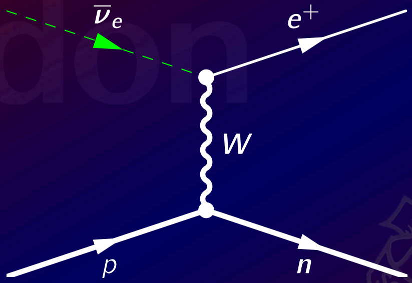
Imperial College London

Oscillations and More at Super-K, T2K & Hyper-K

Yoshi Uchida

Prague Colloquium Neutrino 19

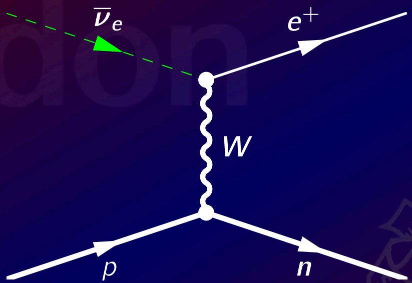
24 October 2019



See preceding talks for reactor neutrino experiments

Neutrino Interactions

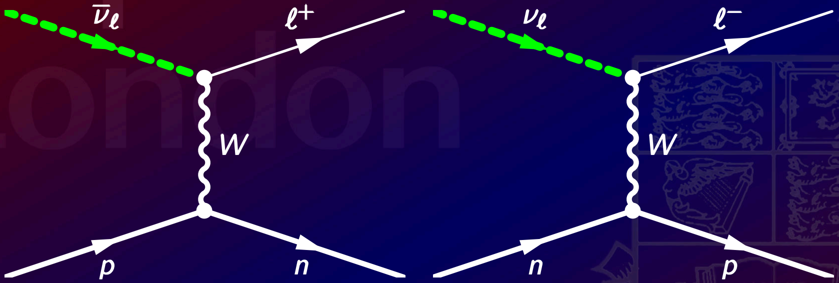
MeV electron antineutrinos on a proton



- A tree-level weak interaction to a good approximation
- Neutron decay gives the matrix element
- Very small cross section uncertainties
- For KamLAND first paper (2003): ν **cross section error was 0.2%** out of a total systematic error of 6.4%

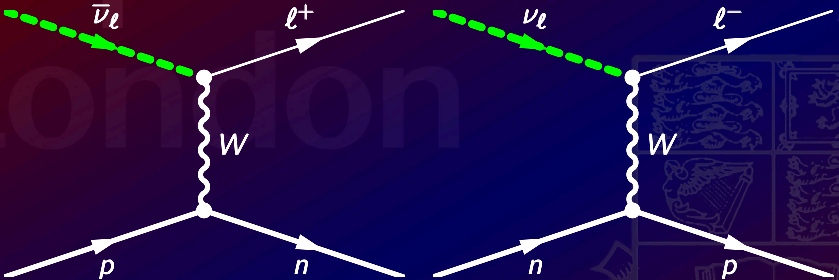
Preceding talks had no need to mention cross-section uncertainties

GeV Neutrino Interactions



Many many more diagrams need to be taken into account in reality

GeV Neutrino Interactions

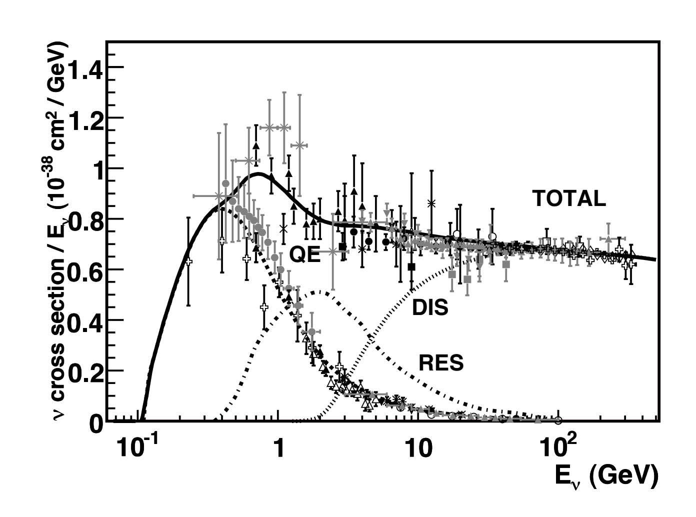


- Proton or nucleon is **inside a nucleus**
- GeV energies start **probing the quark structure inside the nucleons**
- **Excite nucleons to resonances, or produce numerous hadrons**
- **Absorption of particles** within the nucleus
- ⇒ **Cross section** difficult to calculate, **energy** difficult to reconstruct, **nucleus-dependent**
- Past few years have revealed even more complexity....
- **Neutrino-nucleus cross sections:** one of the most critical considerations for long-baseline experiments

Neutrino Interactions

As a function of energy

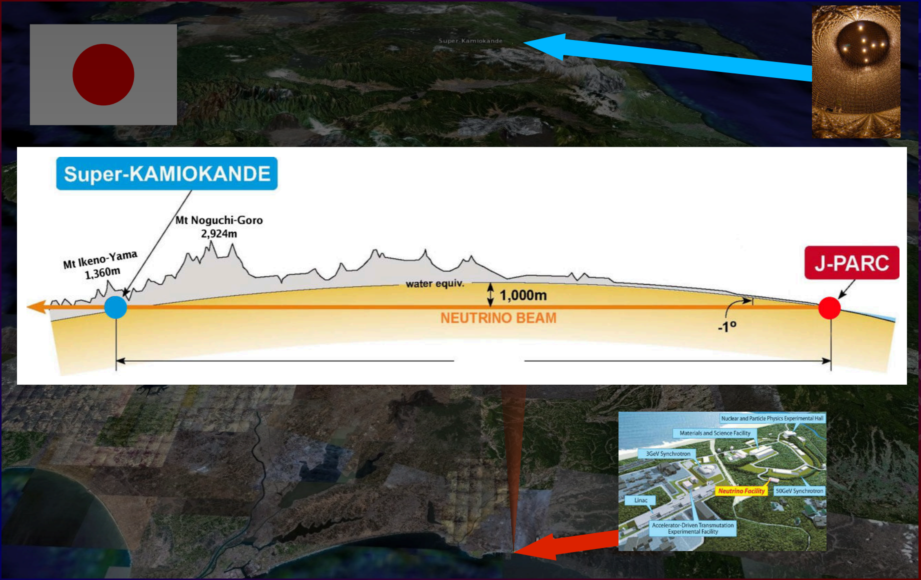
"RES" and "DIS" bring complex behaviour



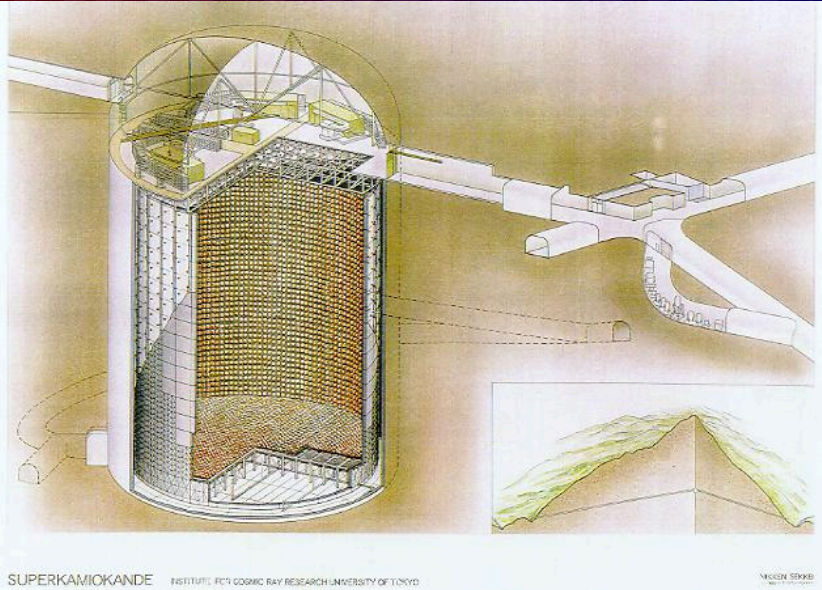
J. Formaggio, G. Zeller; Rev.Mod.Phys. 84 (2012) 1307-1341

