Queen Mary
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Super-Kamiokande and the T2K Experiment

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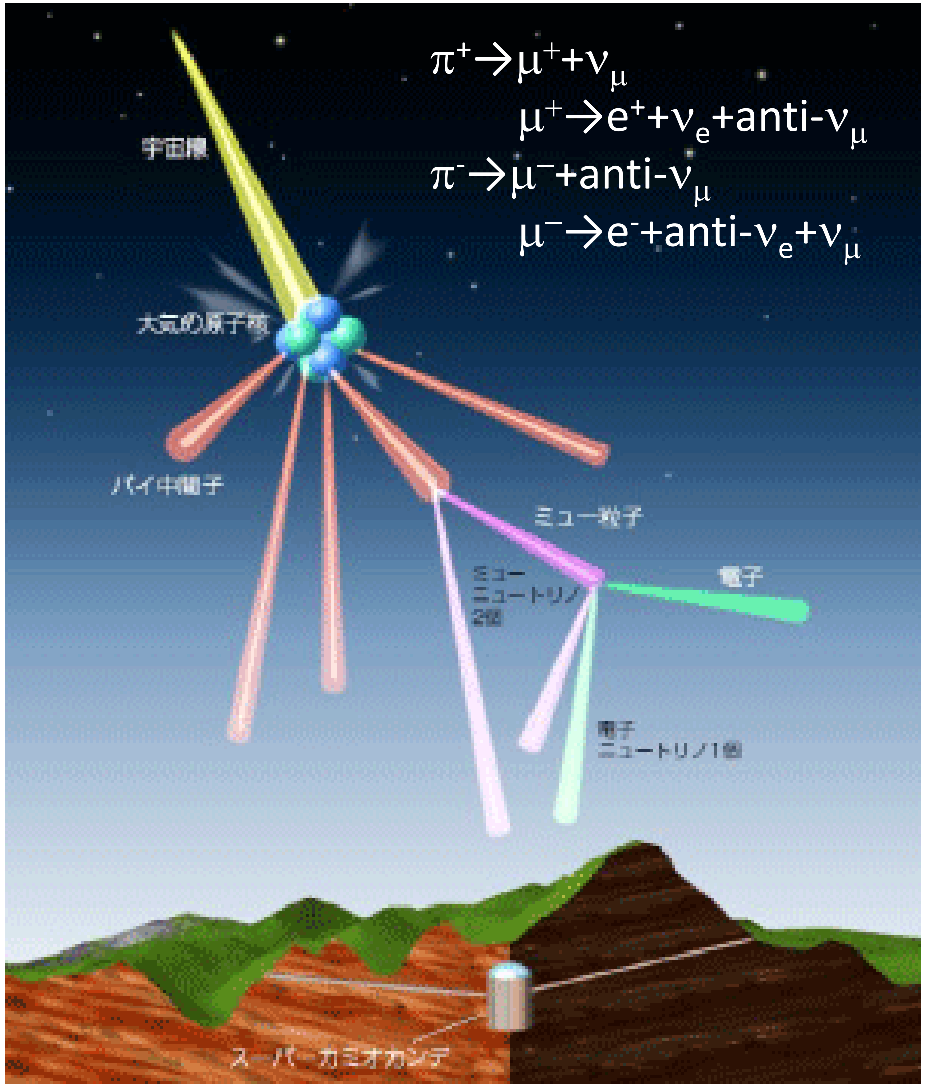
Outline

- Selected history of neutrinos
- Atmospheric Neutrinos
- The Super-Kamiokande Experiment
- Neutrino oscillations
- The T2K Experiment
  - Physics Goals
  - Beamline & Beam
  - Near Detectors
- Outlook

Selected History

- First proposed in 1930 by Pauli to explain beta decay energy spectrum
- First observed by Reines and Cowan in 1956
  - Savannah River experiment records inverse beta decay signal
- Homestake Experiment begins in late-1960s, Solar Neutrino Problem
  - Followed later by the Atmospheric Neutrino Problem
- Early 1980s, IMB becomes the first water Cherenkov experiment
  - Followed soon by the Kamiokande detector
  - Built to look for proton decay
- In 1998 Super-Kamiokande reports that neutrinos have mass
  - First physics beyond the Standard Model

Atmospheric Neutrinos



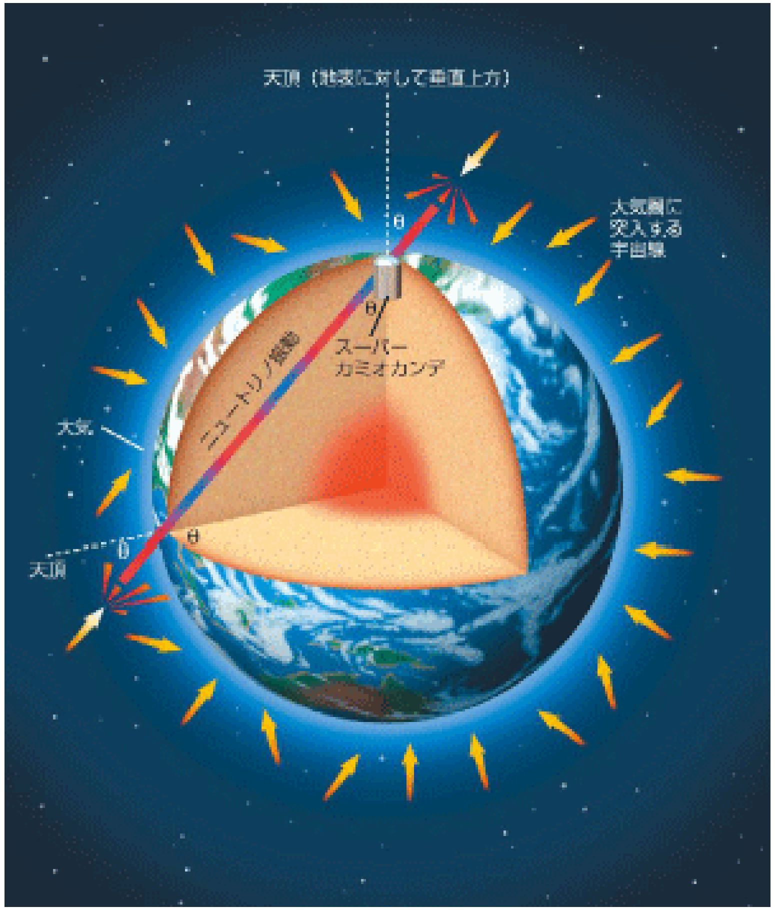
- Have cosmic rays hitting atmosphere
  - Mainly hadronic interactions
- Through charged pion decays, ν_μ and ν_e are produced
- Roughly 2/1 ratio of μ/e neutrino flavors

Atmospheric Neutrino Anomaly

- Double ratio of flavors
  - $R = N(\mu/e)_{Data}/N_{MC}(\mu/e)$
- Early experiments show considerable difference in R
  - Thought to be problem of water Cherenkov detectors since they were a new technology

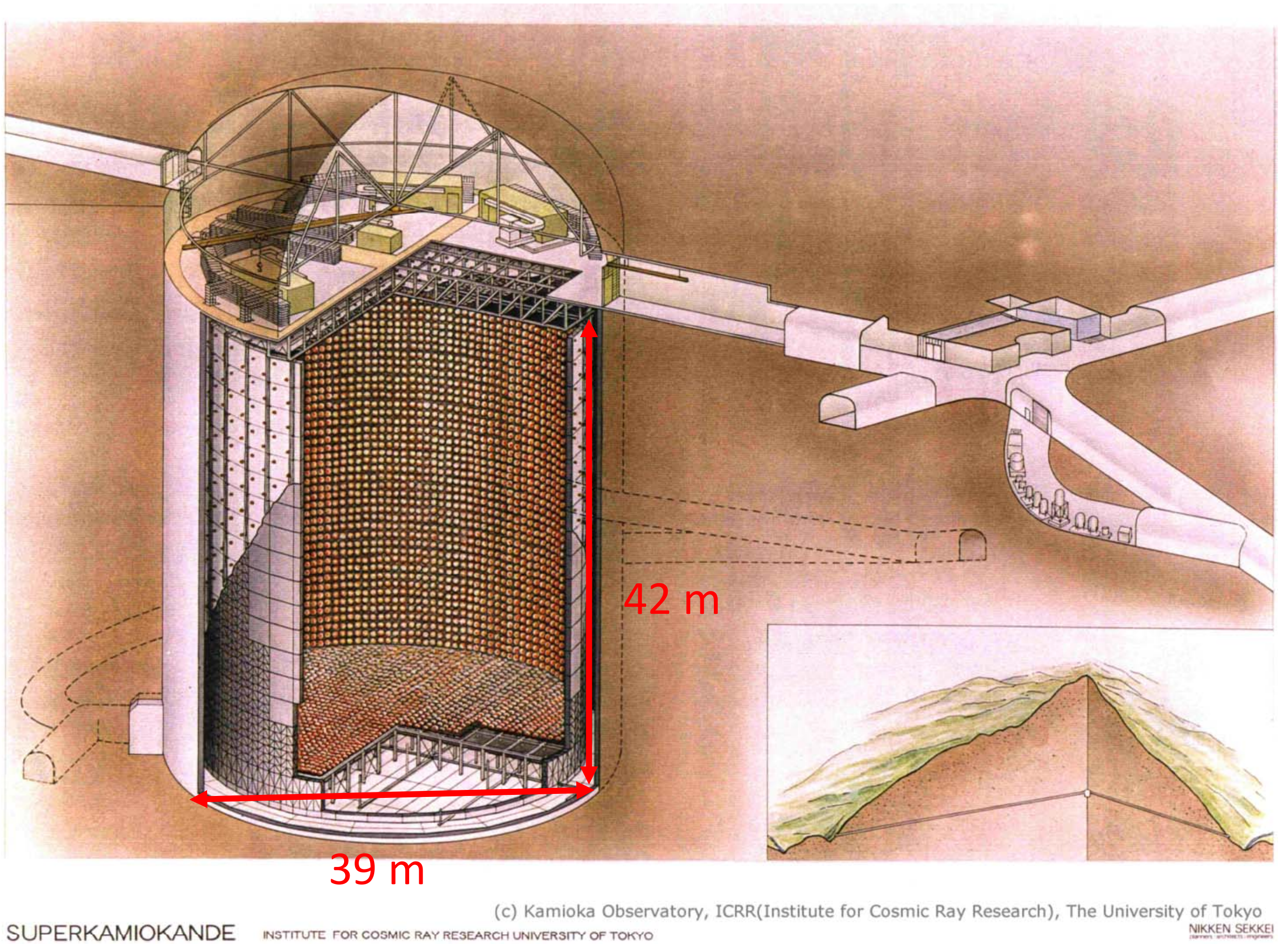
Experiment	Method	Exposure (kt·year)	Flavor Ratio $R(\mu/e)$
IMB	Water Cherenkov	7.7	$0.54 \pm 0.05 \pm 0.012$ (Sub-GeV)
		2.1	$1.40\ ^{+0.41}_{-0.30} \pm 0.3$ (Multi-GeV)
Kamiokande	Water Cherenkov	7.7	$0.60\ ^{+0.06}_{-0.05} \pm 0.05$ (Sub-GeV)
		8.2	$0.57\ ^{+0.08}_{-0.07} \pm 0.07$ (Multi-GeV)
NUSEX	Iron Calorimeter	0.74	$0.96\ ^{+0.32}_{-0.28}$
Fréjus	Iron Calorimeter	1.56	$1.00 \pm 0.15 \pm 0.08$
Soudan-2	Iron Calorimeter	5.1	$0.68 \pm 0.11 \pm 0.06$
Super-K	Water Cherenkov	92	$0.658 \pm 0.016 \pm 0.05$ (Sub-GeV)
		92	$0.702\ ^{+0.032}_{-0.030} \pm 0.101$ (Multi-GeV)

