Status of the T2K Experiment

Jürgen Wendland
UBC

CAP 2006
June 12, 2006

- Three neutrino flavor mixing
- The T2K Experiment
  - SK
  - On-axis detectors
  - Off-axis detectors (ND280)
- Summary

Two Flavor Oscillation

– Conversion probability in vacuum

$$P(\nu_\beta|\nu_\alpha) = \langle \nu_\beta(t)|\nu_\alpha(0)\rangle^2 = \sin^2 2\theta \sin^2\left(\frac{c^3}{\hbar}\frac{\Delta m^2 L}{4E}\right)$$

➔ No mixing for massless ν's

➔ L/E must be large for small mass differences

Atmospheric neutrinos:

$$\approx (\nu_\mu \rightarrow \nu_\tau)$$

$$\Delta m^2_{\mathrm{atm}} = 1.5 - 3.5 \cdot 10^{-3}\,\mathrm{eV}^2$$

$$36.8^\circ < \theta_{\mathrm{atm}} < 45^\circ$$

Solar neutrinos:

$$\approx (\nu_e \rightarrow \nu_\mu)$$

$$\Delta m^2_{\mathrm{solar}} = 8.0^{+0.6}_{-0.4} \cdot 10^{-5}\,\mathrm{eV}^2$$

$$\theta_{\mathrm{solar}} = \left(33.9^{+2.4}_{-2.2}\right)^\circ$$

Three Neutrino Flavor Oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric neutrinos: } \theta_{23} \approx 45^\circ} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor + accelerator } \nu\text{'s: } \theta_{13} < 9^\circ} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar neutrinos: } \theta_{12} \approx 34^\circ} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

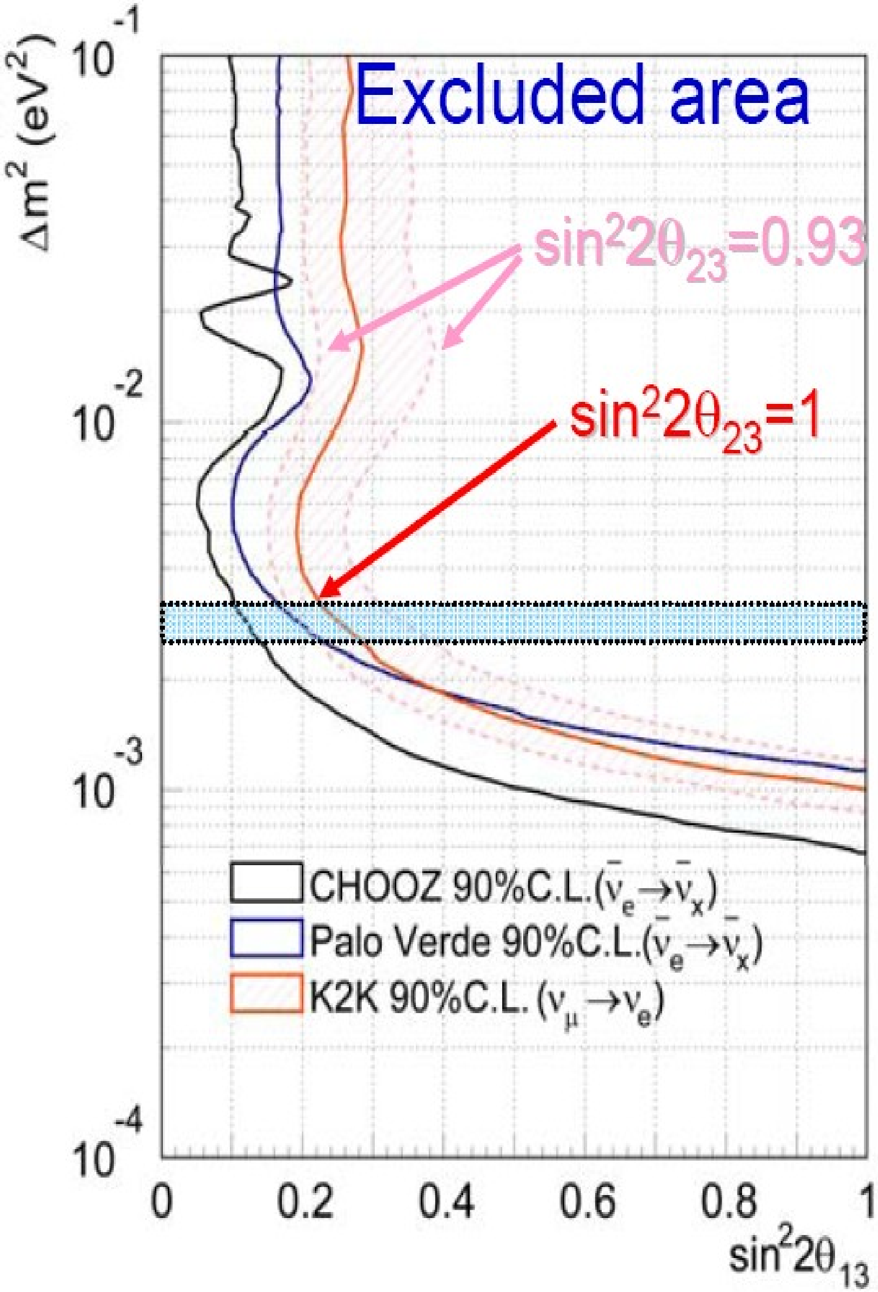
Conversion probability:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2\left(1.27\, \Delta m^2_{ij}\, L/E\right)$$
$$+2 \sum_{i>j} \Im\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin\left(2.54\, \Delta m^2_{ij}\, L/E\right)$$

Described by two Δm^2, three θ's and one CP phase (δ)

Maki-Nakagawa-Sakata Matrix

... Three Neutrino Oscillations



- θ_{13} < 9 degrees
- CP violation
  - Small in quark sector
  - θ_{13} must be > 0
  - Experimental signature:

    $$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$
  - required for leptogenesis

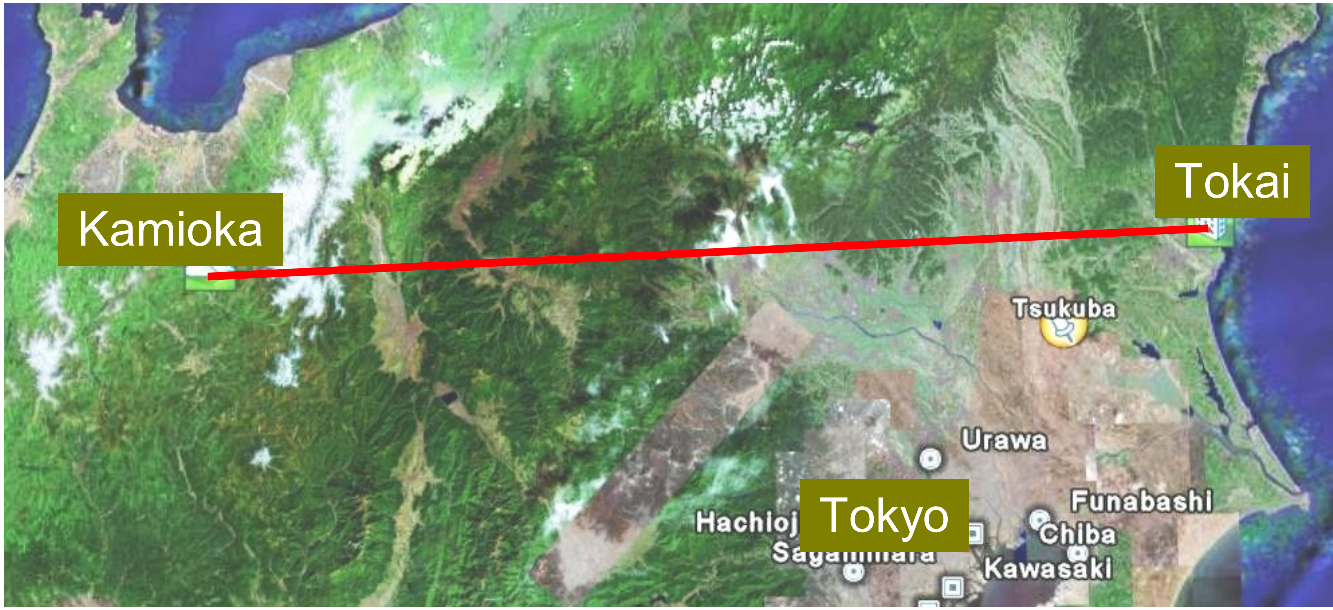
Questions

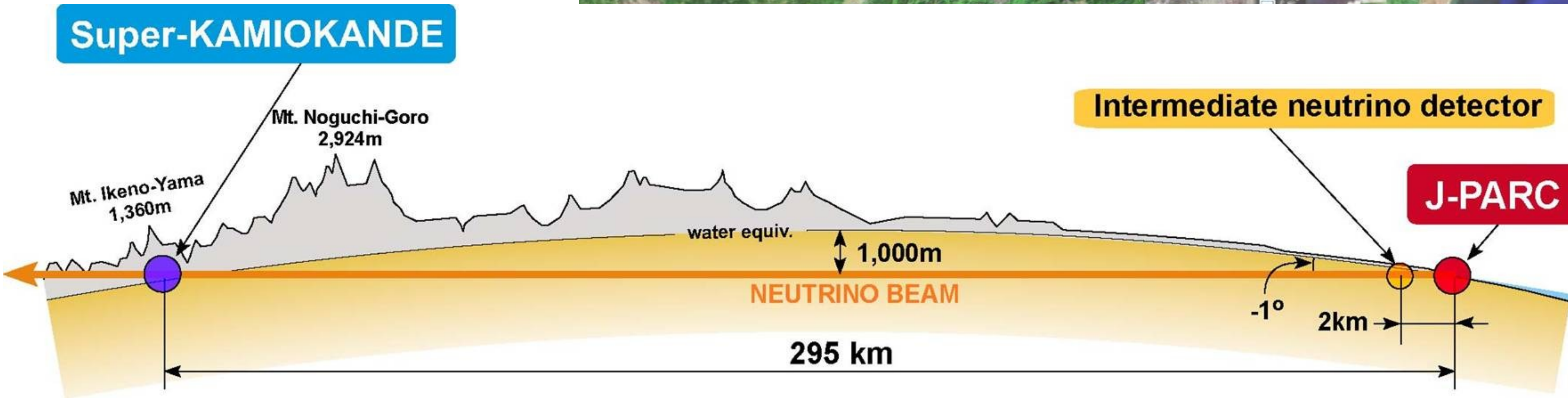
- How many neutrino flavors exist?
- What are the squared mass differences?
- What are the absolute neutrino masses?
- Are neutrinos their own anti-particles?
- What are the mixing angles?
- Does neutrino behavior violate CP invariance?
- ...

~ Tokai-to-Kamioka (T2K)

T2K

- Long baseline neutrino oscillation experiment
- JPARC 50GeV proton synchrotron
- Intense ν_μ beam
- E_ν < 1GeV
- L = 295km





T2K, Phase I – Goals

- Measure **electron neutrino appearance** (look for electron neutrinos at far detector)

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23}$$

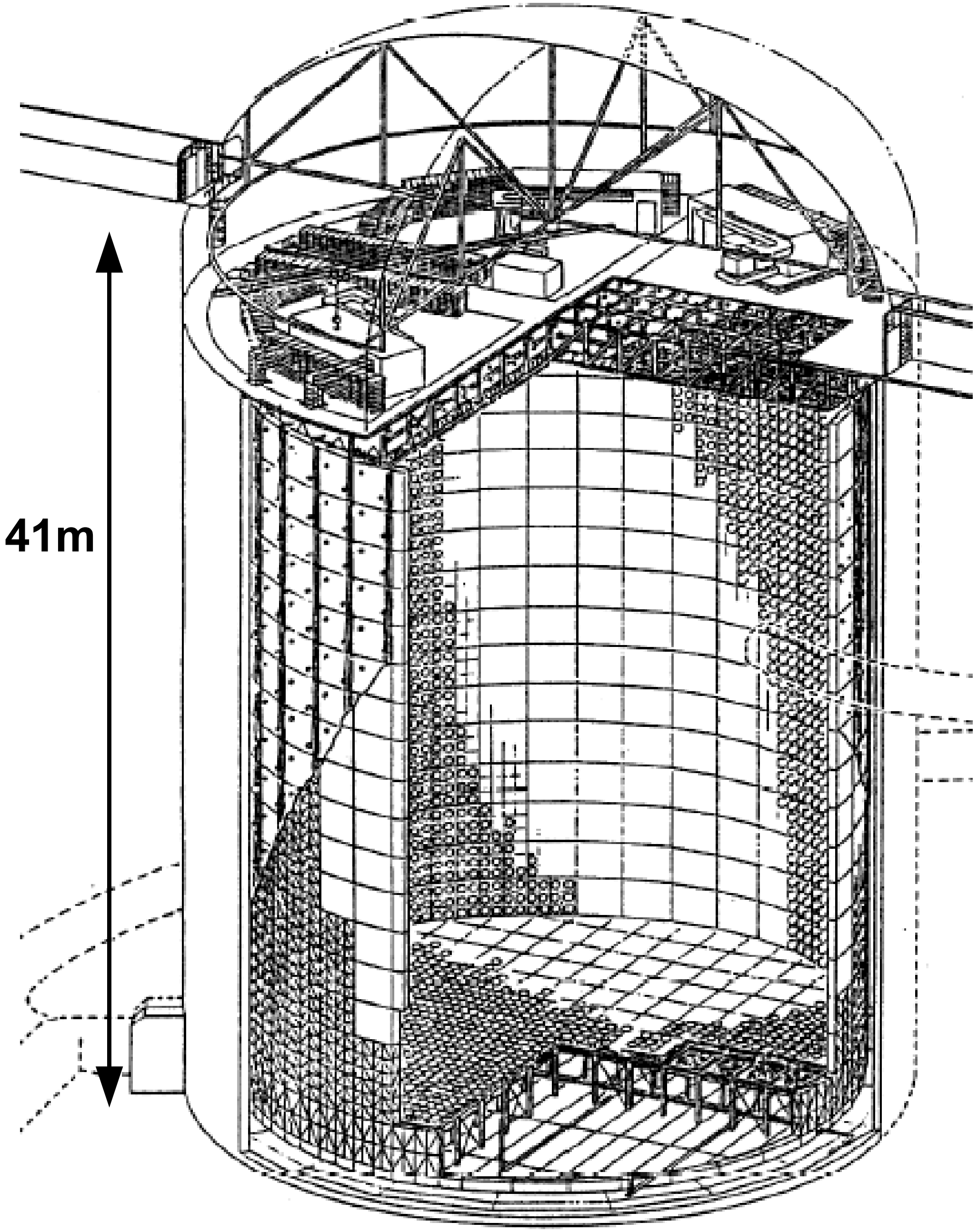
→ first detection of ν_e appearance, or improve upper limit on $\sin^2 2\theta_{13}$ by factor of 20

- Measure **muon neutrino disappearance** (find reduction in muon neutrinos at far detector)

→ Improve precision:

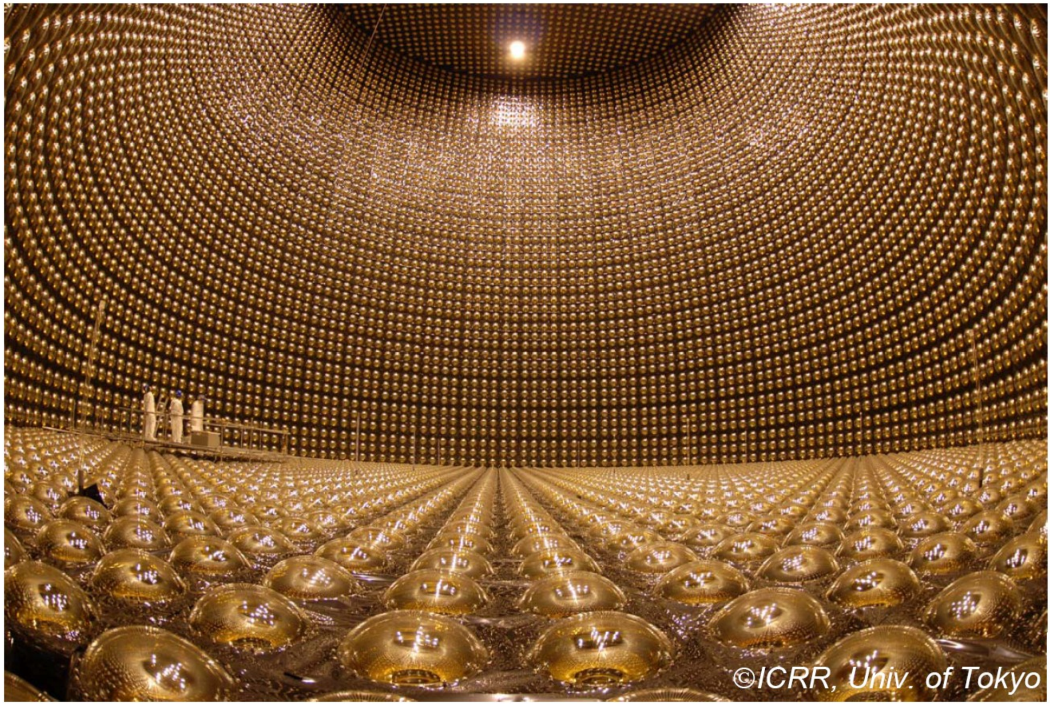
$$\sin^2 2\theta_{23} \rightarrow \approx \pm 1\% \qquad \Delta m^2_{23} \rightarrow \approx \pm 2\%$$

