特別講義BII「高エネルギー加速器科学」

大強度加速器を用いた
素粒子原子核実験(の裏側)入門

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J-PARC Center
素粒子原子核ディビジョン

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素粒子原子核研究所

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今回話すこと

- 大強度加速器J-PARCの概要とハドロン実験施設の建設
- ビーム輸送とビーム光学
- 電磁石の作り方、磁場の測り方
- ニュートリノビームを250km離れた的にあてる方法

長基線ニュートリノ振動実験

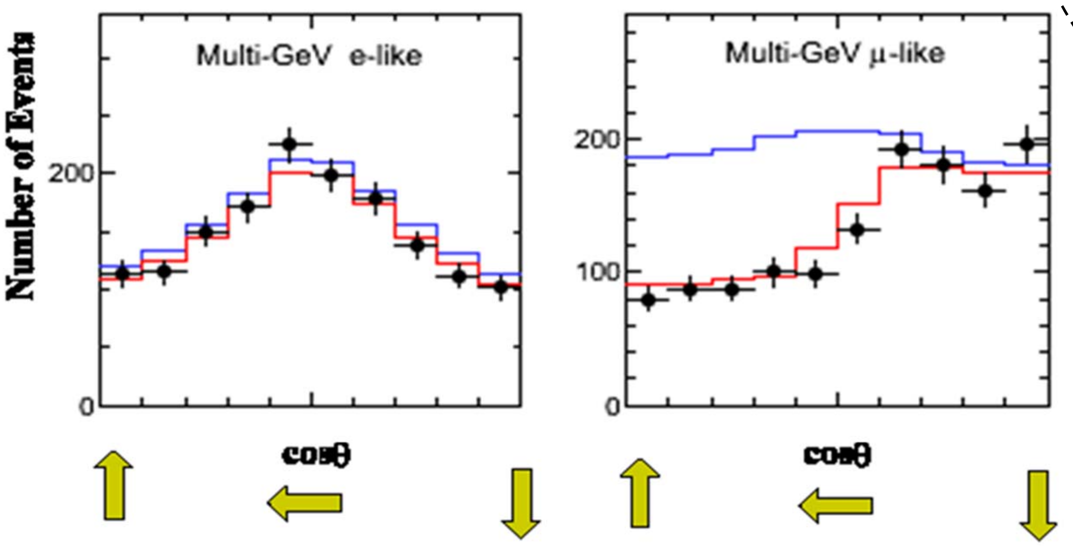
Neutrino

大気ν実験

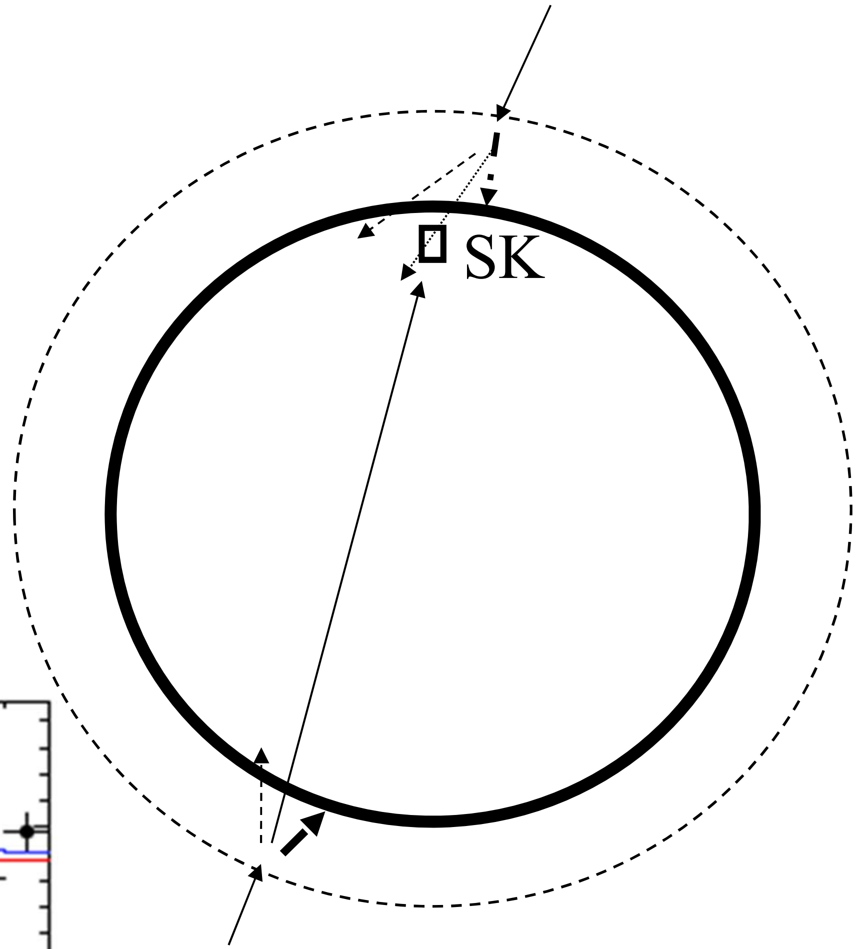
ν振動無し; 青線

$\nu_\mu \rightarrow \nu_\tau$振動を仮定; 赤線

電子ニュートリノ　　　μニュートリノ



ニュートリノの飛来方向

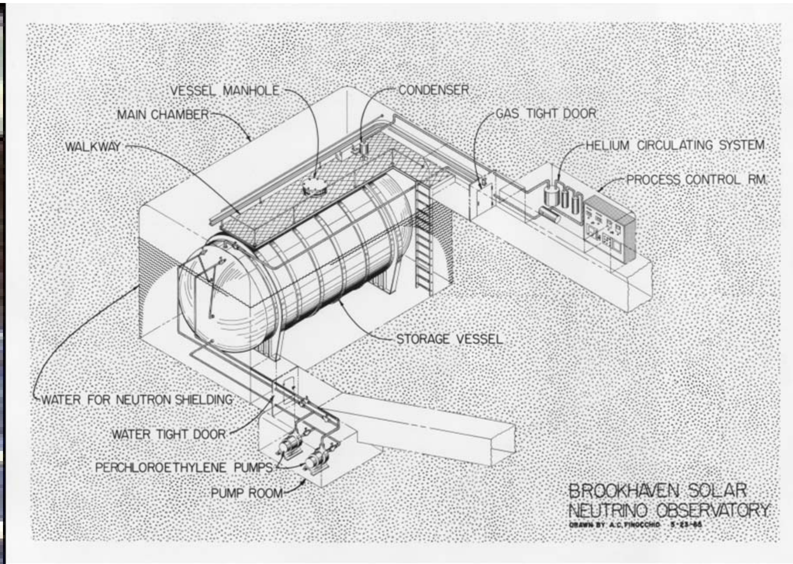


地球の上方から飛んでくるニュートリノの数の方が地球の裏側からのニュートリノより数が多い。この観測からニュートリノ振動が発見された。

戸塚洋二先生

Solar Neutrino Puzzle

地下 1,500 mに 615 トンの4塩化エチレンのタンクを設置

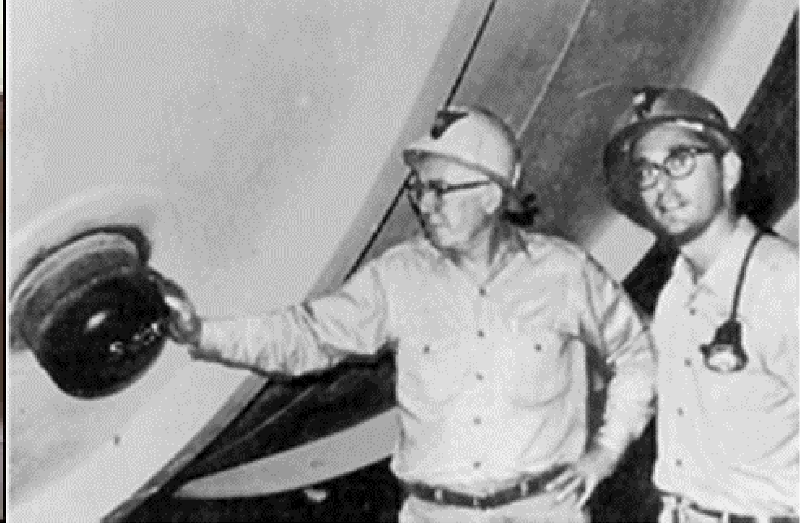


$^{37}Cl + \nu \rightarrow {}^{37}Ar + e$

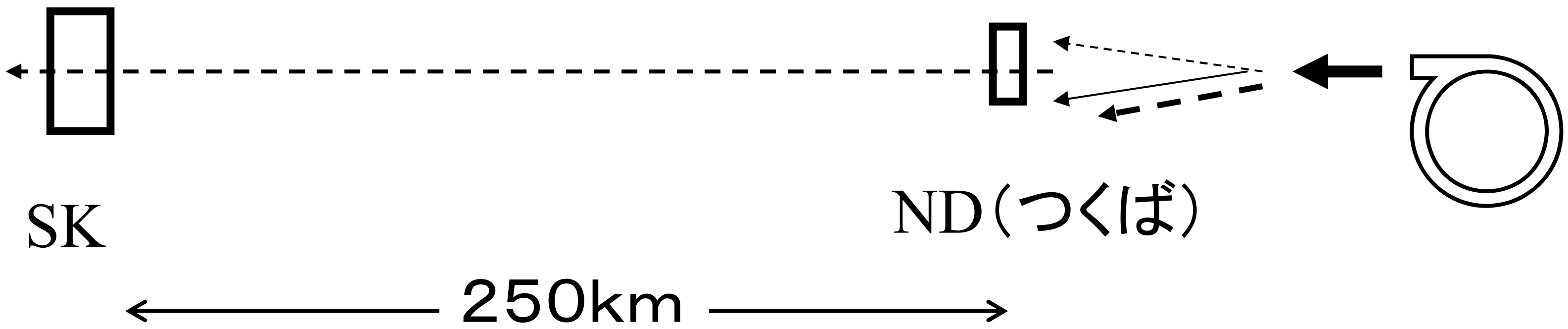
$^{37}Ar(EC) \rightarrow {}^{37}Cl$, $\tau_{1/2}$～35days

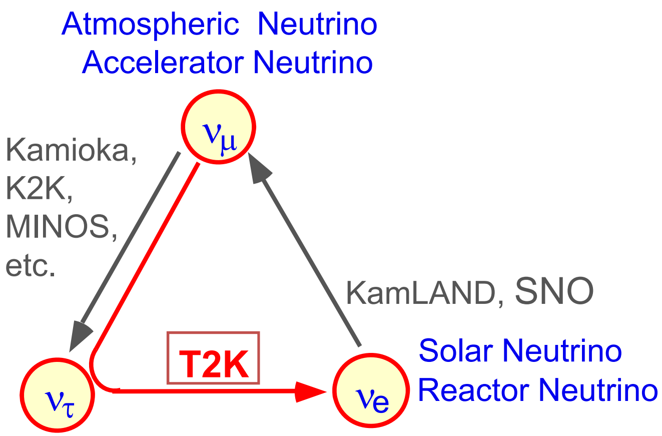
<u>太陽ニュートリノは理論予想値の1/3</u>

Raymond Davis Jr. 教授



最初の人工ν実験(K2K)



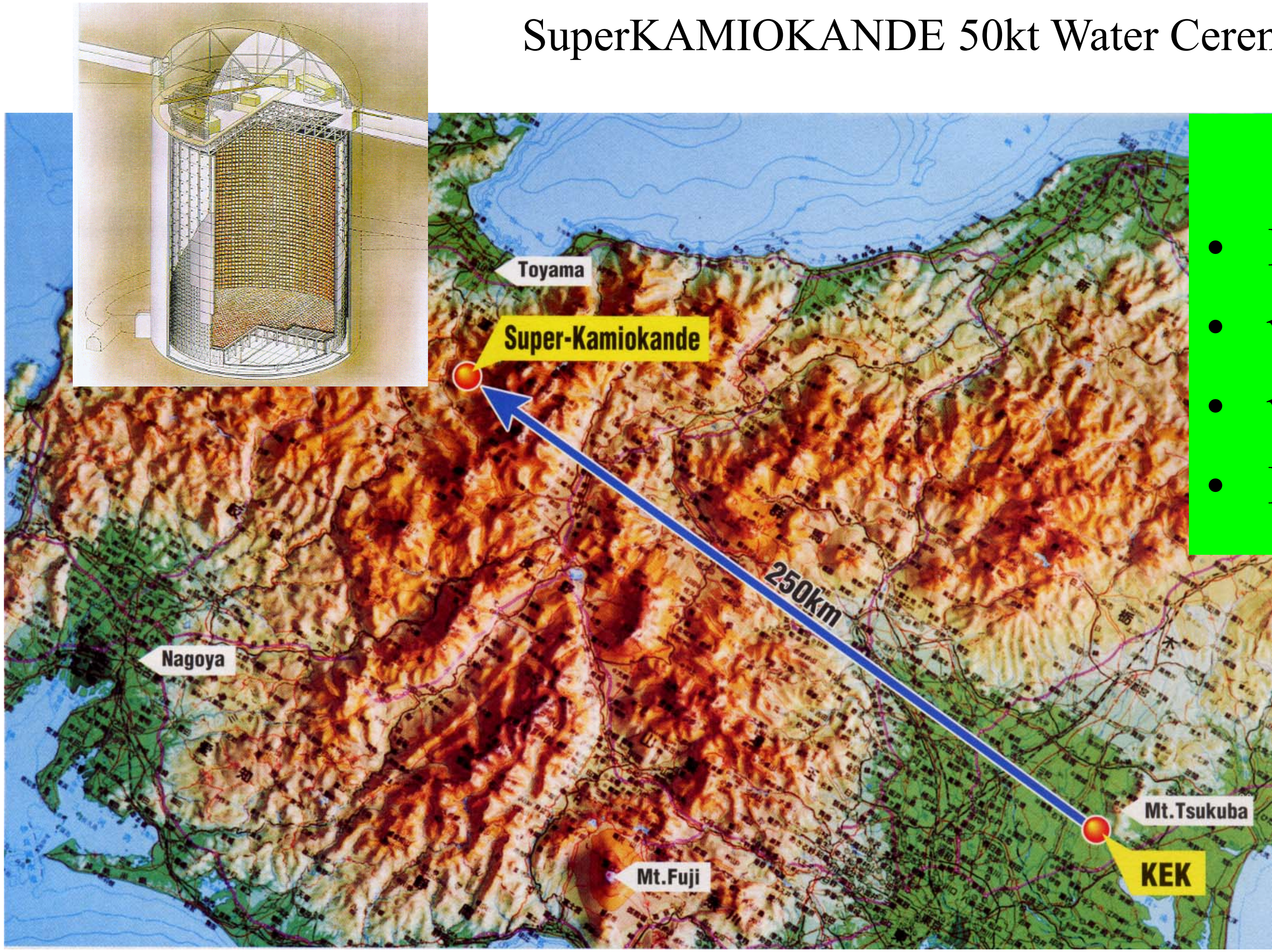


K2K Experiment

Long Baseline Neutrino oscillation Experiment

Far Detector:

SuperKAMIOKANDE 50kt Water Cerenkov Detector



Shooting Side

- KEK 12GeV PS
- νBeam Line
- νBeam Facility
- Front Detectors

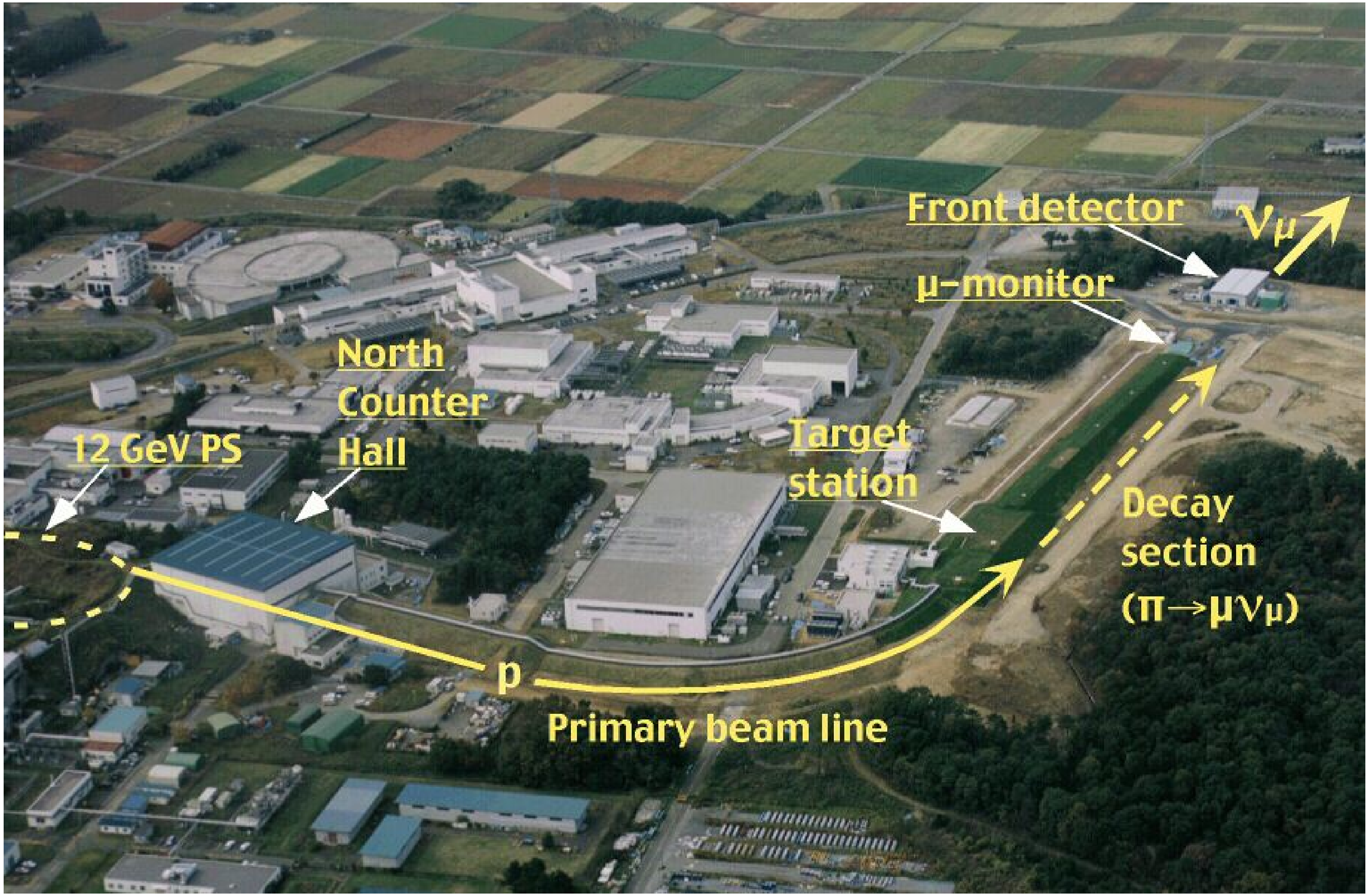
ニュートリノの撃ち方

- ターゲットは250km先
- ターゲットの大きさは直径35mくらい
- がんばって良く狙うが、ビームは、250km先でかなり広がる。
- まあ±250m～±1mradを目指す。

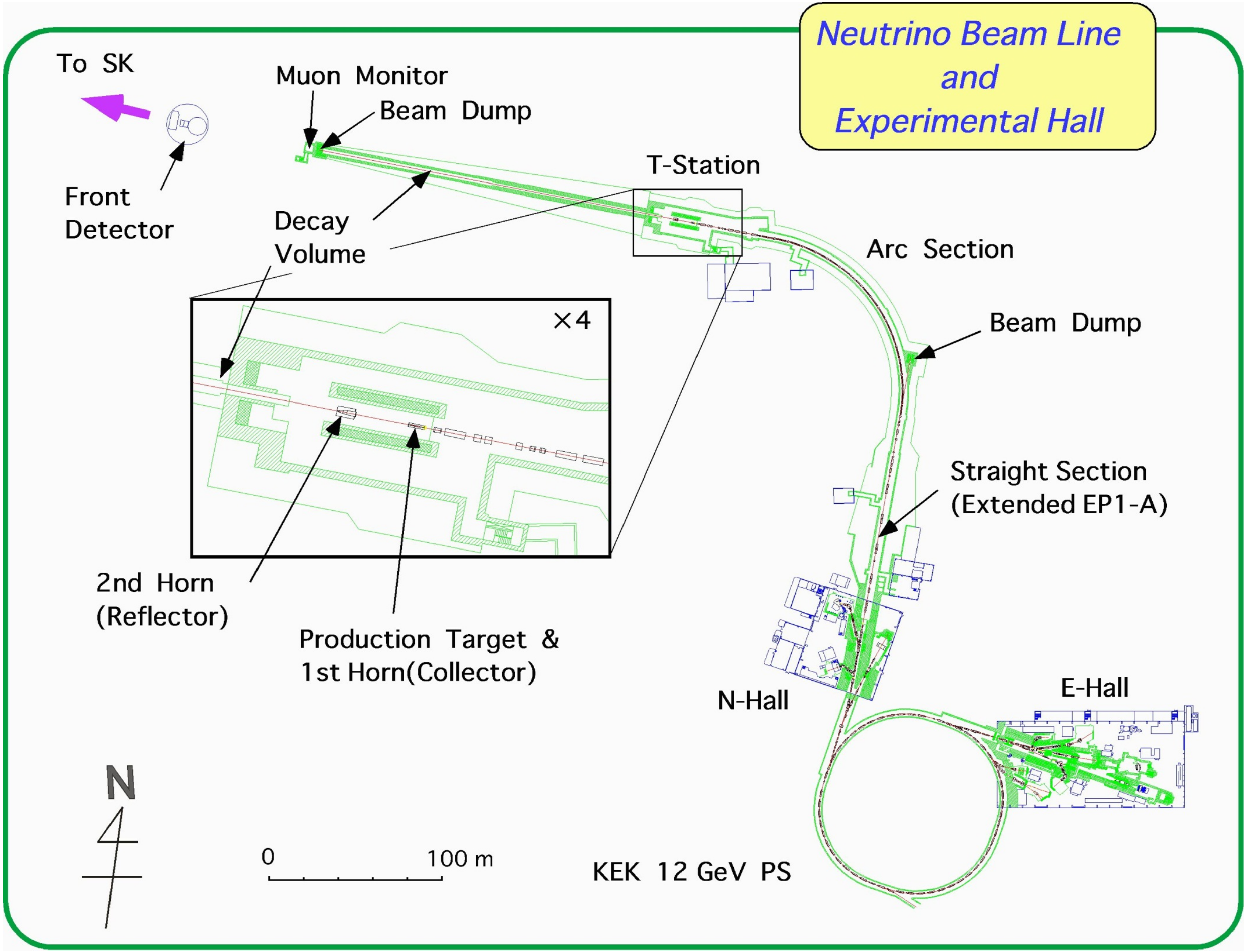
ニュートリノビームの作り方

- $\pi \rightarrow \mu\nu$二体崩壊を用いる。
- 加速器から早い取り出しで陽子を取り出す
- πを高エネルギー陽子の核反応で生成
- ホーンでπを収束して崩壊領域に入射
- 200m長の崩壊領域でνビームに変わる
- 地中を進んで神岡に到着

