Accelerator Neutrino (3)

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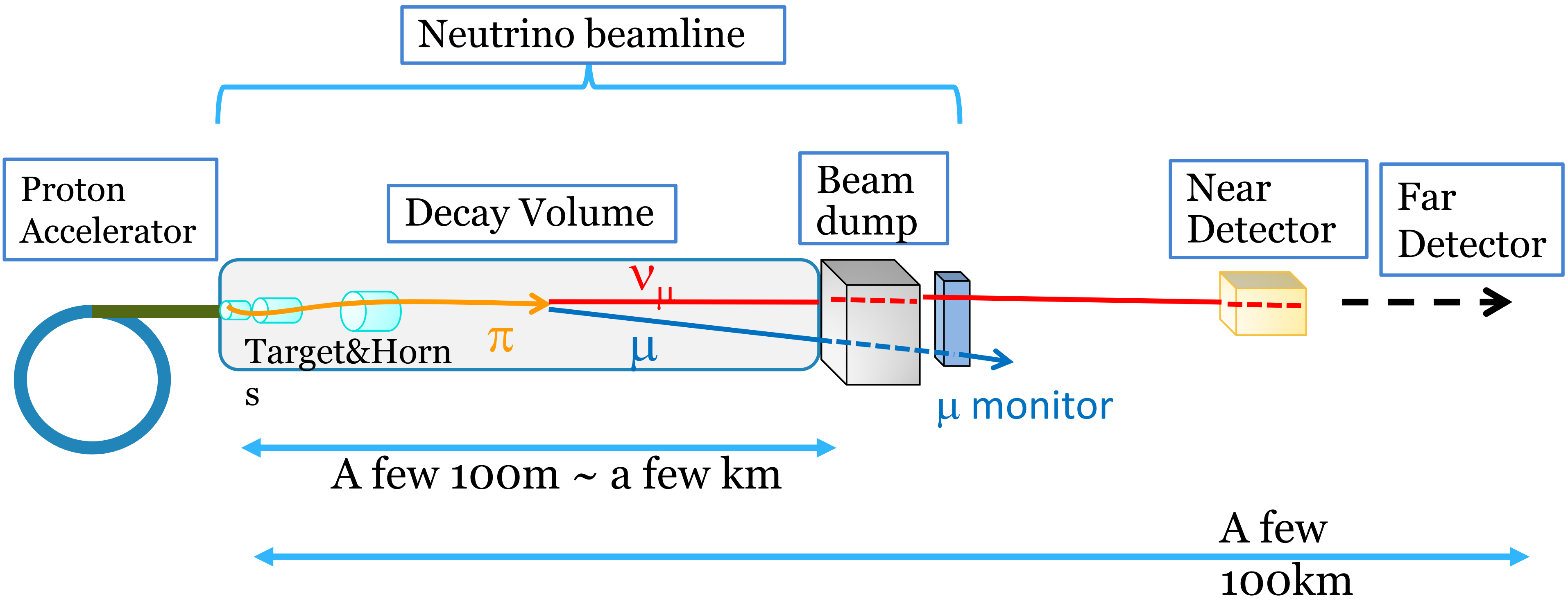
Contents

- 1st Lecture
  - What can we learn by Long baseline accelerator experiments
  - Latest status(1)
- 2nd Lecture
  - Latest status(2)
  - Near future prospect
- 3rd Lecture
  - Technologies in the long baseline accelerator experiments
  - Future prospect

Components of the Long Baseline Neutrino Experiment



Example:
~1ν/cm²/s at T2K Far detector(295km away)
(@750kW proton beam power)

Let's GO through from Upstream to downstream

Proton Machine Intensity Frontier

	Energy	Power		
		Current	Planed	Future
J-PARC/KEK	30 GeV	~0.25MW T2K	0.75MW T2K	~2MW
FNAL	120 GeV	~0.36MW MINOS	0.7MW NOvA	~2MW LBNE/LBNF
CERN	400 GeV/c	0.3MW~0.5MW OPERA/ICARUS	(0.2MW for short baseline: CENF)	0.7~2MW (CN2PY)

BEAM POWER
= (Energy) x (#Protons-per-pulse) x (acceleration-rep-rate)

Achieved = < 0.5 MW
Desired > 1 MW

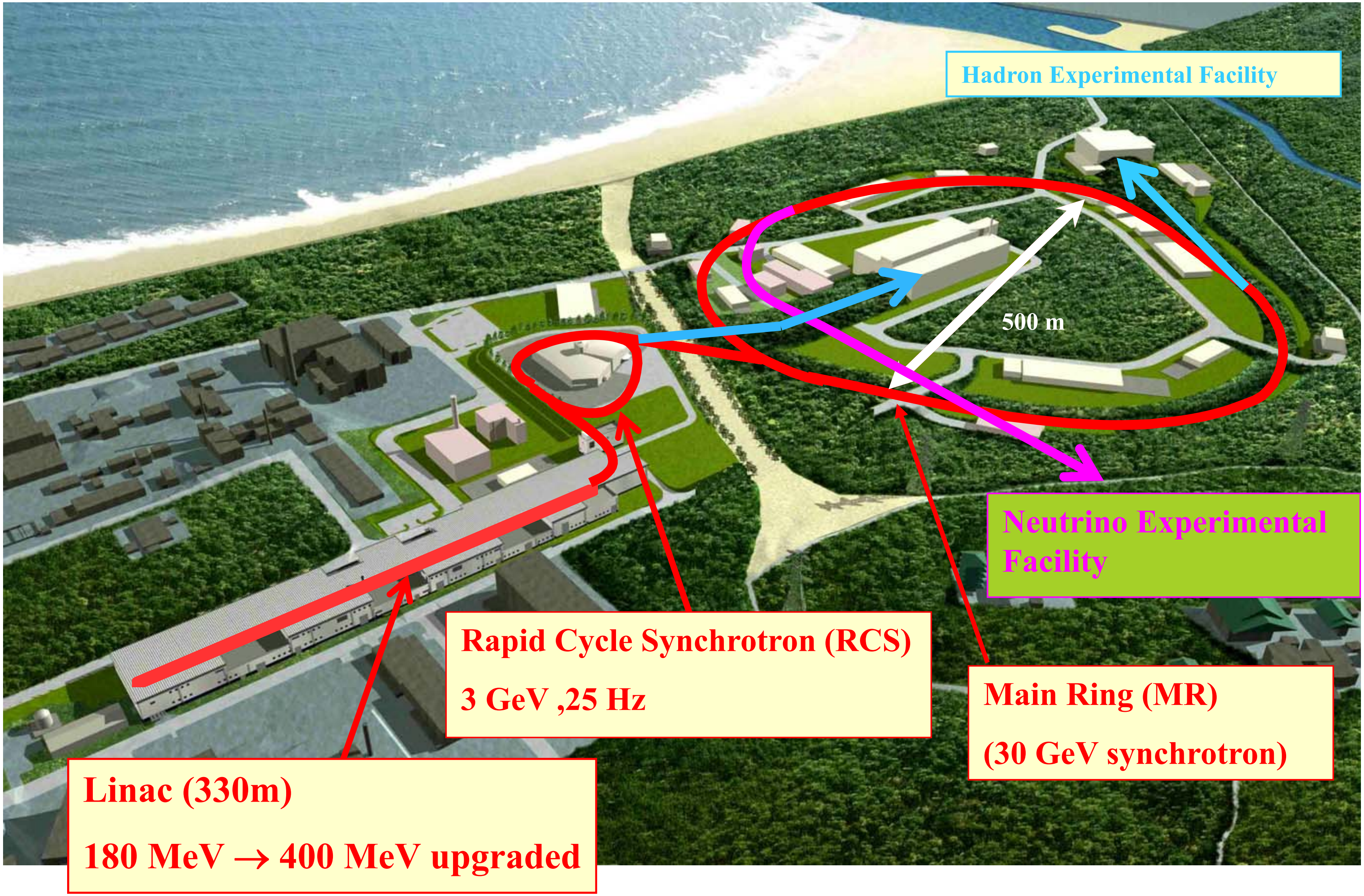
What limits the intensity of proton accelerator?

Space Charge Effect
cause blow up of beam
Larger at lower energy
effect increase **non-linearly** with beam intensity

There can be many reasons. But here, let's highlight Space Charge Effect

- Space charge effect → beam loss → problem on shielding's and maintenance
- Bottle-neck of existing facility
  - NuMI : Injection at booster, J-PARC: Injection at Main Ring, see later slides
- Possible solutions
  - Increase repetition rate , not increasing protons-per-pulse(PPP)
  - Increase injection energy
  - use Linac = one path accelerator (, but difficult to go to high energy

J-PARC


Hadron Experimental Facility
500 m
Neutrino Experimental Facility
Rapid Cycle Synchrotron (RCS)
3 GeV ,25 Hz
Main Ring (MR)
(30 GeV synchrotron)
Linac (330m)
180 MeV → 400 MeV upgraded

J-PARC power upgrade plan

JFY	2013	2014	2015	2016	2017
power(kW)	200-240	200-300	→	→	750
	Linac 180MeV→400MeV	Linac Front-end current 30mA→50mA	Main Ring rep. cycle 2.5s→1.3s w/ new Magnet Power supplies and new high Impedance RF		

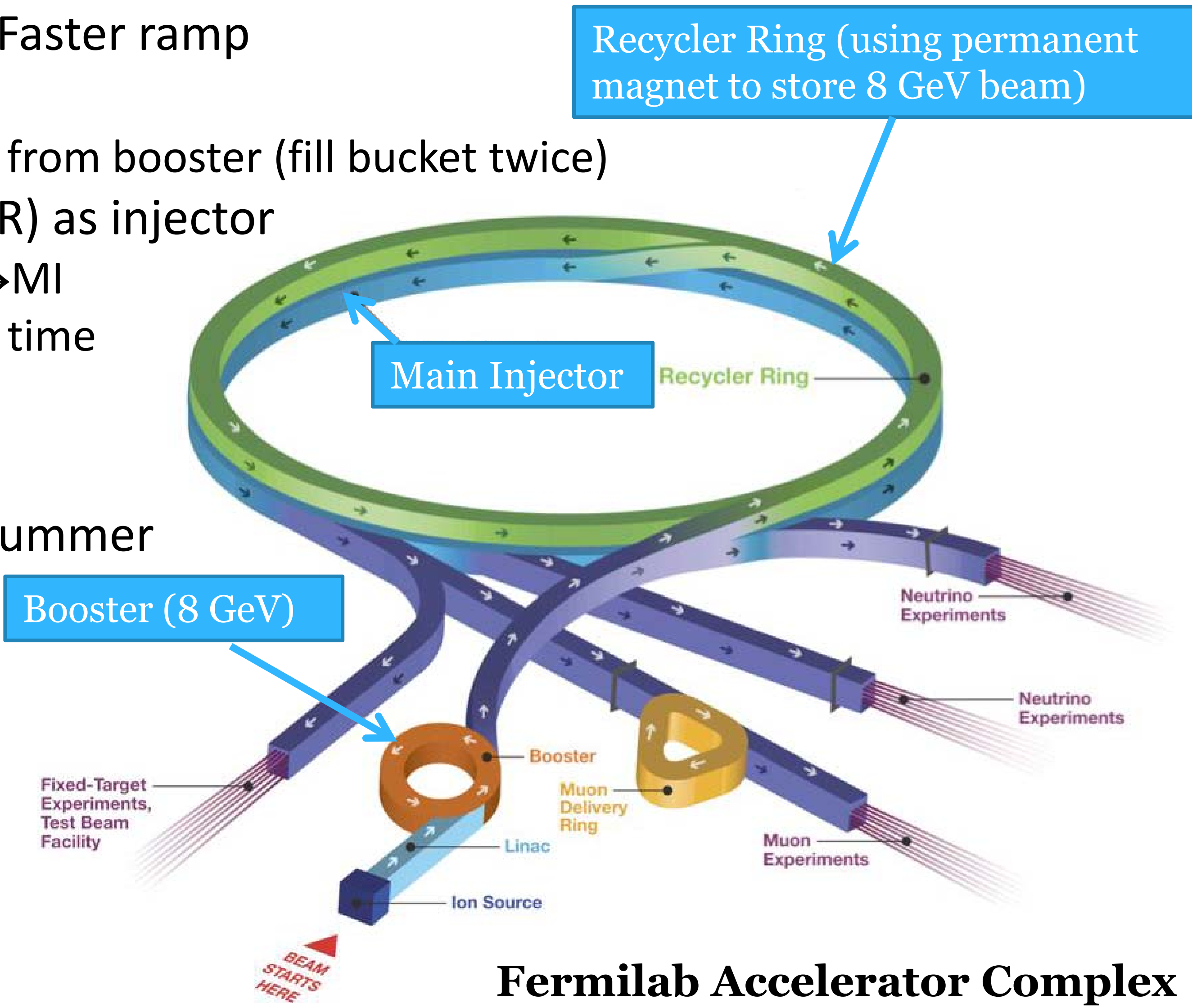
- Current bottleneck
  beam loss at injection to MR
  → can't increase ppp (already world-highest)
  → go higher rep. rate → 0.75 MW
  ✓ New RF R&D completed
  ✓ Small prototype of 1 Hz PS is working.
- Long-term possibility under study
  ✓ New 8 GeV Booster
  ✓ Target > 1~3MW

New high impedance RF

FNAL power present upgrade plan

Booster is the current primary bottleneck.

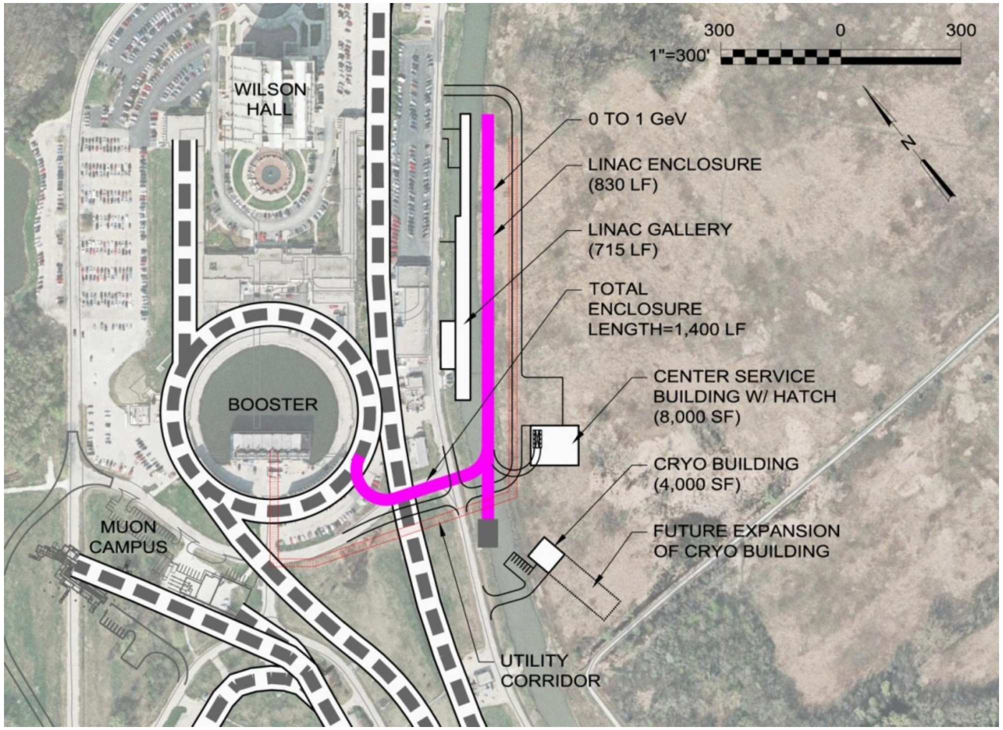
- Main Injector (MI) Faster ramp
- Slip stack
  - ✓ Put two batches from booster (fill bucket twice)
- Use recycler ring(RR) as injector
  - ✓ booster → RR →MI
  - ✓ reduce injection time
- 280 kW →350kW →450kW by the end of this summer
- 700 kW in 2015



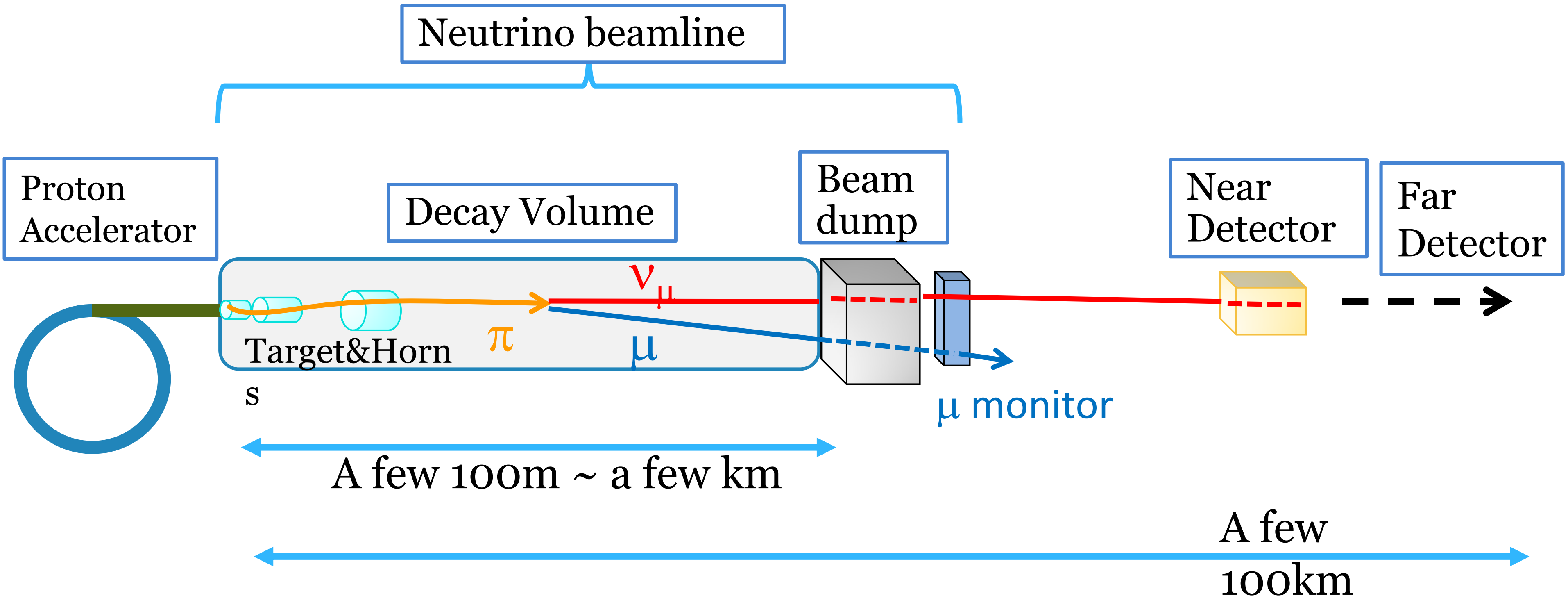
Fermilab Accelerator Complex

FNAL future power upgrade plan -Proton Improvement Plan(PIP) II-

- goal > 1MW (~2025)
- Linac 400 MeV →New 800 MeV super conducting pulsed linac
- Higher energy injection to Booster will reduce beam loss



Components of the Long Baseline Neutrino Experiment



Example:

~1ν/cm²/s at T2K Far detector(295km away)

(@750kW proton beam power)

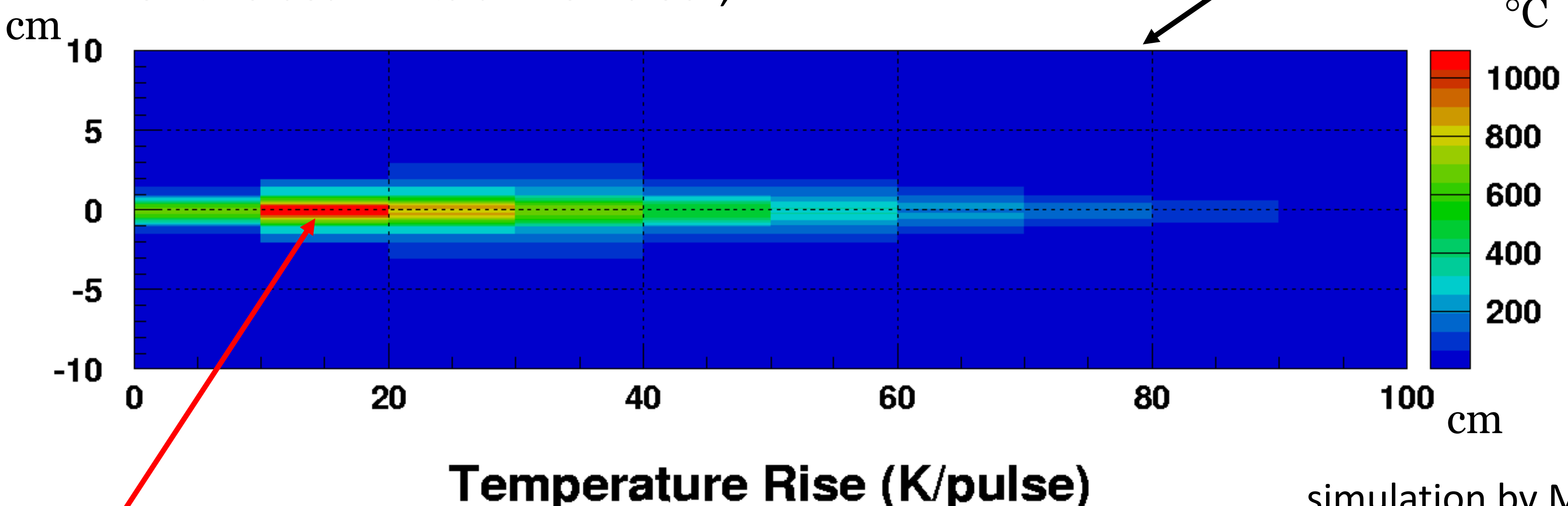
Example : 50 GeV 0.75 MW beam

3.3E14 ppp w/ 5μ pulse

When this beam hits an iron block,

Residual radiation

> 1000Sv/h



simulation by MARS

1100°C

(cf. melting point 1536°C)

✓ Material heavier than iron would melt.

✓ Thermal shock stress

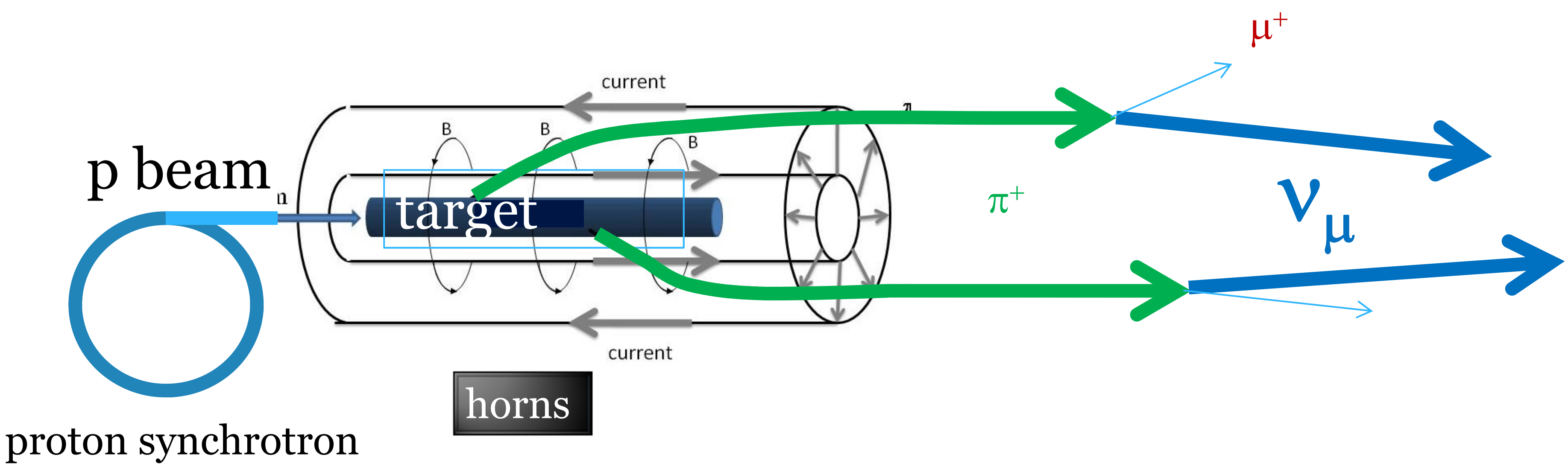
(cf. strength ~300 MPa)

Material heavier than Ti might be destroyed.