Cross sections per nucleon over neutrino energy

The T2K Experiment



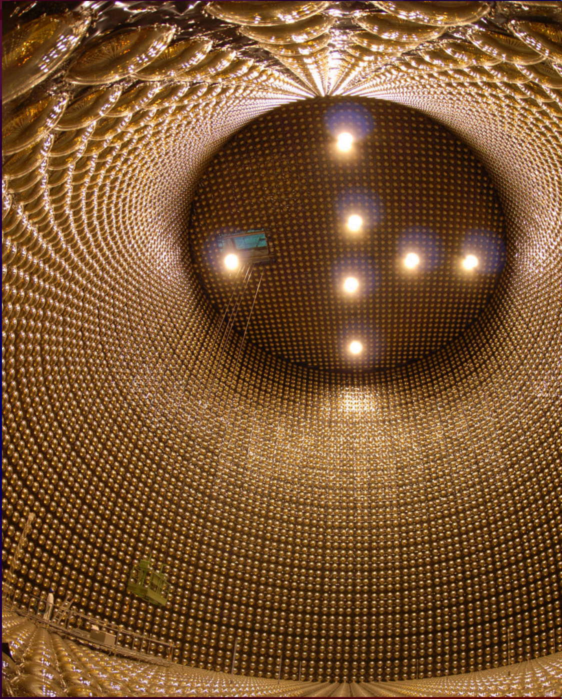
Super-Kamiokande



Super-Kamiokande

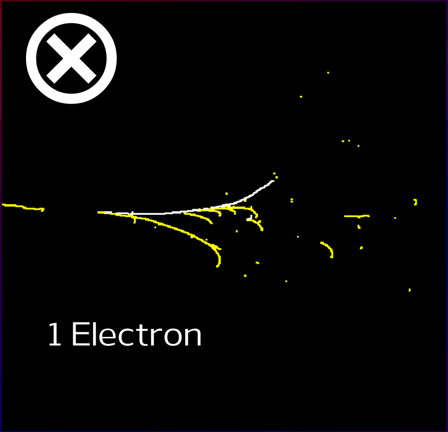
- 40m × 40m cylindrical tank of pure water
- 1 km underground
- 11,146 phototubes in **Inner Detector**

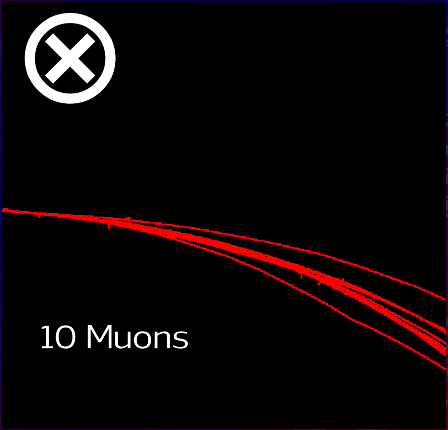
- 1,885 phototubes instrument 2.5 metre-thick **Outer Detector**
- First data in 1996



Particle Transport in Matter

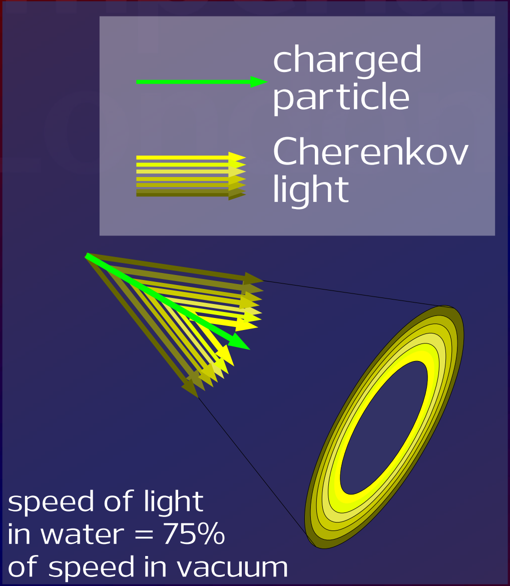
A 1-GeV electron and 10 1-GeV muons (with a magnetic field)





Magnetic fields are for illustration; our Water Cherenkov detectors have no B-field

Cherenkov Light



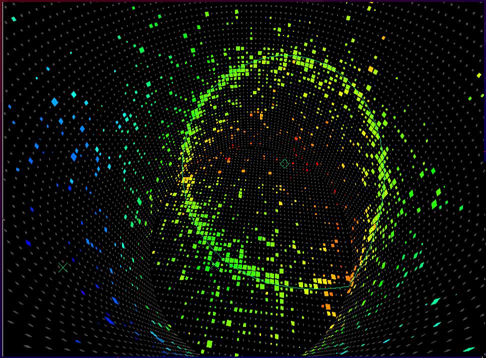
Charged particles (travelling faster than the speed of light in the medium) can emit light in a cone-shape

Perfectly analogous to a "sonic boom"

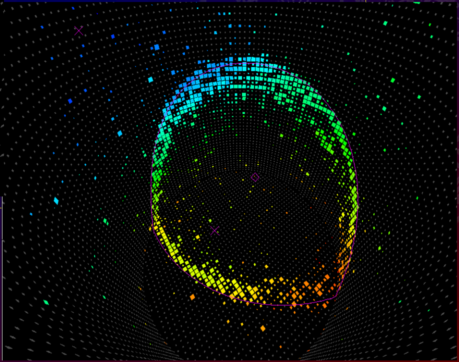
http://hep.bu.edu/~superk/atmnu

Super-Kamiokande

Can distinguish between **electron** and **muon** **neutrinos**, and measure their **direction** and **energy**



electron neutrino
("fuzzy" rings from particles in "shower")



muon neutrino
"clear" single ring

Particle ID in Water Cherenkov Detectors

Initially demonstrated using a beam of particles at KEK with data taken in 1994

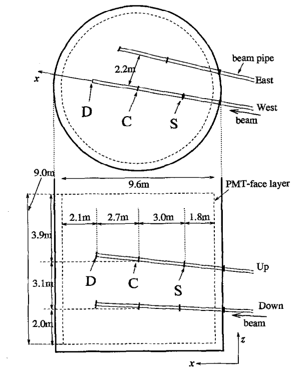


Fig. 1. A cross-sectional view of the water tank and the positions of the particle incidence. The results from the data at the positions C, S and D are presented in this paper.

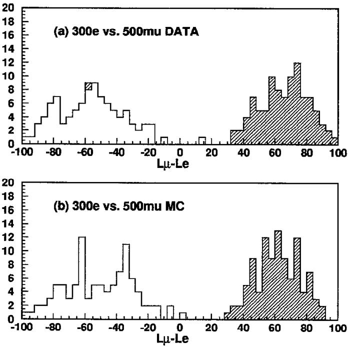
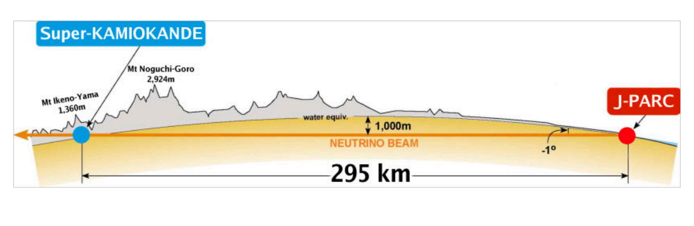


Fig. 2. The $[L_\mu - L_e]$ distribution of (a) data and (b) Monte Carlo samples for e (300 MeV/c) and μ (500 MeV/c) at the position S. The two data samples have about the same total-p.e.'s.

