T2Kの物理

(T2K: Tokai to Kamioka LBL Neutrino Oscillation Experiment)

Ken Sakashita for the T2K collaboration

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Introduction

- “neutrino oscillation”
  - neutrino flavor mixing ← $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$

flavor eigenstates　　mass eigenstates

(2世代の場合の振動確率)

質量二乗差 in eV^2
($\Delta m^2 = m^2 1 - m^2 2$)

飛行距離 in km

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left[\frac{1.27\Delta m^2 L}{E_\nu}\right]$$

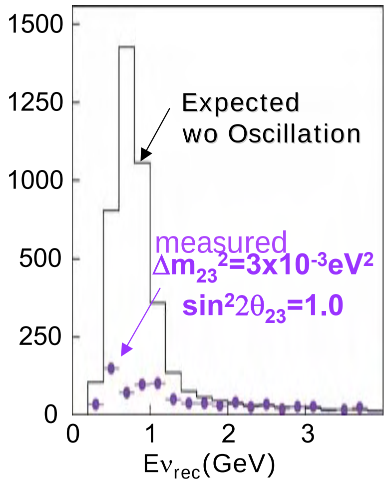
混合角

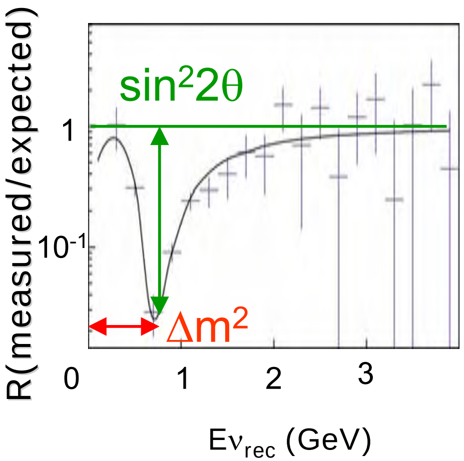
ニュートリノの
エネルギー in GeV

・あるフレーバーのνの数の減少
・Eνα分布のdistortion
・違うフレーバーのνの出現

- θ ≠ 0 and Δm2 ≠ 0ならP≠0
- いくつかの実験でν oscillationが測定されている

→ *non-zero ν mass*





Three flavor mixing

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & \underline{s_{13}e^{-i\delta}} \\ 0 & 1 & 0 \\ \underline{-s_{13}e^{i\delta}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

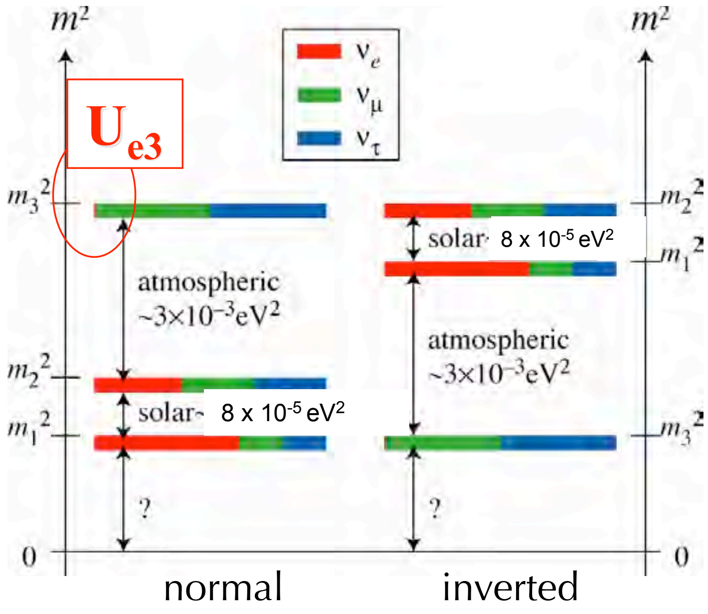
$$\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$$

- 独立なパラメータ：
  - ２つの質量二乗差、３つの混合角と１つの位相(δ)
- CP violationには$\theta_{13} \neq 0$が必要
- θ_{13}とδの値はまだ有限な値として測られていない

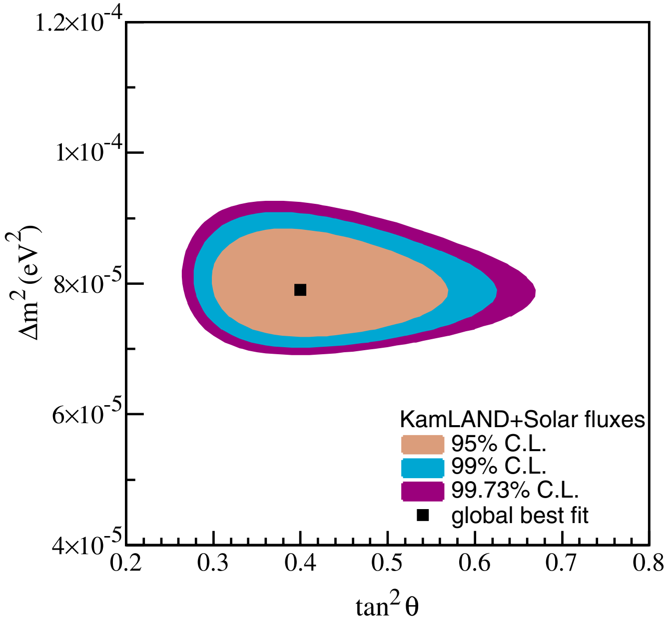
- これまでの実験結果

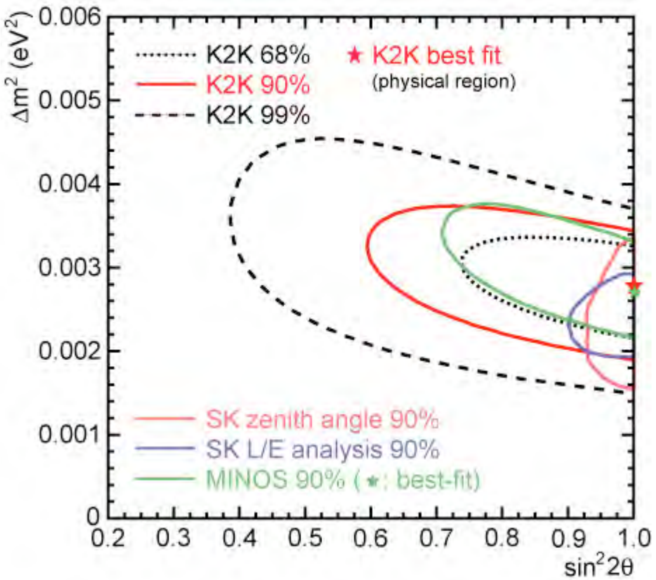
$\Delta m^2_{12} \sim 8 \times 10^{-5}$, $\sin^2(2\theta_{12}) = 0.86^{+0.03}_{-0.04}$
(KamLAND + solar ν)

$\Delta m^2_{23} \sim (2.2\sim3.0) \times 10^{-3}$, $\sin^2(2\theta_{23}) > 0.92$
(SK atm.-ν,K2K,MINOS)

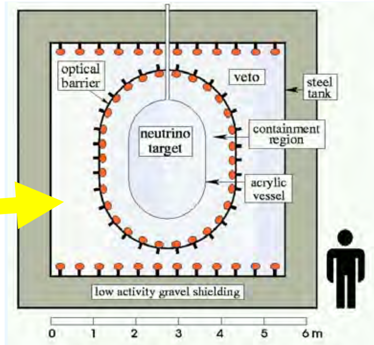


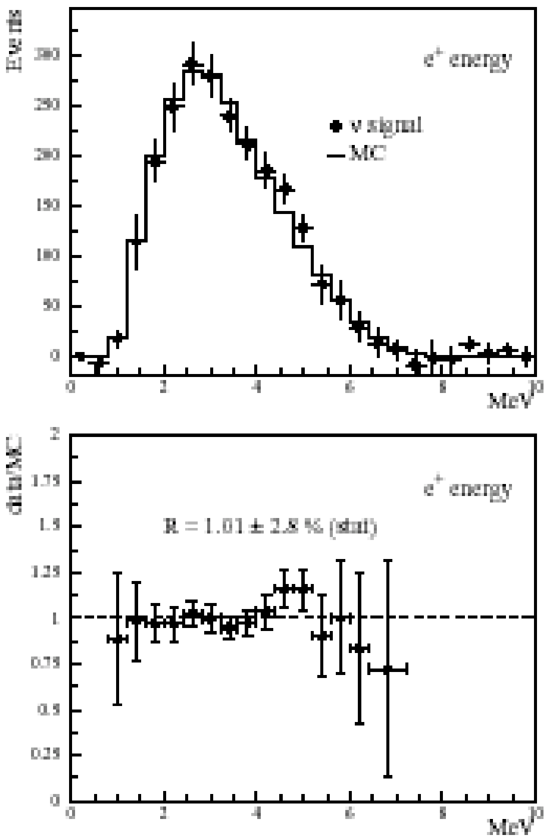
Δm^2_{23} >0 or <0 はまだ分からない





- θ_{13} limit
- CHOOZ experiment
  - Reactor / $\bar{\nu}_e$ disappearance experiment