✓ Target and beam window have to withstand the thermal shock.

Generation of the Neutrino Beam

Another invention by Van Der Meer

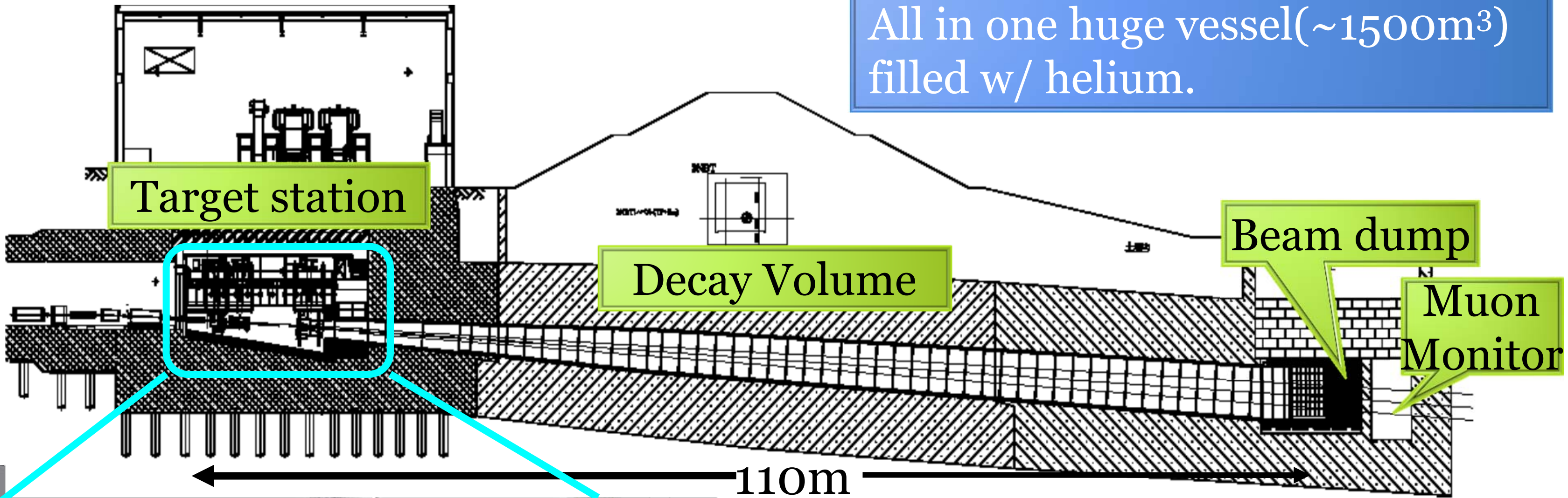


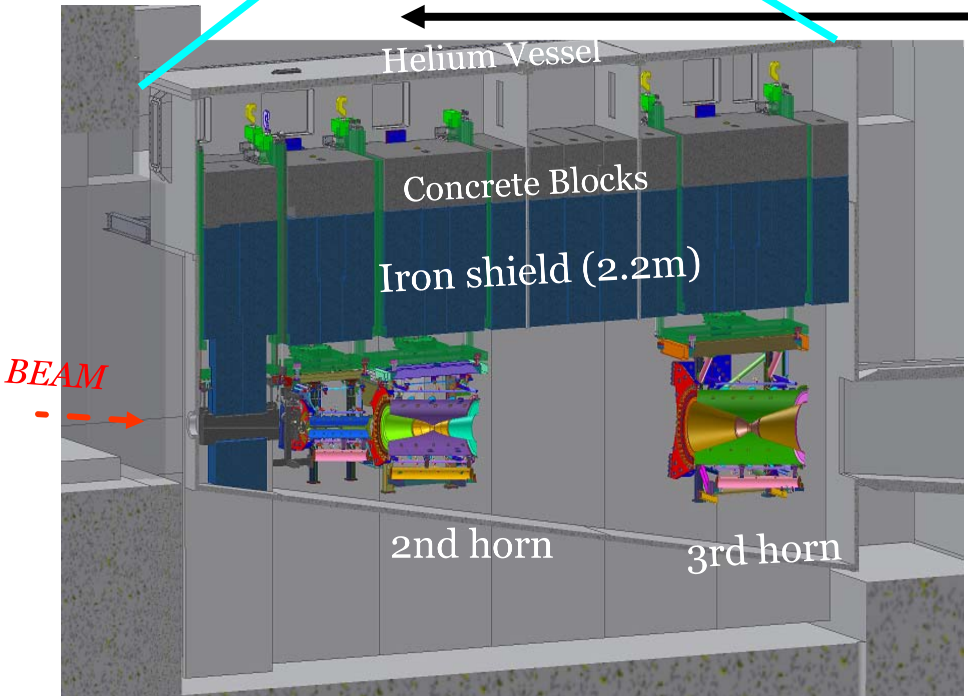
$$\text{Troidal Magnetic Field } B\,[T] = \frac{I\,[A]}{5r\,[m]} \times 10^{-6}$$

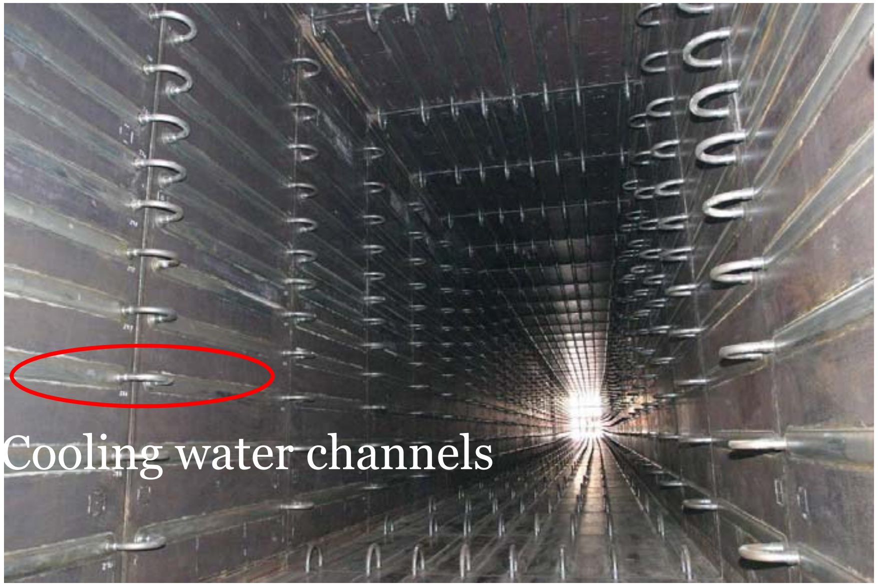
$$B = 2.3\,T\ ,\ r = 28\ mm,\ I = 320kA$$

T2K Secondary beam-line

All in one huge vessel(~1500m^3) filled w/ helium.



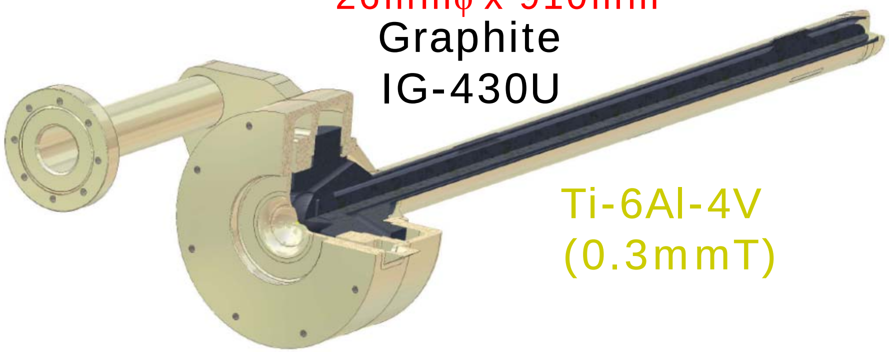


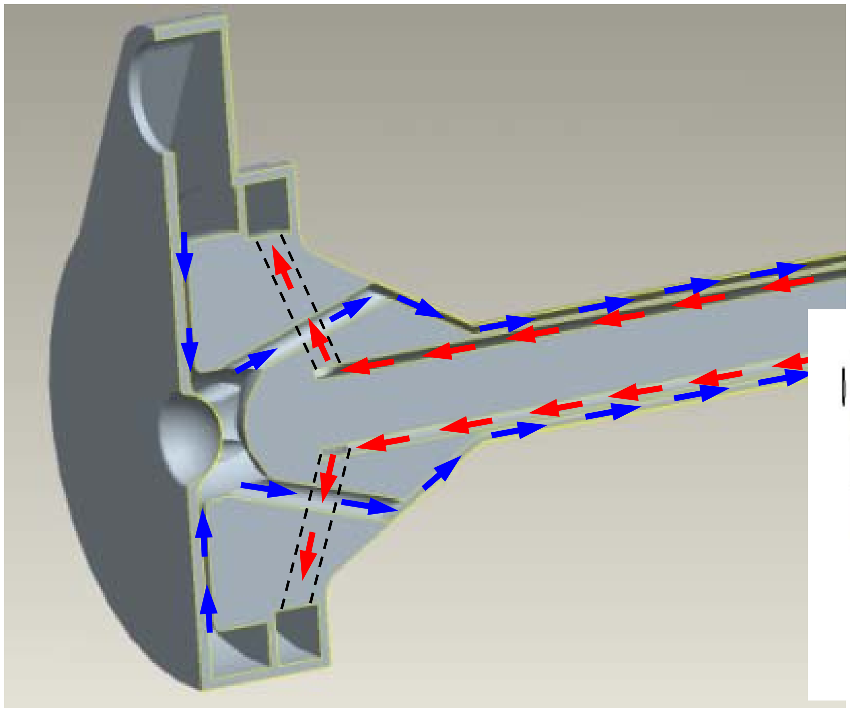


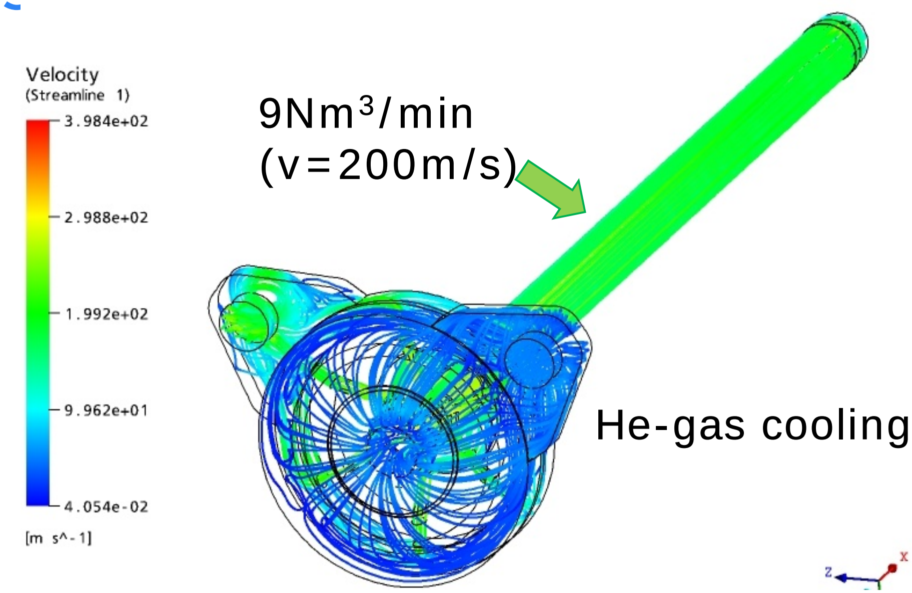
T2K Target

designed for 0.75 MW, He-cooling to avoid water hammer

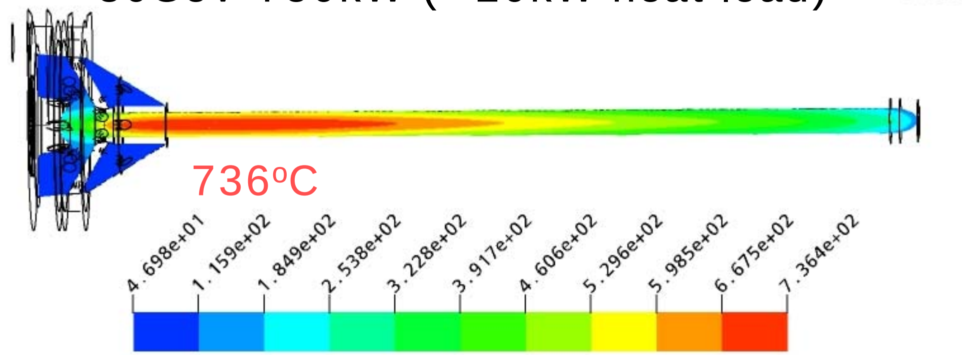
26mmϕ x 910mm







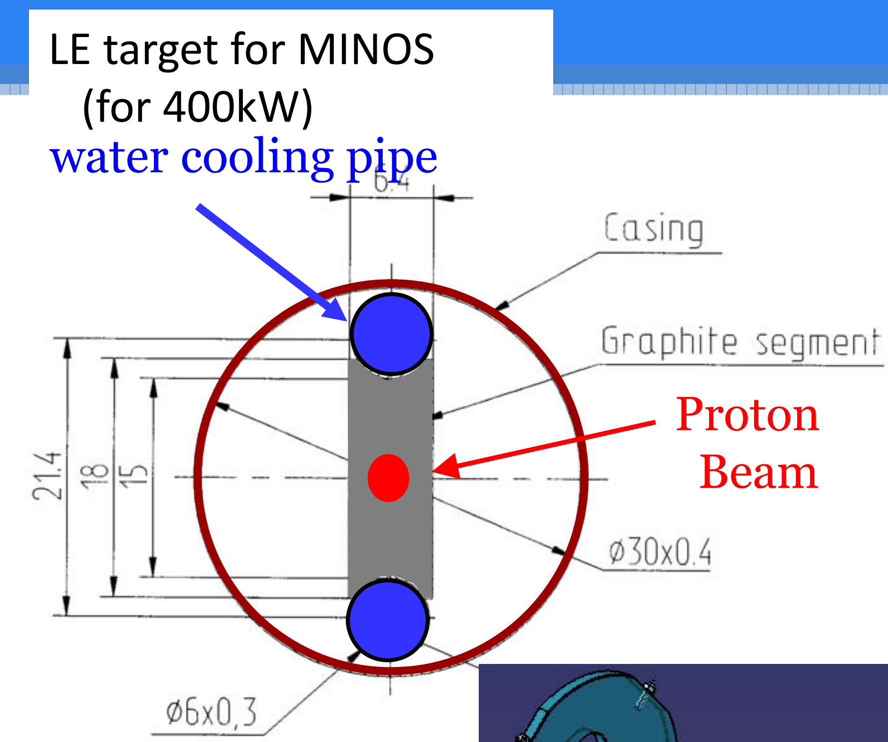
30GeV-750kW (~20kW heat load)

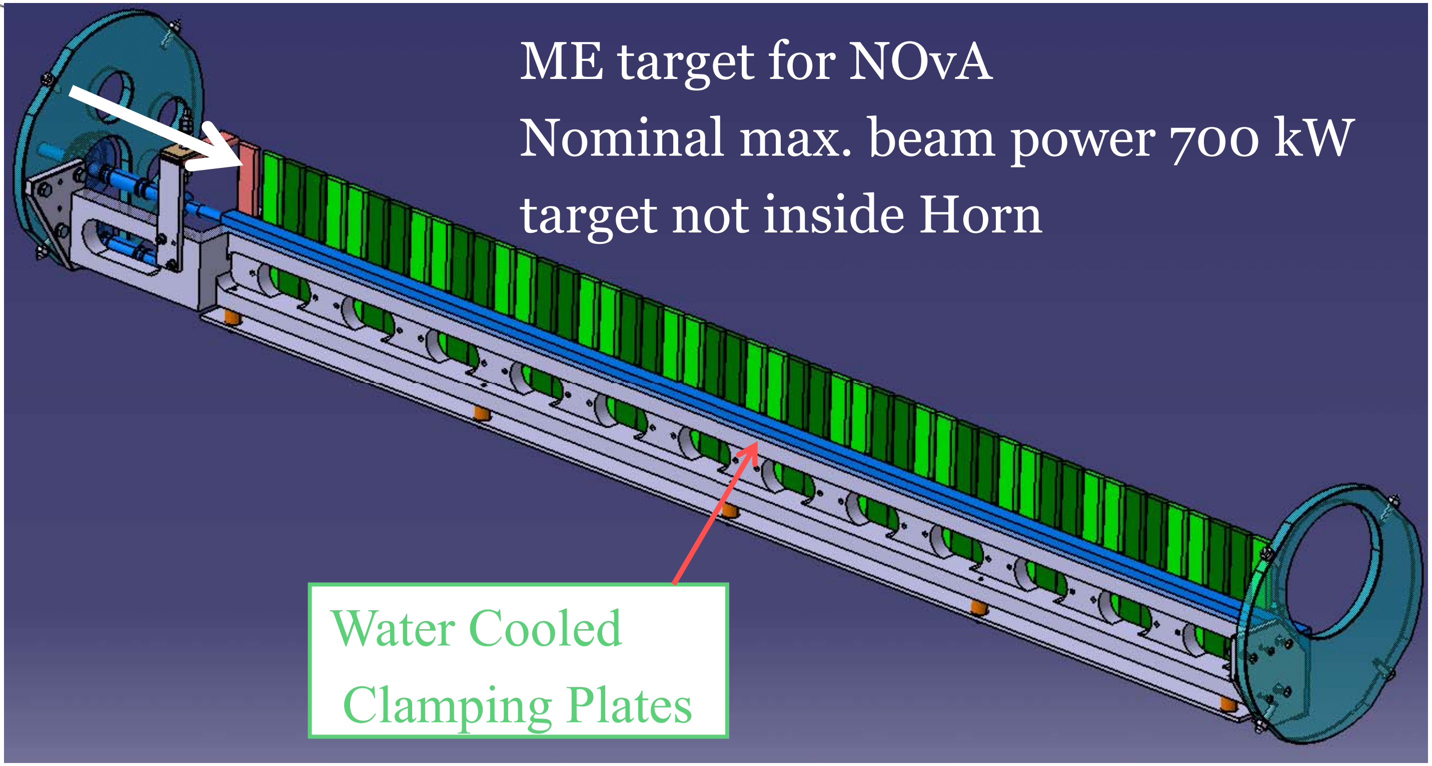


ΔT~200K ~7MPa (Tensile strength 37MPa)

NuMI target

LE target : inserted into horn1
ME target: upstream of horn1

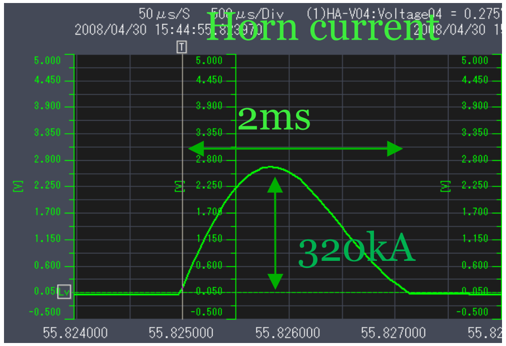




Technology of Electro Magnetic Horn

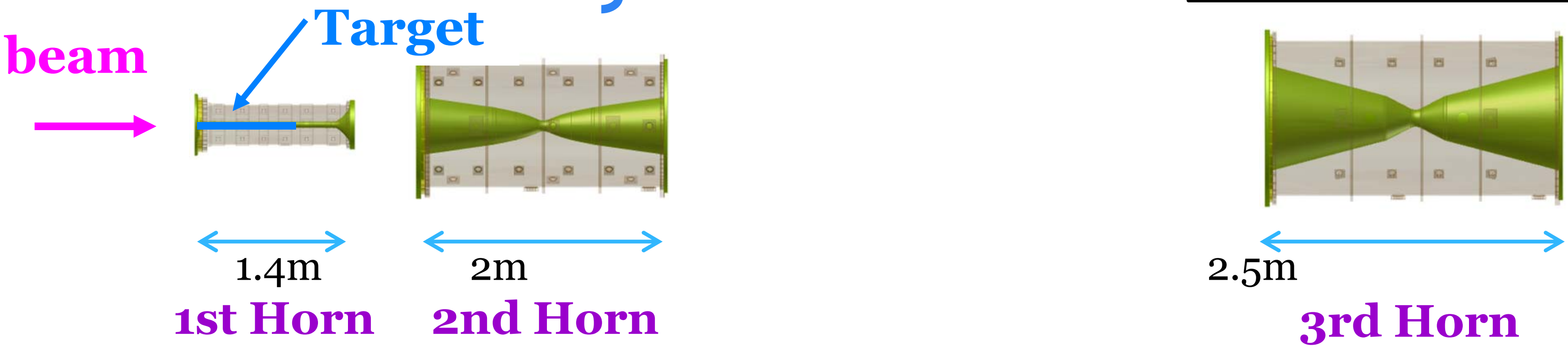
- Material
  - ➢ High radiation environment
    - ✓ Made of metals and ceramics
    - ✓ Remotely exchangeable
  - ➢ Made by aluminum, must be thin (a few mm) not to absorb pions
  - ➢ Thermal stress by beam
- O(100kA) Current
  - ➢ pulsed beam (melt if DC)

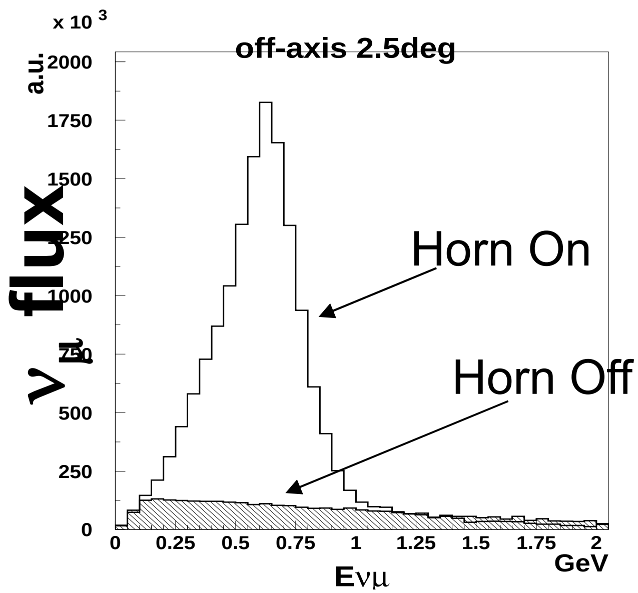
  → Instantaneous Lorentz force ~2MPa by the interaction of current and magnetic field
- Power supply
  - ✓ O(10kA) by capacitors + switches
  - ✓ X10 by transformer

