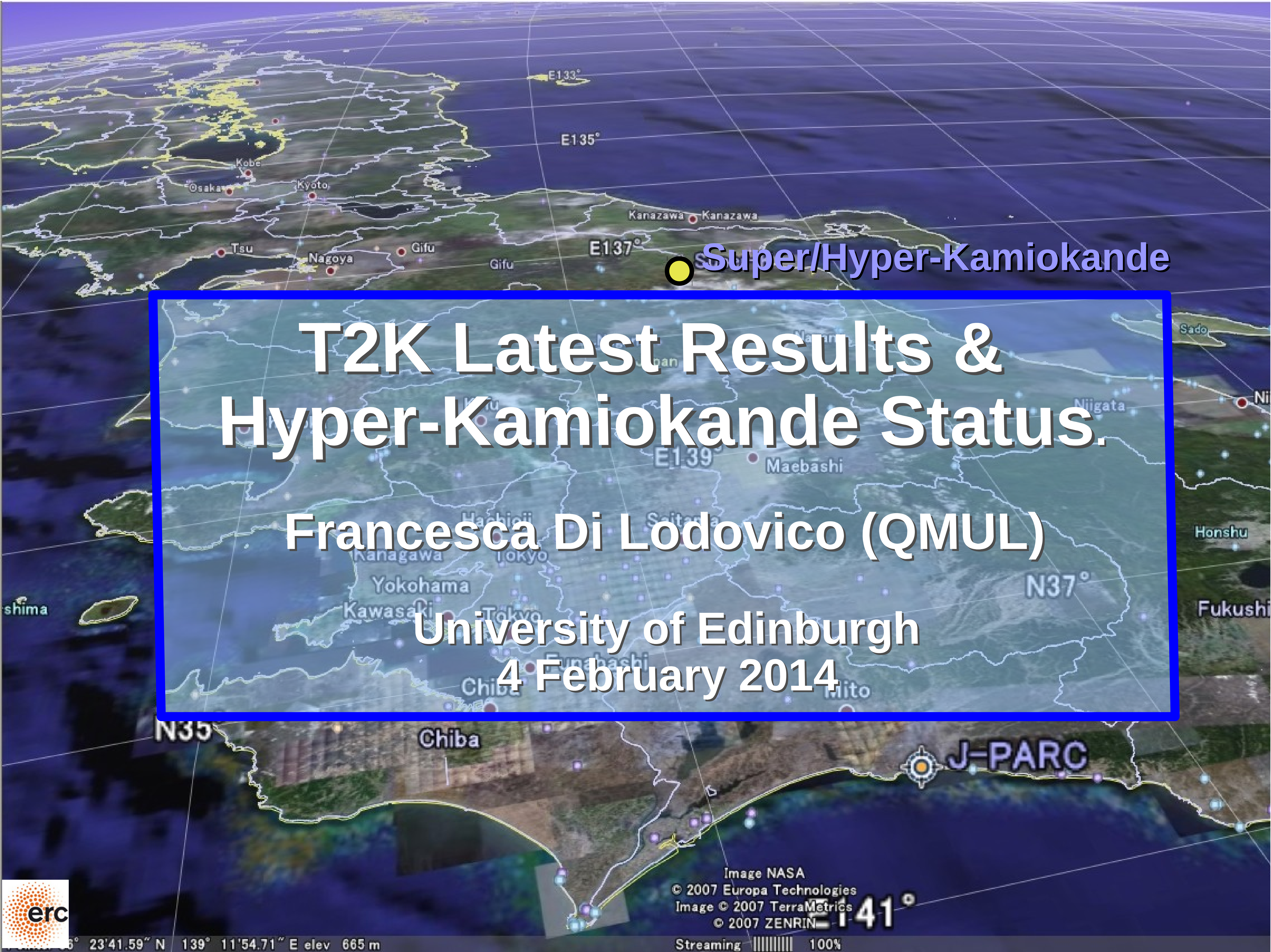
T2K Latest Results & Hyper-Kamiokande Status.

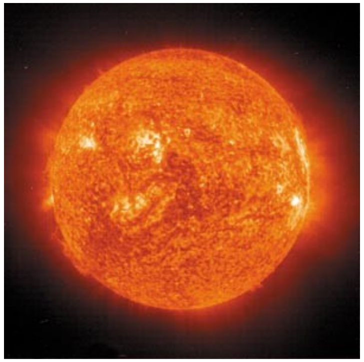
Francesca Di Lodovico (QMUL)

University of Edinburgh
4 February 2014



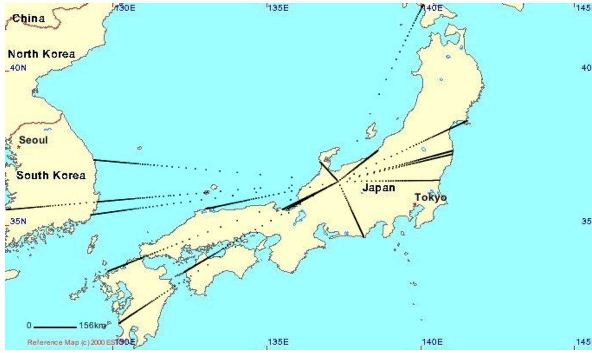
Neutrino Oscillations: Established

Sun



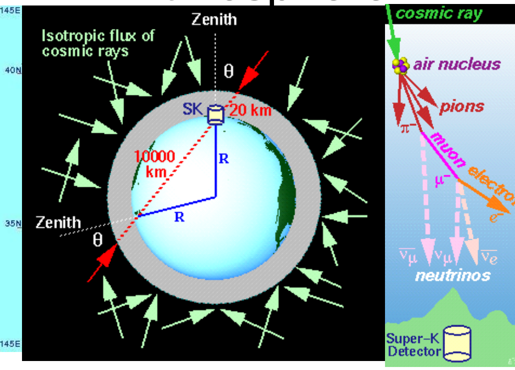
Homestake, SAGE, GALLEX, Super-K, SNO, Borexino

Reactors



KamLAND, Chooz

Atmosphere



Super-Kamiokande

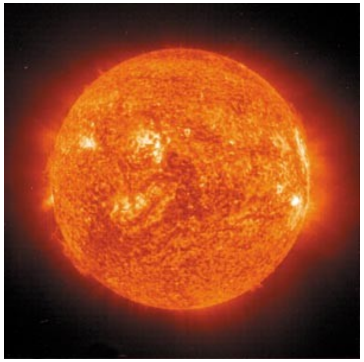
Accelerators

K2K, MINOS, T2K

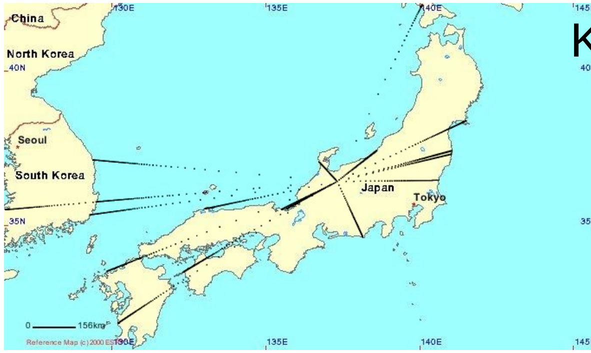
$\nu_\mu \rightarrow \nu_\tau$ or anti-$\nu_\mu \rightarrow$ anti-ν_τ	atmospheric & beam experiments
$\nu_e \rightarrow \nu_{\mu,\tau}$	solar experiments
anti-$\nu_e \rightarrow$ anti-ν_{other}	reactor experiments
(anti-)$\nu_\mu \rightarrow$ (anti-)ν_{other}	atmospheric & beam experiments
$\nu_\mu \rightarrow \nu_e$	beam experiments

Neutrino Oscillations: Established

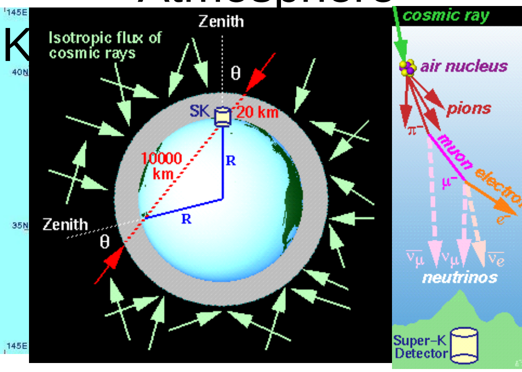
Sun



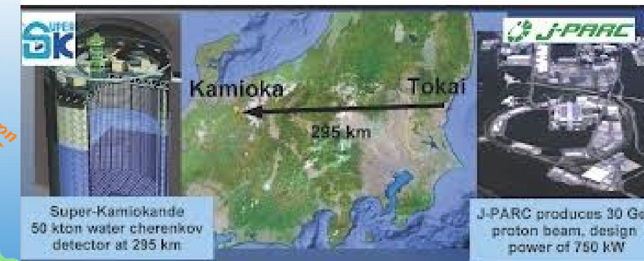
Reactors



Atmosphere



Accelerators



Homestake, SAGE, GALLEX, Super-K, SNO, Borexino

KamLAND, Chooz

Super-Kamiokande

- PMNS (Pontecorvo, Maki, Nagakawa, Sakata) matrix for ν:

Flavour eigenstates (coupling to the W)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates (definite mass)

Unitary PMNS mixing matrix

Open Questions in ν Oscillations (I)

Unknown

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ_{23} : "atm." mixing angle $\quad\theta_{13}\quad$ θ_{12} : "solar" mixing angle

$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

- Free parameters: θ_{12}, θ_{23}, θ_{13}, δ

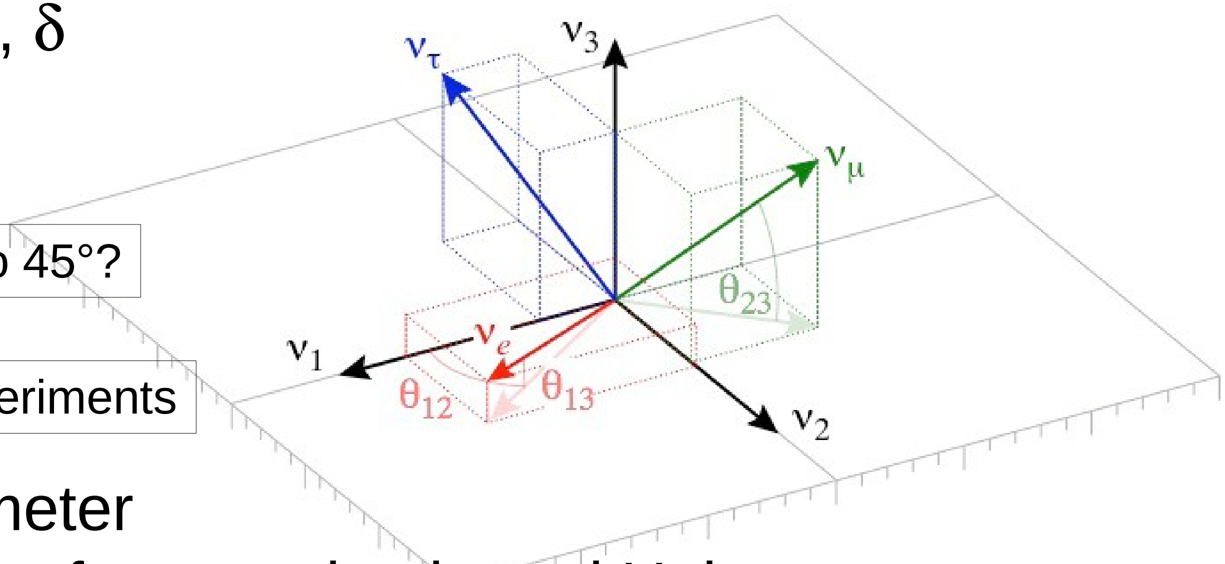
$$\theta_{12} = 34^o \pm 1^o$$

$$\theta_{23} = 40^o + 5^o / -2^o$$

How close to 45°?

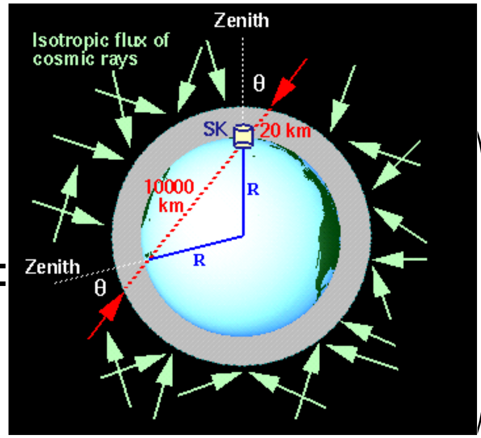
$$\theta_{13} = 9.1^o \pm 0.6^o$$

Reactor experiments



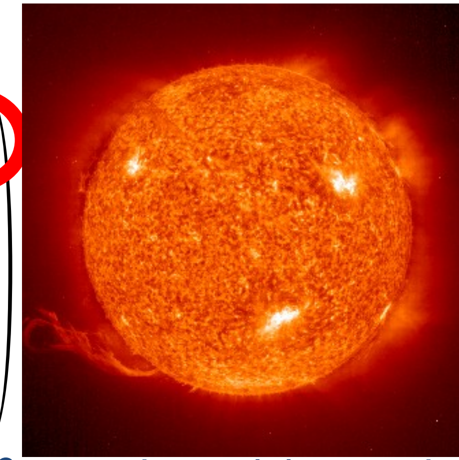
- δ is the only unknown parameter
- Key to understand the origin of matter-dominated Universe (Leptogenesis)

Open Questions in ν Oscillations (I)

$U_{PMNS} =$ 

Unknown

$$\begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix}$$



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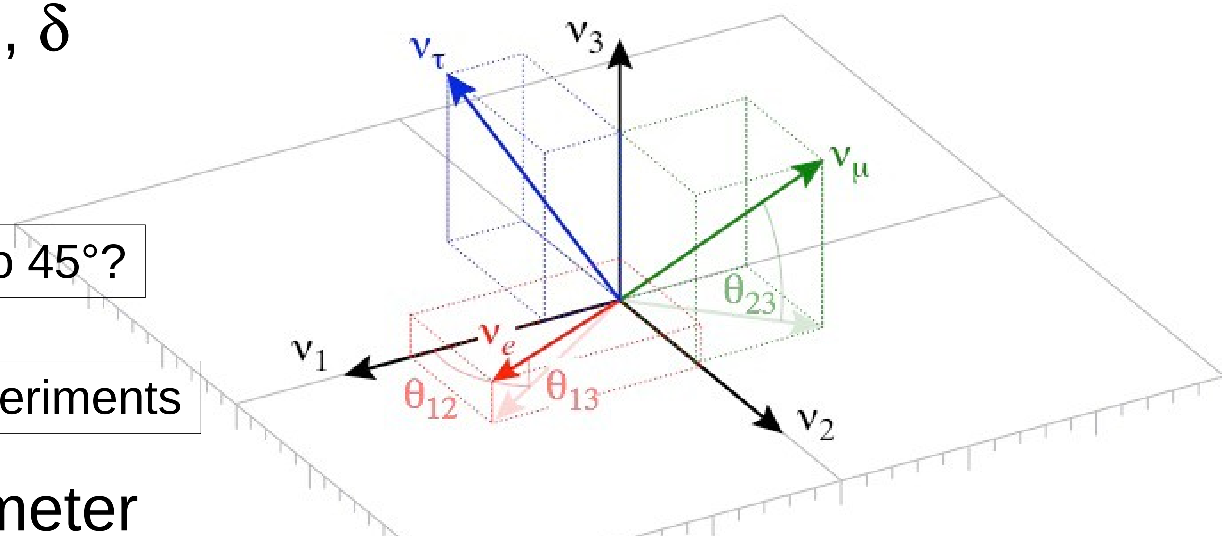


- δ is the only unknown parameter
- Key to understand the origin of matter-dominated Universe (Leptogenesis)

Neutrino Flavour Mixing

As neutrino propagate, the mass eigenstates interfere:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j}\mathrm{Im}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

Probability to observe ν_β after starting with flavour ν_α depends on:

- Mixing matrix elements $U_{\alpha\beta}$
- L(km): Distance the neutrino has travelled
- E(GeV): Energy of the neutrino
- $\Delta m_{ij}^2(eV^2) = m_i^2 - m_j^2$: mass splitting

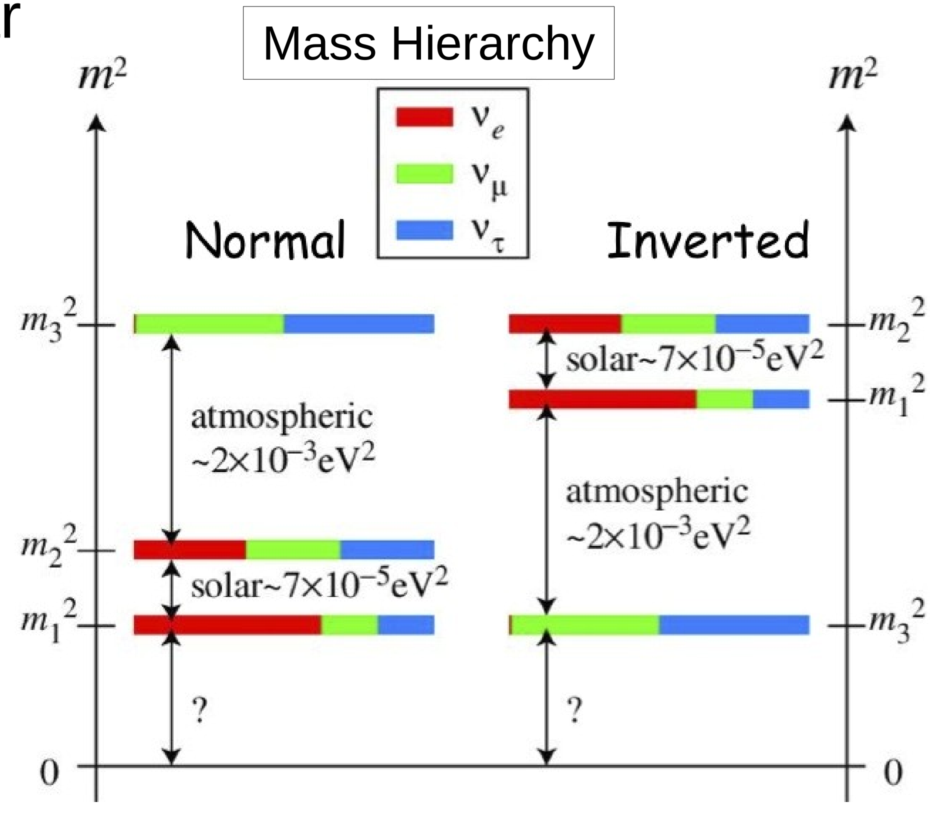
If neutrinos have no mass, or degenerate masses, no interference is possible.

Open Questions in ν Oscillations (II)

Two observed mass splittings, determined from atmospheric and solar neutrino experiments, respectively:

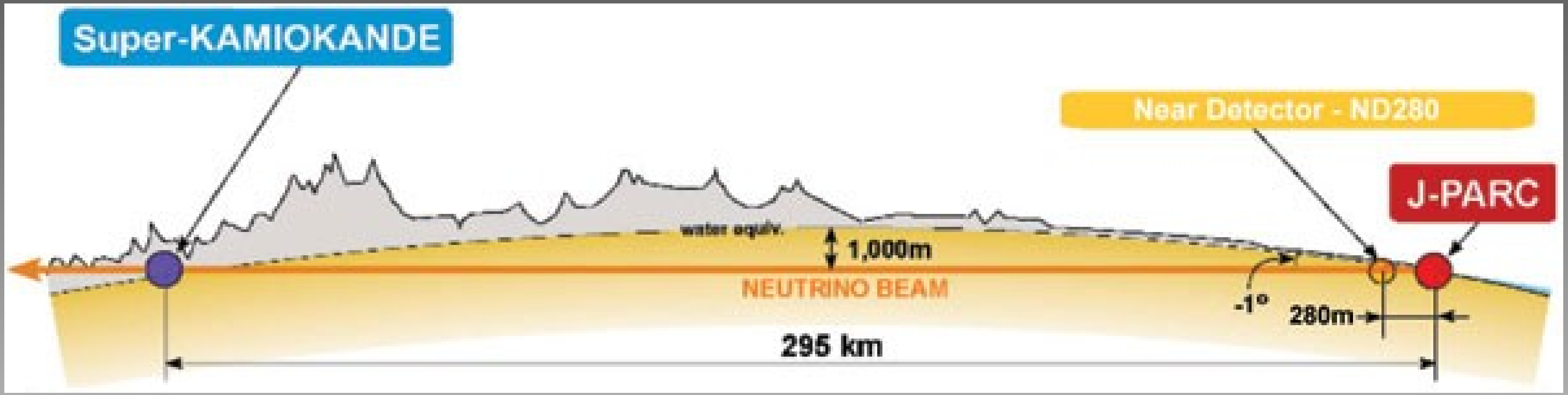
- Δm^2 (atmospheric) = $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}$ eV^2
- Δm^2 (solar) = $\Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV^2

The sign of $|\Delta m^2_{32}|$, or the "mass hierarchy" is still unknown:



- *Normal* mass hierarchy is like quarks (m_1 *is lightest,* $\Delta m^2_{32} > 0$)
- *Inverted* mass hierarchy has m_3 lightest ($\Delta m^2_{32} < 0$)

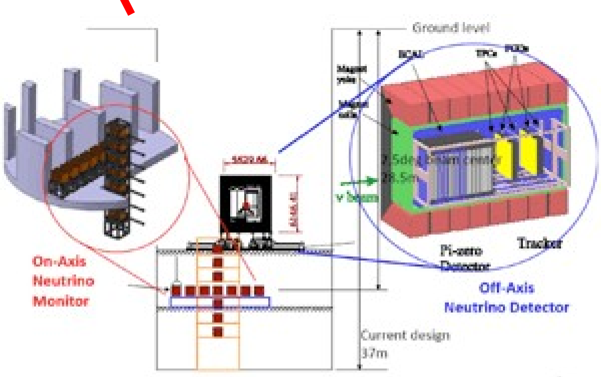
The T2K Experiment




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

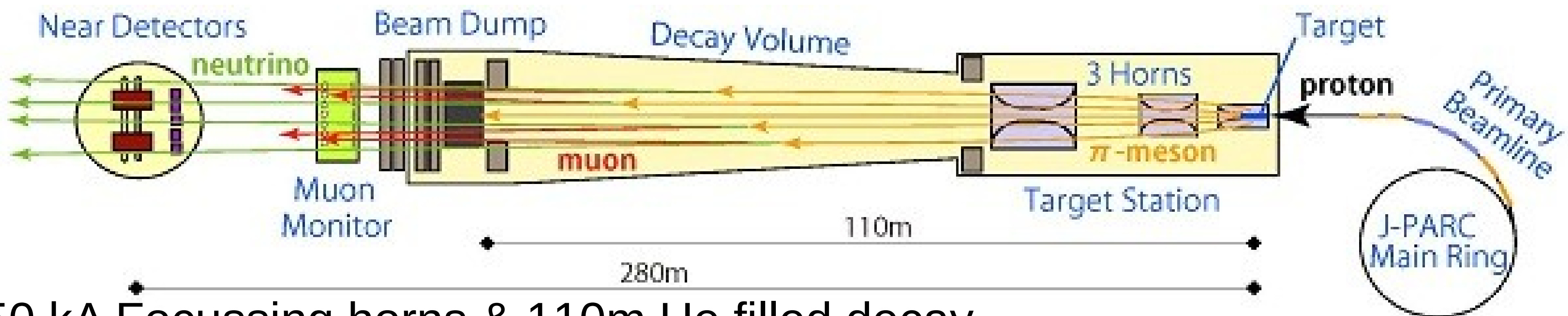
Japan **P**roton **A**ccelerator **R**esearch **C**omplex ν–Beamline

INGRID
on-axis

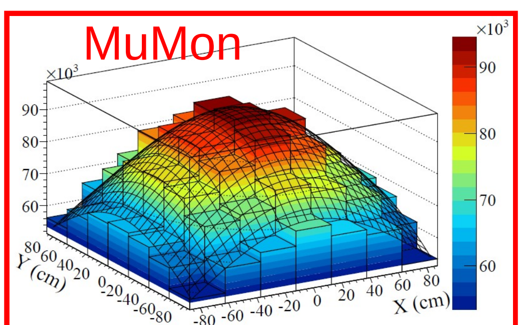


ND280
off-axis

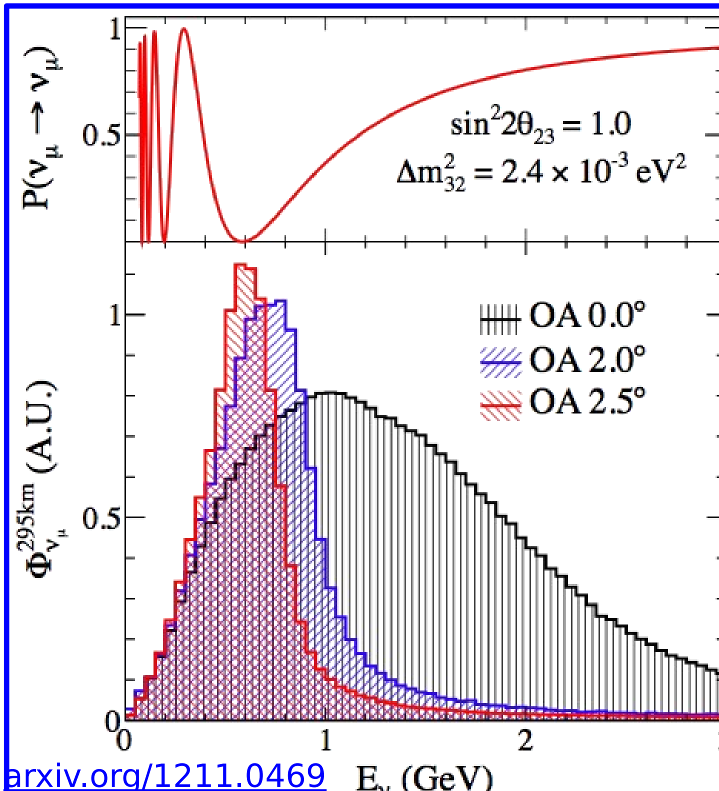
Japan **P**roton **A**ccelerator **R**esearch **C**omplex ν–Beamline



- 250 kA Focussing horns & 110m He filled decay volume
- Series of beam monitors, MuMon muon monitor and INGrid near detector monitors beam centre
  - 2.5o off-axis configuration
  - Reduces peak energy to oscillation maximum
  - Reduces spread of energies around peak.