S. Kasuga et al. Physics Letters B 374 (1996) 238-242

The T2K Experiment



The T2K Collaboration

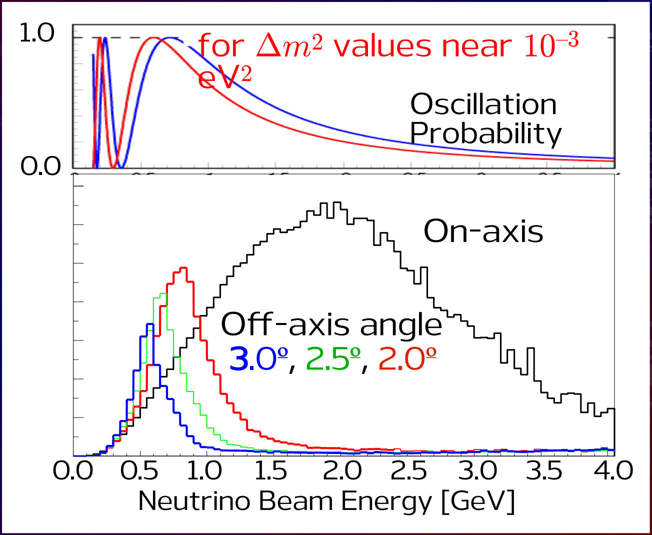
- **Sub-GeV muon neutrino beam: suppress complicating nuclear effects**
- 295 km baseline: **the distance where first oscillation maximum should be,** given atmospheric neutrino oscillations
  - also the distance between the J-PARC proton accelerator, then being built, and the existing Super-Kamiokande
- Peak **beam energy fine-tuned to 0.6 GeV using the "off-axis effect"** (also employed by NOνA)
- Initial goal: **to search for ν_e appearance in a ν_μ beam,** parametrised to first order by θ_{13} (proportional to $\sin^2 2\theta_{13}$)

The Off-Axis Effect

Pion decay kinematics send lower energy neutrinos to higher off-axis angles

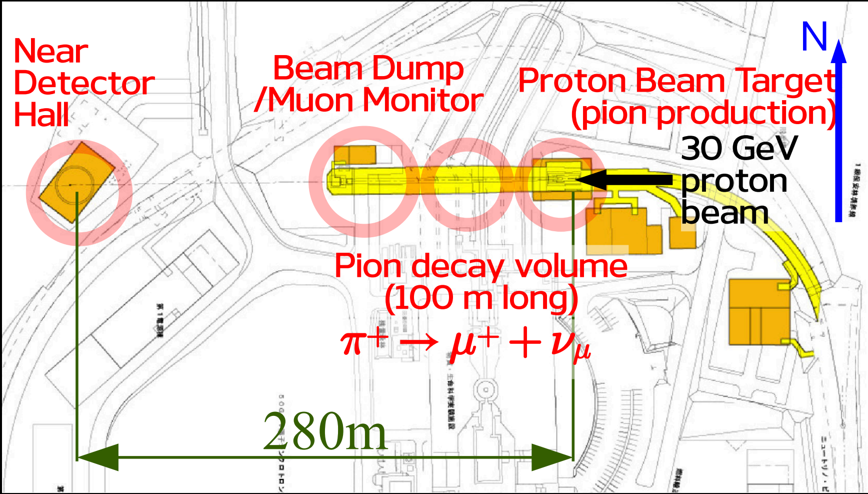
Can create a more intense low-energy beam

Idea originally from Brookhaven, but never implemented before



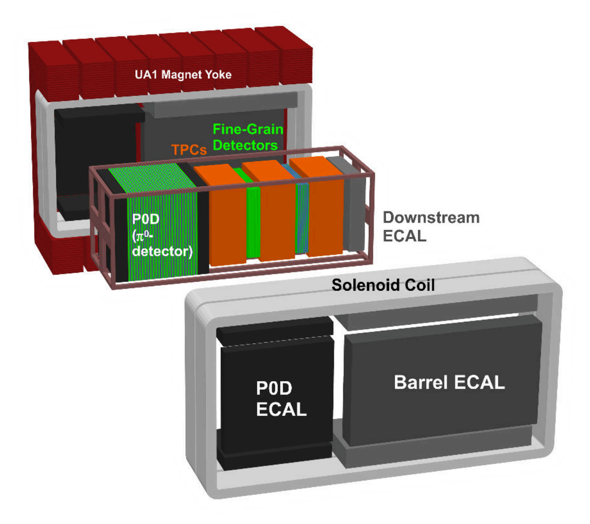
J–PARC

T2K Neutrino Beam Production



Building ND280: The T2K Near Detector

Green areas are where neutrino interactions and their outgoing particles are well-measured



T2K Collaboration (Me actually...)

Building ND280: The T2K Near Detector

First large-scale use of Multi-Pixel Photon Counters in a HEP experiment

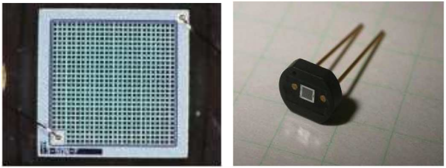
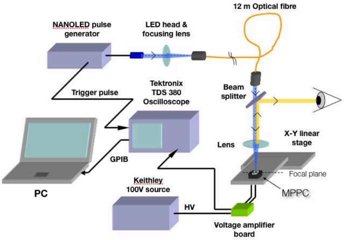


Figure 2: Photographs of an MPPC with a sensitive area of 1.3×1.3 mm^2: magnified face view (left) with 667 pixels in a 26×26 array (9 pixels in the corner are occupied by an electrode); the ceramic package of this MPPC (right).



Vacheret et al., Nucl.Instrum.Meth. A656 (2011) no.1, 69-83)

Building ND280: The T2K Near Detector

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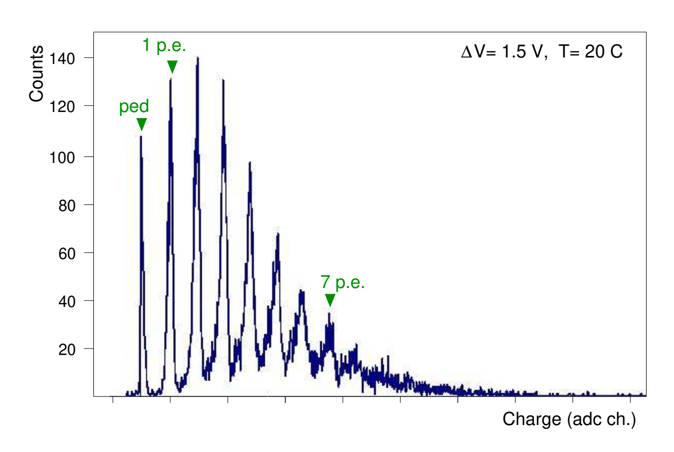

Vacheret et al., Nucl.Instrum.Meth. A656 (2011) no.1, 69-83)