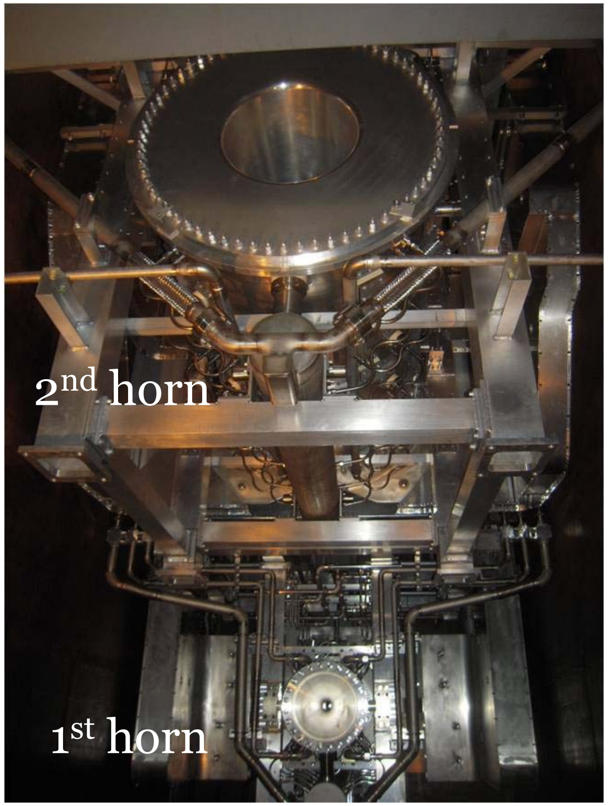


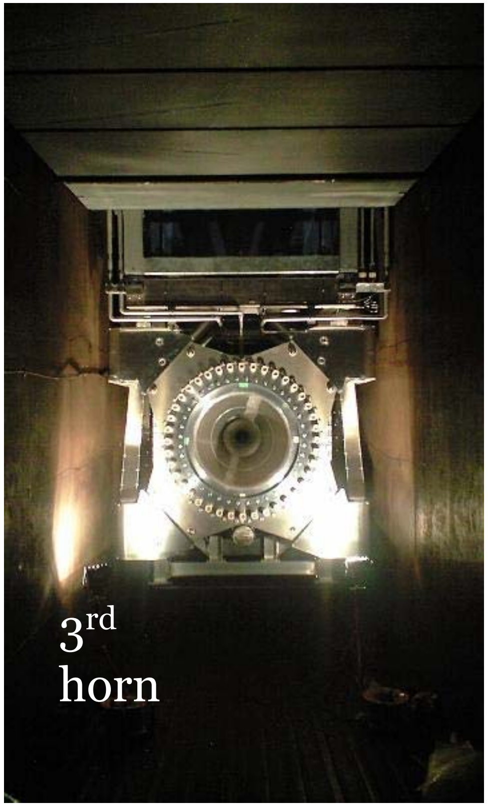
T2K Horn system

Designed for 320kA
Running at 250kA









Intensity Frontier Summary

	Energy	Power		
		Current	Planed	Future
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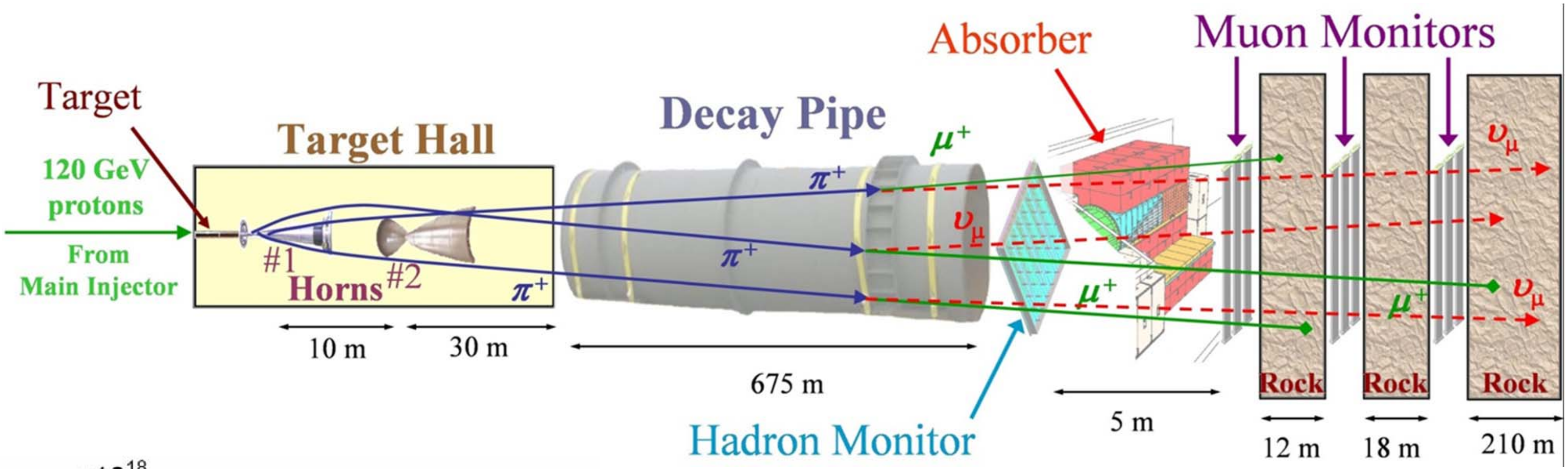
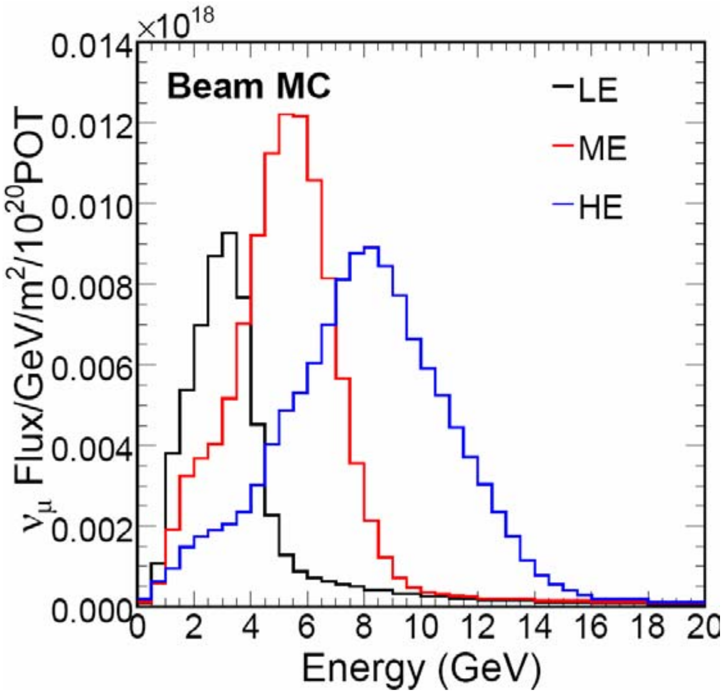
Achieved = < 0.5 MW
Desired > 1 MW
Need tough works to go beyond 0.5 MW
Many innovative works are necessary for power beyond ~0.7 MW

Neutrino beam optimization

- Momentums and angles of pions are widely spreads, and hence those of neutrinos, too.
- Only neutrinos having correct energy oscillate, others generates backgrounds.
- Is there any ways to select neutrinos of interest?

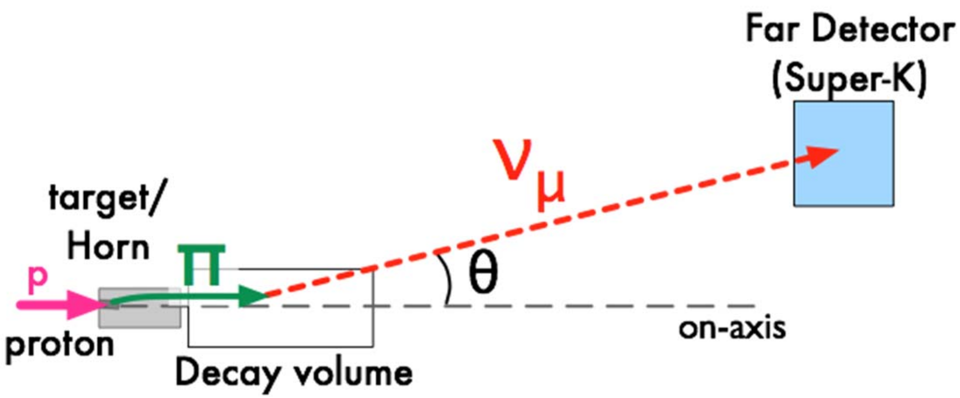
NuMI Beam

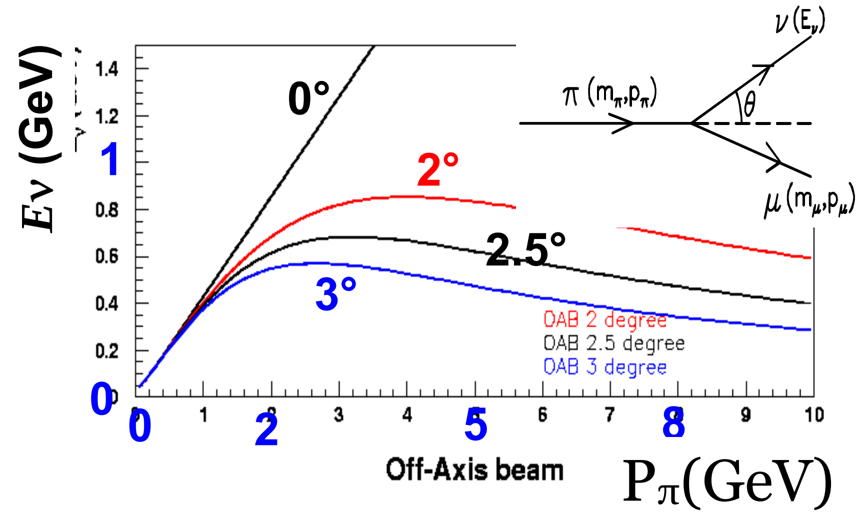


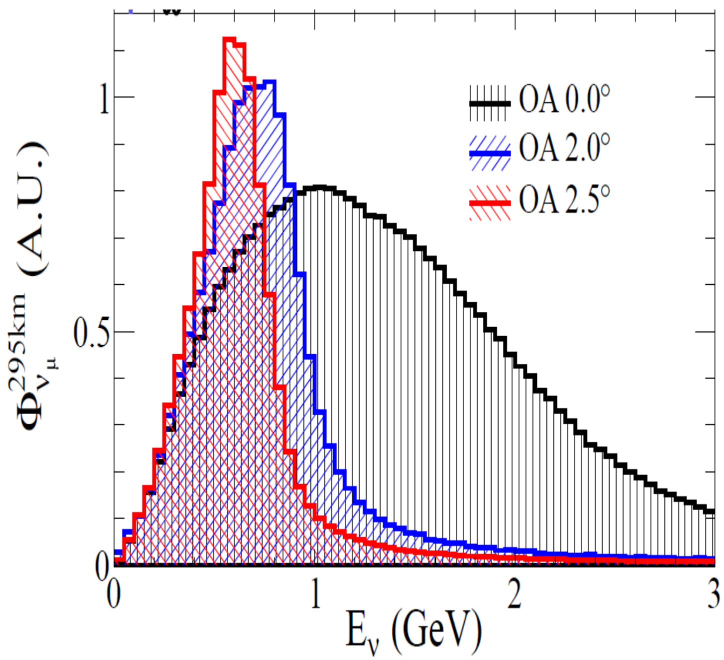


- Target position can be changed to tune the neutrino energy spectrum
- ν_e contamination(1.3%) from $\mu^+ \rightarrow e + \nu_e$

Off-Axis Beam : Intense & Narrow-band Beam







- Pseud monochromatic beam utilizing pion decay kinematics
- T2K off-axis angle is 2.5°
  peak energy at oscillation max.
  (~0.6GeV at L=295km)
  less high energy tail

↓

Maximize Physics Sensitivity

Near Detectors

Purpose

- Measure the properties of neutrinos before oscillation
- Monitor the neutrino beam
  - ✓ Intensity (normalization) and beam direction
- Study the neutrino-nucleus interaction

Requirement

- (Not huge, but) Large mass: O(10) ton
- Material

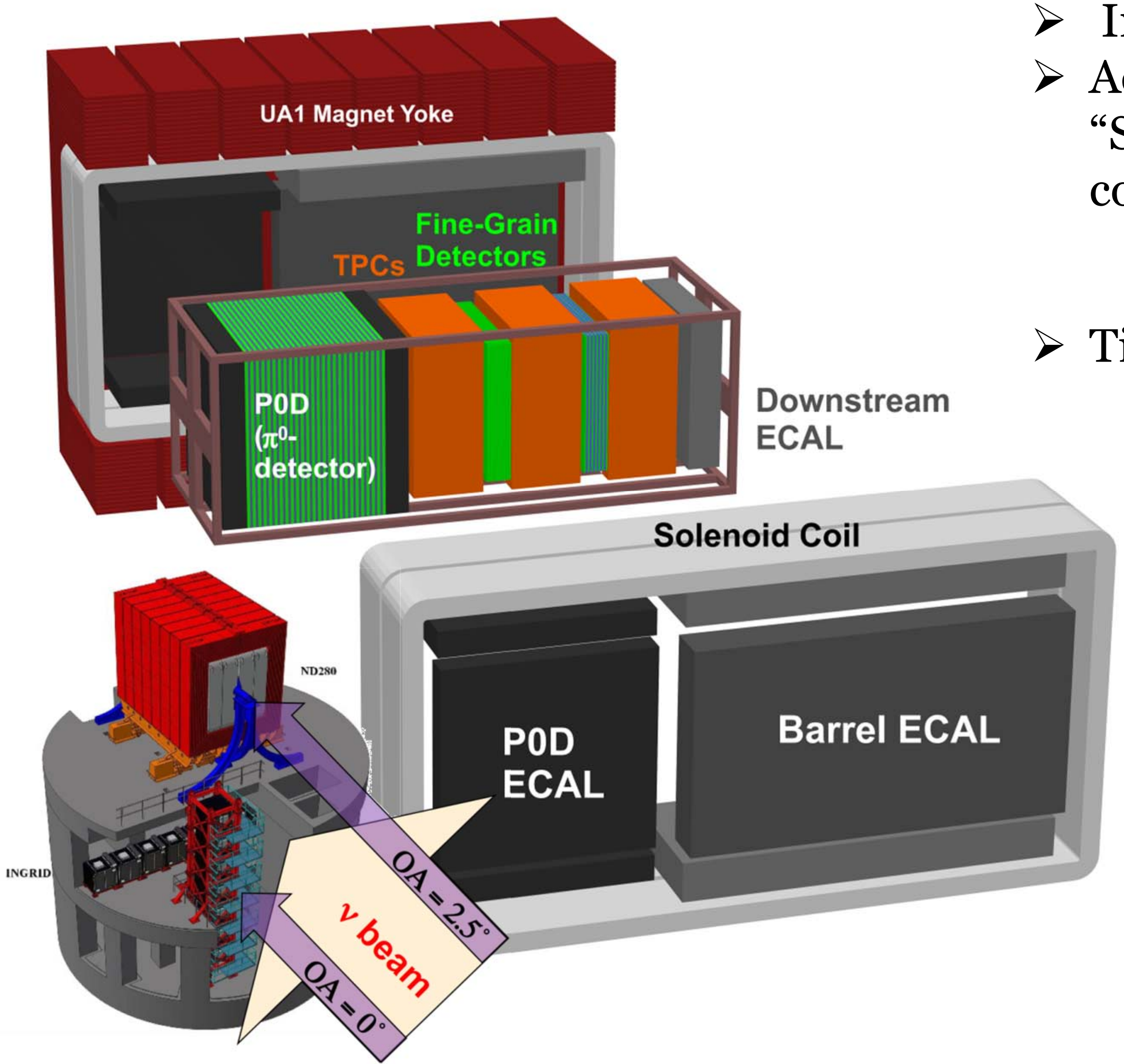
  similar to that of the far detector is favorable
- Back ground rejection

  Main back ground

  particles produced by neutrino interaction outside the detector fiducial volume
  - ✓ Good vertex determination
  - ✓ Large effective mass compared to outside materials
  - ✓ Shielding dose not work, Need active veto.
- Good Particle Identification
  - ✓ $\mu/\pi/p$ separation to discriminate interaction mode
  - ✓ e/μ separation to measure back ground for ν_e appearance experiments
- Tolerance to (relatively) high rate $\rightarrow$ Finely segmented detector
- Good cost performance

T2K off-axis Near Detector: ND280

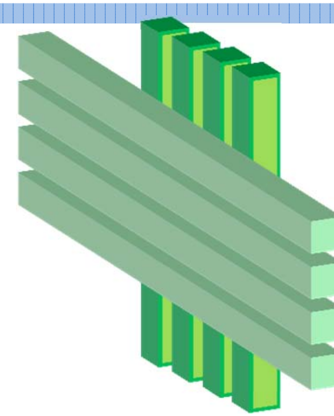
SMRD in Magnet
Yoke air gaps



Separate function

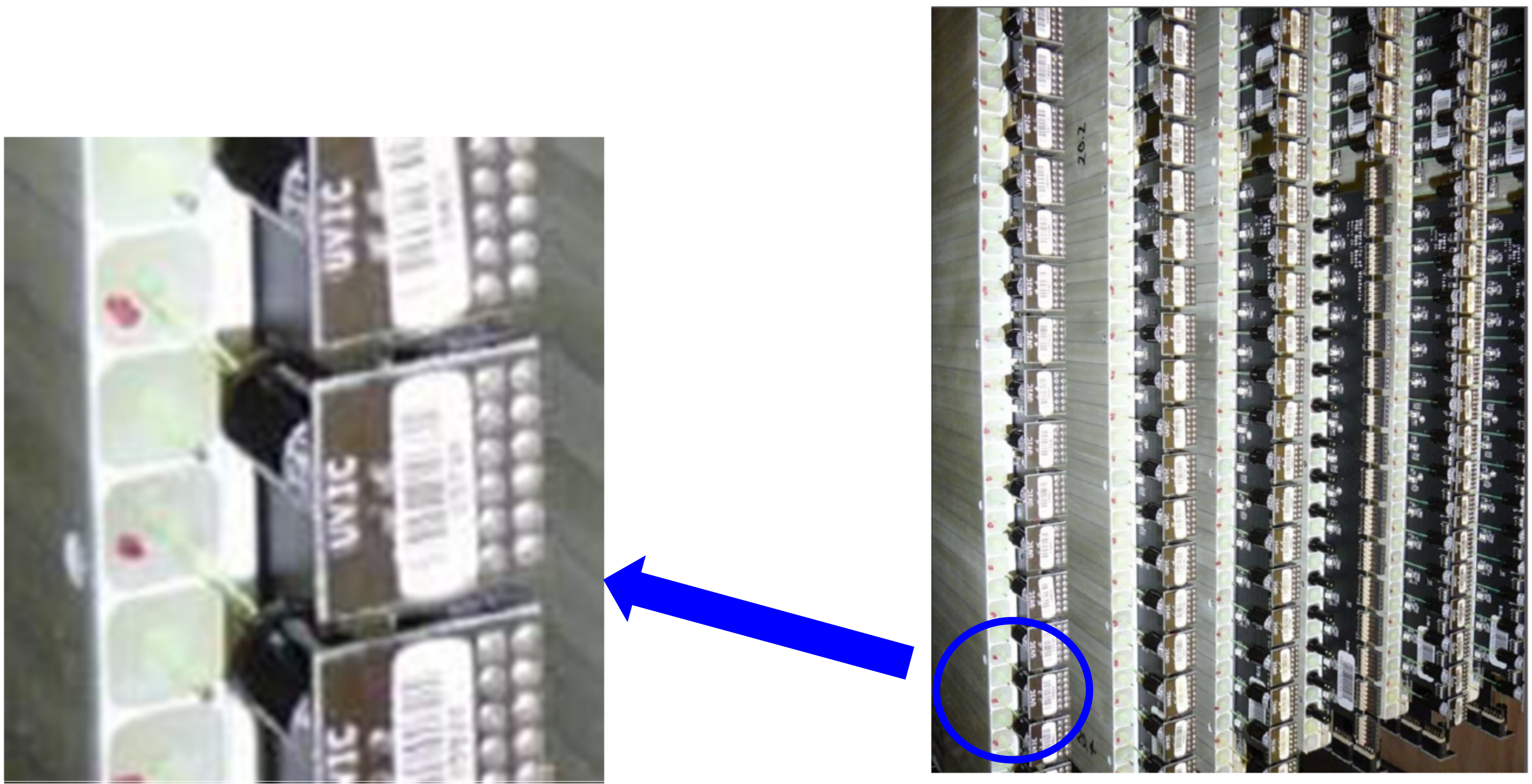
- In magnetic field
- Active Interaction-Target made w/ "Scniti+WLS fiber+MPPC" combination
  - ✓ Fine-Grain Detectors (FGDs)
  - ✓ P0 detector P0D
- Time Projection Chambers (TPCs)
  - ✓ Cover forward
  - ✓ Momentum measurement
  - ✓ PID
- Electric-Calorimeters (ECALs)
  - ✓ Cover side (and forward)
  - ✓ PID
  - ✓ e/γ Energy
- Side Muon Range Detectors
  - ✓ Cover side
  - ✓ Muon energy

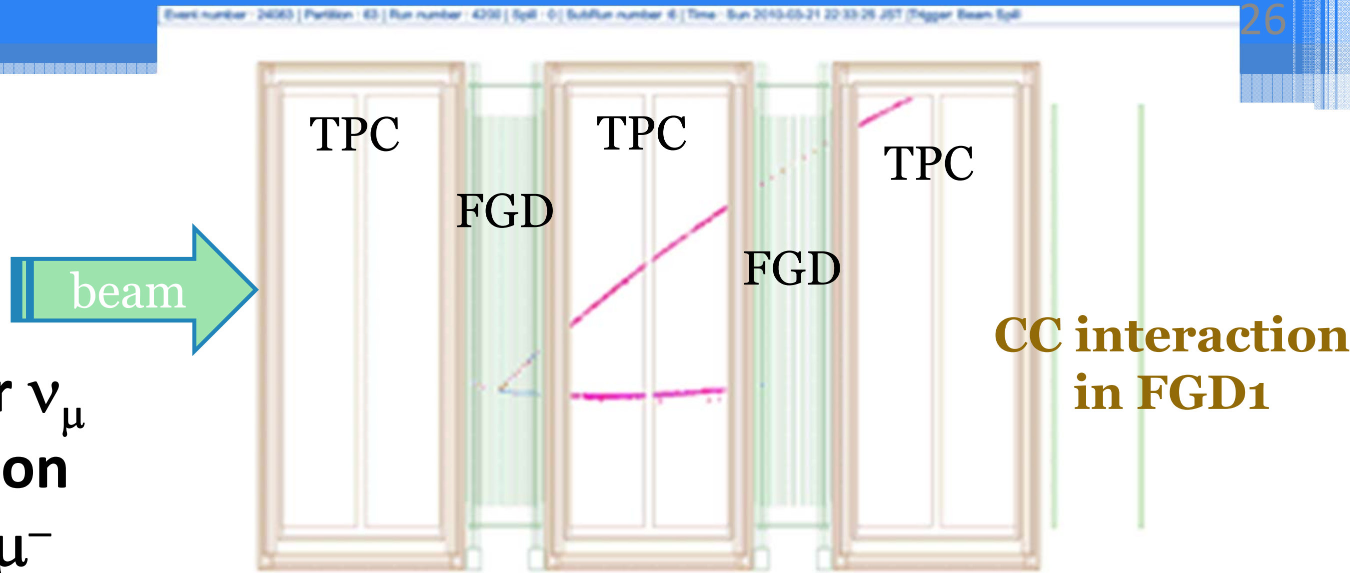
FGD : Fine Grain Detector



- Alternate layer of X-panes and Y-planes

  3D tracking
- Full active neutrino-interaction target

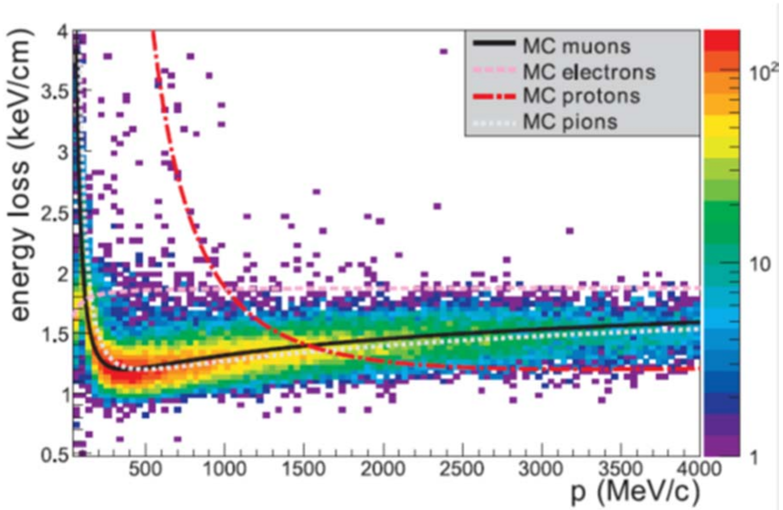




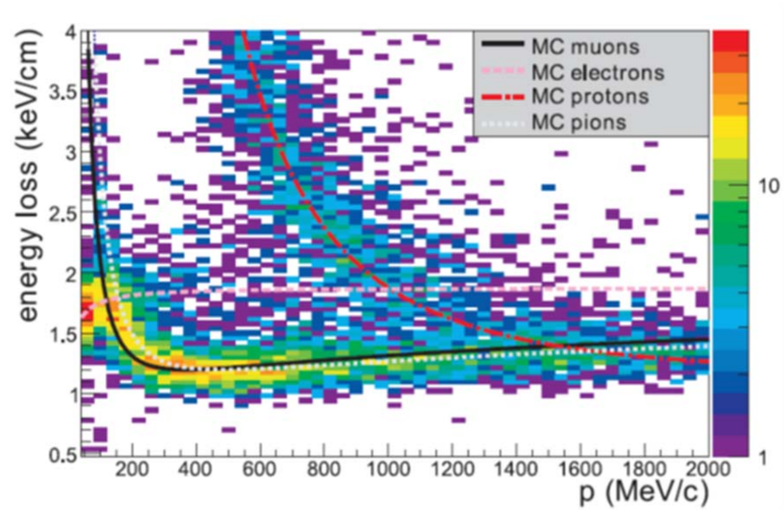
Event selection for ν_μ CC analysis relies on identification of μ^-