Zenith Angle Distributions



- Way to check to see if the atmospheric neutrino ratios are similar based on where in the atmosphere neutrino was created
- Neutrino production should be the same regardless of direction
  - See if systematically different or directionally dependent

Super-Kamiokande



Built as a proton decay experiment, atm. ν a background

50 kton water Cherenkov detector

Located in the Japanese Alps in Western Japan

1000 m rock overburden

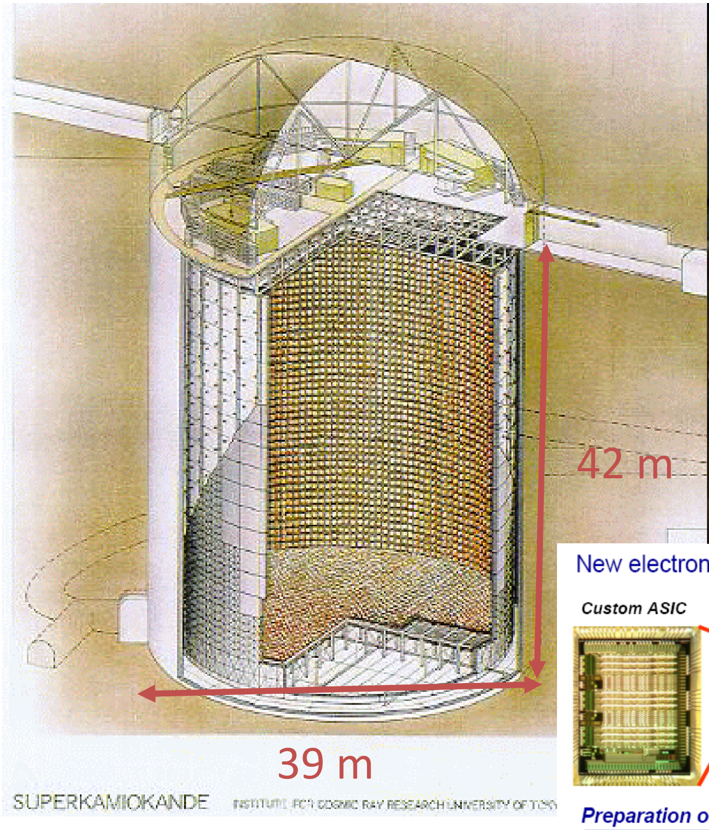
22.5 kton fiducial volume

11129 20" Inner Detector (ID) PMTs , 39% photo-cathode coverage

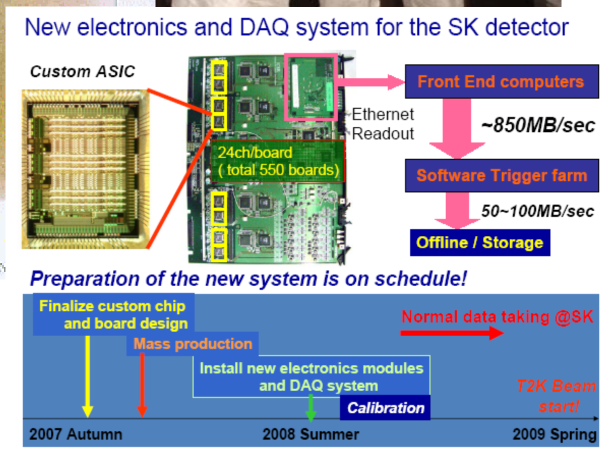
1885 8" Outer Detector (OD) PMTs w/ WLS Plates

ID & OD optically separated

Super-Kamiokande Phases



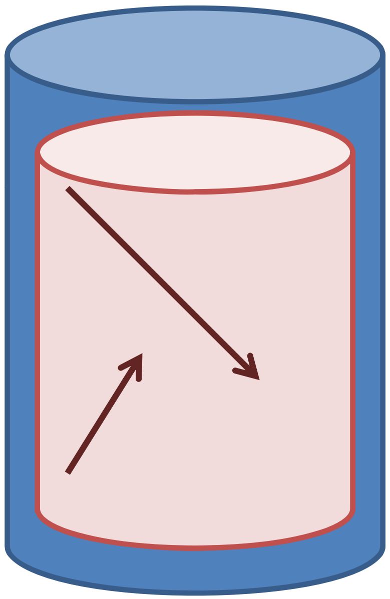
June 1999 – Oct. 2005 K2K
Far Detector



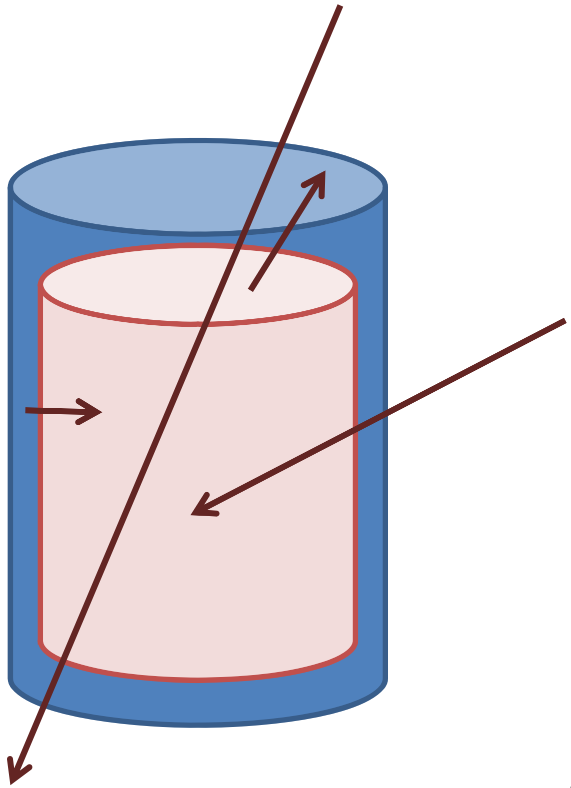
SK-I: 11146 20" PMTs
March 1996 – July 2001
Accident destroys ½ of 20" PMTs
Remaining ones given fiberglass covers to prevent implosion
SK-II:
Dec. 2002 – Oct. 2005
Broken PMTs replaced
SK-III: 11129 20" PMTs
July 2006 – Sept. 2008
Recovered from accident
SK-IV: Sept. 2008 -
Upgrade of electronics and DAQ for T2K and SK-IV
Moves to a software event trigger

Basic Event Classes @ SK

- Fully Contained Events
  - All energy deposited in Inner Detector
  - Little to no activity in Outer Detector