The Far Detector

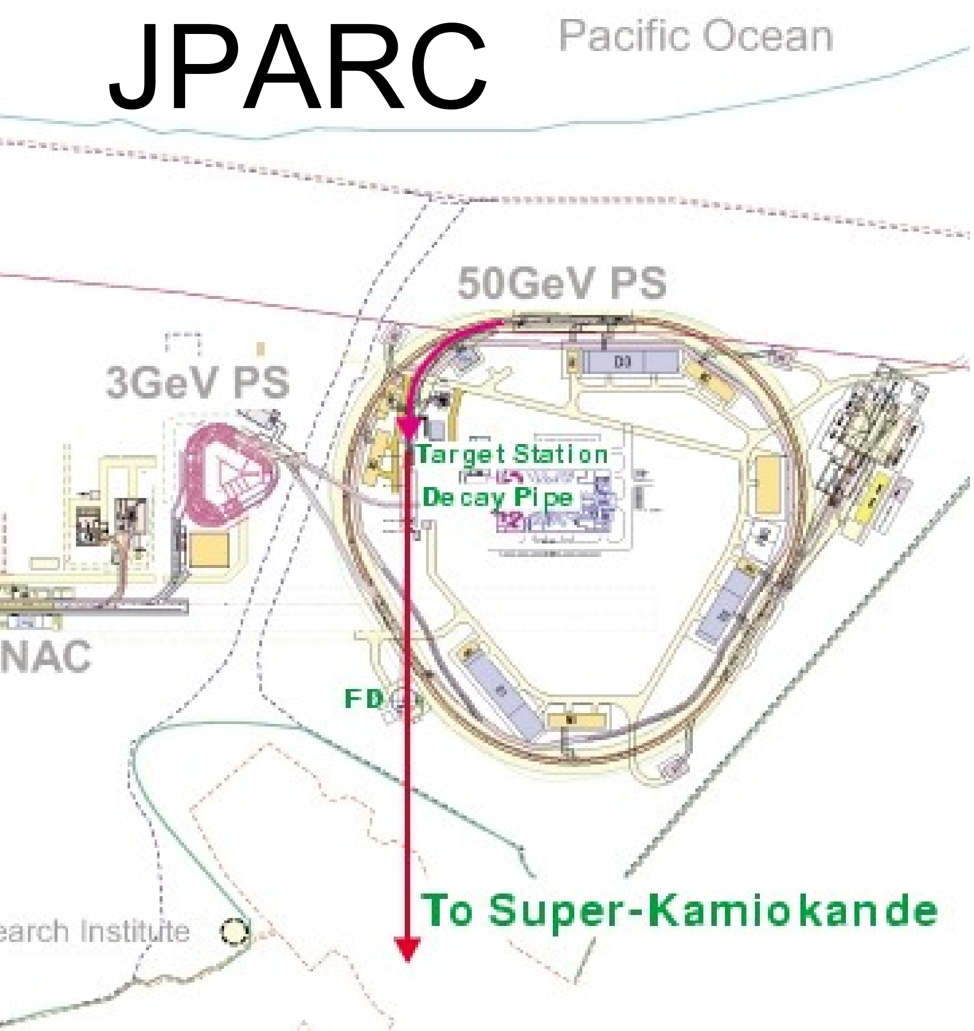


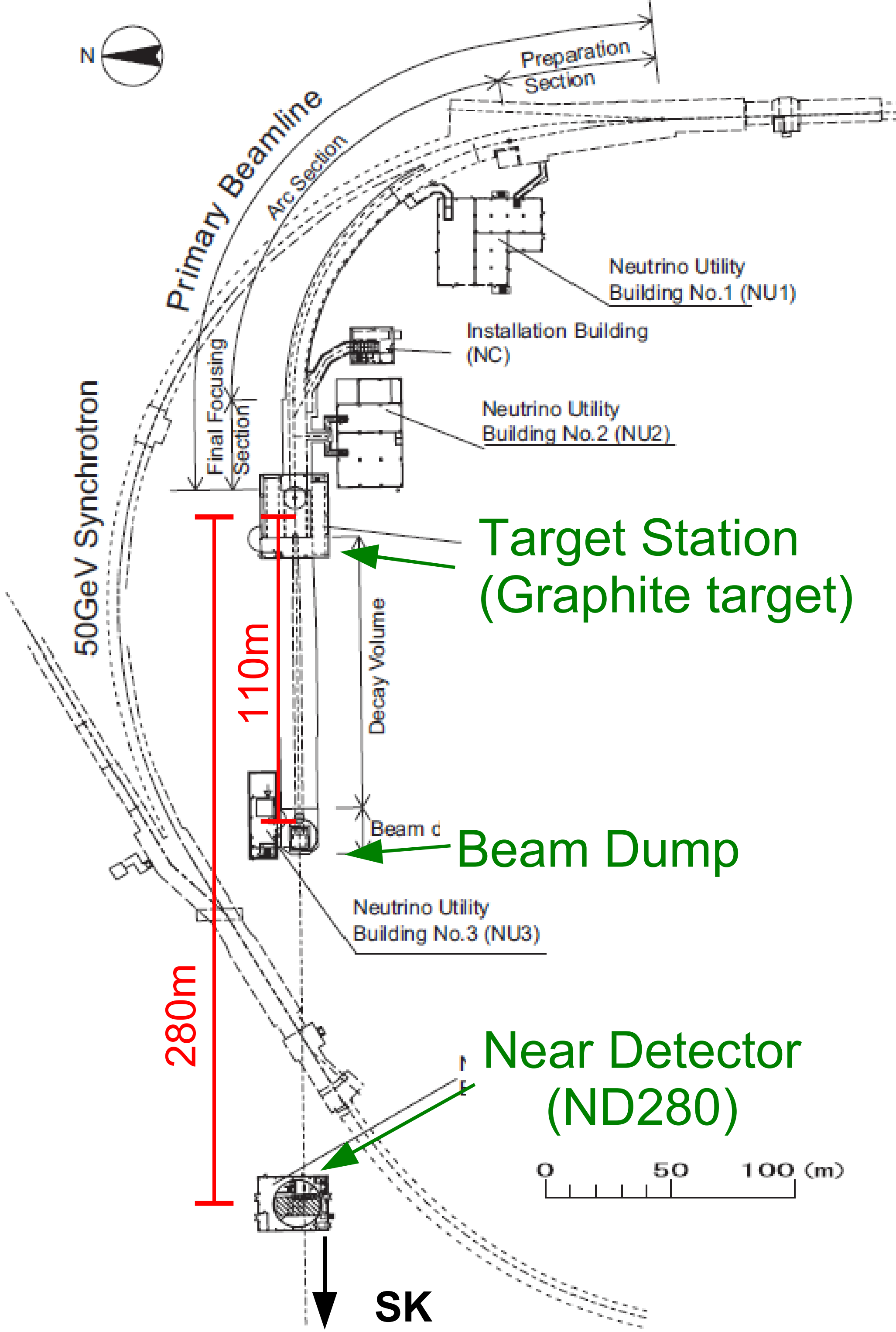
Super-Kamiokande III

- 50 kt water Cerenkov detector
- Depth of 1000m (2700mwe)
- 22.5kt fiducial volume
- 11,465 PMTs
- All tubes fixed as of June 2006



JPARC

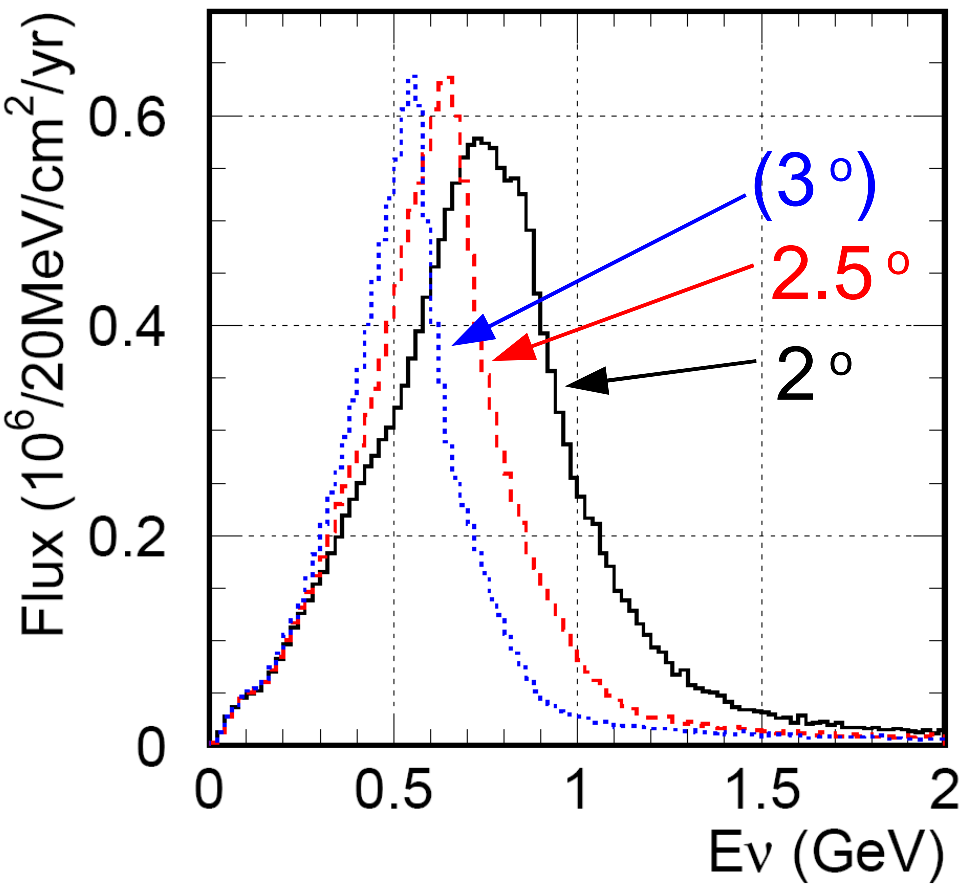


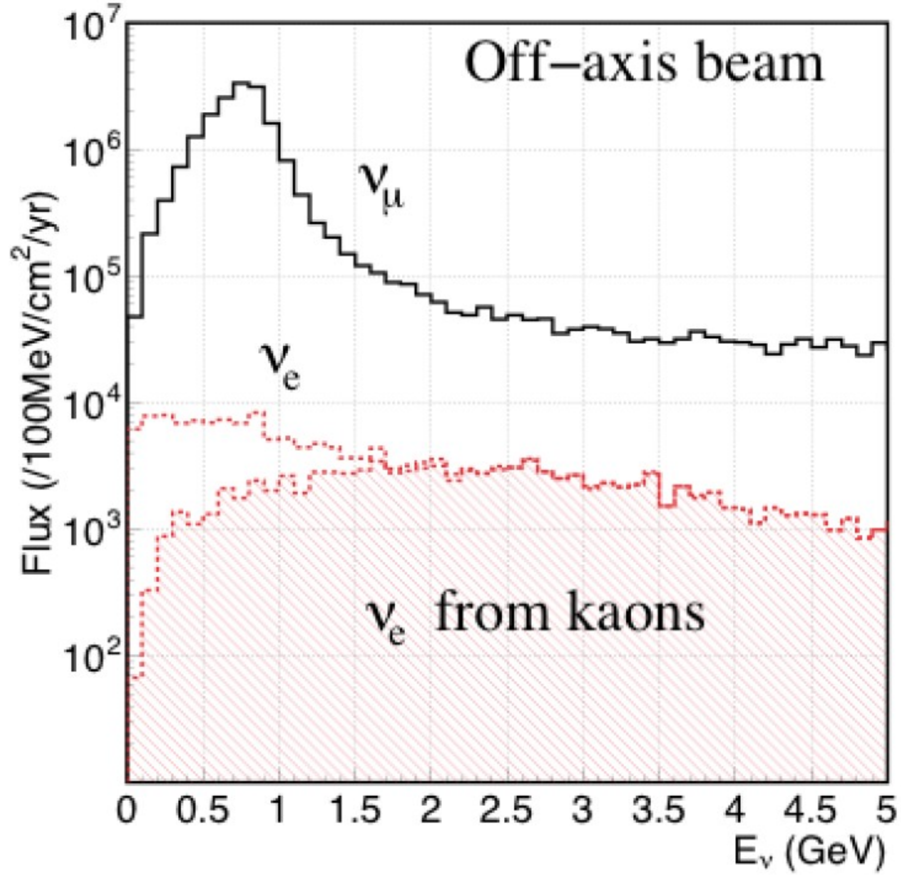


- Design beam power 0.77MW
- Proton spills every 3.4s
- Spill width 5.2μs
- 10^21 POT per year (130 days)

Neutrino Beam

$$p \rightarrow \pi\ X \rightarrow \mu\ \nu_\mu\ \ X$$





➔ *E* tuned to oscillation maximum

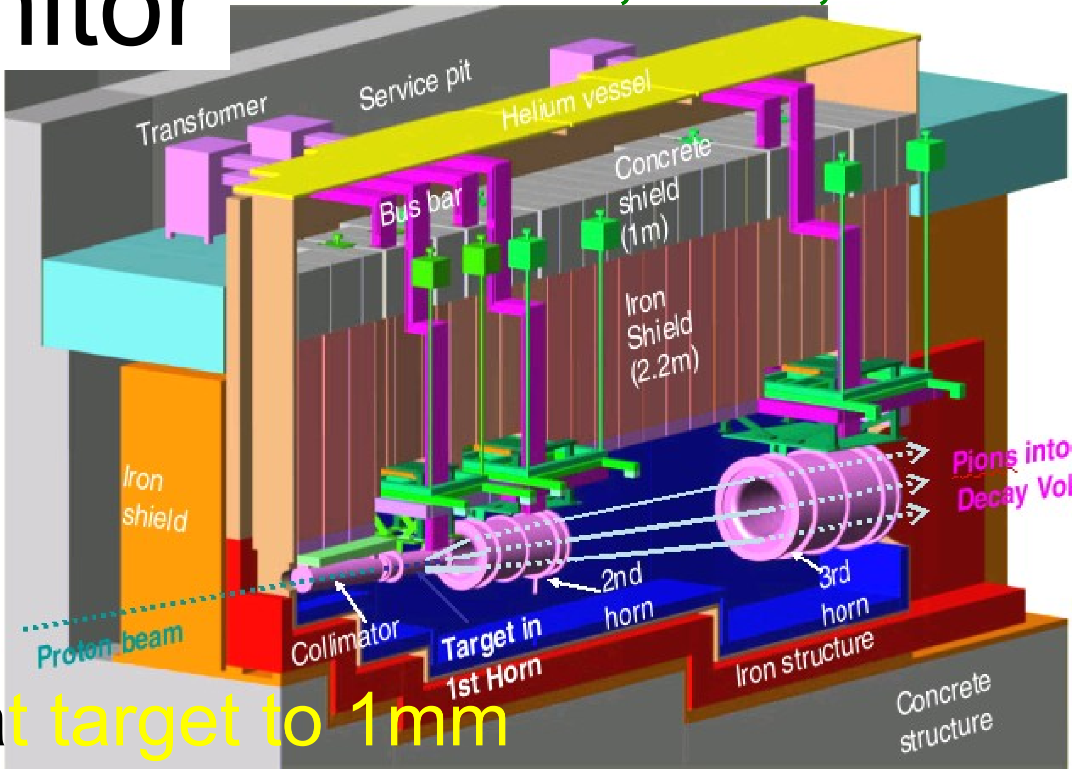
Proton Beam Monitor

York U, U of T, TRIUMF

$$p \rightarrow \pi X \rightarrow \mu \nu_\mu X$$

muon monitor

ND280

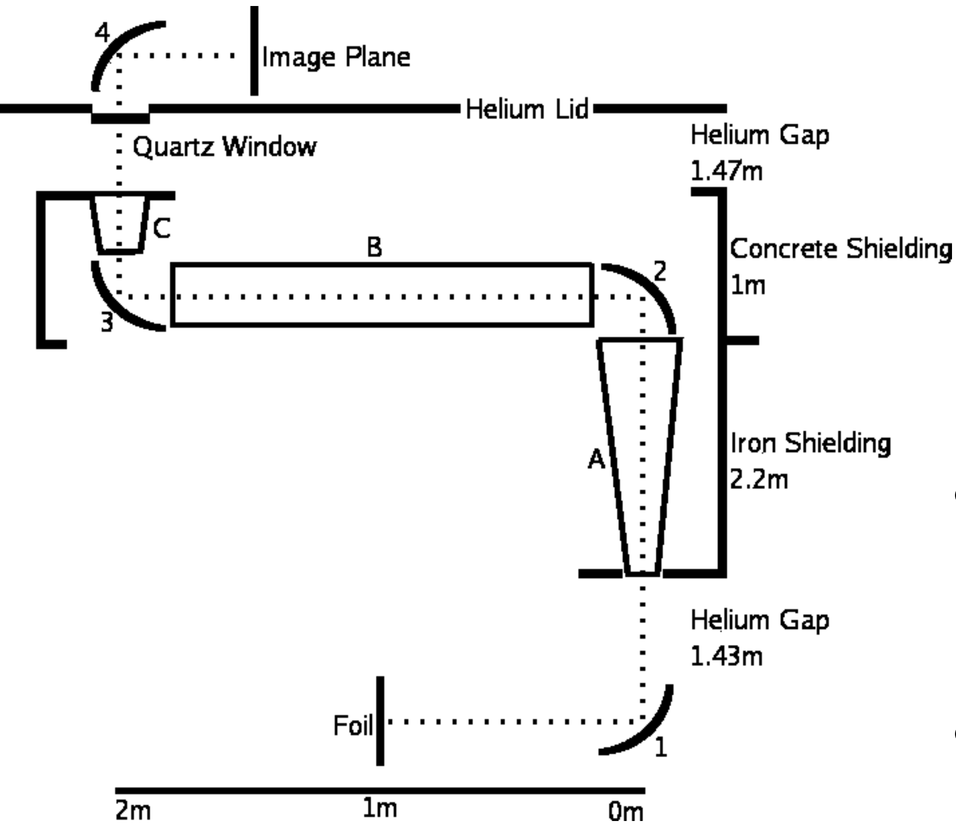


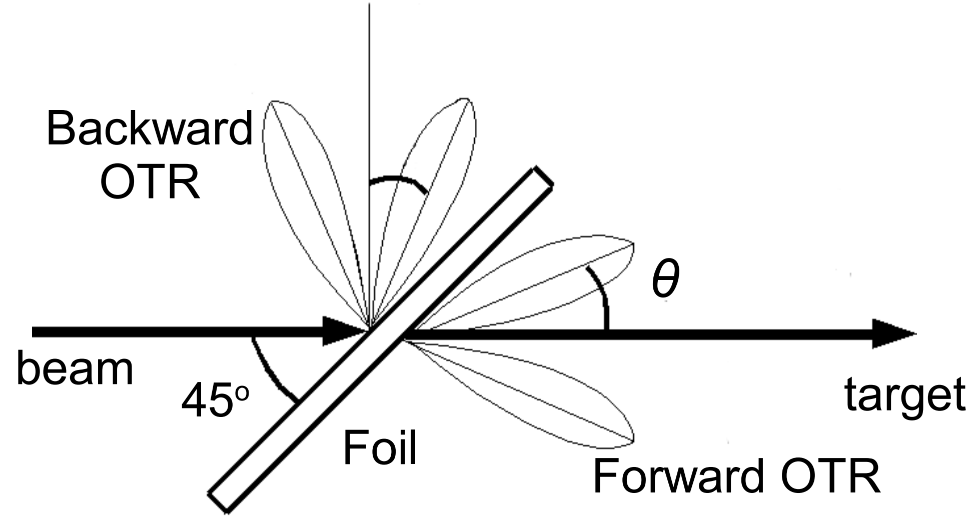
Proton beam monitor:

- Measure beam position at target to 1mm
  - Neutrino energy shifts by 2.2MeV / mm
  - Flux shifts by 0.6% / mm
- Measure beam angle to 0.5mrad
  - 0.9m target: 0.5mrad means position shift <0.5mm
  - Measure in combination with proton monitor 3m upstream
- Real time feedback of beam position to accelerator group

... Optical TR Monitor

York U, U of T, TRIUMF

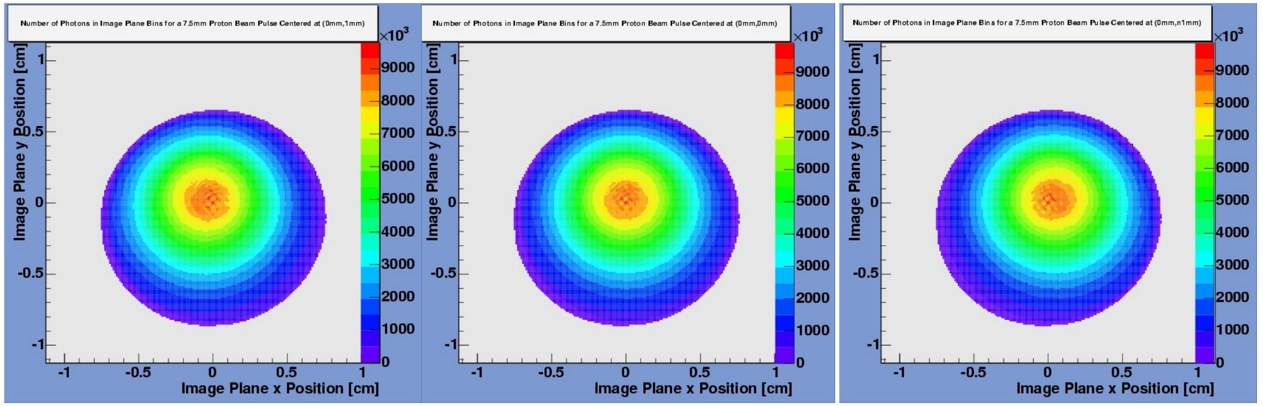




- Transition radiation emitted when charged particle crosses the boundary of two materials with different permittivity
- Light output: 10^13 photons / pulse
- Readout with optical system

Ray tracing simulation of optics:

- Simulation validated with table top optics system
- Here, shift beam position by 1mm; can reconstruct beam position from the centroid:

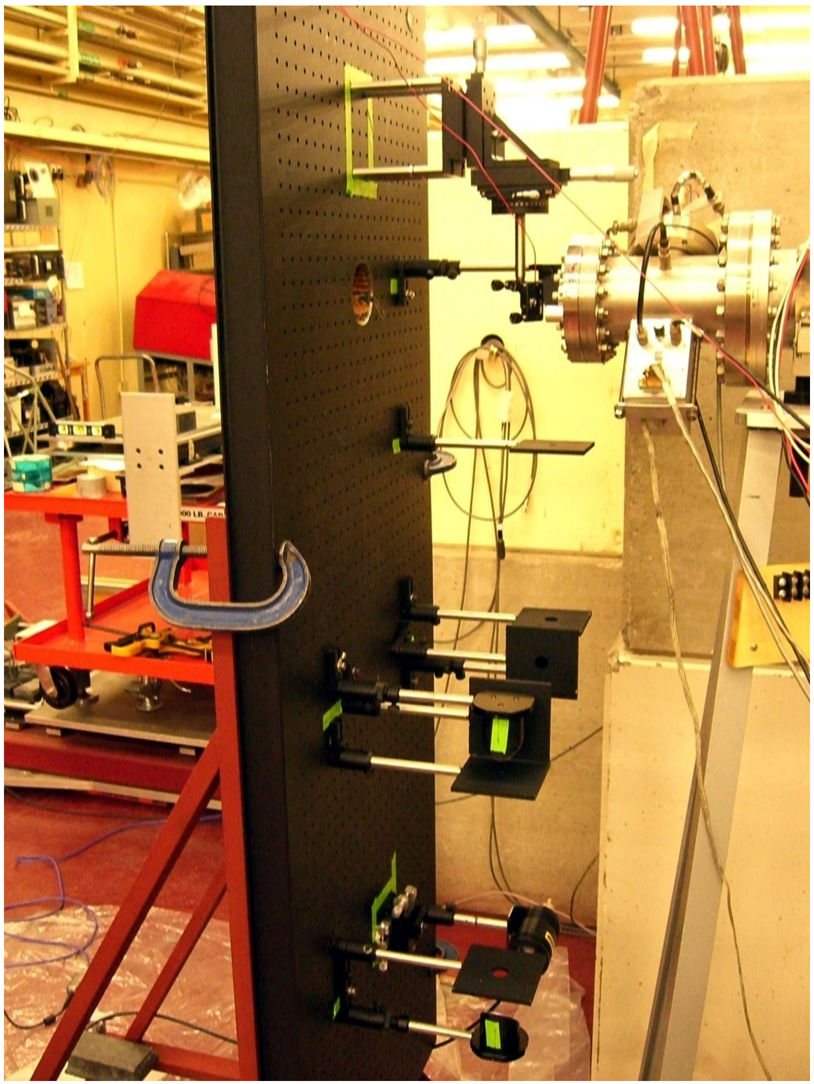


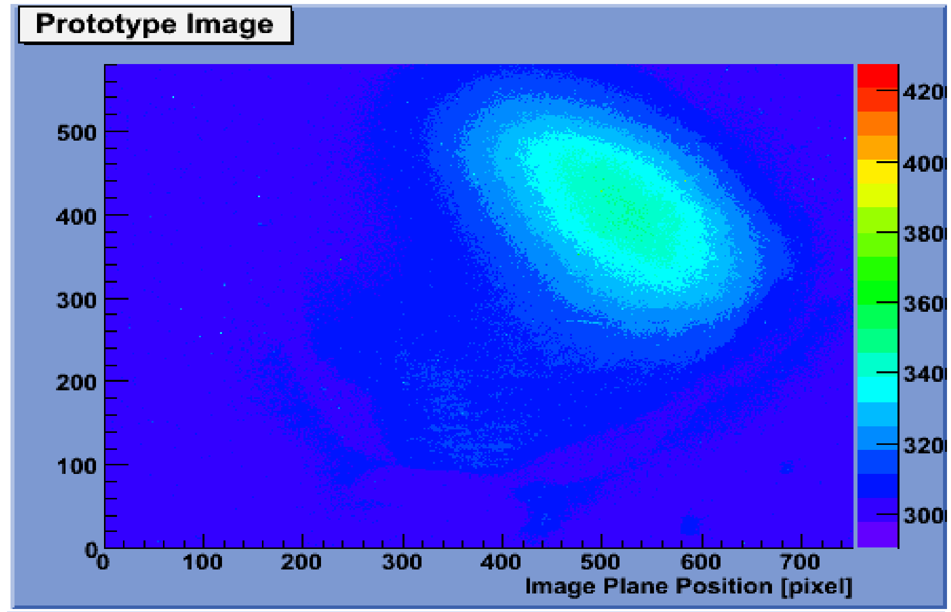
OTR NRC test beam

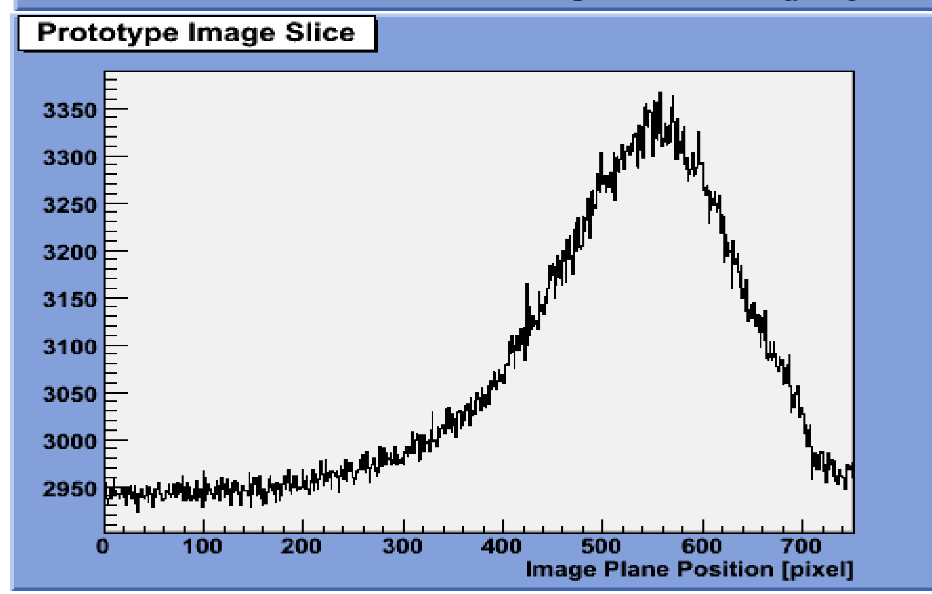
York U, U of T, TRIUMF

- NRC LINAC (20MeV electrons)
- Scaled version (15%) of actual OTR optics

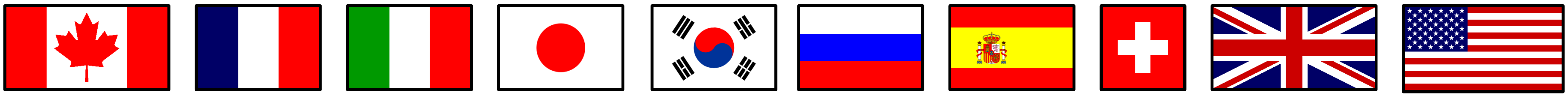
Obtained detailed images of beam width, position, intensity





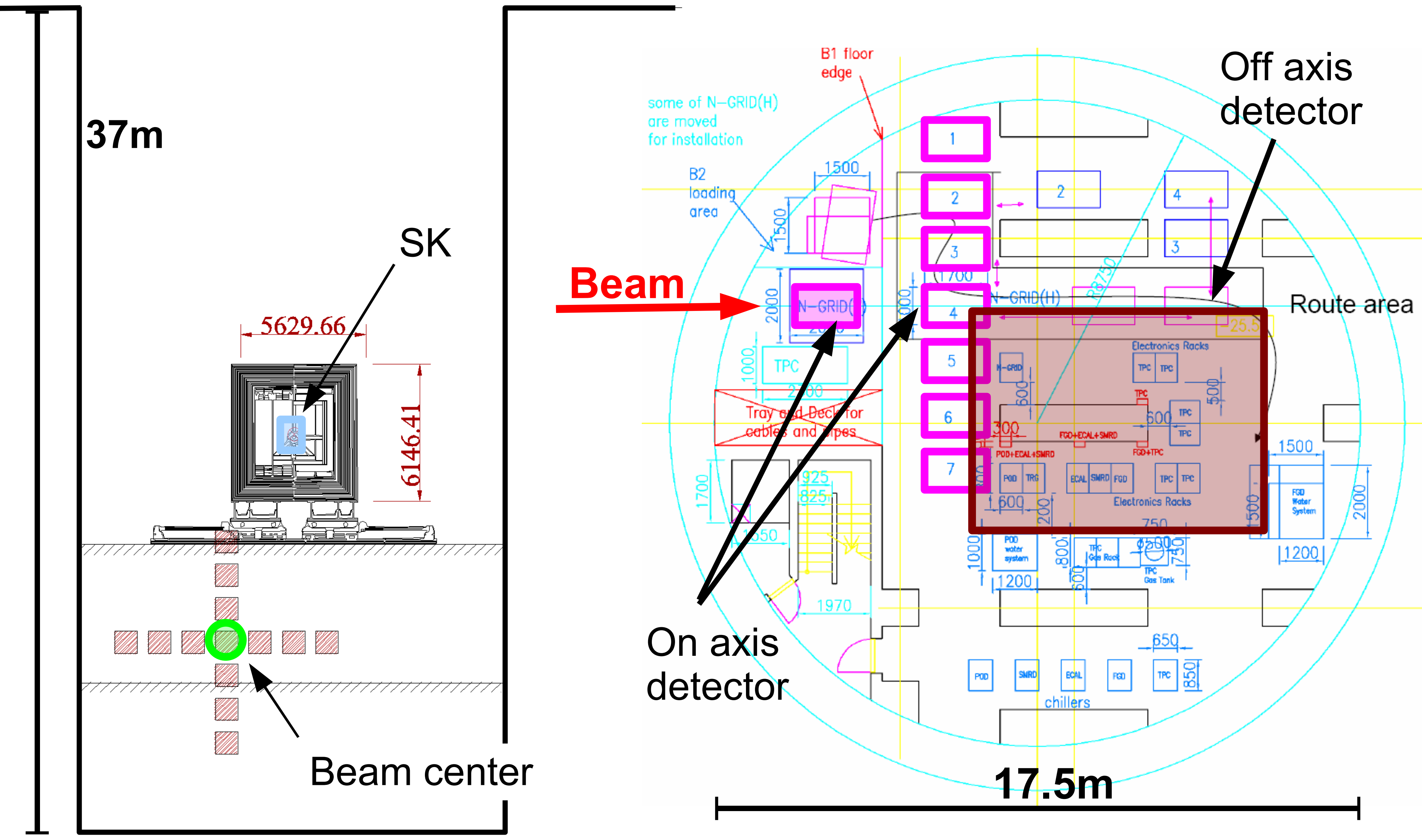


ND280 group



- **Canada**
  - UBC, Regina, Toronto, Victoria, TRIUMF, York
- **France**
  - CEA/Saclay
- **Italy**
  - Bari, Napoli, Padova, Rome
- **Japan**
  - Hiroshima, KEK, Kobe, Kyoto, ICRR, Tokyo
- **Korea**
  - Chonnam, Dongshin, Kangwon, Kyungpook, Gyeongsang, Sejong, Seoul, SungKyunKwan
- **Russia**
  - INR Moscow
- **Spain**
  - Barcelona, Valencia
- **Switzerland**
  - Geneva
- **United Kingdom**
  - Imperial, Lancaster, Liverpool, Queen Mary, CCLRC, Sheffield, Warwick
- **United States**
  - Louisiana State, Colorado State, Stony Brook, Rochester, Washington

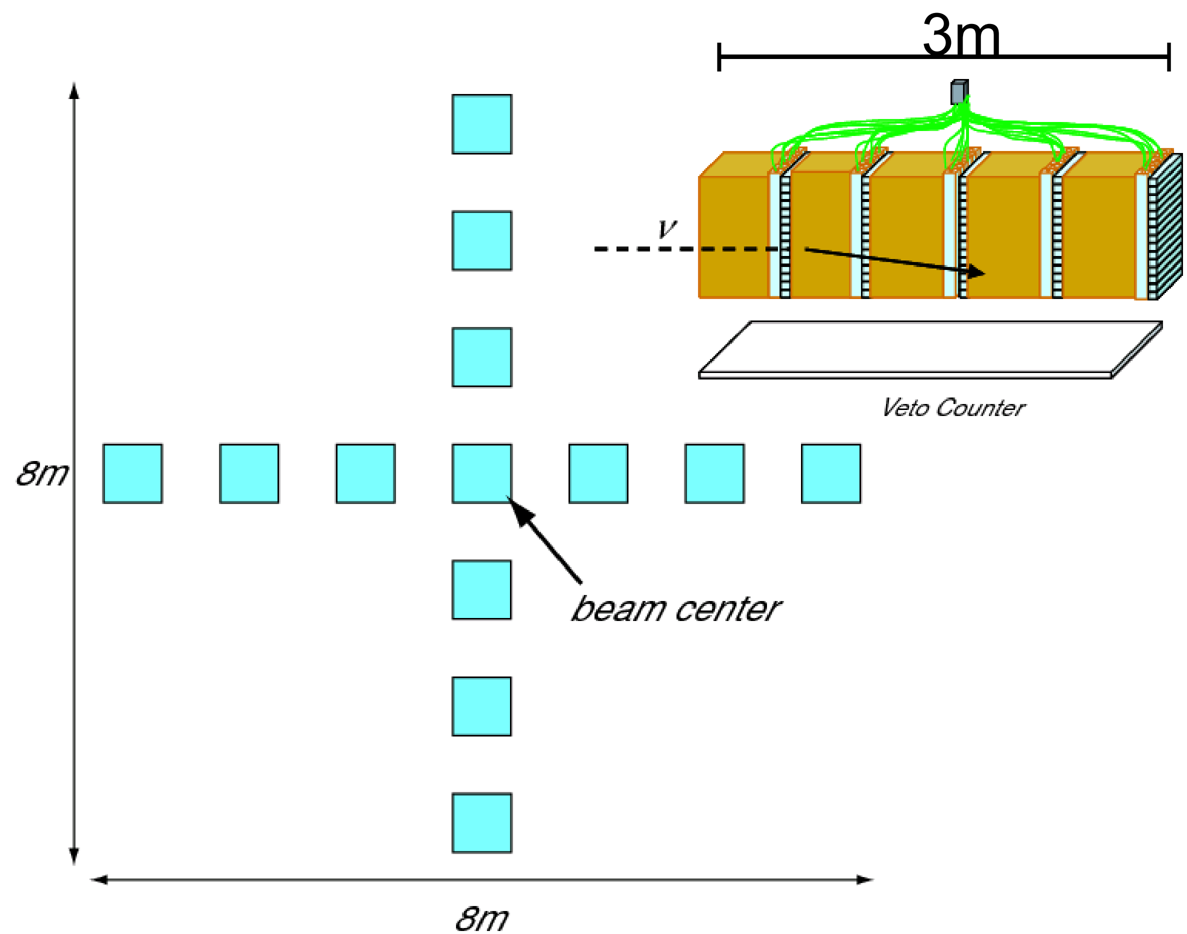
ND280 Hall



37m
SK
5629.66
6146.41
Beam center
Beam
B1 floor edge
some of N-GRID(H) are moved for installation
B2 loading area
Off axis detector
Route area
On axis detector
Tray and Deck for cables and pipes
Electronics Racks
chillers
17.5m

