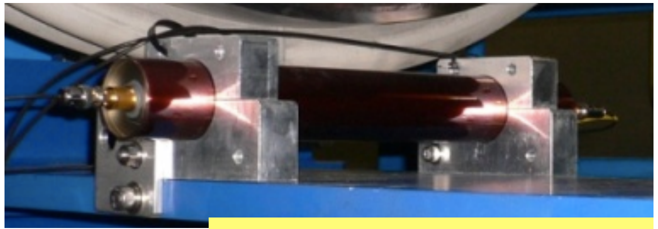


Electro Static Monitor (ESM)

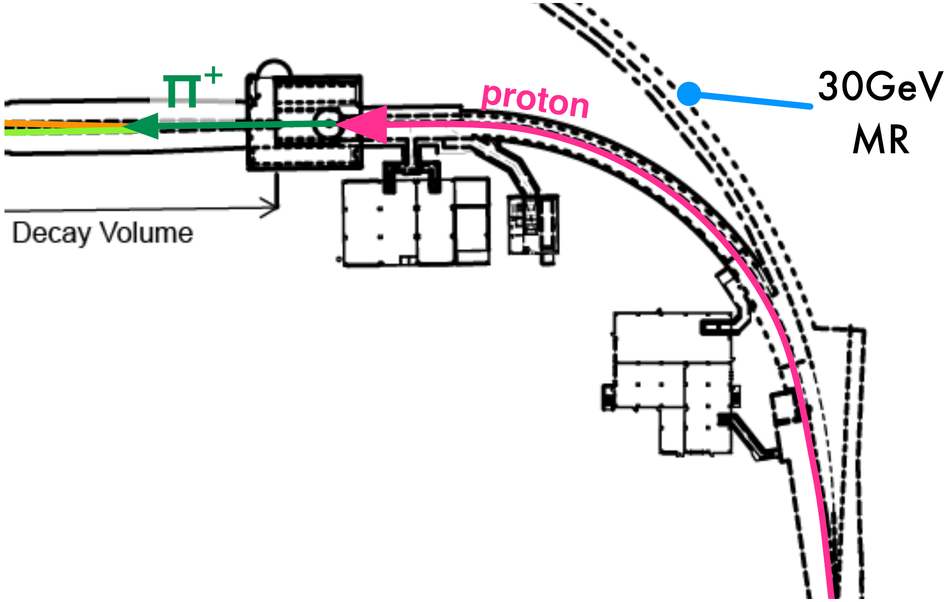
ビームプロファイル

Segmented Secondary Emission Monitor (SSEM)

ビームロス



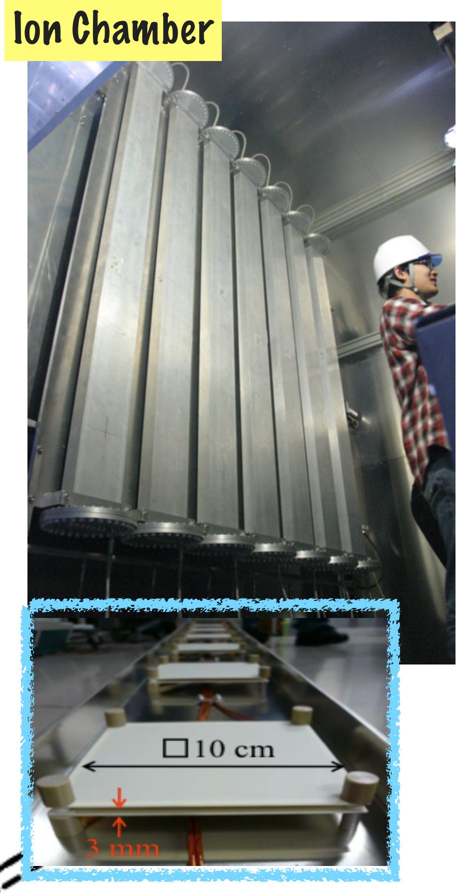
Beam Loss Monitor (BLM)

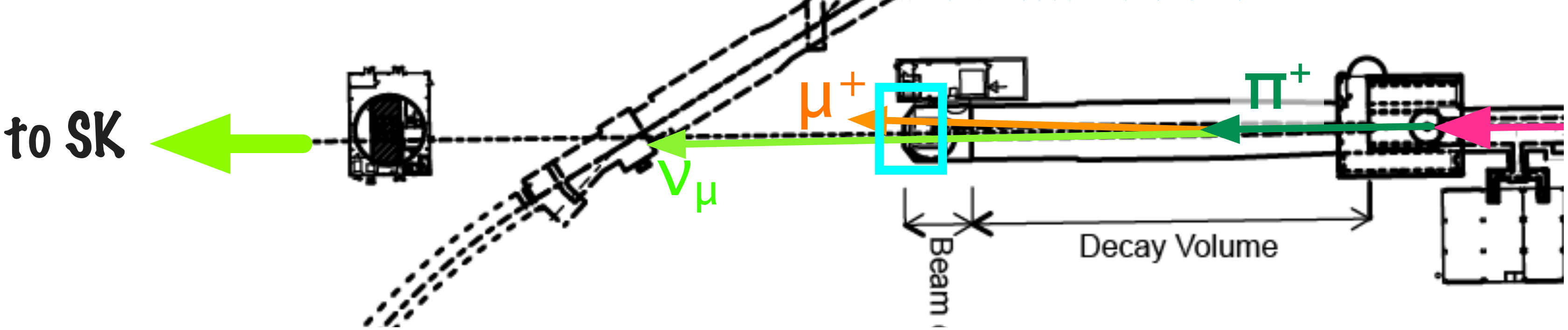


monitor name	purpose	quantity
CT	intensity	5
ESM	position	21
SSEM	profile	19
BLM	loss	50
OTR	profile at target	1

Muon beam monitor

- measure ν beam direction by muon profile every spill
- two independent monitor covering 1.5m x 1.5m area
  - Array of Ionization chamber
  - Array of Silicon PIN photo-diode