TPC PID for particles from ν interactions

negative



positive

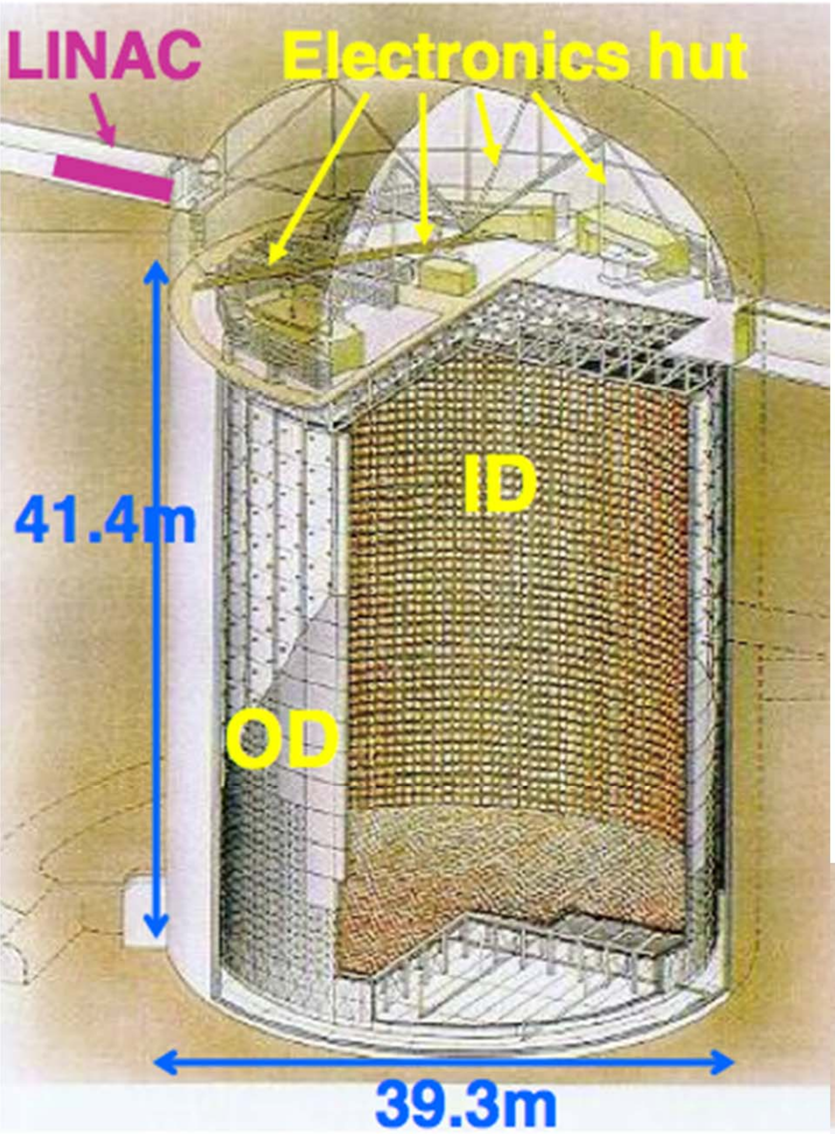


resolution for deposited energy is ~8% for MIPs better than the design requirement of 10%

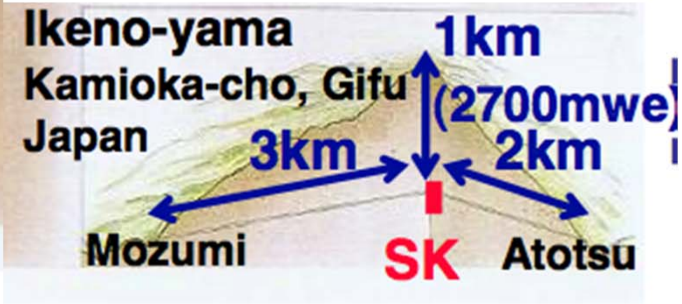
Far Detector

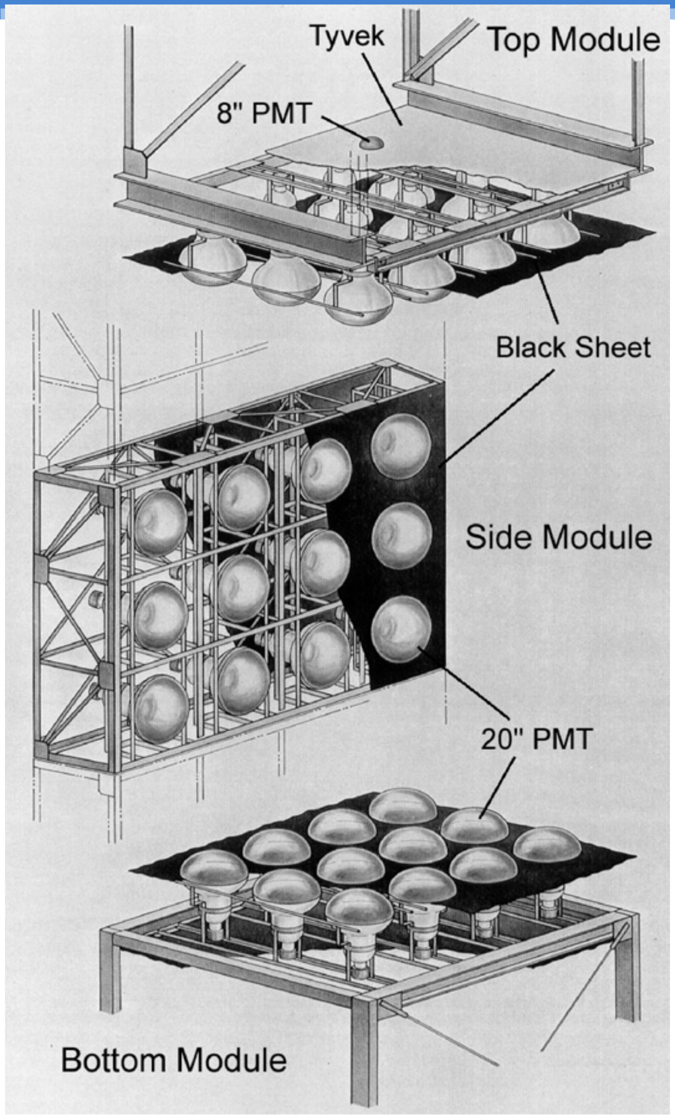
- Requirement
- As large as possible! 10kt ~ 100kt ~ 1 Mt
- Background rejection
  - ✓ Main backgrounds at > 100 MeV are
    - Cosmic muons and neutrino interaction outside fiducial volume ← can be rejected by good vertex determination and (thick) outer veto
    - Atmospheric neutrinos
- Good e/μ separation for ν_e appearance experiment

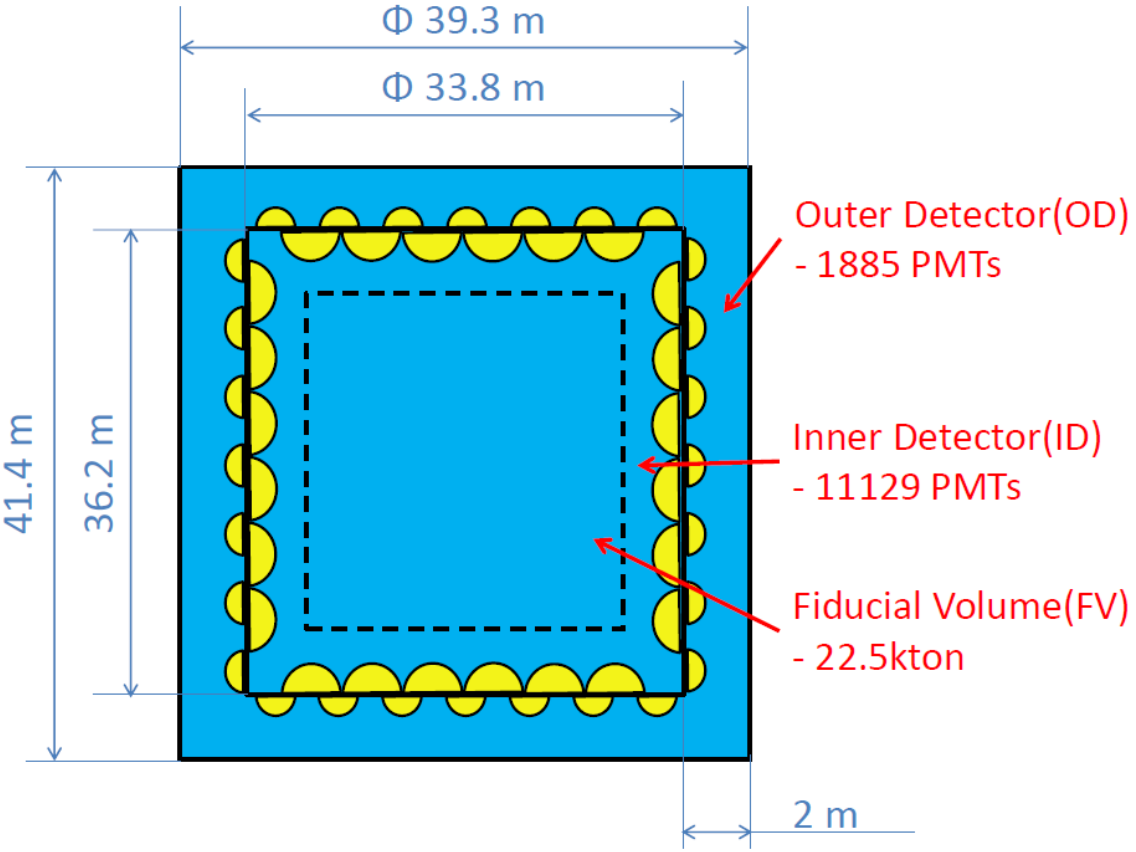
T2K Far detector : Super-Kamiokande



- Since April 1996
- Water Cherenkov detector w/ fiducial volume 22.5kton
  - detect Cherenkov ring from charged particles produced by neutrino interaction
- Detector performance is well-matched at sub GeV
  - **Excellent performance for single particle event**
  - **Good background rejection**
  - **Good e-like(shower ring) / μ-like separation**

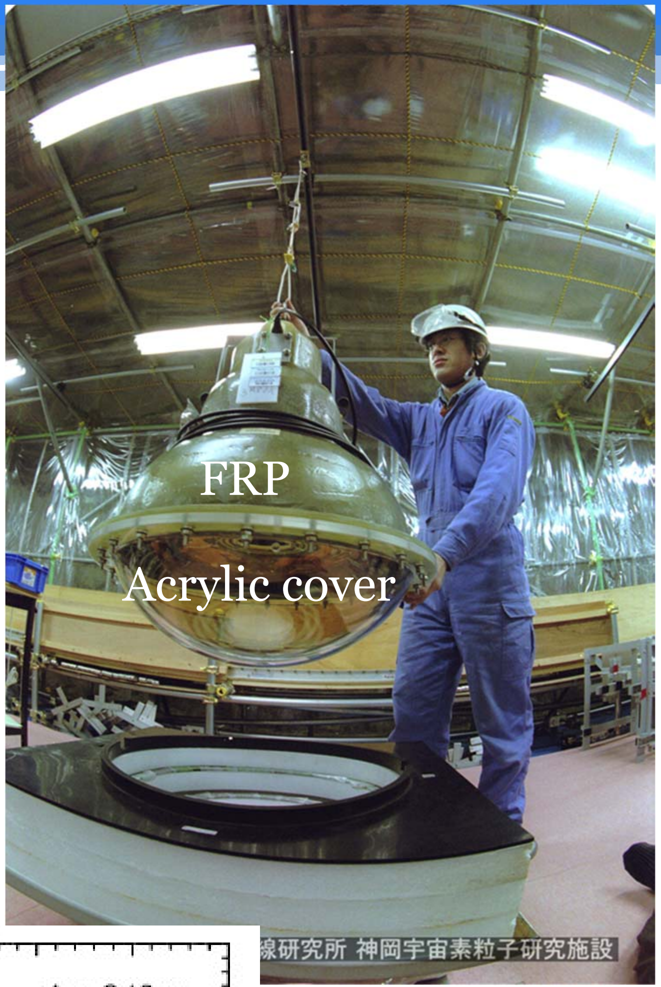


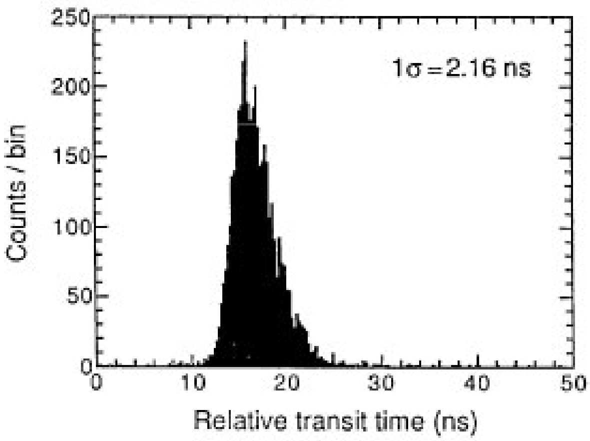

Tyvek
Top Module
8" PMT
Black Sheet
Side Module
20" PMT
Bottom Module

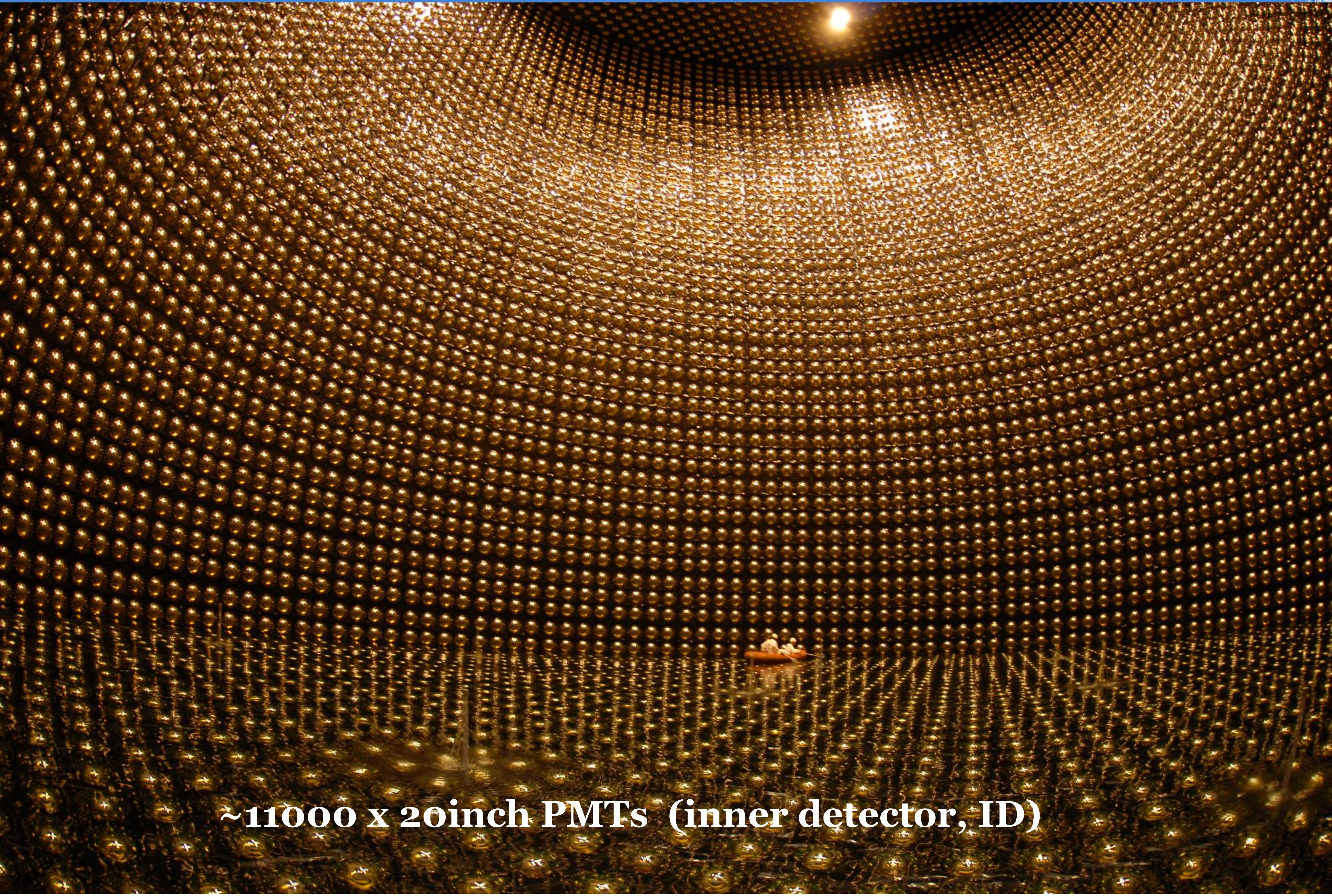

Φ 39.3 m
Φ 33.8 m
41.4 m
36.2 m
2 m
Outer Detector(OD)
- 1885 PMTs
Inner Detector(ID)
- 11129 PMTs
Fiducial Volume(FV)
- 22.5kton

HAMAMATSU 20 inch PMT

40% coverage





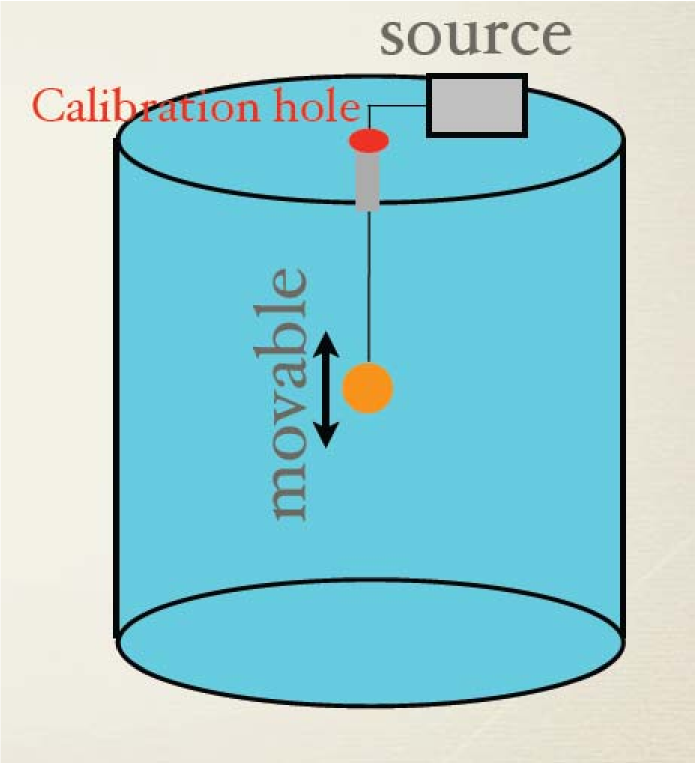


~11000 x 20inch PMTs (inner detector, ID)

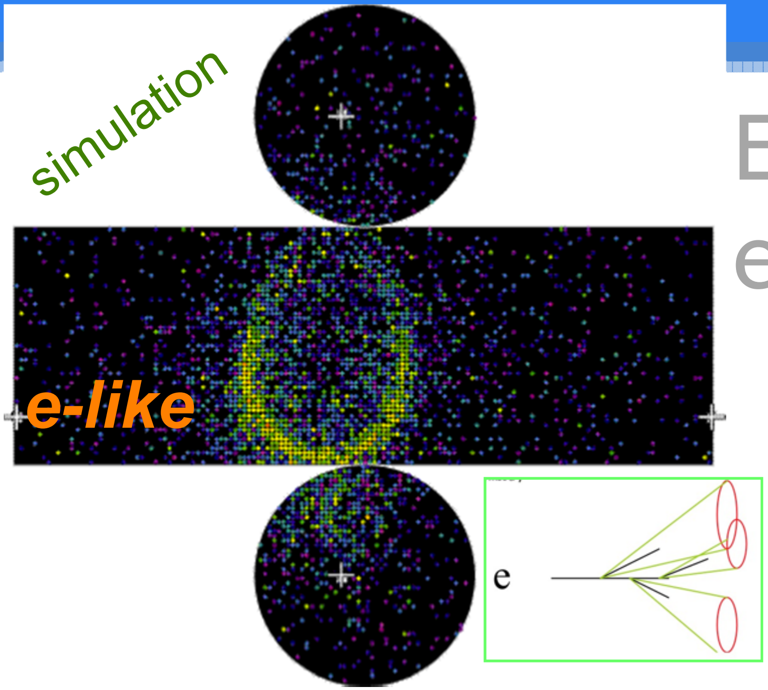
Calibration of Super Kamiokande

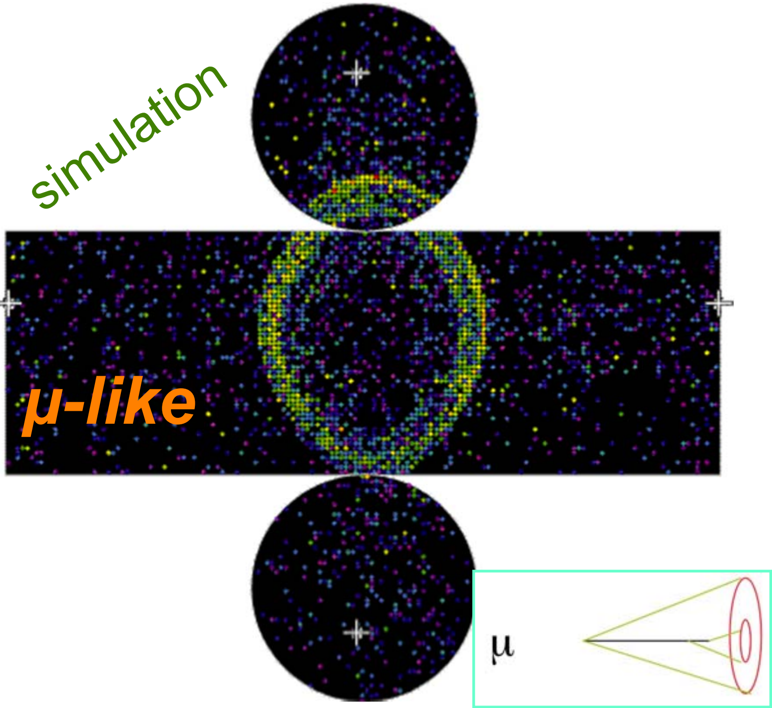
- PMT gain and timing and Water quality
- Insert sources for calibration
  - Xenon lamp + scintillator ball
  - Laser + diffuser ball
  - Ni source
- Energy scale
  - Need sample whose energy is known
  - Compare Range(~1GeV) and Cherenkov angle(200-500MeV/c) of stopping muon
  - Invariant mass of π^0's produced by atmospheric neutrino interactions (130 MeV)
  - electron from muon decay (~50 MeV)
  - Electron from LINAC and DT
  - D+T→He+n, n induces γ's.

