# T2K実験

Ken Sakashita(KEK) for T2K collaboration
Dec/17/2010, 平成22年度共同利用研究成果発表会

1. Introduction of T2K experiment
    - Motivation, Features and Sensitivity
2. Status
    - **T2K physics data taking on-going**
3. Future prospects and Summary

# Motivation

- **$\nu_\mu \to \nu_e$振動の発見** → **a finite $\theta_{13}$**

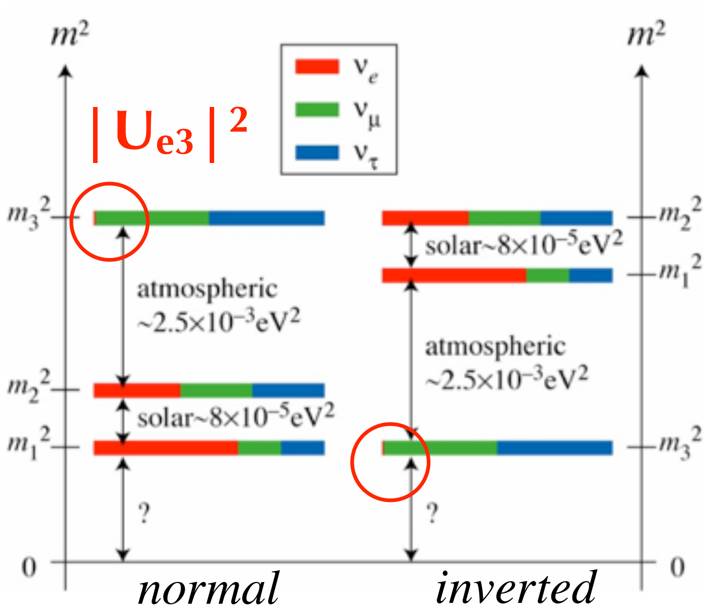
  $\theta_{13}$が有限であれば 将来の実験でCPVの測定が可能

  CP odd term in $P(\nu_\mu \to \nu_e)$ $\propto$ $\sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta$

  **→ レプトンセクターでのCP violationの発見へ**

- **precise measurement**

  Is $\theta_{23}$ maximal ?




これまでの実験結果

$$\theta_{12} = 34^\circ \pm 1^\circ$$

$$\theta_{23} = 45^\circ \pm 18^\circ \quad (90\%\mathrm{CL})$$

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

# Motivation

- **$\nu_\mu \rightarrow \nu_e$振動の発見** ⇒ **a finite $\theta_{13}$** *T2K: $\nu_e$ appearance*

  $\theta_{13}$が有限であれば 将来の実験でCPVの測定が可能

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

  **→ レプトンセクターでのCP violationの発見へ**

- **precise measurement**

  Is $\theta_{23}$ maximal ? *T2K: $\nu_\mu$ disappearance*

これまでの実験結果

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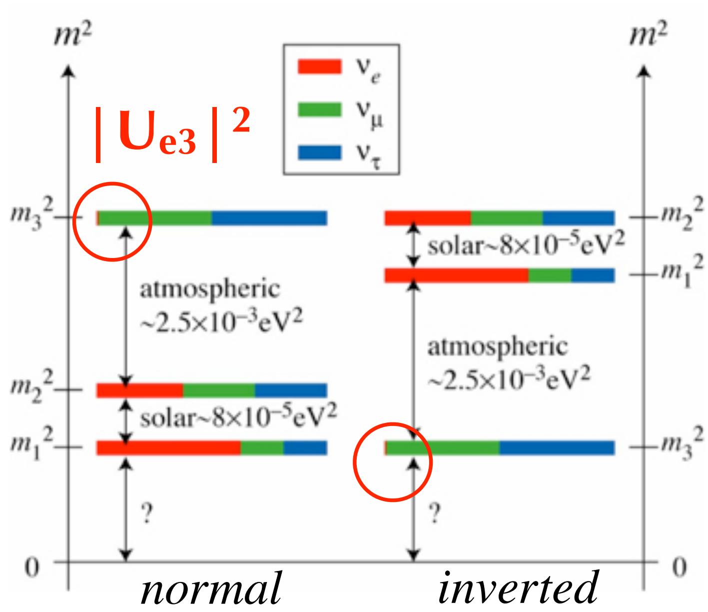
$$\theta_{13} \leq 12° \quad (90\%CL)$$



# Tokai-to-Kamioka(T2K) 長基線ニュートリノ振動実験


*(design intensity 750kW)*

国際コラボレーション（~500 members, 61 institutes, 12 countries）

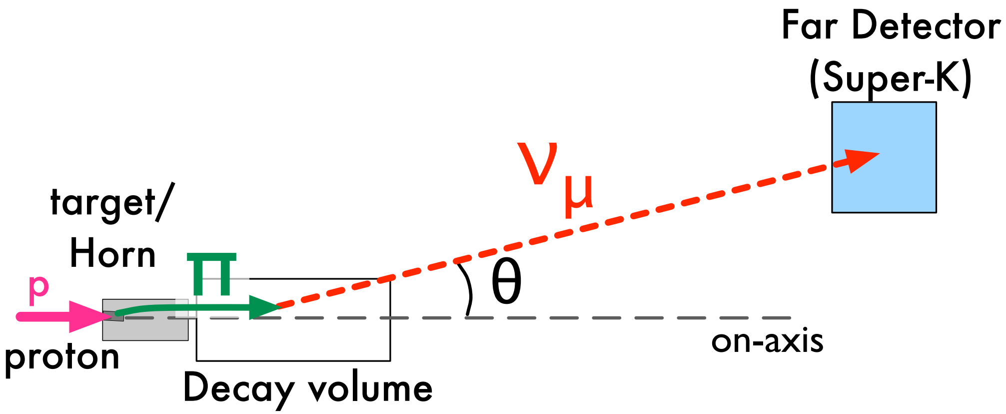
新しいニュートリノ施設@J-PARC：建設 in 2004-2008, コミッショニング in 2009

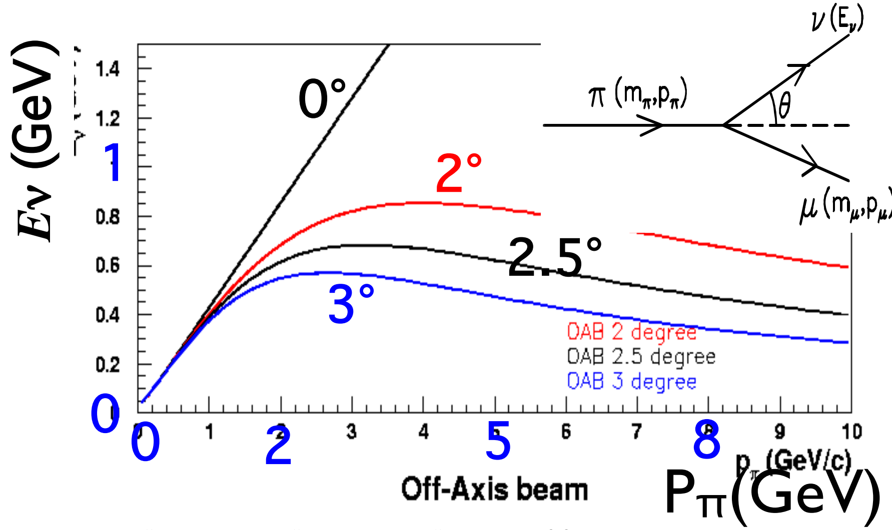
今年から物理データの収集を開始

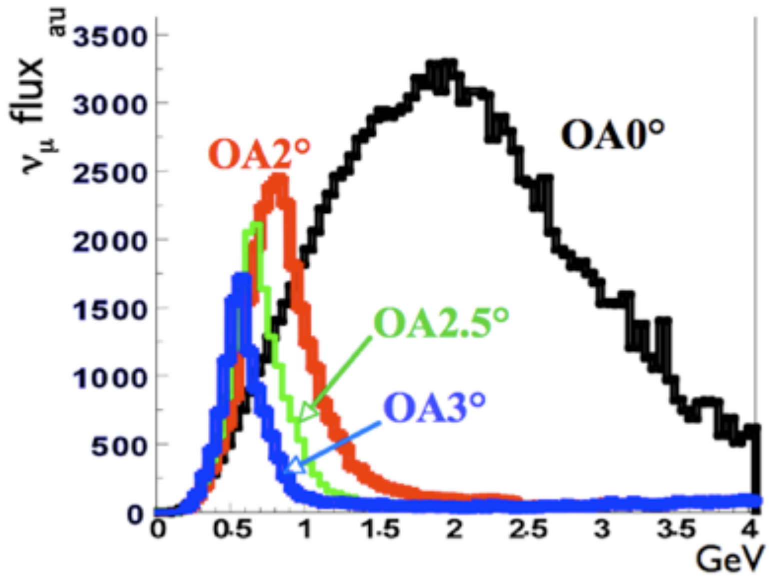
# Features of T2K experiment

- Super-Kamiokande(SK) as main neutrino detector
  - 50kton water cherenkov detector (22.5kton fiducial volume)
  - good PID (e/μ) at sub-GeV, $\delta E_{scale}$ ~ 2%
- High intense neutrino beam
  - conventional beam with ~MW accelerator
  - pure $\nu_\mu$ beam from π/K decays (small $\nu_e$ contamination ~1%)
- Narrow energy band $\nu_\mu$ beam → 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 $\Delta m^2_{23}$ & L=295km)

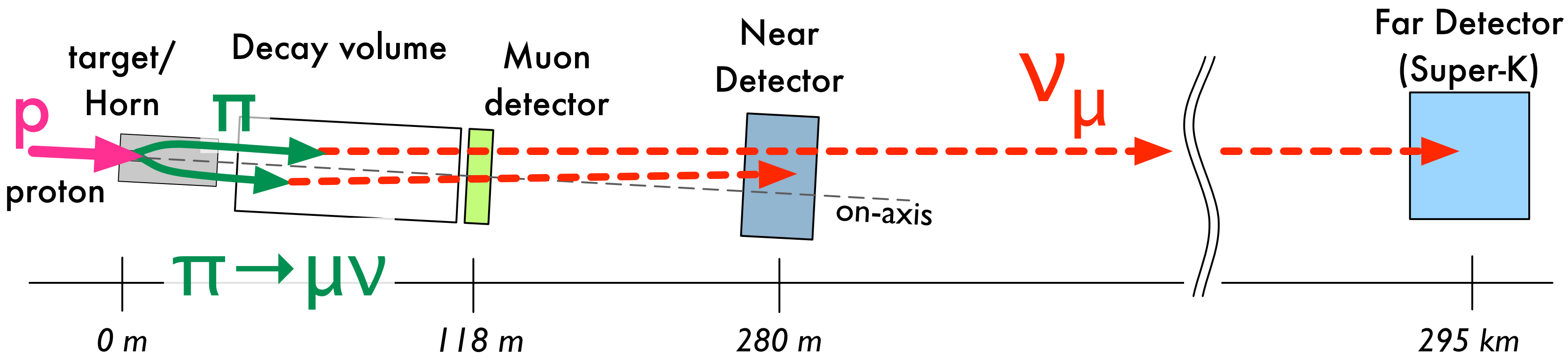
- ~1.2k CC int./year for SK
- small high $E_\nu$ tail (narrow-band)

  → **small # of bkg. for CCQE**

**Important to keep the beam direction stable**

**(monitoring & controlling the beam)**

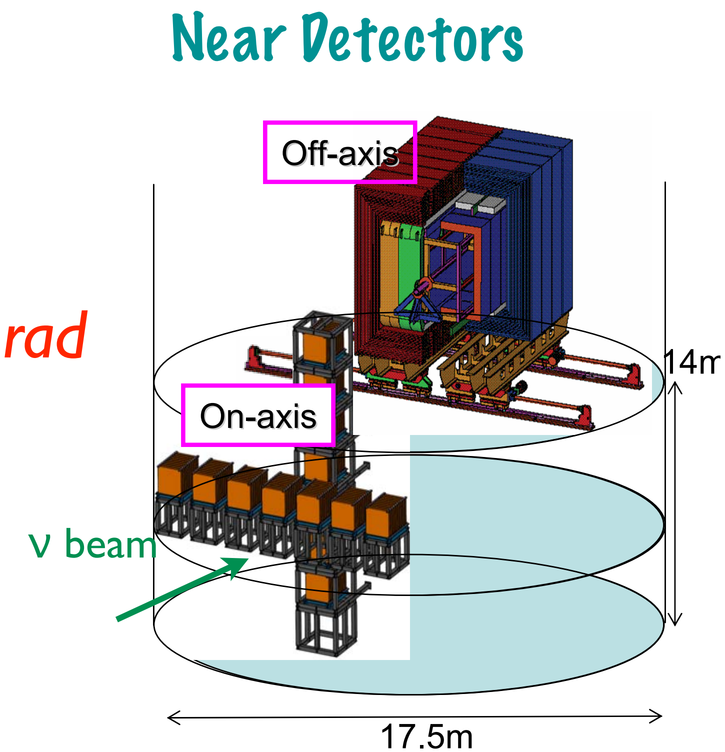
# Experimental setup




- **ビームの方向のモニター**
  - ミューオンモニター (spill by spill)
  - on-axis near detector “INGRID” (day by day)

