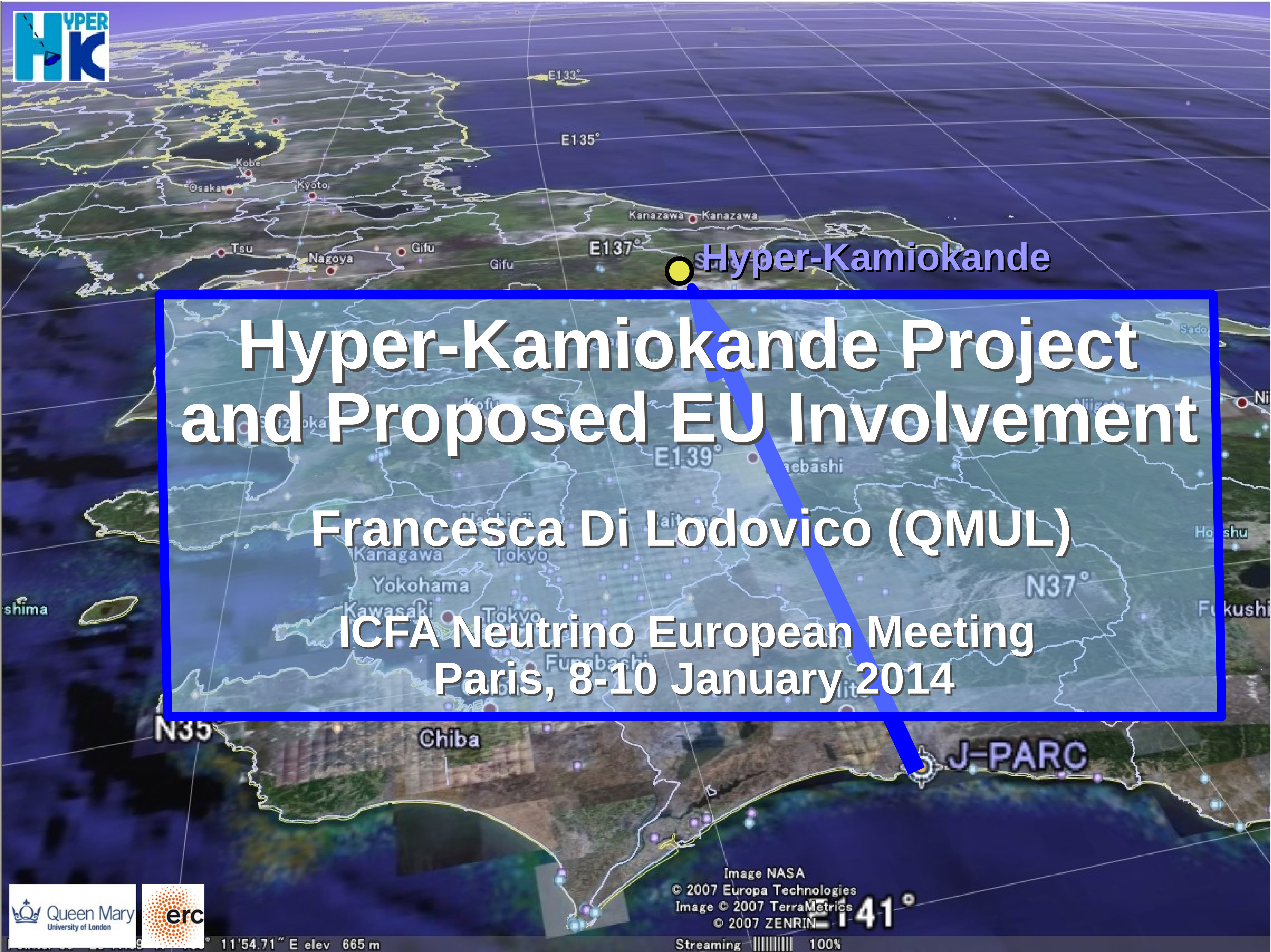
Hyper-Kamiokande Project and Proposed EU Involvement

Francesca Di Lodovico (QMUL)

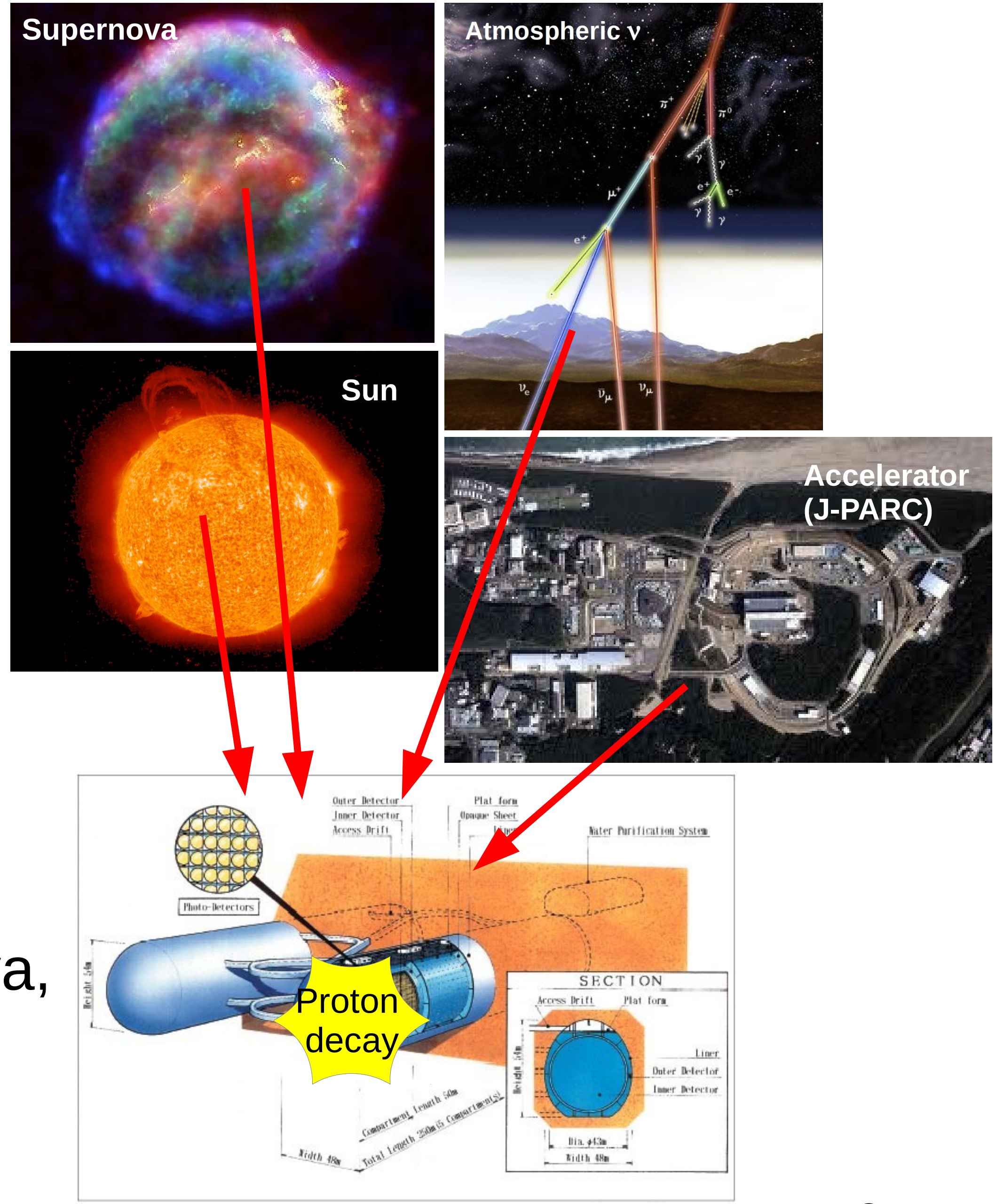
ICFA Neutrino European Meeting
Paris, 8-10 January 2014



The Hyper-Kamiokande Project

Multi-purpose neutrino experiment.
Wide-variety of scientific goals:

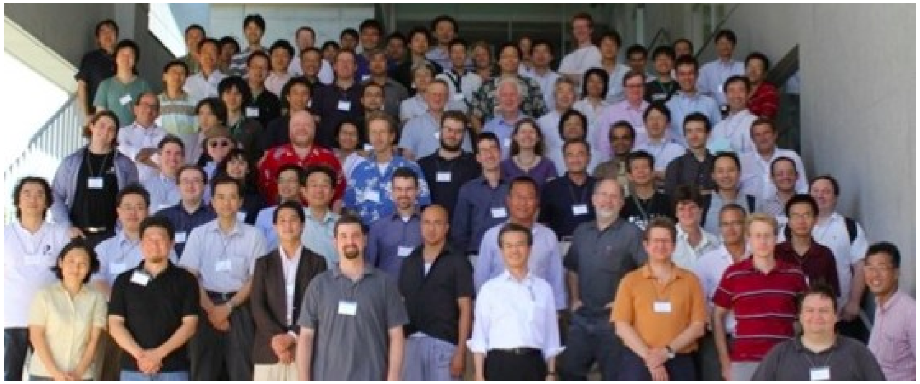
- Neutrino oscillations, using both:
  - Neutrino beam from J-PARC (expected beam > 1MW)
  - Atmospheric neutrinos
- Search for proton decay
- Solar neutrinos
- Astrophysical neutrinos (supernova, dark matter, solar flare, ...)
- Neutrino geophysics



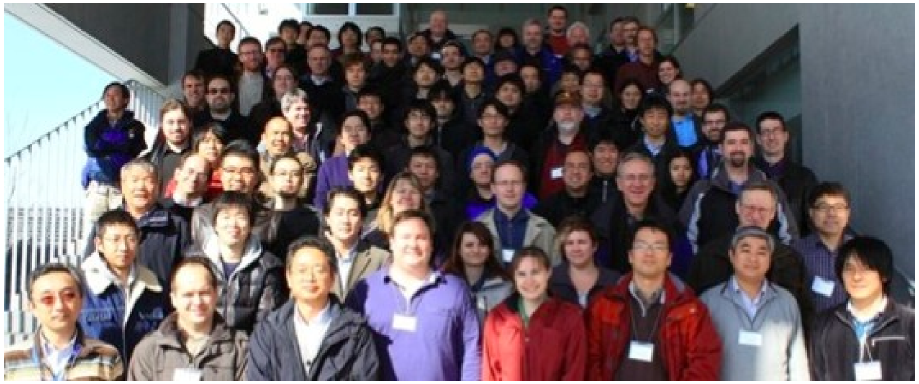
The Hyper-Kamiokande Project

- Three International Open Meetings (2012-2013) @ IPMU, Japan.
- Formed international working groups.

August 21-23, 2012
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=7



August 14-15, 2012
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=10



June 21-22, 2012
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=23

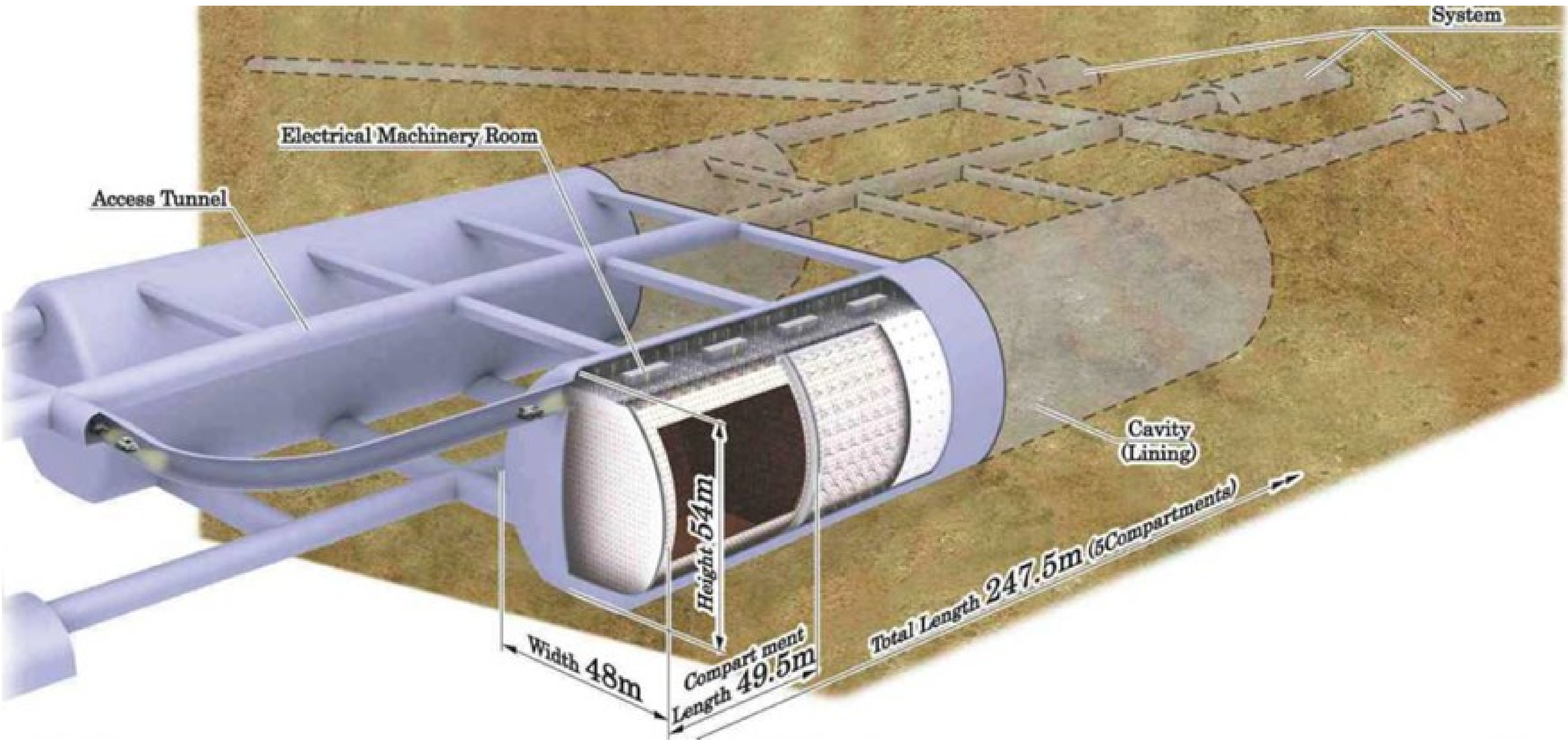
Next meeting:
27-28 January 2014,
Kavli, IPMU.

The Hyper-Kamiokande Project

- First European Open Meeting (18 Dec. 2013, London, QMUL): http://indico.cern.ch/e/HKEUOpenMeeting
- More than 40 participants from 9 Countries.

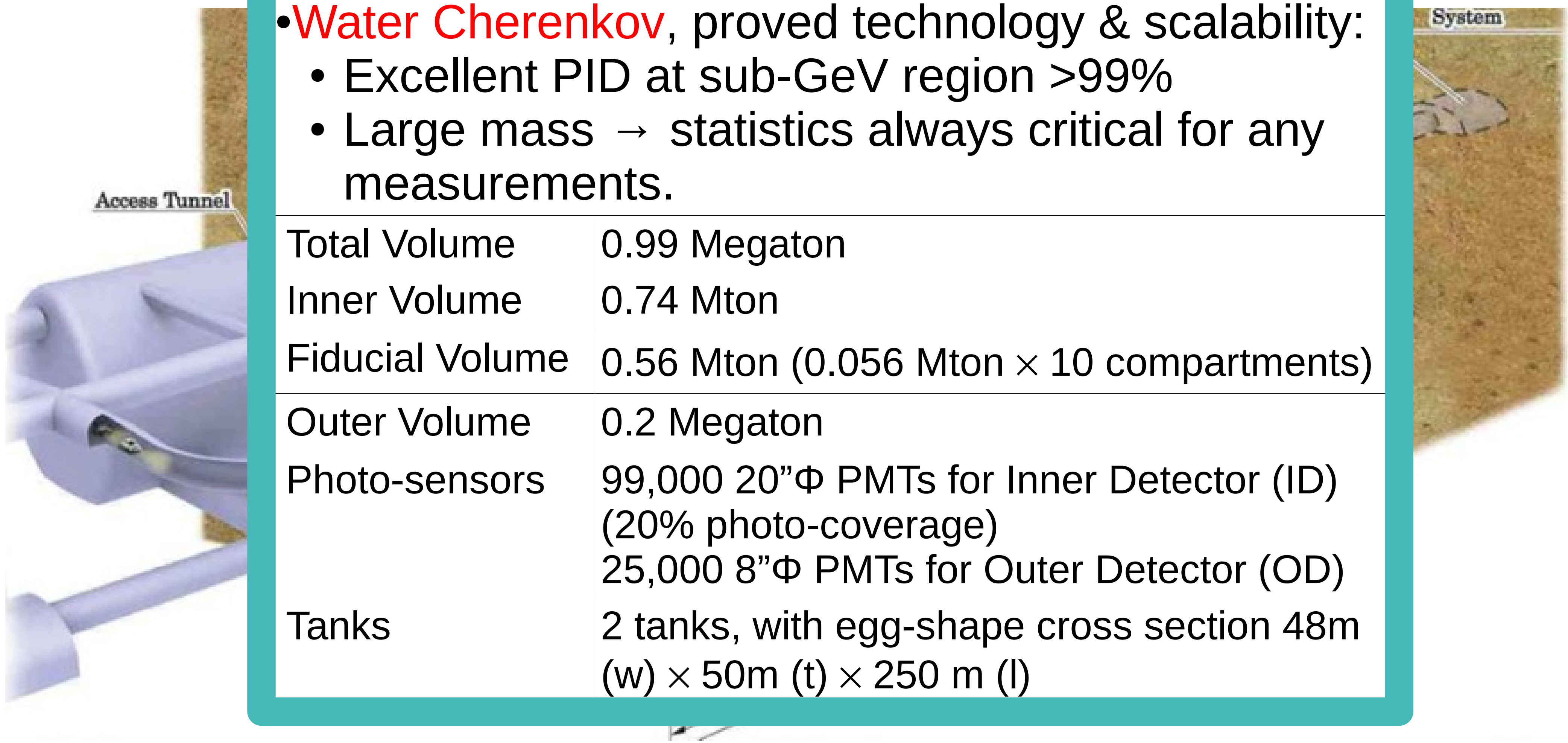
- Discussed common issues. One more open meeting this year.
- Created mailing list <hyper-kamiokande-eu@qmul.ac.uk>

Hyper-Kamiokande Overview



25 x Super-Kamiokande

Hyper-Kamiokande Overview

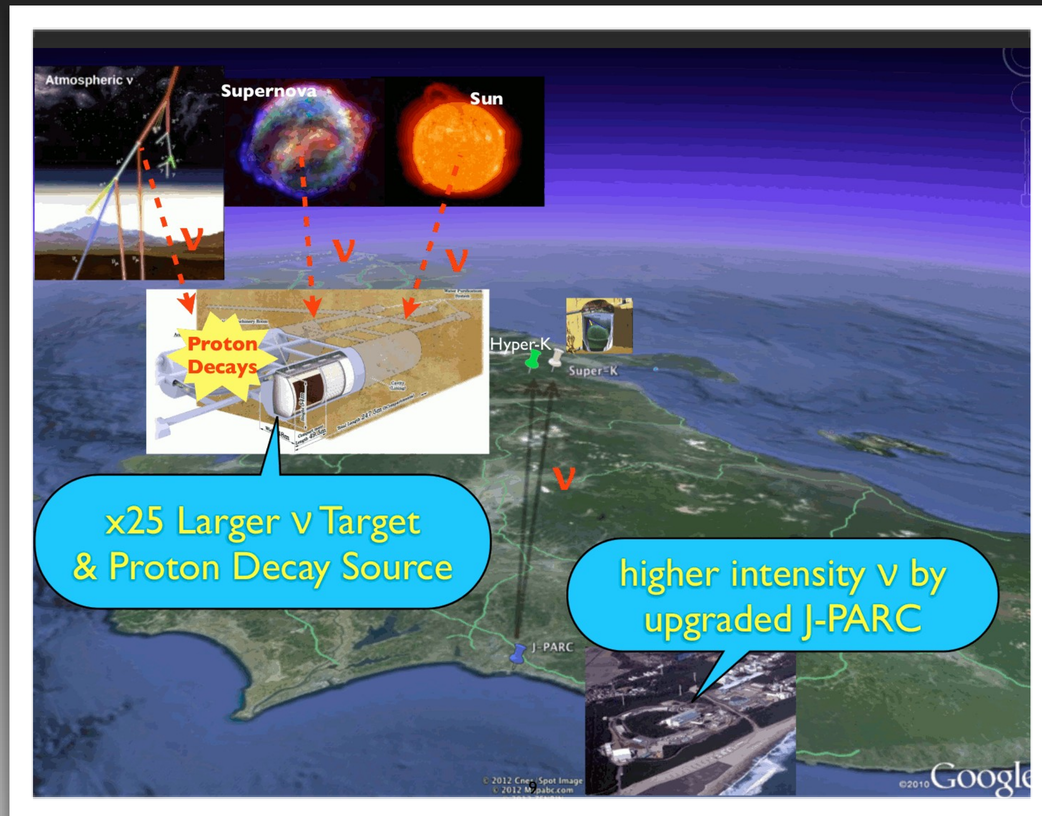


- Water Cherenkov, proved technology & scalability:
  - Excellent PID at sub-GeV region >99%
  - Large mass → statistics always critical for any measurements.

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20”Φ PMTs for Inner Detector (ID) (20% photo-coverage) 25,000 8”Φ PMTs for Outer Detector (OD)
Tanks	2 tanks, with egg-shape cross section 48m (w) × 50m (t) × 250 m (l)

25 x Super-Kamiokande

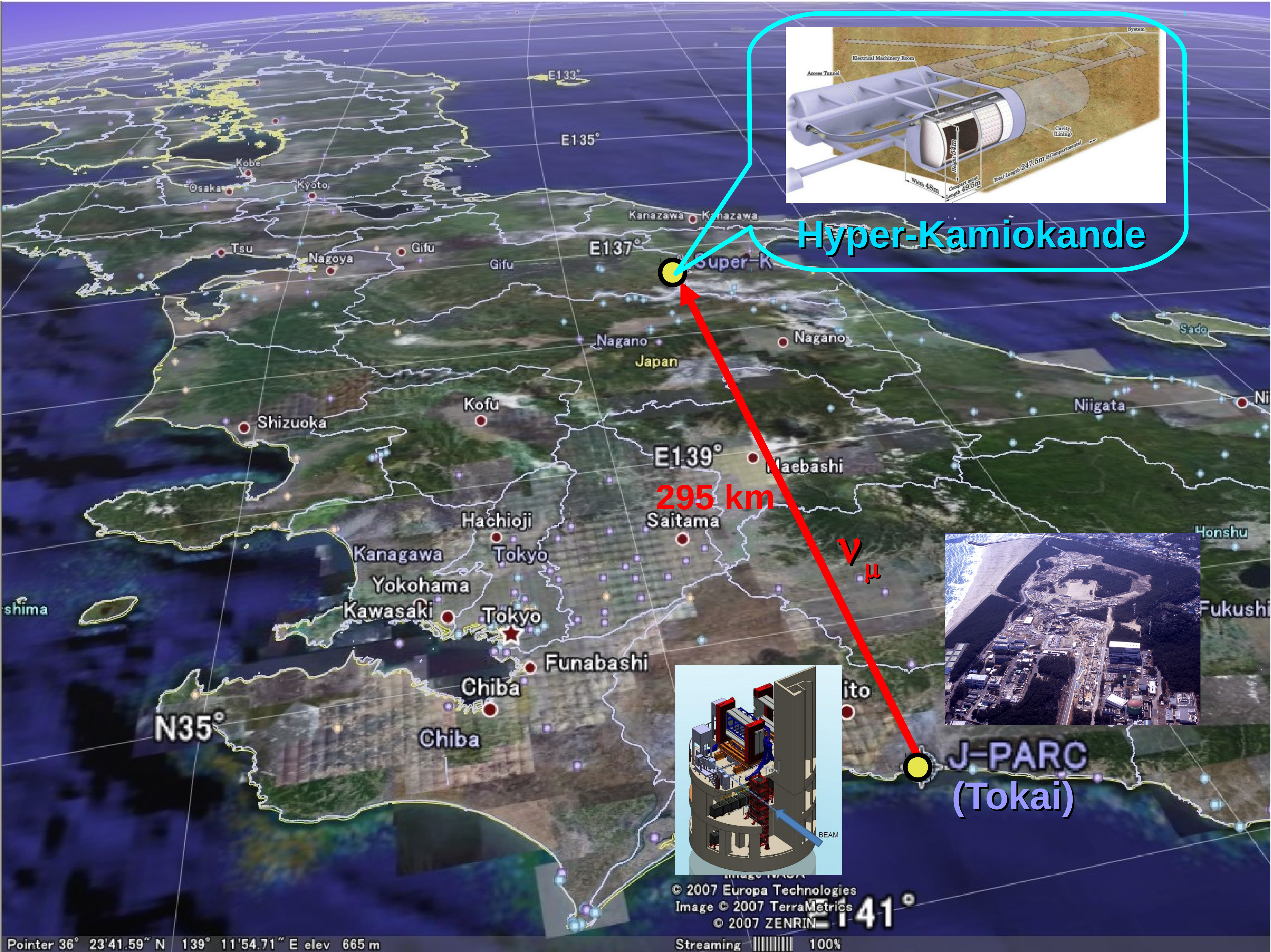
Physics Topics



CAVEAT (Letter of Intent, Hyper-K WG arXiv:1109.3262 [hep-ex])