- Almost monochromatic beam at ~600MeV.
- Take advantage of Lorentz Boost and 2-body kinematics.
- Pure ν_μ beam with <1% ν_e contamination

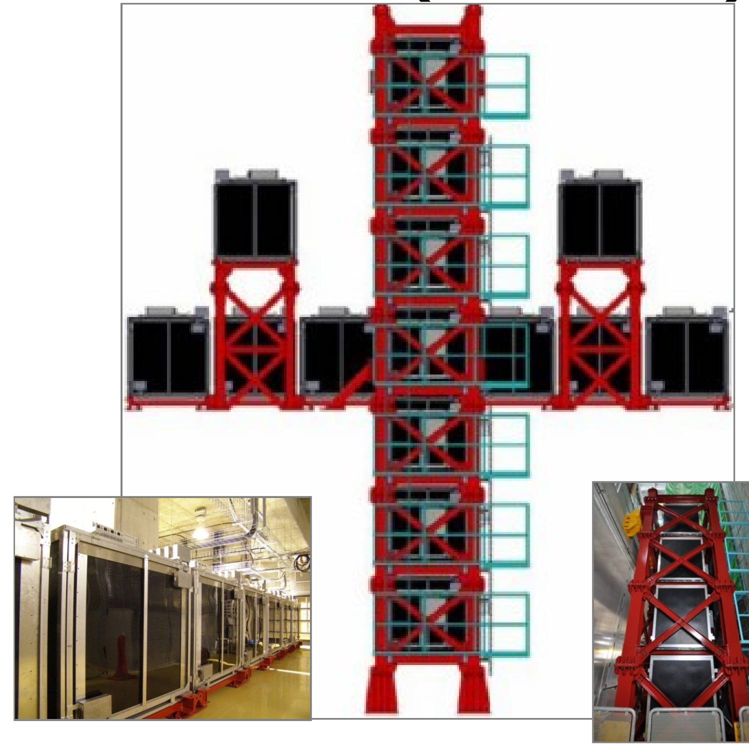


arxiv.org/1211.0469

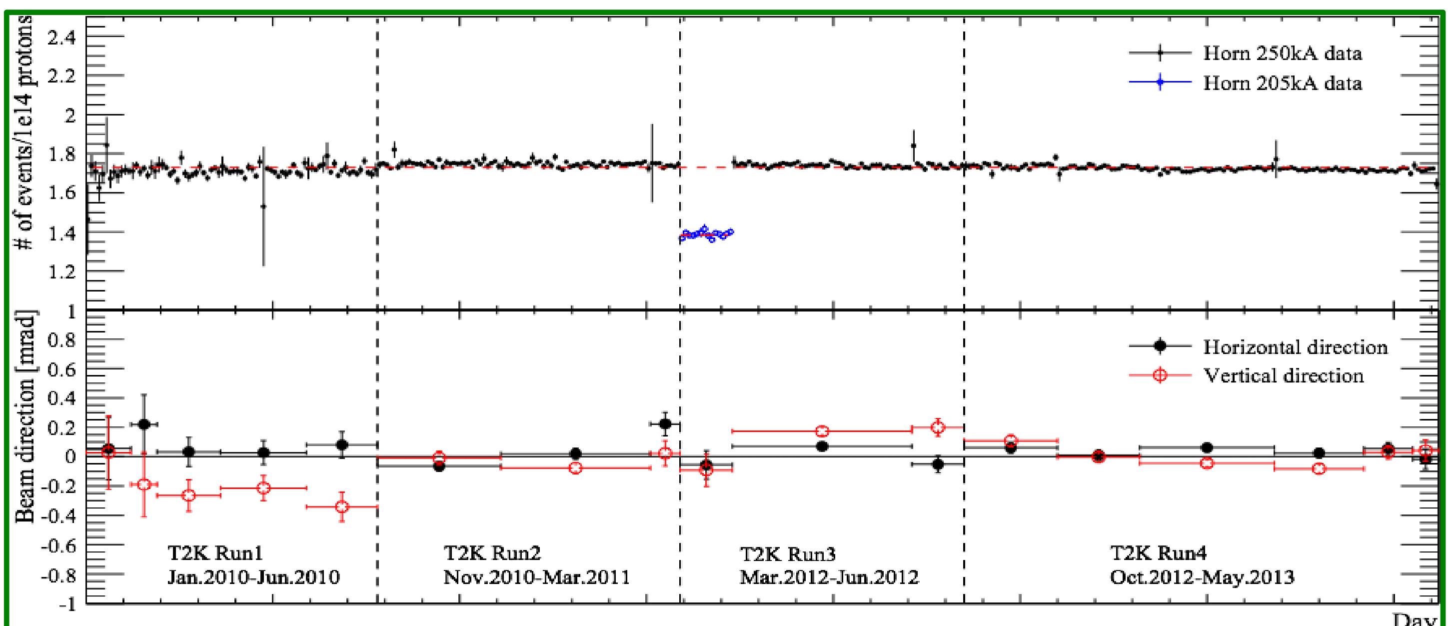
INGRID on-axis near detector (280m)

INGRID (on-axis detector 280m from target):

- Designed to measure neutrino interactions & beam profile (beam intensity, direction &stability)
- Stability of beam direction requested <1mrad to keep the peak energy at SK stable δE<2%
- 7 + 7 modules (iron/scintillator planes sandwiches) in cross shape (central modules on-axis) + 3 extra modules.



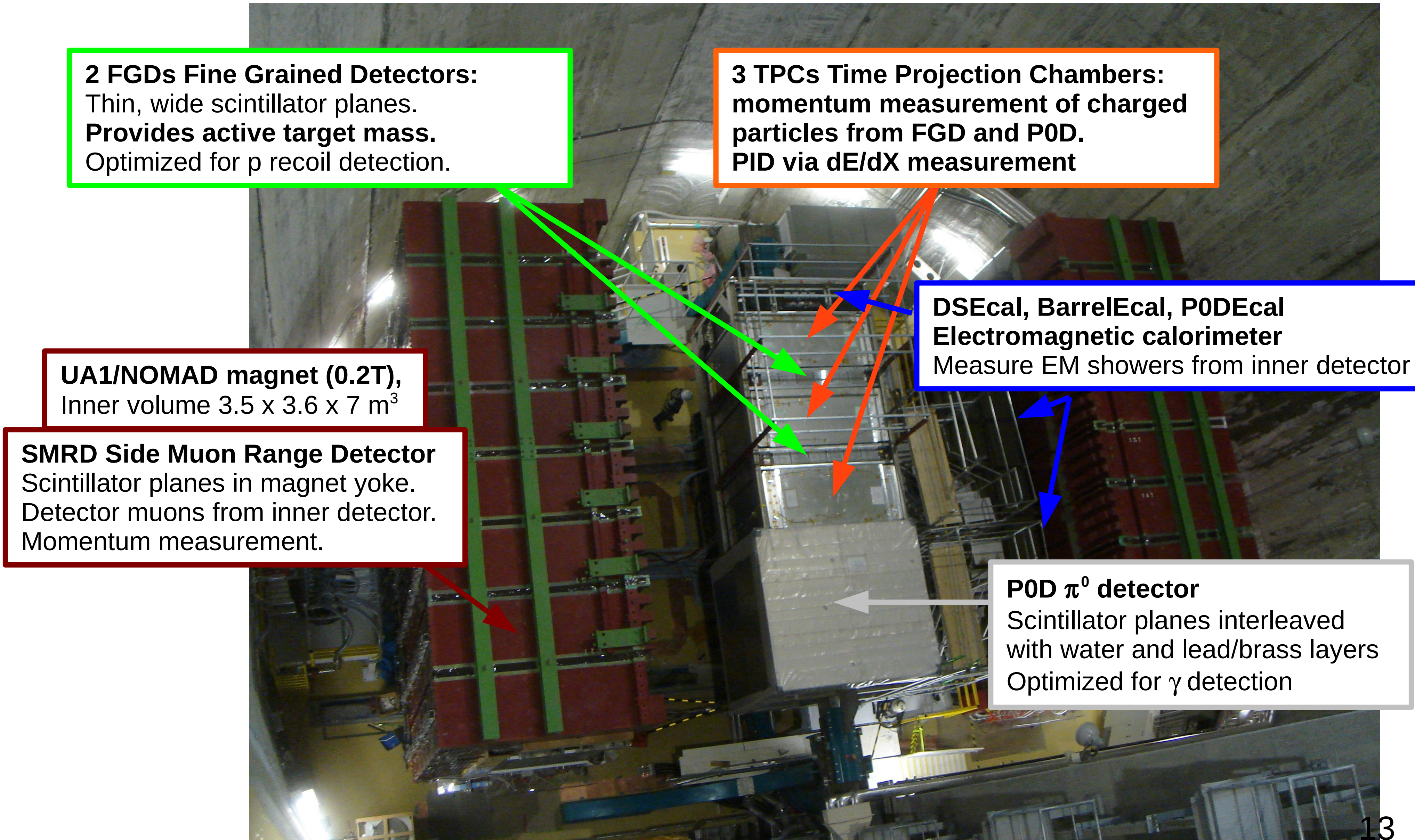
Stability of ν beam direction well within 1 mrad:



ν beam direction stability < 1mrad

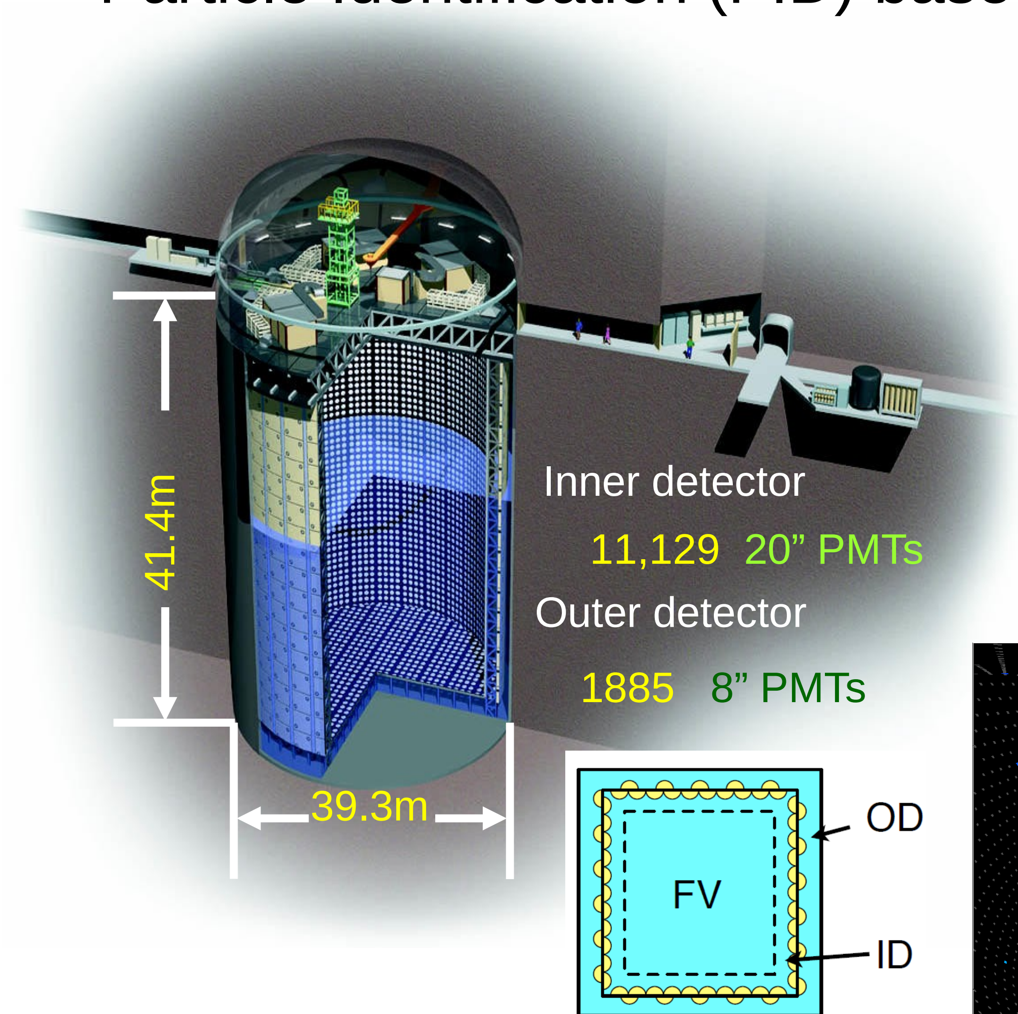
ND280 off-axis near detector (280m)

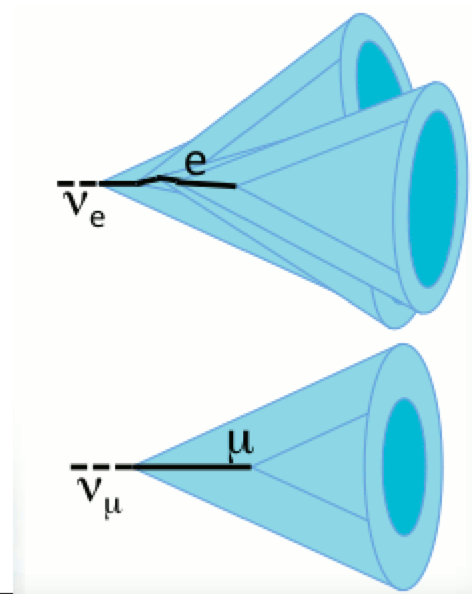
- General purpose detector to measure: CCν_μ events (normalization, E_ν spectrum),
- CCν_e events (background to ν_e appearance), general neutrino interactions.

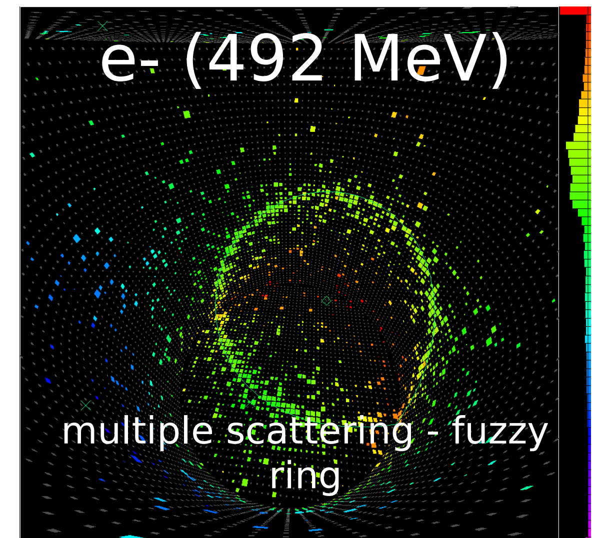


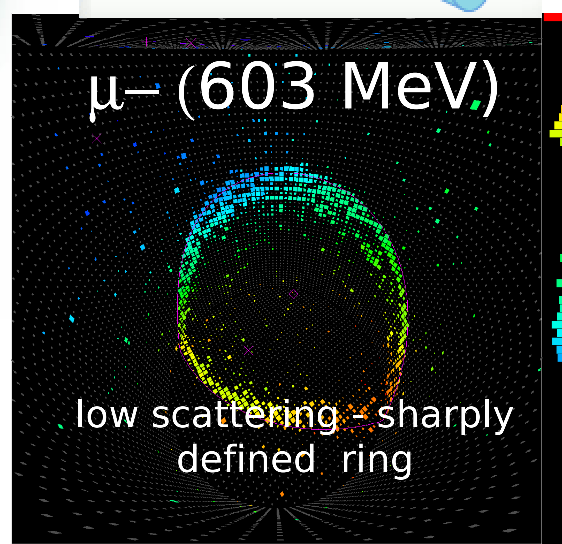
T2K Far Detector: Super-Kamiokande

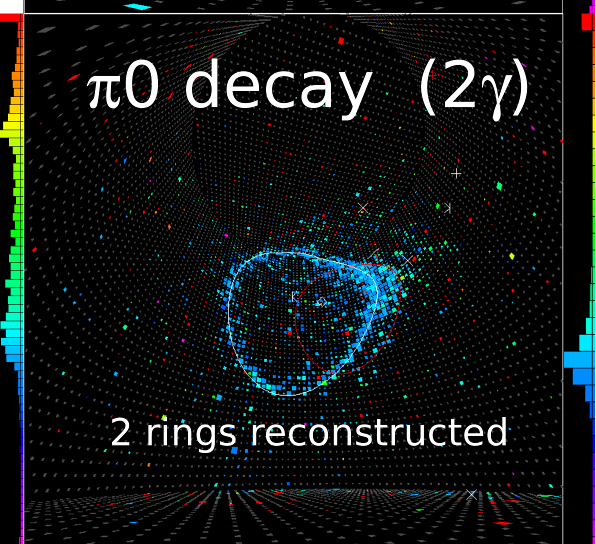
- 50 kton (22.5 kton fiducial) water Cherenkov detector
- Good reconstruction for T2K energy range
- Particle Identification (PID) based on shape of Cherenkov rings





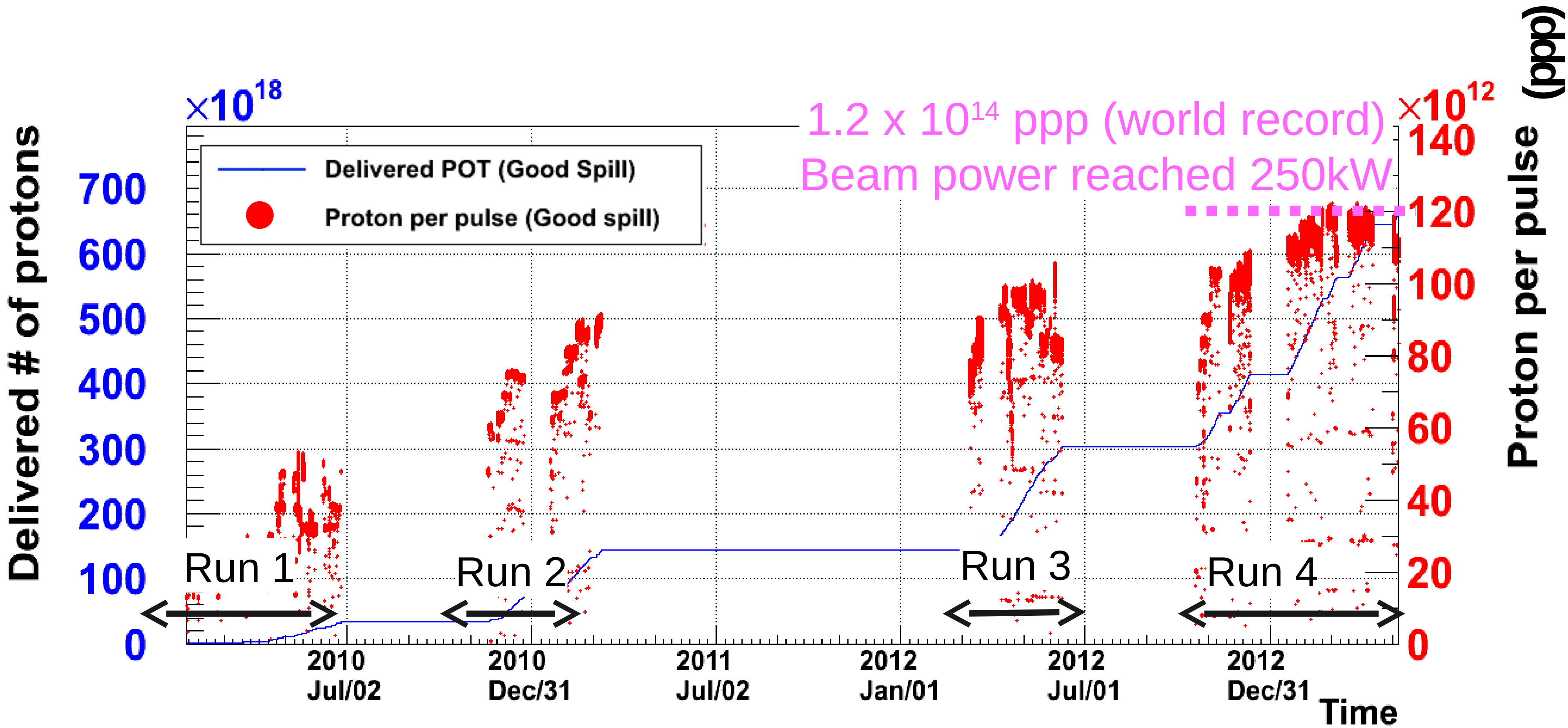






Event displays show Monte Carlo

T2K Dataset



- We collected 6.63×10^{20} protons on target (p.o.t.) so far
- Including 0.21×10^{20} p.o.t. with 205kA horn operation (13% flux reduction at peak) in Run3 (250kA horn current for nominal operation)

(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

NA61/Shine

-at the CERN SPS (North Area, H2 beam line)

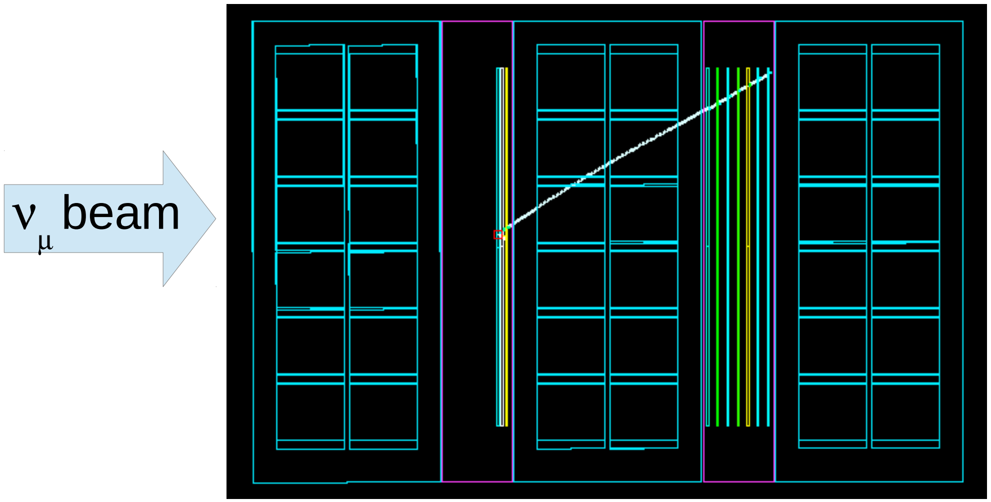
- fixed target experiment on primary (ions) and secondary (ions, hadrons) beams