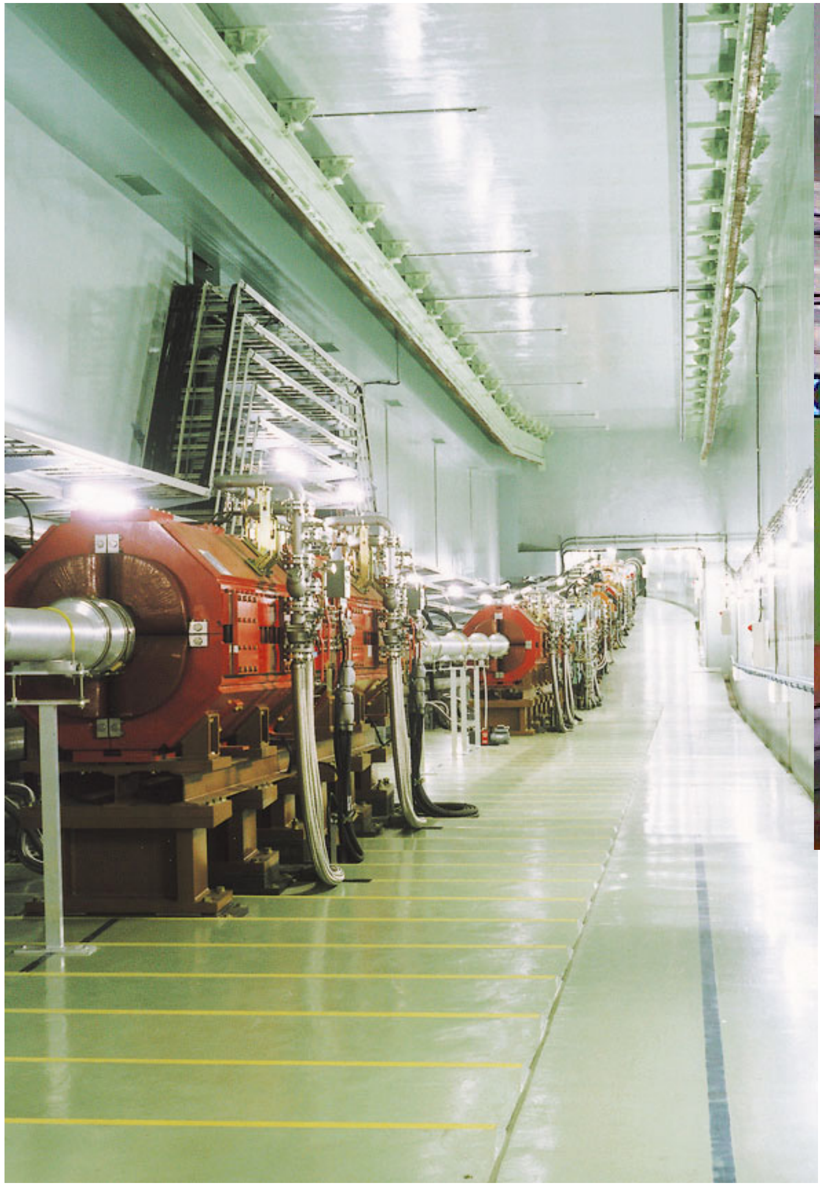
Neutrino Beam Facility



Side View


Neutrino Beam Line
and
Experimental Hall
To SK
Muon Monitor
Beam Dump
Front
Detector
Decay
Volume
T-Station
Arc Section
×4
Beam Dump
Straight Section
(Extended EP1-A)
2nd Horn
(Reflector)
Production Target &
1st Horn(Collector)
N-Hall
E-Hall
N
0
100 m
KEK 12 GeV PS

Primary Proton Beam Line (Extended Part)



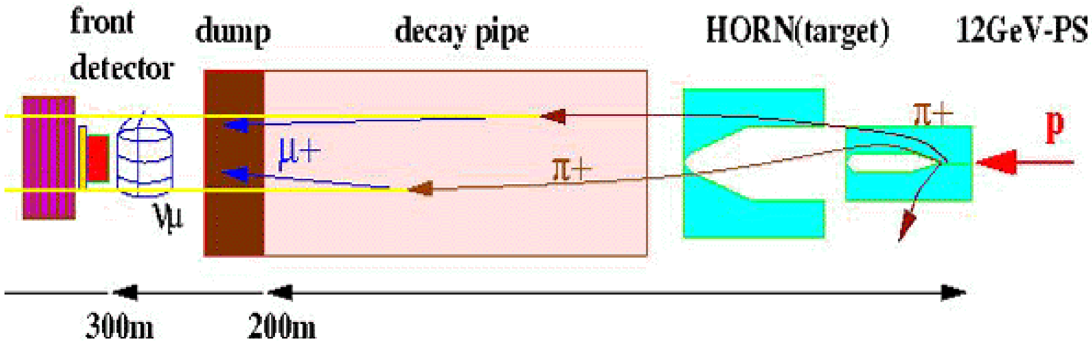
↑Arc (Bending) Section,
No Crane is here.

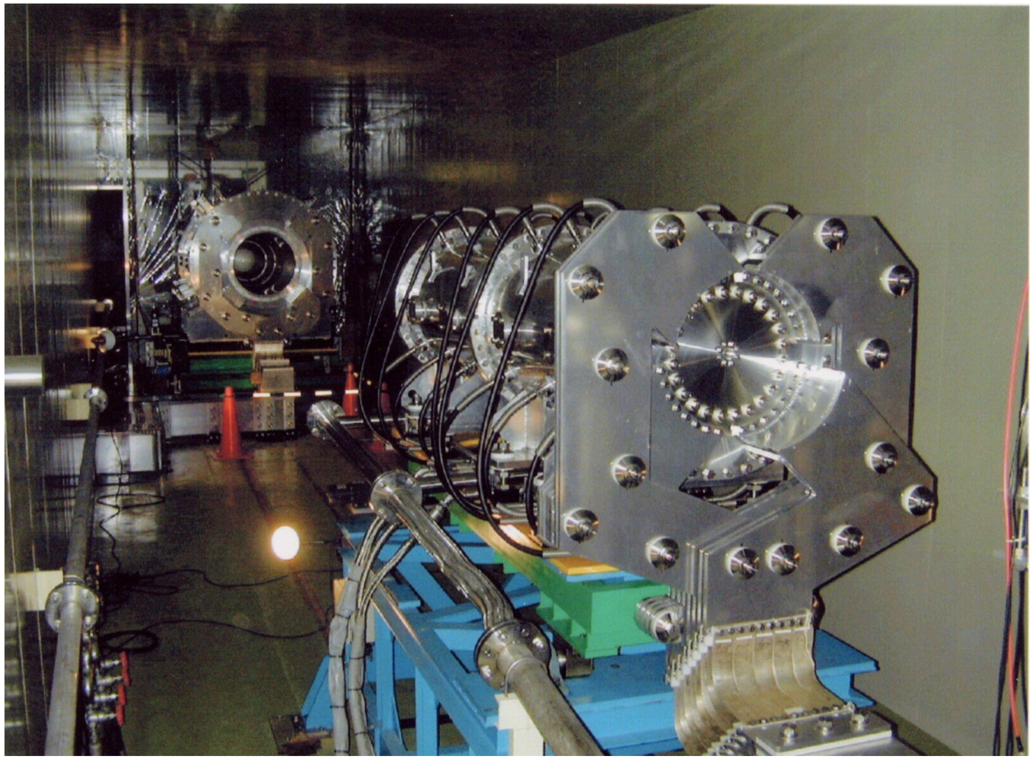
←Slope (Straight) Section,
5m/72m. 20t Crane is here.

Primary Proton Beam Line (Final Focus Part)

Q-triplet and Correction Magnets → Horns

Horns, Target & Decay Volume



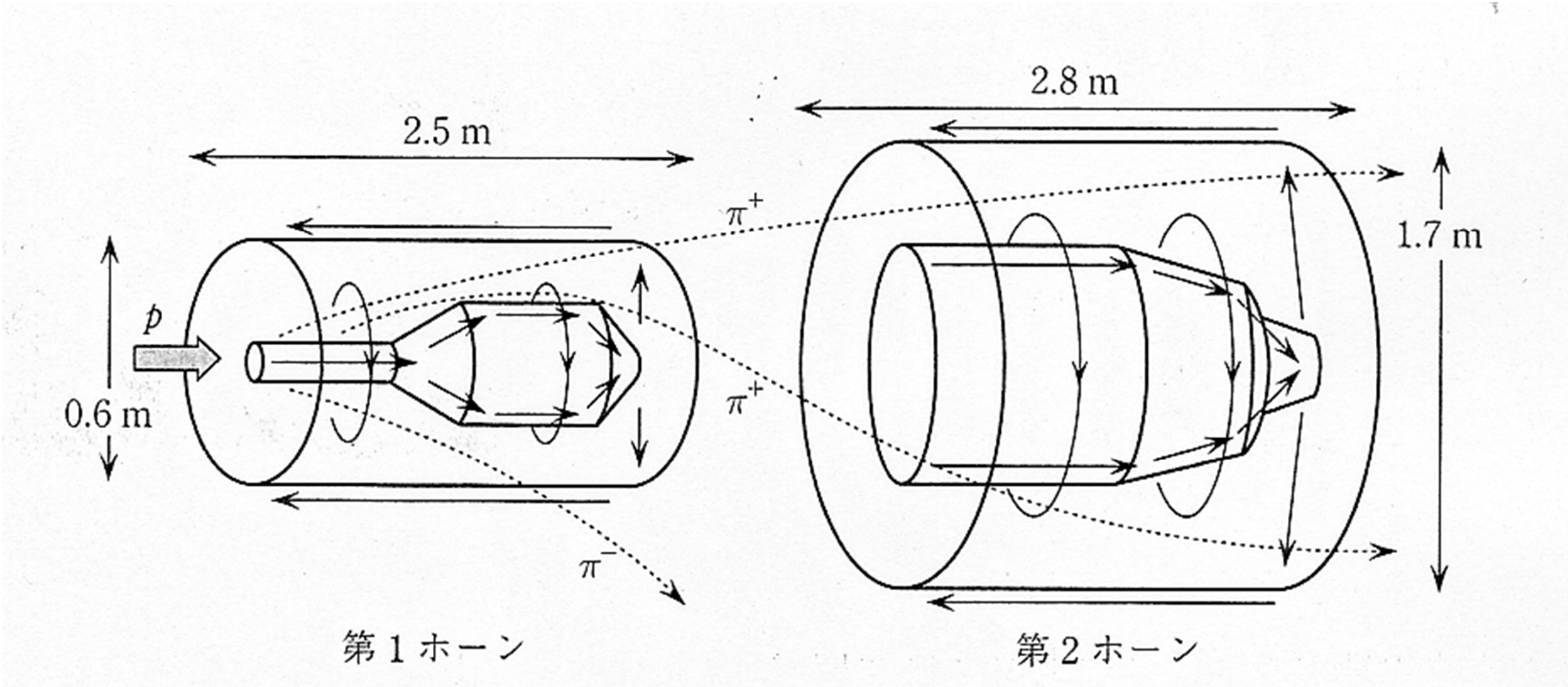


- Two Horns

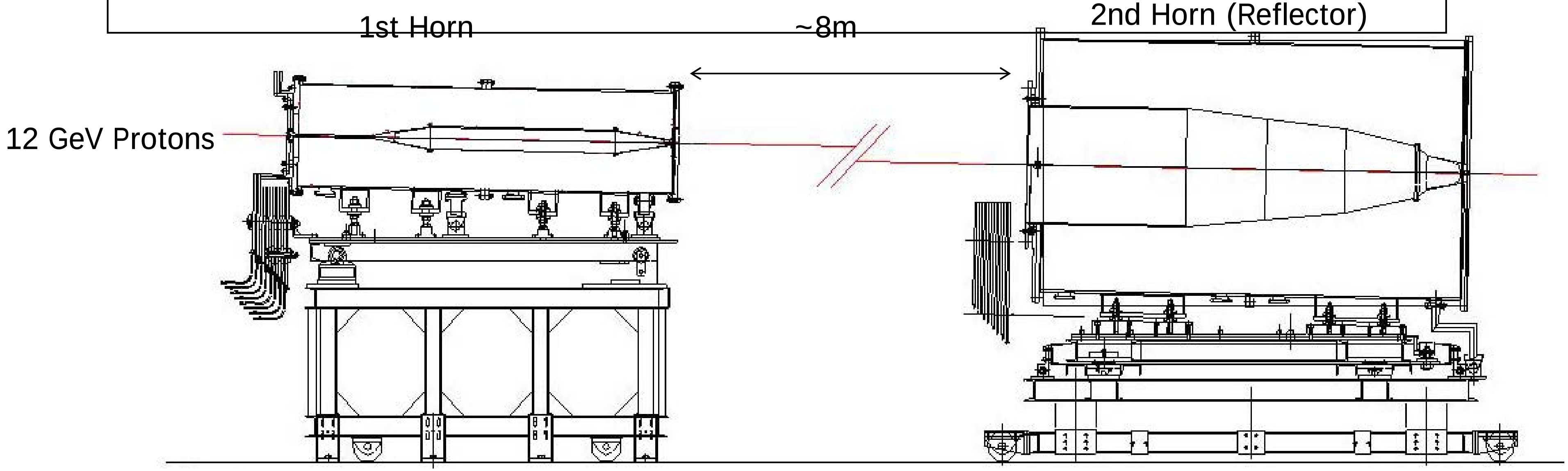
(Collector & Reflector).

- Built-in Target in Collector
- 250kA Operation
- 10M Excitation with 30mmφTarget
- Transformer near-by
- 200m Decay Volume filled with He.

KEKホーン

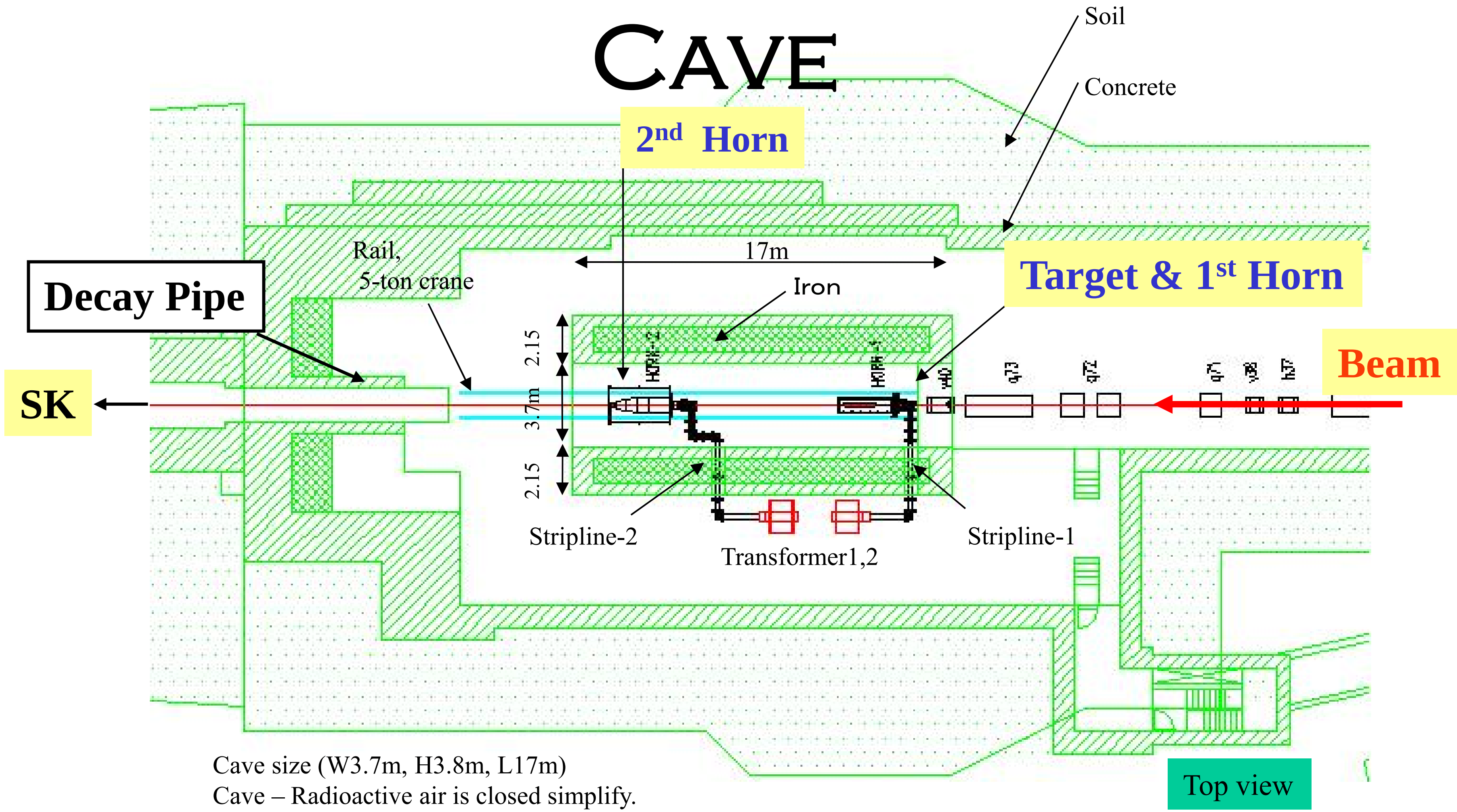


Horns for Pion Focusing



- Tandem horn system (1st horn+2nd horn)
- Operation current 250kA at both horns
- High pulsed current 2.5ms width, 2.18s cycle
- Total joule's heat=7740 kcal/h

Target and Horns in Cave

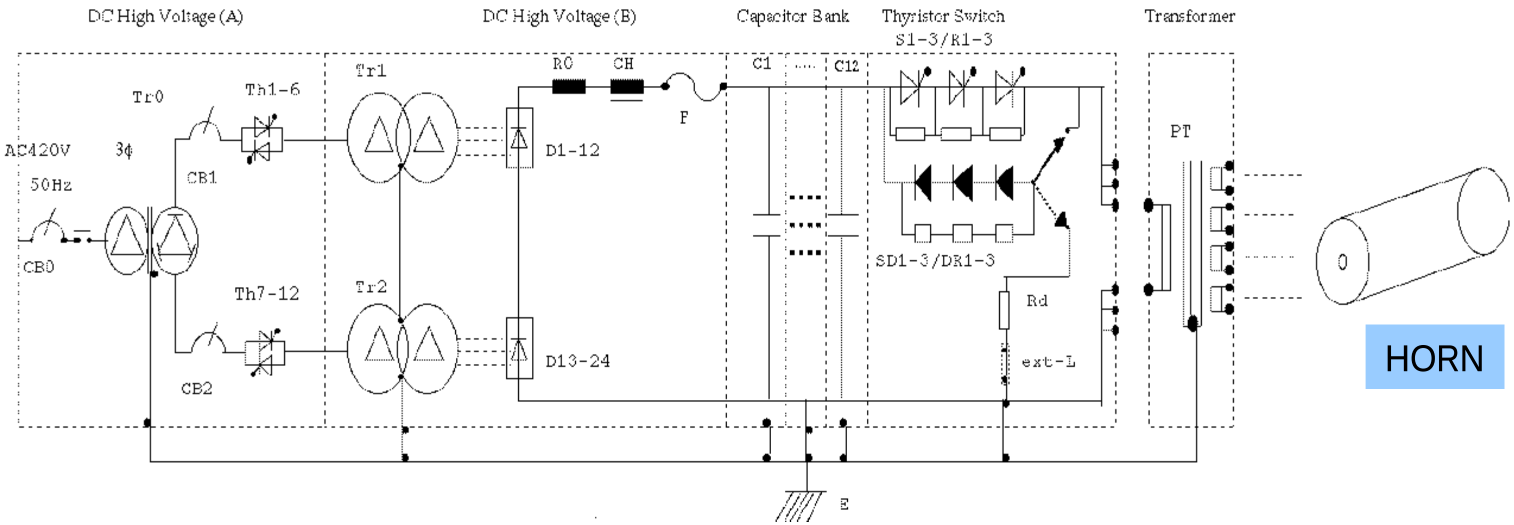


Cave size (W3.7m, H3.8m, L17m)
Cave – Radioactive air is closed simplify.
Both transformers is set inside beam line.
Stripline-1 : 9.3m, (Cross section t15mmx320mm)
Stripline-2 :12.0m, (Cross section t15mmx320mm)

Power Supply

Peak Current =250kA peak,
Pulse Width =2.5ms

:

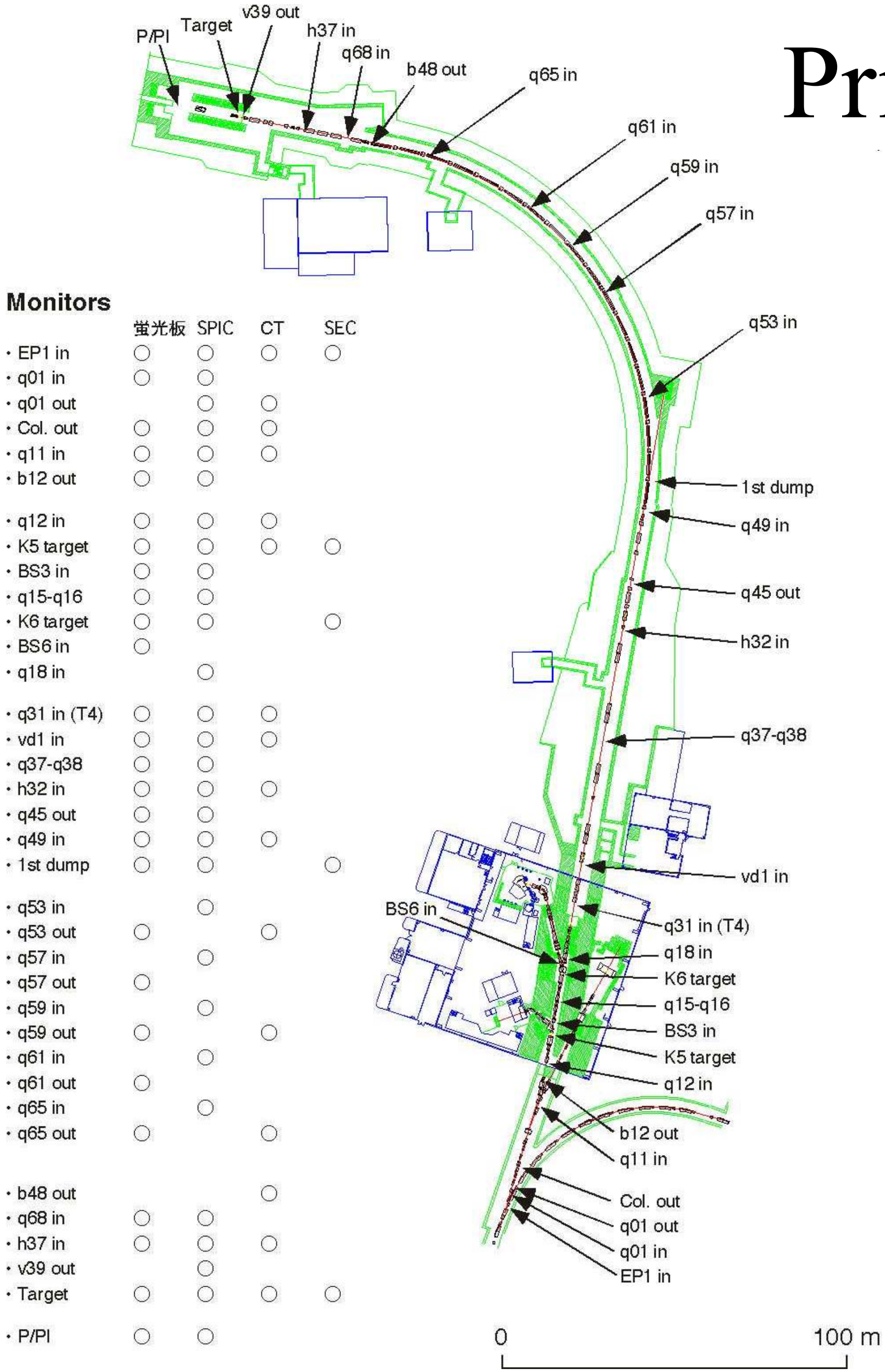


- Capacitor (500µF/unit) :

  7 units @1st Horn, 8 units @2nd Horn
- Thyristor Switch (1.2kV, 3000A) : 3 units in Series
- Trasformer Ratio =20:2

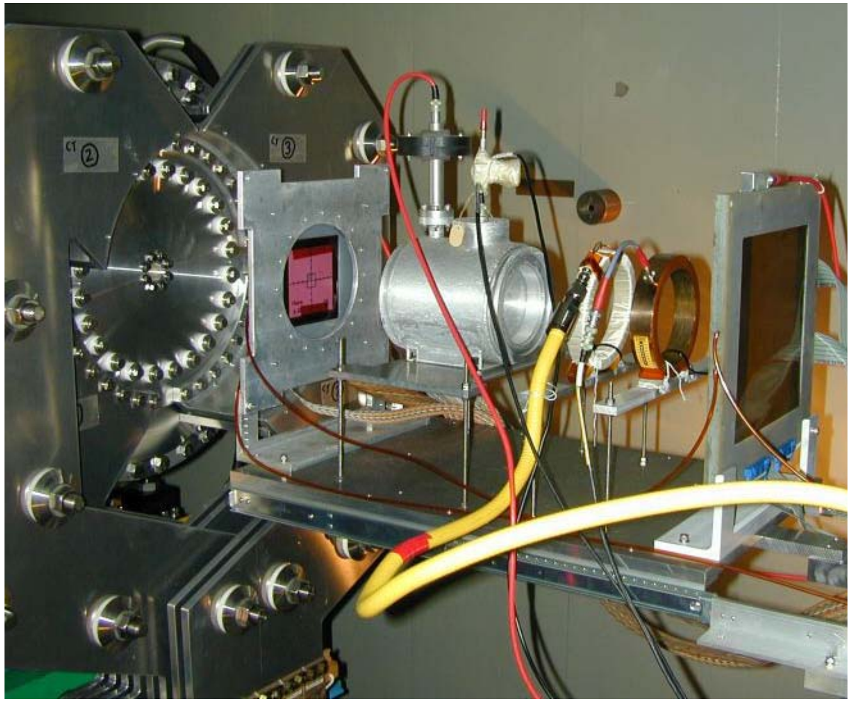
Primary Proton Monitors

- Profile
  - Luminescence Screen（蛍光板）
  - SPIC
- Intensity
  - CT
  - SEC

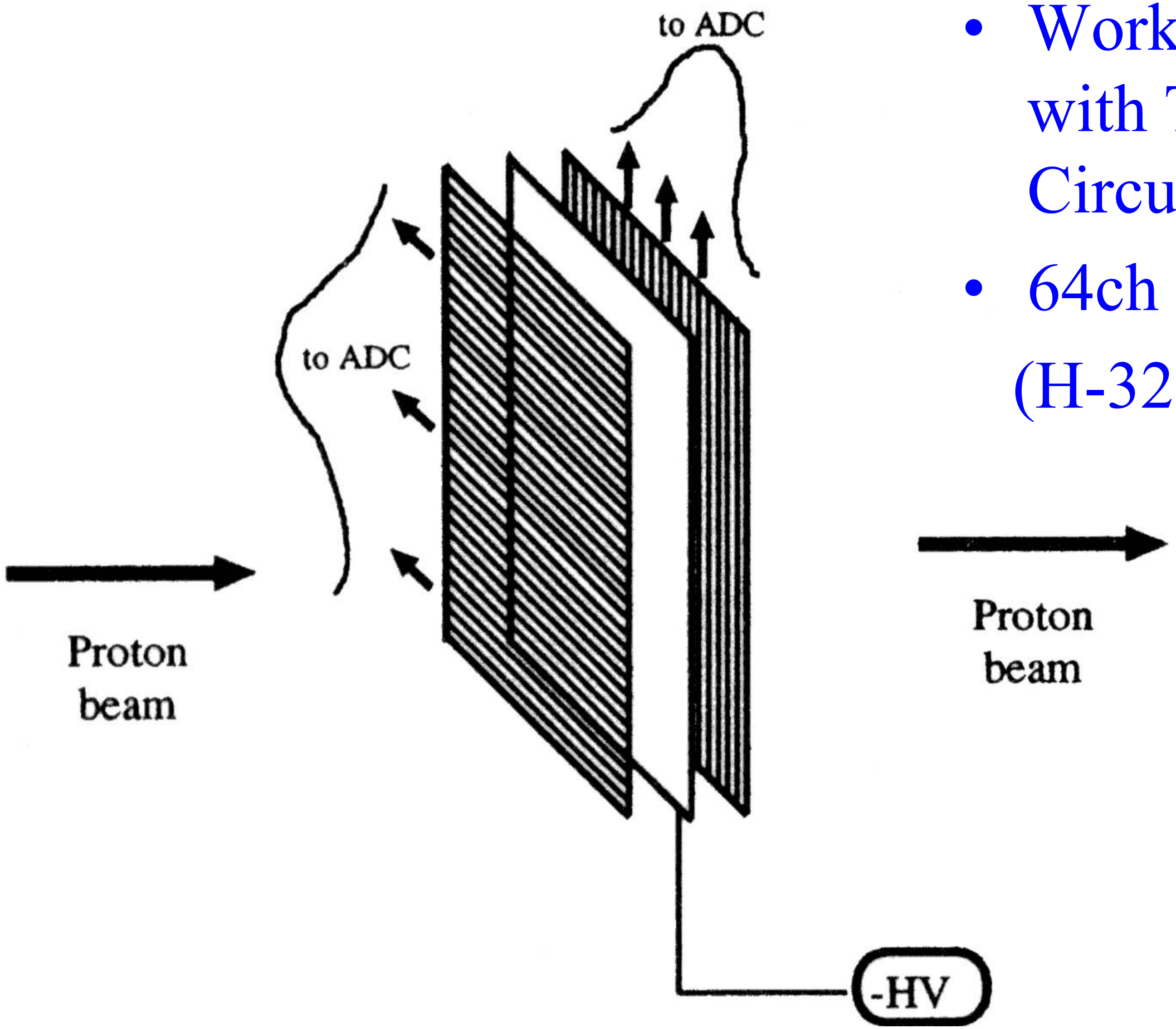


Monitors

	蛍光板	SPIC	CT	SEC
• EP1 in	○	○	○	○
• q01 in	○	○		
• q01 out		○	○	
• Col. out	○	○	○	
• q11 in	○	○	○	
• b12 out	○	○		
• q12 in	○	○	○	
• K5 target	○	○	○	○
• BS3 in	○	○		
• q15-q16	○	○		
• K6 target	○	○		○
• BS6 in	○			
• q18 in		○		
• q31 in (T4)	○	○	○	
• vd1 in	○	○	○	
• q37-q38	○	○		
• h32 in	○	○	○	
• q45 out	○	○		
• q49 in	○	○	○	
• 1st dump	○	○		○
• q53 in		○		
• q53 out	○		○	
• q57 in		○		
• q57 out	○			
• q59 in		○		
• q59 out	○		○	
• q61 in		○		
• q61 out	○			
• q65 in		○		
• q65 out	○		○	
• b48 out			○	
• q68 in	○	○		
• h37 in	○	○	○	
• v39 out		○		
• Target	○	○	○	○
• P/PI	○	○		

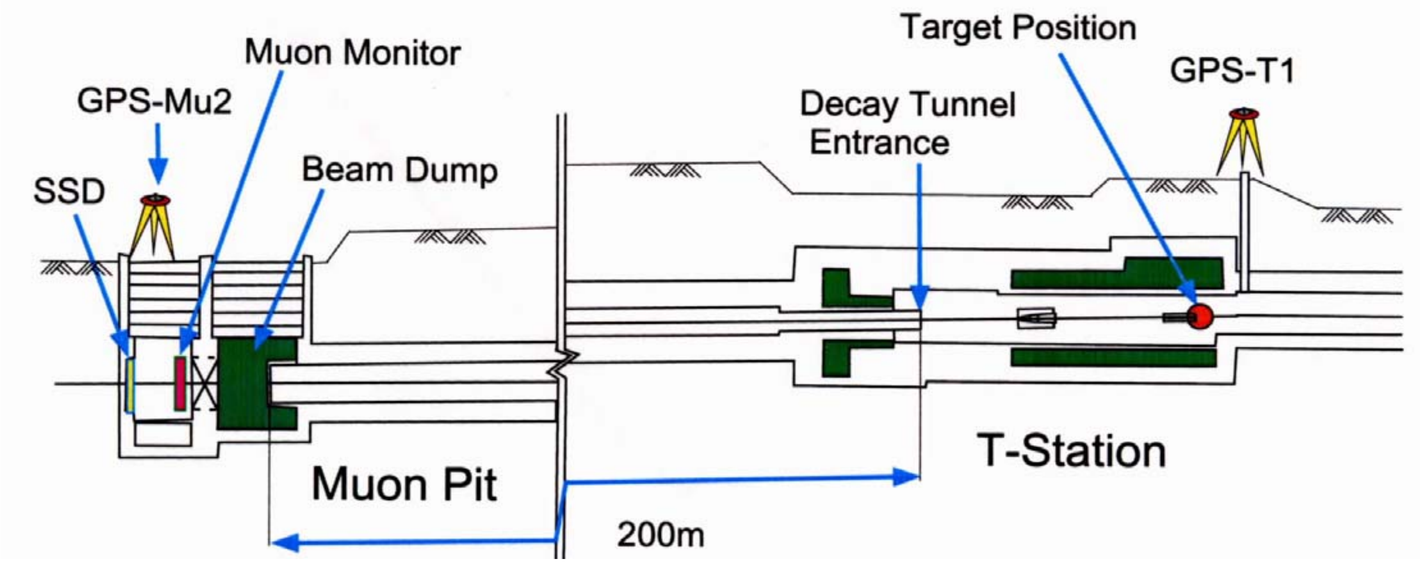


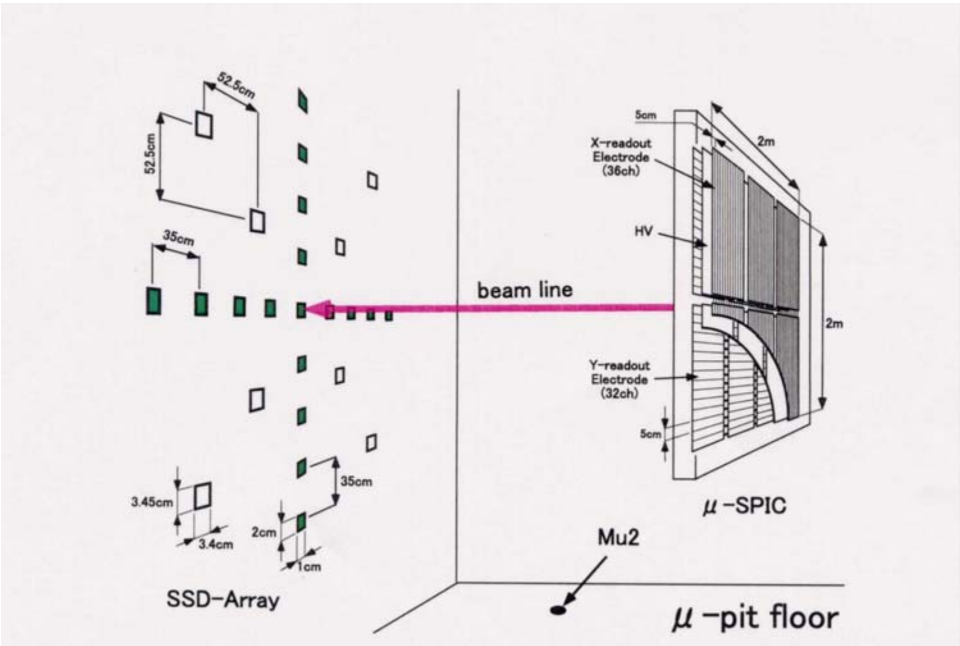
Segmented Parallel Plate Ion Chamber (SPIC)

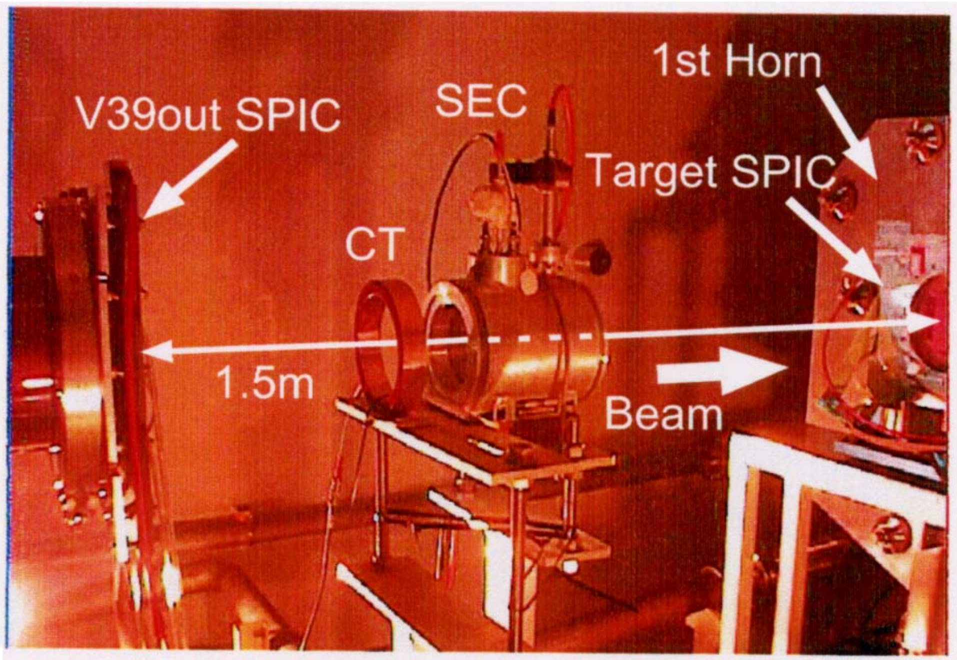


- Operated in He.
- Work in fast Beam with Time Constant Circuit.
- 64ch ADC readout (H-32ch, V-32ch)