Achieved 1%~3% precision

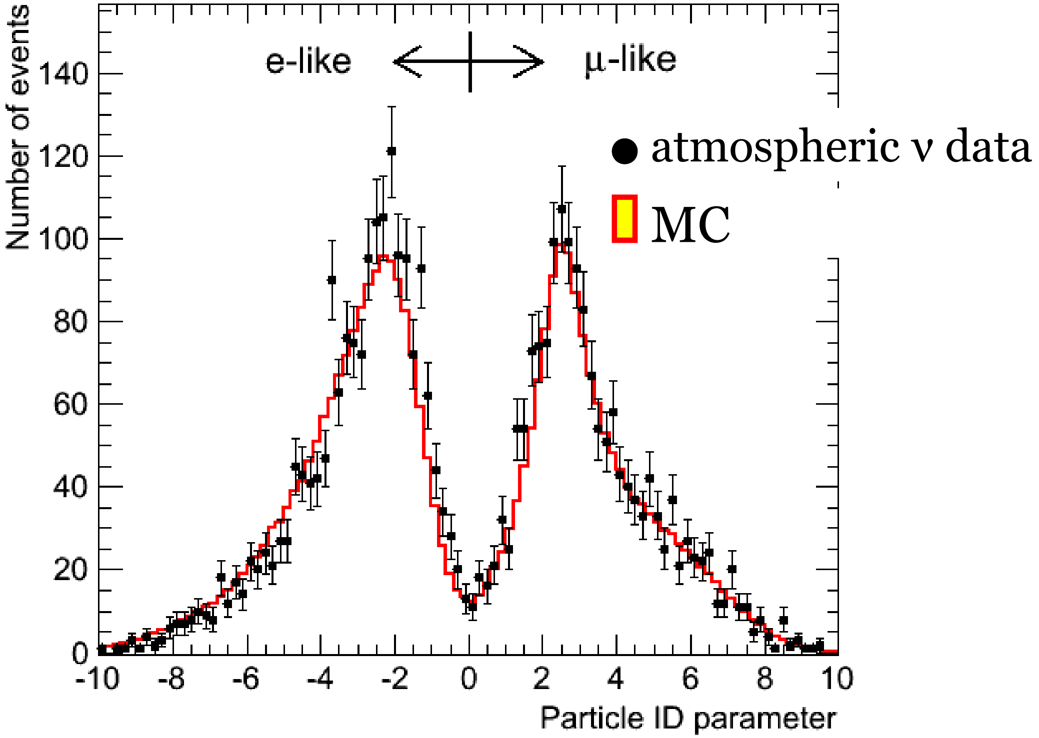


Electron-like and muon-like event at SK



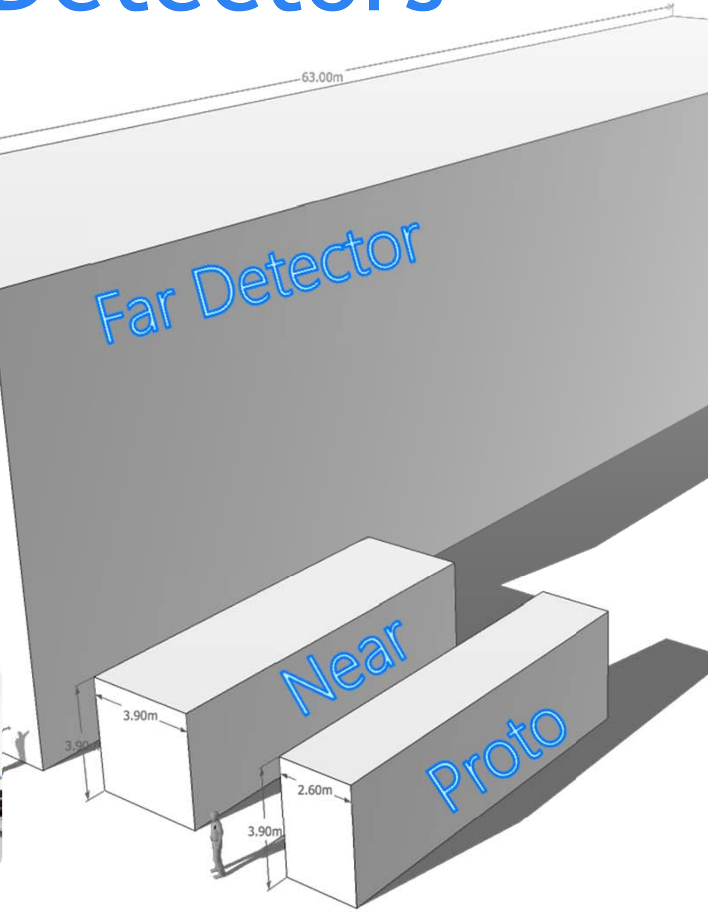


Particle identification using ring shape & opening angle



Probability that μ is mis-identified as electron is ~1%

NOvA Detectors



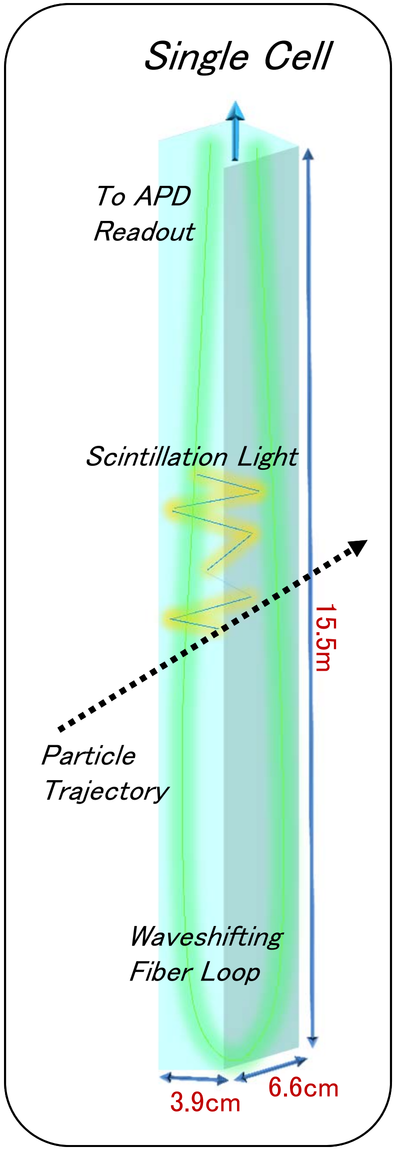
Far Detector

- *Surface Detector*
- 14 kt "Totally Active", Low Z, Range Stack/Calorimeter
- Liquid Scintillator filled PVC
- 896 alternating X-Y planes
- Optimized for EM shower reconstruction & muon tracking, $X_0 \approx 40$cm, $R_m \approx 11$cm
- Dims: 53x53x180 ft
- "Largest Plastic Structure built by man"
- Started Operations May 2013
- First Beam Aug 2013
- Completed April 2014

A.J.Norman, Neutrino2014

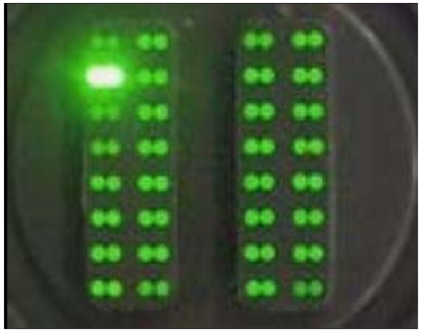
The Readout Cell

A.Norman, ν
2014

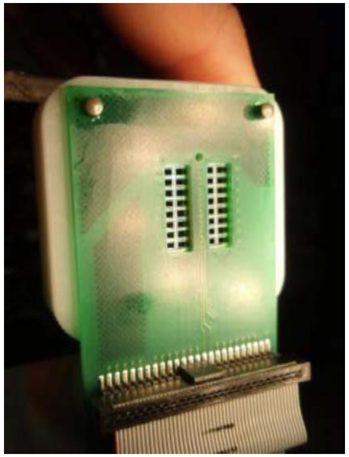


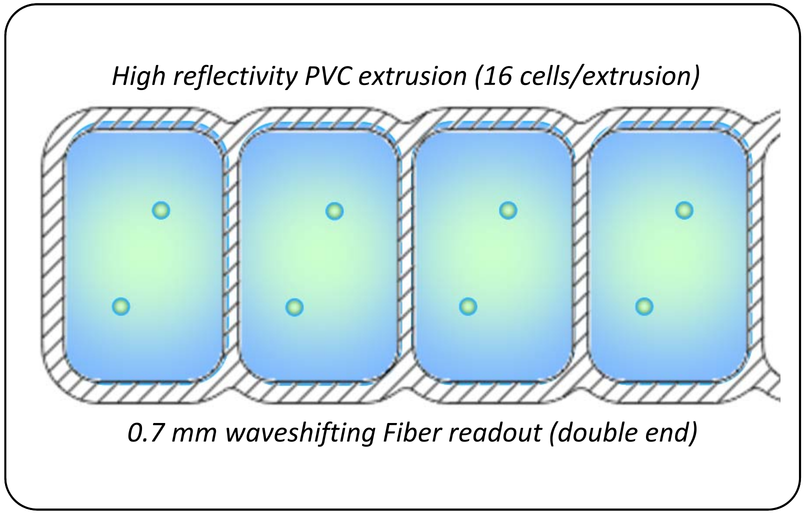
NOvA Detection Cell

- 15.5 m long, 3.9x6.6cm tube,
- Made of reflective PVC structure,
- Filled with liquid scintillator,
- Wavelength shifting fiber for light transport,
- Read out by an avalanche photodiode
  - Passage of MIP through the cell results in dE/dx ≈12.9 MeV across the cell.
- Need the light output to be 30-38 p.e. from the **FAR END** end to give a 10:1 signal/noise

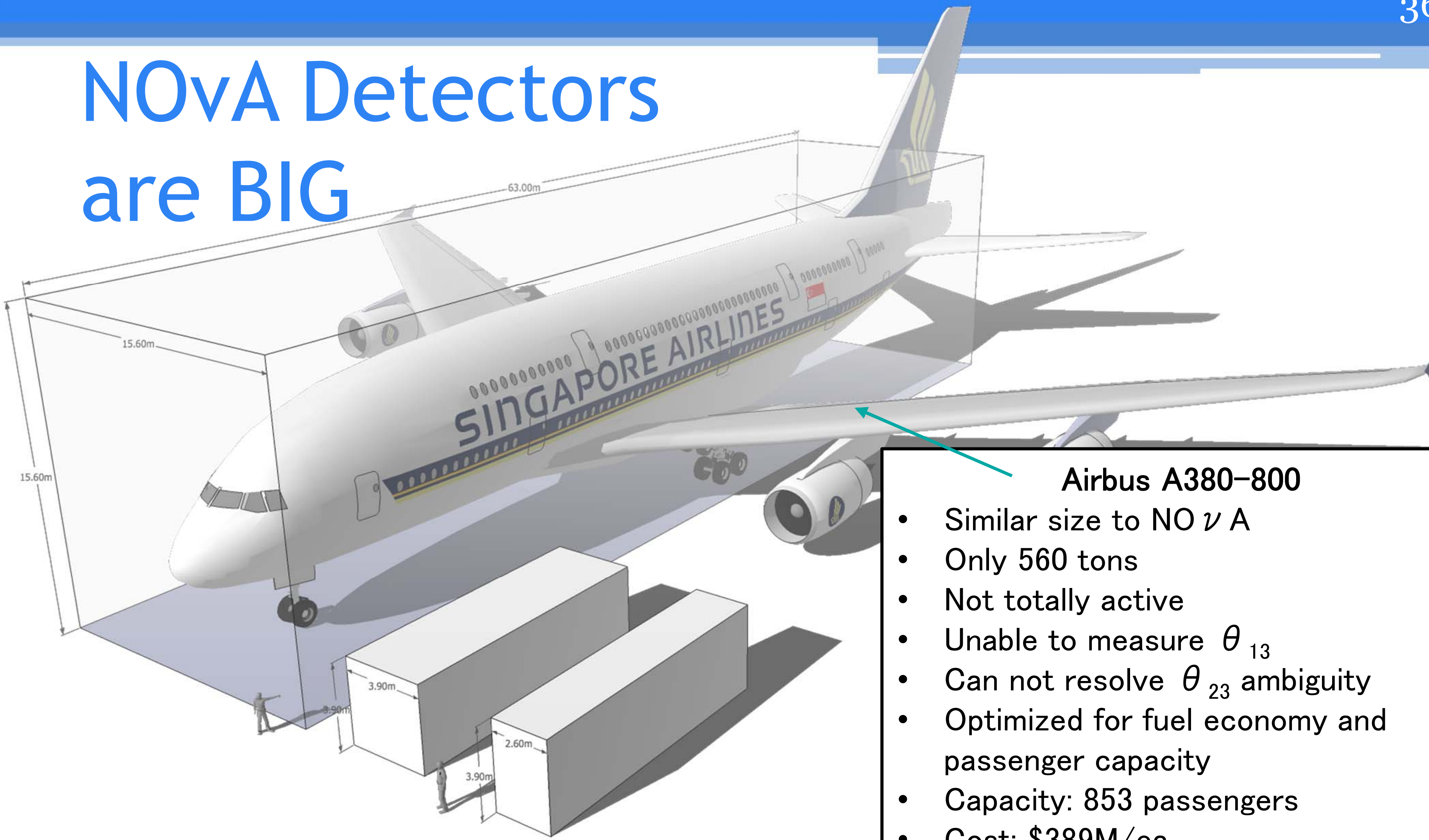


Waveshifting fiber readout and 32pixel APD used for cell digitization





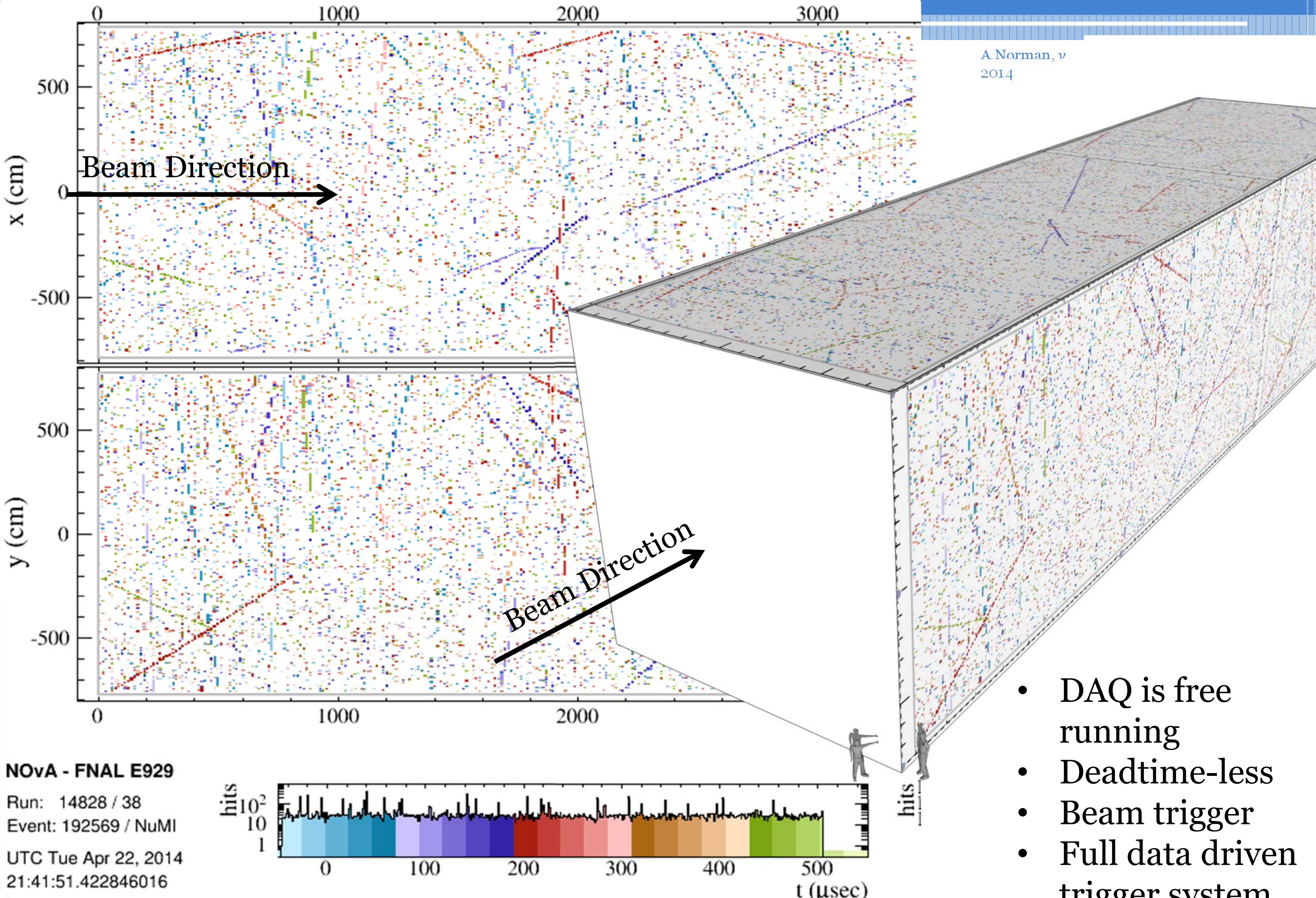
NOvA Detectors are BIG



Airbus A380-800

- Similar size to NOνA
- Only 560 tons
- Not totally active
- Unable to measure θ_{13}
- Can not resolve θ_{23} ambiguity
- Optimized for fuel economy and passenger capacity
- Capacity: 853 passengers
- Cost: $389M/ea
- "Largest commercial aircraft built by man"
- Construction start 2004
- First operation Oct. 2007 (Singapore Airlines)

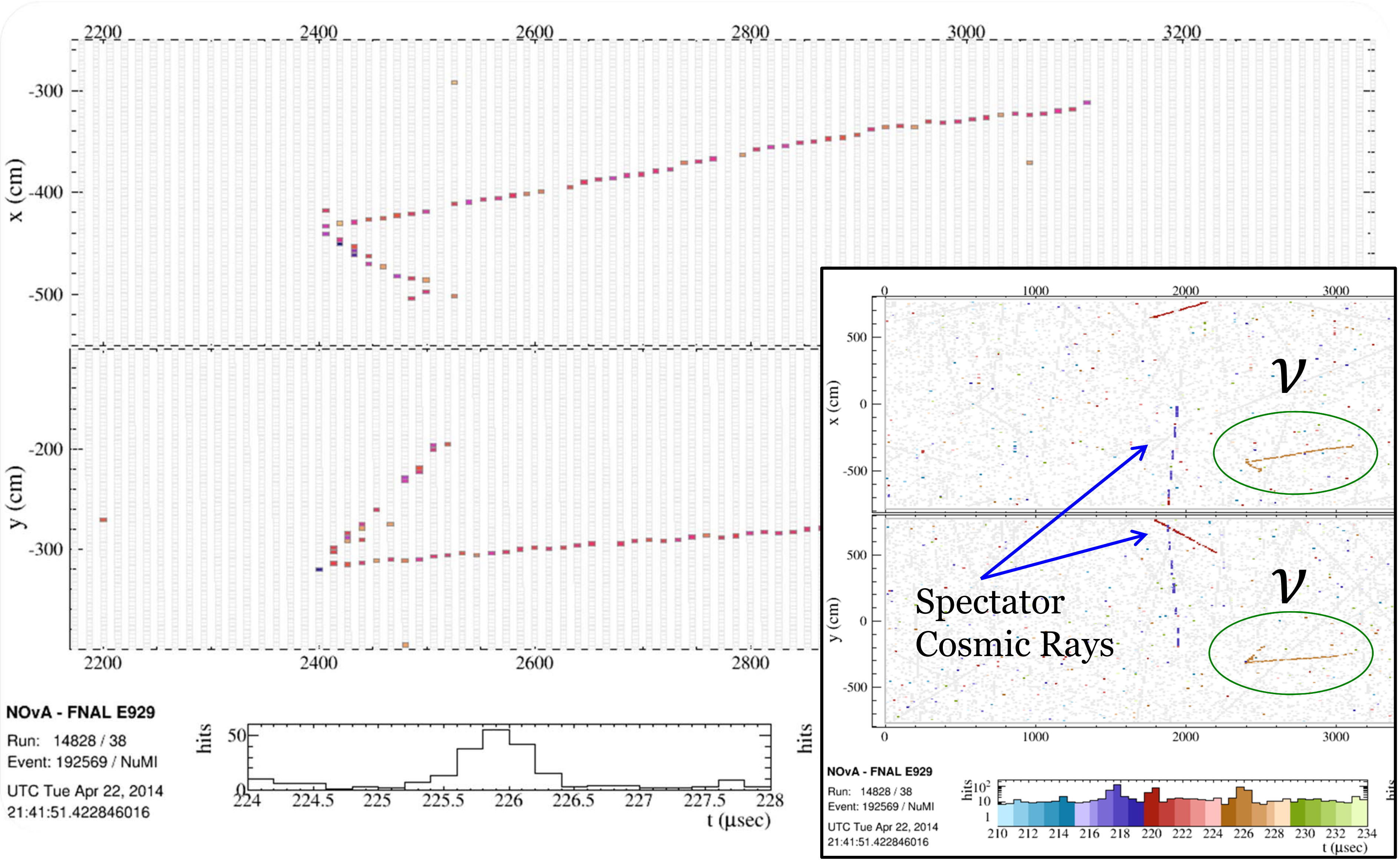
A.J.Norman, Neutrino2014



- DAQ is free running
- Deadtime-less
- Beam trigger
- Full data driven trigger system