Constraint from ND280 Data

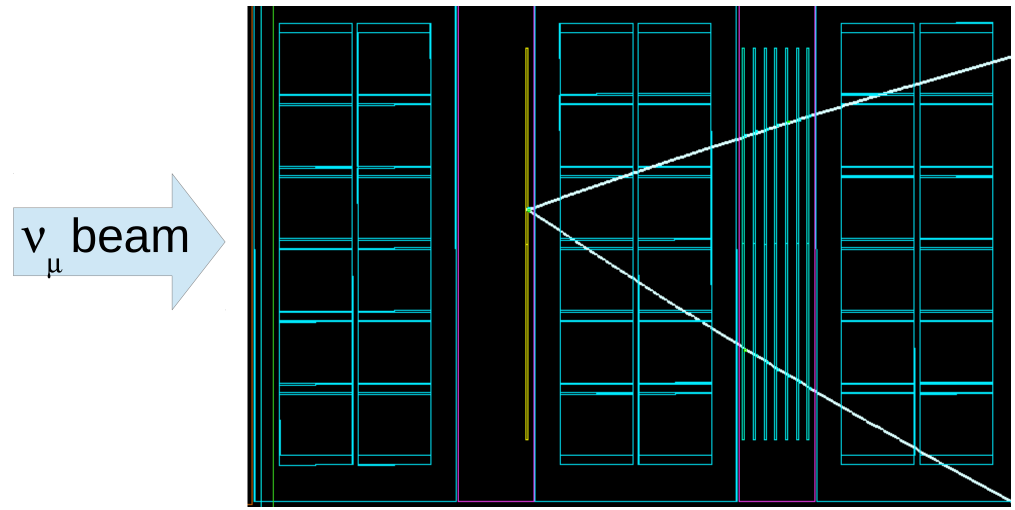
- Input: CC interactions with 0, 1 or multiple pions
- Fit to data constrains flux, and cross section parameters
- Constrained SK flux parameters and subset of cross section parameters are used to predict SK event rates

ND280 Event Categories

Charged current (CC) with 0π



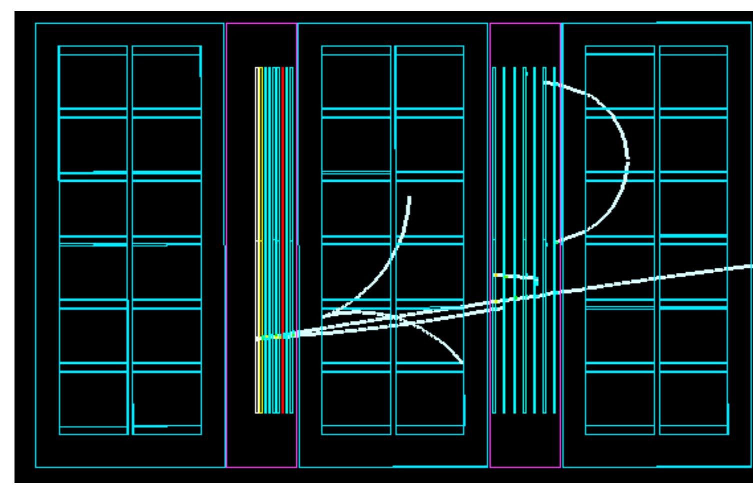
CC 1π^+



CC Other ($\geq$1π^- or π^0 , or >1 π^+)

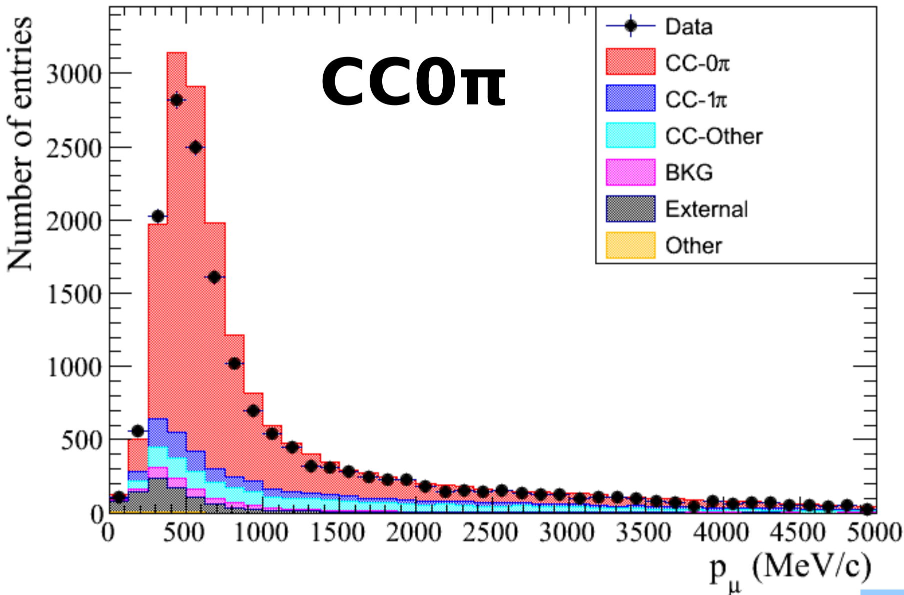
– π^0 candidates have identified electrons in the TPC

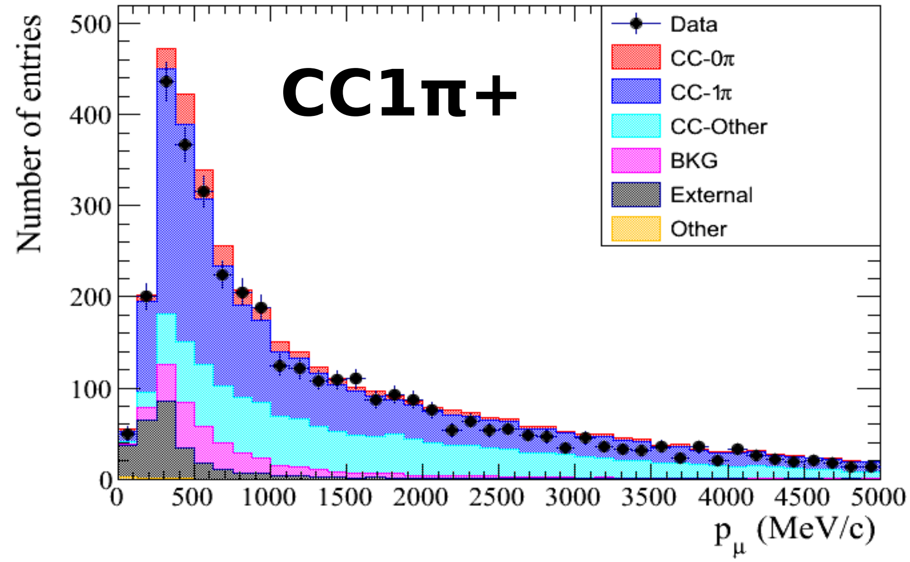
- Disappearance analysis joins CC 1π^+ and CC other together

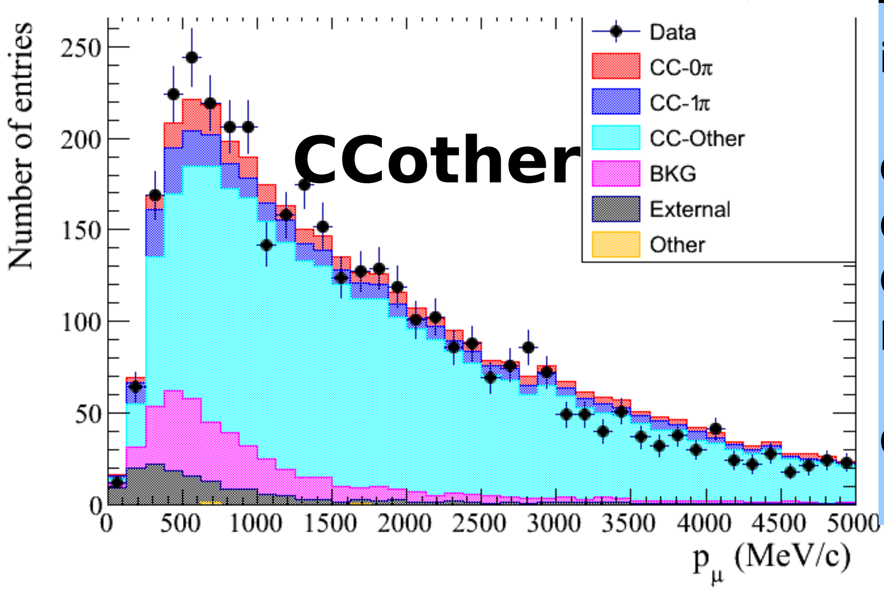


The event displays show only the tracking system at ND280

Muon Momentum in ND280

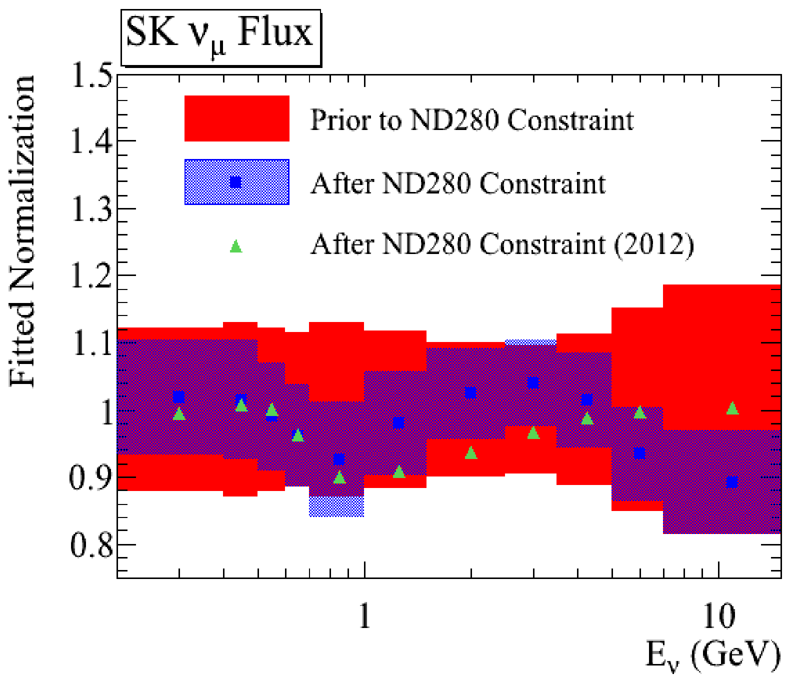






True identification of interaction	CC0π sample	CC1π sample	CCother sample
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-nu)	2.3%	6.8%	8.7%
Out of FGD1 Fid Vol	5.1%	6.5%	3.9%

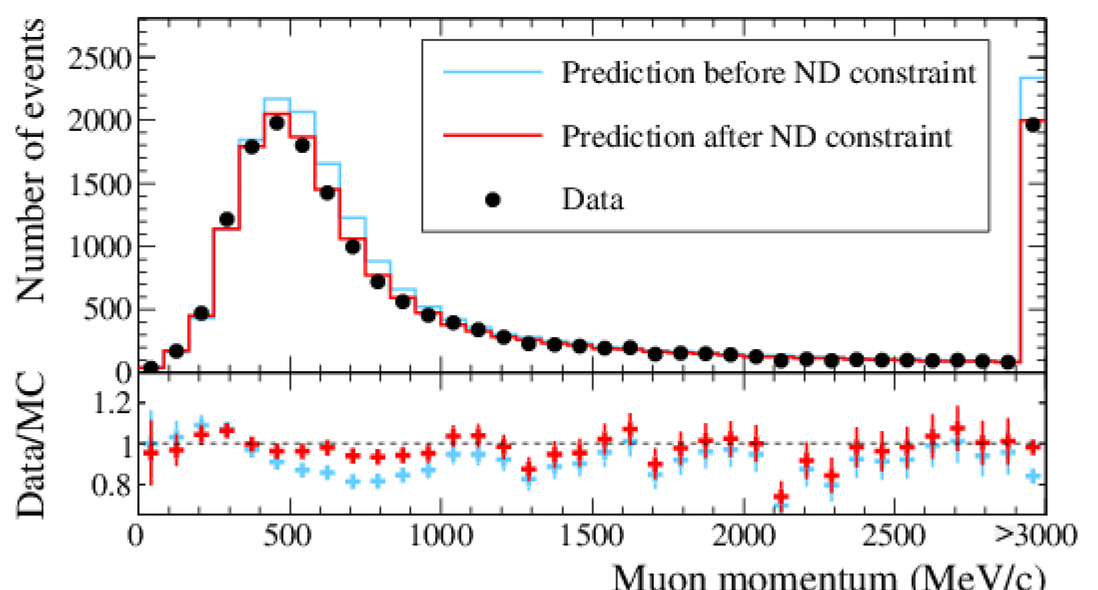
Flux and X-Sections after Constraint



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

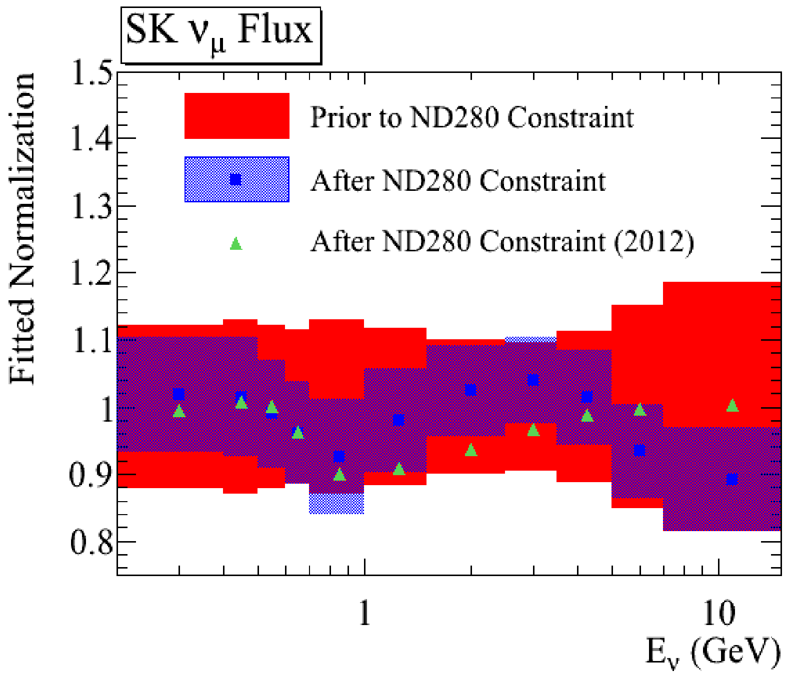
- ND280 constraint reduces both flux and cross-section model uncertainties individually
  - Note reductions on the "M_A" parameters which set Q^2 shape of these events



M_A^{QE} = mass parameter in the axial dipole form factor for QE interactions

M_A^{RES} = mass parameter in the axial dipole form factor for resonant pion interactions

Flux and X-Sections after Constraint



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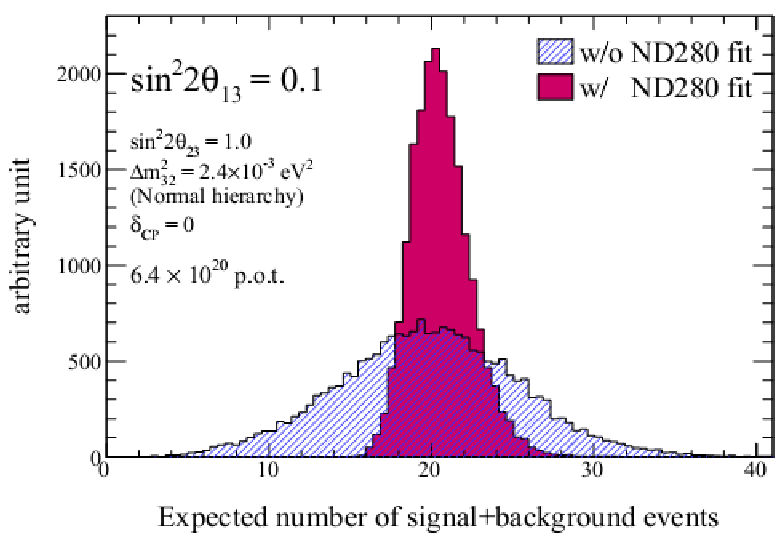
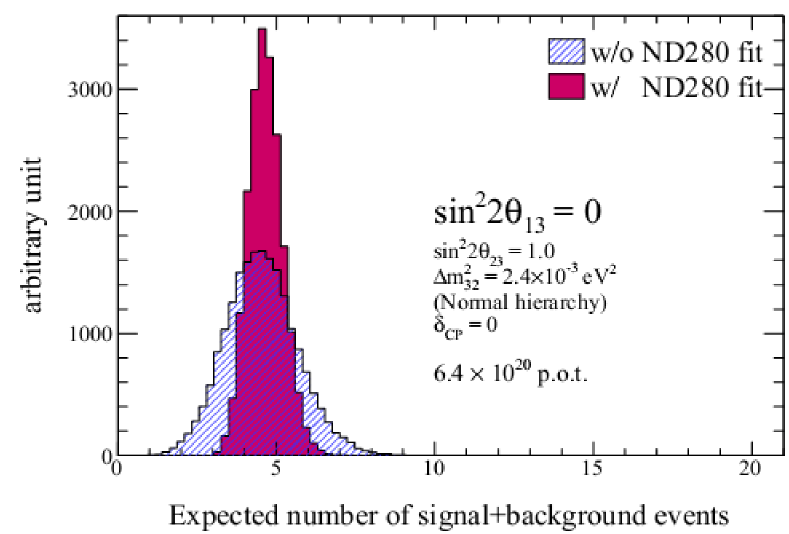
Far detector prediction uncertainties after ND280 constraint

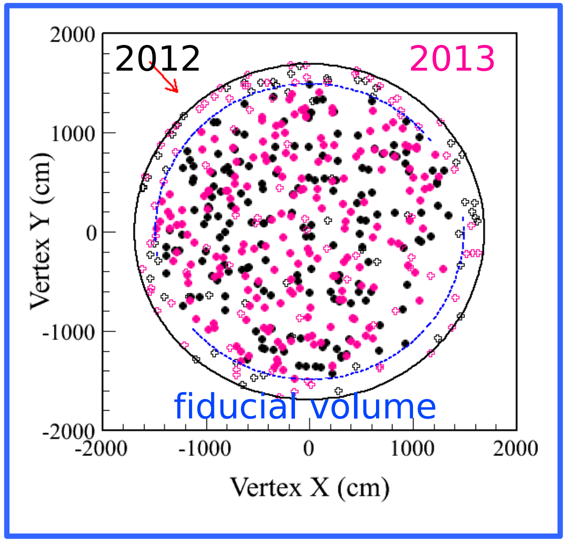


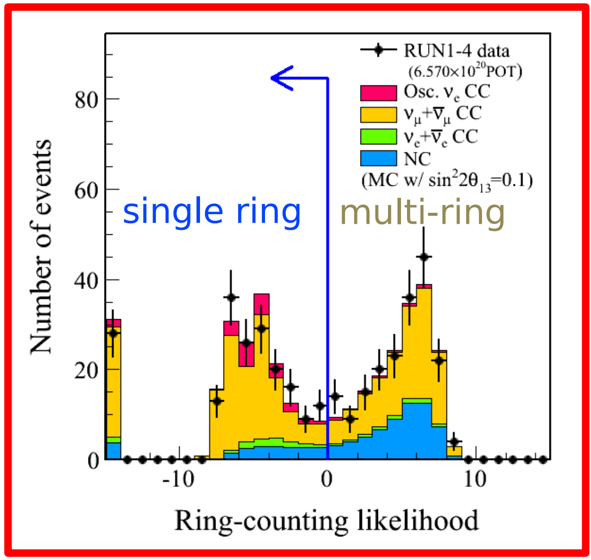


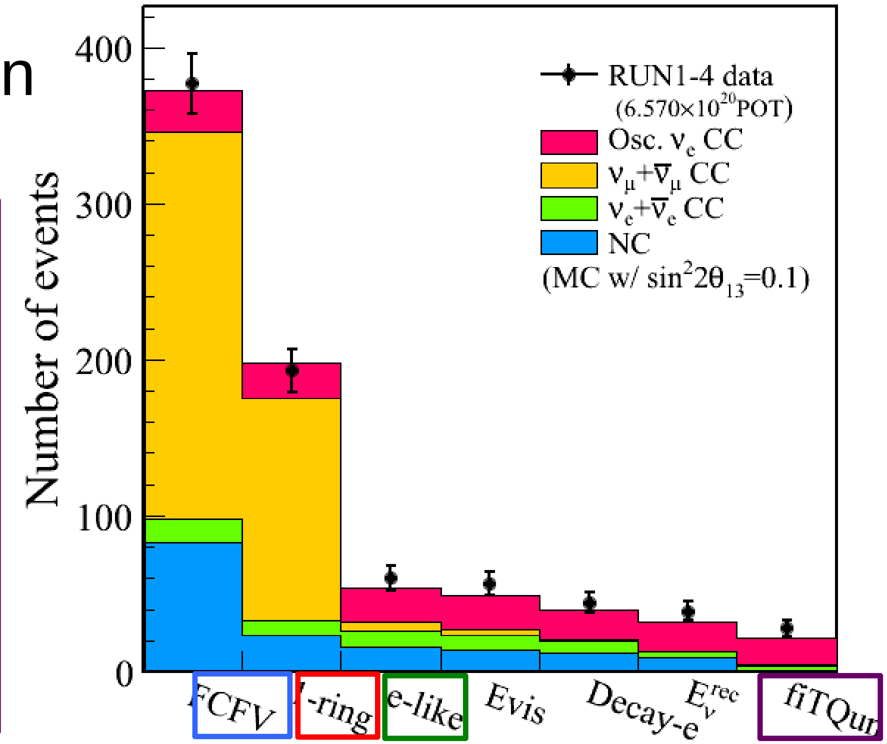
$\nu_\mu \rightarrow \nu_e$ Event Selection

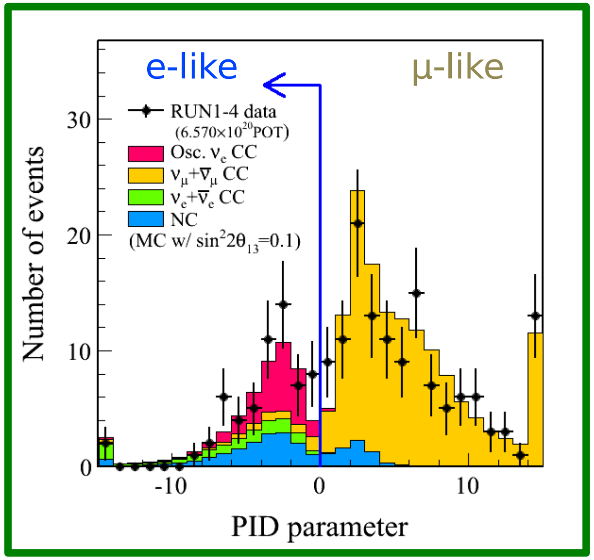
Event selection:

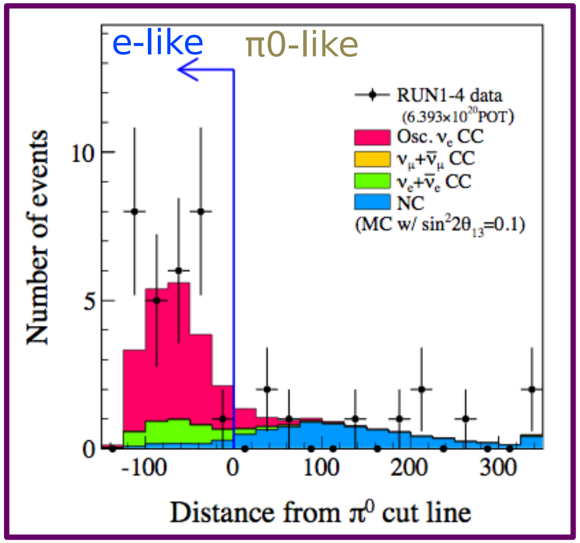
- Fully contained in fid. volume
- Only one reconstructed ring
- Ring is electron-like
- Visible energy > 100MeV
- No Michel Electrons
- Reconstructed energy < 1.25 GeV
- New SK reconstruction (~30% reduction in π^0 background)