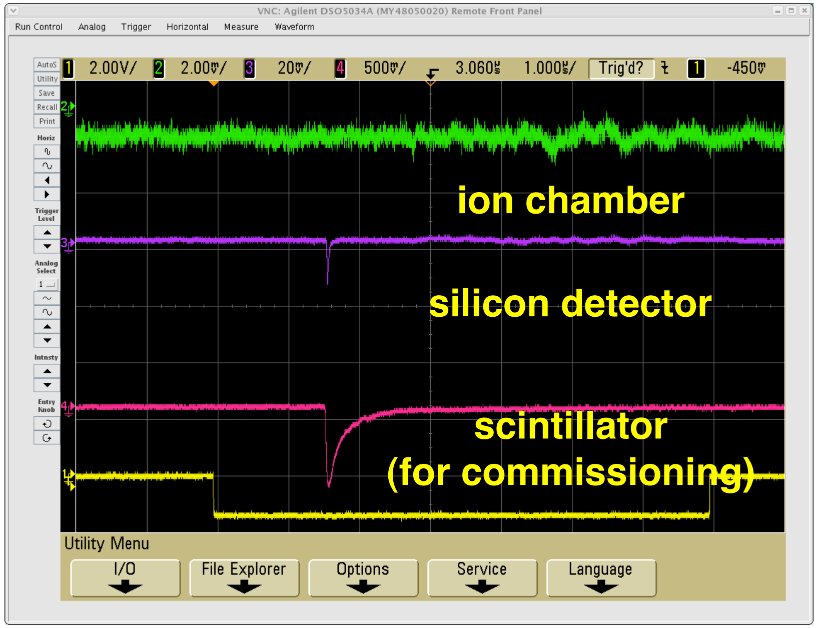


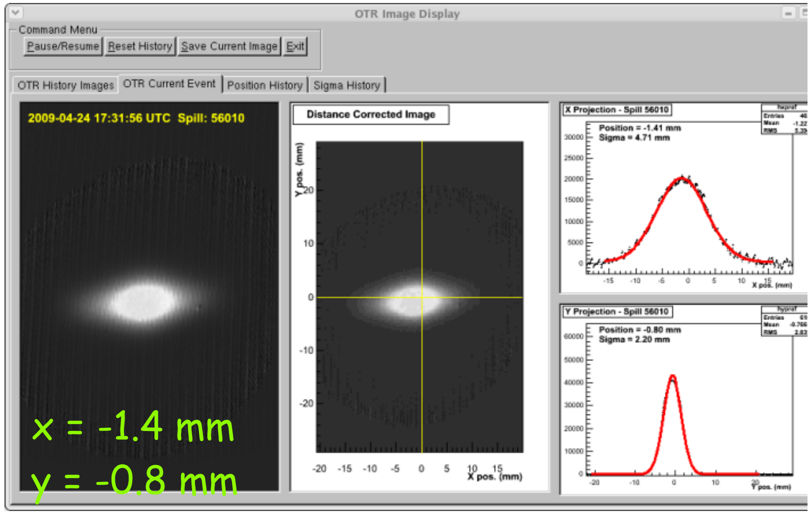
T2K beam-line この1年

2009 Feb~March	preparation for first beam
April	First neutrino beam
May	Beam commissioning
June ~ November	Horn 2,3 installation Helium filled in TargetStation/DecayVolume Horn operation test in He environment
November	Beam commissioning
December	Beam commissioning
2010 January	Beam commissioning

First T2K neutrino beam produced on April/23/2009

Muon monitor signal
at 1st shot after SC turned on





proton profile just in front of the target
after 9 shots beam tuning
(fluorescence plate)

T2K beam-line この1年

2009 Feb~March	preparation for first beam
April	First neutrino beam
May	Beam commissioning
June ~ November	Horn 2,3 installation Helium filled in TargetStation/DecayVolume Horn operation test in He environment
November	Beam commissioning
December	Beam commissioning
2010 January	Beam commissioning

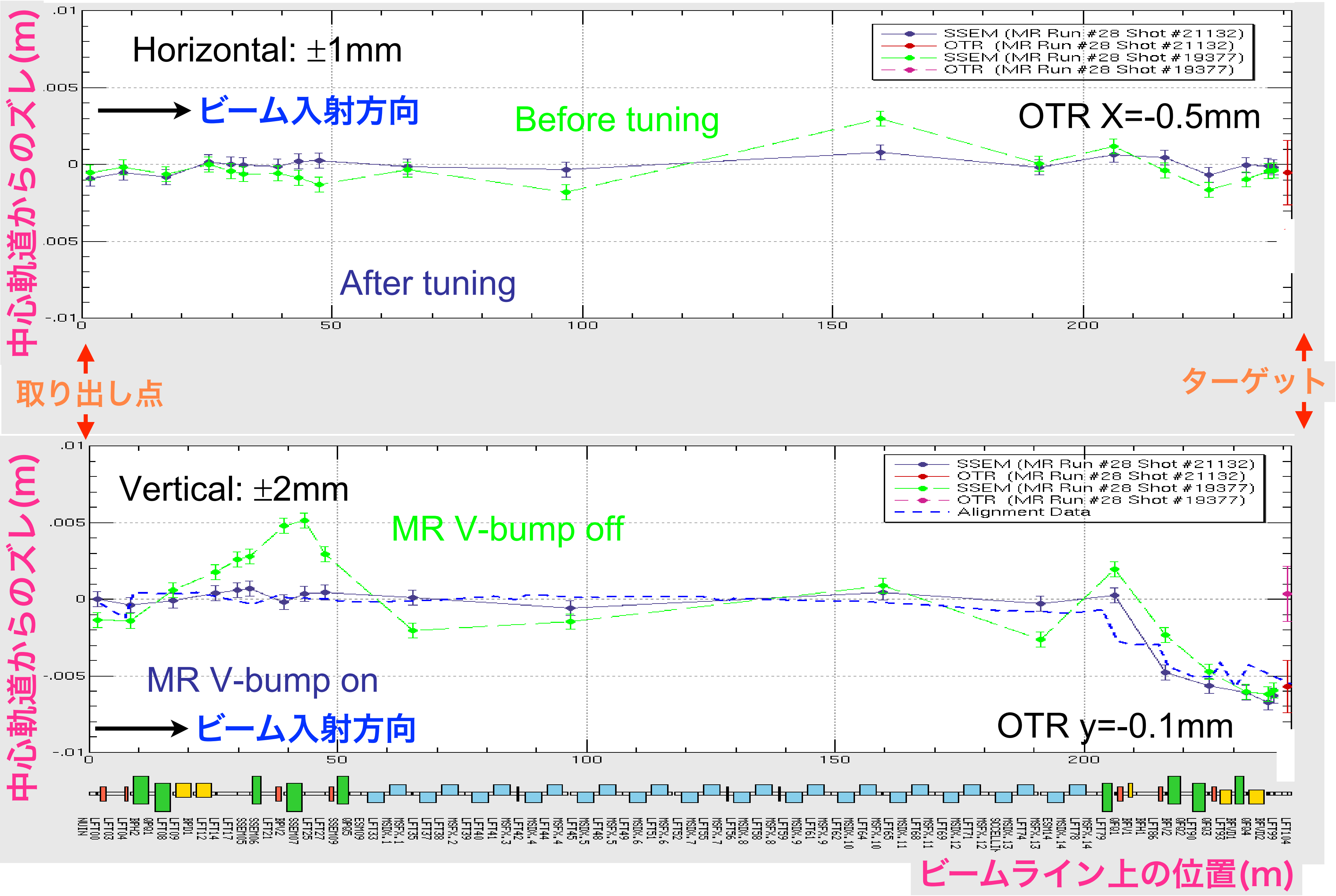
Beam commissioning

- Goal
  - establish operation of beam monitors (at high beam intensity)
  - tune beam orbit and beam position and size on the target
  - tune neutrino beam direction by Mumon & INGRID

period	beam condition		total # of protons	highlights
2009.4~5	6 sec repetition 4~8e11 ppp (single/two bunch)	only Horn1	~ 2 x 10^{14}	check all the components work as expected
2009.11	3.52 repetition ~20kW (a few shots)	no Horn	~ 8 x 10^{14}	beam monitor studies First neutrino event in INGRID
2009.12	~20kW (<30min) ~50kW (a few shots)	Horn 1,2,3	~ 4 x 10^{16}	3 Horns operation high power trial First neutrino event in Off-axis
2010.01	~20kW(continuous)	Horn 1,2,3	~ 5 x 10^{17}	high power continuous run