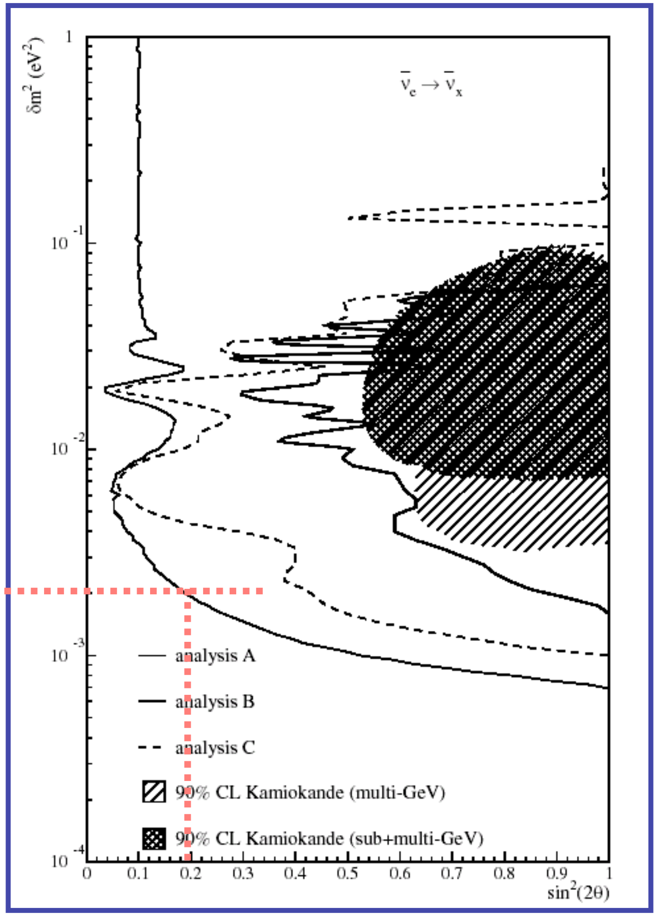
signal:

$\bar{\nu}_e\, p \rightarrow e^+\, n$

$n\, Gd \rightarrow Gd' + \gamma's$

$\sin^2(2\theta_{13}) < 0.2$

at $\Delta m^2_{23} = 2.0 \times 10^{-3}\ eV^2$



T2K実験 (J-PARC E11)

- Motivation
  - 残されたパラメータ: θ_{13}とδの測定
  - パラメータの精密測定
    - θ_{23}はmaximal mixingか否か

neutrino flavor mixingの解明

<u>T2K(1st-phase)の主な目的</u>

✓ ***discover a finite θ_{13} by observing ν_e appearance***

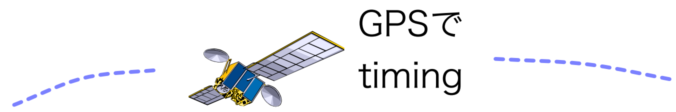
- T2K-Iでθ_{13}を有限な値として測定 → δの測定(CPV) in T2K 2nd-phase

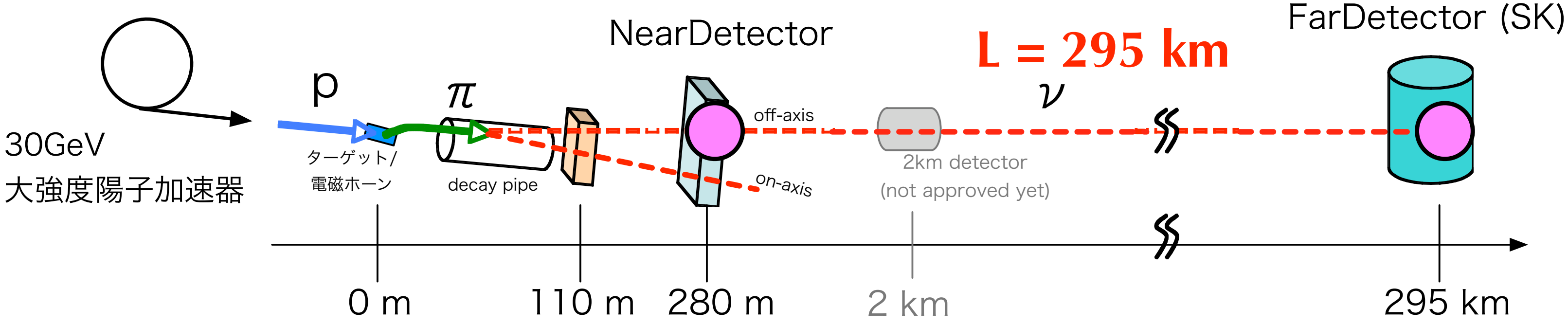
✓ ***precisely measure θ_{23}, Δm^2_{23}***

SK
(ready for T2K)

J-PARC 750kW
(under construction)

- 実験概要と特徴

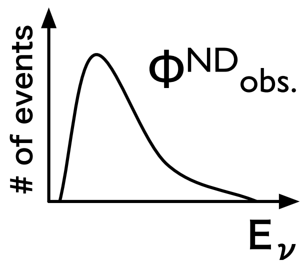




(1) ***narrow-band intense***
ν beamの生成

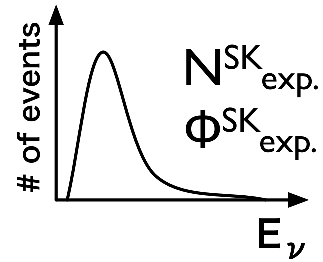
(2) ニュートリノの検出

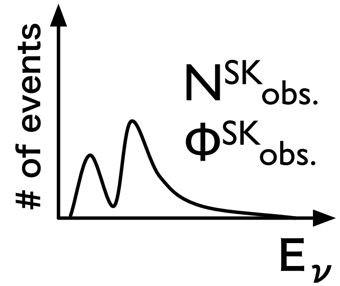
- **準弾性散乱相互作用(CCQE)**
- E_νの再構築
- 測定量 = Φ x σ(cross section)



x $R_{F/N}$ →

Far-to-Near ratio





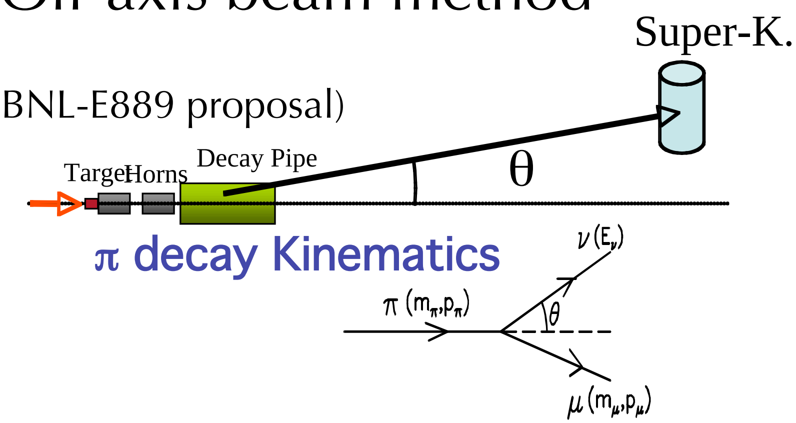
(3) νの親粒子(π,K)の分布から求めた
NDとSKのΦ(E_ν)の比と、実際に
測定したNDのΦ(E_ν)から
SKの分布Φ(E_ν)を見積もる

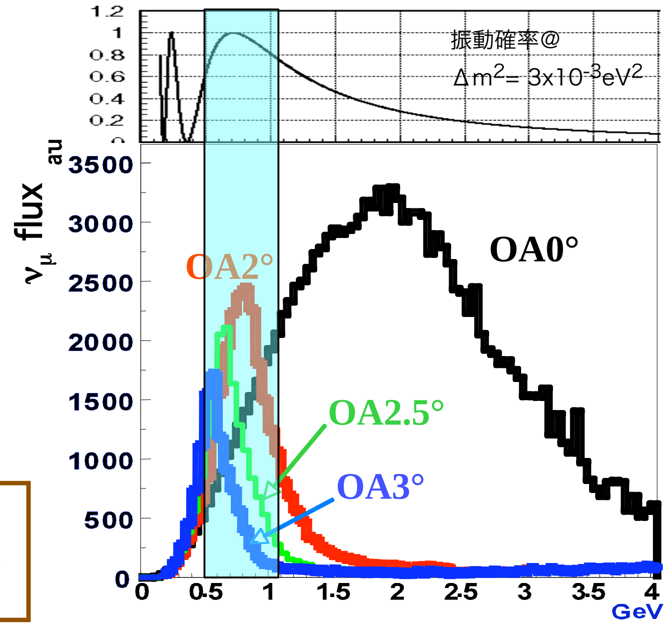
(4) 数($N^{SK}_{exp.}$, $N^{SK}_{obs.}$)とE_ν分布
($\Phi^{SK}_{exp.}$, $\Phi^{SK}_{obs.}$)を比較して
パラメータ($\sin^2(2\theta)$, Δm^2)を求める