Decay Volume & Muon Monitor

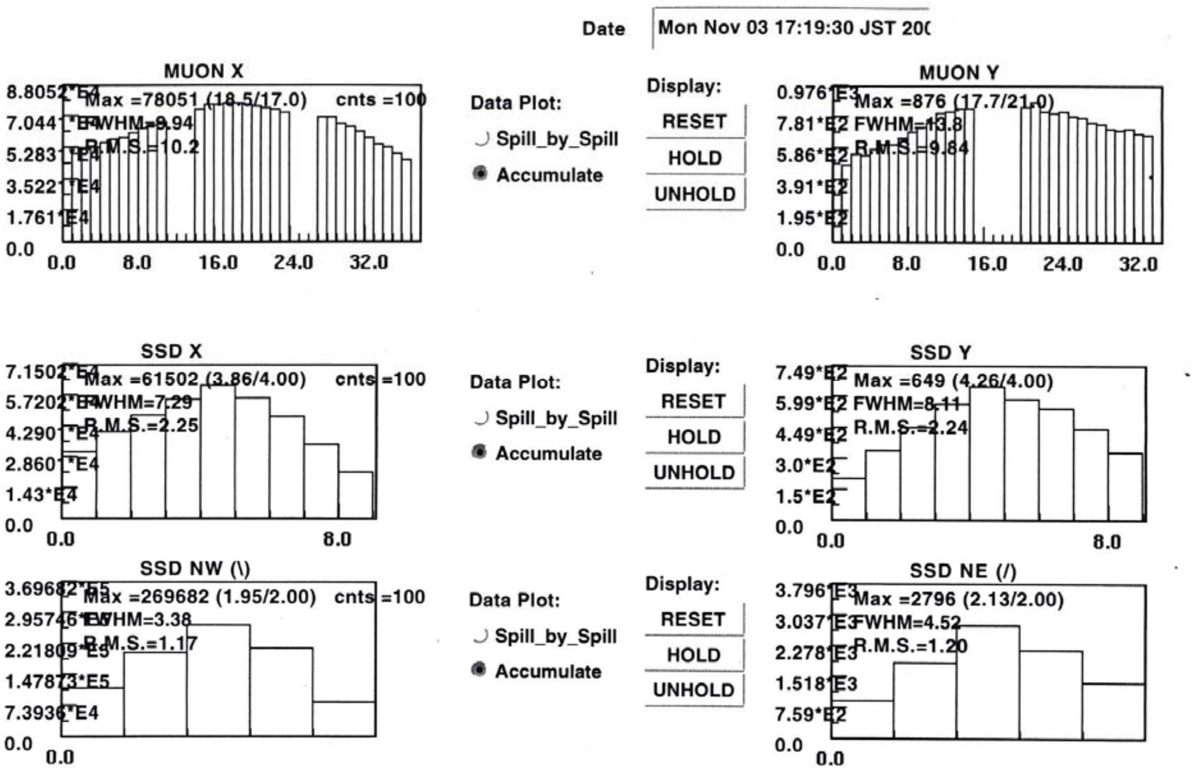


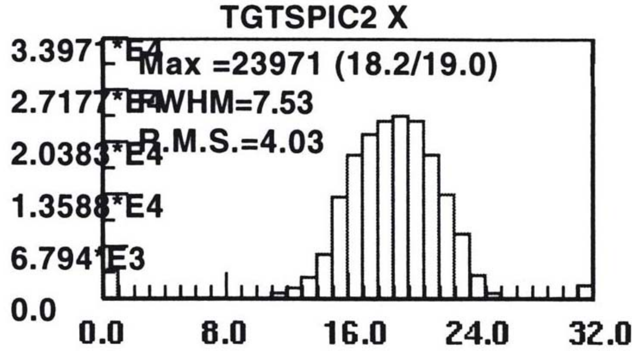




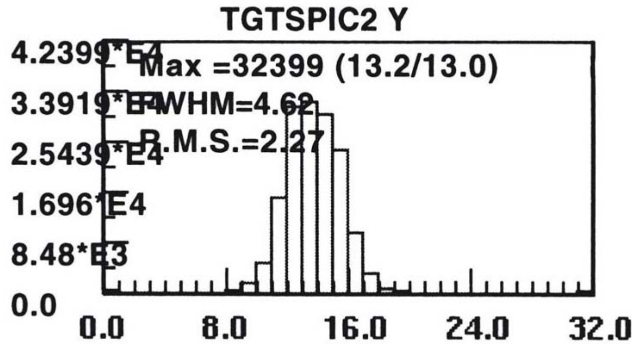
Muon/Proton Beam profiles

Proton Profile measured by SPIC. ↓



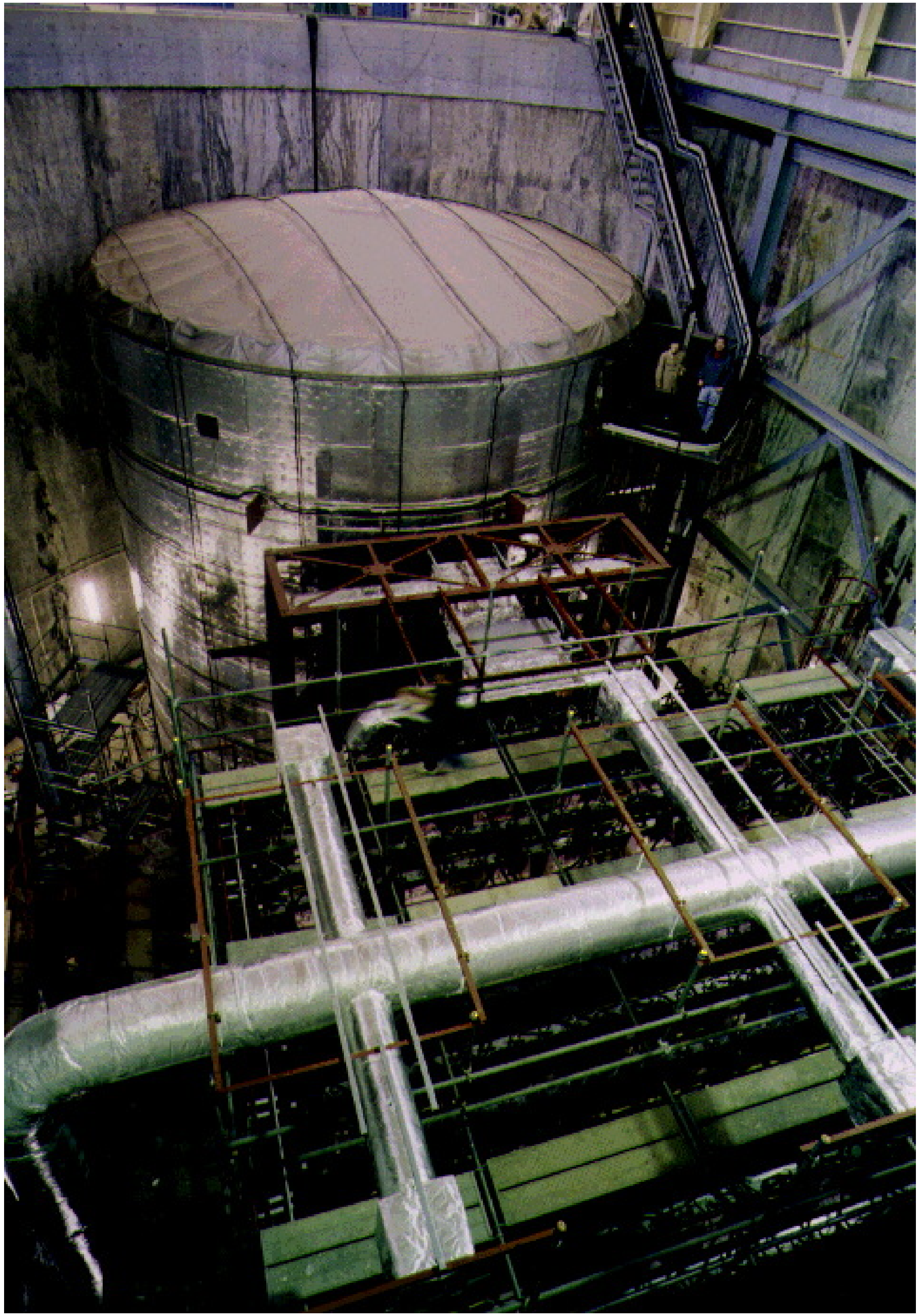


1ch=1.27mm



↑Muon Profile measured by Muon Chamber and SSD's.

Front Detector as Neutrino Beam Monitor



Front Detector Photograph

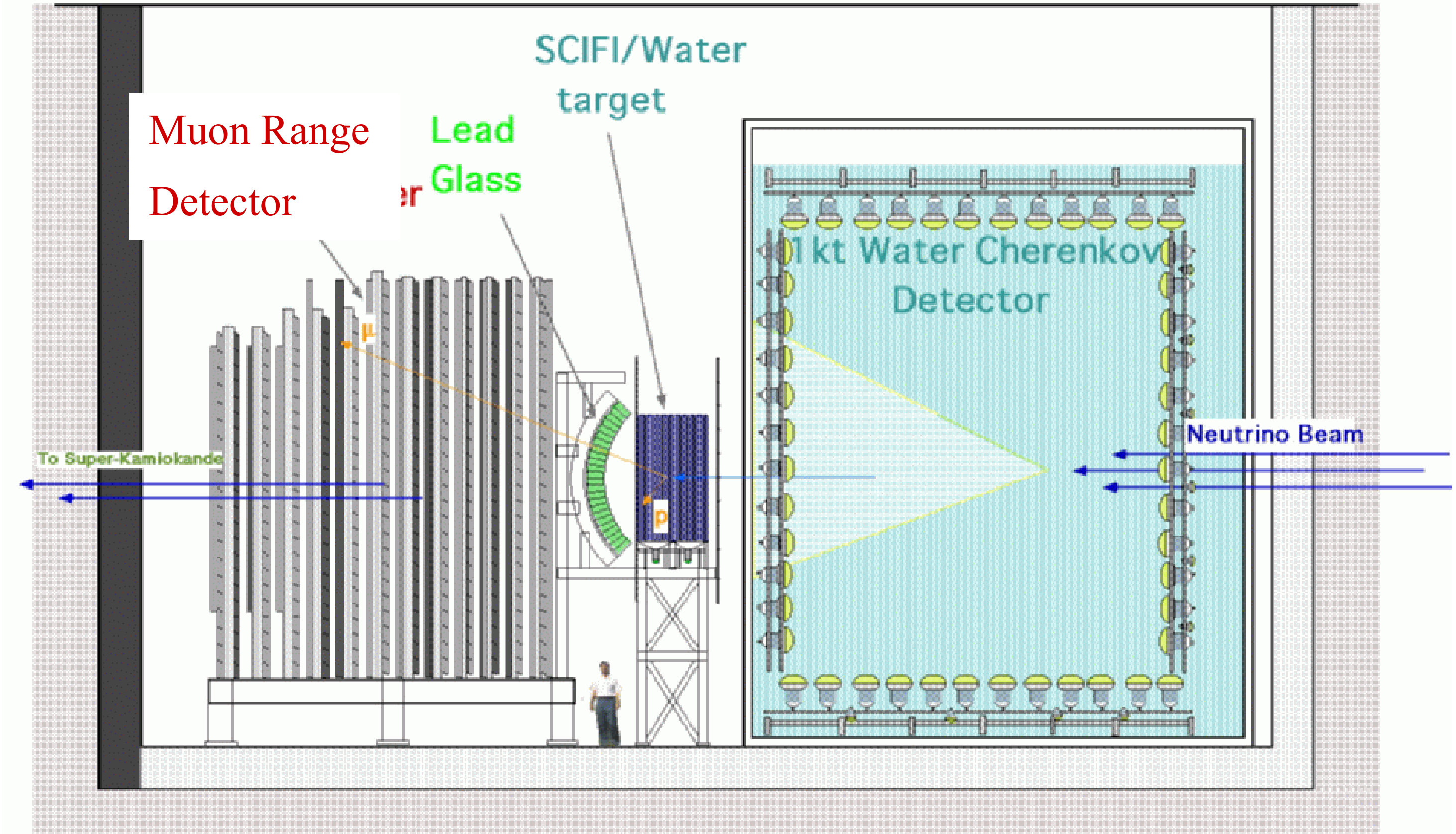
←1kt Baby Kamioka

←SciFi

←Lead Glass

←Muon Range
Detector

Front Detector Configuration

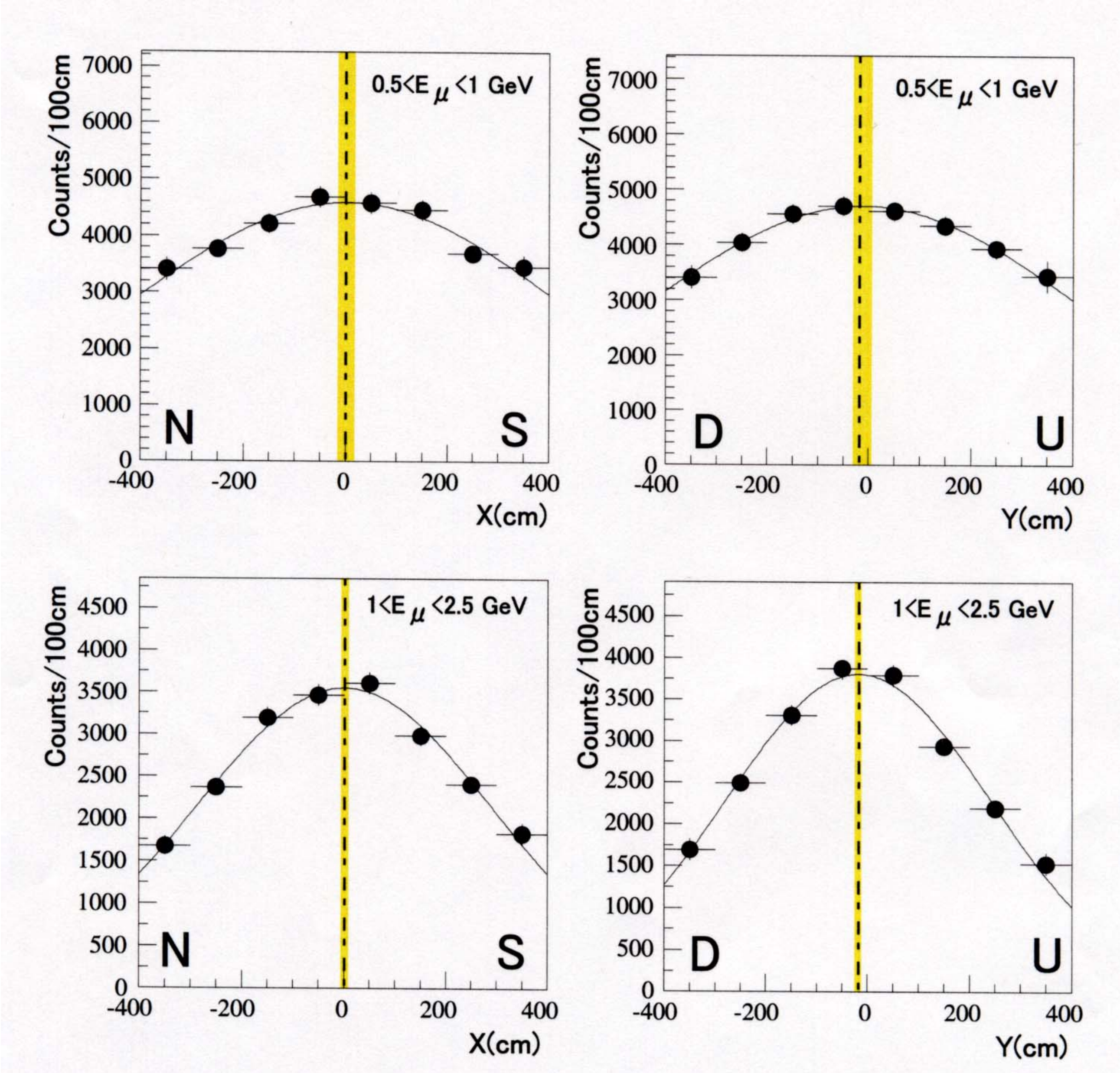


1ktWCD: Same Type Detector as SK

MRD and SciFi: Fine Grained Precise ν Detector

MRD: Massive and Large Solid Angle ν Detector

Neutrino Beam Profile (MRD)



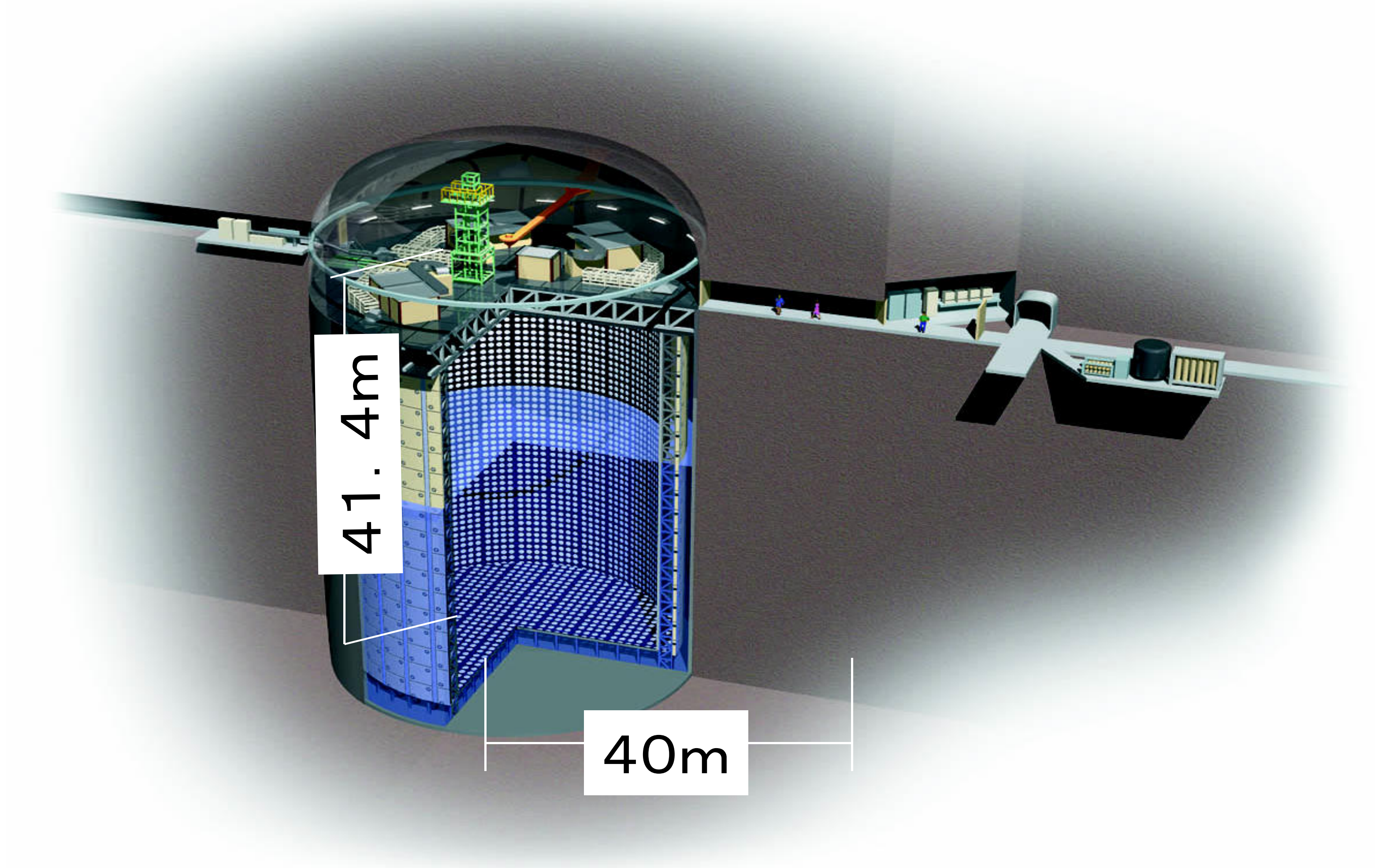
- One Month Data
- Yellow belt: Fitting Error
- Dot-dashed line: Center from GPS survey

Super-Kamiokande

(Completed in April, 1996)

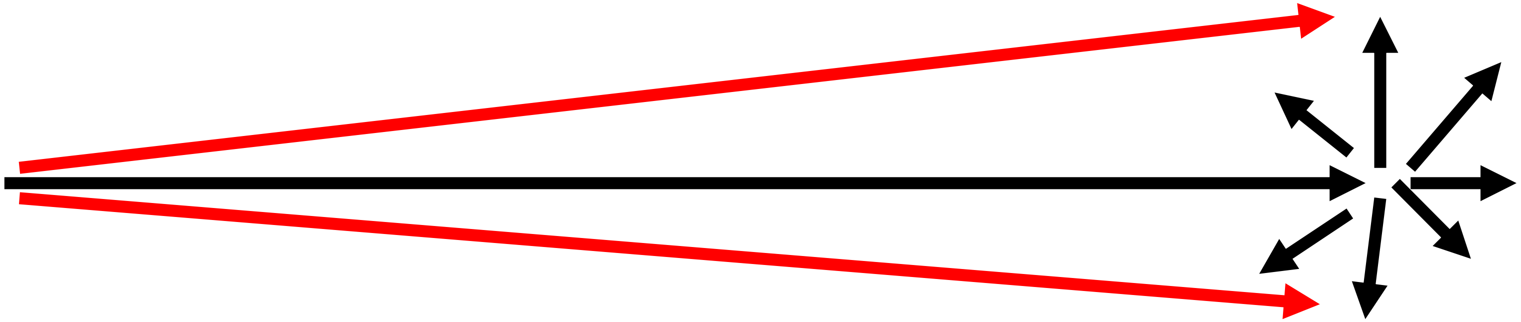
50,000 ton water Cherenkov detector (22.5 kton fiducial volume)

Livetime (exposure): 1289 days (79.3 kt・yr)



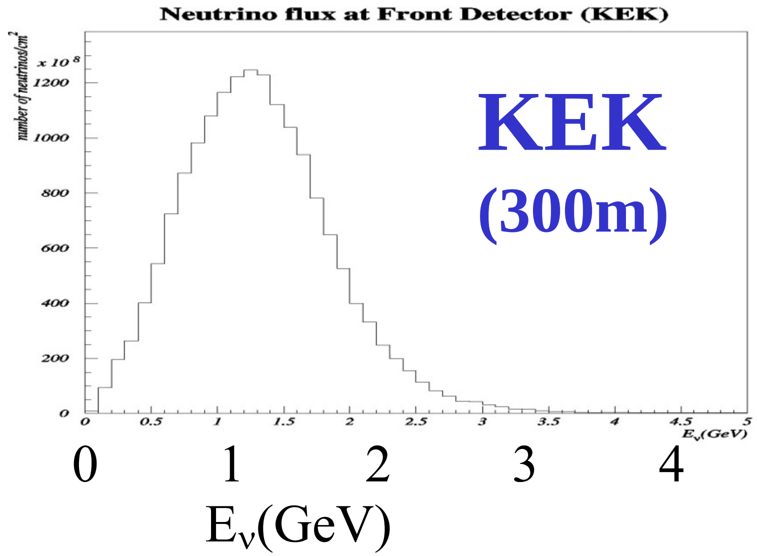
•ニュートリノビームをSKに当てる！

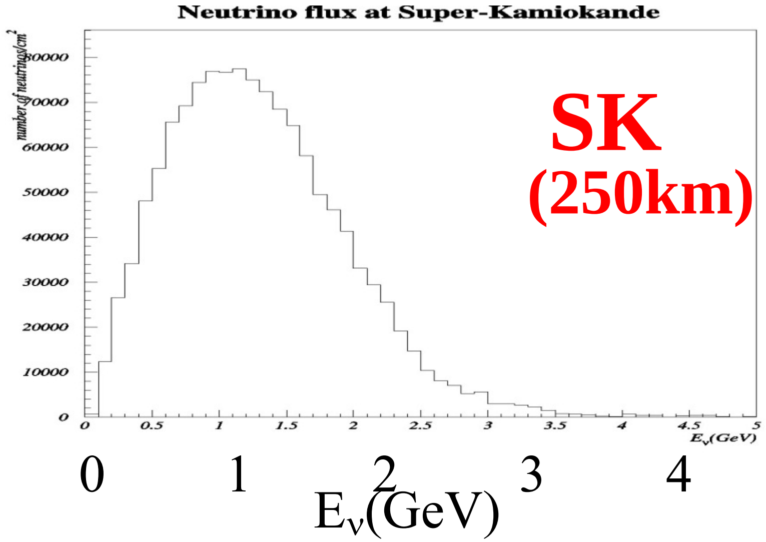
人工ニュートリノビーム



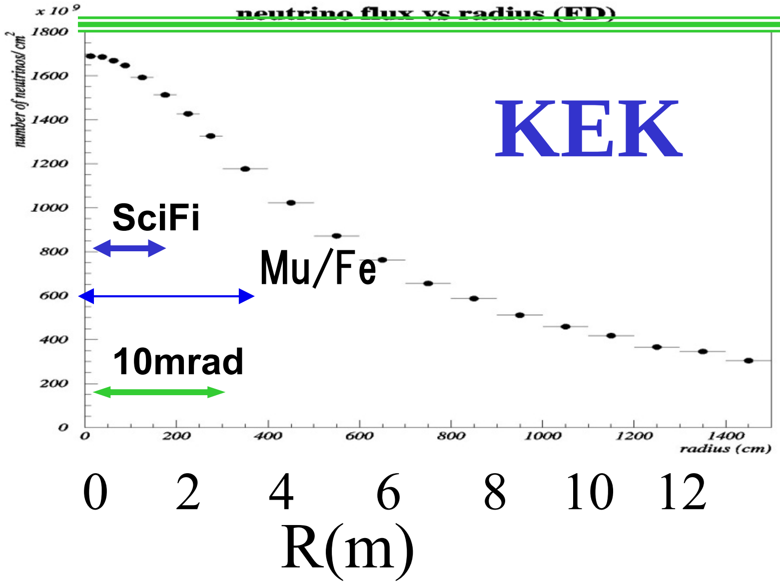
- 成分比が完全に判る！
- 必ず～30／1000の自然幅が存在する

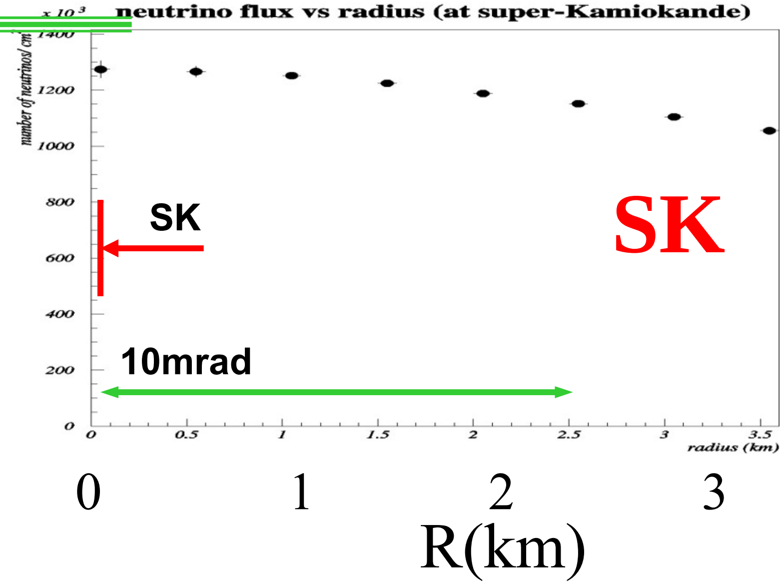
Neutrino Energy (Monte Carlo)