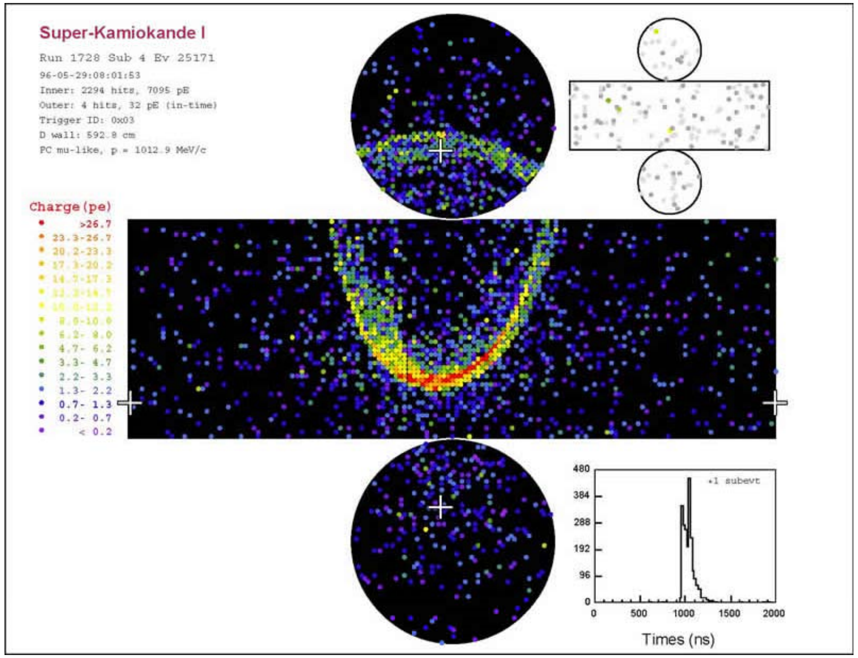


- Partially Contained Events
  - Lots of OD activity in clusters



Reconstruction

FC event

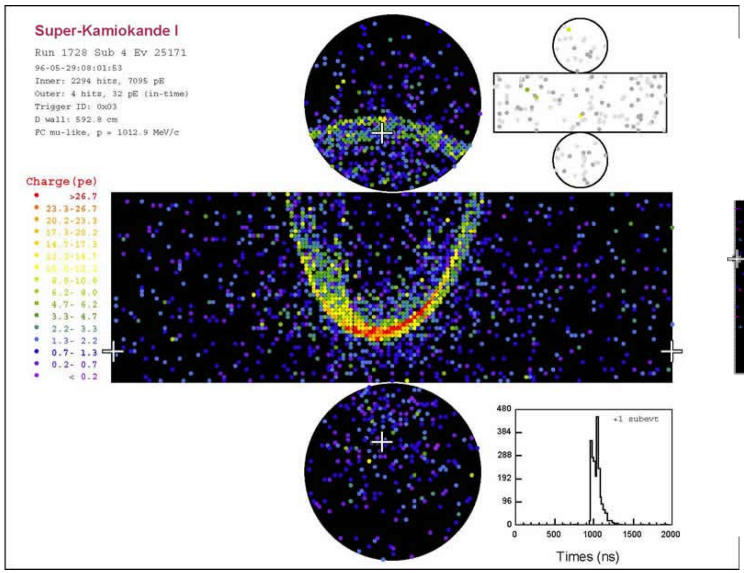


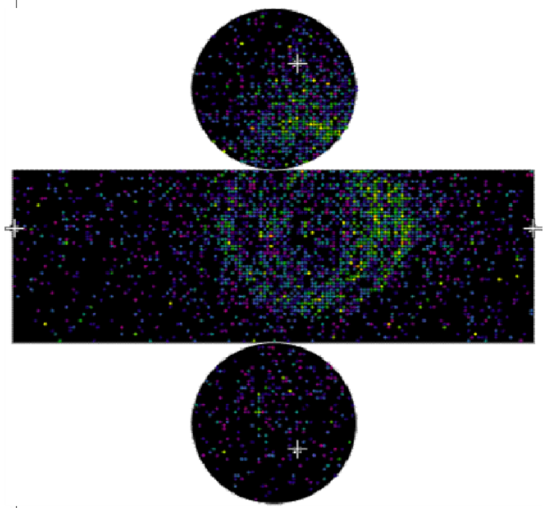
- Electronics record PMT charge and time information
  - From charge and time info., can reconstruct: position, direction, momentum, Cherenkov angle, # of rings, PID, # of decay electrons, etc.

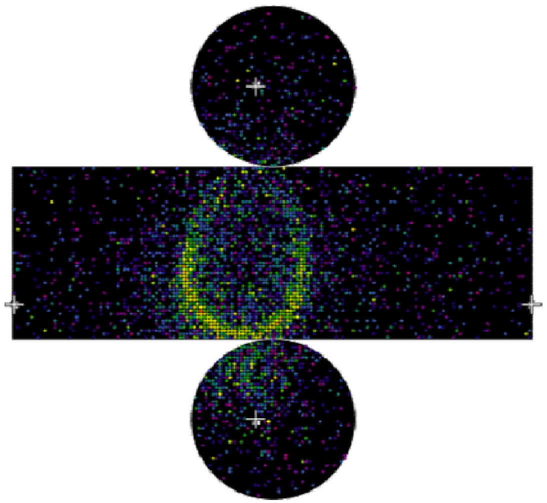
Ring Types & Particle ID

muons leave rings with sharp edges
electrons undergo pair production , producing a fuzzy ring

non-showering | multi-ring | showering







muon, charged pion, proton | electron, photon

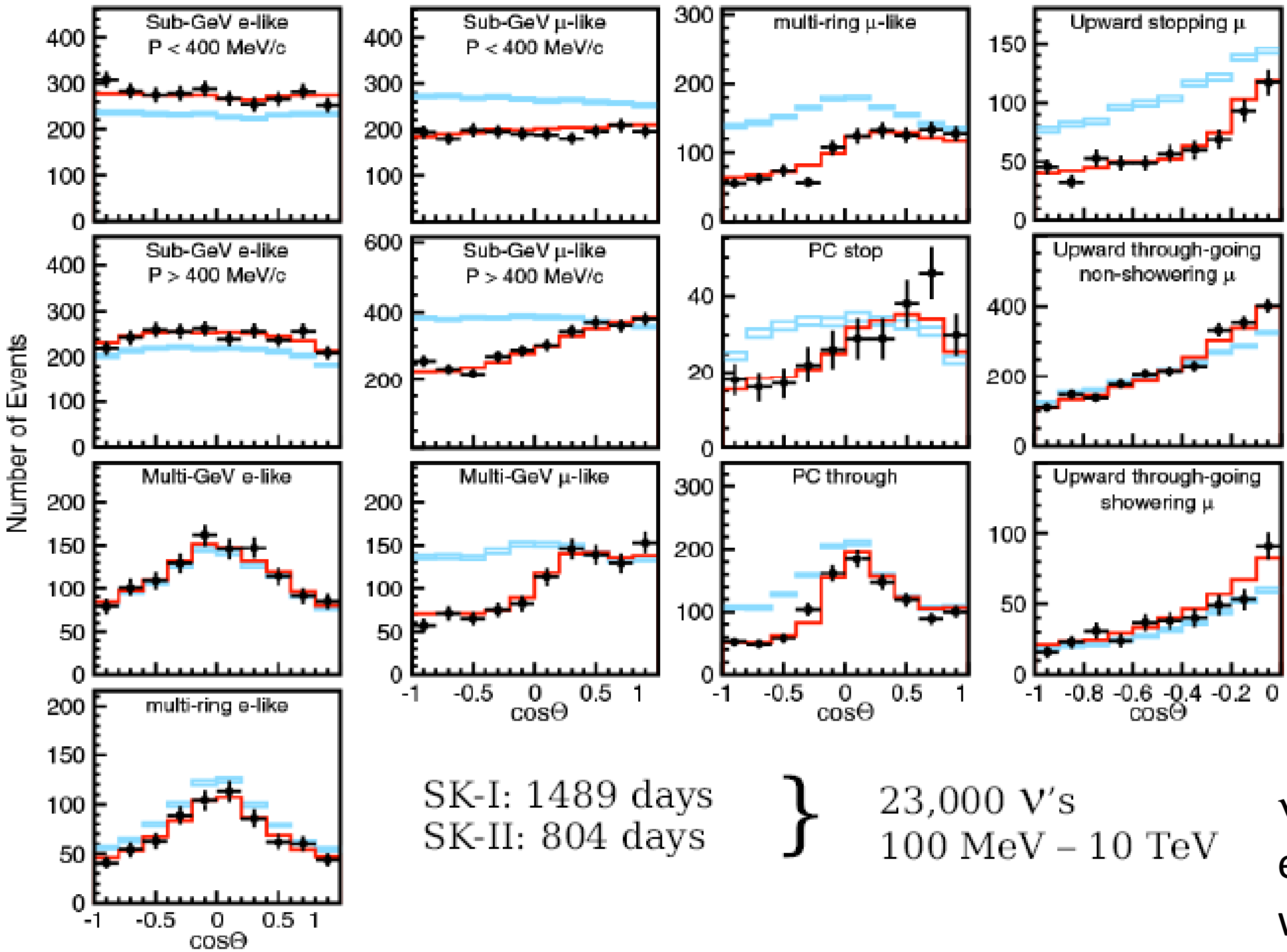
μ-like | e-like

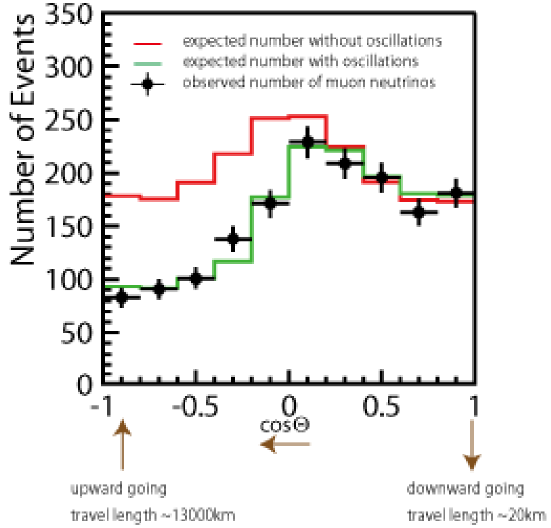
PID verified @ KEK test
beam w/ 1kton detector

Zenith Angle Event Selection

- Fully contained:
  - Inside Fiducial Volume
  - Divided between sub- and multi-GeV
    - cut at 1.33 GeV in visible energy
  - One ring
    - (e-)μ-like
    - p>(100)200 MeV/c
  - Multi-ring
    - most energetic ring μ-like, with p>600 MeV/c
- Partially Contained
  - Survives reduction
  - Inside Fiducial Volume
- Upward-going muons
  - only entrance signal in OD
  - between 8,000 & 1.75 million photoelectrons

SK-I&II Zenith Angle Distributions





SK-I: 1489 days
SK-II: 804 days } 23,000 ν's
100 MeV – 10 TeV

$\nu_\mu \rightarrow \nu_\tau$ osc.
e-like events are consistent with expectation

Neutrino Oscillations

Superposition of mass eigenstates, observe flavor eigenstates
Simple quantum mechanical mixing

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric ν — solar ν

2 flavor approximation:

$$P\left(\nu_\alpha \overset{\alpha\neq\beta}{\rightarrow} \nu_\beta\right) \approx \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2 L}{E}\right)$$

$$P(\nu_\alpha \rightarrow \nu_\alpha) \approx 1 - \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2 L}{E}\right)$$