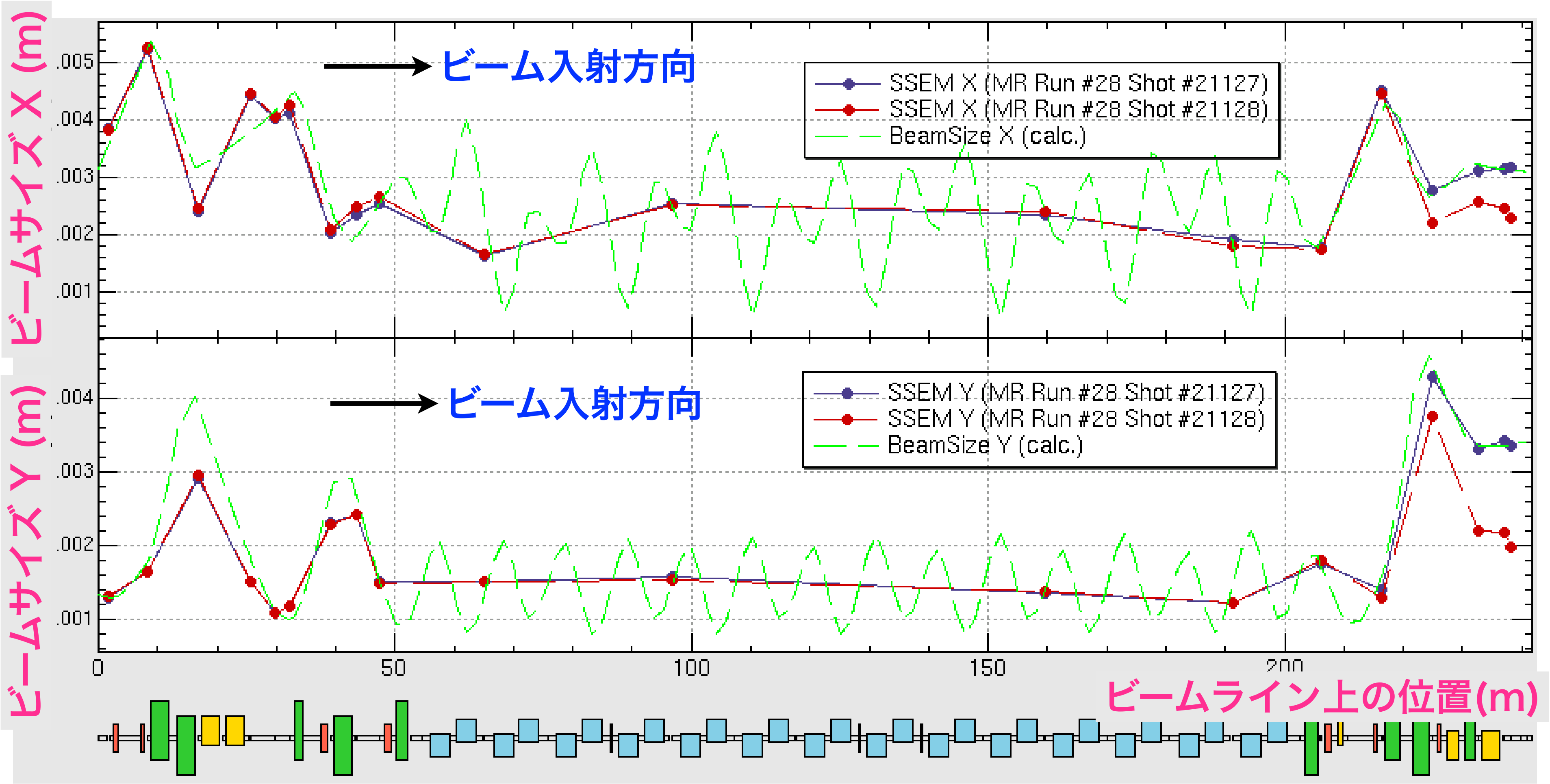
Beam orbit

各点はビームモニターの測定結果



Beam size

Beam size manipulation at target demonstrated



σ_x = 2.3mm, σ_y = 2.0mm ←→ σ_x = 3.2mm, σ_y = 3.4mm (SSEM19)

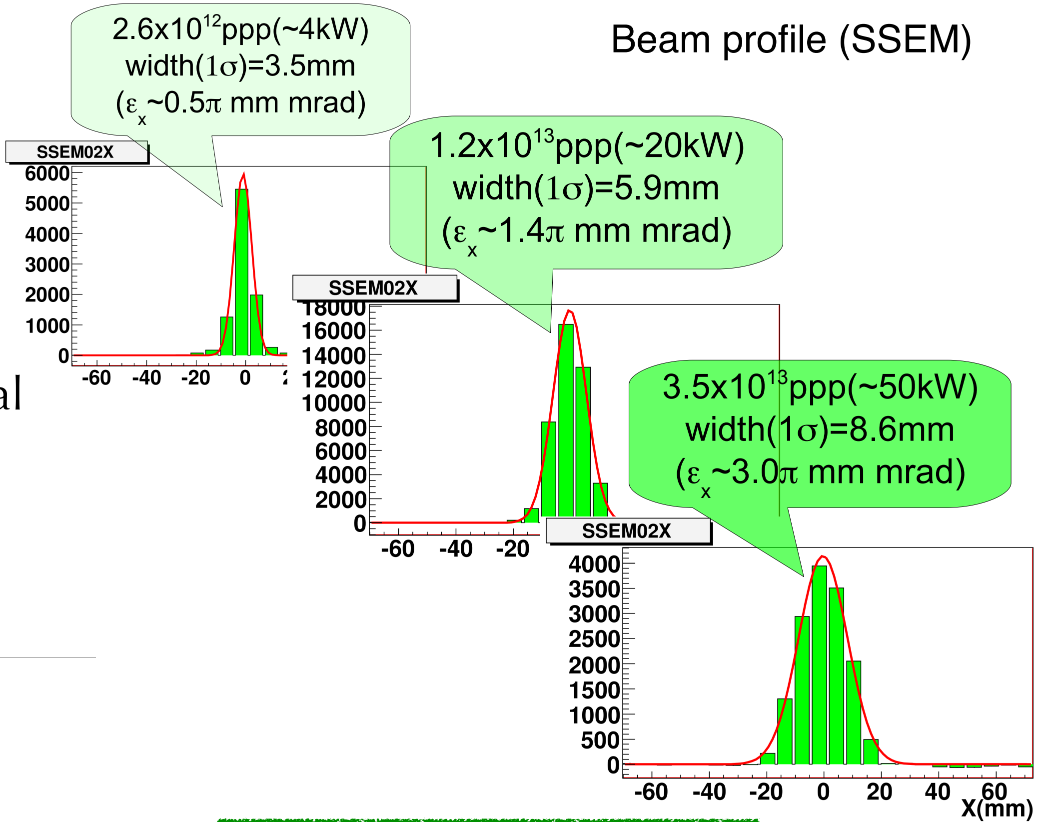
Beam size @ 50kW trial : σ_x = 6.0mm, σ_y = 6.5mm (intentionally enlarged)

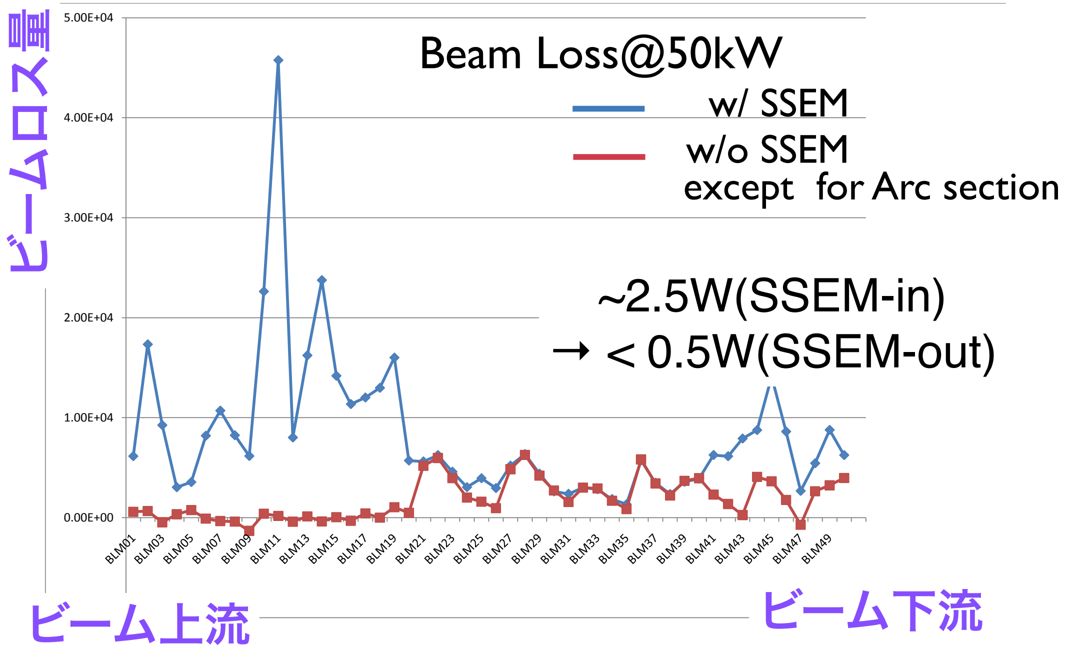
Design: σ_x = 4.3mm, σ_y = 4.3mm

Beam monitor works well at high intensity

- Observed emittance increases at high intensity as expected
- Low enough beam loss for high intensity beam
  - loss size was studied by putting material (other beam monitor) in the beam
- OTR signal (Ti target) was observed

