First Neutrino Oscillation Results from the T2K Experiment

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for the T2K Collaboration

XIV International Workshop on Neutrino Telescopes
Venice, March 15-18th 2011

Message from KEK

Japan experienced very severe earthquake on March 11th 2011 at 14:46 JST. J-PARC facility suffered damages for some extent. There are no reports of casualties and all staff, graduate students, and foreign visitors have been located and as of evening Sunday March 13th all T2K members have been evacuated from Tokai area.

Fortunately enough, the Tsunami tidal wave did not hit J-PARC. We will start the investigation of the facilities. We will update the announcement as we learn the detail of the entire damage.

Our present priority is to restore life-supporting infrastructure such as electricity, water supply and gas at J-PARC. It may take some time, but we promise the full recovery of the J-PARC accelerator and T2K experiment in the near future.

I thank you for the messages of solidarity and sympathy.

Director of the Institute of Particle and Nuclear Studies, KEK
Koichiro Nishikawa

Spokesperson of the T2K experiment
Takashi Kobayashi

Contents of talk

- ***T2K experimental setup***
- ***Physics data taking during Jan 2010-Mar 2011***
- ***Release of first oscillation analyses results on the 2010a data***
  - ➠*electron appearance: search for excess of ν_e CC events → first T2K θ_{13} result*
  - ➠*muon disappearance: measurement of ν_μ CC rate → consistency check with atmospheric oscillation parameters (first T2K Δm^2_{23}, θ_{23} result to be released in the near future)*
- ***Conclusion***

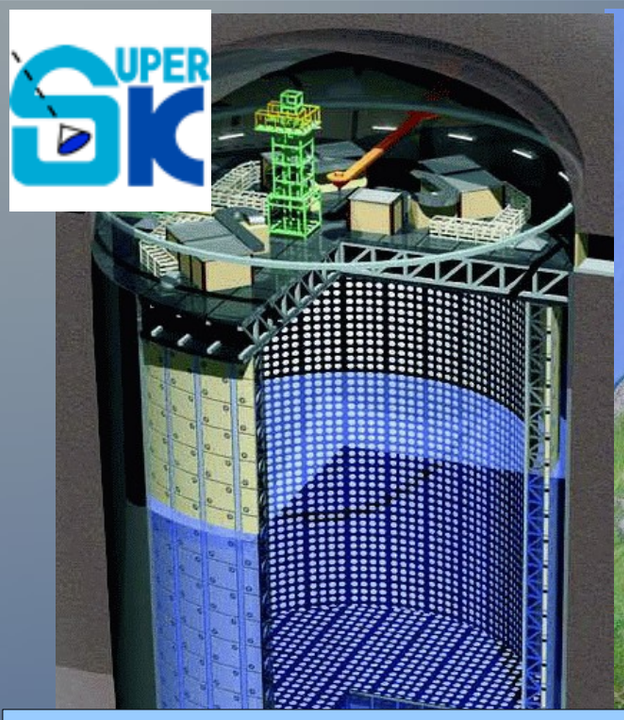
T2K Collaboration

12 countries, 59 institutions, ~500 members

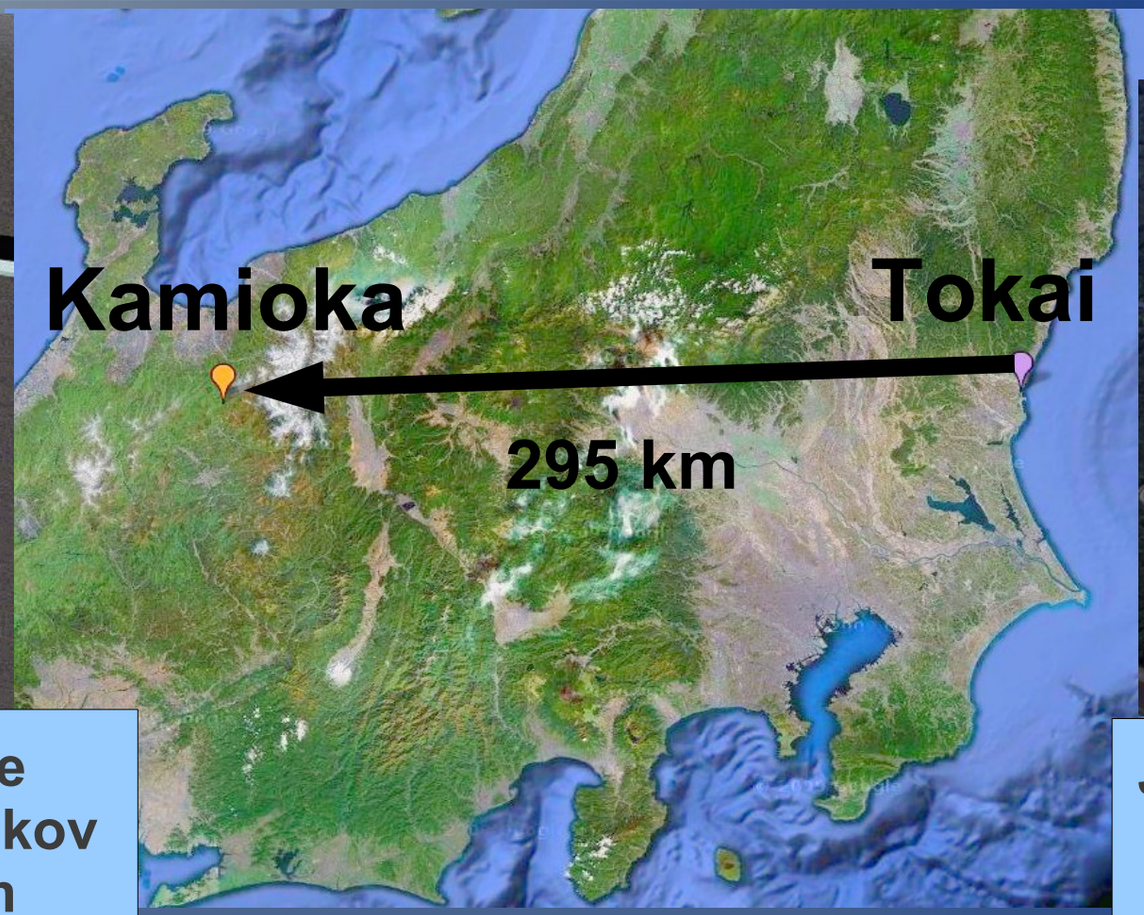
Canada
U. Alberta – U. B. Columbia – U. Regina – U. Toronto – TRIUMF – U. Victoria – York U.
France
CEA Saclay – IPN Lyon – LLR E. Poly. – LPNHE Paris
Germany
RWTH – Aachen U.
Italy
INFN, U. Bari – INFN, U. Napoli – INFN, U. Padova – INFN, U. Roma
Japan
ICRR Kamioka – ICRR RCCN – KEK – Kobe U. – Kyoto U. – Miyagi U. Edu. – Osaka City U. – U. Tokyo
Poland
A. Soltan, Warsaw – H.Niewodniczanski, Cracow – U. Silesia, Katowice – T. U. Warsaw – U. Warsaw – U. Wroclaw
Russia
INR
S Korea
N. U. Chonnam – U. Dongshin – N. U. Seoul
Spain
IFIC, Valencia – U. A. Barcelona
Switzerland
ETH Zurich – U. Bern – U. Geneva
UK
Imperial C. L. – Lancaster U. – Liverpool U. – Queen Mary U. L. – Oxford U. – Sheffield U. – STFC/RAL – STFC/Daresbury – Warwick U.
USA
Boston U. – B.N.L. – Colorado S. U. – U. Colorado – Duke U. – U. C. Irvine – Louisiana S. U. – U. Pittsburgh – U. Rochester – Stony Brook U. – U. Washington

T2K (Tokai to Kamioka) Experiment

First experiment purposely built for θ_{13} measurement



Super-Kamiokande
50 kton water cherenkov detector at 295 km



J-PARC produces 30 GeV proton beam, design power of 750 kW

- *High intensity ν_μ beam from J-PARC to Super-Kamiokande @ 295km*
- *Discovery of ν_e appearance ➠ determine θ_{13}*
- *Precise meas. of ν_μ disappearance ➠ θ_{23}, Δm^2_{23}*

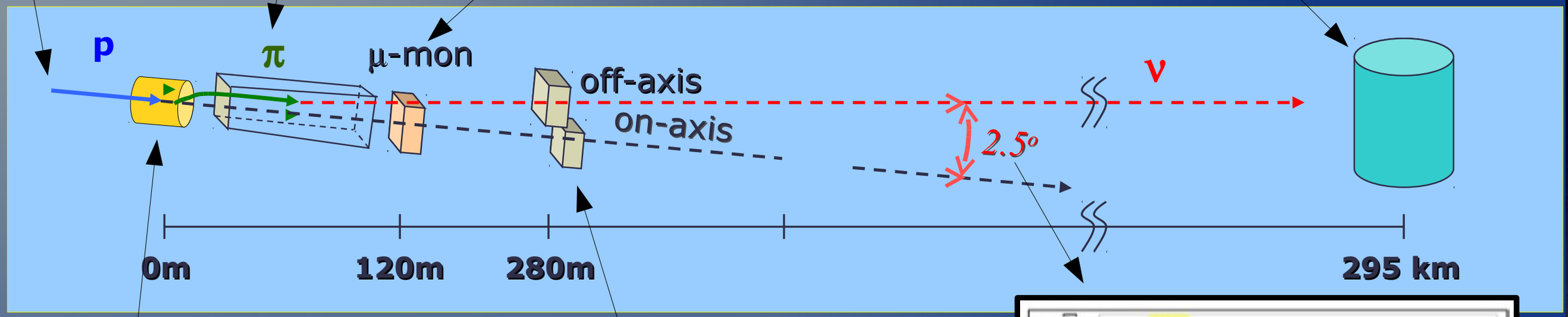
T2K Overview

30 GeV proton beam from J-PARC Main Ring (MR)

Pions decay in ≈100m decay volume

MUMON monitor measures muons from pion decay

Off-axis at 295 km, Super-Kamiokande (SK) water cherenkov detector measures oscillated flux

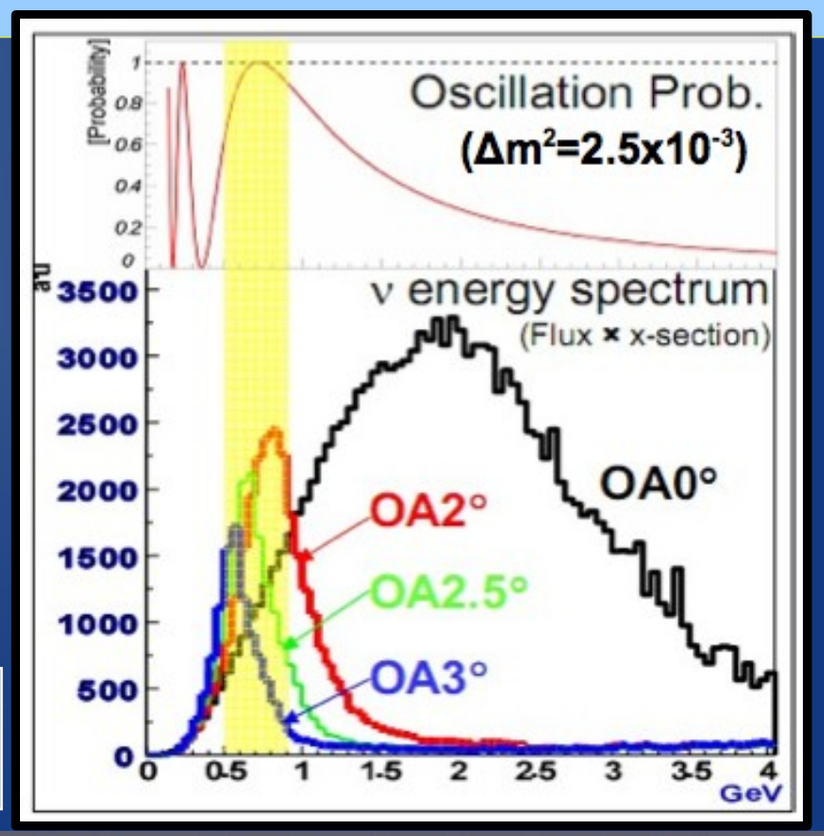


Beam on 90 cm graphite target

3 magnetic horns focus positively charged hadrons

At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

Off-axis ND280 detector measures spectra for various neutrino interactions



Beam peaked at 1st max E≈600 MeV

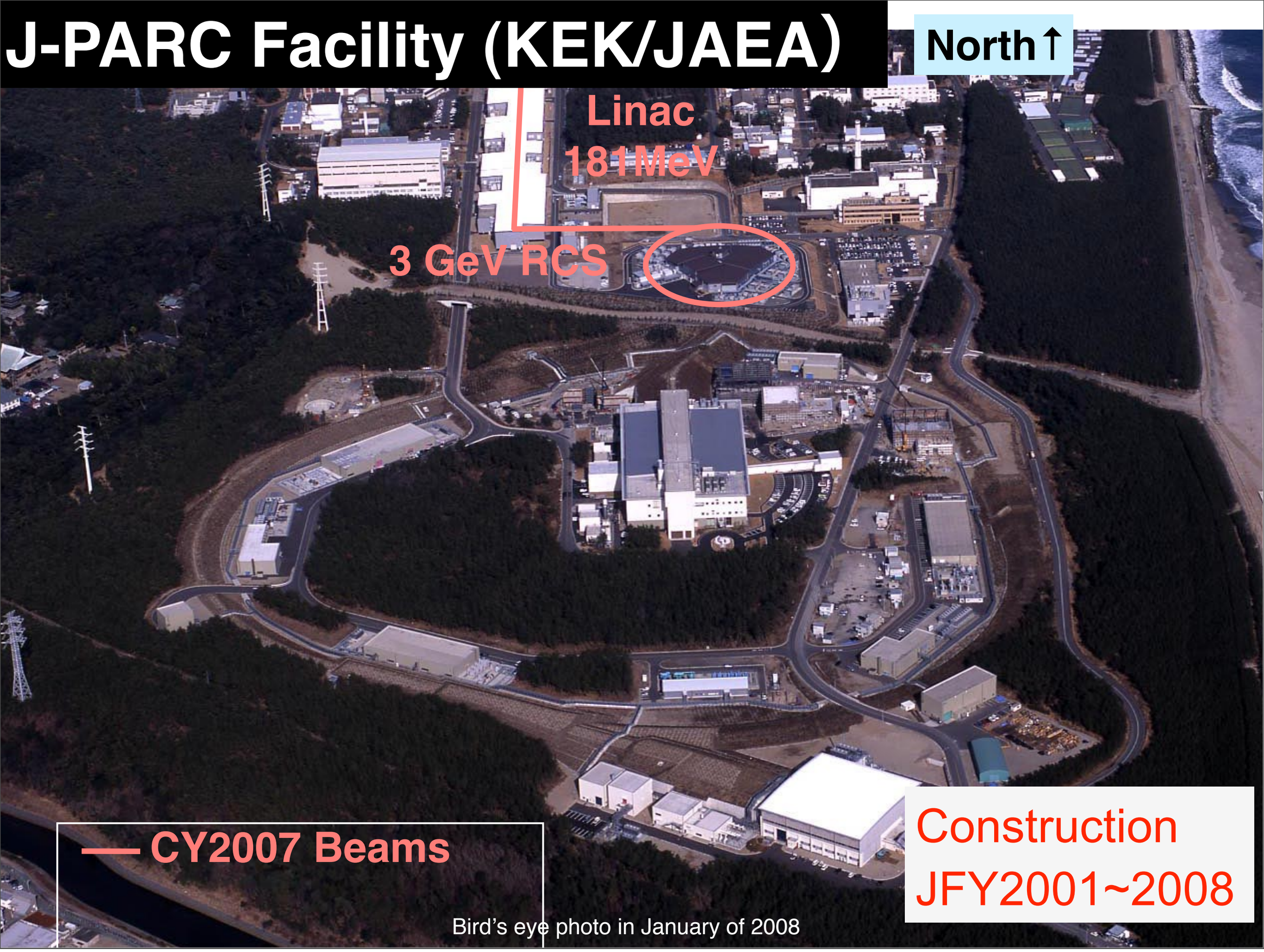
J-PARC Facility (KEK/JAEA)

North↑

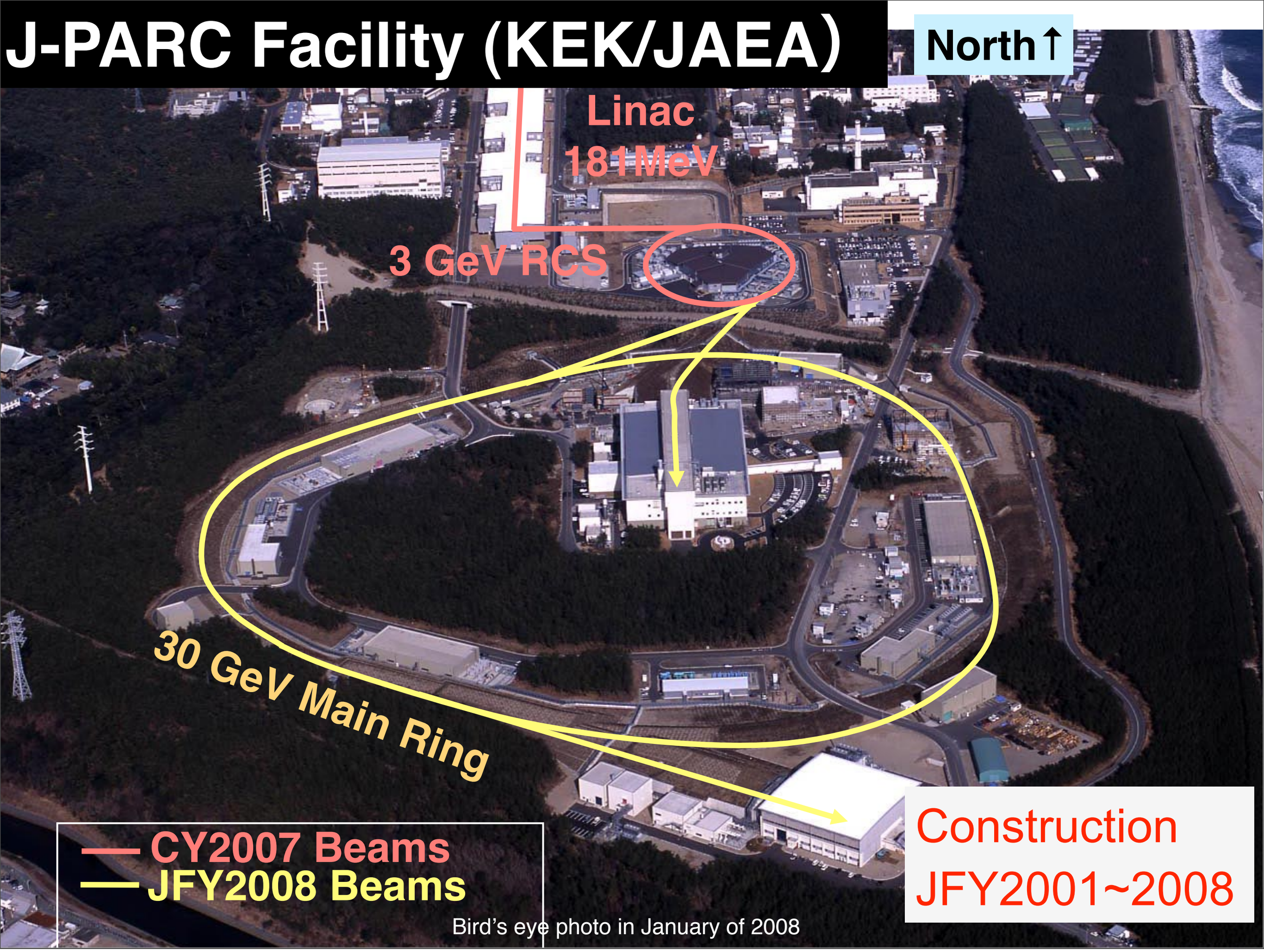
Construction
JFY2001~2008

Bird's eye photo in January of 2008

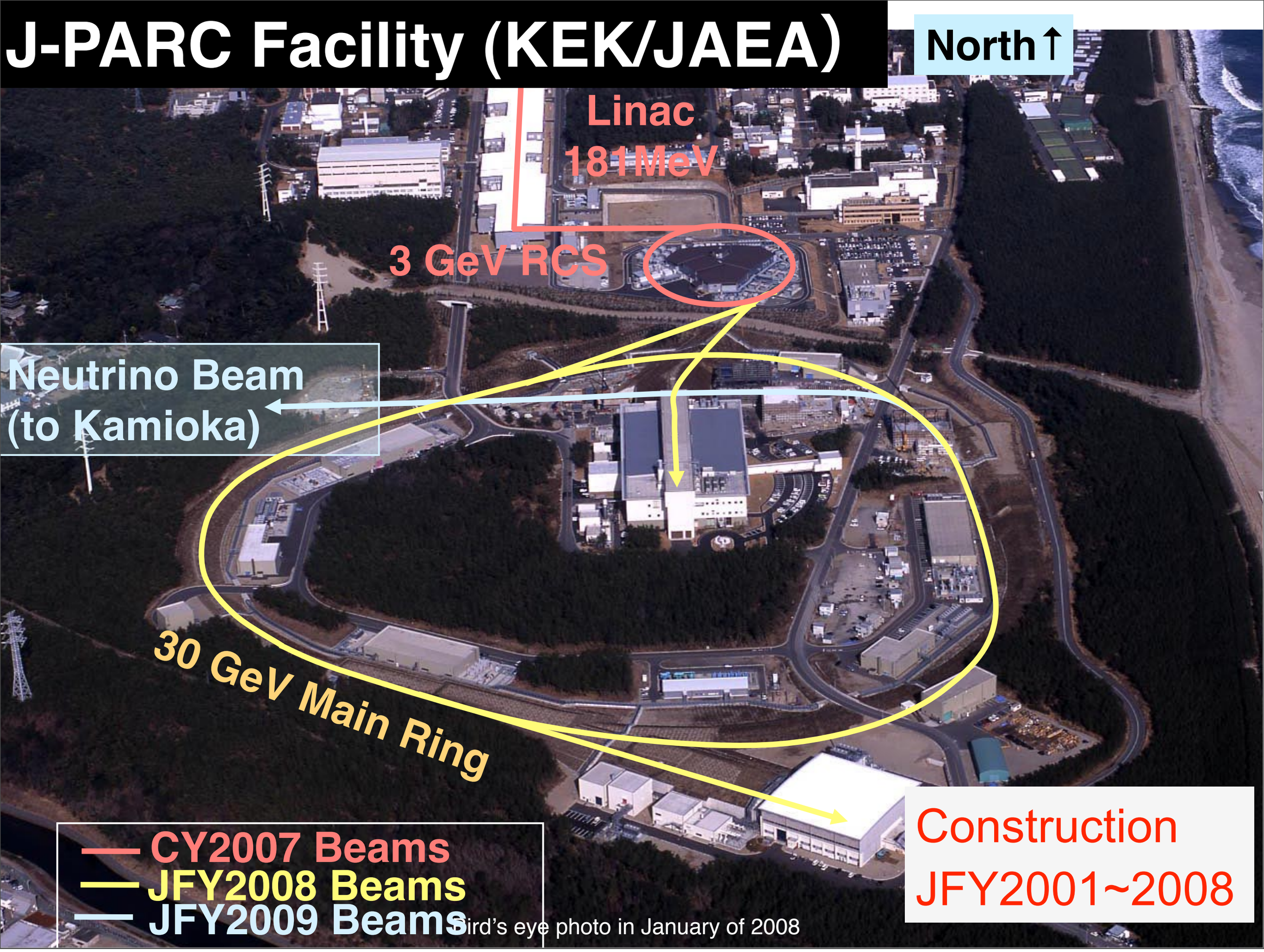
J-PARC Facility (KEK/JAEA)



J-PARC Facility (KEK/JAEA)

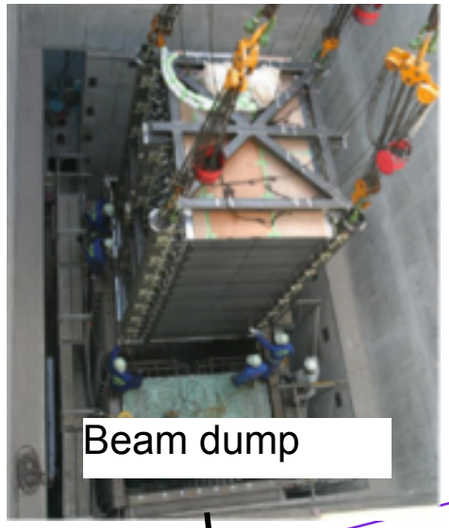


J-PARC Facility (KEK/JAEA)

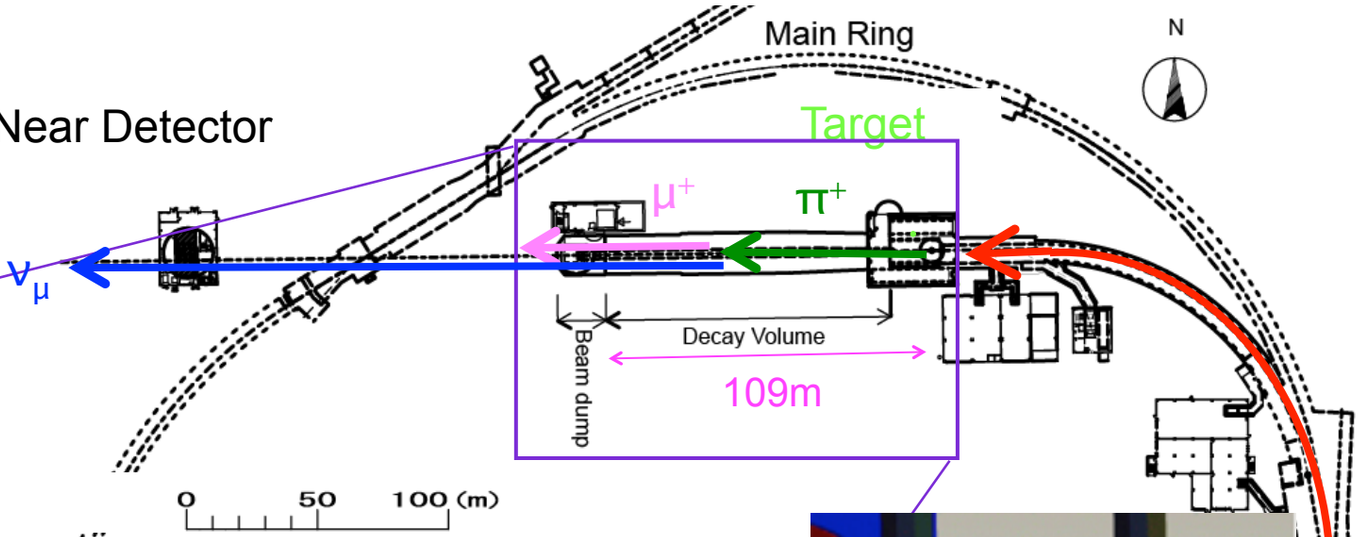


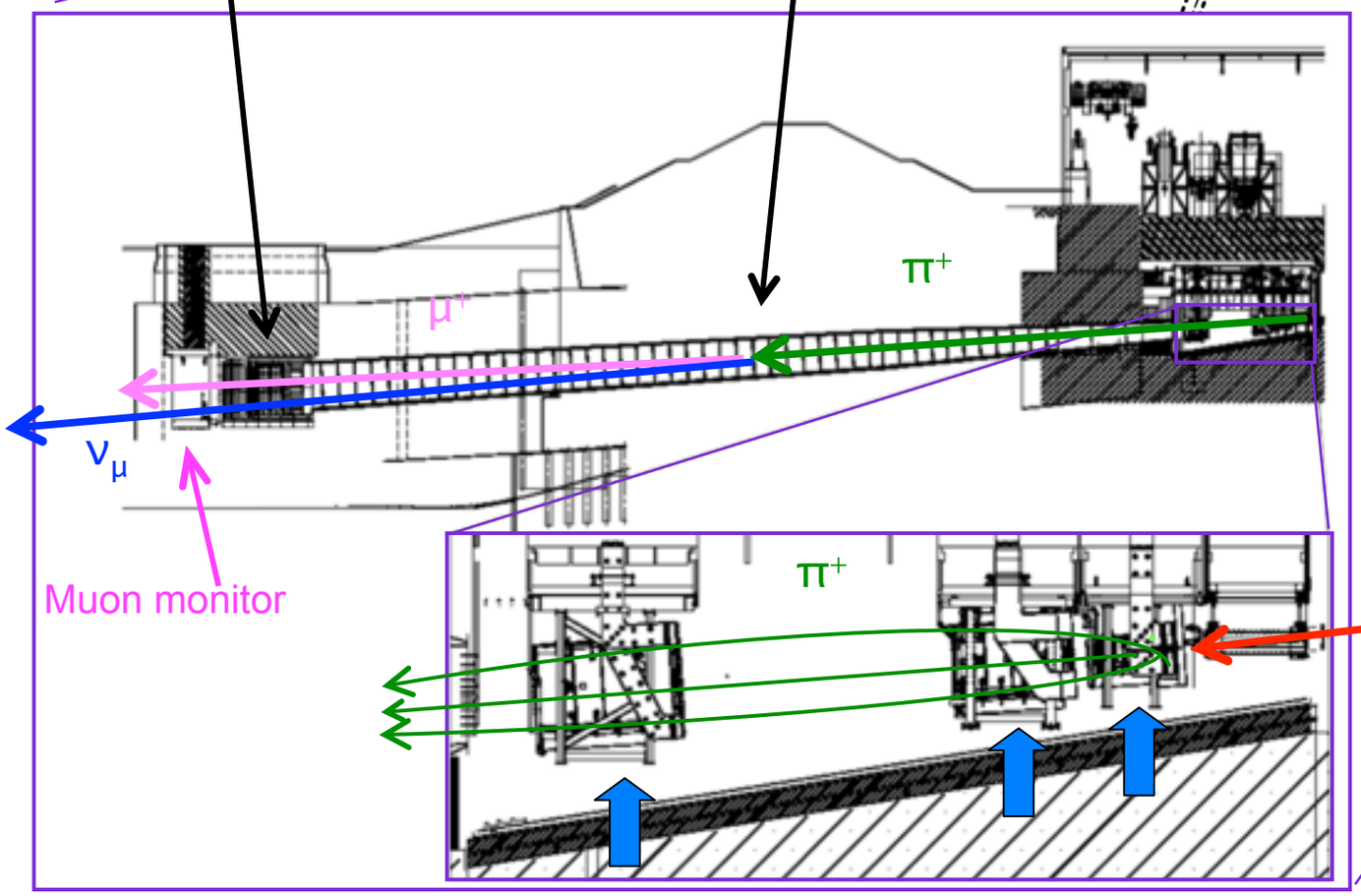
Bird's eye photo in January of 2008

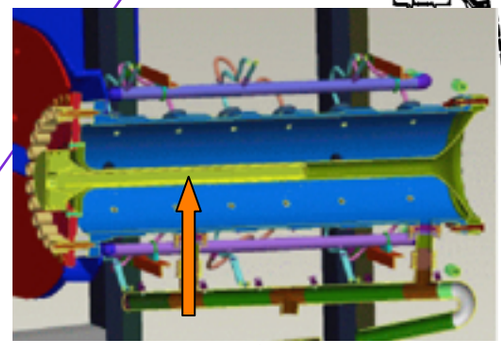
J-PARC neutrino beamline overview



Decay volume (He gas filled)







Target installed in 1st horn.

Pions are focused by
3 electromagnetic Horns.

J-PARC beamline components overview

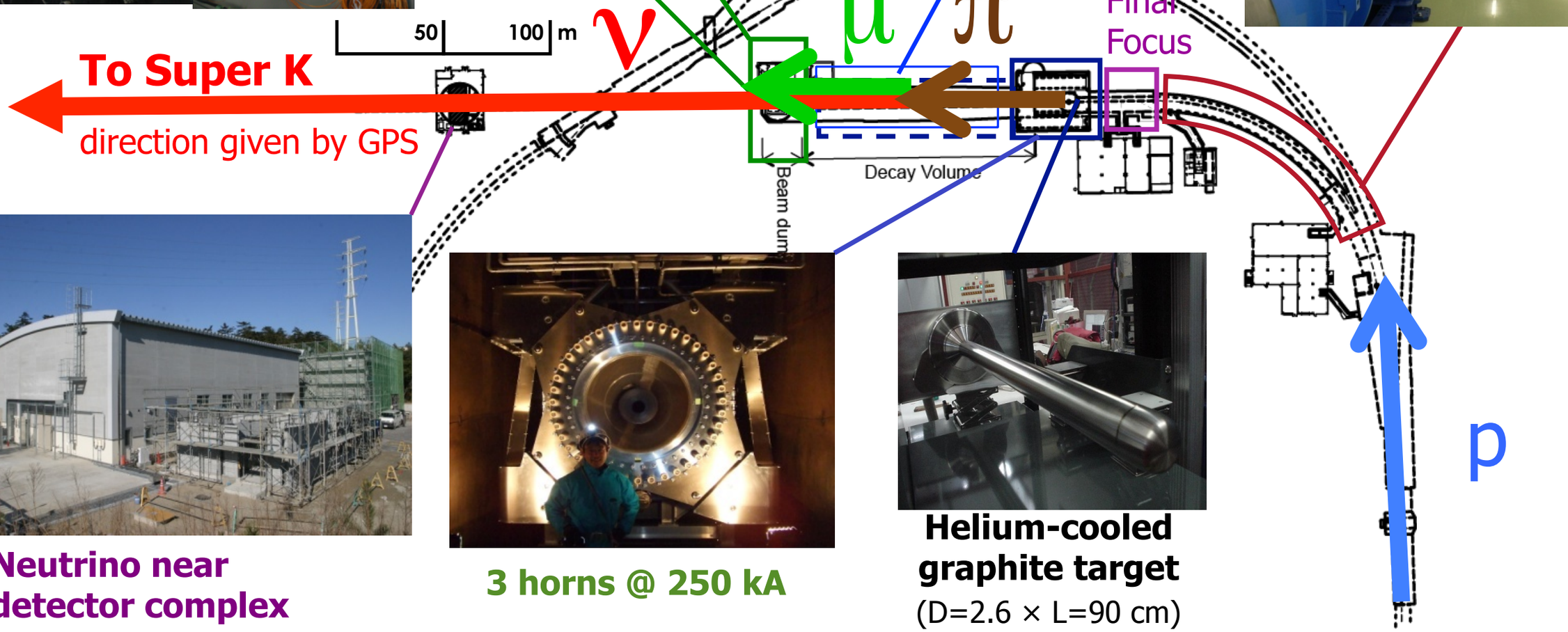
Secondary beam monitors
- muon profile after beam dump: ionisation chambers and SiPIN (MUMON)
- Emulsion exposures (low intensity)

Beam dump
Hadron absorber
graphite modules

Decay pipe
94 m long
Helium filled

Fast extracted beam
- 8 bunches/spill (6<Fall 2010)
- SCFM for proton transport

Primary beam monitors
Intensity (CT), position (ESM), profile (SSEM), beam loss (IC), beam profile at target (OTR)



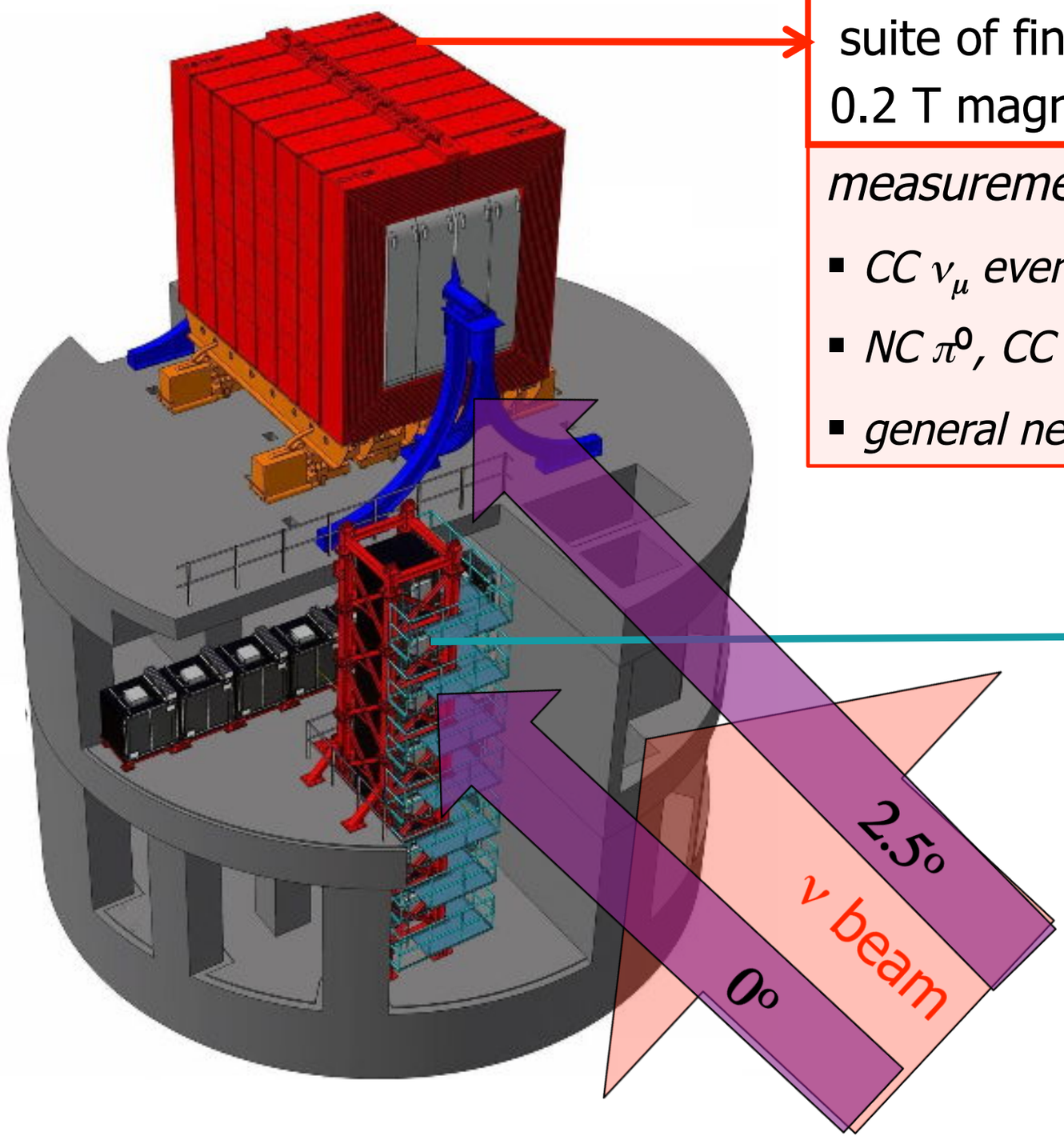
Neutrino near detector complex

3 horns @ 250 kA

Helium-cooled graphite target
(D=2.6 × L=90 cm)

ND280 (Near) Detector complex

ND280



Off-Axis (ND280)
suite of fine grain detectors/tracker in 0.2 T magnetic field (UA1/NOMAD magnet)

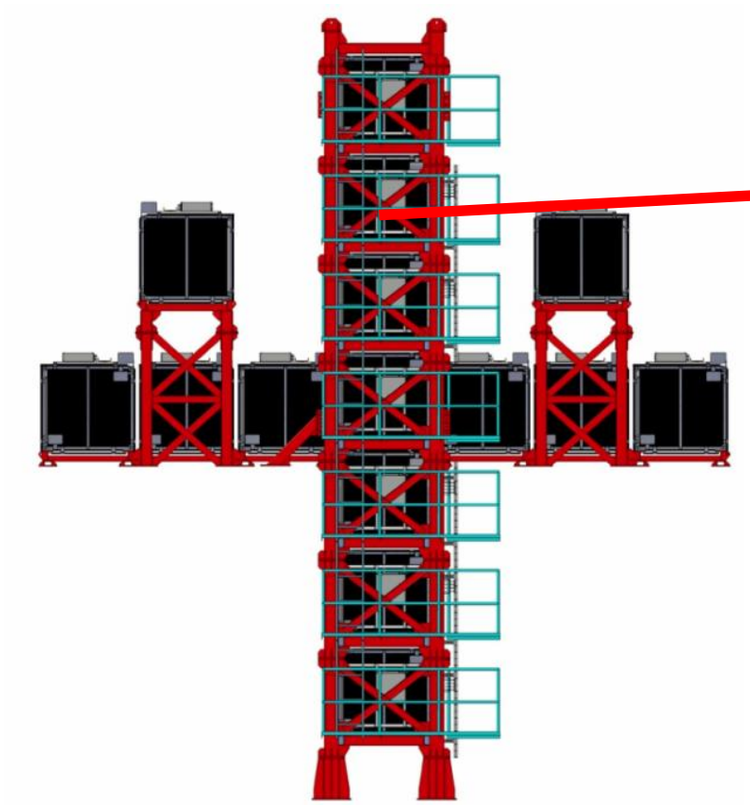
measurements of

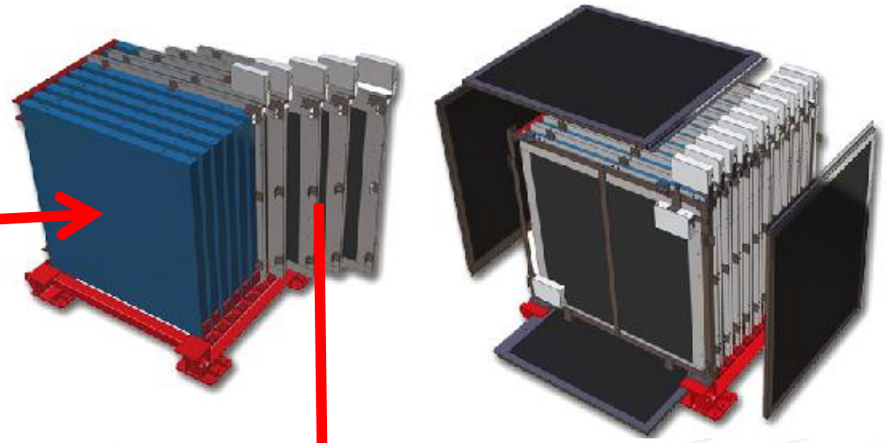
- *CC ν_μ events* (normalization, E_ν-spectrum)
- *NC π^0, CC ν_e events* (backgrounds to ν_e appearance)
- *general neutrino interaction properties*