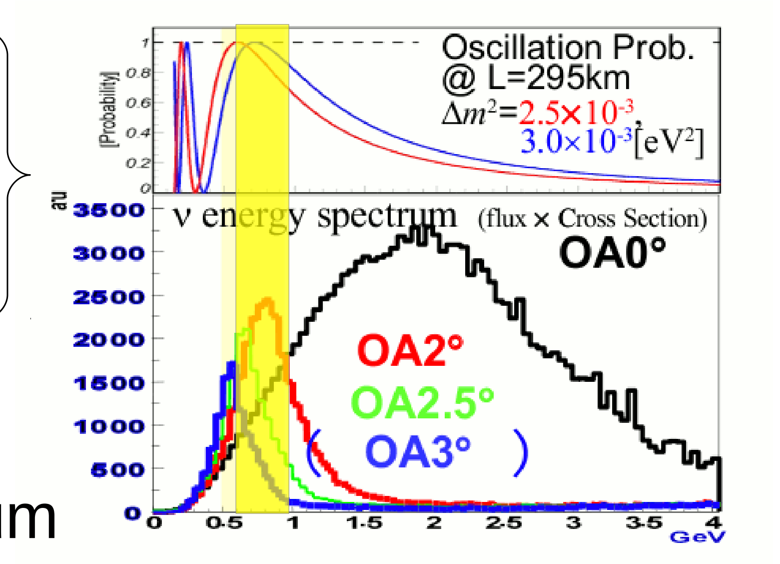
- 5% overall systematic error
- 3y:7y ν-beam:ν-beam sharing
- No fiTQun used (⇒ higher π^0 background)
- No new near detector

<u>New updated results expected by Summer 2014 (LoI to J-PARC).</u>

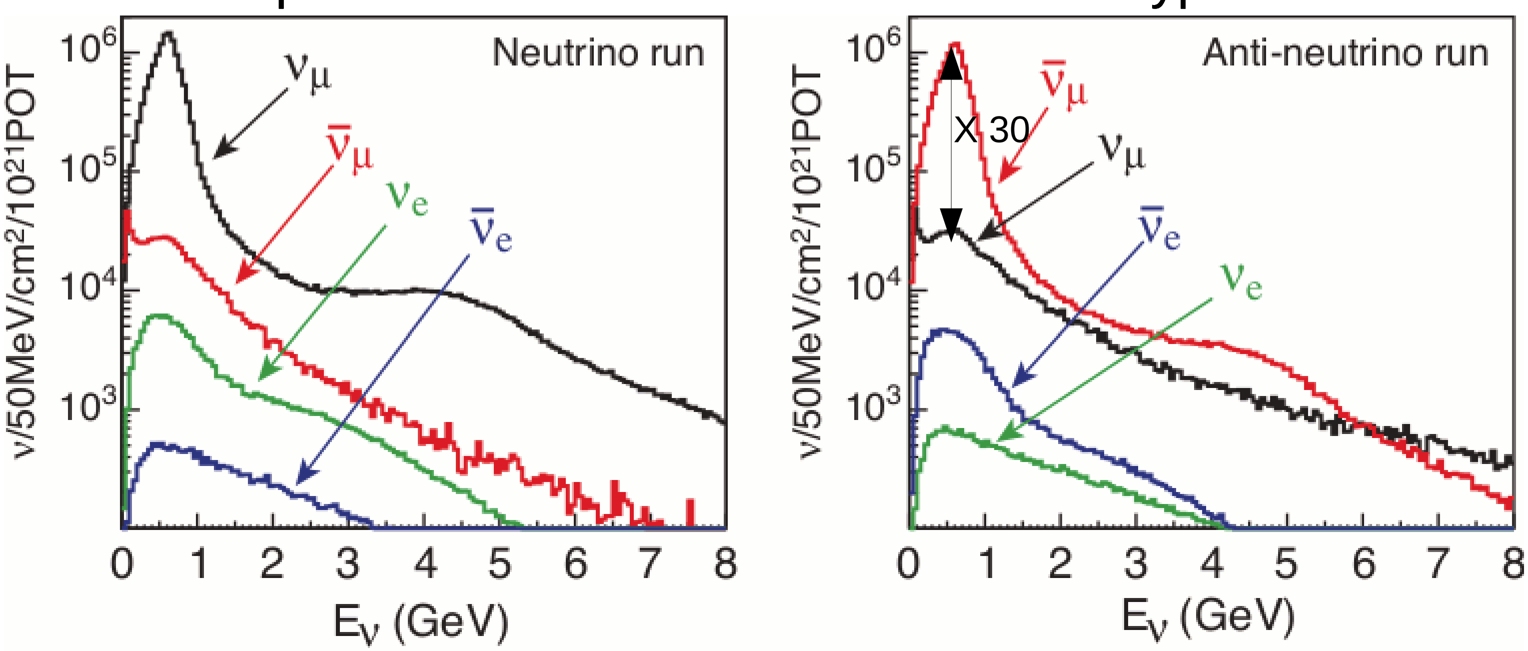

Hyper-Kamiokande
Super-K
295 km
ν μ
J-PARC
(Tokai)
BEAM
E133°
E135°
E137°
E139°
E141°
N35°
Kobe
Osaka
Kyoto
Kanazawa
Tsu
Nagoya
Gifu
Nagano
Japan
Sado
Niigata
Kofu
Shizuoka
Maebashi
Hachioji
Saitama
Honshu
Kanagawa
Tokyo
Yokohama
Kawasaki
Funabashi
Chiba
Fukushi
© 2007 Europa Technologies
Image © 2007 TerraMetrics
© 2007 ZENRIN
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%

Tokai-2-Hyper-Kamiokande

- Natural extension of the technique being proven by the success of T2K:
  - Off-axis narrow band beam: suppress background from high energy component (ν_τ negligible)
  - E_ν~0.6 GeV: peaked at oscillation maximum



Expected unoscillated neutrino flux at Hyper-K

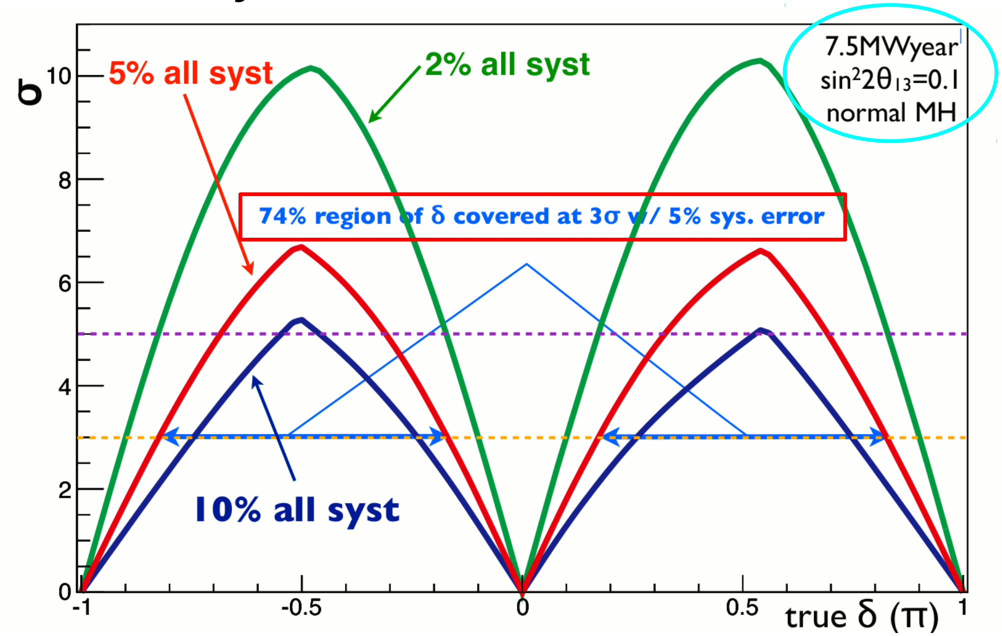


Beam sharing between neutrinos and anti-neutrinos

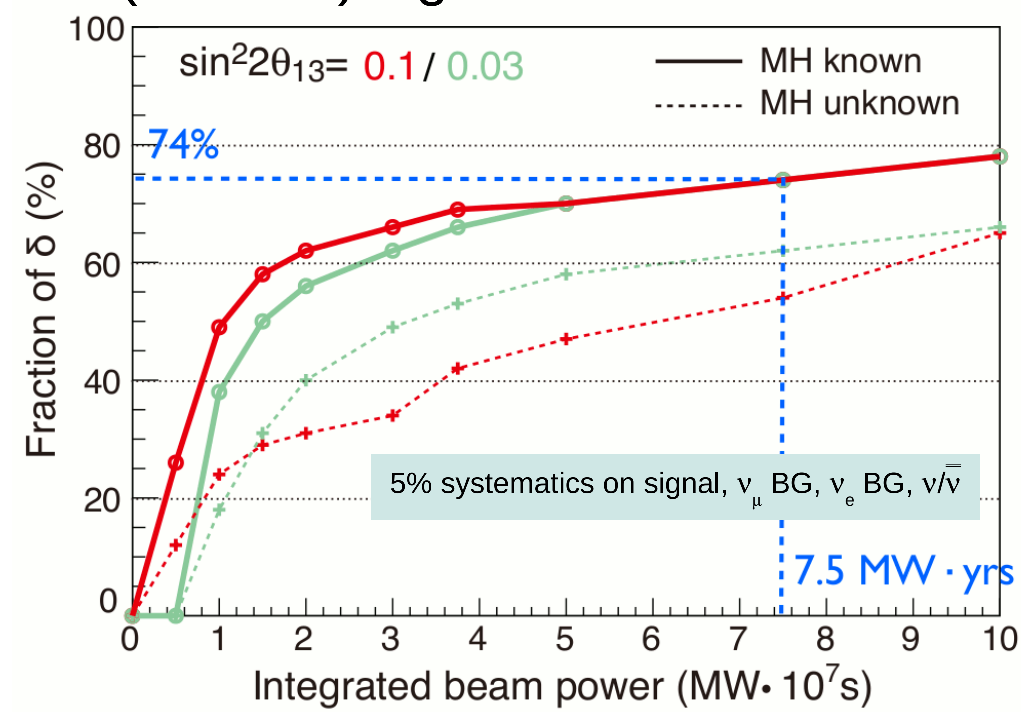
ν-mode: $\bar{\nu}$-mode
3y : 7y

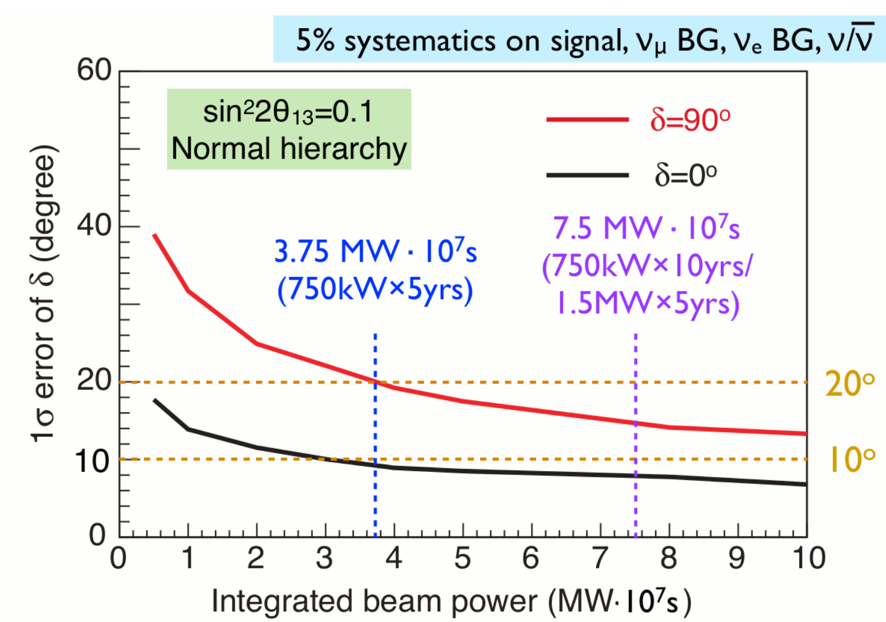
Expected Sensitivity to CP Violation

CPV discovery sensitivity w/ mass hierarchy known.



Fractional region of δ(%) for which the CPV (sin δ ≠0) significance is > 3σ





δ coverage:

CPV > 3σ (5σ) for 74%(55%) of δ

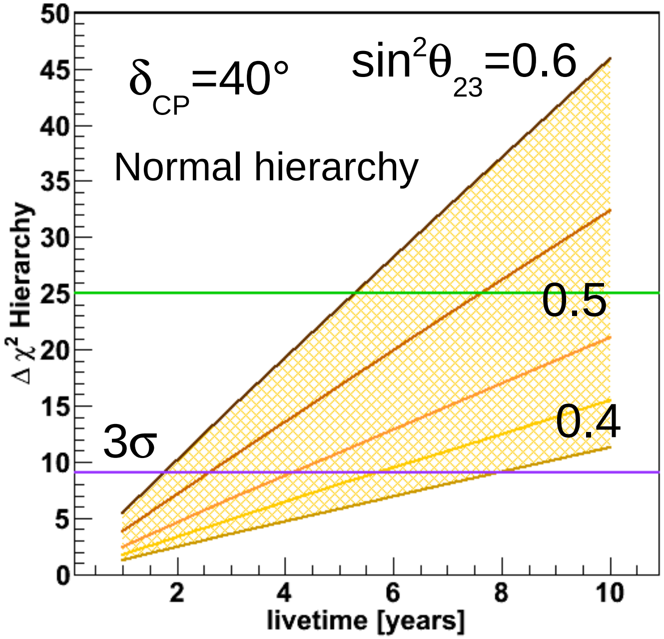
1σ uncertainty of δ as a function of the beam power:

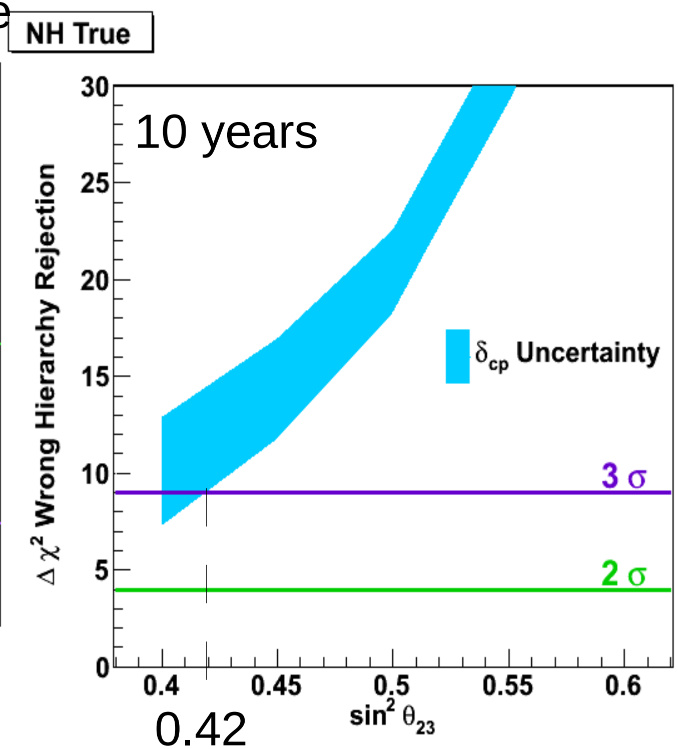
< 20°(10°) for δ = 90°(0°)

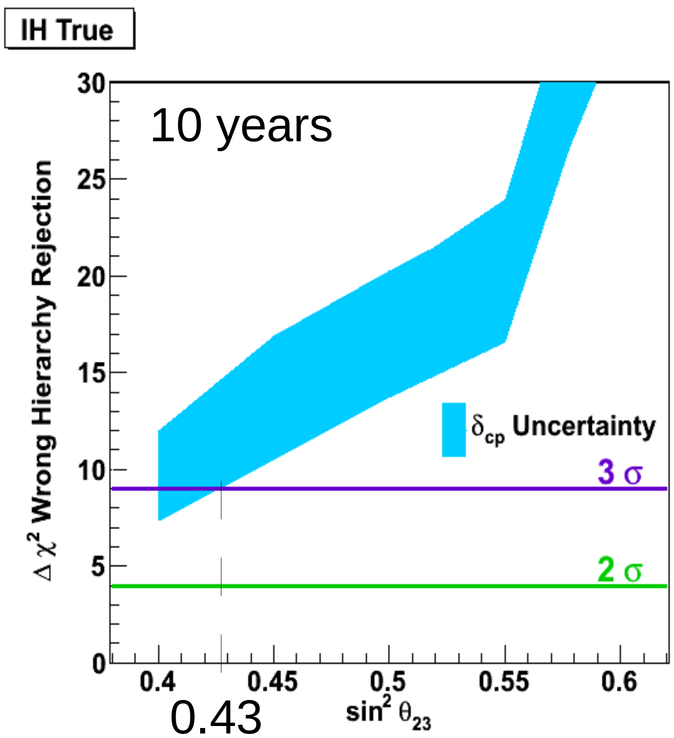
Modest dependence on θ_{13}

Mass Hierarchy Sensitivity

Significance for MH determination
as a function of Hyper-K lifetime



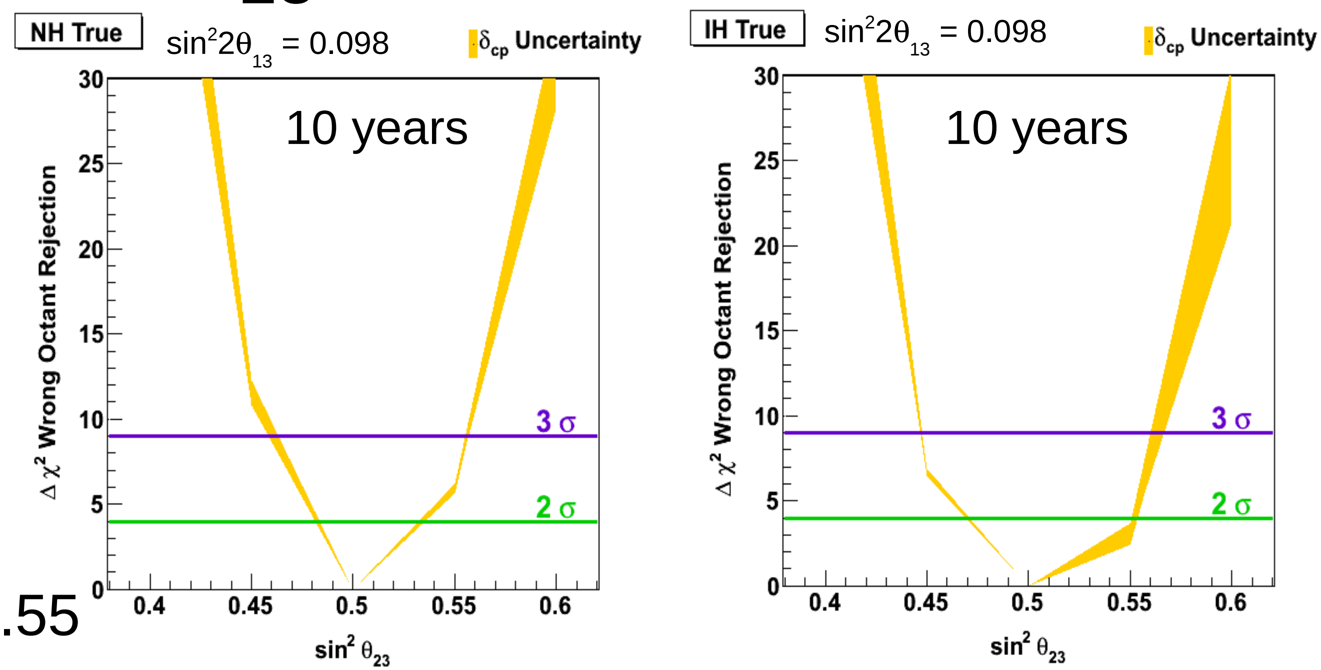




- Sensitivity mainly depends on θ_{23}, δ and slightly on the MH itself.
- 3σ mass hierarchy determination for $\sin^2\theta_{23}$ > 0.42 (0.43) for normal (inverted) hierarchy for 10y data taking.
- Caveat: the $\Delta\chi^2$ method to determine the number of σ's is used.

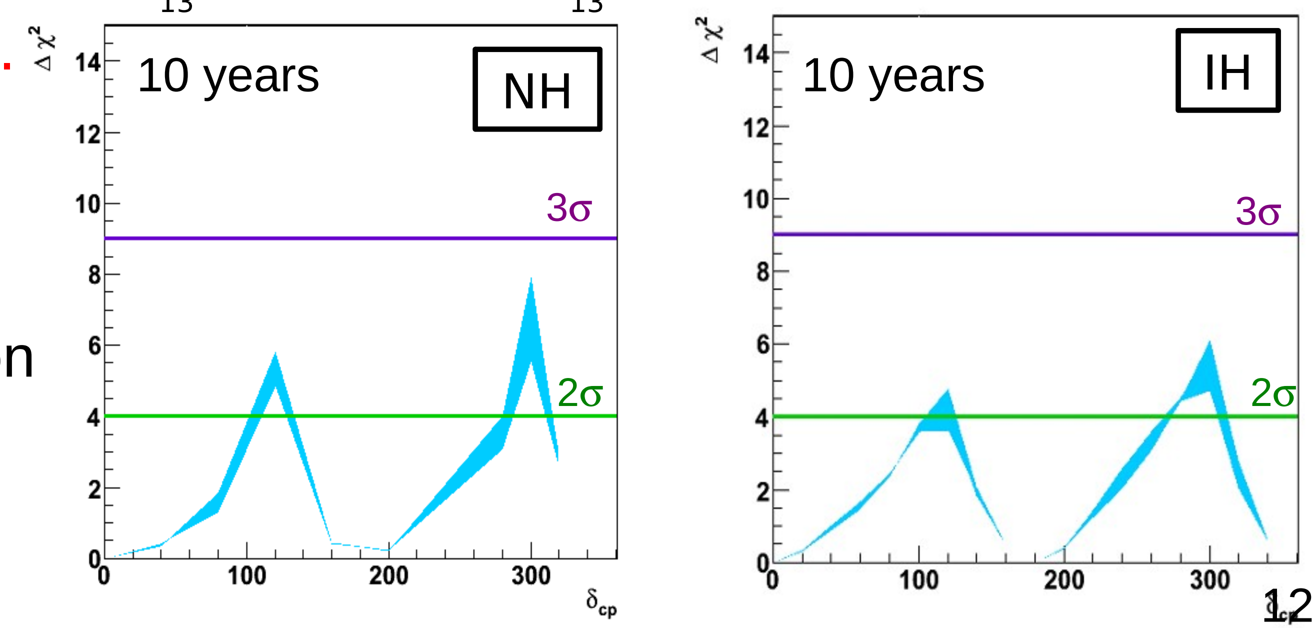
Sensitivity for θ_{23} Octant and CPV

- θ_{23} octant sensitivity.
- Thickness of the band corresponds to the uncertainty from δ_{CP}.
- We can expect discrimination between $\sin^2\theta_{23}$ 0.4-0.6, w/ limited discrimination b/w 0.45-0.55

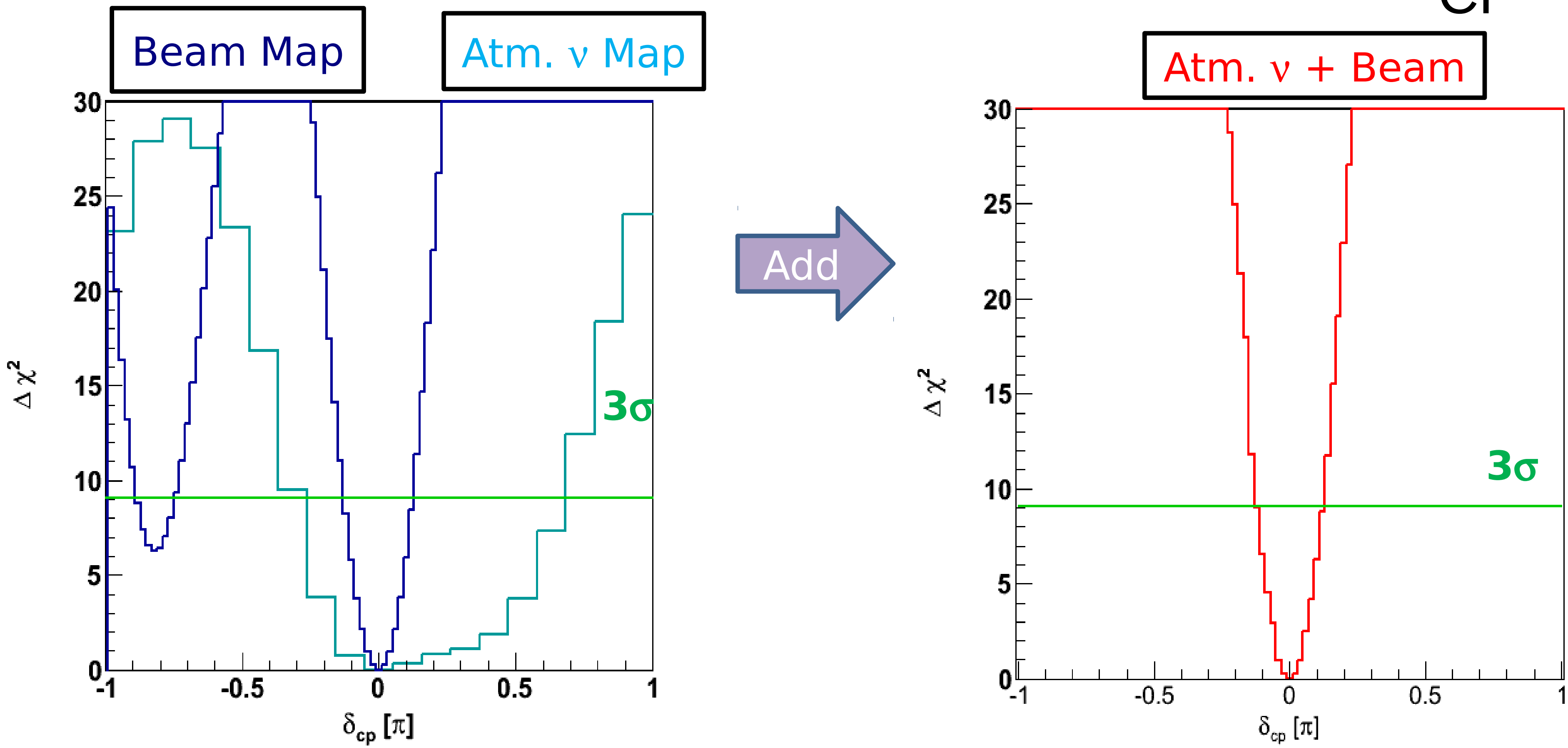


θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.099$

- Excluded 3σ δ_{CP} fraction.
- Thickness of the band corresponds to the uncertainty from $\sin^2 2\theta_{23}$
- Sensitivity to CP-violation is limited under both hierarchy assumptions.

