Long Baseline Oscillations: Towards Japan

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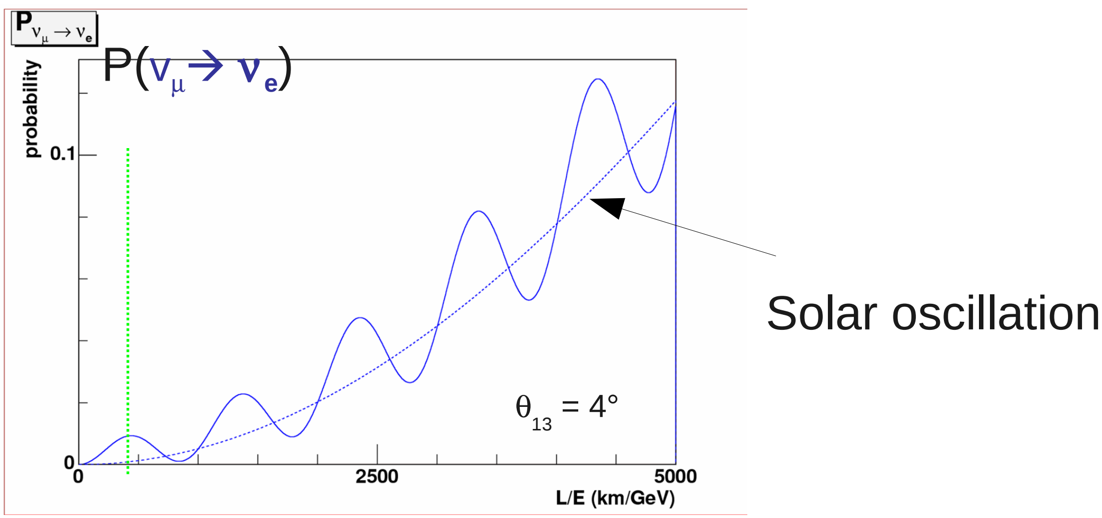
Why join the US/Japan collaborations of K2K & T2K

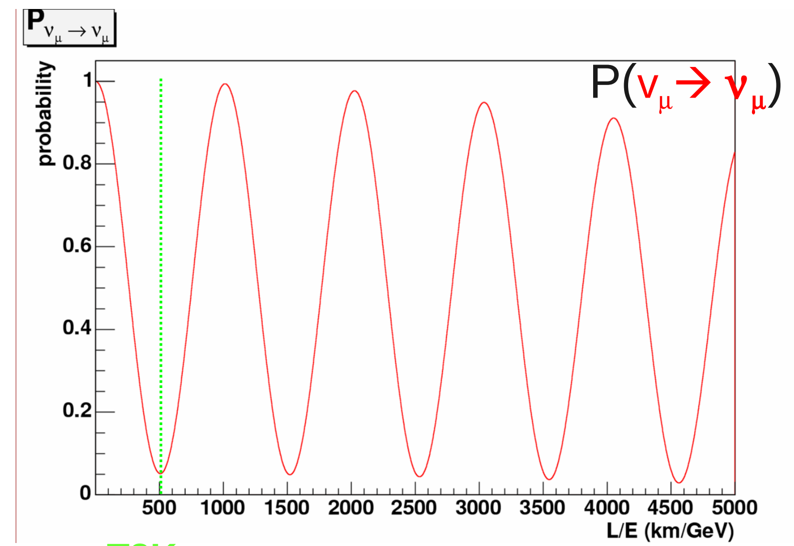
- Unique expertise in giant water Cherenkov detectors
- The aim was to “learn” and then possibly apply the knowledge in a future generation of experiments
- EU collaborators joined K2K in late 2002, after SK was rebuilt following its accident in Nov 2001
- T2K started with EU input from the beginning

Three flavor neutrino oscillations

- **Goal of K2K** : confirm Super-K's 1998 result by observing ν_μ disappearance
- **Goal of T2K** : find evidence of small $\nu_\mu \rightarrow \nu_e$ flavor change driven by θ_{13}



T2K



T2K

$$P(\nu_\mu \rightarrow \nu_e) \approx P_{atm} + P_{sol} + P_{interference}$$

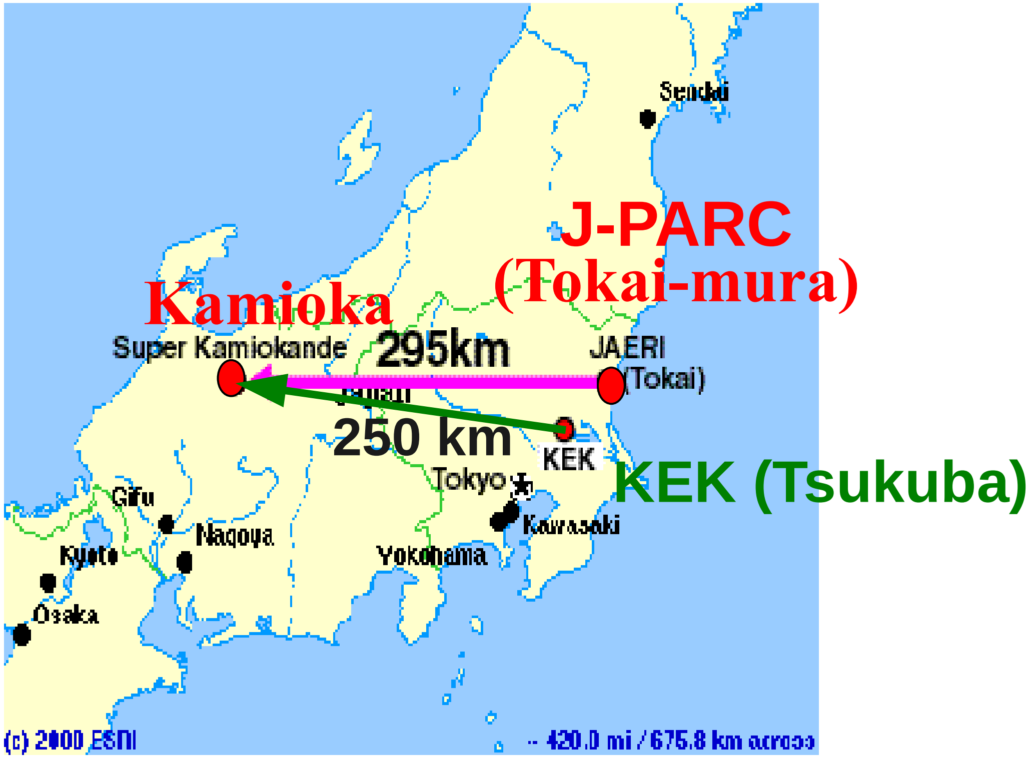
$$= \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{1.27\,\Delta m_{23}^2 L}{E}$$

$$+\cos^2\theta_{23}\sin^2 2\theta_{21}\sin^2\frac{1.27\,\Delta m_{12}^2 L}{E}$$

$$+\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\left(\delta - \frac{1.27\,\Delta m_{23}^2 L}{E}\right)\frac{\Delta m_{12}^2 L}{E}\sin\frac{1.27\,\Delta m_{23}^2}{E}$$

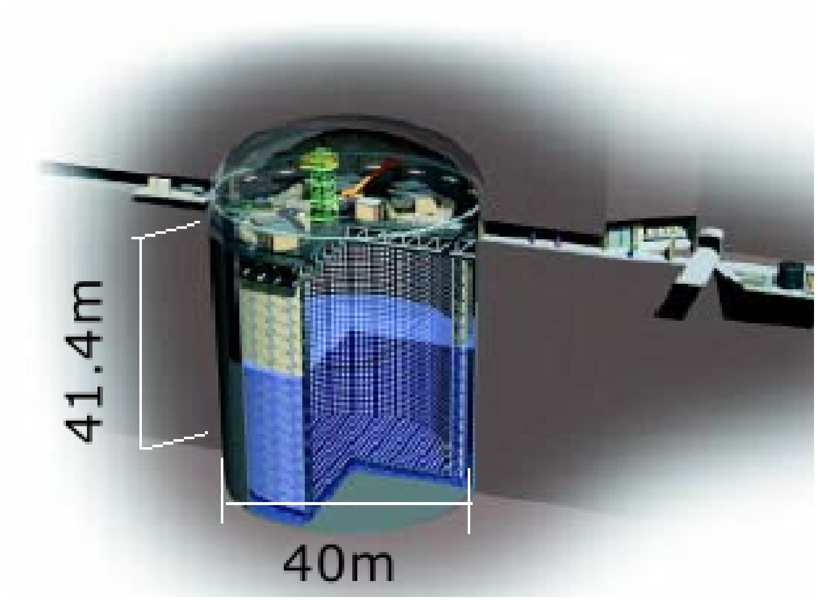
The “X”2K experiments

- Produce a neutrino beam (ν_μ) at a proton accelerator in Japan
- Use Super-Kamiokande as the far detector
- Install a cluster of detectors near the beam's production point in order to control the beam normalization & spectrum “before oscillations”
- Can also be used for measurement of ν-nucleus cross-sections

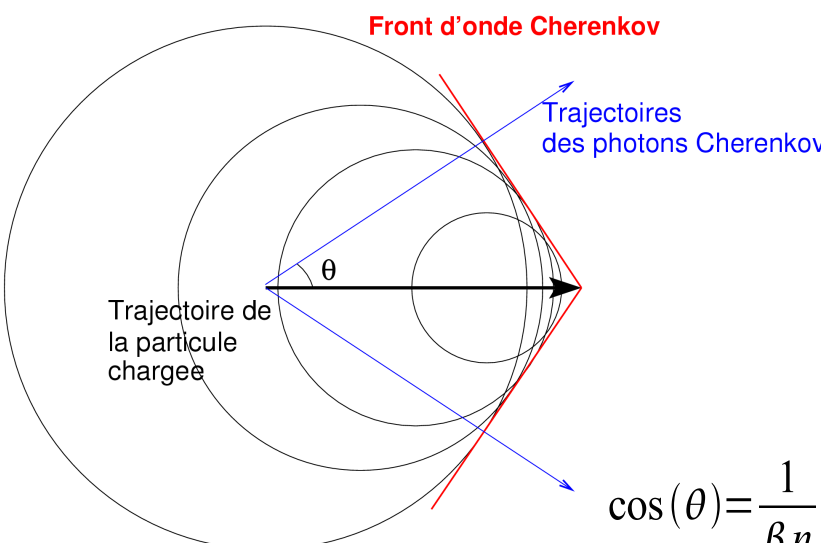


M. Fechner,Journée Jacques Bouchez, Nov 2010

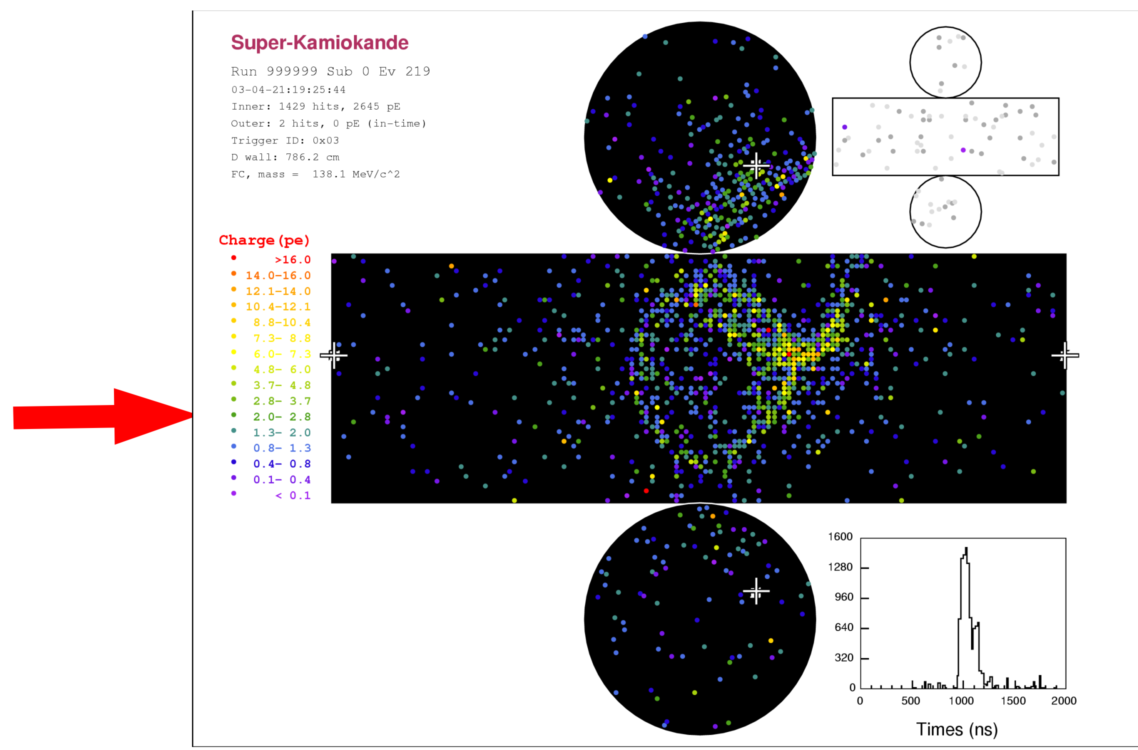
Super-Kamiokande



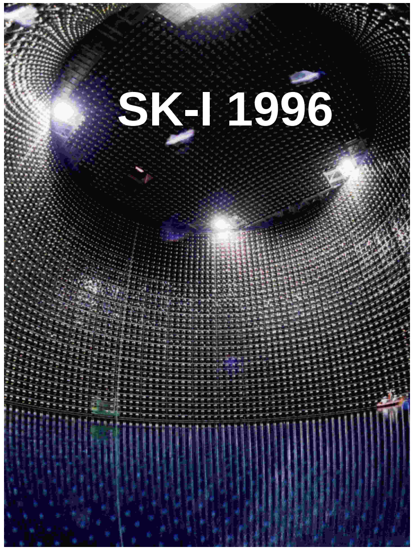
- Water Cherenkov detector
- ~11,140 PMT (20”) facing inwards
- 1,885 PMT (8”) facing outwards in 2-m thick veto
- 50,000 tons of ultra pure water
- 32,000 tons in inner volume
- 22,500 tons in fiducial volume