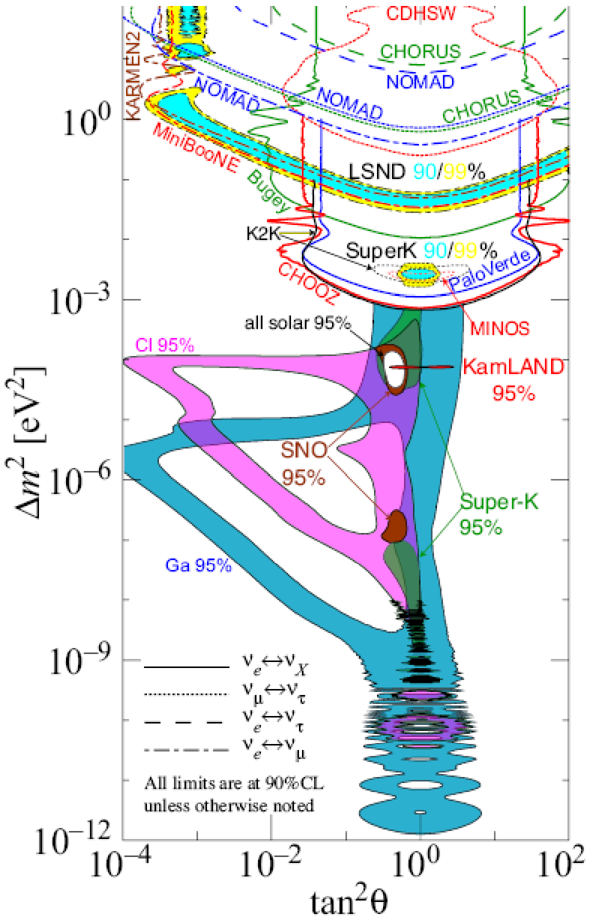
$$\Delta m^2 = m_i^2 - m_j^2$$

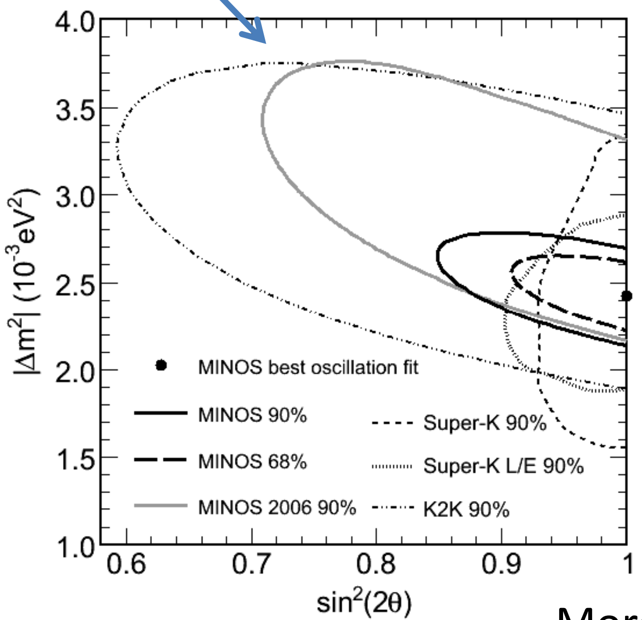
L [km]
E [GeV]
Δm^2 [eV^2]

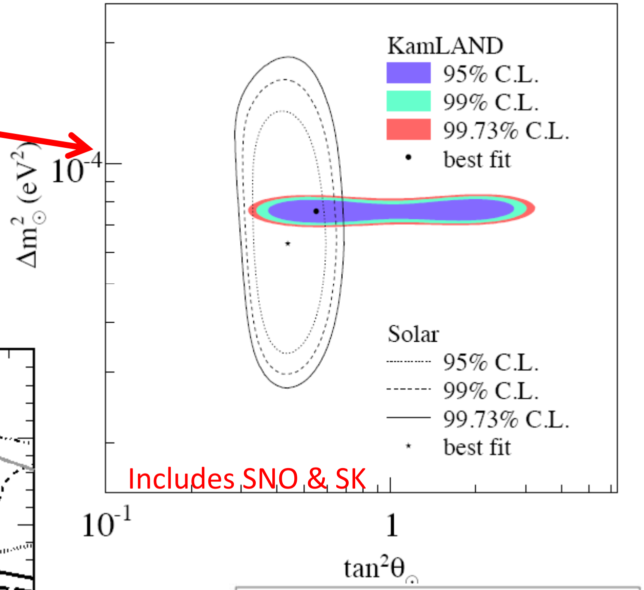
Assuming 3 flavors only
Assume U is unitary
Assume ν is a Dirac particle

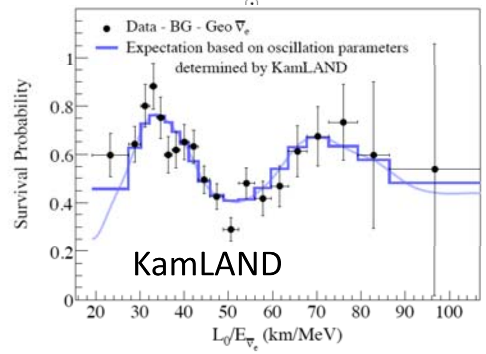
Current Status of Neutrino Oscillation Parameters

$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$
$\Delta m^2_{21} = (7.59 \pm 0.20) \times 10^{-5}\ \text{eV}^2$
$\sin^2(2\theta_{23}) > 0.92$ [i]
$\Delta m^2_{32} = (2.43 \pm 0.13) \times 10^{-3}\ \text{eV}^2$ [j]
$\sin^2(2\theta_{13}) < 0.19,\ \text{CL} = 90\%$



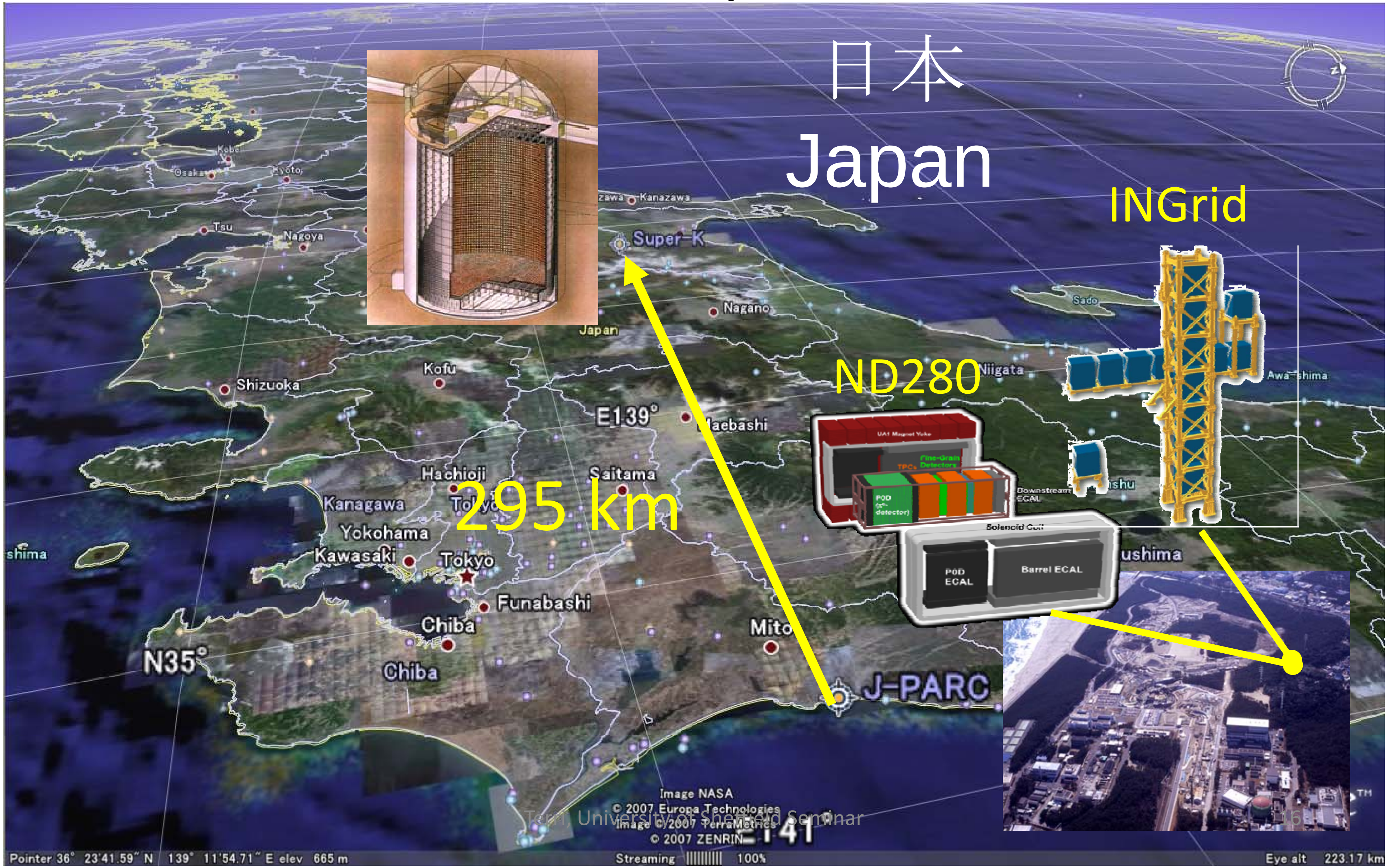






More exotic models are not as consistent with the data or have conflicting experimental results