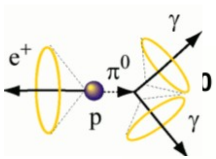


Beam + Atmospheric ν: Allowed δ_{CP}

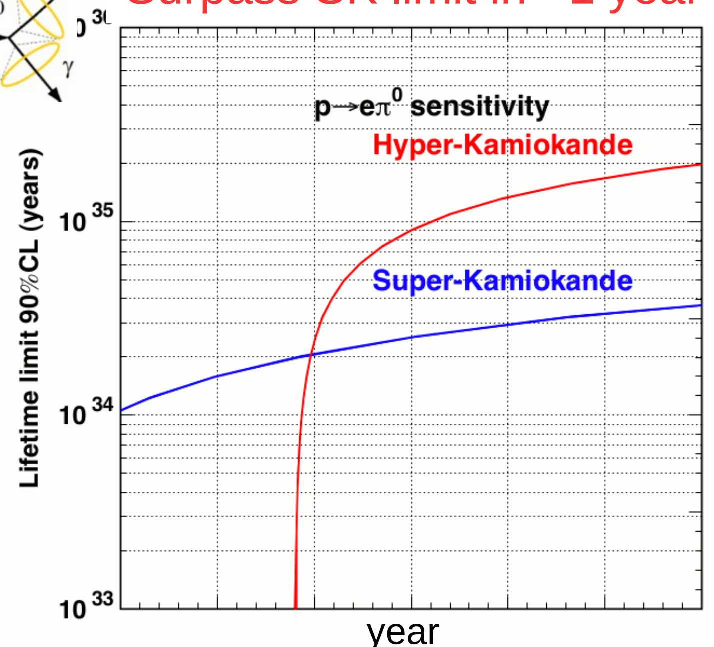


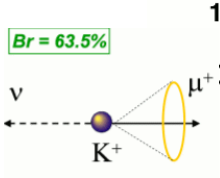
- Hierarchy is unknown, but NH is true.
- True δ_{CP} = 0.0; $\sin^2 2\theta_{13}$ = 0.10; Maximal mixing $\sin^2 2\theta_{23}$ = 1.0
- Degenerate solution exists at 3σ in the beam only case.

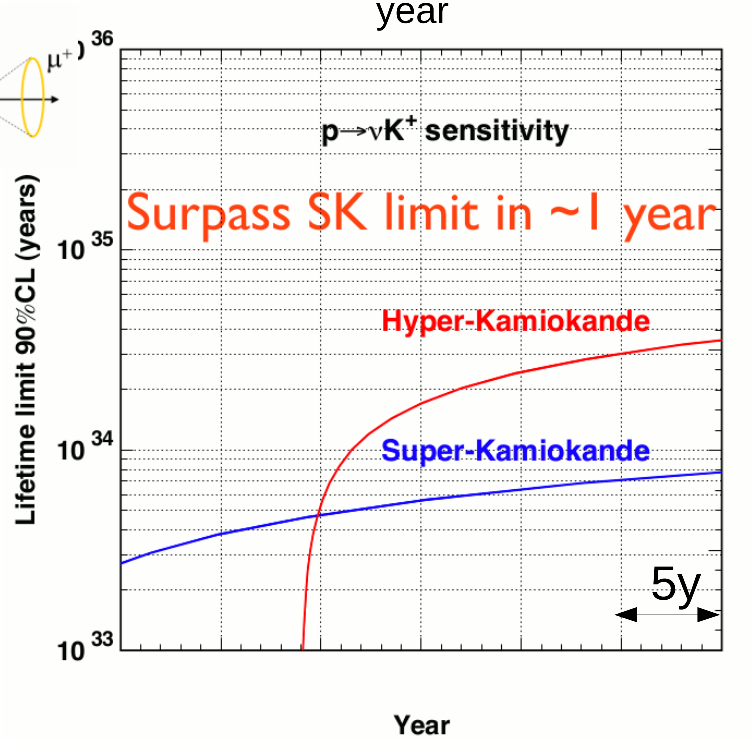
Proton Decay Sensitivities



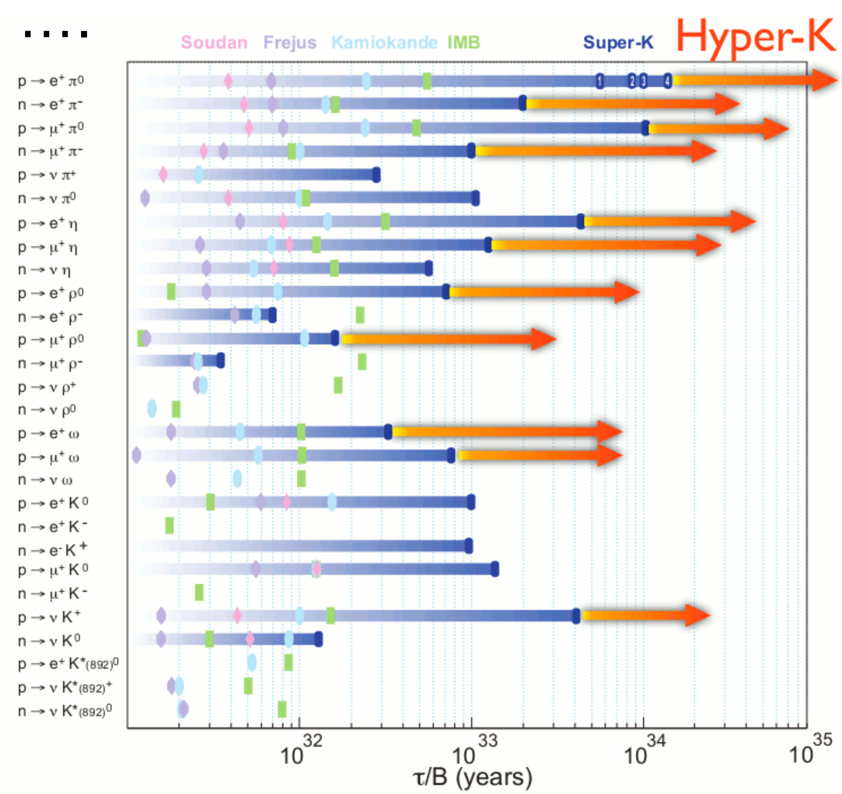
Surpass SK limit in ~1 year







- 10 times better sensitivity than Super-K
- Hyper-K surpasses SK limits in ~1y
  - $p \to e\pi^0$: 1.3×10^{35} y at 90%CL
  - $p \to \nu K^+$: 2.5×10^{34} y at 90%CL
  - Many other modes:
    - $P(n \to e,\mu) + (\pi,\rho,\omega,\eta)$; 10^{14}-10^{35}
    - K^0 modes
    - $\nu\pi^0$, $\nu\pi^+$
    - ….

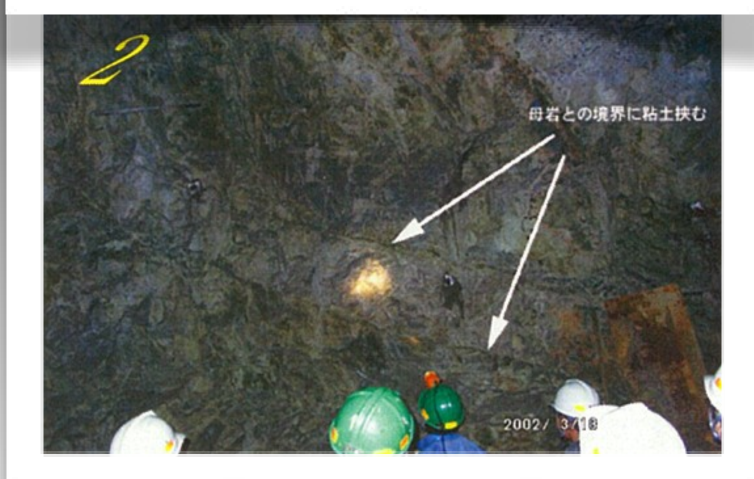


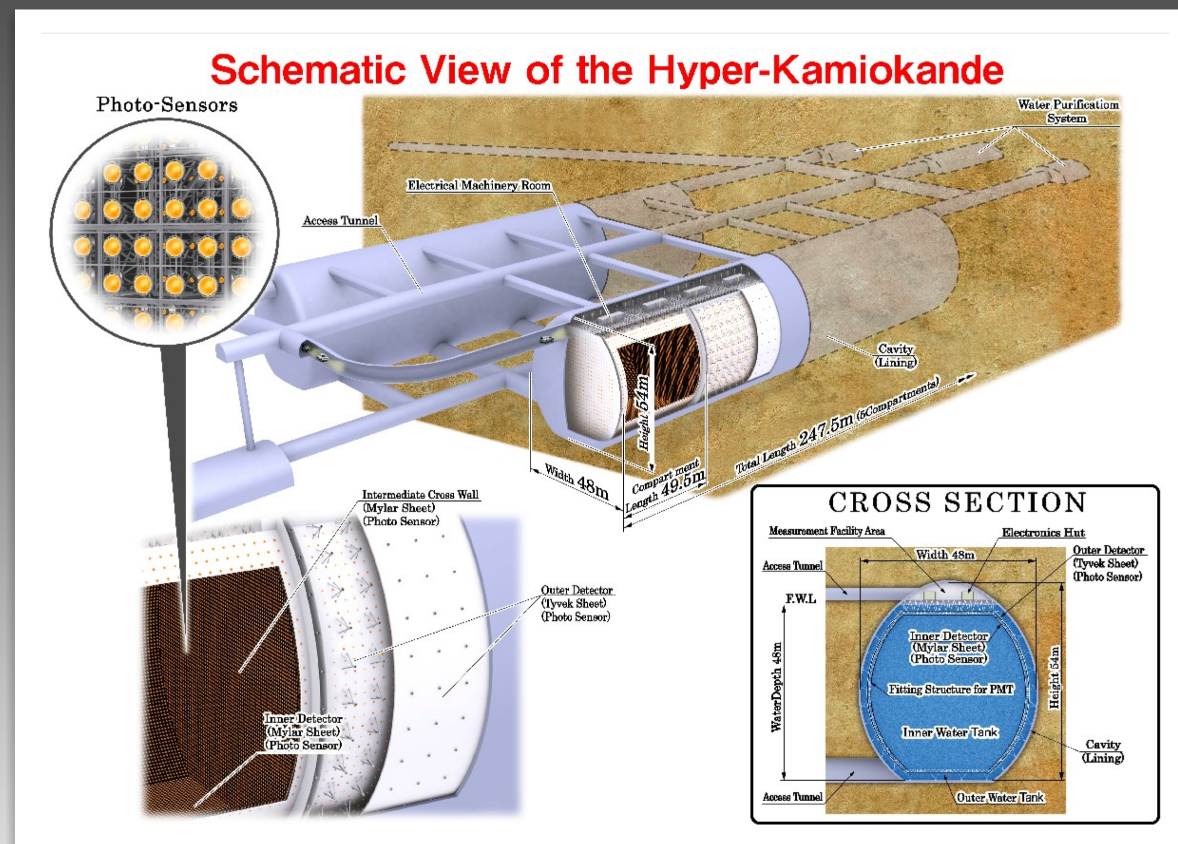
“Other” Physics Topics at Hyper-K

More physics topics than the ones described can be investigated by Hyper-Kamiokande:

- Solar Neutrinos: 200 ν’s / day from Sun → day/night asymmetry of the solar neutrinos flux can be precisely measured at HK.
- Solar flares can be discovered at Hyper-K (important information about particle acceleration at work in solar flares)
- Astrophysical neutrinos:
  - 200k ν’s from Supernova at Galactic center (10kpc) → time variation & energy can be measured with high statistics
- Indirect dark matter search, excellent capabilities at low mass region.
- Neutrino geophysics: neutrino radiography w/ atmospheric neutrinos for surveying the internal structure of the Earth.

Cavern & Detector





Candidate Site: Tochibora Mine

- Located under “Nijugo-yama” (Mt. 25), ~8km south from Super-K
- Identical baseline (295km) and off-axis angle (2.5º) to T2K
- Overburden ~650m (~1755 m.w.e.)

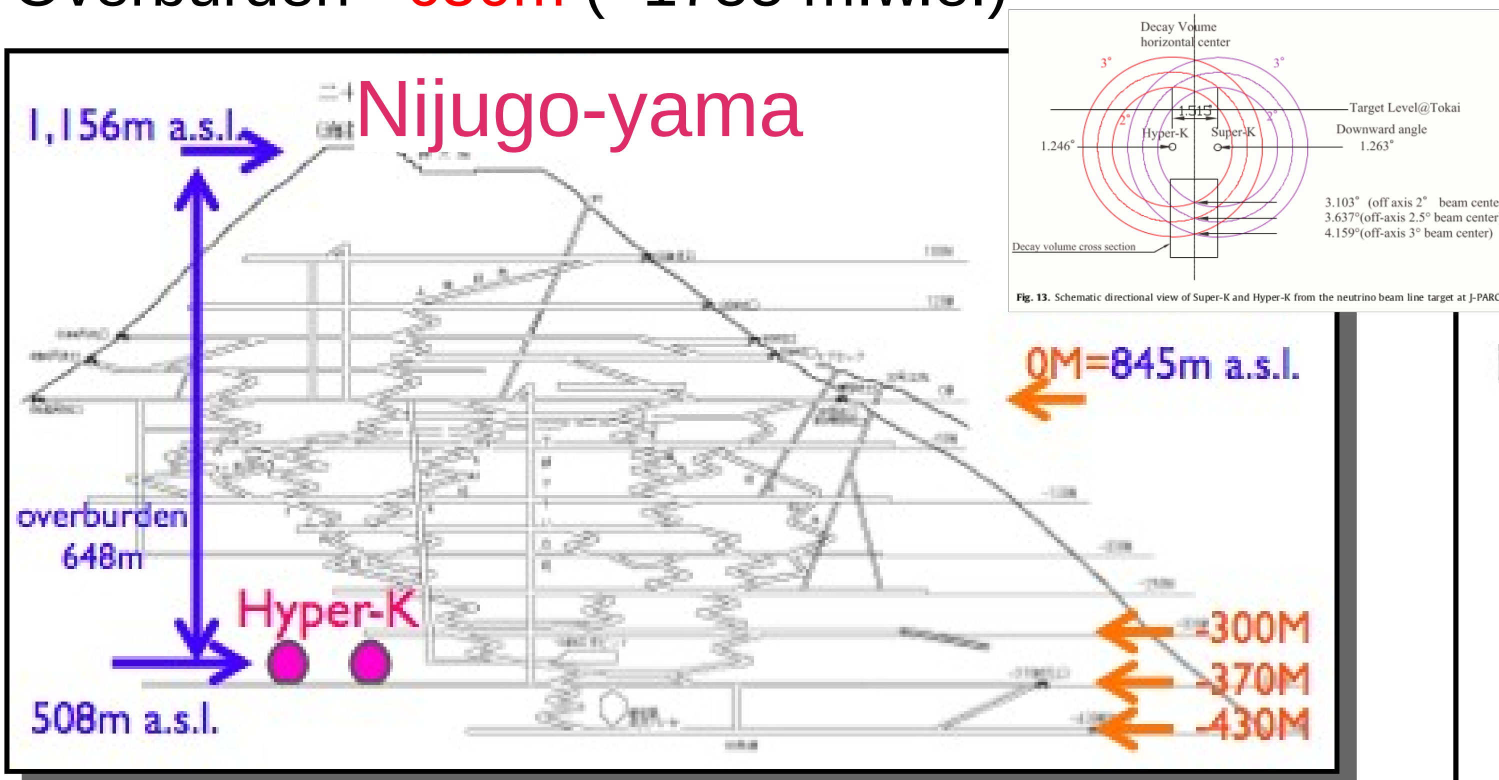
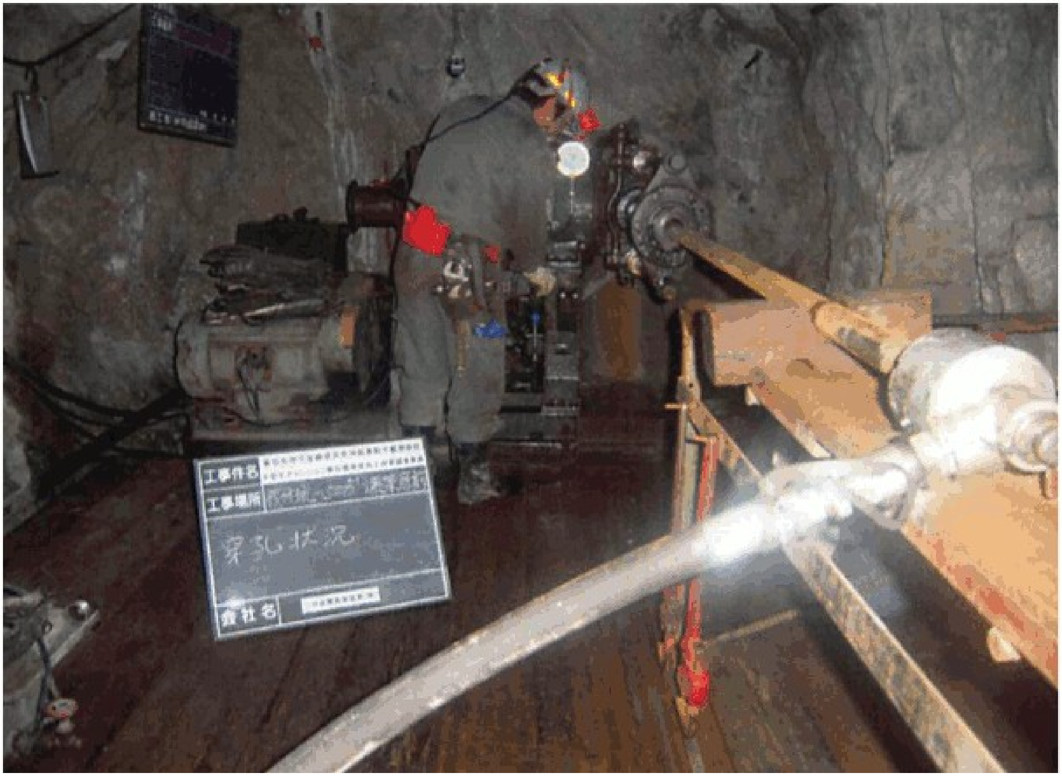


Fig. 13. Schematic directional view of Super-K and Hyper-K from the neutrino beam line target at J-PARC.

- The candidate site vicinity used for mining. Many existing tunnels and shafts.
- Historically many surveys have been done in wide area and at several levels/depths, especially mapping the location of faults.
- Confirmed that he HK cavern can be constructed w/ existing techniques.

Geological Survey at Mozumi Mine

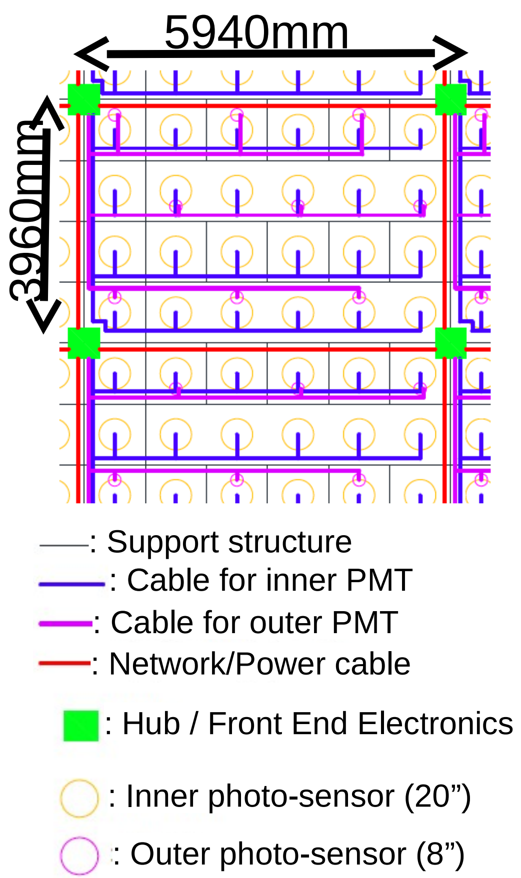
- Geological survey at the Mozumi mine, already used for Super-K, recently started, to have a deeper cavern (~800m).
- First rock mass characterization has been done: rock quality at Mozumi-site is comparable with Tochibora-site.
- More tests under way to complete the geological survey.
- Note: Tochibura and Mozumi are on the opposite sides of the beam, but same off-axis angle (2.5°).



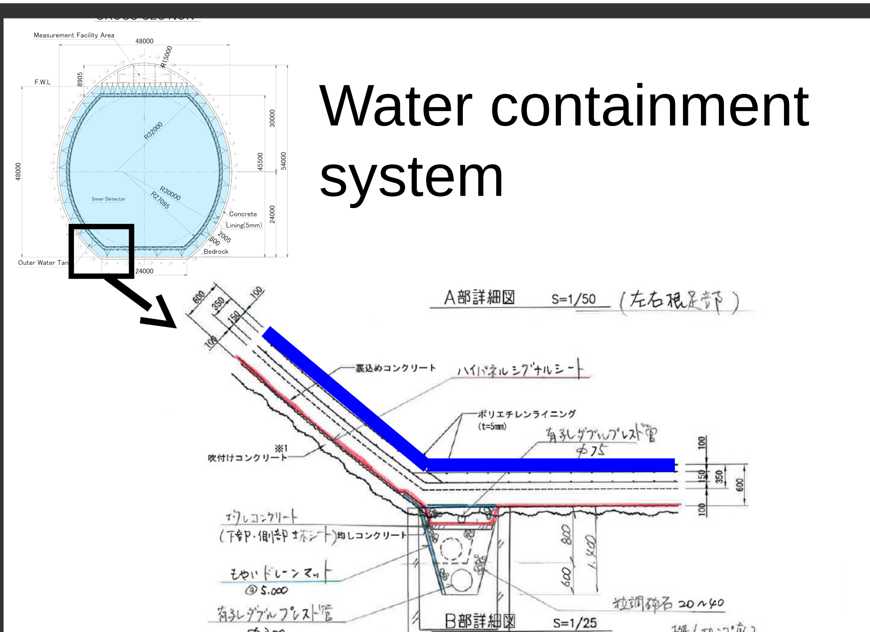
Design Work...

- All major part of HK tank has been designed, water containment system, photosensors support, layout of water pipes, front-end electronics, cables, calibration holes, plug manholes, ... etc.