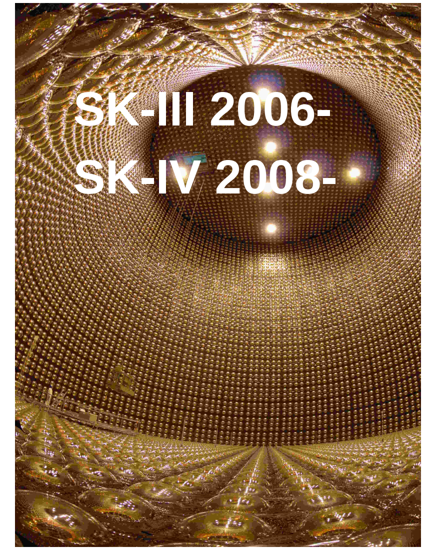


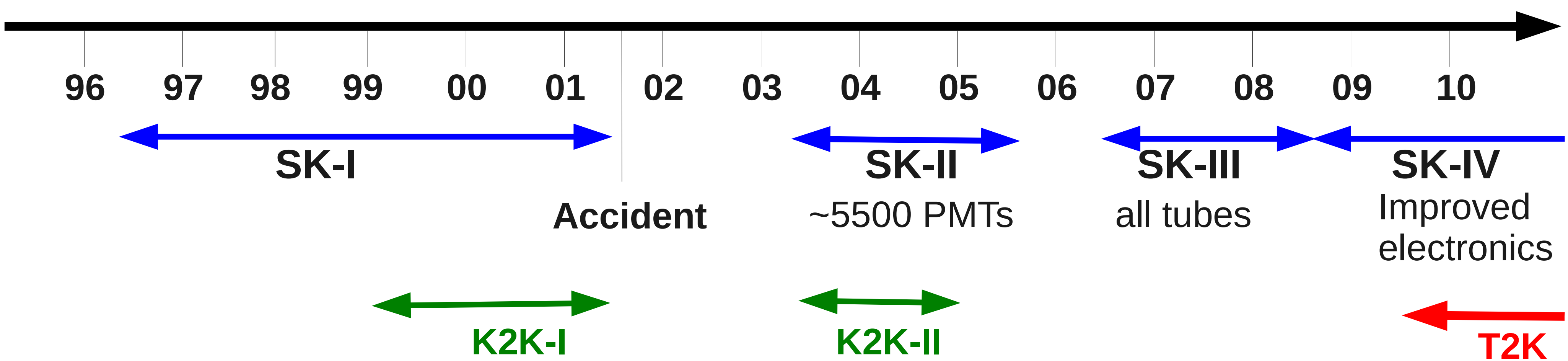
$$\cos(\theta) = \frac{1}{\beta n}$$



14 years since SK's first data

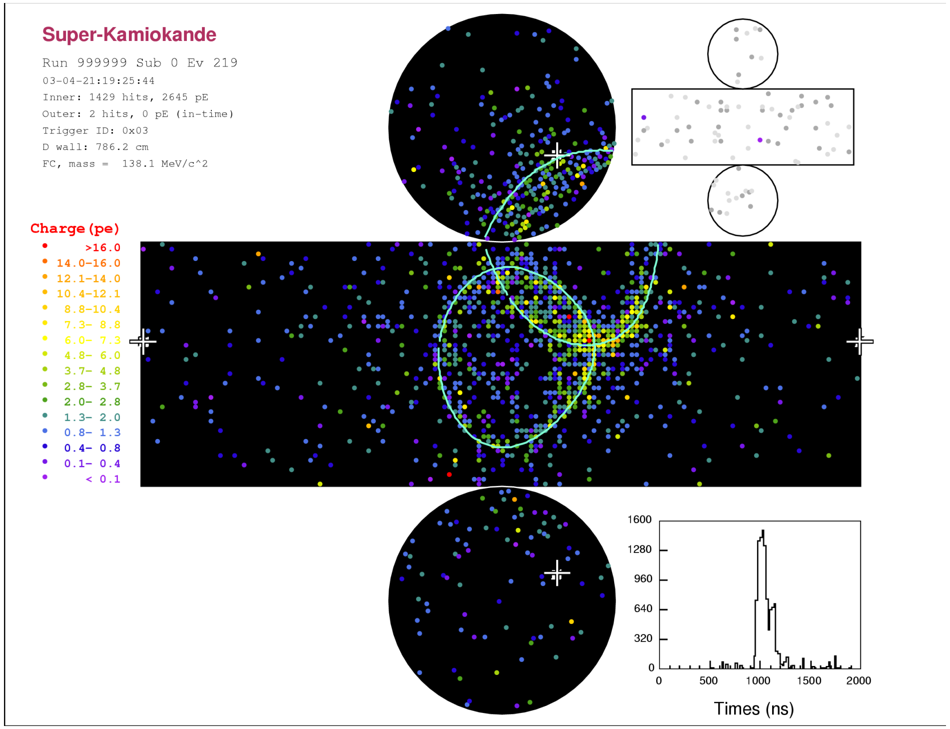




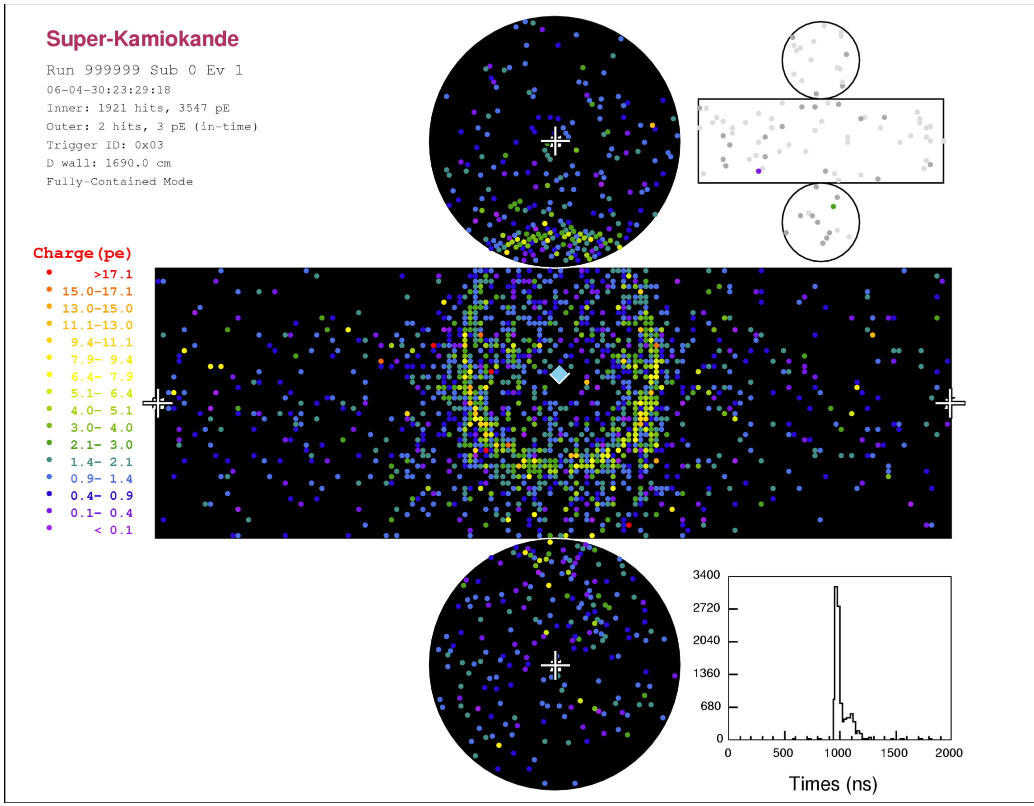


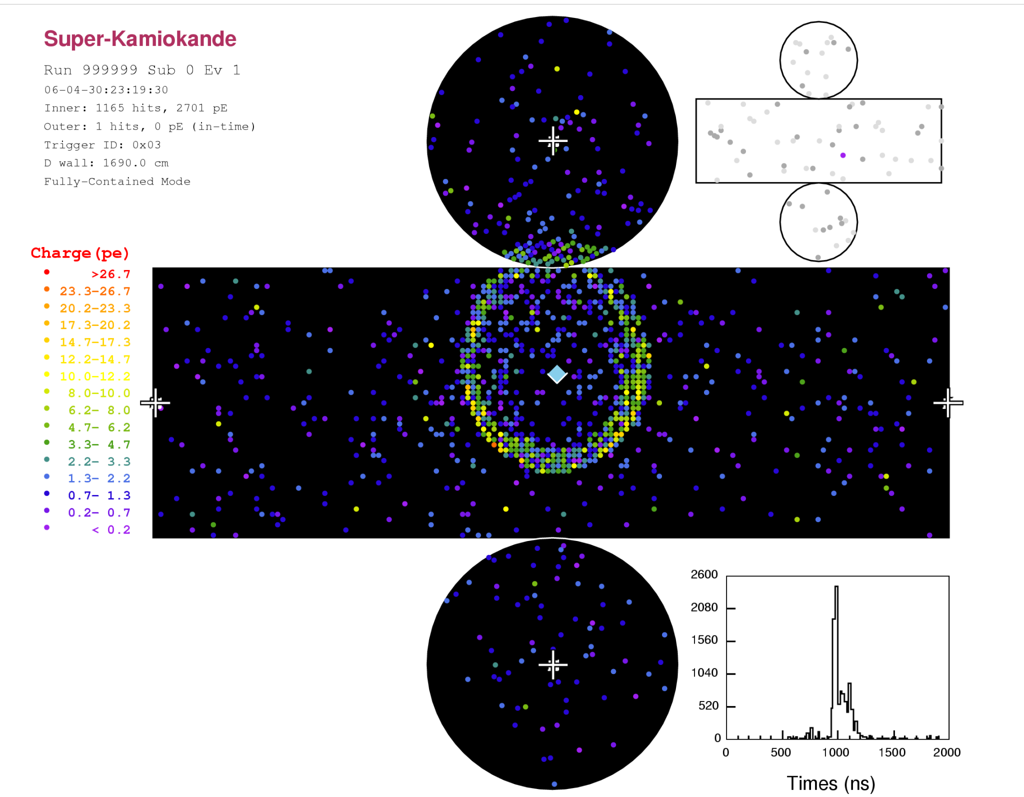
SK: Cherenkov ring imaging technique

- Each track produces a ring on the detector's inner wall. Each PMT records an integrated charge (0-200 pe's) and the impact time of the first photon hit.
- Event reconstruction is complex and iterative:
  - Fit the event's vertex
  - Count the number of rings & apportion charge between them
  - Identify each ring's type: e-like (shower) or mu-like (muon)
  - Find particles' energies
  - e/π^0 separation



electron/muon separation





400 MeV electron

500 MeV muon

EM shower → “fuzzy ring”, edge not well defined

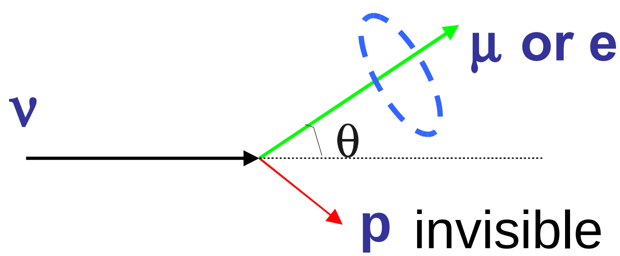
No shower : sharp edges

mis-identification rate below 1.5%

Neutrino detection at Super-K

The golden events are charged-current quasi elastic (CCQE)

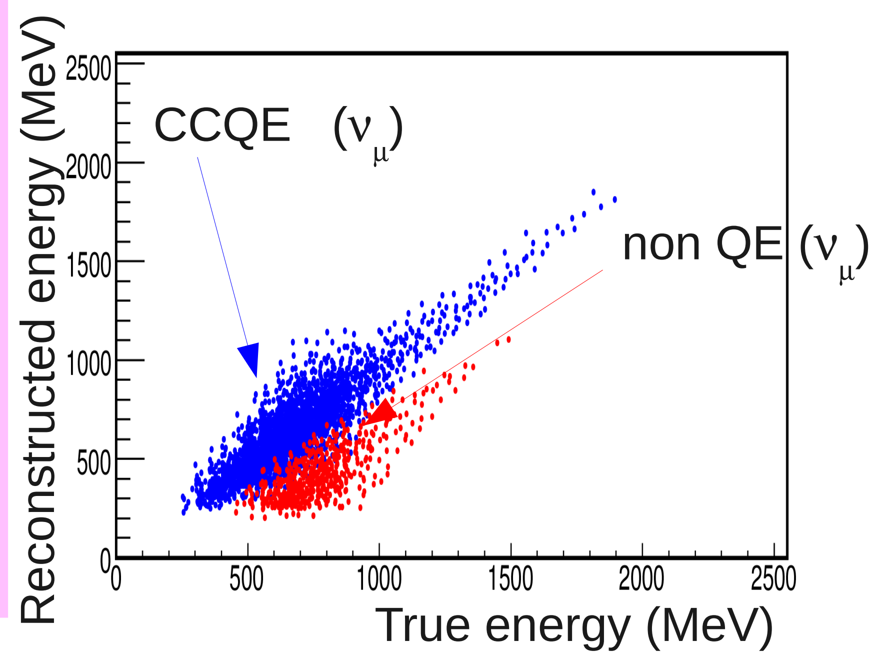
$\nu_l + n \rightarrow l + p$



Only kind of events that allow to reconstruct the neutrino's energy:

$$E_\nu = \frac{m_p^2/2 - m_n^2/2 - m_l^2/2 + m_n E_l}{m_n - E_l + p_l \cos\theta}$$

- High Cherenkov threshold in water of p/π/K...
  - Contamination with non CCQE events with biased reconstructed energy
- Fermi motion & other nuclear effects
- Need to **measure backgrounds at near detectors with other detection technique & lower thresholds**
- **Avoid ν-nucleus cross-section systematics**
  - **use water as a target material at the near site as well**