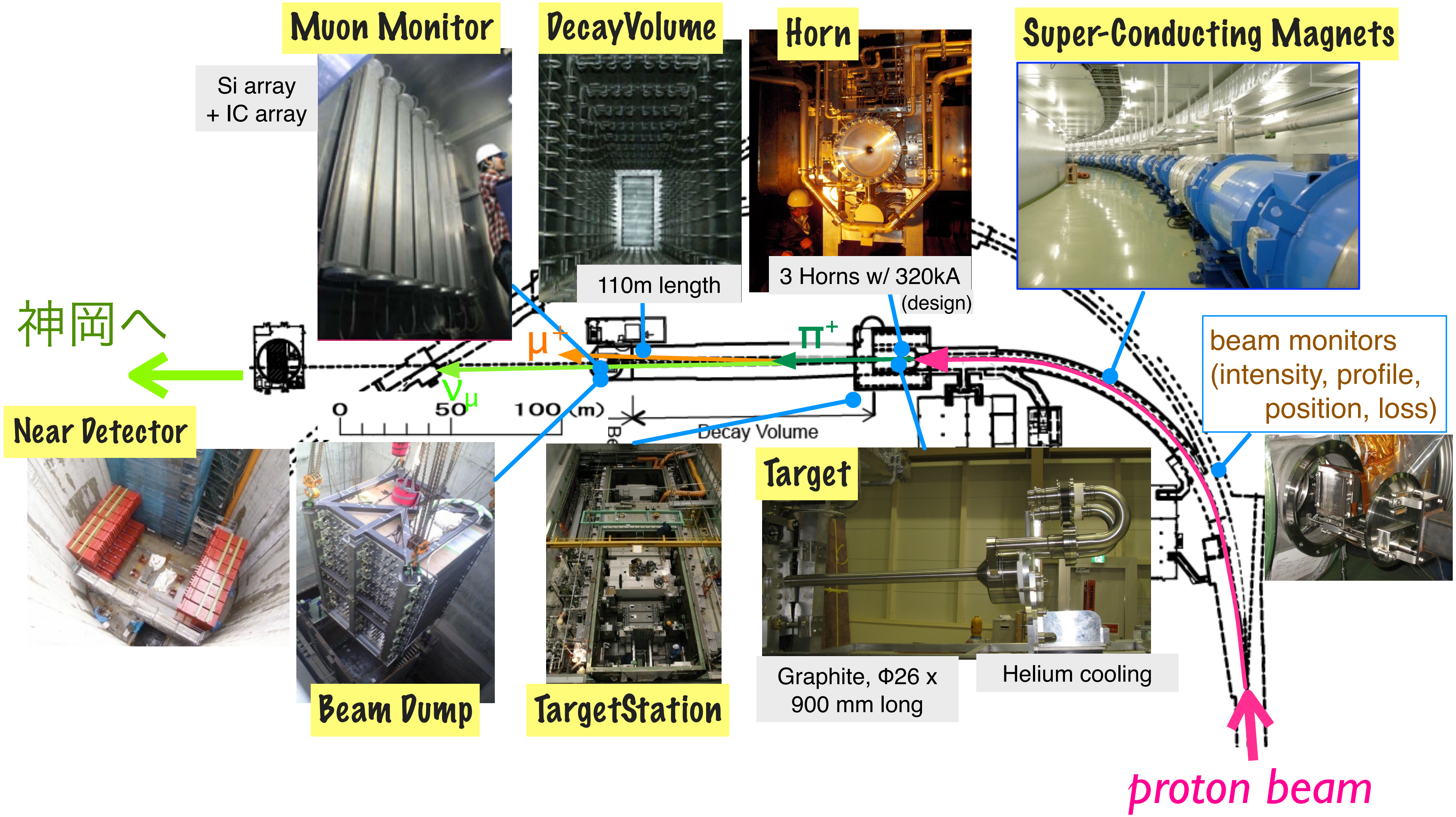
  *uncertainty of beam direction should by <1mrad*

- **ビームのabs. flux, spectrum, $\nu_e/\nu_\mu$の測定、ν相互作用の測定**
  - off-axis near detector (ND280)



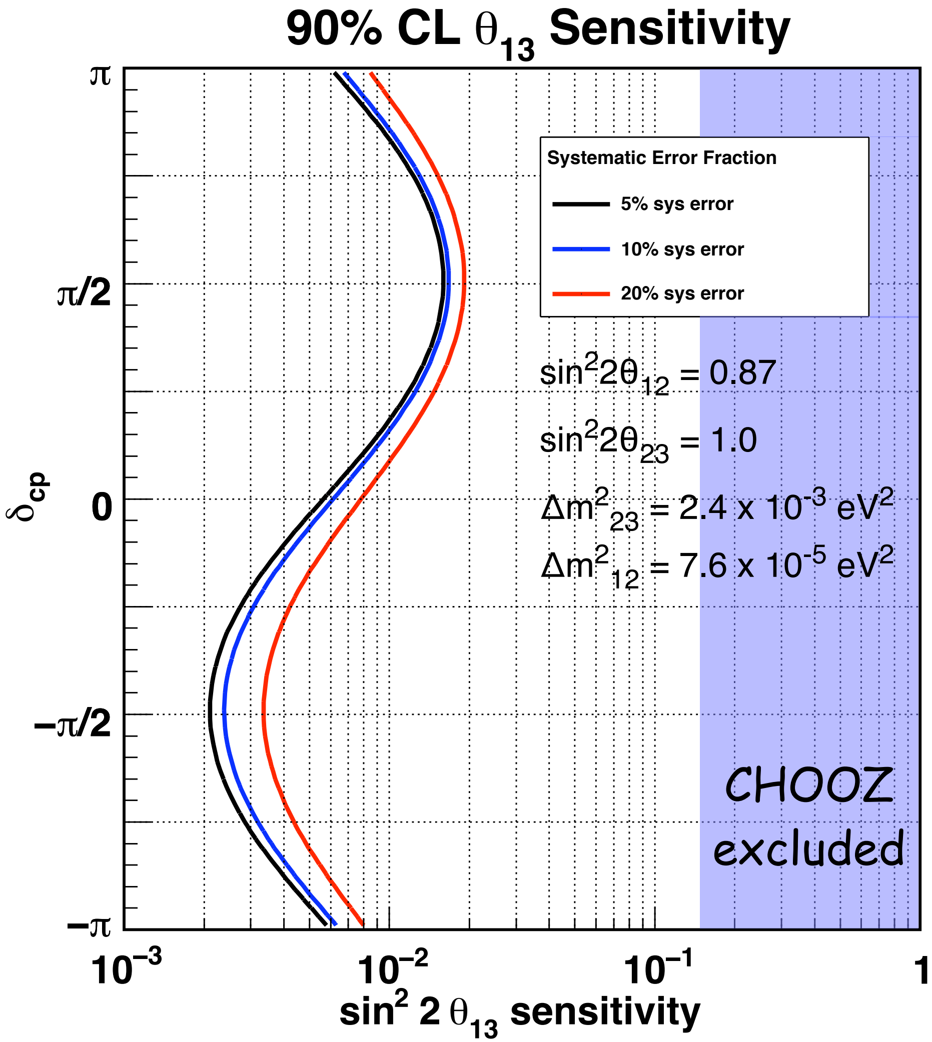
# J-PARC Neutrino beam facility

(大改造なく) 2MWまでのビーム運転可能 ← 世界最大の施設



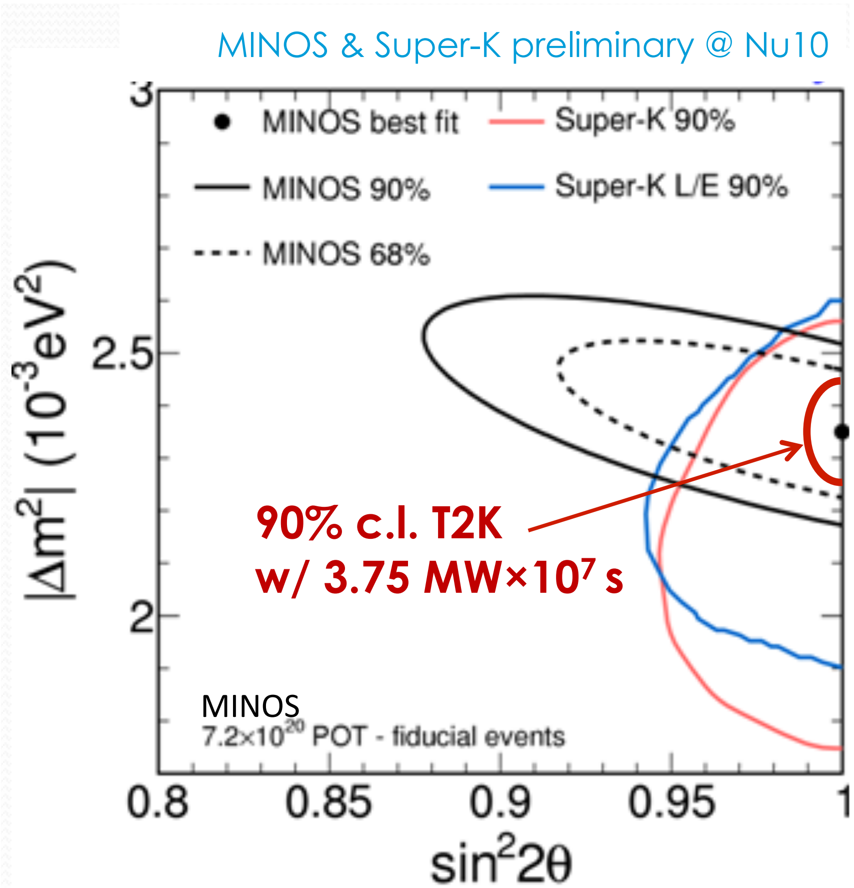
# sensitivity @ 8 x $10^{21}$ protons(30GeV) on target

## $\nu_e$ appearance




**> x10 improvement from CHOOZ limit**

## $\nu_\mu$ disappearance




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

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

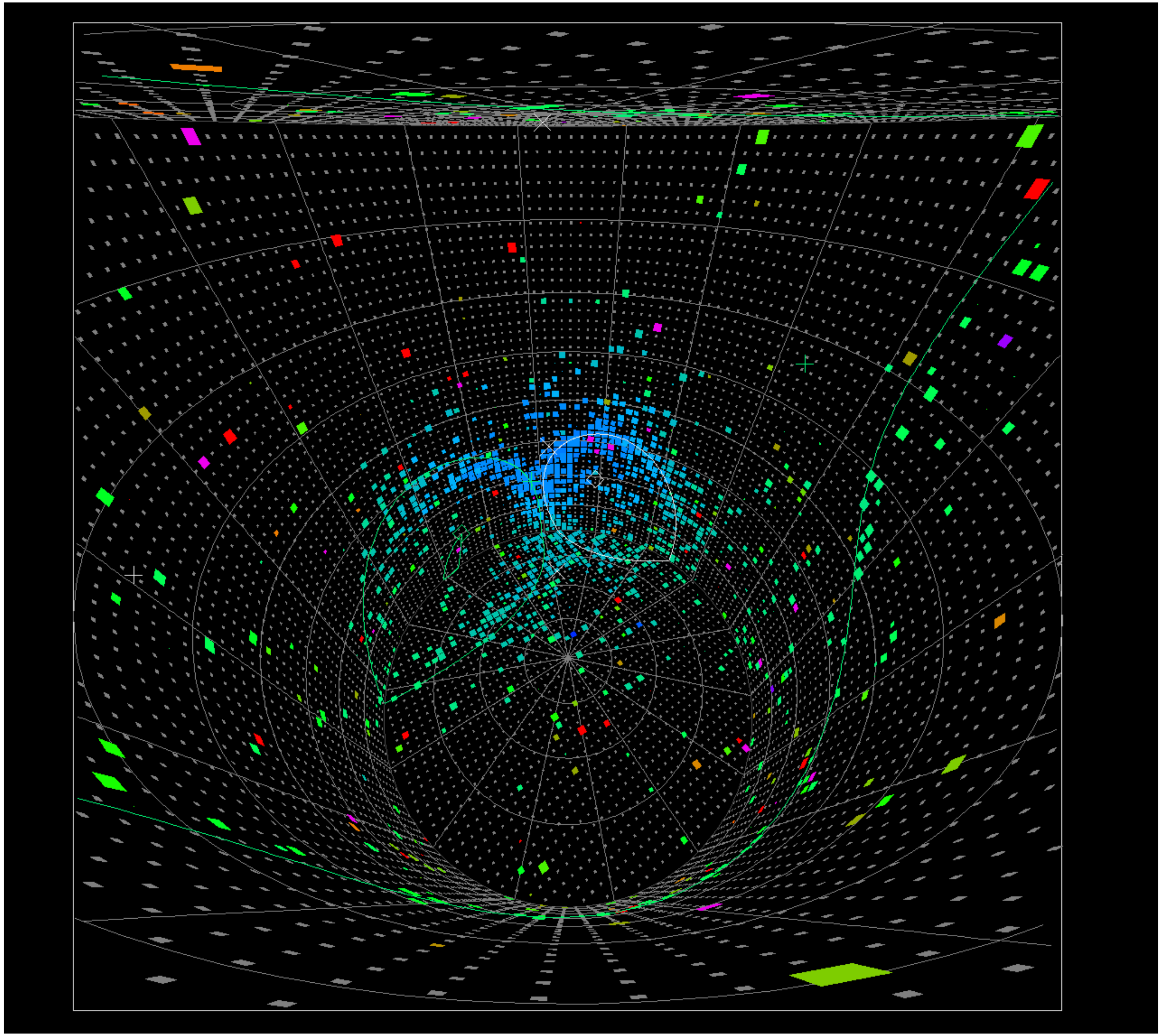
# Status of data taking

2009年4月~12月まで断続的にビームコミッショニング

→ ビームの理解、検出器の立ち上げ

2010年1月から物理データ収集を開始

# First T2K beam event at SK



@2010/Feb./24 6:00

GPSを用いた

beam spill timingで

トリガー

3 rings event

$1^{st}$ ring(showering)