Neutrino Profile (Monte Carlo)





Positioning Precision from KEK to SK

Experimental Requirement:

±1mrad (Long Term)

- Positioning by GPS and Optical Survey

  $\triangle_{\text{Horizontal}}$=1.2m, $\triangle_{\text{Vertical}}$=0.7m,

  〜±0.005mr,

- Beam Line Alignment and Monitoring

  Horizaintal〜±0.02mr,

  Vertical 〜±0.05mr,

- Beam Control and Tuning (Short Term)

  Horizaintal〜±0.03mr,

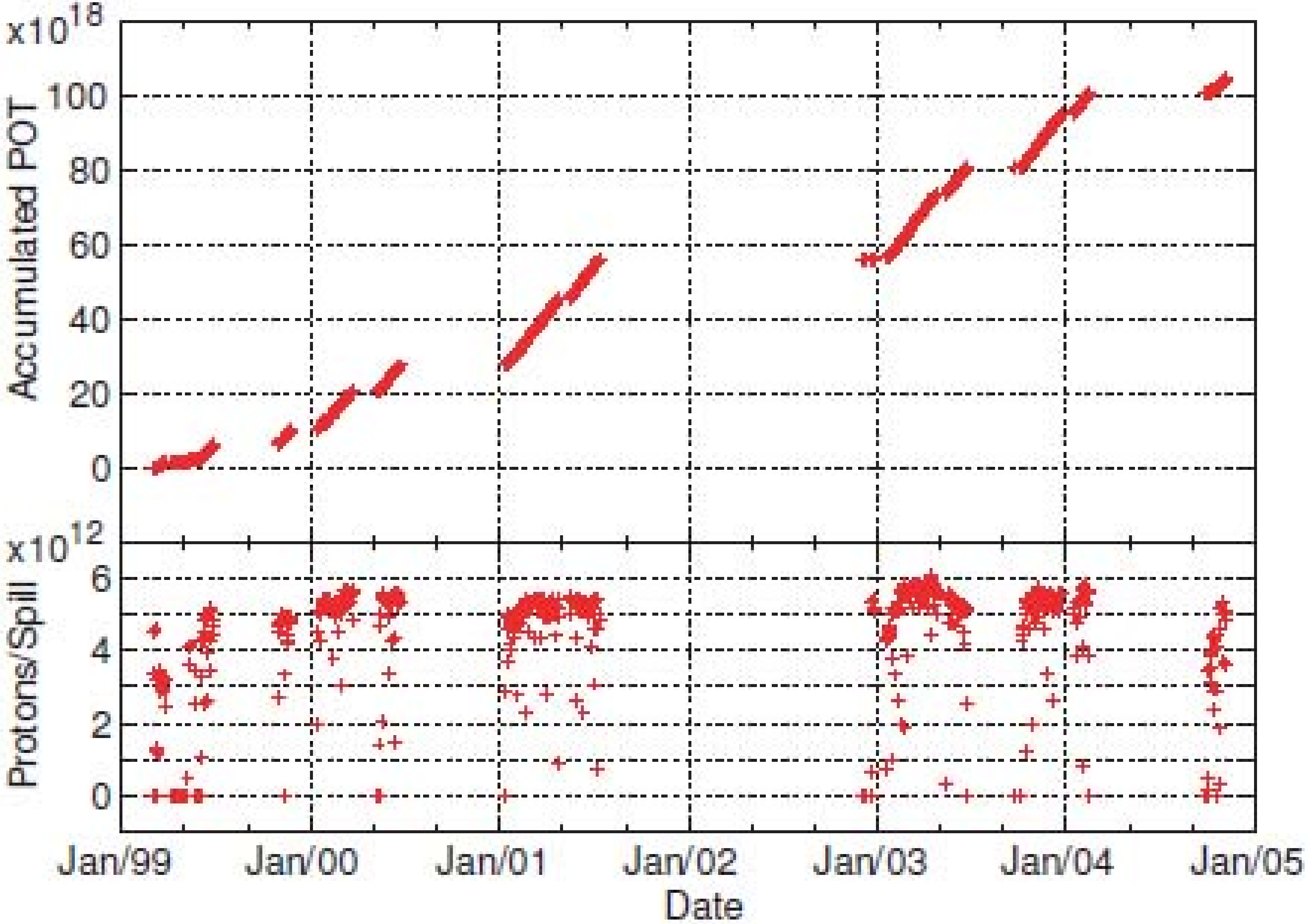
  Vertical 〜±0.06mr,

±1mradの精度

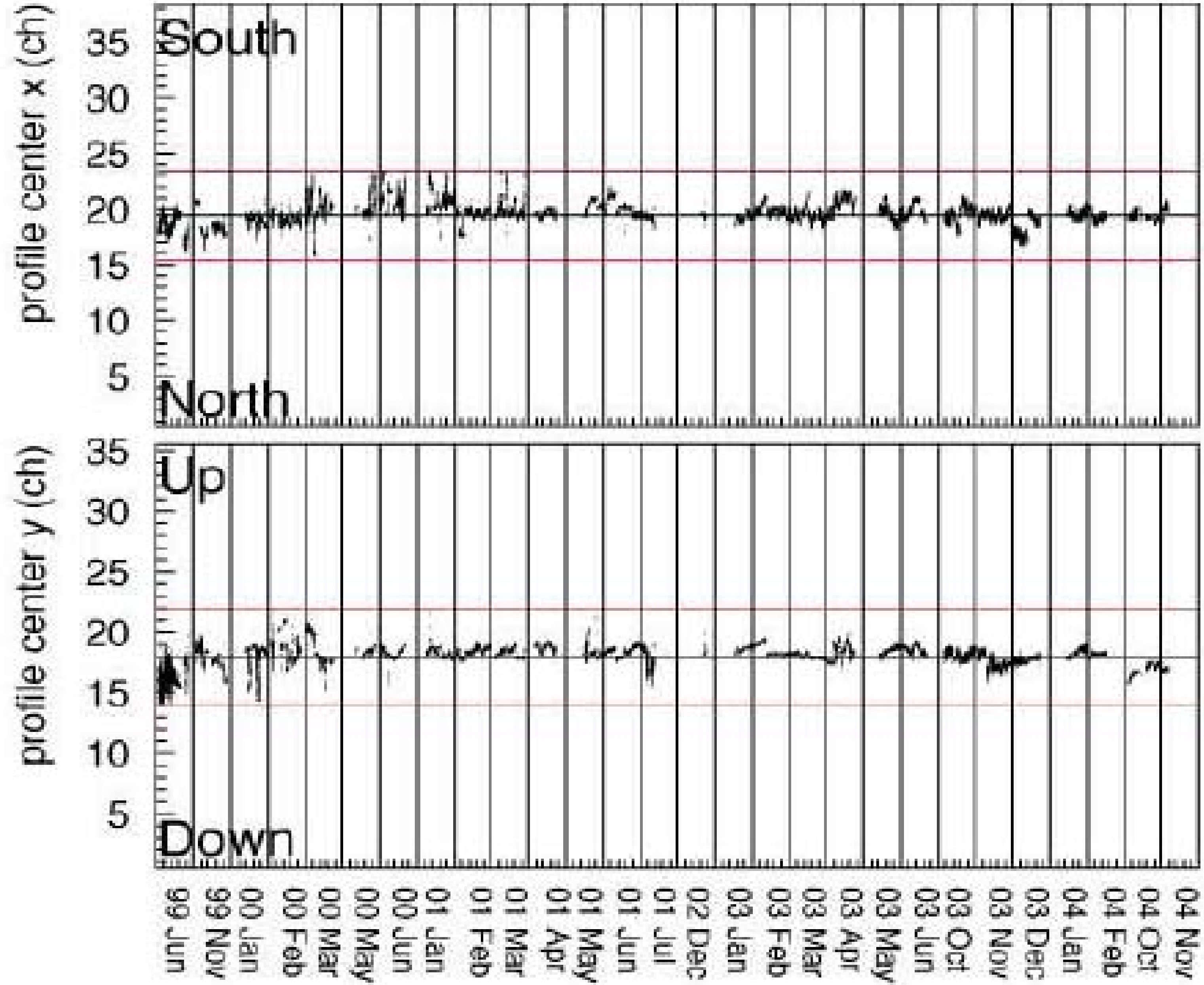
- ２５０m先で、±２５cmの精度
- 装置の設置精度は十分に良いので
- ビームの位置検出精度が１／１０００より十分によければ、必ず当たる！
- ならばミューオンモニターの空間分解能をcmからインチにしておけば十分。
- ミューオンモニターで１ch～２chの中にミューオンプロファイルの中心を止まらせる！

運転実績

Delivered Protons on Target (POT)



Muon Profile: Centoroid Stability(全データ)



Horizonral

← +1 mrad

← -1 mrad

Vertical

← +1 mrad

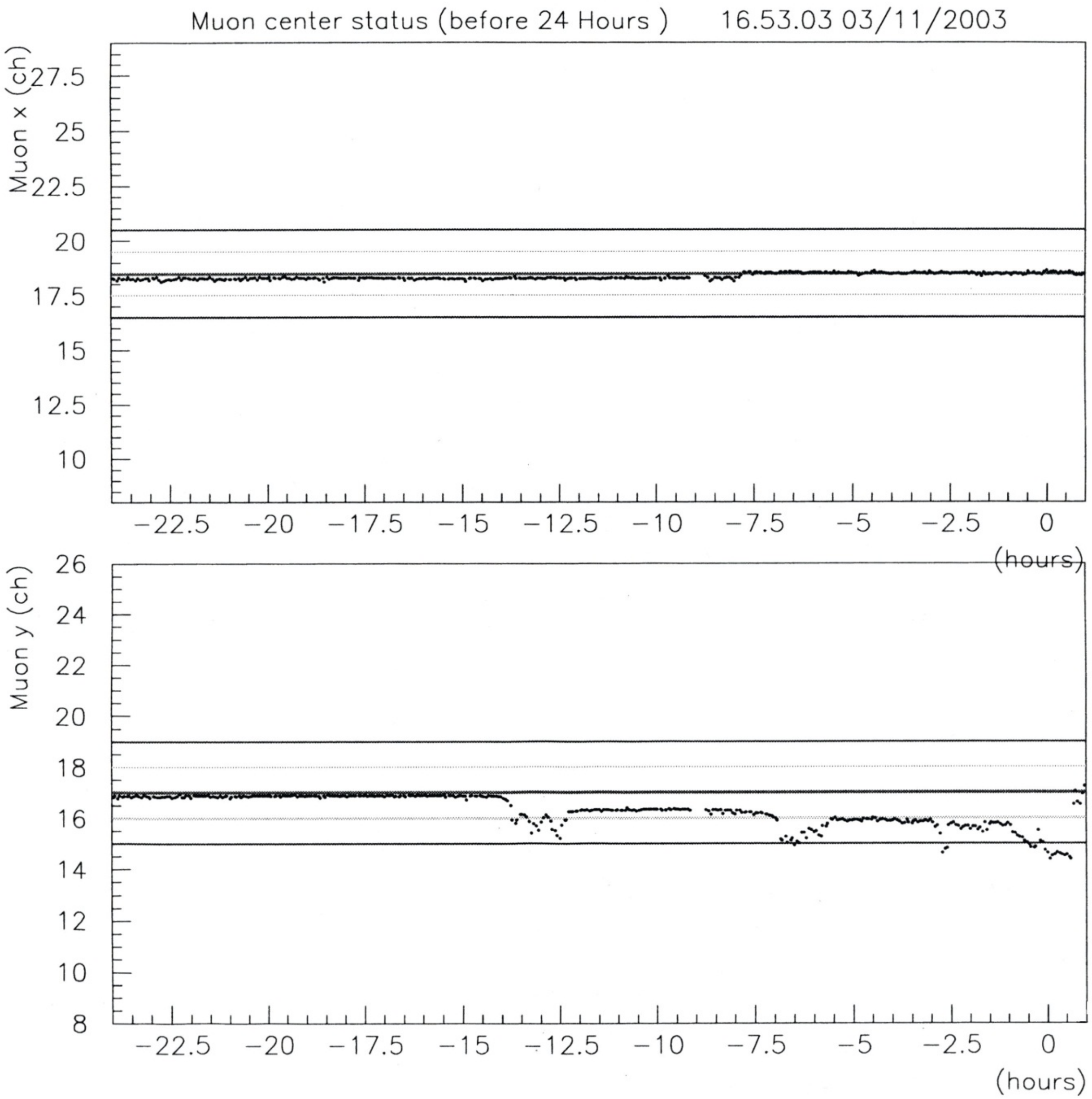
← -1 mrad

Beam Shift Correction

- 1ch shift (day)
- 2ch shift (night)

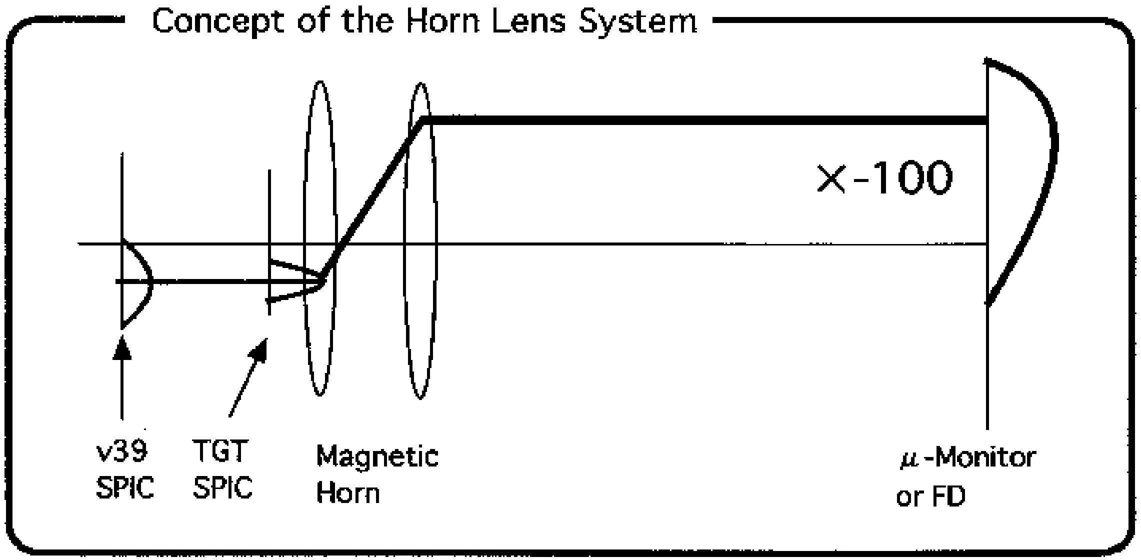
↓

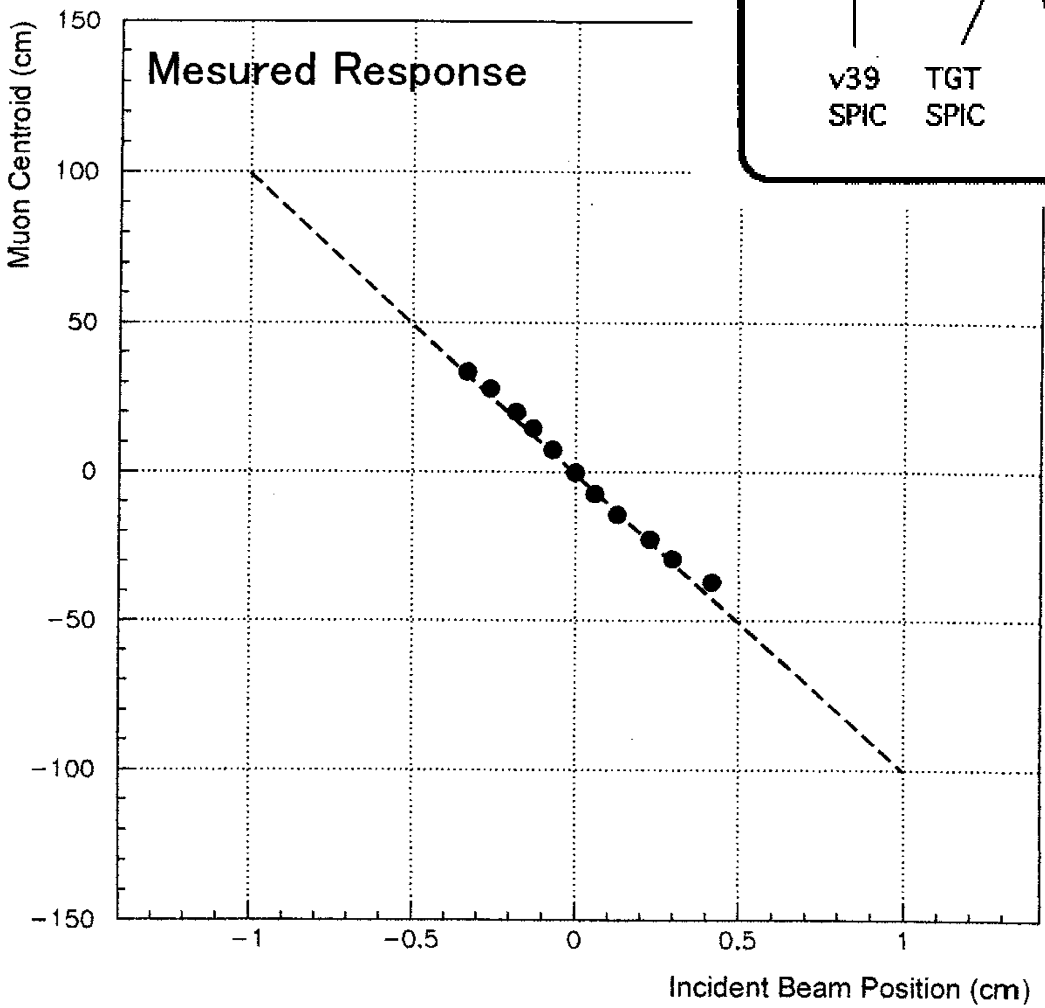
Human Correction



- DCCT error?
- Magnet coil?
- Ion source?
- EX septum?

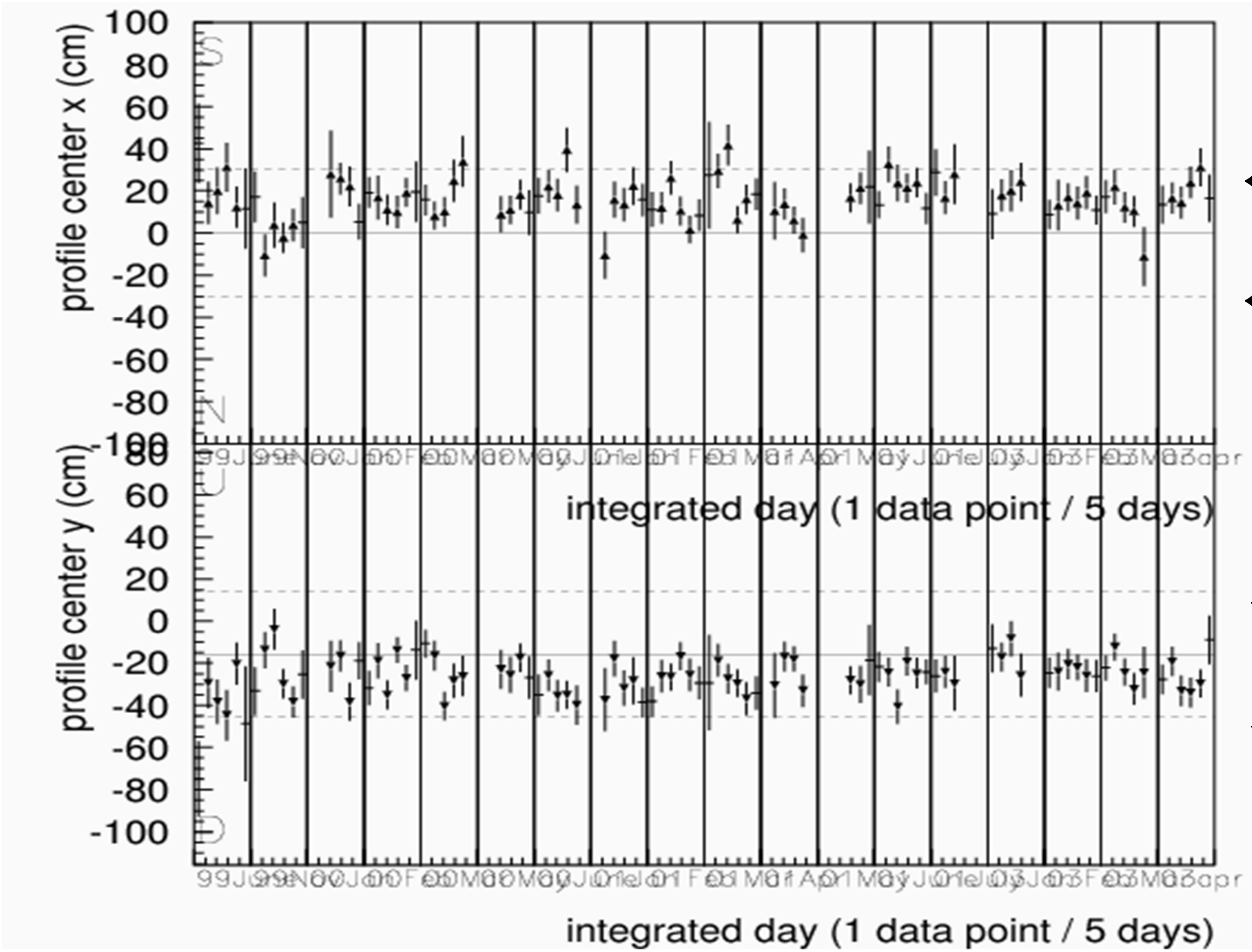
Muon/Proton Correlation





- Horn is –100 times Image Magnifier.
- For accurate aiming, stable positioning of proton beam on target is essential.
- Beam monitors of primary protons are very important.