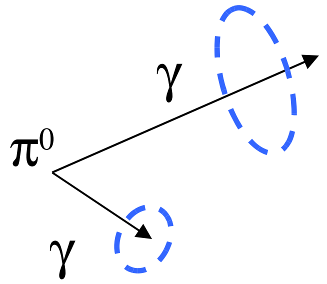
Backgrounds for ν_e detection in SK

Signal : Single-ring, e-like events from CC ν_e interactions

- Can reconstruct the energy

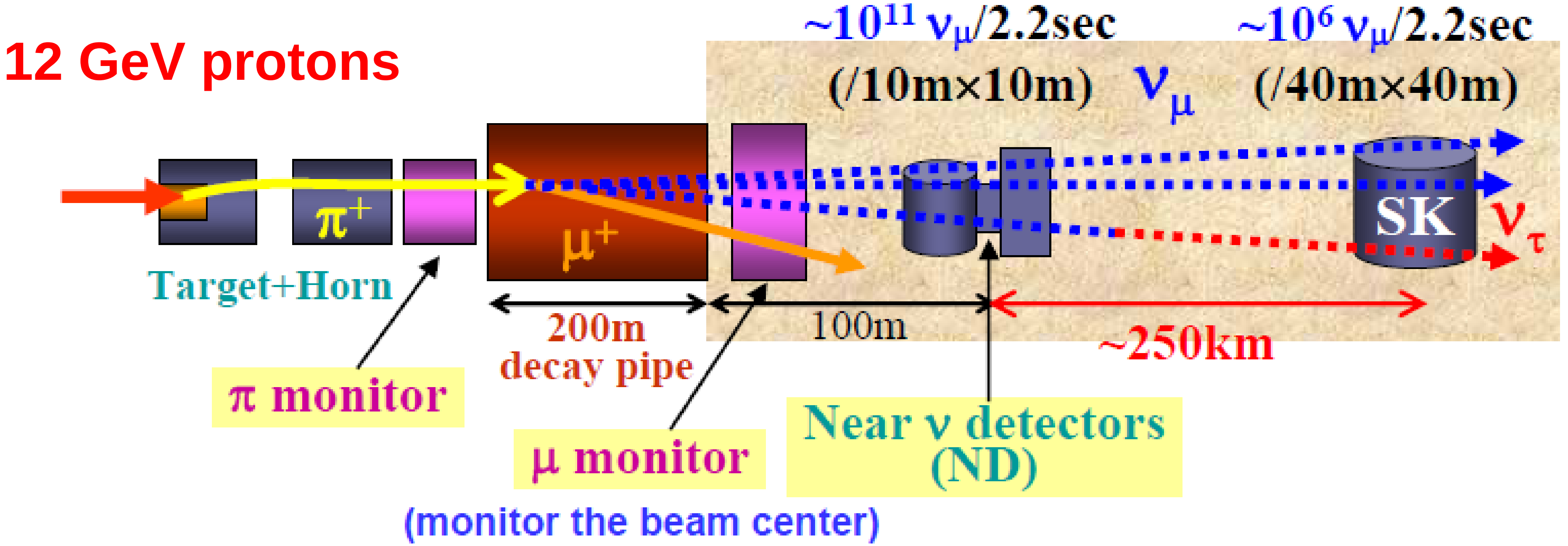
Backgrounds in single-ring, e-like sample

- Mis-identified ν_μ events: very weak
- Beam ν_e events: irreducible background
- Neutral current π^0 events ($\nu + X \longrightarrow \nu + \pi^0 + Y$)
  - Overlapping γ rings
  - Asymmetric disintegration with very weak γ



Can be
1 ring e-like !

The K2K experiment

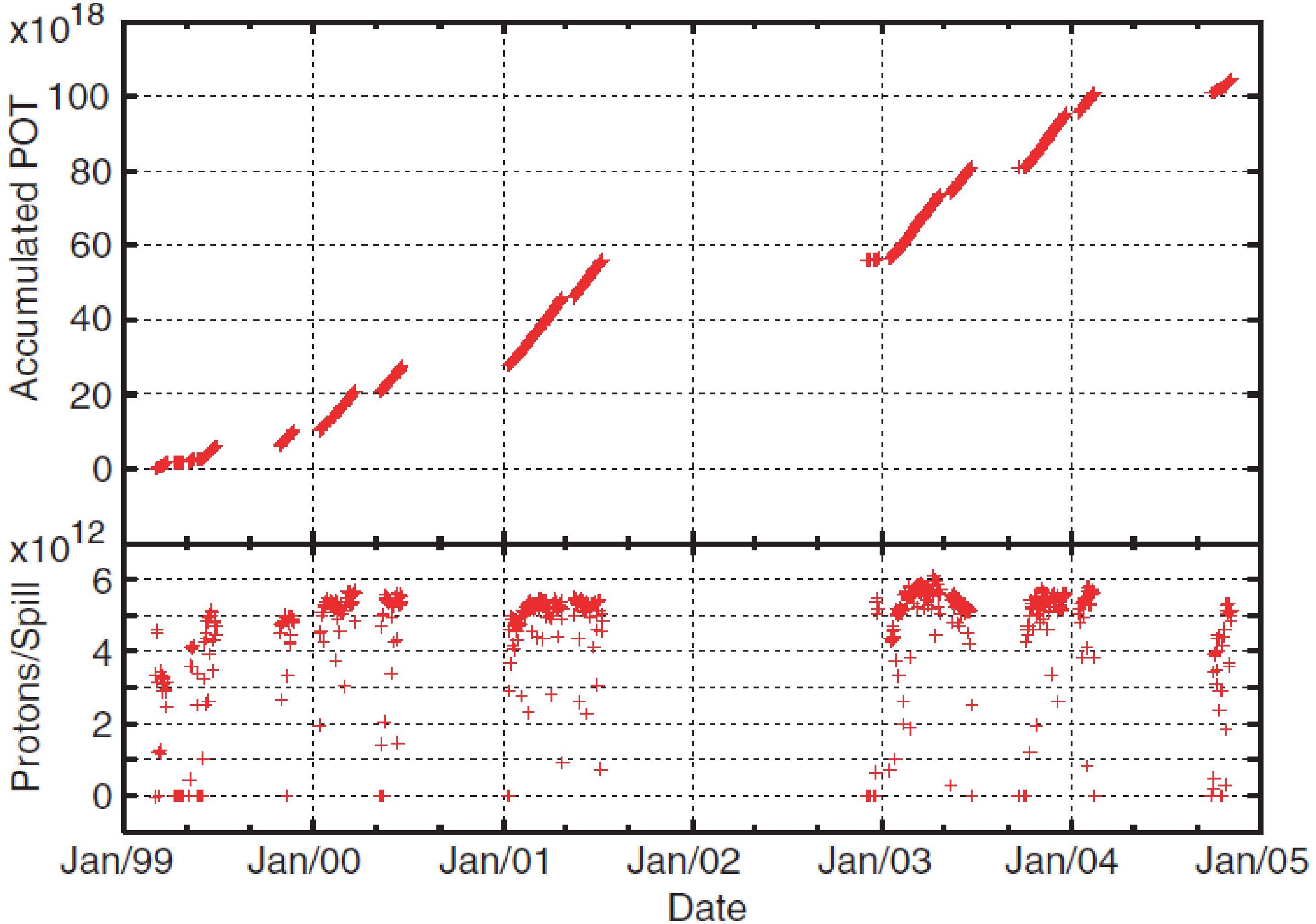


- Beam power 15 kW
- **About 1 ν event every 2 days at SK**

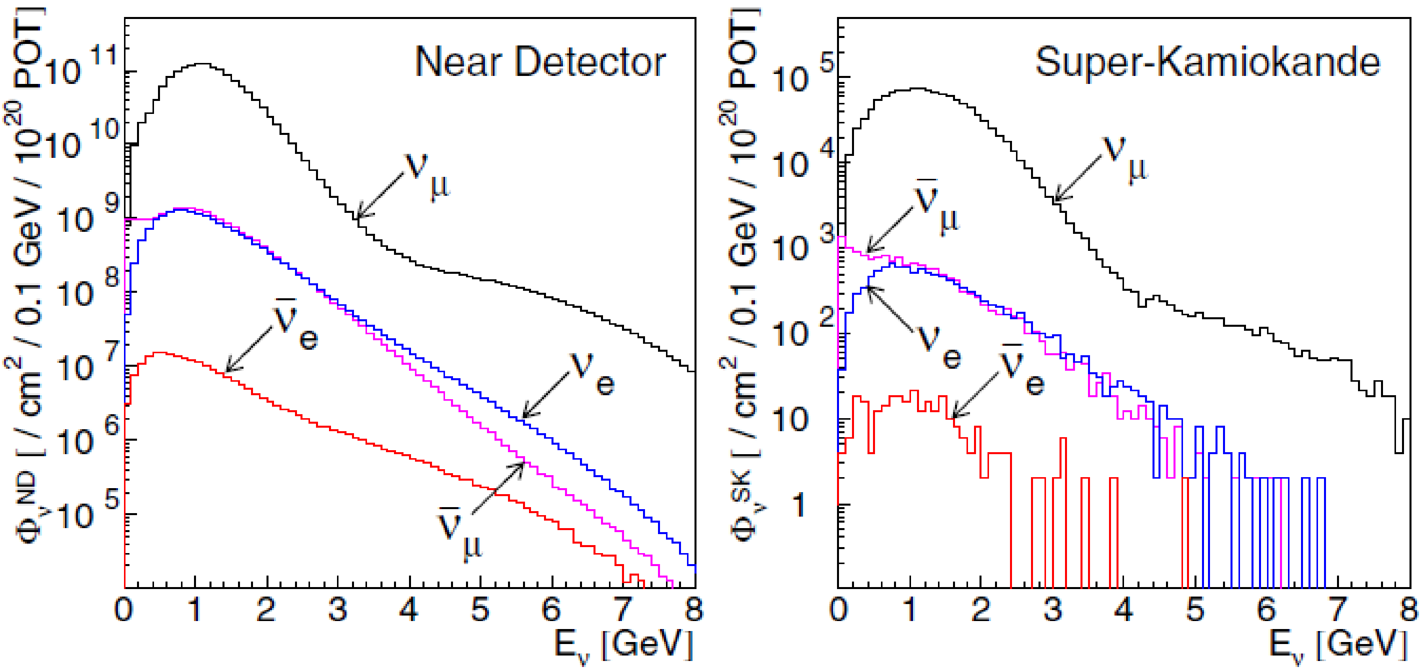
References: Phys. Rev. D 74, 072003 (2006)
T. Nakaya's talk at Neutrino 2004

K2K data taking

Protons on target: 1.049 10^{20} accumulated



The K2K beam

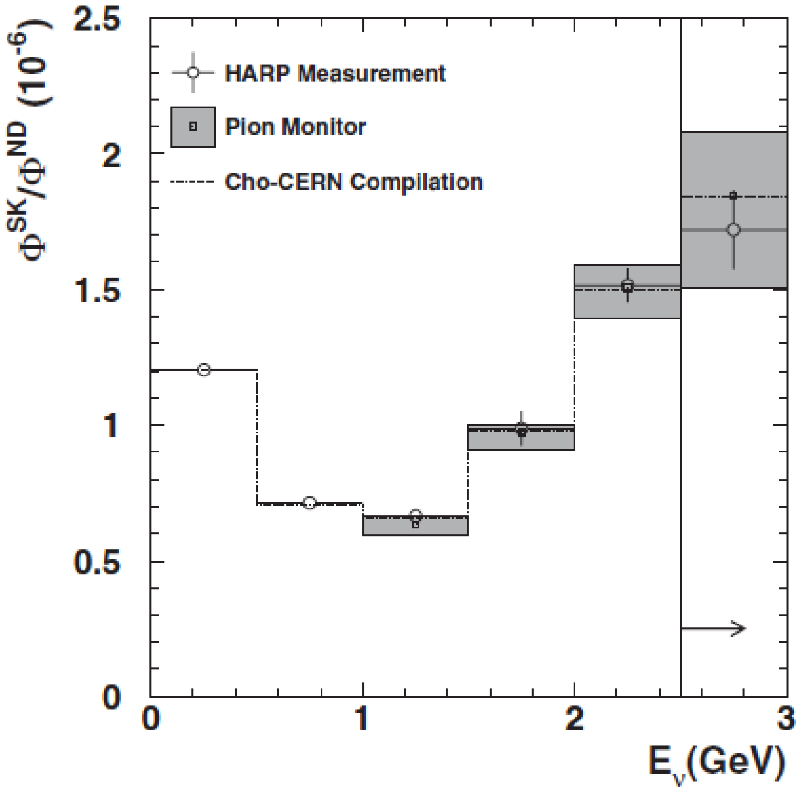


- Finite size of decay volume
- Close proximity of ND to decay volume (300m)
  - The spectra at 300 m and SK are different
  - Flux ratio Near/Far not just $1/L^2$
  - Nead simulation & measurements to obtain **energy dependant Far/Near ratio**

$$R^{F/N} = \frac{\Phi^{SK}(E_\nu)}{\Phi^{ND}(E_\nu)}$$

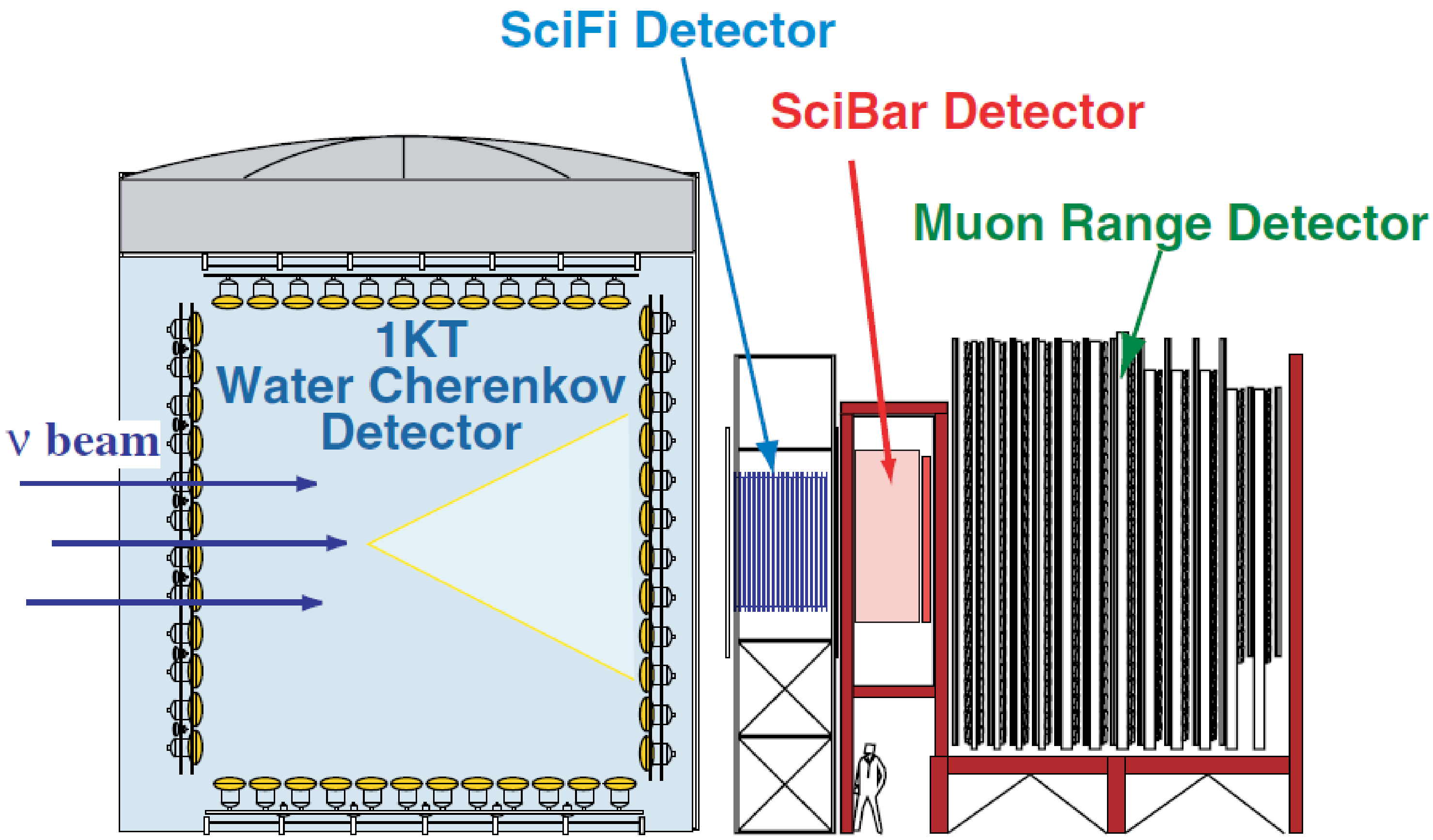
Far/Near ratio calculation

- Rely on beam Monte-Carlo to provide F/N ratio
- Need accurate modeling of hadron production at target
  - MC simulations known to have potentially large errors
- Monte-Carlo tuned & constrained thanks to
  - **PIMON measurement**: direct *in-situ* measurements of pions after target with dedicated Cherenkov detector called PIMON
  - **HARP data**: HARP (CERN PS T9 beamline) measured pion production with 12.9 GeV/c proton beam on identical Al target