On axis neutrino detector (NGrid)

- E_ν at beam center
- Massive detector
  - Scintillator + iron
  - $1m^2 \times 3m$ elements
- Proton beam position with 3mm precision



Off-axis near detector (ND280)

Measure flux and spectrum:

- ν_μ in CCQE: $\nu_\mu + n \rightarrow p + \mu^-$ ⇨ $\Phi_{near}\sigma_{CCQE}$
- backgrounds to CCQE: ⇨ $\sigma_{non\text{-}CCQE} / \sigma_{CCQE}$

$$\mathrm{CC}1\pi^+:\ \nu_\mu + p \rightarrow p + \pi^+ + \mu^- \qquad \mathrm{NC}1\pi^+:\ \nu_\mu + p \rightarrow n + \pi^+ + \nu_\mu$$

$$\mathrm{NC}1\pi^0:\ \nu_\mu + N \rightarrow N + \pi^0 + \nu_\mu \qquad \text{Beam } \nu_e \qquad \text{photons} \ \ldots$$

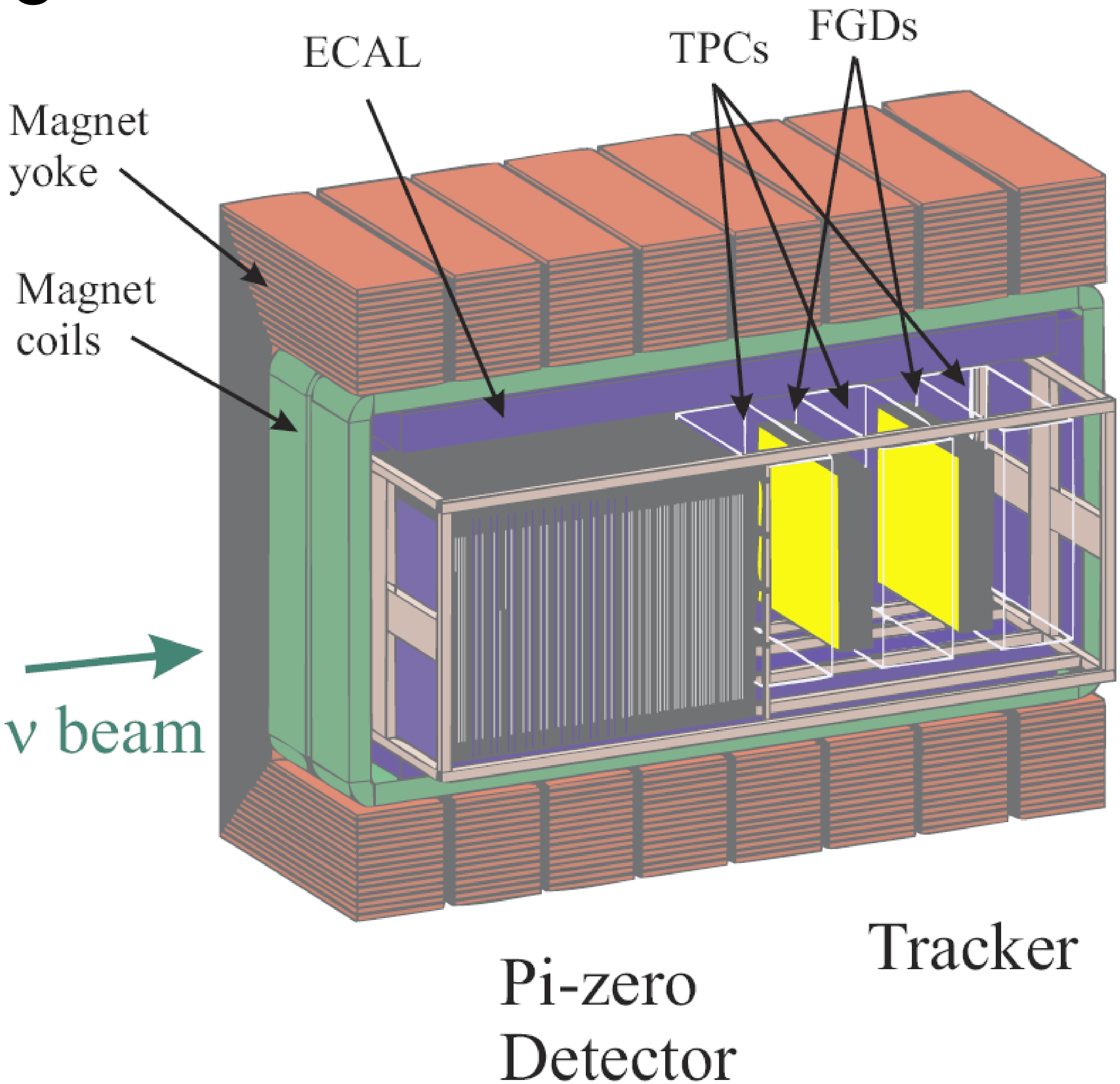
- ν_e flux, spectrum, and cross sections
- CCQE theoretically well understood

Extrapolate to SK with beam MC

⇨ A highly segmented large volume detector capable of charged and neutral particle ID and energy measurements.

Off axis ND280

- UA1 magnet at 0.2 T
- Photons and π^0's:
  - Ecal+P0D
  - ➔ Backgds to CCQE
- Charged particles:
  - Tracker (TPC+FGD)
  - ➔ Flux and spectrum via CC quasi-elastic
- Large angle μ's:
  - Side MRD
  - ➔ Improve CCQE+bgds

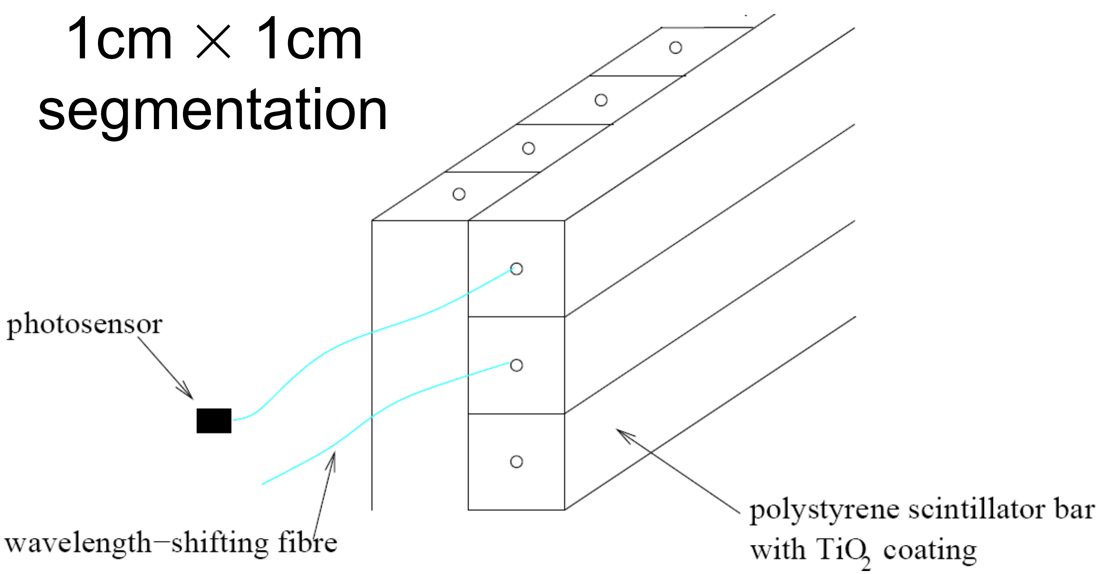


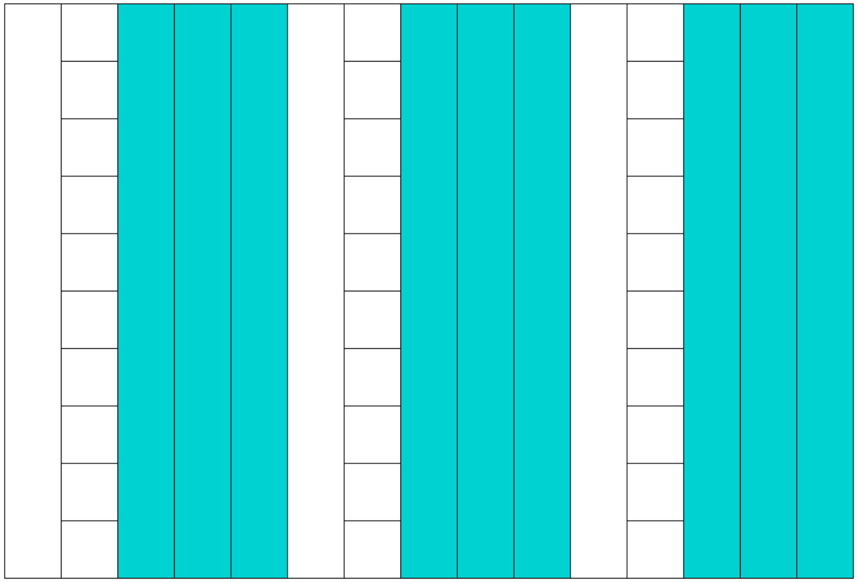
UBC, TRIUMF

Tracker: FGD

- Measure CCQE:
  - track all charged particles in massive detector
  - Expect 355k CCQE evts for 10^21 POT
- Two modules read out with WLS fibers
  - Plastic scintillator (1.2 t)
  - Plastic scintillator and passive water (0.52 t water)