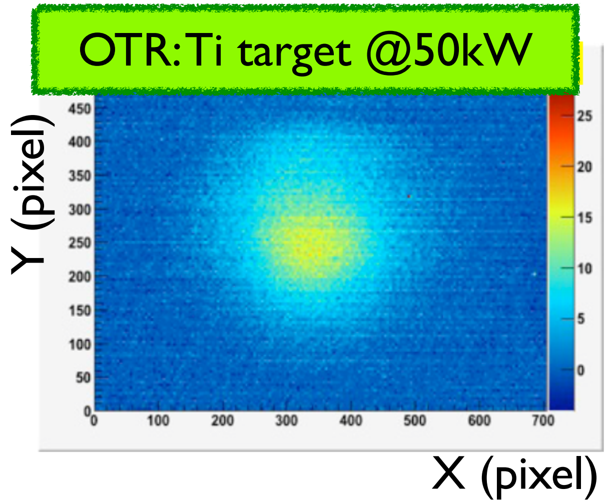
Beam profile (SSEM)





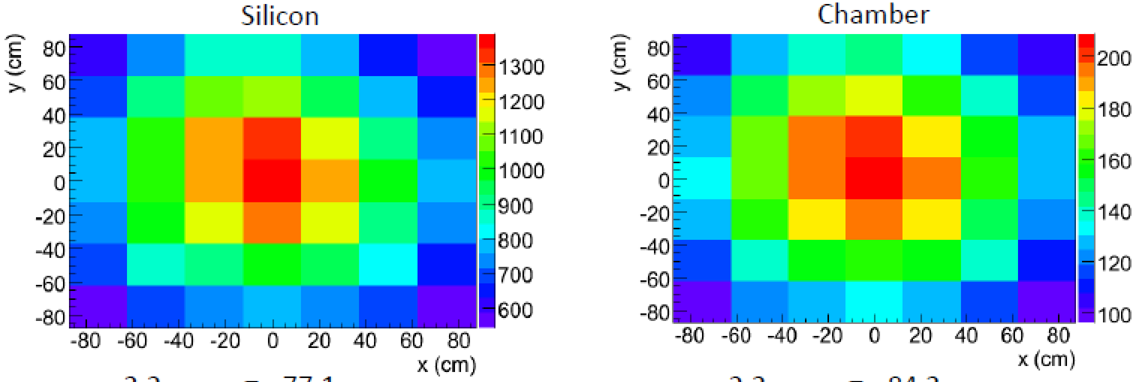
~2.5W(SSEM-in)
→ < 0.5W(SSEM-out)

OTR:Ti target @50kW



Muon monitor measurement

Muon monitor [4.5 x 10^{12} ppb, 1bunch 3Horns@320kA]



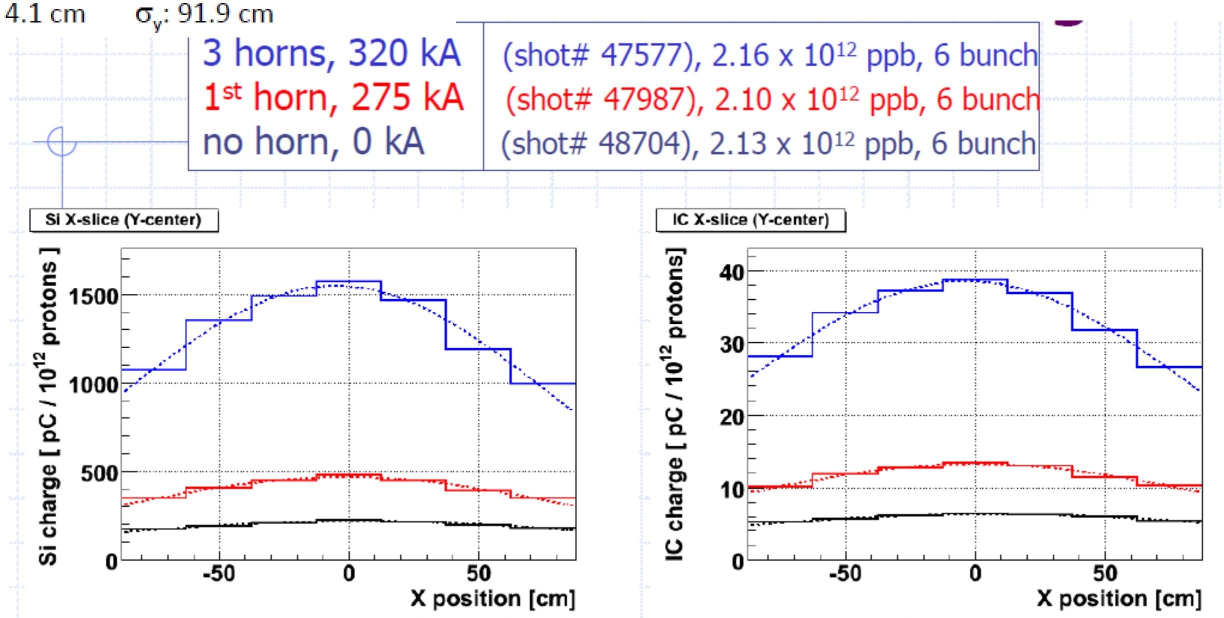
x: −3.2 cm σ_x: 77.1 cm
y: 3.0 cm σ_y: 81.9 cm

x: −2.3 cm σ_x: 84.3 cm
y: 4.1 cm σ_y: 91.9 cm

Muon profile measured by Silicon and Chamber detector

measurement is consistent each other

Horn focusing effect observed by Muon monitor


3 horns, 320 kA (shot# 47577), 2.16 x 10^{12} ppb, 6 bunch
1st horn, 275 kA (shot# 47987), 2.10 x 10^{12} ppb, 6 bunch
no horn, 0 kA (shot# 48704), 2.13 x 10^{12} ppb, 6 bunch

x7.1
x2.1

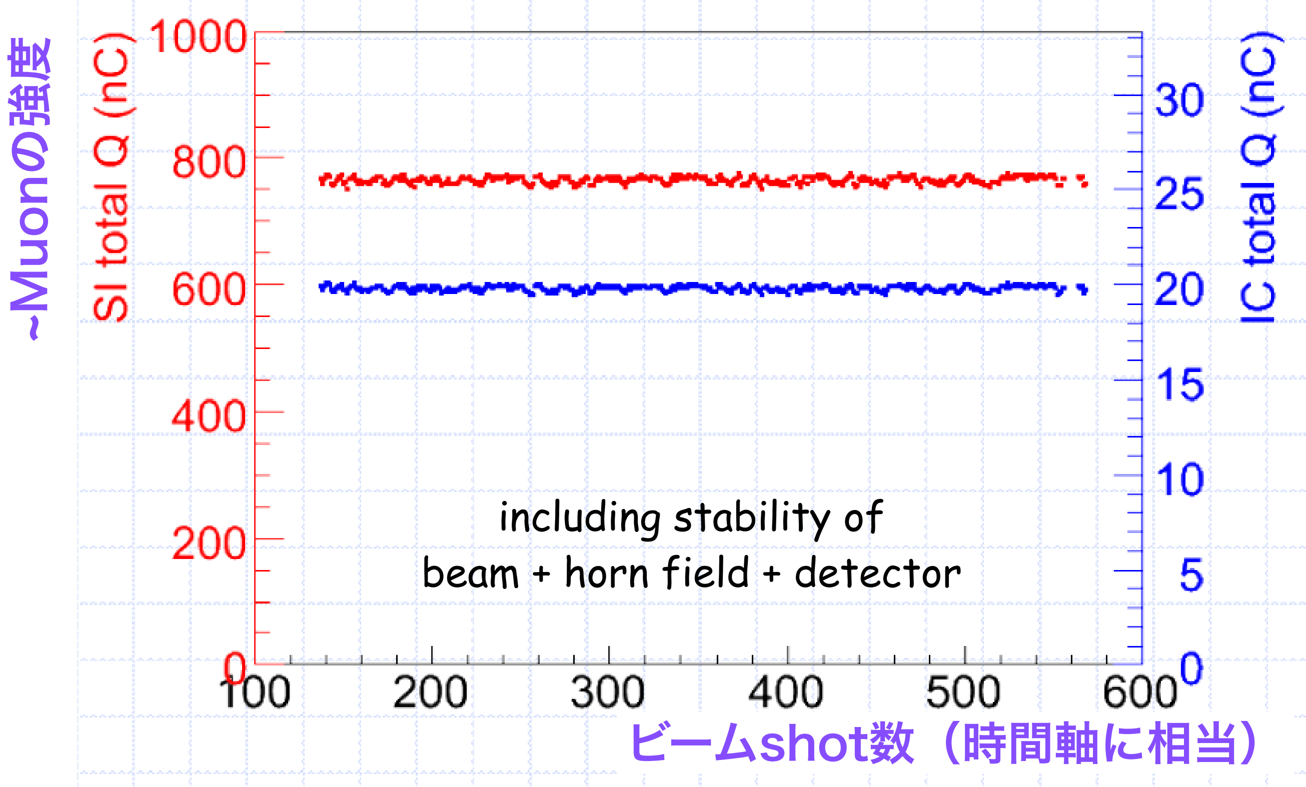
peak	sigma	peak	sigma
1551 pC	82 cm	38.5 pC	90 cm
467 pC	95 cm	13.2 pC	103 cm
219 pC	109 cm	6.3 pC	125 cm