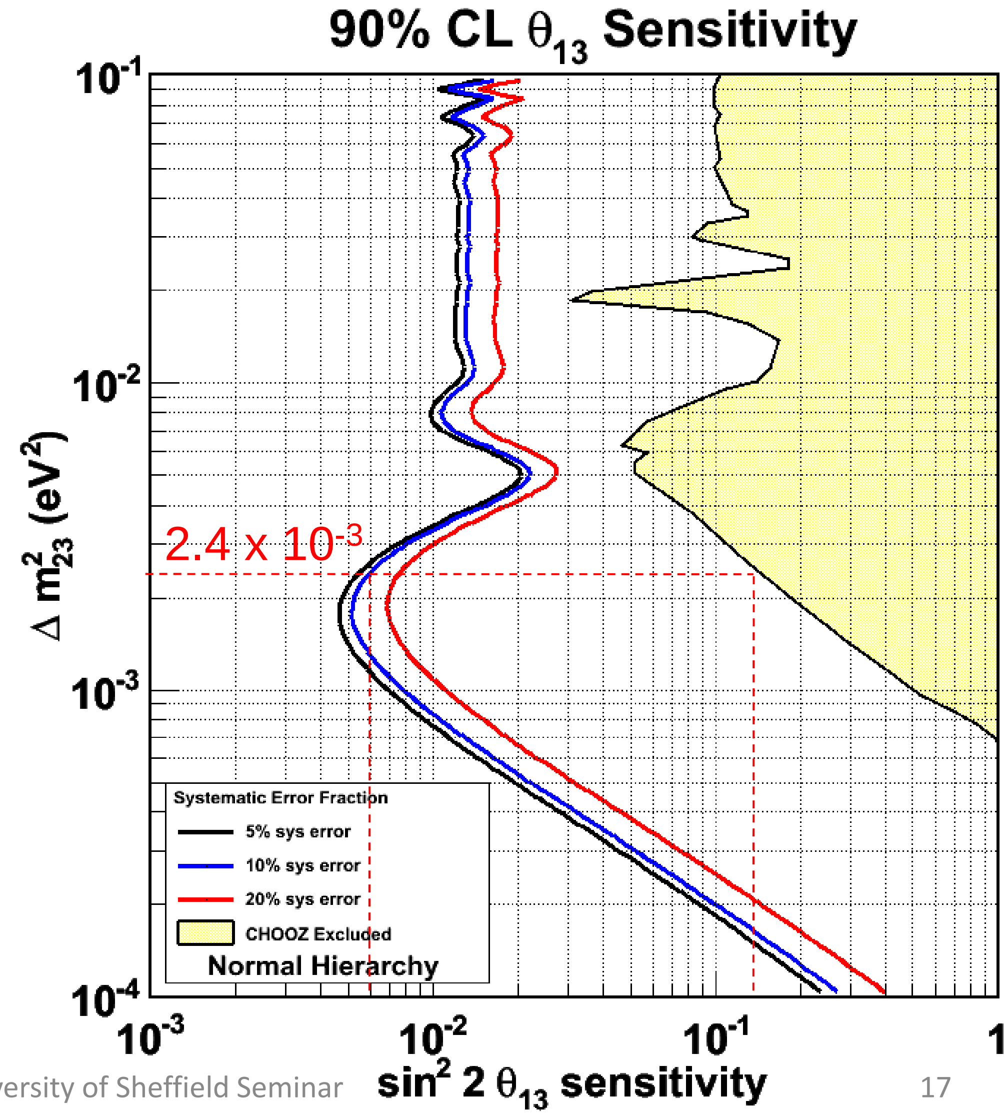
The T2K Experiment



Oscillation Physics Goals

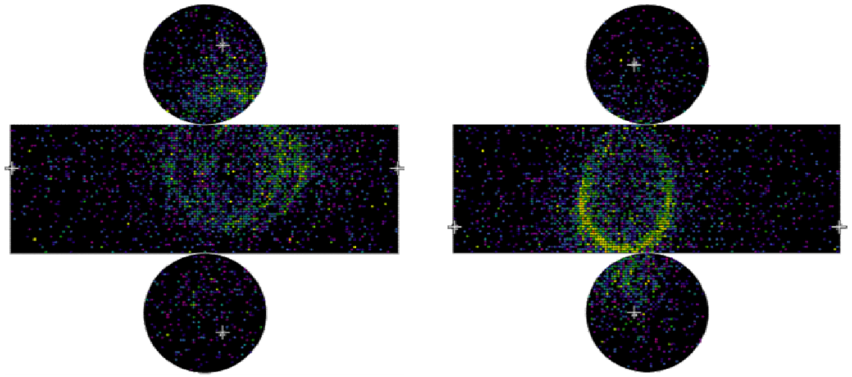
- Precision measurement of atmospheric neutrino parameters
  - Is θ_{23} maximal?
- First measurement of θ_{13}
  - … or at least best limit
  - If we can measure θ_{13}, what is δ_{CP}?

(0.75 kW beam x 10^7s)
$\sin^2 2\theta_{12}$= 0.8704 $\sin^2 2\theta_{23}$ = 1.0
Δm^2_{12} = 7.6x10-5eV² δ_{CP}=0



Limitations @ SK

Types of appearance background



$\sin^2\theta_{13}$	Backgrounds			Signal
	ν_μ induced	Beam ν_e	Total	
0.1	10	16	26	143

Mostly from NC1π^0 interactions
No difference between this and signal (must rely on phase space differences)

$$E_\nu^{rec} = \frac{m_N E_\mu - \frac{1}{2} m_\mu^2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

- Single is a single ring (e)μ-like event
  - CCQE enhanced
- For appearance and disappearance analysis:
  - Need good knowledge of beam flux
  - Need reduced errors on cross sections
    - current total error ~20%
  - Need to reduce (2)1 type(s) of background

J-PARC Beamline

1: 400 MeV LINAC

2: 3 GeV Synchrotron (RCS)