Narrow-band intense neutrino beam

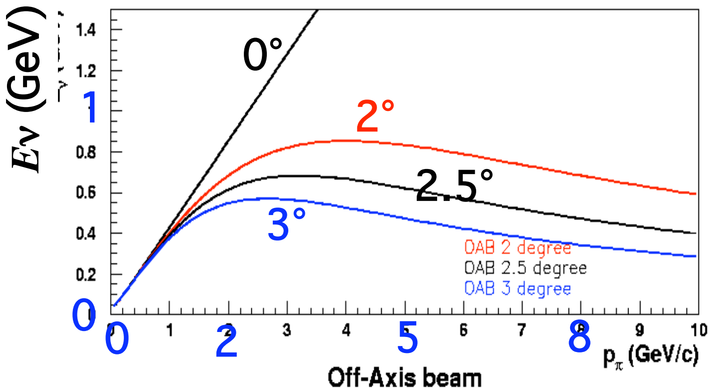
- Off-axis beam method

(ref. BNL-E889 proposal)





L = 295 km *Δm^2_{23} = (2.2~3.0) x 10^{-3} eV^2*	➡	*Oscillation max.* *E_ν = 0.5~0.7 GeV*



✓ ピークを振動確率最大の所に

- x 2~3 intense than OA 0°

✓ 少ないhigh energy ν

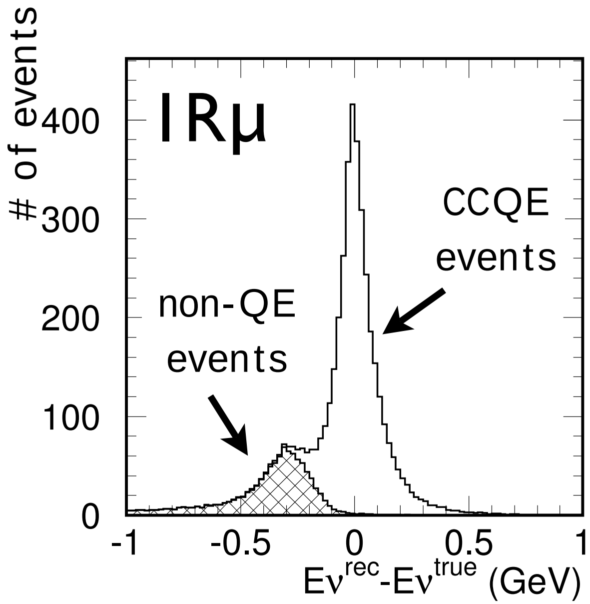
- backgroundを減らす

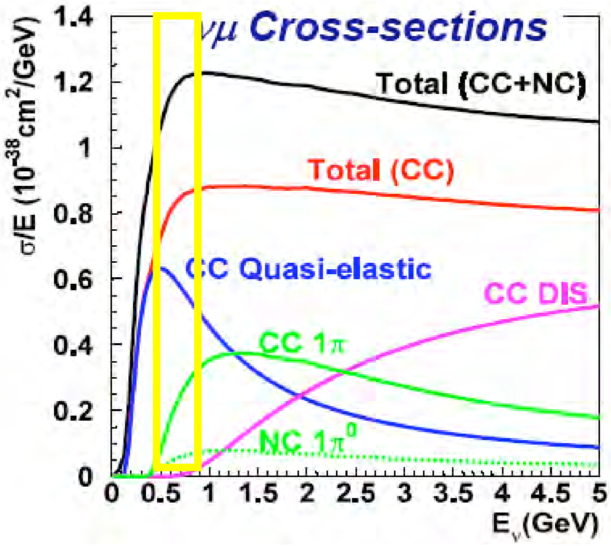
✓ ν_e ~0.4% at ν_μ peak

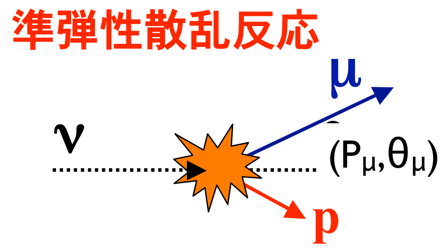
ニュートリノエネルギーの再構成

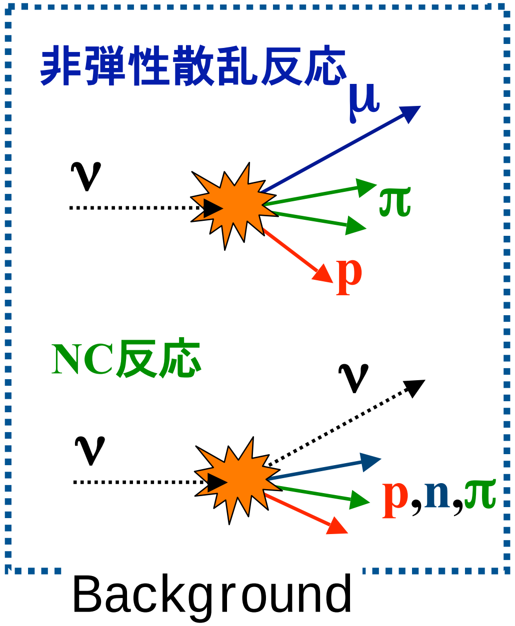
- E_ν ~ sub-GeV → 準弾性散乱反応(CCQE)が主な相互作用
  - $\nu + n \rightarrow \mu + p$