Electronics & cable layout



Water containment system



Water piping layout

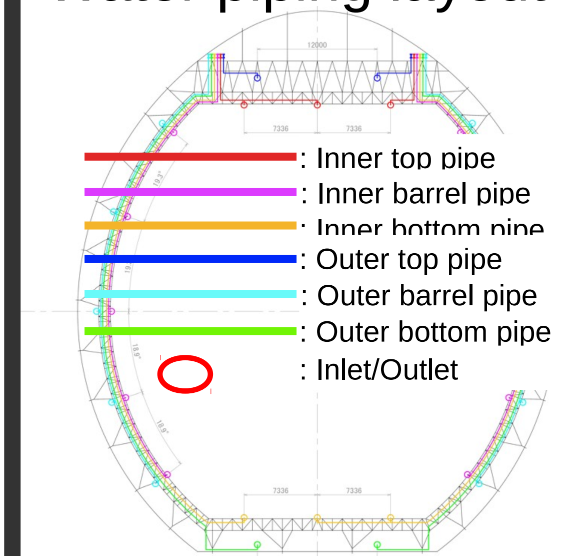
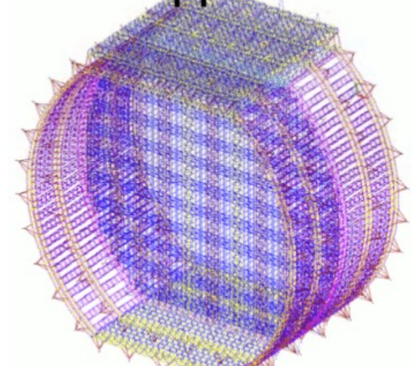
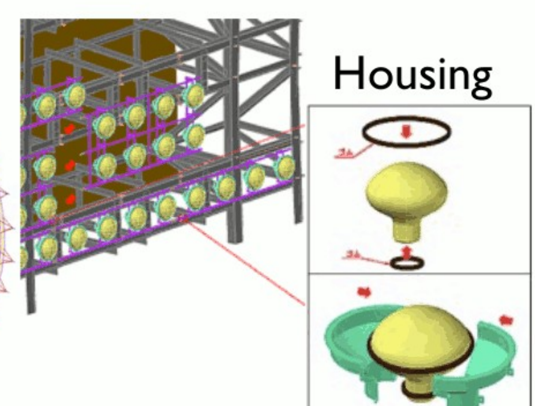


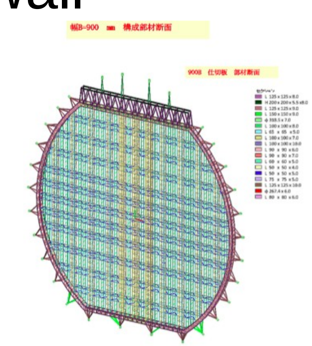
Photo-sensor support



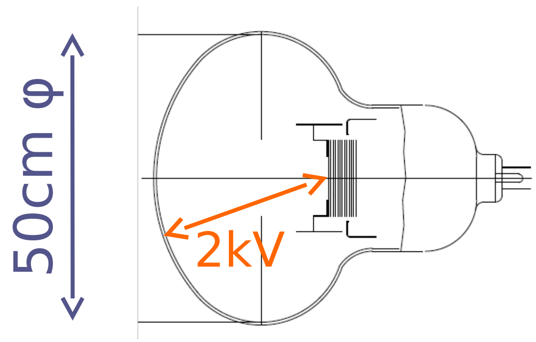
Mounting Photo-sensor

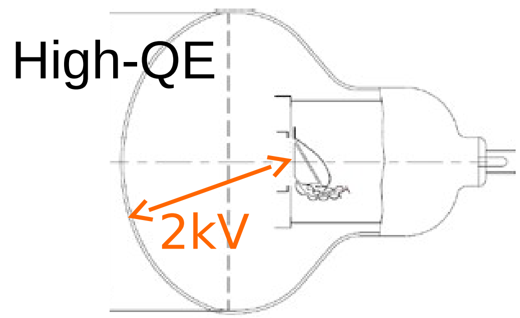


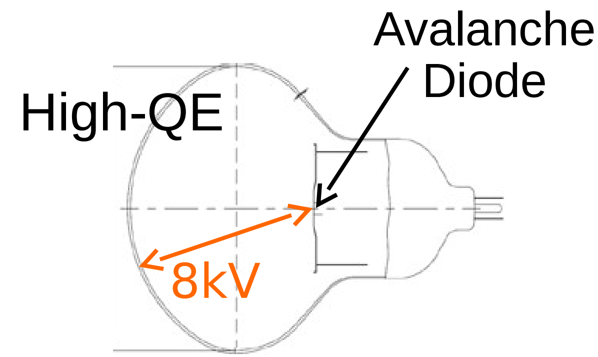
Separation wall



Photosensors Candidates







20″ PMT
(Venetian-Blind dynode)

- Super-K ID PMTs
- Used for ~20 years
  →Guaranteed
- Complex production
  → Expensive

20″ Improved PMT
(Box&Line dynode)

- Under development
- Better performance
- Same technology
  → Lower risk

20″ HPD
(Hybrid Photodetector)

- Under development
- Far better performance
- Simple structure
  →Lower cost
- New technology
  →Higher risk

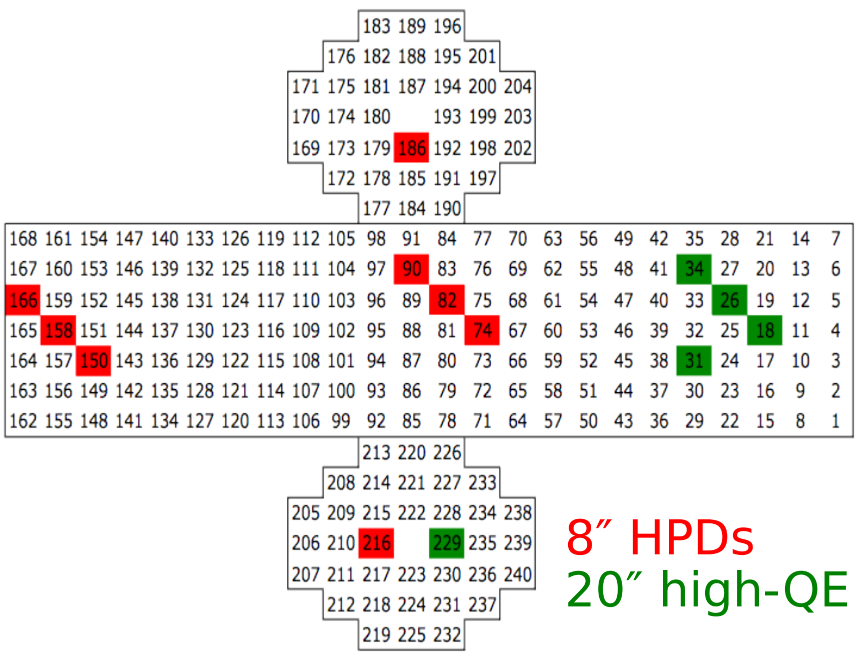
Lower Risk

Higher Performance

Tests in a Water Cherenkov Detector

- EGADS detector : a 200 ton scale model of Super-K
  - To demonstrate the safety and effectiveness of "SK + Gadolinium"
  - 240 inward-facing photodetectors
  - Electronics : ATMs (used in SK-1,2,3), to be upgraded to QBEEs (SK4)

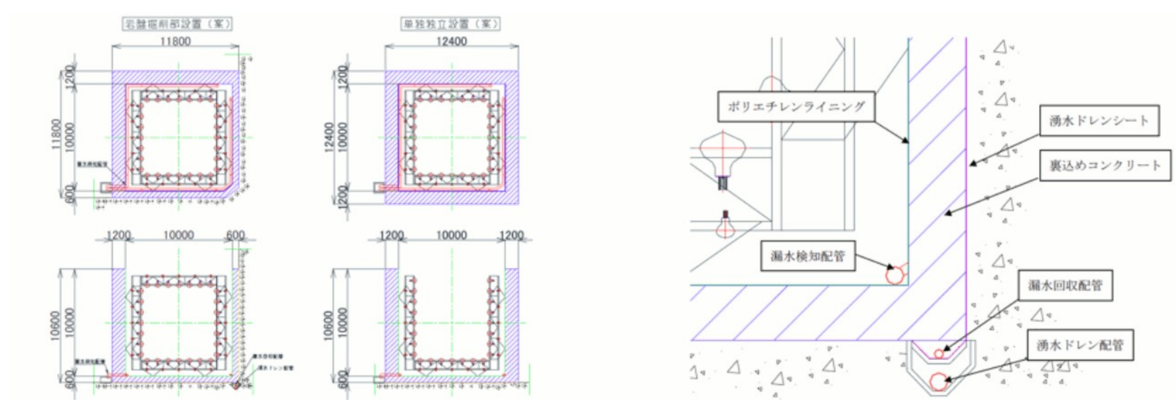
- Eight 8″ HPDs and five 20″ high-QE PMTs were mounted
  - Other 227 photodetectors are R3600, and can be used as references for the new photodetector evaluation



8″ HPDs
20″ high-QE PMTs

1kton WC Prototype

- Prototype (1kton, ~10×10×10 m^3) for R&D test approved in Japan as Grant-in-Aid: ~ USD 1.7M/5 years (2013-17).
- It's one of the 20 proposals selected each year from all areas in science.
- Main feasibility studies:
  - Photosensor and corresponding support structure
  - Liners
  - Leak water collection detection
  - DAQ
  - Electronics
  - Calibration system
  - ….



- Location site (J-PARC, KEK, Kamioka) being discussed.

Europe

The T2K Collaboration

Canada

U. Alberta
U. B. Columbia
U. Regina
U. Toronto
TRIUMF
U. Victoria
U. Winnipeg
York U.

France

CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany

U. Aachen

Italy

INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan

ICRR Kamioka
ICRR RCCN
KAVLI IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metropolitan
U. Tokyo

Poland

A. Soltan, Warsaw
H.Niewodniczanski, Cracow
U. Silesia, Katowice
T. U. Warsaw
U. Warsaw
U. Wroclaw

Russia

INR

Total:
~500 members
59 institutes
11Countries

Spain

IFIC, Valencia
U. A. Barcelona

Switzerland

ETH Zurich
U. Bern
U. Geneva

UK

Imperial C. L.
Lancaster U.
Liverpool U.
Queen Mary U. L.
Oxford U.
Sheffield U.
STFC/RAL
STFC/Daresbury
Warwick U.

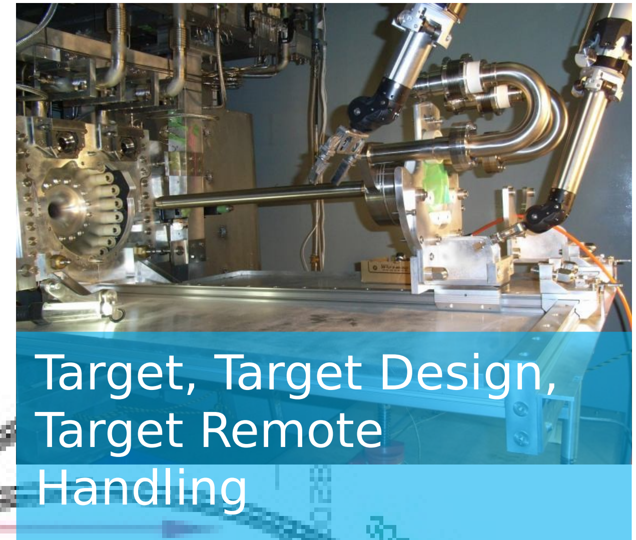
USA

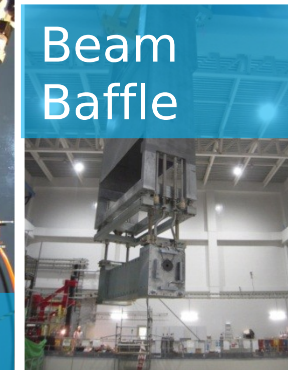
Boston U.
Colorado S. U.
U. Colorado
Duke U.
U. C. Irvine
Louisiana S. U.
U. Pittsburgh
U. Rochester
Stony Brook U.
U. Washington

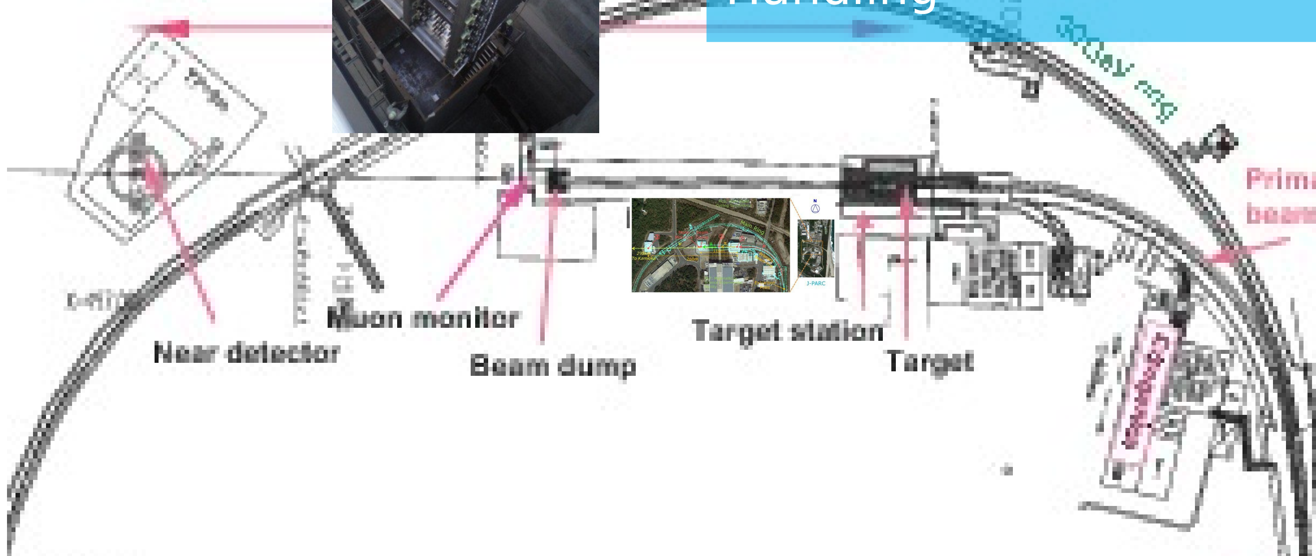
<u>Europe</u>
8 Countries; 30 Institutes
> 50% members are from Europe.
Largest European neutrino experiment

Near & Far sites: KEK/JAEA ICRR

European Contributions to T2K Beamline





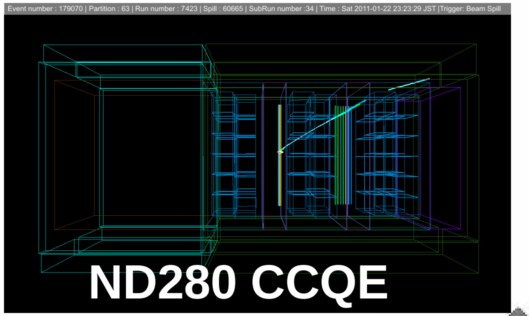


Demonstrates the ability of Europe to make significant contributions to facilities which are not in Europe!

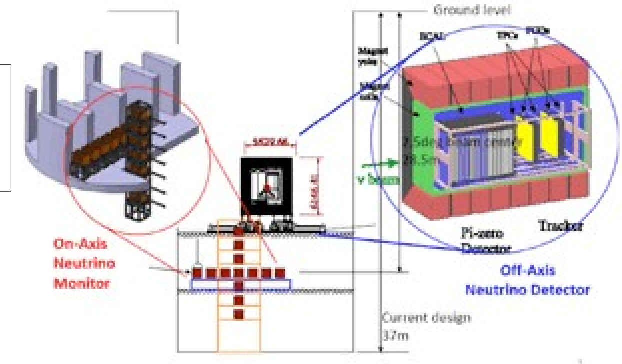
Ongoing work for the T2K upgraded beam power (up to 750MW) and for multi MW beams (HK) ⇒ see C. Densham's talk

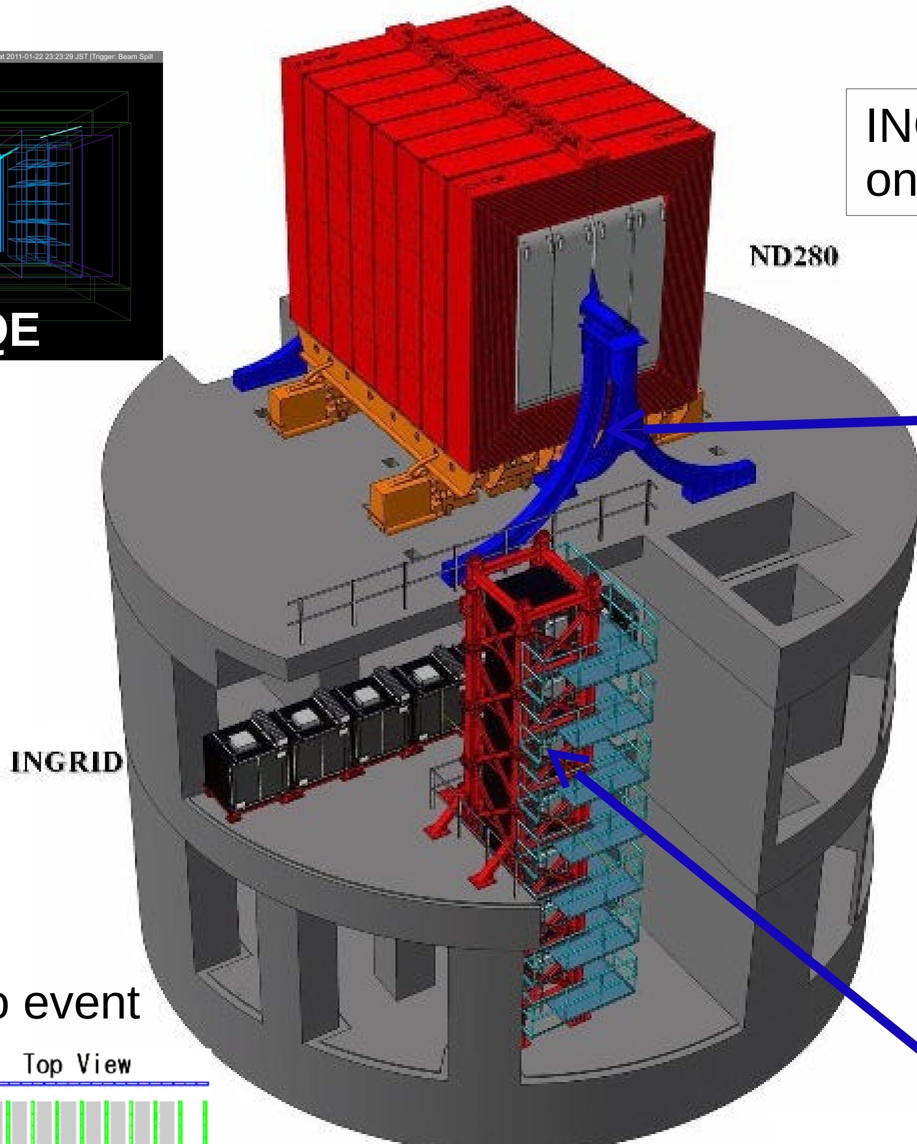
T2K Near Detector Suite

ND280
off-axis



INGRID
on-axis

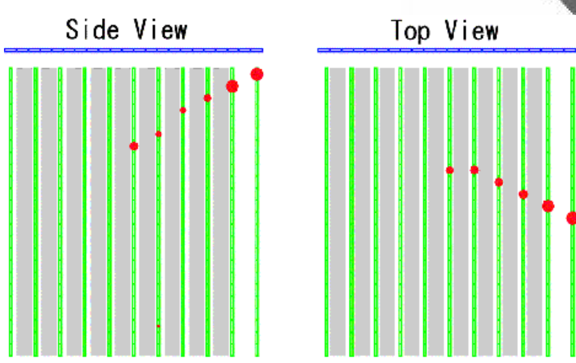




European Contributions:

- UA1/NOMAD Magnet
- TPC MicroMegas
- TPC/FGD Electronics
- Contributions to INGRID
- ECAL
- SMRD
- Trip-T electronics
- DAQ
- Software
- Analysis

INGRID neutrino event



- ND280: neutrino spectrum, neutrino interaction properties
- INGRID: beam energy and profile

See C. Andreopoulus' talk

(2013) Near Detector Constraint to SK

Neutrino Flux Model:

- Data-driven: NA61/SHINE, beam monitor measurements

Neutrino Cross Section Model (NEUT):

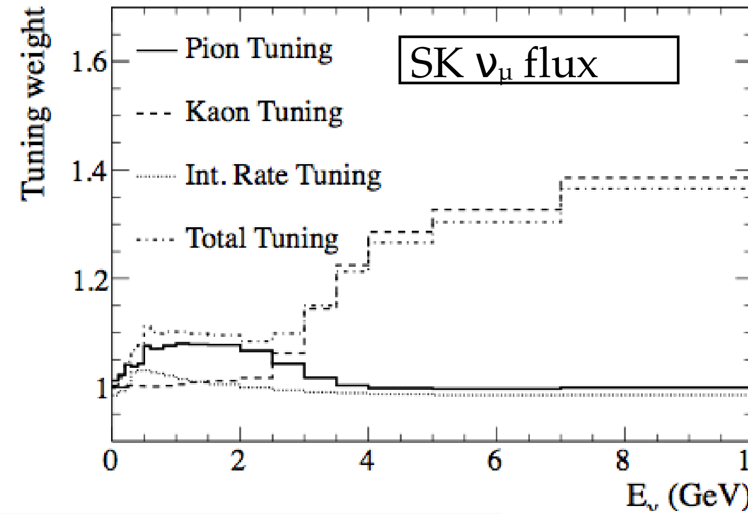
- Data-driven: External neutrino, electron, pion scattering data

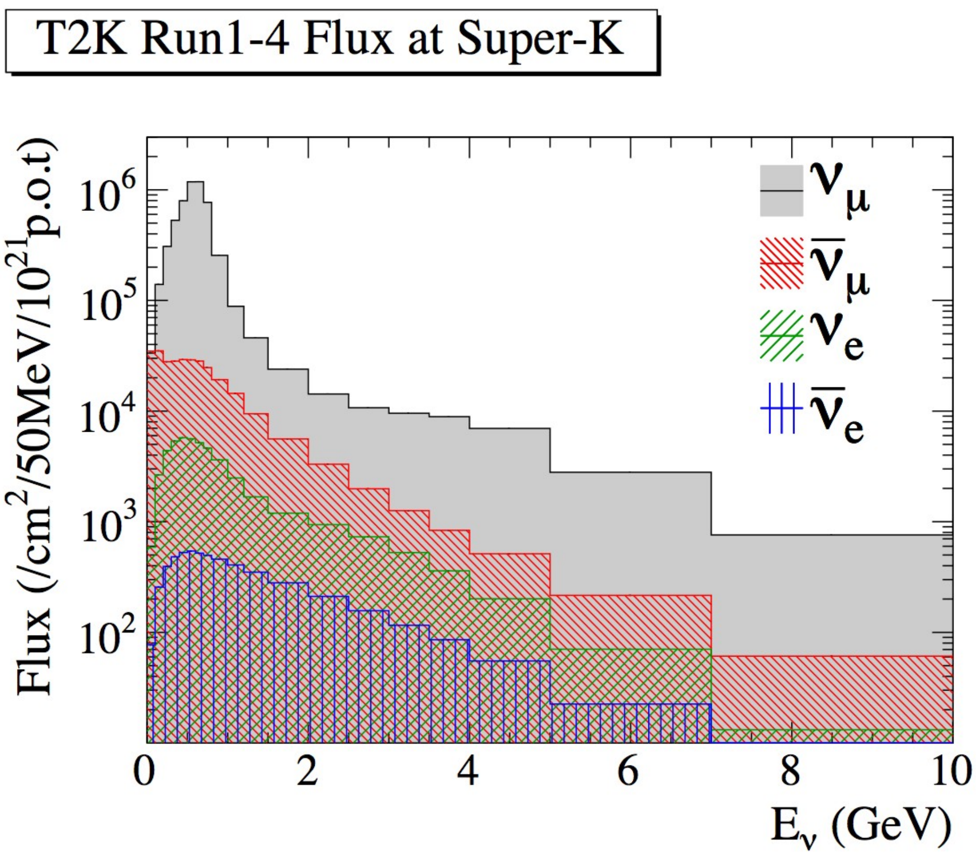
Constraint from ND280 Data

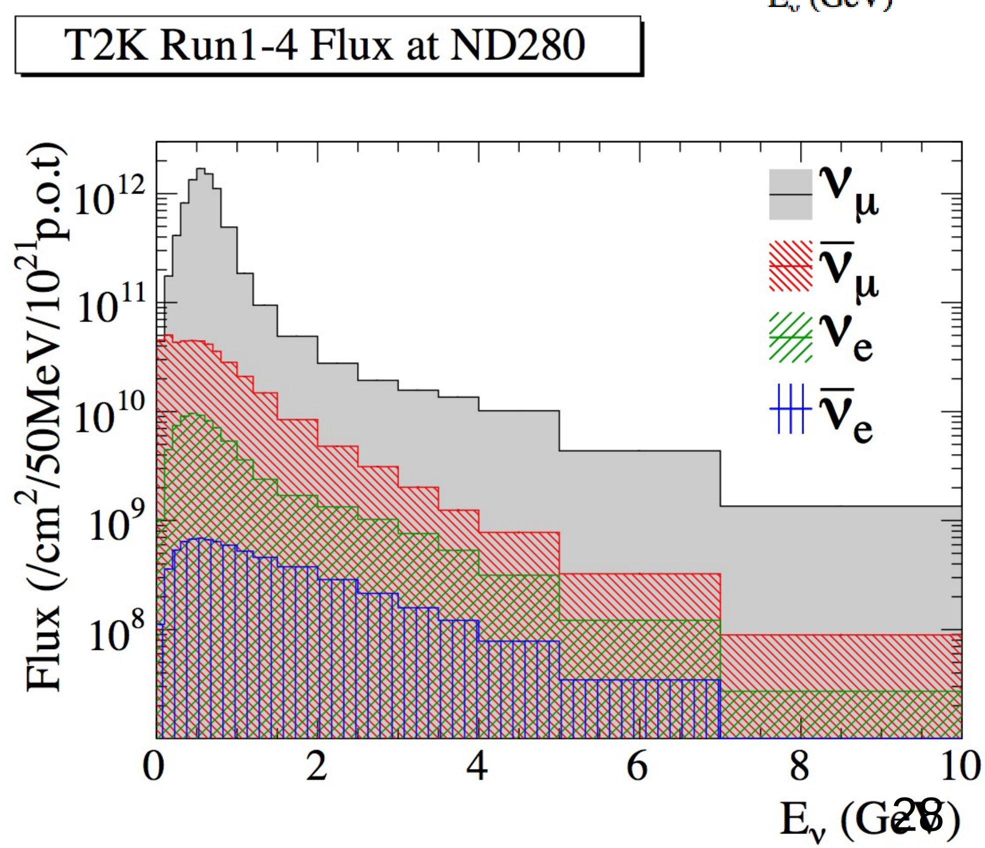
- Input: CC interactions with 0, 1 or multiple pions
- Fit to data constrains flux, and cross section parameters
- Constrained SK flux parameters and subset of cross section parameters are used to predict SK event rates

Beam flux prediction

Beam flux is predicted based on NA61/SHINE π, K production measurements and T2K proton beam measurements



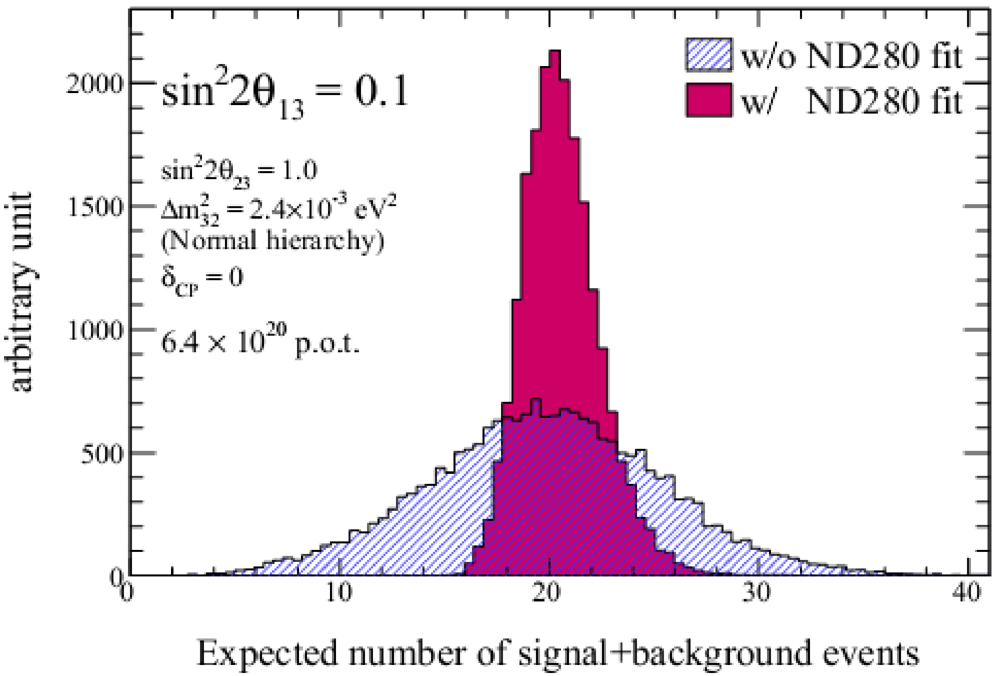




SK Predicted Events after Constraint

Error on Number of SK Events (%)

$\sin^2 2\theta_{13}$=0.1	w/o fit	w/ fit (T2K)
NA61, ND280 Constraint	25.9	2.9
Other ν-interations	7.5	7.5
SK/FSI	3.5	3.5
Total	27.2	8.8

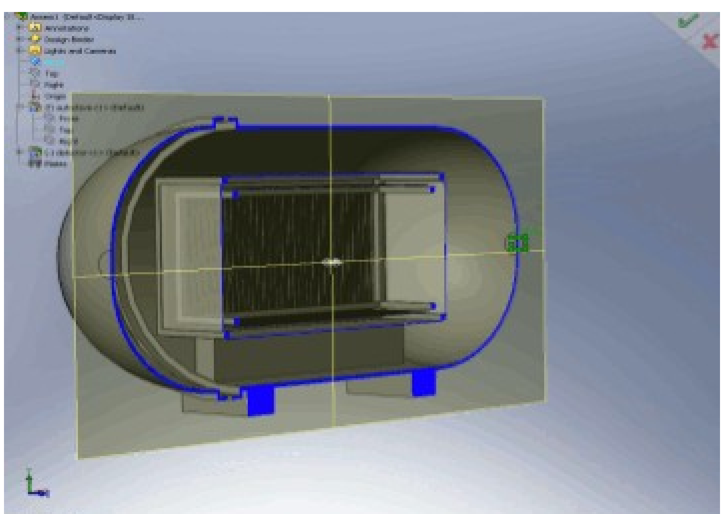


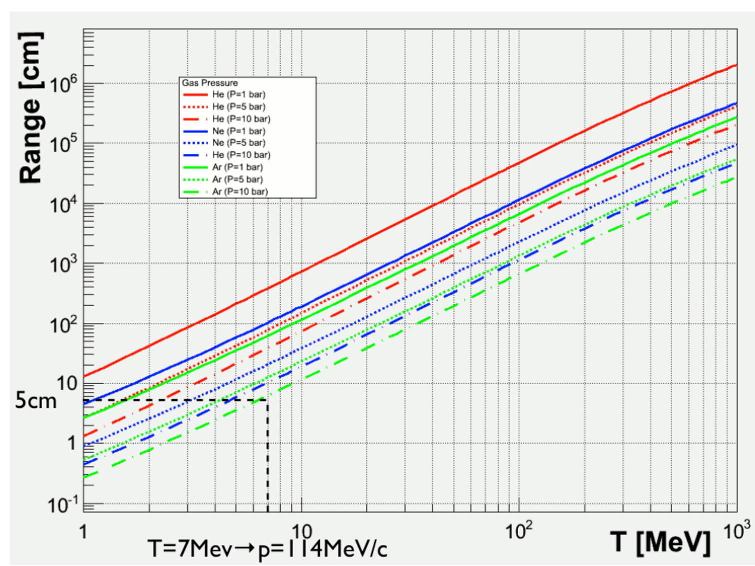
Near Detector and Hadronization constraints vital for reducing the errors

ND280 Upgrade

- Several studies being performed for a possible upgrade → beneficial for Hyper-K as well. Undergoing study.