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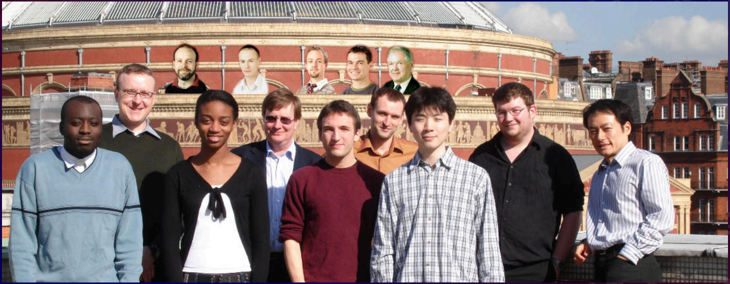
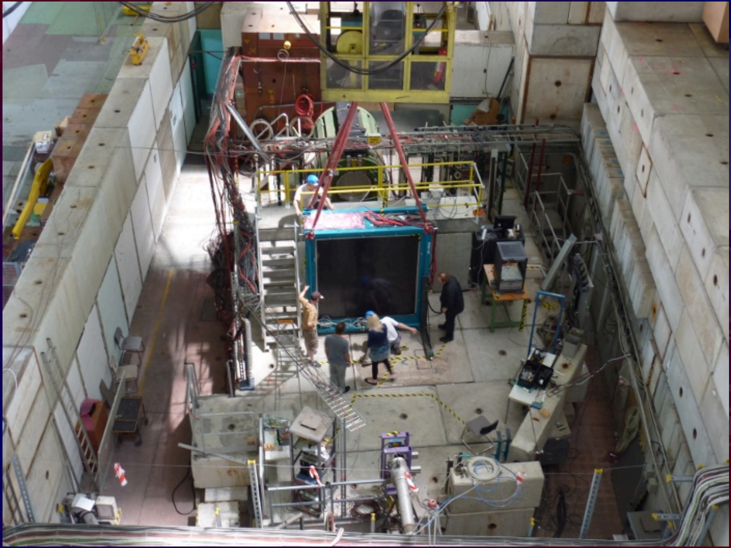


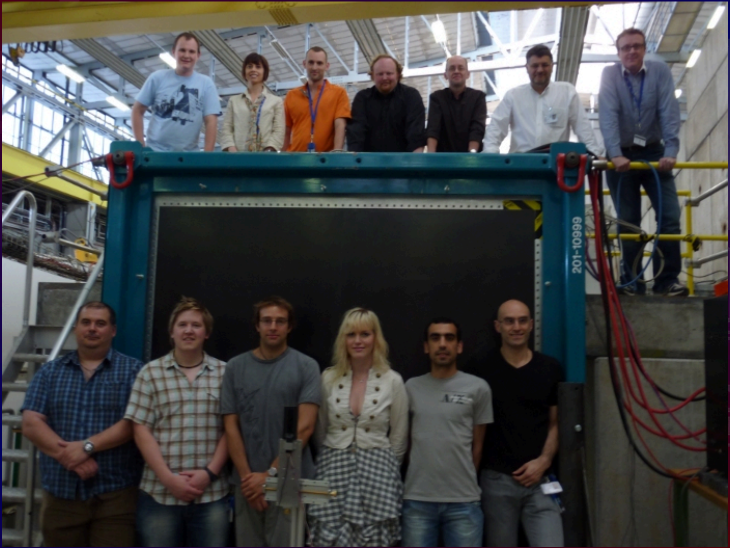
Imperial College T2K Group, 2007

Building ND280: The T2K Near Detector



ND280 ECAL Test Beam at CERN, 2009

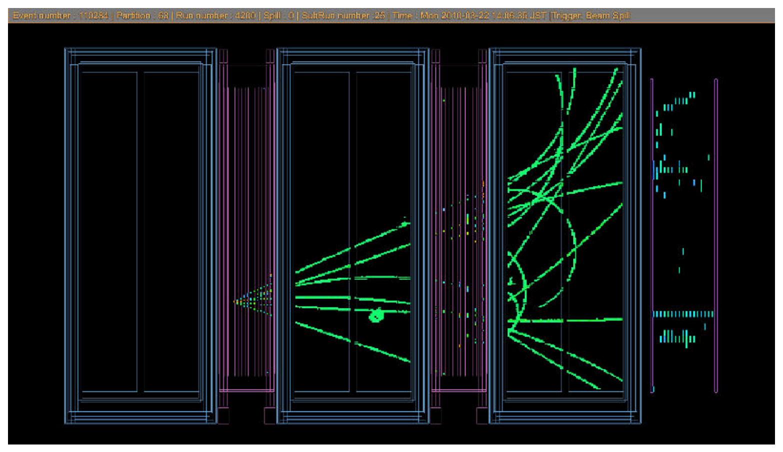
Building ND280: The T2K Near Detector



ND280 ECAL Test Beam at CERN, 2009

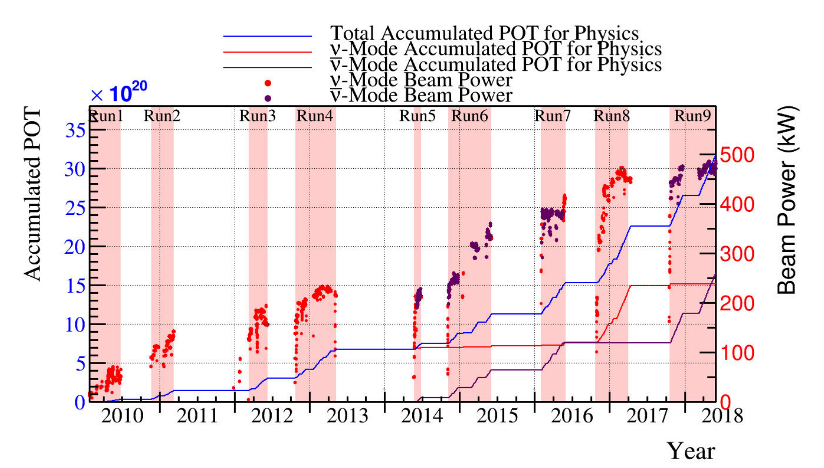
Building ND280: The T2K Near Detector

Event display with neutrino beam



T2K Collaboration

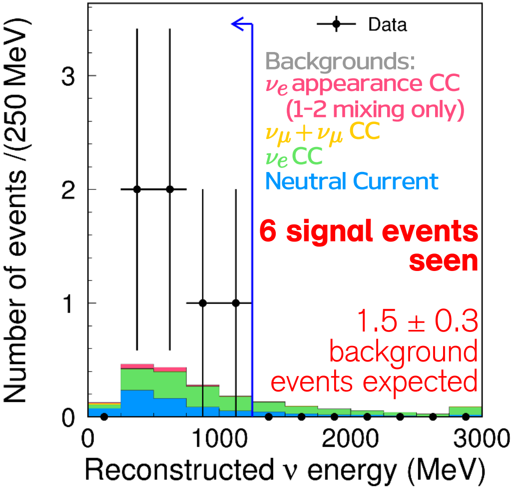
T2K Beam: Protons-on-Target



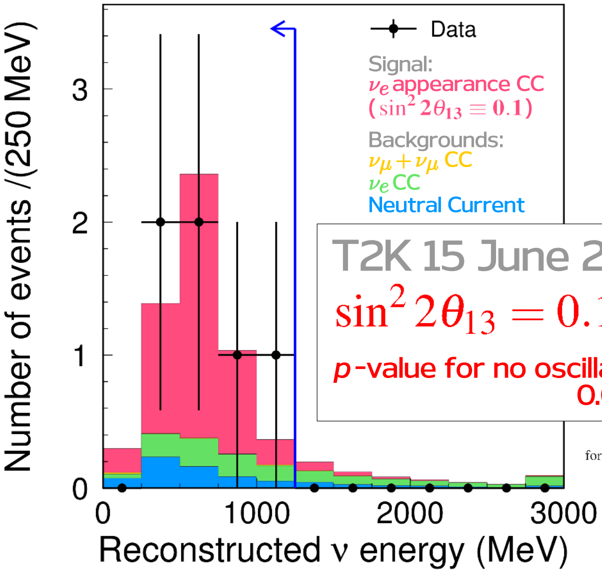
Result in next slide came out during the gap in 2011