$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$





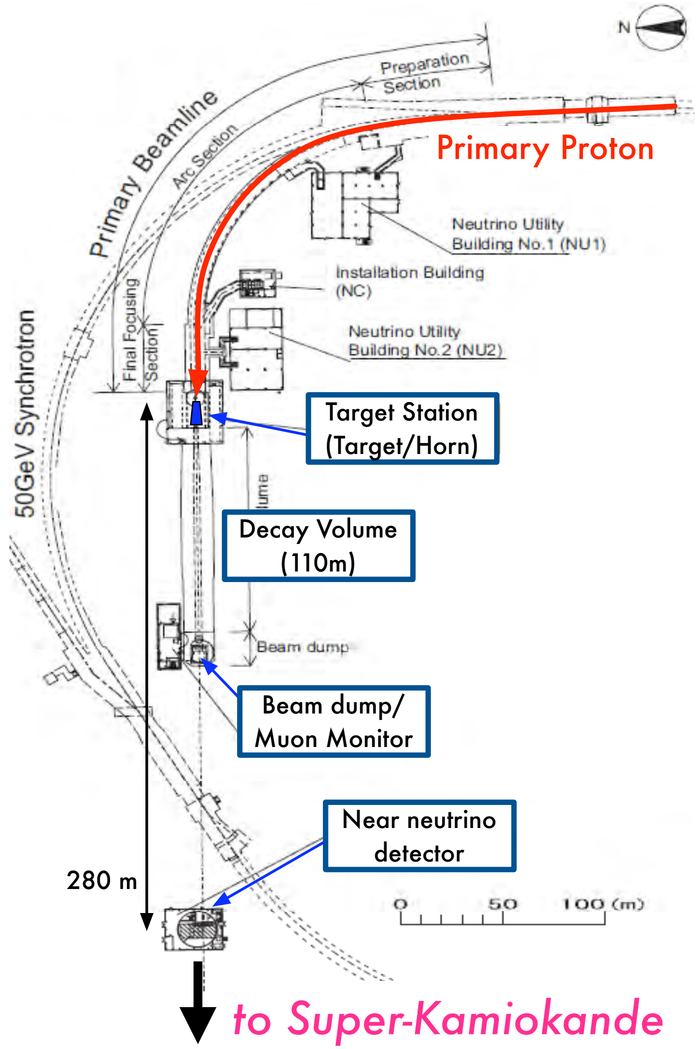


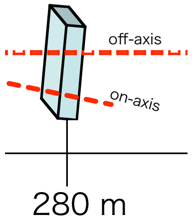


Neutrino beam line

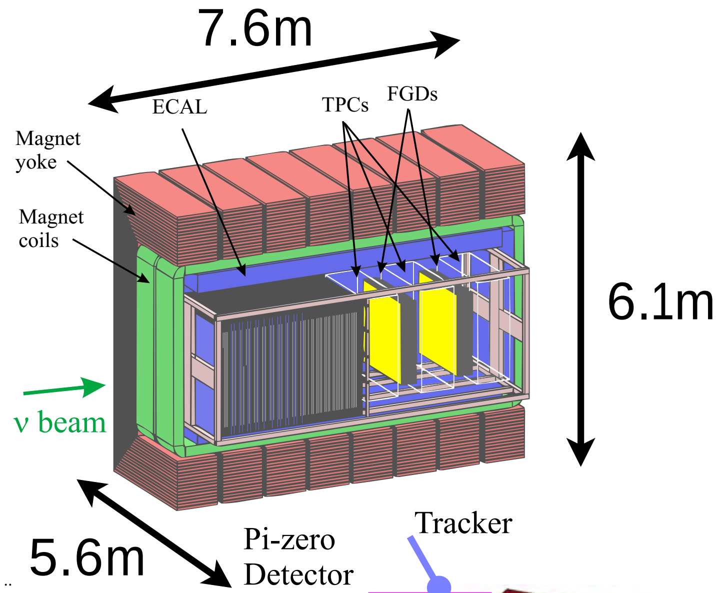
- 0.75 MW (3×10^{14} pot/spill)
- 超伝導電磁石を用いてSKの方向へ
- グラファイトターゲット
- 電磁ホーン(320kA) x 3台

- Requirement on the direction : **< 1 mrad**
  - Δm^2_{23}の系統誤差を統計誤差よりも小さく
  - target上のproton beamの位置精度 < 1mmに対応 → targetの保護
- GPSを用いた機器アライメント + secondary μとν自身の方向のモニター





Near detector @ 280m

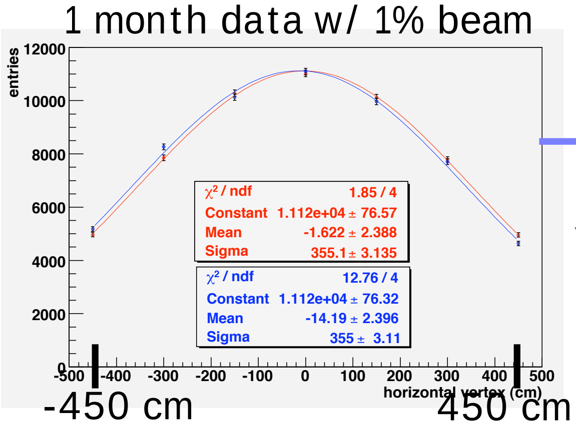


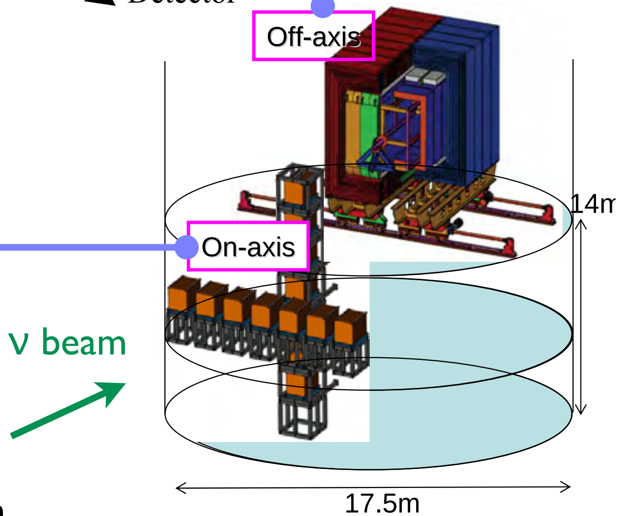
Off-axis detectors

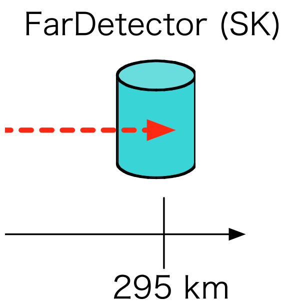
- flux, E_νを測定 (ν_μ, $\overline{\nu_\mu}$, ν_e)
- ν cross section(non-QE/QE)の測定
  - background見積もり
- UA1 magnet(0.2T), Tracker(FGD,TPC), Pi0 detector, EM calorimeter