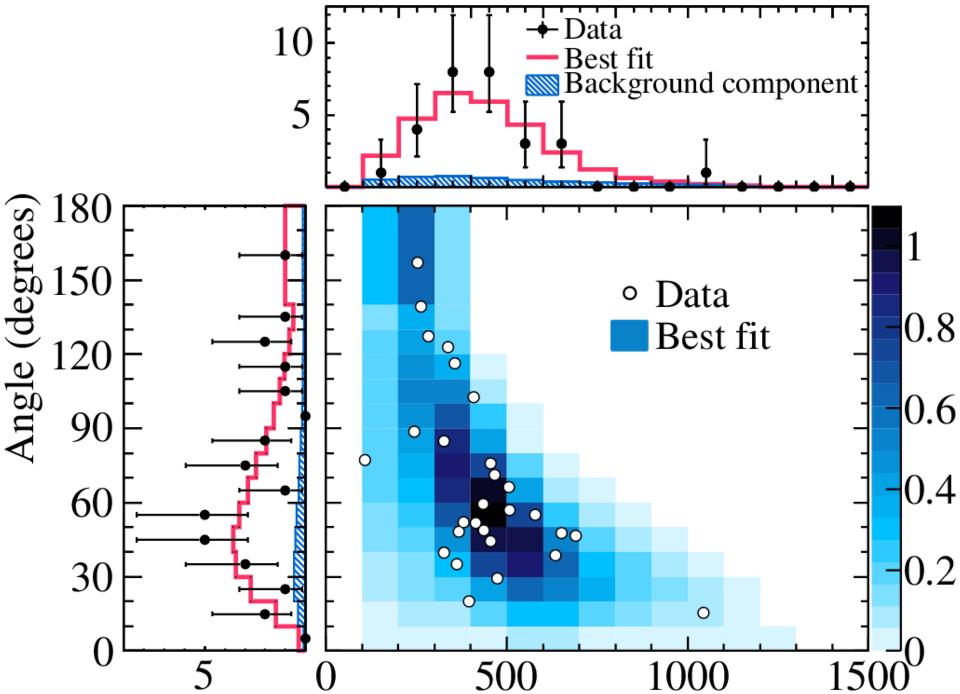




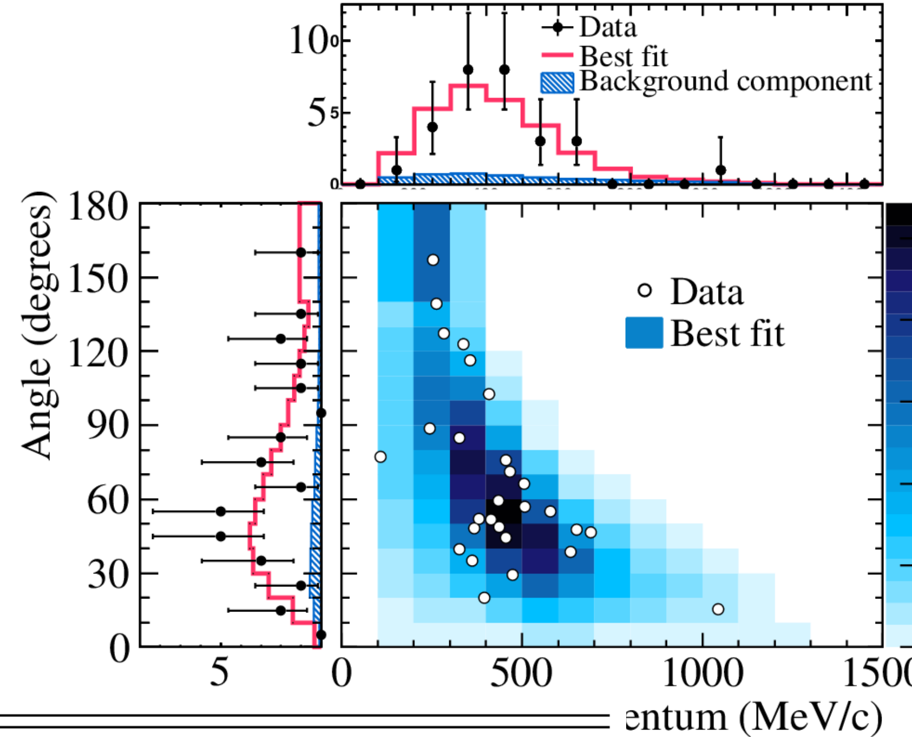


Results

Normal Hierarchy



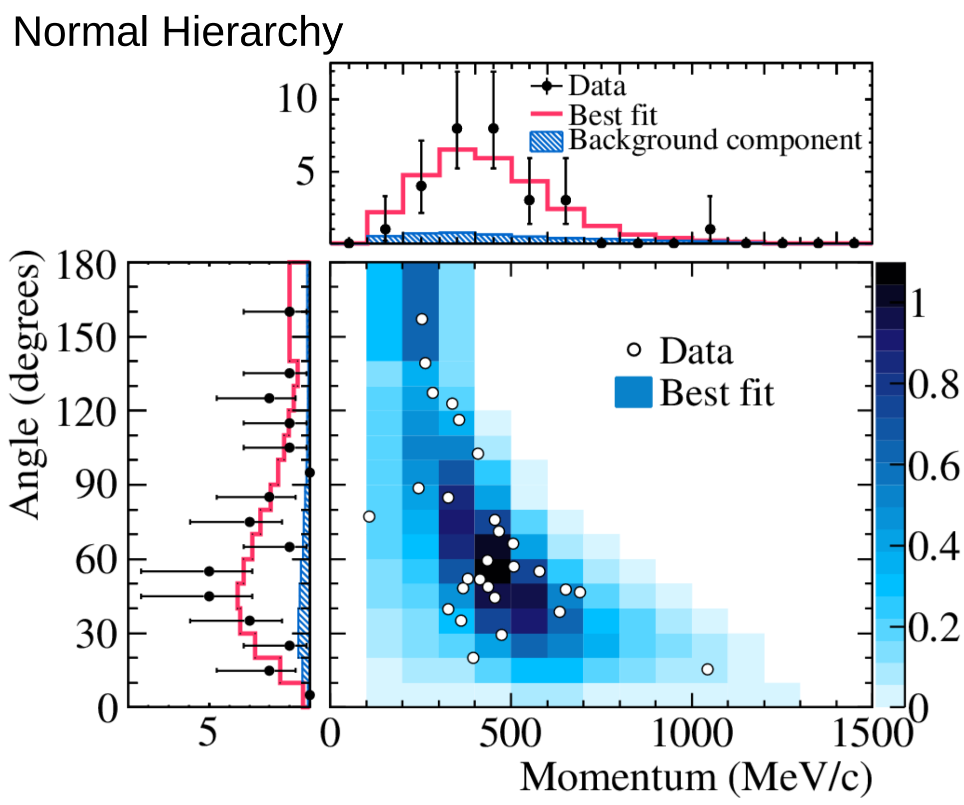
Inverted Hierarchy

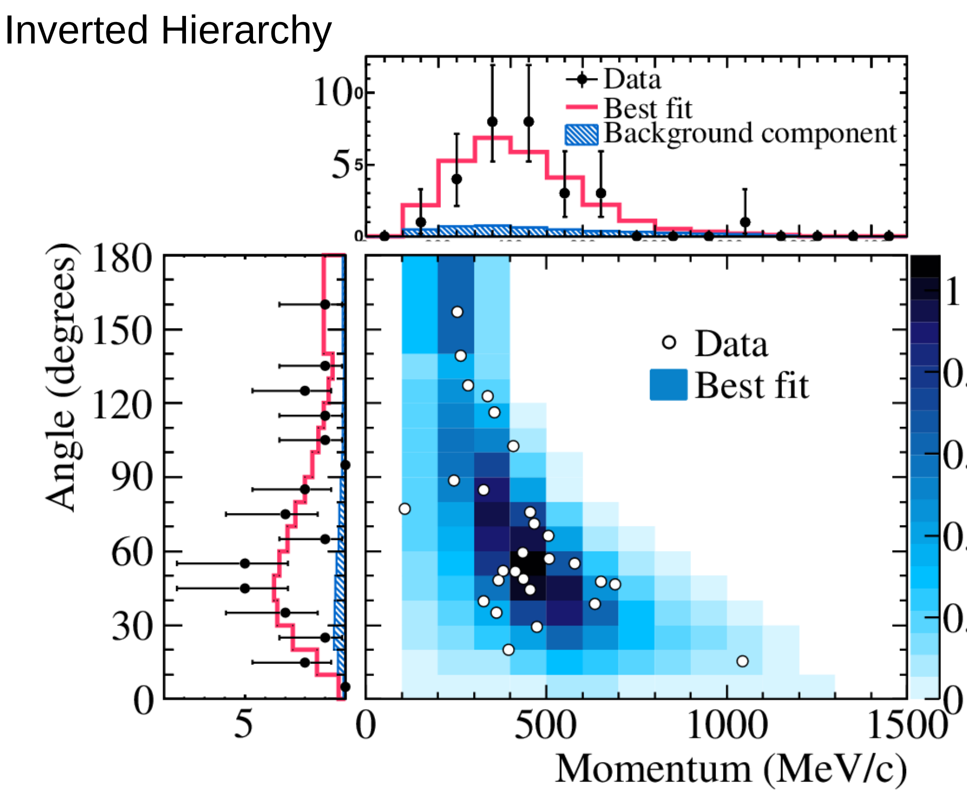


Event category	The predicted number of events $\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	4.92	21.56
ν_e signal	0.40	17.30
ν_e background	3.37	3.12
ν_μ background	0.94	0.94
$\bar{\nu}_\mu$ background	0.05	0.05
$\bar{\nu}_e$ background	0.16	0.15

Data: 28

Results





	$\sin^2 2\theta_{13} = 0$		$\sin^2 2\theta_{13} = 0.1$	
Error source	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	w/ ND280 fit
BANFF	21.7	4.8	25.9	2.9
ν int. (other than BANFF)	6.8	6.8	7.5	7.5
SK+FSI	7.3	7.3	3.5	3.5
Total	24.0	11.1	27.2	8.8
2012 analysis	21.0	13.0	24.2	9.9

arXiv:1311.4750 [hep-ex]

T2K ν_e Appearance Fit Results

- Fit using (p,θ) distributions
- Best fit value at 68% CL for $\delta_{CP} = 0$

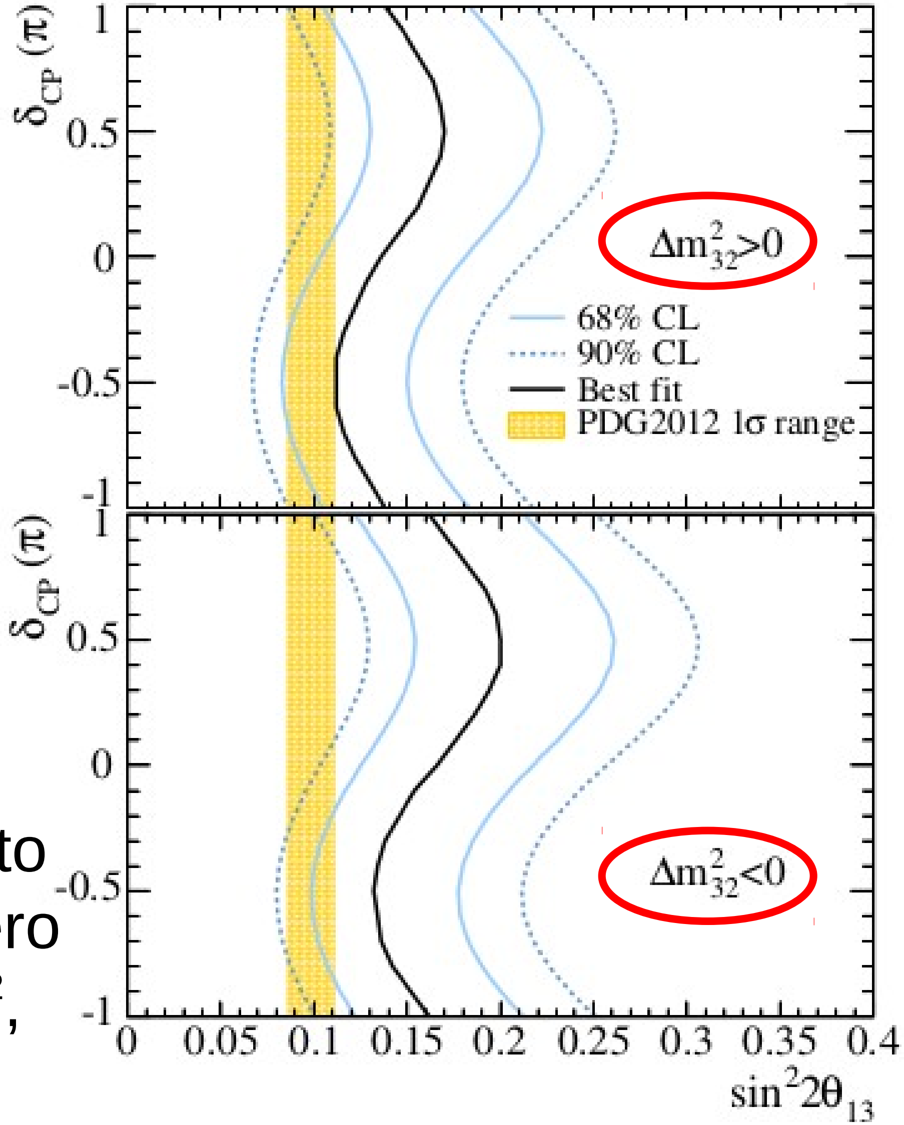
normal hierarchy:

$$\sin^2 2\theta_{13} = 0.136^{+0.044}_{-0.033}$$

inverted hierarchy:

$$\sin^2 2\theta_{13} = 0.166^{+0.051}_{-0.042}$$

- Comparing the best p-θ fit likelihood to null hypothesis gives a 7.4σ for non-zero θ_{13}, for $\sin^2\theta_{23}=0.5$, $|\Delta m^2_{32}|=2.4\times10^{-3}eV^2$, $\delta_{CP}=0$, and normal mass hierarchy.
- First ever observation (>5σ) of an explicit ν appearance channel



NB: These are 1D contours for values of δ_{CP}, not 2D contours in δ_{CP}-θ_{13} space

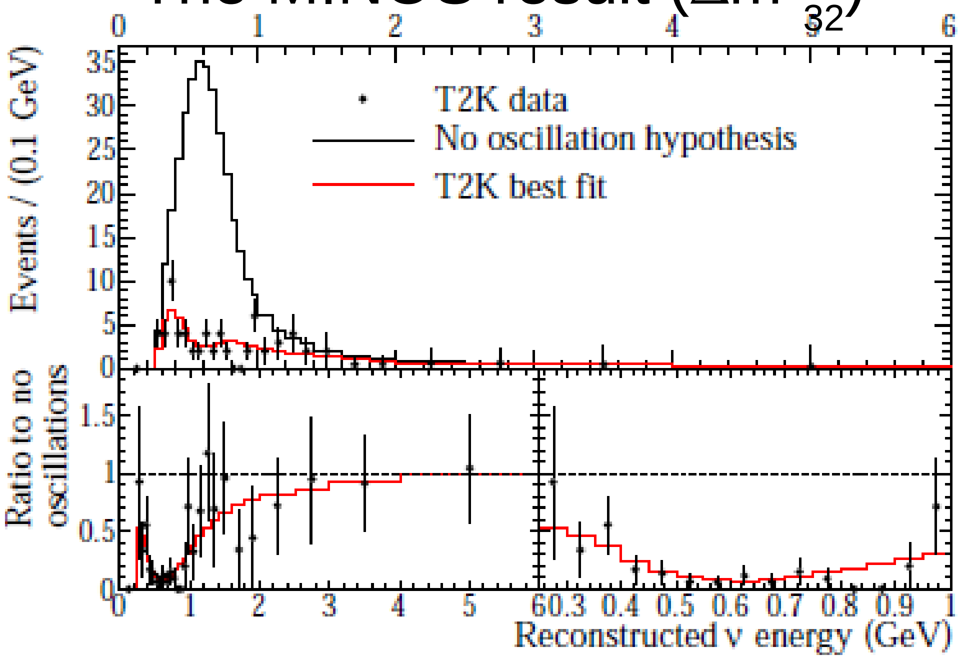
arXiv:1308.0465v2 [hep-ex] Accepted for Publication by Physical Review Letters

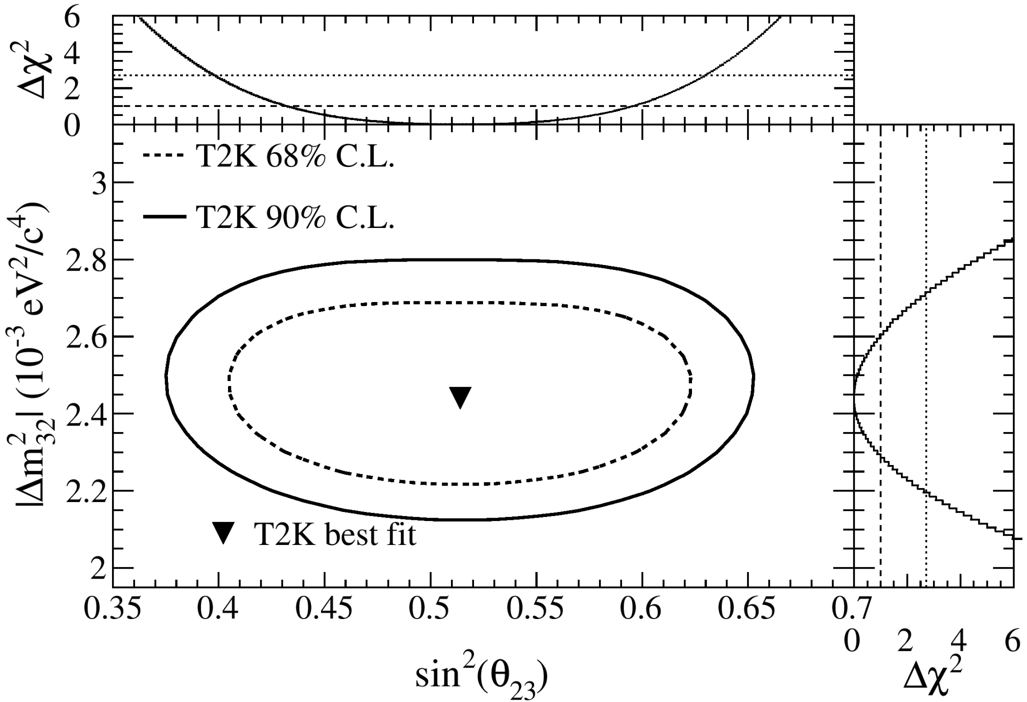
$\nu_\mu \rightarrow \nu_\mu$ T2K Result

- Best-fit oscillation parameter values:

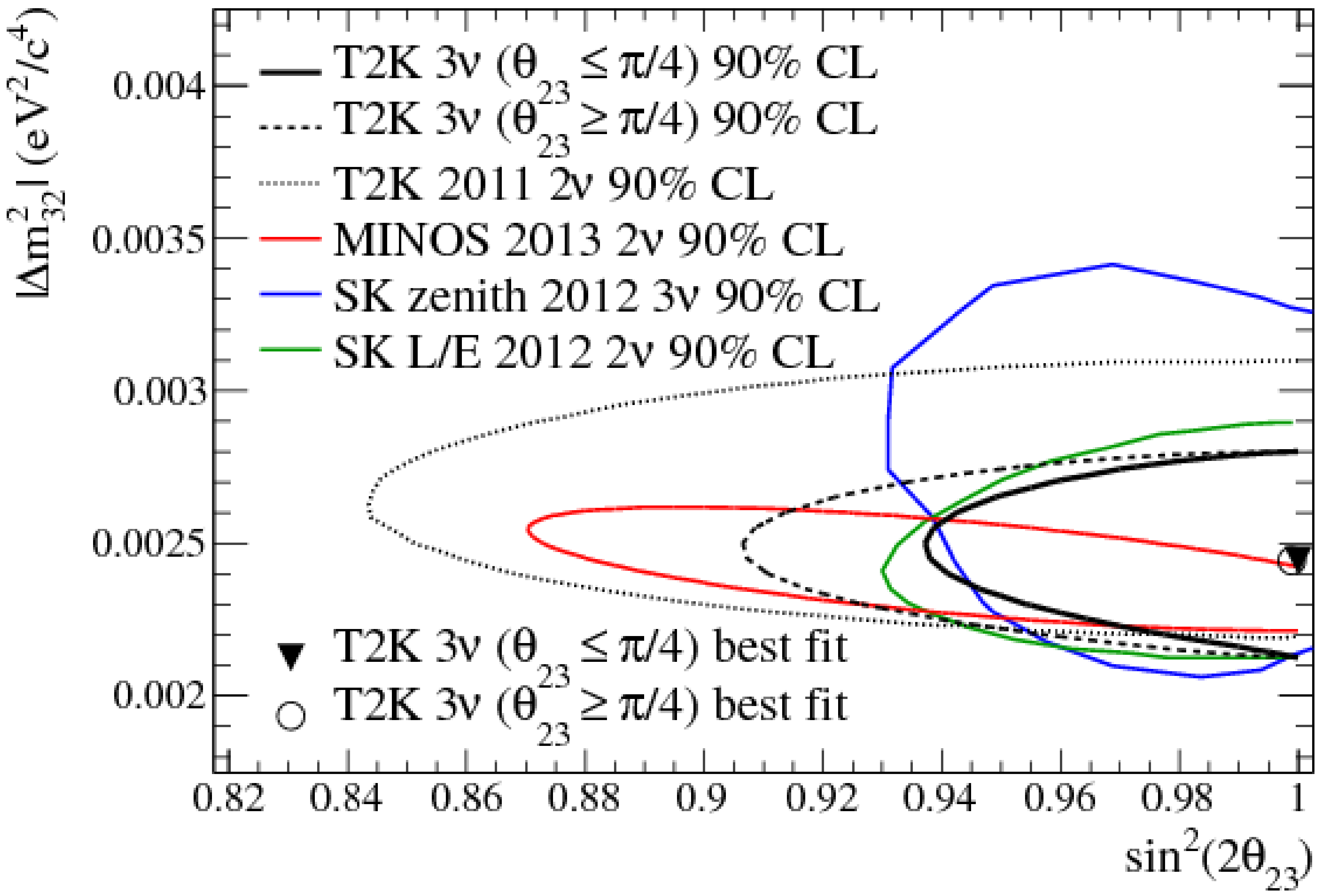
$$\sin^2\theta_{23} = 0.514 \pm 0.082 \qquad |\Delta m^2_{32}| = 2.44^{+0.17}_{-0.15} \times 10^{-3} eV^2/c^2$$

- Events: 58 (observed), 57.92 (predicted), 205 ± 17(no oscillation)
- Data prefers 2nd θ_{23} octant
- 1σ confidence intervals are consistent with:
  – Maximal mixing ($\sin^2\theta_{23}$)
  – The MINOS result (Δm^2_{32})