Stability of beam

20kW continuous operation

- Beam position from MR is stable(<0.2mm day by day)
- Stability of Muon yield <1%
- Stability of beam angle (by Mumon) is ~0.03mrad
- Beam loss is small and stable during the run

→*Good beam stability*



Achievements in beam commissioning

☑ basic functionality of beam monitors and beam-line equipment (e.g. Super-conduction combined magnet) was confirmed

☑ Spill information successfully transfers to SK w/o any troubles

☑ high intensity trial succeeded (~50kW x ~10shots)

  - beam monitor/equipment works fine & small beam loss

☑ beam direction was tuned

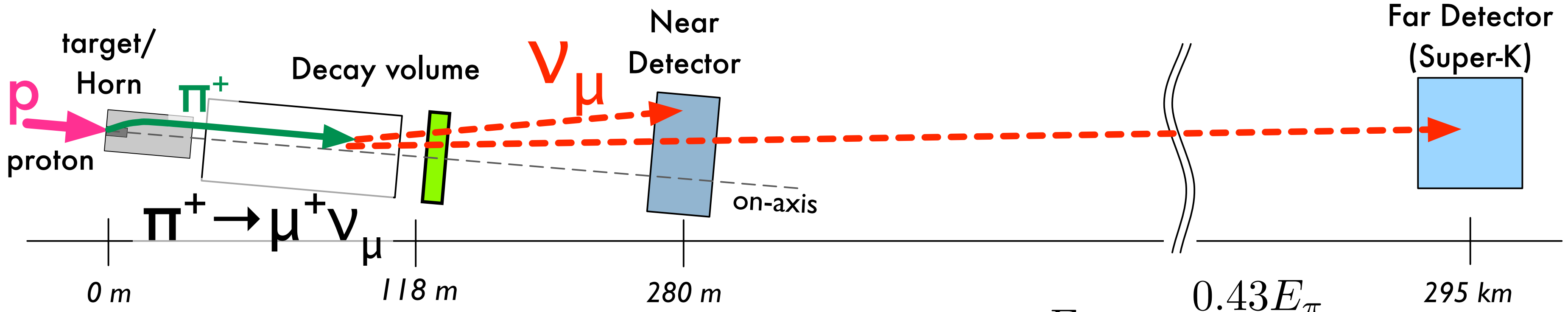
☑ perform continuous operation w/ 20kW

  - confirm good enough beam stability

T2K beam-line is basically ready for physics run

Hadron production measurement

Hadron production measurement

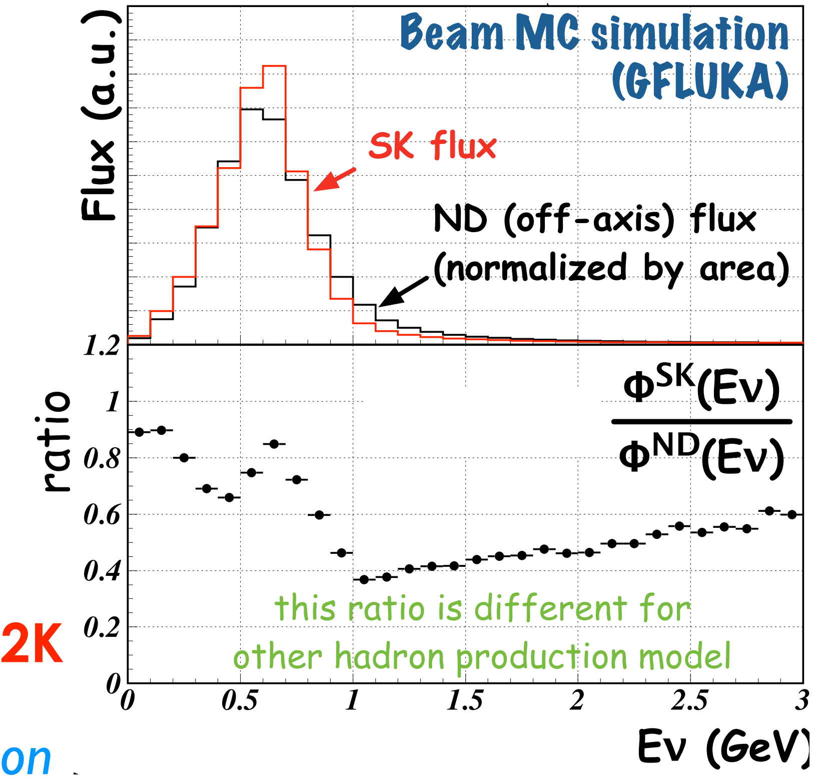


$$E_\nu = \frac{0.43E_\pi}{(1+\gamma_\pi^2\theta_\nu^2)}$$

- E_ν distribution is different between ND and SK
  - π や Kの生成分布 (運動量-生成角度分布)

    と geometrical acceptance に依存

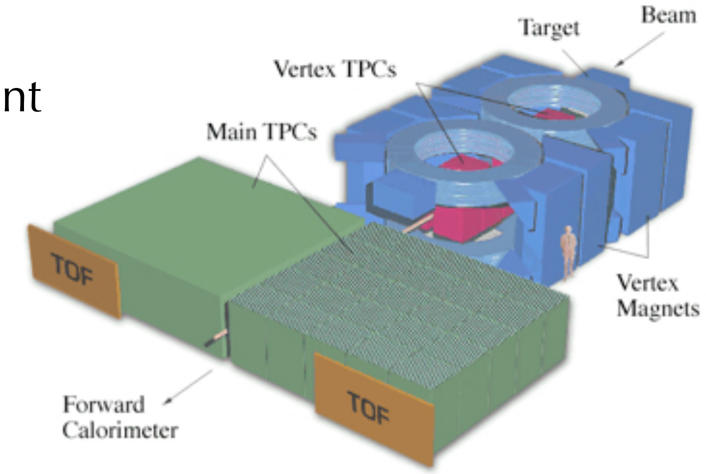
- so far, no measurement of π,K production distribution from 30GeV proton + C interaction