On-axis (INGRID)
scintillator-iron detectors

measurement of beam direction and profile

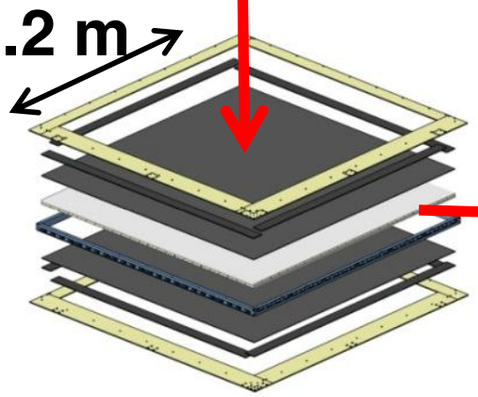
ND280 on-axis detector overview

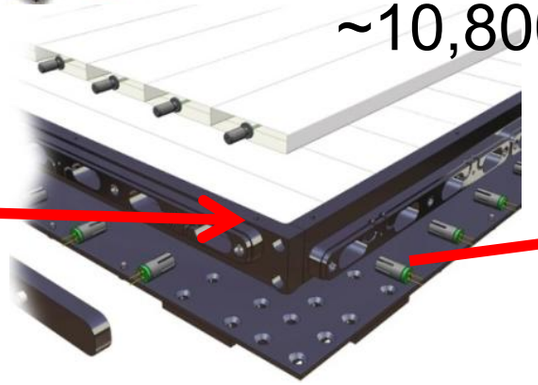


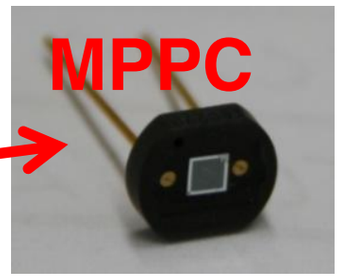


First large scale application of MPPC (~56,000 MPPCs are used for ND280 /INGRID)

~10,800 ch. in INGRID







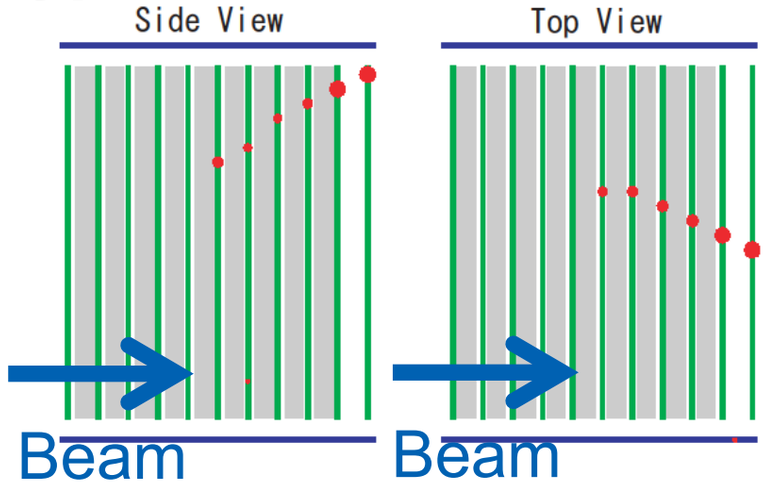
- **14 identical modules + 2 off-cross modules**
  - Beam coverage ~ **10×10 m²**, Iron target mass ~ **7 ton/module**
  - Sandwiched scintillator/iron planes + veto planes
  - Plastic scintillator + WLS fiber + Multi-Pixel Photon Counter (MPPC)
- **Monitor neutrino beam profile/direction/intensity**
  - ~700 ν interactions/day at 50 kW operation
  - Off-axis angle precision goal is <1 mrad
    (1 mrad corresponds to 2% change in the SK flux at the peak energy)

ND280 on-axis detector performance

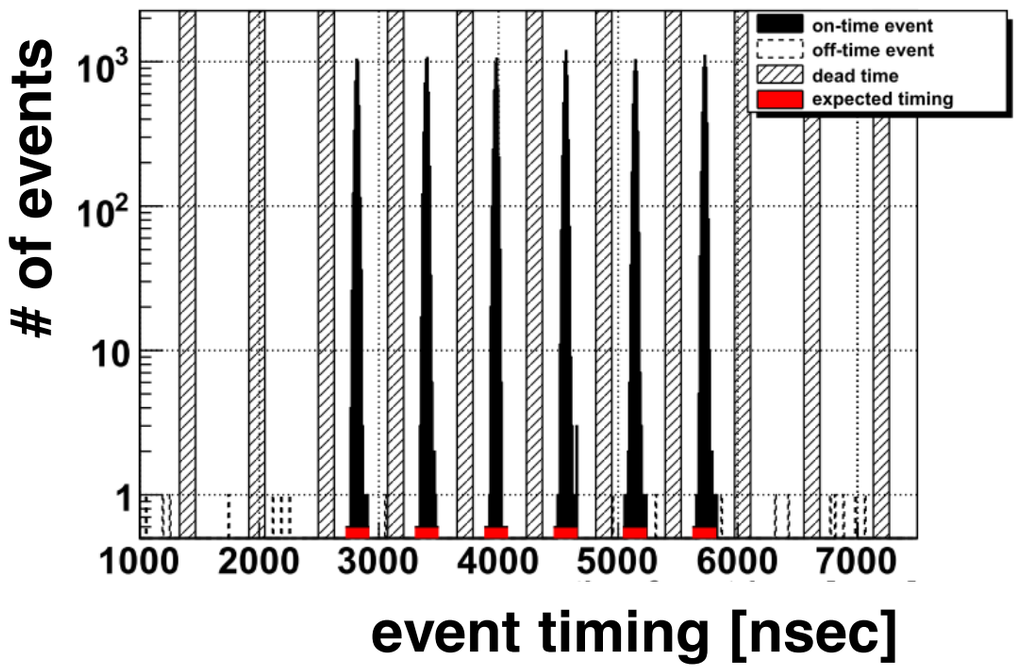
- **Data taking efficiency is 99.9 % during 2010a**
- **ν event selection:**

  (1) Tracking → **(2)** veto cut → **(3)** FV cut

Typical ν event

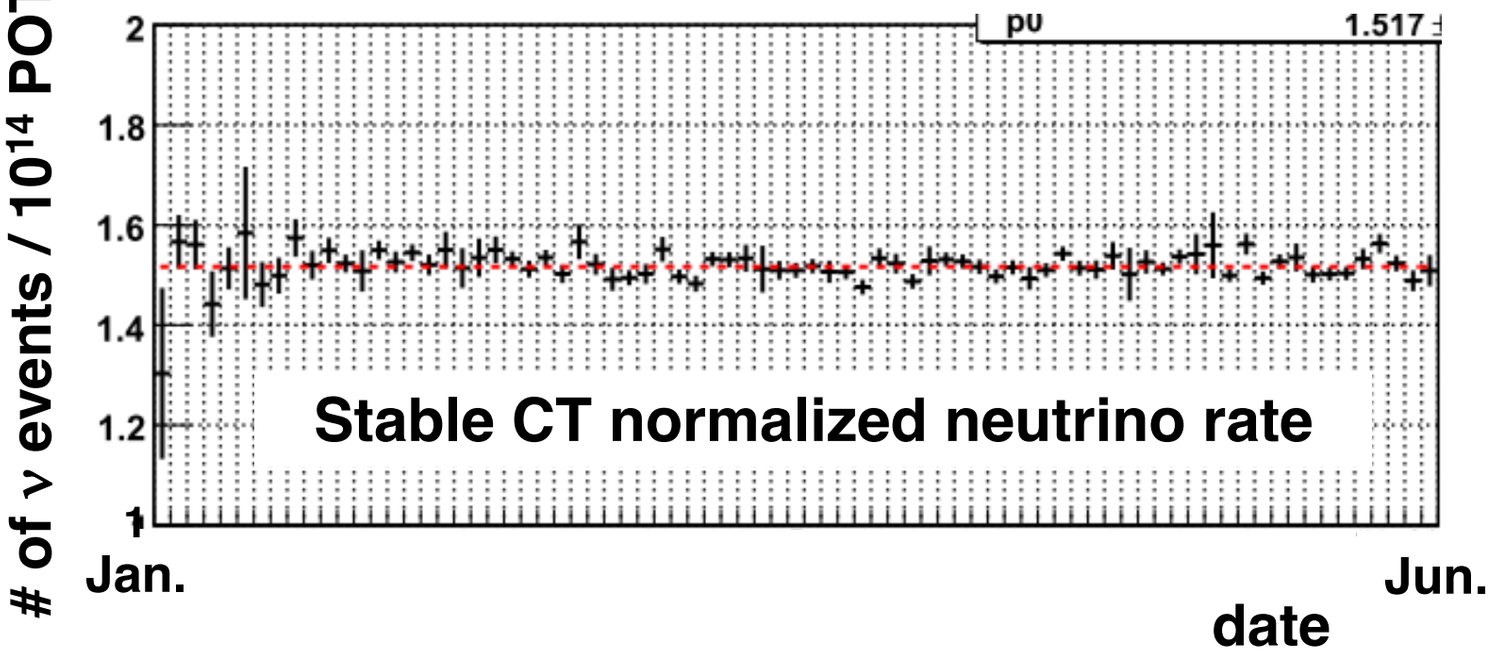


Event timing of ν events



→ Clear 6 bunch structure
(581 ns bunch period)

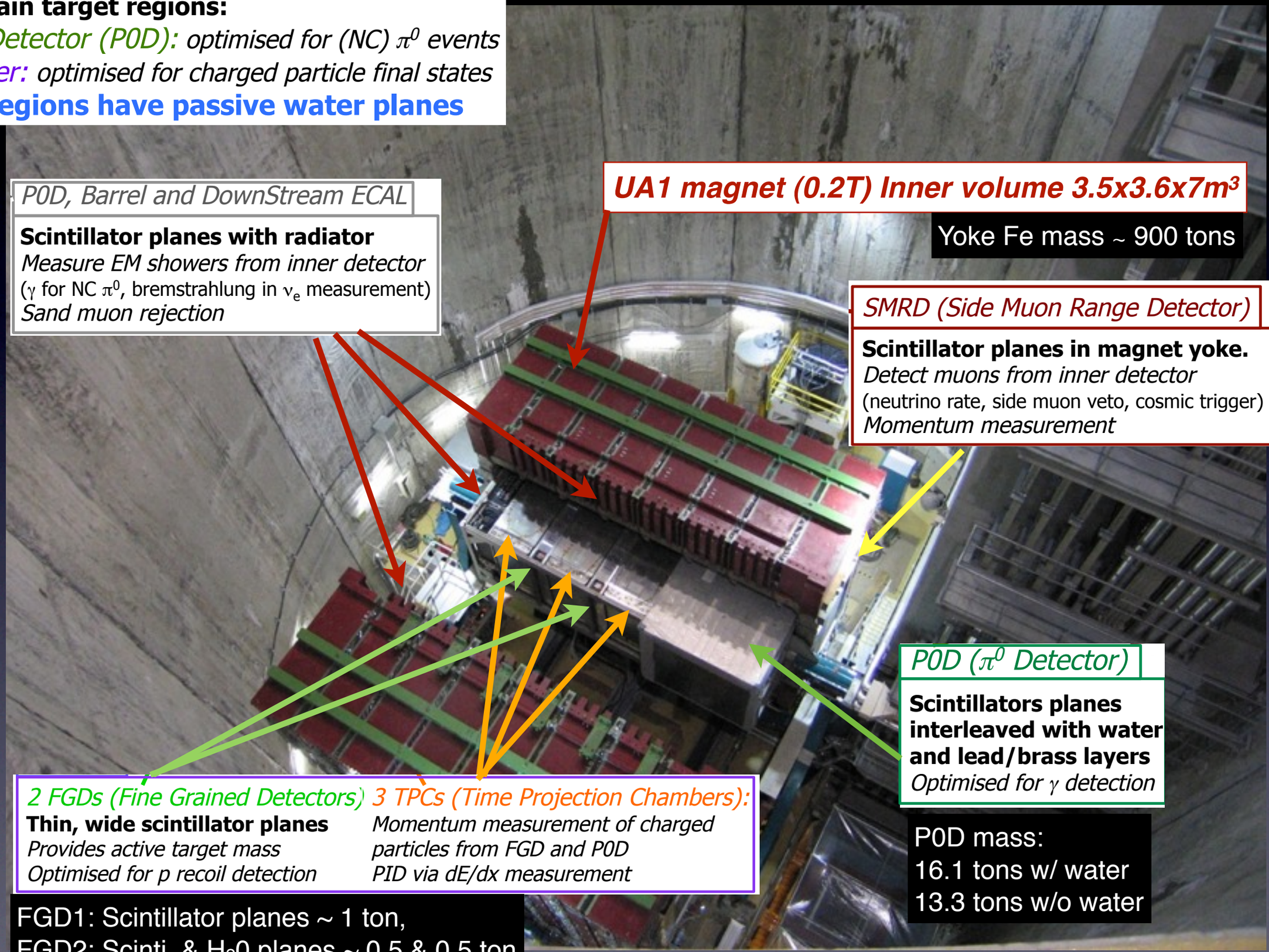
ν beam intensity
(normalized by proton beam intensity)



ND280 off-axis detector overview

Two main target regions:
- *Pi-0 Detector (P0D):* optimised for (NC) π^0 events
- *Tracker:* optimised for charged particle final states

Both regions have passive water planes



P0D, Barrel and DownStream ECAL

Scintillator planes with radiator
Measure EM showers from inner detector
(γ for NC π^0, bremstrahlung in ν_e measurement)
Sand muon rejection

UA1 magnet (0.2T) Inner volume 3.5x3.6x7m³

Yoke Fe mass ~ 900 tons

SMRD (Side Muon Range Detector)

Scintillator planes in magnet yoke.
Detect muons from inner detector
(neutrino rate, side muon veto, cosmic trigger)
Momentum measurement

P0D (π^0 Detector)

Scintillators planes interleaved with water and lead/brass layers
Optimised for γ detection

P0D mass:
16.1 tons w/ water
13.3 tons w/o water

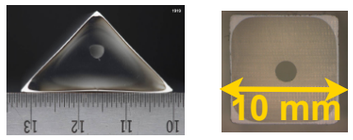
2 FGDs (Fine Grained Detectors):
Thin, wide scintillator planes
Provides active target mass
Optimised for p recoil detection

3 TPCs (Time Projection Chambers):
Momentum measurement of charged particles from FGD and P0D
PID via dE/dx measurement

FGD1: Scintillator planes ~ 1 ton,
FGD2: Scinti. & H_20 planes ~ 0.5 & 0.5 ton

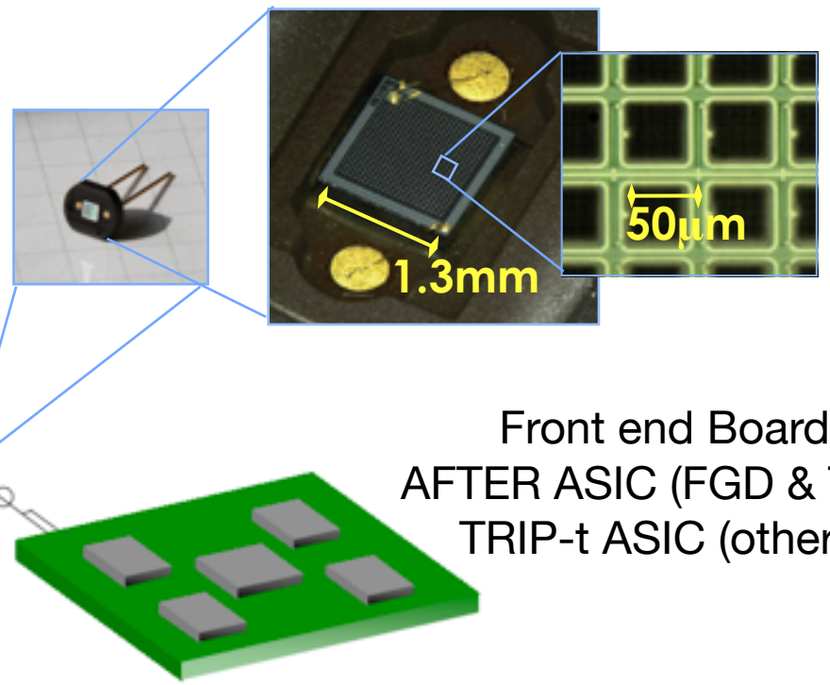
ND280 detector technologies

P0D FGD



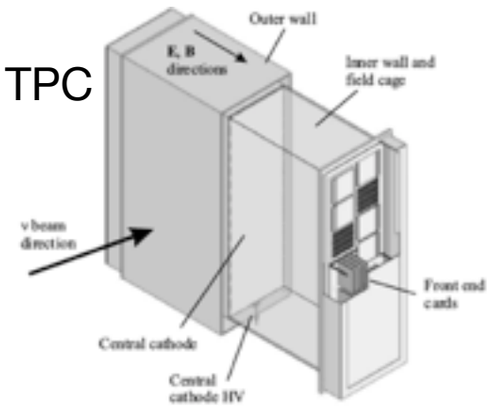
Various shapes of Plastic scintillator with Y-11 fibre

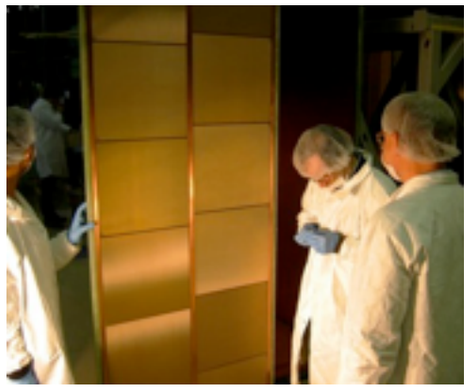
HAMAMATSU MPPC 667 Pixels array



Front end Board
AFTER ASIC (FGD & TPC)
TRIP-t ASIC (others)

TPC





Scintillator + WLS fibre read out by novel MPPC ND280

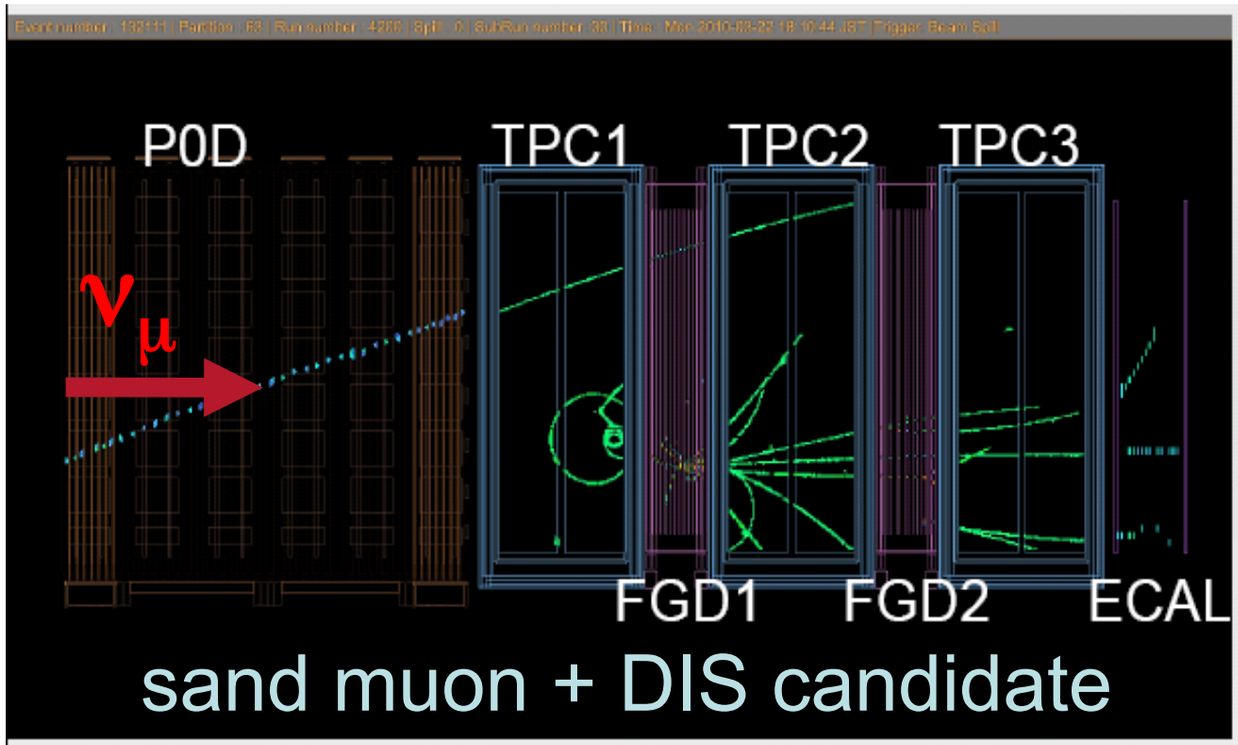
- Low cost high performance and uniformity detector element
- novel solid state photosensor insensitive to magnetic field

- Photon counting, high PDE, low power consumption, ceramic package
- ~ 56 800 channels
- T2K first experiment to use MPPC at such a large scale

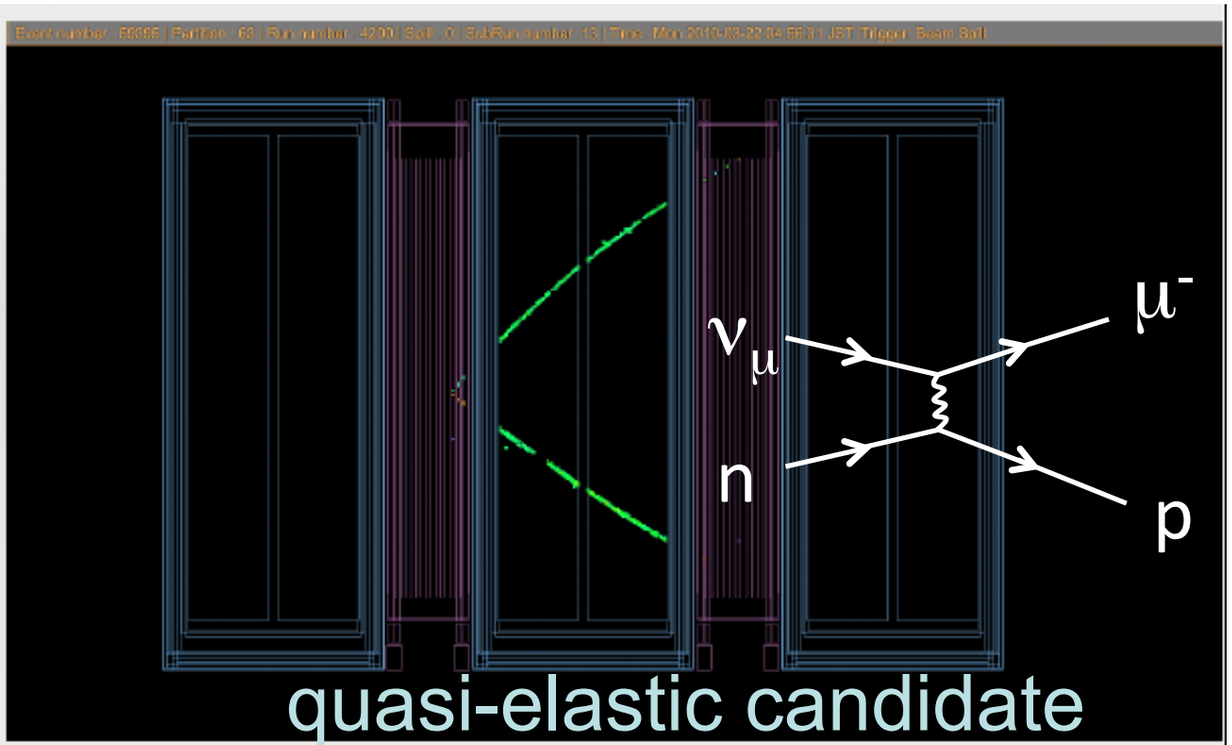
Very Large TPC based on MicroMegas read out

- 3x large modules with double wall structure
- Sensitive volume 180 x 200 x 70 cm
- Precise assembly, commissioning and alignment within mm
- 124 000 channels

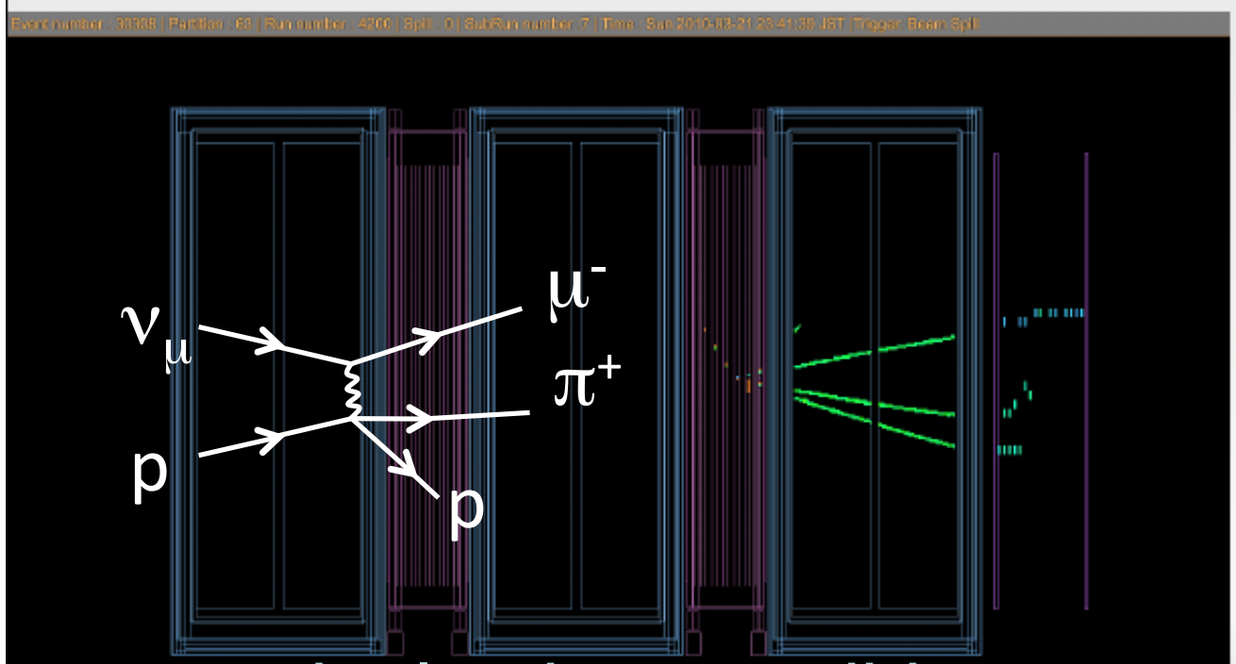
ND280 off-axis event gallery



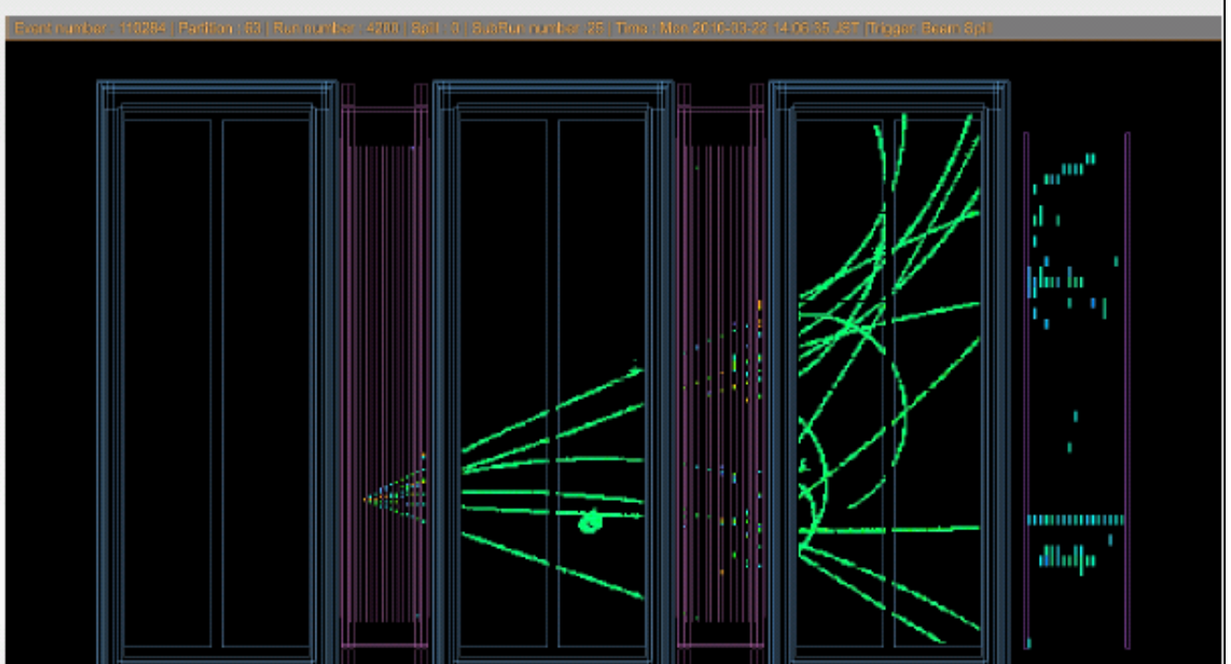
sand muon + DIS candidate



quasi-elastic candidate



single pion candidate

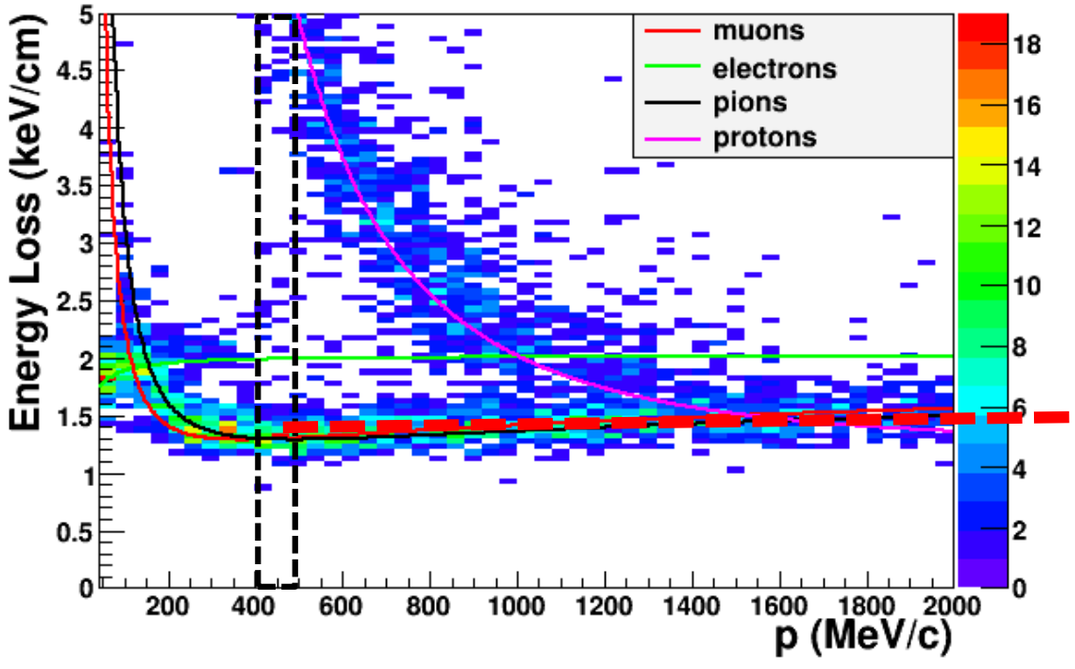

DIS candidate

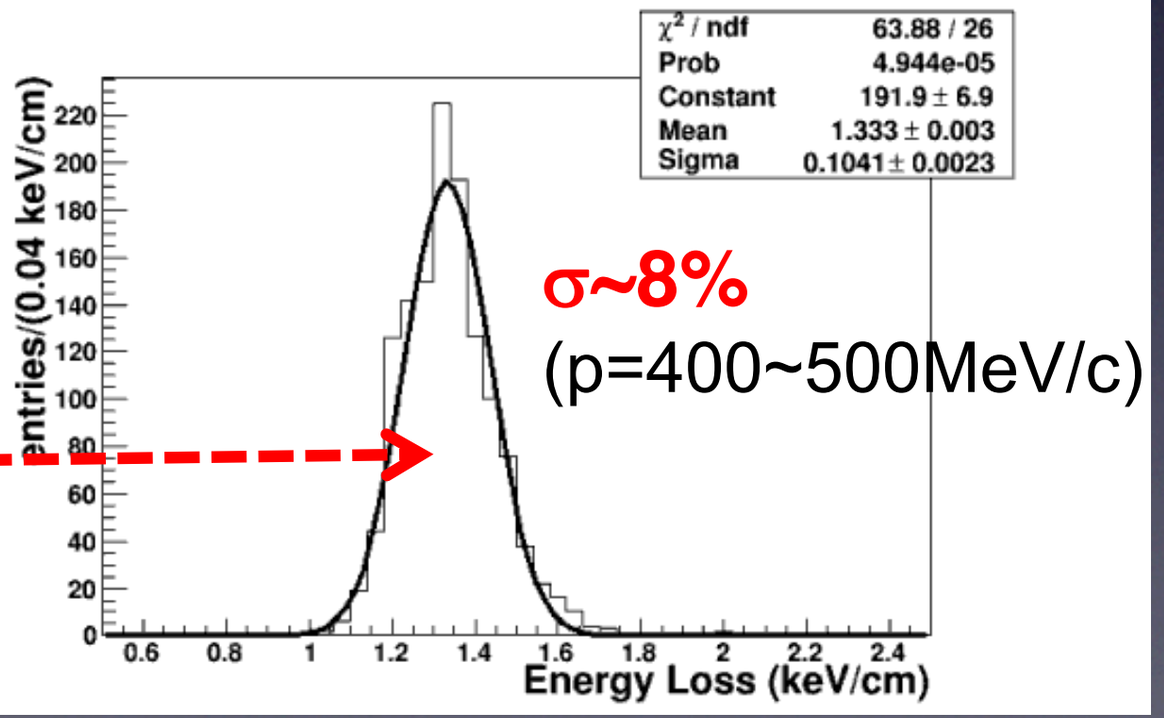
ND280 off-axis performance

Detector	Channels	Bad ch.	Bad fraction
ECAL (DSECAL)	22,336 (3,400)	35 (11)	0.16% (0.32%)
SMRD	4,016	7	0.17%
P0D	10,400	7	0.07%
FGD	8,448	20	0.24 %
INGRID	10,796	18	0.17 %
TPC	124,416	160	0.13 %

Subdetectors have small fractions of bad channels

dE/dx from TPC

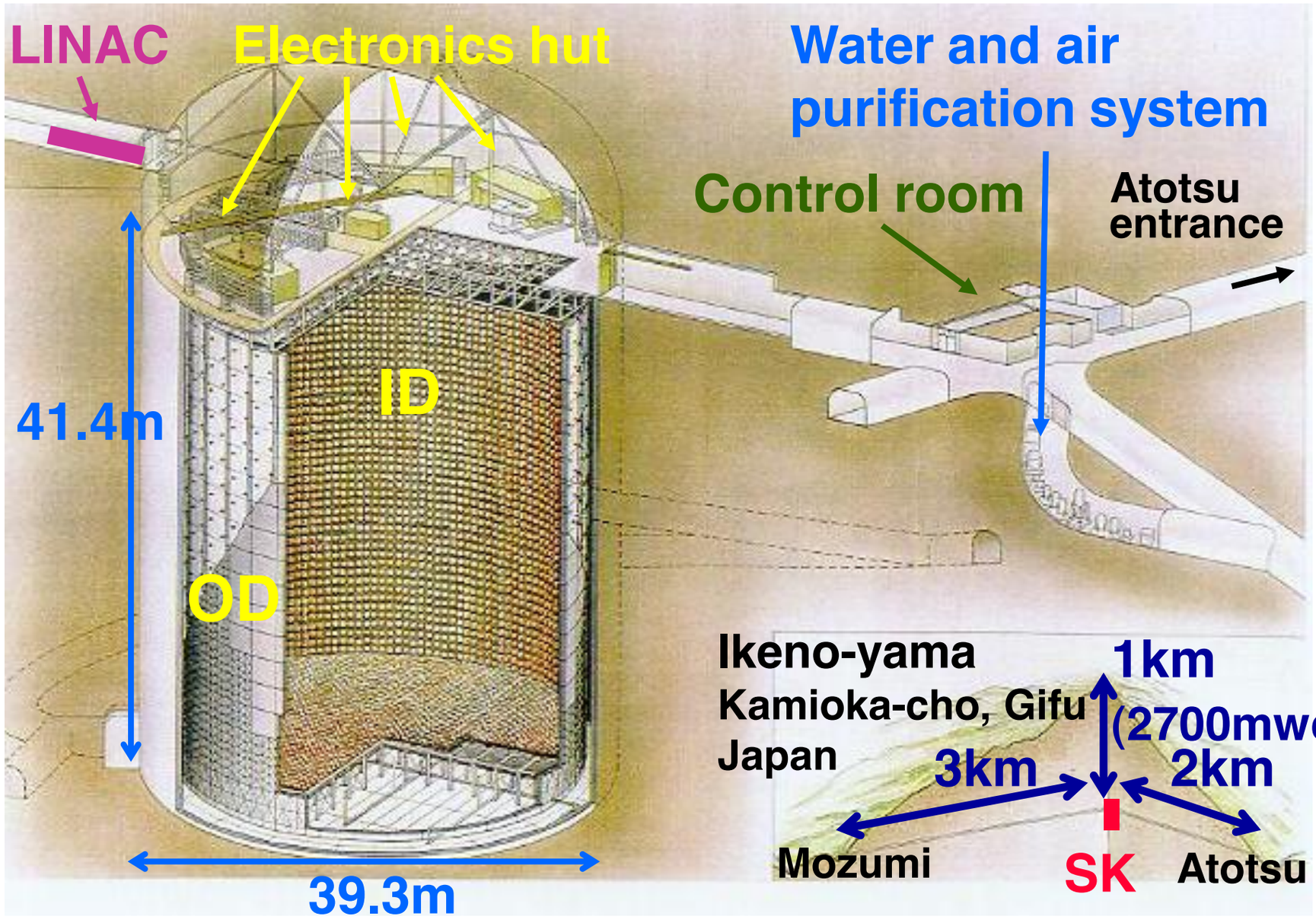




σ~8%
(p=400~500MeV/c)

SuperK (Far) Detector

See J. Wilkes' talk



- 50kton water
- 32kt ID viewed by 20-inch PMTs
- ~2m OD viewed by 8-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- E_{total}=~4.5MeV energy threshold
- SK-I: April 1996~
- SK-IV is running

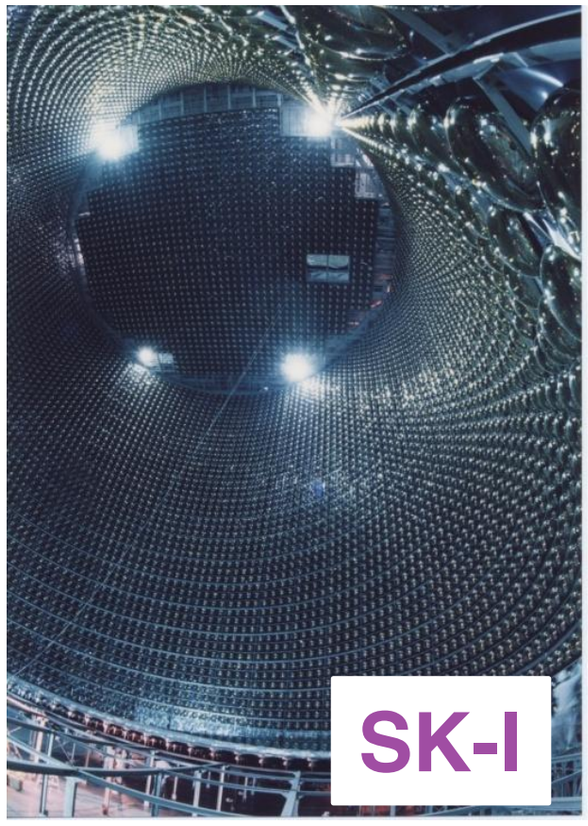
Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