- Dominant undertainty from HARP data
- Uncertainties vary from ~2%-9% per bin

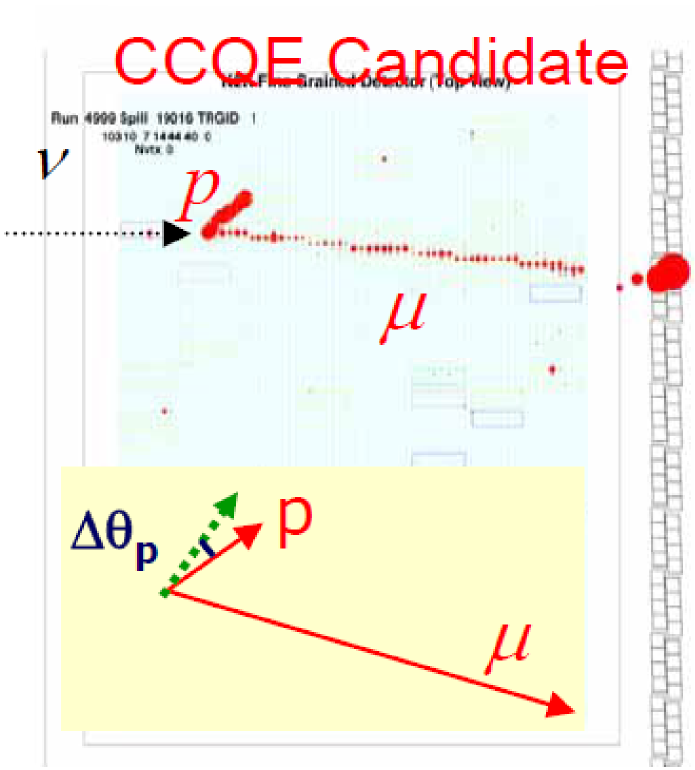
Detectors at the near site

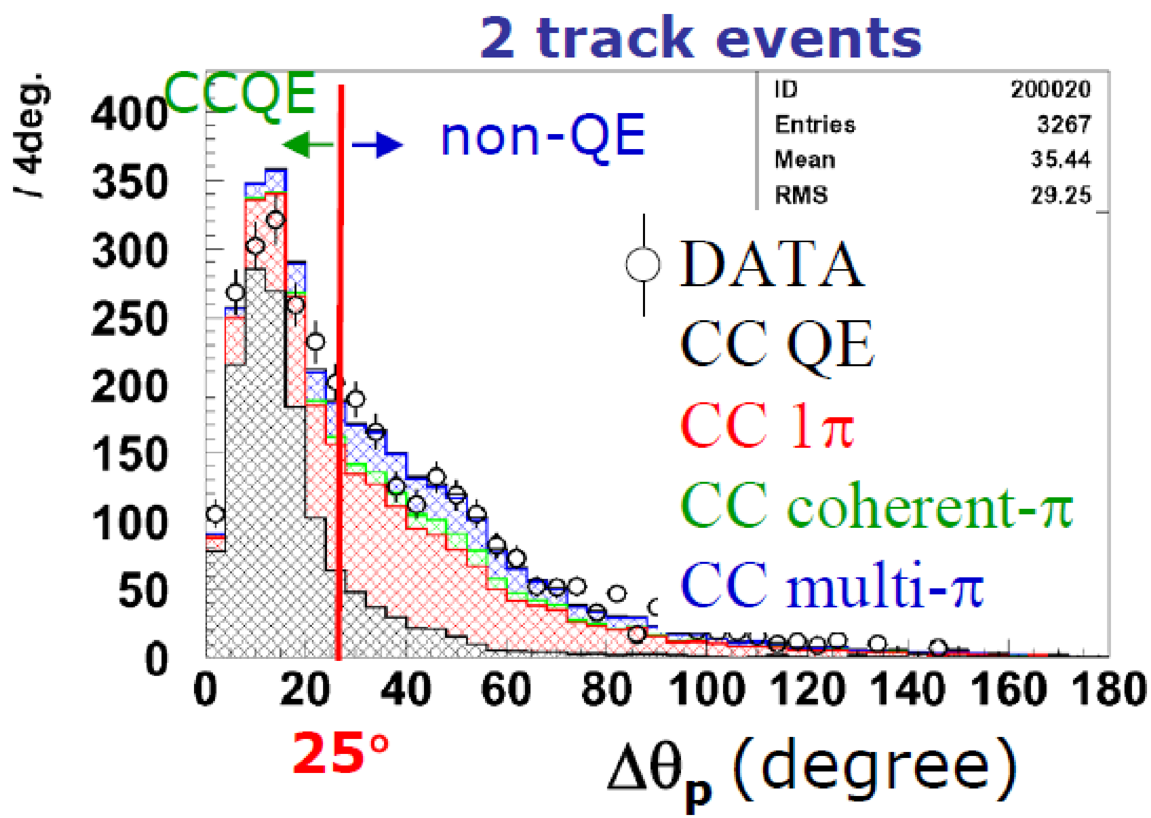


- 1000 ton water Cherenkov detector
- Scintillating Fiber/ Water sandwich detector (SciFi)
- Lead Glass calorimeter (before 2002)
- Extruded scintillator bars fine grained detector (SciBar) after 2003
- Muon range detector (MRD)

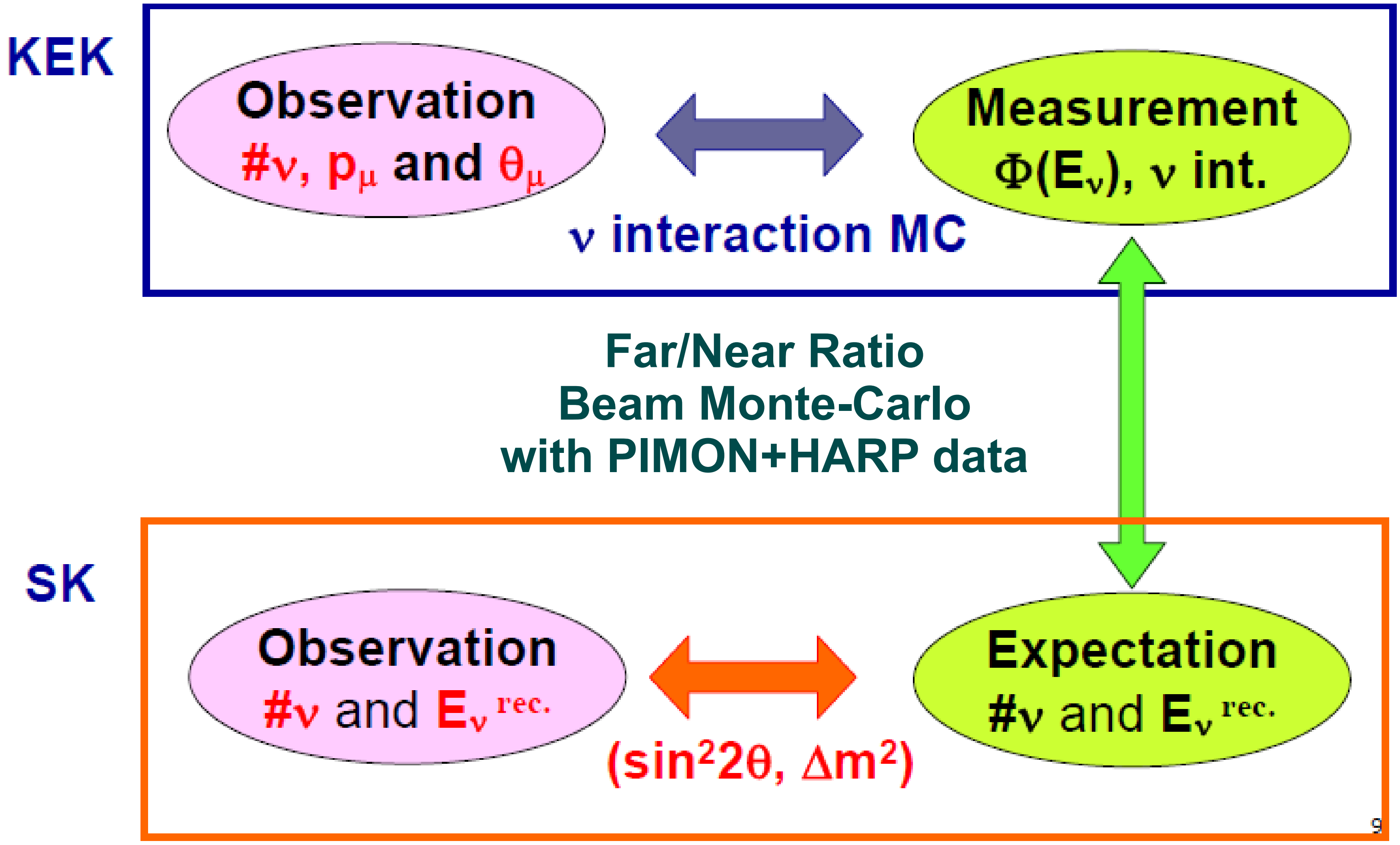
Example of QE/non QE separation in SciBar

- Fully active detector
- Can detect the proton track & fully tag CCQE events based on proton direction