$2^{nd}$ ring(showering)

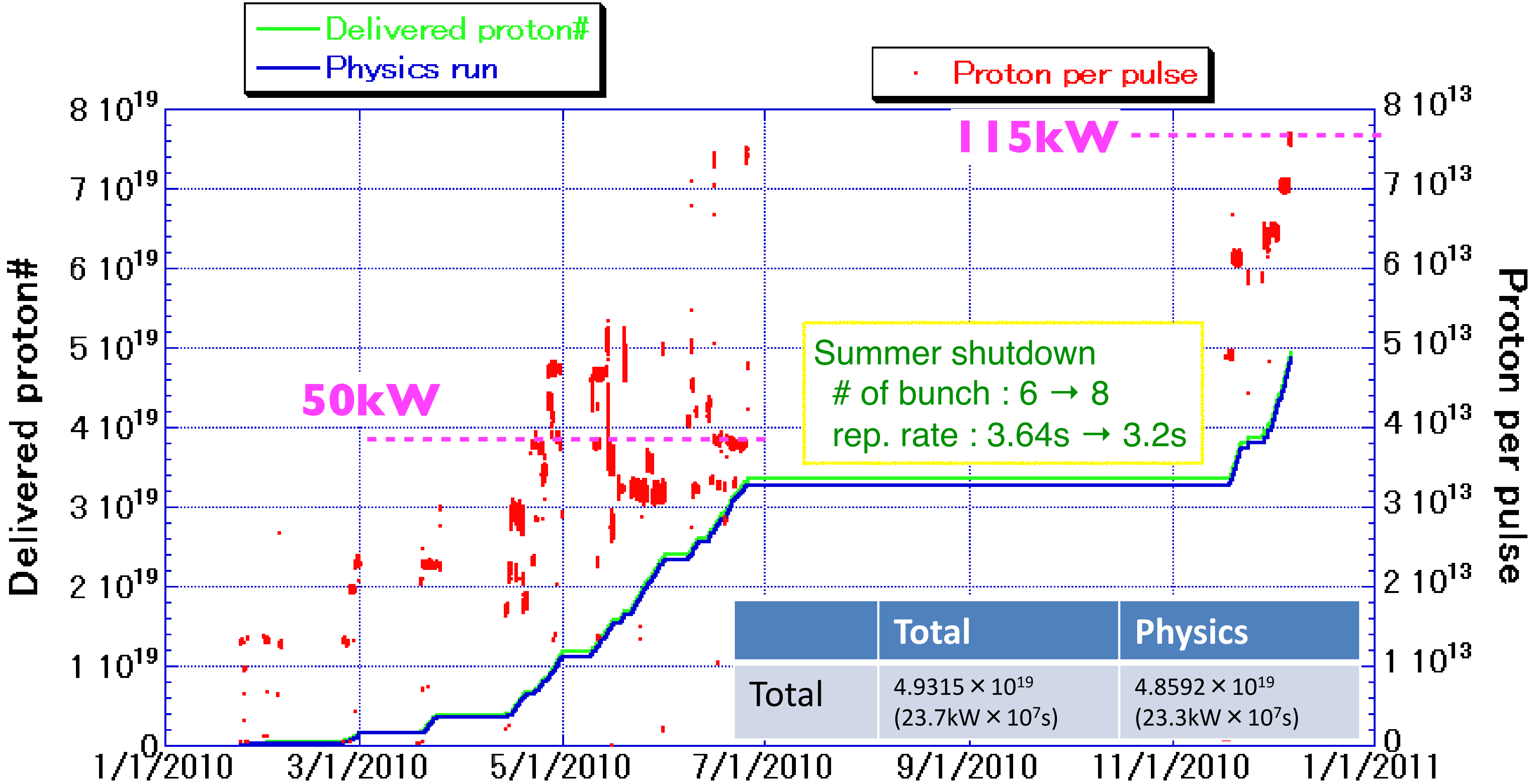
$3^{rd}$ ring (non-showering)

$1^{st}$ + $2^{nd}$

invariant mass : 133 MeV/$c^2$

momentum : 148 MeV/c

# Beam performance



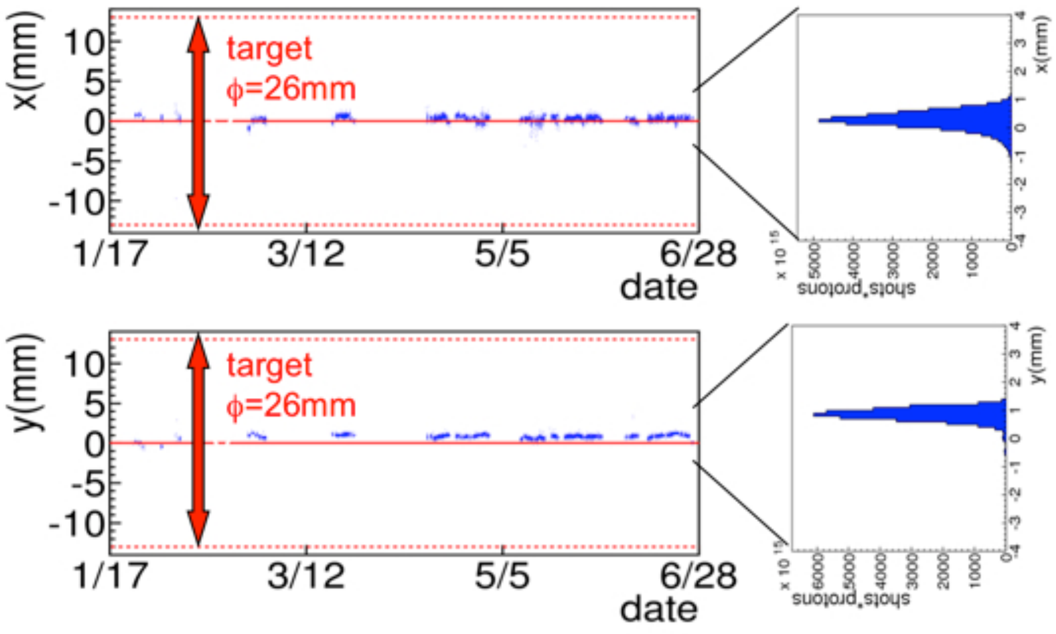

| | Total | Physics |
|---|---|---|
| Total | $4.9315 \times 10^{19}$ ($23.7kW \times 10^7 s$) | $4.8592 \times 10^{19}$ ($23.3kW \times 10^7 s$) |

1st run (Jan. to Jun.) : ~50kW operation, $3.23 \times 10^{19}$ protons for physics analysis

2nd run started from Nov. : increase beam power up to 115kW

# Stable beam operation

**Stability of proton beam position on the target (Jan-Jun)**



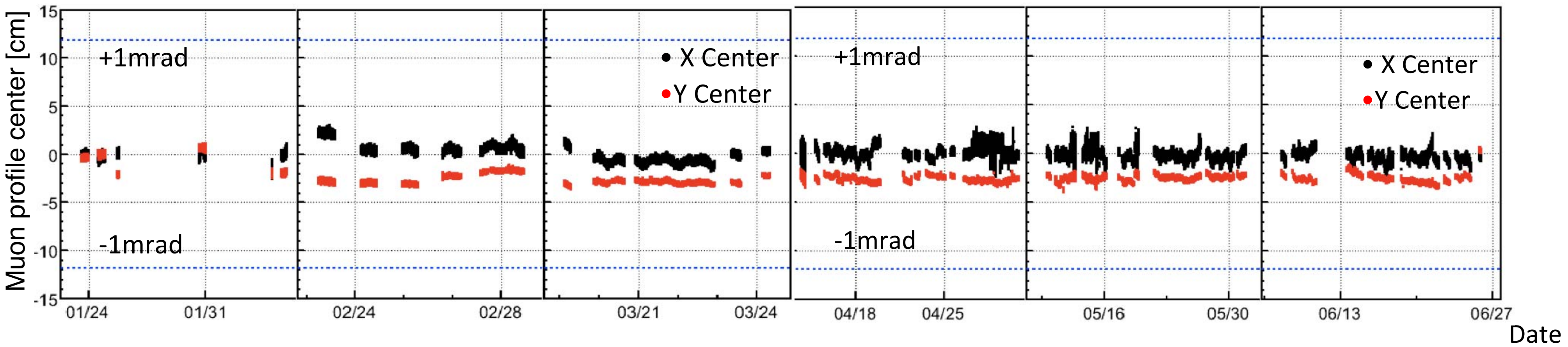

陽子ビームのターゲット上での位置が

1mm以下のずれでコントロールできている

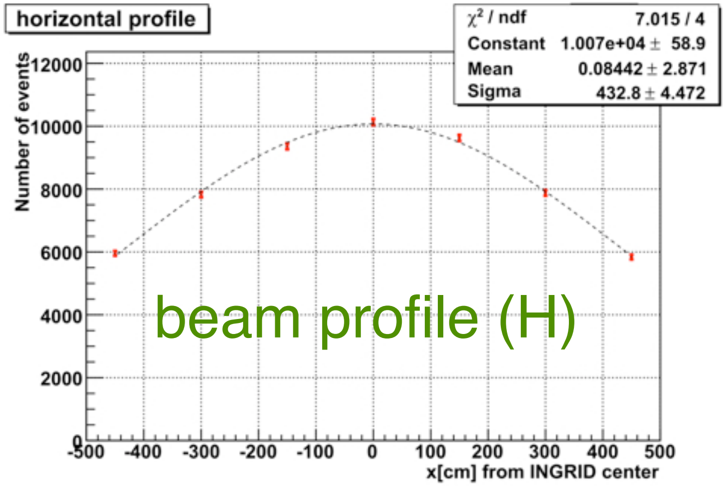
ビームの方向が1mrad以下で

安定している

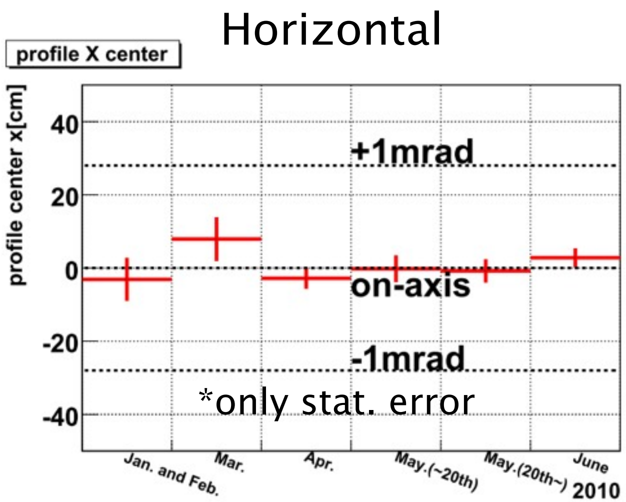
**Stability of beam direction measured by MUMON (Jan-Jun)**