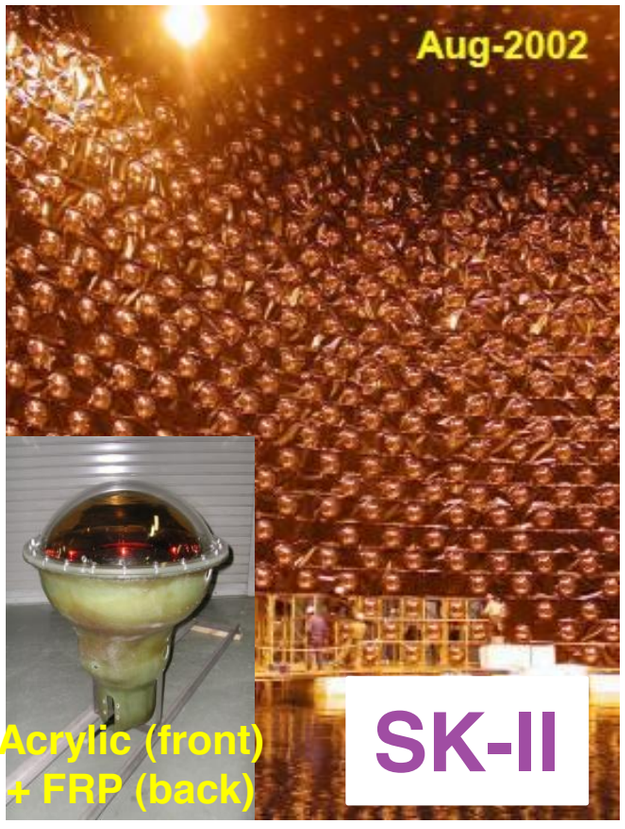
History of SuperK

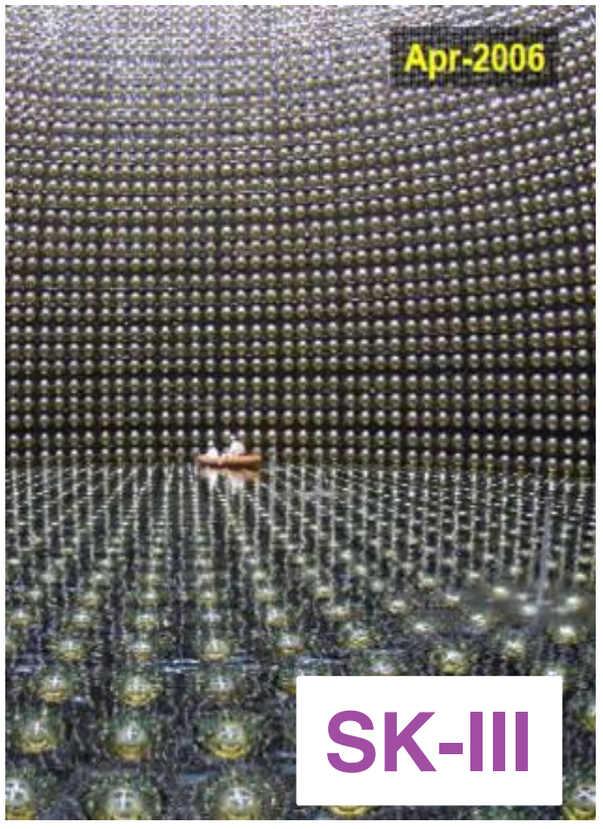
See J. Wilkes' talk

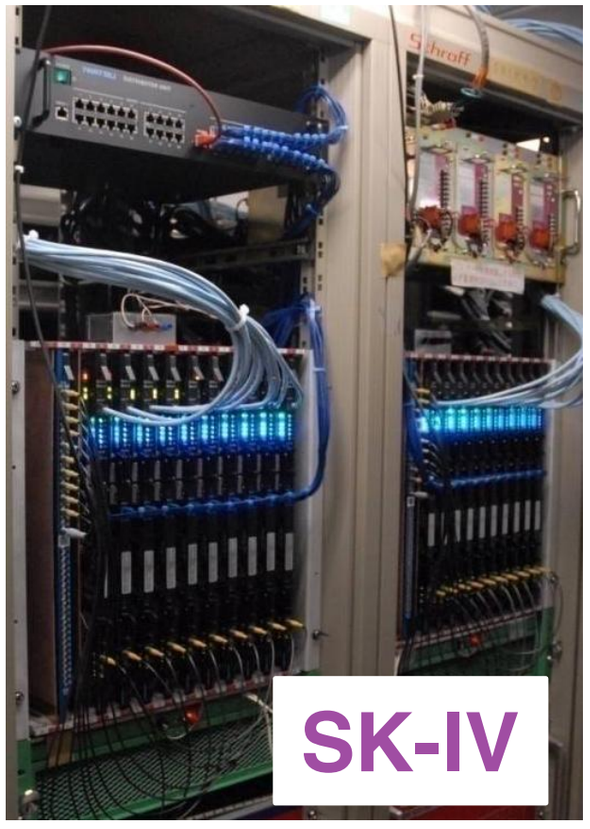
1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

SK-I SK-II SK-III SK-IV







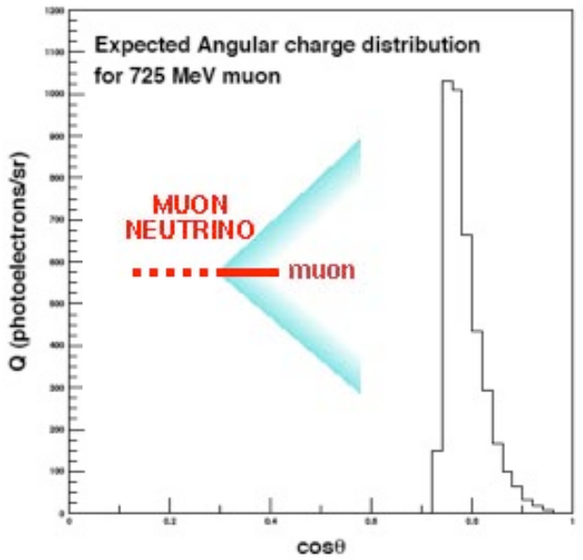


	SK-I	SK-II	SK-III	SK-IV
	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade
Energy Threshold	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV → 4.0 MeV
(Total energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV → ~3.5 MeV
(Kinetic energy)				Current / Target

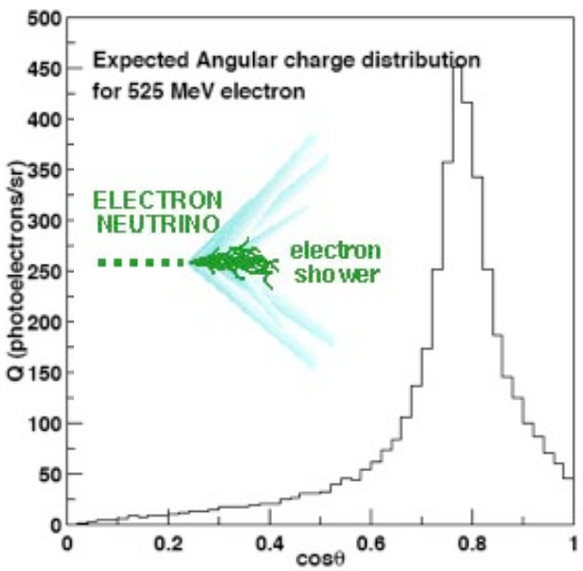
Water Cerenkov Imaging

Water Cherenkov: e/μ identification

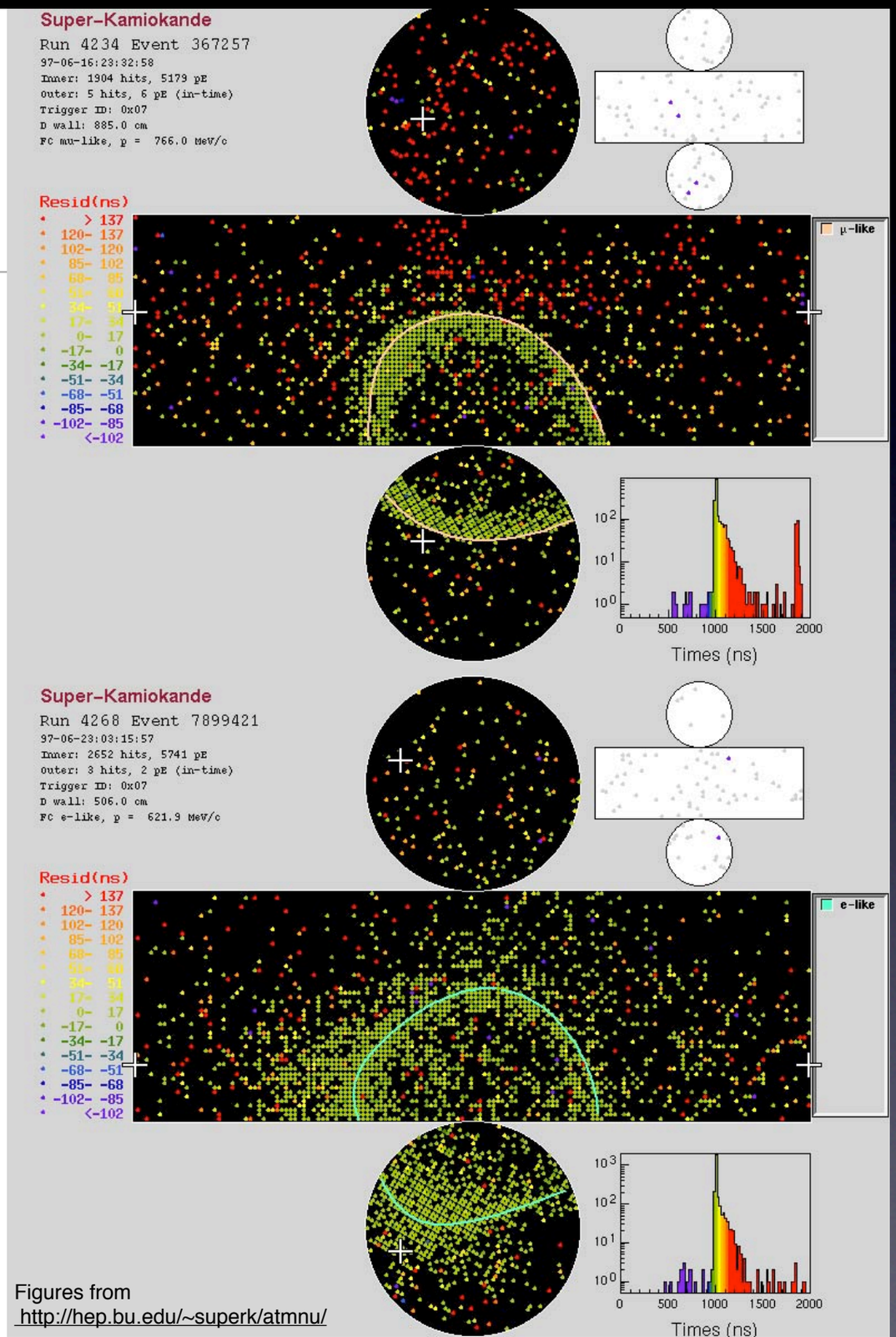
- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have "collapsed" rings while electrons are ~always at 42º.



- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are "crisp", electron showers are "fuzzy". See plots and figures at the right.



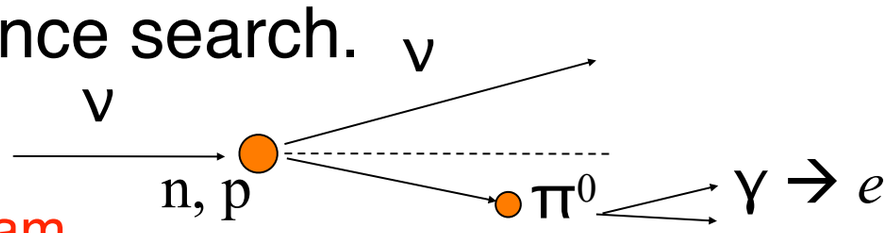
Figures from M. Earl's PhD Thesis

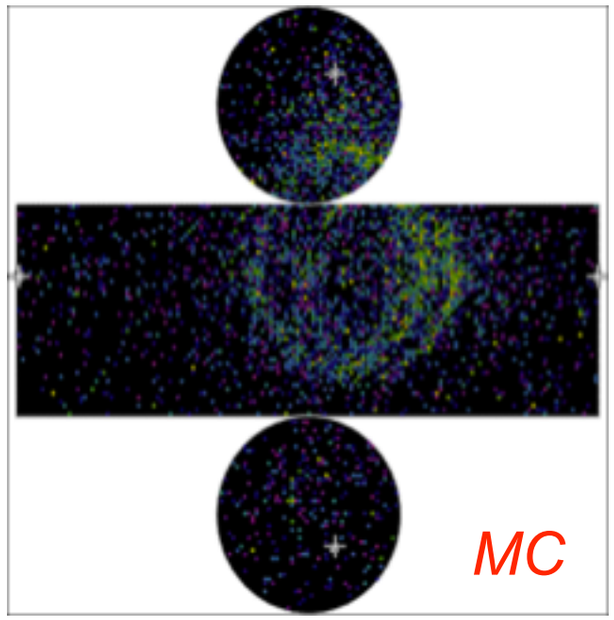


Figures from
http://hep.bu.edu/~superk/atmnu/

Backgrounds for main T2K analyses

- Background for ν_e appearance search.
  - π^0 from NC events
  - Intrinsic ν_e contaminated in ν_μ beam
    - ← Dominant sources are μ^+ decay and K^+ decay
      - ✓ Estimate from π, K production at target.
      - ✓ Measure the flux by Near Detector.



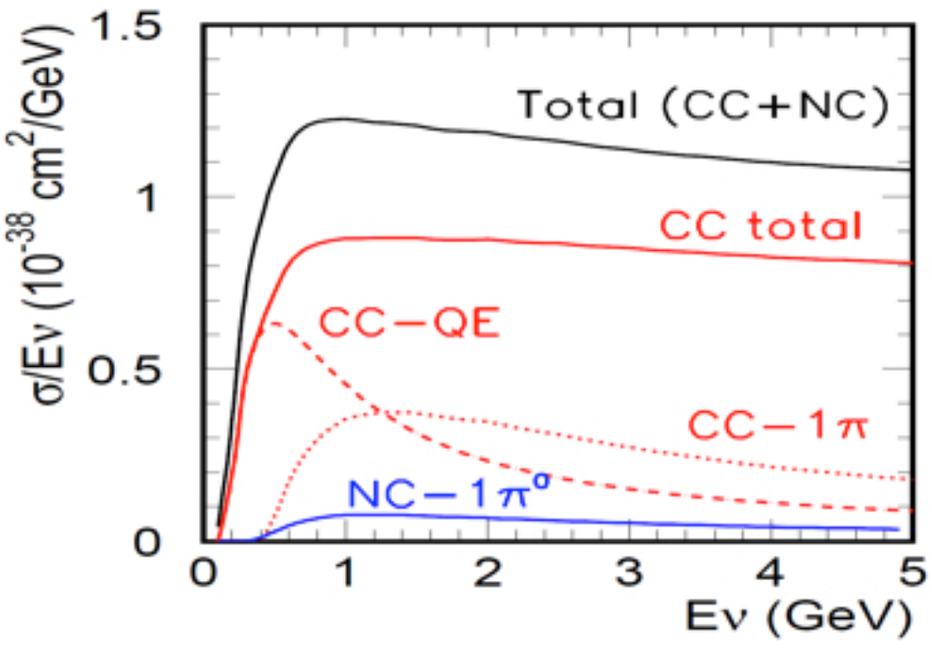


NC π^0 production

- Background for ν_μ disappearance
  - CC non-QE events w/ missing particle … E_ν reconstruction is not correct.

- Interaction cross section for background events become large as the neutrino energy become large.

→Reducing high energy ν flux is important to maximize S/N ratio

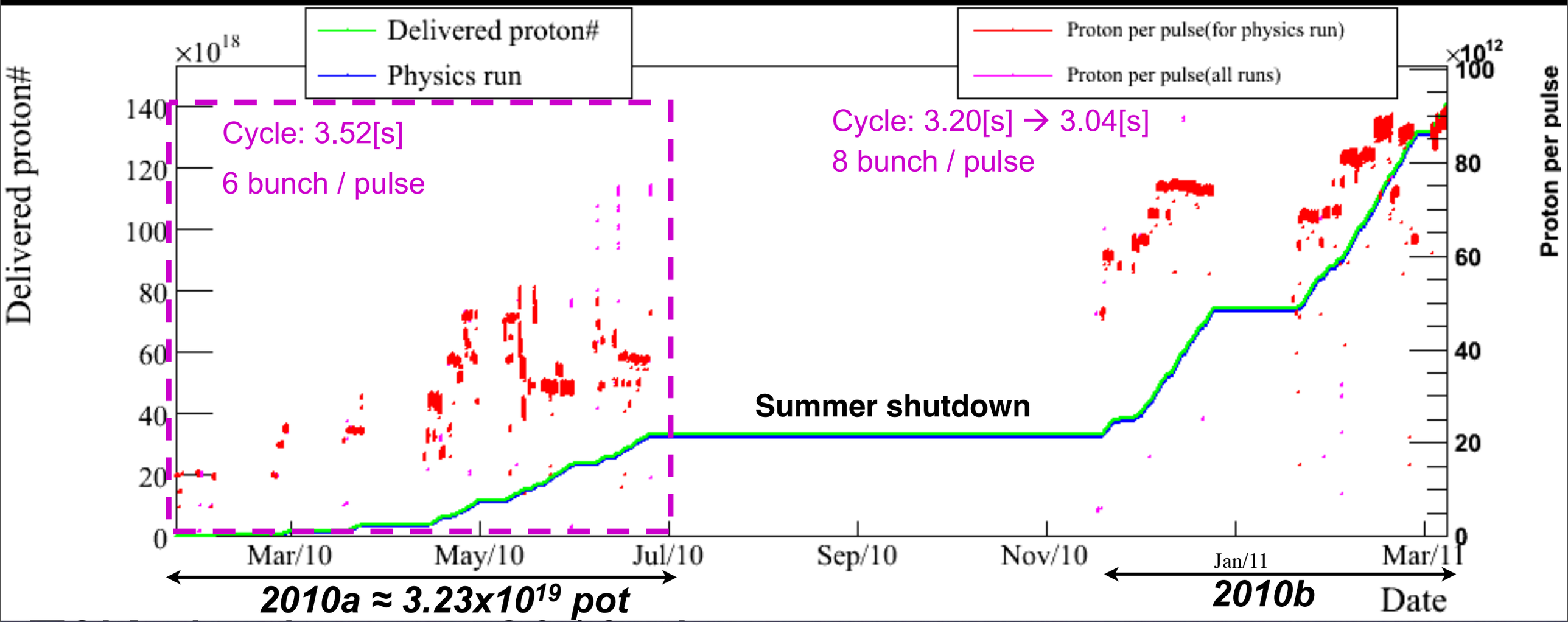


T2K data taking history

Running period: MR fast extraction program aims at actual running time >10^7 s per year

- *MR and beam line commissioned in 2008-09*
- ***Jan 2010 : start physics run 2010a***
- *Feb 24, 2010: first T2K event in Superkamiokande !*
- ***June 26, 2010: finish run 2010a***
- *November 16, 2010: start run 2010b*
- *December 25-January 20: end of year shutdown*
- *Until March 11: continuous running with increasing beam power*
- *Scheduled to run until July 1, 2011... ????*

MR protons# delivered



Run 2010a (Jan-Jun 2010)

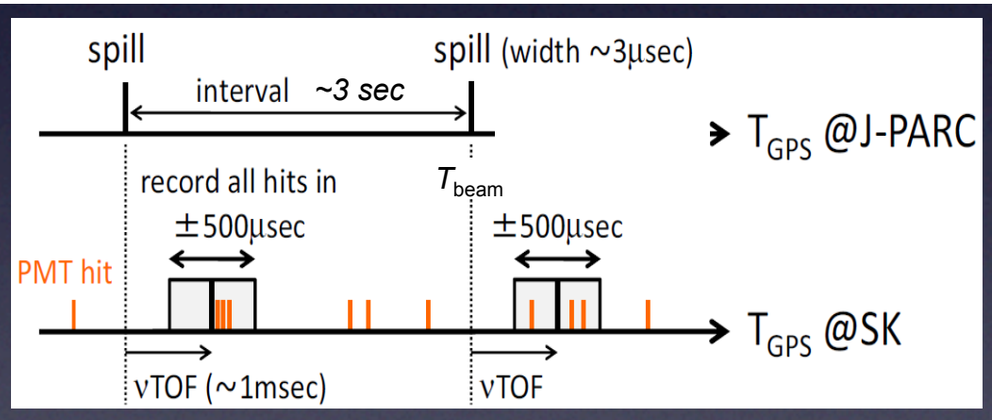
- 6 bunches/spill, cycle: 3.52 sec
- **3.23x10^{19} p.o.t** for T2K analysis
- 50kW stable beam operation (trials at 100 kW)
- Super-K live time >99%

Run 2010b (Nov 2010-??? 2011)

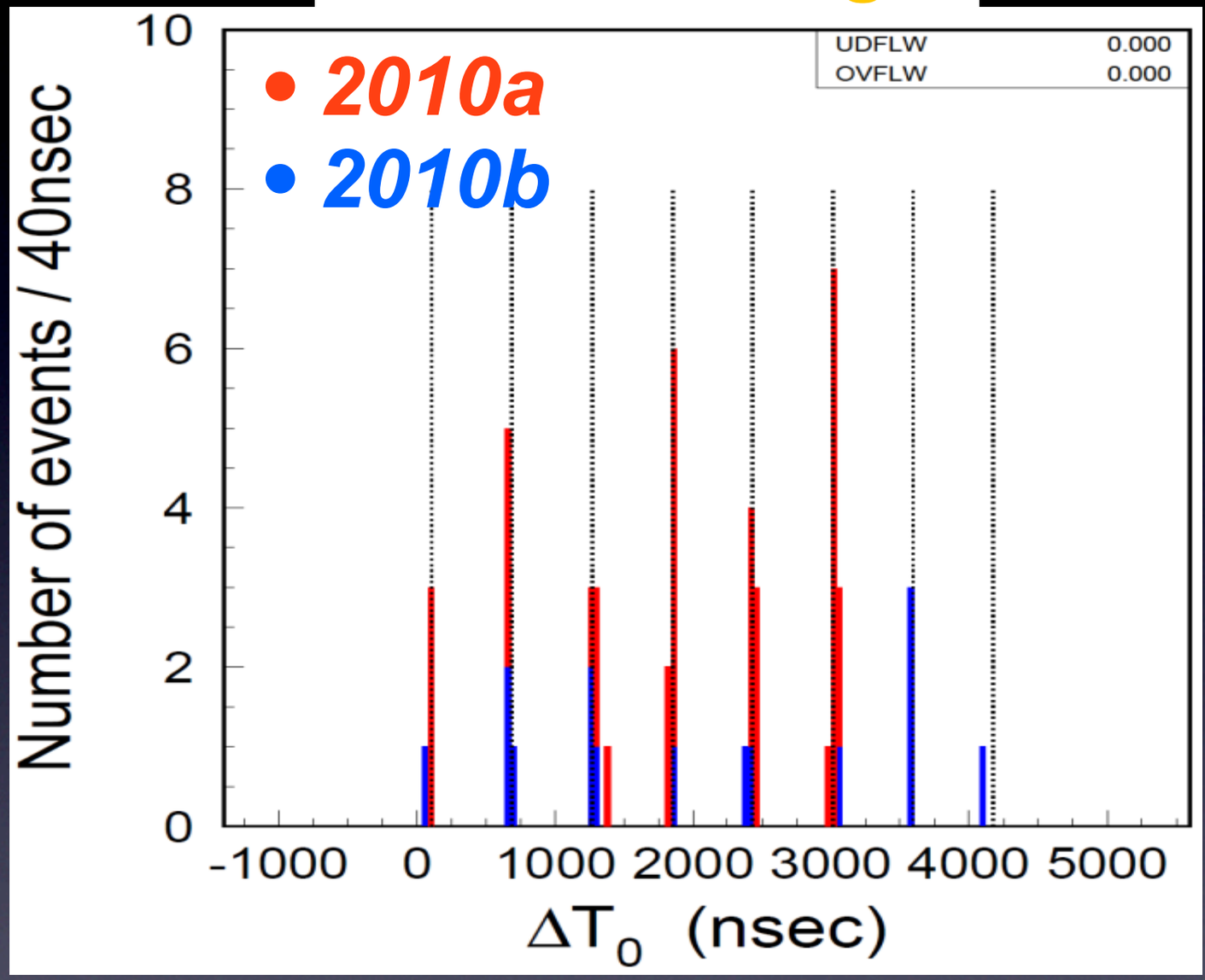
- 8 bunches/spill, **9x10^{13} ppp**
- cycle: 3.52 sec → **3.04 sec**
- 135kW → **145 kW beam power**
- **1.45x10^{20} p.o.t** accumulated so far
- MR intensity limited by losses

SK-spill synchronization

- Baseline measurement (Survey)
  - $L = 295{,}335 \pm 7$ m
    → ToF of $\nu = 985.132 \pm 0.02$ μsec (≡ νTOF)
  - Expected event timing @ SK ($\equiv T_{SK}$)
    = Spill timing @ Tokai ($\equiv T_{beam}$) + νTOF.
- DAQ synchronization
  - SK signals in ±500μs timing window are recorded as "T2K beam events".
  - Stability of GPS is checked by comparing 2 GPS hardware and atomic clock.
    → Require |GPS1-GPS2| < 200nsec

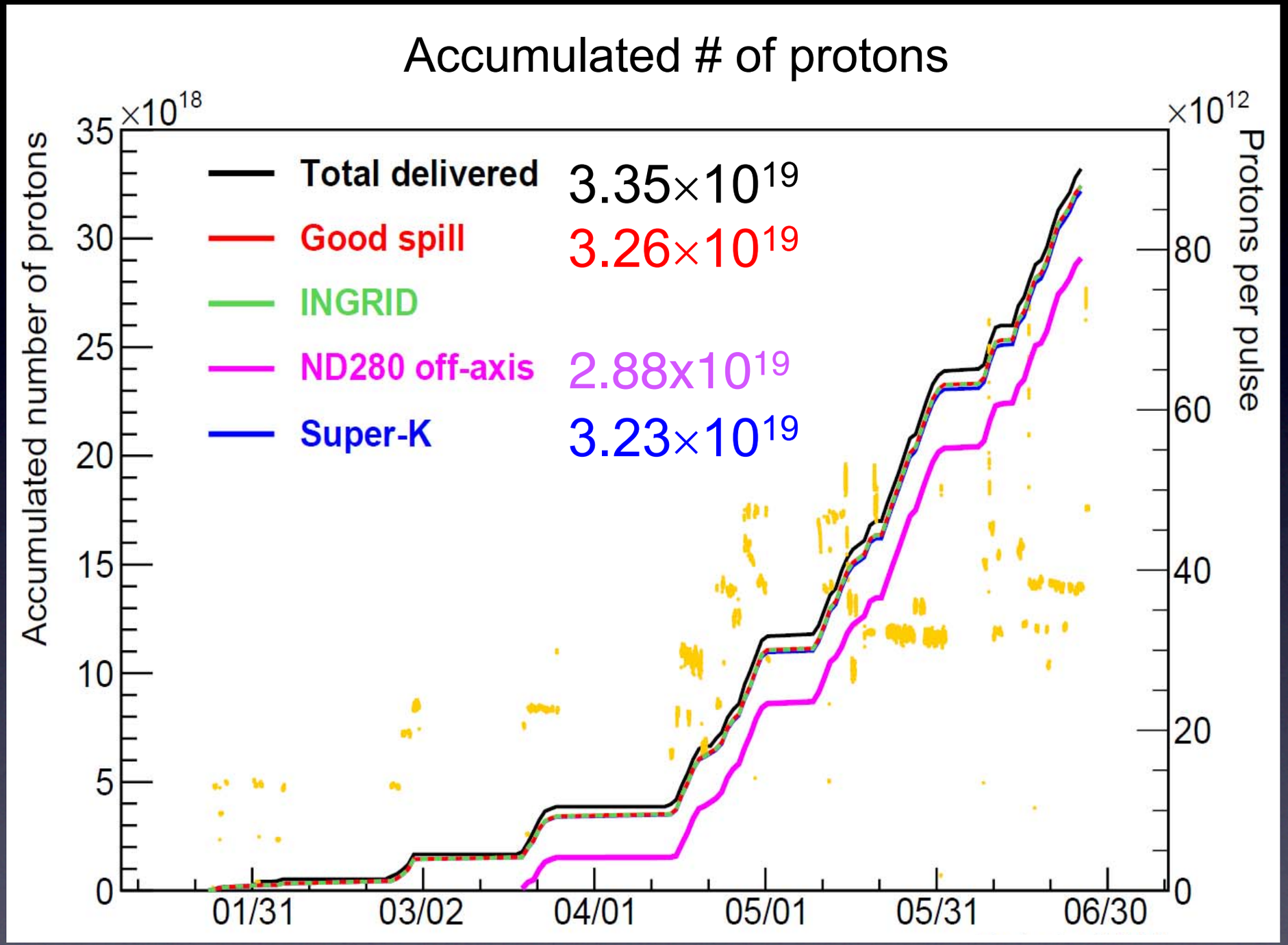


Event timing



- *Event time distribution clearly shows MR beam bunch structure : very good synchronization between T2K beam and Super-K*
  Typical accuracy ~ 20 ns (worst case 150 ns)

#protons for analysis 2010a

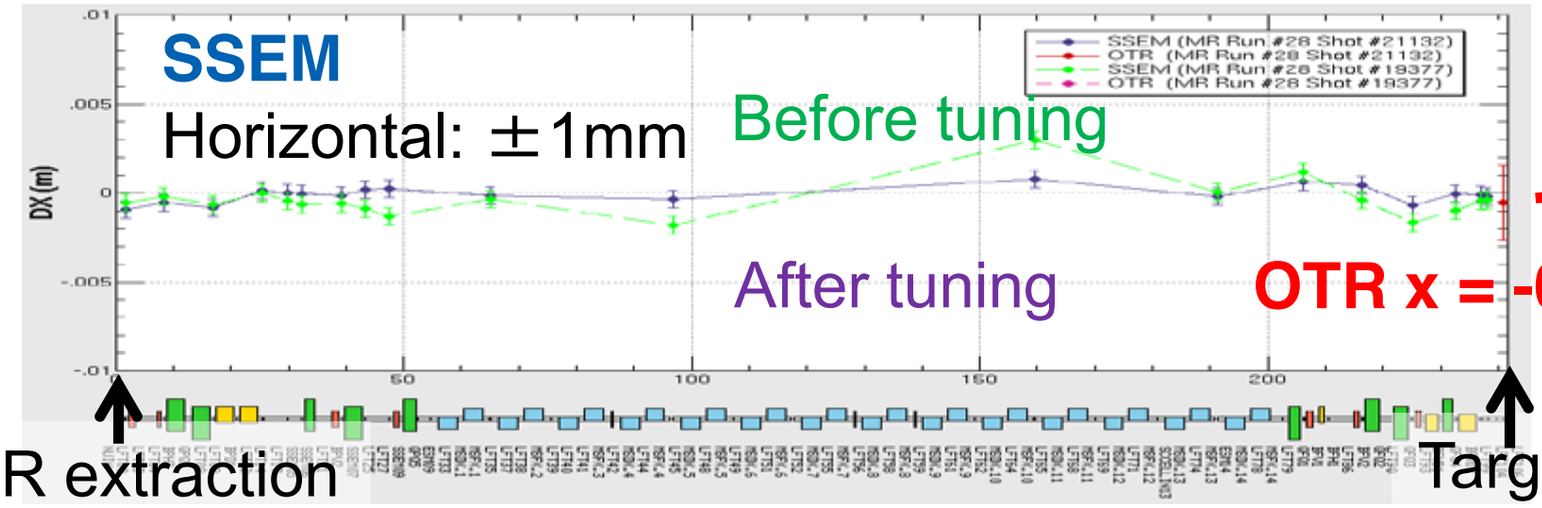


- ***After good spill and SK selection: 3.23×10^{19} POT = 15.5 kW$\times 10^7$ s***

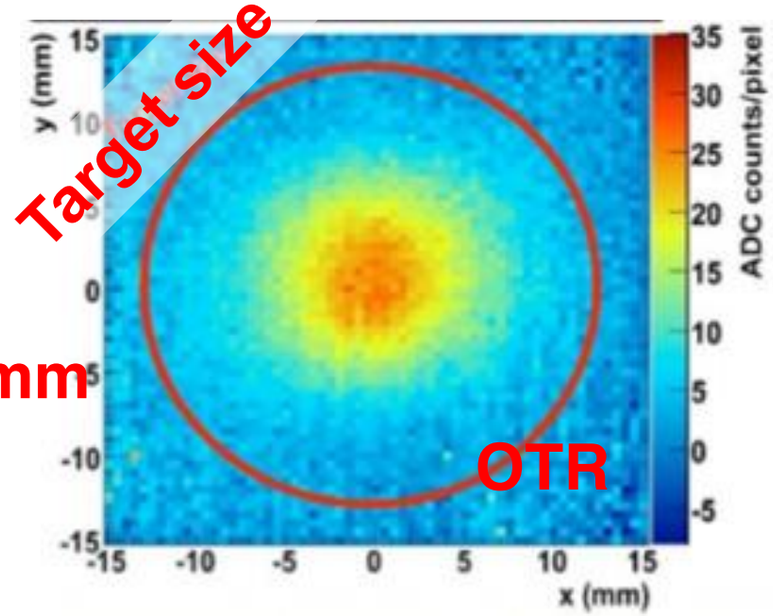
Primary protons monitor

Primary proton beam monitoring

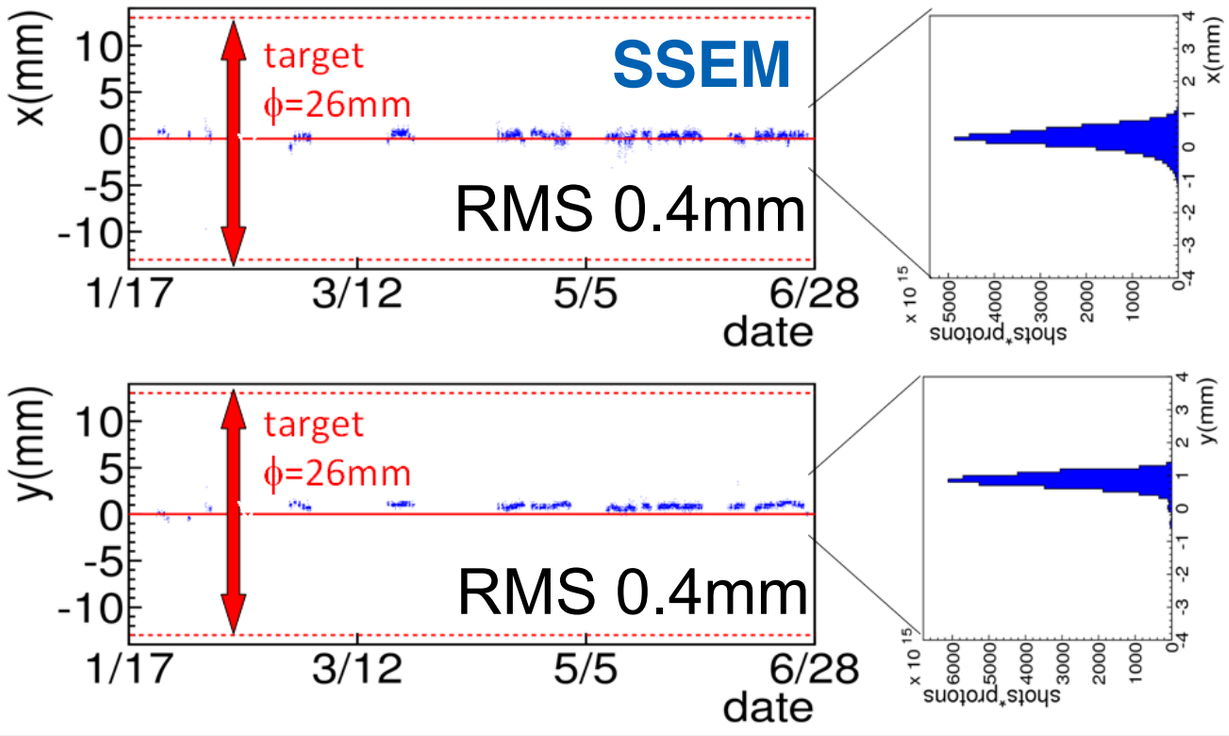
- **Beam orbit:** tuned within 2mm from design orbit.
  (Critical for controlling beam loss)



Proton beam hits center of target



- **Beam position on target:**
  Succeeded to control < 1mm
  during long term operation



SSEM:

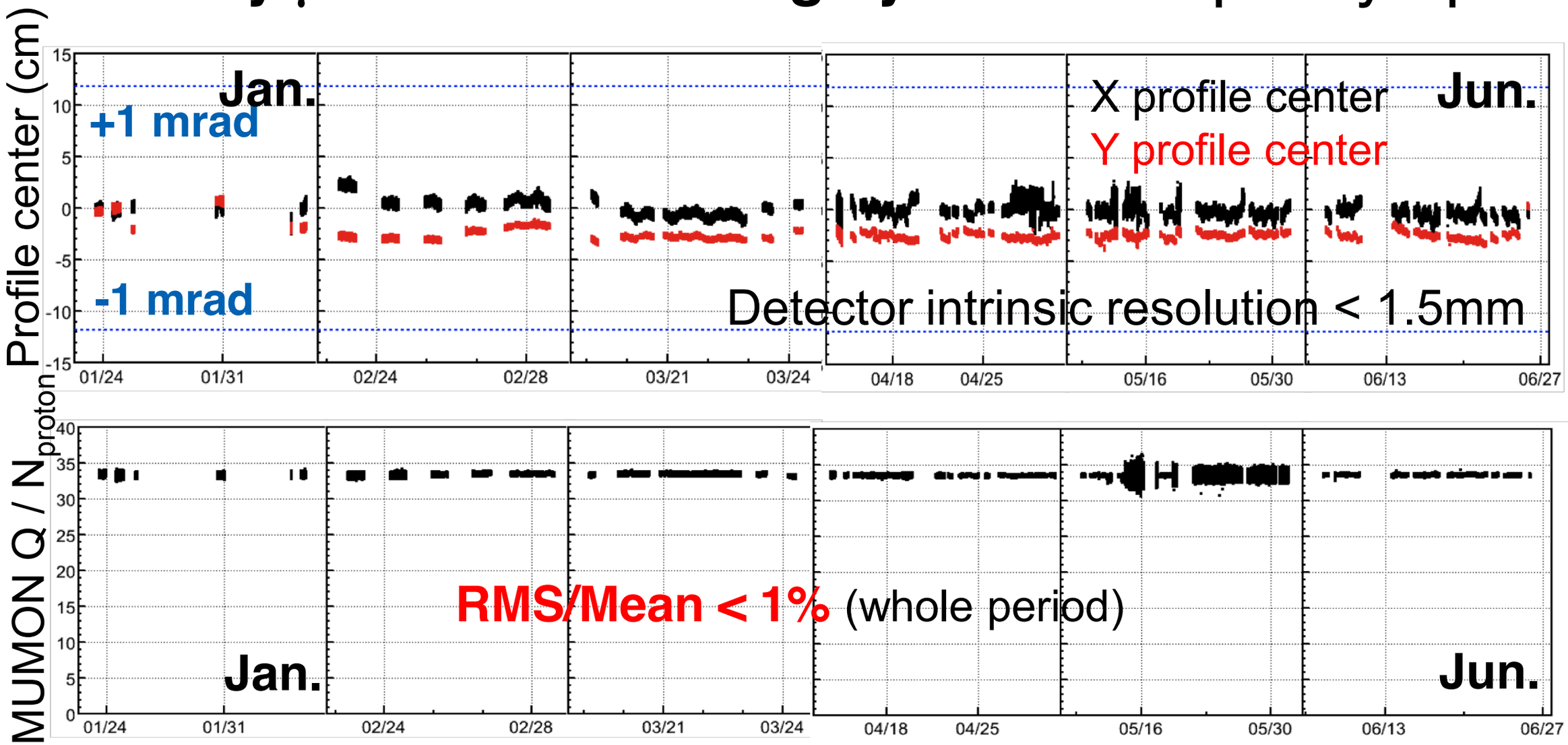
Segmented Secondary Emission Monitor

OTR:

Optical Transition Radiation detector

Muon beam monitor

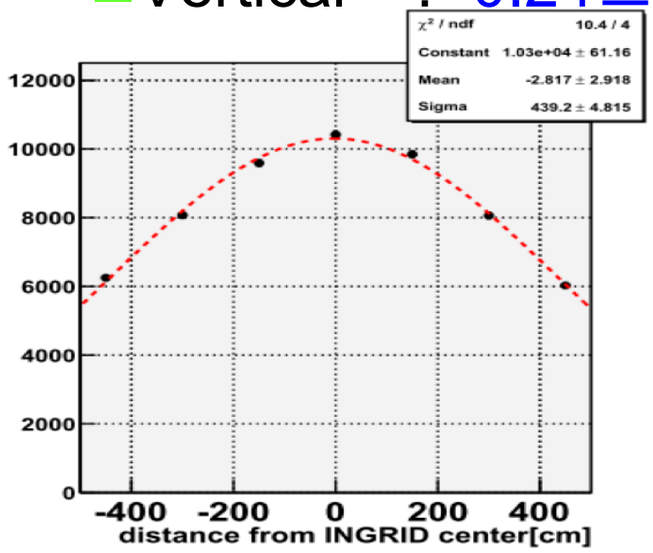
Secondary μ beam monitoring by MUMON spill-by-spill

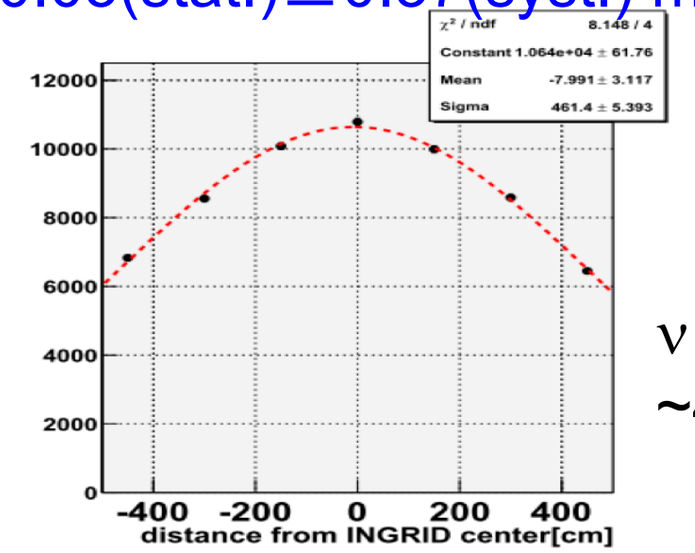


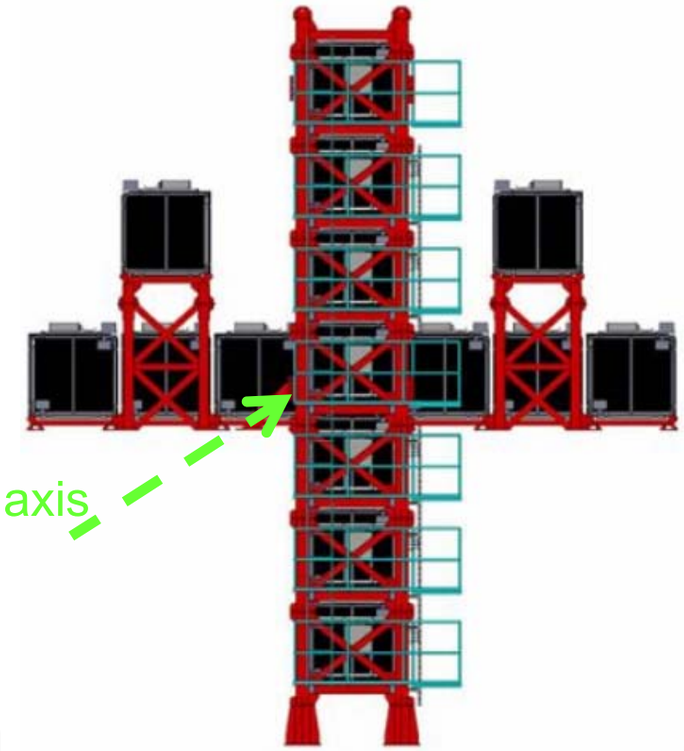
- **Beam direction** is controlled well within **1 mrad**. (1 mrad corresponds to 2% change in the SK flux at the peak energy, E_ν = 0.5 – 0.7 GeV)
- **Secondary beam intensity** (normalized by proton intensity) is stable within **1%** → reflects stability of targeting, horn focussing, etc