On-axis detector

- νビームの方向を測定 (δ~1mrad)
- 鉄/シンチレータ block x 14台

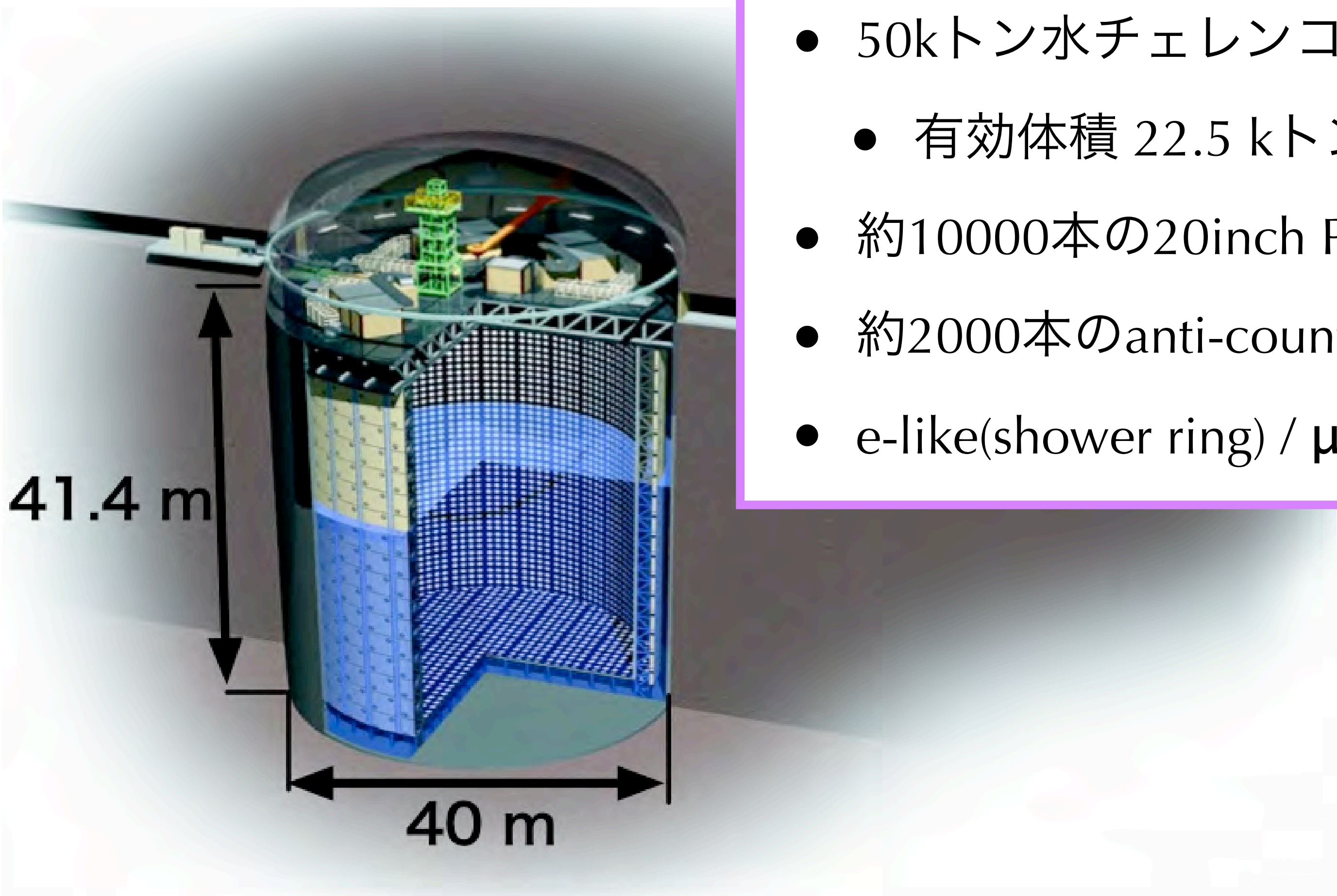






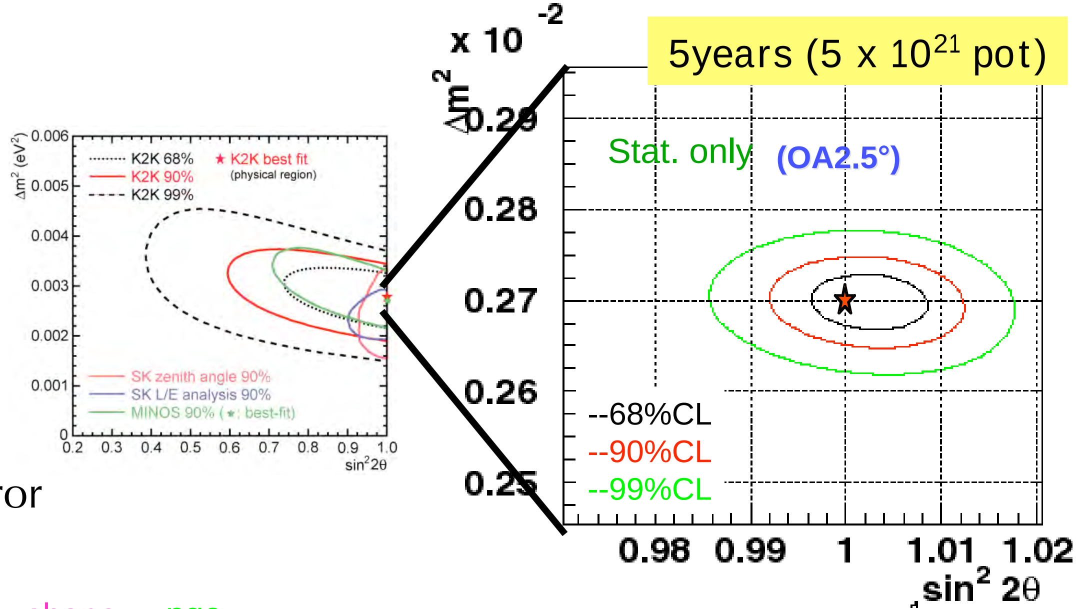
Super Kamiokande

- 神岡鉱山内の地下1kmに設置
- 50kトン水チェレンコフ検出器
    - 有効体積 22.5 kトン
- 約10000本の20inch PMTs (内側)
- 約2000本のanti-counter PMTs (外側)
- e-like(shower ring) / μ-likeの識別



物理感度(T2K-I) : ($\theta_{23}, \Delta m^2_{23}$)

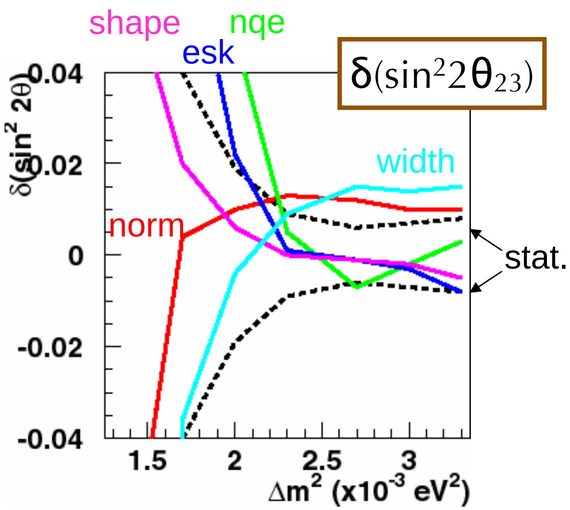
- ν_μ disappearance
- goal
  - $\delta(\sin^2 2\theta_{23}) \sim 0.01$
  - $\delta(\Delta m^2_{23}) \sim <1 \times 10^{-4}$

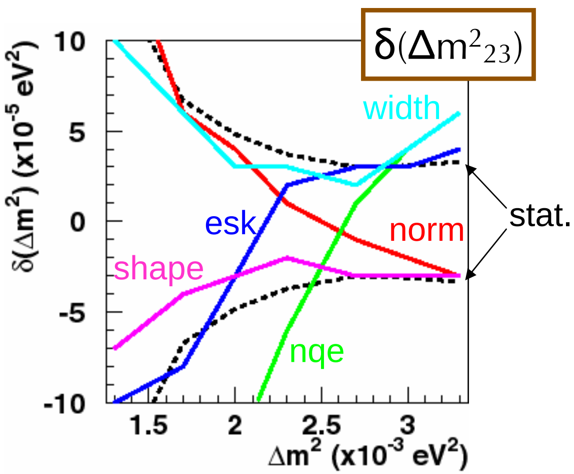


<u>requirements</u> on systematic error

- **flux normalization : <10%**
- **Non-QE/QE ratio : <5%**
- **Energy scale : <2%**
- **Spectrum shape (FLUKA/MARS) : <20%**
- **Spectrum width : <10%**

hadron-productionを測り
Far-to-Near ratioを
算出して、このエラーを減らす





θ_{13} in T2K-I

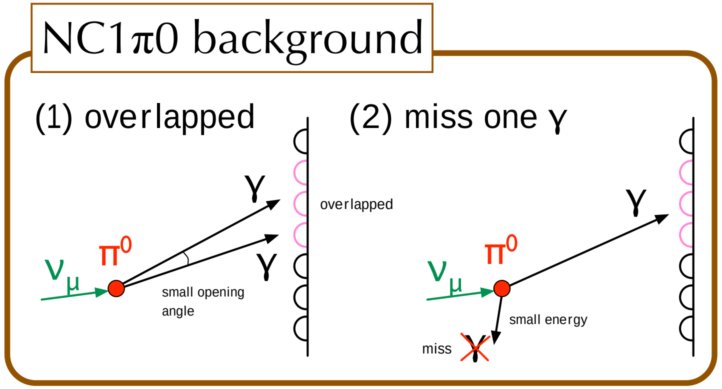
- ν_e appearance

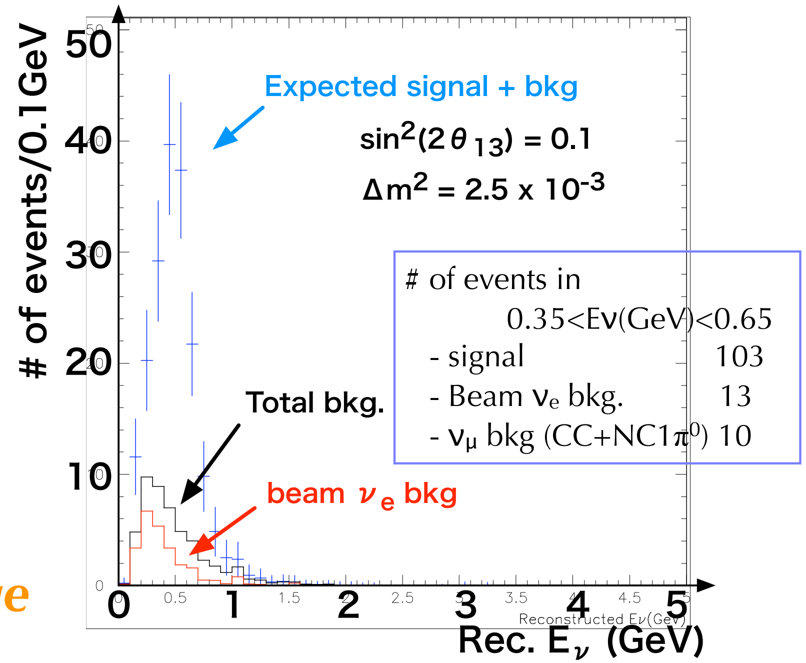
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin\left[\frac{1.27\Delta m^2_{31}[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right]$$

(Simplified Oscillation Prob.)

- signal : $\nu_e + n \to e^- + p$
  - single ring electron
- background
  - ν_μ NC1π^0 events, in which π^0 is misidentified as e^-
    - apply e/π separation cuts
  - beam intrinsic ν_e