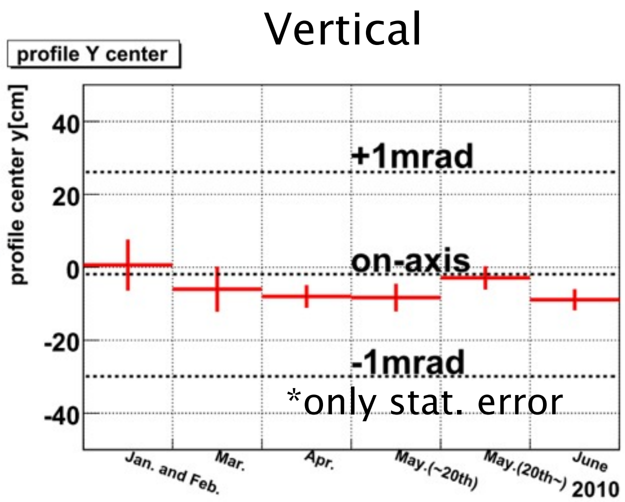


# on-axis前置検出器(INGRID)の測定

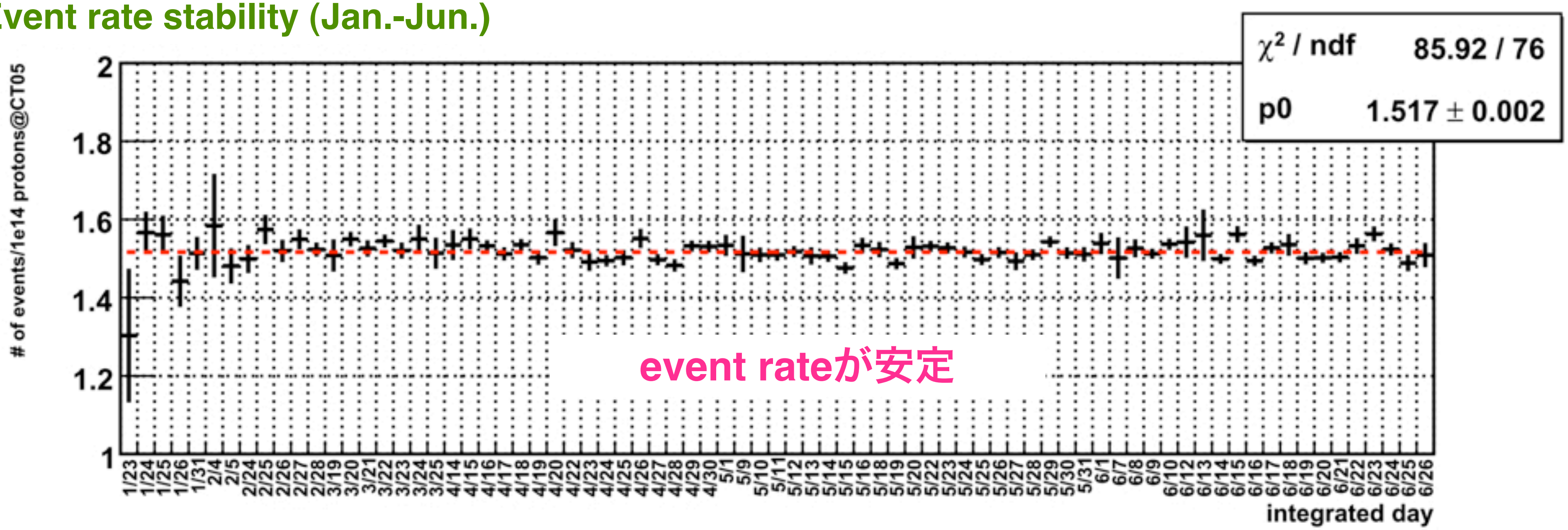



**ν beam方向も安定**

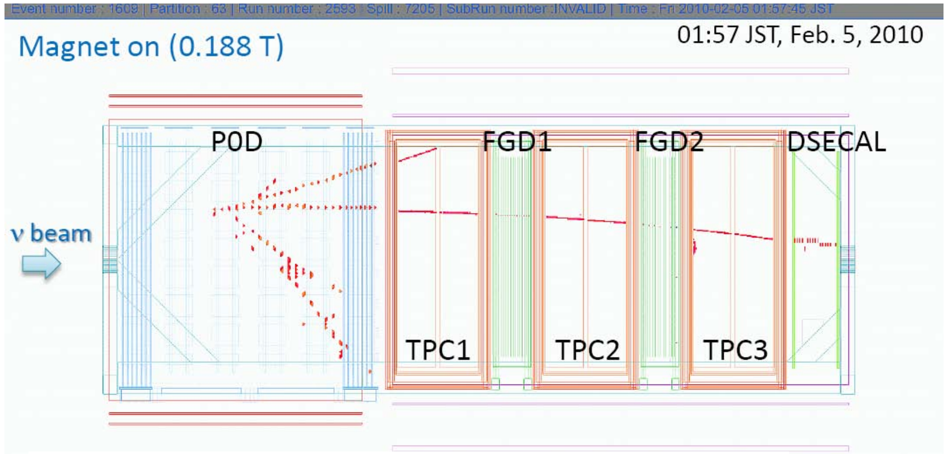



**Event rate stability (Jan.-Jun.)**



# off-axis前置検出器

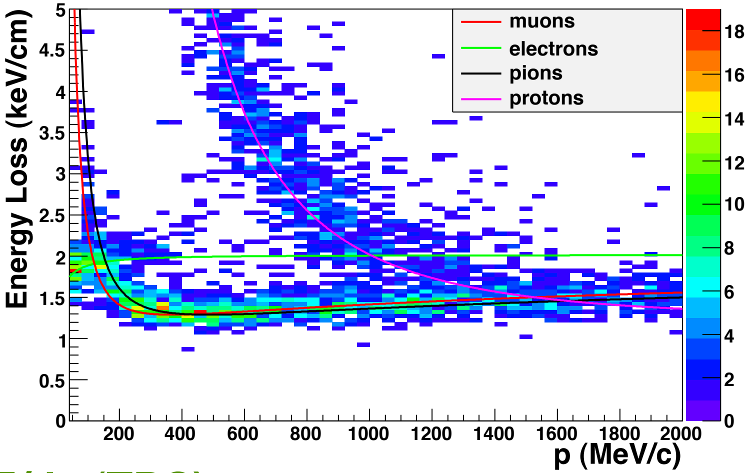



安定してデータ収集している

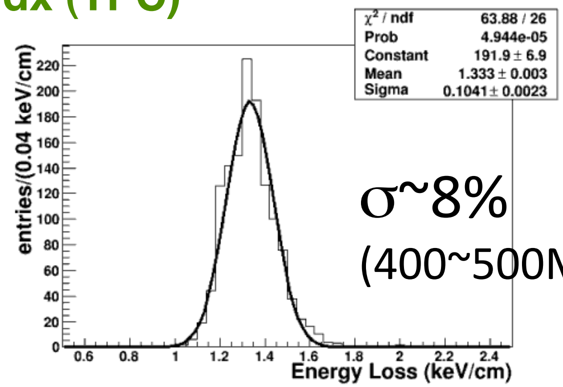
2010前半のデータを解析中

| System | Channels | Bad chan. | Fraction |
|---|---|---|---|
| DSECAL | 3400 | 11 | 0.3% |
| SMRD | 4016 | 3 | 0.07% |
| P0D | 10400 | 7 | 0.07% |
| INGRID | 8360 | 8 | 0.1% |
| TPC | 124416 | 12 | 0.01% |
| FGD | 8448 | 32 | 0.4% |

small # of bad channels



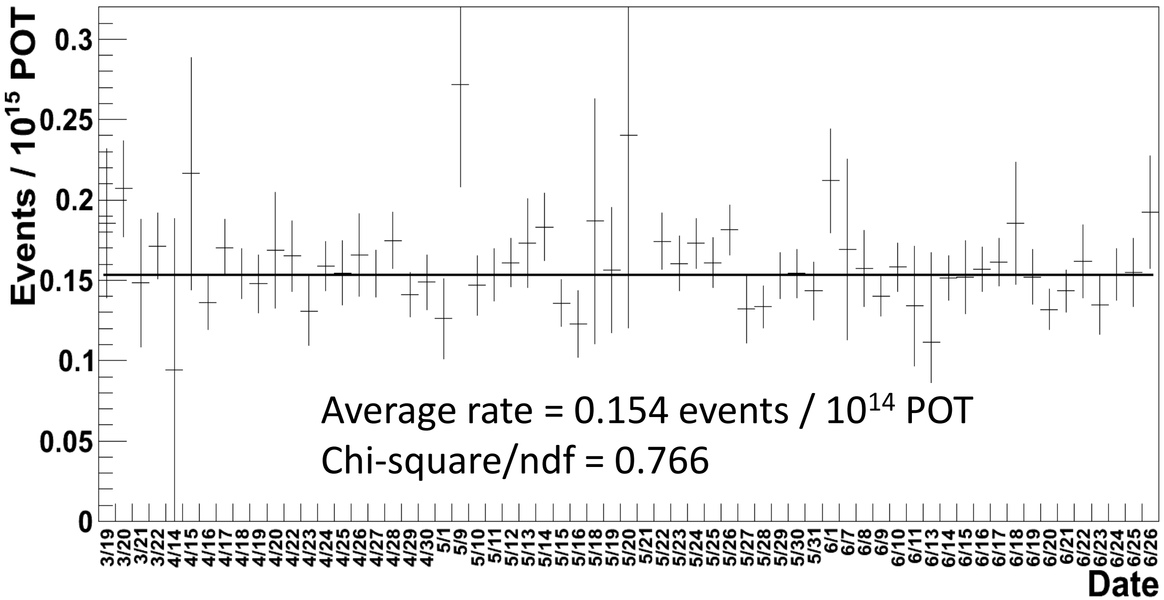

## dE/dx (TPC)




σ~8%

(400~500MeV/c)

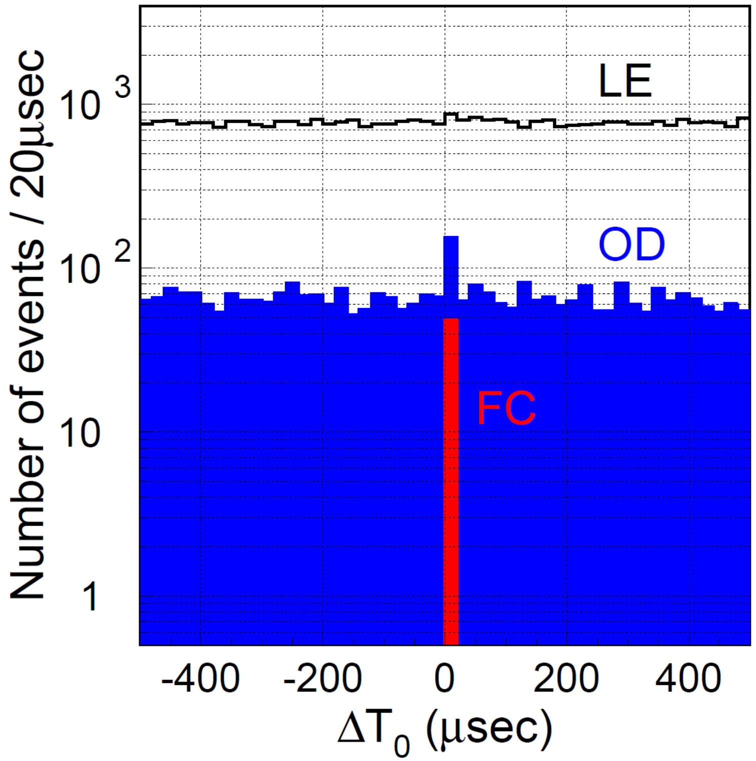
## Event rate stability (FGD)



# T2K beam events @ Super-Kamiokande

T2K beam eventsは GPSを用いたイベント時間でセレクト

relative event timing to the spill timing (Jan-Dec.6)