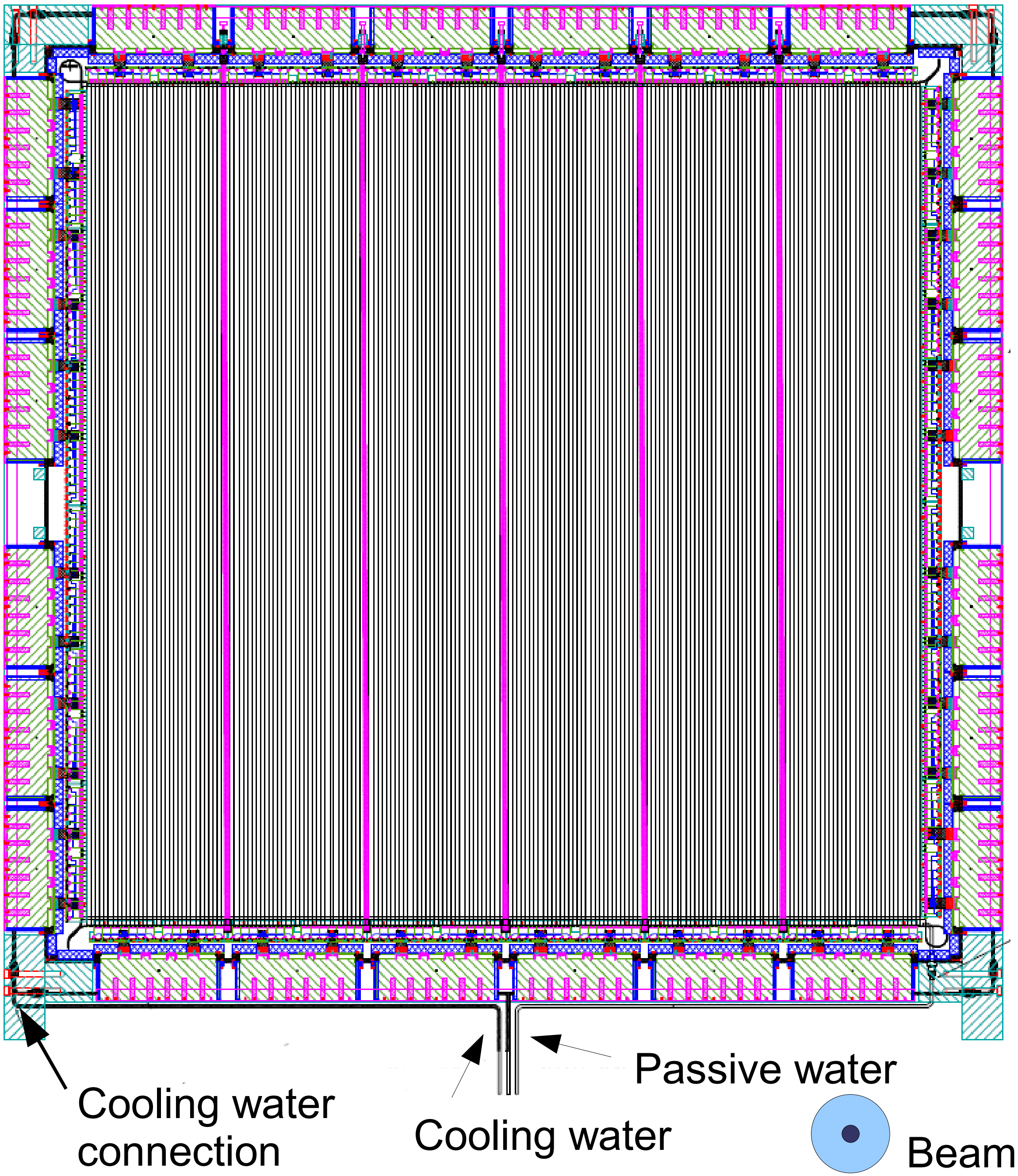
1cm × 1cm segmentation

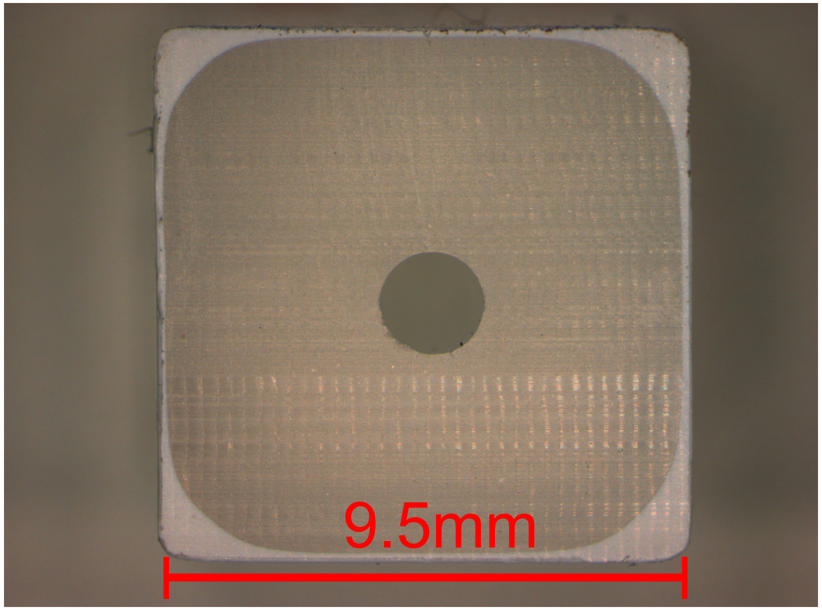




Tracker: FGD

UBC, TRIUMF



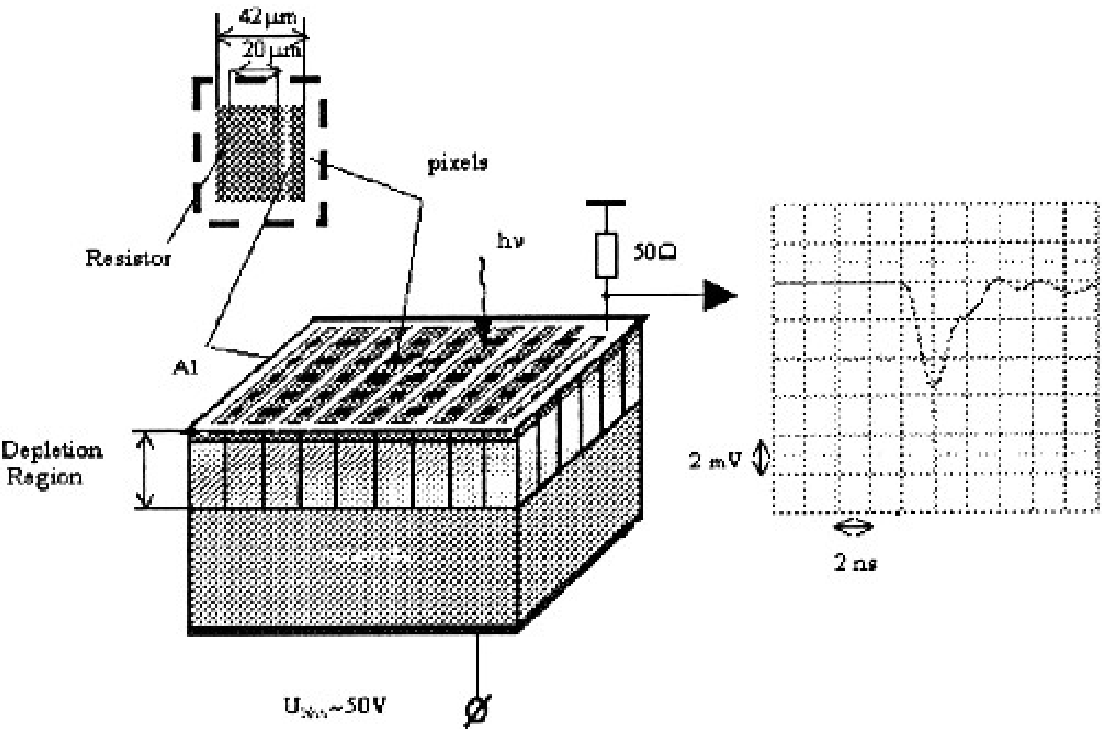


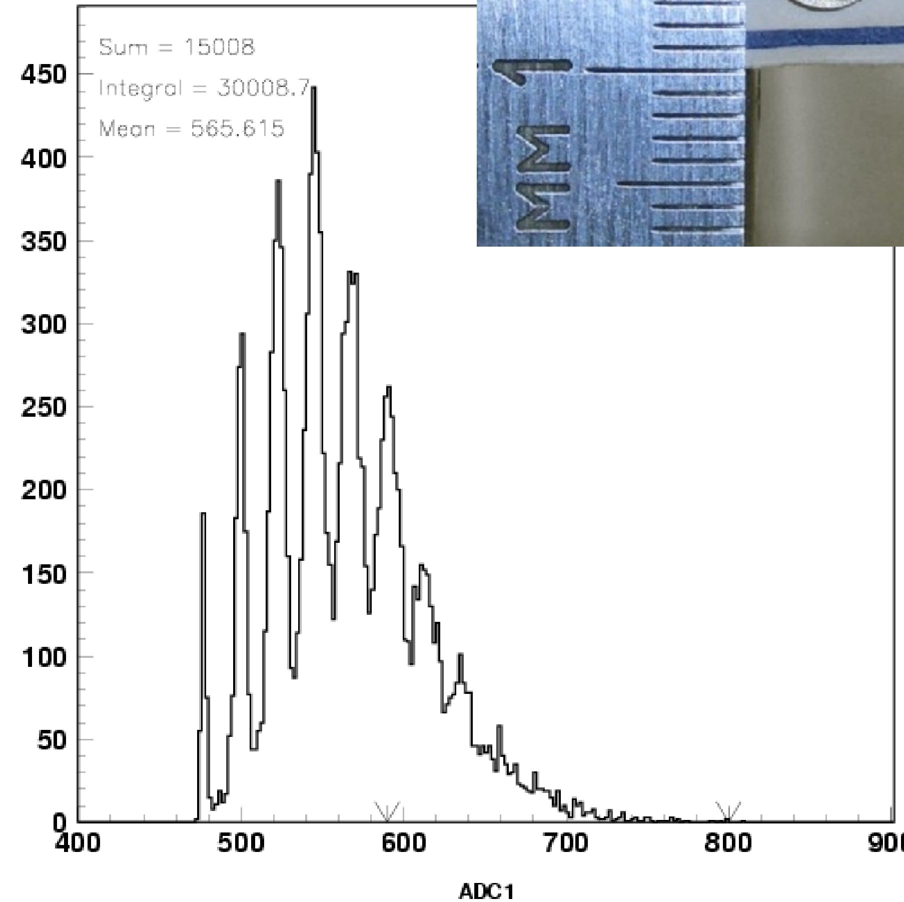
- Bars will hang in ND basket
- Scintillator bars to be extruded near Vancouver
- Test extrusion successful
- Beam tests underway ...

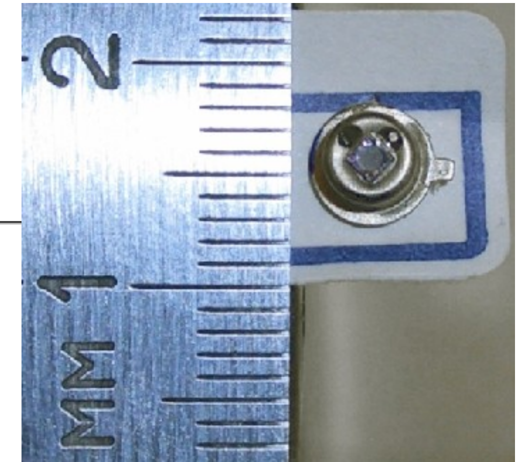
Photo-Sensors

Silicon PM:

- multipixel APD in Geiger mode
- ~ 100 - 3000 pixel
- High QE, fast response, immune to magnetic fields



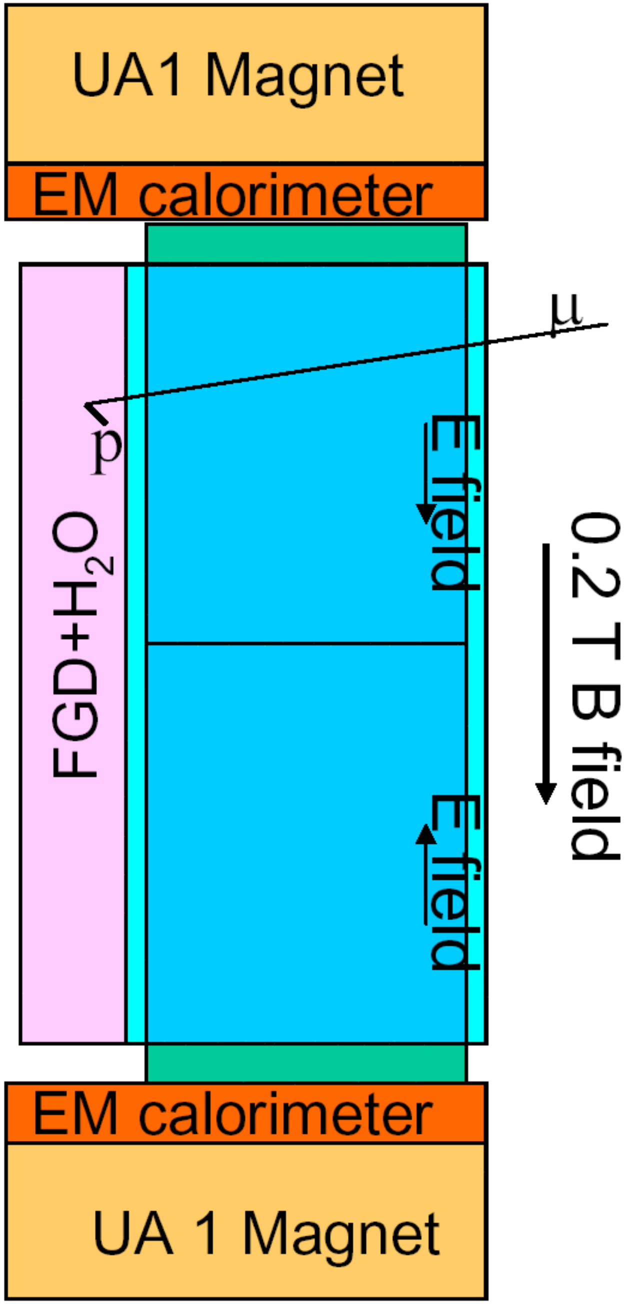




- Gain ~10^6
- Recovery time: ~100ns/pixel
- Op. voltage: ~50 V
- Noise rate: ~100-1000 kHz

Time Projection Chamber

UVic, UBC, TRIUMF

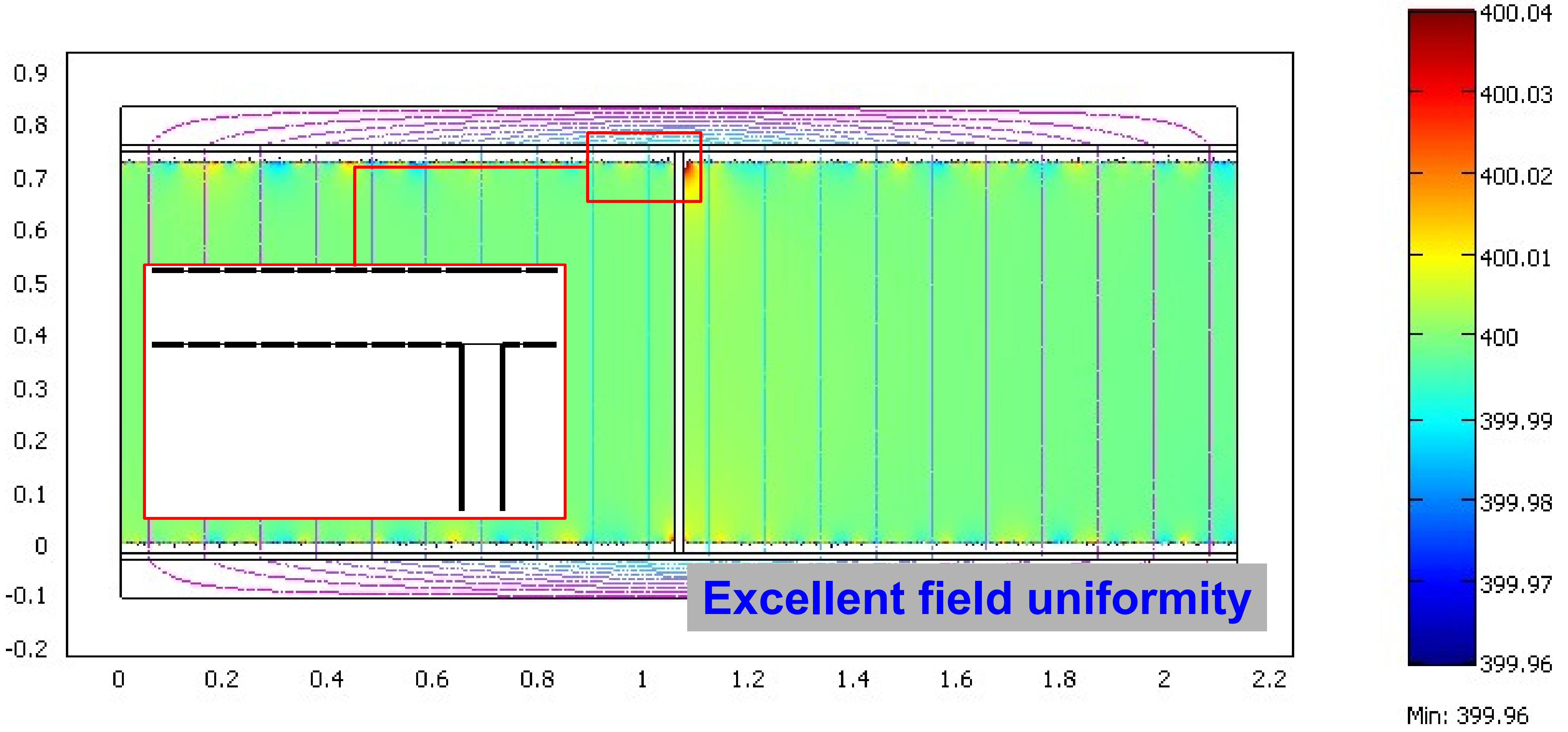


- Gas TPC, 2.5m × 2.5m × 0.9m
- *E*, *B* fields parallel, perpendicular to beam
- Outer skin at ground
- Purpose:
  - ◇ Measure $\vec{p}$ of μ's produced in CCQE
  - ➔Measure neutrino spectrum
  - ◇ Determine charges of reaction products
- Requirements:
  - ◇ Momentum resolution <10%
  - ◇ Minimize amount of inactive space

TPC Field Cage

UVic, UBC, TRIUMF

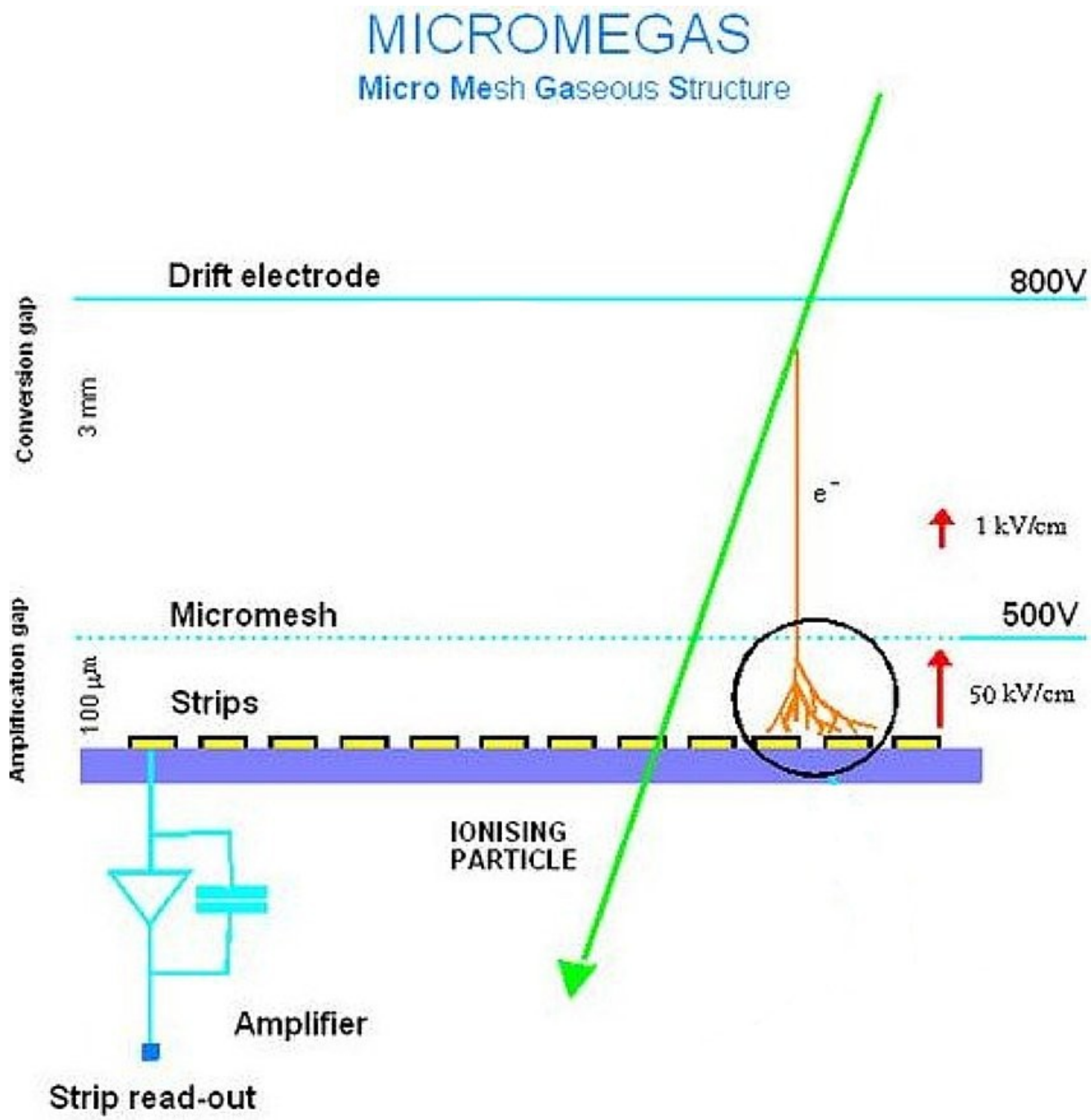
- Central Cathode <50kV
- Design resembles STAR field cage
- Potential degrader realized by copper strips on composite walls
- Gas envelope reduces gas contamination, drops high voltage



Gas Amplification

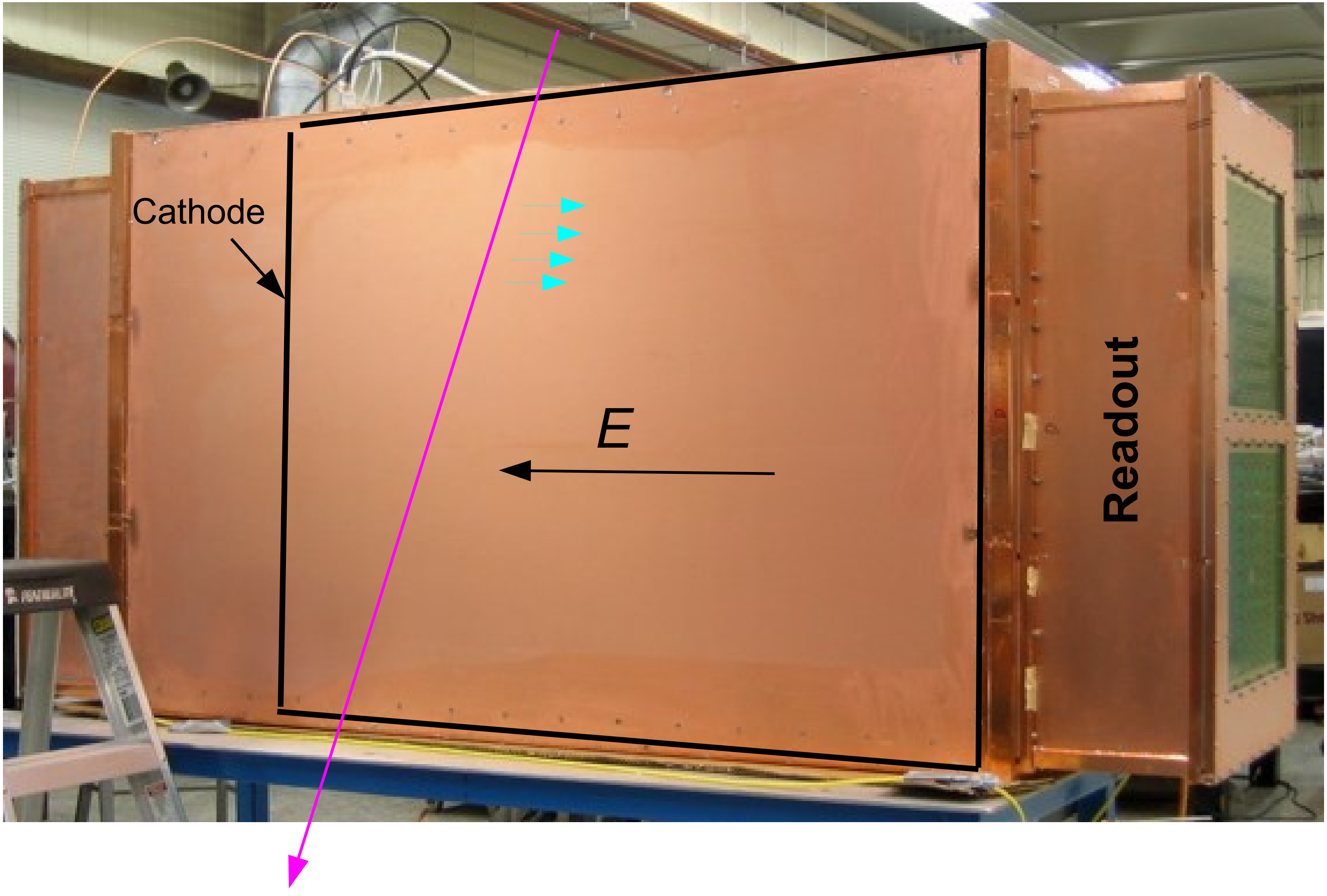
- Readout using micro-pattern devices

μMEGAS:



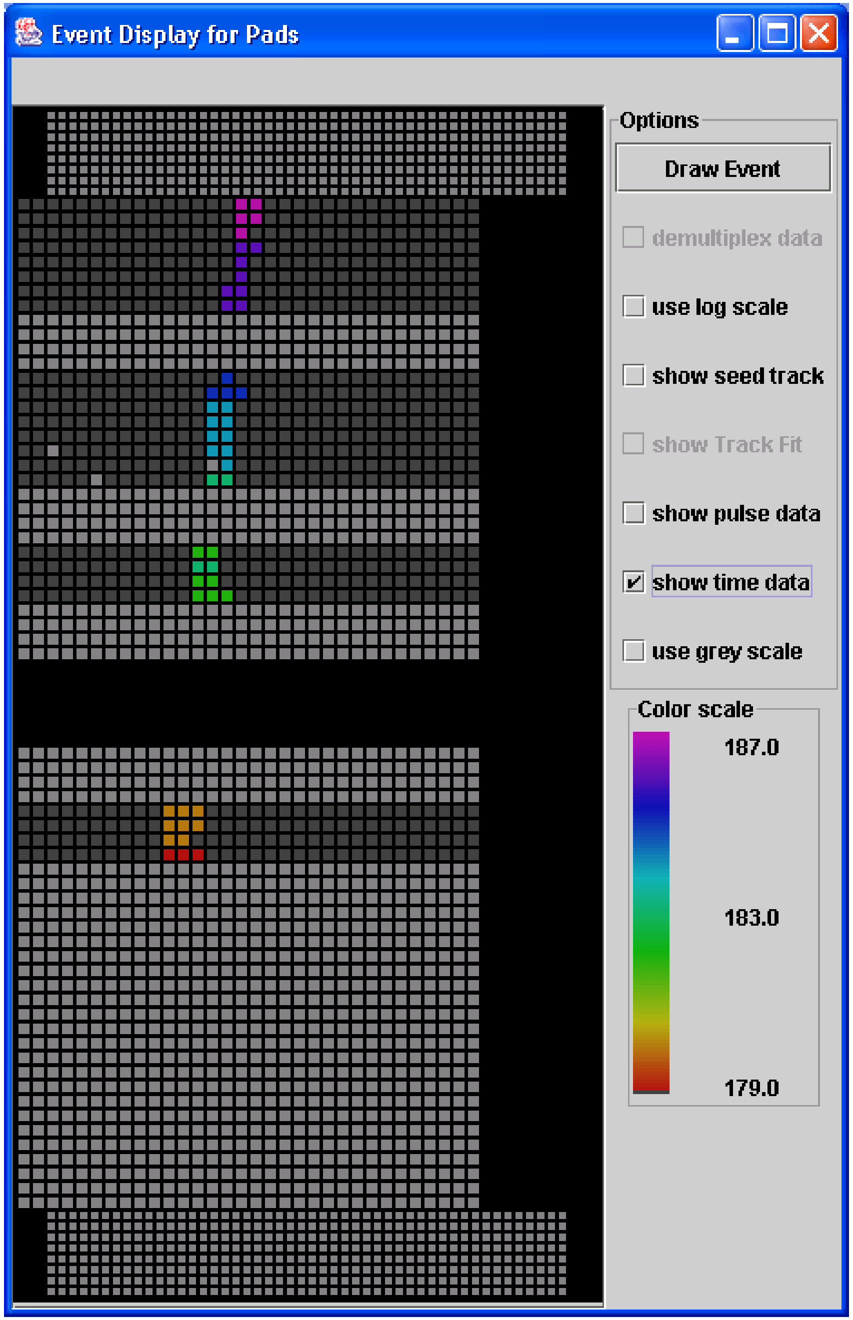
TPC Prototype

UVic, UBC, TRIUMF



First Events in January

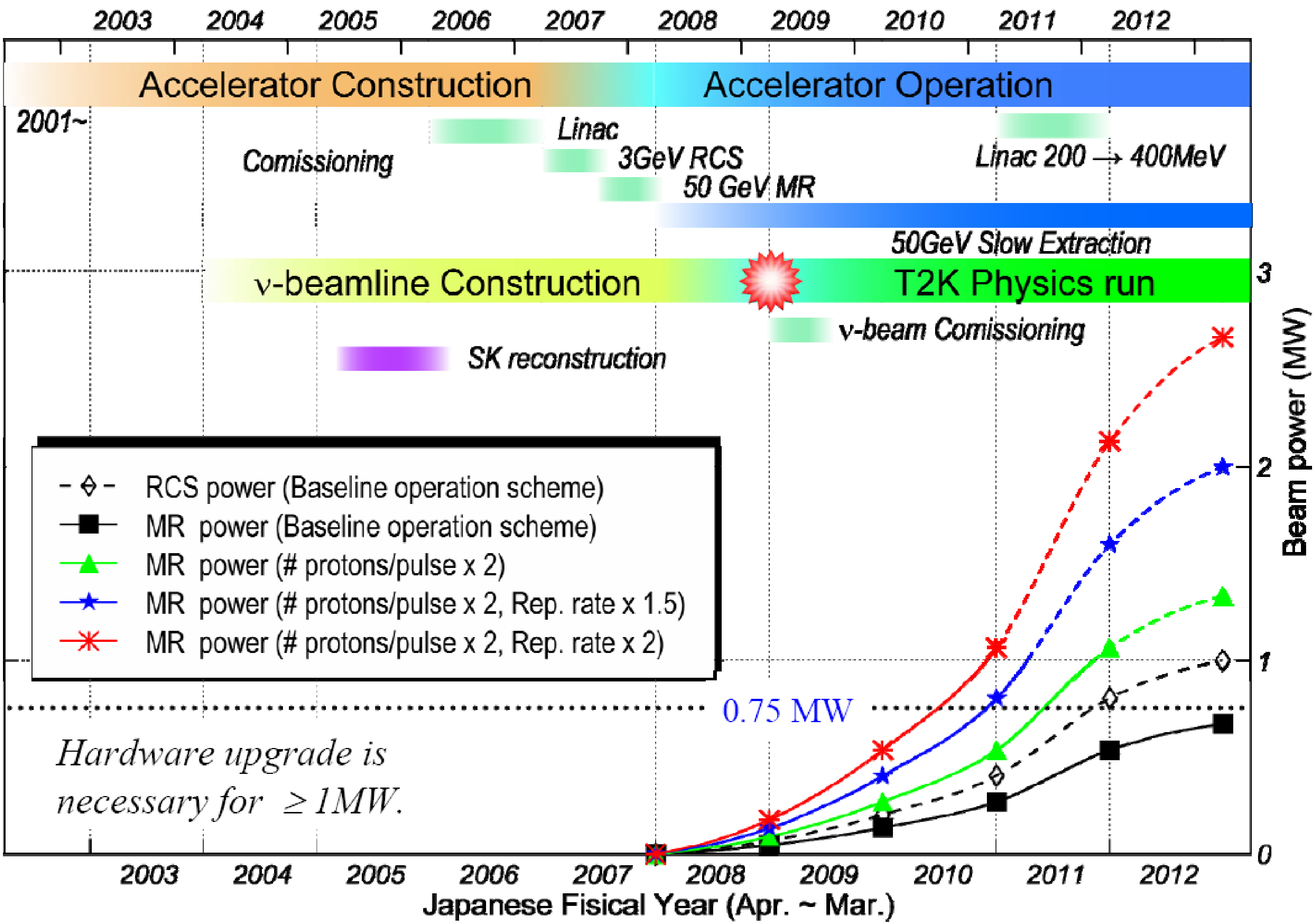
UVic, UBC, TRIUMF



Colored by arrival time

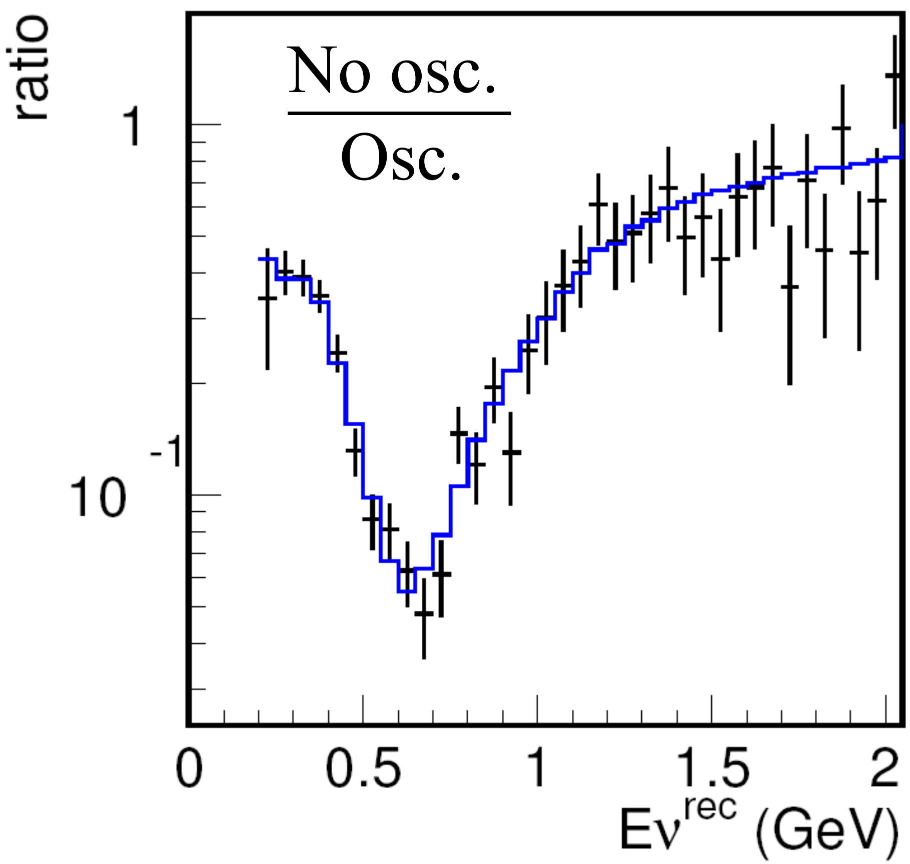
T2K Timeline

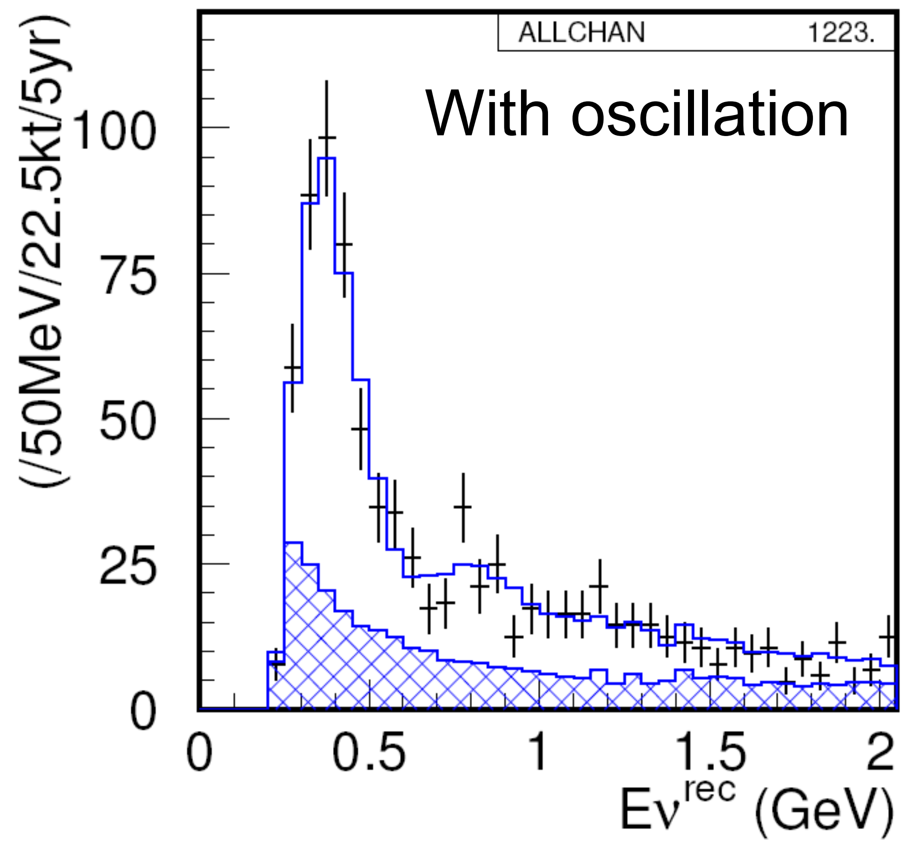
Black squares: original proposal
green triangles: current expectation



Signals at The Far Detector

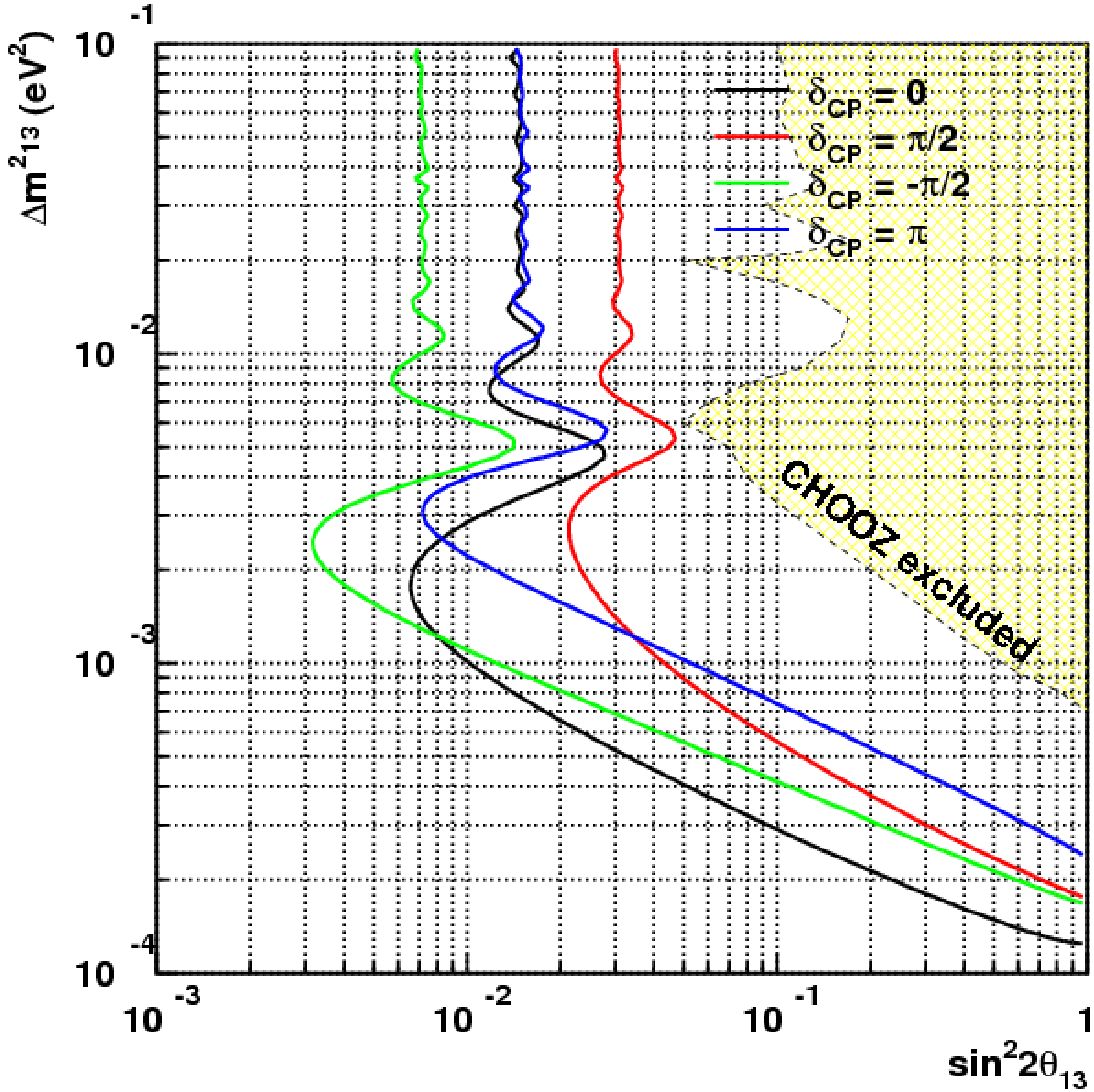
muon neutrino disappearance:





$$\sin^2 2\theta_{23} = 1.0 \quad \Delta m^2_{23} = 2.7 \cdot 10^{-3}\,\mathrm{eV}^2$$