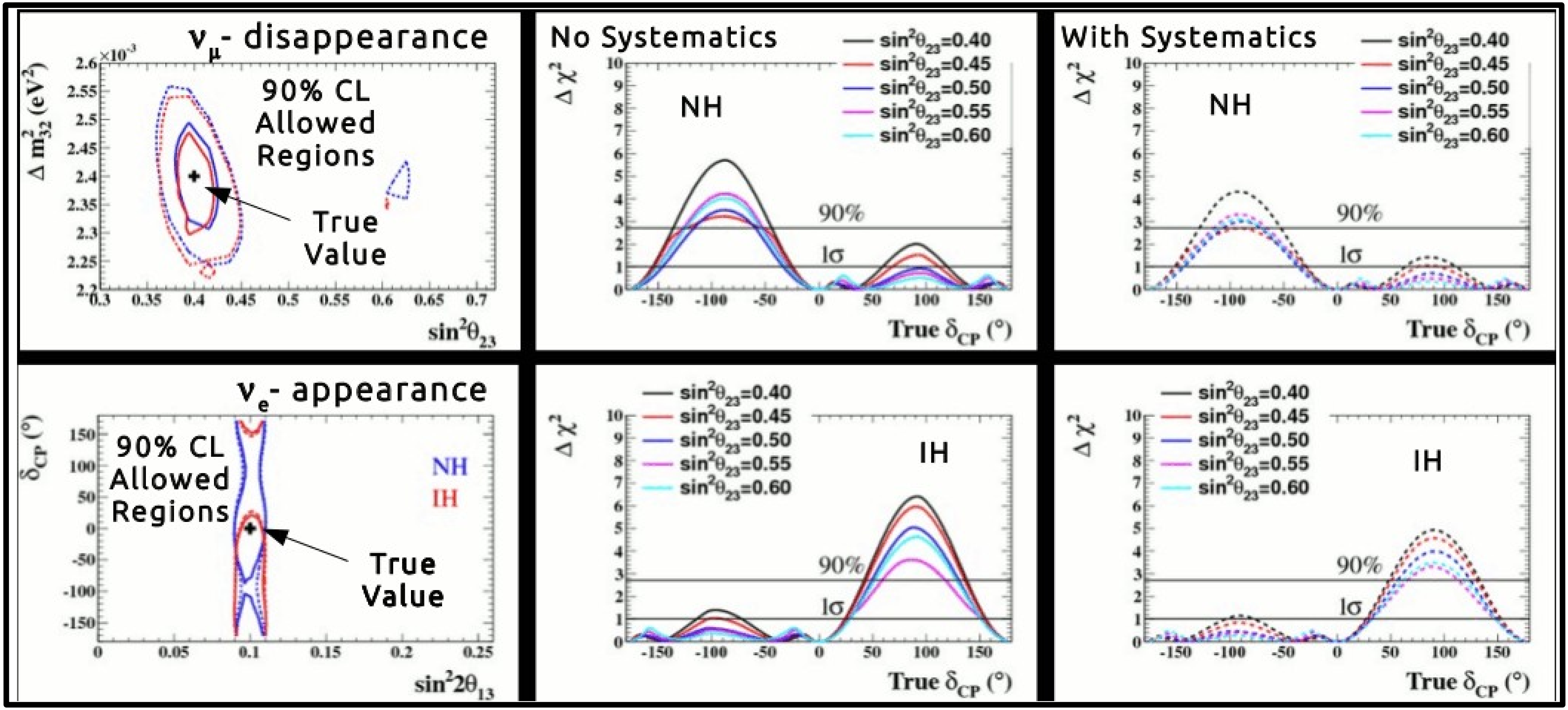
Results



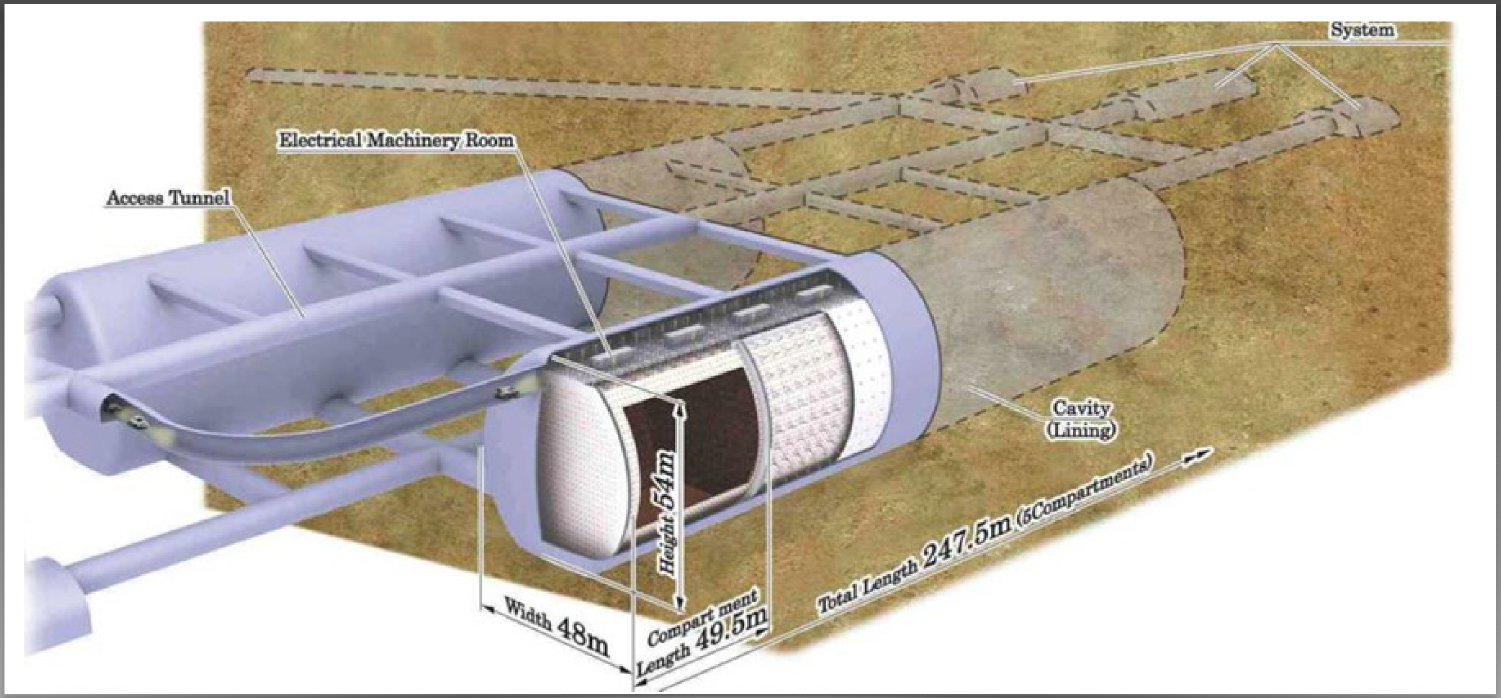
T2K 3ν (θ23 ≤ π/4) 90% CL
T2K 3ν (θ23 ≥ π/4) 90% CL
T2K 2011 2ν 90% CL
MINOS 2013 2ν 90% CL
SK zenith 2012 3ν 90% CL
SK L/E 2012 2ν 90% CL
T2K 3ν (θ23 ≤ π/4) best fit
T2K 3ν (θ23 ≥ π/4) best fit
|Δm²32| (eV²/c⁴)
0.004
0.0035
0.003
0.0025
0.002
0.82
0.84
0.86
0.88
0.9
0.92
0.94
0.96
0.98
1
sin²(2θ23)

T2K and J-PARC Run Plans

- Ongoing sensitivity studies to determine future potential and running conditions (neutrino vs anti-neutrinos)
- Combined studies with NovA for neutrino mass hierarchy ongoing.
- Assuming 50% neutrino and 50% antineutrino for T2K and combination with Daya Bay:



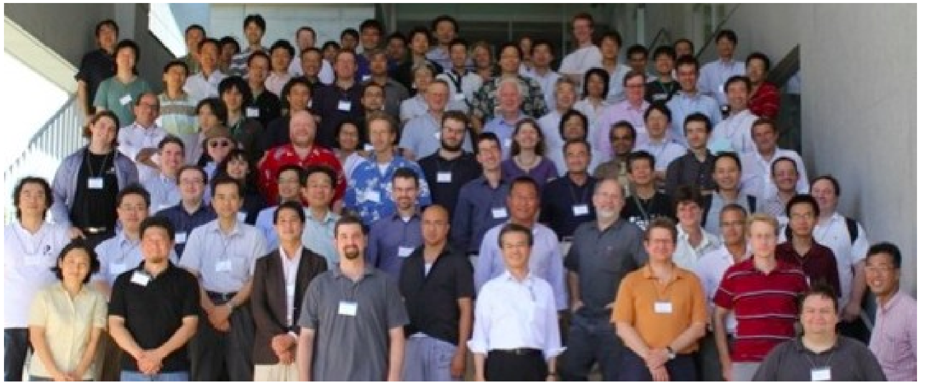
Hyper-Kamiokande



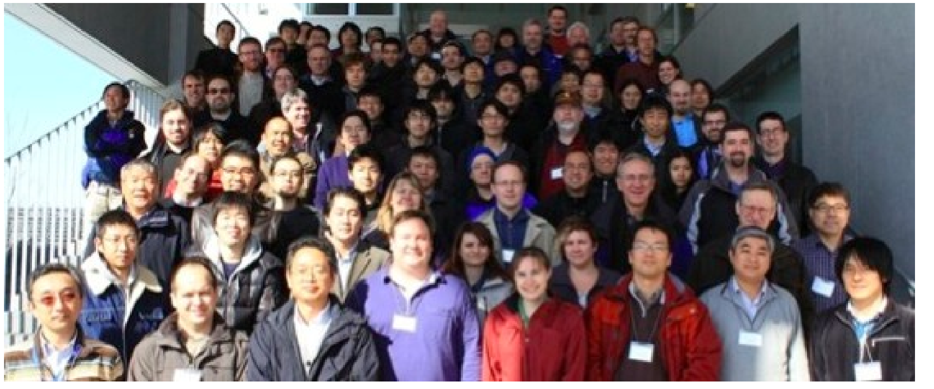
The Hyper-Kamiokande Project

- Four International Open Meetings (2012-2014) @ IPMU, Japan.
- Formed international working groups.

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



January 14-15, 2013
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=10



June 21-22, 2013
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=23

January 27-28, 2014
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=29

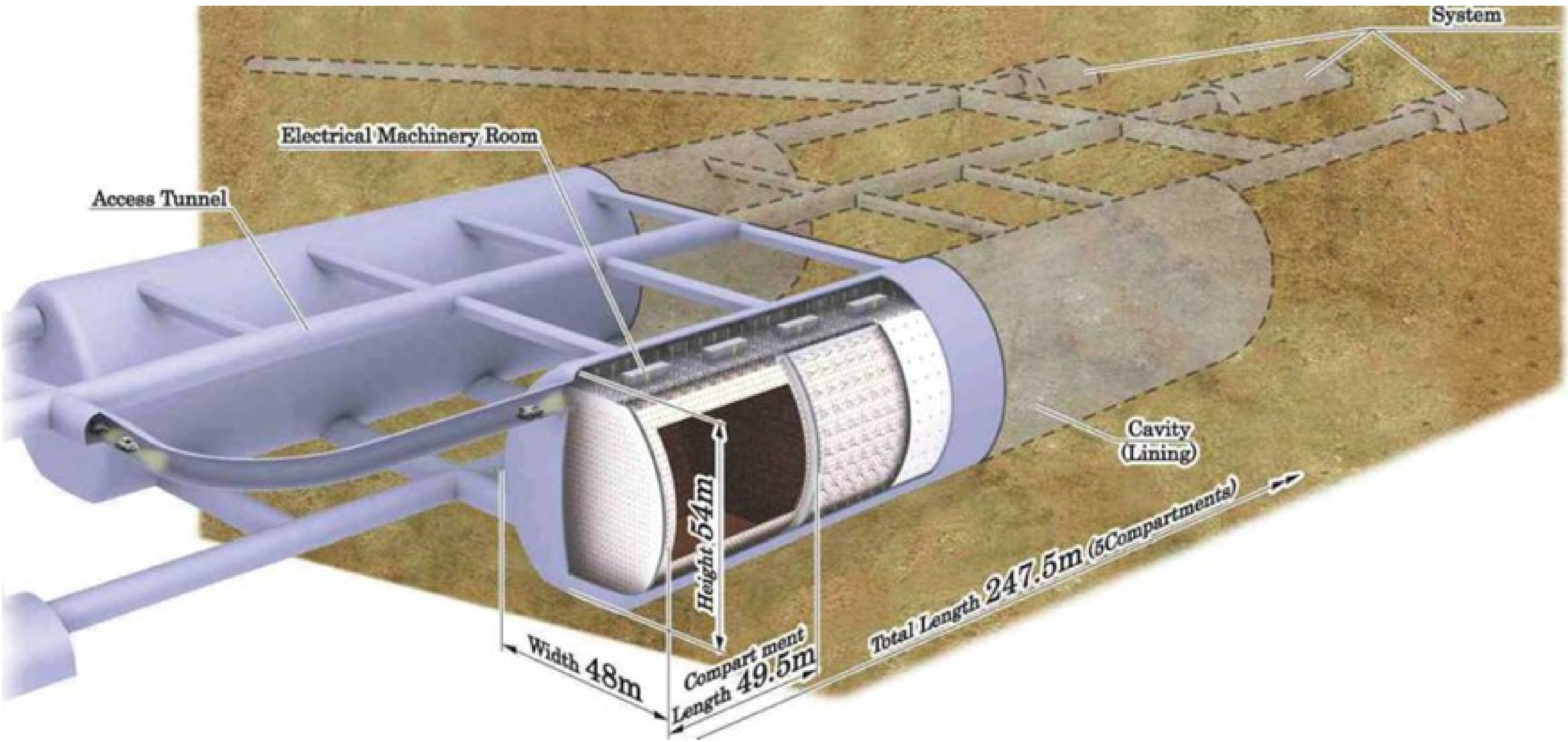
Please look at the slides from the meetings for detailed information on topics

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.

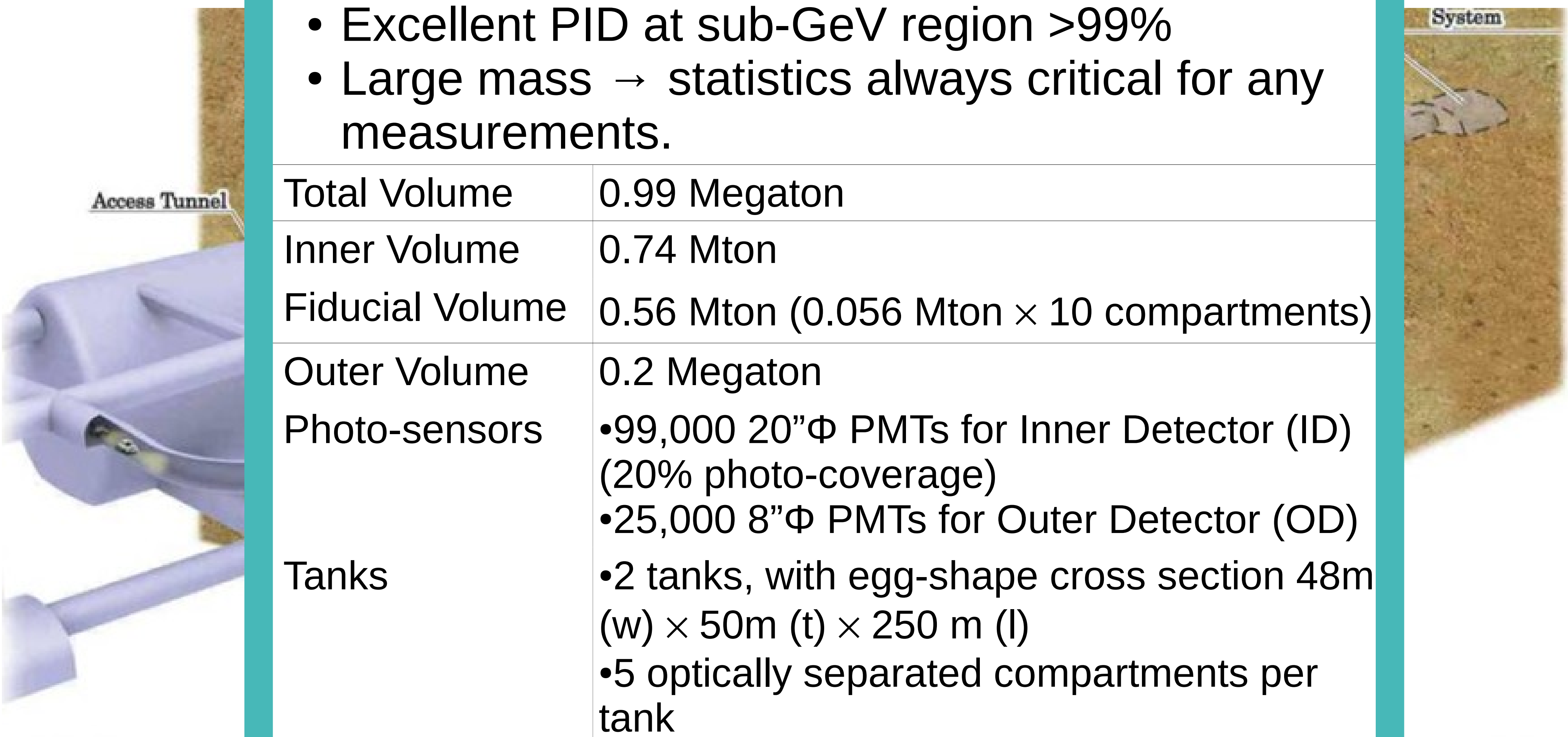
- Discussed common issues. One more open meeting this year.
- Created mailing list <hyper-kamiokande-eu@qmul.ac.uk>

Hyper-Kamiokande Overview



25 x Super-Kamiokande

Hyper-Kamiokande Overview

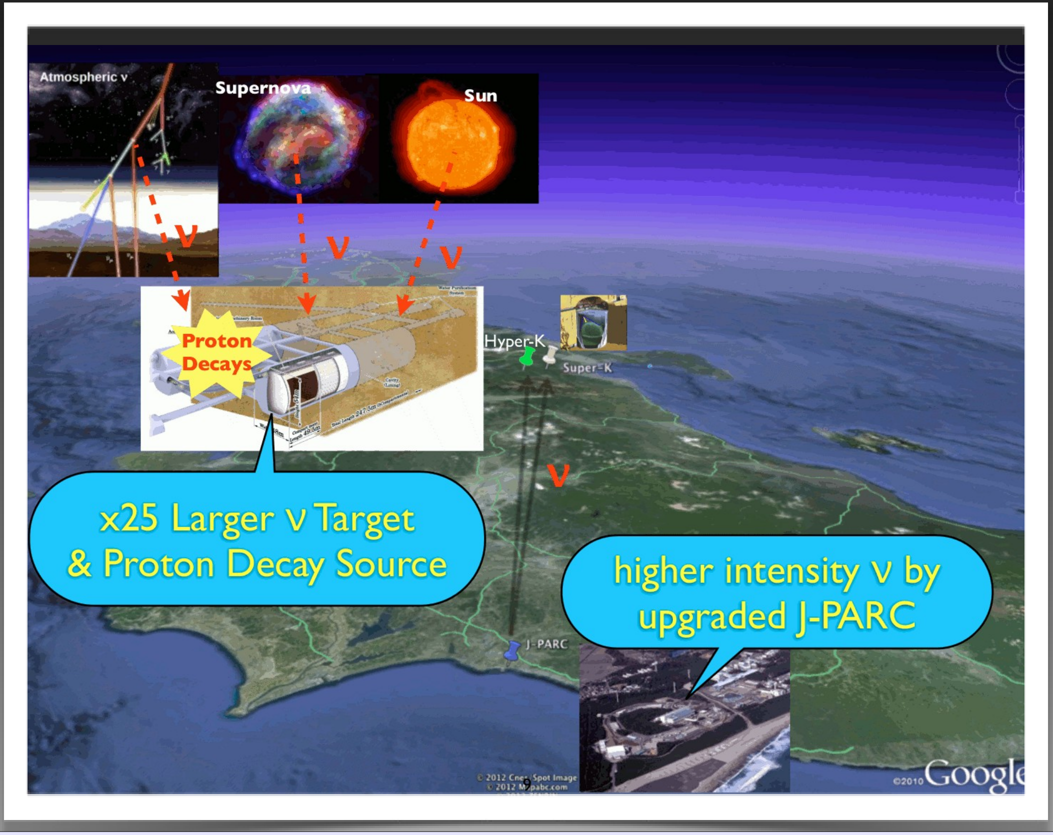


- Water Cherenkov, proved technology & scalability:
  - Excellent PID at sub-GeV region >99%
  - Large mass → statistics always critical for any measurements.

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) •5 optically separated compartments per tank

25 x Super-Kamiokande

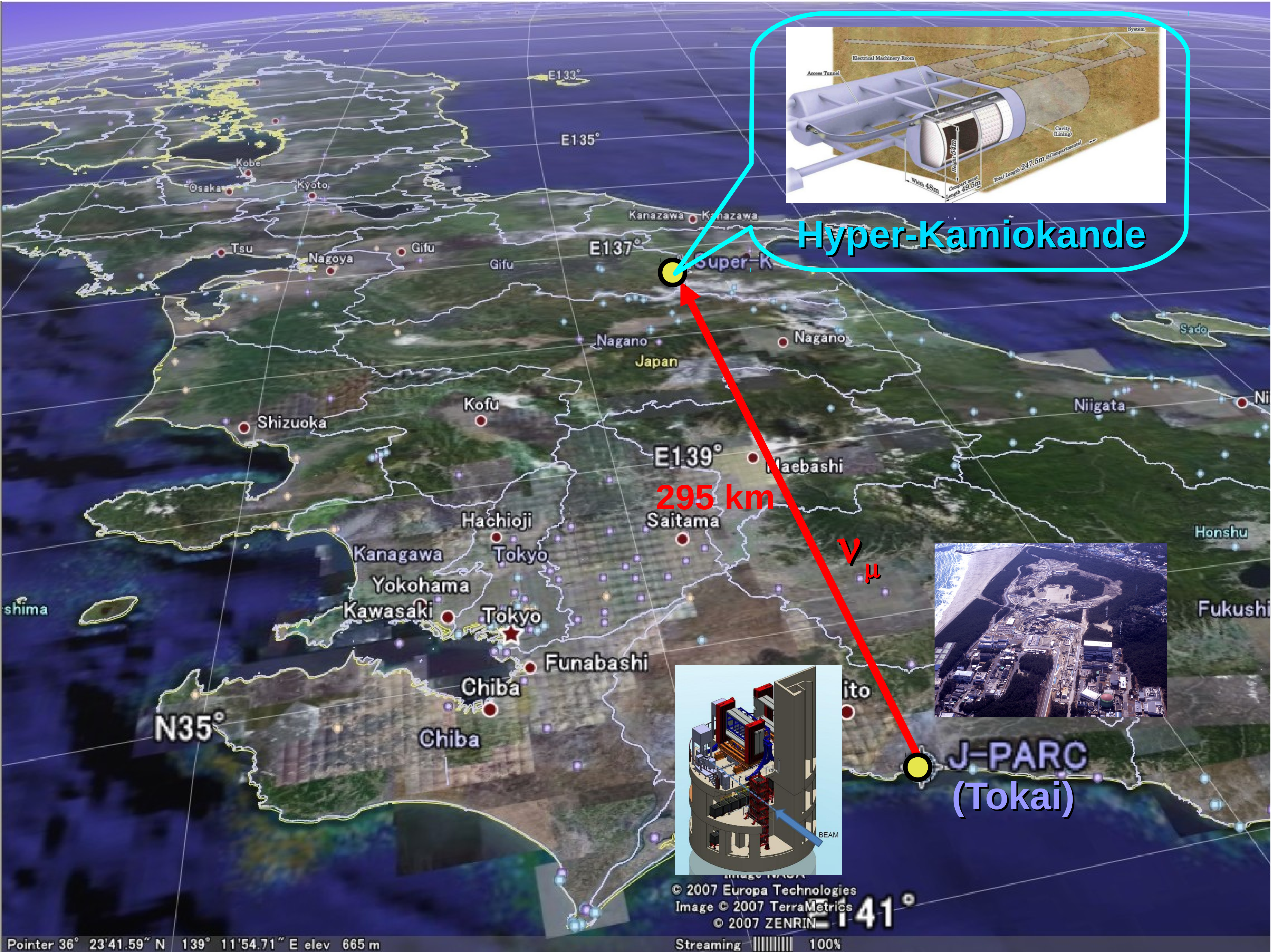
Physics Topics



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

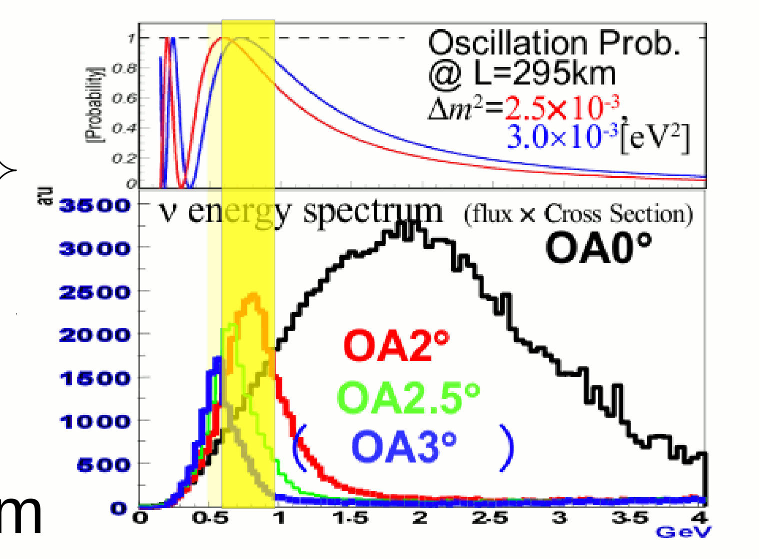
- 5% overall systematic error
- 3y:7y ν-beam:ν-beam sharing
- No new SK reconstruction used (⇒ higher π^0 background)
- No new near detector