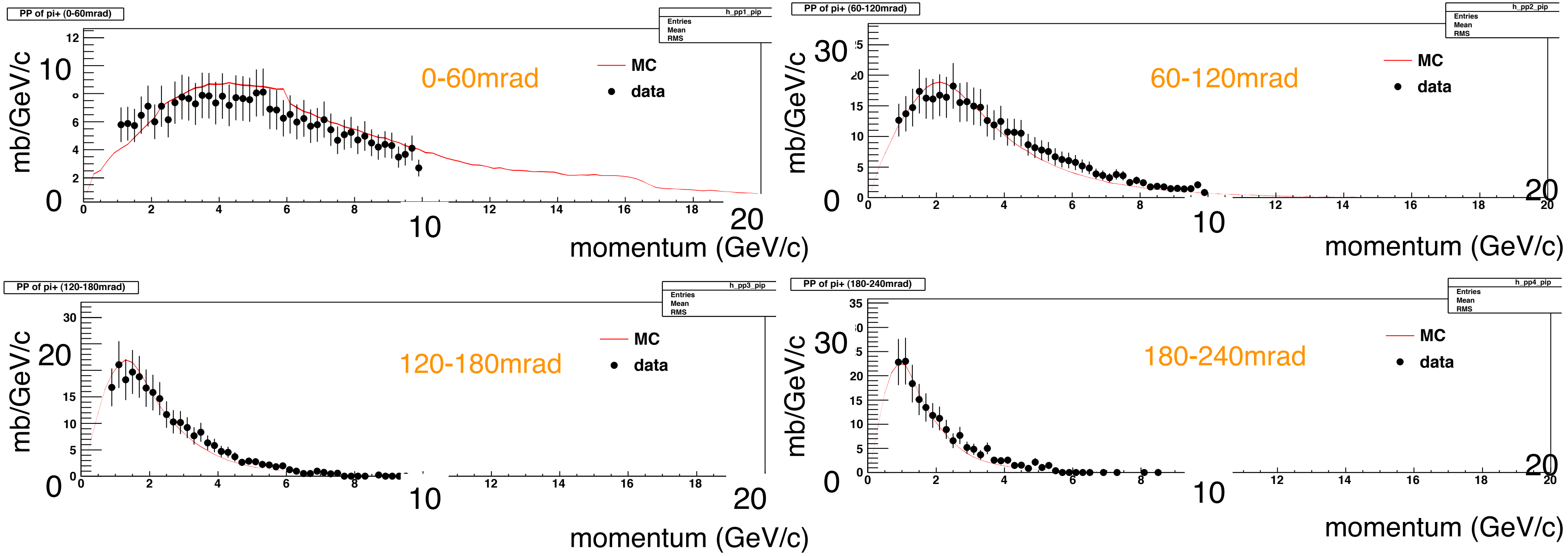
hadron production is a large uncertainty in T2K

→ *measure hadron production*

- measure hadron production in CERN NA61 experiment
  (data was taken in 2007, 2009)
- comparison data with T2K beam-MC
  - GEANT FLUKA (old FLUKA) used in MC



preliminary results of π^+ production (31GeV proton + 2cm Carbon target)



→ 物理解析に向けた準備も進行中

Prospects & Schedule

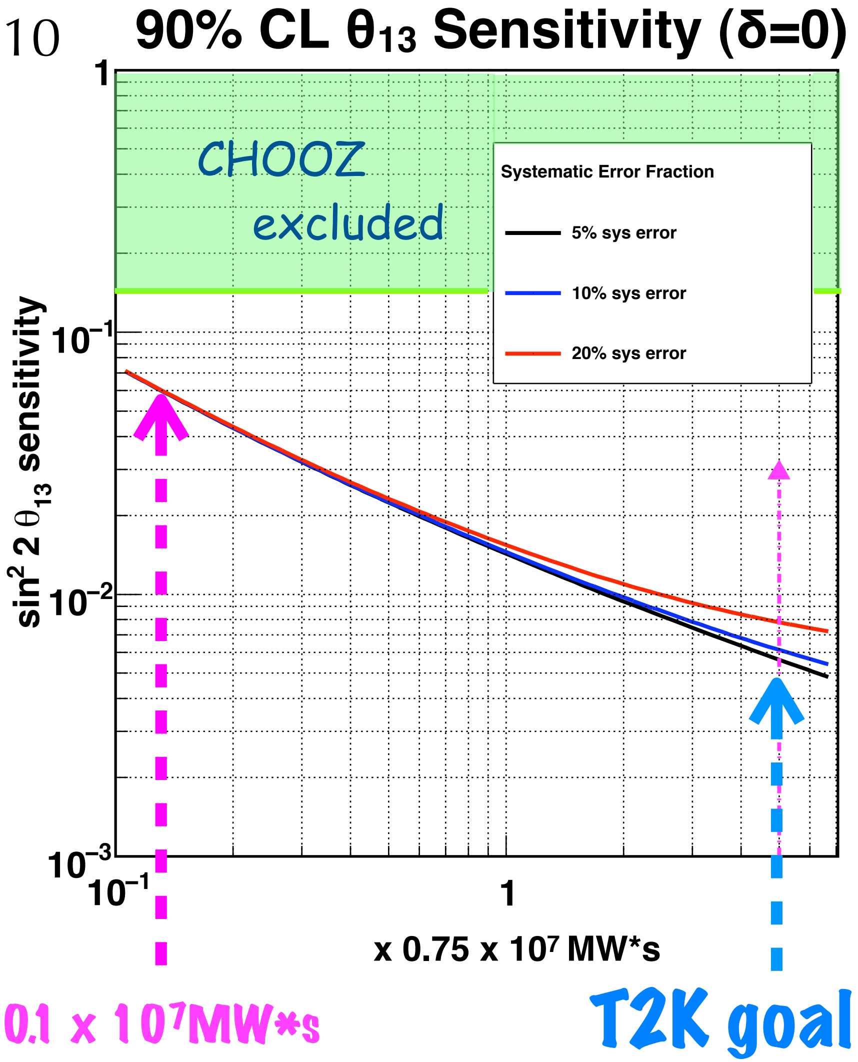
We aim for better sensitivity than the current limit by CHOOZ using data of physics run of 2010 as a first step

- assigned beam time from Feb/23 to June 2010
- physics run will start as soon as possible

*Next : We hope to discover ν_e appearance with 1-2 x 10^7 MW*sec in a few years*

- $\sin^2 2\theta_{13}$ = 0.05 (3σ discovery @ 1MW*10^7sec)
  0.03 (3σ discovery @ 2MW*10^7sec)

*Final results with 3.75 x 10^7 MW*sec*
(8×10^{21} p.o.t.)



Summary

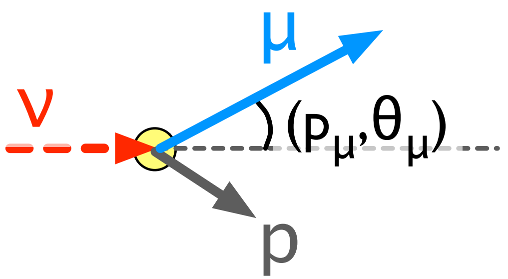
- T2K neutrino oscillation experiment, our goals are
  - discover $\nu_\mu \rightarrow \nu_e$ appearance (a finite θ_{13})

    one order of magnitude sensitivity improvement from the current limit
  - ν_μ disappearance for precise measurement of $\sin^2 2\theta_{23}$, Δm^2_{23}
- **T2K neutrino beam-line operation starts**
  - confirmed good enough stability of beam (δbeam angle << 1mrad)
  - beam commissioning almost finish → move to physics data taking
- Aim for better sensitivity than the current limit by CHOOZ as a first step

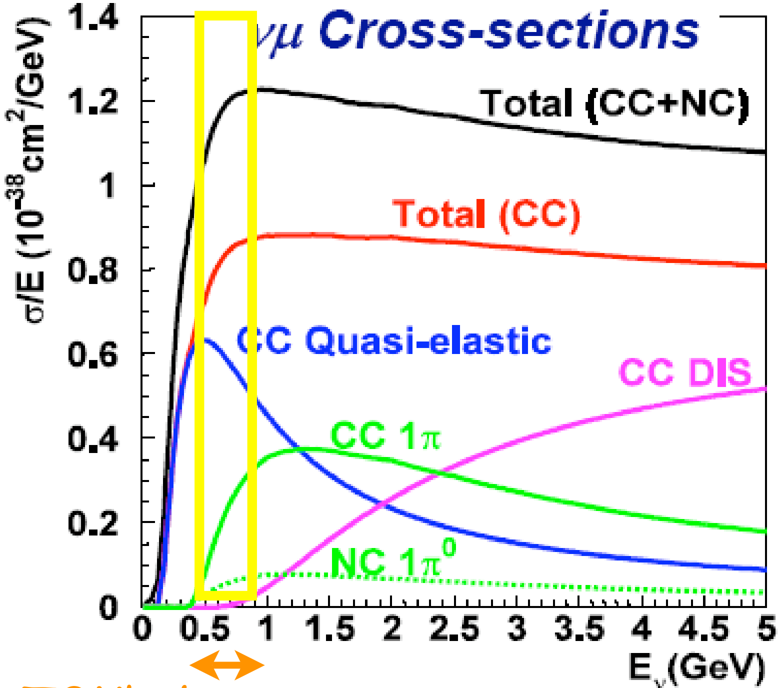
backup

ν Energy Reconstruction

- ν's Energy reconstruction is possible for CC Quasi-Elastic interaction (CCQE: $\nu_{\mu(e)} + n \rightarrow \mu(e) + p$)