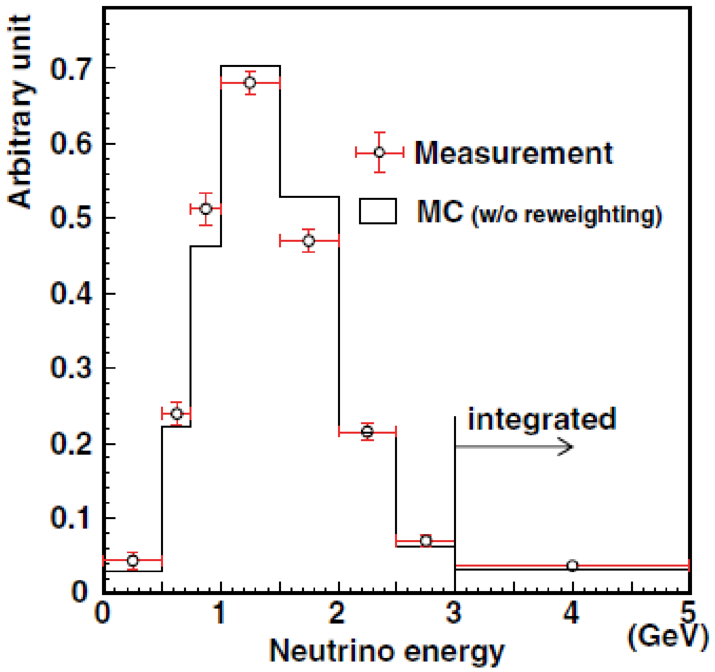


Oscillation analysis method

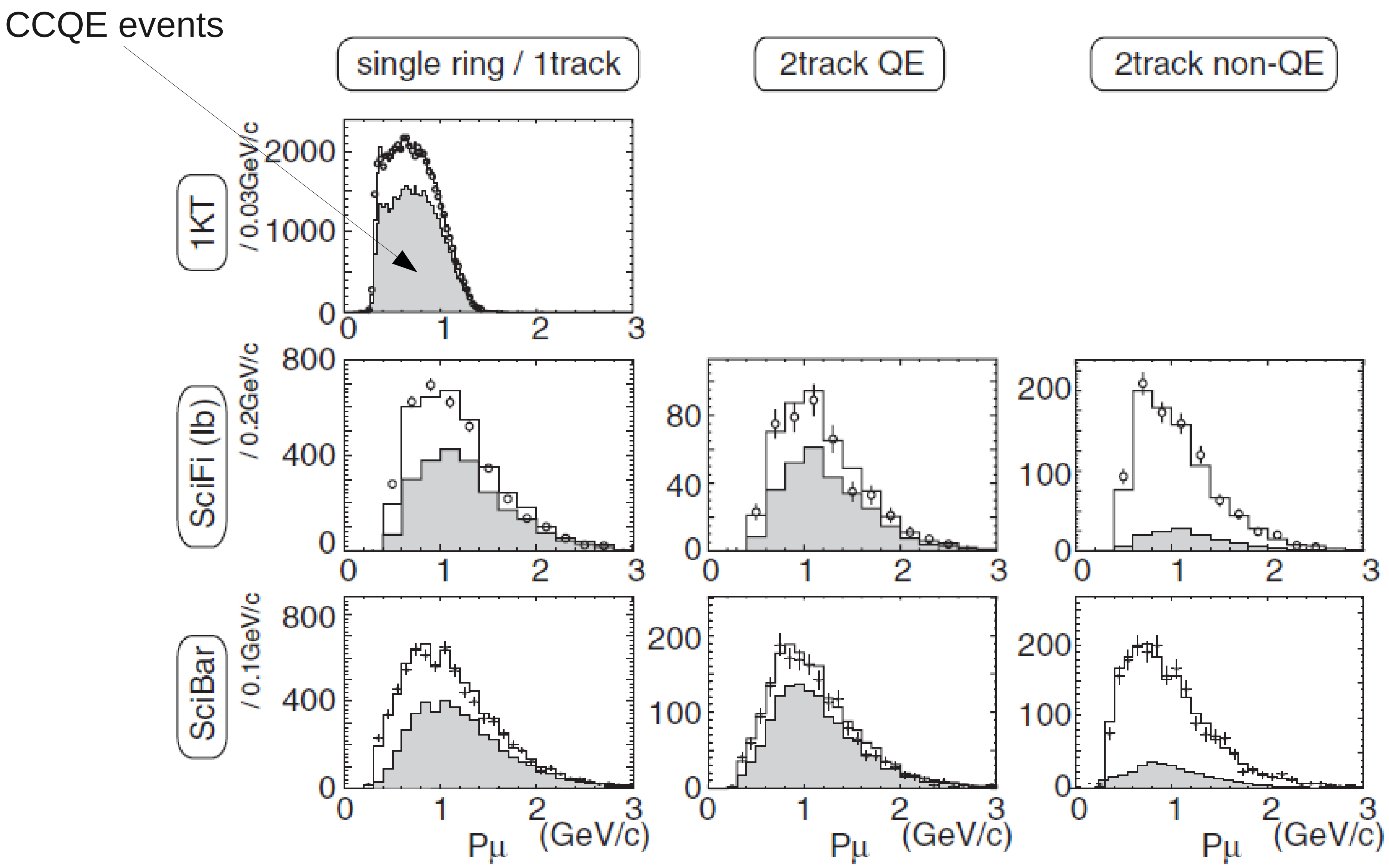


Flux measurement with near detectors

- **1KT detector** : same technology as Super-K, sensitive to low energy neutrinos
  - Select events with 1 mu-like , fully contained track
- **SciBar detector:**
  - 1 track, 2 track QE events, 2 track non QE with one muon track
- **SciFi detector**:
  - 1 track, 2 track QE events, 2 track non QE with one muon track
- Combined fit of (P_μ,θ_μ) distributions, adjusting 8 flux MC reweighting parameters and the non-QE/QE fraction

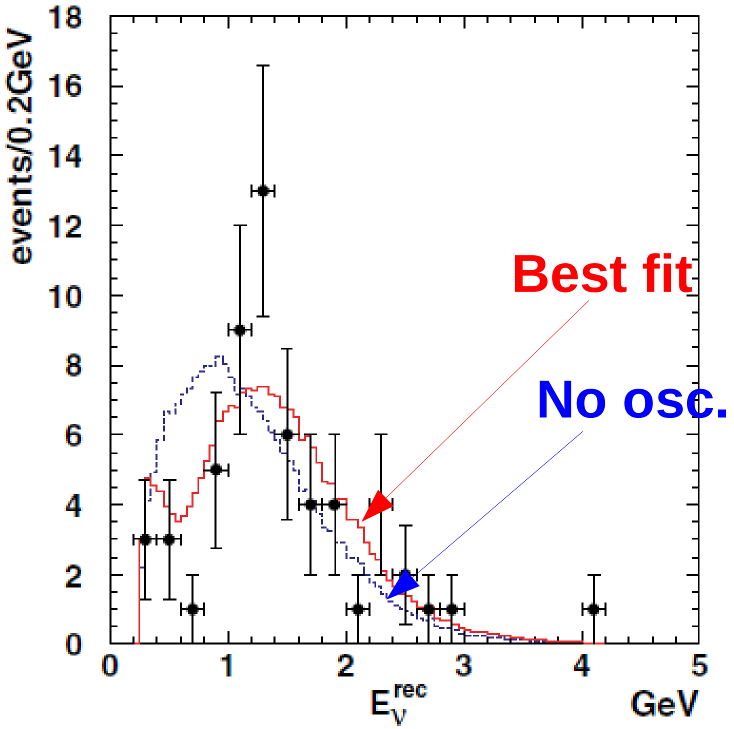


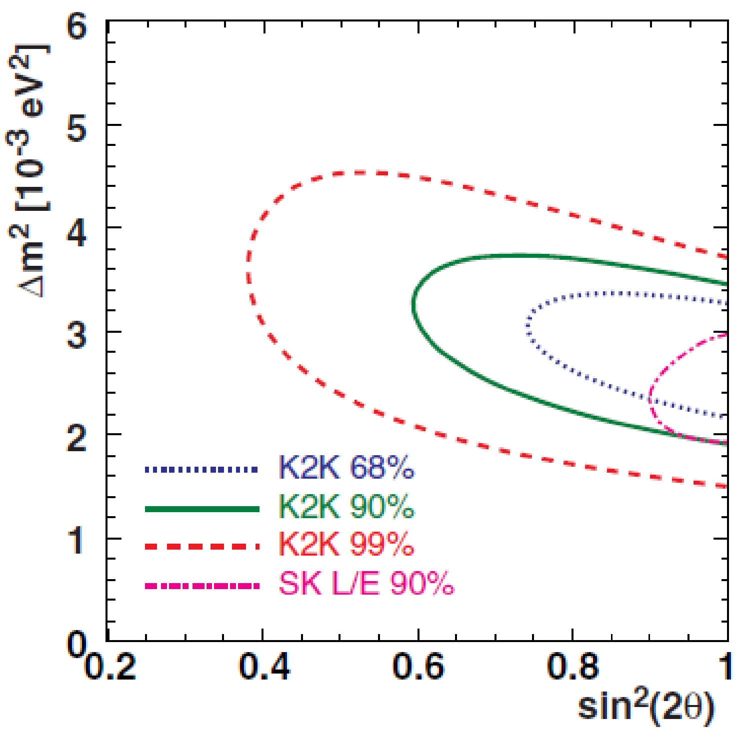
Combined Pμ after flux fit



K2K results on ν_μ disappearance

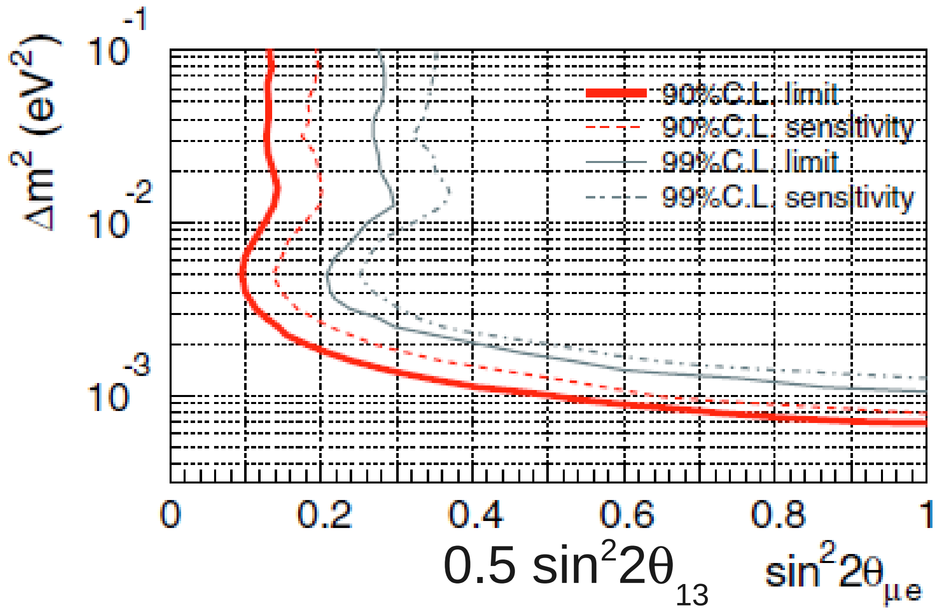
- Select mu-like events in SK's fiducial volume, in time with beam
  - Observe **112 events**
  - **58 of those** are 1 ring and used for energy spectrum reconstruction
- Extrapolating from 1KT detector, $158.1^{+9.2}_{-8.6}$ events were expected if no osc.
- Full fit to observed spectrum shape + norm : $(\Delta m^2_{23}, \sin^2 2\theta_{23}) = (2.55\ 10^{-3}\ \mathrm{eV}^2, 1.19)$





K2K ν_e appearance results

- Using full data set
- Search for ν_e appearance: Single ring, e-like events in SK
- Backgrounds:
  - beam ν_e events from ν_e contamination
  - π^0 production by neutral current events with π^0 faking single ring e-like event
  - These are the main backgrounds in T2K
  - Special e/π^0 separation algorithm used for the first time in SK data
- In K2K systematics were very large (>15%)
- **1 event observed in SK**
- **0.8 expected background events**
- **Not competitive with Chooz bound**
- Jacques was J. Argyriades's thesis supervisor on this particular topic

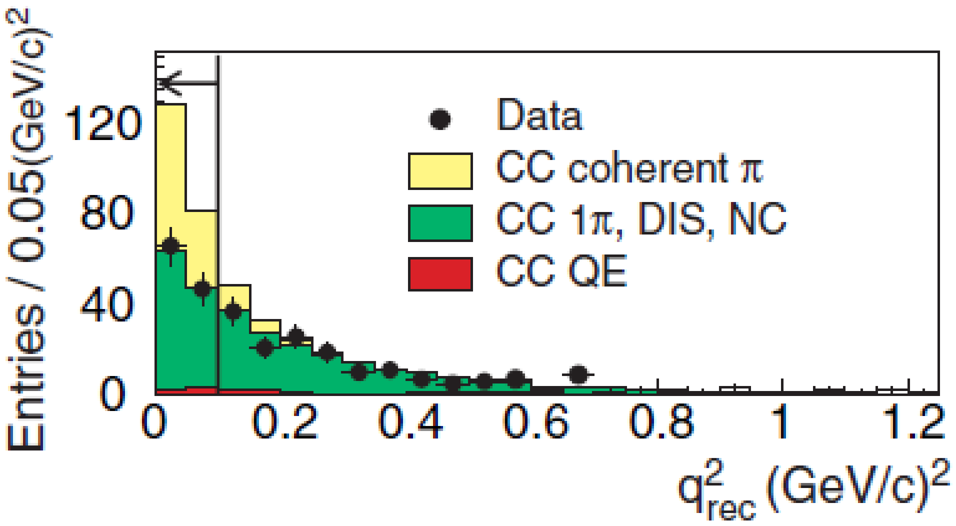


Results on CC coherent pion production

$\nu + A \rightarrow \mu^- + \pi^+ + A$

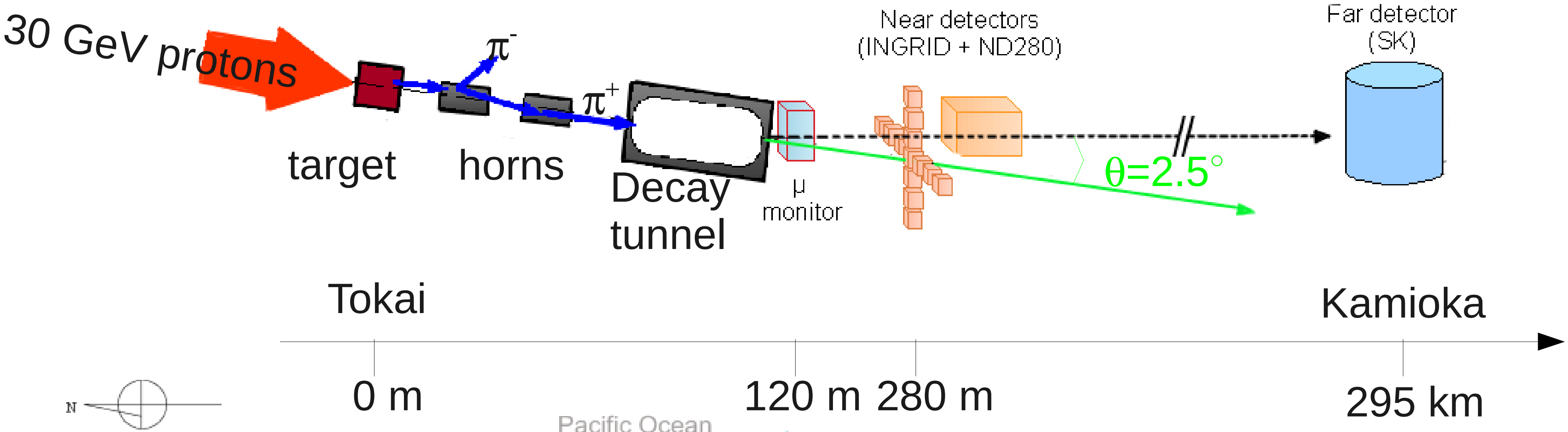
Phys. Rev. Lett. 95, 252301 (2005)

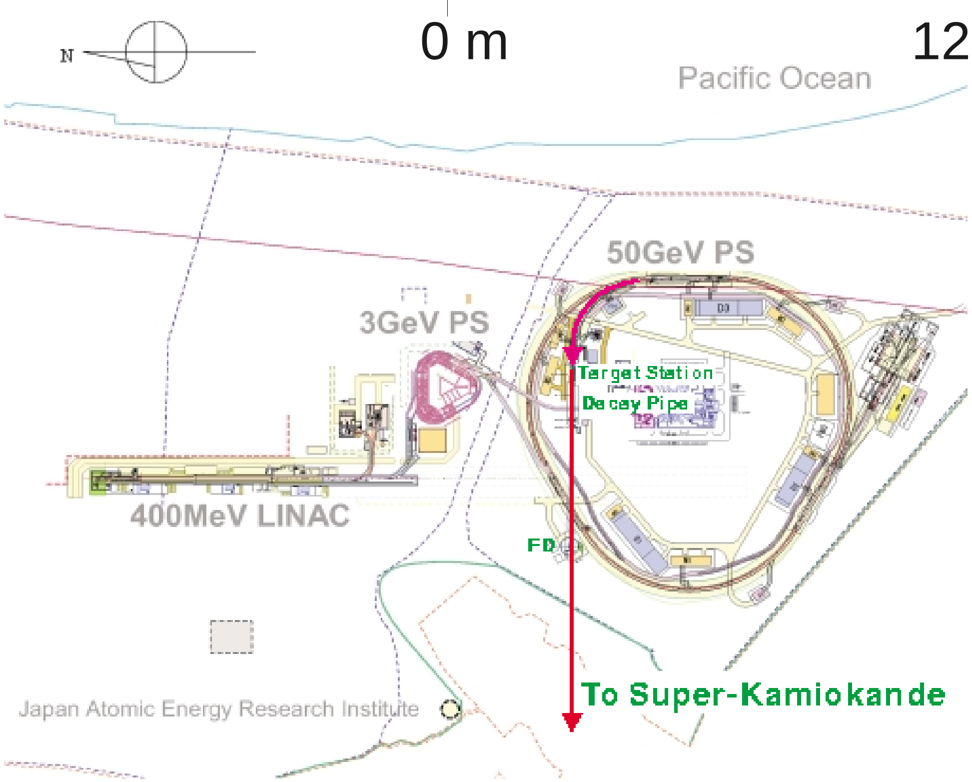
- K2K observed no evidence of this interaction mode in SciBar data
- σ(CC coherent π) / σ(ν_μ CC) < 0.6 10^{-2}
- SciBoone also does not see it (using the same detector)