A.J.Norman, Neutrino2014

A.Norman, ν
2014

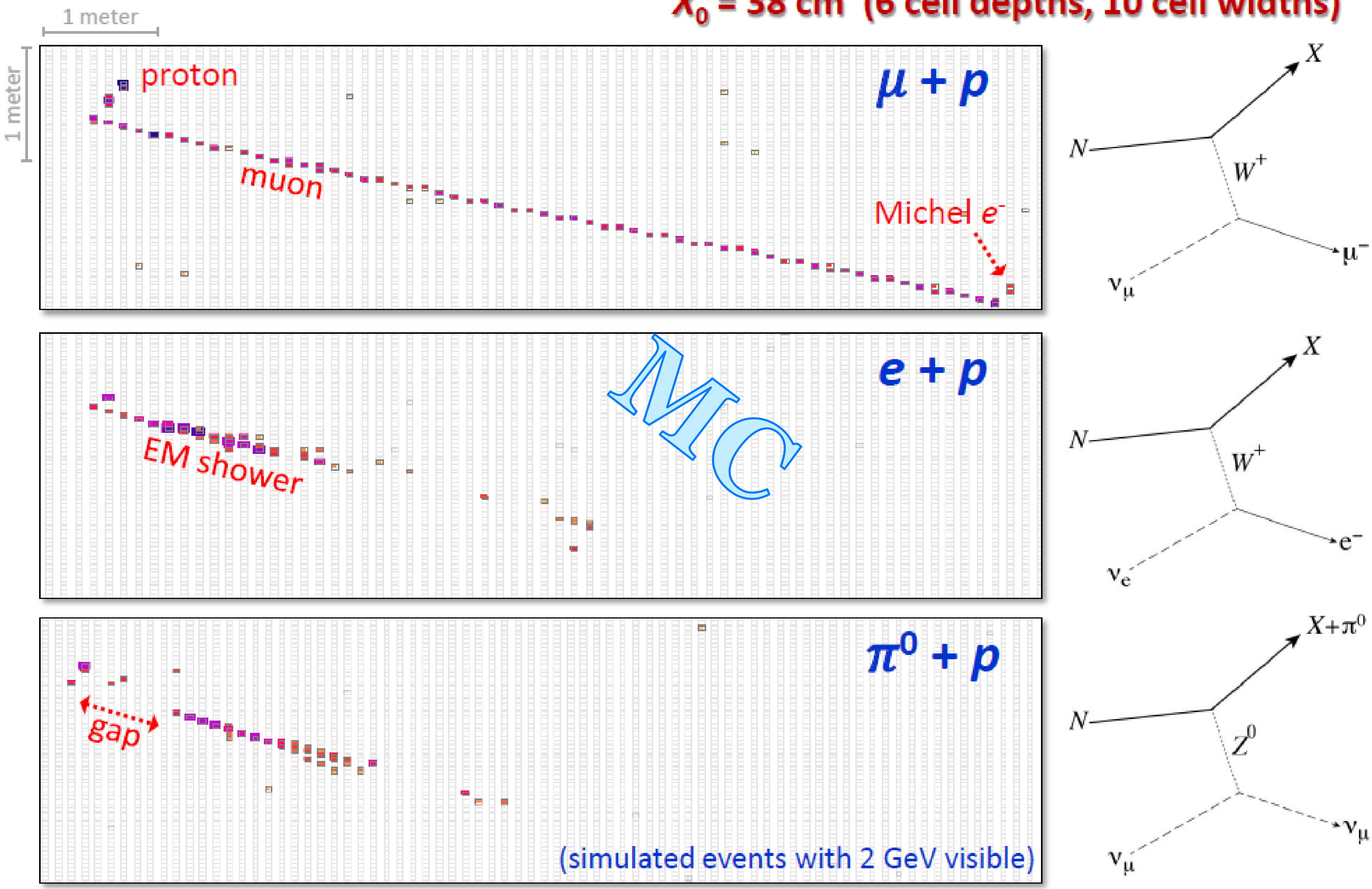


A.J.Norman, Neutrino2014

Events in NOνA

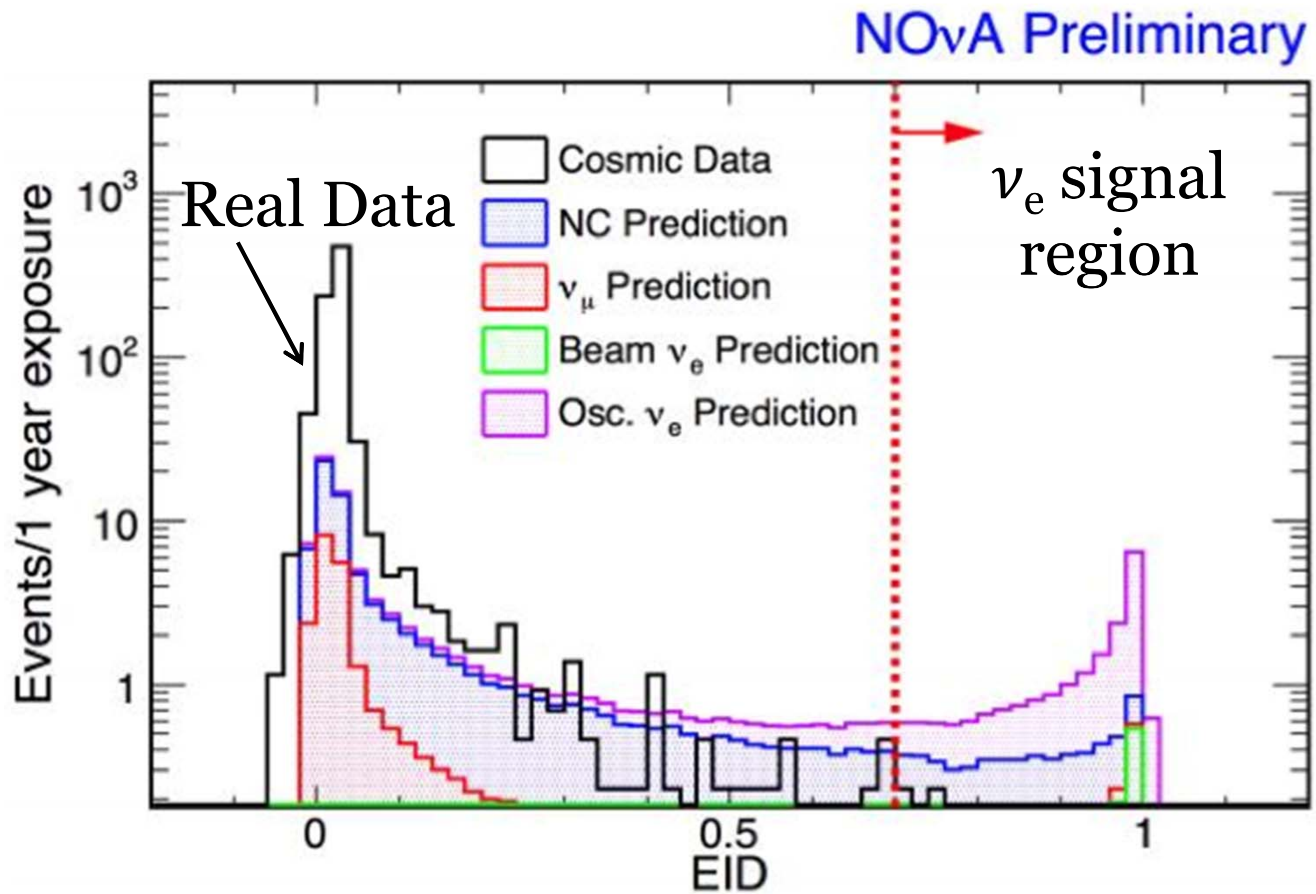
Superb spatial granularity for a detector of this scale

X_0 = 38 cm (6 cell depths, 10 cell widths)



ν_e Selection

A.Norman, ν 2014



Complimentary Methods of PID

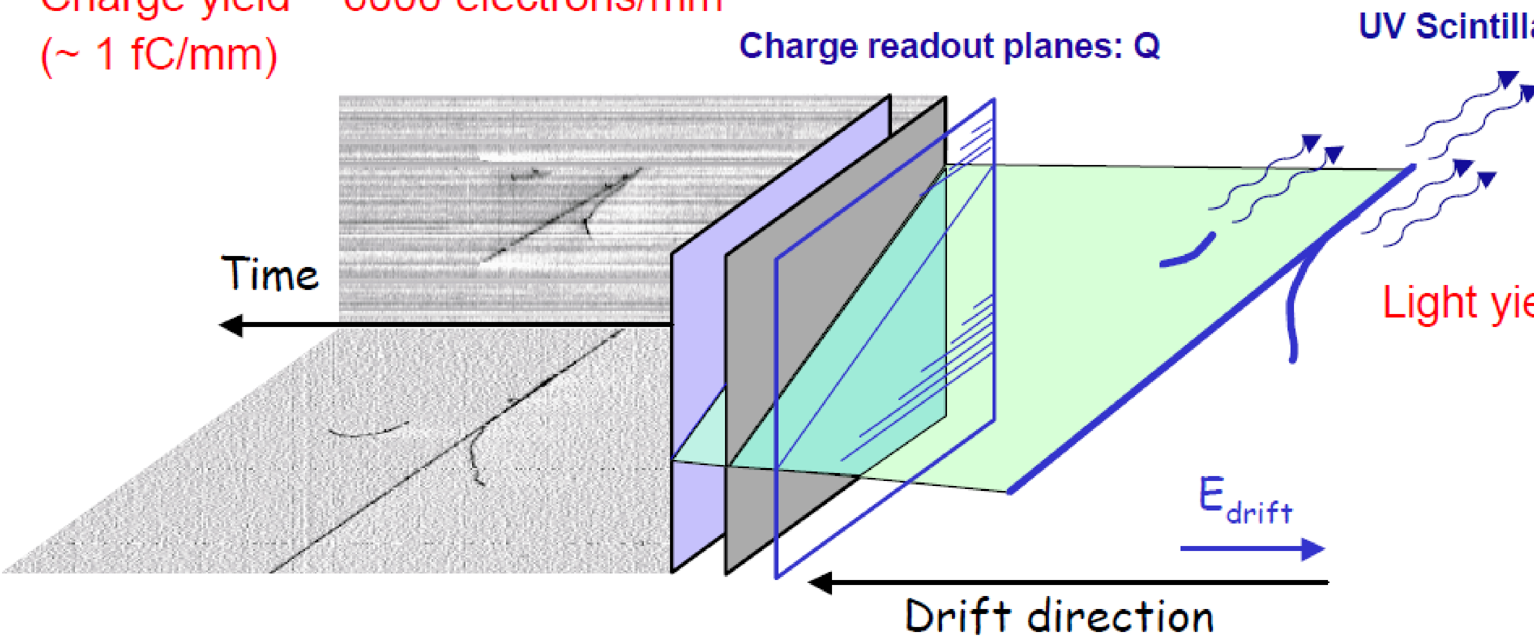
- EID - Neural net based on EM shower profile
- Library Event Matching (LEM) – Template method based on event topology

A.J.Norman, Neutrino2014

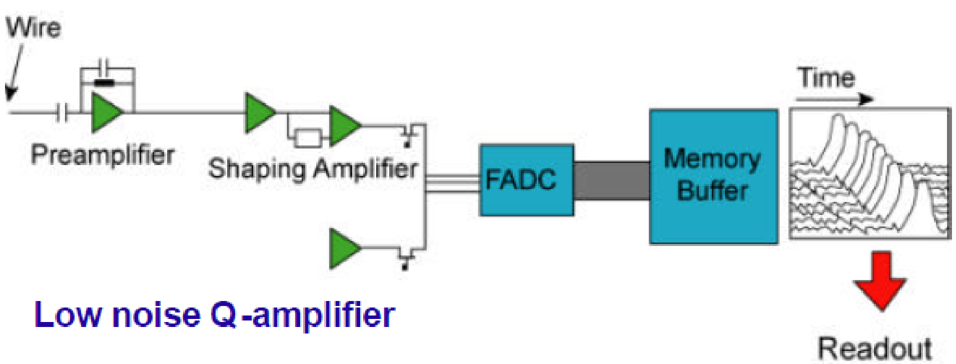
Antonio Ereditato (INFN Naples)
André Rubbia (ETH Zürich)

ICARUS Liquid Ar TPC

Charge yield ~ 6000 electrons/mm
(~ 1 fC/mm)



Light yield ~ 5000 γ/mm

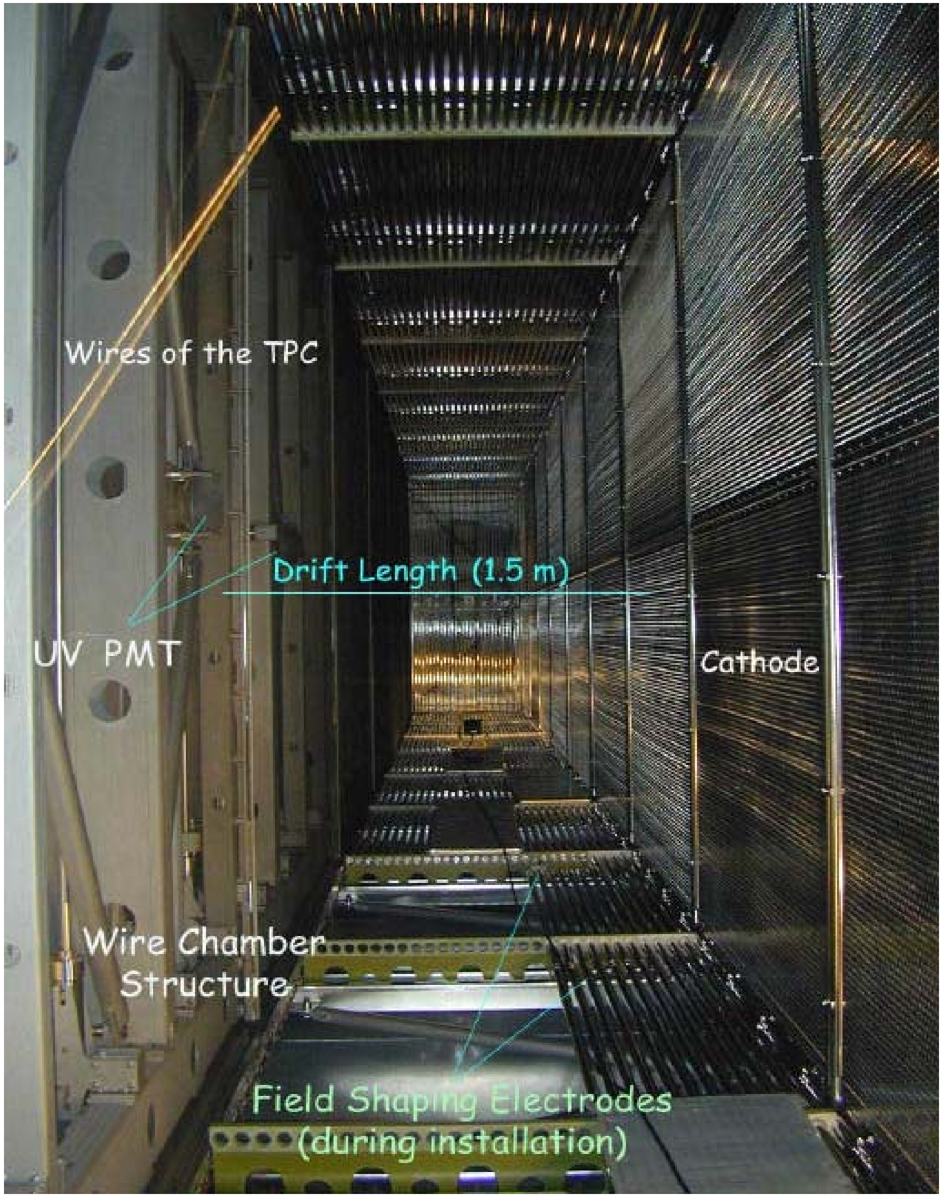


Low noise Q-amplifier

Continuous waveform recording

Sensitive to all particles.
Interaction vertex and conversion point(for γ or n) can be seen.
PID
- e shower or not
- Conversion or not

ICARUS 300ton module x 2



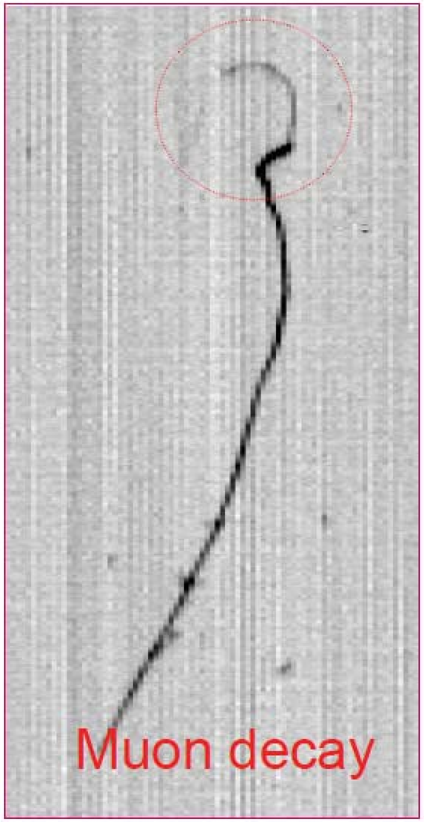
Antonio Ereditato (INFN Naples)
André Rubbia (ETH Zürich)

Charge

Cosmic rays events in the ICARUS T300

25 cm

85 cm



Run 960, Event 4   Collection Left

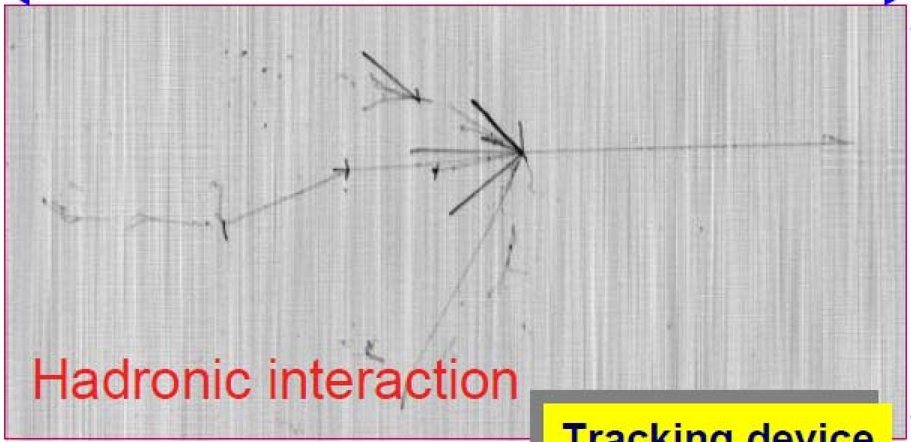
Measurement of local energy deposition dE/dx

176 cm

434 cm

265 cm

142 cm



Run 308, Event 160   Collection Left

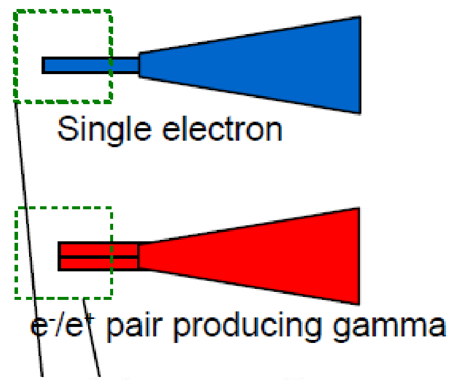
Antonio Ereditato (INFN Naples)
André Rubbia (ETH Zürich)

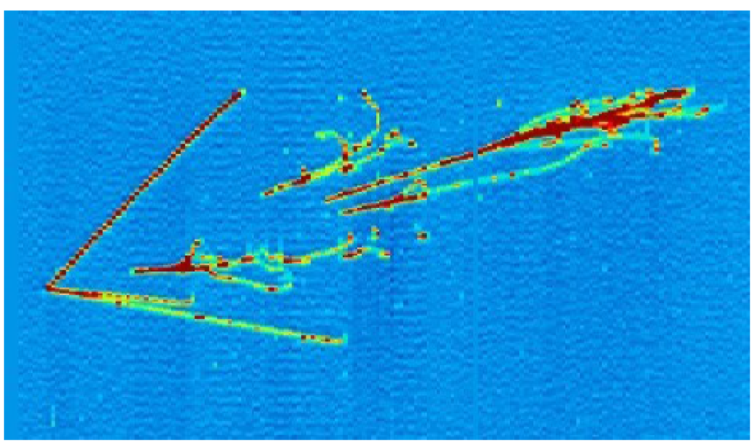
ArgoNeuT

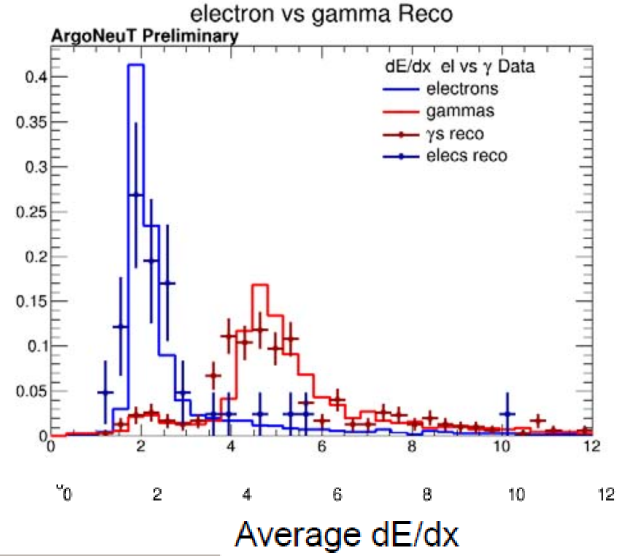
- 0.3 ton Lquid Ar TCP placed in front of MINOS near detector

Electron/gamma separation

- An EM shower that starts after a gap from the vertex is always background (especially if you can see two of them).
- Even if the gap is very small all is not lost.
  - We can reconstruct the charge at the start of the shower - “dE/dx discrimination”.





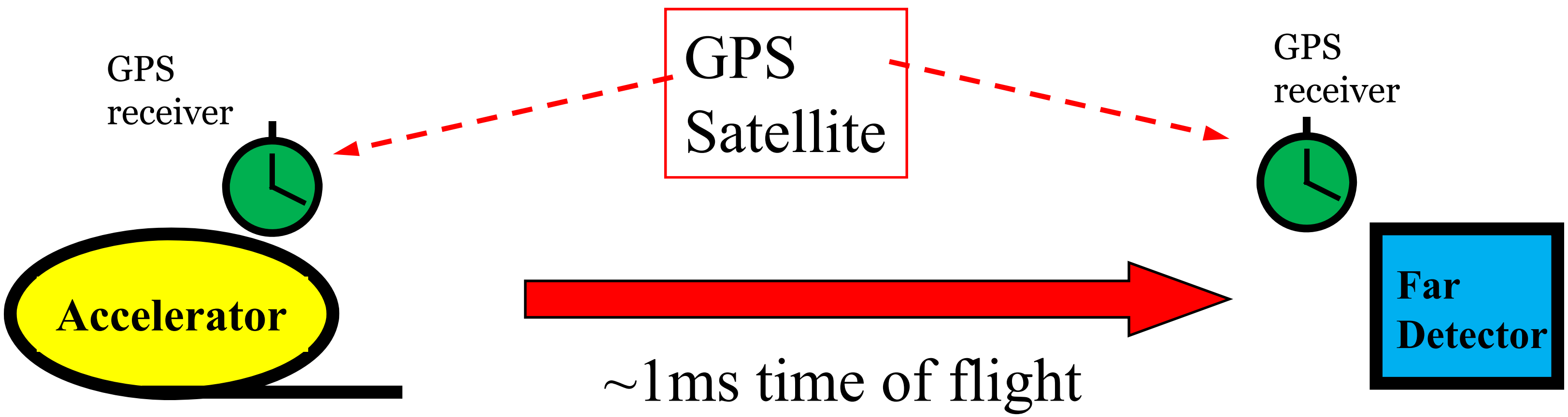


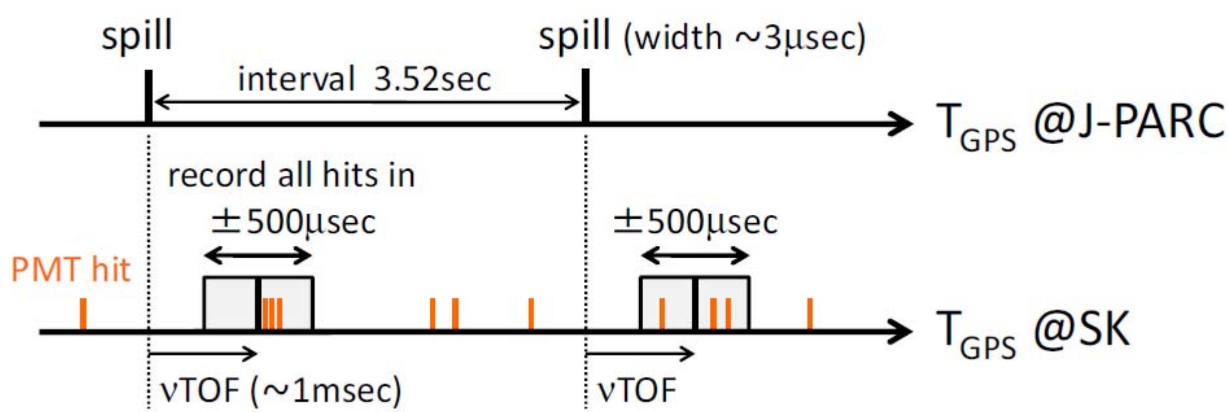
How to identify neutrinos from accelerator?

- Per day, ~10^{12} neutrinos are injected to Super-K from J-PARC (@750kW).
- Among those, about 50 will be detected, while ~10 atmospheric neutrinos are being detected per day.

Event synchronization by GPS

Distinguish the accelerator produced neutrinos from the atmospheric neutrinos by timing.