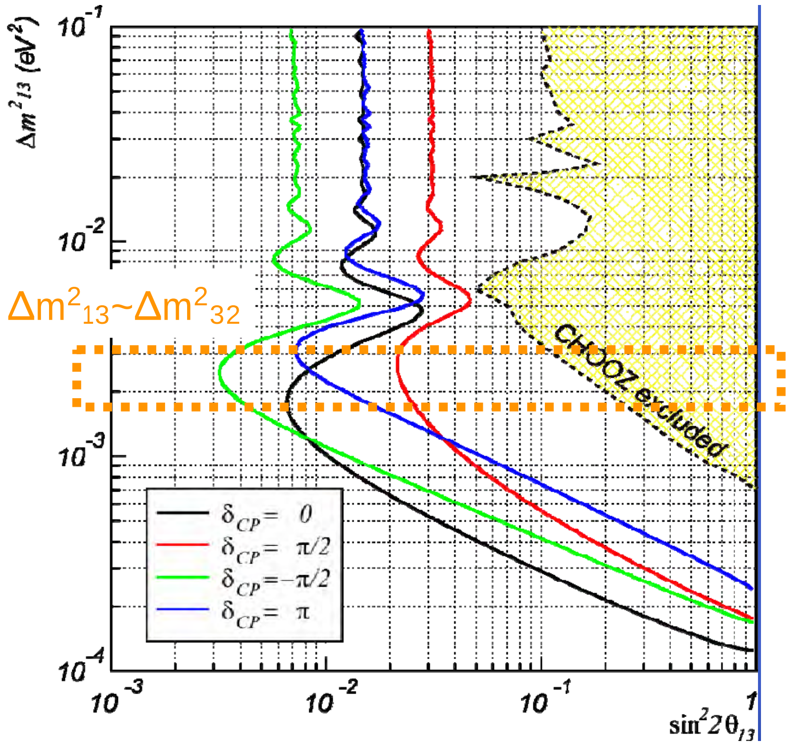
understanding background is key issue



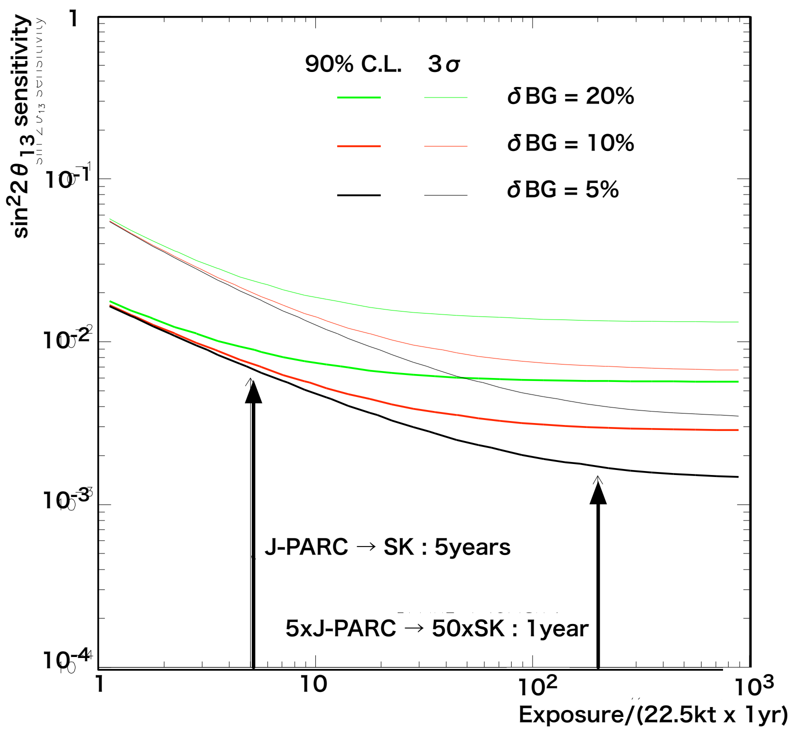


Expected sensitivity of θ_{13}

- > x10 improvement from CHOOZ results
  $\sin^2(2\theta_{13}) = 0.008$ (90% C.L.) for $\delta=0$, $\Delta m^2_{13}=2.5\times10^{-3}$ eV^2



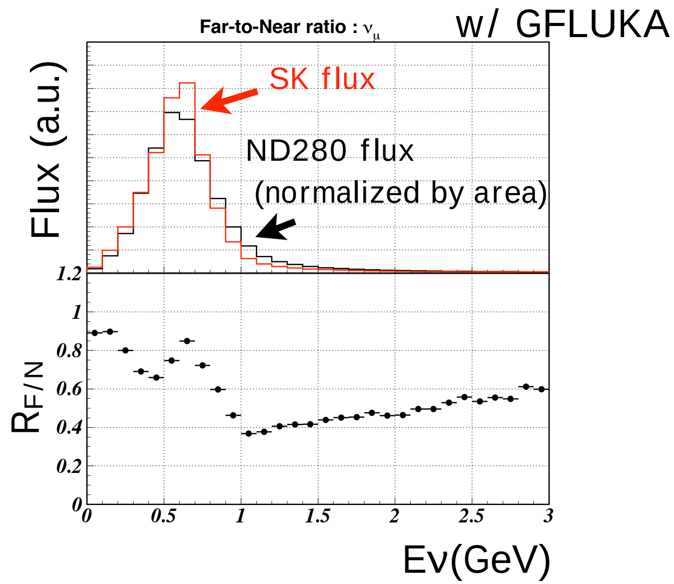
90%C.L. sensitivity @5years (5 x 10^{21} pot)
w/ stat. + 10% bkg. systematic error



10% background measurement is necessary

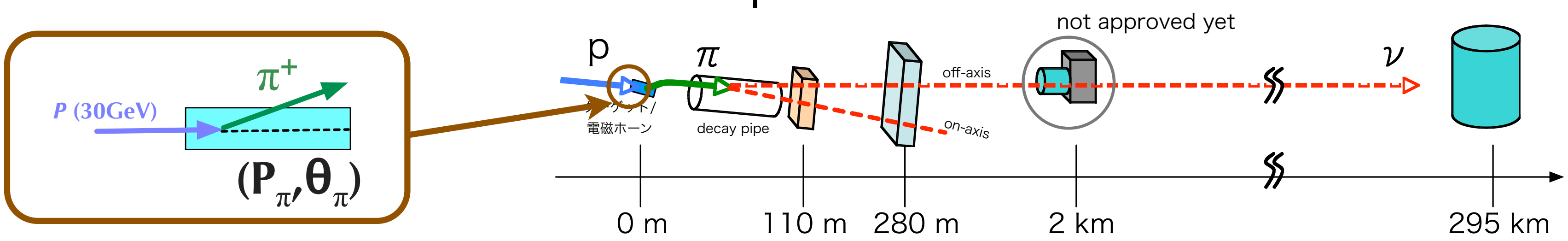
To achieve T2K-I physics goals

- $R_{F/N}$を精度よく求める必要がある
  - $\Phi^{SK}_{exp.} = R_{F/N} \times \Phi^{ND}_{obs.}$
  - ν_μ disappearance
    - ✓ keep syst. error less than stat. error
  - ν_e appearance
    - ✓ $\delta(N_{bkg.})$ to be less than 10% → **$\delta(R_{F/N})$ to be less than 2~3%**



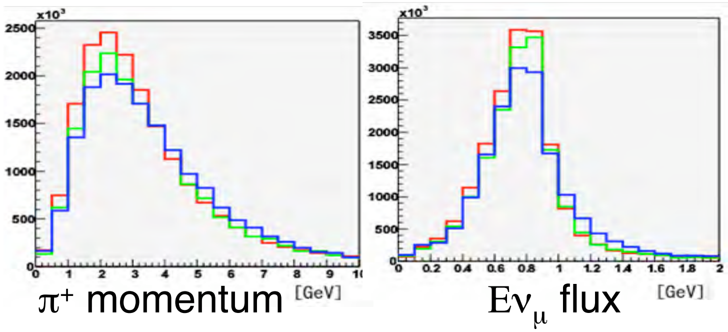
$R_{F/N}$ is sensitive to kinematics of parent particle (π,K)

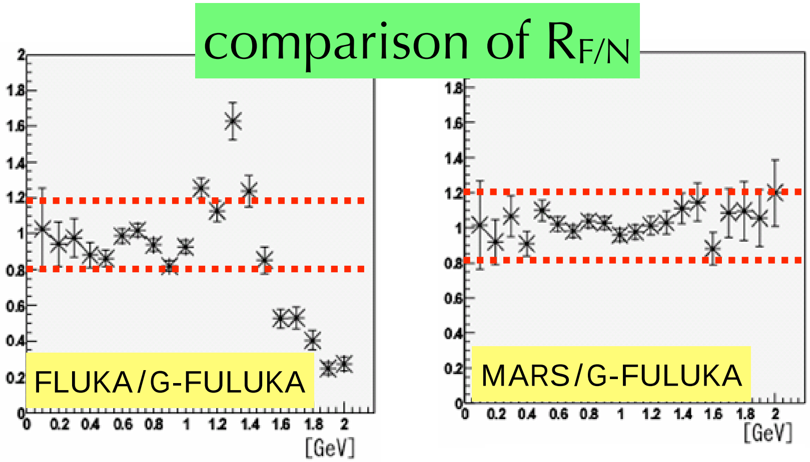
- but there is no data for 30GeV proton + C



- 仮に$R_{F/N}$をMCを用いて見積もる

G-FLUKA vs. MARS vs. FLUKA





~20% difference @ E_ν < 1GeV

systematic error from $\delta(R_{F/N})$

ν_e appearance

$\delta(N_{bkg})$ ~15%

ν_μ disappearance

$\delta(\sin^2 2\theta_{23})$ ~ ±(1.5~3)%

$\delta(\Delta m^2_{23})$ ~ ±(5~10) x 10^{-5} eV^2

T2K-I goal

ν_e appearance

$\delta(N_{bkg})$ < 10%

ν_μ disappearance

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

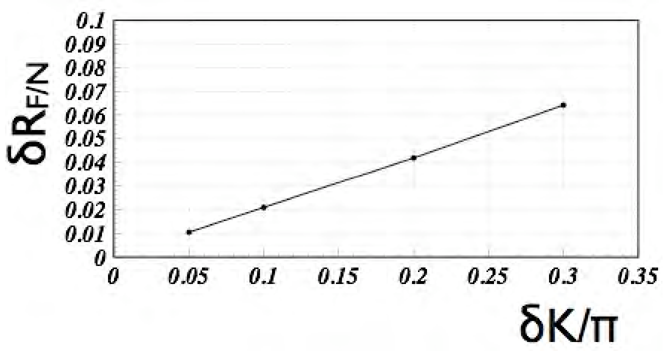
$\delta(\Delta m^2_{23})$ < 1 x 10^{-4} eV^2

measurement of the hadron production is necessary !!