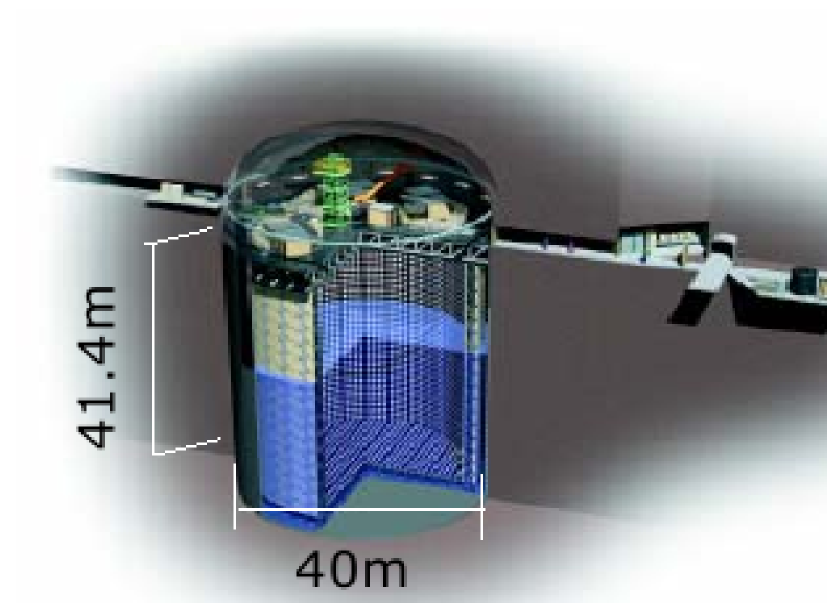


T2K

T. Kobayashi's talk at Nu 2010
T. Nakaya's talk at ICHEP 2010
F. Blaszczyk talk at ICHEP 2010

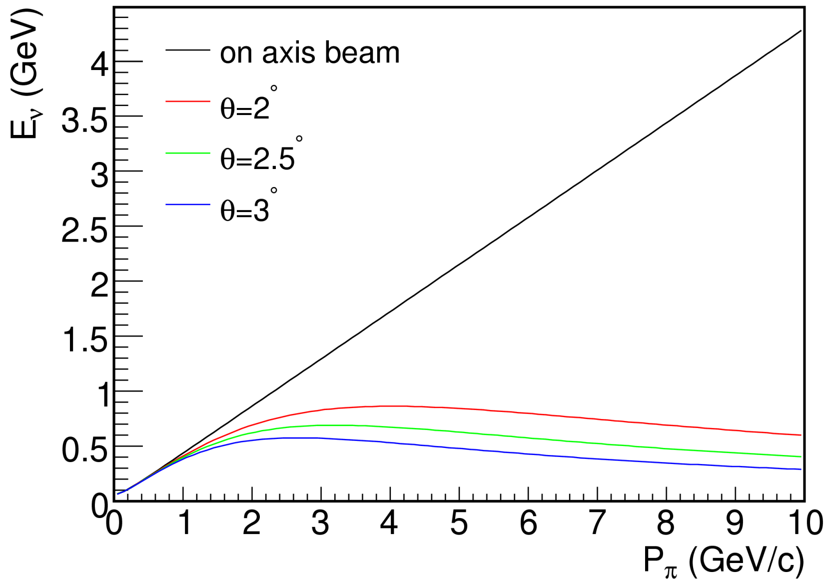


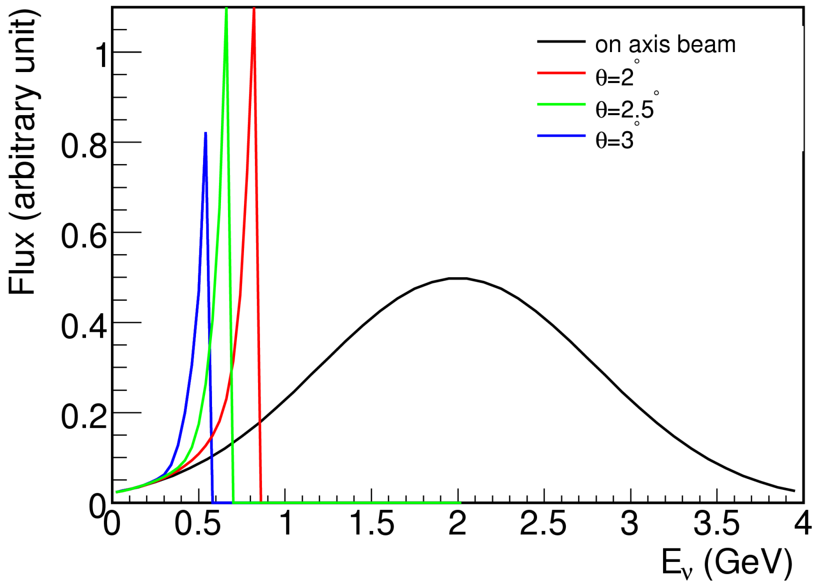




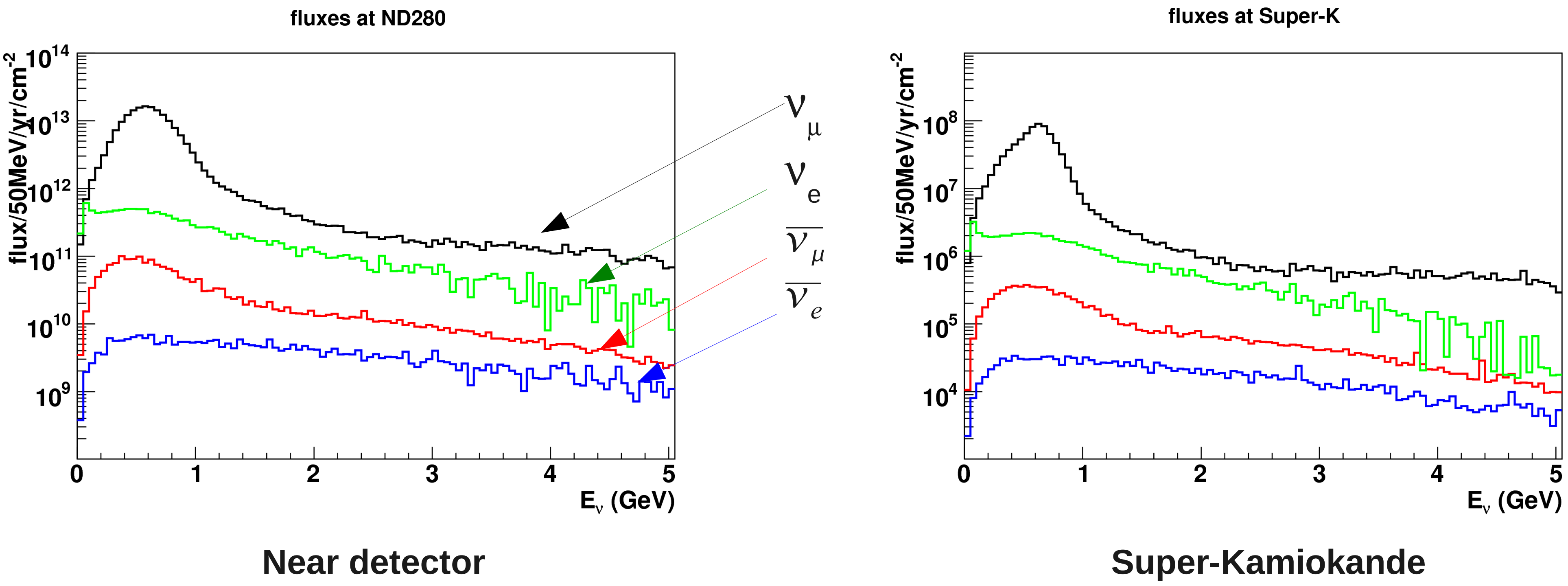
Off-axis beam

- Off-axis trick: use 2-body decay kinematics of pion decay
  - Narrow spectrum
  - No high energy tail to reduce backgrounds, lower relative ν_e contamination
- Off-axis angle set to 2.5 degrees
  - Spectrum peak at ~ 600 MeV, **exactly at the first maximum of the oscillation**
- **Very precise measurement of atmospheric osc. parameters**
- **Search for ν_e appearance in beam caused by θ_{13}**



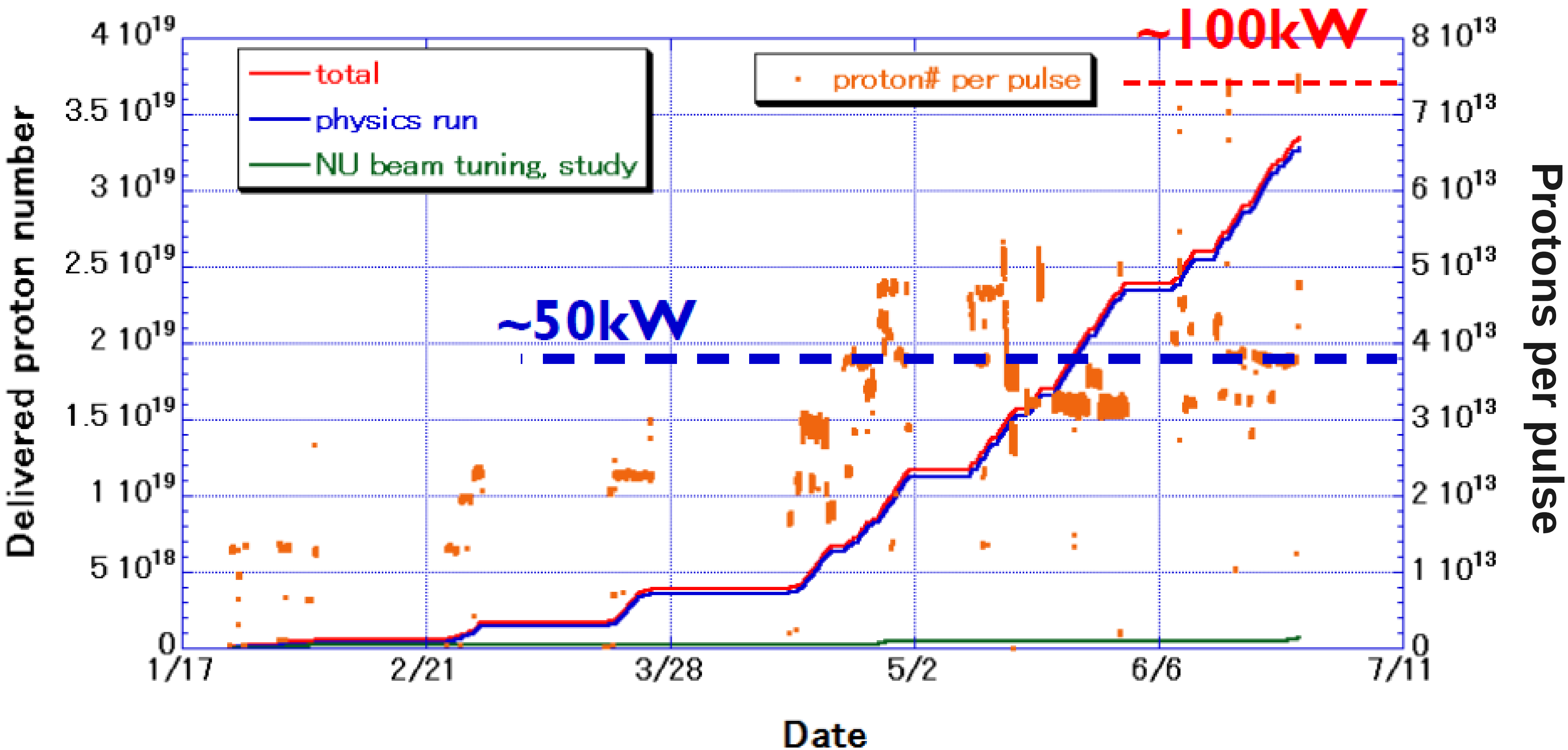


T2K beam spectra



- ν_μ fluxes different at ND280 & SK
  - Need precise beam MC, along with hadron production measurements (NA61)
- ν_e fluxes fairly similar at ND280 & SK
  - Need ND280 to measure contamination at SK (irreducible background)