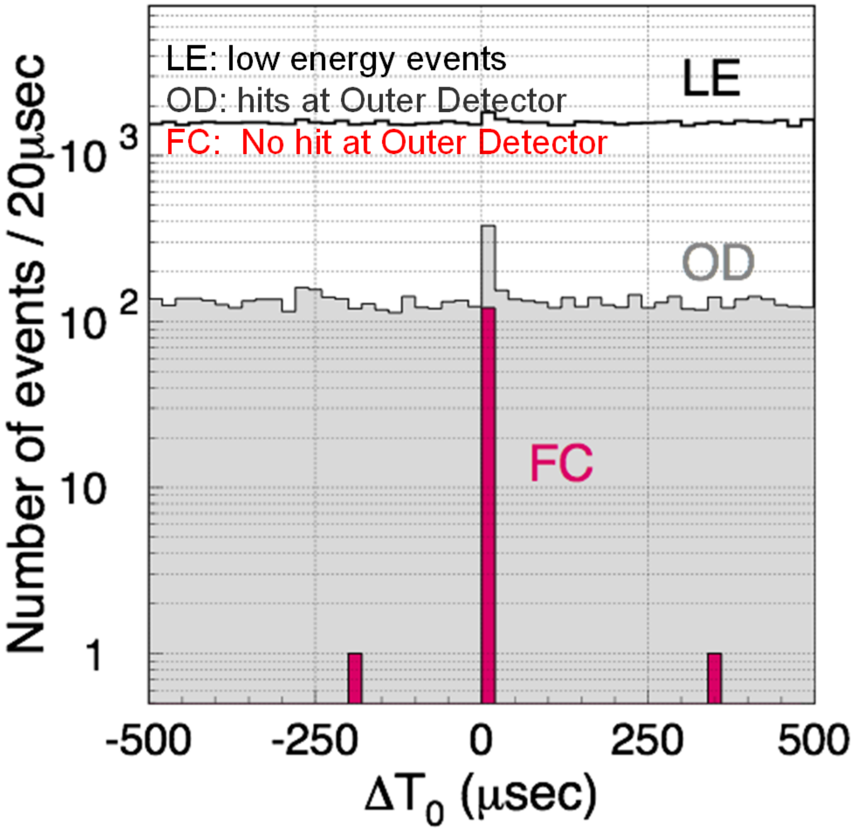




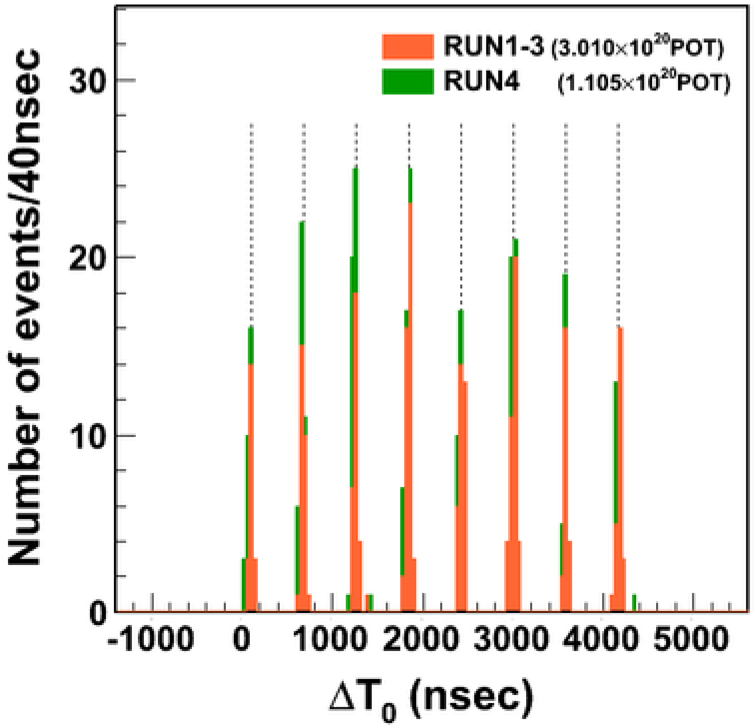
T2K SK events in beam timing

- Events in the T2K beam timing
- Propagation time of Cerenkov photons are corrected.

relative event timing to the spill timing



Clear beam structure !

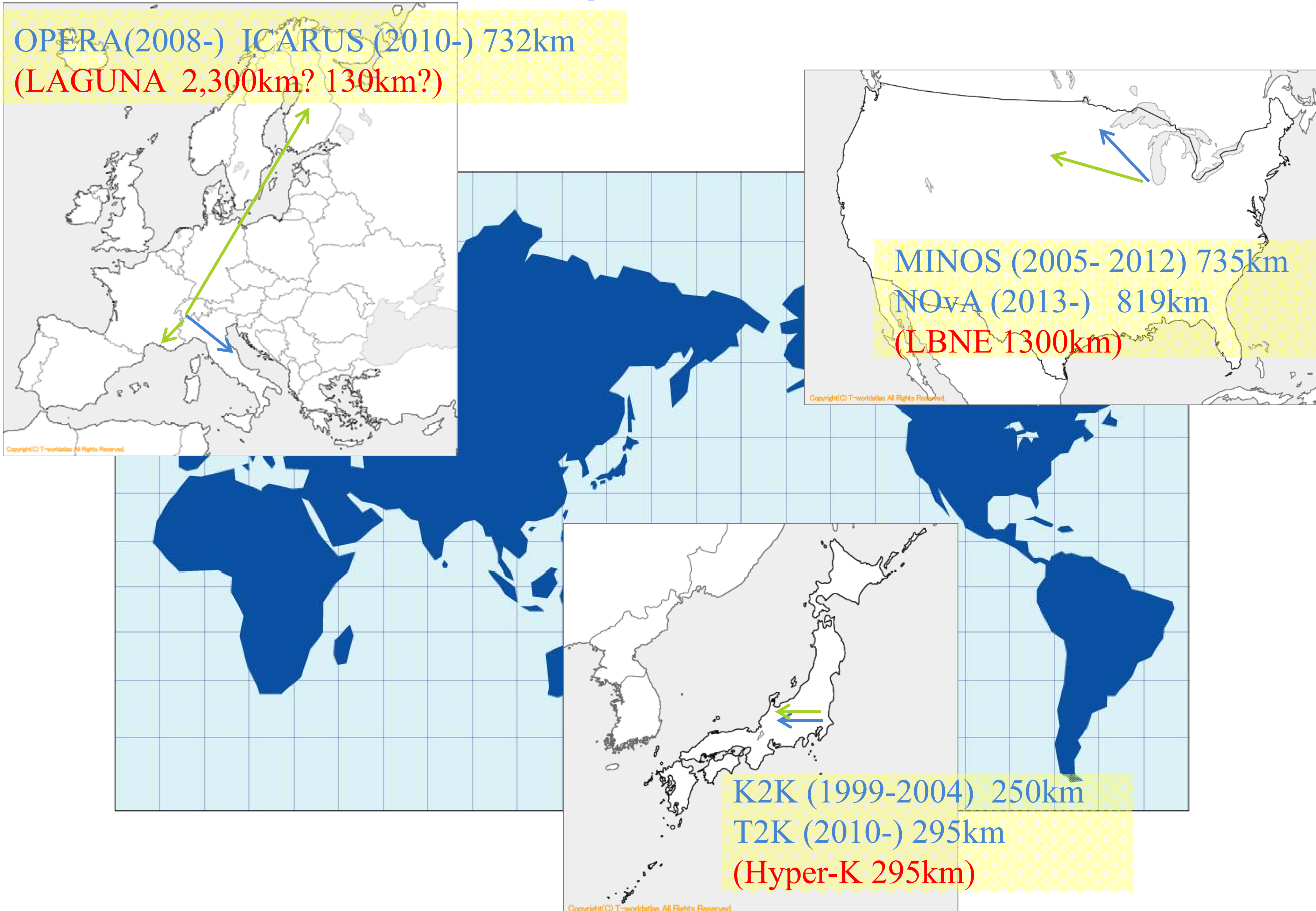


$\Delta T_0 = T_{GPS}@SK - T_{GPS}@J\text{-}PARC - TOF(\sim 985\mu sec)$

LBL Next Generation experiments

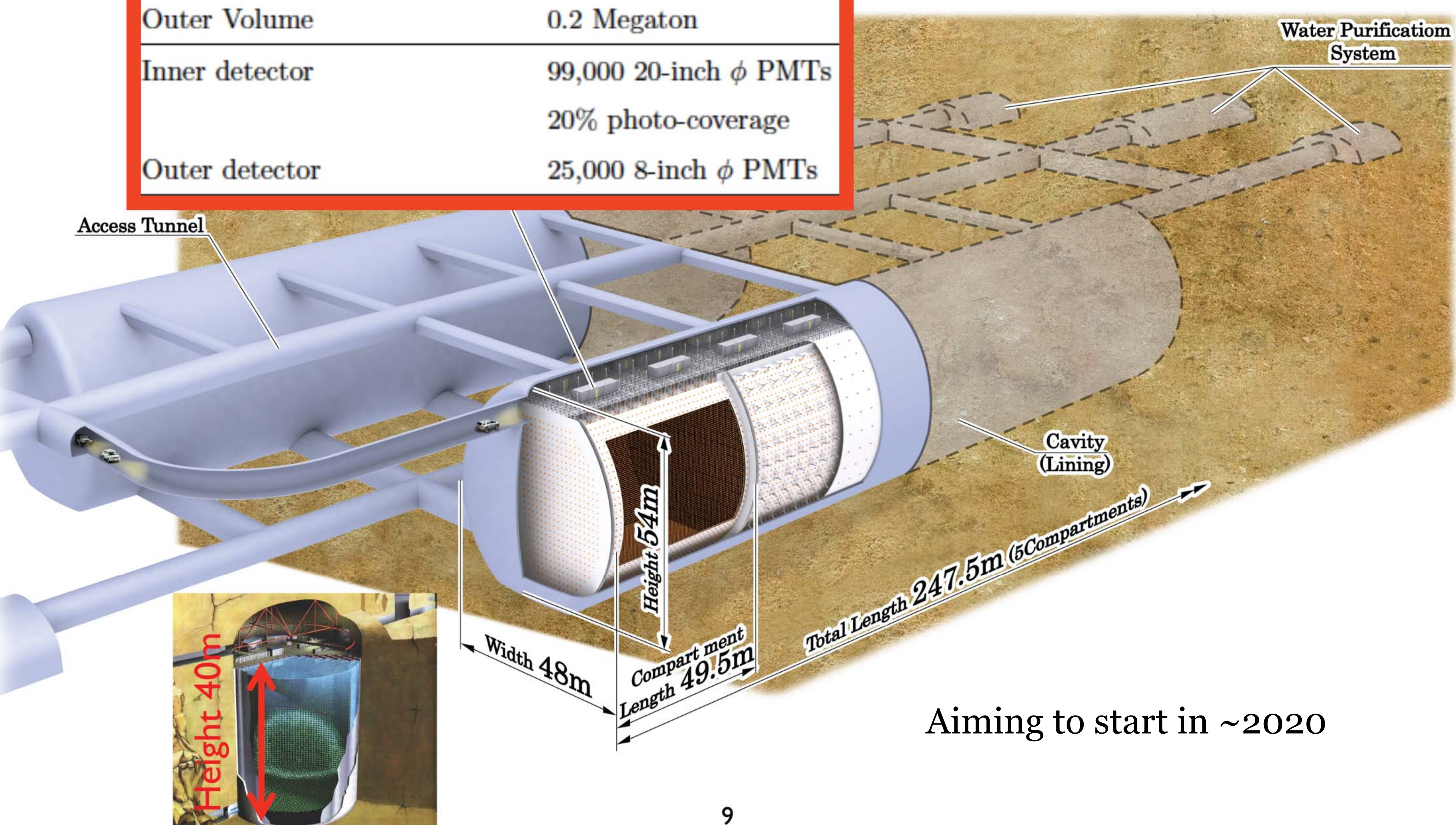
T2K and NOvA sensitivity would be around ~90%.
Need larger detectors or stronger sources for >3σ discovery for all parameter space.

World LBL experiments



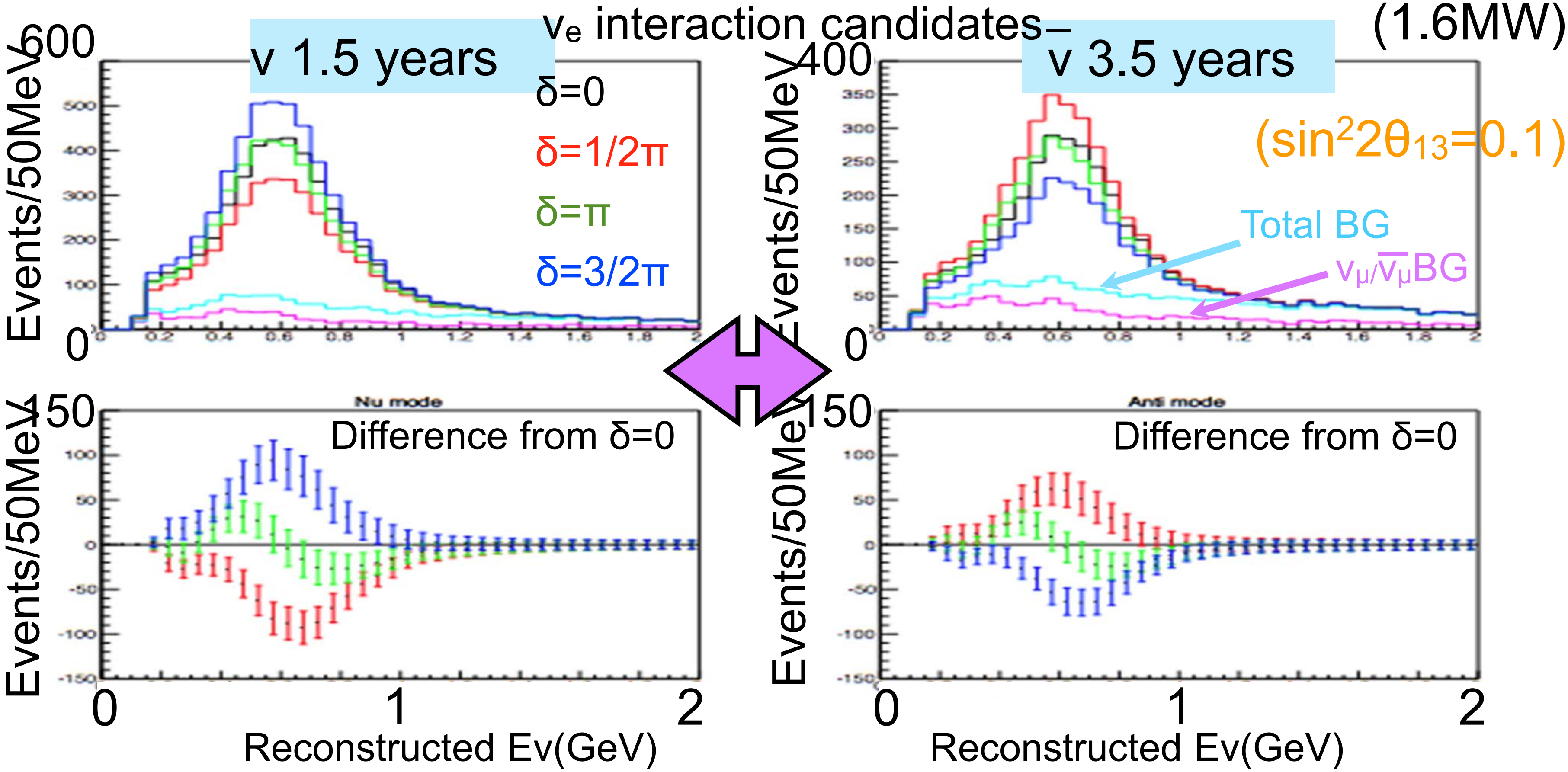
Hyper-Kamiokande

Total Volume	0.99 Megaton
Inner Volume (Fiducial Volume)	0.74 (0.56) Megaton
Outer Volume	0.2 Megaton
Inner detector	99,000 20-inch ϕ PMTs
	20% photo-coverage
Outer detector	25,000 8-inch ϕ PMTs



Aiming to start in ~2020

Hyper-K CP asymmetry



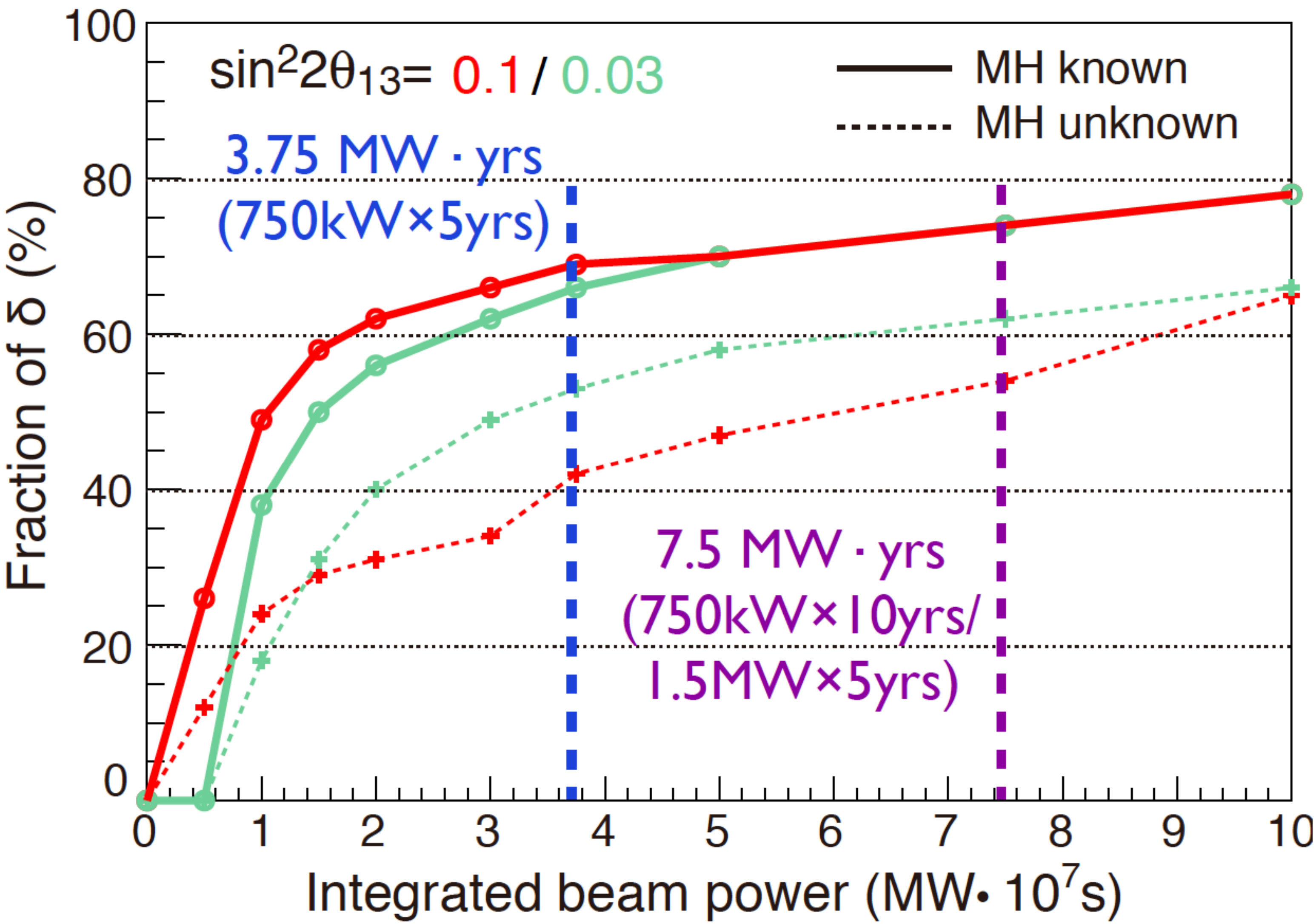
Compare $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\sin\delta \neq 0 \rightarrow$ CP violation!

Full simulation with latest J-PARC / Super-K (20% cov.) MC

Sensitivity to CP violation (sinδ≠0)

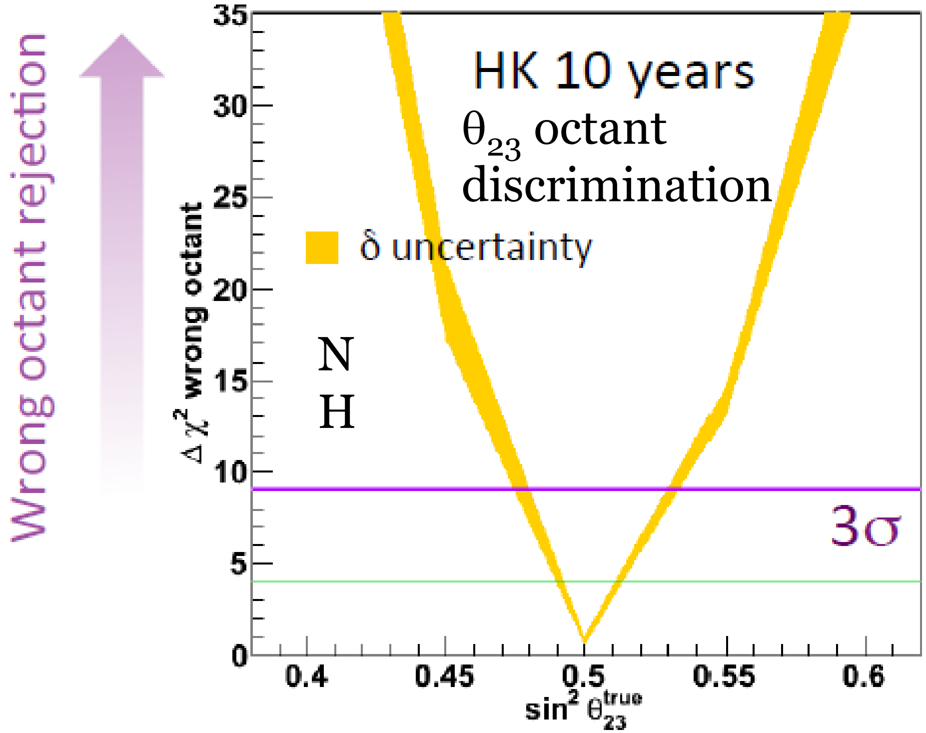
Fraction of δ for which sinδ=0 is excluded w/ >**3σ**

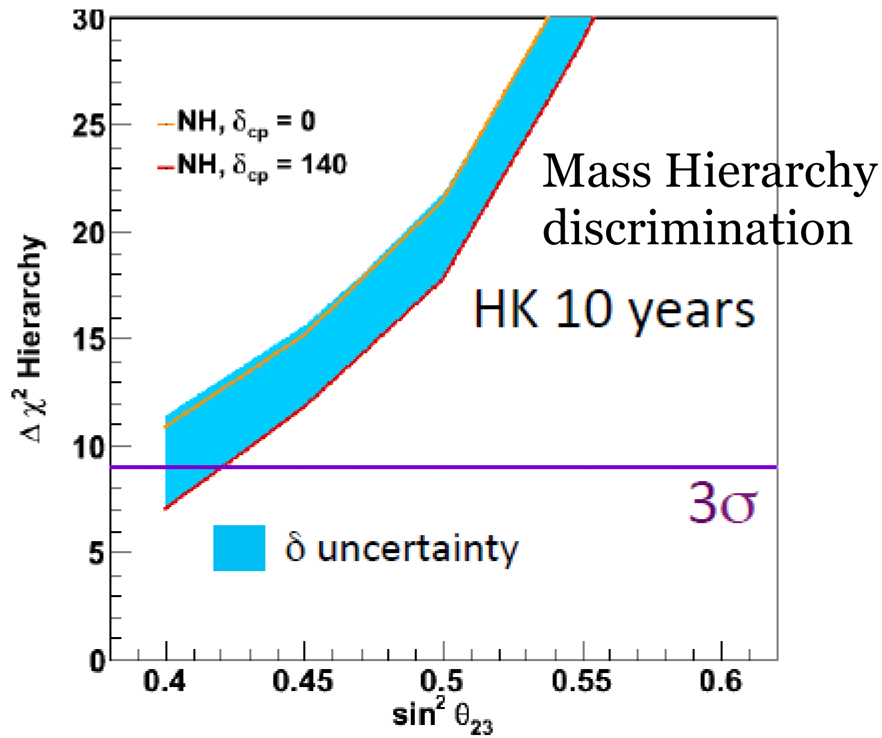


Hyper-Kamiokande project:
covering a wide range of particle physics/astrophysics

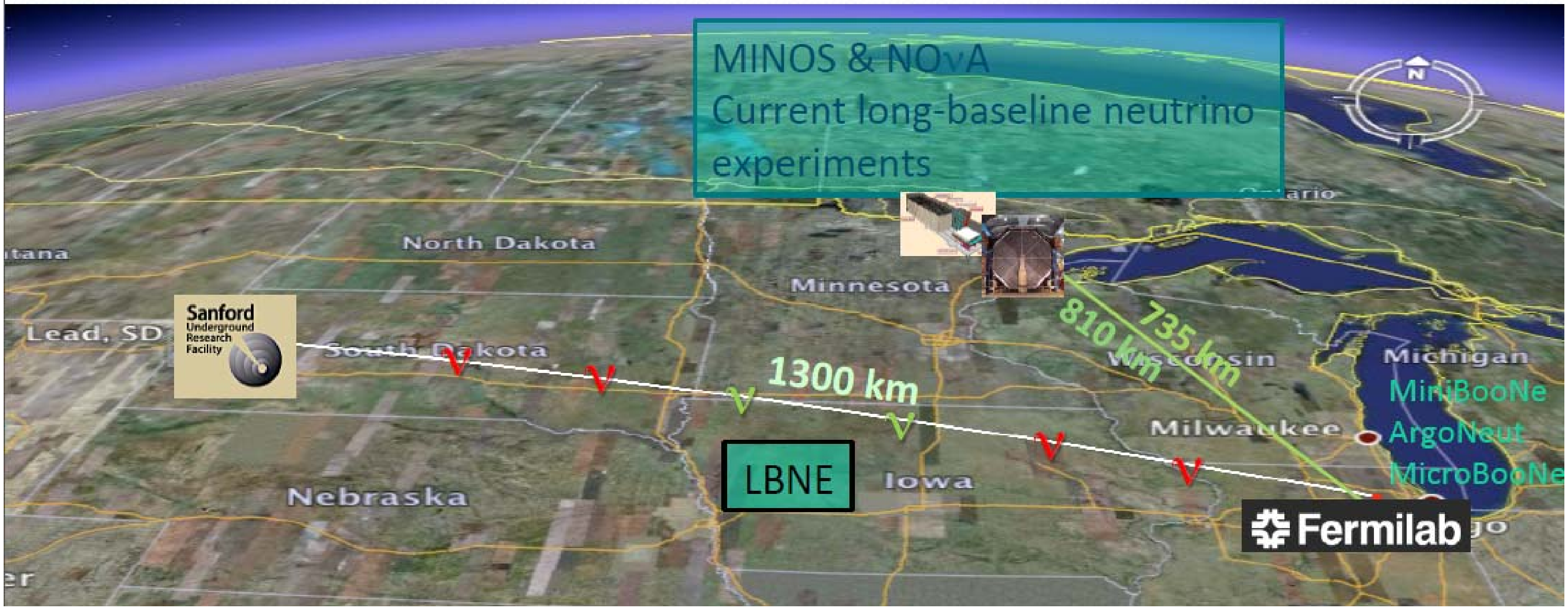
- Search for nucleon decay >x10 sensitivity
- Atmospheric neutrino
- Solar neutrino
- Supernova neutrino
- WIMP, GRB, ...