Neutrino Profile: Centroid Stability
(Muon Range Detector)



Horizontal

←+1 mrad

← -1 mrad

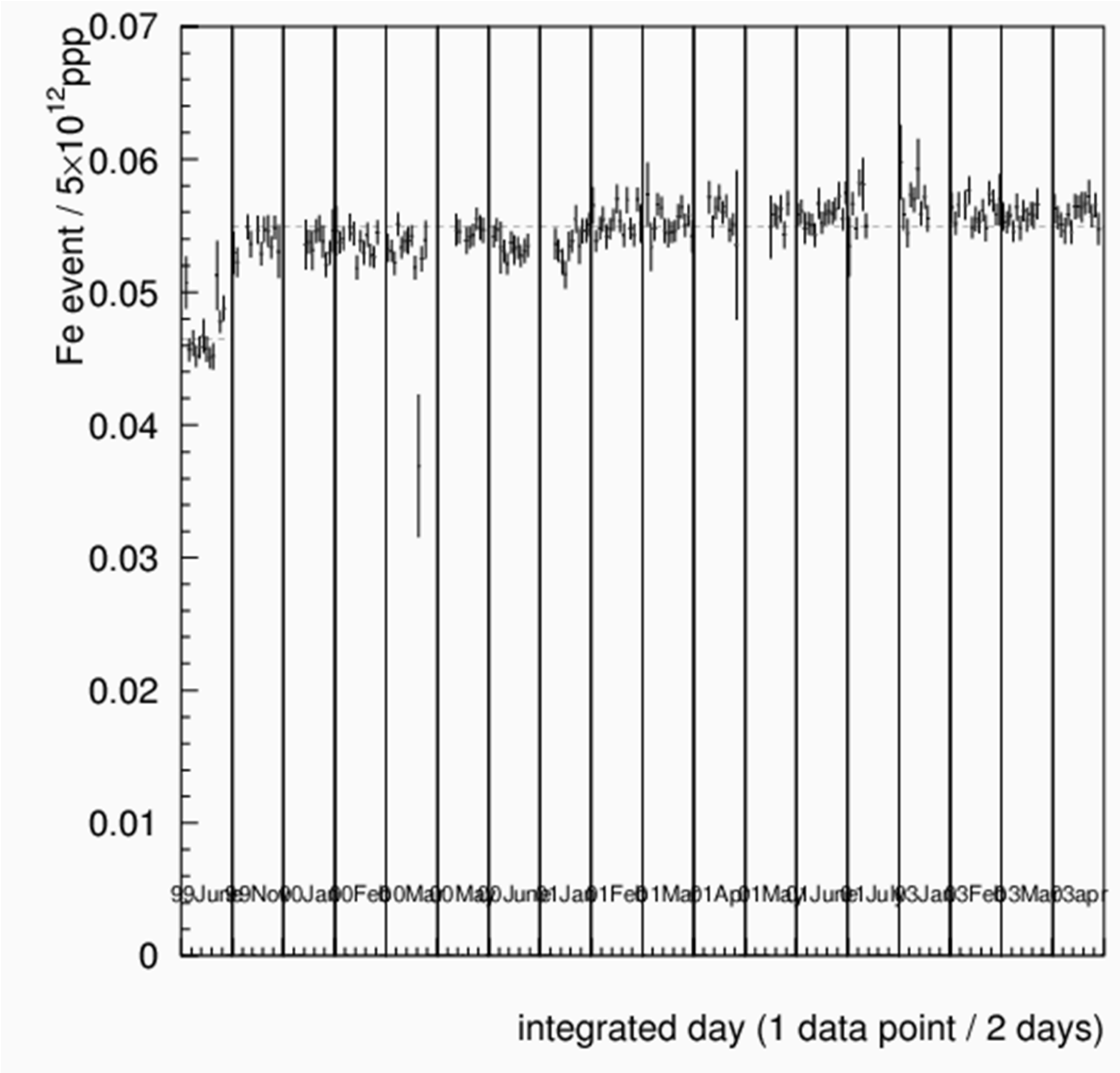
Vertical

←+1 mrad

← -1 mrad

Neutrino Event Rate Stability

(Muon Range Detector/POT)



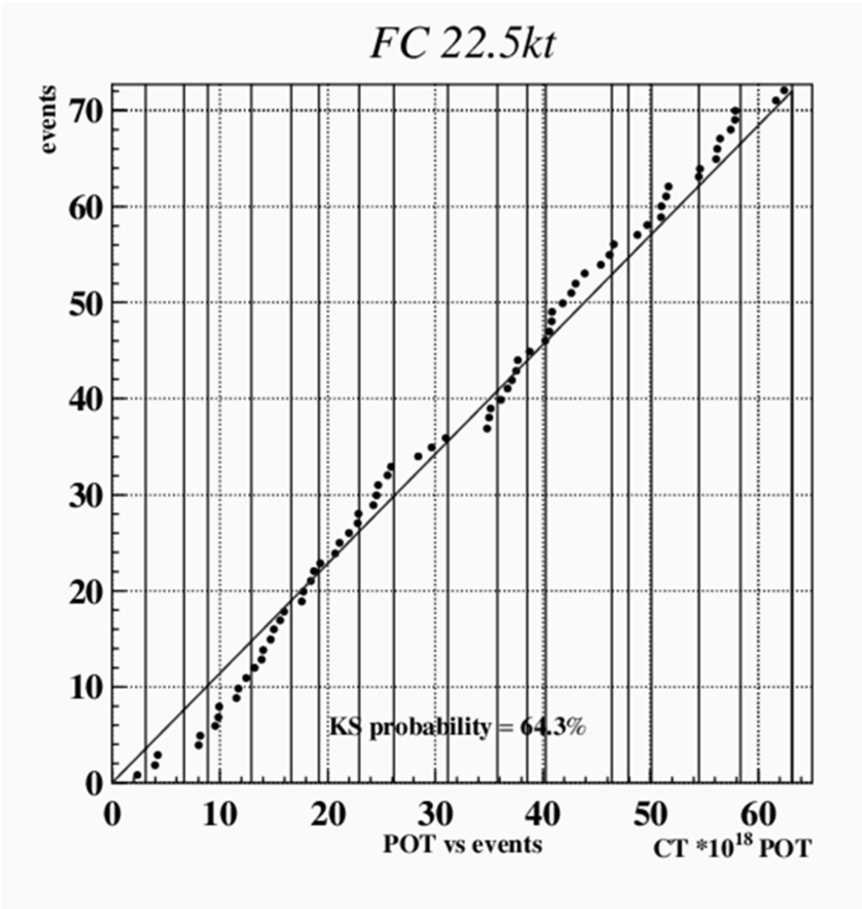
Horn 250kA

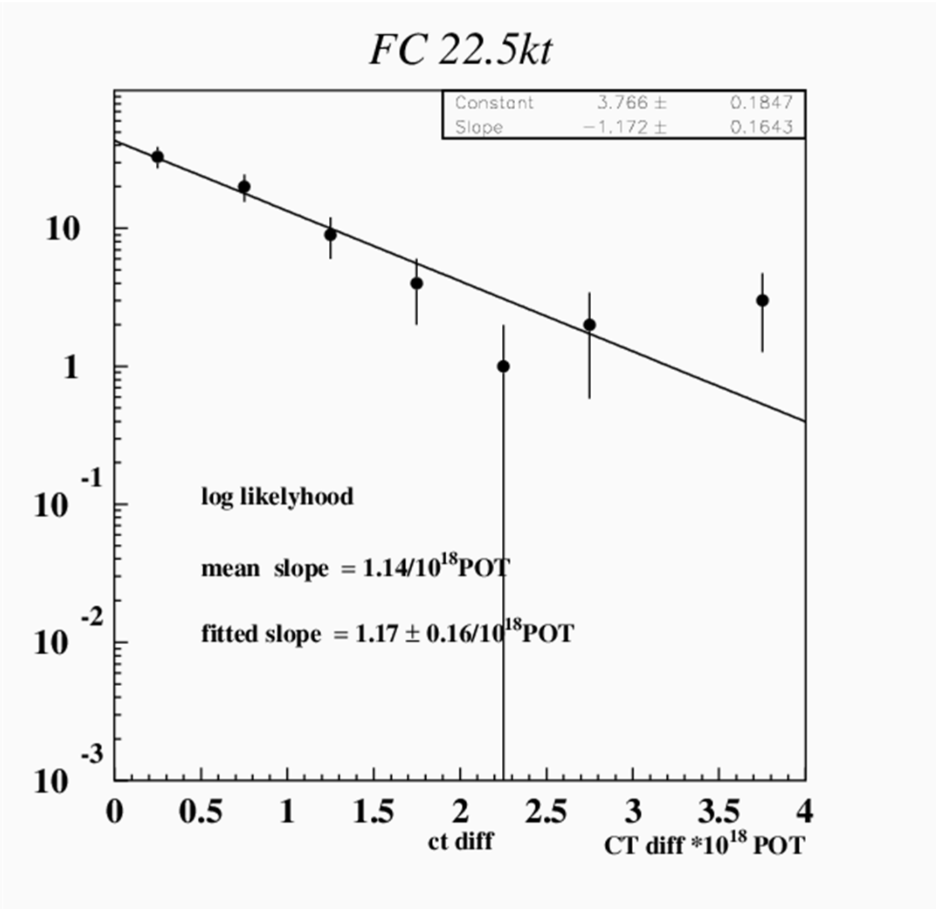
← Target 30 mmφ

← Horn 200kA

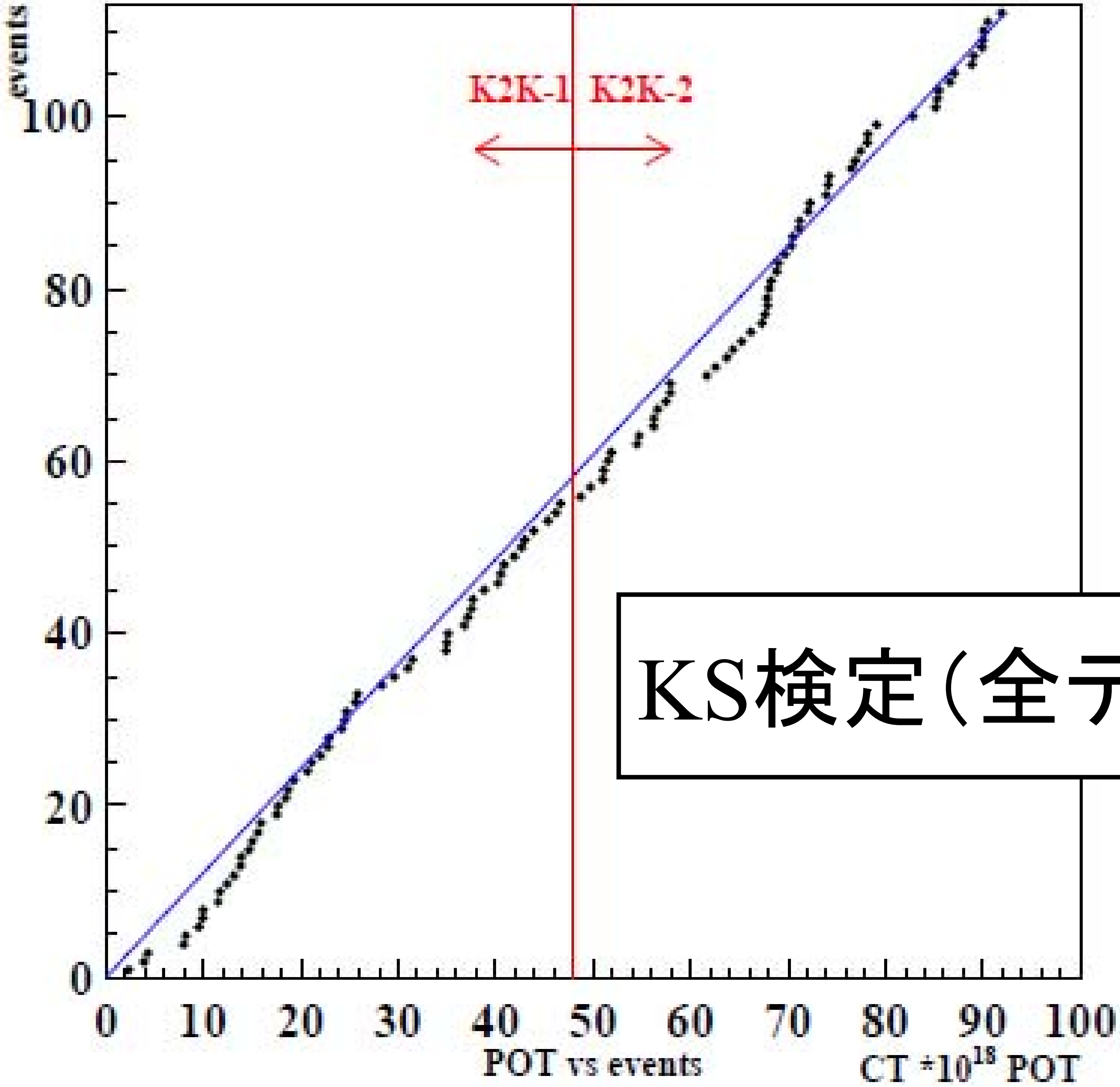
Target 20 mmφ

Event Number at SK/POT



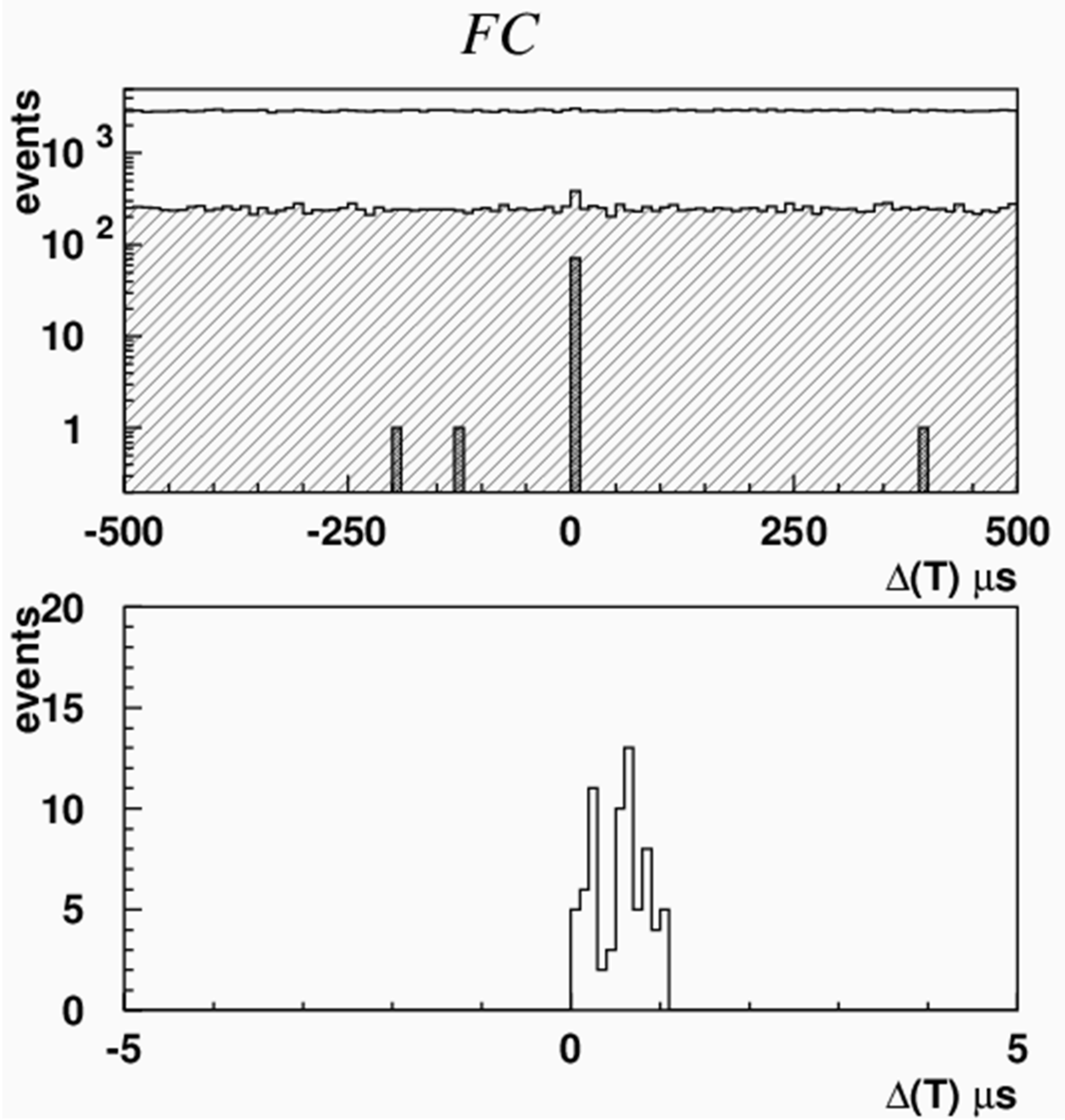


こるもごろふすみるのふ検定


events
100
80
60
40
20
0
K2K-1
K2K-2
0
10
20
30
40
50
60
70
80
90
100
POT vs events
CT ÷10^18 POT

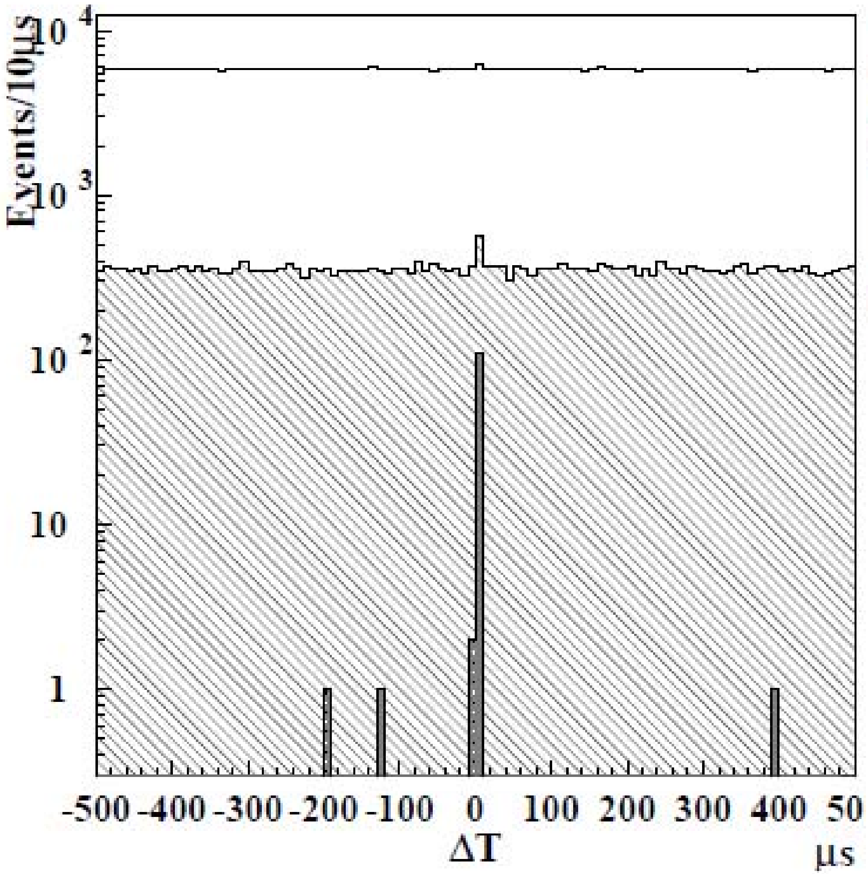
KS検定（全データ）

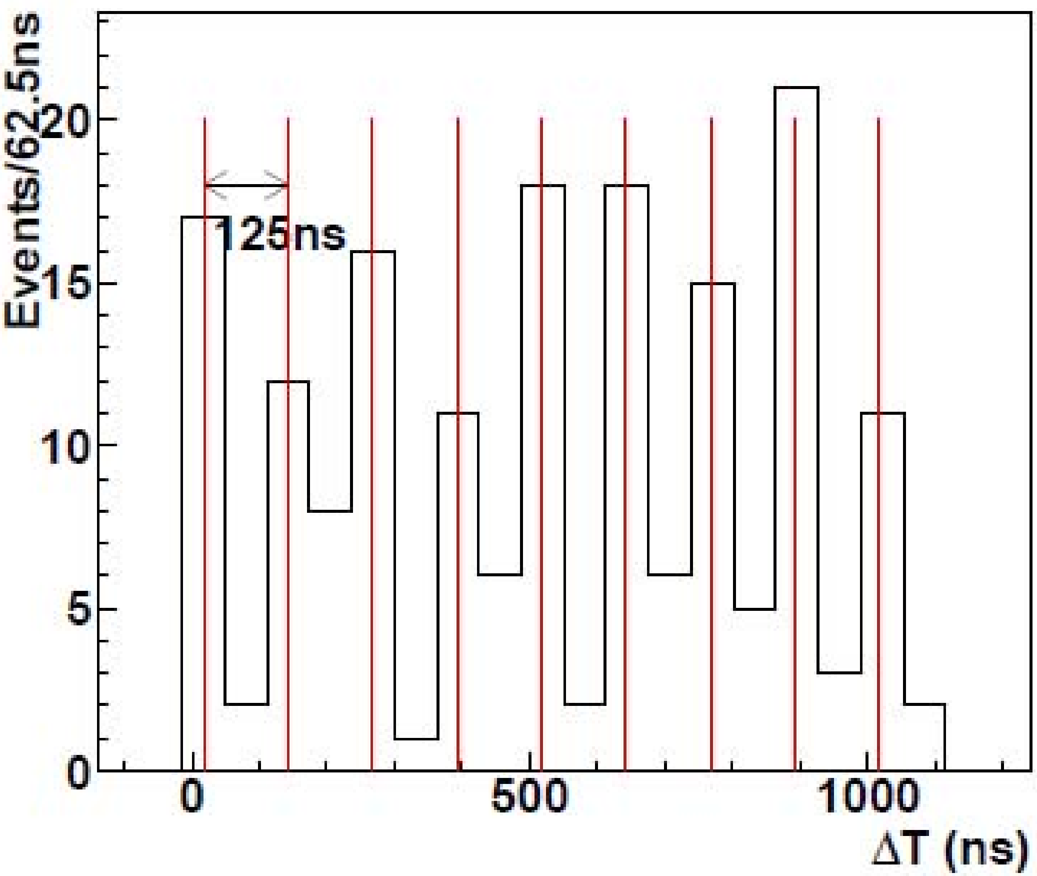
SK Event: Time Resolution



$-0.2\mu sec \leqq \Delta T = T_{sk} - T_{kek} - TOF \leqq 1.3\mu sec$

SKでのタイミング（全データ）





Observed SK events

4.8×10^{19}pot (Jun99–Jul01)