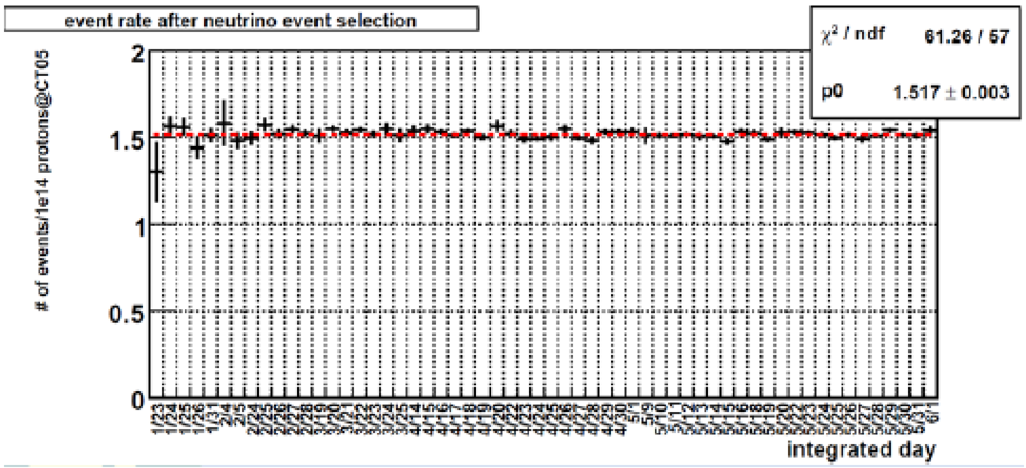
Beam power & data taking so far

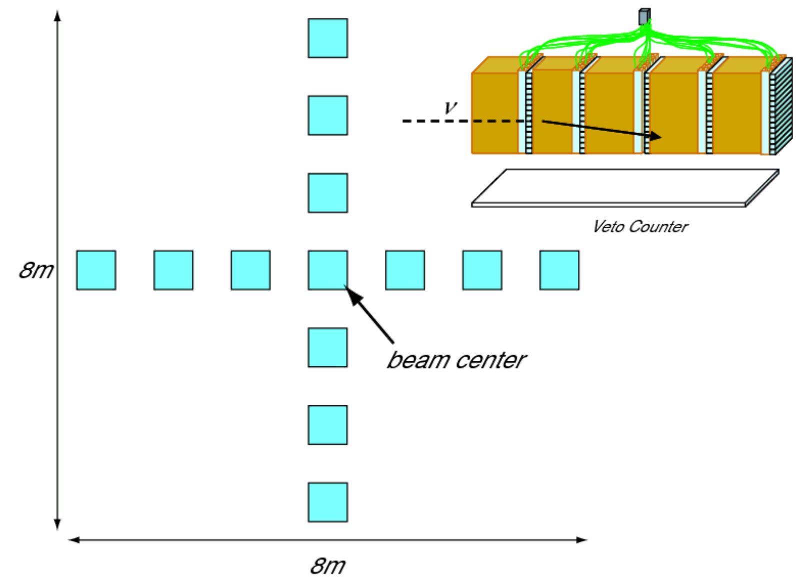


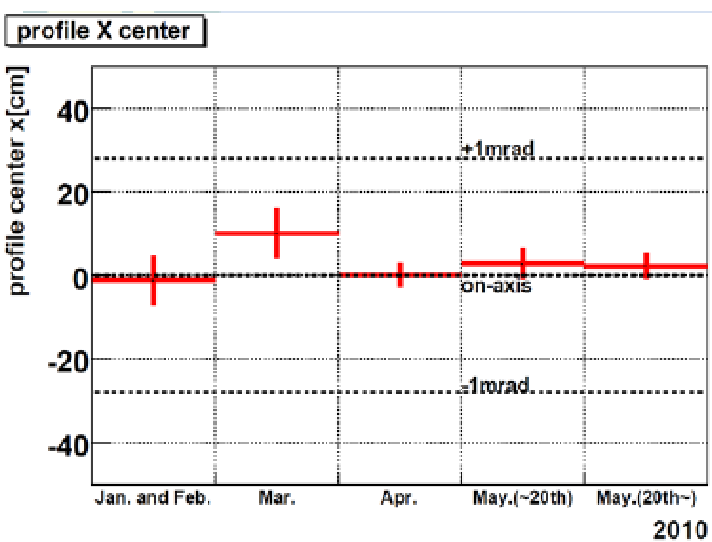
- 3.28 10^{19} protons on target for physics (as of June 2010)
- Continuous run at 50 kW
- Succesful trial run at 100 kW
- Upgrade during Summer-Fall 2010

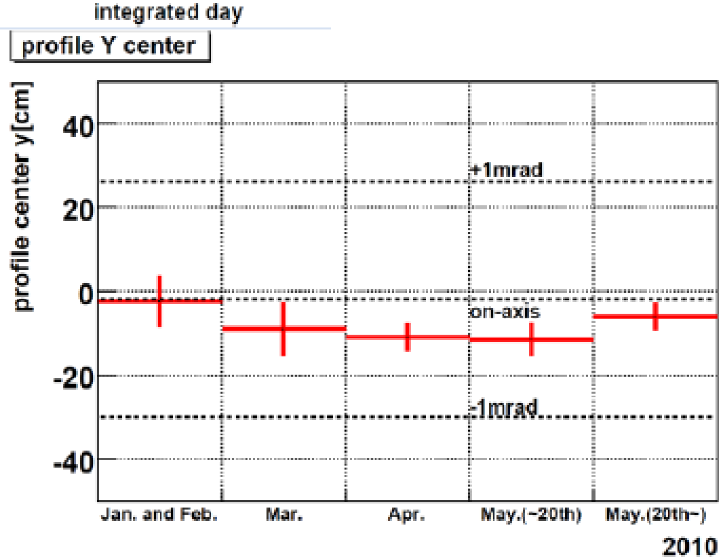
On-axis near detector INGRID

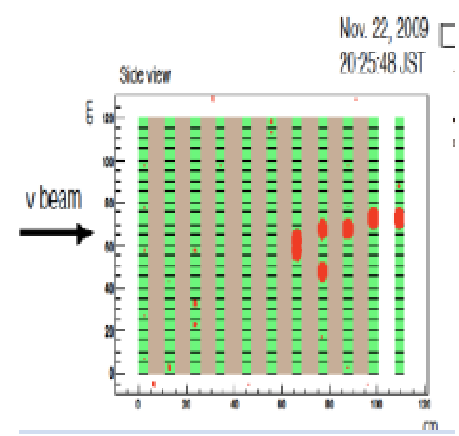
- Scintillator tracker & iron sandwich
- On axis: control the beam's “aim”
  - Beam centered to < 1mrad, well within requirements



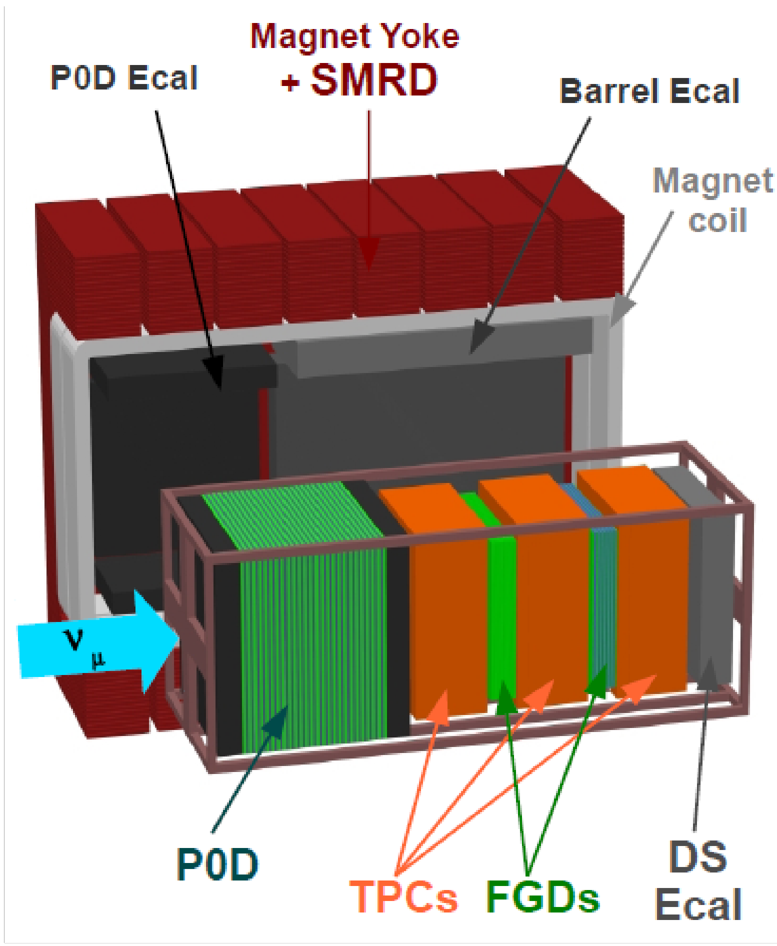








Off-axis near detector

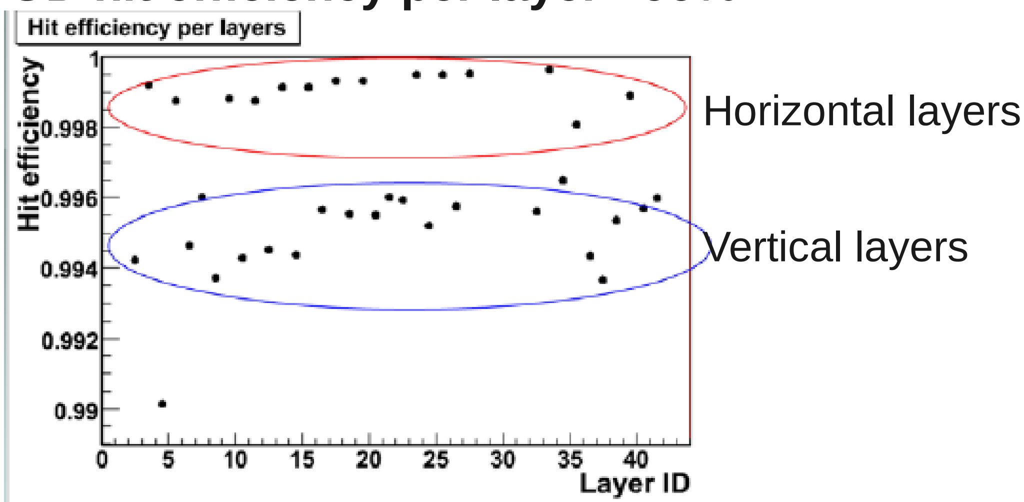


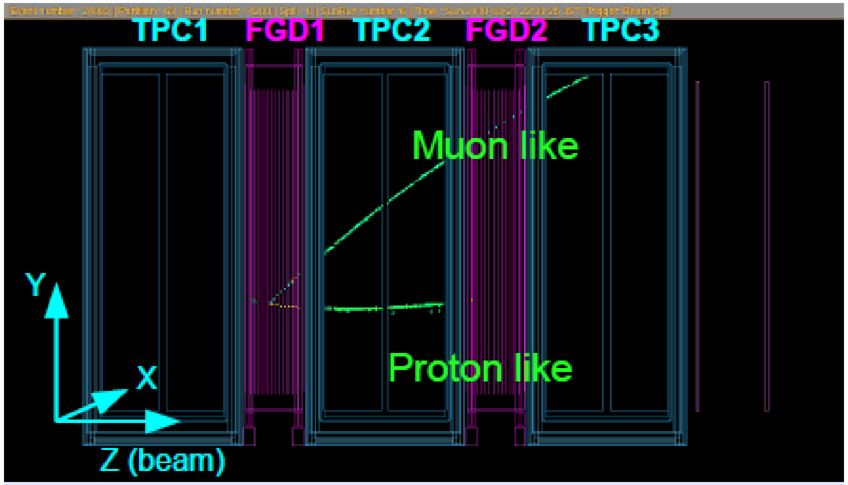
- 2.5 deg off-axis, 280 m from target
- Goal: measure flux, ν_e fraction, beam direction, ν interaction cross-sections
- **POD : π^0 detector**, measure NC production
  - lead+scintillator bars.
  - Interspersed with water passive target
- **Tracker:**
  - **FGD: fine grained detector**
    - Plastic scintillator bars in x-y planes
    - Passive water target in back FGD
  - **TPC: three TPC modules**
    - Bulk Micromegas detector planes
    - Readout based on AFTER ASIC
    - Particle identification based on dE/dX
    - Momentum resolution <10% at 1 GeV
  - **EM calorimeter (ECAL)**
  - **Side Muon rande Detector (SMRD)**
- **UA1 magnet**: 0.2T magnetic field

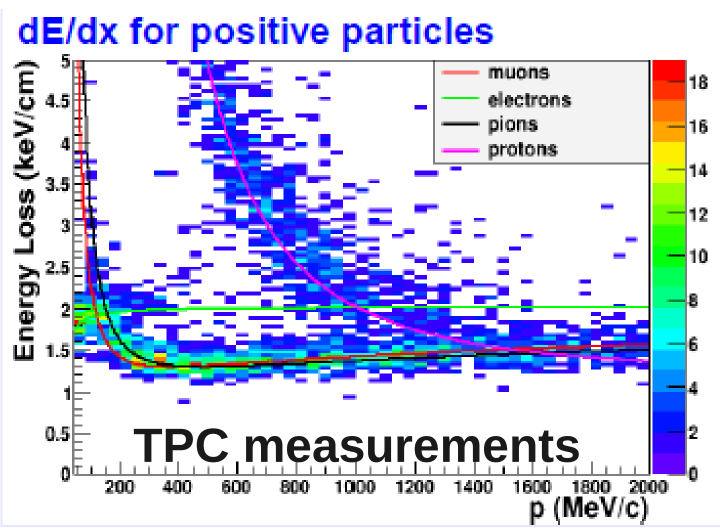
ND280 results

- All detectors commissioned & taking data
- Barrel ECAL installed last summer

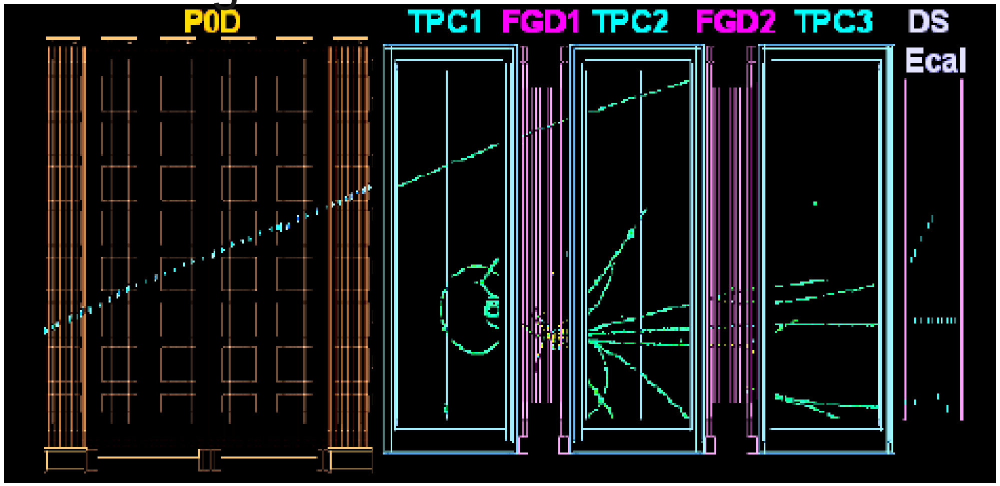
FGD hit efficiency per layer >99%







Entering muon + DIS ν event



Event selection at SK

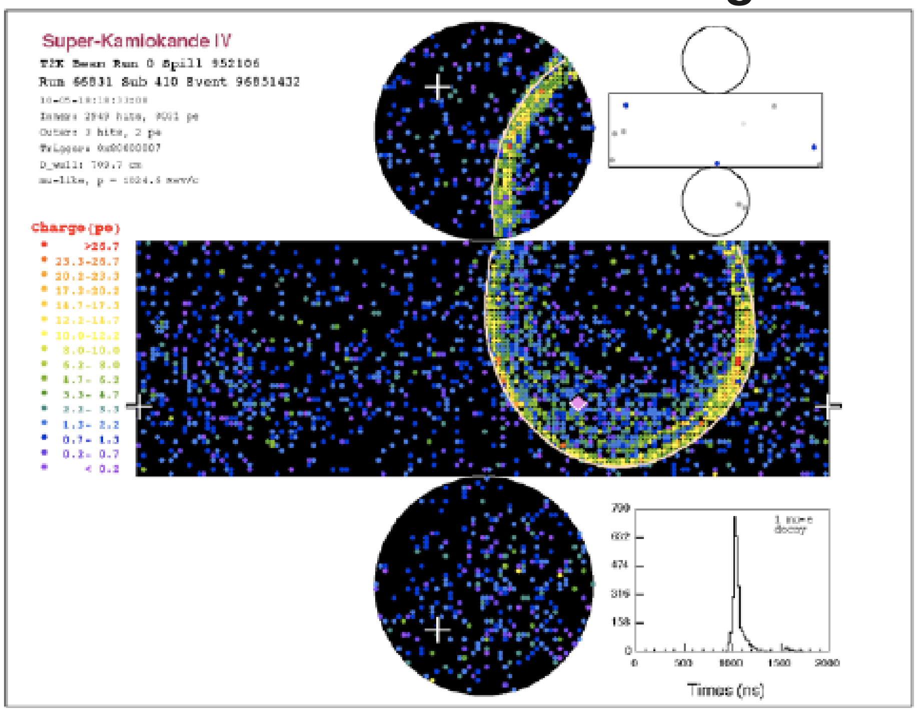
- Select neutrino beam candidates with GPS timing
- SK has been under study for 14 years
  - Data selection cuts are already decided
  - Unbiased analysis
  - 22 fully contained beam events as of May 2010