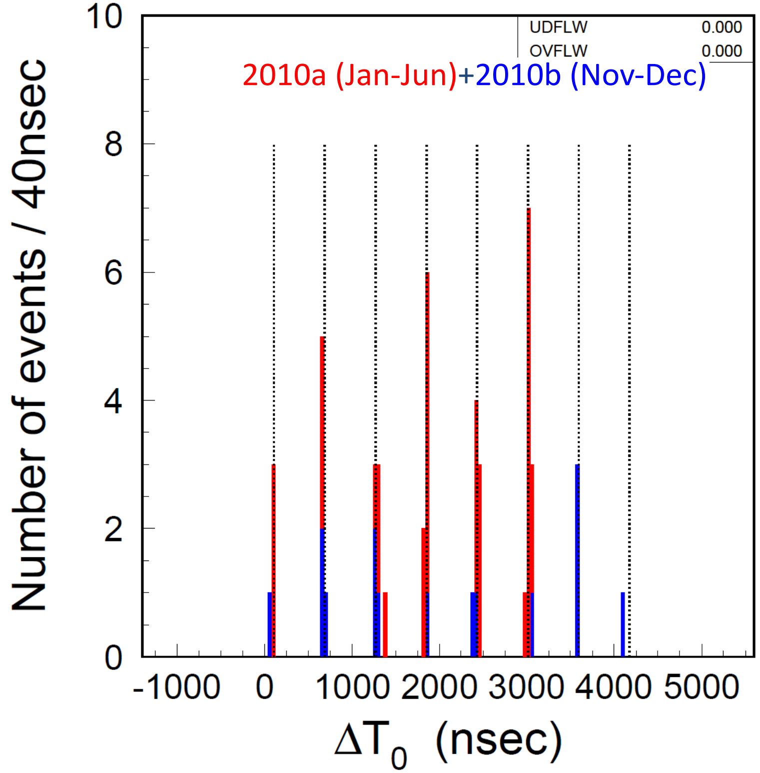



LE: low energy events($E_{vis}$>5MeV)

OD: Outer層に一定以上のヒットあり

FC: Outer層にヒットなし。$E_{vis}$>20MeV

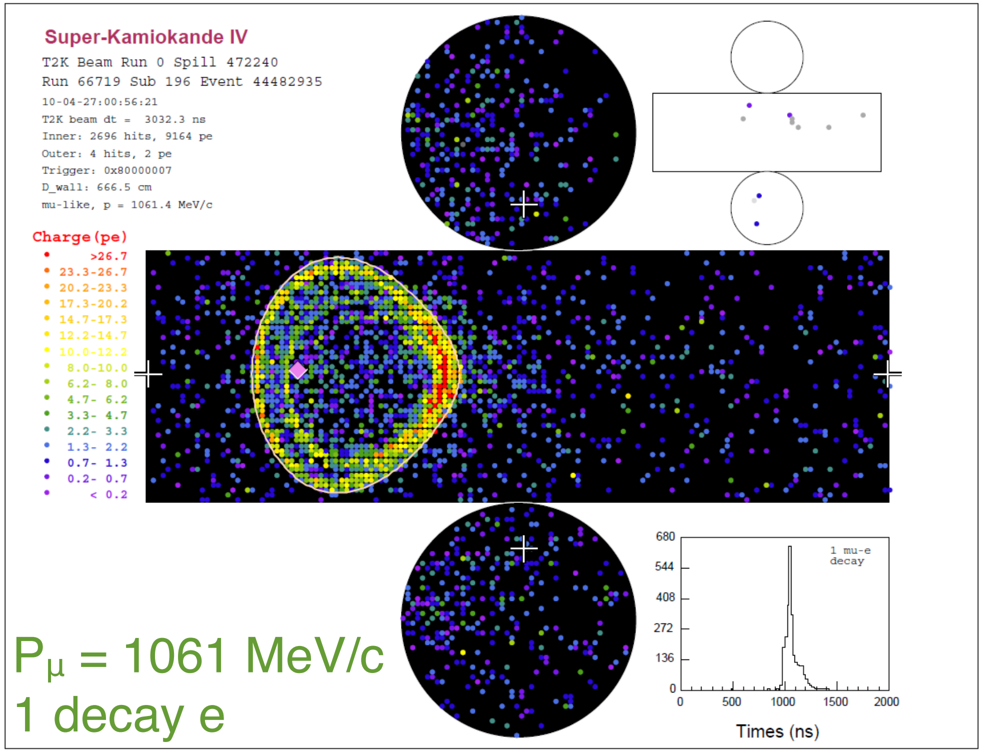
(FC eventsのみ)




J-PARC beam 構造(581nsec間隔 x 8bunch)に一致している

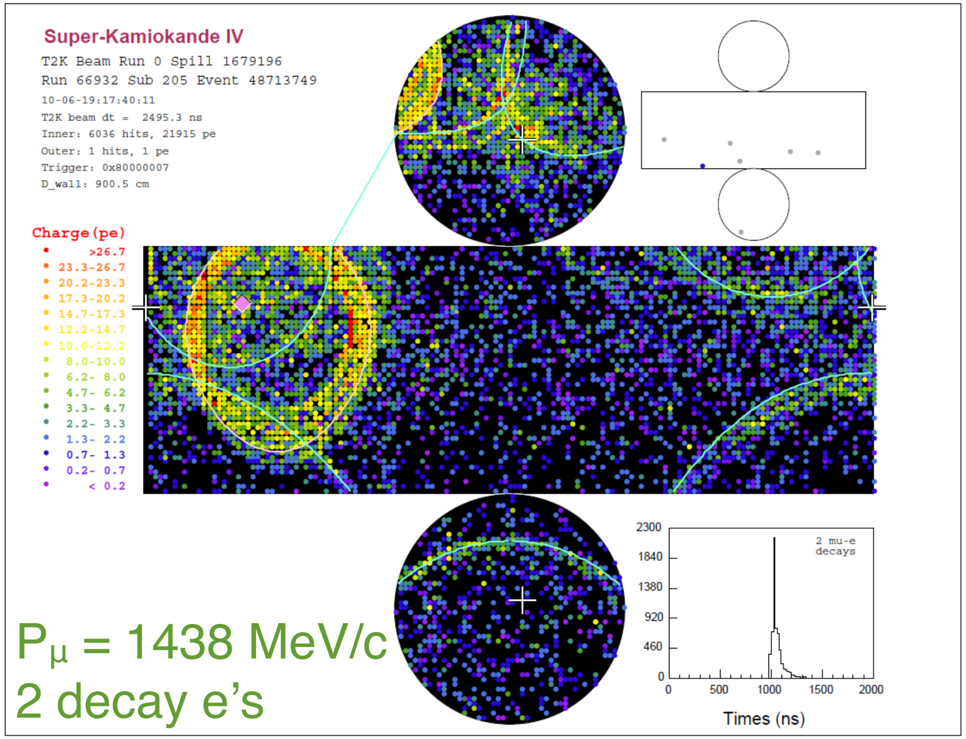
# Observed T2K beam events @SK

single-ring μ-like event




$P_\mu$ = 1061 MeV/c
1 decay e

multi-ring μ-like event




$P_\mu$ = 1438 MeV/c
2 decay e's

| Jan-June 2010 | # of events |
|---|---|
| Fully-Contained (FC) | 33 |
| + fiducial volume cut<br>+ visible E > 30 MeV (FCFV) | 23 |

# Super-Kamiokande event selection

SK analysis is well established

* >20years experiences w/ Water Cherenkov detector

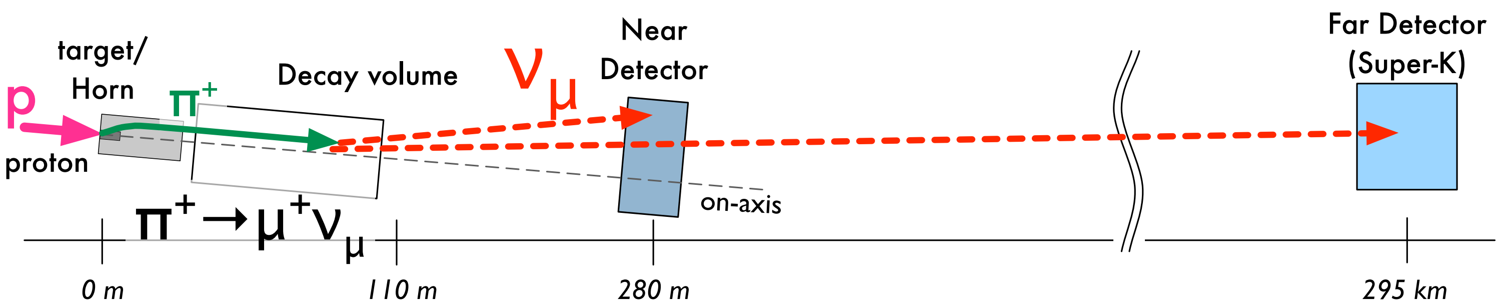
Event selection & cut value are fixed already

→ Unbiased selection

| For $\nu_\mu$ disappearance analysis | For $\nu_e$ appearance search |
|---|---|
| Timing coincidence w/ beam timing (+TOF) | |
| Fully contained (No OD activity) | |
| Vertex in fiducial volume (Vertex >2m from wall) | |
| Evis > 30MeV | Evis > 100MeV |
| # of ring =1 | |
| μ-like ring | e-like ring |
| | No decay electron |
| | Inv. mass w/ forced-found $2^{nd}$ ring < 105MeV |
| | $E_\nu^{rec}$ < 1250MeV |

2010前半データの物理解析が進行中

# analysis strategy

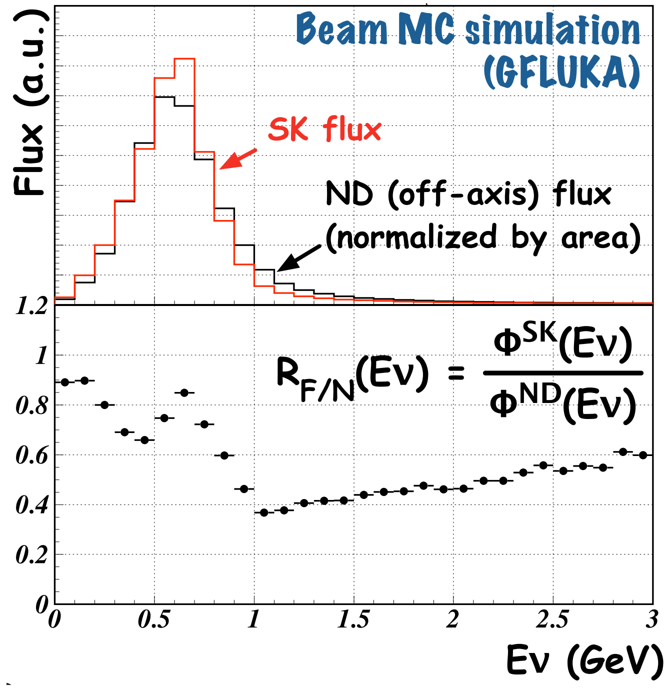



$N^{SK}_{obs}(E^{rec})$

SKでのν事象数、spectrumの測定値を
予想値と比較して解析

$N^{SK}_{exp}(E^{rec})$ =

$P_{osc.}(E) \times \Phi^{SK}(E) \times \sigma(E) \times \varepsilon(E) \times M(E,E^{rec})$

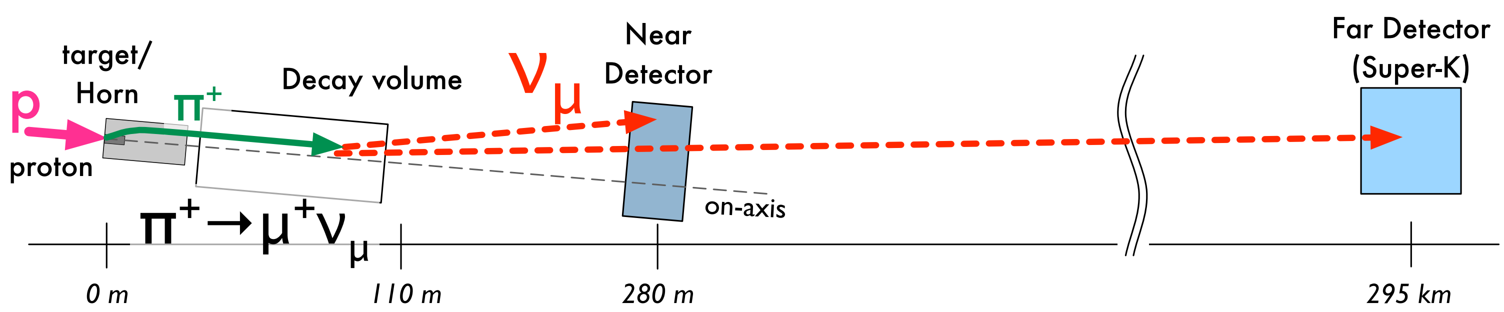



Φ : Flux
σ : ν int. xsec
ε : efficiency
E: ν true energy
$E^{rec}$ : ν reconst. energy
$M(E,E^{rec})$ :
detector response

ND spectrum測定から$\Phi^{ND}(E)$を求め、
beam MCの情報を使って外挿

$\Phi^{ND}(E) = N^{ND}_{obs}(E) / (\sigma(E) \times \varepsilon(E))$

# analysis strategy




$N^{SK}_{obs}(E^{rec})$

SKでのν事象数、spectrumの測定値を
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$\updownarrow$