Sensitivity to θ_{13}



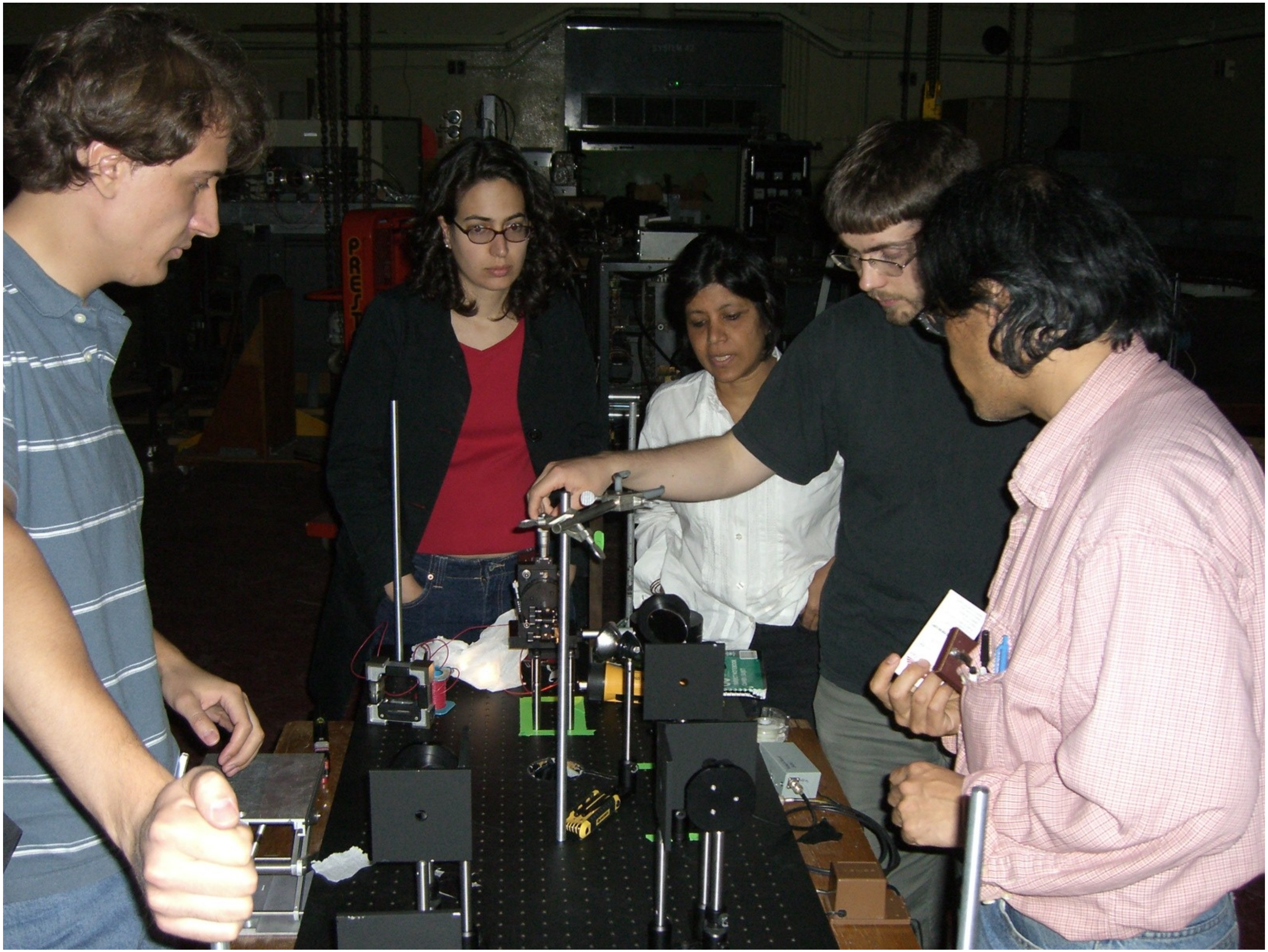
- 90% CL contours
- 5 years
- 5×10^{21} POT

Summary

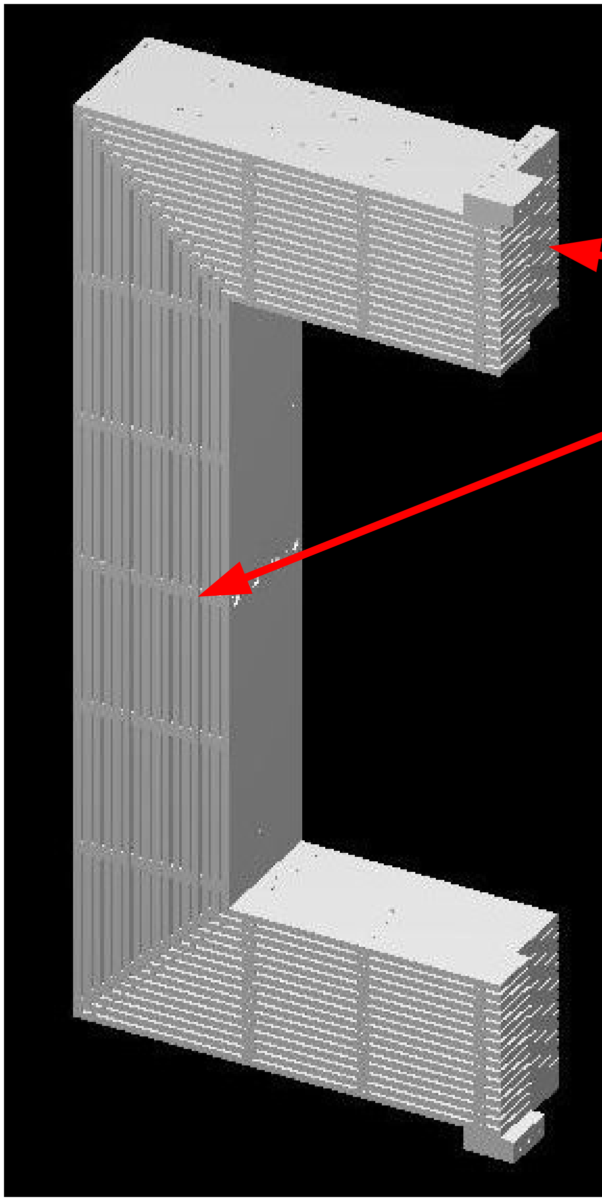
- T2K I to improve measurement of θ_{13} and of atmospheric oscillation parameters
- CP violation in phase II
- Superkamiokande rebuilt
- Near detector R&D in good shape
  - OTR observed with scaled OTR prototype
  - FGD design well advanced, extrusion run of scintillators successful, beam tests underway
  - TPC prototype in operation since January

Extras

The OTR Team



Side muon range detector (SMRD)

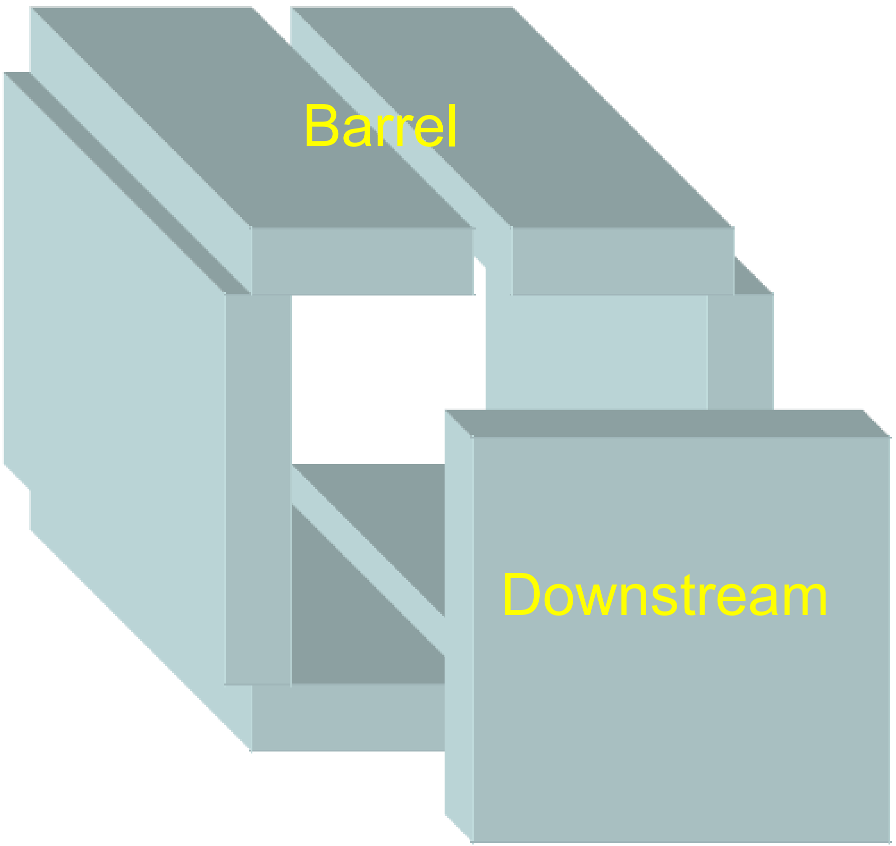


Measure large angle muons

Active component:

- Extruded scintillator (87 x 17 x 1 cm^3)
- light collected with WLS shifting fiber
- read out by Silicon PMs on both sides

Electromagnetic calorimeter



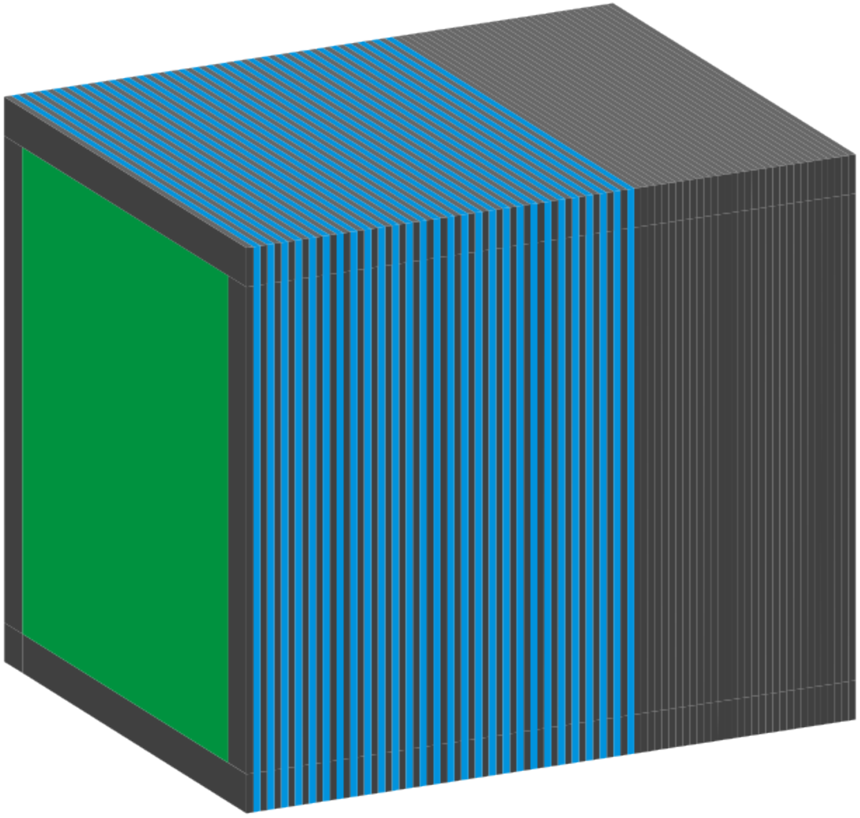
- Purpose
  - Energy detection around P0D
  - Pi0 recon. around tracker
  - Charged particle ID
- Barrel ECAL ($10.3X_0$):
  - 25 scintillator layers (4cm x 1cm)
  - Pb layers interleaved
- Downstream ECAL ($11.6X_0$):
  - 29 scintillator layers (4cm x 1cm)
  - Pb layers interleaved

Pi Zero Detector – P0D

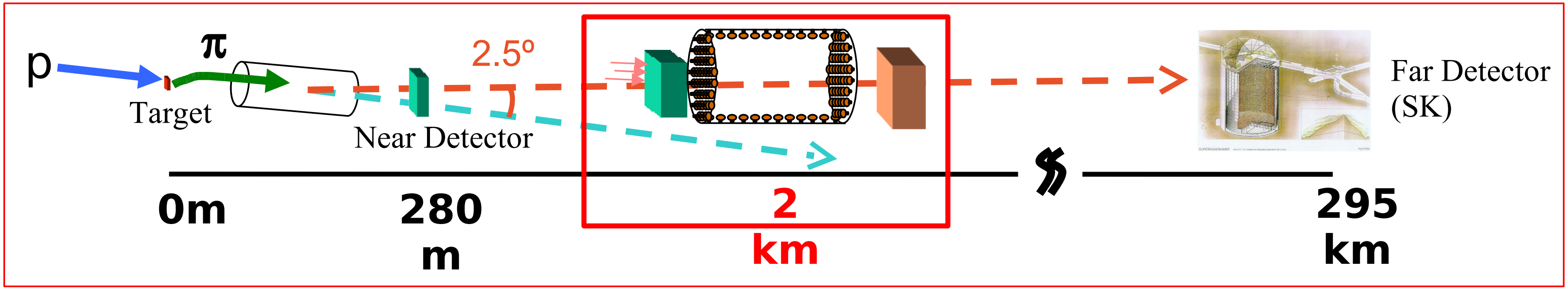
For high statistics measurements of e+m showering particles.

- scintillating bar tracking planes
- front section interleaved with 1.7 tonnes of passive water layers

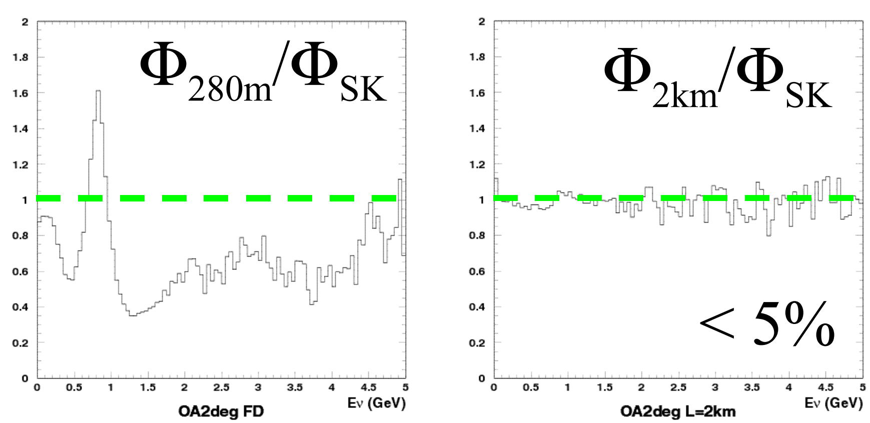
➔ statistical subtraction of events in rear from front used to determine oxygen cross sections