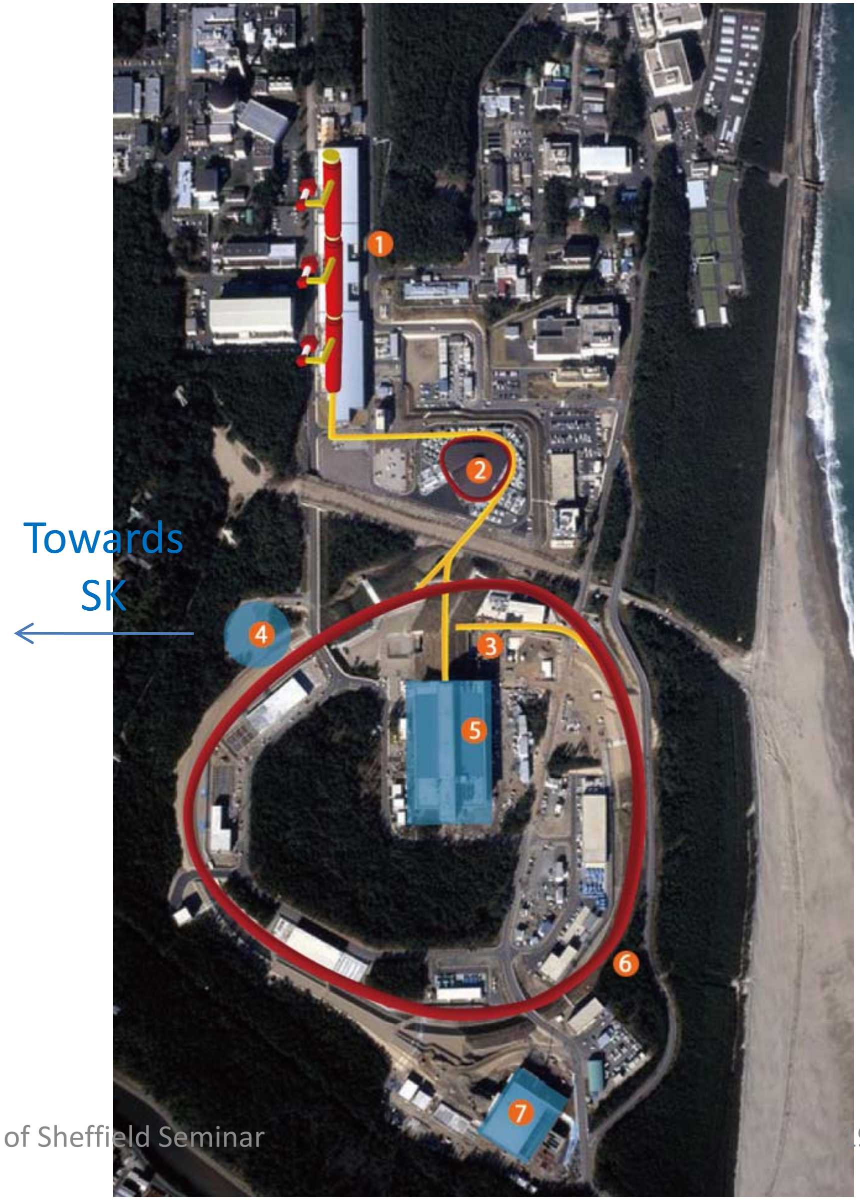
6: 30 GeV Main Ring

- 6 or 8 bunches w/ 581 ns between each bunch
- 0.3 Hz rep rate

3: Neutrino Beamline & Target Station

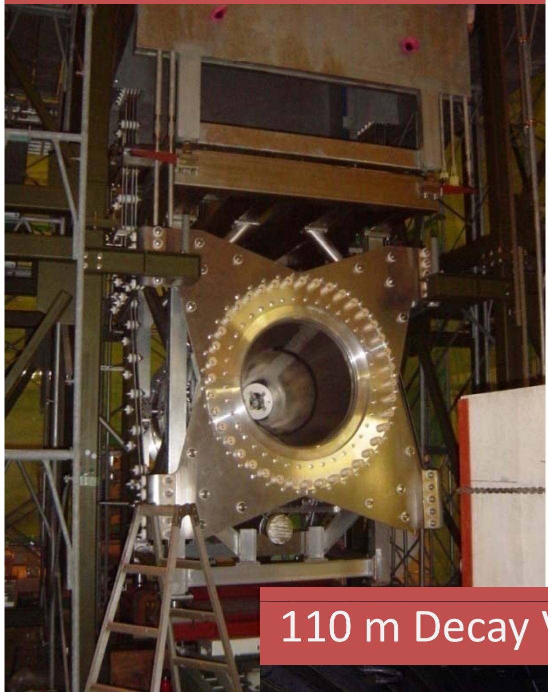
4: The Pit

- 280 m downstream
- Houses on- and off-axis Near Detectors

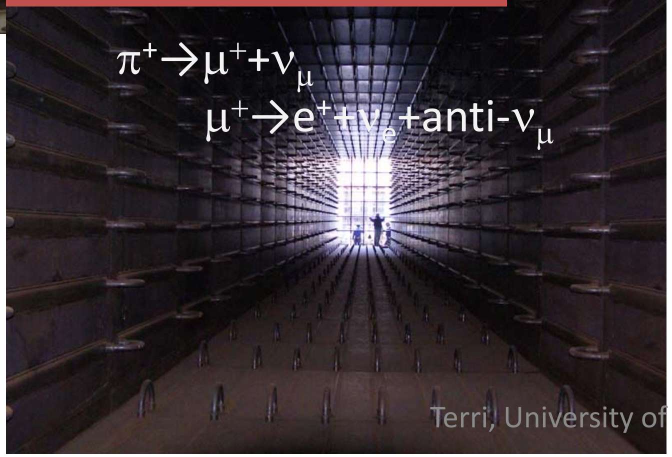


Target Station/Decay Volume

Horn operation at 320 kA



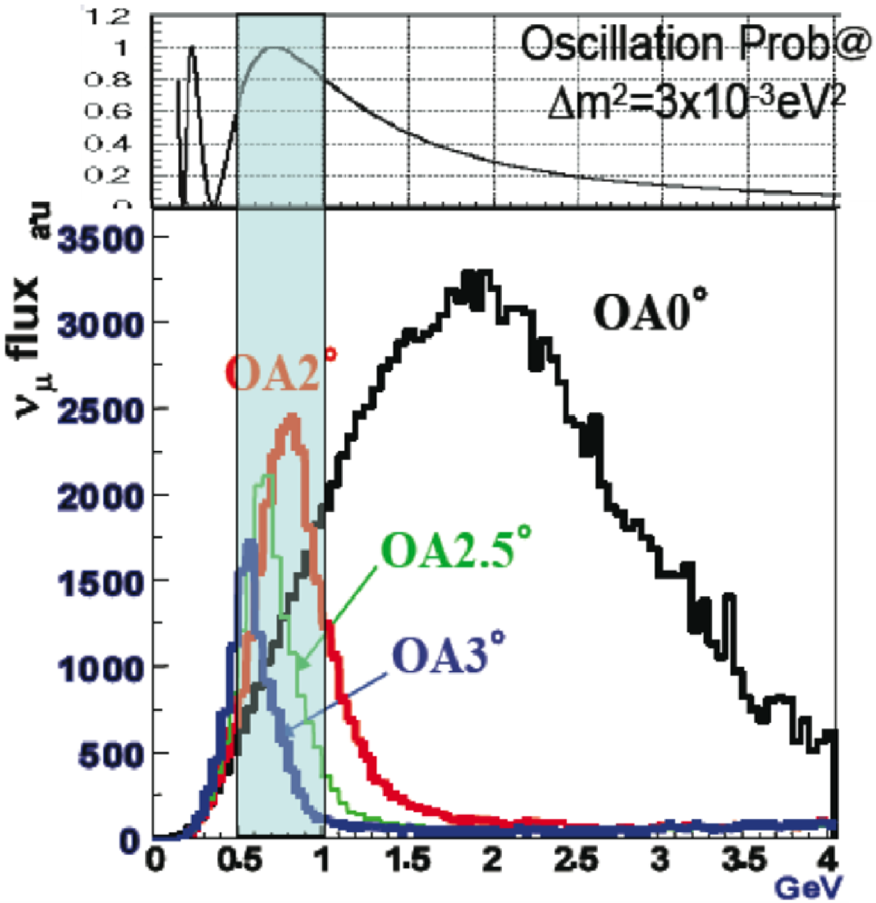
110 m Decay Volume

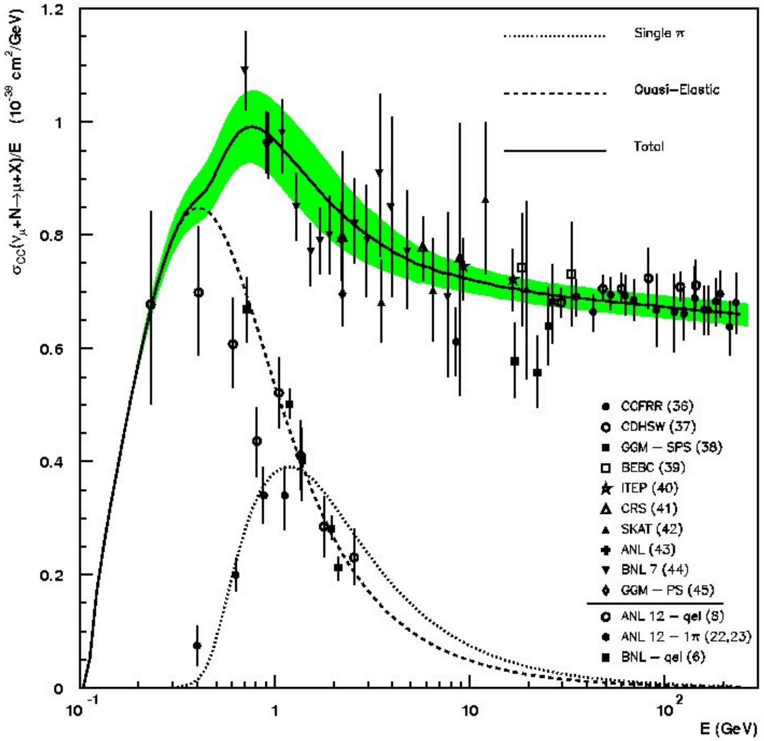


- 30 GeV protons collide with graphite target
- Mesons produced (mostly pions)
- Charged particles focused by 3 horns
  - target embedded in first horn
- Creates neutrino beam ~95% ν_μ
  - Backgrounds from kaons, π^-, and μ decays
- Muon monitor at end of decay volume to check beam direction

Neutrino Beam Flux

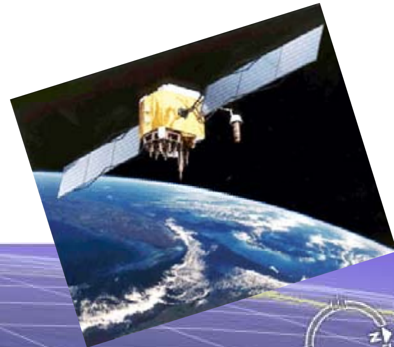
$$\sin^2\left(1.267\frac{\Delta m^2 L}{E}\right)\approx 1$$





Off-axis angle of 2.5°
Beam closer to monoenergetic
Suppressed high energy tail
Fewer non-CCQE interactions

Beam Timing



GPS timers at the end of the proton beam and @ SK

Make TOF cut based on when beam hit target and when it should be at SK

Have ~200 ns error between GPS systems

SK events will fall into beam window (should see beam bunch structure with enough statistics)

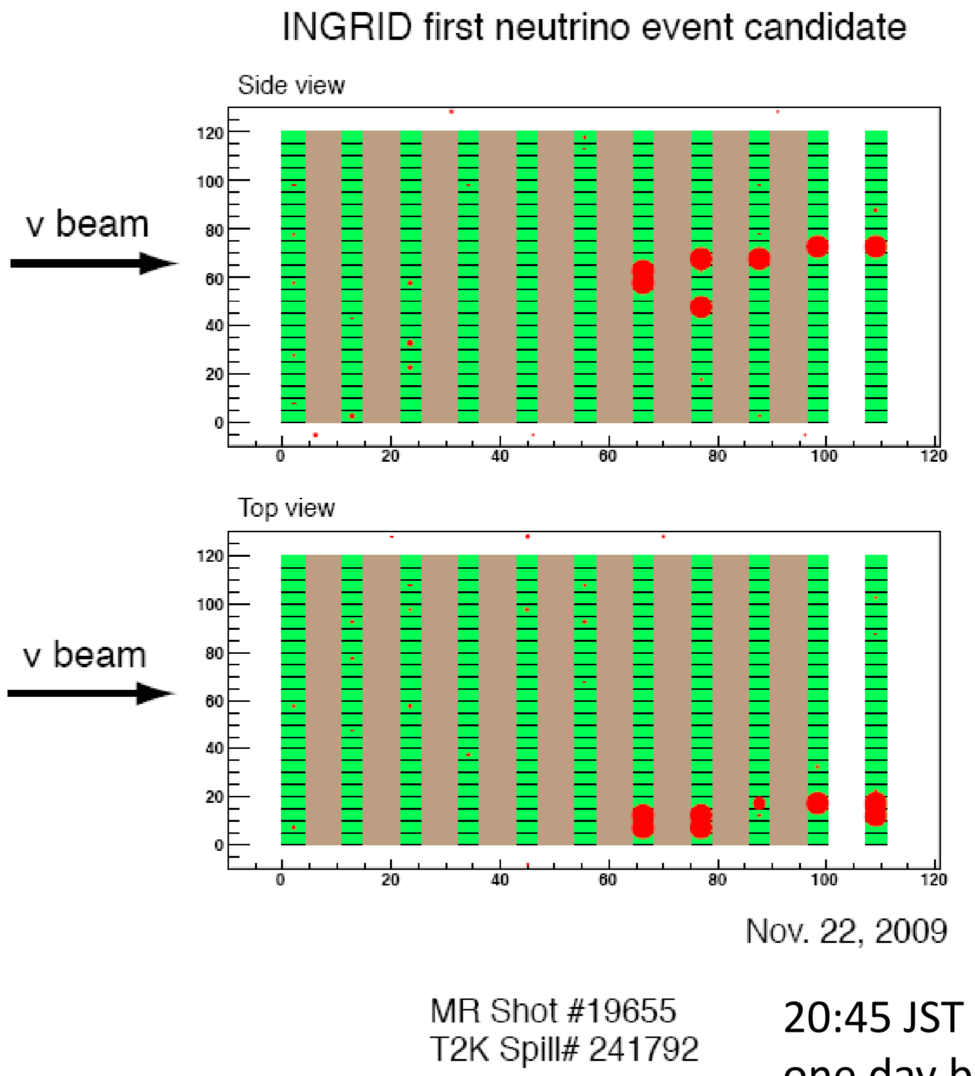
Will also be able to see bunch structure at Near Detector

On Axis – The INGRID Detector

- Modular Detector
  - 16 Modules
- Each Module has:
  - 10 Scintillator Bar Layers, 9 Fe Layers
  - Surrounding Veto Planes
  - Wavelength Shifting Fiber → Hamamatsu MPPCs
- Can give beam direction every few hours
- Check beam MC for change in flux as a function of off-axis angle