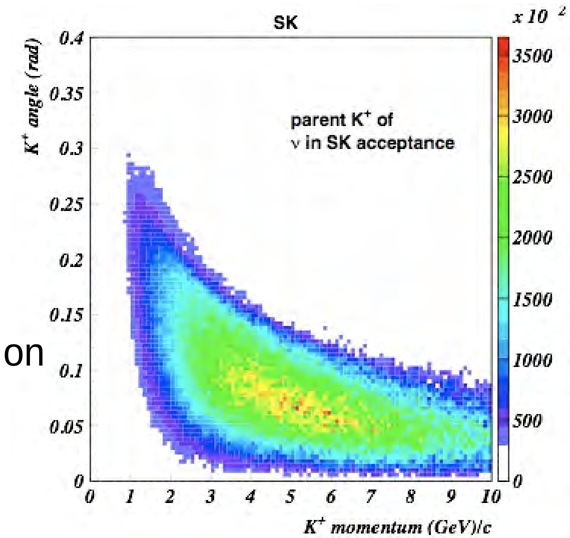
Hadron production measurement

- use 30GeV proton and the same target material (C)
- Measure ($P\pi$,$\theta\pi$) distribution
  - less than 10% statistical error of each P_π bin and θ_π bin → **δ ($R_{F/N}$) < 1%**

    (P_π 200MeV/bin x 50 bins, θ_π 20mrad/bin x 20 bins)
- Measure π/K ratio w/ less than 10% accuracy → **δ ($R_{F/N}$) ~2%**
  - high energy ν_μ from Kaon decays

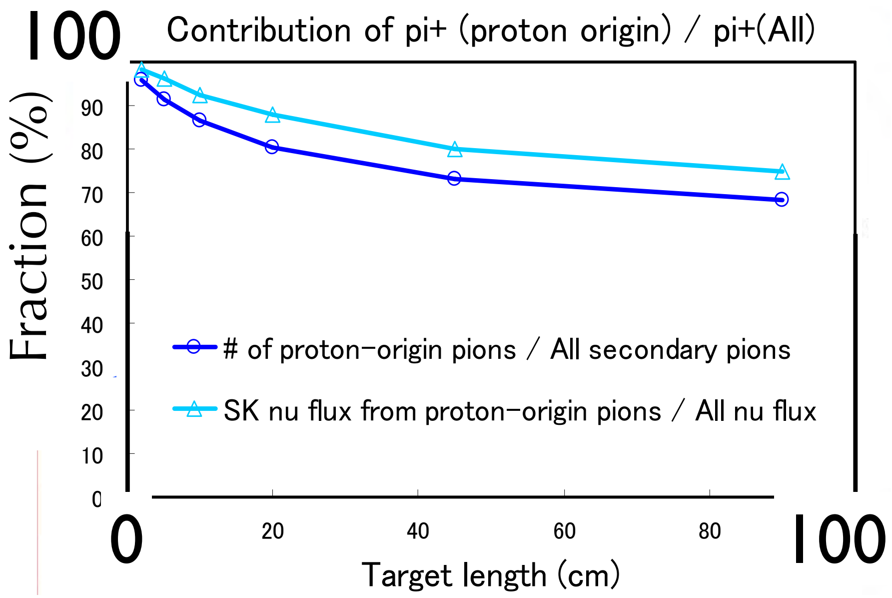


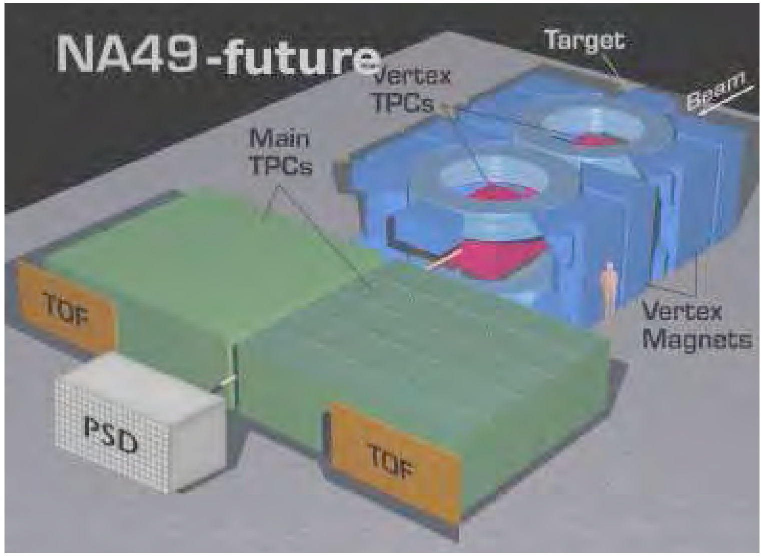
Need to measure the number of K+ in the region $1 < P(GeV/c) < 20$ and $0 < \theta(mrad) < 300$



CERN NA49 experiment

- 2007 run (30days) is nearly approved
- measure w/ 3 kinds of target
  - thin (~1cm, 2%) , middle(10cm, 20%) and replica (90cm)
  - take data to achieve the requirements for all the target





CP violation (δ) の測定

- T2K-Iで$\theta_{13} \neq 0$と測定された場合、T2K-IIでCPV phase(δ)の測定に
  - ✓ 厳密な$P(\nu_\mu \to \nu_e)$はδや物質効果を含むが、T2KのL=295km、小さいE_νでは物質効果は小さい
  - ✓ $\nu_\mu \to \nu_e$の数と$\overline{\nu_\mu} \to \overline{\nu_e}$の数を比較してδを測定

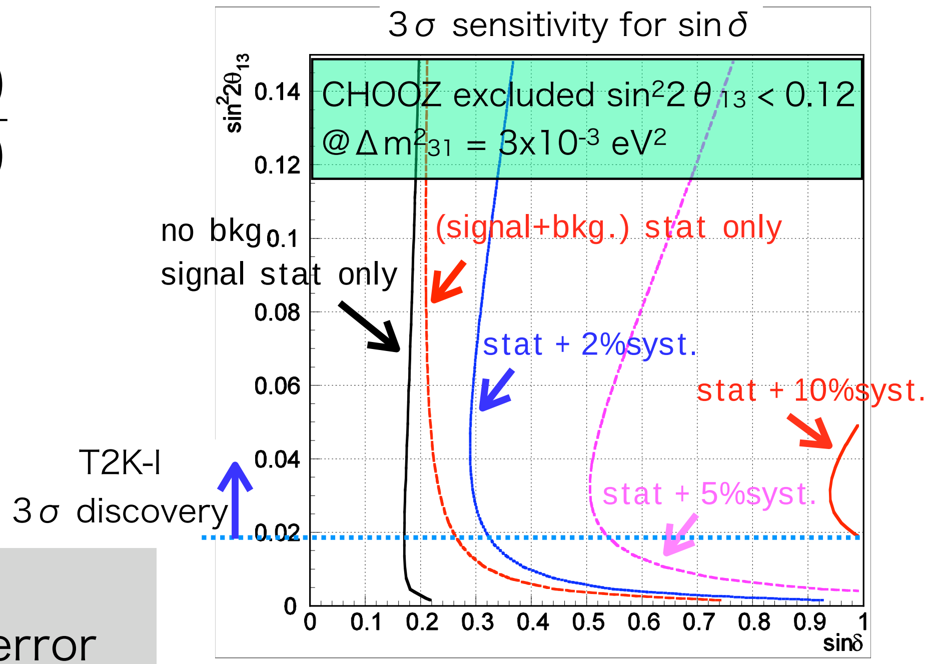
$\Delta m_{21}^2 = 6.9 \times 10^{-5} eV^2$
$\Delta m_{32}^2 = 2.8 \times 10^{-3} eV^2$
$\theta_{12} = 0.594$
$\theta_{23} = \pi/4$