Neutrino beam direction stability

- Targeting efficiency of proton beam ~99%.
- ν Beam direction measured by INGRID from 2010 Jan. ~ Jun.
  - Horizontal: +0.01 ± 0.05(stat.) ± 0.33(syst.) mrad
  - Vertical : -0.24 ± 0.05(stat.) ± 0.37(syst.) mrad

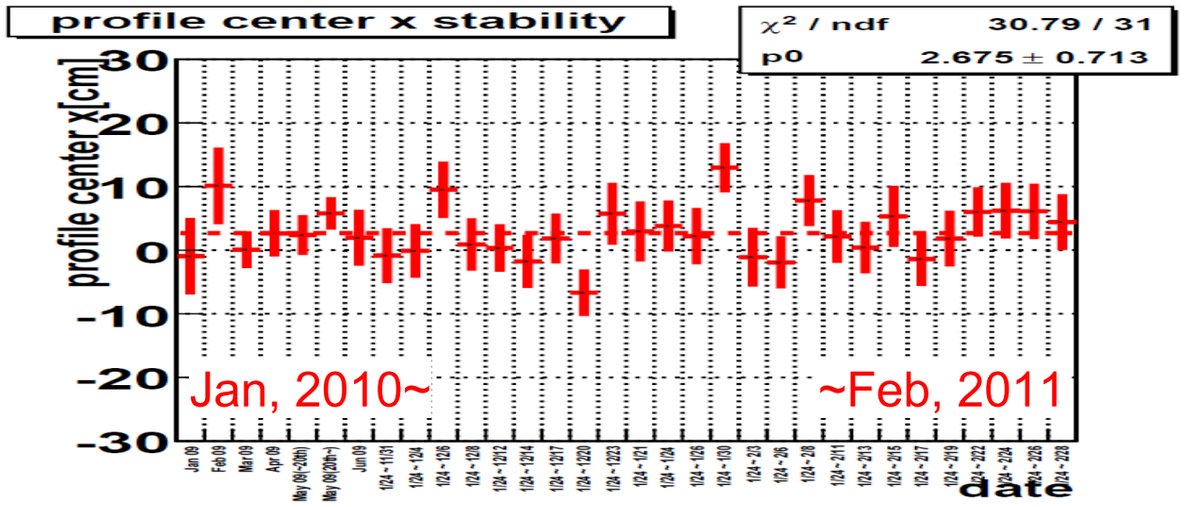


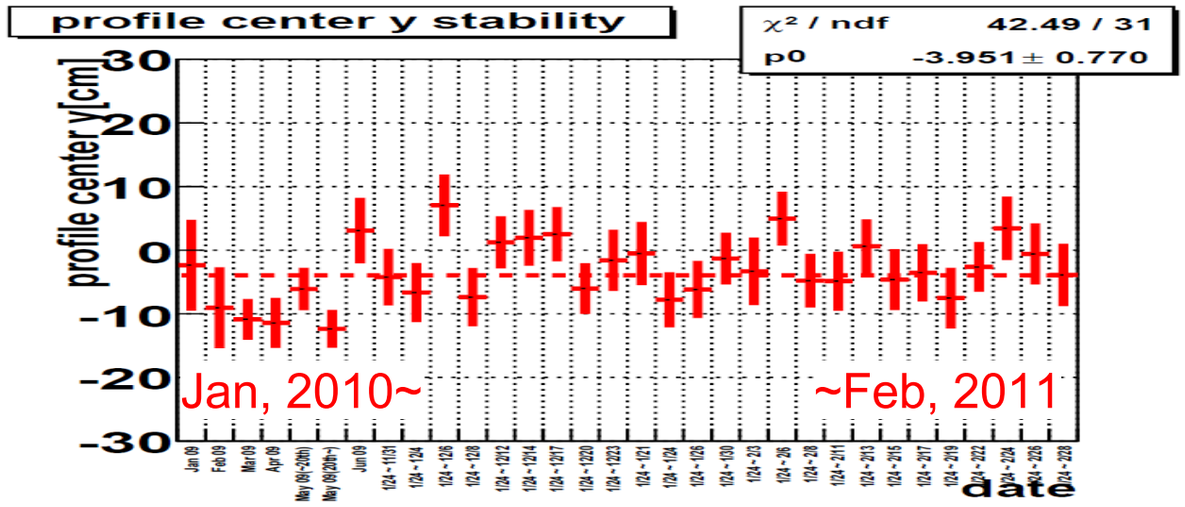




ν beam width
~4.5m @ 280m

Stability: Vertical

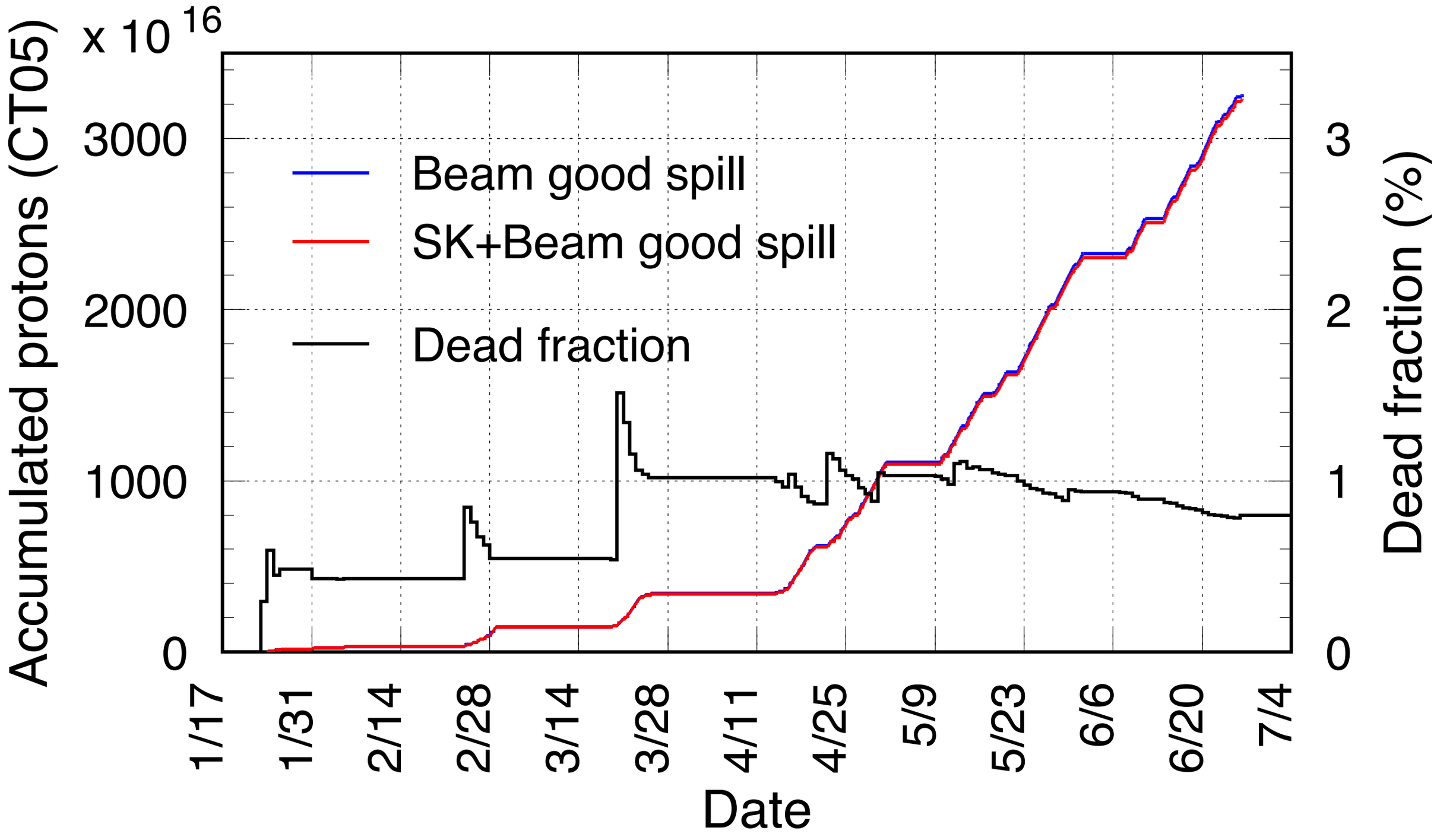




- **Event rate:** expectation vs. observation
  → $R_{data/MC} = 1.073 \pm 0.001(stat.) \pm 0.040(syst.)$

preliminary

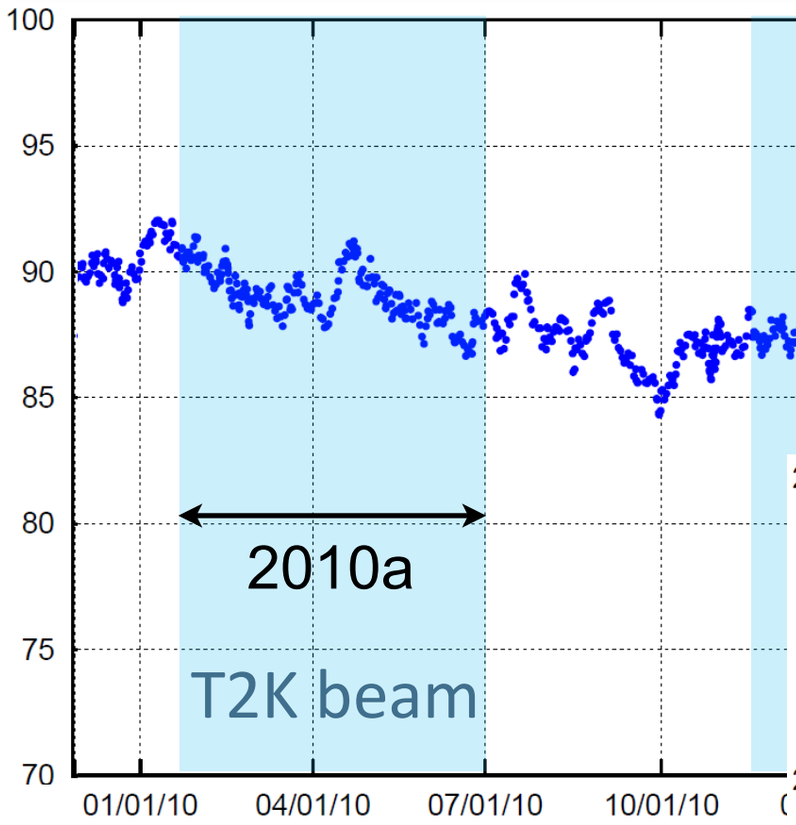
SK livetime (2010a)



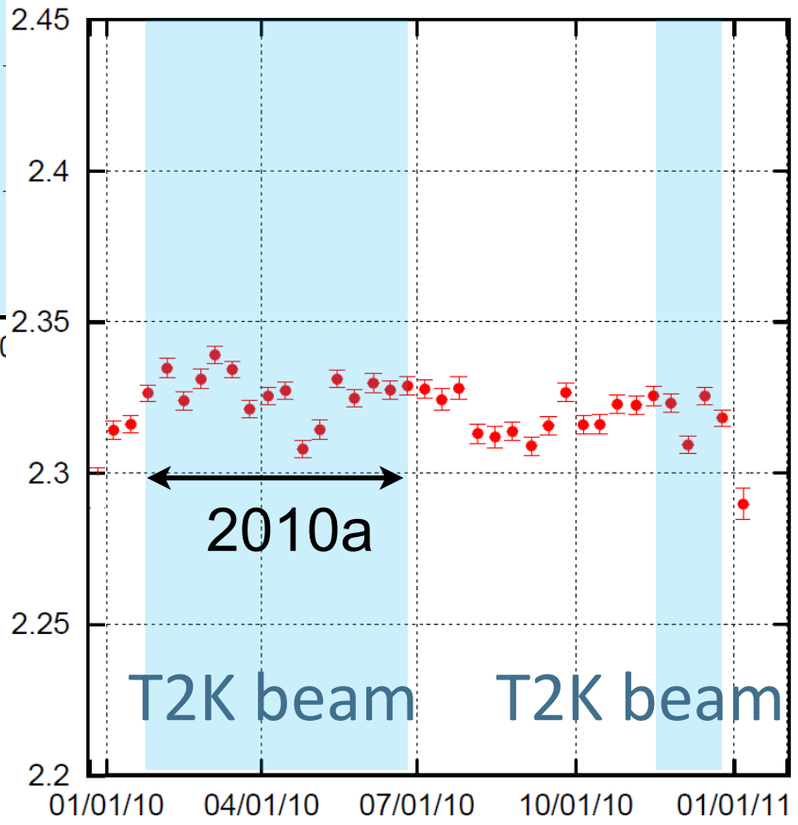
SK DAQ eff > 99.9% and SK eff for physics >99%

SK stability monitoring

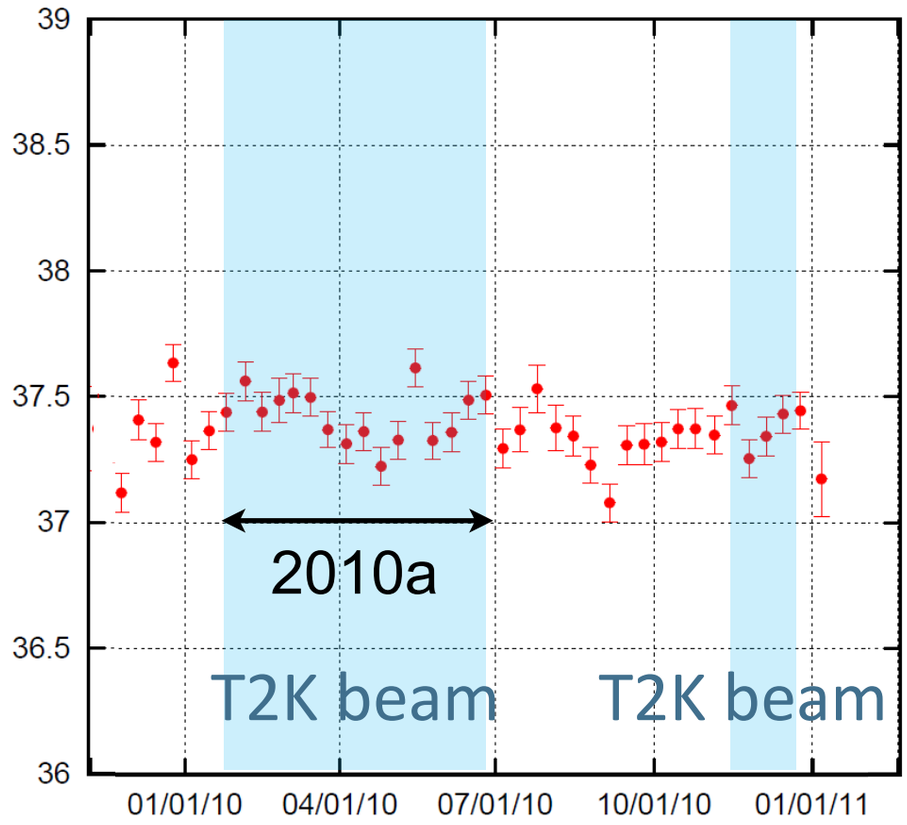
Attenuation length (m)



Stopping μ momentum/range (MeV/c/cm)



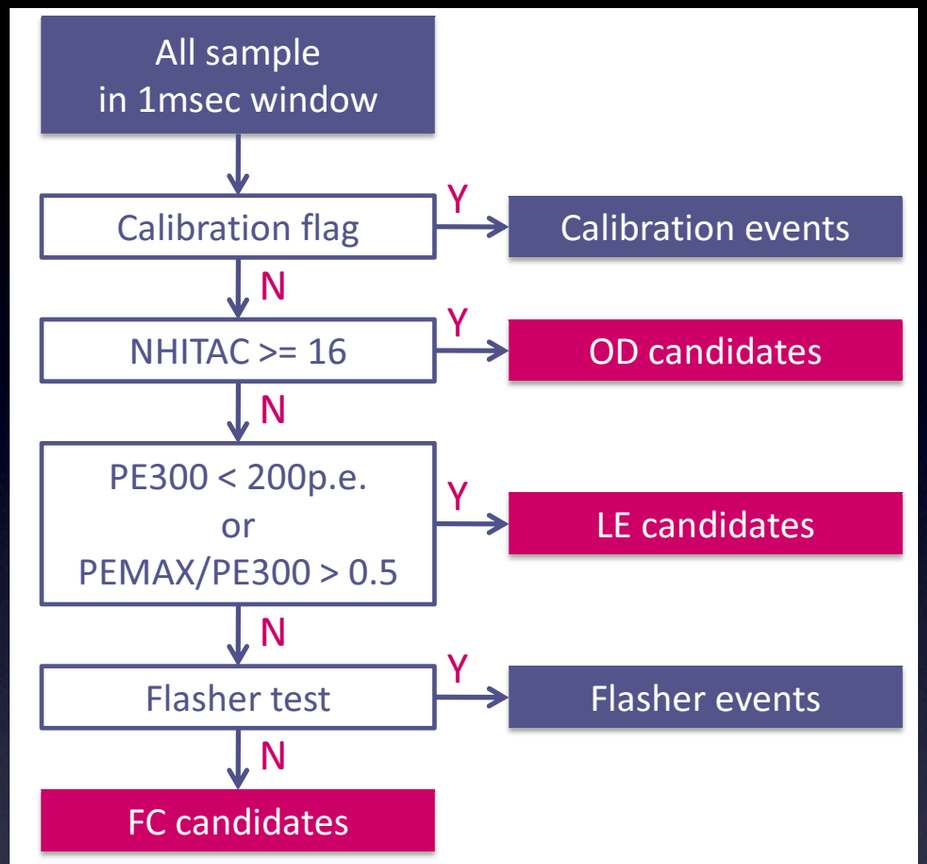
Decay-e momentum (MeV/c)



Stable.

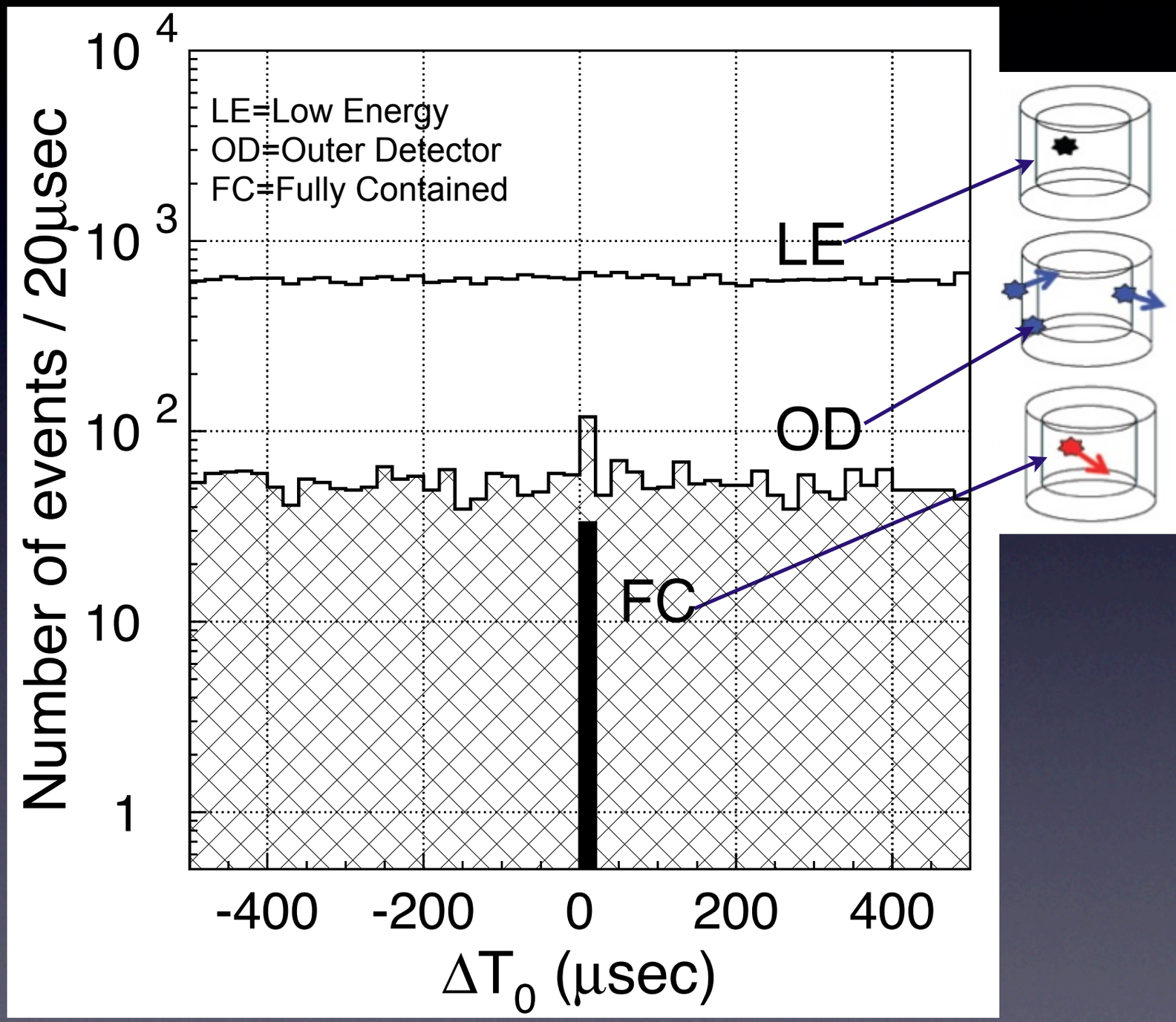
T2K-SK event reduction (2010a)

Reduction of sample collected in ±500μs window around T2K spill



PE300 = sum ID-PMT (p.e.) in 300ns window
PEMAX = maximum charge (p.e.) in a single ID-PMT hit

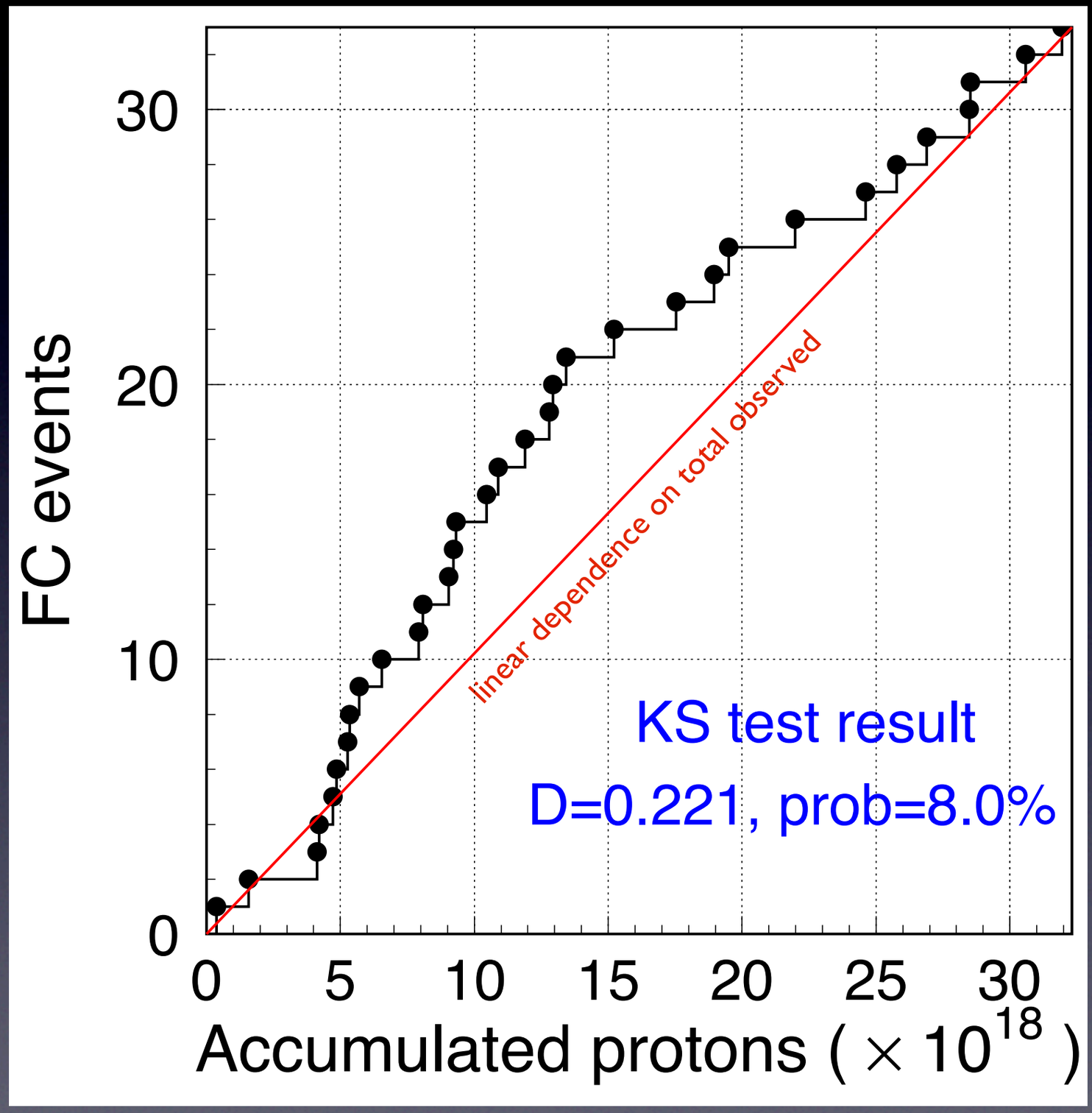
Number of neutrino candidates observed in SK:
Fully Contained (FC) = 33
Flasher events = 2
Accidental background = 0.0094±0.0067(stat)



T2K-SK event reduction (2010a)

Observed FC events versus accumulated POTs

K-S test shows consistency with linear dependence of observed events on p.o.t.



T2K-SK event reduction (2010a)

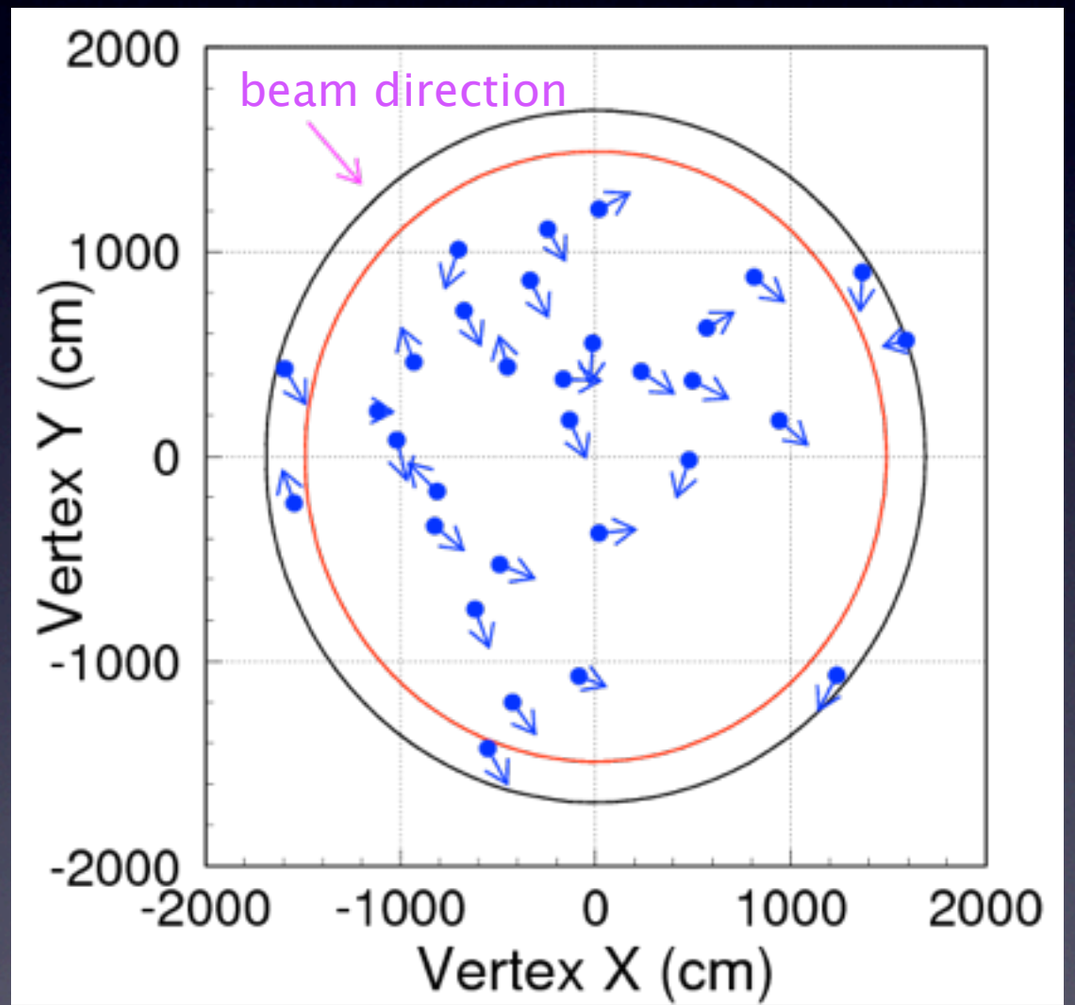
Fully contained, fiducial volume (FCFV) selection, ring counting and 1-ring PID classification

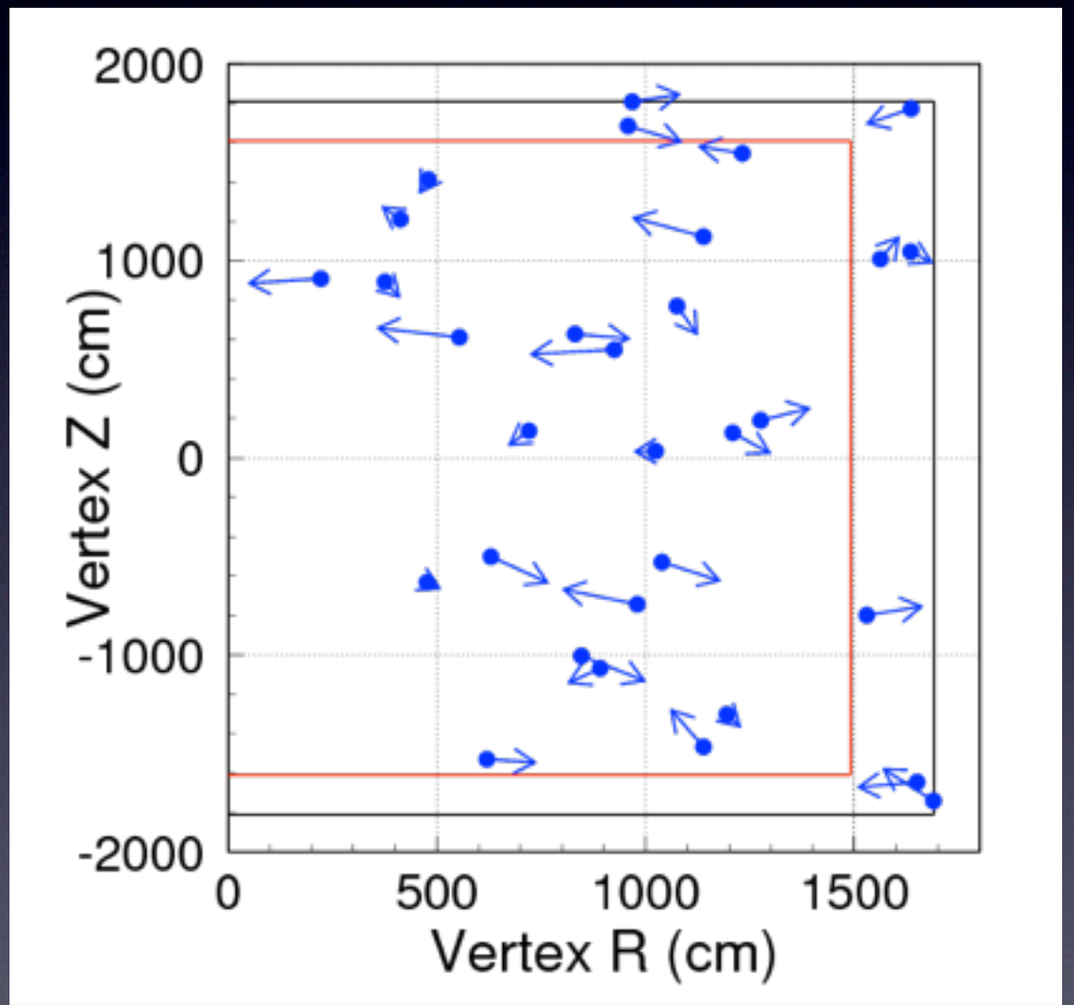
T2K-SK events Fiducial cut: D_{wall} > 200 cm, total fiducial target = 22.5 kton	Data
Fully-Contained	33
Fiducial Volume, E_{vis} > 30MeV	23
Single-ring μ-like (P_{μ}>200MeV/c)	8
Single-ring e-like (P_{e}>100MeV/c)	2
Multi-ring	13

T2K-SK event vertex (2010a)

FC events with visible energy above 30MeV

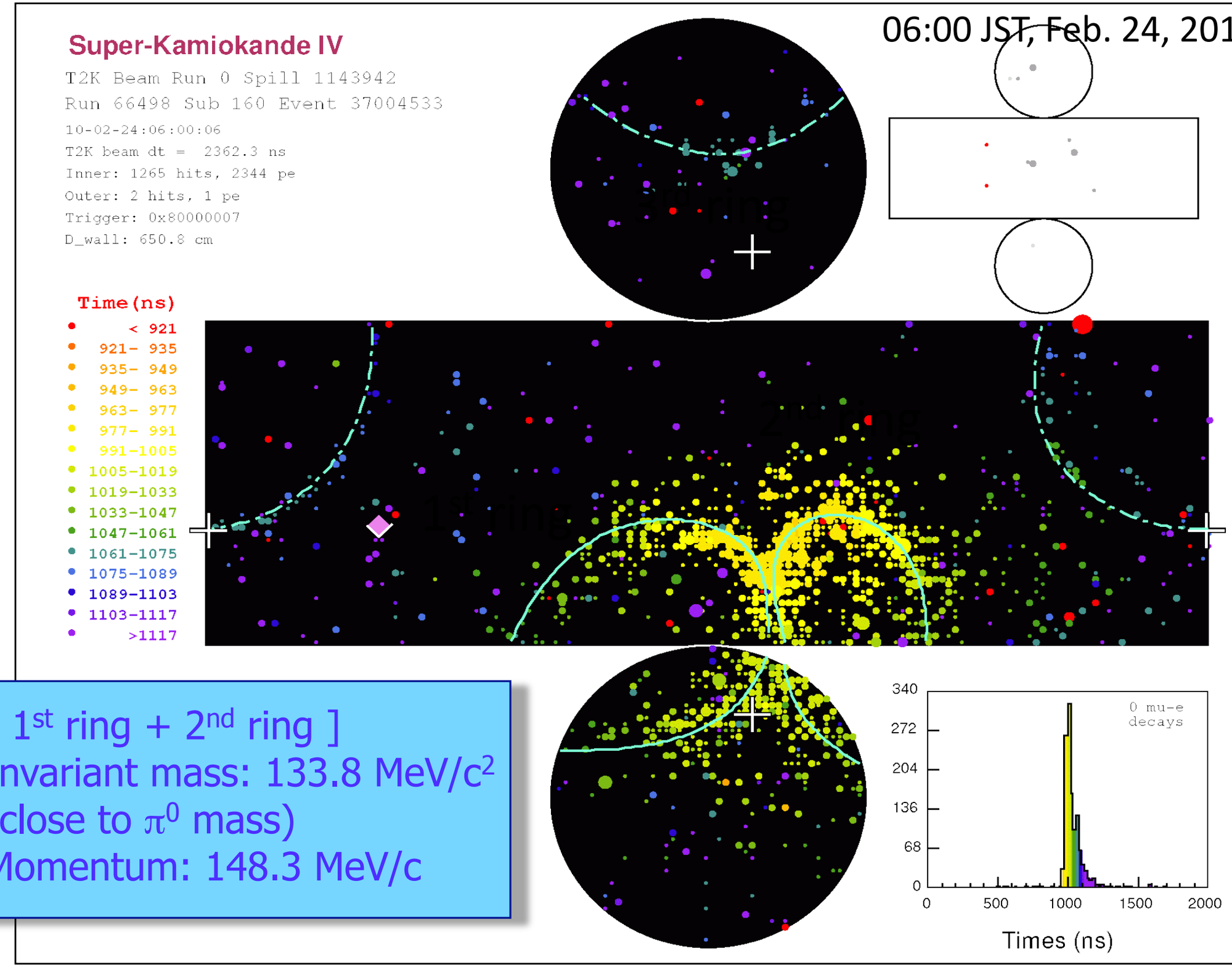
Reconstructed vertices distributions





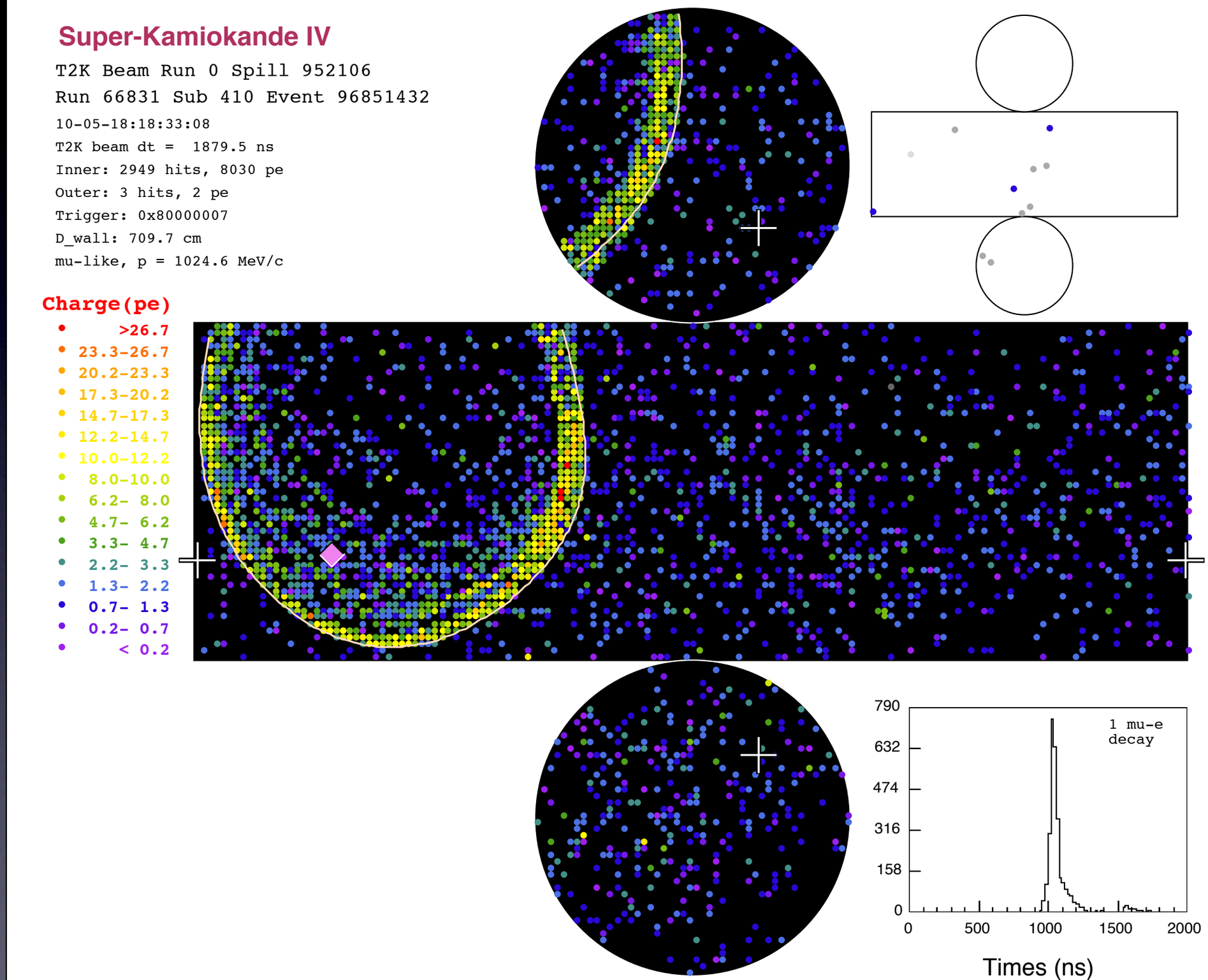
The arrow shows the direction of the most energetic reconstructed Cerenkov ring.
black circle = inner detector wall
red circle = boundary of the fiducial volume

First T2K ν candidate

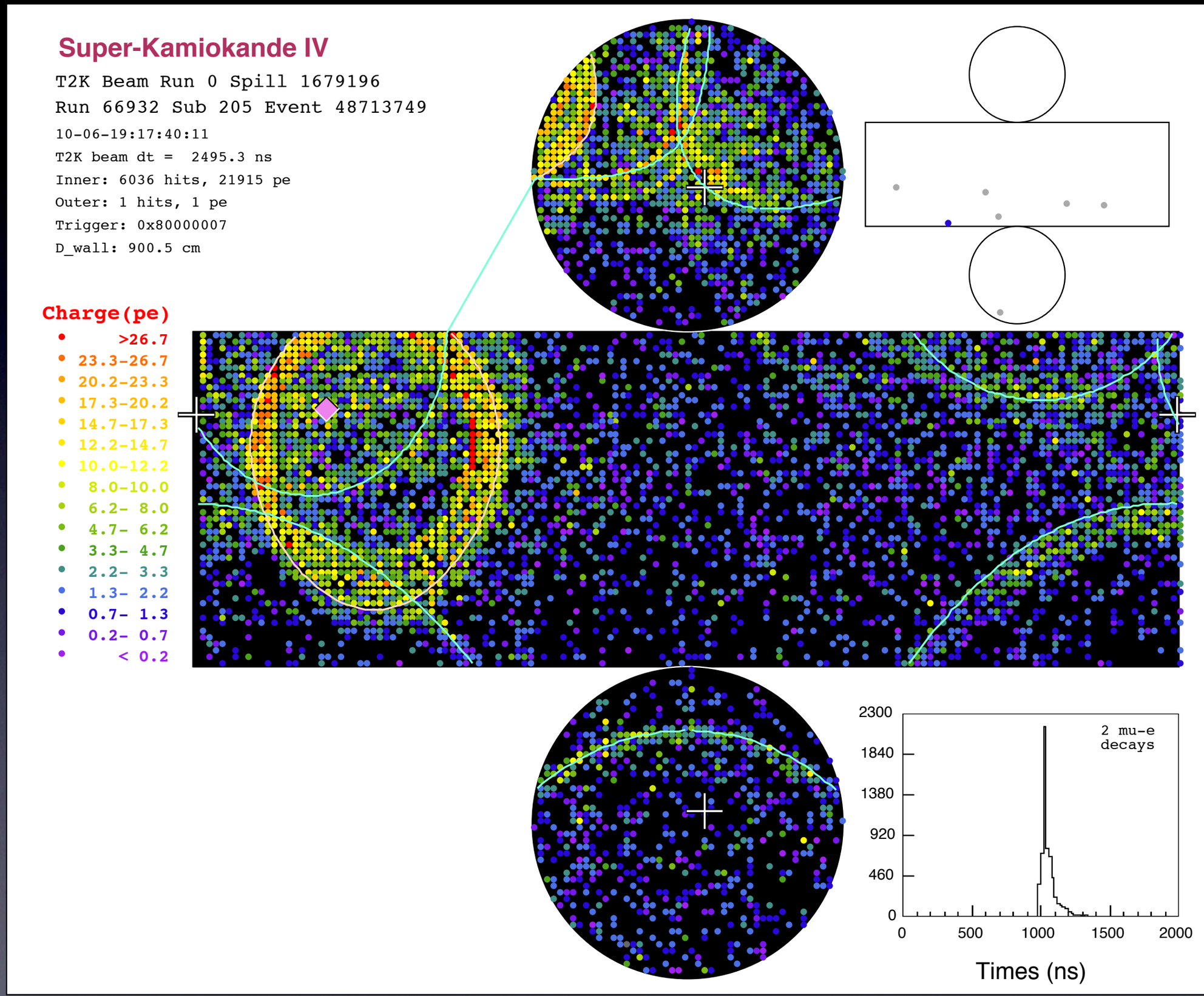


[1st ring + 2nd ring]
Invariant mass: 133.8 MeV/c^2
(close to π^0 mass)
Momentum: 148.3 MeV/c

T2K 1-ring μ-like candidate(2010a)



T2K multi-ring μ-like candidate (2010a)



Analysis strategies (2010a)

(A) ν_μ disappearance analysis:

- *T2K-SK data reduction 1-ring μ-like*
- *Prediction of expected events under two hypotheses:*
  1. *null oscillation*
  2. *oscillations with* $\Delta m^2_{23}=2.4\times10^{-3}eV^2$, $\sin^2 2\theta_{23}=1.0$
- *Comparison observed with expectation*

(B) ν_e appearance analysis:

- *T2K-SK data reduction 1-ring e-like*
- *Additional cuts for background suppression*
- *Prediction of expected events under two hypotheses:*
  1. *"background only" = oscillations with* $\Delta m^2_{23}=2.4\times10^{-3}eV^2$, $\sin^2 2\theta_{23}=1.0$, *and* $\theta_{13}\equiv0$
  2. *"signal+background" = same as 1. but with* $\sin^2 2\theta_{13}=0.1$
- *Oscillation parameters fit*

Analysis flow (2010a)

Neutrino flux prediction

- Proton beam data
- Hadron production data

ND280 (near) Detector Measurements

- ν_μ CC inclusive selection
- Measure: $R_{Data/MC} = \frac{N^{Data}_{\mu CC, ND280}}{N^{MC}_{\mu CC, ND280}}$

Neutrino cross-sections

- Tuning to external data
- Interaction models and parameters variation

SK (far) Detector Measurements

- Data reduction and classification
- Compute signal and background expectations (counting)

$$N^{MC}_{signal} = \int dE_\nu \underbrace{\Phi_\mu(E_\nu)}_{\text{flux}} \times \underbrace{\sigma(E_\nu)}_{\text{cross-section}} \times \underbrace{\varepsilon(E_\nu)}_{\text{efficiency}} \times \underbrace{P(\nu_\mu \to \nu_e; E_\nu; \theta_{13}, \Delta m^2_{13})}_{\text{oscillation}}$$

- Correct normalization using ND280 measurement

$$N^{\exp}_{SK} = R_{Data/MC} \times \left(N^{MC}_{signal} + N^{MC}_{bkg} \right)$$

- Evaluate systematic errors
- Extract oscillation parameters

[In the current analyses we do not use the measured near spectrum and the near/far ratio.]