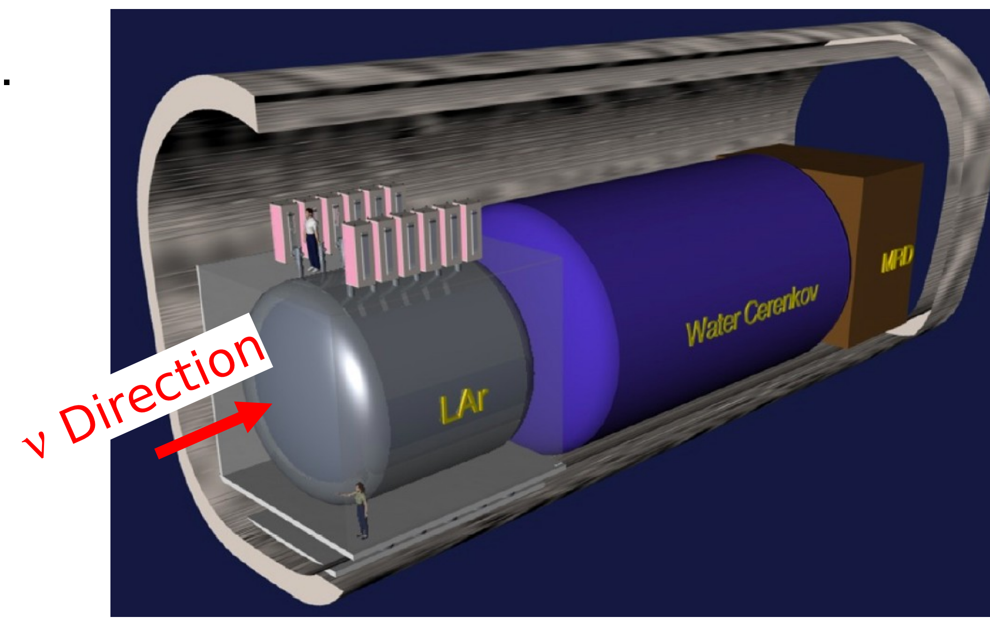


Intermediate detector @ 2km



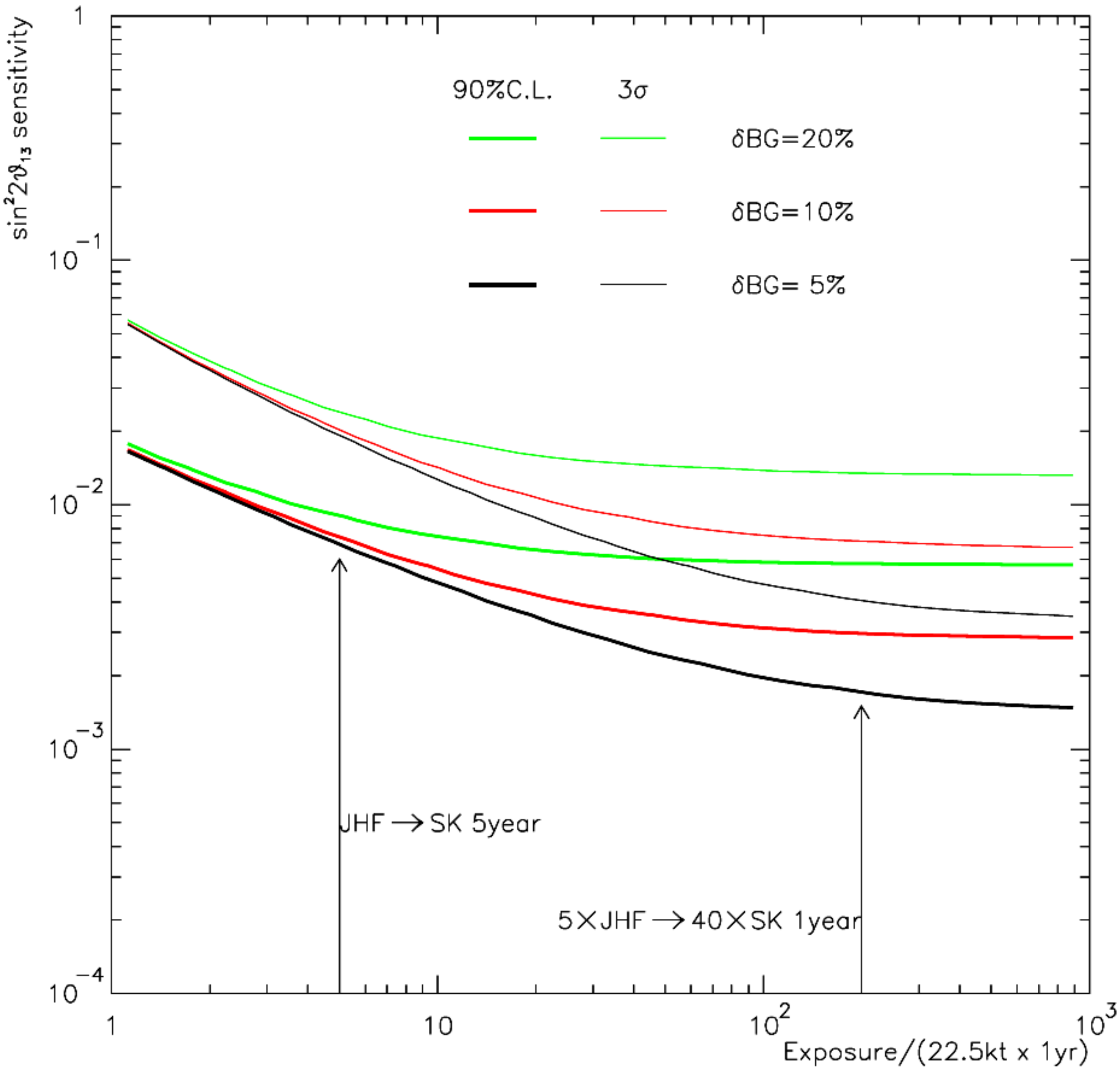
- E_ν spectrum @ 2km ~ E_ν spectrum @ SK w/o oscillation
  → Uncertainties from Far/Near ratio are smaller than wrt ND280m.
- Liquid Ar TPC + Water Cherenkov + Muon Range Detector
  - Very similar ν detection to SK
    … Reduce systematic uncertainties.
  - Excellent Tracking by LAr-TPC
    … Precise measurement of
    ν-nucleus interactions.



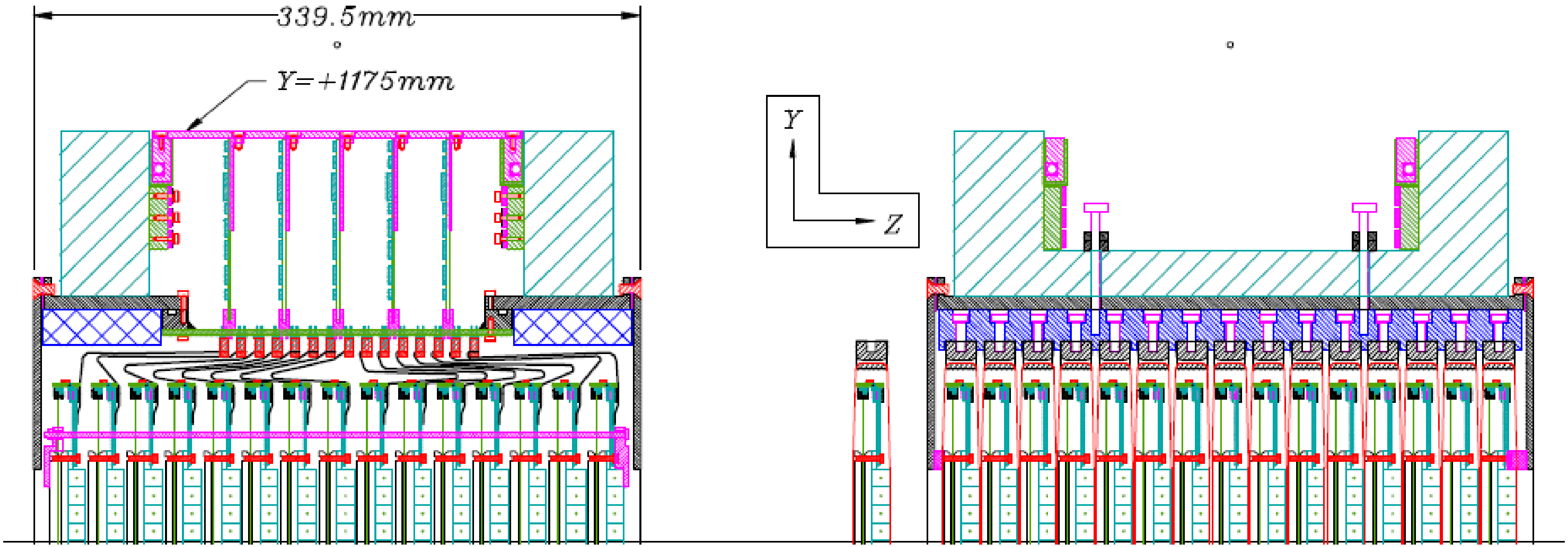


The experimental facility for 2km detector is not approved yet.

Sensitivity to θ_{13}

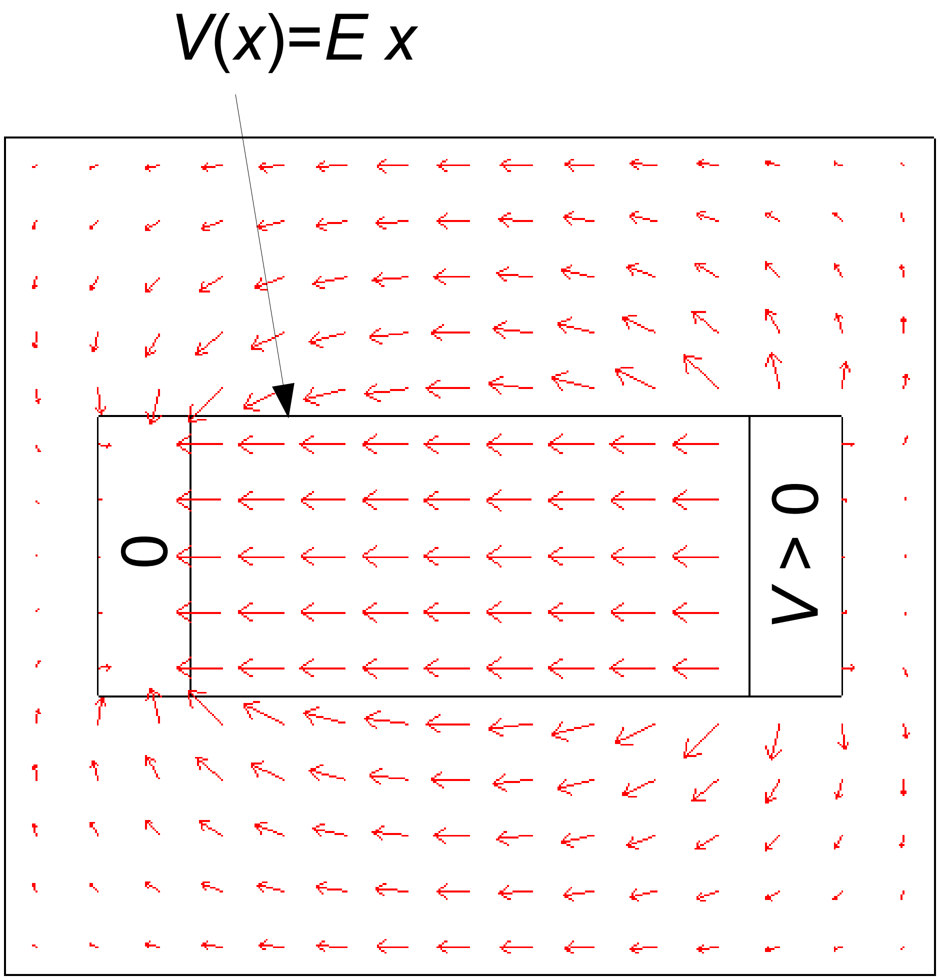


FGD Design Details



A TPC's Field Cage

- Accurate tracking requires uniform electric field



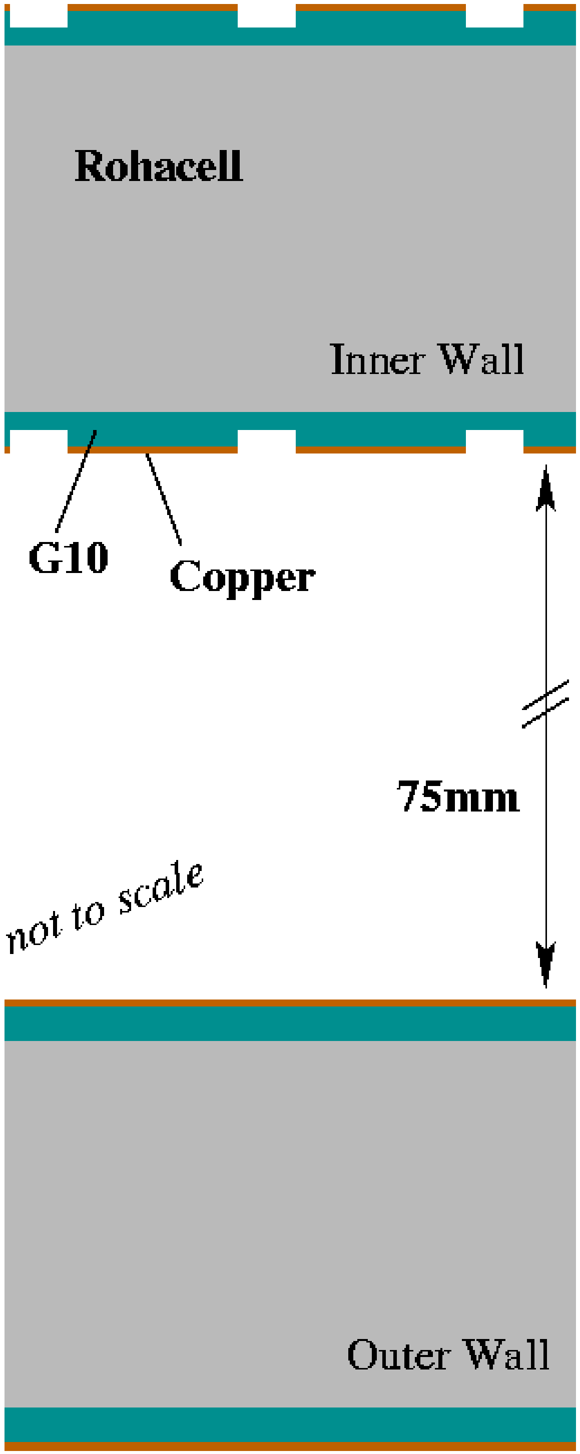
- Approximate continuous field cage with discrete grid

Field cages used by

- ALICE
  - suspended mylar strips (aluminized)
- STAR
  - edged copper on Kapton
- ...

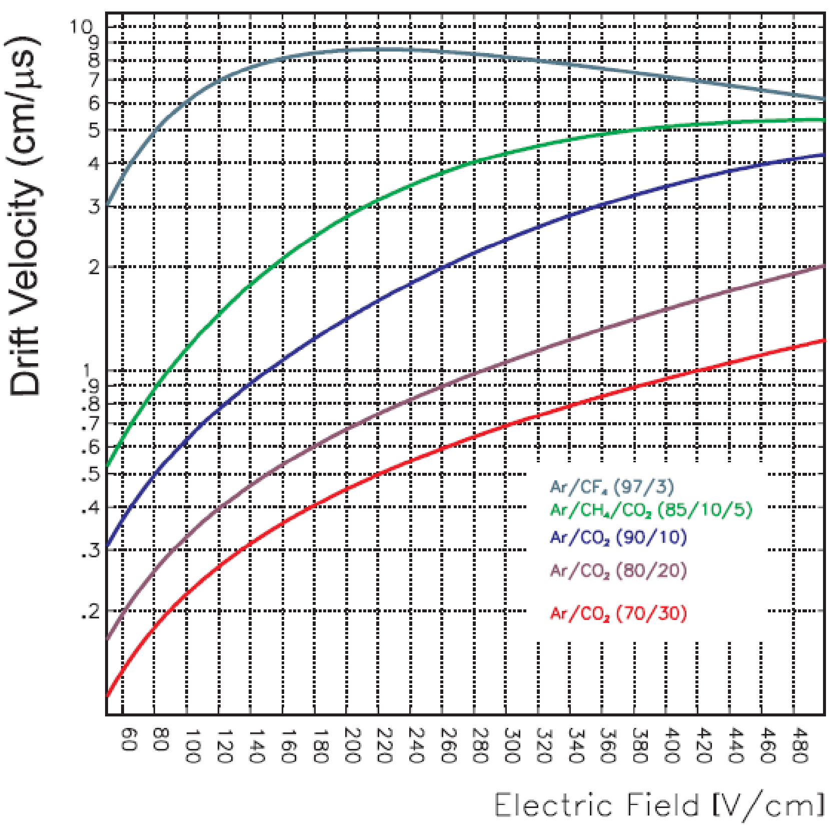
Wall Construction

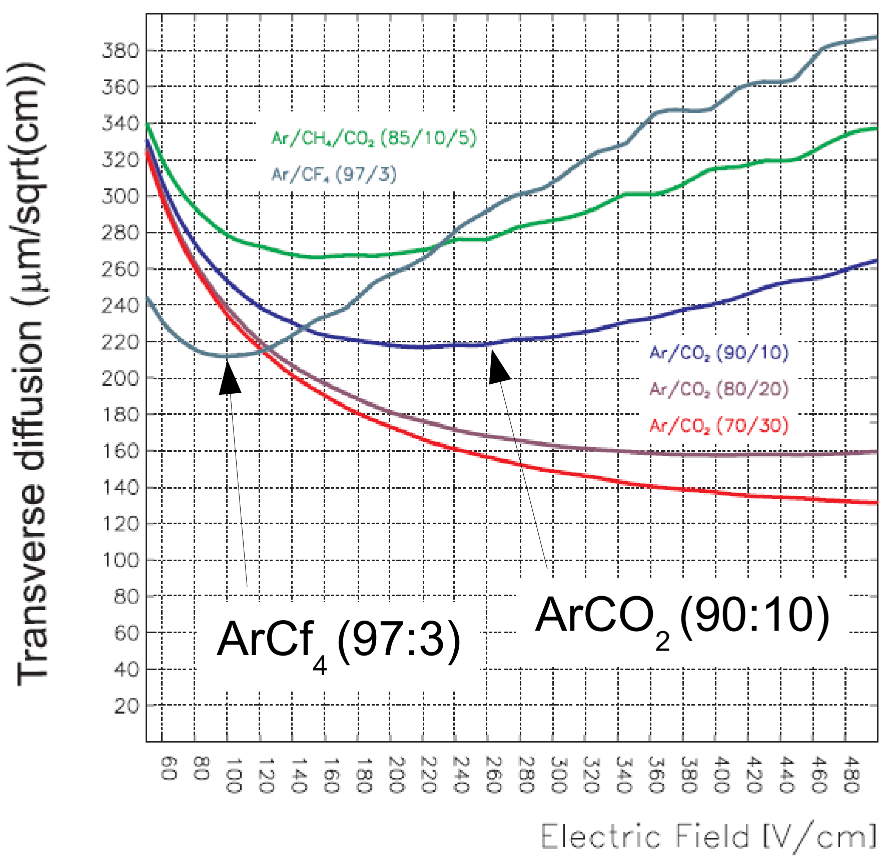
- Composite Wall
  - 0.02mm Copper
  - 1mm G10
  - 10mm Rohacell
- 2.84% radiation length
- Grooves define strips
  - Cut with router
  - Reduce impact of surface charges



ND280 – TPC: Gas choice

- Many space points along the track (90 e^-/cm)
- Minimize diffusion (D < 260μm/(cm)$^{1/2}$)
- Slow gas acceptable b/c 3.5s btw spills
  - ✔ low diffusion, insensitive to E×B distortions and 5μs spill width
  - ✗ electron attachment on O_2





Tracker – FGD and TPC

Study reactions that produce charged particles:

- ν_μ CC quasi-elastic (CCQE) scattering to measure the ν_μ flux and spectrum prior to oscillation
- ν_μ CC in-elastic scattering that can be misinterpreted by SK as CCQE, thus assigning an incorrect ν_μ energy
- ν_μ NC in-elastic scattering that produce π^+ and π^- which can be misinterpreted by SK to be CCQE
- ν_e CCQE scattering to determine the ν_e flux and spectrum, a main background to ν_e appearance at SK

The Off Axis Near Detector (ND280)

Requirements:

- Operate in “high” neutrino rate environment
- Measure neutrino beam before oscillation
  - Muon neutrino flux and spectrum
  - Electron neutrino flux and spectrum
- Measure neutrino interactions and cross sections
  - Understand processes at SuperK

⇨ A highly segmented large volume detector capable of charged and neutral particle energy measurements and particle identification