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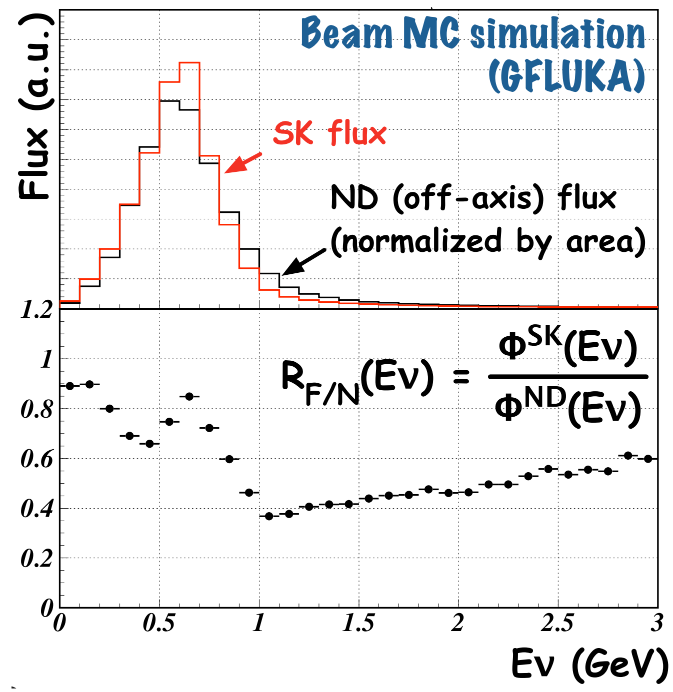
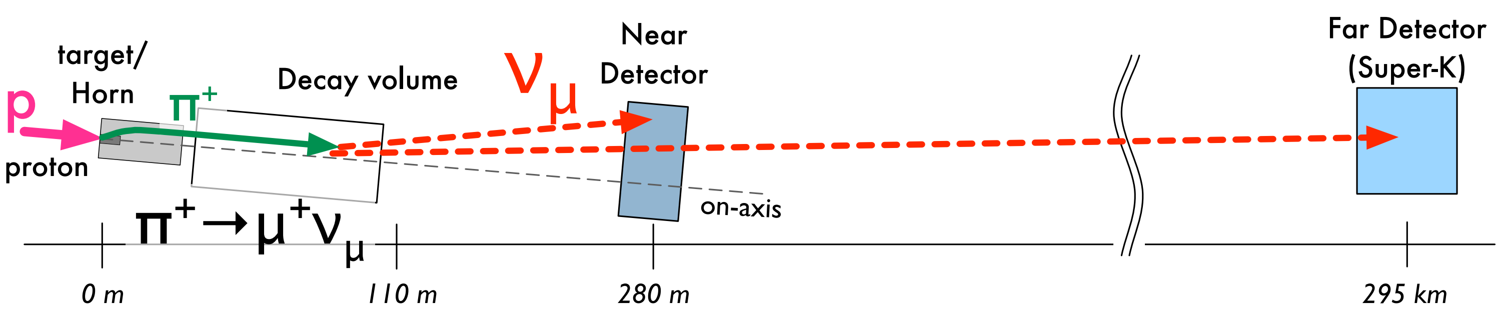



精度を上げるためには

◯ **(1) near-to-far extrapolation (beam MCのprediction)** ← Hadron production測定

# analysis strategy




$N^{SK}_{obs}(E^{rec})$

↕

SKでのν事象数、spectrumの測定値を予想値と比較して解析

$N^{SK}_{exp}(E^{rec}) = P_{osc.}(E) \times \Phi^{SK}(E) \times \sigma(E) \times \varepsilon(E) \times M(E, E^{rec})$

Φ : Flux
σ : ν int. xsec
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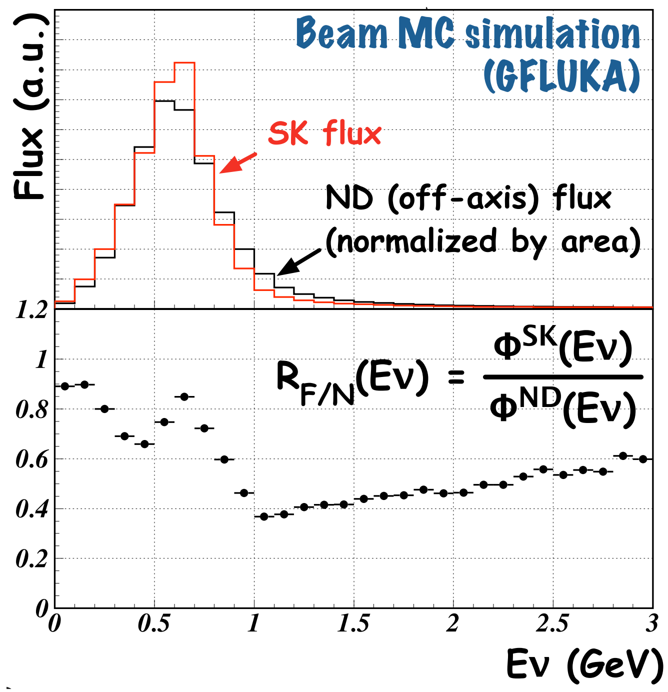



精度を上げるためには

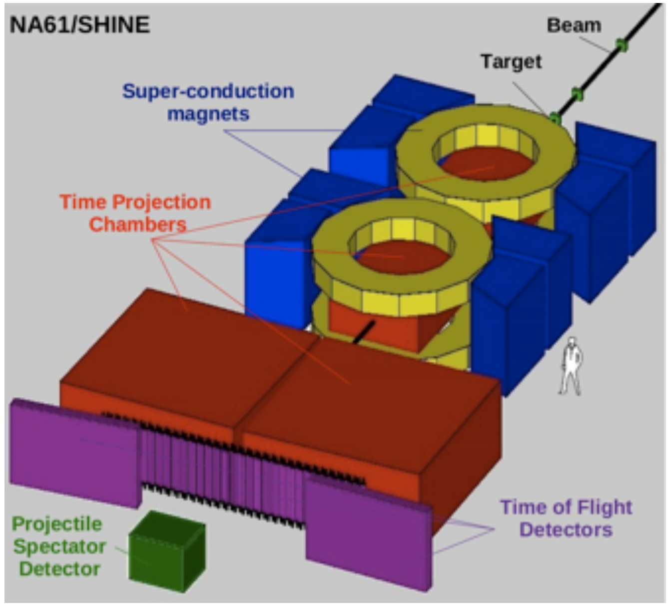
◯ **(1) near-to-far extrapolation (beam MCのprediction)** ← Hadron production測定

◯ **(2) neutrino interaction cross section** ← ND280の測定 + これまでの実験結果

# Hadron production 測定

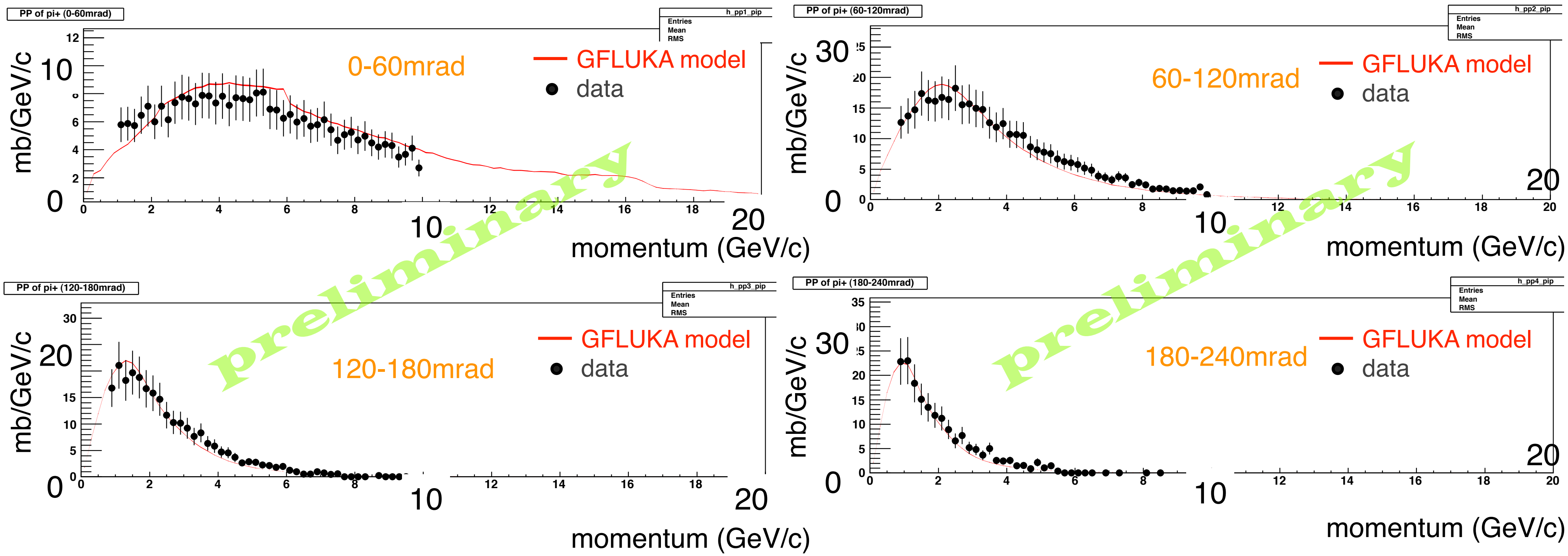
CERN NA61実験

p + C → π(or K) + X




- pilot run in 2007 and high stat. run in 2009
  - 30GeV p + C (thin target 4%$\lambda_I$ and T2K replica target)

preliminary results of $\pi^+$ production from thin target
(only ’07 data, 20% systematic error)

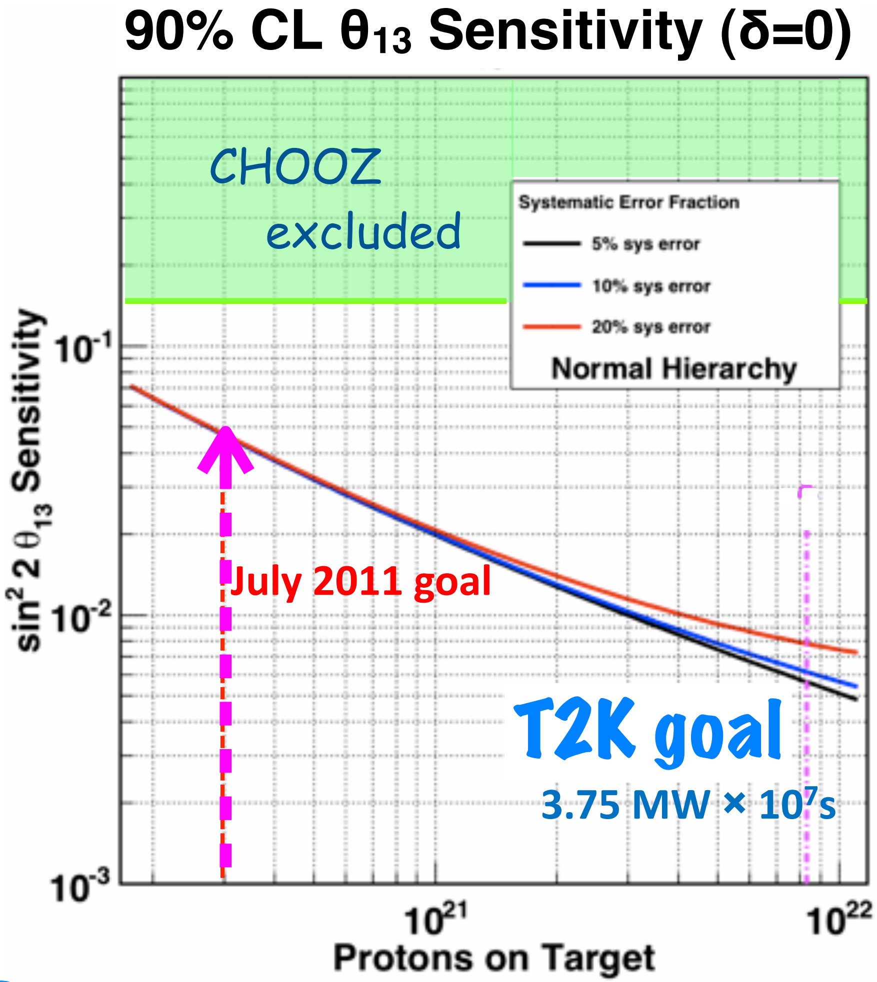



implement in beam MC → reduce T2K systematic uncertainty

# Prospects

- 2010 2nd run started in Nov. 18th
  - increasing the beam power (115kW at present)
  - aim to accumulate **150kW * $10^7$ sec** by next summer

- **Next step : 1MW x $10^7$sec in a few years**
  - $\sin^2 2\theta_{13} = 0.05$ (3σ discovery @ 1MW*$10^7$sec)




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

# まとめ

- T2K長基線ニュートリノ振動実験
  - discovery of $\nu_e$ app. & precise measurement of $\nu_\mu$ disapp.
- **物理データ収集を開始**
  - 1st run January - June 2010
    - beam power ~50kWで運転。ビーム・検出器ともに安定
    - Observed # of FCFV events : 23
    - Expect first results by winter 2011 conference
  - 2nd run Nov. - Summer 2011
    - 現在のビームパワー 115kW
    - Aim for 150kW x $10^7$ sec → $\sin^2 2\theta_{13} \sim 0.05$ (90% C.L.)