Analysis flow (2010a)

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- Extract oscillation parameters

[In the current analyses we do not use the measured near spectrum and the near/far ratio.]

Neutrino fluxes prediction (2010a)

Fluxes are calculated starting from specific MC models and tuning on experimental data

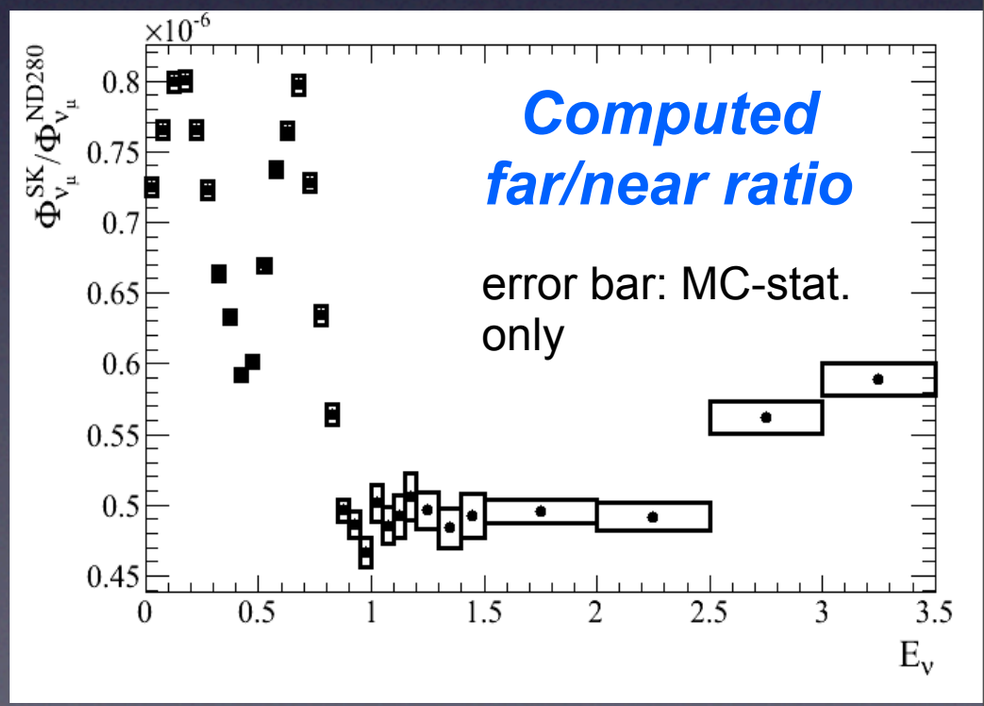
1. Hadron production model	2. Secondary and optics simulation	3. Meson decay
Hadron production by p+C interaction and secondary interaction in target is simulated using FLUKA 2008.	*Propagation of produced hadrons (π, K, etc) including Horn focusing is simulated using GEANT3 framework.*	*Meson decay producing ν's is simulated. Geometrical acceptance is calculated.*

- *Pion production differential cross section is corrected using dedicated CERN NA61 data*
- *Measured protons and beam profile at target*

# of Protons: CT monitors with 2% uncertainty
Beam Shape: SSEM and OTR with 0.4-1.0 mm uncertainty

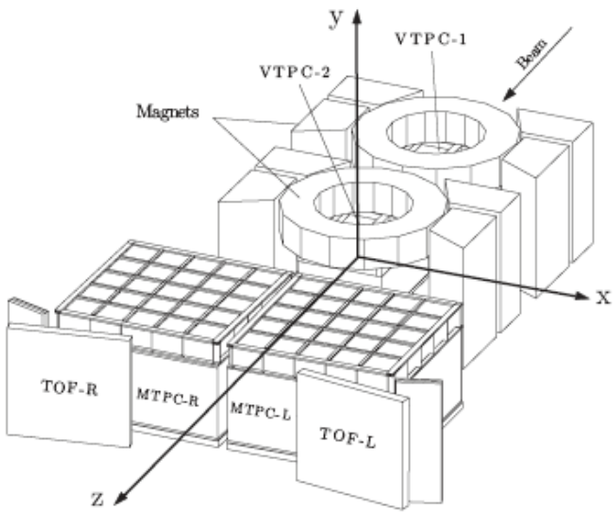
- *Secondary interaction cross sections are corrected using experimental hadronic data.*

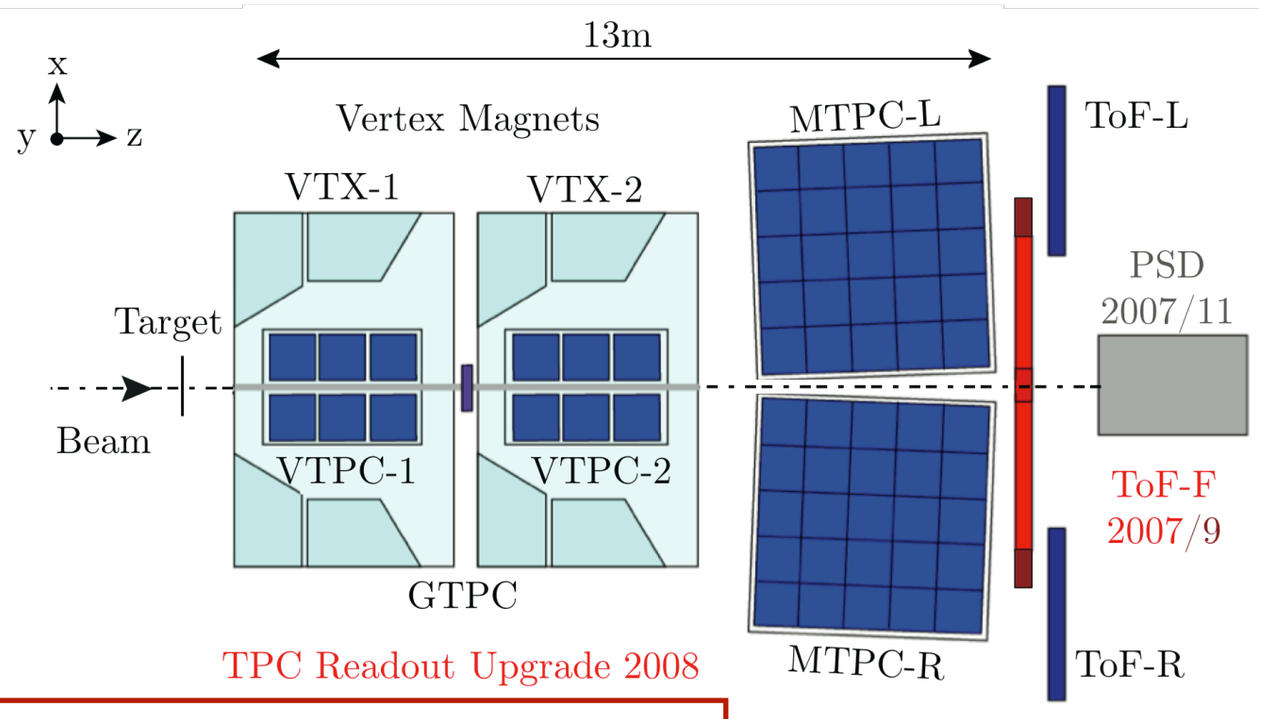
- *ν flux obtained at ND & SK*



CERN NA61 measurements

Evaluation of Particle Yields in 30 GeV p+C Inelastic Interactions and in the T2K replica target





Large acceptance spectrometer:

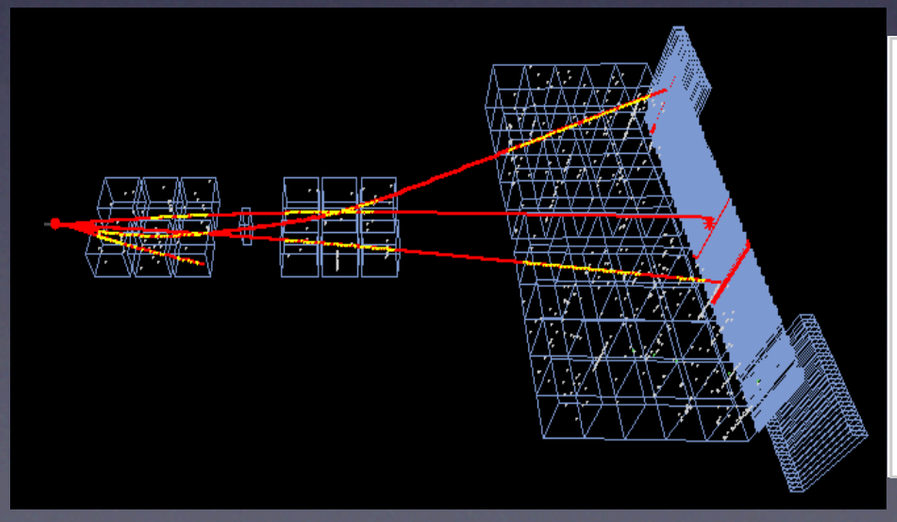
5 TPCs
2 dipole magnets
$\sigma(p)/p^2 \approx 10^{-4}$ (GeV/c)$^{-1}$
$\sigma(dE/dx)/\langle dE/dx\rangle \approx 0.04$

3 ToFs
σ(ToF-F) ≈ 120 ps
σ(ToF-L/R) ≈ 60 ps

Full Coverage of T2K phase space

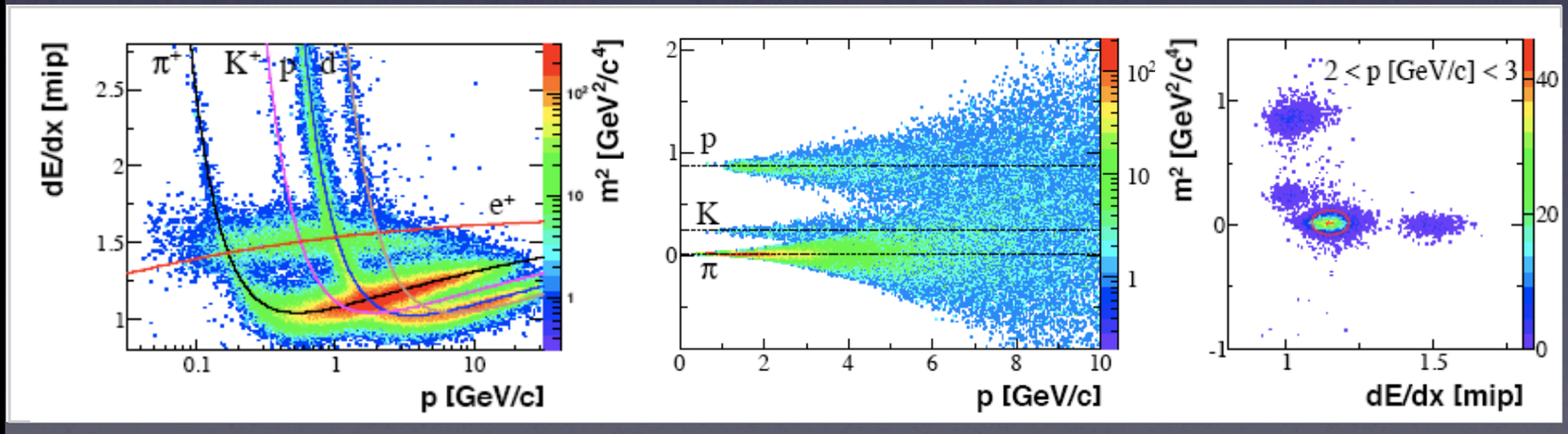
thin target: 2.5x2.5x2 cm^3 int. length ~ 0.04 ~600k triggers in 2007

p+C @ 31 GeV/c



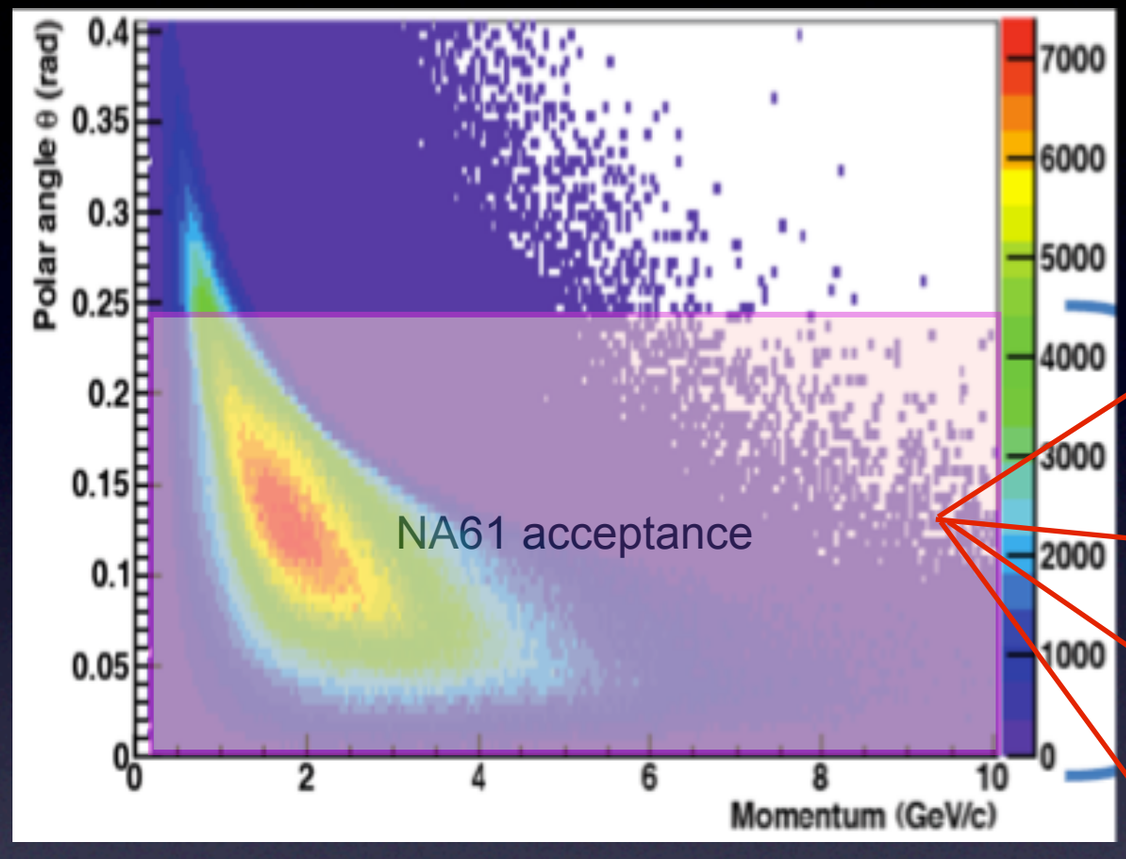
Particle ID methods used:

1) dE/dx (p < 1 GeV/c, p > 4 GeV/c)
2) Combined dE/dx + ToF (1 < p [GeV/c] < 4)
3) Negatively charged hadron h- analysis (π- only)



Inclusion of NA61 preliminary measurements

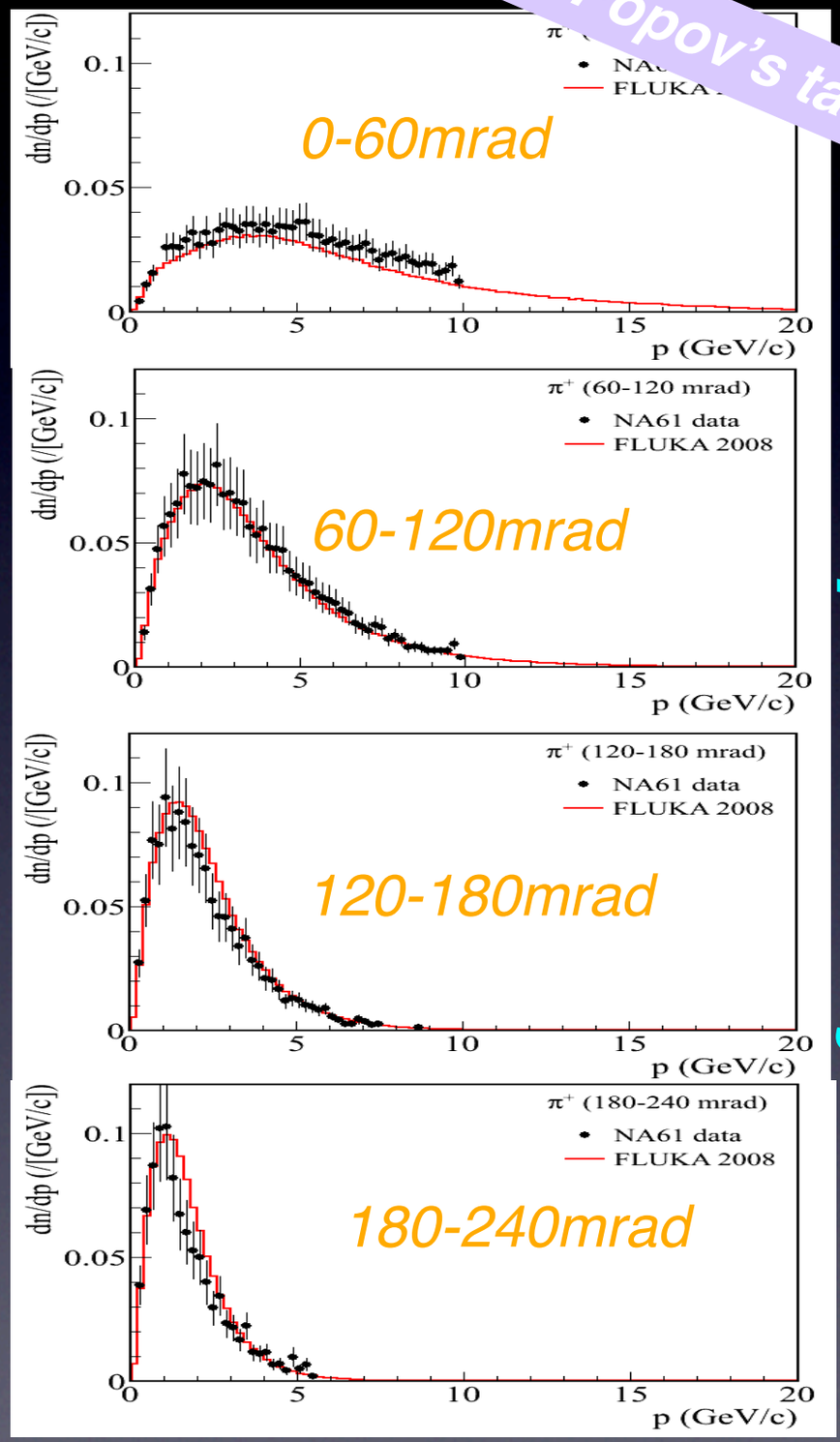
Pion phase space weighted by probability of neutrino interacting at SK



- Analyzed data was taken in 2007
  - p (30GeV) + C (thin target 2cm)
- $\pi^{\pm}$ production model in T2K is tuned to NA61 preliminary results which was released in Dec. 2009.
- Conservative systematic uncertainties
  - ±10% : Inelastic p + C cross section
  - ±20% uncorrelated systematic uncertainty for pion multiplicity
  - External kaon data

NA61 2007 data: π^+

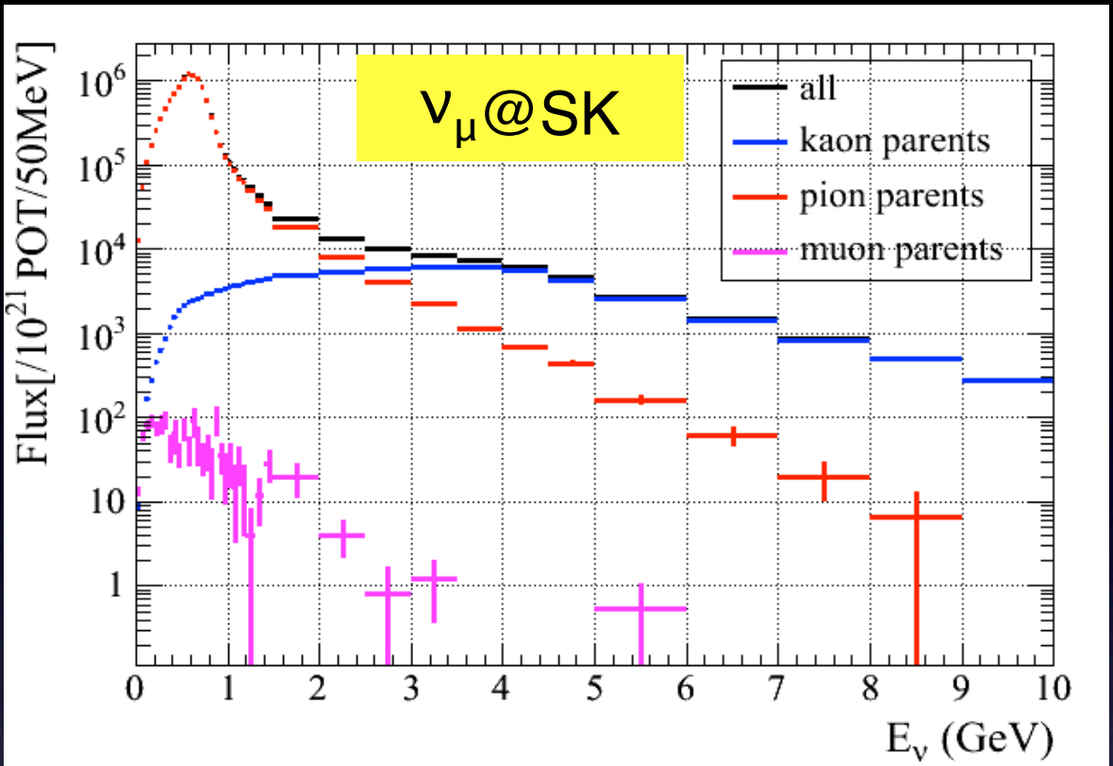
See B. Popov's talk

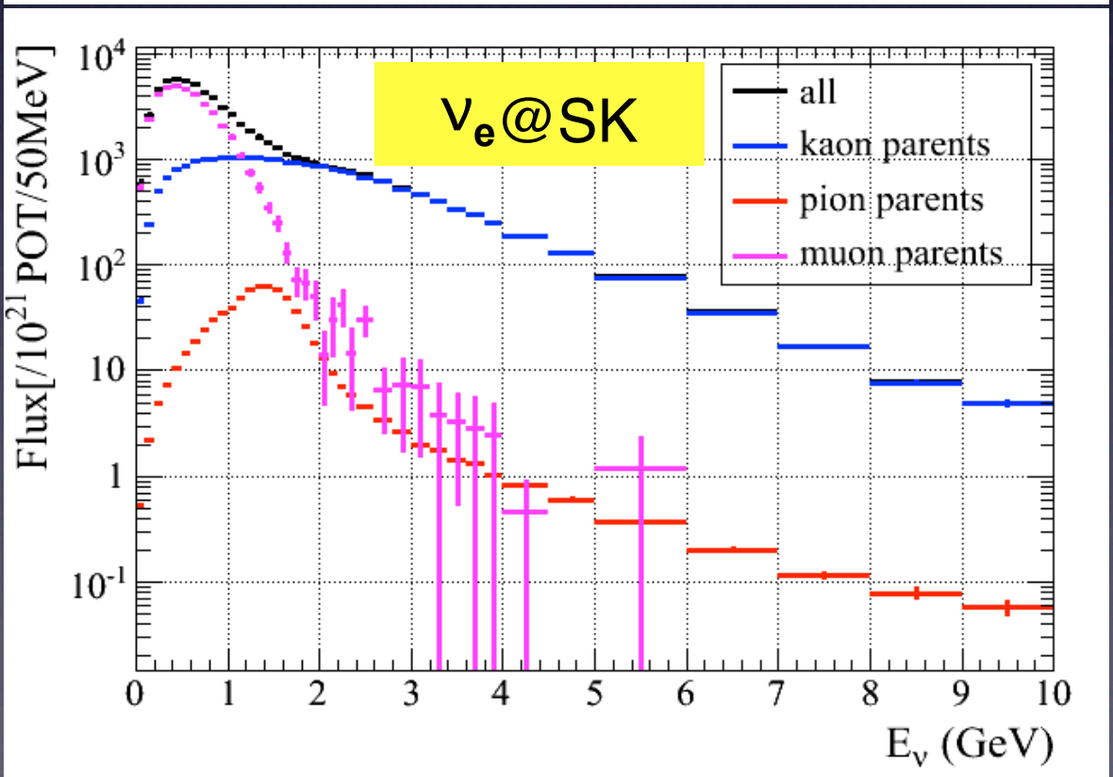


NA61 preliminary

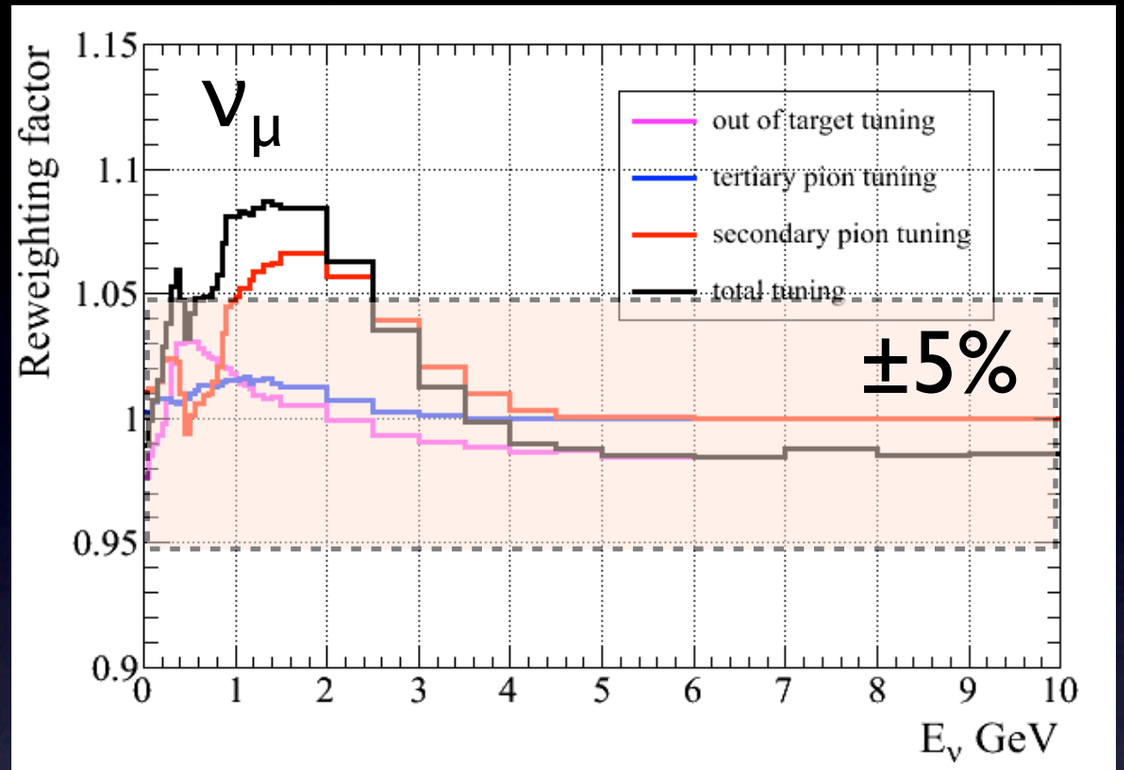
Tuned SK neutrino fluxes

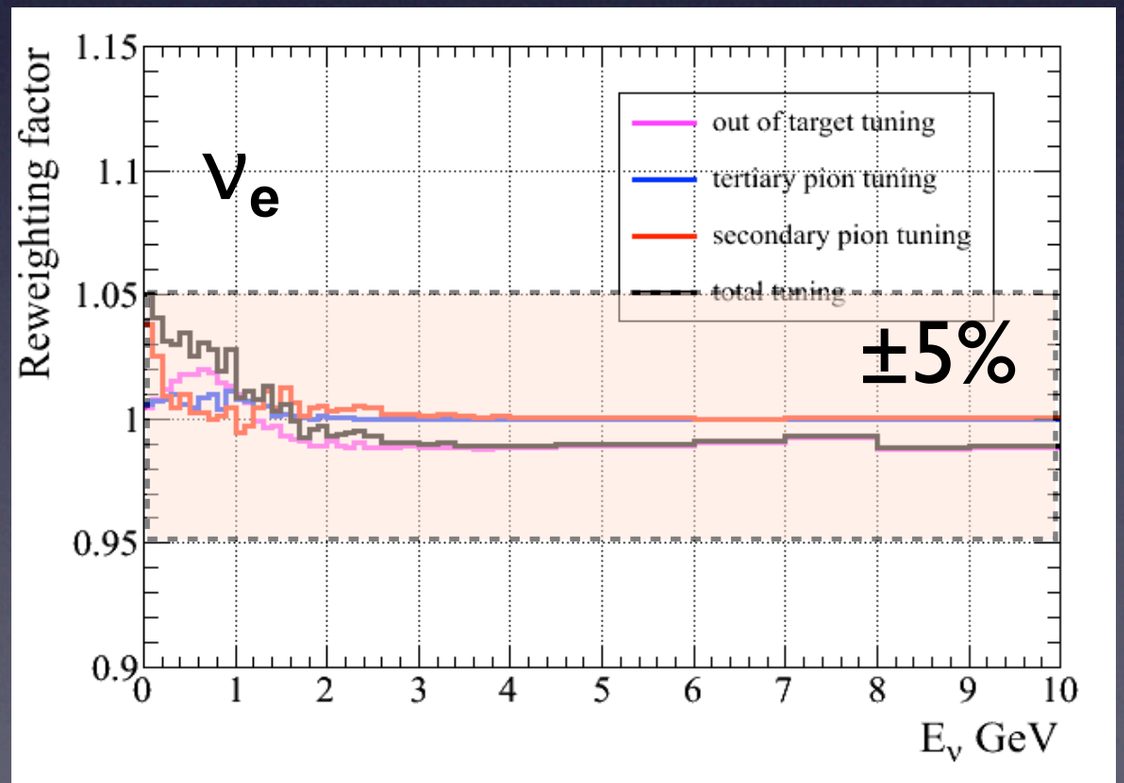
Tuned neutrino fluxes at SK





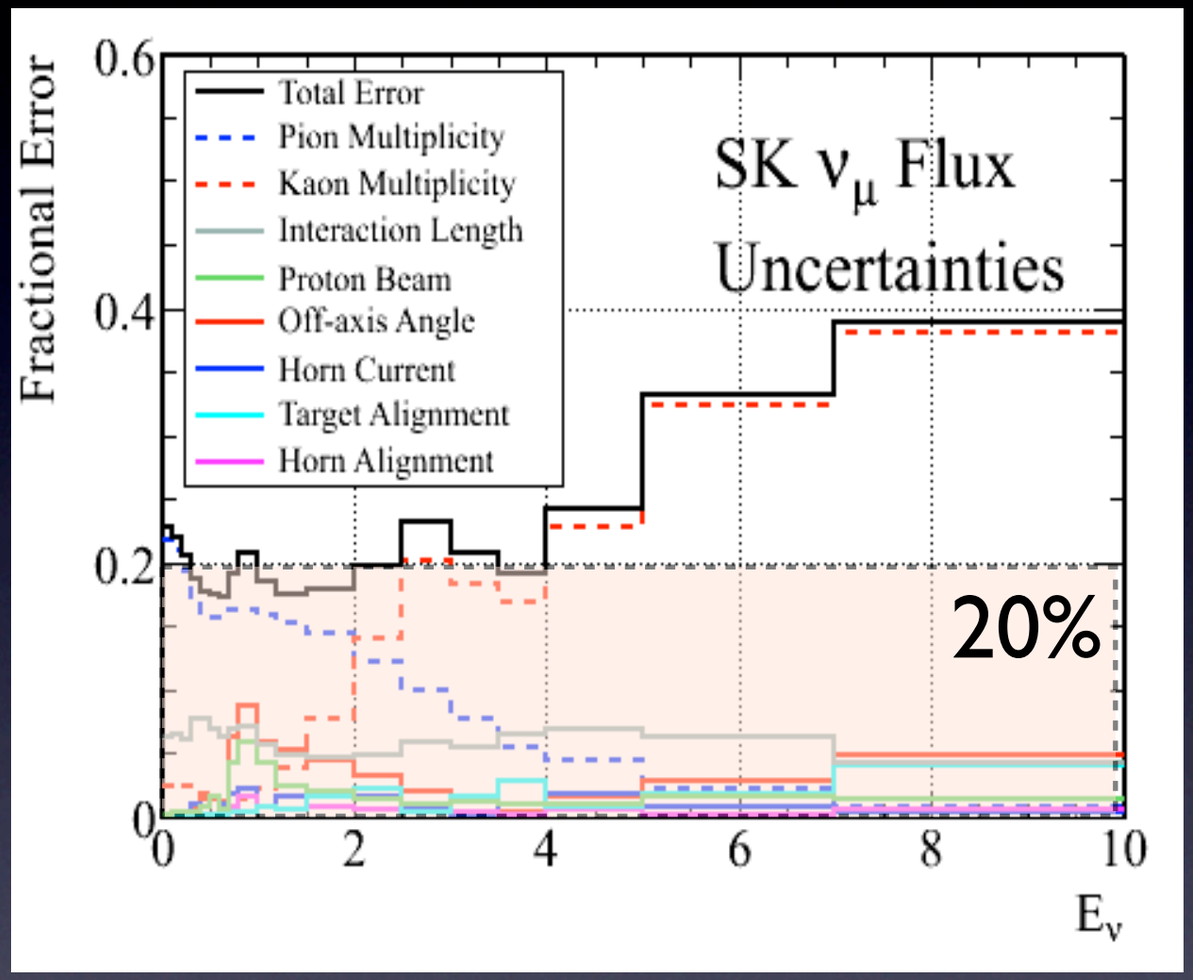
Applied weight factors vs neutrino energy

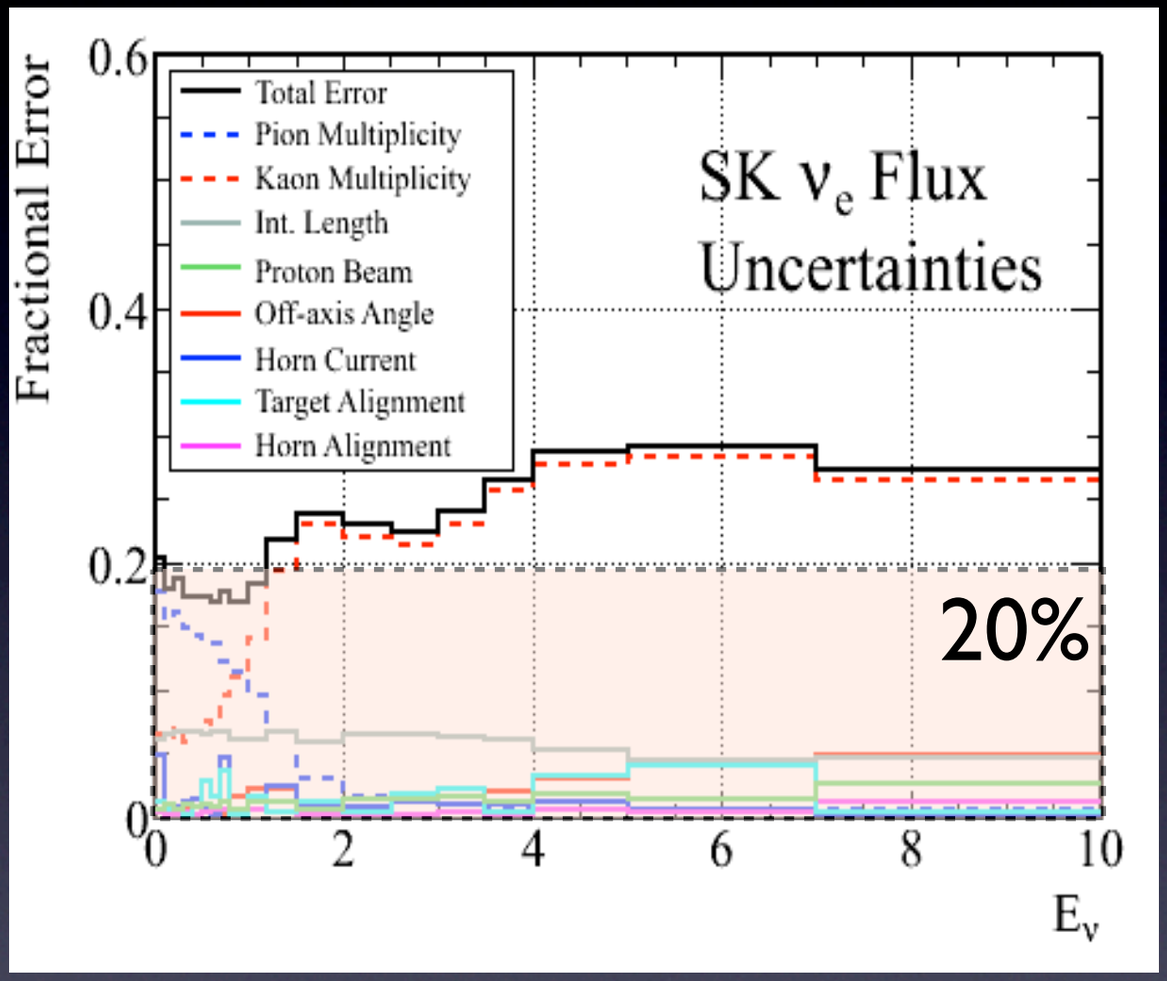




Neutrino fluxes systematic uncertainties

Fractional systematic flux errors at SK vs neutrino energy





Errors (~20-40%) presently dominated by hadron-production uncertainties (π at low Eν and K at high Eν). Anticipate improvements with published NA61 data.