Atmospheric neutrino

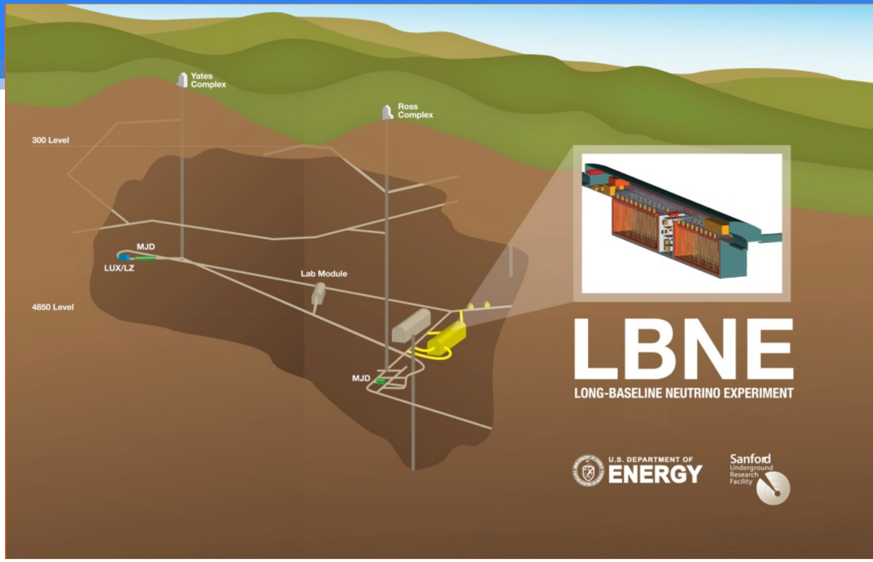




LBNE (Long Baseline Neutrino Experiment) (or LBNF)

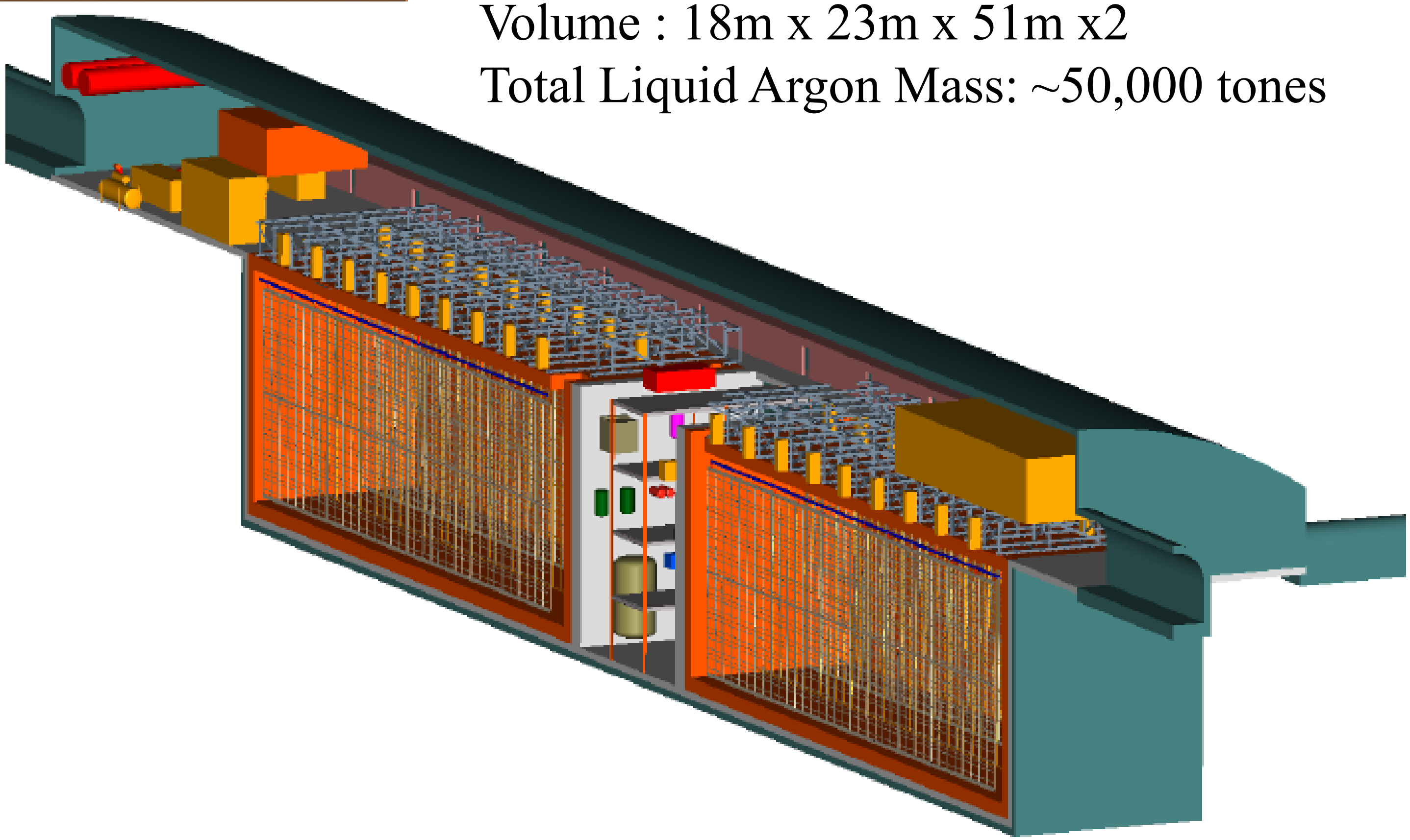


1.2MW proton beam
(upgradable to > 2 MW)



LBNE Liquid Argon TPC

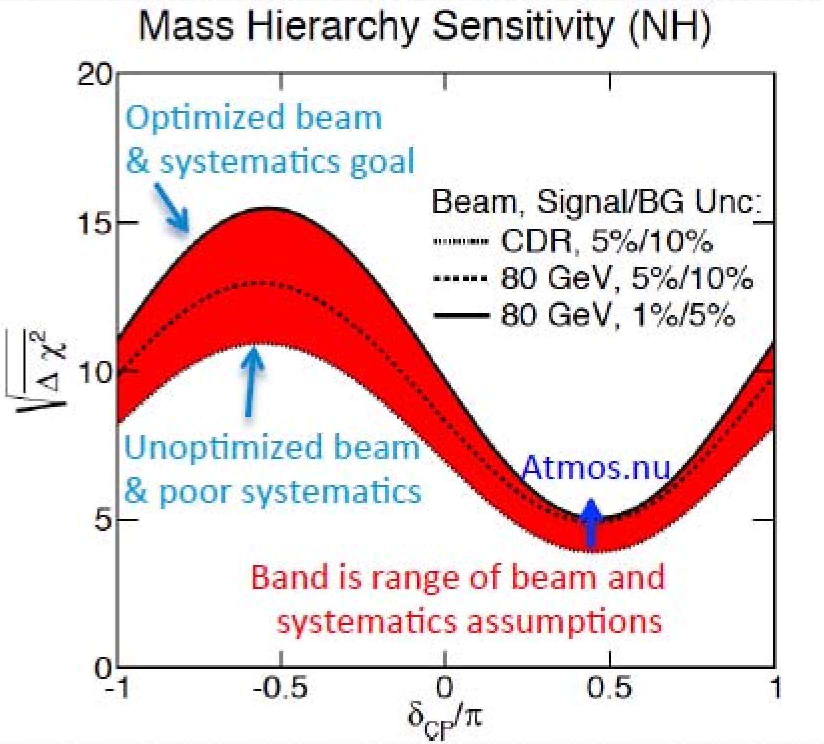
Goal: > 35 kt fiducial mass
Volume : 18m x 23m x 51m x2
Total Liquid Argon Mass: ~50,000 tones

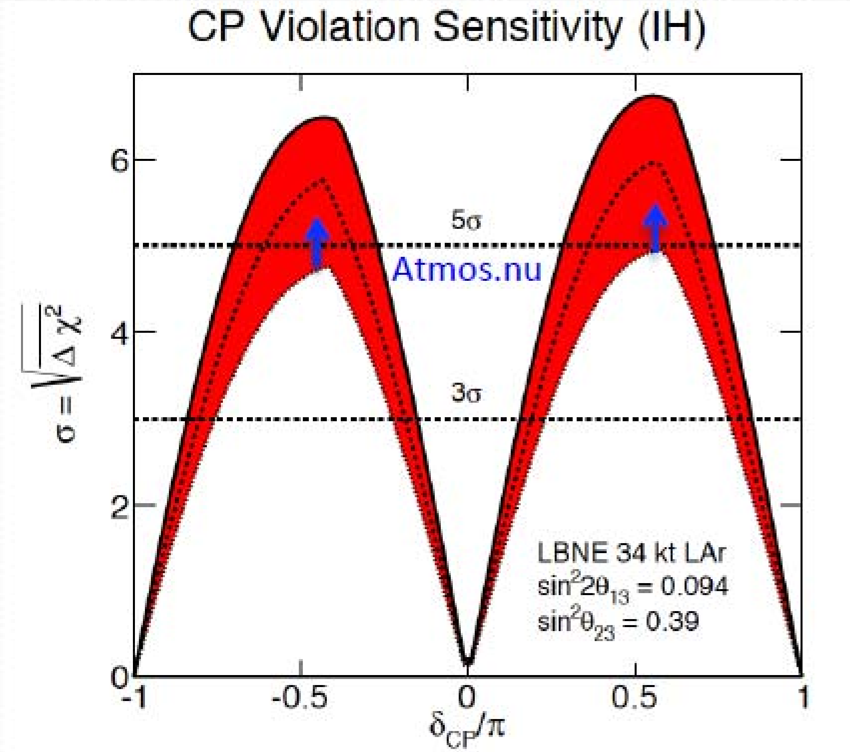


Mass Hierarchy and CP Violation Sensitivity

Exposure 245 kt.MW.yr

34 kt x 1.2 MW x (3ν+3$\bar{\nu}$) yr



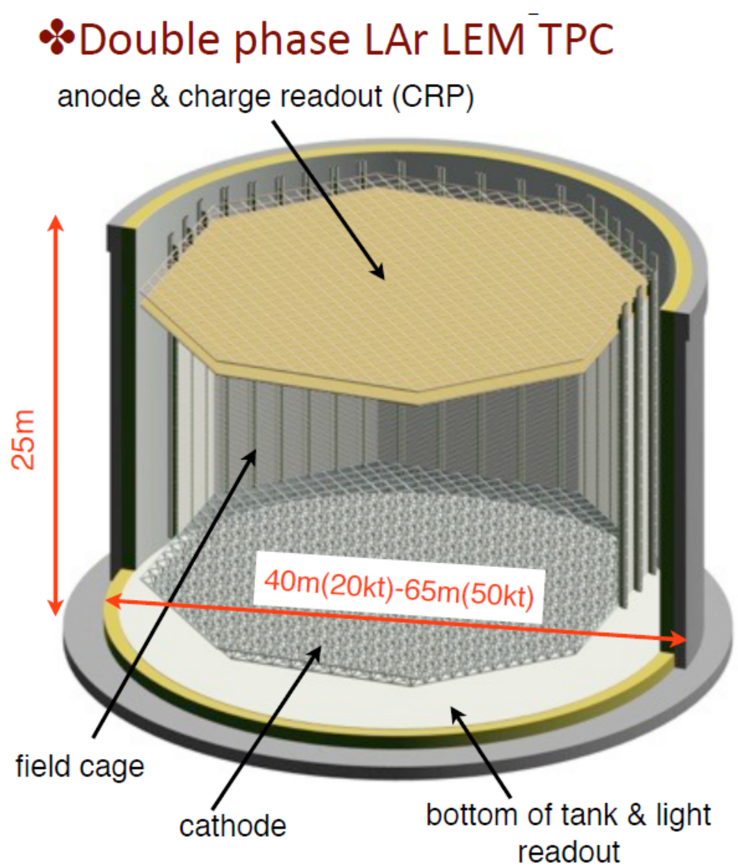


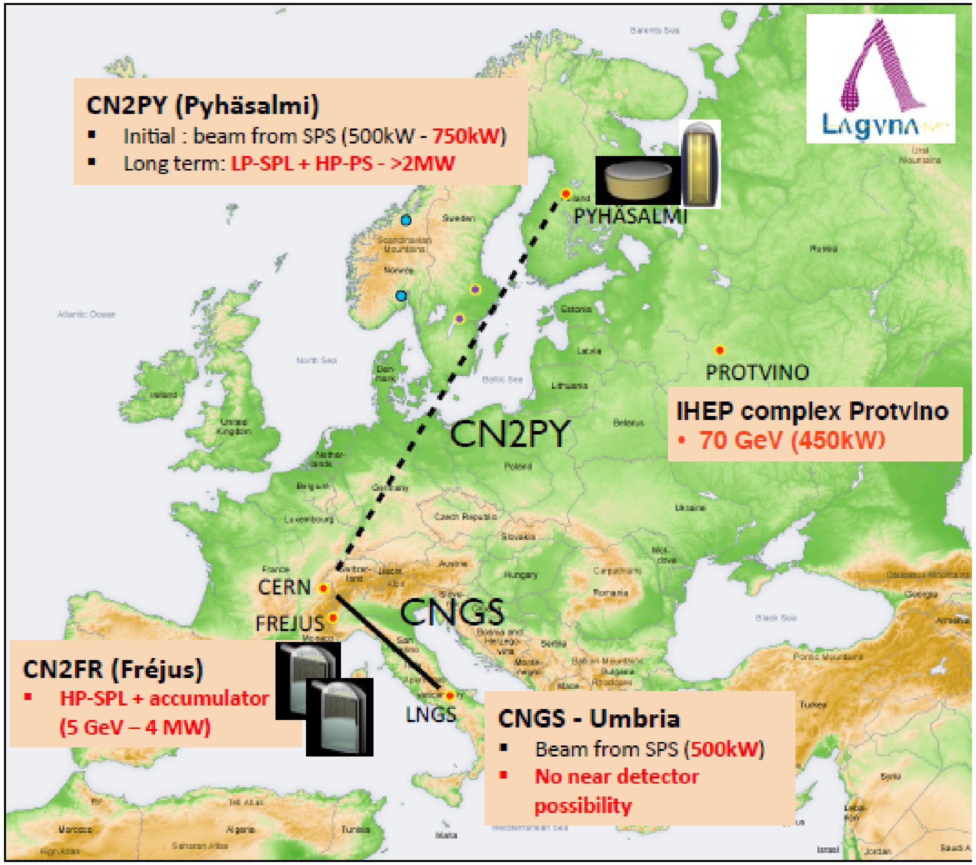
- Mass hierarchy is very well determined over most of δ_{CP} range
- CPV > 3σ over most of range and > 5σ for maximal CPV
- Atmospheric neutrinos in LBNE provide
    - an independent ~$\Delta\chi^2$=4 cross-check on MH
    - ~1σ increased CPV sensitivity if combined with beam

Robert J. Wilson, neutrino 2014

LAGUNA-LBNO
Large Apparatus for Grand Unification and Neutrino Astrophysics – Long Baseline Neutrino Oscillations

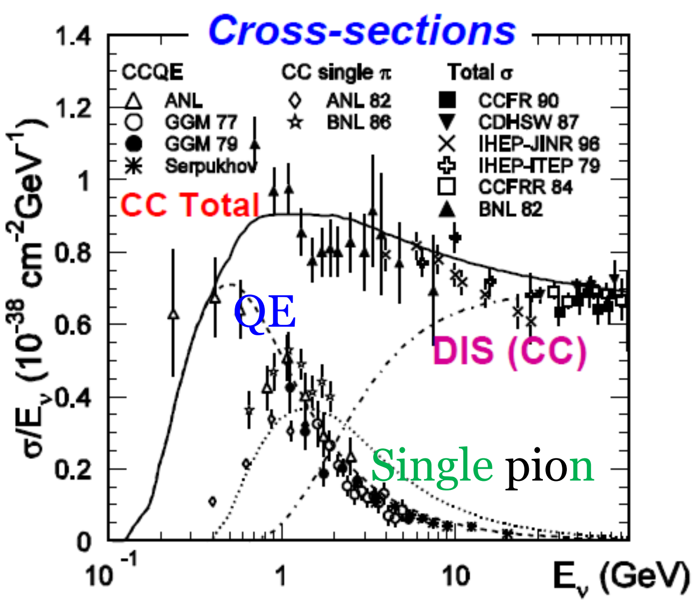
- Many options under discussion





- **Detector options:** 20, 50, 100 kton LAr; 50 kton LSc and 540 kton WCD

Water Cherenkov v.s. Liquid Argon -my personal view-



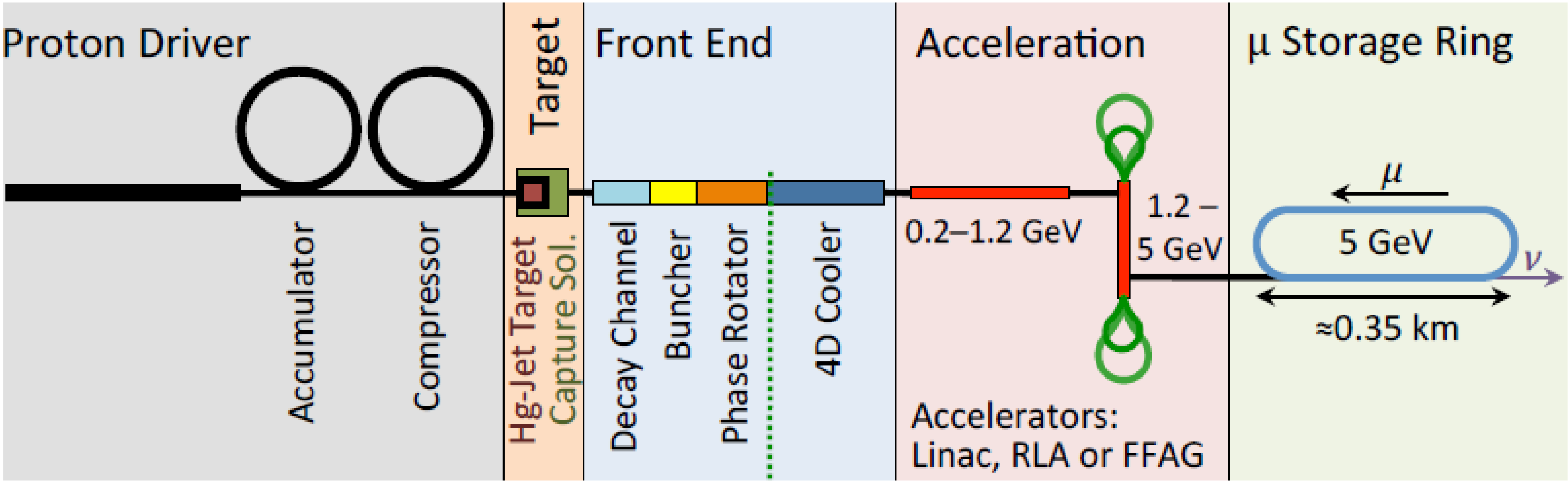
Water Cherenkov

- ✓ Technology well established
- ✓ Feasible to scale up (Water is easy to get)
- ✓ ν_e selection is good at sub GeV, but bad at >1GeV → ν_e and anti-ν_e run
- ✓ **good for O(100km) : need MH answer to maximize sensitivity**

Liquid Argon

- ✓ Technology need to be established. (600t is maximum so far)
- ✓ ν_e selection and energy measurement are supposed to be good. (Need proof) good for O(1000km) : → 1st & 2nd peaks method

Another direction-Neutrino Factory-



- Use $\overline{\nu_\mu}$ and ν_e from $\mu^+ \to e^+ + \overline{\nu_\mu} + \nu_e$ (and charge conjugate)
- $\overline{\nu_e} \to \overline{\nu_\mu}$ can be searched for with a magnetized detector.
- Clean and property well-known w.r.t ν's from hadron decay
- μ detection is cleaner (no γ or π^0 background)
- Difficulty
  - have to catch $p + A \to \pi^+ + X$ and cool

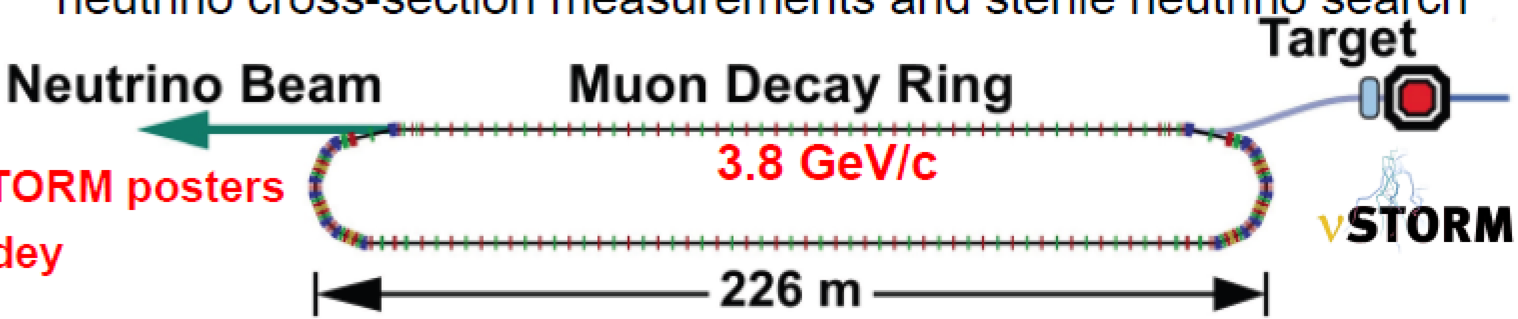
    $$\to \mu^+ + \nu_\mu$$

  - μ lifetime is 2.2μs (cτ=660m)

Stage 1: nuSTORM

- nuSTORM is entry-level neutrino factory from 3.8 GeV/c muons that can be realised now without any new technology
  - Pions captured in horn, transported and stochastically injected into ring
  - 52% of pions decay to muons before first turn: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - For 10^{20} POT, we expect flash of neutrinos from 8.6×10^{18} pion decays
  - Muons within momentum acceptance (3.8 GeV ± 20%) circulate in ring.
  - Muon lifetime is 27 orbits of decay
  - For 10^{20} POT, we expect 2.6×10^{17} μ^+ that decay: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

    New horn optimisation: 3.2×10^{17} μ^+ decays (poster Ao Liu, A Bross)
  - Hybrid beam from pion and muon decay: rich physics programme of neutrino cross-section measurements and sterile neutrino search



nuSTORM posters
D. Adey

arXiv:1308.6822

Conclusion

! Caution
Physics in Progress
Look Before Crossing