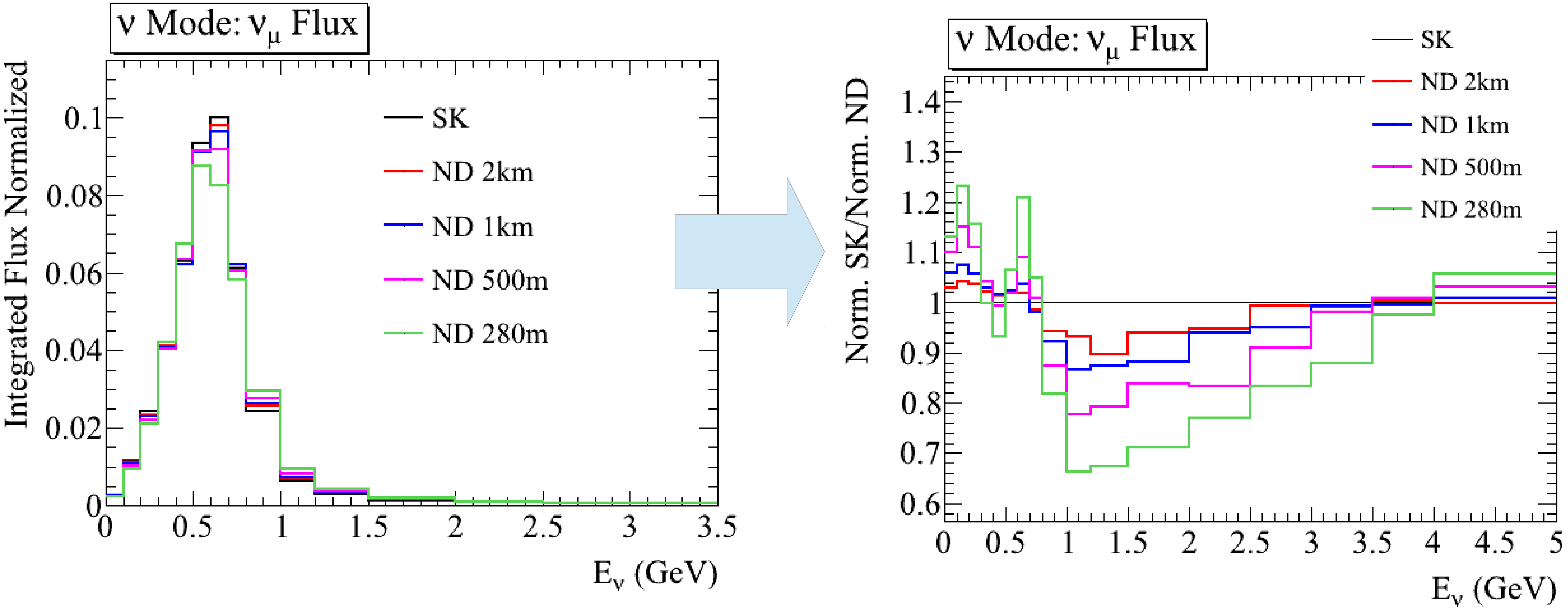
- Improve ND280 to optimize cross-section measurements.
- Proposed high pressure TPC to access the low energy nuclear debris and help in the study for neutrino-nucleus interactions. Investigated 3 basic gases (He, Ne, Ar and CF4) and 2 pressures.





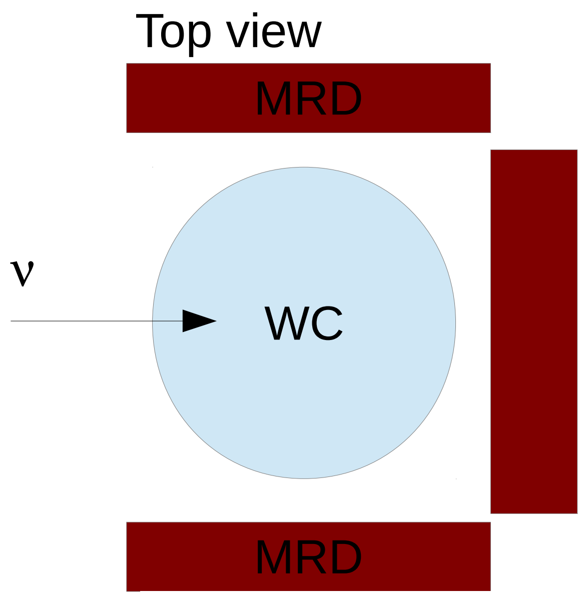
High Pressure TPC (Barcelona)

New Near Detector

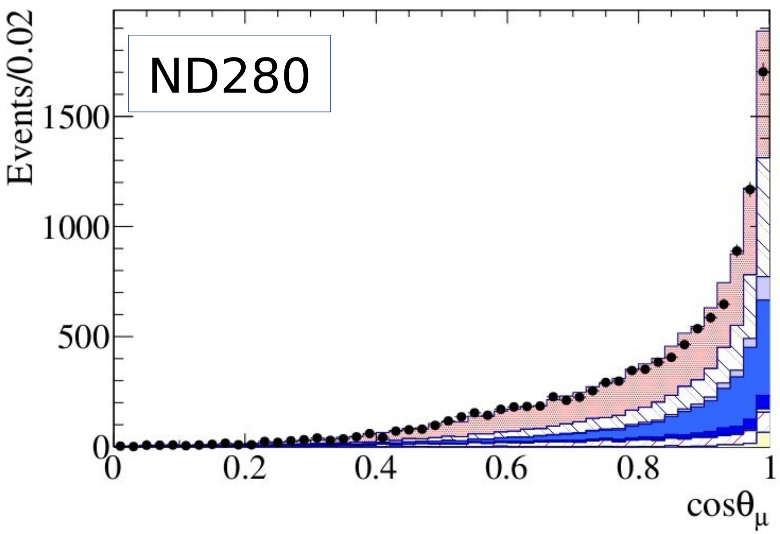


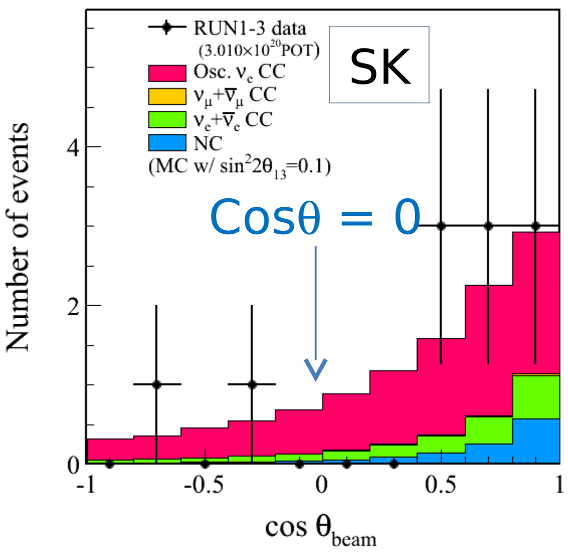
- At 280m: neutrino source not point-like, spectral differences with respect to SK
- Neutrino spectra at SK and 2KM are almost the same: ~same beam → energy spectrum
- To improve our current precision we need to improve our errors on the flux predictions

Design Work On-going



- Adopted technology is WC. Same detector as far detector → minimize error propagation.
- "Nominal" 1kton, size 11mx11m as K2K 1kton.
- Muon Range Detector (MRD) to measure the muon energy. Possibly looking at a MIND-type detector as well.
- "Nominal" local baseline at 2km.



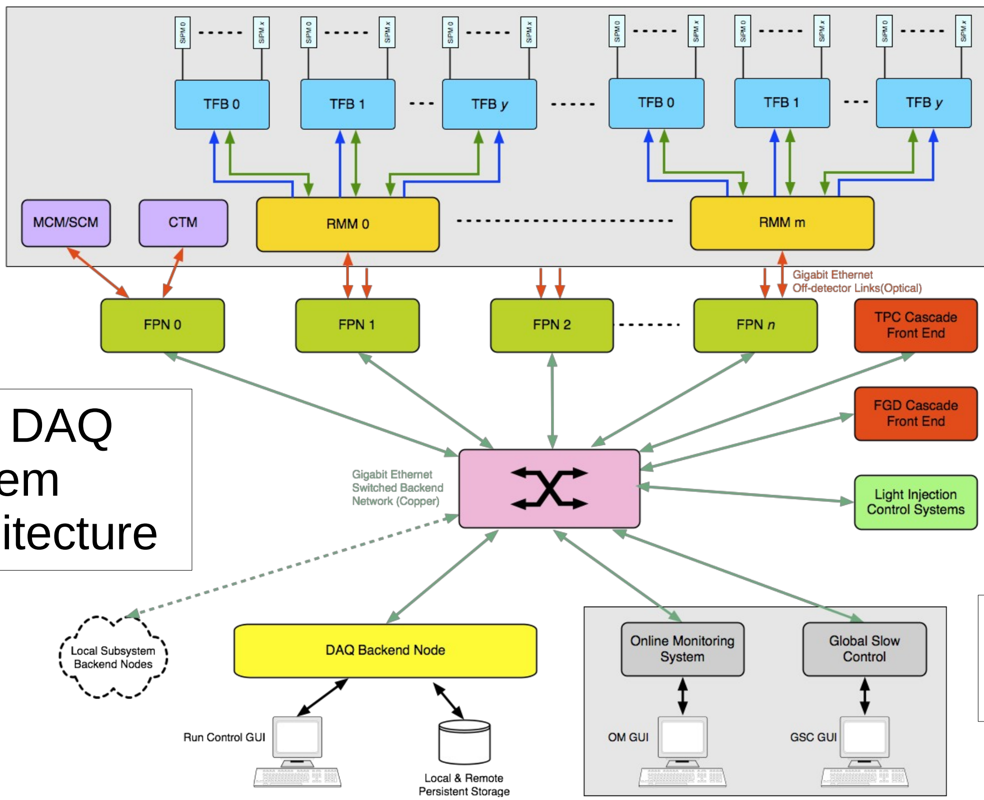


- Further advantages:
  - Full 4π coverage for new near and HK detectors.
  - Measure NCπ^0 rate in water.

Detector Sites

- Site optimization:
  - compromise between physics and land availability.
- A site at ~2-3km will see similar spectrum to Hyper-K.
- Ongoing work on cross section errors, pile-up, size, location, etc.
- Very first expected proposal by the end of February 2014, to be added to the J-PARC LoI.

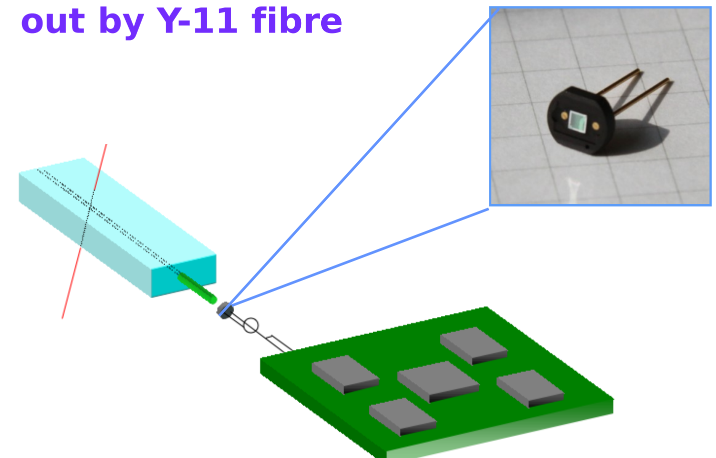
DAQ & Electronics (for Hyper-K and new ND)



T2K DAQ system architecture

Plastic scintillator read out by Y-11 fibre

solid state photon detector (MPPC)



dedicated front-end electronics

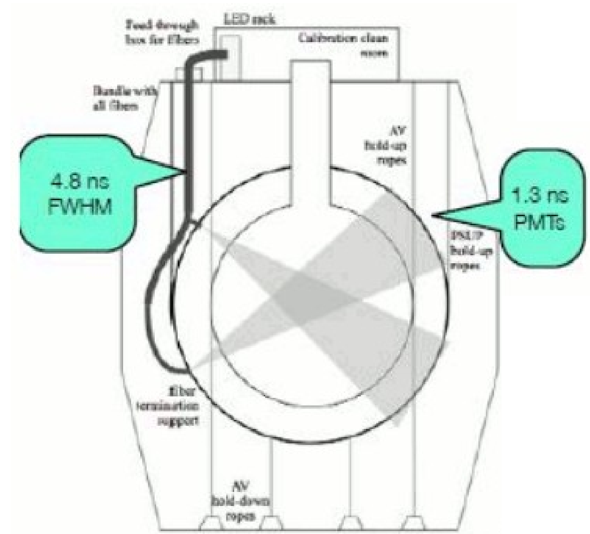
ND280 electronics for MPPC-based detectors

- DAQ & electronics run stably since the start of T2K.
- Based on the previous experience, we are devising the DAQ for HK and the new ND – new ideas/design being discussed.
- We are also interested in the electronics based on both T2K and other experiment expertise.

Calibration Strategy (for Hyper-K and new ND)

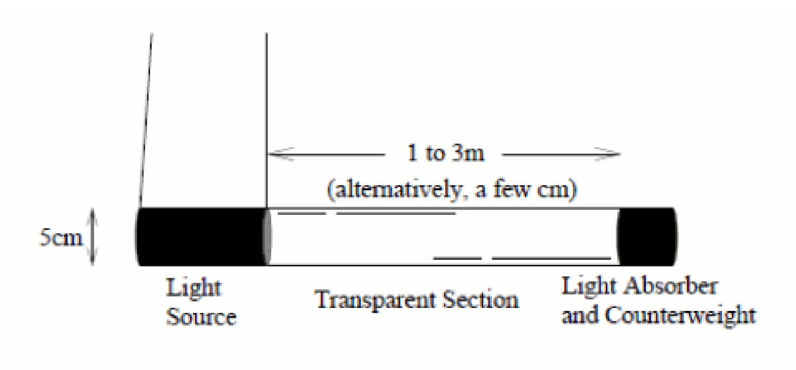
- Exploit current expertise (e.g. SNO+, ANTARES..)

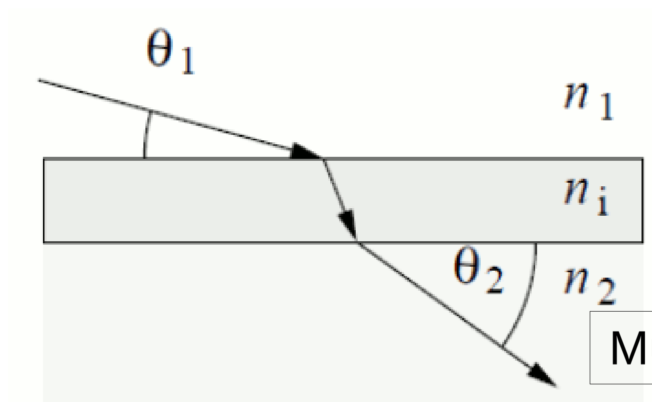
ANTARES Beacon



SNO+ Detector

- Some initial work:
  - Development of updated LED drivers for HK (UK)
  - A source to simulate muons and test reconstruction (UK)



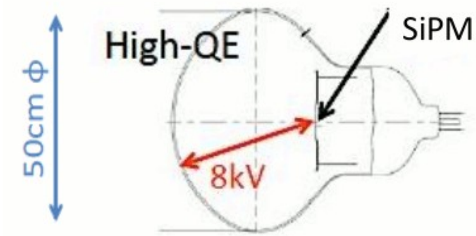


Muon Source Design (UK)

Photo-sensors Studies (for Hyper-K and new ND)

- Studying new generation of photosensors for much improved performance.

Vacuum Silicon PhotonMultiplier (Naples)

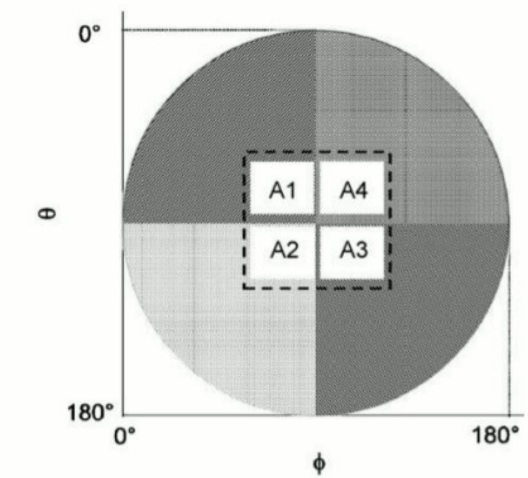


Very Large Photocathode for the VSiPMT

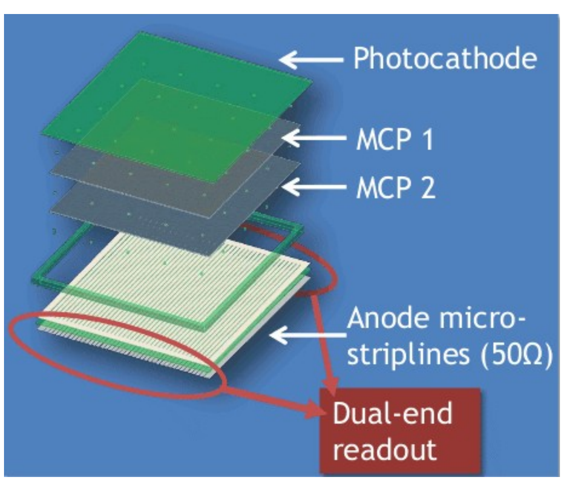
Advantages with respect to the HPD solution: higher gain

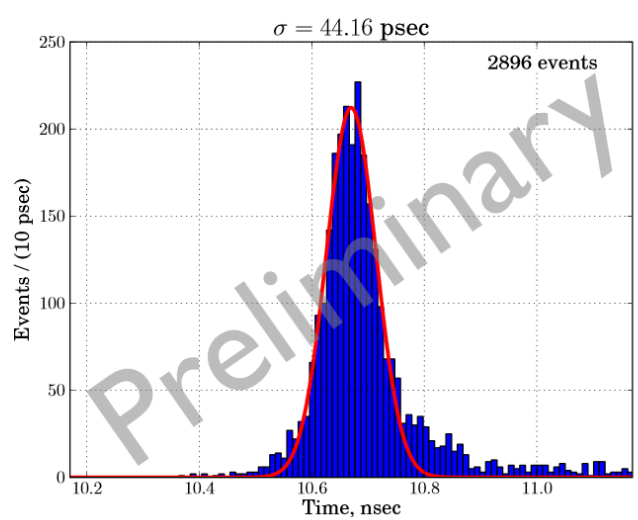
Segmented Photocathode VSiPMT

Each segmented part focusing on a SiPM

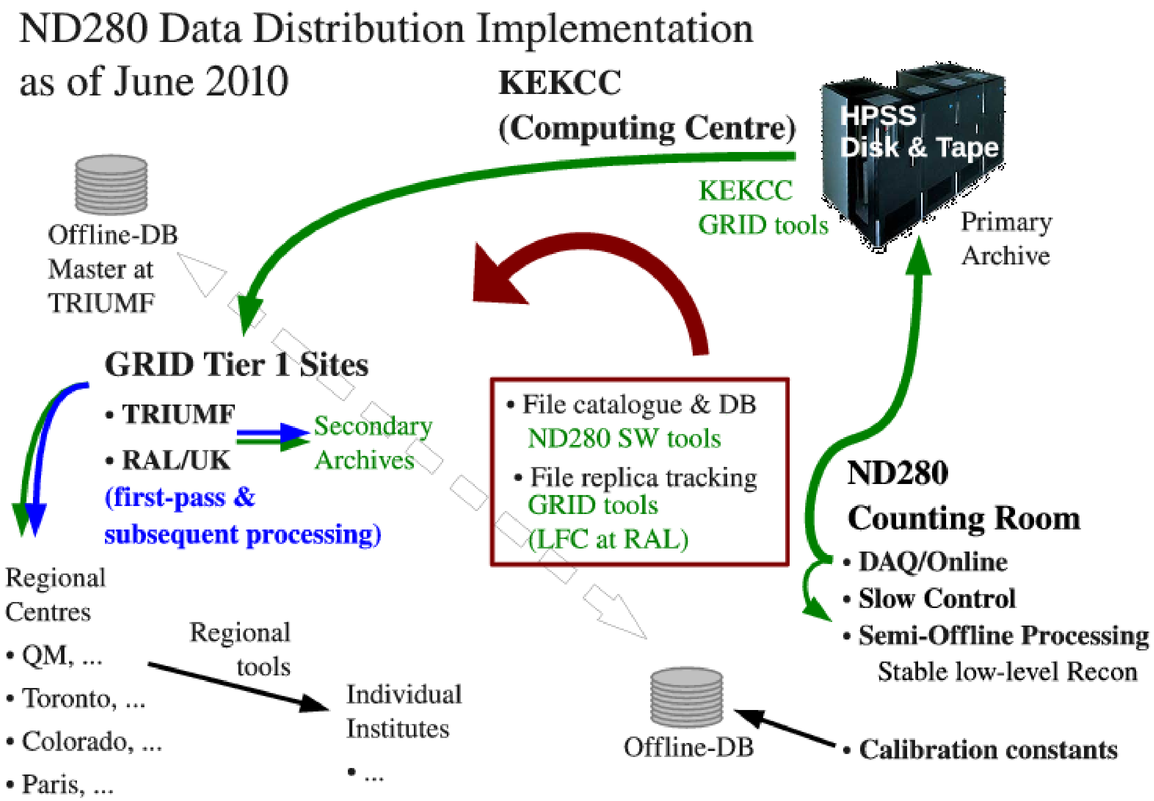


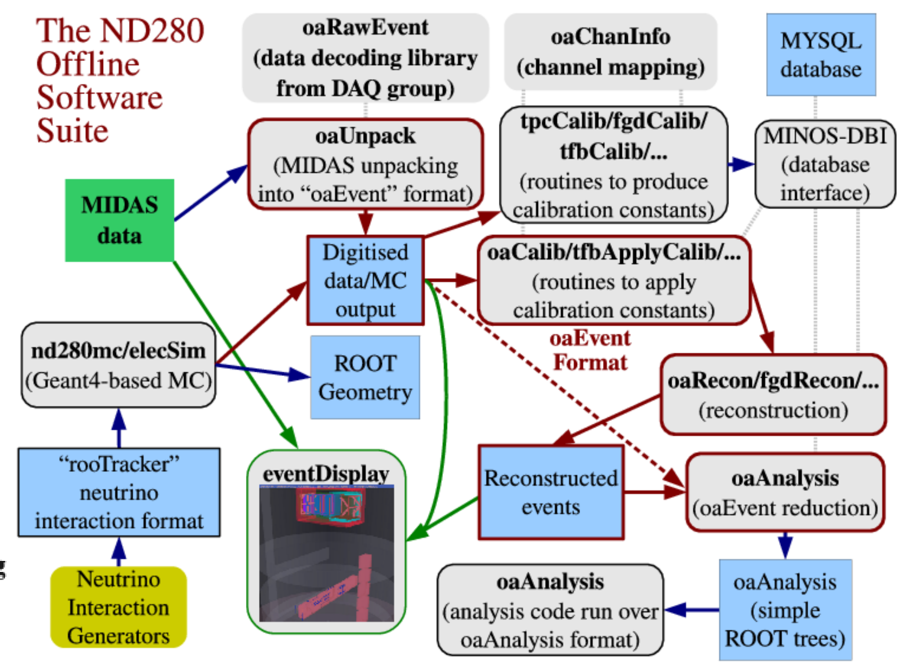
Large Area Picosecond Photo-Detector (UK)