Analysis flow (2010a)

Neutrino flux prediction
- Proton beam data
- Hadron production data

ND280 (near) Detector Measurements
- ν_μ CC inclusive selection
- Measure: $R_{Data/MC} = \frac{N^{Data}_{\mu CC, ND280}}{N^{MC}_{\mu CC, ND280}}$

Neutrino cross-sections
- External data
- Interaction models and parameters variation

SK (far) Detector Measurements
- Data reduction and classification
- Compute signal and background expectations (counting)

$$N^{MC}_{signal} = \int dE_\nu \; \underbrace{\Phi_\mu(E_\nu)}_{\text{flux}} \times \underbrace{\sigma(E_\nu)}_{\text{cross-section}} \times \underbrace{\varepsilon(E_\nu)}_{\text{efficiency}} \times \underbrace{P(\nu_\mu \to \nu_e; E_\nu; \theta_{13}, \Delta m^2_{13})}_{\text{oscillation}}$$

- Correct normalization using ND280 measurement

$$N^{\exp}_{SK} = R_{Data/MC} \times \left(N^{MC}_{signal} + N^{MC}_{bkg} \right)$$

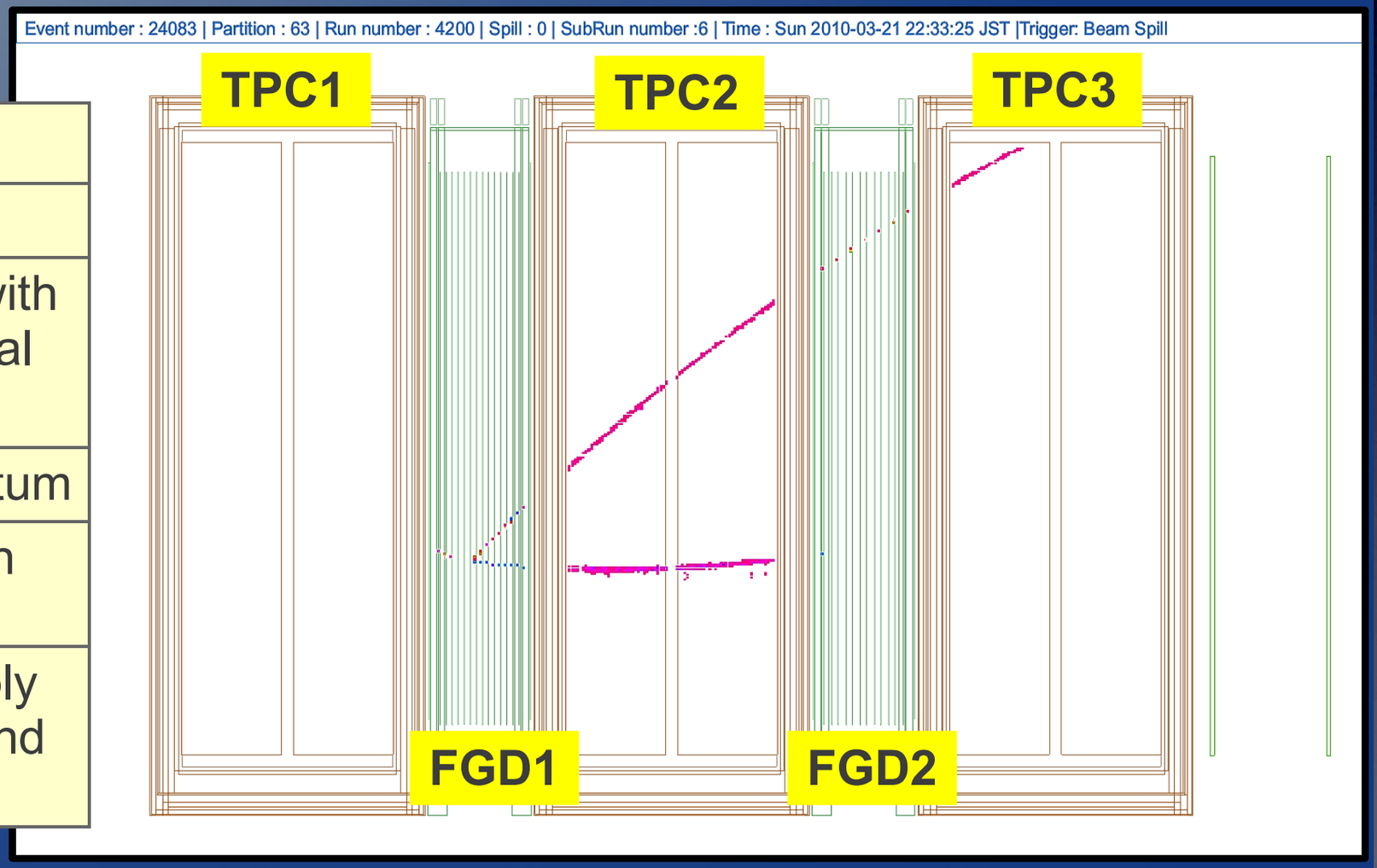
- Evaluate systematic errors
- Extract oscillation parameters

[In the current analyses we do not use the measured near spectrum and the near/far ratio.]

ν_μ CC selection in ND280

- Analysis using low level reconstructed objects
  - Use FGD hits and and tracks reconstructed in single TPC
  - High Purity: 90% ν_μ CC and 50% CCQE

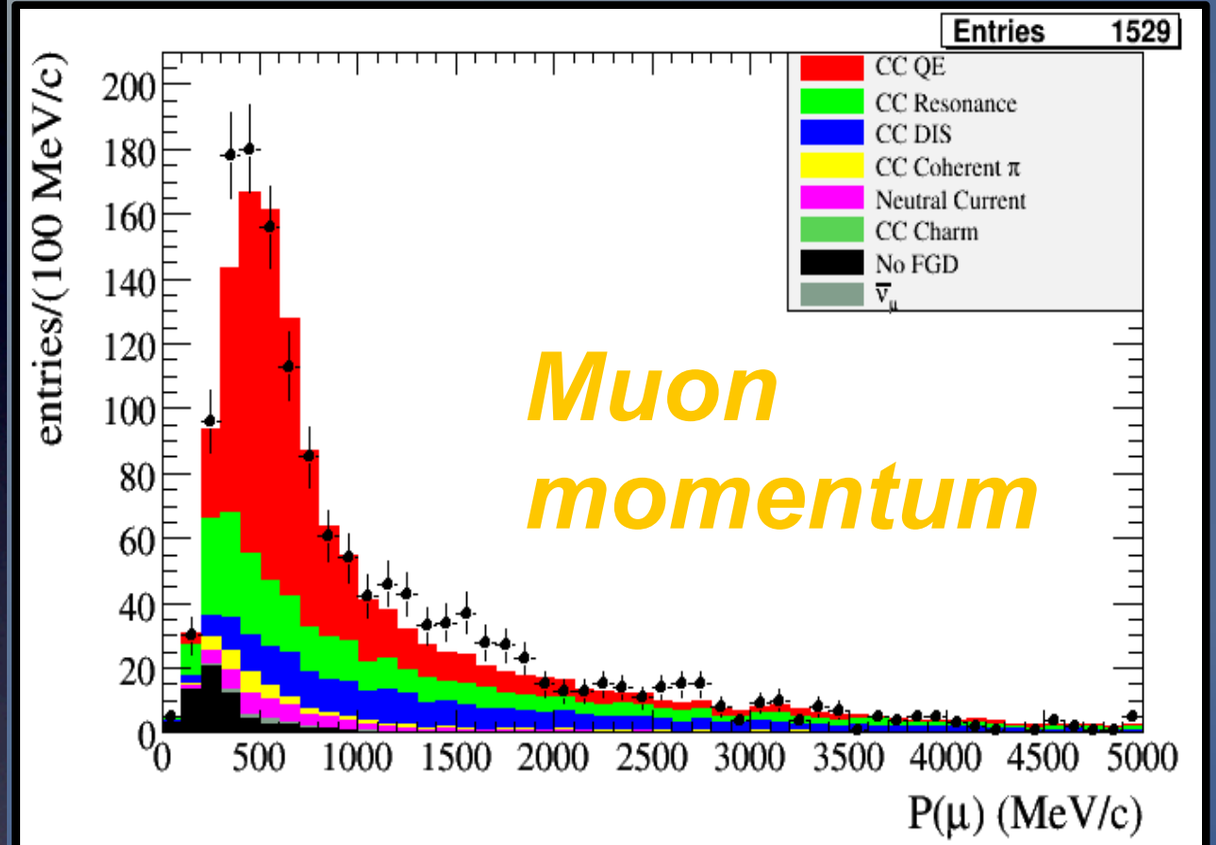
Event Selection
No tracks in first TPC
At least 1 track in second TPC with starting point in first FGD fiducial volume, p>50 MeV/c
Select track with highest momentum
TPC dE/dx cuts to select muon candidates, exclude electrons
If no tracks in second TPC, apply selection to third TPC and second FGD

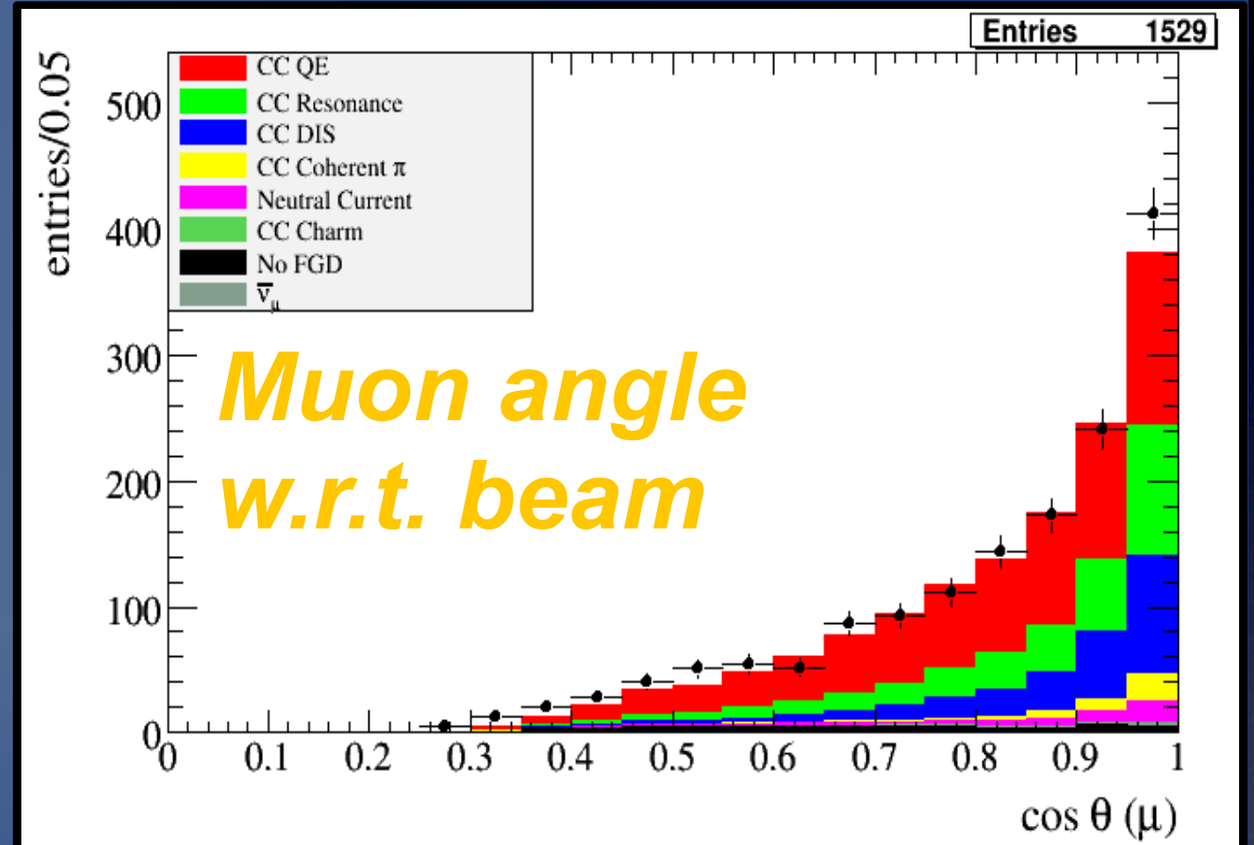


Normalization correction from ND280 (near) Detector

Observed kinematical quantities in ν_μ CC selection

2010a used : 2.88 x 10^{19} POT





$$R_{data/MC} = 1.061 \pm 0.028(stat.)^{+0.044}_{-0.038}(det.\,sys.) \pm 0.039(phys.\,model)$$

Includes:
TPC-FGD matching, dE/dx pull distributions, TPC tracking efficiency

Analysis flow (2010a)

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Neutrino cross-sections
- Tuning to external data
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SK (far) Detector Measurements
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- Correct normalization using ND280 measurement

$$N^{\exp}_{SK} = R_{Data/MC} \times \left(N^{MC}_{signal} + N^{MC}_{bkg} \right)$$

- Evaluate systematic errors
- Extract oscillation parameters

[In the current analyses we do not use the measured near spectrum and the near/far ratio.]

Interaction model systematic errors

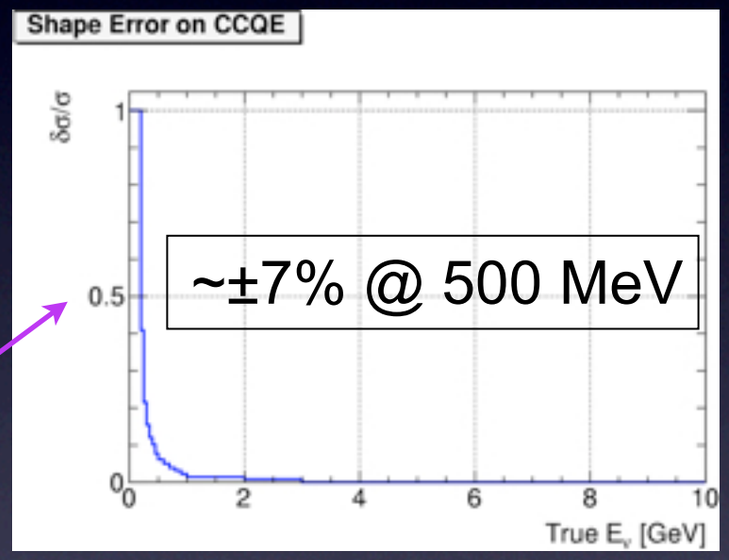
Estimated systematic error on cross-sections from uncertainties in neutrino interaction models at low energy for the electron appearance analysis

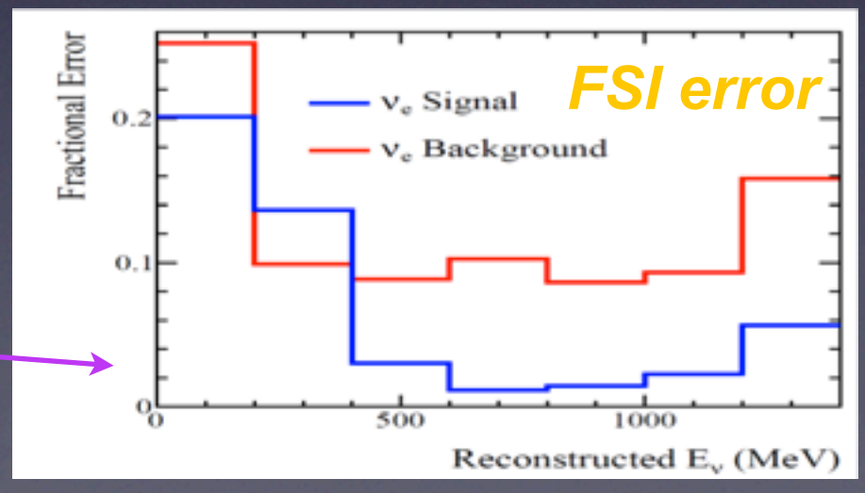
Method: Comparisons of NEUT/GENIE predictions to external data and the effect of systematic parameter variations on SK and ND280 event rate predictions and detector efficiencies. Estimation of Nuclear Final State Interaction (FSI) uncertainties.

For electron appearance analysis:

Category	Error [%]
CC QE	Depends on true neutrino energy
CC 1π	30 (E_ν<2 GeV) 20 (E_ν>2 GeV)
CC coherent π	100
CC other	30 (E_ν<2 GeV) 25 (E_ν>2 GeV)
NC $1\pi^0$	30 (E_ν<1 GeV) 20 (E_ν>1 GeV)
NC coherent	30
NC other	30
FSI error	Depends on reconst. neutrino energy

* uncertainty of $\sigma(\nu_e) / \sigma(\nu_\mu) = \pm 6\%$





Analysis flow (2010a)

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- Correct normalization using ND280 measurement

$$N^{\exp}_{SK} = R_{Data/MC} \times \left(N^{MC}_{signal} + N^{MC}_{bkg} \right)$$

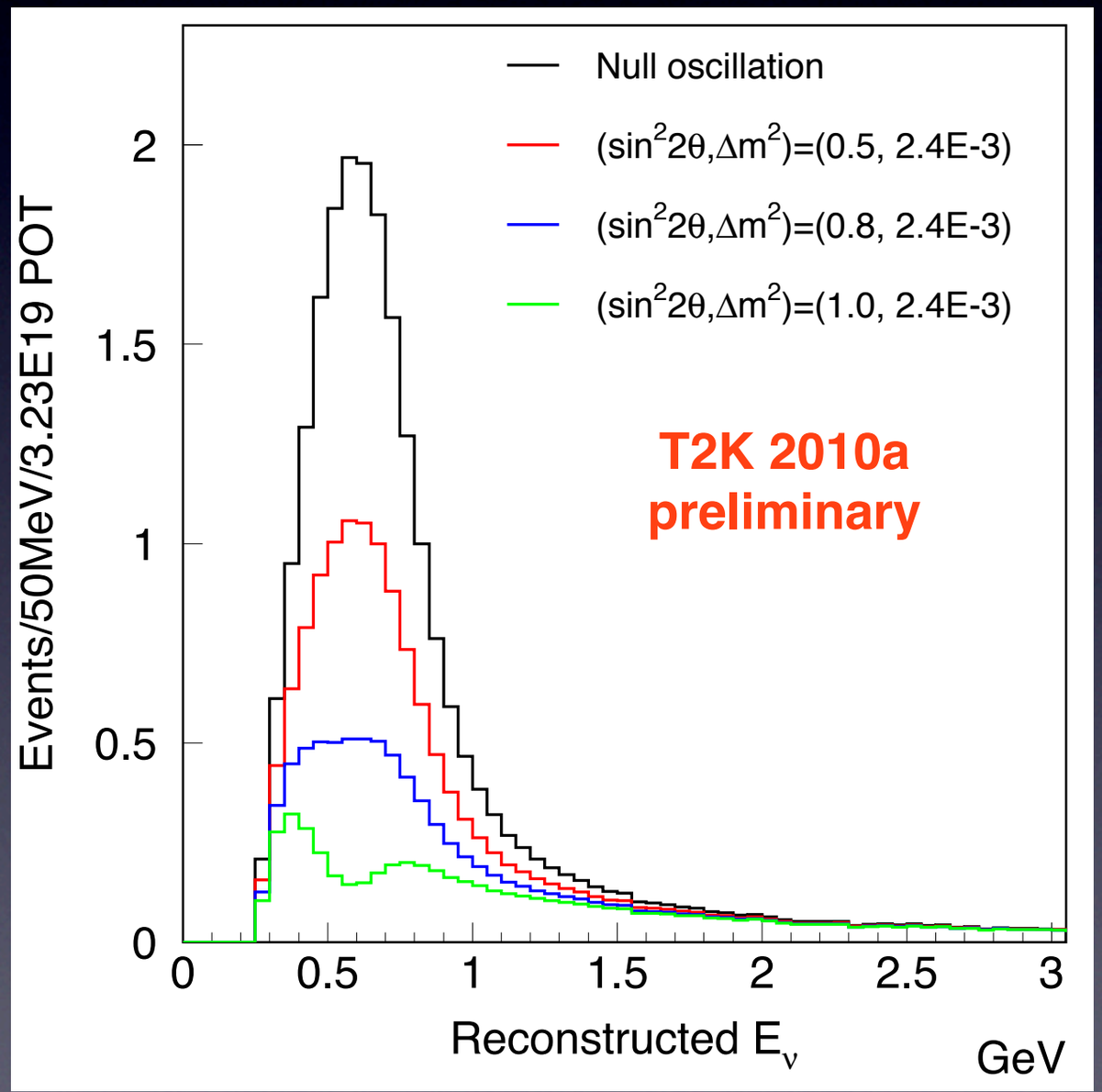
- Evaluate systematic errors
- Extract oscillation parameters

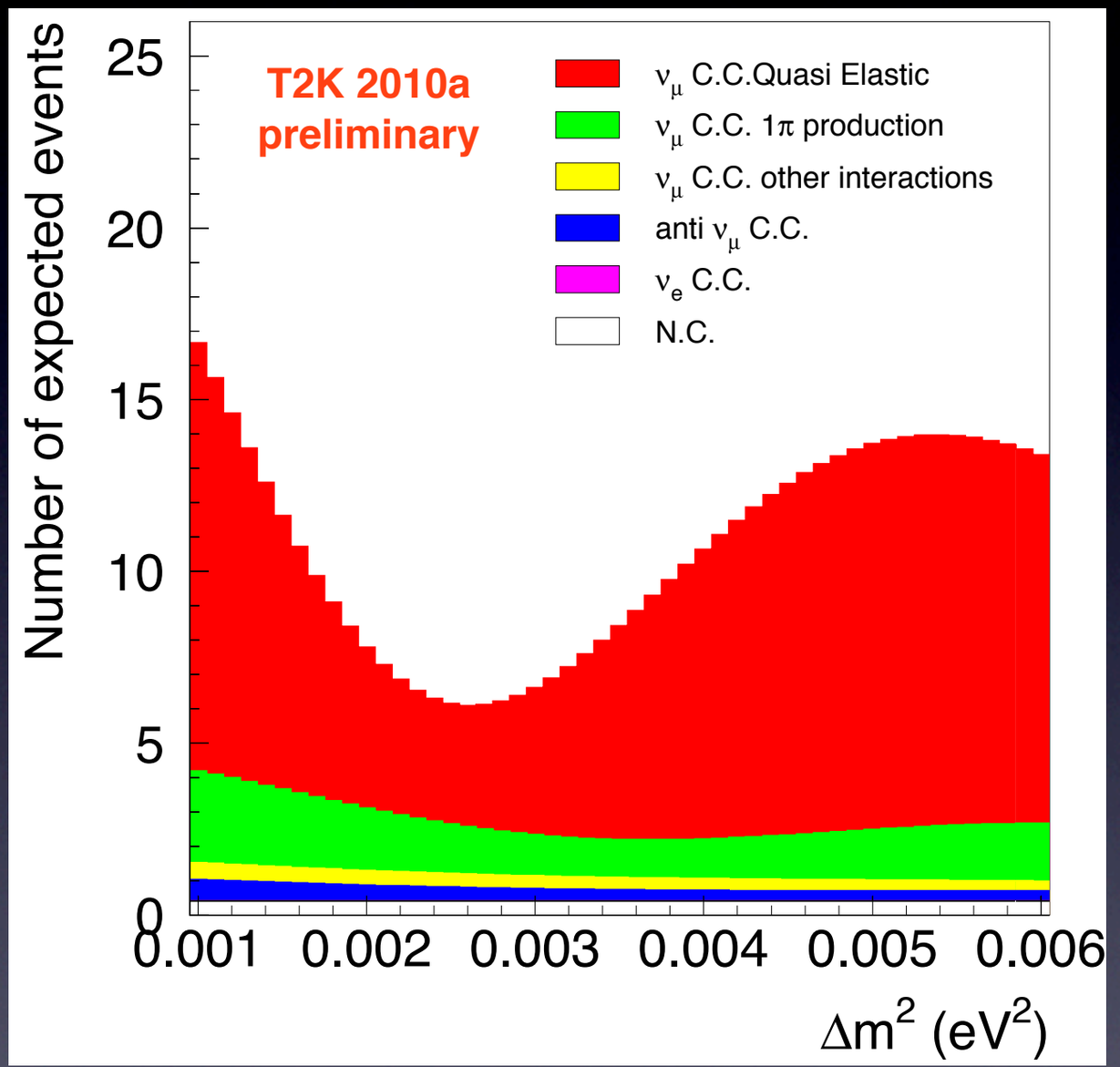
[In the current analyses we do not use the measured near spectrum and the near/far ratio.]

ν_μ disappearance analysis

Aimed at precise measurement of 23-sector

Expected spectrum for different oscillation parameter hypothesis





T2K off-axis configuration ➠ strong dependence on oscillation parameters in region of interest

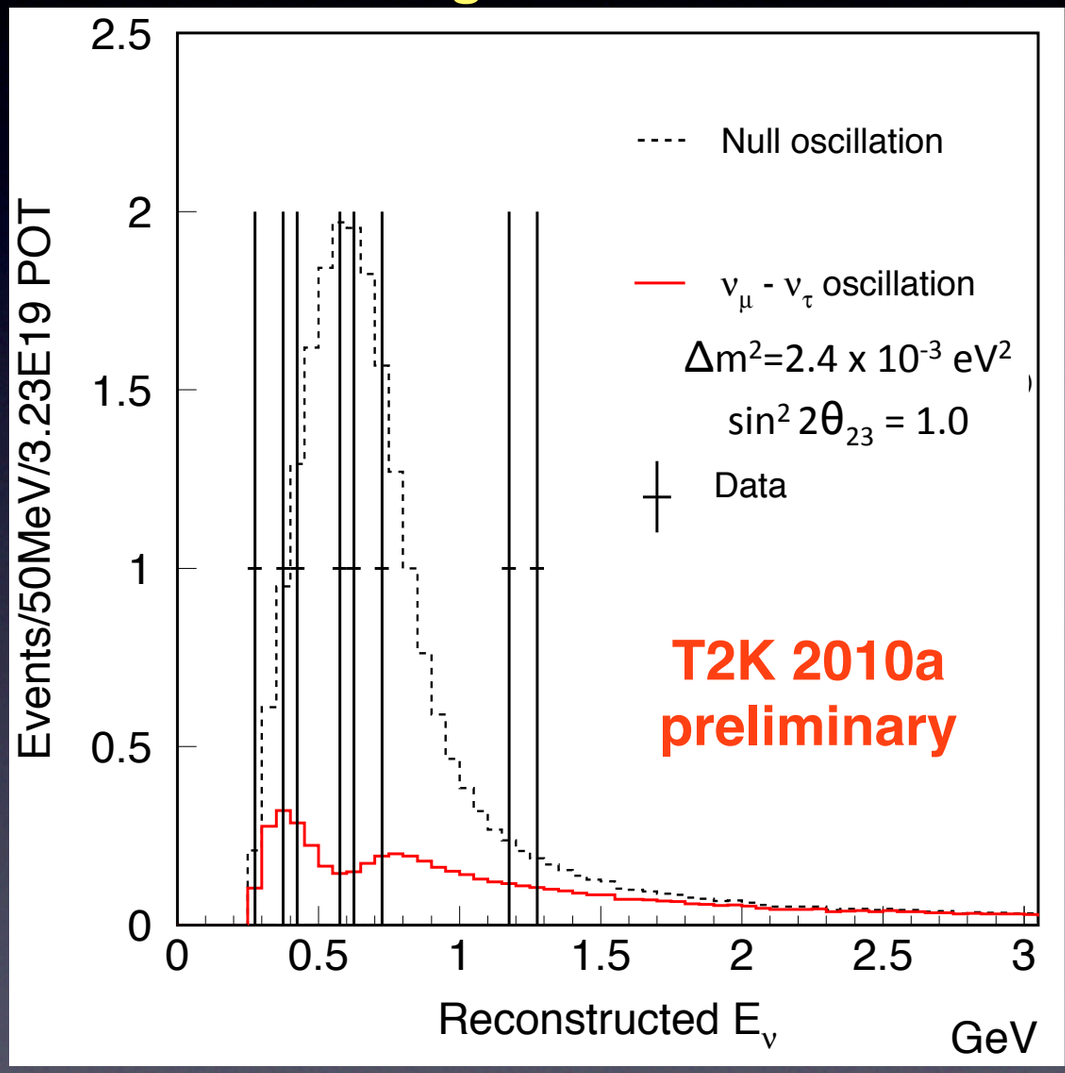
ν_μ disappearance analysis

Event selection for muon disappearance measurement

T2K-SK events	Data	MC		Acc.BG (12μs window)
		No oscillation	W/ oscillation	
Fully-Contained	**33**	54.5	24.6	0.0094
Fiducial Volume, E_{vis} > 30MeV	**23**	36.8	16.7	0.0011
Single-ring μ-like P_μ>200MeV/c	**8**	24.5±3.9	7.1±1.3	-
+ number decay-e <=1 & Erec<10 GeV	**8**	22.8±3.2	6.3±1.0	-

$\Delta m^2=2.4 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1.0$

Reconstructed energy assuming QE kinematics



- Consistent with oscillation parameters measured by MINOS / SK / K2K
- Parameter fitting underway – T2K plans to release result in the near future

ν_e appearance analysis

Event selection for electron appearance search

T2K-SK events	Data	MC		Acc. BG (12μs window)
		No oscillation	With oscillation and $\theta_{13}=0$	
Fully-Contained	**33**	54.5	24.6	0.0094
Fiducial Volume, E_{vis} > 30MeV	**23**	36.8	16.7	0.0011
Single-ring e-like P_e>100MeV/c	**2**	1.5±0.7	1.3±0.6	-

Assumed oscillation parameters:
$\Delta m^2=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$
and $\theta_{13} = 0$

Apply additional background reduction cuts:

- # of decay electron ($\mu \rightarrow e+\nu_e$) =0
- Reconstructed invariant mass assuming 2γ rings exist <105MeV
- Reconstructed ν energy < 1250 MeV

Cut criteria were frozen before data collection to avoid bias

After all cuts: 65.9% signal efficiency

Sequential selection cuts

Sequential cuts - surviving number of events

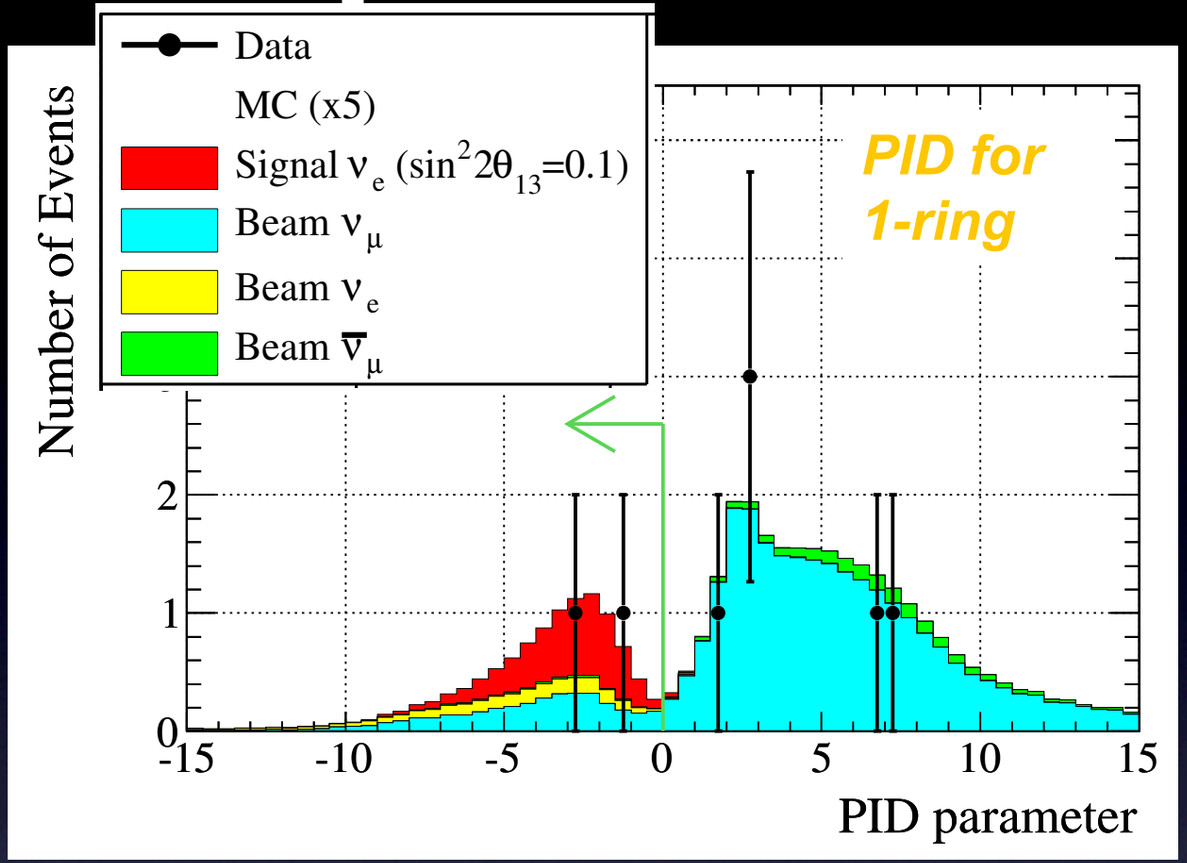
Cut	Events
Fully contained, fiducial cut (FCFV)	23
Single ring e-like, E>100 MeV	2
# of decay electron =0	1
Reconstructed invariant mass assuming 2γ rings exist <105MeV	1
Reconstructed ν energy < 1250 MeV	1
Events in 2010a sample	**1**

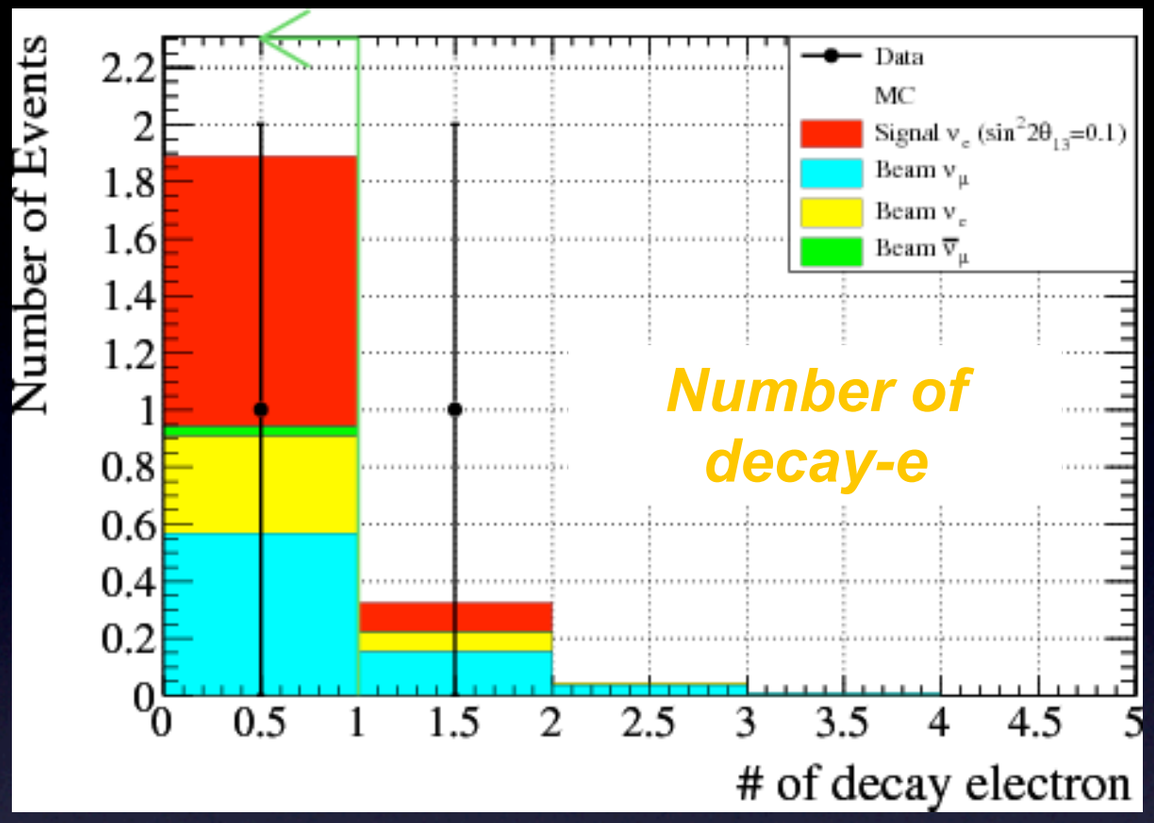
T2K preliminary (2010a)

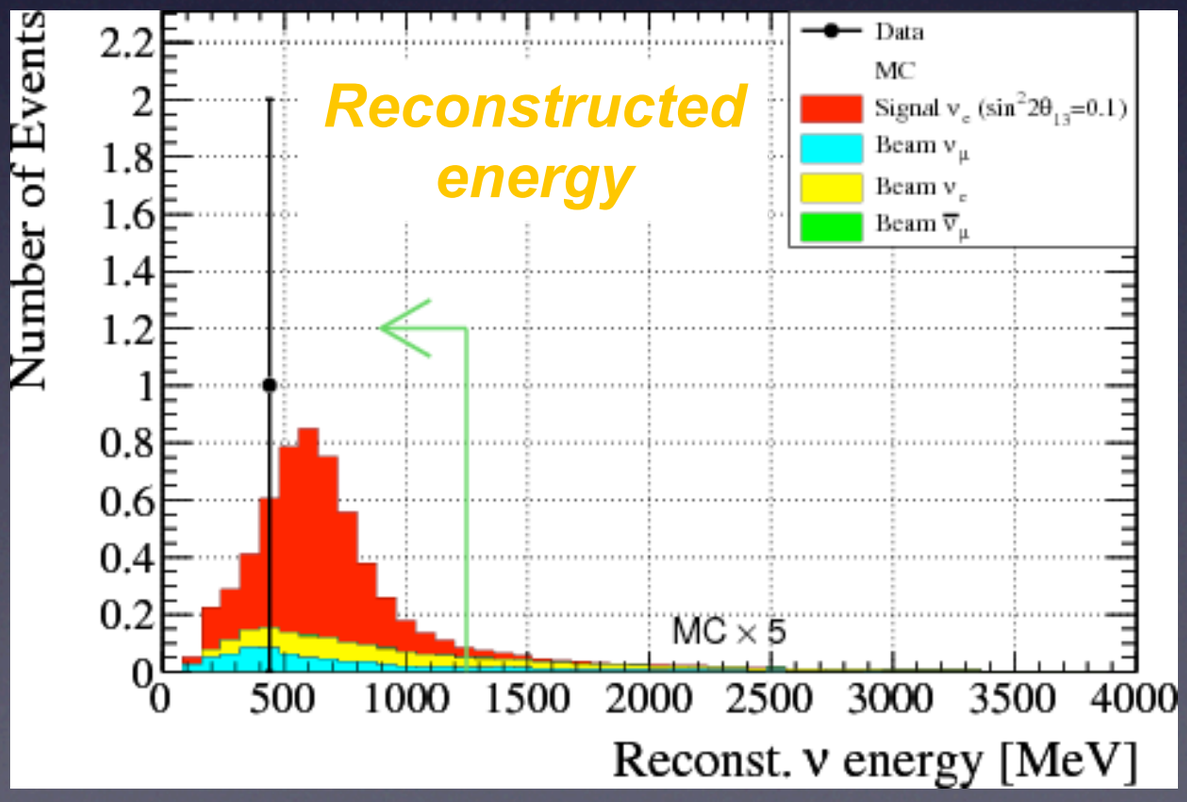
1 candidate exists!