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\overline{\nu_\mu} \to \overline{\nu_e})}$$

$$\approx \frac{\Delta m_{12}^2 L}{E} \cdot \frac{\sin(2\theta_{12})}{\sin(\theta_{13})} \cdot \sin\delta$$

例えば、 4MW+540kトン-HKで
２年ν run, 6年$\overline{\nu}$ run

3σ sensitivityで |δ|>20°
@ $\sin^2 2\theta_{13}$ = 0.01 and 2% syst. error



Summary

2009年4月
実験開始

- T2K実験
  - $L=295km$ & Δm^2_{23} → E_ν sub-GeV
  - narrow-band intense beam w/ OAB method
  - CCQE ν-interaction → possible to reconstruct E_ν
- 物理感度のprospects
  - ν_μ disappearance : **$\delta(\sin^2\theta_{23}) \sim 1\%$, $\Delta m^2_{23} < 1 \times 10^{-4}$ eV^2**
  - ν_e appearance : **$\sin^2\theta_{13} = 0.008$ @ 90% C.L.**
  - $\theta_{13} \neq 0$ → CPV phase δの測定 in T2K-II
- $R_{F/N}$を精度良く求めるためにhadron-production experimentが進行中

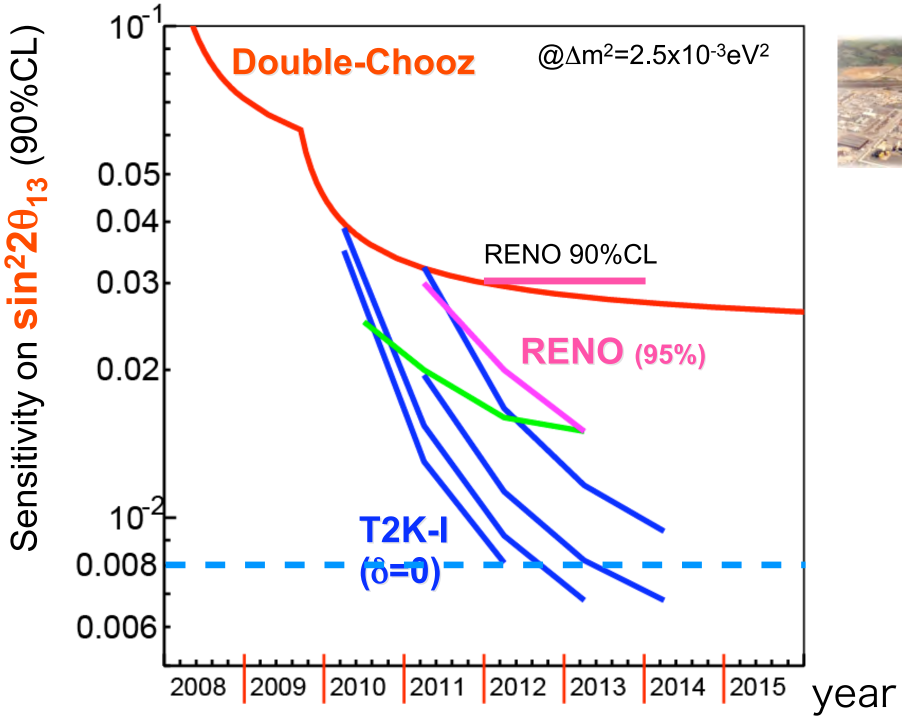
backup slides

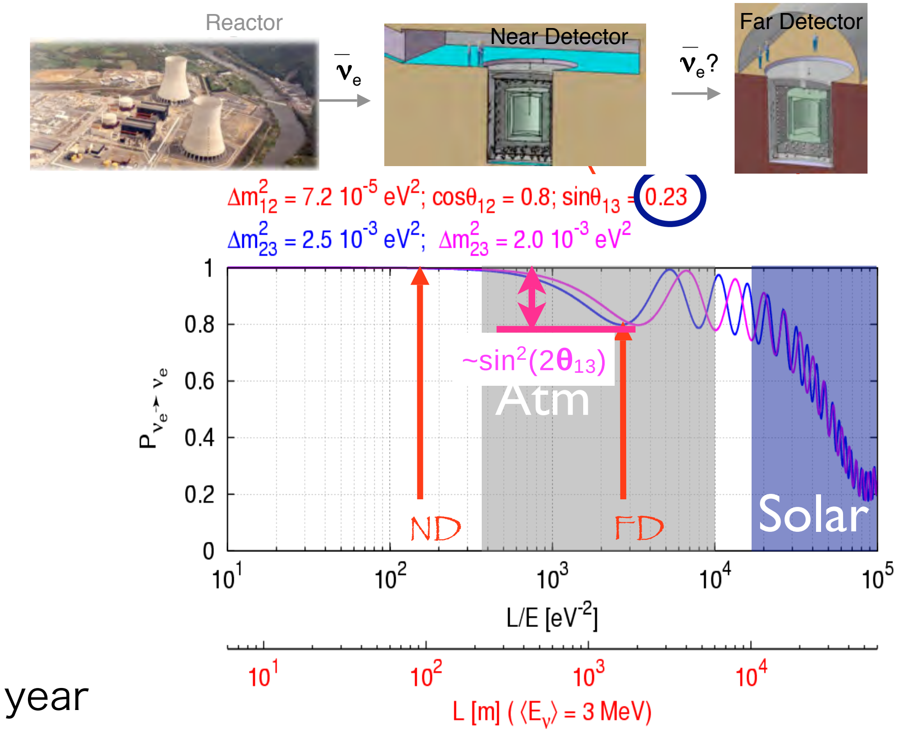
他のθ$_{13}$測定実験

- Reactor experiments [Double CHOOZ(フランス), RENO(韓国) ...]
  - ν_e disappearance → almost pure θ_{13} measurement

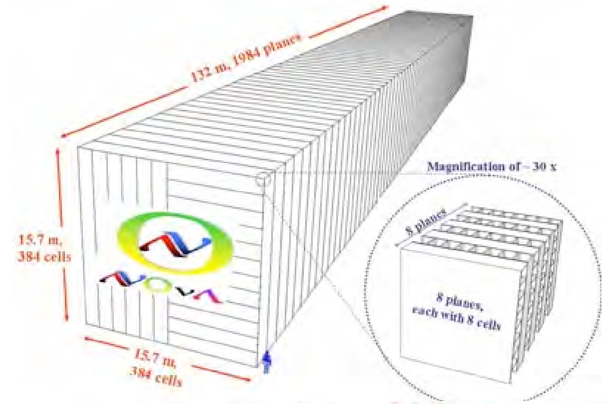
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2(1.27\Delta m^2_{31} L/E) + O(\Delta m^2_{21}/\Delta m^2_{31})$$

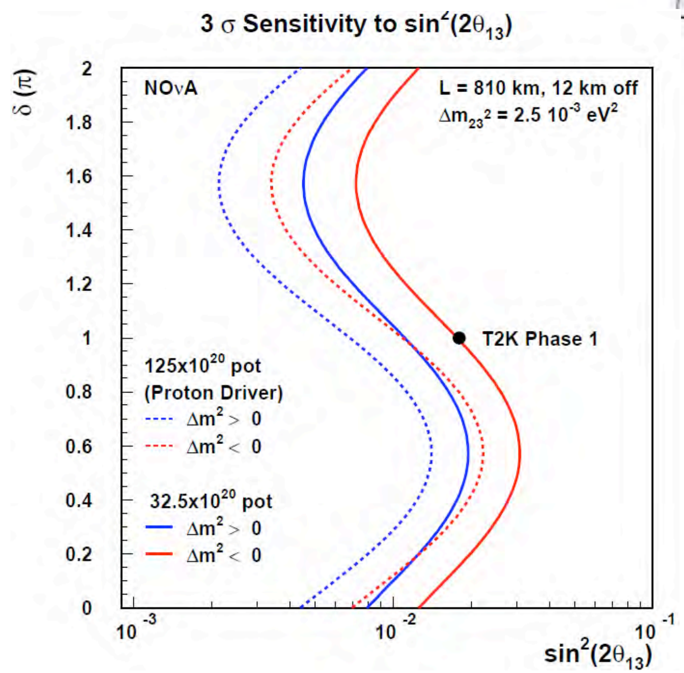
  - small deficit → systematic dominated





- NOvA (accelerator LBL exp.)
  - ν_e appearance
  - NuMI off-axis beam (L=810km) & 30kton liquid scintillator detector
  - similar sensitivity to T2K





NOvA sensitive to matter effect