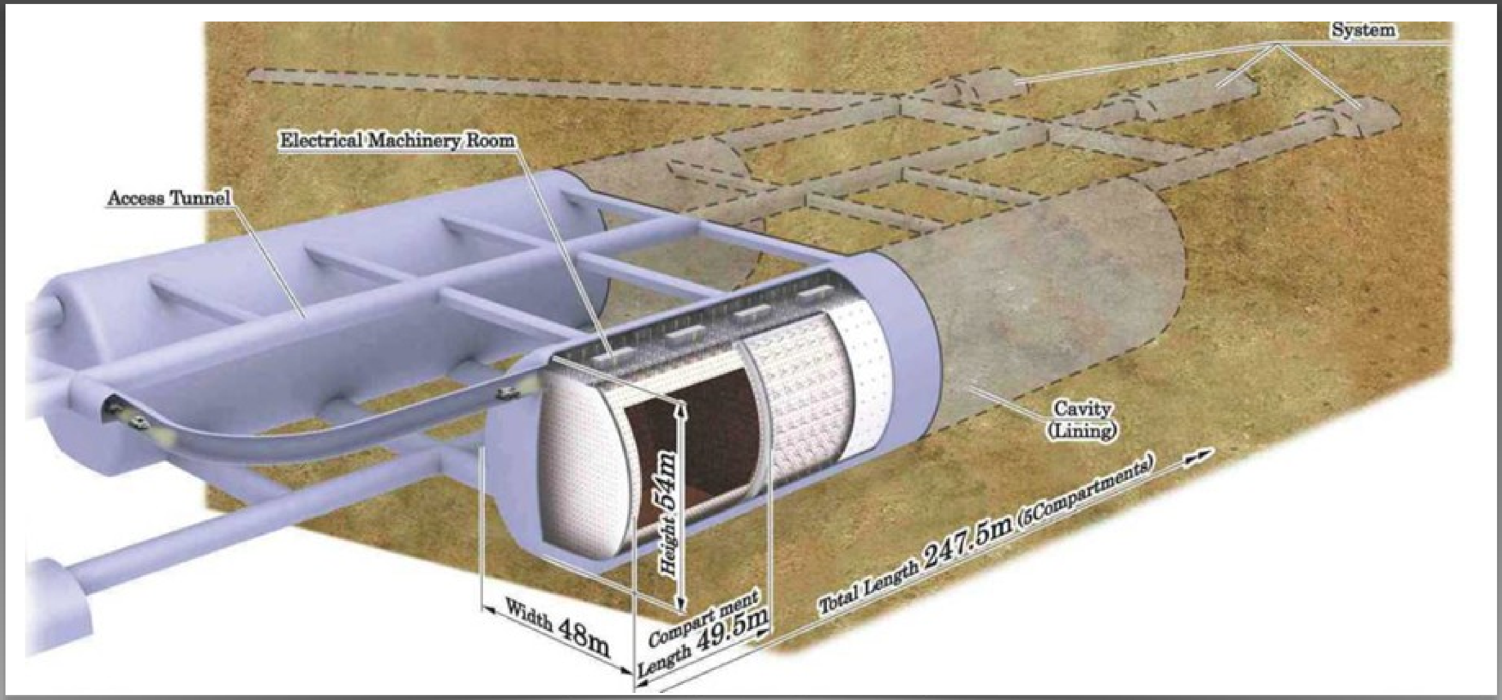
Software/Computing





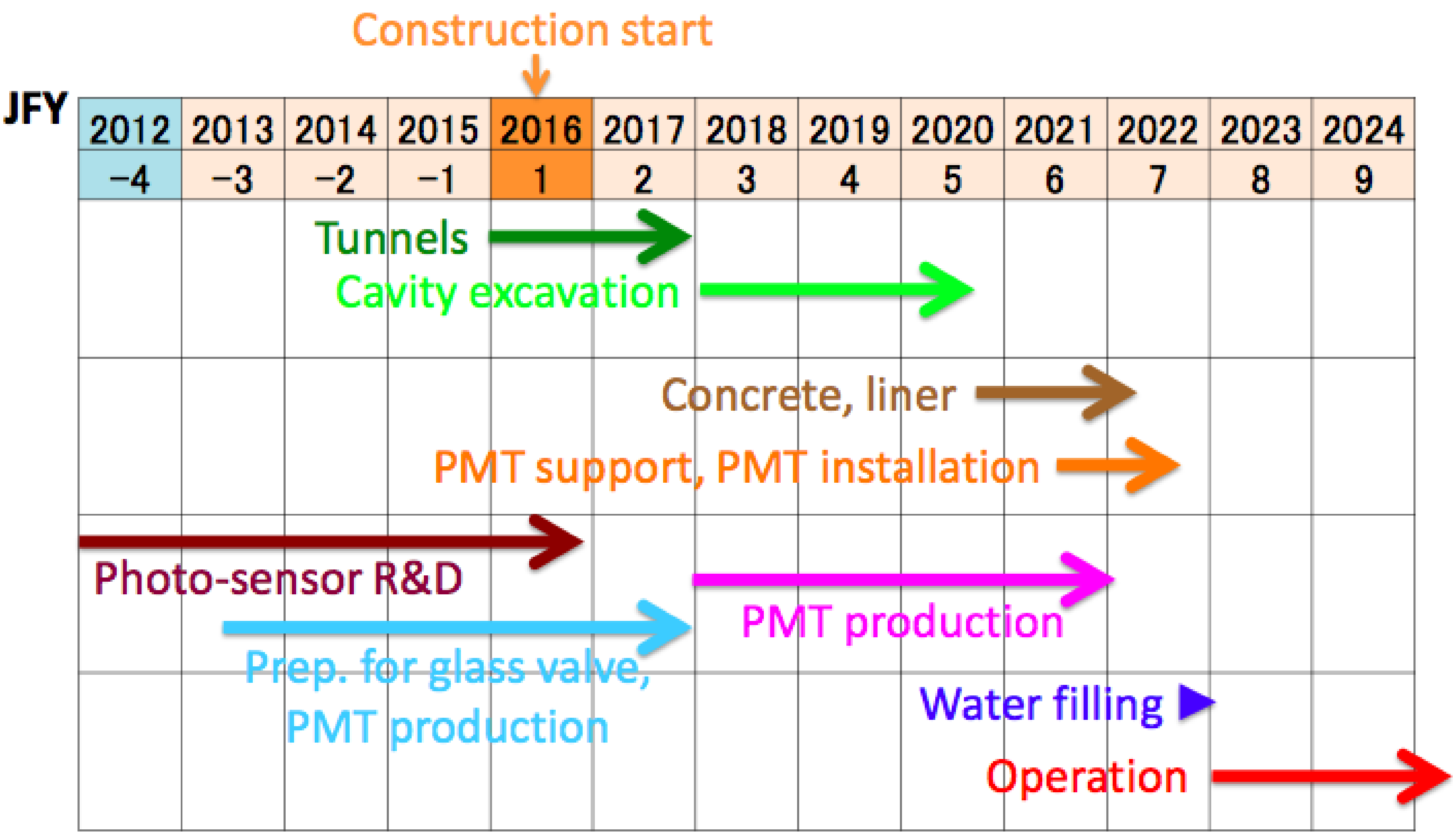
- Central role in software/computing for T2K.
- Already working on Hyper-K computing model.
- Currently producing Hyper-K simulated events.

Schedule & Summary



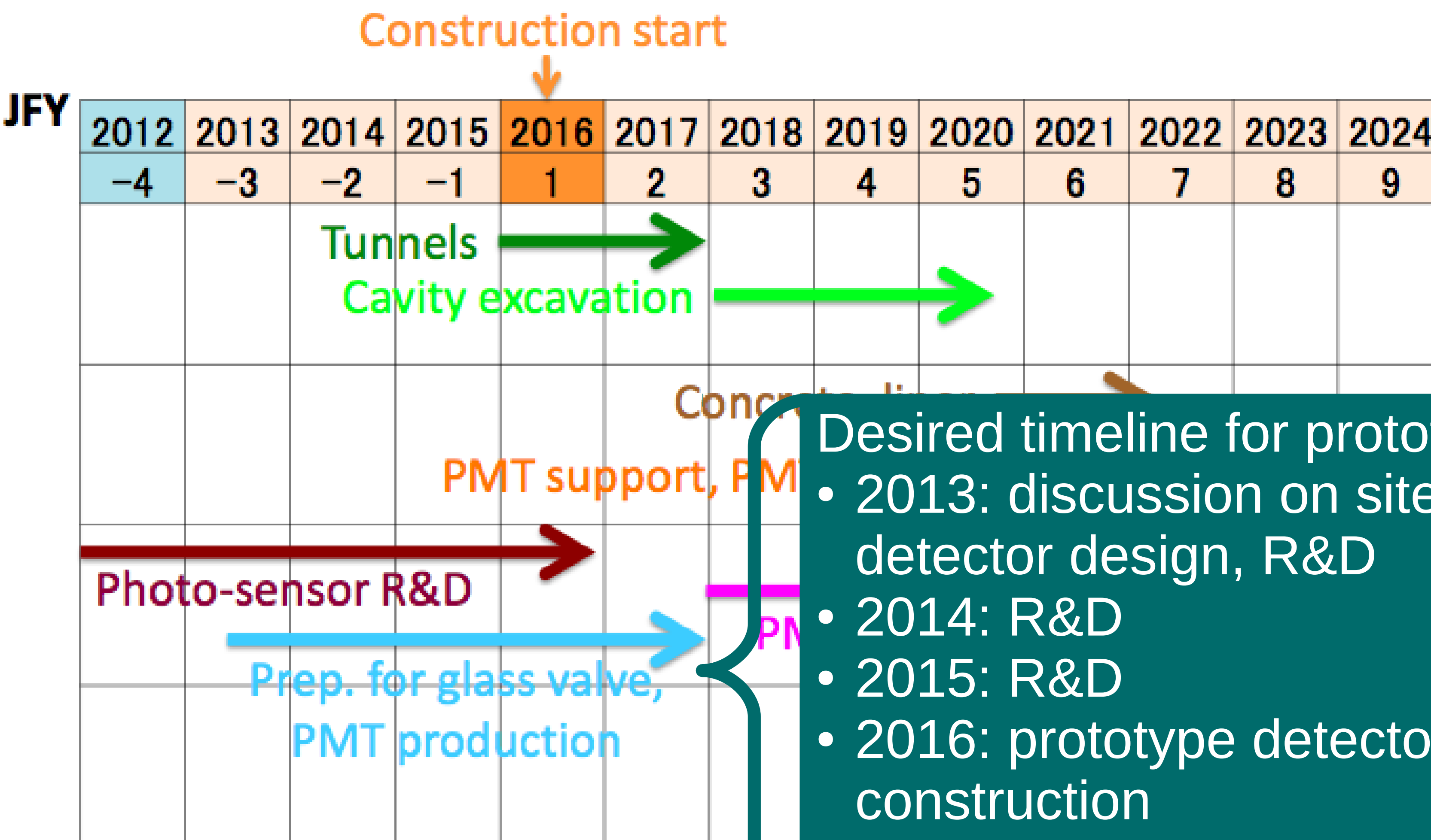
Overall Project Schedule

- Overall HK construction: ~7 years
- Assuming full funding starting in 2016.



Overall Project Schedule

- Overall HK construction: ~7 years
- Assuming full funding starting in 2016.



Desired timeline for prototype
- 2013: discussion on site, detector design, R&D
- 2014: R&D
- 2015: R&D
- 2016: prototype detector construction
- 2017: operation and conclusion on components

Approval Status in Japan

- Approval of the experiment happens in just one phase that allocates the total funds for the experiment, in a given timeline.
- Community consensus crucial → bottom-up approach.
- R&D budget (w/ WC proto-type) for Hyper-K approved in 2013.
- Recommended by HEP community as one of the two major large scale projects:
http://www.jahep.org/office/doc/201202_hecsubc_report.pdf
- KEK Roadmap includes Hyper-K:
http://kds.kek.jp/getFile.py/access?sessionId=1&resId=0&materialId=0&confId=11728
- Cosmic Ray community endorses HK as large scale project.
- Science Council of Japan master plan:
  - Proposal submitted, expecting outcome soon.
- MEXT:
  - Based on the SCJ master plan the MEXT will update the roadmap of the big projects. We should prepare report to MEXT in 2014.
- LoI to submit to J-PARC for T2HK in April 2014

Approval Status outside Japan

- EU:
  - Statement-of-interest approved in the UK (2014). Proposal to STFC to be submitted in May 2014. Awarded “bridging” money to fill the gap up to the proposal approved.
  - Hyper-Kamiokande strongly supported in other T2K Countries. New non-T2K Countries interested.
- Canada:
  - Proposal to Canadian Foundation per innovation under preparation to submit around June 2014.
  - Green light from TRIUMF to proceed.
- US:
  - Under discussion in P5.
  - Historically strong commitment to Super-K, K2K, T2K, and generally experiments in Japan (e.g. KamLAND, KamLAND-Zen, ...)

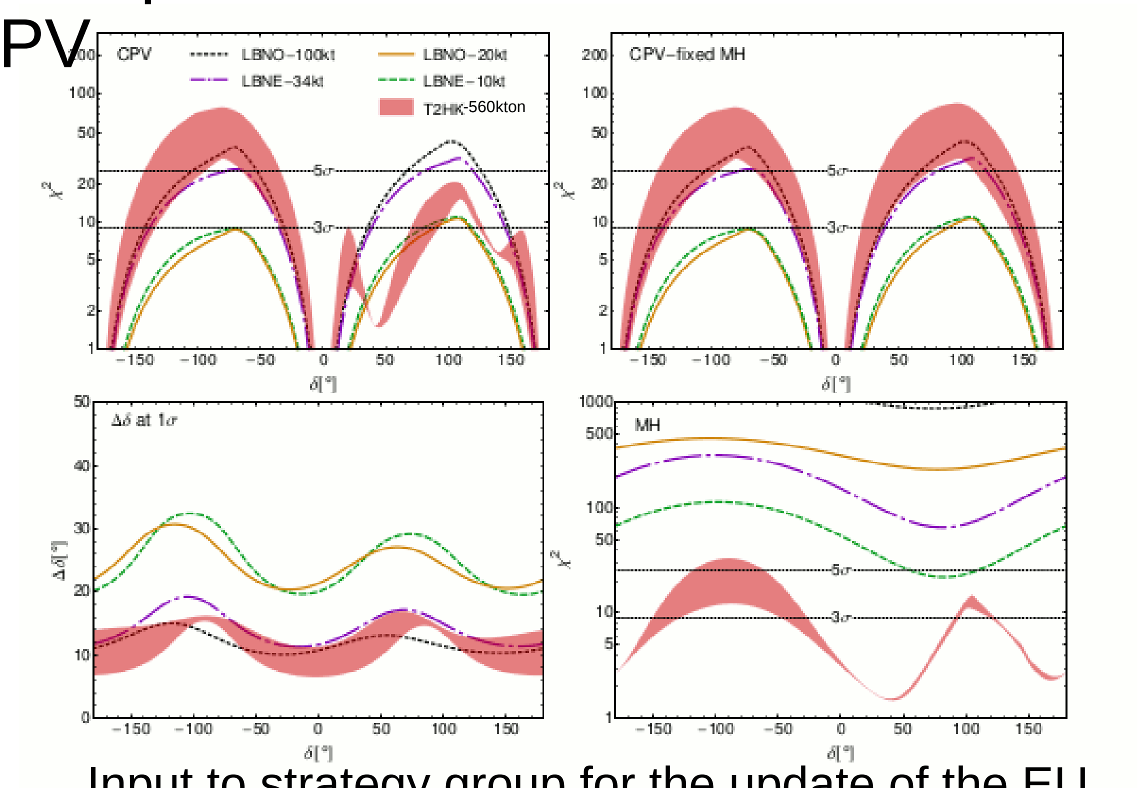
Overall Cost Estimate

Total	800M USD	
Cavern	300M USD	
Tank & structure	200M USD	
Photo-sensors	200M USD	High QE HPD
Near Detector	30M USD	@Tokai

- Costs estimated based on the current design and including a new near detector.
- Proportional sharing of costs between the interested Countries is expected.

Summary

- Hyper-K - extremely large physics portfolio
  - Excellent performance for CPV
  - Atmospheric neutrinos
  - Nucleon decay search
  - Astrophysical neutrinos



Input to strategy group for the update of the EU strategy http://cds.cern.ch/record/1628377/files/Briefing_book.pdf (2013). Beam power: LBNE 700kW 10years, T2HK 1.66 MW 5 years, LBNO 800kW 10 years).

- Japan HEP community:
  - Hyper-K at highest priority
  - LoI for T2HK (April 2014)
  - CDR (2014-2015)
  - TDR

- Next Hyper-K Open Meeting: January 27-28, Kamvli, IPMU

- It's a very powerful upgrade of T2K
  - Largest European neutrino experiment
  - Many contributions from Europe in many areas

Summary of areas of Interest

Beam	contributed to T2K. Already intense work towards a ~MW beam.
NA61/SHINE	crucial for reweighting the beam flux
ND280 upgrade	neutrino interaction measurements
New Near Detector	work started towards the optimization of the design at ~2-3 km. To make basic choices (site, size etc) by February 2014.
DAQ & Electronics	extremely successful performance in T2K. New ideas being investigated.
Calibration	huge expertise. Starting to work on it.
Photosensors	original work ongoing to improve current performance.
Software/Computing	working on computing model.

Backup Slides

$\nu_\mu \rightarrow \nu_e$ Probability

$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}$

$\Phi = \Delta m^2_{ij} \frac{L}{4E_\nu}$

$$P(\nu_\mu \rightarrow \nu e) = 4C^2_{13} S^2_{13} S^2_{23} \sin^2\Phi_{31}$$

Leading term — θ_{13}

$$+8C^2_{13} S_{12} S_{13} (C_{12} C_{13} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{32} \sin\Phi_{21}$$

CPC

$$-8C^2_{13} C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$

CPV

$\delta \rightarrow -\delta$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$$+4S^2_{12} C^2_{13} (C^2_{12} C^2_{23} + S^2_{12} S^2_{23} S^2_{13} - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21}$$

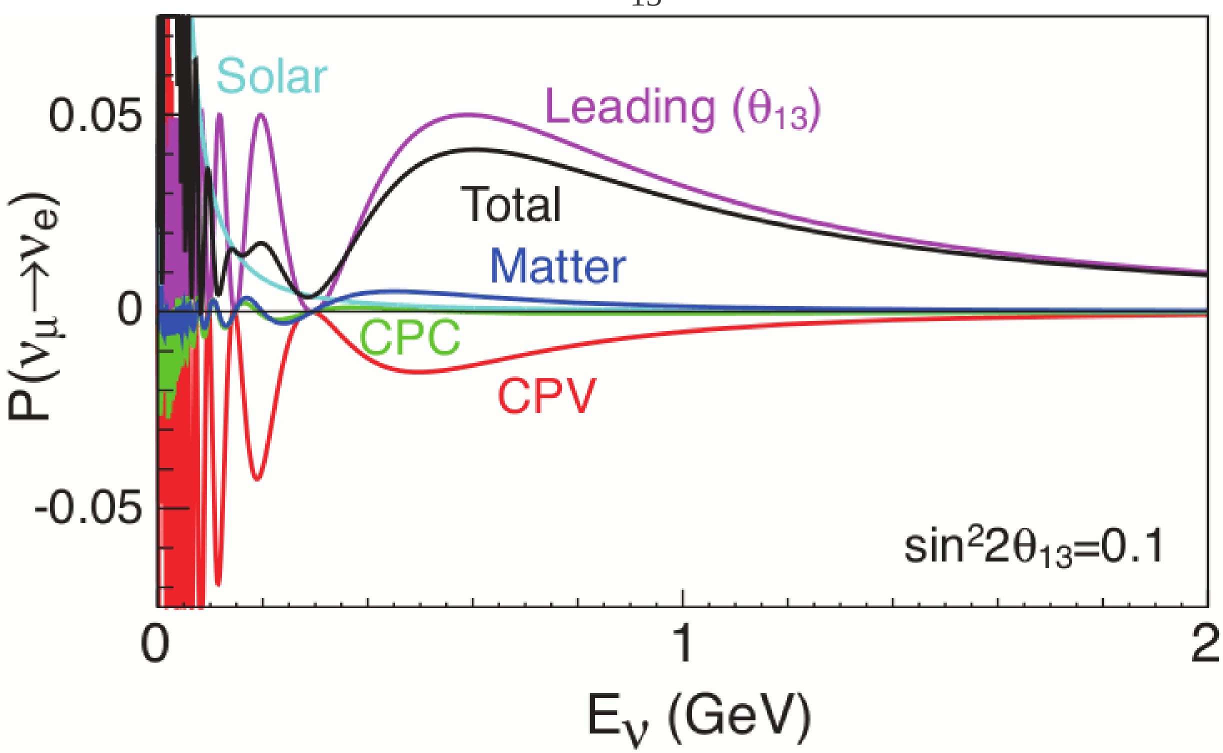
Solar

$$-8C^2_{13} S_{12} S^2_{23} \frac{aL}{4E_\nu} (1 - 2S^2_{13}) \cos\Phi_{32} \sin\Phi_{31}$$

$$+8C^2_{13} S^2_{13} S^2_{23} \frac{a}{\Delta m^2_{13}} (1 - 2S^2_{13}) \sin^2\Phi_{31}$$

Matter Effect

$$a = 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} eV^2 \frac{\rho}{gcm^{-3}} \frac{E}{GeV}$$



Leading Term μ $\sin^2 2\theta_{13}$

CPV Term μ $\sin 2\theta_{13}$

Matter Effect μ $\sin^2 2\theta_{13}$

For large $\sin^2 2\theta_{13}$:

Signal ↑, CP Asymmetry ↓,

Matter/CP ↑

$\nu_\mu \rightarrow \nu_e$ Probability

$C_{ij} = \cos\theta_{ij},\ S_{ij} = \sin\theta_{ij}$

$\Phi = \Delta m_{ij}^2 \frac{L}{4E_\nu}$

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}$$ Leading term θ_{13}

$$+8C_{13}^2 S_{12} S_{13}(C_{12}C_{13}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{32}\sin\Phi_{21}$$ CPC

$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$ CPV

$\delta \rightarrow -\delta$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$$+4S_{12}^2 C_{13}^2(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21}$$ Solar

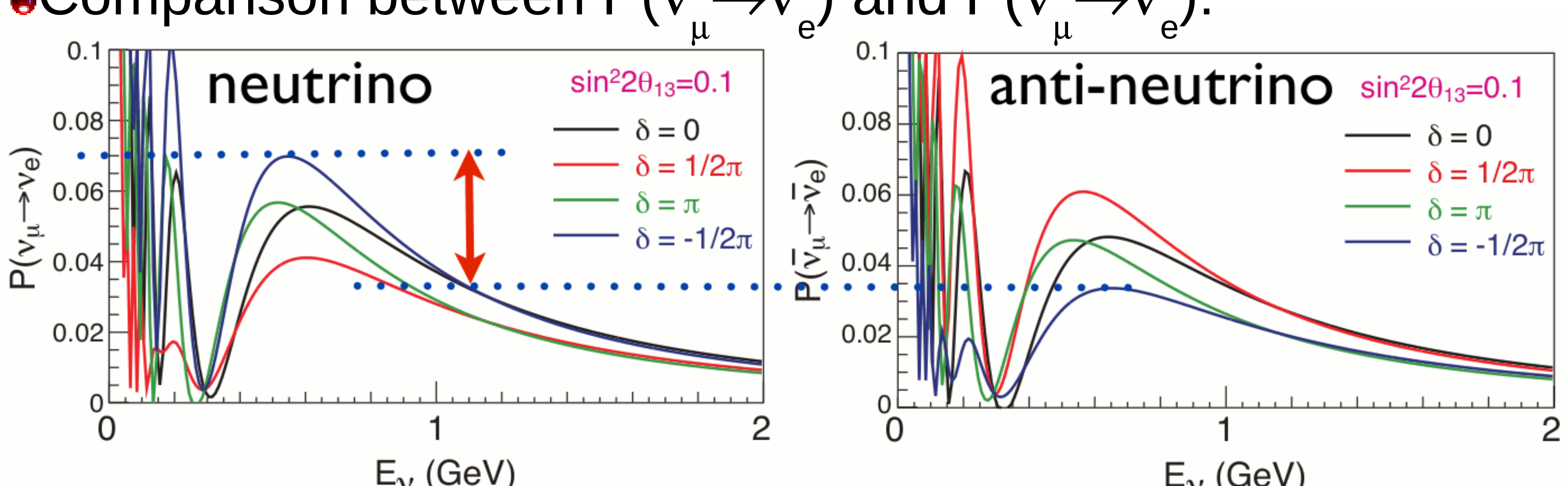
$$-8C_{13}^2 S_{12} S_{23}^2 \frac{aL}{4E_\nu}(1-2S_{13}^2)\cos\Phi_{32}\sin\Phi_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2}(1-2S_{13}^2)\sin^2\Phi_{31}$$

Matter Effect

$a = 2\sqrt{2} G_F n_e E = 7.56\times10^{-5} eV^2 \frac{\rho}{gcm^{-3}} \frac{E}{GeV}$