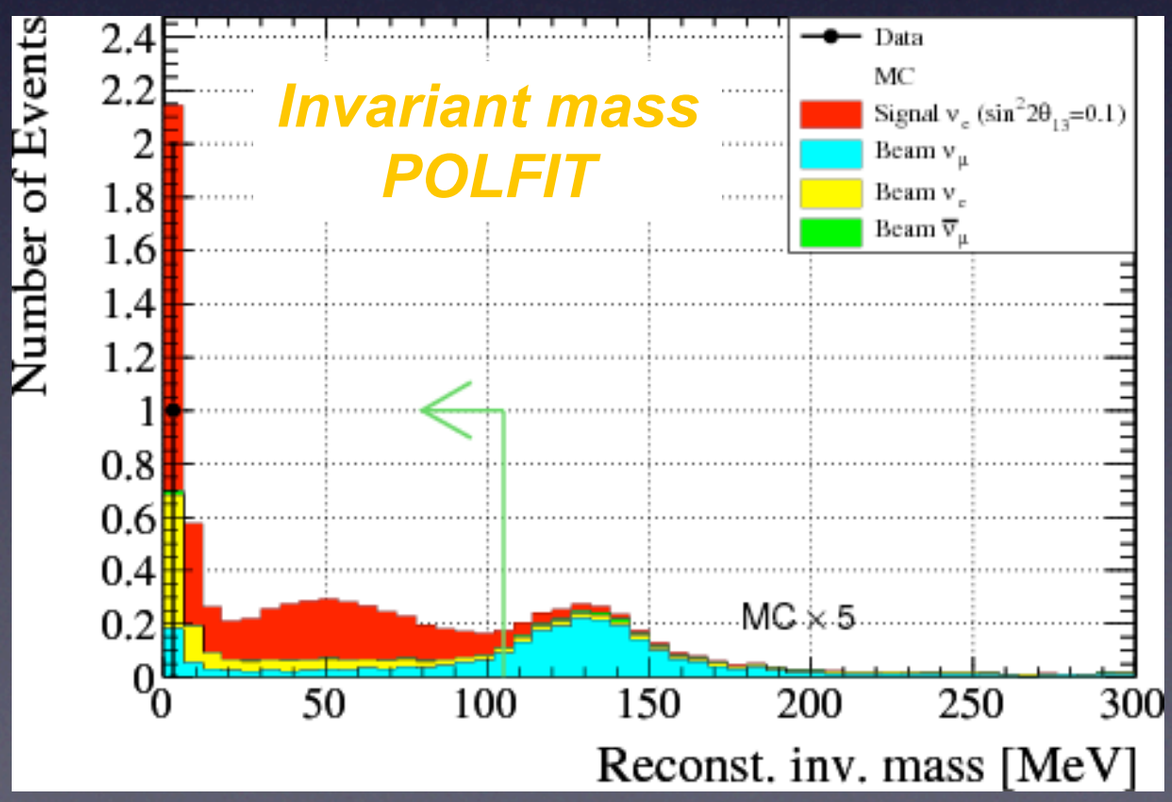
$N_{\mathrm{SK}}^{\mathrm{obs}} = 1$

Sequential selection cuts



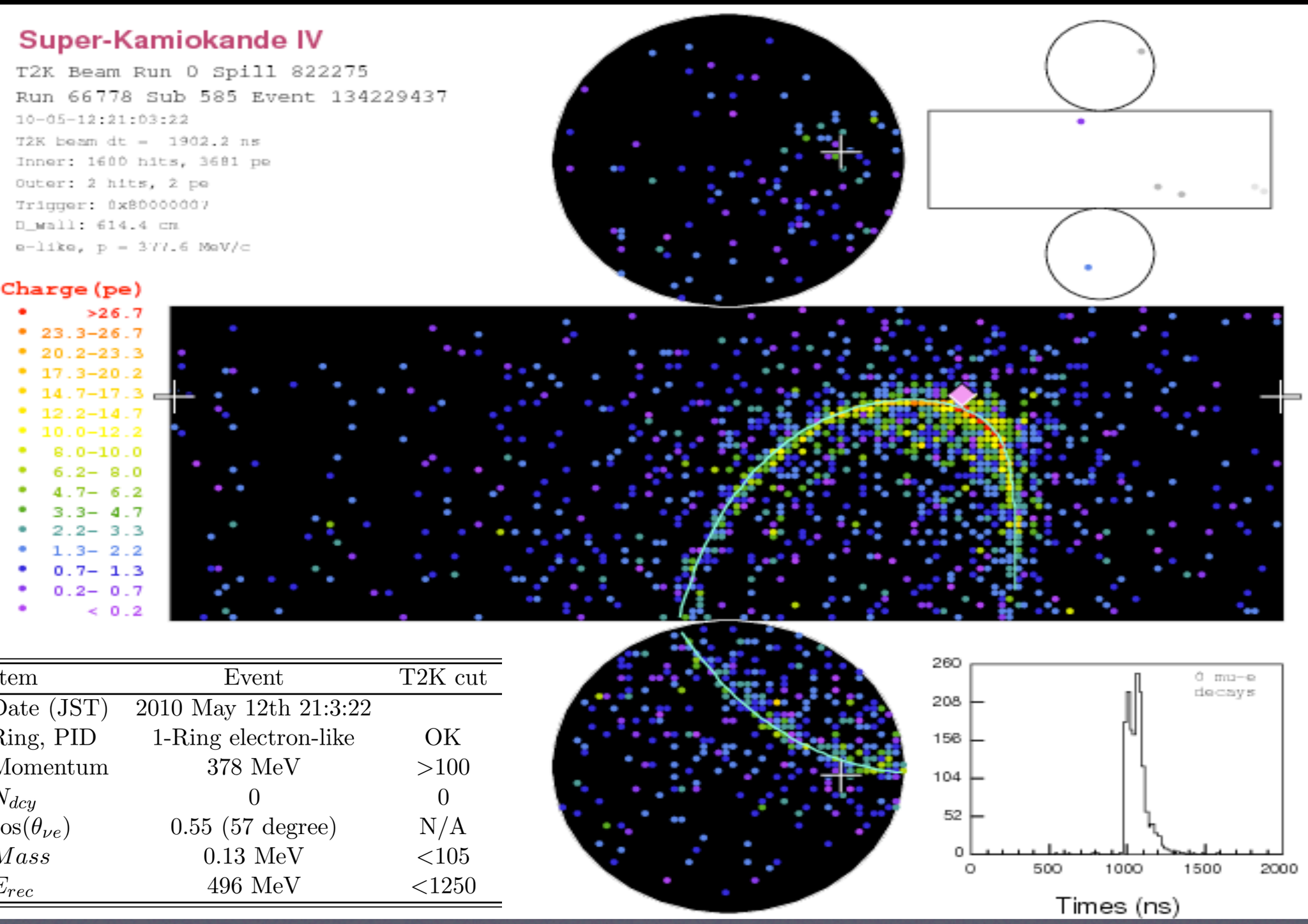






T2K ν_e CC signal candidate (2010a)

Signal candidate event passing all cuts



Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250

SK selection systematic error

Estimated systematic error from SK event selection

***Methods**: atmospheric neutrino events observed in SK and "hybrid π^0" used as control samples to estimate uncertainties*

Parameter	Error source	Signal	Background
f^{SKnorm}	Normalization	1.4 %	1.4 %
f^{Energy}	Energy scale	0.3	0.5
$f^{N_{ring}}$	Ring counting	3.9	8.4
$f^{PID\mu}$	Muon PID		1.0
f^{PIDe}	Electron PID	3.8	8.1
f^{POLfit}	POLfit mass cut	5.1	8.7
$f^{N_{dcy}}$	Decay electron finding	0.1	0.3
$f^{\pi^0 eff}$	π^0 rejection		5.9
Total uncertainty:		7.6%	15.8%

Combined systematic errors

Estimated combined total systematic error from each source group on electron events in SK, constrained by ND280 normalization

Error source	N_{SK}^{sig}	N_{SK}^{bkg}	N_{SK}^{s+b}	N_{ND}	N_{SK}^{bkg}/N_{ND}	N_{SK}^{s+b}/N_{ND}
SK Efficiency	$\pm$ 7.6	$\pm$ 15.8	$\pm$ 9.5		$\pm$ 15.8	$\pm$ 9.5
Cross section	$\pm$ 9.7	$\pm$ 13.9	$\pm$ 9.9	$\pm$ 8.4	$\pm$ 14.3	$\pm$ 10.6
Beam Flux	$\pm$ 22.0	$\pm$ 18.1	$\pm$ 20.5	$\pm$ 19.8	$\pm$ 8.9	$\pm$ 11.9
ND Efficiency				$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$
Overall Norm.					$\pm$ 2.7	$\pm$ 2.7
Total	$\pm$ 25.2%	$\pm$ 27.8%	$\pm$ 24.7%	$^{+22.2}_{-22.1}$%	$^{+23.9}_{-23.8}$ %	$^{+19.5}_{-19.4}$%

★ ~24% total systematic error for background only hypothesis

★ ~20% total systematic error for signal + background hypothesis

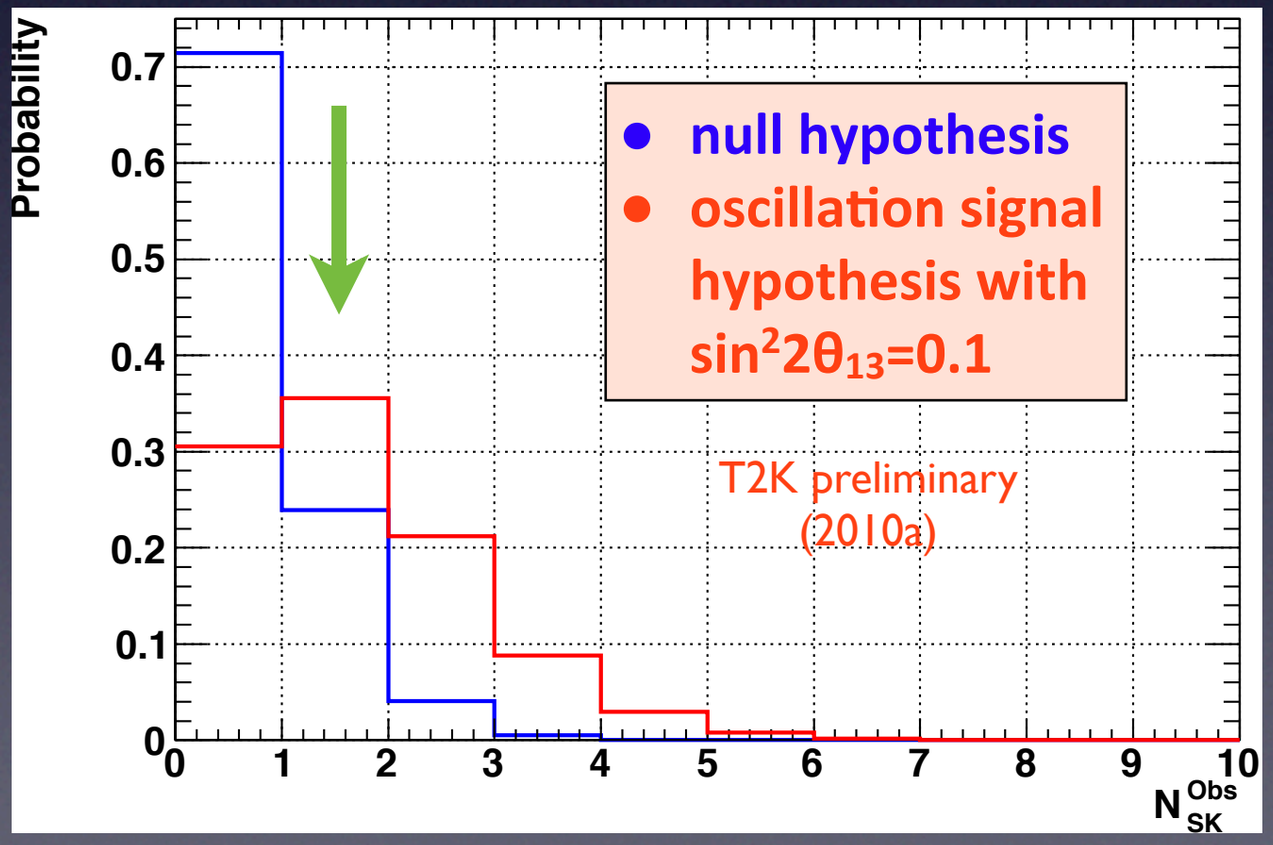
$\Delta m^2_{23}=2.4\cdot10^{-3}eV^2$
$\sin^2 2\theta_{23}=1.0$, $\sin^2 2\theta_{13}=0.1$
$\delta_{CP} = 0$

Expected #SK events

Source	Estimated number
Beam ν_μ (CC+NC)	0.13
Beam $\overline{\nu}_\mu$ (CC+NC)	0.01
Beam ν_e (CC)	0.16
Total background	**0.30 ± 0.07 (syst.)**
Total sig.+background	**1.20 ± 0.23 (syst.)**

- #events normalized to p.o.t. and corrected for ND280 ν_μ CC measured normalization
- Assumed oscillation parameters for signal:

$\Delta m^2_{23}=2.4\cdot10^{-3}eV^2$
$\sin^2 2\theta_{23}=1.0$
$\sin^2 2\theta_{13}=0.1$
$\delta_{CP}=0$



T2K preliminary (2010a)

~29% probability to observe >=1 event when expected average = 0.3 event

1 data candidate!

$N_{SK}^{obs} = 1$

T2K appearance upper limit results

Two independent statistical procedures

T2K preliminary (2010a)

Assuming $\Delta m^2_{23}=2.4\cdot10^{-3}eV^2$ and $\sin^2 2\theta_{23}=1.0$, $\delta_{CP}=0$:

(A) Feldman-Cousins

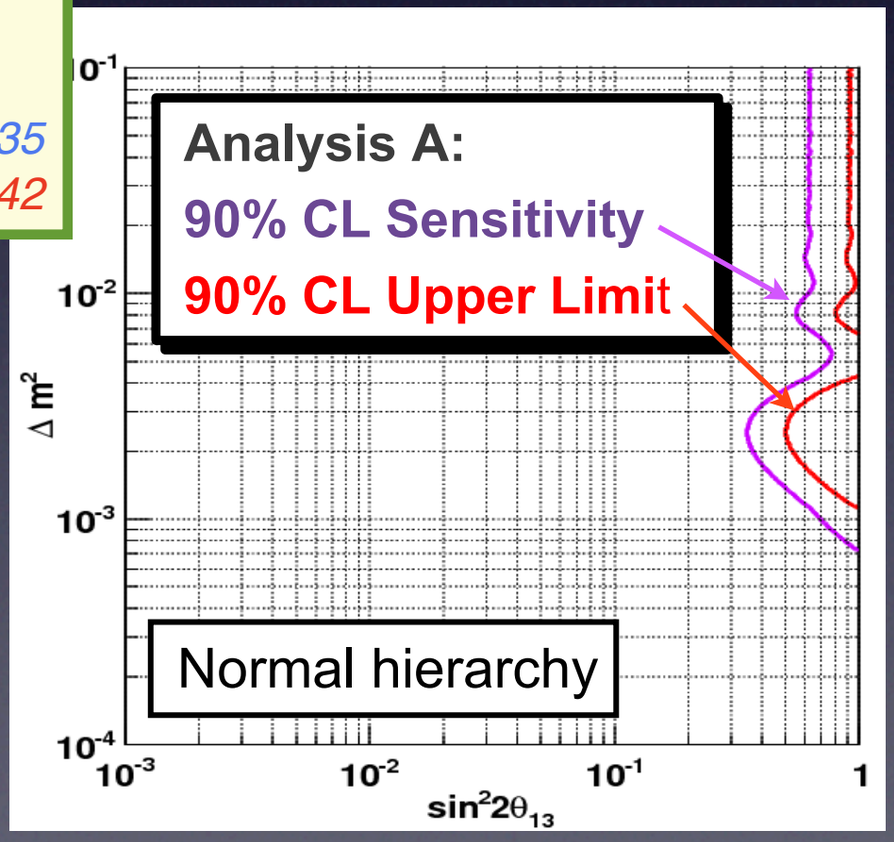
Normal Hierarchy : $\sin^2(2\theta_{13}) < 0.50$ (90%C.L.)
Inverted Hierarchy : $\sin^2(2\theta_{13}) < 0.59$ (90%C.L.)

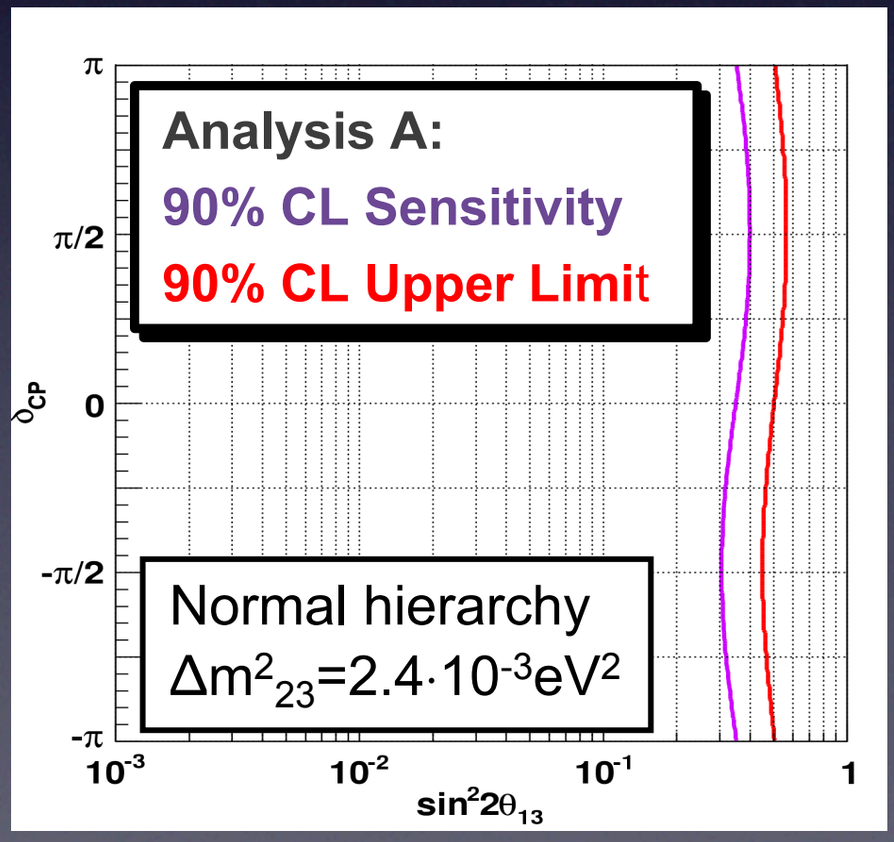
(B) Classical one-sided

Normal Hierarchy : $\sin^2(2\theta_{13}) < 0.44$ (90%C.L.)
Inverted Hierarchy : $\sin^2(2\theta_{13}) < 0.53$ (90%C.L.)

T2K 2010a 90%C.L. sensitivity (Analysis A):
Normal Hierarchy : $\sin^2(2\theta_{13}) < 0.35$
Inverted Hierarchy : $\sin^2(2\theta_{13}) < 0.42$

- More collected data on tape
- Analyses underway

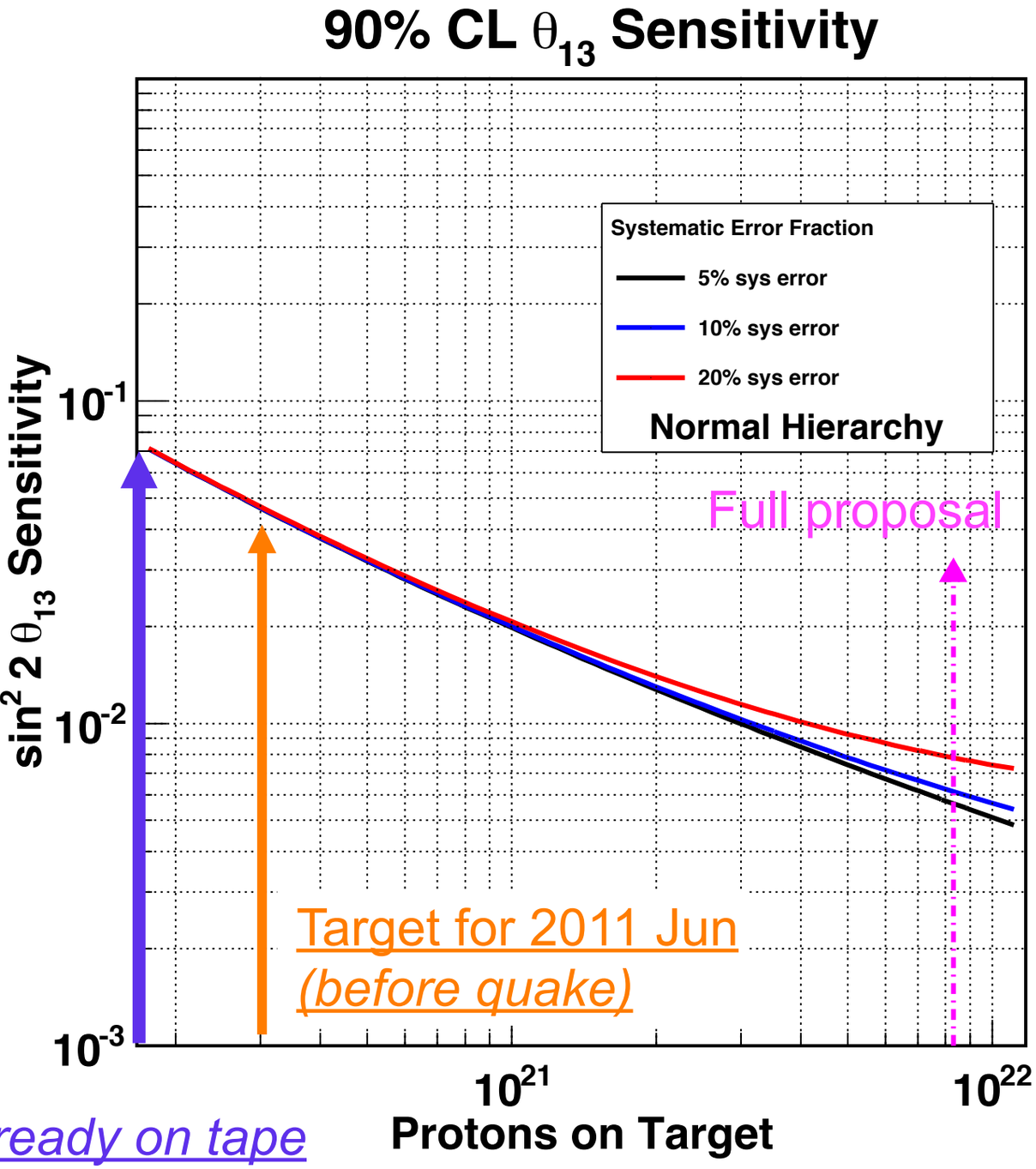




Prospects for updated results

- 1.45x10^{20} p.o.t. on tape = 73kW*1e7 s = 4.5x(2010a)
- Aim at 3x10^{20} p.o.t. = 150kW*1e7 s by July 2011 (quake→??)
- Analysis improvements underway
  - New NA61 results → Systematic error uncertainty from hadron production will be reduced.
  - Spectrum measurement in ND and near/far ratio to reduce model dependence

Signal sensitivity vs p.o.t.



Conclusions

- *T2K searches for $\nu_\mu \rightarrow \nu_e$ & $\nu_\mu \rightarrow \nu_x$ oscillations and aims at determining the atmospheric sector parameters*
- *T2K started physics running from Jan. 2010.*
- *We reported results from the first $\nu_\mu \rightarrow \nu_e$ oscillation analysis based on 3.23×10^{19} p.o.t. (2010 Jan.~ Jun):*
  - *# of observed events surviving all cuts = 1*
  - *# of expected background = 0.30 ± 0.07 (w/ θ_{13}=0)*
- *The observed ν_μ CC candidates are consistent with the neutrino oscillation parameters measured by SK, K2K and MINOS.*
- *The total integrated proton intensity accumulated until the earthquake is 1.45×10^{20} p.o.t. and events are being analyzed. With this increased statistics, we expect a θ_{13} sensitivity better than that of CHOOZ. In addition, the analysis strategy will be improved.*
- *The full extent of the impact of the earthquake on future T2K running is at present unknown.*

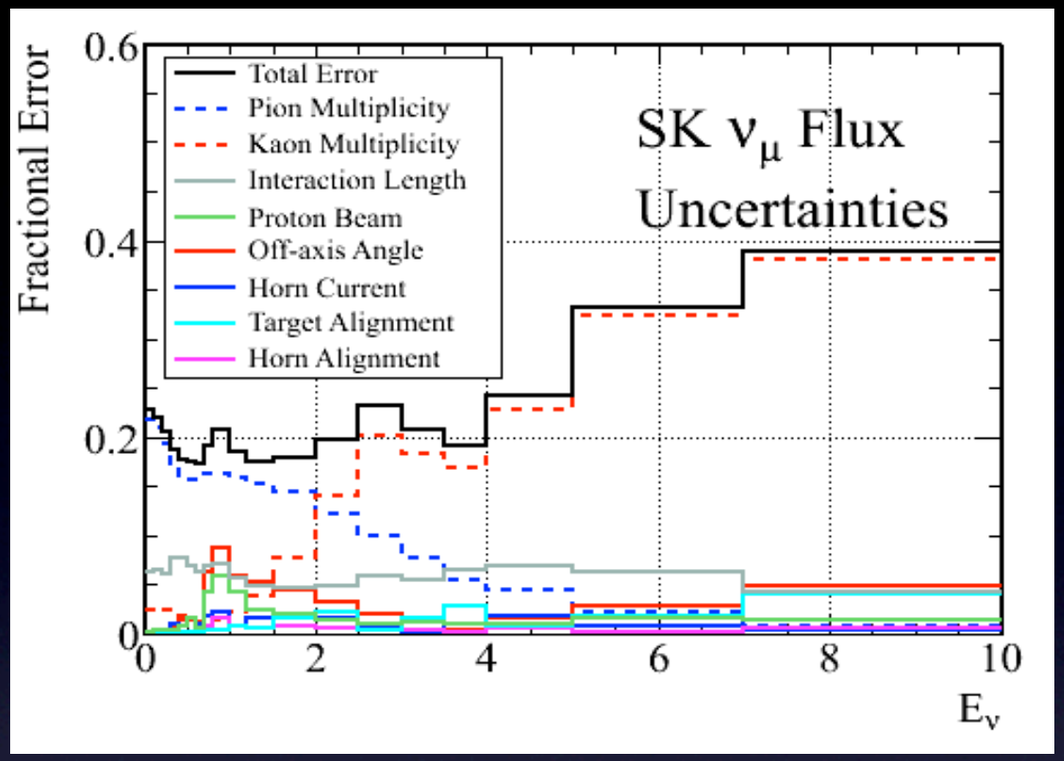
Backup slides

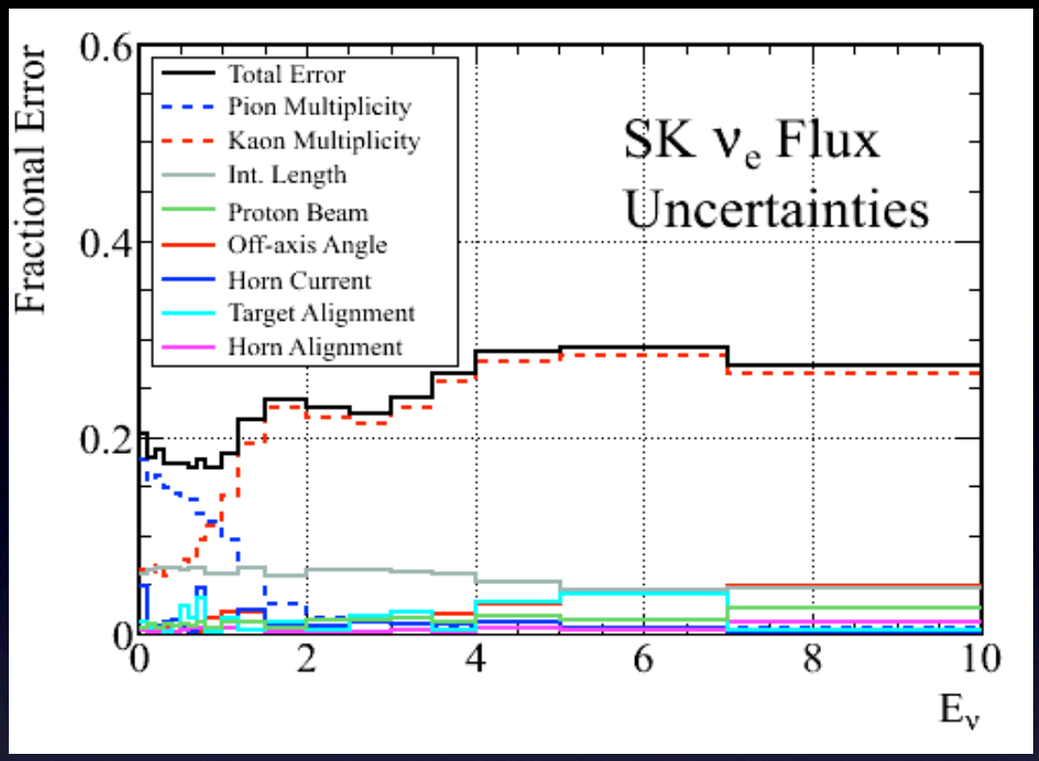
Beam related systematic error

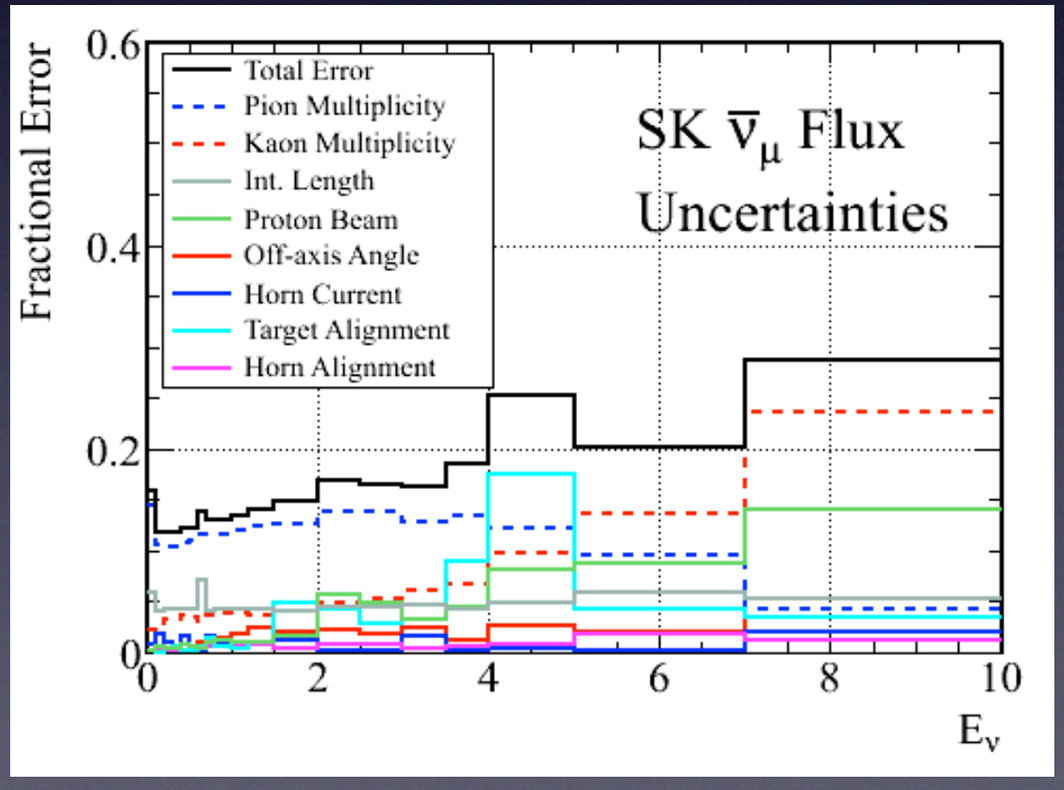
Sources of uncertainty for the neutrino flux prediction

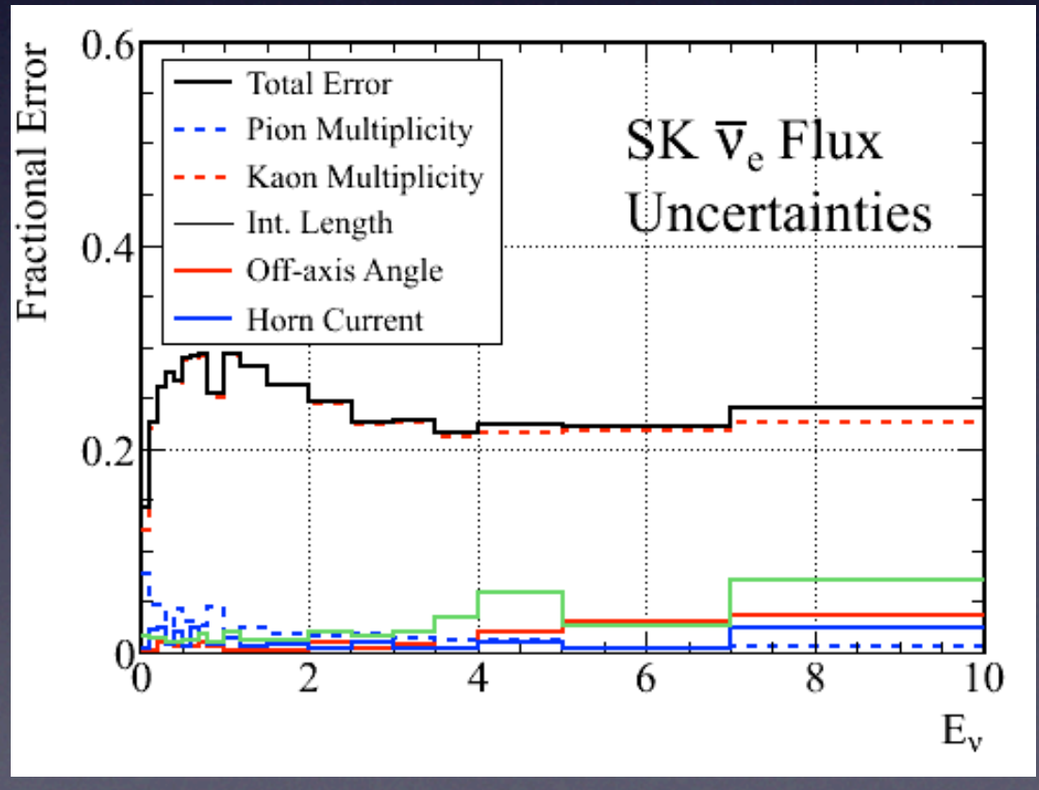
Source	Uncertainty	Change at Peak	Max Change(<3GeV)
Pion Multiplicity	20%	16%	22%
Kaon Multiplicity	20-25%	1%	20%
Prod. Cross Sections	10-50%	7%	8%
Proton Beam	0.5mm, 0.3mrad	3%	9%
ν Beam Direction	0.44mrad	1%	8%
Target Alignment	1.3mrad	<1%	1%
Horn Alignment	1mm	1%	3%
Horn Current	5kA	2%	2%
Horn Field Asym,	1.25%	0.5%	1%

Tuned neutrino fluxes uncertainties









Detailed systematic errors

Electron appearance analysis

Error source		N_{SK}^{sig}	N_{SK}^{bkg}	N_{SK}^{s+b}	N_{ND}	N_{SK}^{bkg}/N_{ND}	N_{SK}^{s+b}/N_{ND}
SK Norm.	f^{SKnorm}	$\pm$ 1.4	$\pm$ 1.4	$\pm$ 1.4	$\pm$ 0.0	$\pm$ 1.4	$\pm$ 1.4
SK Energy Scale	f^{Energy}	$\pm$ 0.3	$\pm$ 0.5	$\pm$ 0.4	$\pm$ 0.0	$\pm$ 0.5	$\pm$ 0.4
SK Ring Counting	$f^{N_{ring}}$	$\pm$ 3.9	$\pm$ 8.4	$\pm$ 5.0	$\pm$ 0.0	$\pm$ 8.4	$\pm$ 5.0
SK PID Muon	$f^{PID\mu}$	$\pm$ 0.0	$\pm$ 1.0	$\pm$ 0.3	$\pm$ 0.0	$\pm$ 1.0	$\pm$ 0.3
SK PID Electron	f^{PIDe}	$\pm$ 3.8	$\pm$ 8.1	$\pm$ 4.9	$\pm$ 0.0	$\pm$ 8.1	$\pm$ 4.9
SK POLfit Mass	f^{POLfit}	$\pm$ 5.1	$\pm$ 8.7	$\pm$ 6.0	$\pm$ 0.0	$\pm$ 8.7	$\pm$ 6.0
SK Decay Electron	$f^{N_{dcy}}$	$\pm$ 0.1	$\pm$ 0.3	$\pm$ 0.2	$\pm$ 0.0	$\pm$ 0.3	$\pm$ 0.2
SK π^0 Efficiency	$f^{\pi^0 eff}$	$\pm$ 0.0	$\pm$ 5.9	$\pm$ 1.5	$\pm$ 0.0	$\pm$ 5.9	$\pm$ 1.5
CC QE shape	$f^{CCQEshape}$	$\pm$ 4.9	$\pm$ 2.6	$\pm$ 4.3	$\pm$ 0.0	$\pm$ 2.6	$\pm$ 4.3
CC 1π	$f^{CC1\pi}$	$\pm$ 4.3	$\pm$ 3.8	$\pm$ 4.1	$\pm$ 5.9	$\pm$ 2.2	$\pm$ 1.8
CC Coherentπ	f^{CCcoh}	$\pm$ 0.3	$\pm$ 0.2	$\pm$ 0.3	$\pm$ 3.3	$\pm$ 3.1	$\pm$ 3.0
CC Other	$f^{CCother}$	$\pm$ 0.1	$\pm$ 0.3	$\pm$ 0.1	$\pm$ 4.8	$\pm$ 4.4	$\pm$ 4.6
NC $1\pi^0$	$f^{NC1\pi^0}$	$\pm$ 0.0	$\pm$ 5.9	$\pm$ 1.5	$\pm$ 0.0	$\pm$ 5.8	$\pm$ 1.4
NC Coherentπ	f^{NCcoh}	$\pm$ 0.0	$\pm$ 2.5	$\pm$ 0.6	$\pm$ 0.00	$\pm$ 2.5	$\pm$ 0.6
NC Other	$f^{NCother}$	$\pm$ 0.0	$\pm$ 3.8	$\pm$ 1.0	$\pm$ 1.1	$\pm$ 2.7	$\pm$ 0.2
$\sigma(\nu_e)$	$f^{\sigma(\nu_e)}$	$\pm$ 6.0	$\pm$ 3.2	$\pm$ 5.3	$\pm$ 0.0	$\pm$ 3.2	$\pm$ 5.3
FSI	f^{FSI}	$\pm$ 3.8	$\pm$ 10.3	$\pm$ 5.5	$\pm$ 0.0	$\pm$ 10.3	$\pm$ 5.5
Beam Norm.	$f^{\phi}_{SK/ND}$	$\pm$ 22.0	$\pm$ 18.1	$\pm$ 20.5	$\pm$ 19.8	$\pm$ 8.9	$\pm$ 11.9
ND Efficiency	$f^{\epsilon_{ND}}$	$\pm$ 0.0	$\pm$ 0.0	$\pm$ 0.0	$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$
Overall Norm.	f^{norm}	$\pm$ 0.0	$\pm$ 0.0	$\pm$ 0.0	$\pm$ 0.0	$\pm$ 2.7	$\pm$ 2.7
Total		$\pm$ 25.2%	$\pm$ 27.8%	$\pm$ 24.7%	$^{+22.2}_{-22.1}$%	$^{+23.9}_{-23.8}$%	$^{+19.5}_{-19.4}$%

Detailed neutrino model systematic errors

Variation of the NEUT MC input parameters

Source	Central Value	Variations
M_A^{QE} [(GeV/c)^2]	1.21	± 0.2
M_V^{QE} [(GeV/c)^2]	0.84	± 0.1
M_A^{RES} [(GeV/c)^2]	1.21	± 0.2
M_V^{RES} [(GeV/c)^2]	0.84	± 0.1
M_A^{COH} [(GeV/c)^2]	1.0	± 0.5
CCQE p_F [MeV/c]	225	± 25
CCQE E_B ^{16}O [MeV]	26.6	$+23.2$
CCQE κ	1.00	$+0.007$
DIS Bodek-Yang Corr.	on	off
$^{\dagger}\pi$: absorption		$^{+60}_{-40}\%$
$^{\dagger}\pi$: inelastic		$^{+60}_{-40}\%$
$^{\dagger}\pi$: charge exchange		$\pm 60\%$
$^{\dagger}\pi$: π production		$\pm 50\%$
Δ absorption	20%	$\pm 20\%$
π/Δ abs. $\rightarrow$ nN	off	on