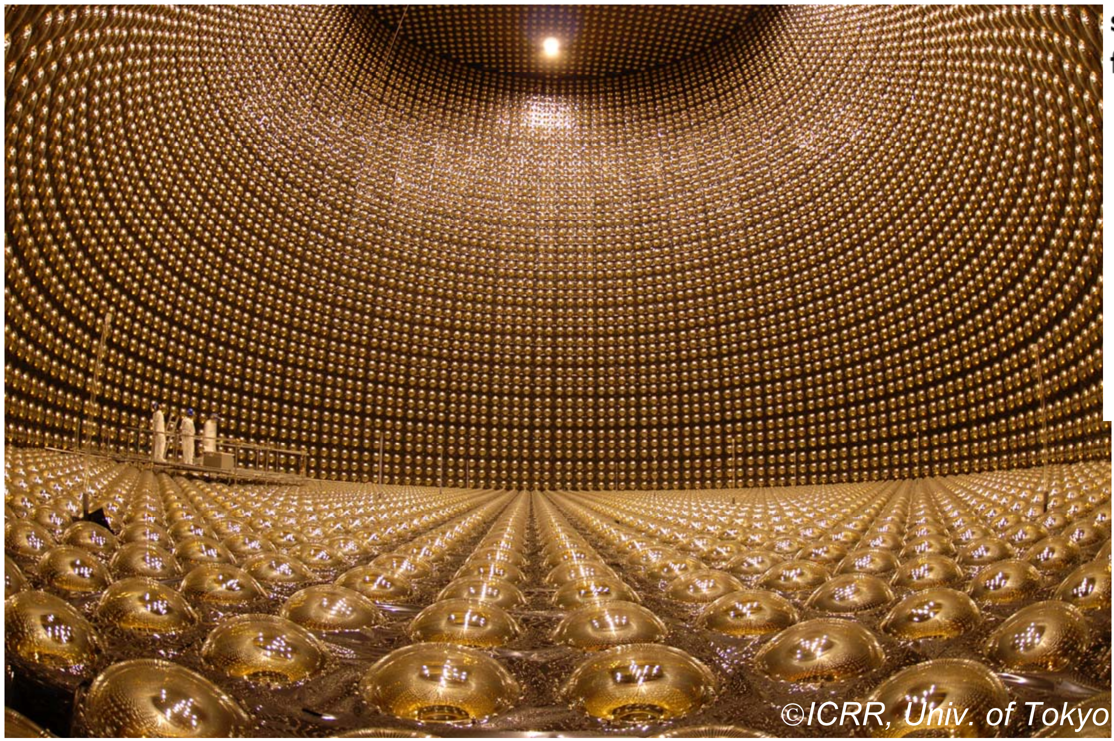
査定金額：8万円（T2KSKシフトの旅費の一部として使用)

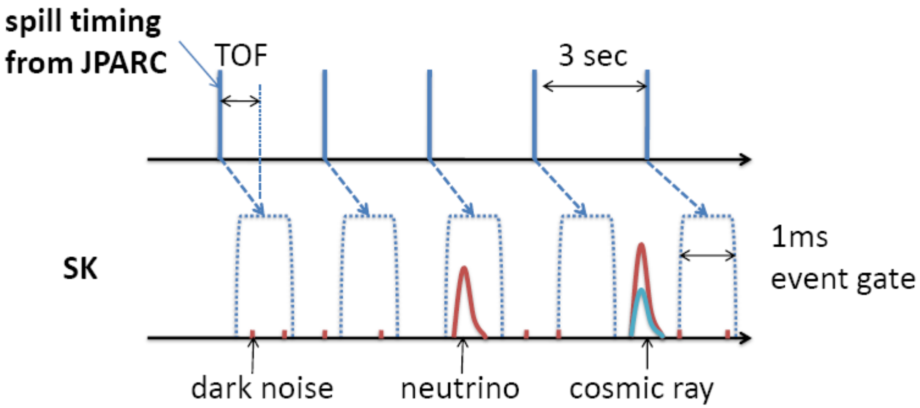
backup

# Super Kamiokande (far detector)

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

→ trigger of T2K event



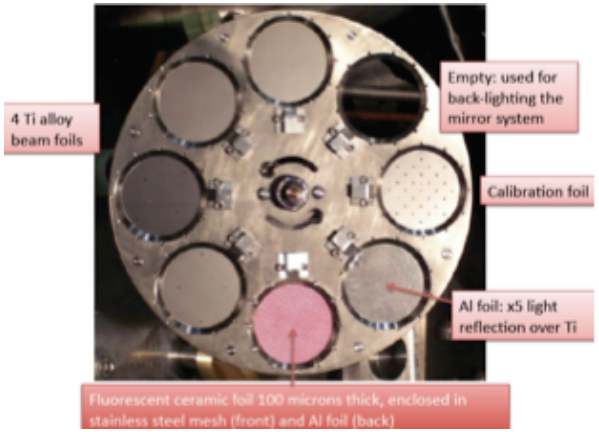




T2K trigger = spill timing ± 500μsec

~11000 x 20inch PMTs
(inner detector)

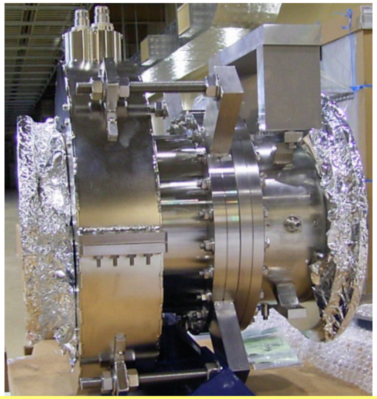
# Proton beam monitor

ターゲット直前の
ビームプロファイル



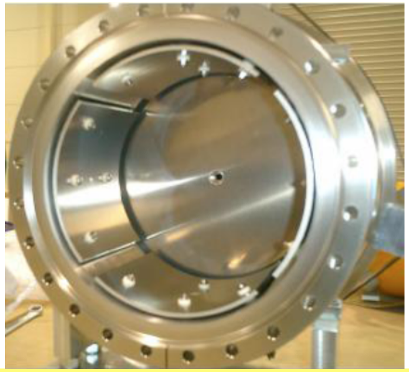

Optical Transition Radiation (OTR)

ビーム強度



Current Transfomer (CT)

ビーム位置

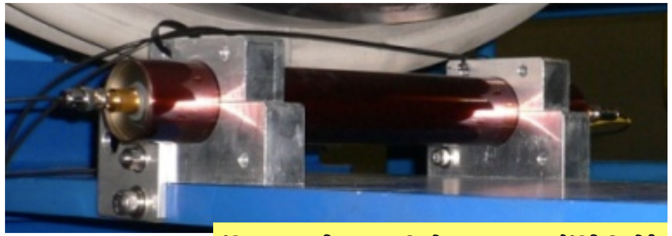


Electro Static Monitor (ESM)

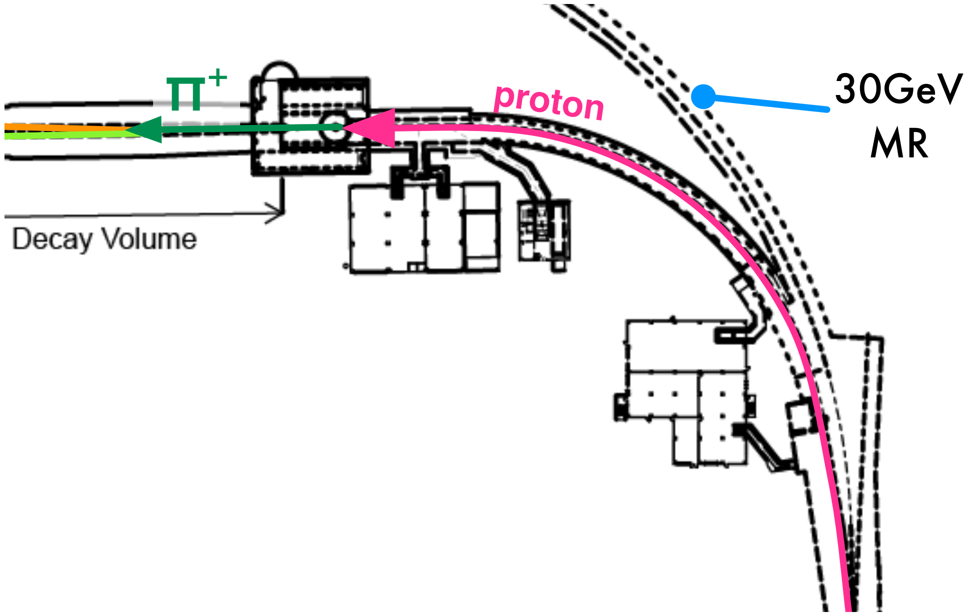
ビームプロファイル

Segmented Secondary Emission Monitor (SSEM)

ビームロス



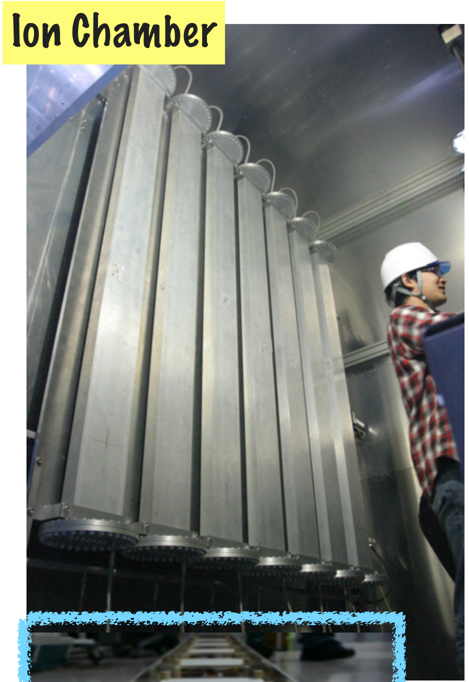
Beam Loss Monitor (BLM)



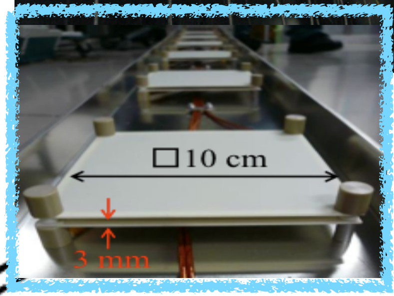

| monitor name | purpose | quantity |
|---|---|---|
| CT | intensity | 5 |
| ESM | position | 21 |
| SSEM | profile | 19 |
| BLM | loss | 50 |
| OTR | profile at target | 1 |