First Electron-Neutrino Appearance Result

T2K July 2011: T2K ν_e Candidates



First Electron-Neutrino Appearance Result



T2K 15 June 2011

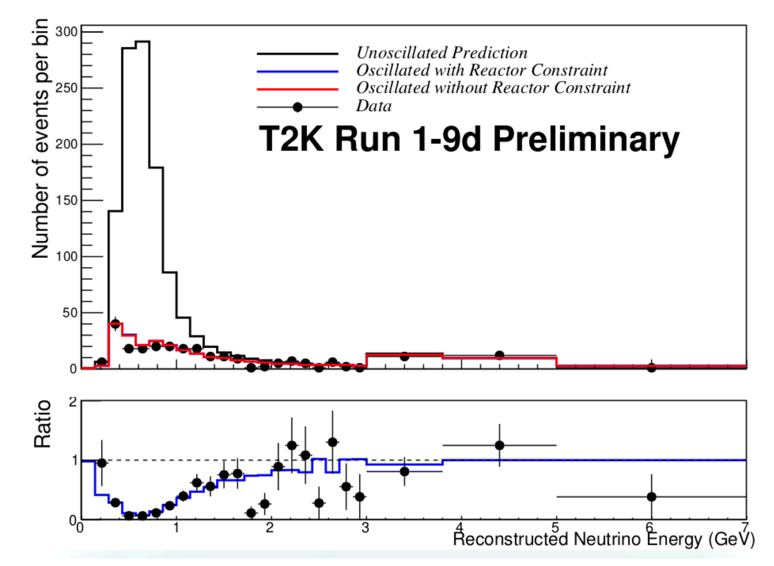
$$\sin^2 2\theta_{13} = 0.11^{+0.10}_{-0.06}$$

p-value for no oscillations: 0.007 (2.5σ)

(at 68% C.L. for $\delta_{CP} = 0$, $\sin^2 2\theta_{23} = 1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$, normal hierarchy)

Latest Results from T2K

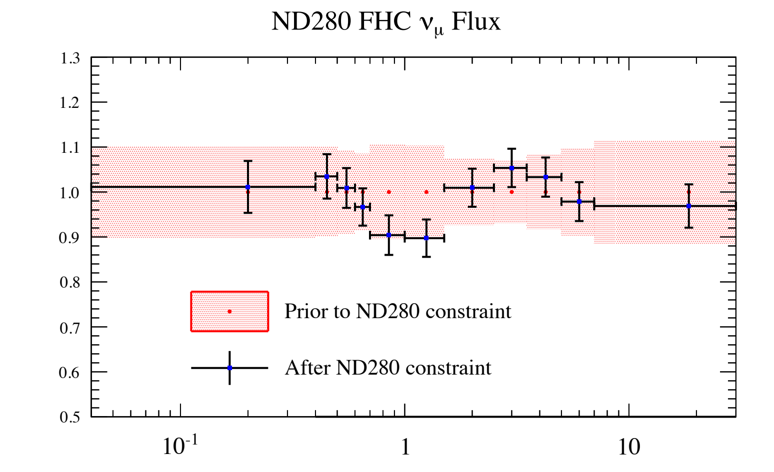
Disappearance of ν_μ from a ν_μ beam



T2K Collaboration 2019

Latest Results from T2K

Constraints on our neutrino flux from ND280 events

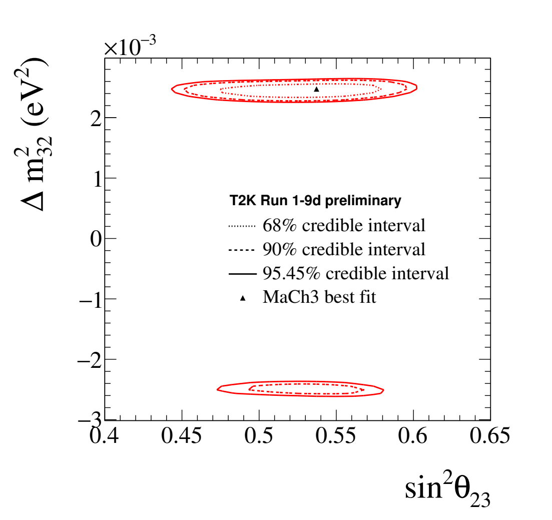


When information that is seen in the ND280 events is included, our knowledge reduces the uncertainties in flux, and moves the central values

T2K Collaboration 2019

Latest Results from T2K

Neutrino oscillation parameter constraints



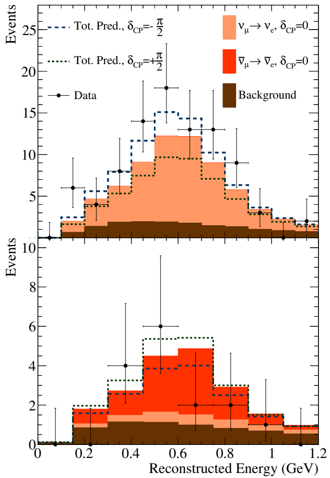
T2K Collaboration 2019

Upper region is the Normal Ordering, lower region is the Inverted

Latest Results from T2K

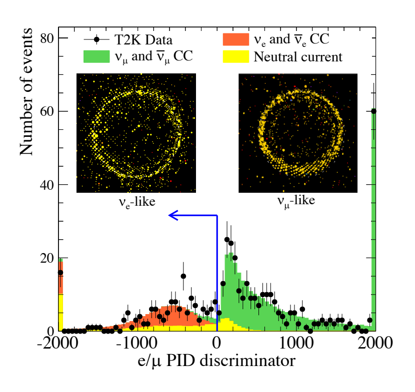
CP Violation

Current version of the 2011 plot, now for both neutrinos and antineutrinos, and how the appearance signal is affected by CP violation



Sample	ν-mode Events	$\bar{\nu}$-mode Events
Single Electron	75 (74.8)	15 (17.2)
Charged Pion	15 (7.0)	N/A

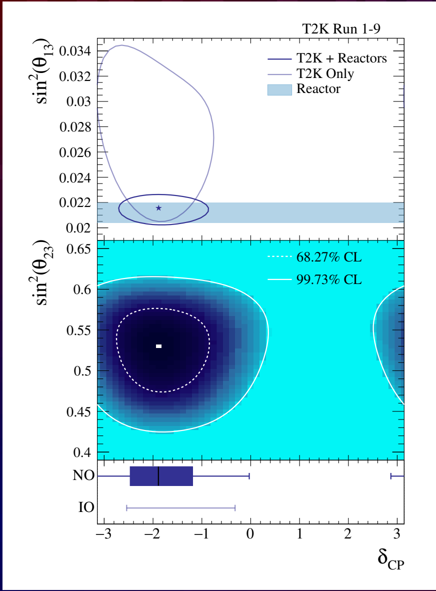
T2K Collaboration arXiv:1910.03887; paper forthcoming)



T2K Collaboration arXiv:1910.03887; paper forthcoming)

- Data taken between 2009 and 2018
- Electron-neutrino appearance in both neutrino and antineutrino mode running

Latest Results from T2K



T2K Collaboration arXiv:1910.03887; paper forthcoming)

- Upper two plots: Normal mass ordering
- Bottom: intervals for CP-violating δ_{CP}
- **World's first exclusion of any value of δ_{CP} at the 3-σ level, for both orderings; 40% of Normal Ordering values excluded**

Super-Kamiokande

- First data-taking in **1996**
- Since then, **major upgrade in detector electronics carried out (2008)**
- As well as continuous improvements in water quality, backgrounds etc.
- Currently undergoing largest transformation yet: **"SK-Gd"**

GADZOOKS! Antineutrino Spectroscopy with Large Water Čerenkov Detectors

John F. Beacom[1] and Mark R. Vagins[2]

[1] *NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500*
[2] *Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697*

(Dated: 25 September 2003)