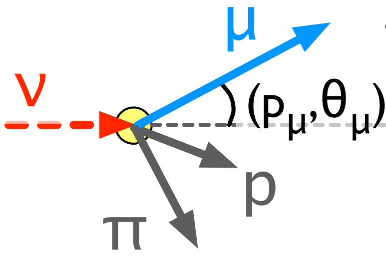


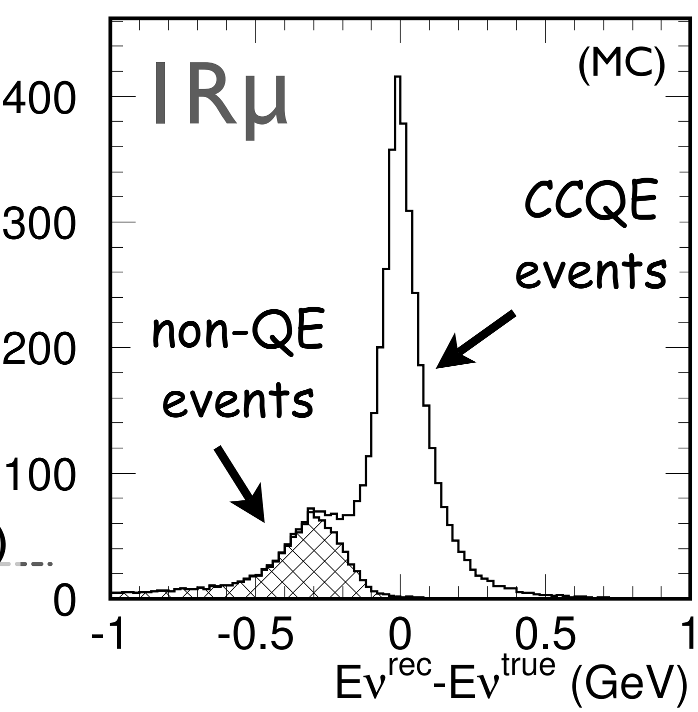
$$E_\nu^{\mathrm{rec}} = \frac{m_n E_\mu - m_\mu^2/2 - (m_n^2 - m_p^2)/2}{m_n - E_\mu + p_\mu \cos\theta_\mu}$$



T2K's beam energy

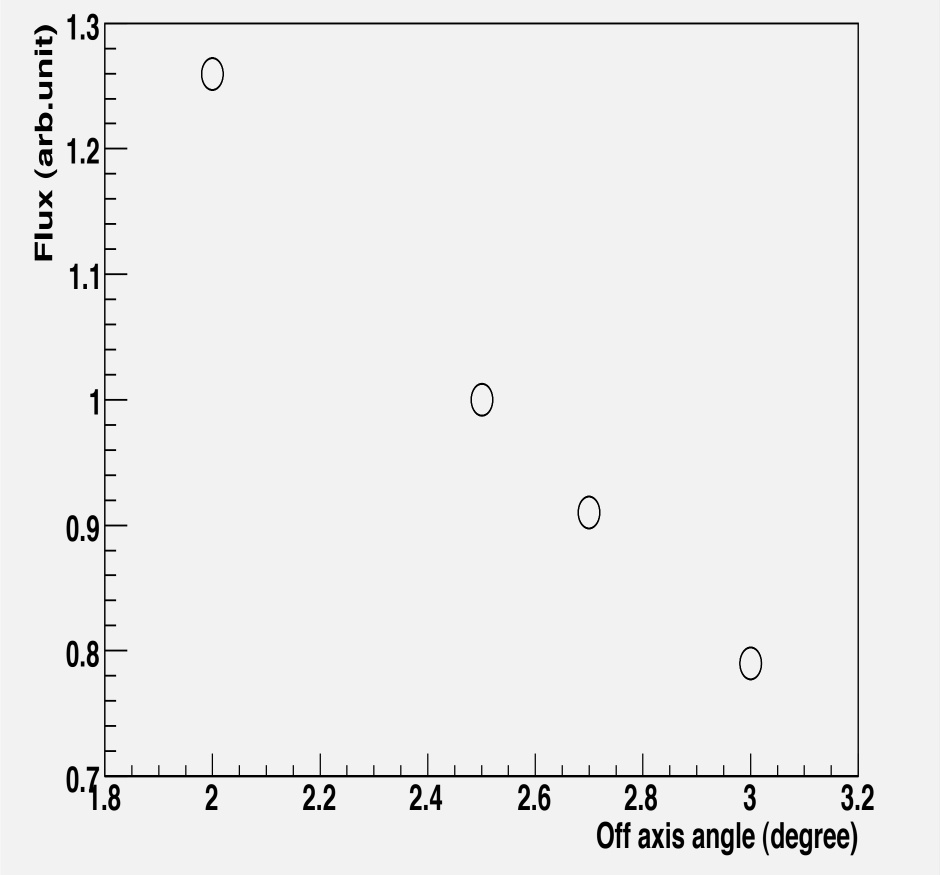
CC1π



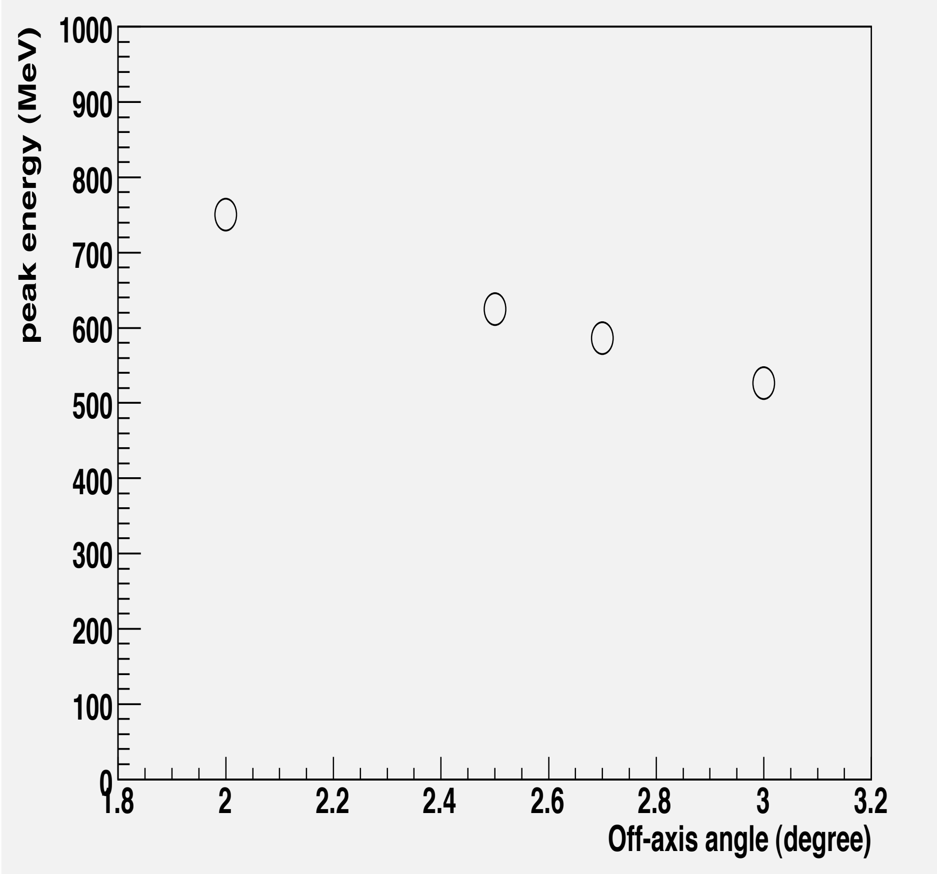


- ニュートリノビーム方向の安定性精度
  - SKでのE_ν peakを<2%で抑える← Δm^2_{23}の系統誤差
  - ビーム方向を±1mrad以下で抑える