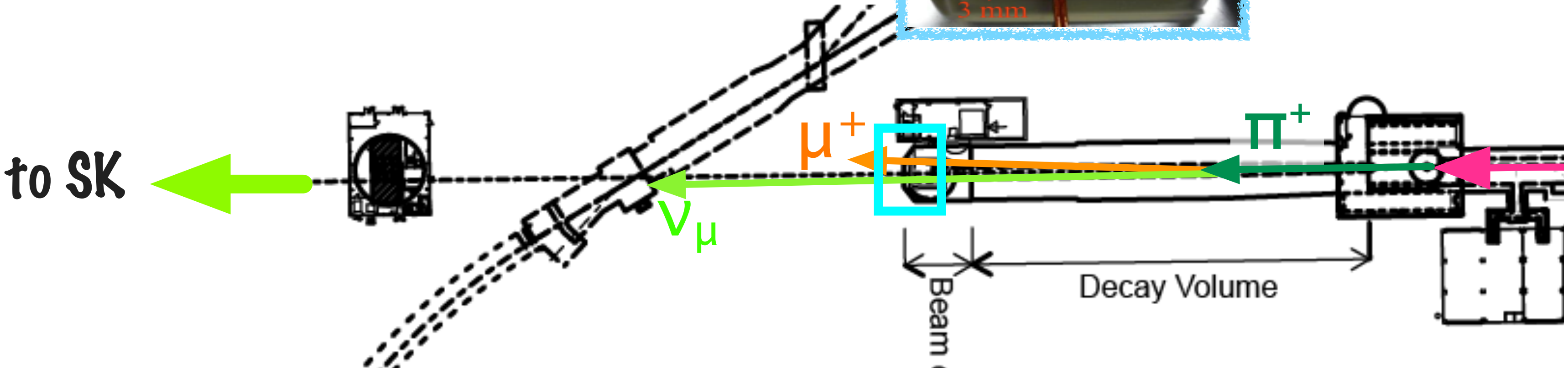
# Muon beam monitor

- 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



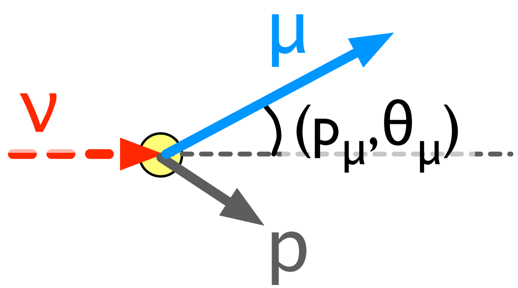




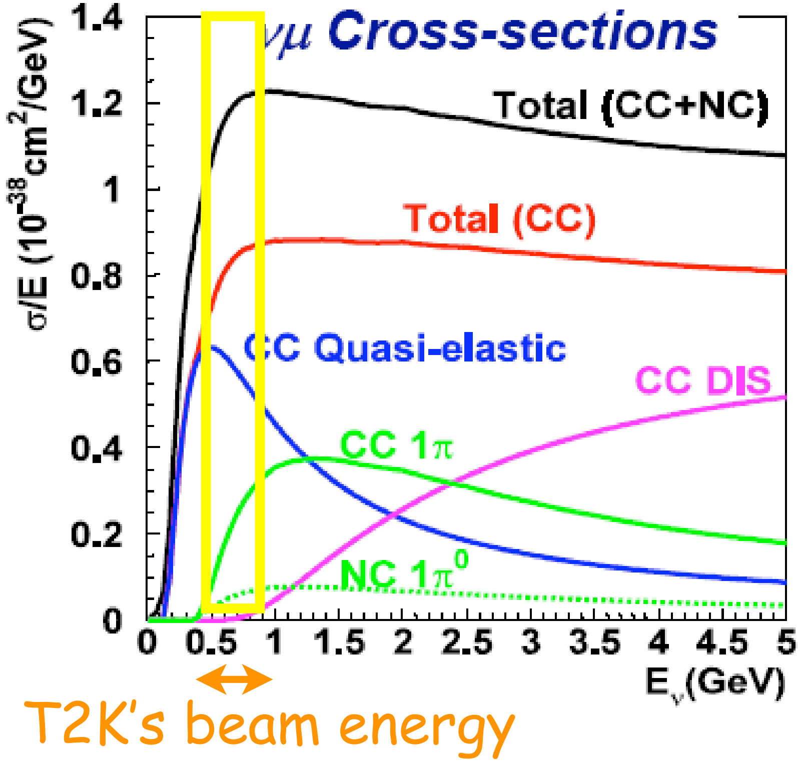



# ν Energy Reconstruction

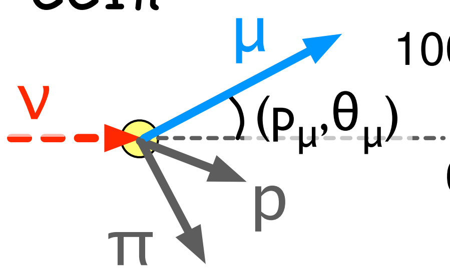
- ν's Energy reconstruction is possible for CC Quasi-Elastic interaction (CCQE: $\nu_{\mu(e)} + n \rightarrow \mu(e) + p$)

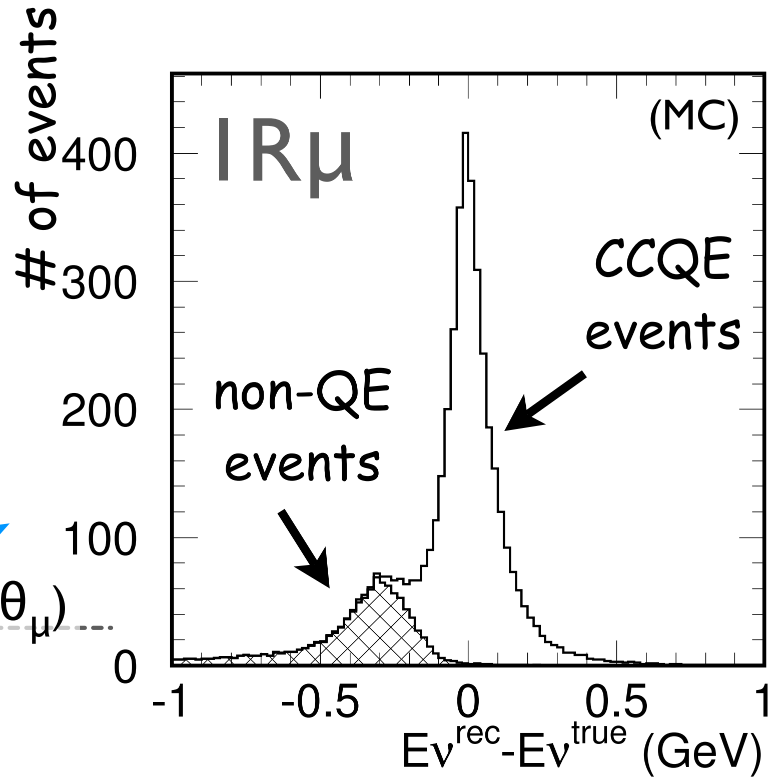



$$E_\nu^{rec} = \frac{m_n E_\mu - m_\mu^2/2 - (m_n^2 - m_p^2)/2}{m_n - E_\mu + p_\mu \cos\theta_\mu}$$




CC1π



# $\theta_{13}$ measurement by $\nu_e$ appearance

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

$\theta_{13}$

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

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

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

matter effect (small in T2K)

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

$\sin\Phi_{21} \sim 0.05$

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

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

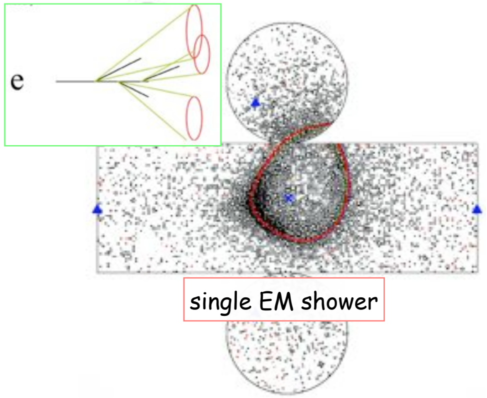
- $P(\nu_\mu \to \nu_e) \to \sin^2(2\theta_{13})$ : some ambiguity due to unknown params.
- It is possible to measure CPV by comparing $\nu$ and $\bar{\nu}$

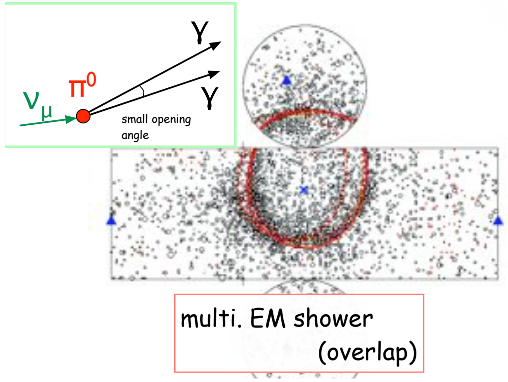
# Sensitivity of $\nu_e$ appearance

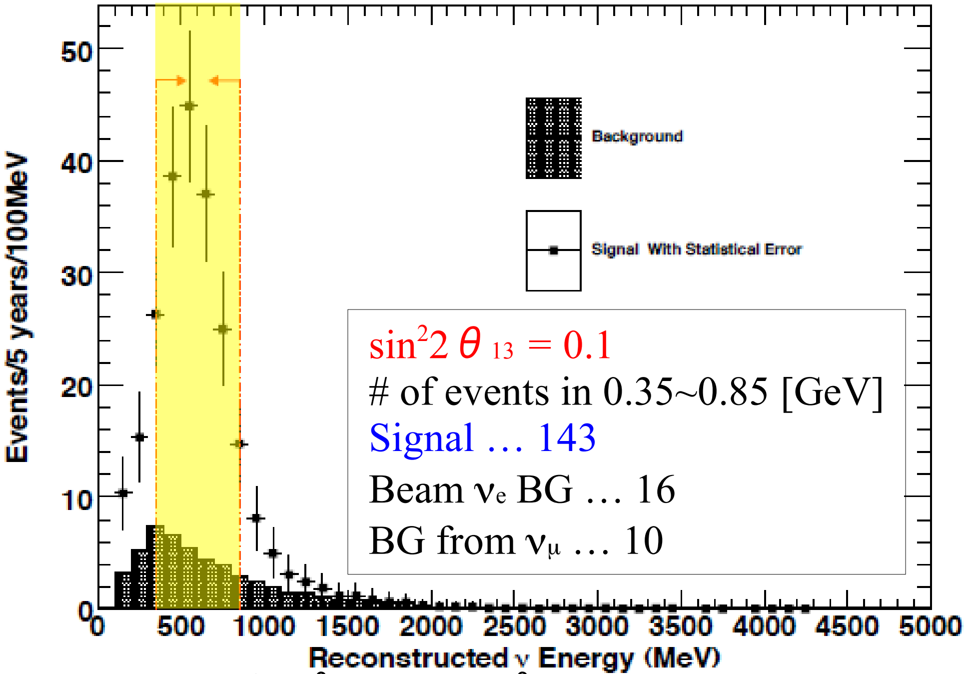
signal

beam $\nu_e$ background

$\pi^0$ background

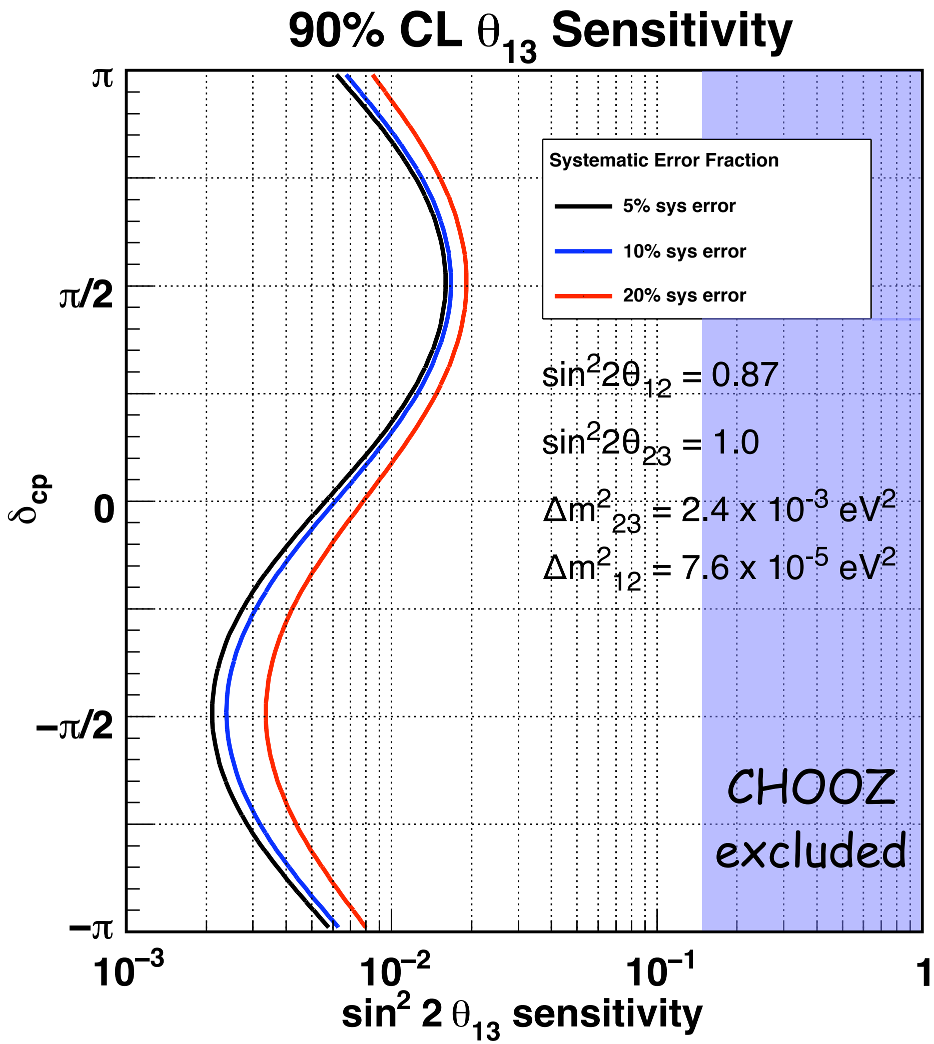



$\Delta m^2 = 2.4 \times 10^{-3}$, 10% sys. error

@ $8 \times 10^{21}$ protons(30GeV) on target




> x10 improvement from CHOOZ limit