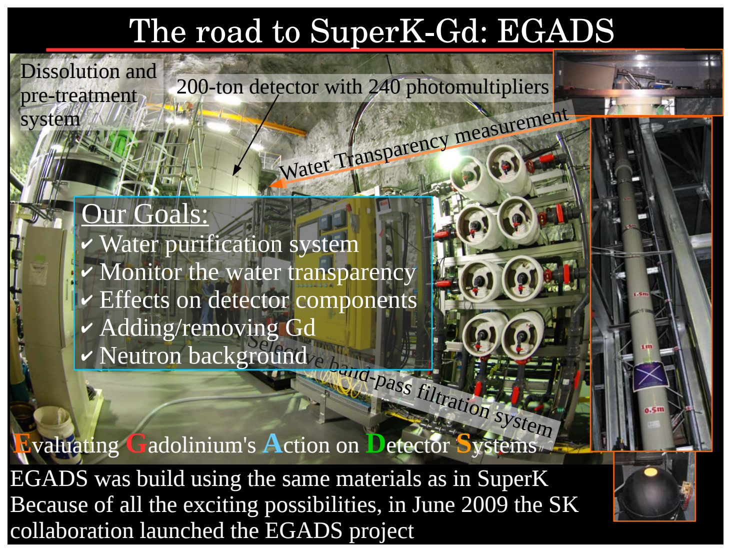
We propose modifying large water Čerenkov detectors by the addition of 0.2% gadolinium trichloride, which is highly soluble, newly inexpensive, and transparent in solution. Since Gd has an enormous cross section for radiative neutron capture, with $\sum E_\gamma = 8$ MeV, this would make neutrons visible for the first time in such detectors, allowing antineutrino tagging by the coincidence detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ (similarly for $\bar{\nu}_\mu$). Taking Super-Kamiokande as a working example, dramatic consequences for reactor neutrino measurements, first observation of the diffuse supernova neutrino background, Galactic supernova detection, and other topics are discussed.

Beacom and Vagins; Phys.Rev.Lett. 93 (2004) 171101

- **Gd captures of neutrons produce 8 MeV gamma cascades** (as opposed to 2.2 MeV for protons), and much closer to the interaction vertex ⇒ neutron tagging at Super-K

R&D Since the GADZOOKS Paper

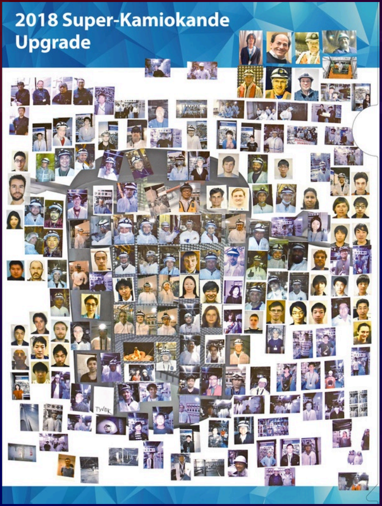
The EGADS detector, next doors to Super-K

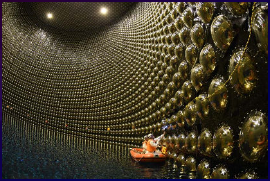


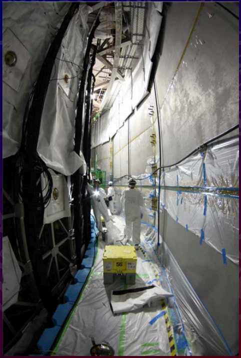
Llus Mart Magro, ICRC 2019

Super-Kamiokande Tank-Open Work for SK-Gd

Summer 2018







Super-Kamiokande Tank-Open Work for SK-Gd

Summer 2018

Super-K is a detector made by hand; many of them

Super-Kamiokande Tank-Open Work for SK-Gd

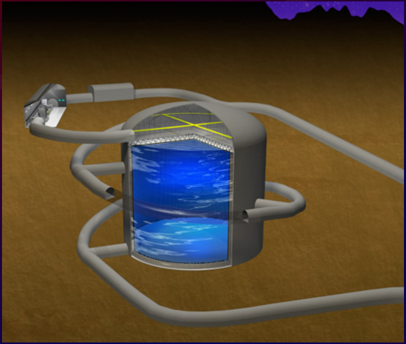
Summer 2018

- Walls, floor and structure **inside the tank cleaned**
- Some **inner-detector PMTs introduced** with much-improved timing and charge performance and quantum efficiency
- Many **outer-detector PMTs replaced**
- **Leaks repaired**
- **New water piping system** allows for finer control of flow (outer and inner, top and bottom)
- **Gadolinium sulfate to be introduced in 2020**

which is different from the salt in the GADZOOKS! paper, another outcome of the R&D effort

Hyper-Kamiokande

The successor to Super-K



Hyper-Kamiokande Design Report, arXiv:1805.04163

- Much larger fiducial volume: **from 22.5 kt to 188 kt**
- Higher power of proton beam which produces neutrinos: **from 500 kW to 1.3 MW**
- Improved photosensor technologies
- Incorporates the neutrino beam from J-PARC
- **Increase in event rate of 20 times compared to T2K**

Hyper-Kamiokande

Host-nation funding status

文部科学省：建設費を令和２年度予算概算要求に

Hyper-Kamiokande

Systematics

Much increased event rate, hence improved statistical uncertainties, requires much improved systematic uncertainties:

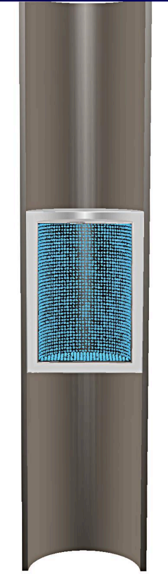
- Better understanding of the neutrino beam
- Means to extract the ways neutrinos interact at different energies
- Disentangling the physics of particles in detectors from the detector responses to them; more advanced calibration methods
- Many more improvements across the experiment

Generally aiming for 1 or 2%-level systematic uncertainties

Hyper-Kamiokande

An "Intermediate" Water Cherenkov detector

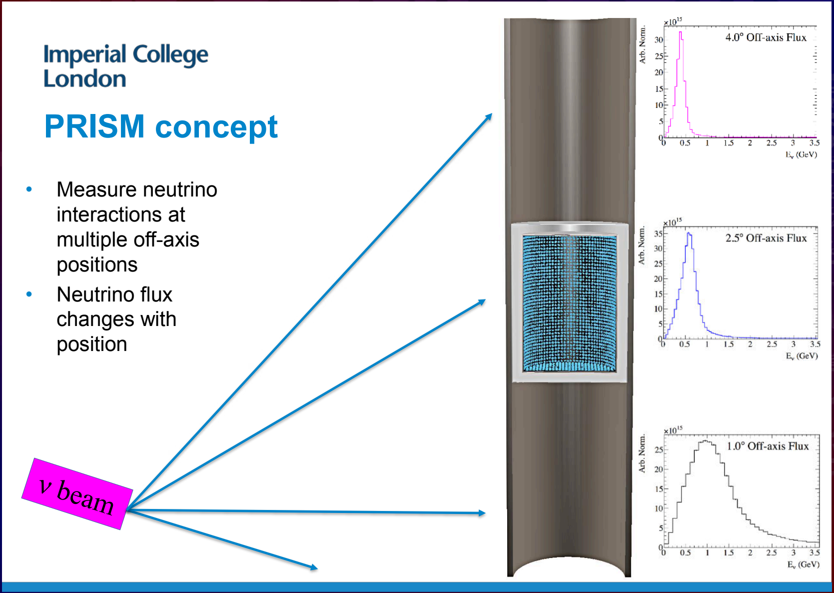
- "Intermediate" since located farther than the "near" detectors
- Near detectors with different technologies to the far detector are valuable; but also detectors with similar technologies
- Water Cherenkov detectors need to be large; cannot be too close to the beam source
- Roughly a kilometre away from the beam origin



- Historical names for such detectors for Hyper-K include **TITUS**, **nu-PRISM** and **E61**, but for now we are going with:
- **IWCD**, for Intermediate Water Cherenkov Detector

IWCD

Pioneered the “nu-PRISM” concept (arXiv: 1412.3086):