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

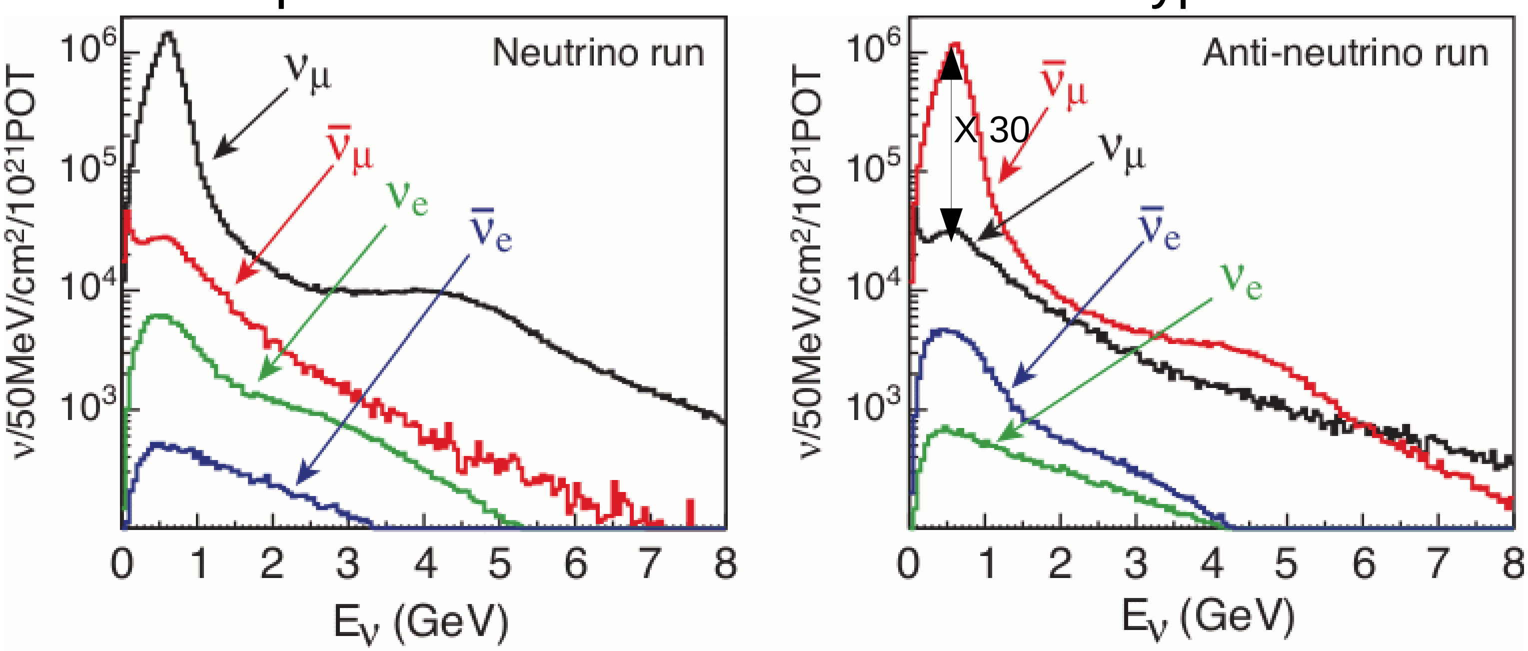

Hyper-Kamiokande
Super-K
295 km
ν_μ
J-PARC
(Tokai)
BEAM
E133°
E135°
E137°
E139°
E141°
N35°
Kobe
Osaka
Kyoto
Kanazawa
Tsu
Nagoya
Gifu
Nagano
Japan
Kofu
Shizuoka
Maebashi
Saitama
Hachioji
Kanagawa
Tokyo
Yokohama
Kawasaki
Funabashi
Chiba
Niigata
Sado
Honshu
Fukushi
© 2007 Europa Technologies
Image © 2007 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

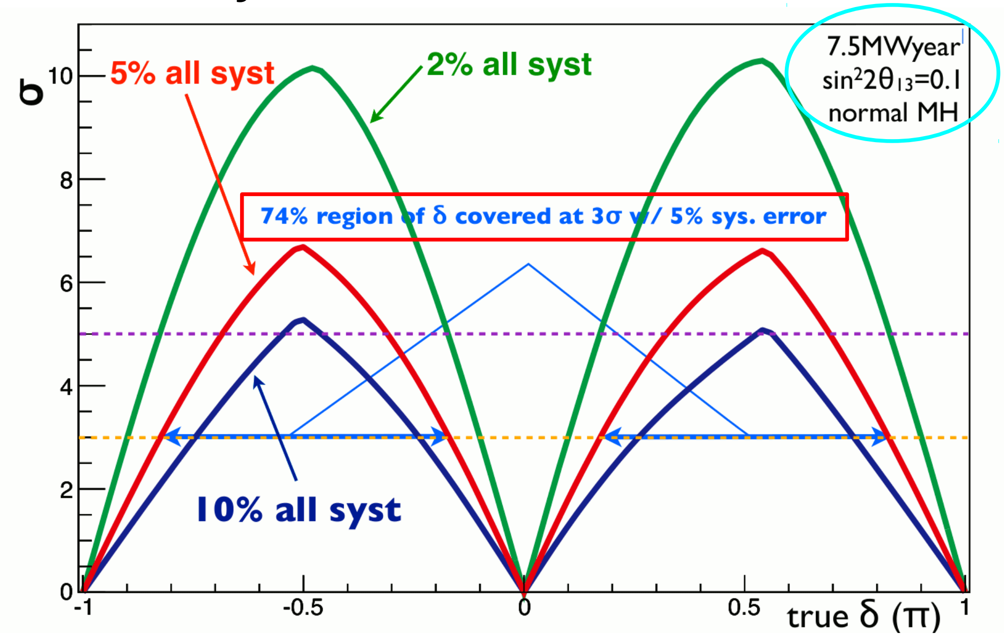


Beam sharing between neutrinos and anti-neutrinos

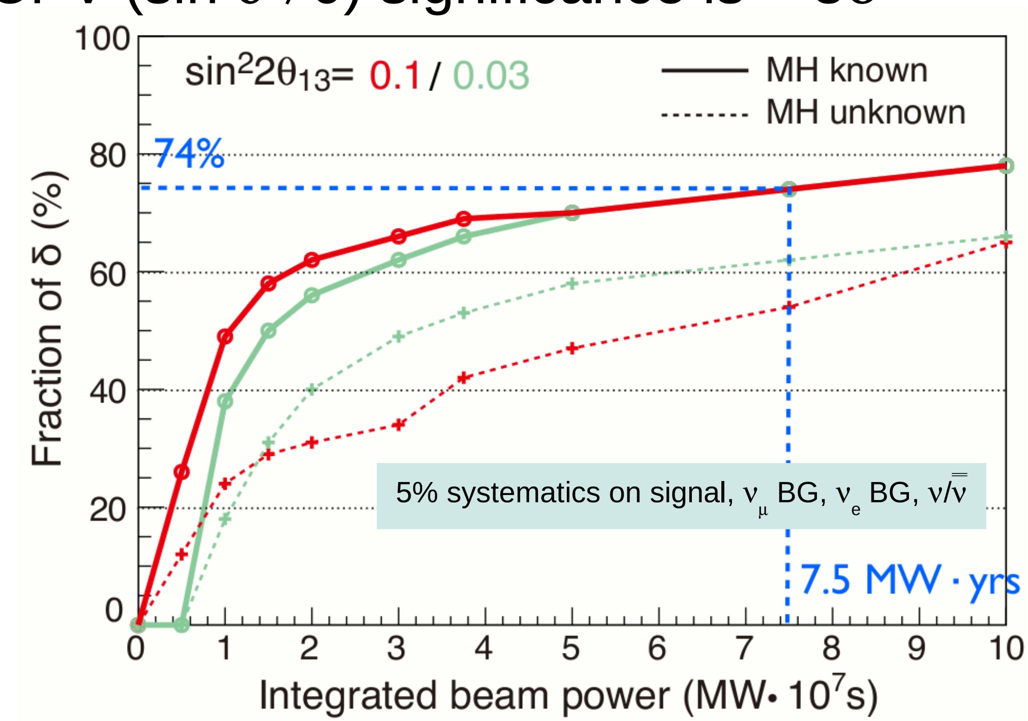
ν-mode: $\bar{\nu}$-mode
3y : 7y

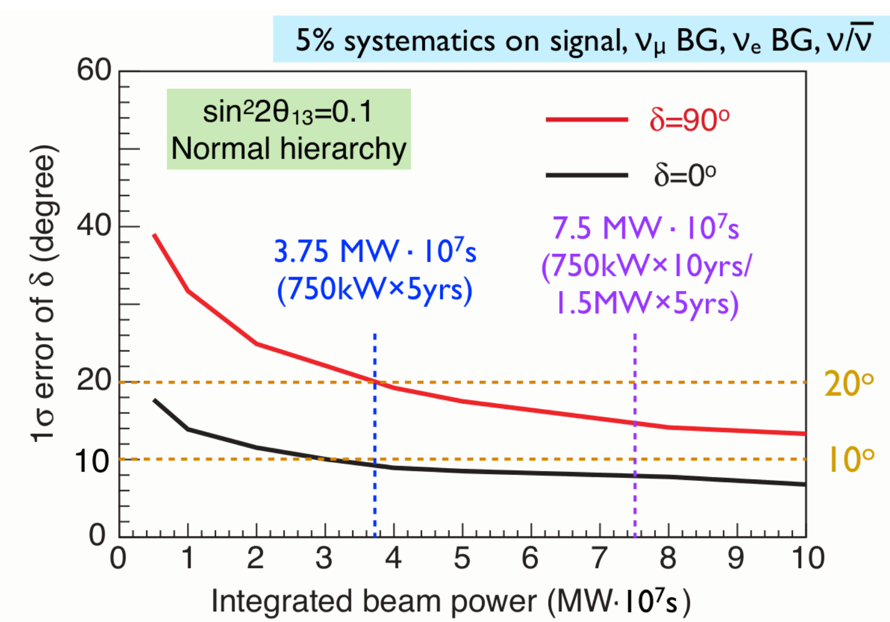
Expected Sensitivity to CP Violation

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

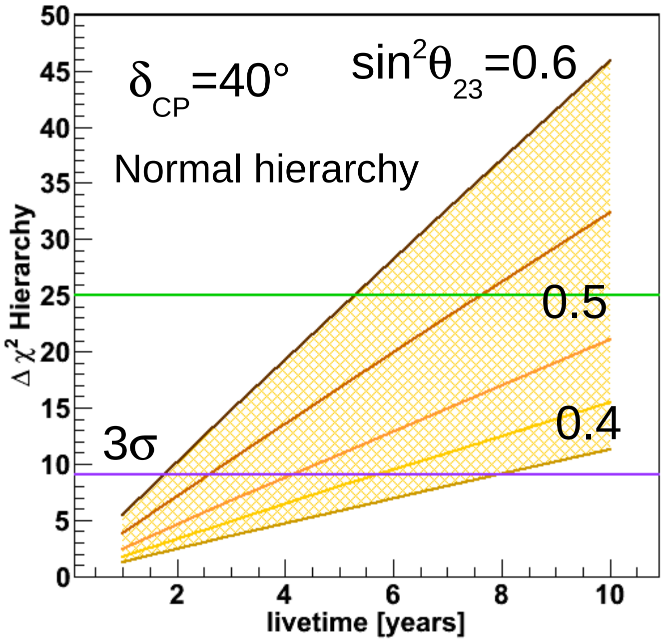
1σ uncertainty of δ as a function of the beam power:

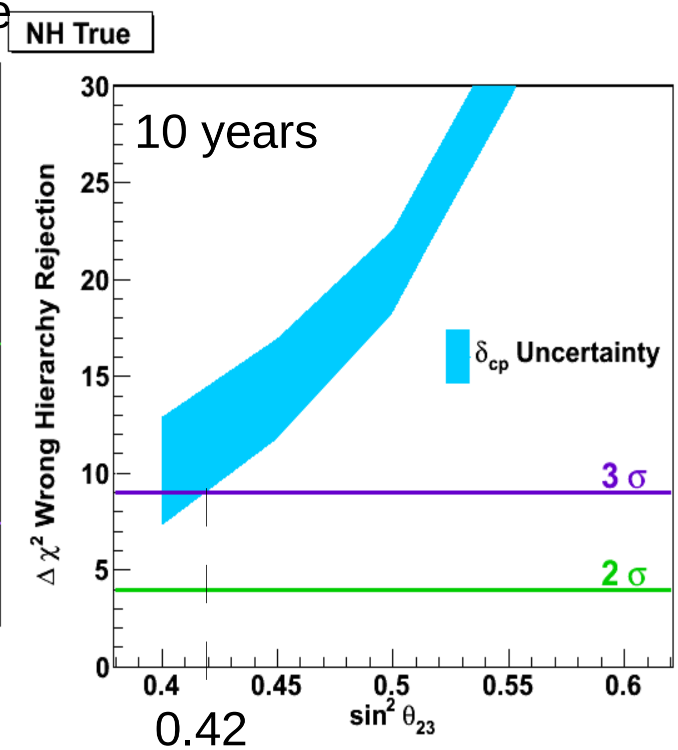
< 20°(10°) for δ = 90°(0°)

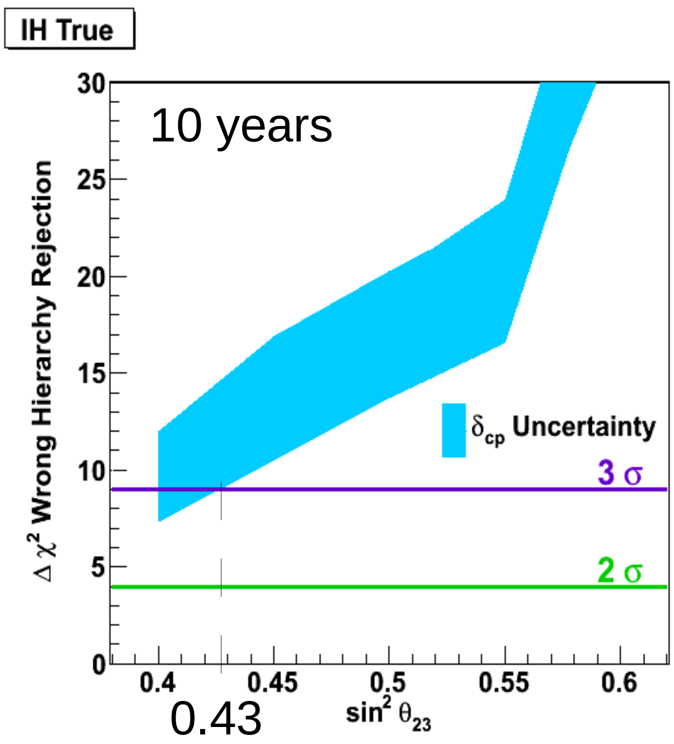
Modest dependence on θ_{13}

Mass Hierarchy Sensitivity

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



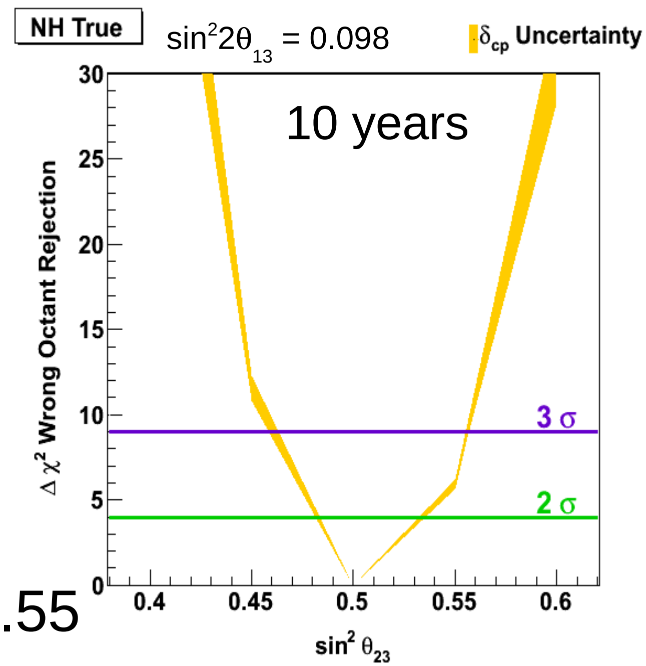


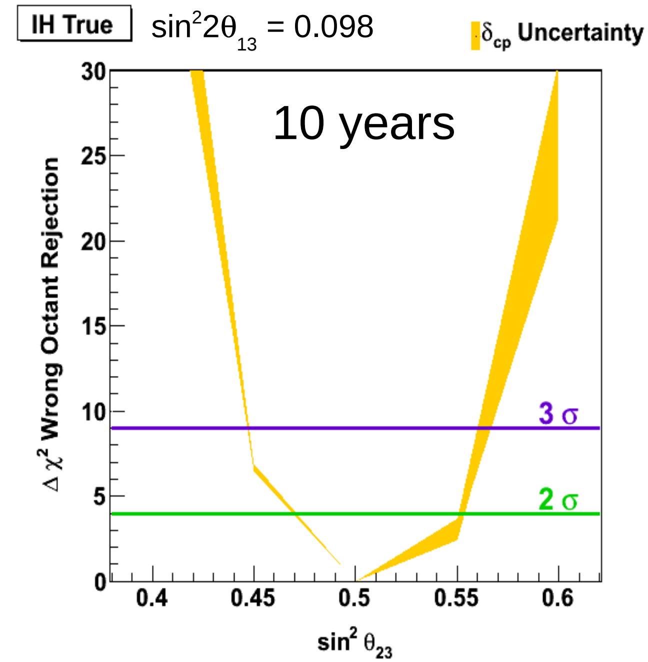


- Sensitivity mainly depends on θ_{23}, δ and slightly on the MH itself.
- 3σ mass hierarchy determination for $\sin^2\theta_{23} > 0.42$ (0.43) for normal (inverted) hierarchy for 10y data taking.
- Caveat: the $\Delta\chi^2$ method to determine the number of σ's is used.

Sensitivity for θ_{23} Octant and CPV

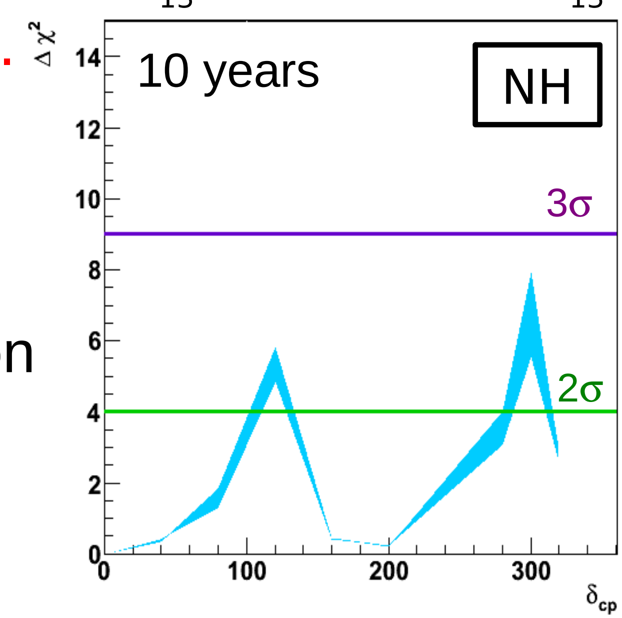
- θ_{23} octant sensitivity.
- Thickness of the band corresponds to the uncertainty from δ_{CP}.
- We can expect discrimination between $\sin^2\theta_{23}$ 0.4-0.6, w/ limited discrimination b/w 0.45-0.55

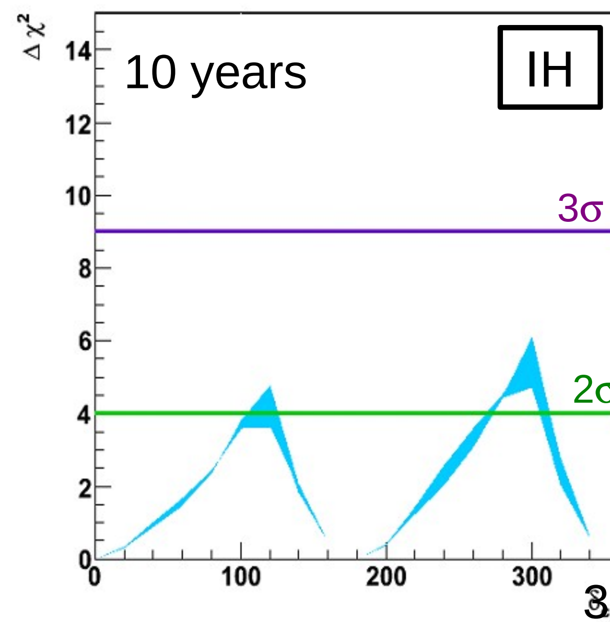




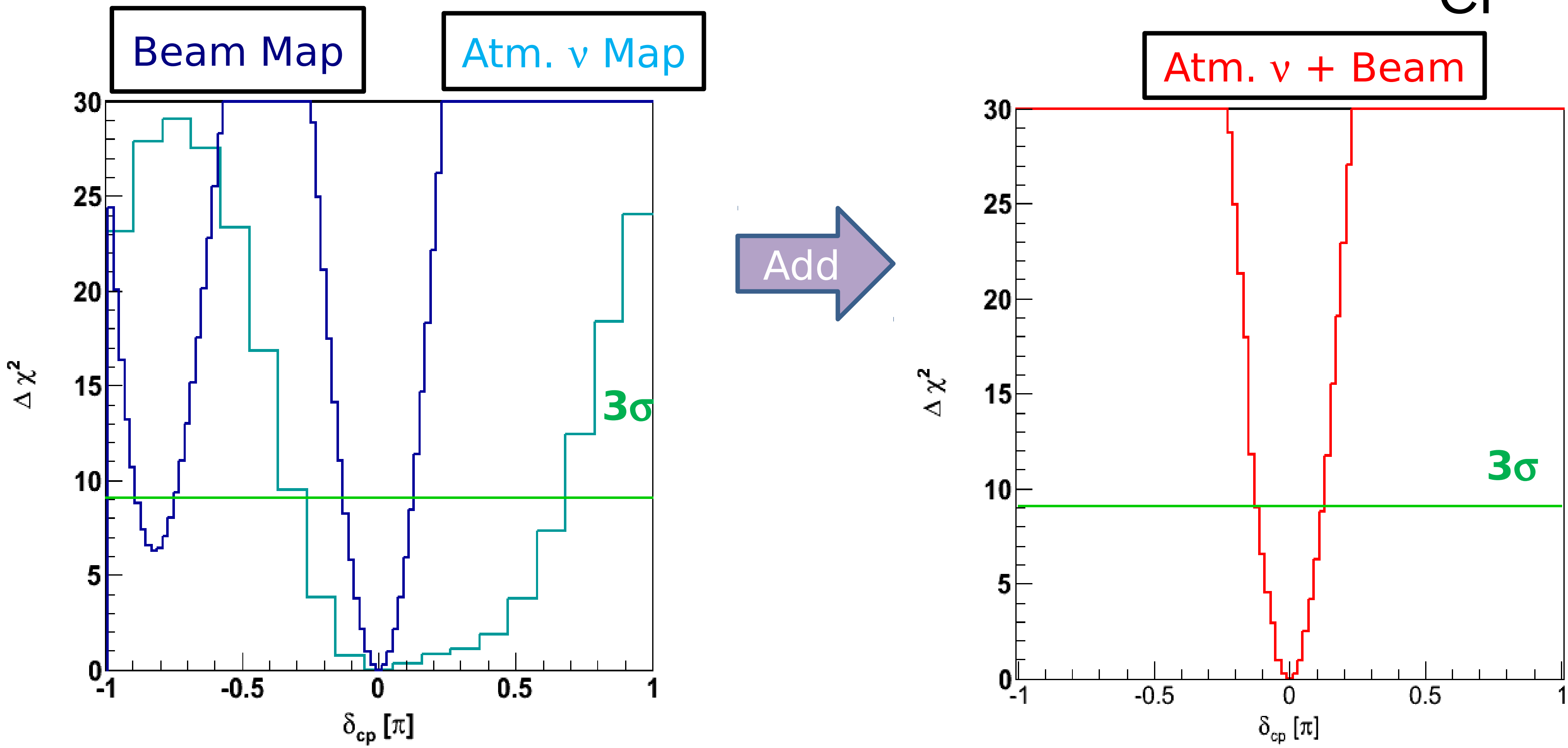
θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.099$

- 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.