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

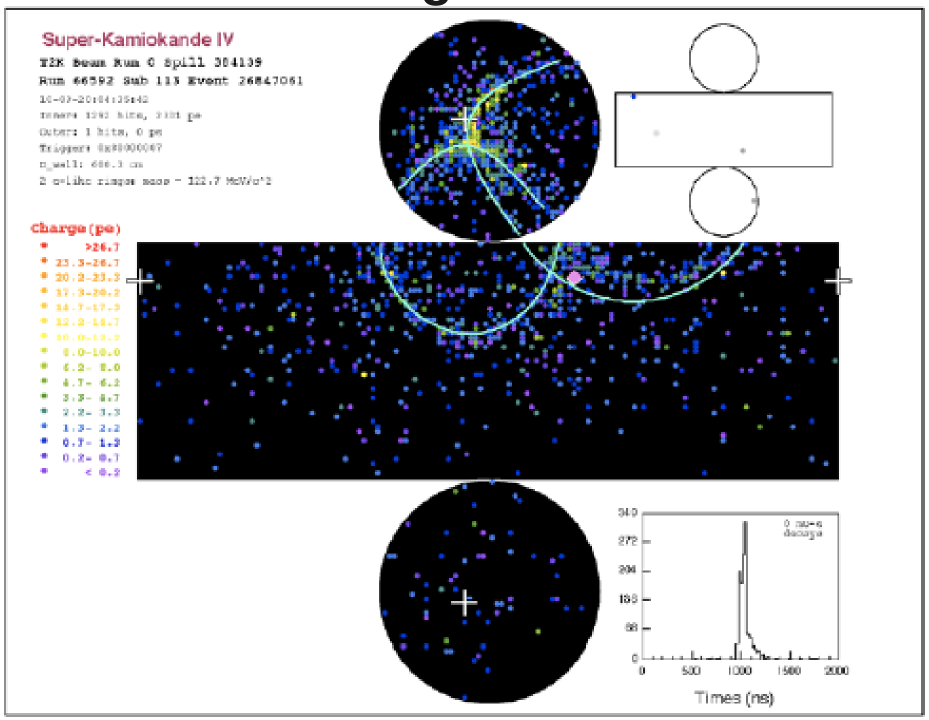
Main backgrounds: π^0 production & beam ν_e contamination

Event displays

Event with 1 mu-like ring



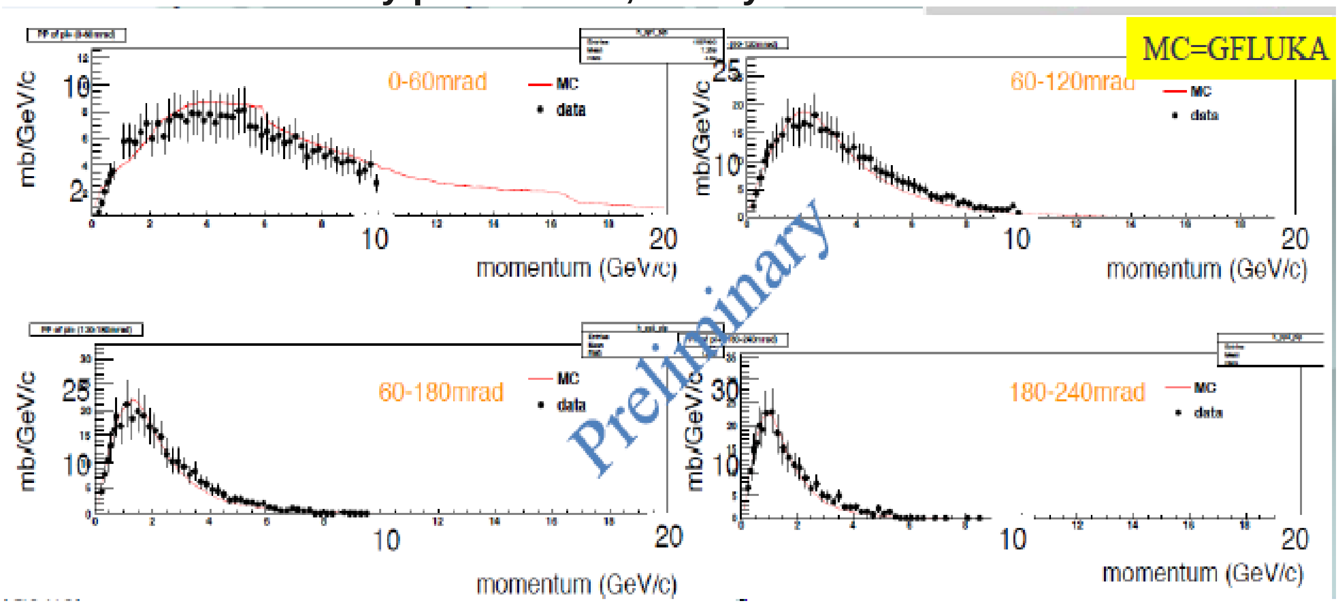
2 ring event

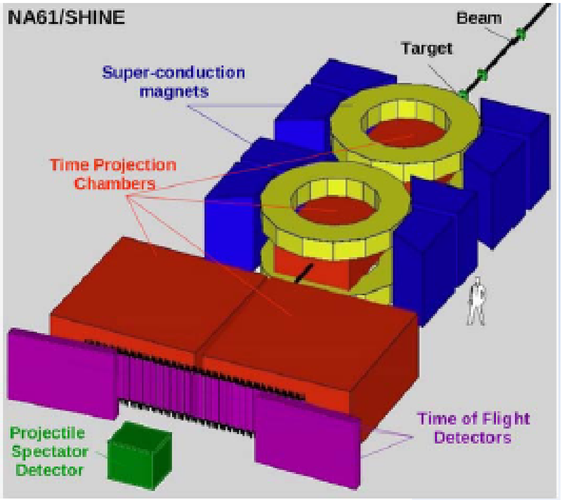


Extrapolation from ND280 to SK

- Strategy similar to that of K2K
- Measure ν_μ flux and ν_e contamination at ND280
- Use results in beam Monte-Carlo to extrapolate the flux at SK from ND280
  - Need NA61-SHINE hadron production data to calculate "Far/Near ratio"
  - Pilot run in 2007, high statistics in 2009
  - 30 GeV protons, thin target & T2K replica target
  - Analysis in progress...

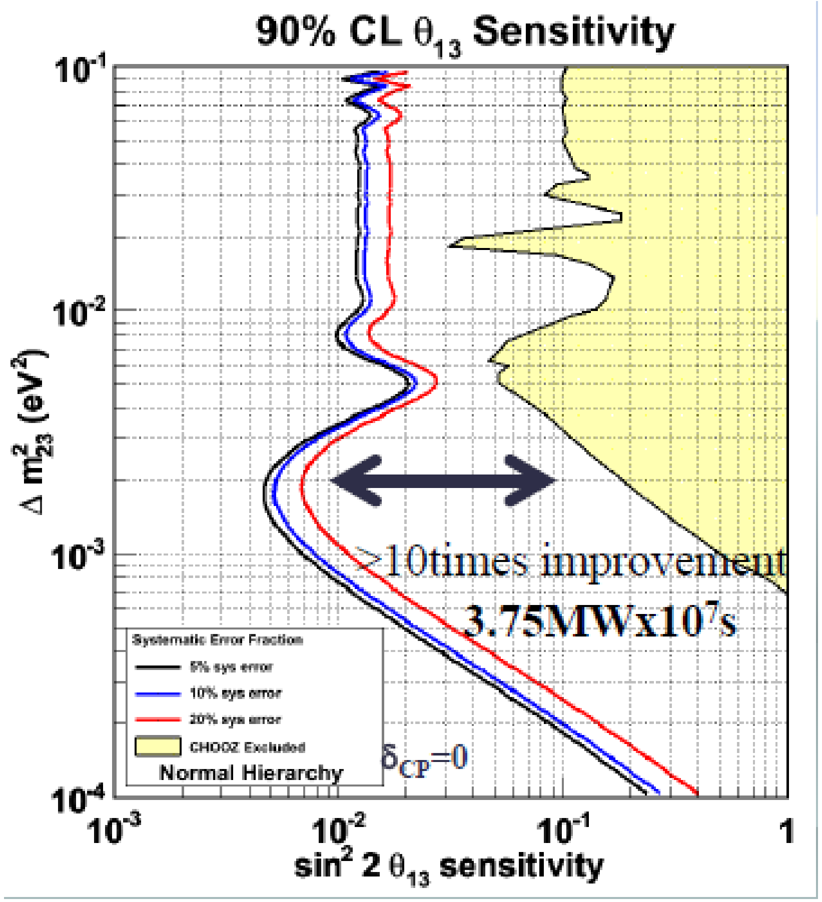
Preliminary pion results,20% systematics



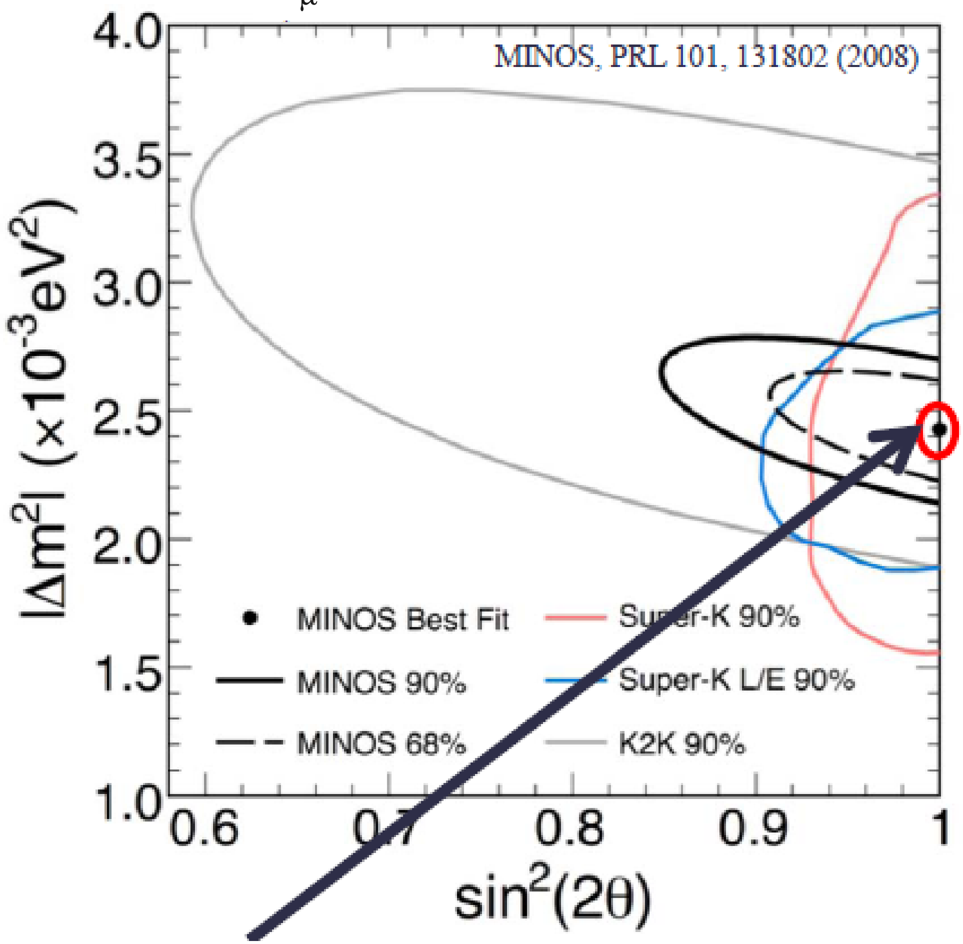


Expected sensitivity

ν_e appearance



ν_μ appearance



Goal for 3.75 MW.10^{7}s: 10^{-4} eV^2 precision on Δm^2
0.01 precision on $\sin^2 2\theta_{23}$

Conclusion

- K2K was the first long-baseline experiment
  - Confirmed SK's observation of atmospheric oscillations
  - As expected, no competitive result on θ_{13}
  - Excellent learning experience for next generation experiment
- T2K is now fully constructed, commissioned & taking data
  - Beam power ~ 50 kW with trials at 100 kW
  - Now increasing from 100 kW to design power
  - Aim to accumulate 0.75 MW x 5 10^7 s = 3.75 10^7 MW s
  - ν_e appearance search:
    - $\sin^2 2\theta_{13}$ down to 0.018 (3σ discovery potential), 0.008 (90% CL sensitivity) at fixed δ_{CP}
  - ν_μ disappearance :
    - 10^{-4} eV^2 precision on Δm^2 and 0.01 precision on $\sin^2 2\theta_{23}$