INGRID Module Construction

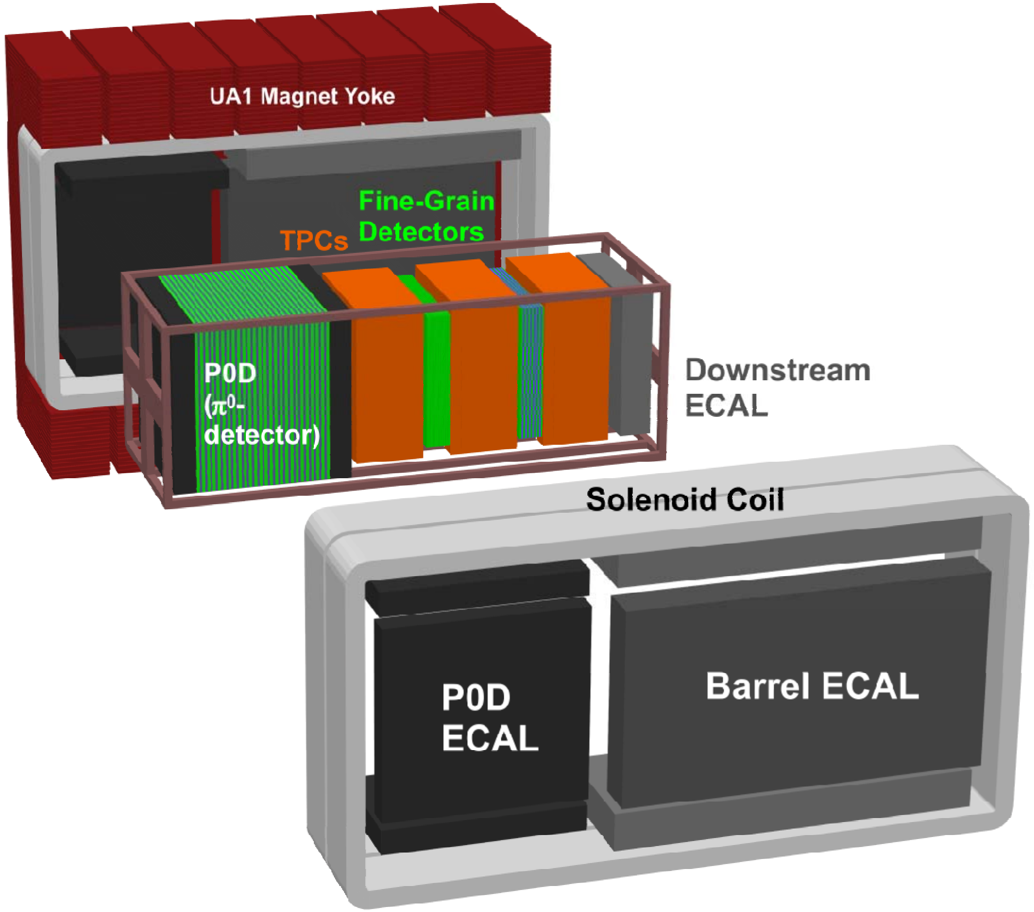
First Neutrino Event Candidate



20:45 JST
one day before LHC turned on

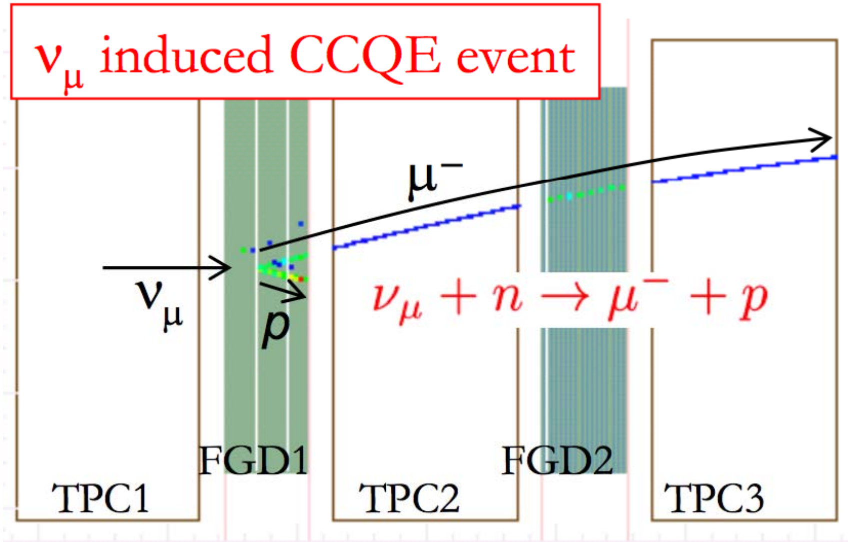
The Off-Axis Detector

- UA1 Magnet 0.2 T field
- Includes a water target in P0D and Tracker
  - Understand interactions at SK
- Tracker Region
  - Fine Grained Detectors (FGDs) & TPCs
  - Particle Tracking
- P0D
  - Measure NC π^0 rate
- ECAL
  - Surrounds tracker and P0D
  - Capture EM energy
- SMRD
  - Muon ranging instrumentation in the magnet yoke