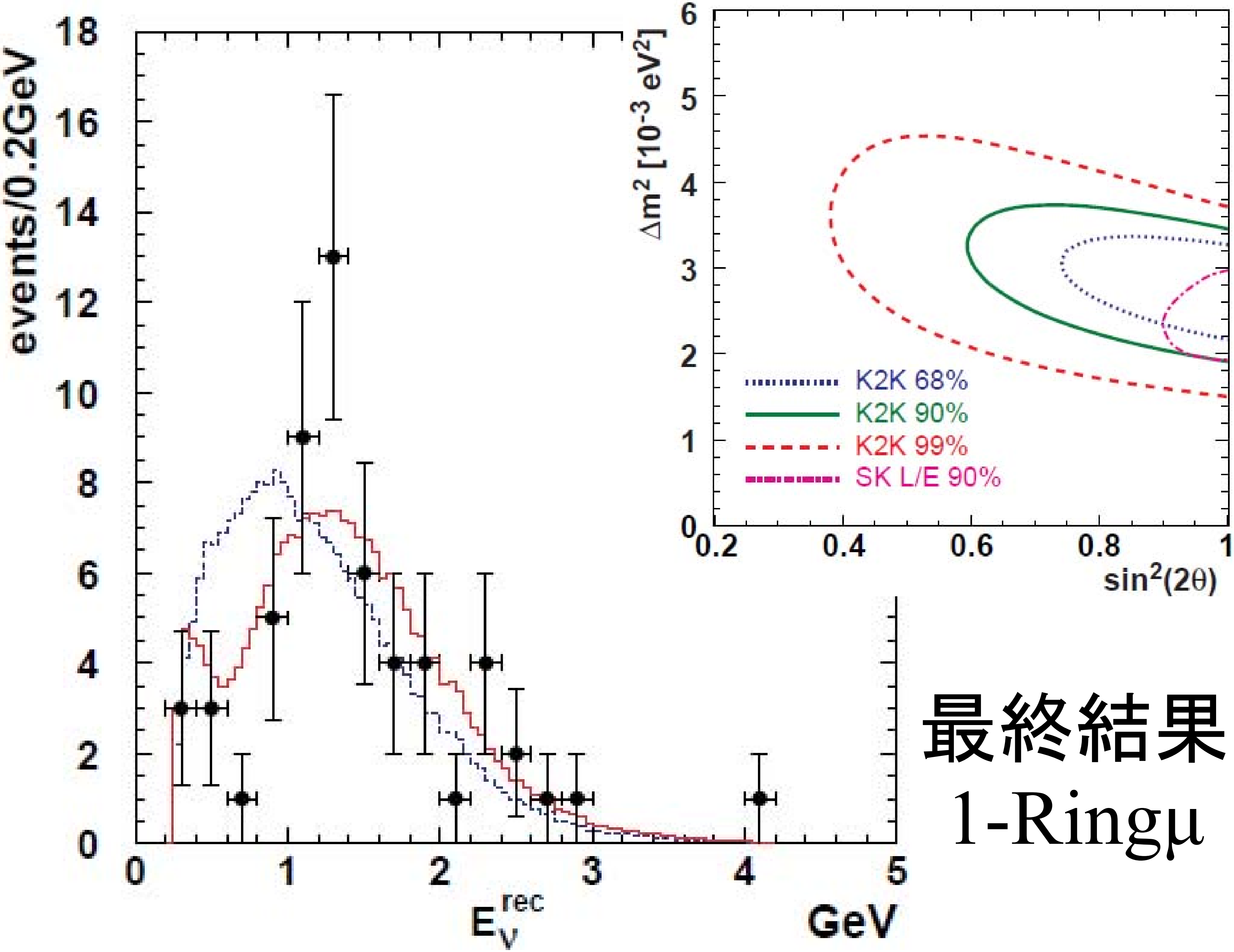
\# of observed events and expected events
1999/06-2001/07

	Obs.	No Ocsi.	$\Delta m^2 (\times10^{-3} eV^2)$ 3	5	7
FC 22.5kt	56	$80.6^{+7.3}_{-8.0}$	52.4	34.6	29.2
1-ring	32	48.4 ± 6.7	28.1	17.8	16.6
μ-like	30	44.0 ± 6.8	24.4	14.6	13.5
e-like	2	4.4 ± 1.7	3.7	3.2	3.0
multi ring	24	32.2 ± 5.3	24.3	16.8	12.6

FC 25.5kt 16 $26^{+2.3}_{-2.1}$ 1.5×10^{19}pot (Jan.03–April03)

Cf. MRD: $87.4^{+12.7}_{-13.9}$ SciFi : $87.3^{+11.9}_{-11.9}$

No oscillation hypothesis is disfavoured at 97% CL.

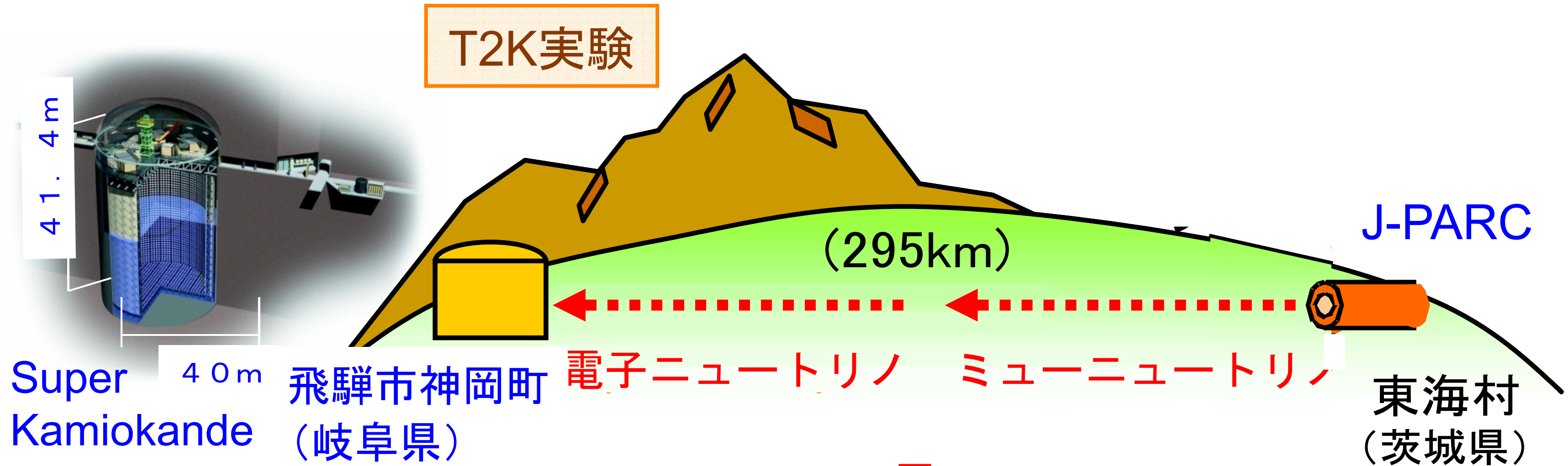

events/0.2GeV
E_ν^{rec}
GeV
Δm^2 [10^{-3} eV^2]
$\sin^2(2\theta)$
K2K 68%
K2K 90%
K2K 99%
SK L/E 90%

最終結果
1-Ringμ

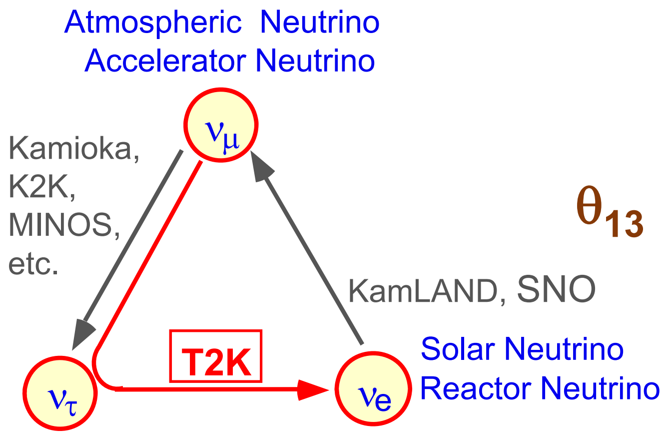
Ｔ２Ｋ実験へ

- 素粒子の標準模型ではニュートリノの質量をゼロと仮定している

  ニュートリノに質量！⇐ ニュートリノ振動



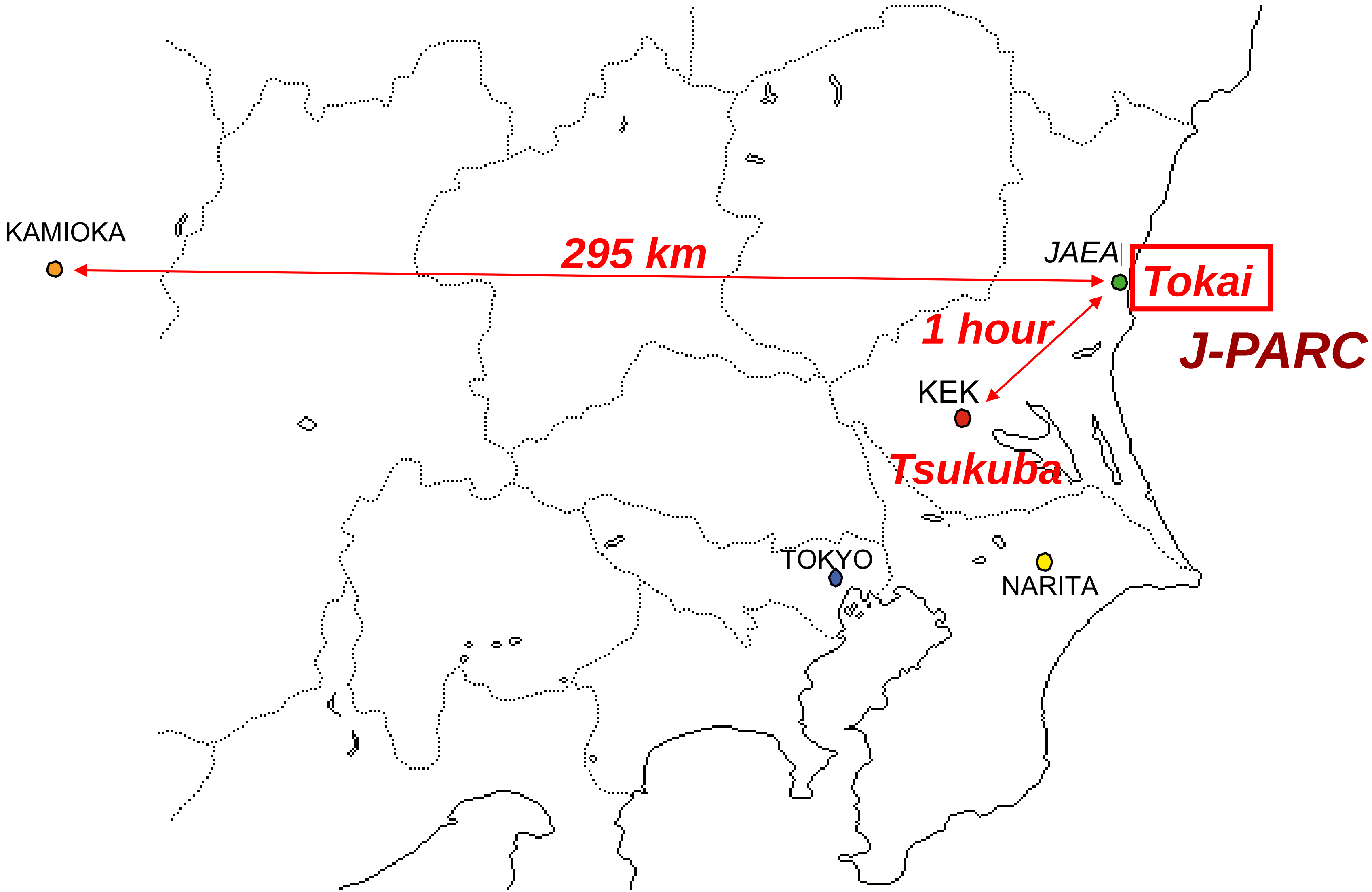
第1と第3のニュートリノ混合角を世界で初めて測定



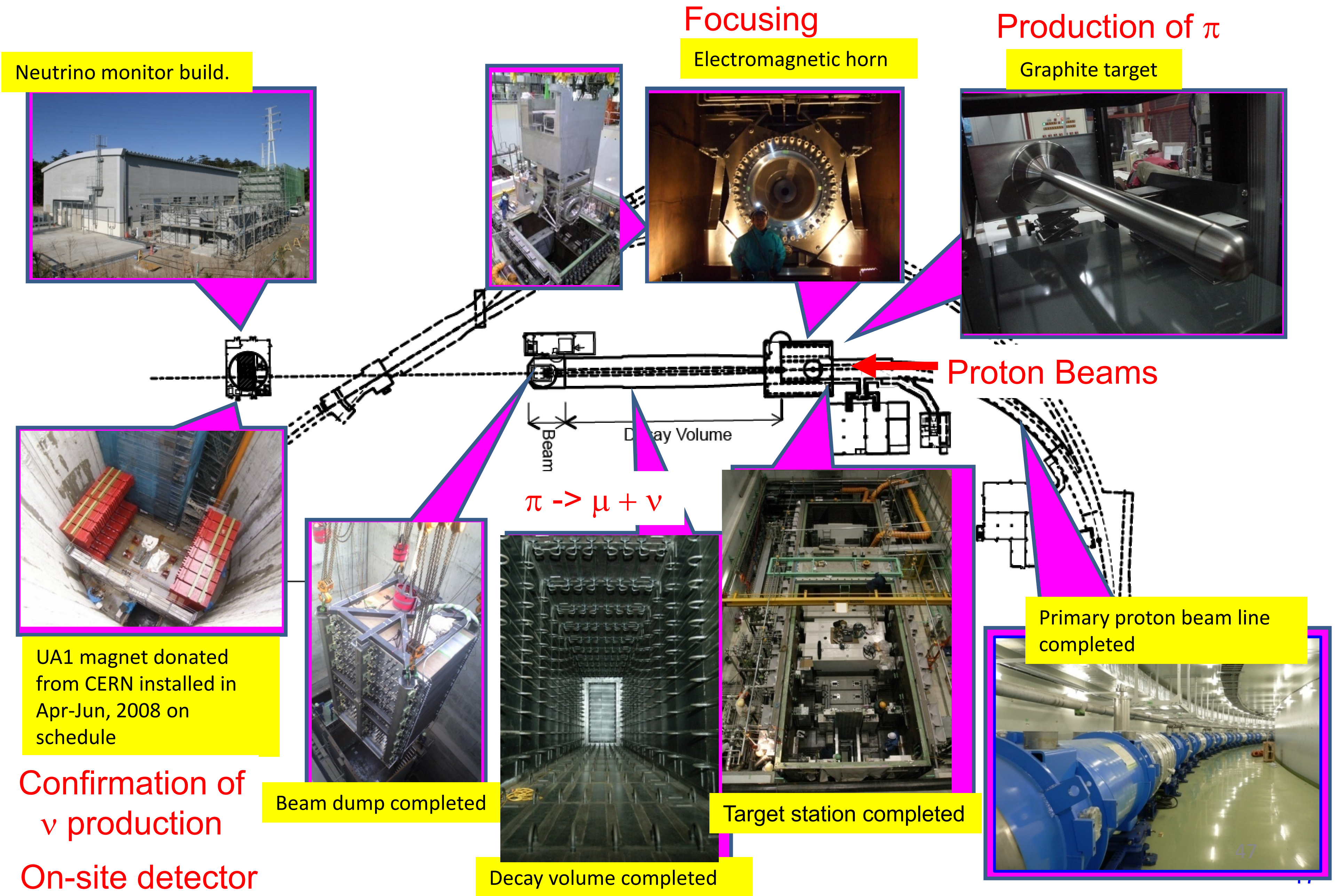
θ_{13} **Mixing between the 1st and 3rd generation**

Competition with Double Chooz, Diya Bay, FNAL, etc.

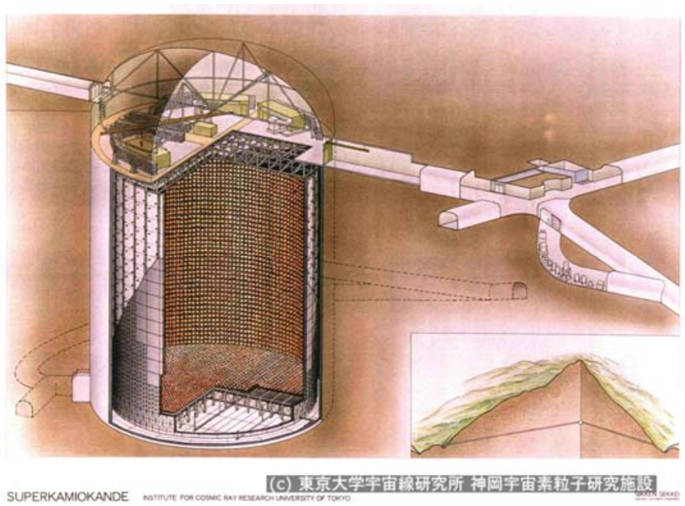
Location of J-PARC at Tokai

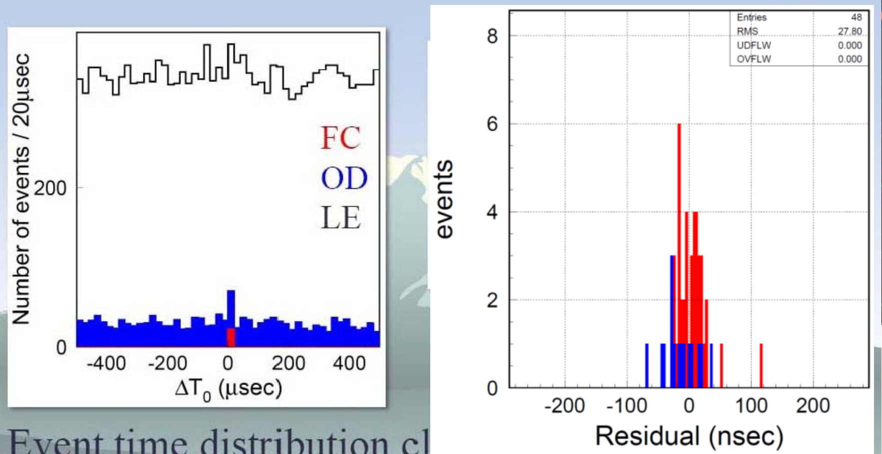


Neutrino beamline



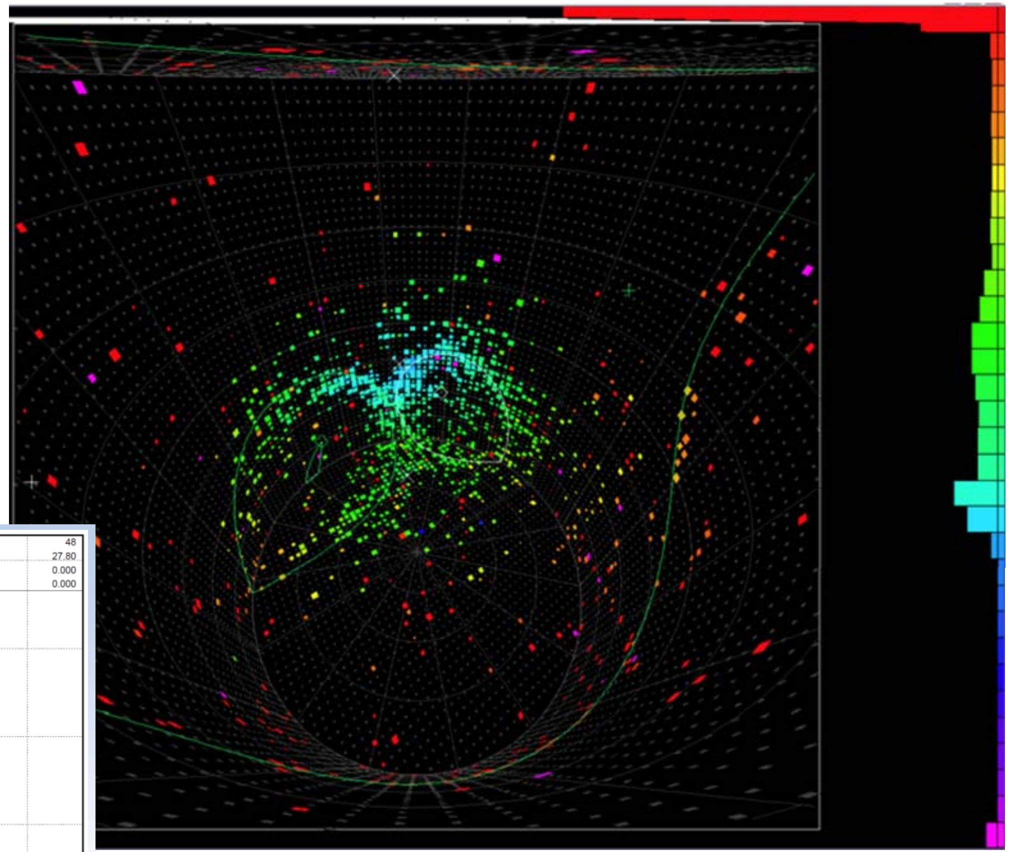
SuperK でのニュートリノ検出





- Event time distribution cl
- Observed # of Fully contained events: 22 (by Mid. May)
- Expected non-beam BG: <10^{-2}evts