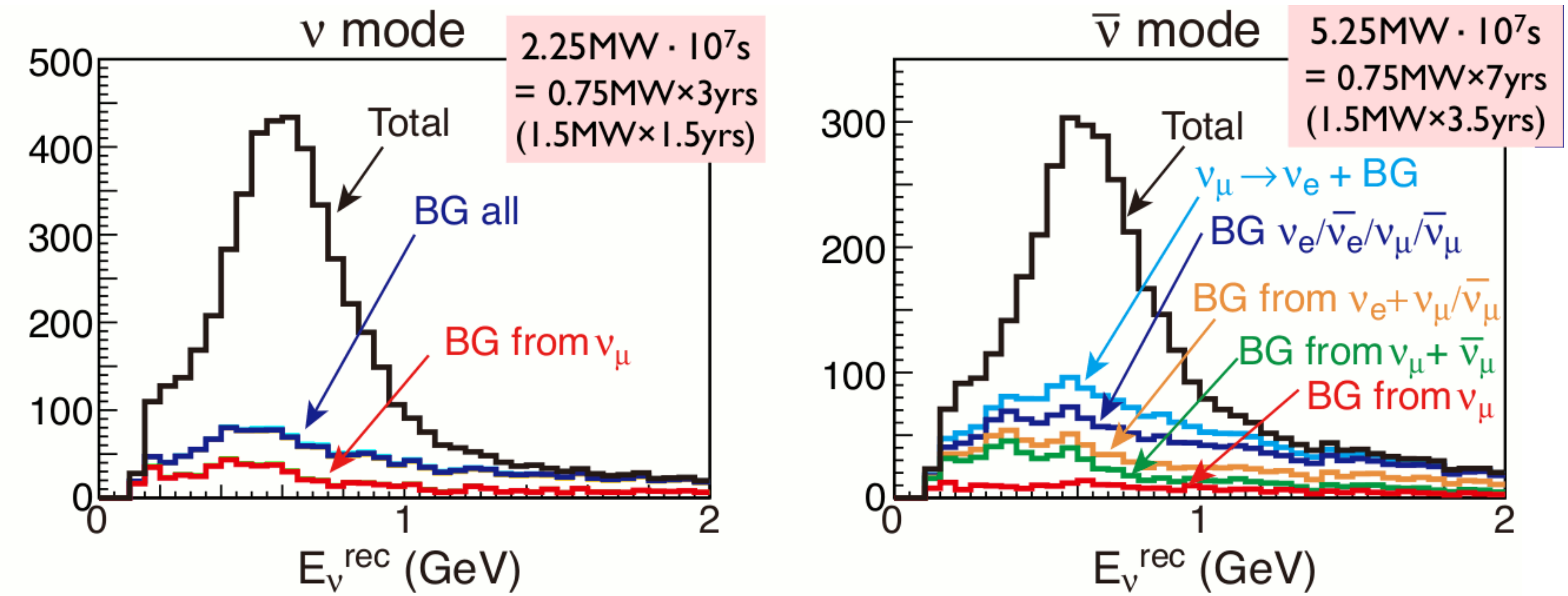
- Comparison between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$:



Difference $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ as large as ~ ±27% at nominal (δ=3/4)

Simulated ν_e Candidates after Selection

- Full simulation of ν beam, detector response and reconstruction
- PMT Coverage: ~20%



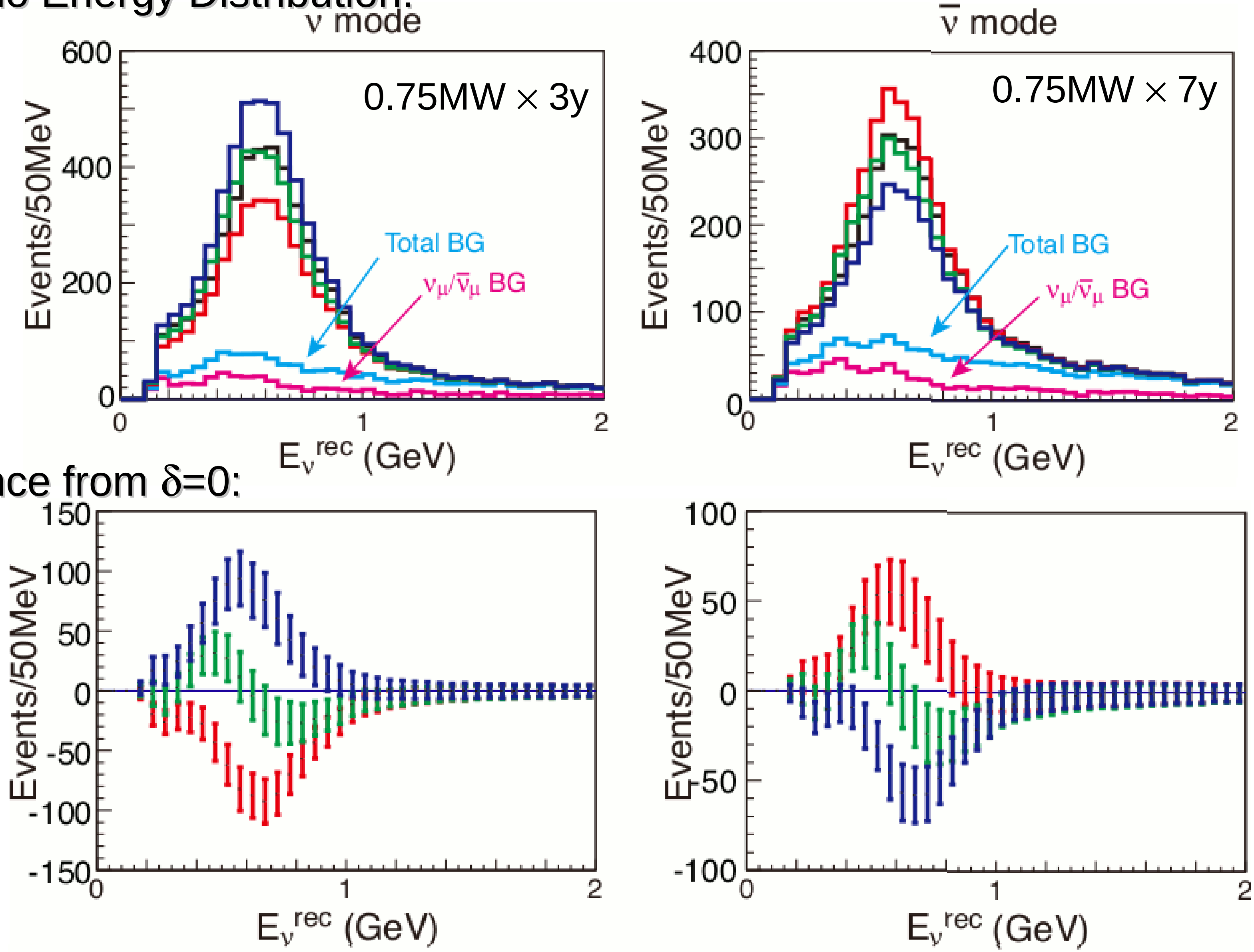
	Signal ($\nu_\mu \rightarrow \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν (2.25MW · 10^7s)	3,560	46	35	880	649
$\bar{\nu}$ (5.25MW · 10^7s)	1,959	380	23	878	678

NC background can be further reducted by fiTQun

- ~2000 ~ 3600 events in $\bar{\nu}$ and ν beams, respectively
- Major backgrounds: beam $\nu_e/\bar{\nu}_e$ and NC-π^0

Effect of δ

Neutrino Energy Distribution:



Difference from δ=0:

$\delta = ½\,\pi$

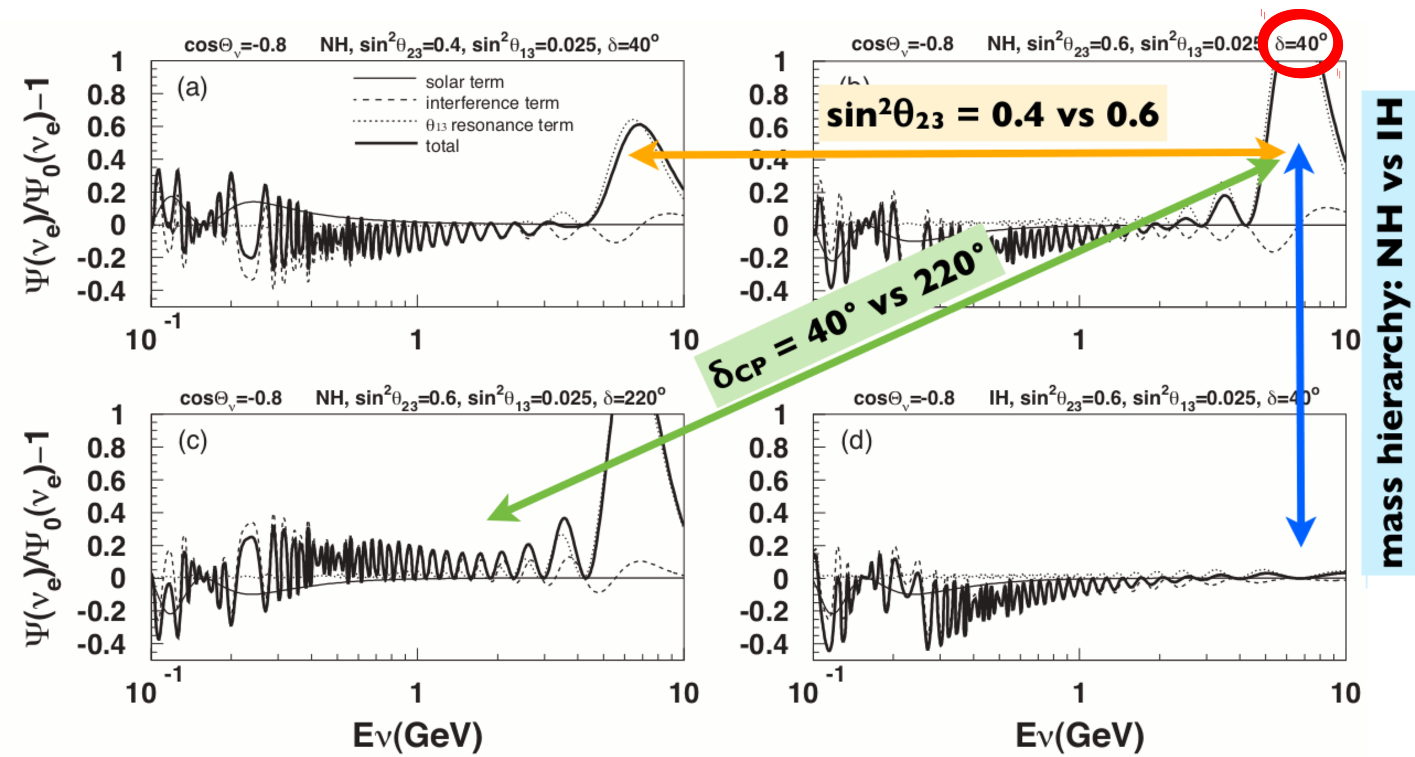
$\delta = \pi$

$\delta = 3/2\,\pi$

- Number + shape sensitive to all values of δ

Atmospheric Neutrinos

Oscillated ν_e flux relative to the non-oscillated flux as a function of the neutrino energy for the up-ward going neutrinos with zenith angle 0.8



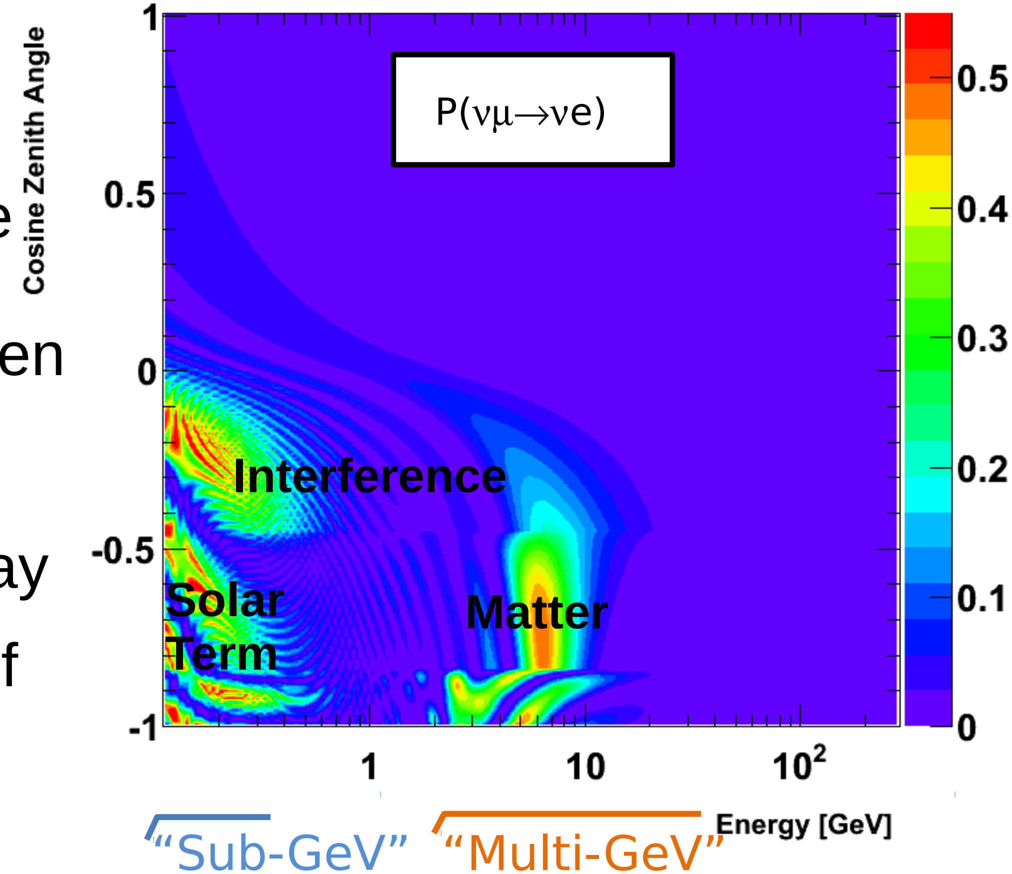
Through matter effect (MSW), we study:

- Mass Hierarchy: asymmetry between ν and $\bar{\nu}$
- Octant of θ_{23}: ν_e appearance and ν_μ disappearance interplay
- δ_{CP} (and θ_{13}): interference effects in ~GeV region

Atmospheric Neutrinos

ν_e appearance and ν_μ distortion are expected due to the MSW effect in the Earth's matter:

- Mass hierarchy: asymmetry between neutrinos and antineutrinos
- Octant of oscillation: appearance (and $\nu_\mu \rightarrow \nu_\mu$ disappearance) interplay
- CP phase δ (and θ_{13}): magnitude of resonance effect.



$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \sim P_2 (r \cos^2\theta_{23} - 1)$$ Solar Term

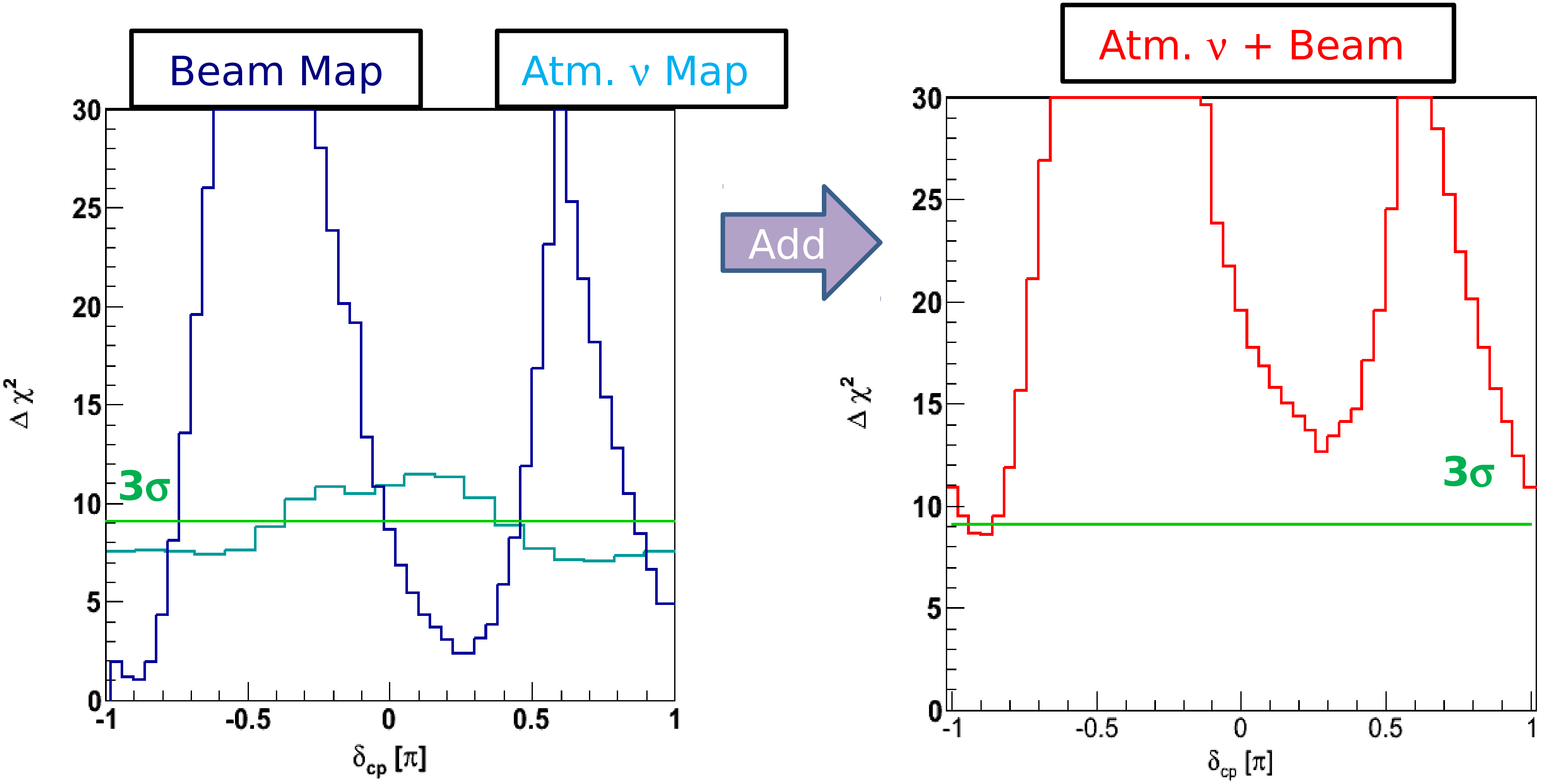
$$- r \sin\tilde{\theta}_{13} \cos^2\tilde{\theta}_{13} \sin 2\theta_{23} (\cos\delta R_2 - \sin\delta I_2)$$ Interference

$$+ 2 \sin^2\tilde{\theta}_{13} (r \sin^2\theta_{23} - 1)$$ Matter Effect

$P_2 = P(\nu_e \rightarrow \nu_{\mu,\tau})$

R_2 and I_2 are the oscillation amplitudes for CP even and odd terms

Beam + Atmospheric ν: Hierarchy sensitivity



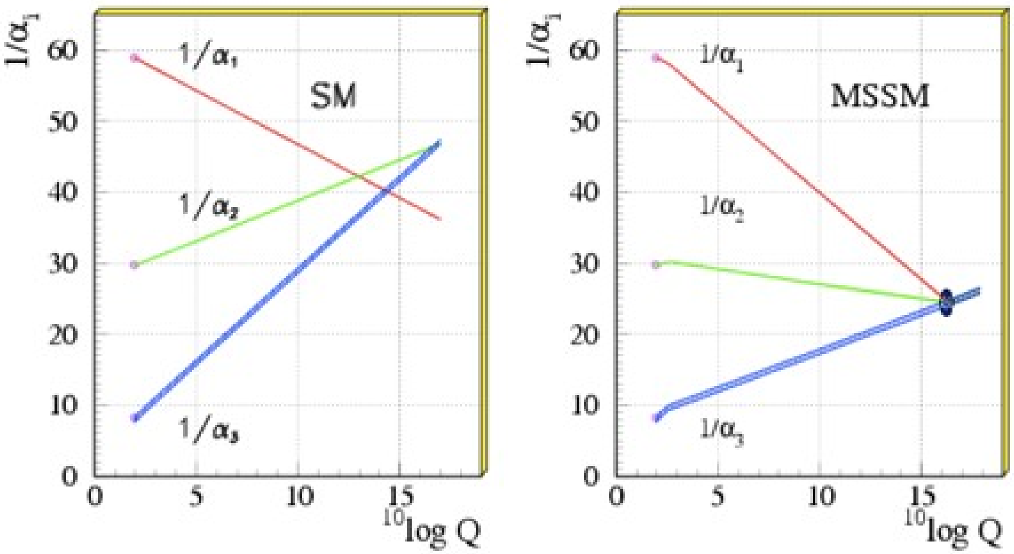
- Hierarchy is unknown, but the NH is true.
- True δ_{CP} = 0.4; True $\sin^2 2\theta_{13}$ = 0.10; $\sin^2 2\theta_{23}$ = 0.4
- Even under a conservative assumption its possible to achieve ~3σ discrimination or all values of δ_{CP} if the true hierarchy is normal.

Atmospheric Neutrino Sensitivity Summary

Objective		Normal	Inverted	Comment
Hierarchy	2σ	$\sin^2 2\theta_{23} > 0.96$	$\sin^2 2\theta_{23} > 0.96$	5 years
	3σ	$\sin^2 \theta_{23} > 0.4$	$\sin^2 \theta_{23} > 0.4$	10 years
Octant	2σ	$\sin^2 2\theta_{23} > 0.997$	$\sin^2 2\theta_{23} > 0.99$	5 years
	3σ	$\sin^2 2\theta_{23} > 0.99$	$\sin^2 2\theta_{23} > 0.97$	5 years

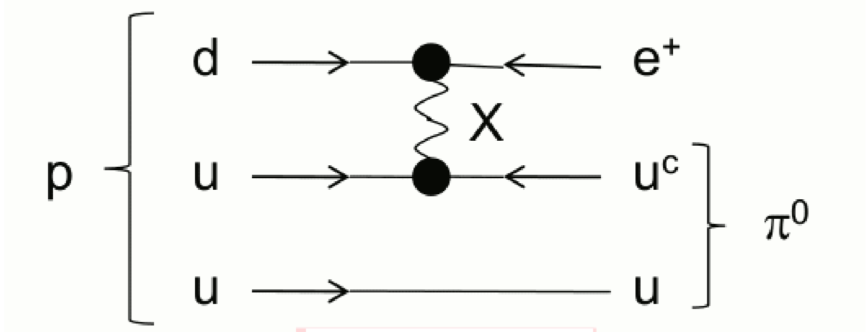
Nucleon Decays

- Only direct probe of Grand Unified Theories

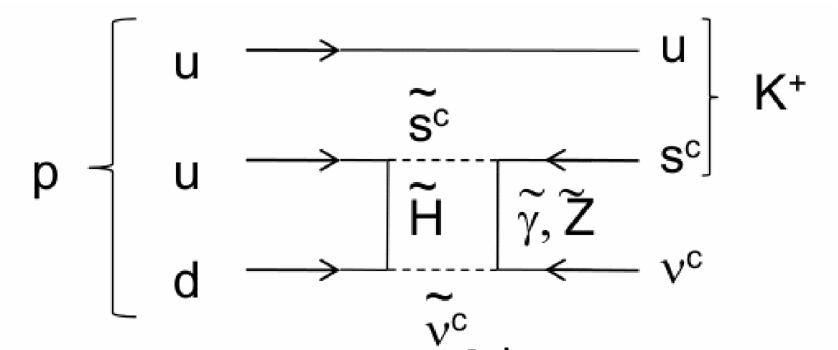


- Many GUT models predict decays of protons and bound neutrons with $\tau = O(10^{34\text{-}35})$ years.

- Two modes favoured by many models:



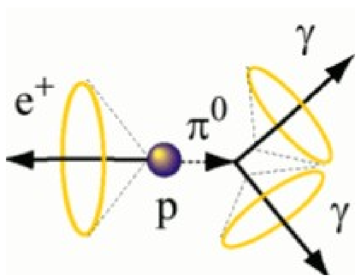
$p \rightarrow e^+\pi^0$



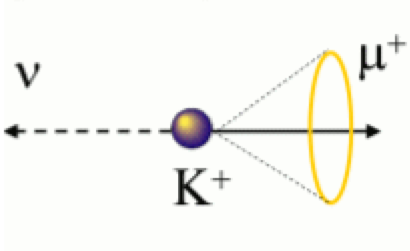
$p \rightarrow \nu k^+$

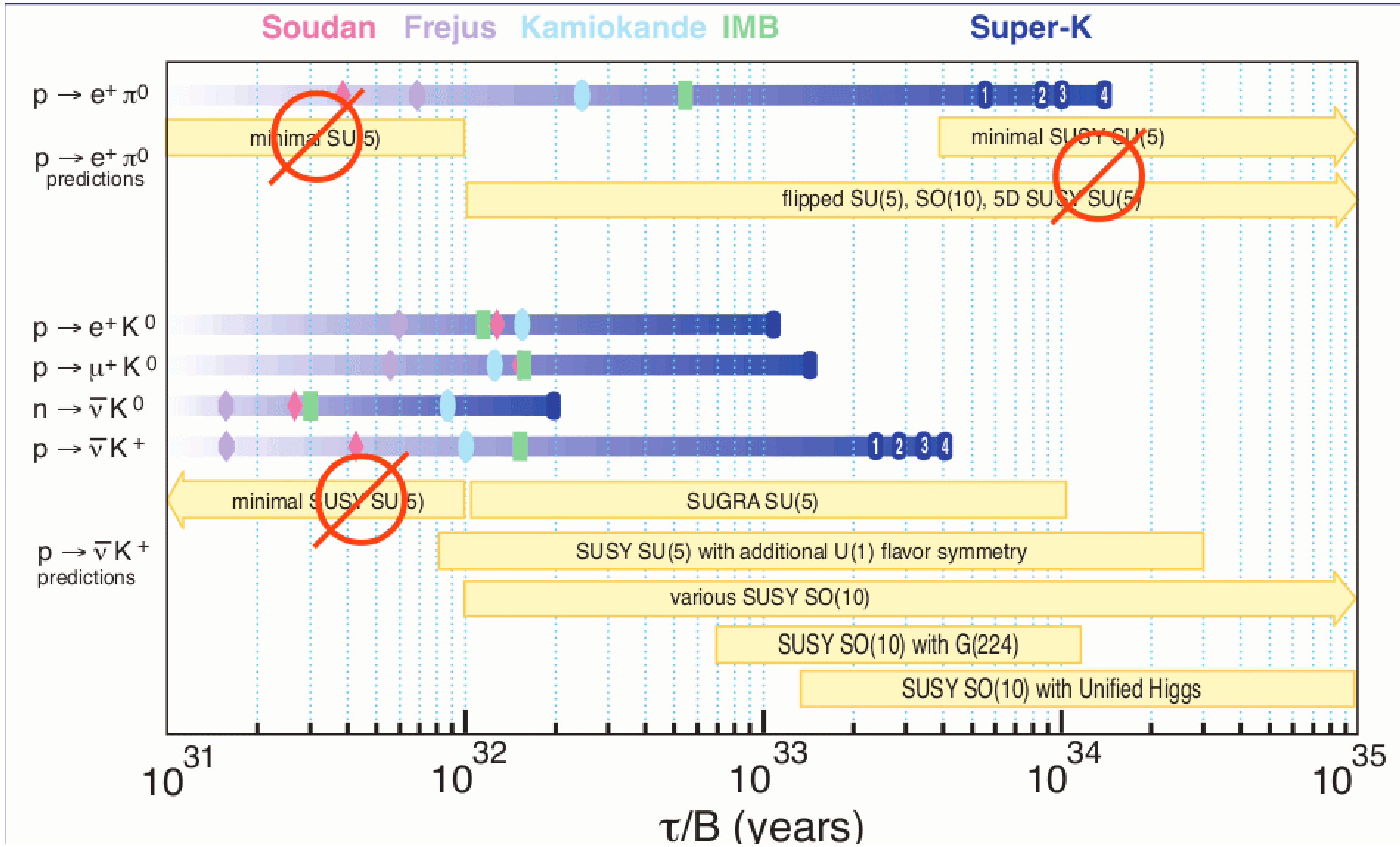
- Other modes are also important.