SK fluxの変化



SK E_ν peakの変化



θ_{13} measurement by ν_e appearance

θ_{13}

$$P(\nu_\mu \to \nu_e) = \boxed{4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 \sin^2 \Phi_{31}}$$

$$+8C_{13}{}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\underline{\cos\delta} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

CPC

$$-8C_{13}{}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

CPV

$$+4S_{12}{}^2 C_{13}{}^2(C_{12}{}^2 C_{23}{}^2 + S_{12}{}^2 S_{23}{}^2 S_{13}{}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21}$$

solar

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

matter effect
(small in T2K)

L = 295 km, <E$_\nu$> ~0.6GeV
sinΦ_{21} ~ 0.05

$$\delta \to -\delta,\ a \to -a \text{ for } P(\bar{\nu_\mu} \to \bar{\nu_e})$$

$$\frac{aL}{4E} = 7.6 \times 10^{-5}[\mathrm{eV}^2]\left(\frac{\rho}{[\mathrm{g/cm}^3]}\right)\left(\frac{E}{[\mathrm{GeV}]}\right)\frac{L}{4E}\ \propto L$$

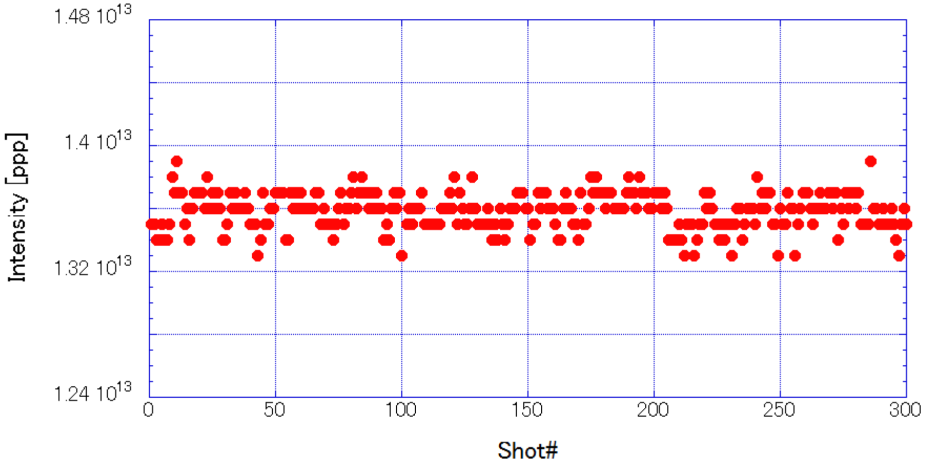
- $P(\nu_\mu \to \nu_e) \to \sin^2(2\theta_{13})$: some ambiguity due to unknown params.
- It is possible to measure CPV by comparing ν and $\bar{\nu}$

Stability of beam

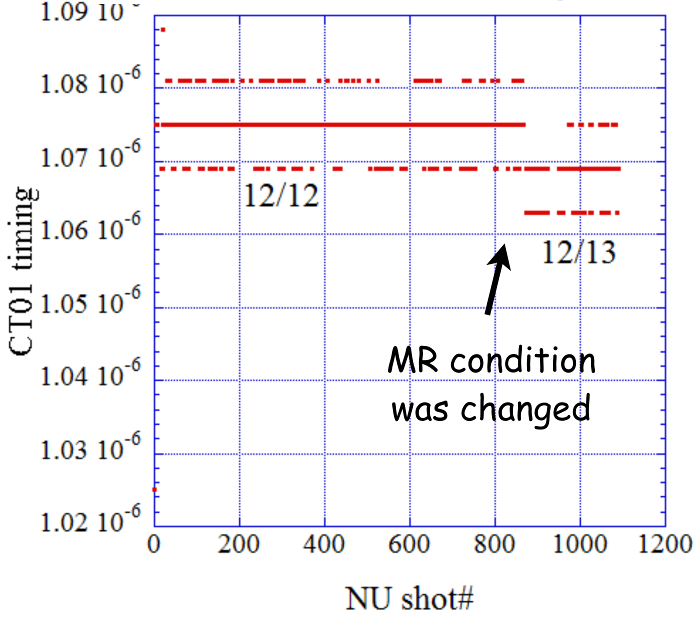
20kW continuous operation

- Stability of beam timing < 4 nsec during a day
- Stability of proton intensity ~3% during a day

proton beam強度の安定性



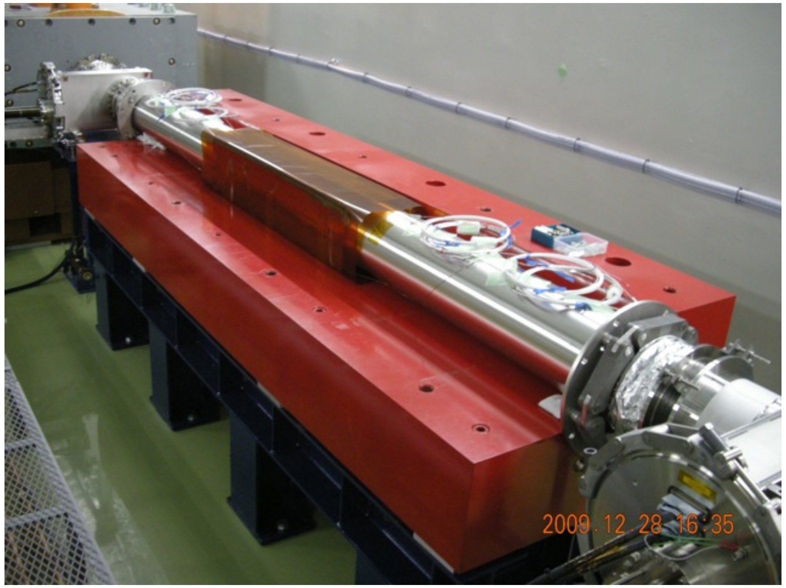
beam取り出しtimingの安定性

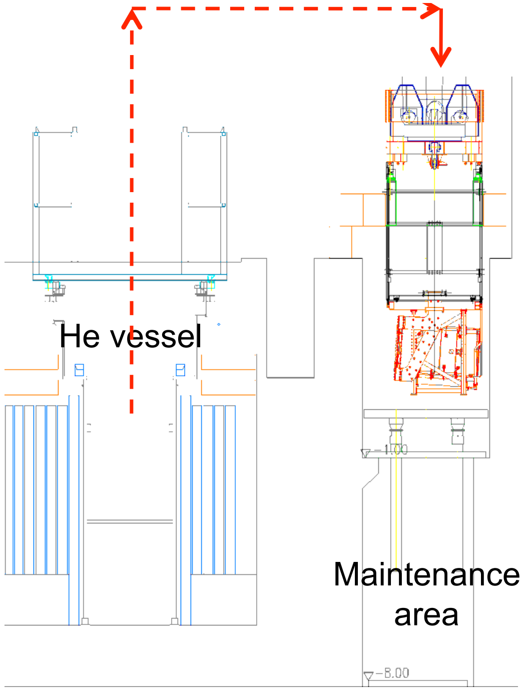


Hardware upgrade

- collimator in the primary beam-line
- remote-controllable attenuator module
- new Horn power supply
- prepare spare target & Horn magnets
- establish remote maintenance scenario at TS

collimator





Horn/Target remote maintenance