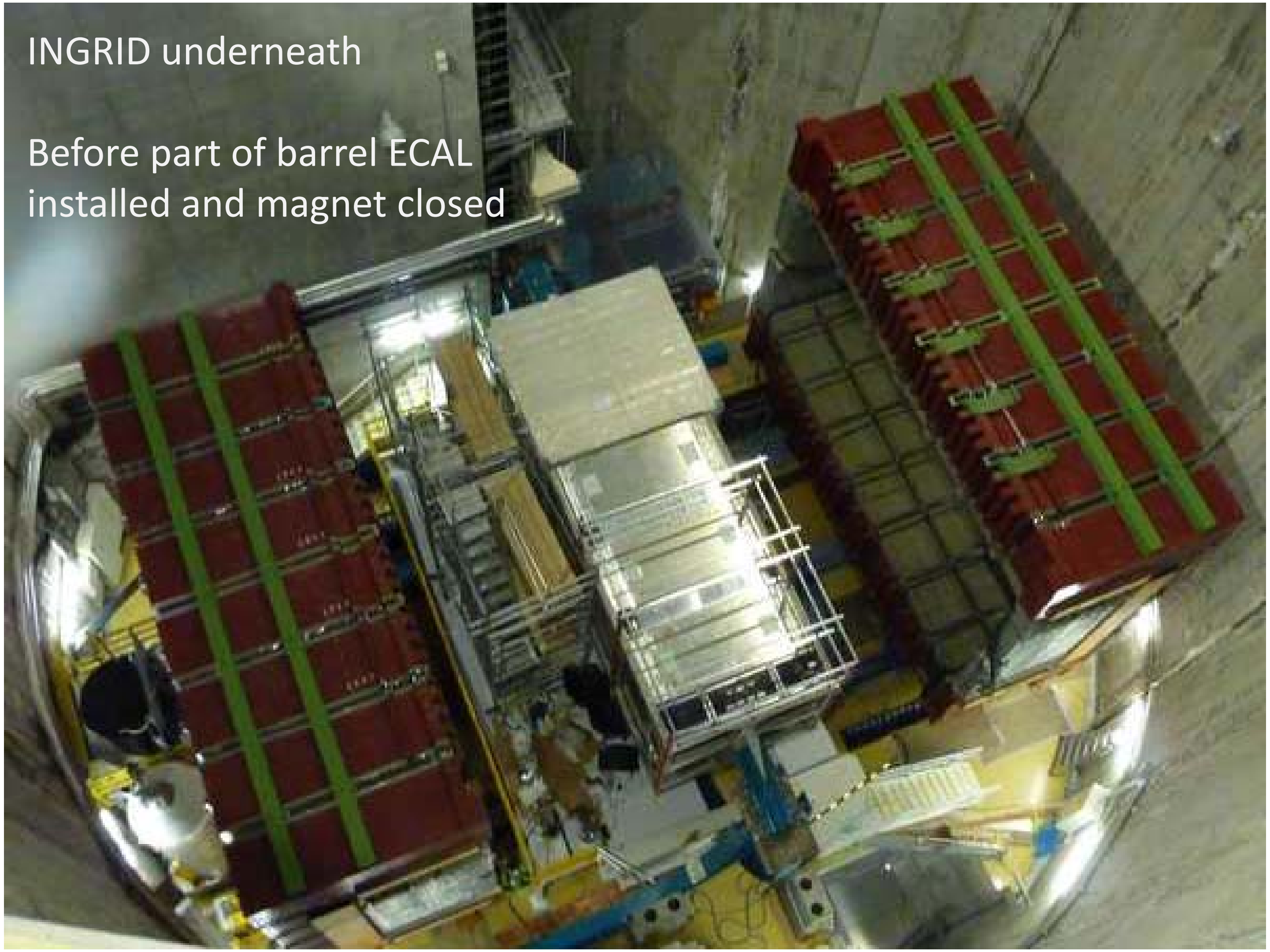


Near Detector Physics

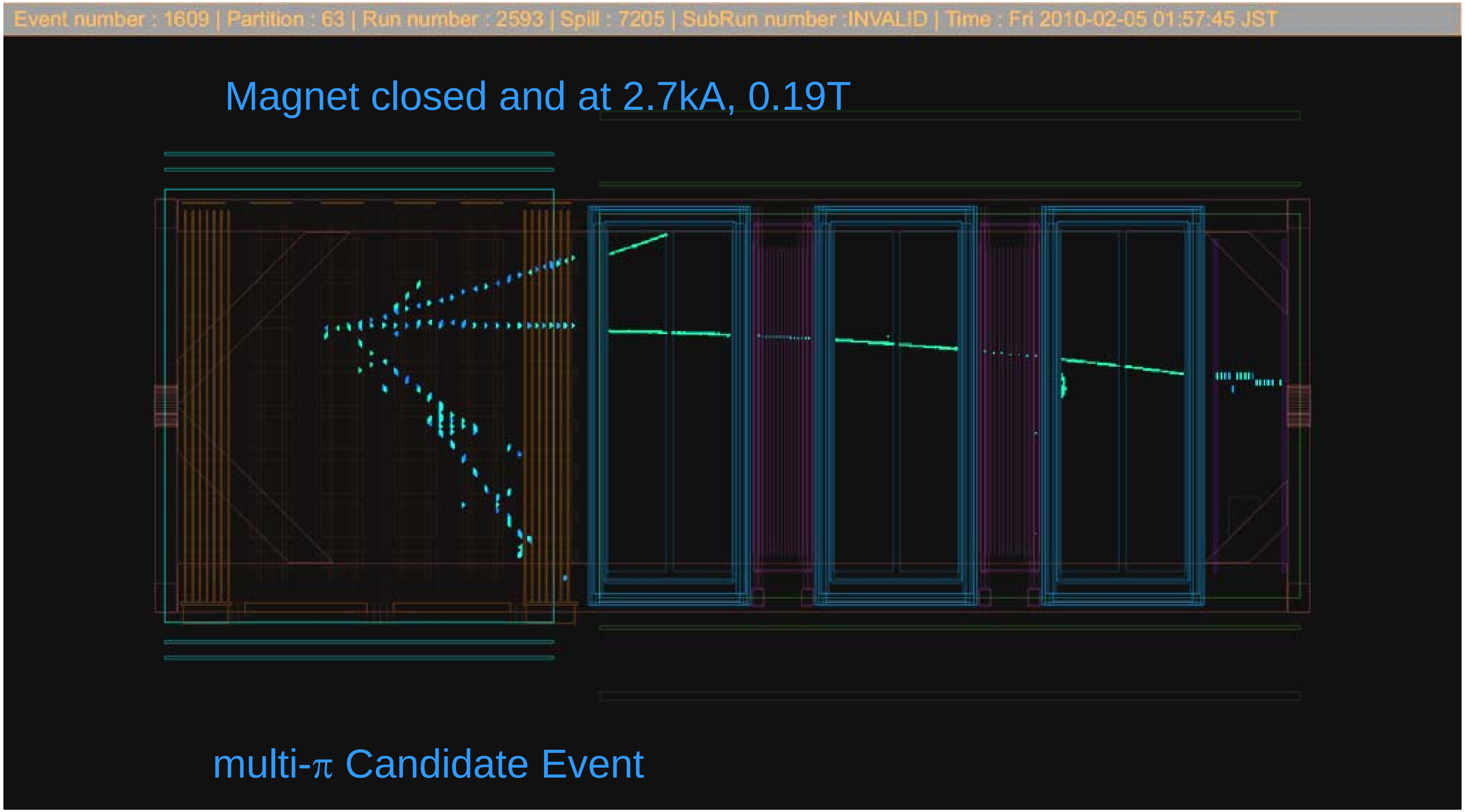
- Measure ν_e & ν_μ flux, E-spectrum
  - Mainly through CCQE interactions
- Measure ν cross-sections and kinematics
- Measure nuclear recoil
- Water-in vs. water-out subtraction for cross-sections for P0D



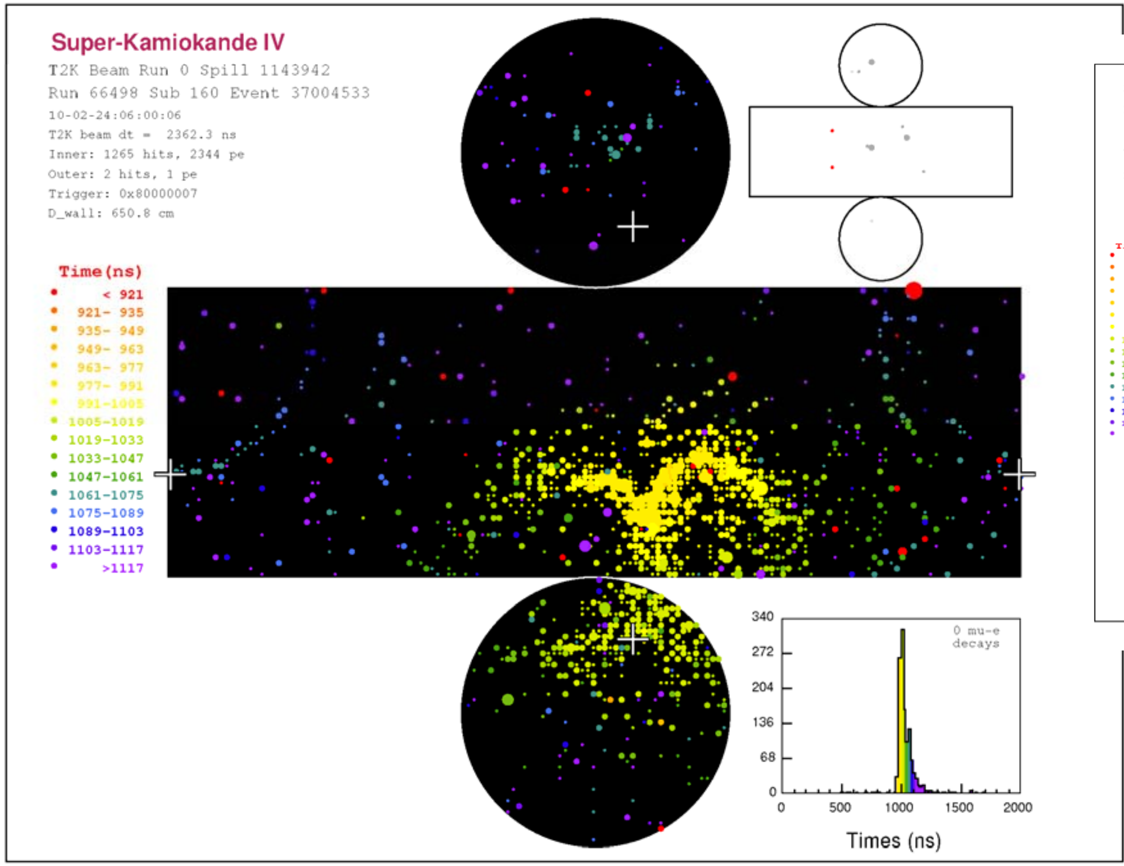
ND280 Construction

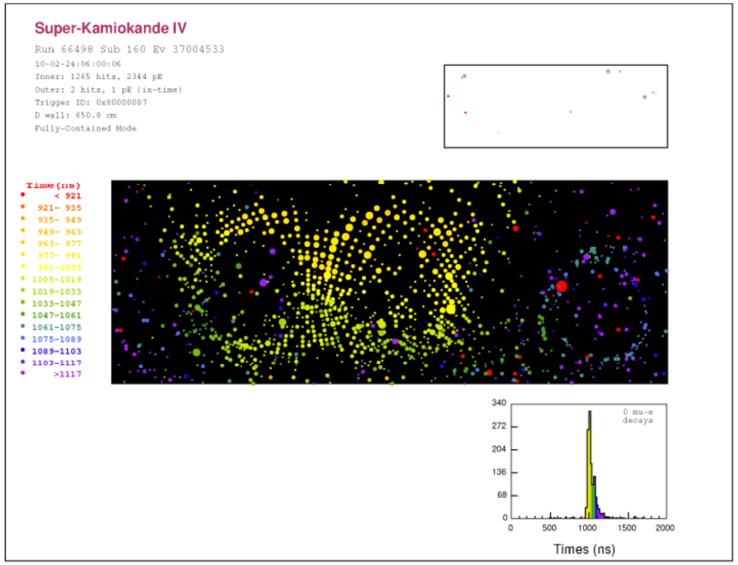


Off-axis Event Candidate



First Event Candidate At Super-K





Fully Contained, in the fiducial volume

2 showering rings:

invariant mass = 133 MeV/c2

momentum = 148 MeV/c

Outlook/Summary

- Super-Kamiokande is taking data on its own and as T2K's far detector
  - In addition to improved neutrino osc. measurements, it is waiting for a supernova or proton decay
- T2K is now data taking and is looking to publish first analyses by the end of the year
  - Precision measurement of atm. ν parameters
  - Search for ν_e appearance
- We have physics beyond the Standard Model
  - Just how far does it go?

BACKUPS

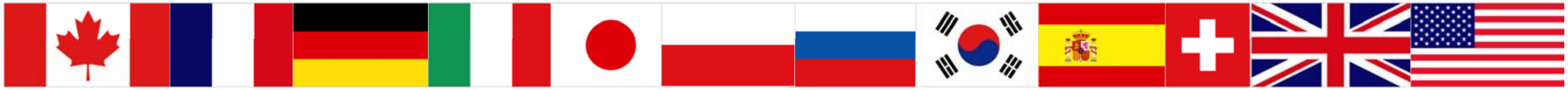
Fully Contained Reduction

- Visible energy above 30 MeV
- First reduction
  - at least 200 photoelectrons (p.e.s)in 300 ns window
  - PMT w/ most charge <0.5 of total charge
  - less than 25 OD hits in 800 ns window
  - more than 100 μs between events
- Second reduction
  - no more than 10 OD hits w/in 8 m of potential muon track
  - more than 50 hits in ID in 50 ns residual time window
- Third reduction
  - Remove "flashers," PMTs emit corona discharges
- Fourth reduction
  - Remove 10 OD hits w/in 200 ns coincidence
  - Remove cosmic ray muons
- Fifth reduction
  - in fiducial volume (200 m away from closest ID wall) and at least 30 MeV visible energy

Partially Contained Reduction

- First reduction
  - Must have at least 1000 p.e.s in ID
- Second reduction
  - Remove events w/ time residual of 260 ns
- Third reduction
  - less than 10 hits in OD w/in 8 m of backtrack of event
  - remove flashers
- Fourth reduction
  - Angle subtended from earliest PMT hits must be at least 37 degrees
  - Remove corner clippers by 1.5 m from top or bottom or track >30 m long
- Fifth reduction
  - Must have at least 9 hits in OD cluster
  - minimum 3000 p.e.s in ID
  - remove if OD clusters are more than 20 m
  - quality cuts on OD timing and ID energy
  - vertex w/in FV (at least 2 m away from ID wall)

The T2K Collaboration



~500 members, 62 Institutes, 12 countries

Sources

- Super-Kamiokande Collaboration, PRL **81**, 1562 (1998)
- Super-Kamiokande Collaboration, PRD **71**, 112005 (2005), hep-ex/050164
- PDG: http://pdg.lbl.gov
- T. Kato, Ph.D. thesis
- M.C. Gonzalez-Garcia & M. Maltoni, hep-ph/0704.1800