Experimental Limits



Br = 63.5%





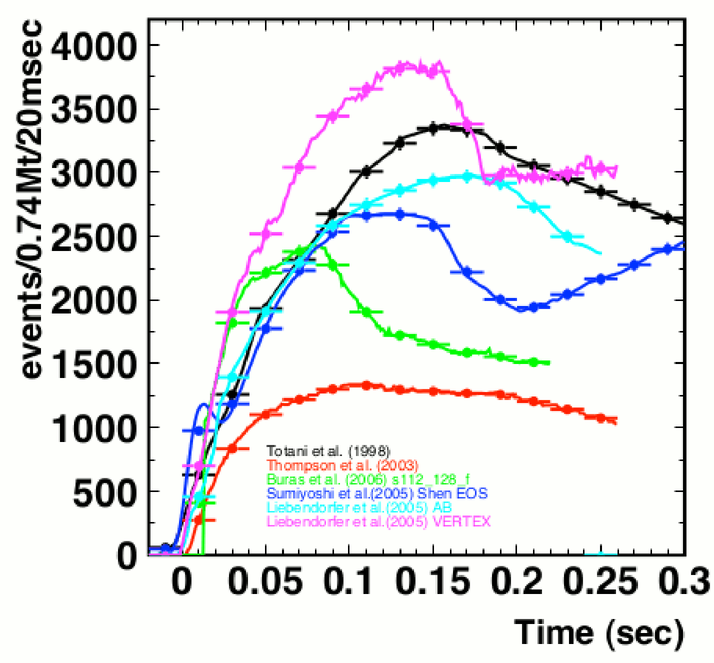
- Most stringent limits from Super-K for many decay modes.
- No signal evidence has been found → give constraints on models.
- After 15y Super-K running (220kton years):

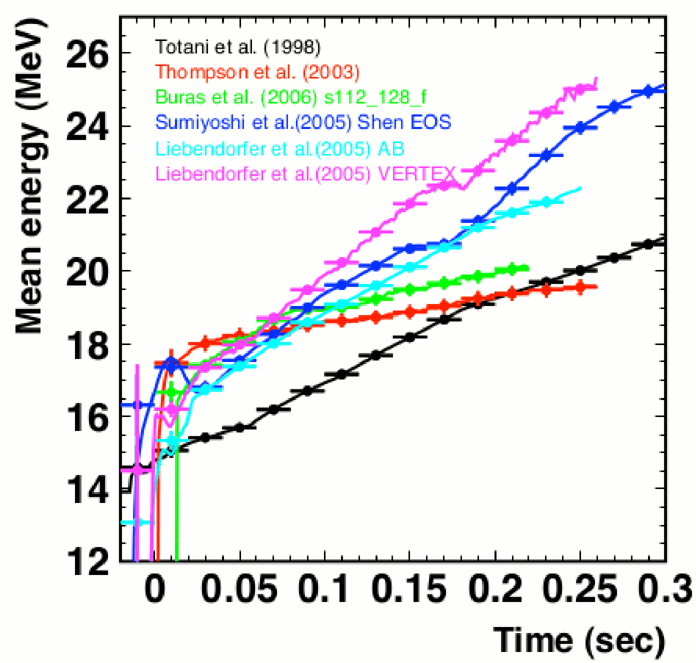
  $\tau(p \rightarrow e^{+}\pi^{0}) > 1.3\times10^{34}$ y $\tau(p \rightarrow \nu k^{+}) > 4.0\times10^{33}$ y   @90%CL
- Order of magnitude necessary to be significant.

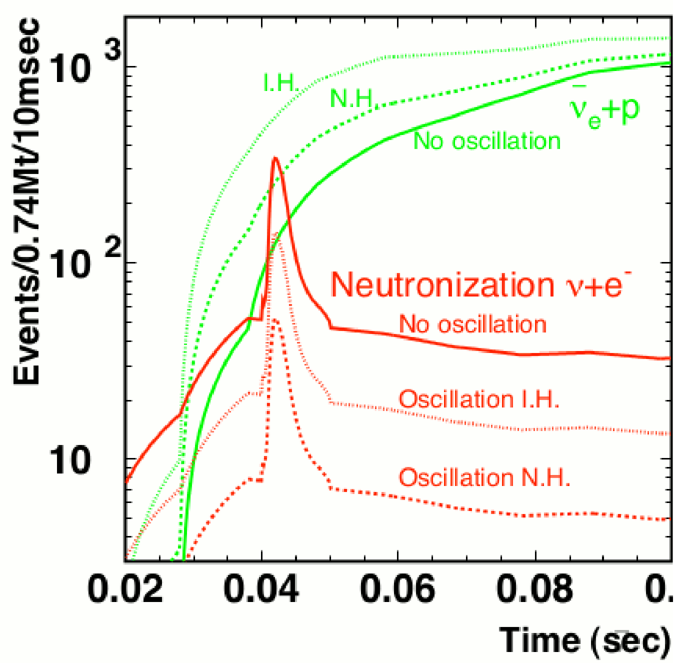
Cosmic Neutrinos

High statistical observation by 200,000 ν events

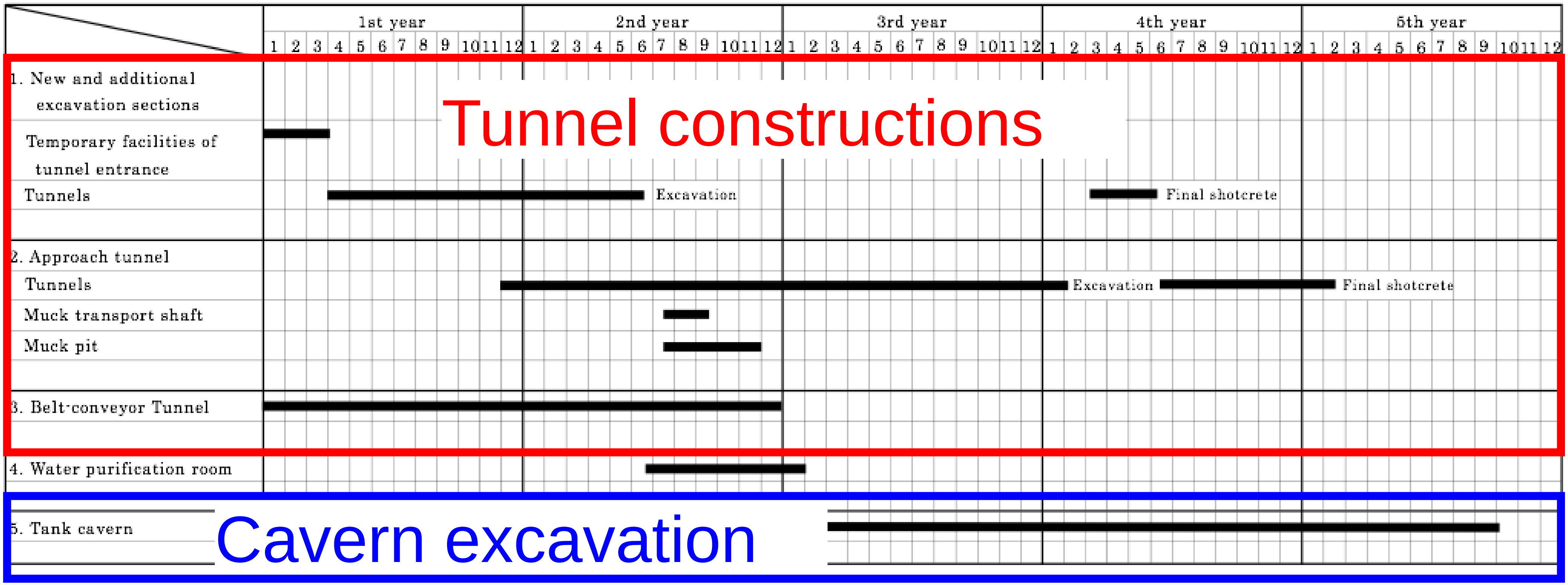
- Time variation of ν luminosity, temperature, flavour
- Explore core collapse and mechanism (model)
  - Exp'd ν from neutronization is 20 (NH) or 56 (IH) in 10 msec duration → precise moment when a neutron star is born
  - Precise time determination ~1ms → combined study with optical and gravitational wave observation
- Absolute ν mass (ν's TOF) → 0.3-1.3 eV
- Energy spectrum transition by ν mass hierarchy





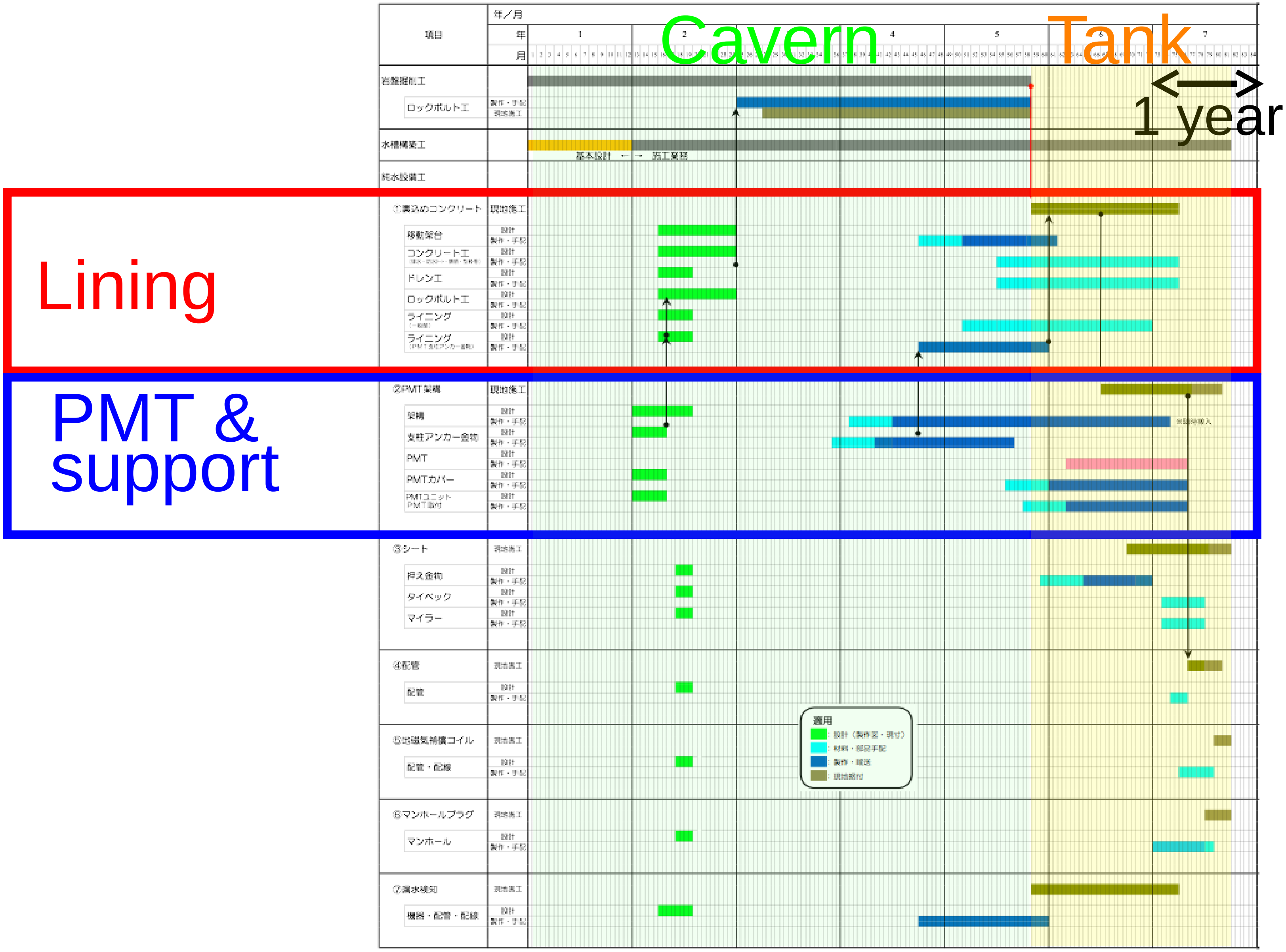


Excavation Schedule



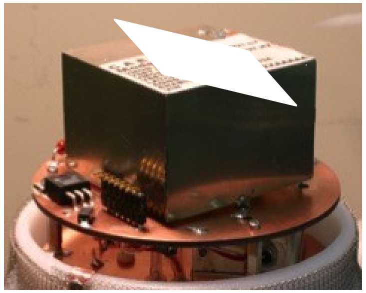
- Cavern construction period: ~5 years
- Transport / approach tunnels: ~3 years
- Excavation of caverns: ~3 years

Tank construction schedule



- Tank construction: ~2 years
- Lining: 1+ years, PMT installation: ~1 year

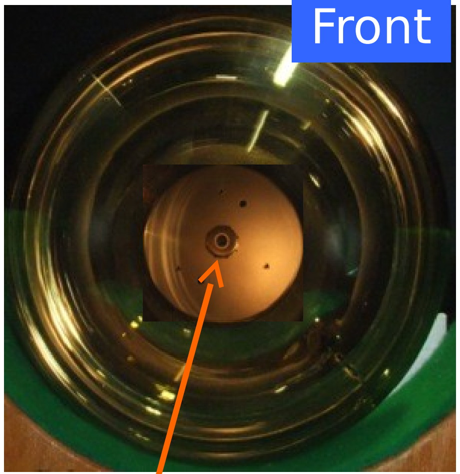
8" HPD Prototype

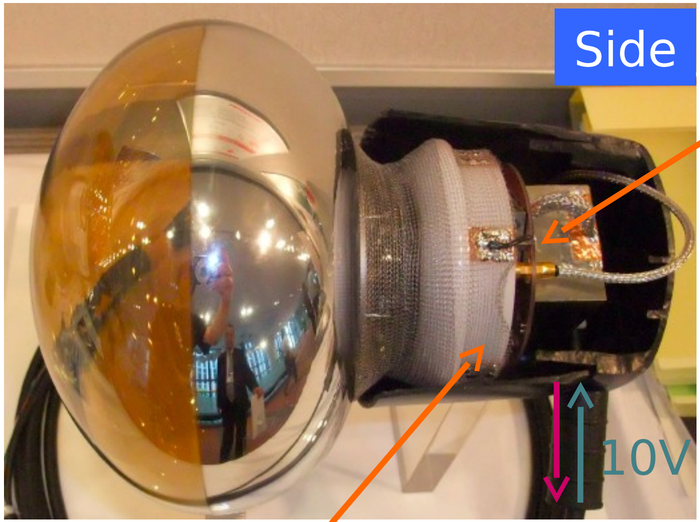


High voltage module
(2ch 10kV/500V Max.)

30cm

20cm





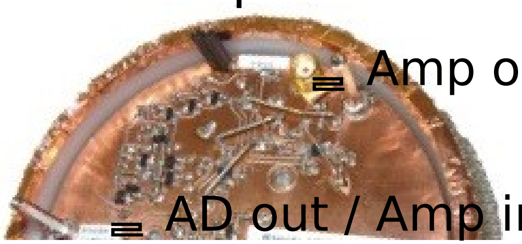
HV module and preamplifier are packed and waterproofed

→ No HV line in water

Signal

5mmφ AD

Preamp board



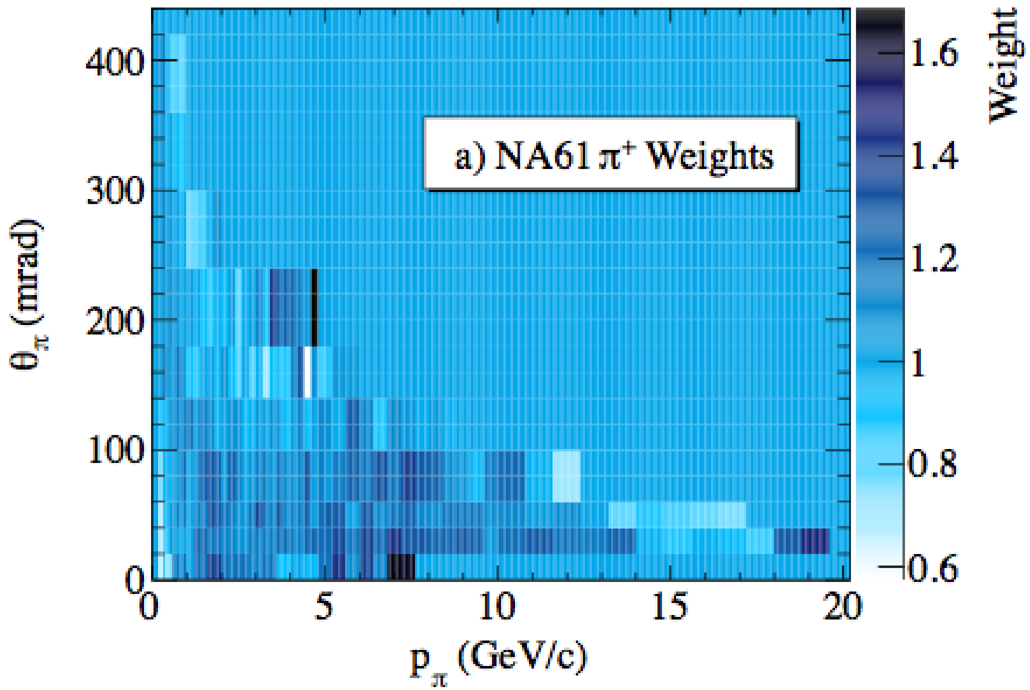
Spectral response		300 - 650 (420 max.) nm
Photocathode		Bialkali
Window material		Borosilicate glass
Gain		4 - 9 x 10^4
Time	Rise	1.7 ns
	Fall	2.7 ns
	T.T.S.	0.62 ns (σ)
Dynamic range		100 pC (1.5 x 104 p.e.)

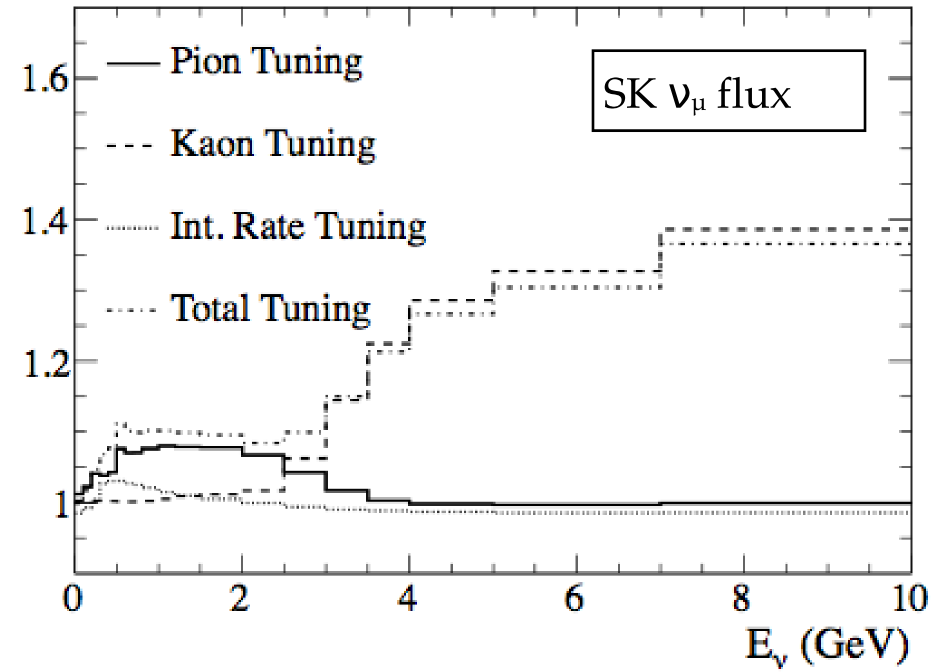
Ten 8″ HPDs were made for long-term testing

See A. Bravar's talk

Hadron Production with External Data

- Reweight flux for each energy to match MC prediction to data.
- External data : NA61/SHINE **[1][2]**, Eitchen *et al.* **[3]**, Allaby *et al.* **[4]**





[1] N. Abgrall *et al*. (NA61/SHINE Collaboration), Phys. Rev. C 84, 034604 (2011)

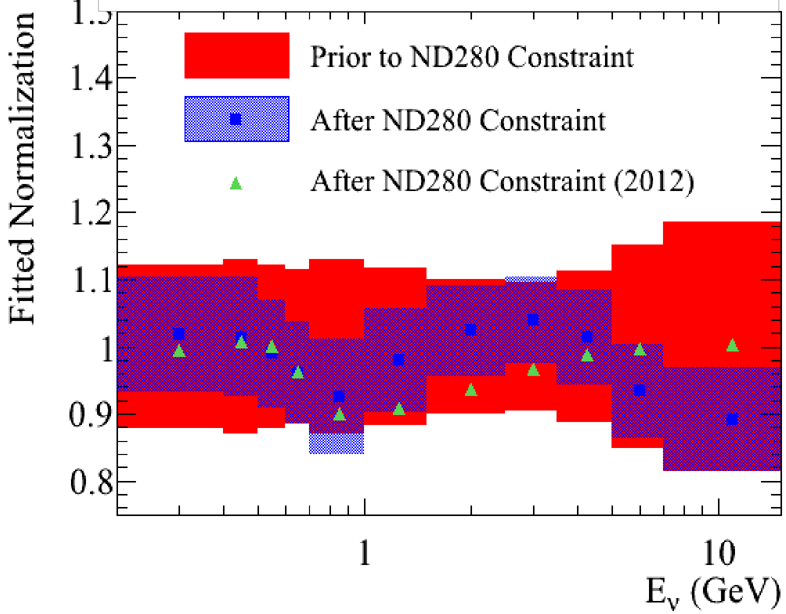
[2] T. Eichten *et al.*, Nucl. Phys. B 44 (1972)

[3] N. Abgrall *et al*. (NA61/SHINE Collaboration), Phys. Rev. C 85, 035210 (2012)

[4] J. V. Allaby *et al.*, Tech. Rep. 70-12 (CERN,1970)

Flux and X-Sections after Constraint

SK Flux Normalization



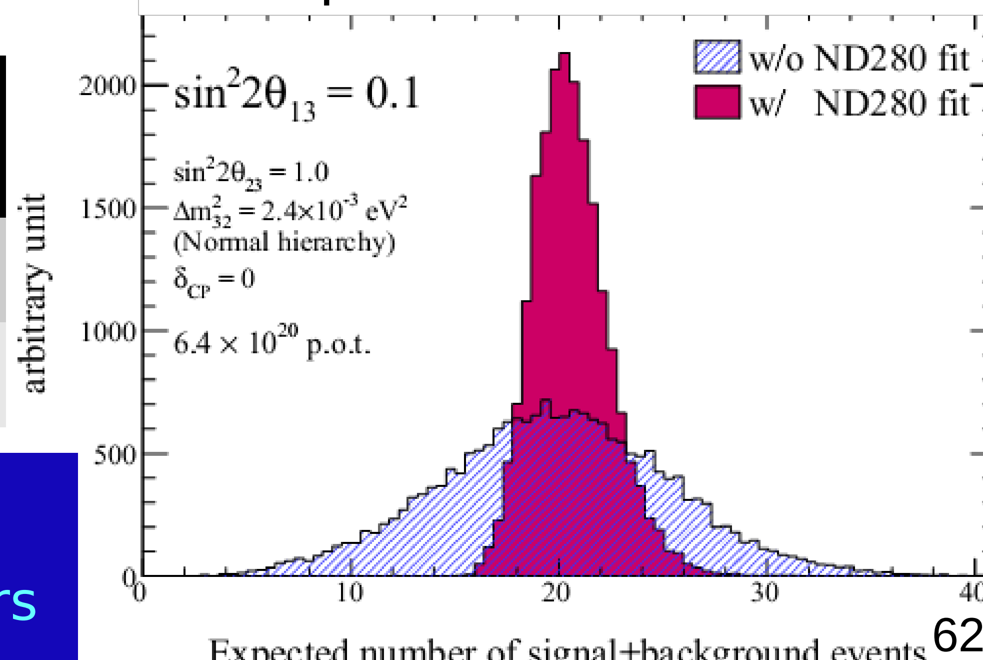
Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.22 ± 0.07
CCQE Norm.*	1.00 ± 0.11	0.96 ± 0.08
M_A^{RES} (GeV)	1.41 ± 0.22	0.96 ± 0.06
CC1π Norm.**	1.15 ± 0.32	1.22 ± 0.16

*For Eν<1.5 GeV **For Eν<2.5 GeV

$\sin^2 2\theta_{13}=0.1$

	ν_e Prediction (Events)	Error from Constrained Parameters
No ND280 Constraint	18.4	25.9%
ND280 Constraint	17.3	2.9%

SK Expected Number of Events



Near Detector and Hadronization constraints vital for reducing the errors