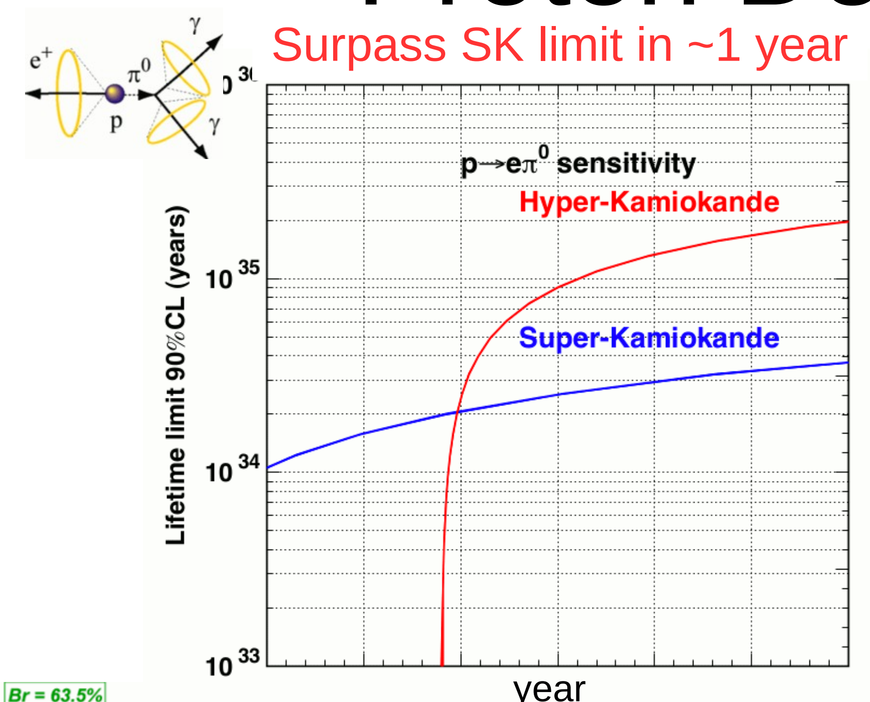
Beam + Atmospheric ν: Allowed δ_{CP}

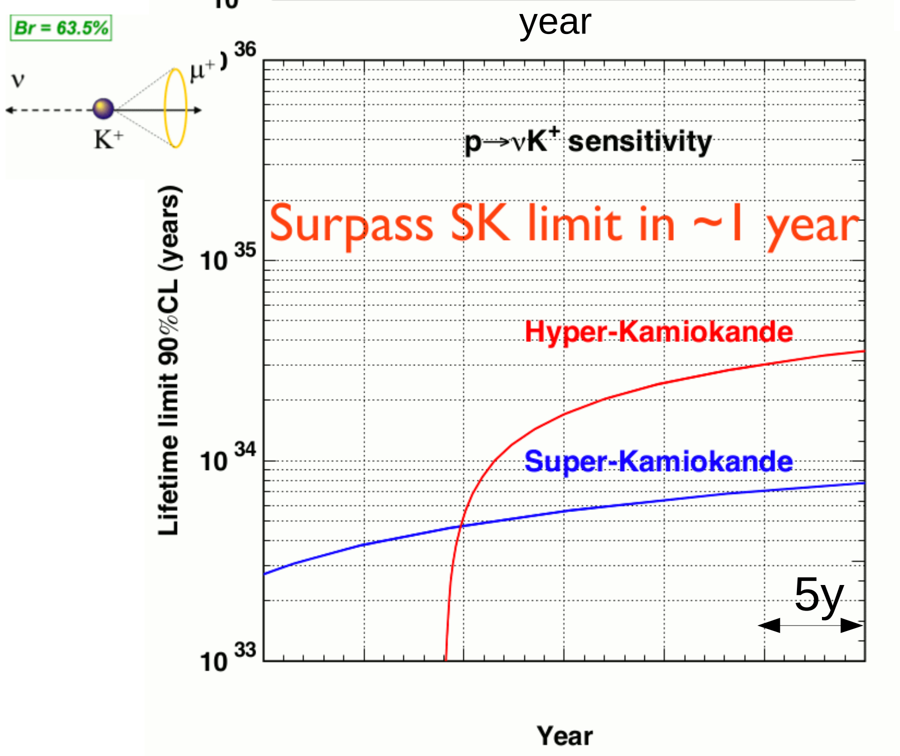


- Hierarchy is unknown, but NH is true.
- True δ_{CP} = 0.0; $\sin^2 2\theta_{13}$ = 0.10; Maximal mixing $\sin^2 2\theta_{23}$ = 1.0
- Degenerate solution exists at 3σ in the beam only case.

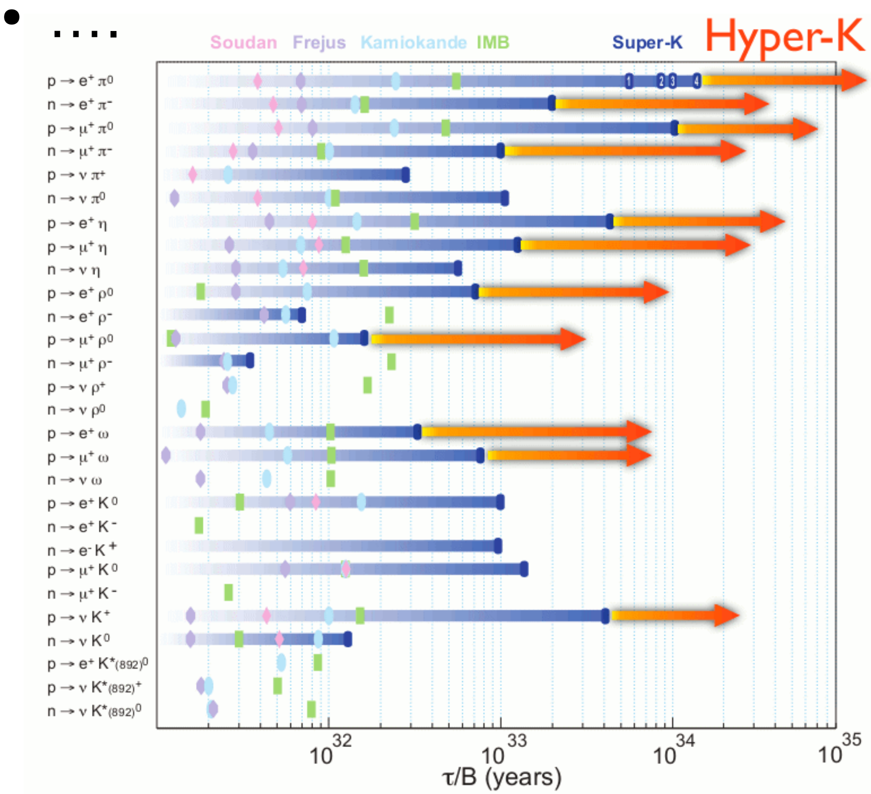
Proton Decay Sensitivities

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
  - $p \to \bar{\nu}K^+$: 2.5×10^{34} y at 90%CL
  - Many other modes:
    - P(n → e,μ) + (π,ρ,ω,η); 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.

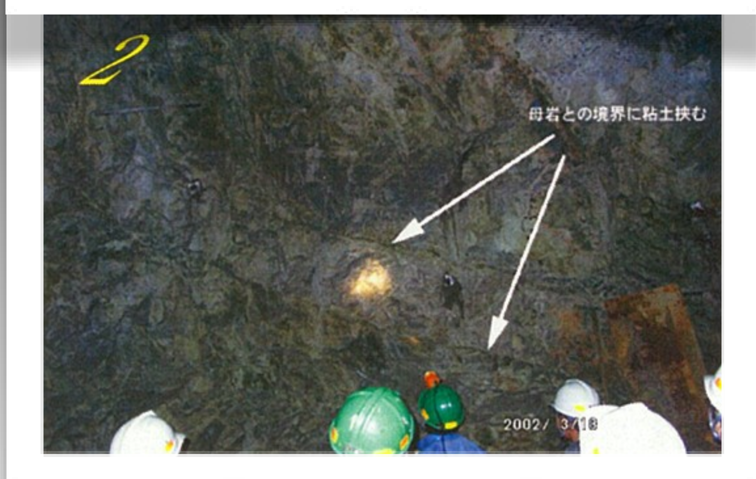
- Solar flares can be discovered at Hyper-K (important information about particle acceleration at work in solar flares)

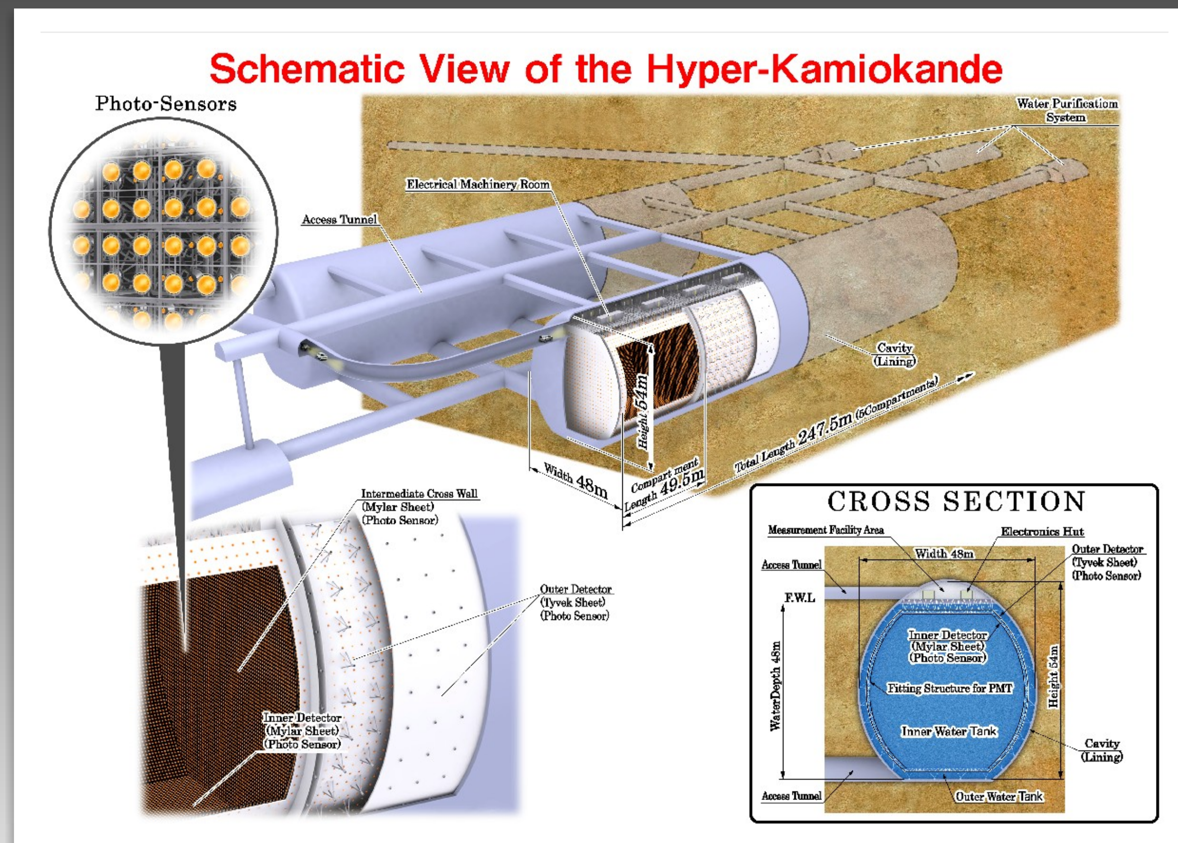
- Astrophysical neutrinos:
  - 200k ν's from Supernova at Galactic center (10kpc)
    → time variation & energy can be measured with high statistics

- 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.

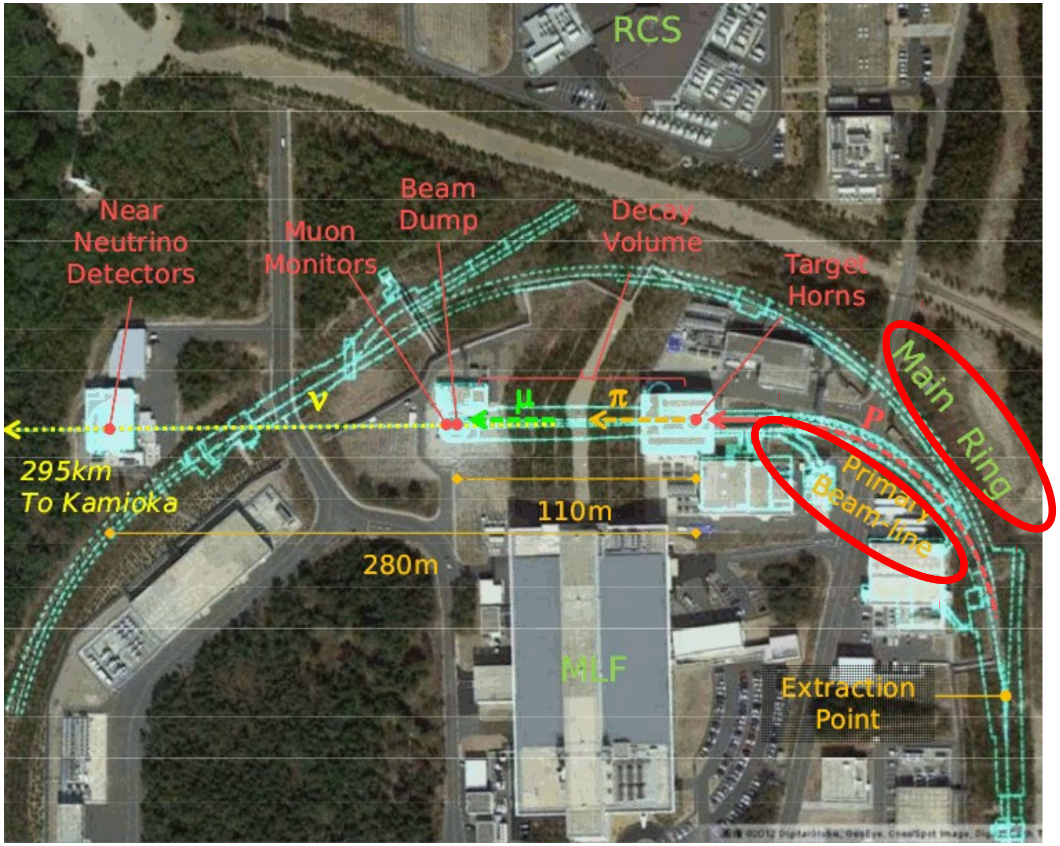
Experiment Status





Beam for Tokai-2-Hyper-Kamiokande

- Next upgrade (intermediate plan) towards a 750kW operation.
- UK/RAL contributions for T2K and planned for Hyper-K.
- The upgrade will concern:
  - Upgrade plan for J-PARC accelerators.
  - Upgrade plan for the neutrino beam-line to accept a 750MW beam.



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.)

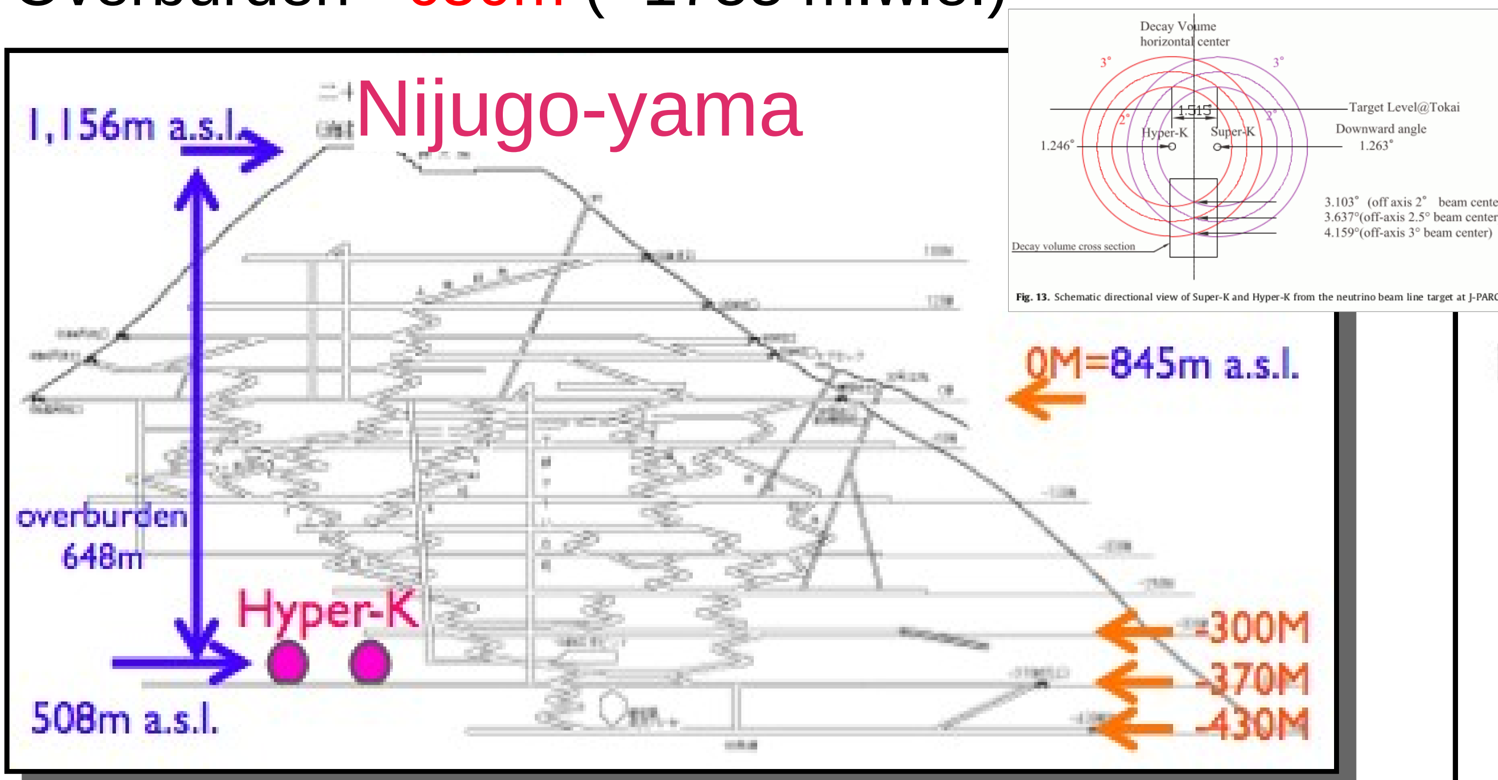


Fig. 13. Schematic directional view of Super-K and Hyper-K from the neutrino beam line target at J-PARC.

- 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.

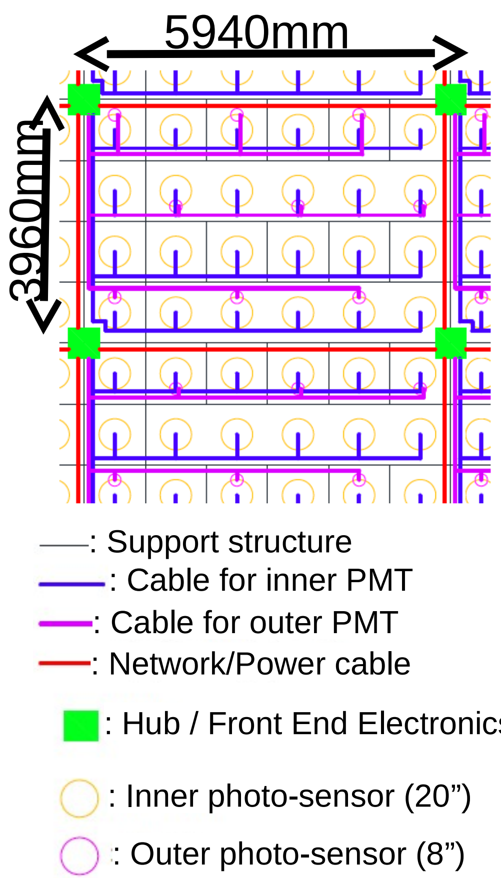
Geological Survey at Mozumi Mine

- 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°).

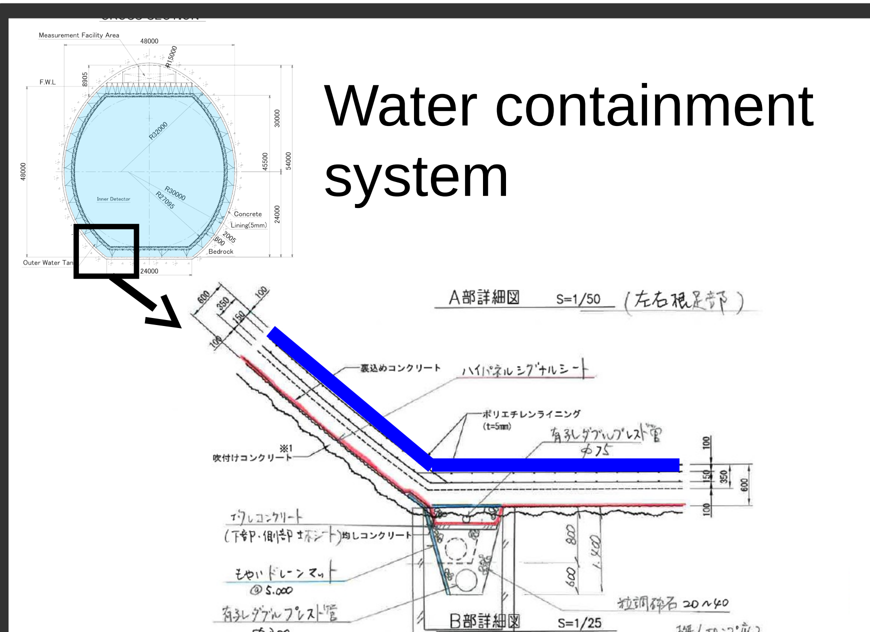
Design Work...