21



2010年2月24日
検出に成功

同年末までに48事象を観測
（現在１日１個のニュートリノ観測、
最高強度では１日７個）！

ν_e appearance at T2K

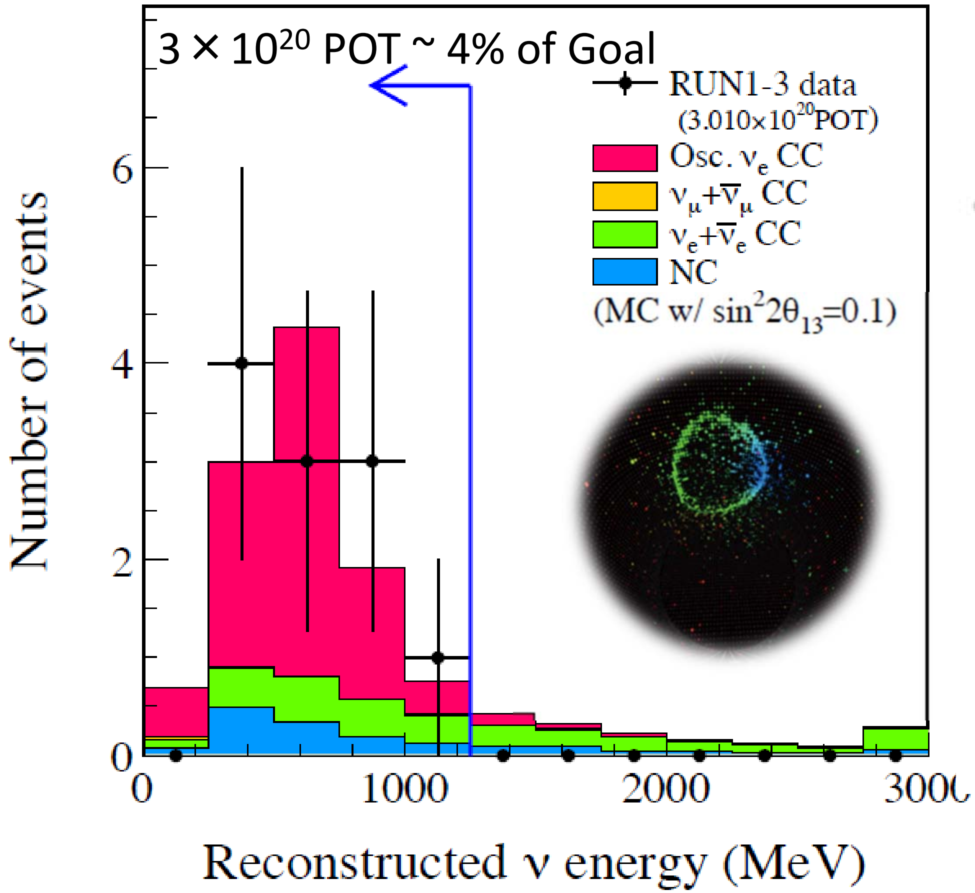
- June 2011:

6 ν_e events ⇒ 2.5 σ, Indication?

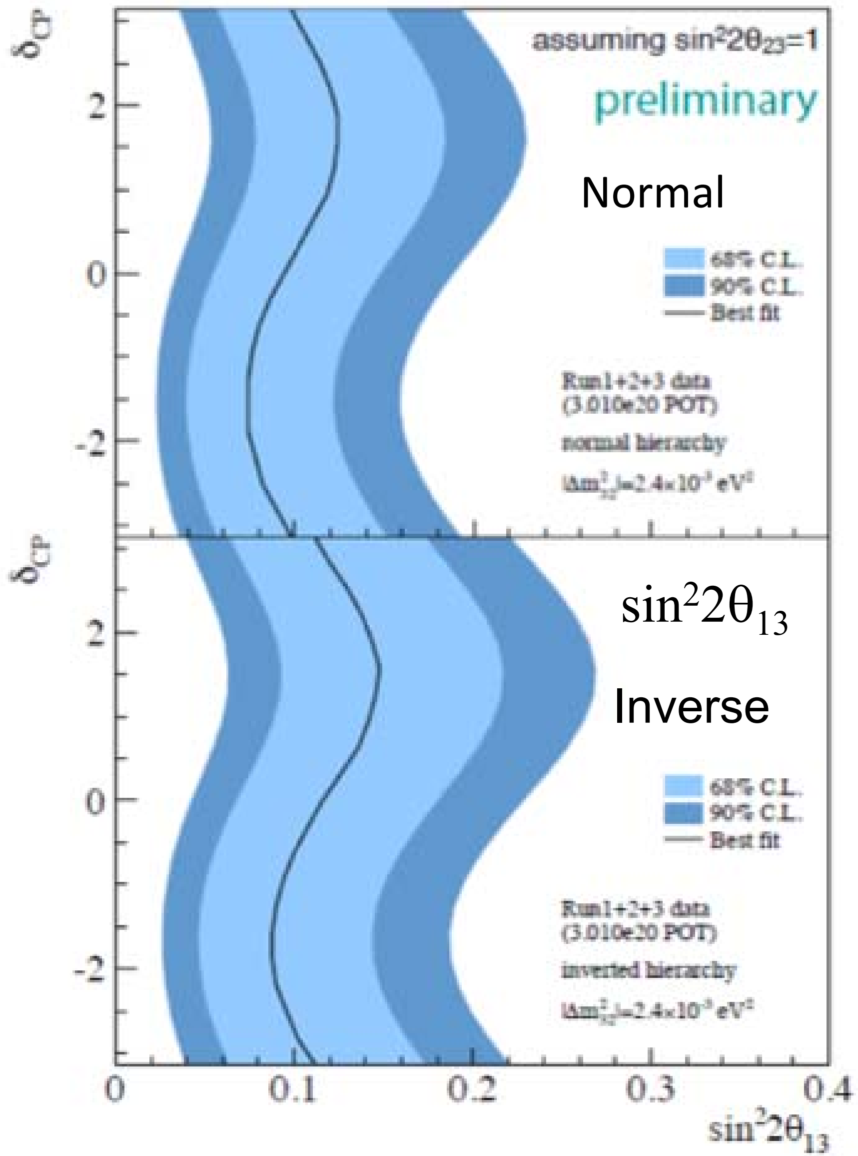
- June 2012:

11 ν_e events ⇒ 3.2 σ, ***Evidence!***

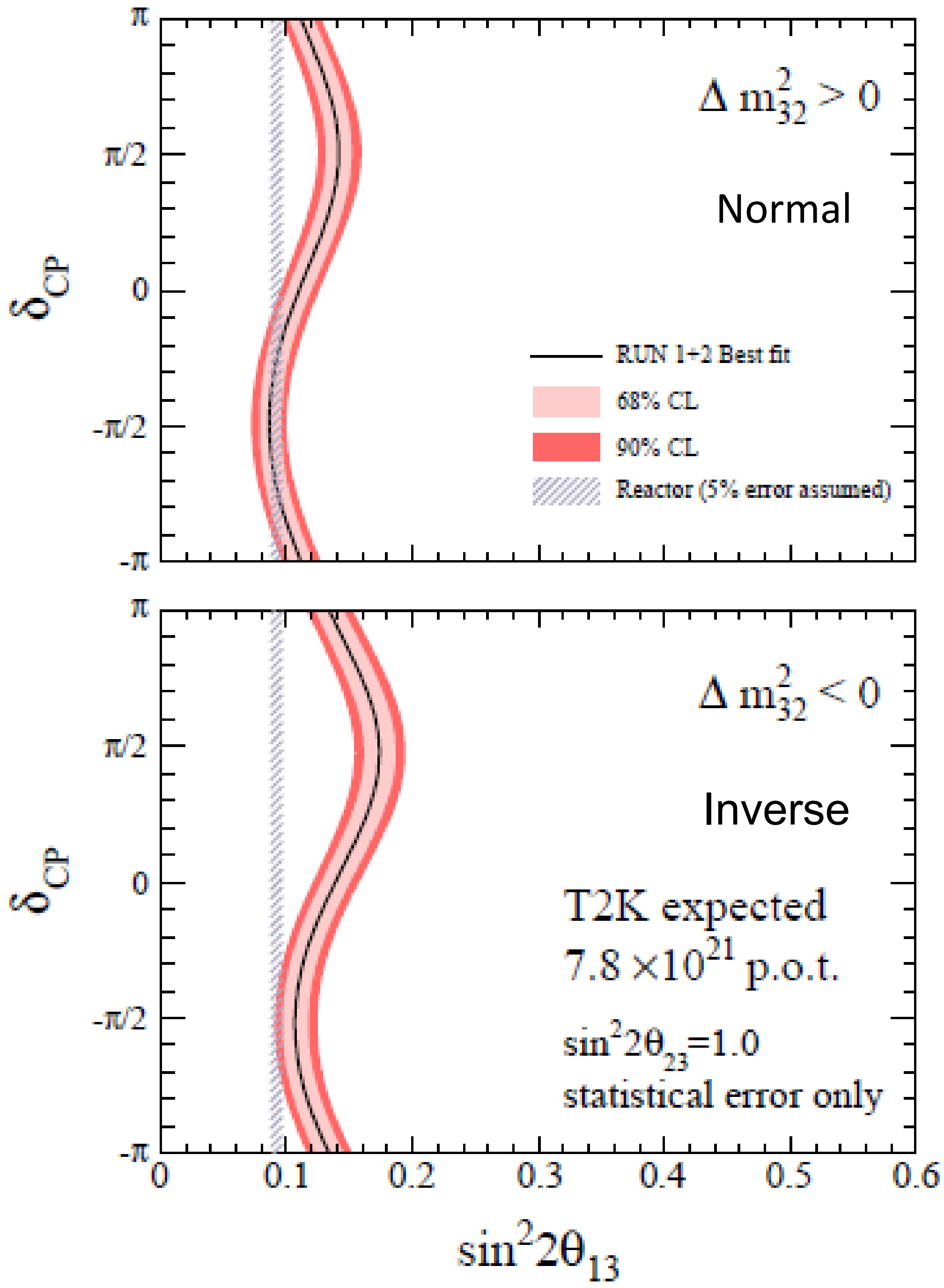
(Expected **BG** (θ_{13}=0) is **2.73±0.37**)



$\sin^2 2\theta_{13}=0.104^{+0.060}_{-0.045}$ @ $\delta_{CP}=0$



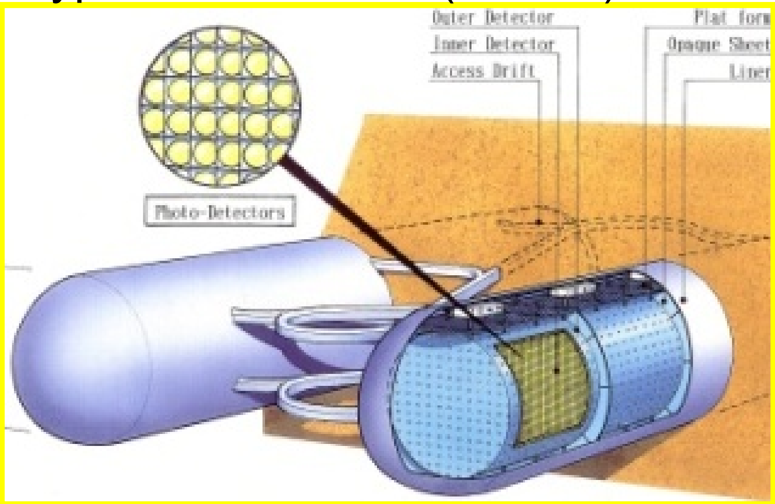
$\sin^2 2\theta_{13}=0.128^{+0.070}_{-0.055}$ @ $\delta_{CP}=0$



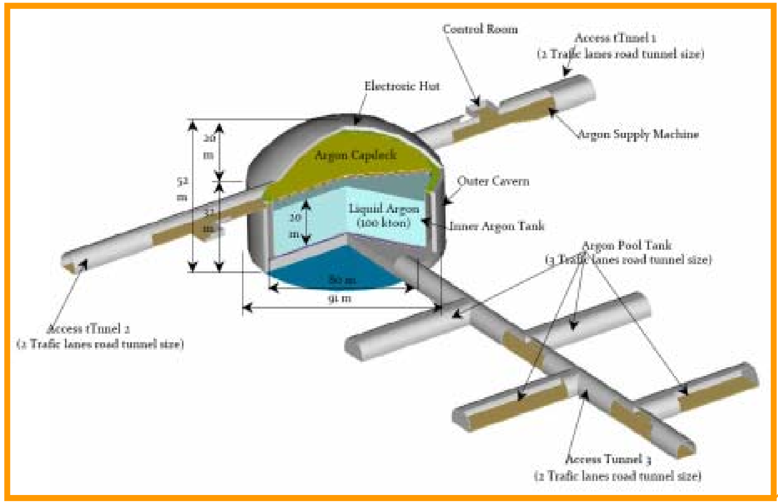
$\Delta m^2_{32} > 0$
Normal
RUN 1+2 Best fit
68% CL
90% CL
Reactor (5% error assumed)
$\Delta m^2_{32} < 0$
Inverse
T2K expected
7.8×10^{21} p.o.t.
$\sin^2 2\theta_{23}$=1.0
statistical error only
δ_{CP}
π
$\pi/2$
0
$-\pi/2$
$-\pi$
0
0.1
0.2
0.3
0.4
0.5
0.6
$\sin^2 2\theta_{13}$

Next Step Far Detector

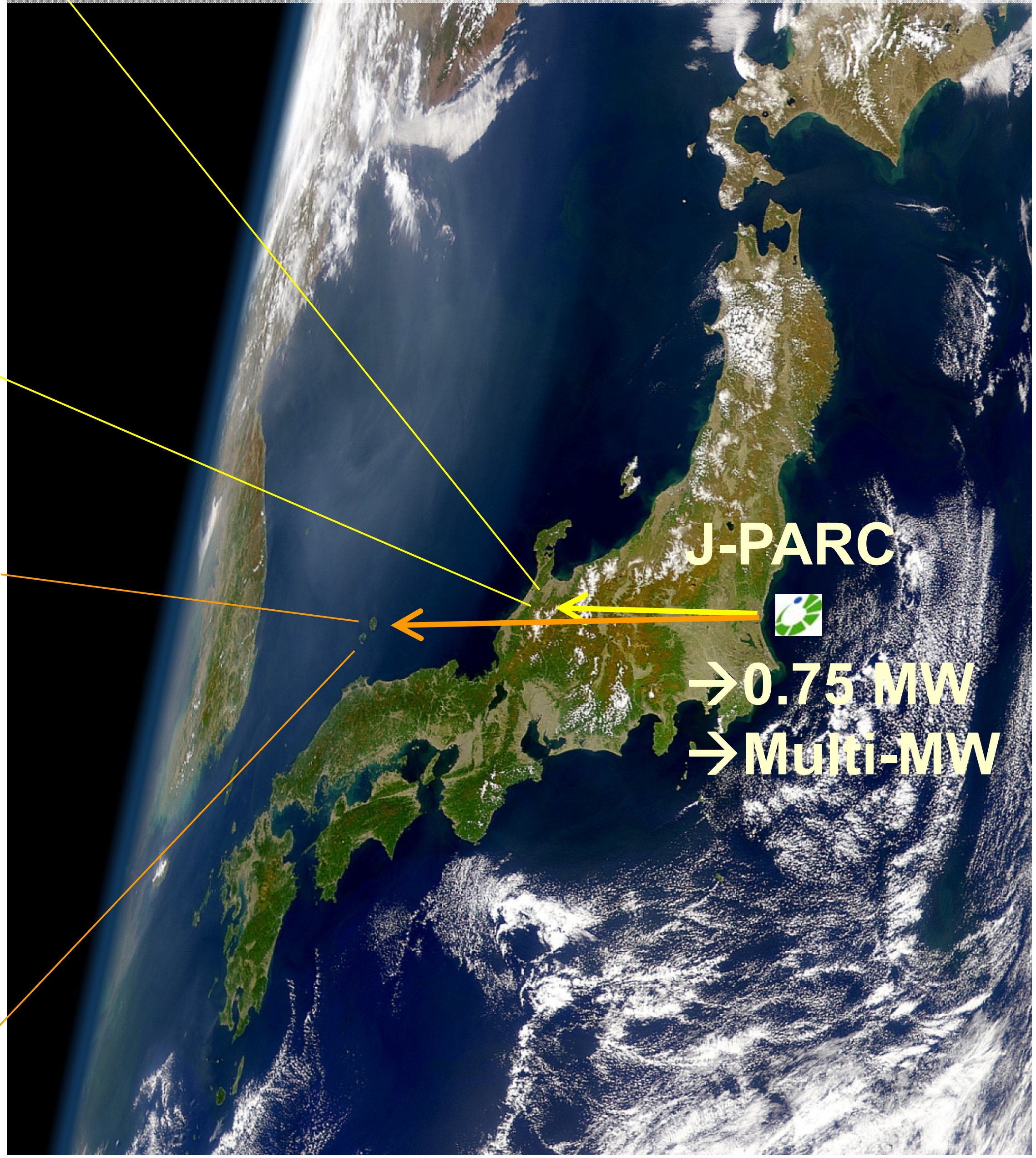
Hyper-Kamiokande (Mt WC)



Aiming for Neutrino CP Violation!

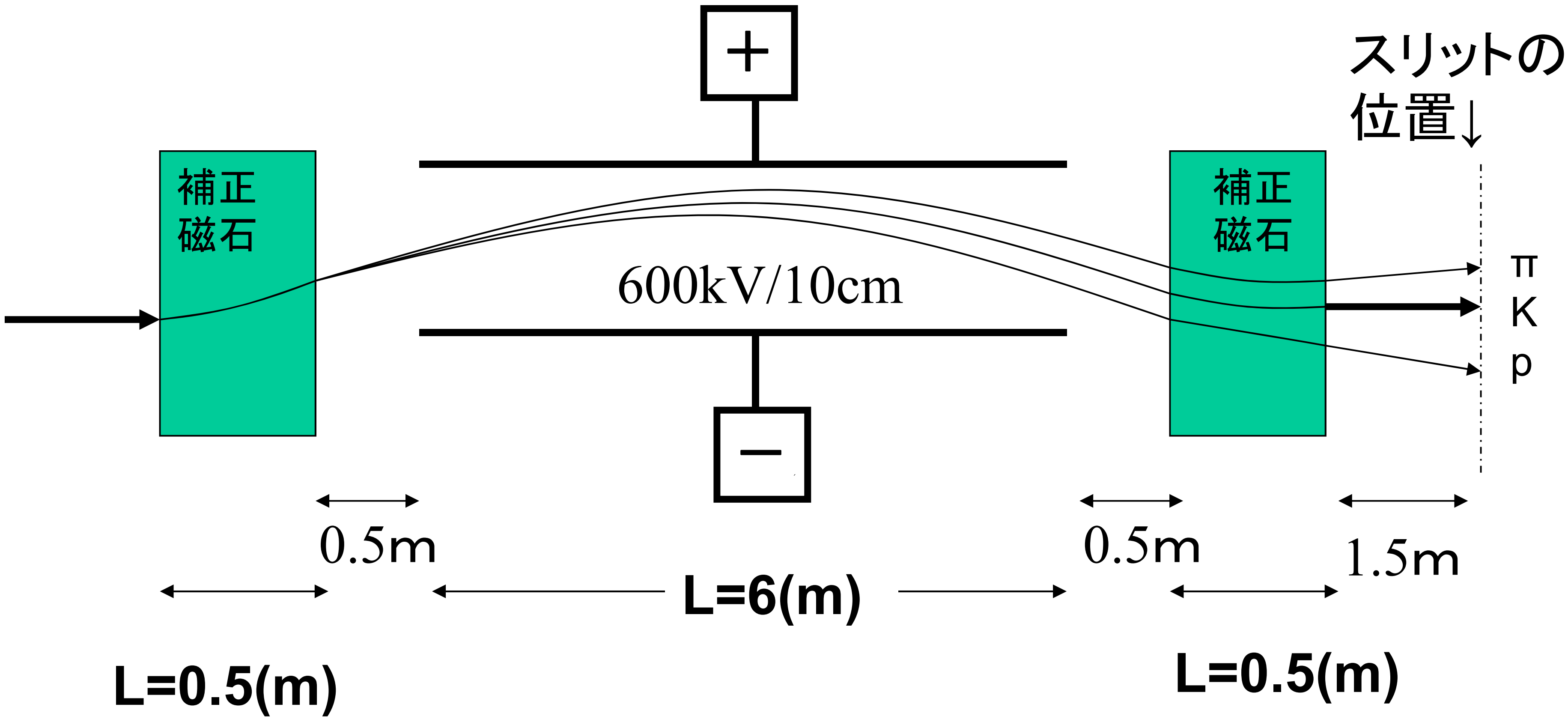


100kt-Liq. Ar TPC



写真を見る！

課題：静電分離装置ESSの設計



•2GeV/cのK中間子用のESSを作りたい。補正磁石の強さはどれくらいか？スリット位置でのK、π、陽子の分離距離も求めよ。