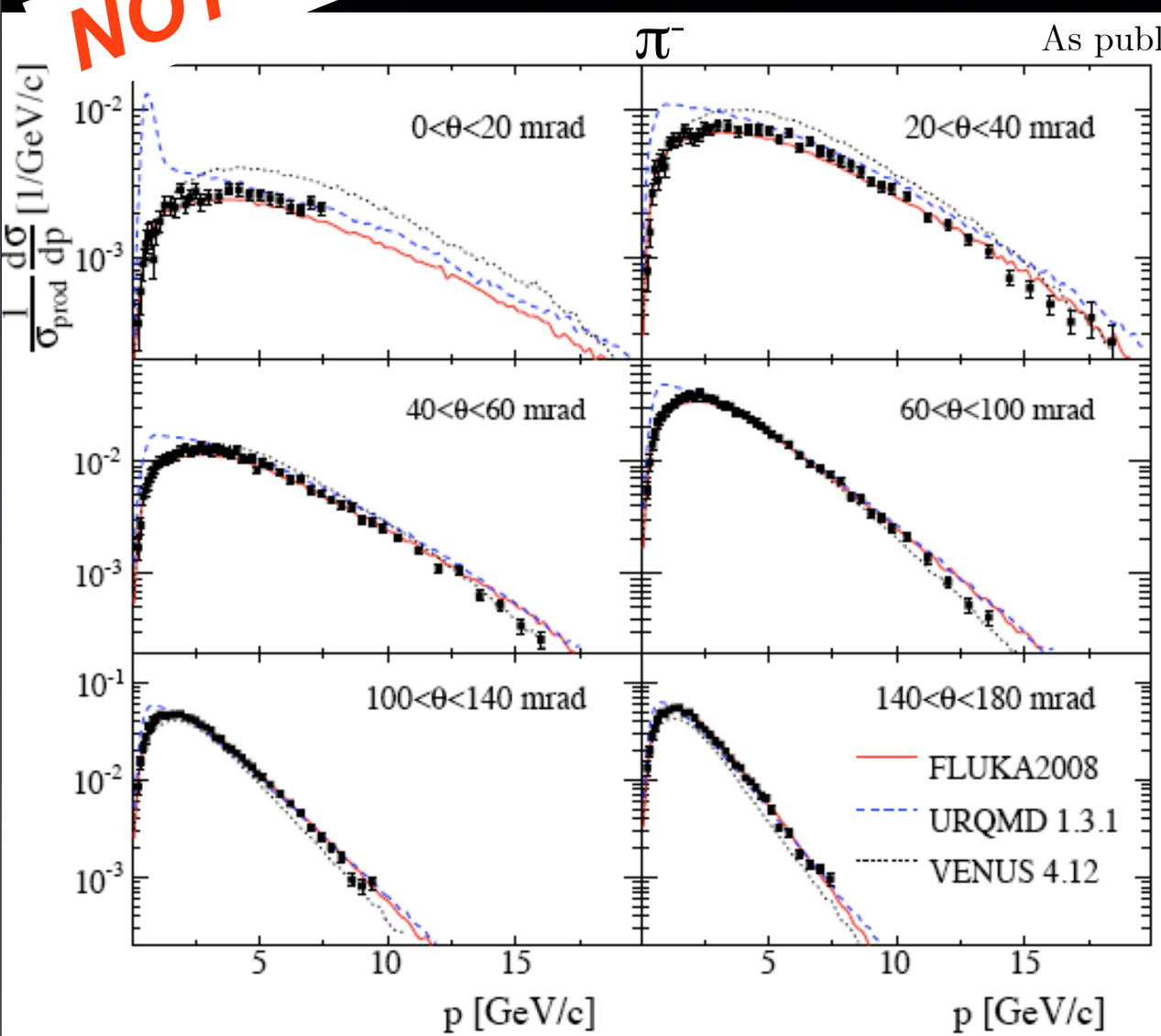
CERN NA61 π publication

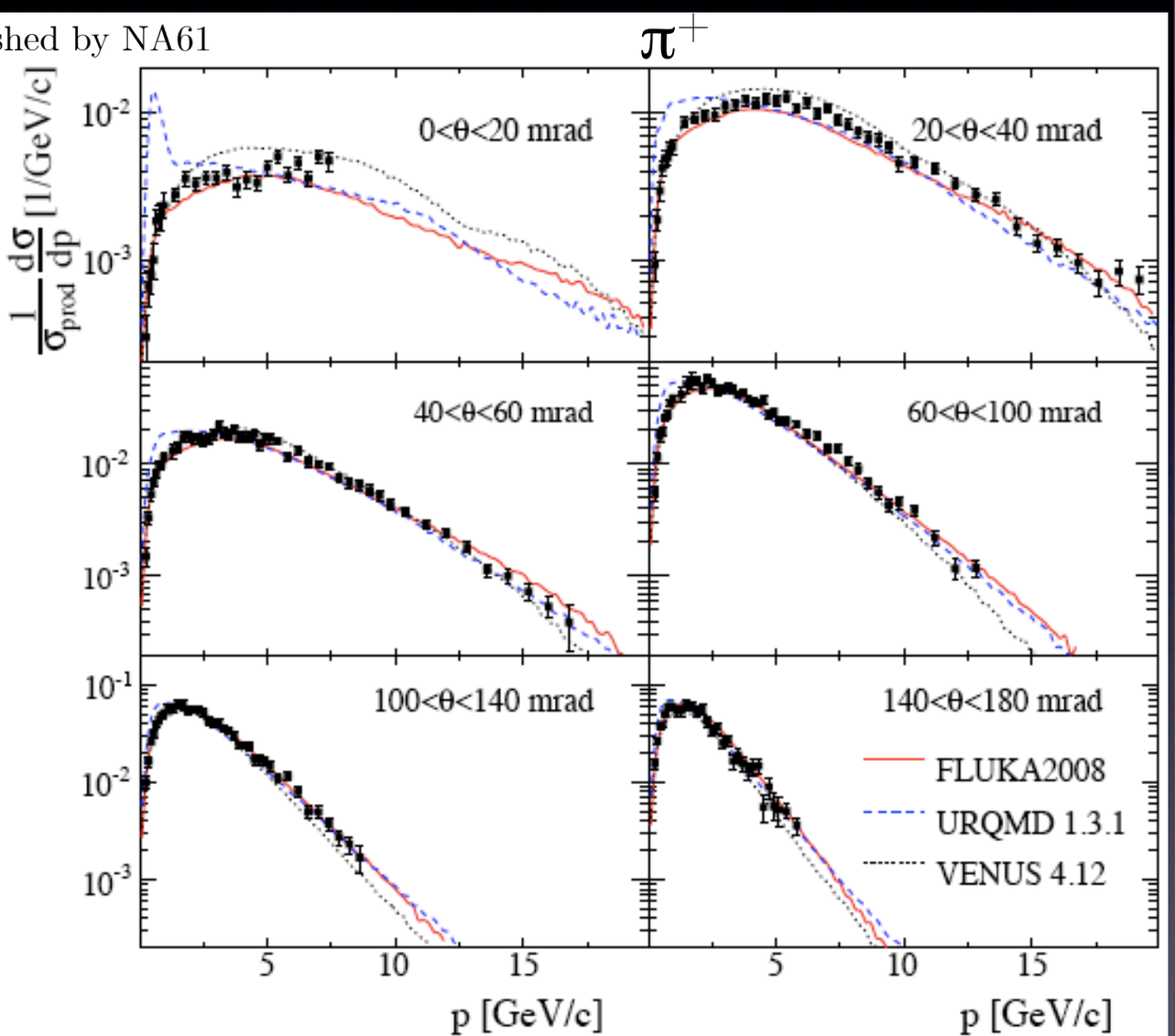
NOT YET USED IN T2K

Available as [illegible]Xiv:1102.0983 [hep-ex], submitted to Phys. Rev. C

Comparison of data with FLUKA2008, URQMD 1.3.1 and VENUS 4.12

As published by NA61



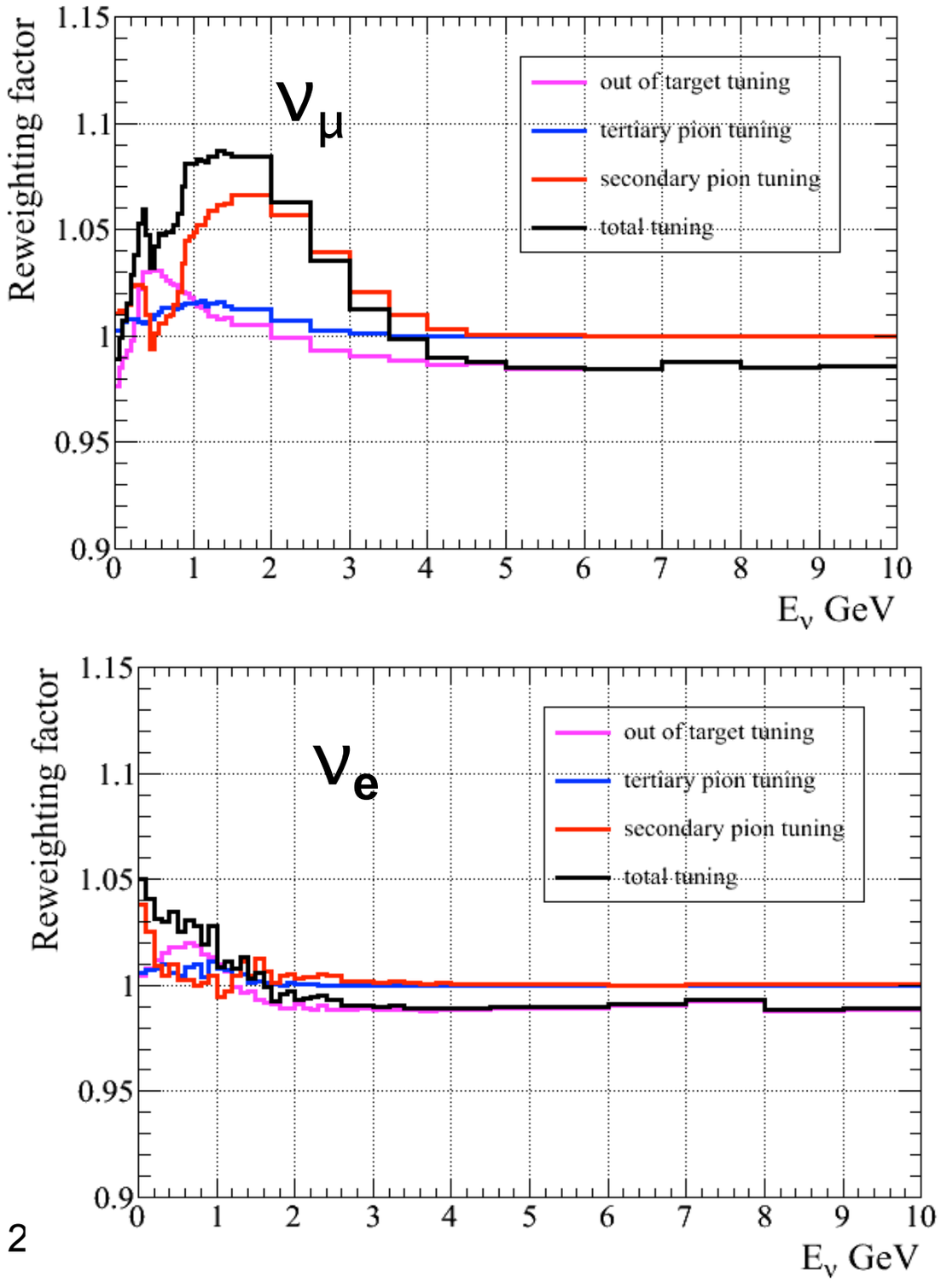


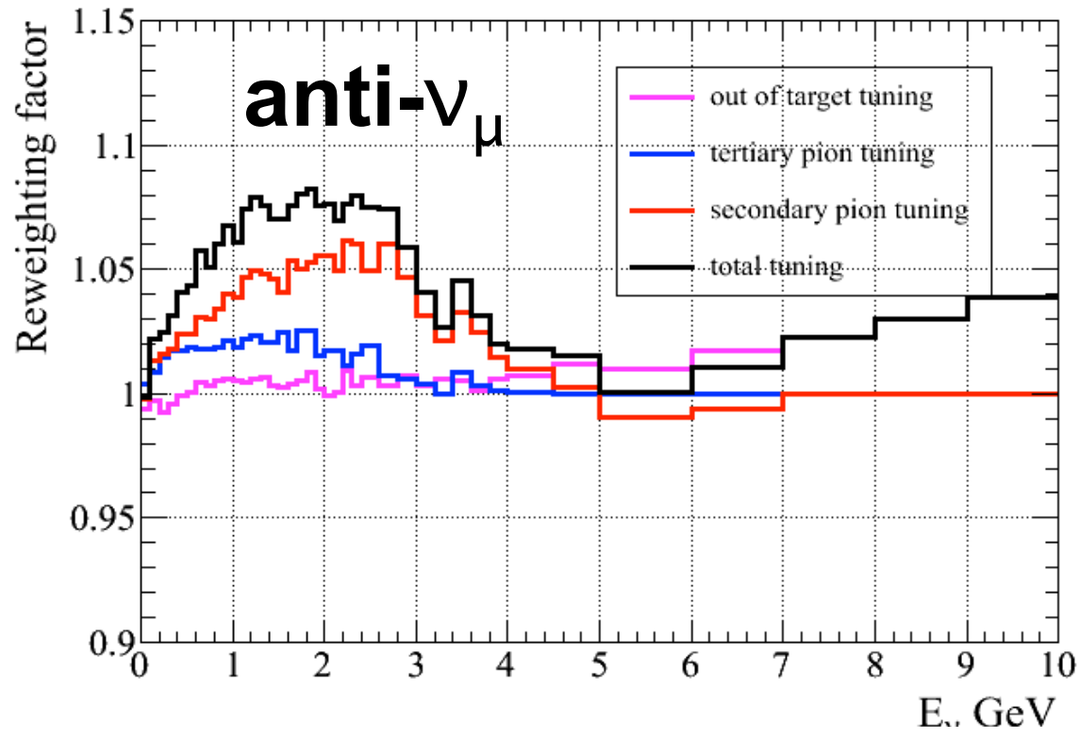
Polar angle bins 180-240, 240-300, 300-360, 360-420 mrad not shown here

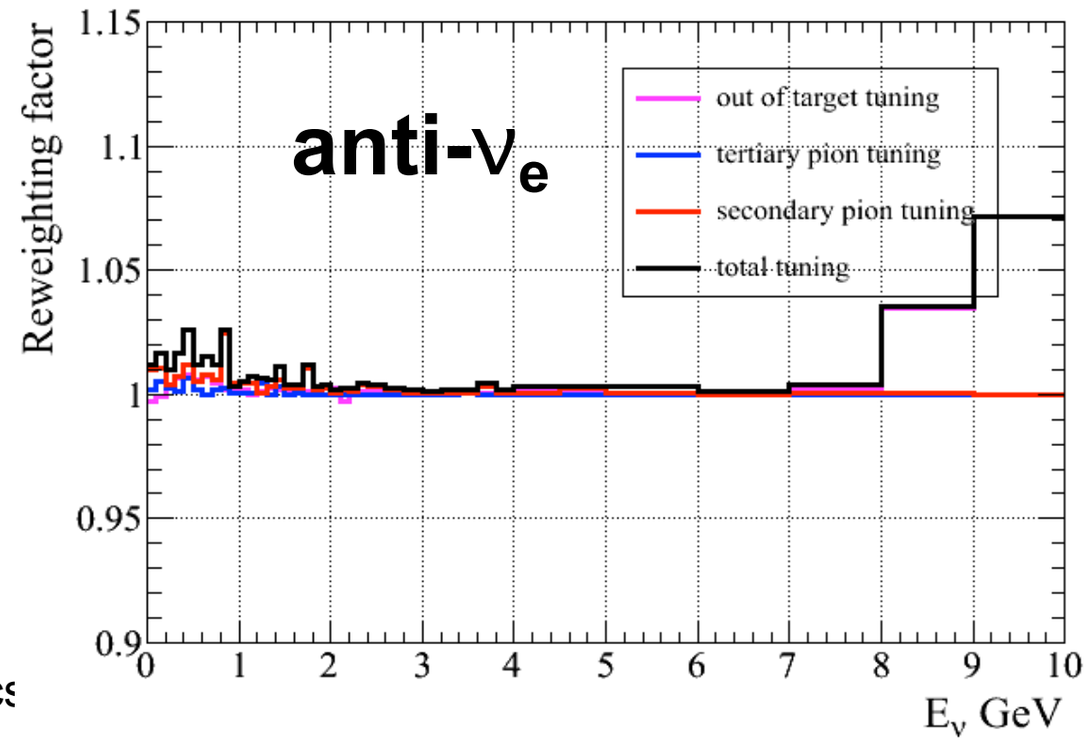
Estimated systematic error on differential cross-section bin ≈ 6%

NA61 measured production cross-section : σ_{prod} = (229.3 ± 1.9 ± 9.0)mb

Tuned/original ratio for SK flux (original flux is obtained w/ FLUKA2008





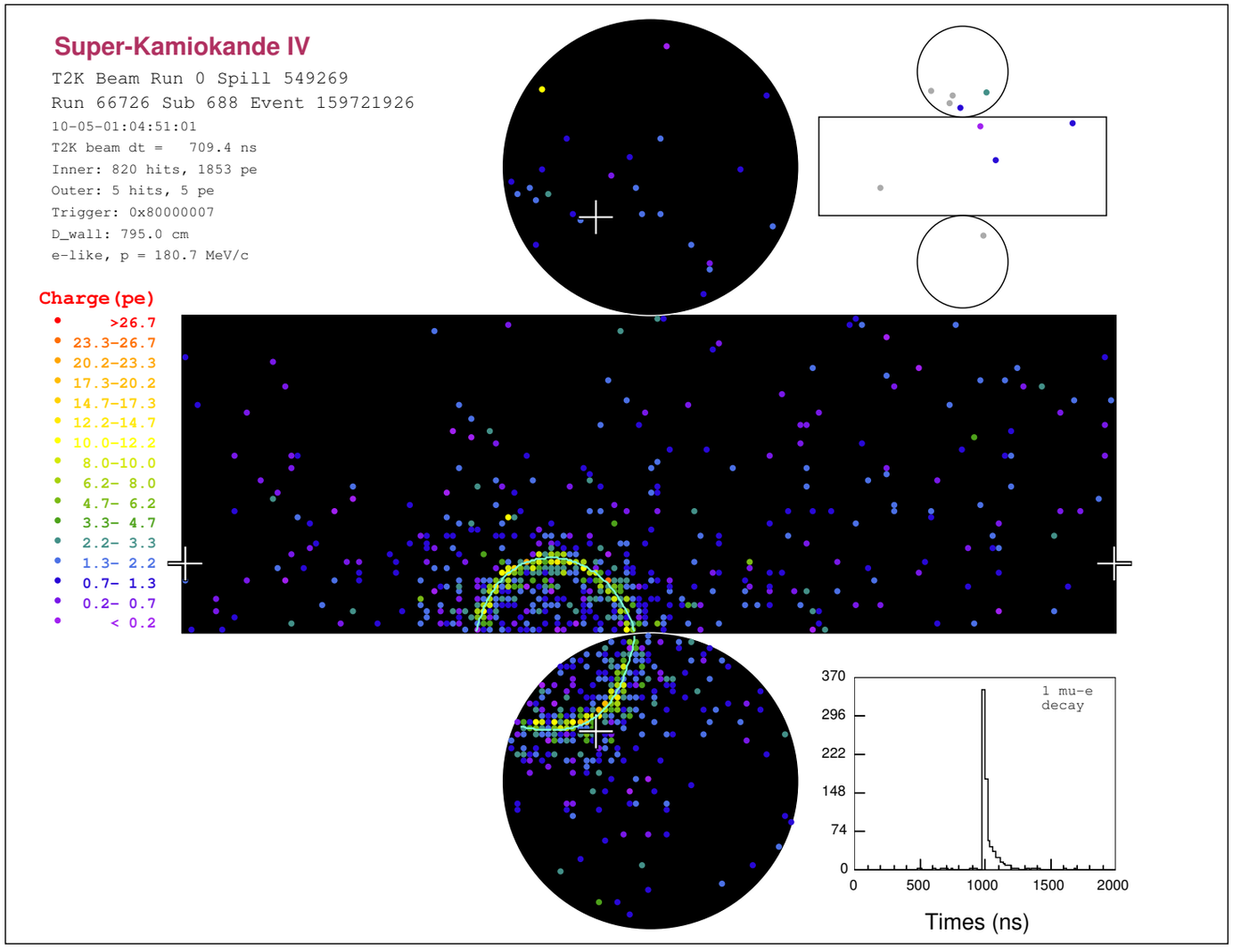


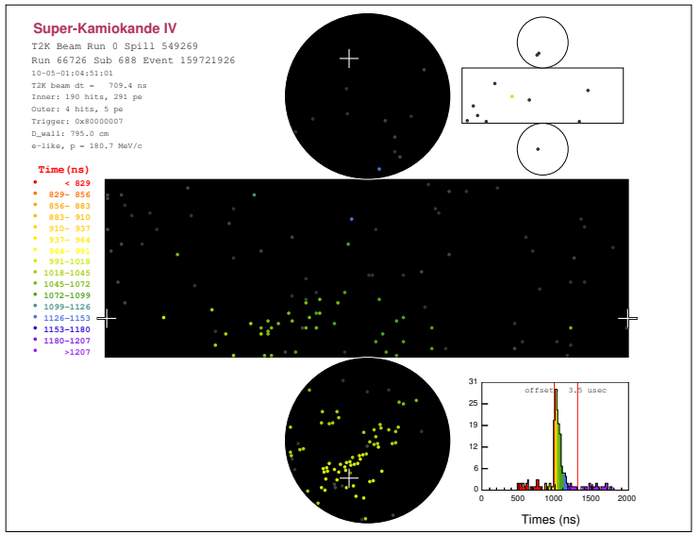
2

ics

T2K ν_e CC candidate (2010a)

Event removed by decay electron cut

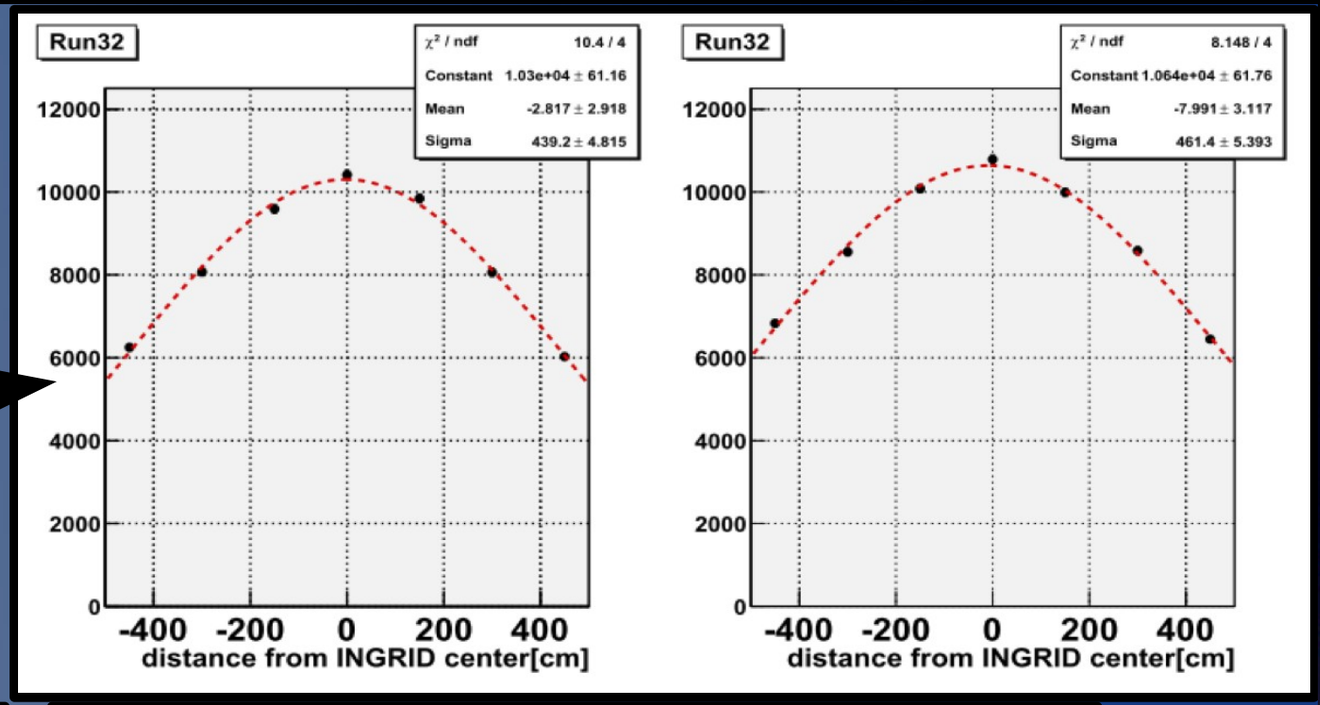


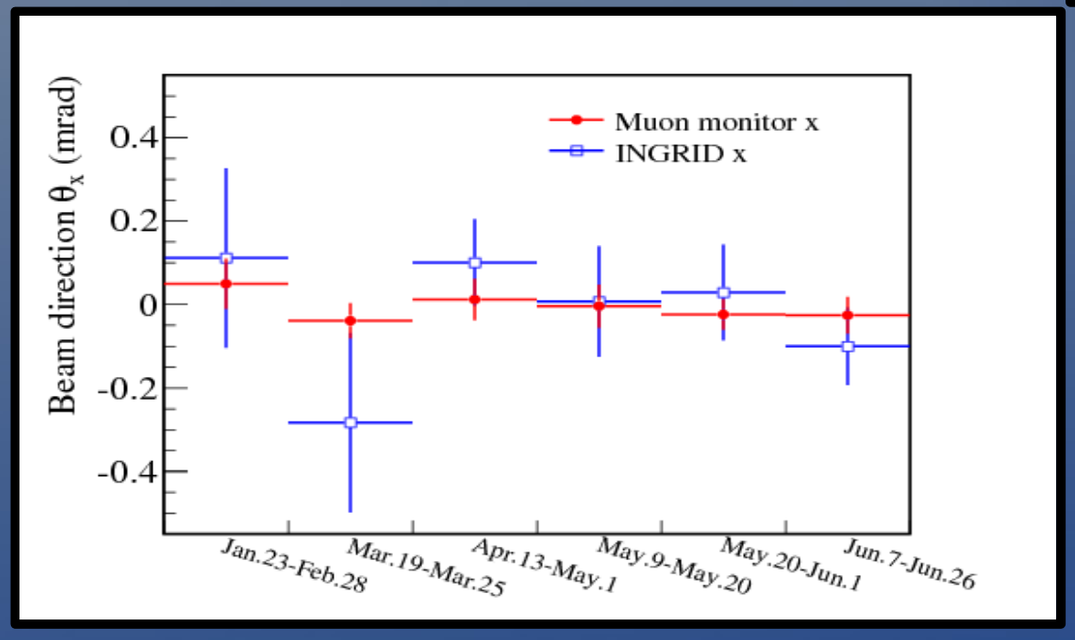


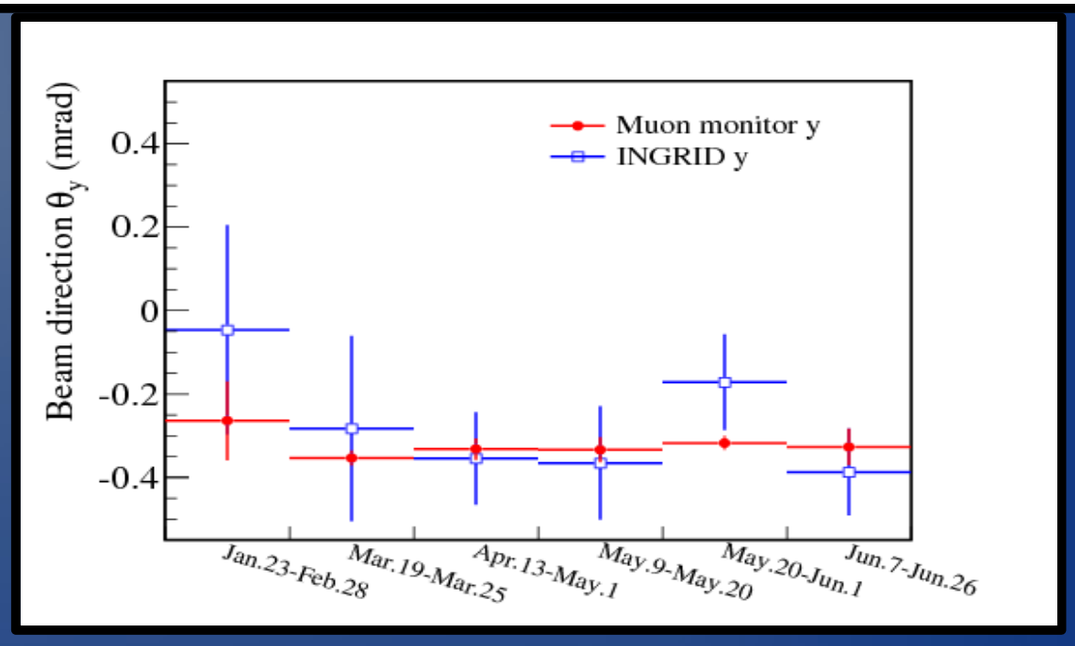
Item	Event	T2K cut
Date (JST)	2010 May 1st 4:50:58	
Ring, PID	1-Ring electron-like	OK
Momentum	181 MeV	>100
N_{dcy}	1	0
$\cos(\theta_{\nu e})$	0.026 (89 degree)	N/A
$Mass$	46.6 MeV	<105
E_{rec}	257 MeV	<1250

Beam direction monitoring

- **MUMON: 2D profile of muons from pion decays**
- **INGRID: neutrino beam profiles in x and y**

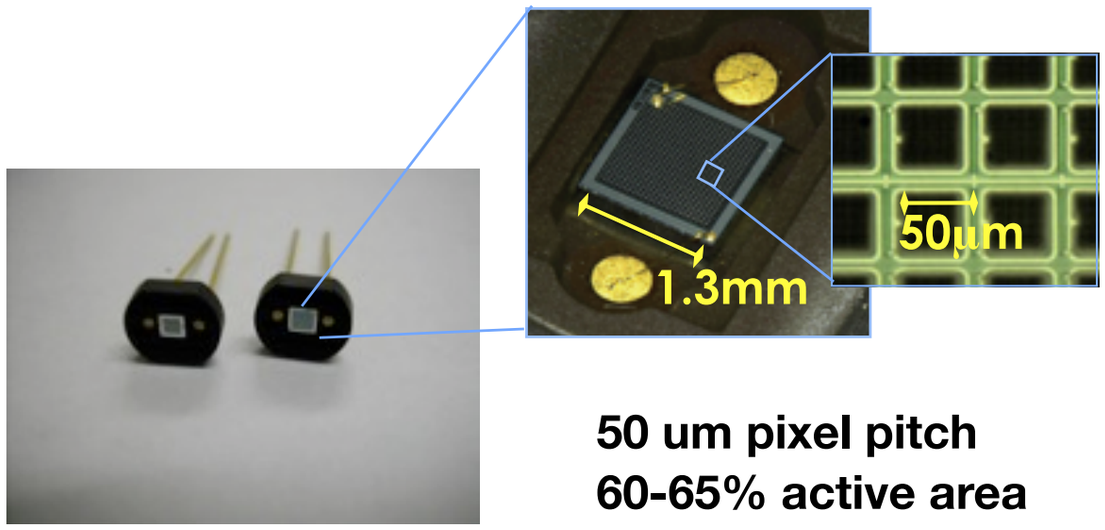




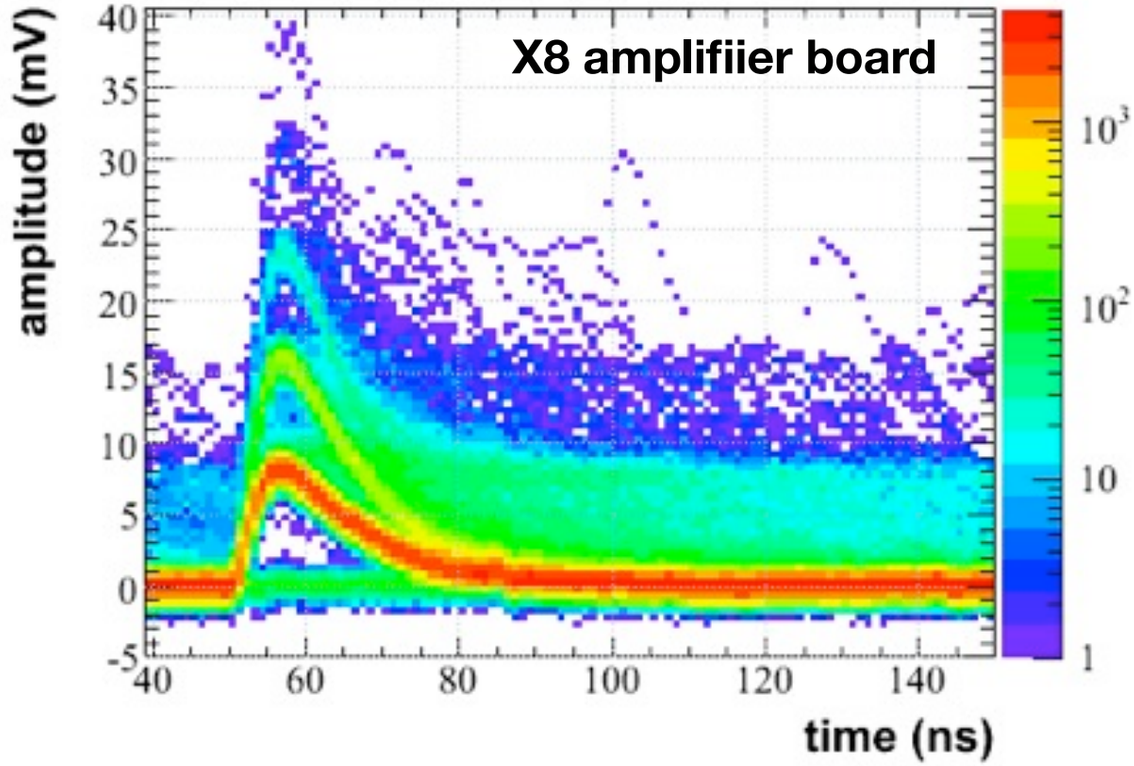


- **MUMON and INGRID measurements in good agreement**
- **Beam direction is stable and within 1 mrad tuning goal**

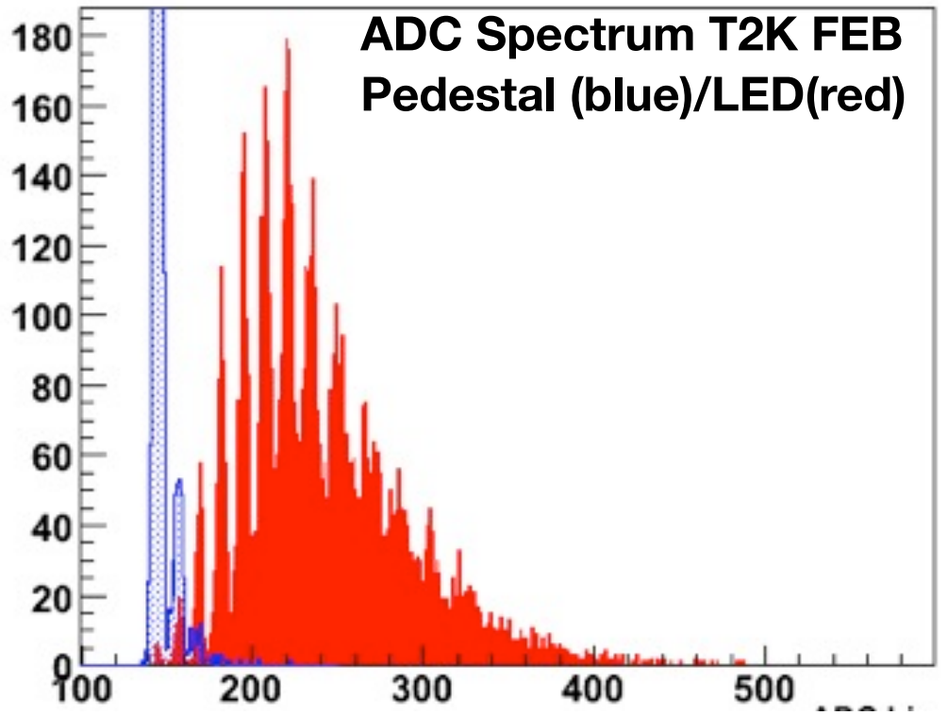
Multi-Pixels Photon Counter (MPPC)



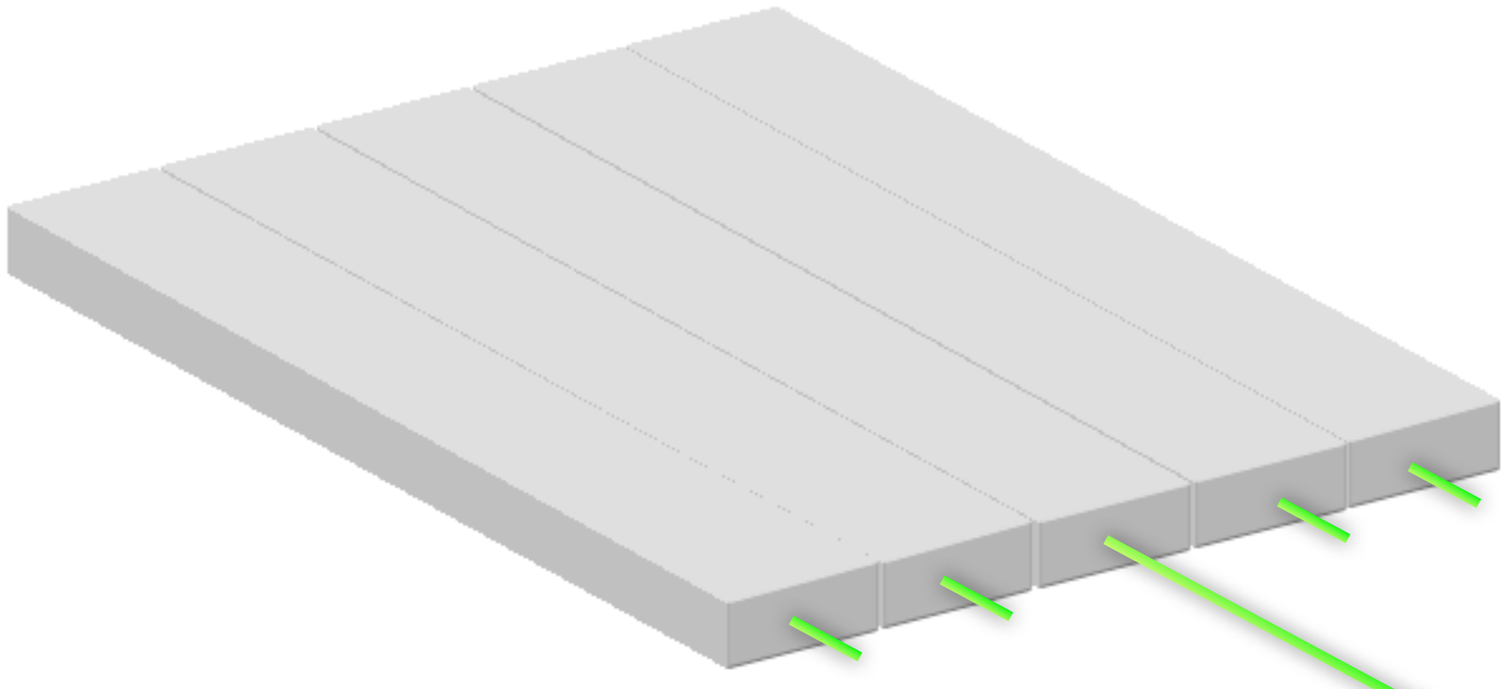
50 um pixel pitch
60-65% active area
Pixel capacitance : 97.5 fF
Passive quenching 150 MΩ
Pixel RC cnst~13 ns



1.3 mm x 1.3 mm (T2K device)
667 pixels (50um pitch)
Nominal gain : 7.5x10E5
PDE (500 nm) ~ 20%
Timing resolution ~ 200-600 ps
Noise 500 MHz/mm^2 at ºC
Cross-talk and after-pulsing ~ 15%



Sampling scintillator + MPPC

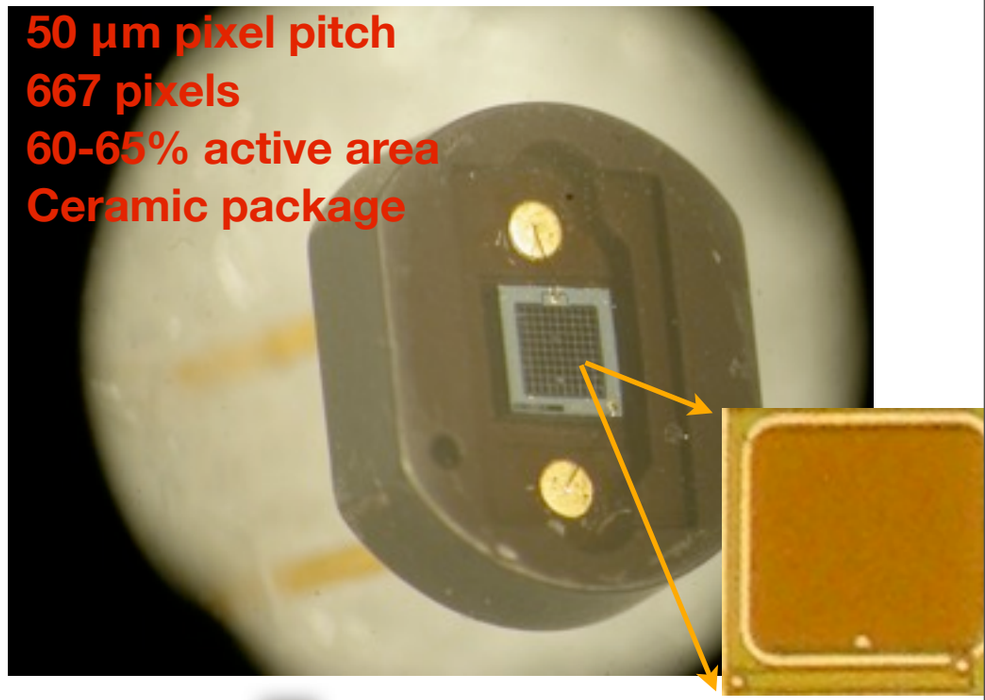


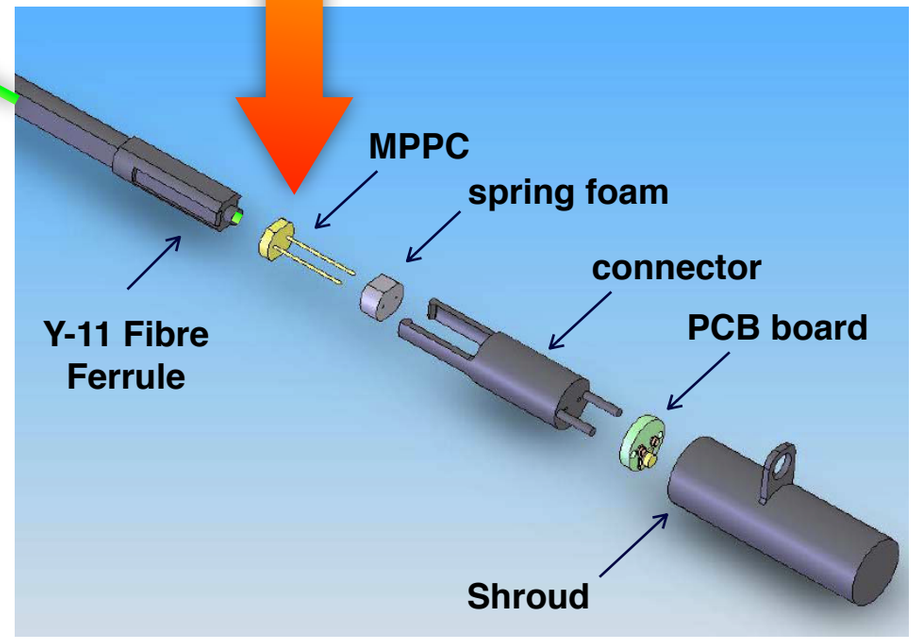
Basic element of the near detector scintillator sub-systems (INGRID, P0D , FGD, ECAL, SMRD) :

- **Extruded scintillator bar with embedded Y-11 fibre read out by individual MPPC in coupler**
- **56 000 channels in total**

T2K custom device 1.3 mm x 1.3 mm

50 µm pixel pitch
667 pixels
60-65% active area
Ceramic package





Connector design for P0D/ECAL/SMRD