M. Scott, UK HEP Forum 2019; Next 10 Years for Long-Baseline Neutrino Experiments

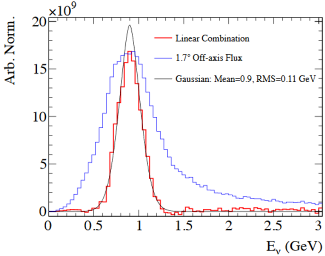
IWCD

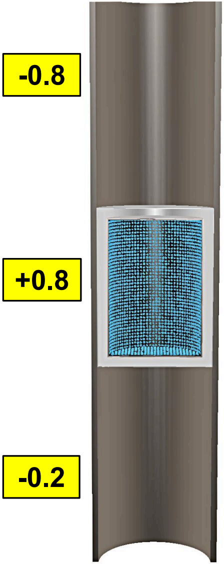
Pioneered the "nu-PRISM" concept (arXiv: 1412.3086):

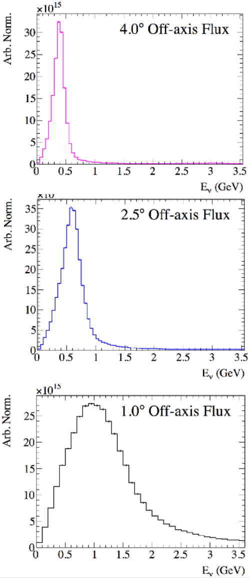
Imperial College London

PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis 'slices'
- Produce Gaussian energy distribution







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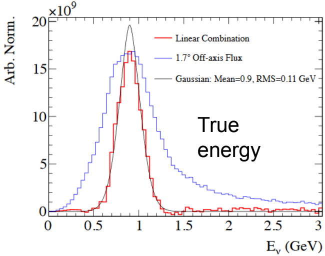
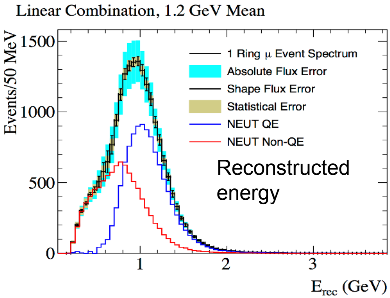


- Measure at a known energy
- Map out true-reco relationship
- Energy range determined by off-axis range



M. Scott, UK HEP Forum 2019; Next 10 Years for Long-Baseline Neutrino Experiments

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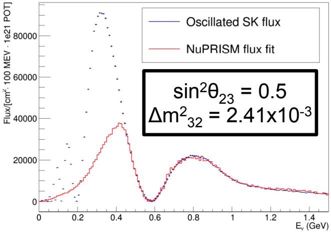
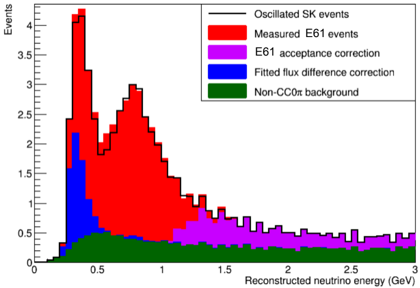
Pioneered the "nu-PRISM" concept (arXiv: 1412.3086):

Imperial College London

PRISM benefits - 3

- Can have different linear combination
- Recreate oscillated flux using near detector data





- Use data to directly predict oscillated spectrum (red)
- Backgrounds (green) can be measured in-situ
- Oscillation analysis minimally dependent on neutrino interaction model

M. Scott, UK HEP Forum 2019; Next 10 Years for Long-Baseline Neutrino Experiments

Many new calibration technologies being developed for Hyper-K; this is but one non-entirely unbiased example

μ-Calibration with Production of Fake Cerenkov

Curvature at end could allow rings to collapse

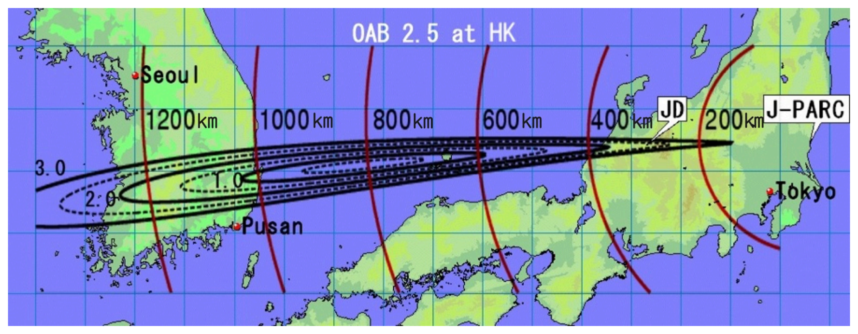
Light travels at c inside cavity, c/n outside

2.5 m line source for 500 MeV muon simulation

Much shorter version would still be useful for MC comparisons

Second Detector in South Korea

Under study as an attractive possibility

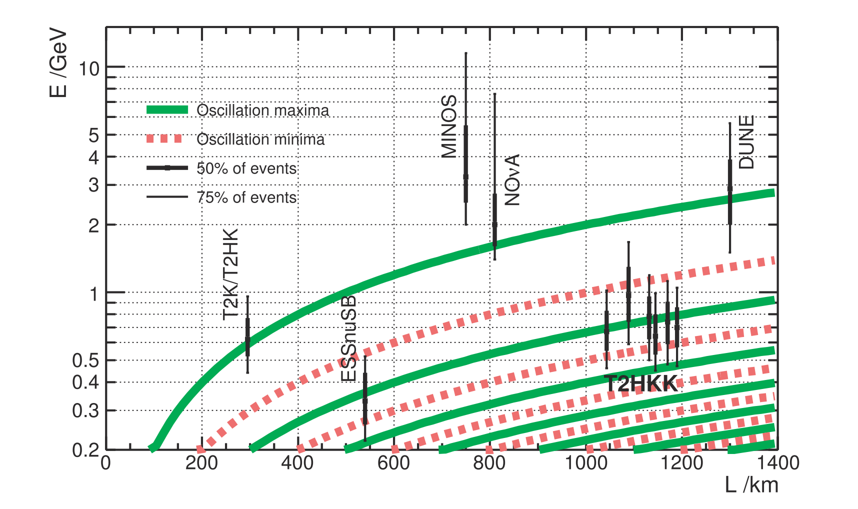


Hagiwara, Okamura and Senda Phys.Rev. D76 (2007) 093002

Distances and off-axis angles (lower energies at greater angles) for the T2K/Hyper-K beam

Second Detector in South Korea

Under study as an attractive possibility

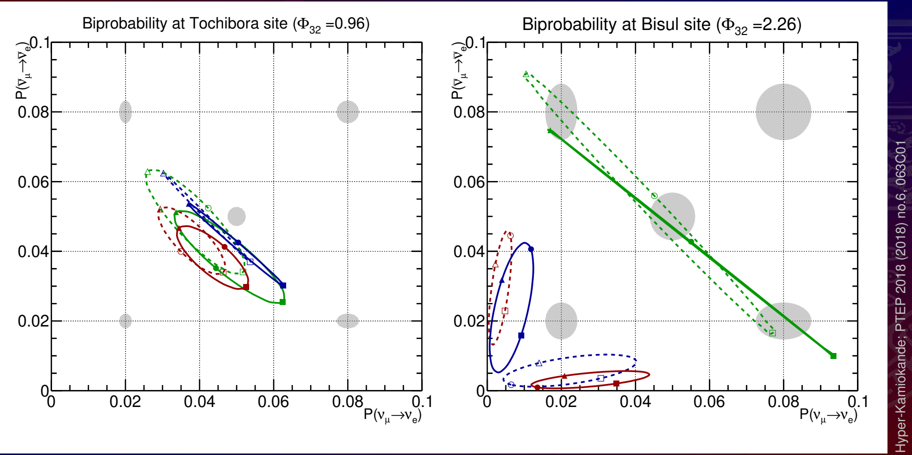


Hyper-Kamiokande; PTEP 2018 (2018) no.6, 063C01

Oscillation parameter space regions spanned by different long-baseline neutrino experiments

Second Detector in South Korea

Under study as an attractive possibility

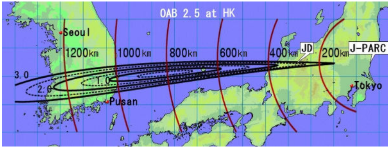


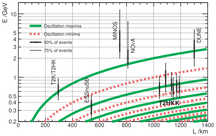
Muon neutrino-to-electron neutrino appearance biprobabilities at the Japanese detector and a possible detector in Korea

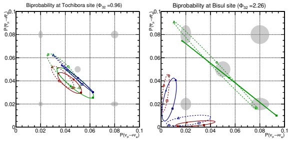
Colours indicate energy points in the beam spectrum, ovals are guides as to the statistical precision that is possible

Second Detector in South Korea

Under study as an attractive possibility



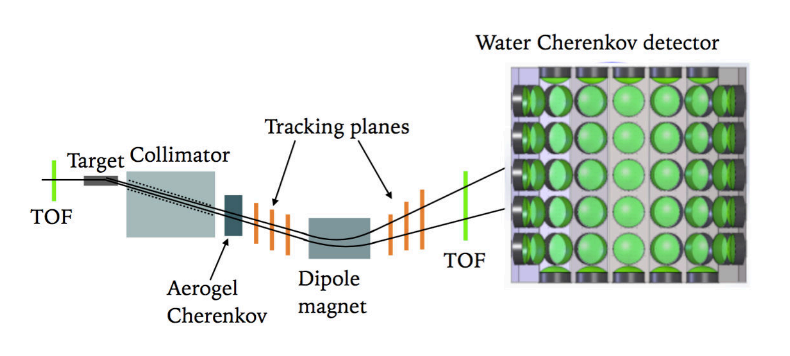




- Several possible locations in South Korea studied
- Two particularly attractive sites at 1.3 degrees and 2.3 degrees off-axis
- Probes for very different oscillation regimes with the same beam and similar detectors
- Sensitivity to non-standard oscillations
- Larger overburden (about 1000 m) expected than Japanese site (650 m); valuable for astrophysics

New Water Cherenkov Test-Beam Experiment

Proposed and being developed to run at CERN in the next couple of years

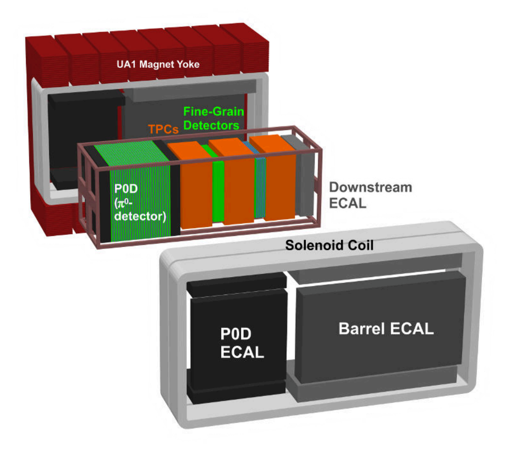


M. Hartz, Water Cherenkov Test Experiment Meeting, July 2019

Advances in **photodetector technologies**, **calibration techniques** and **reconstruction algorithms** require further testing, as well as a better understanding of **what is needed from charged-particle ID** to extract knowledge of the underlying neutrino interaction

ND280 Detector Upgrade

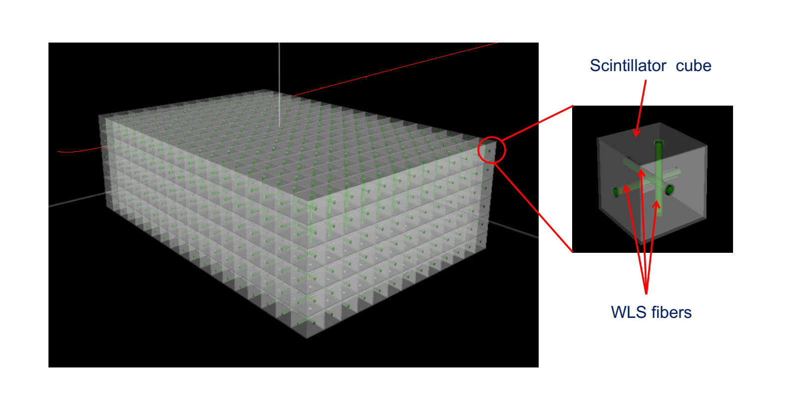
The Existing detector



T2K Collaboration

ND280 Detector Upgrade

Super-FGD Detector

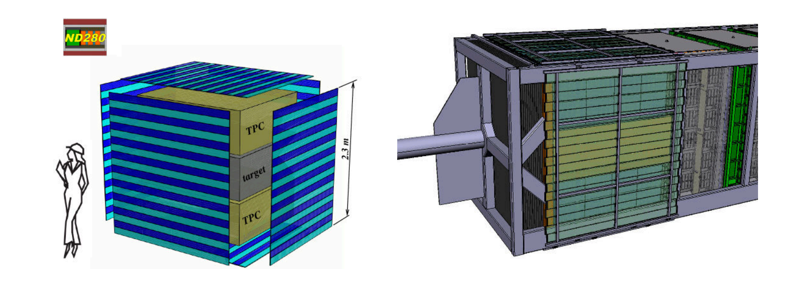


T2K ND280 Upgrade TDR, CERN-SPSC-2019-001 (SPSC-TDR-006) arXiv:1901.03750

Moving from 1 cm-thick bars laid out in "stereo" planes to 1 cm cubes that are read out in a multiplexed, but individual, way

ND280 Detector Upgrade

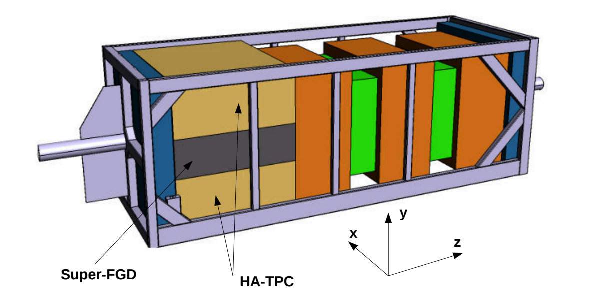
Time-of-Flight counters



T2K ND280 Upgrade TDR,
CERN-SPSC-2019-001 (SPSC-TDR-006)
arXiv:1901.03750

Fast Time-of-Flight counters to augment the inner scintillator and gaseous inner detectors (150 ps resolution)

ND280 Detector Upgrade



T2K ND280 Upgrade TDR, CERN-SPSC-2019-001 (SPSC-TDR-006) arXiv:1901.03750

- **Improvements in angular acceptance:** "sideways" events previously did not make it into the TPCs
- **Full three-dimensional reconstruction of tracks** at the neutrino interaction vertex
- New ability to **distinguish electrons from gamma conversions**
- **Discrimination between outbound and inbound particles,** to separate neutrino interactions from external backgrounds
- Currently testing prototypes in particle beams; full installation at J-PARC in 2021

Kamioka, Gifu

A lovely place to visit (and to live, according to my student)

Conclusions

Apologies: I realised the "and More" in the title was a little overambitious as I was rehearsing the talk for time...

- A selective path through the past, present and future of these experiments
- Super-K and T2K have been highly successful in oscillation physics discovery and beyond
- T2K is already making great inroads into *CP*-violation in the lepton sector
- Super-K being reborn with Gadolinium doping: opening up entirely new physics potential
- New detectors also being brought into T2K ND280: major improvements in interaction reconstruction
- Hyper-K is the next major leap into the future
- Solar neutrino studies also extremely important, as well as astrophysics
- Large Water-Cherenkov detectors: a tested and proven method of neutrino oscillation
- New methods and technologies across the board being brought in to achieve our physics goals