- 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

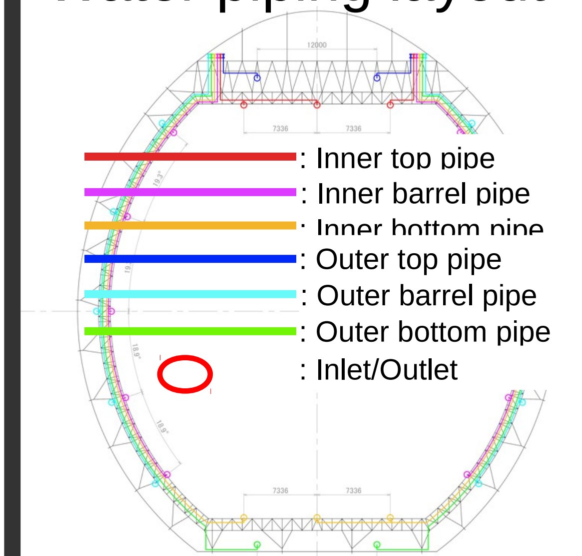
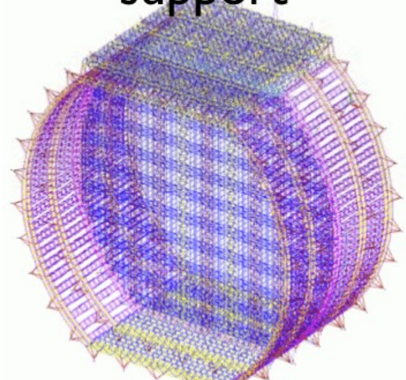
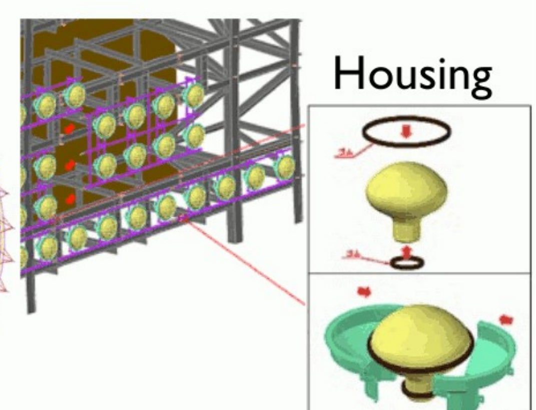


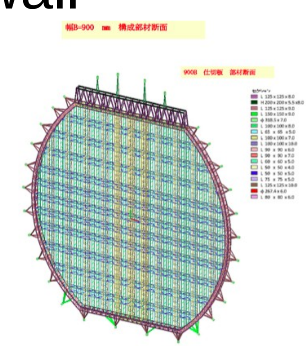
Photo-sensor support



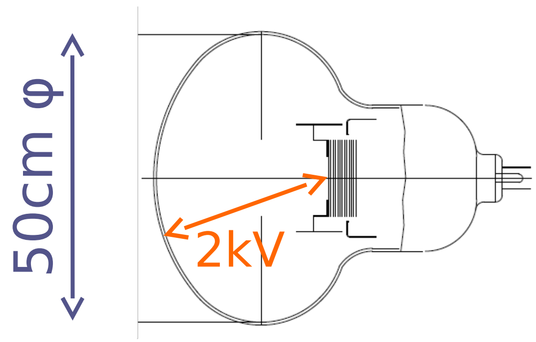
Mounting Photo-sensor

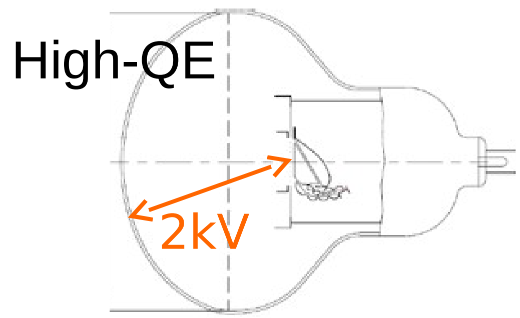


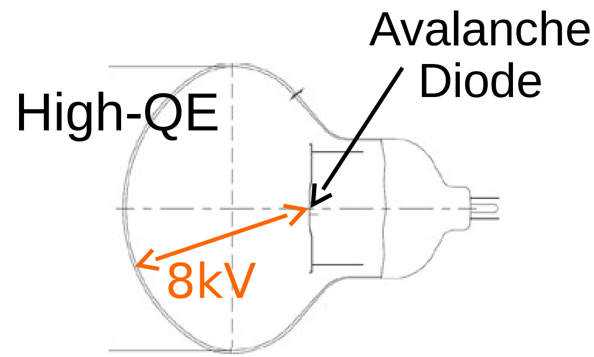
Separation wall



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

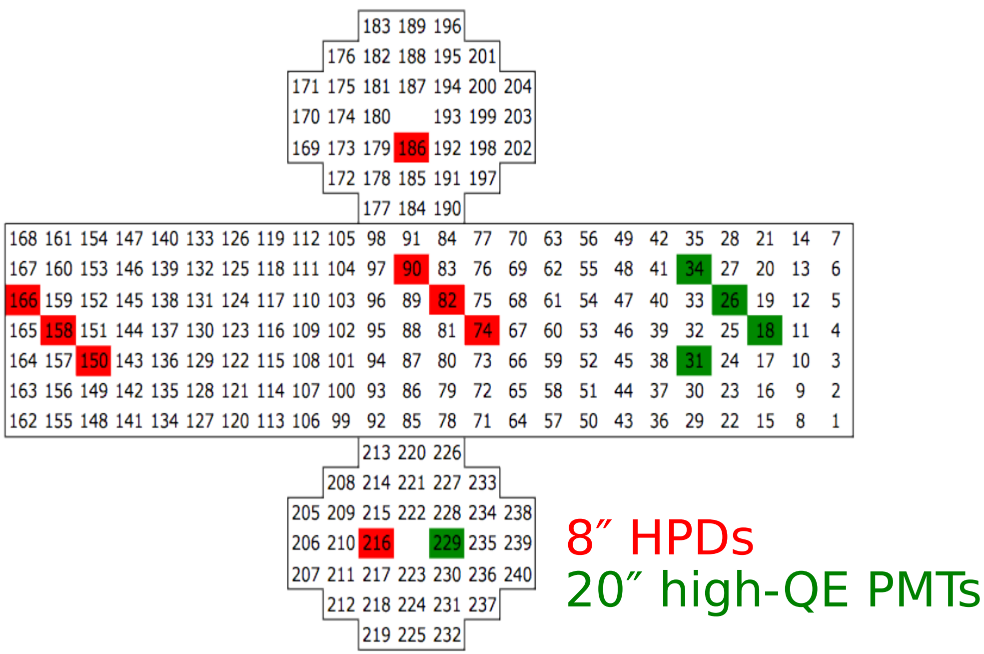
Lower Risk

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

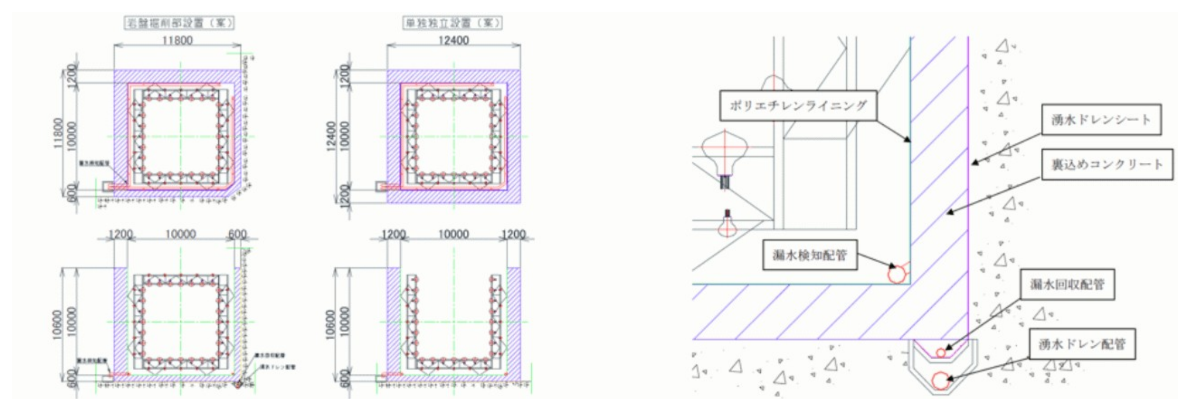


1kton WC Prototype

- 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).

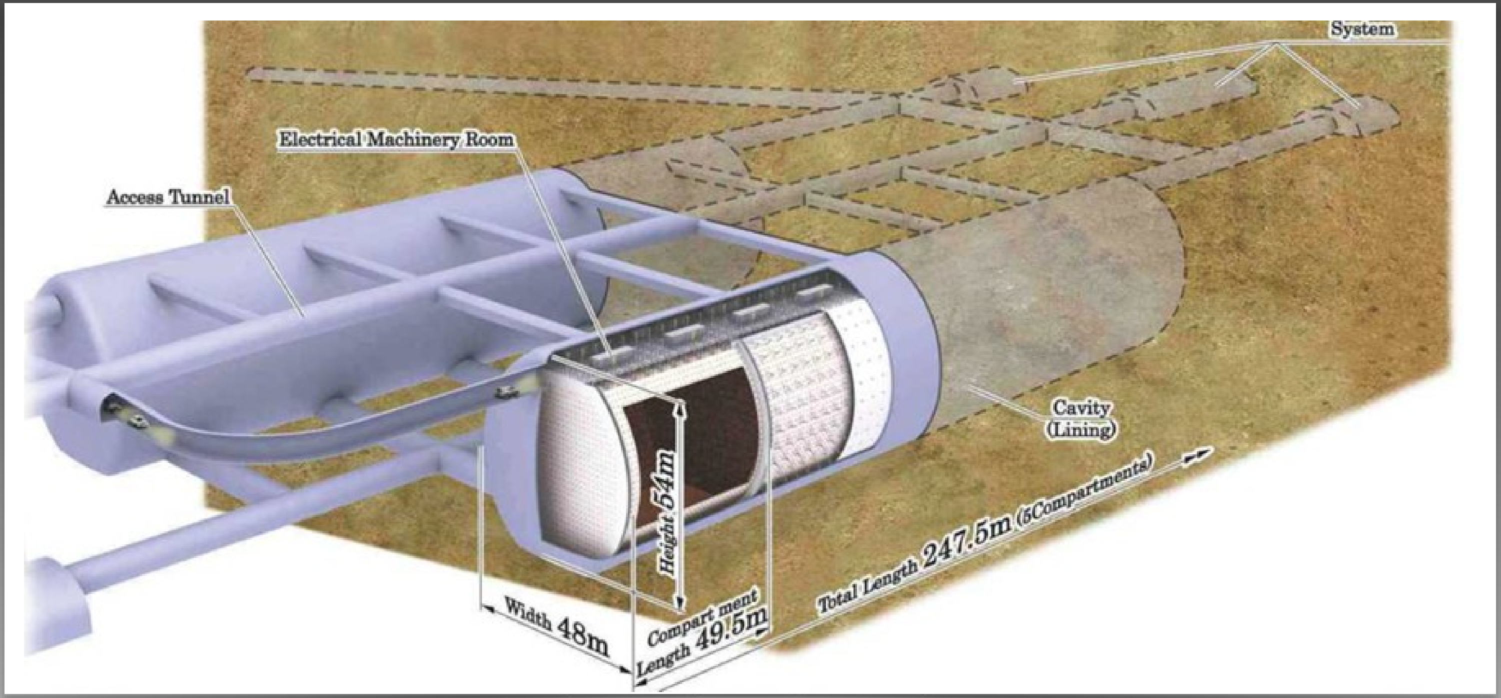
- It's one of the 20 proposals selected each year from all areas in science.

- 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.

UK Interests



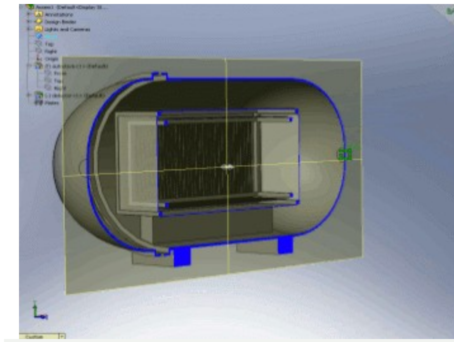
Summary of Current Areas of Interest

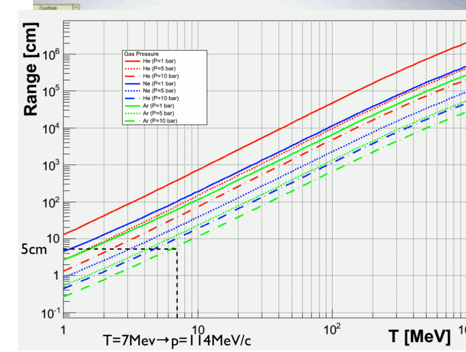
Beam	contributed to T2K. Already intense work towards a ~MW beam.
ND280 upgrade	neutrino interaction measurements
Intermediate Detector	work started towards the optimization of the design and requirements for an intermediate detector at ~2km.
DAQ & Electronics	very successful performance in T2K. New ideas being investigated.
Calibration	huge expertise (mainly SNO, SNO+). Starting to work on it.
Photosensors	LAPPDs for Intermediate detector.
Software/Computing	working on computing model.

ND280 Upgrade for T2K (T2HK)

- Several studies being performed for upgrade → beneficial for T2HK as well, if keeping ND280.

- Water target with vertex information
  - water based scintillator for P0D/FGD
  - high pressure TPC, fiber tracker:
    - Access the low energy debris and help in the study of neutrino-nucleon interactions
    - close to Oxygen, much lower energy threshold
  - water detector at the basement (B2) of ND280

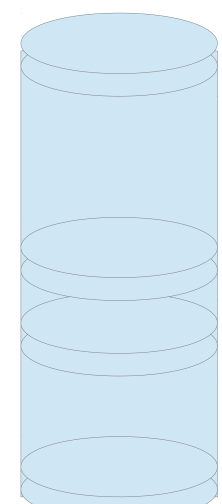




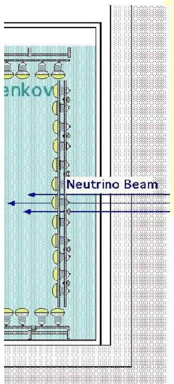
- Enhancement on side/backward going tracks
  - Trip-t electronics upgrade or better calibration

- Neutrino-nucleon cross section for model input
  - D2O and CH2 targets for FGD/P0D

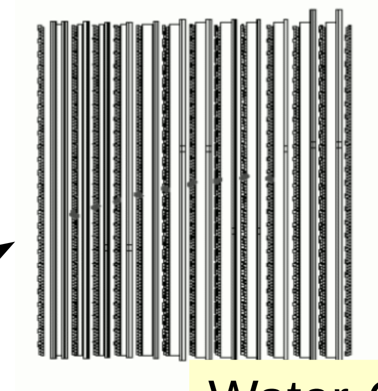
- New “water-column” detector at ~1km
  - Minimize dependence on neutrino interactions by sampling the beam at several off-axis angles.



Intermediate Detector

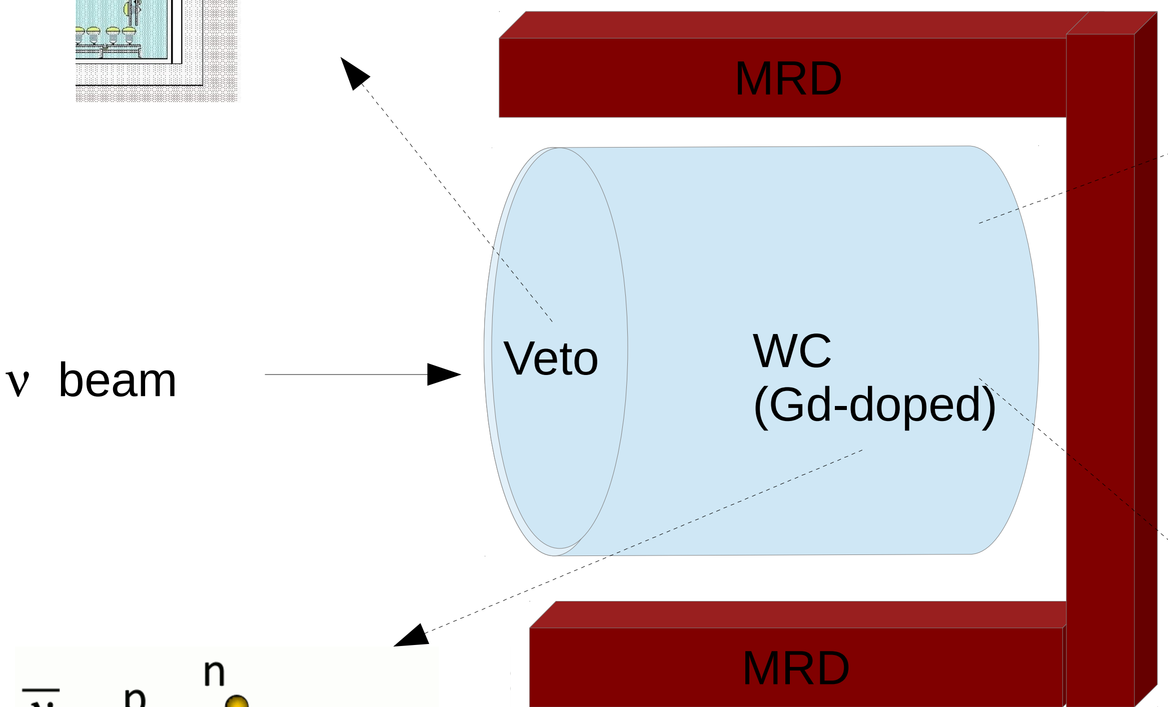


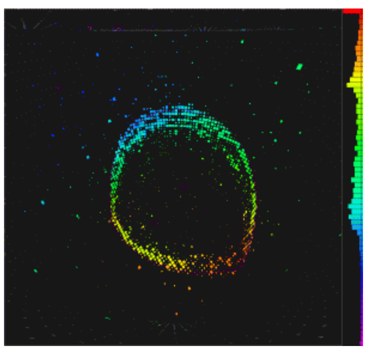
PMTs facing outwards in the veto region to reject particles that enter or are produced outside the detector



To measure energy, angle and production point of muon from CC interactions

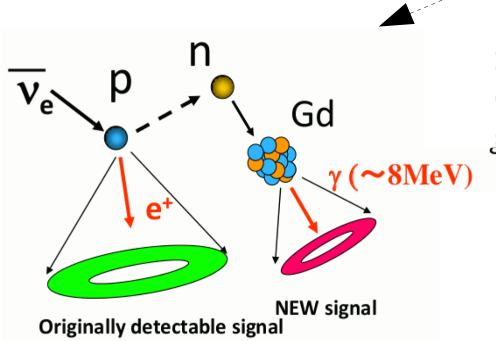
Water-Cherenkov target



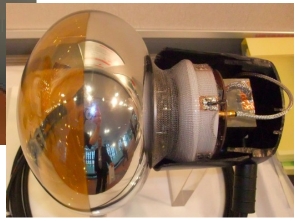


Aim to use LAPPDs (w/ HPD)

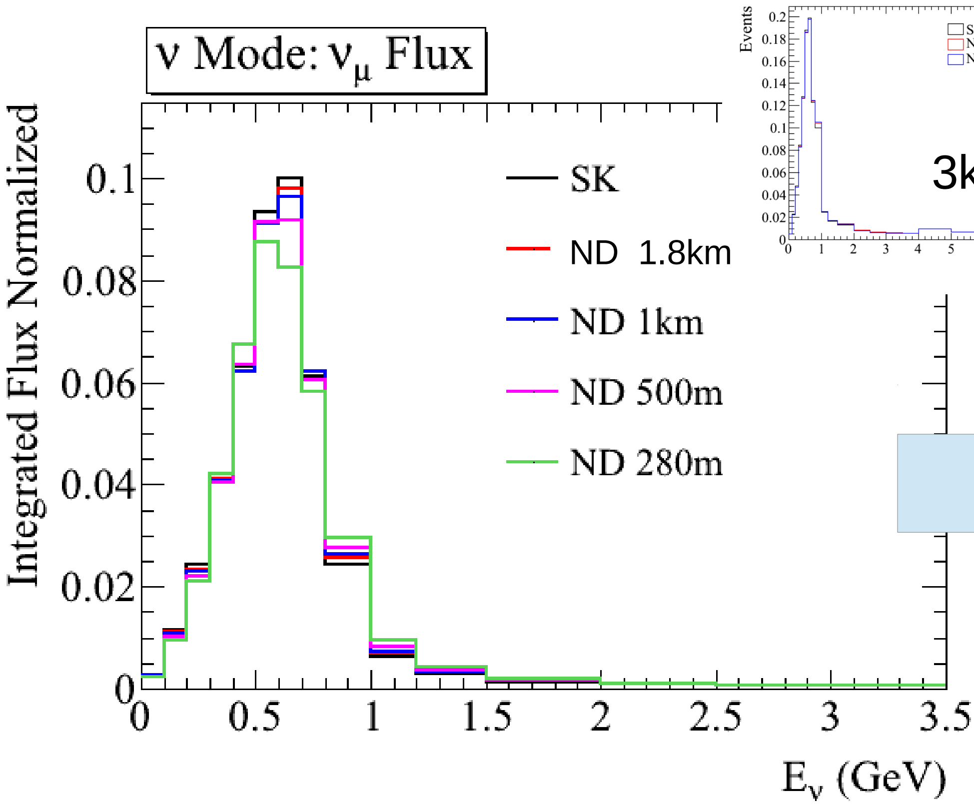
Large Area Picosecond Photo-Detector (micro-channel plate photosensor)

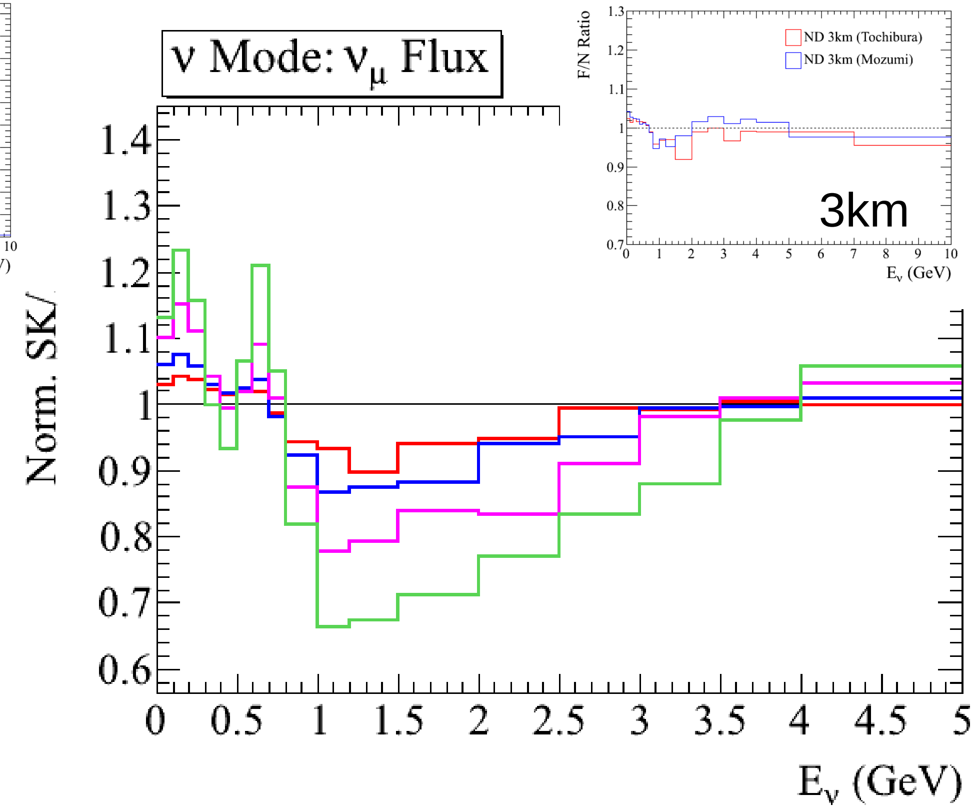


Aiming for Gd doped water.



Intermediate Detector





- At 280m: neutrino source not point-like, spectral differences with respect to SK
- Neutrino spectra at SK and 3km are almost the same: ~same beam → energy spectrum
- To improve our current precision we need to improve our errors on the flux predictions

Detector Sites

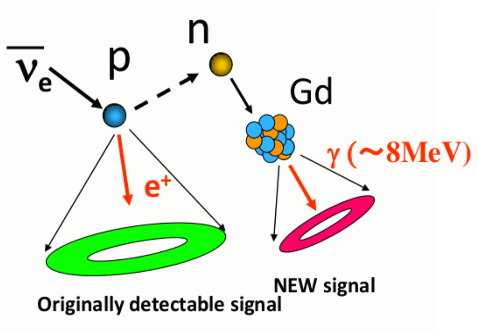
- Site optimization:
  - compromise between physics and land availability.
- A site at ~2-3km will see similar spectrum to Hyper-K.
- Ongoing work to study cross section errors, pile-up, size, location, etc.
- In the past, already performed investigations at 1.8 GeV.

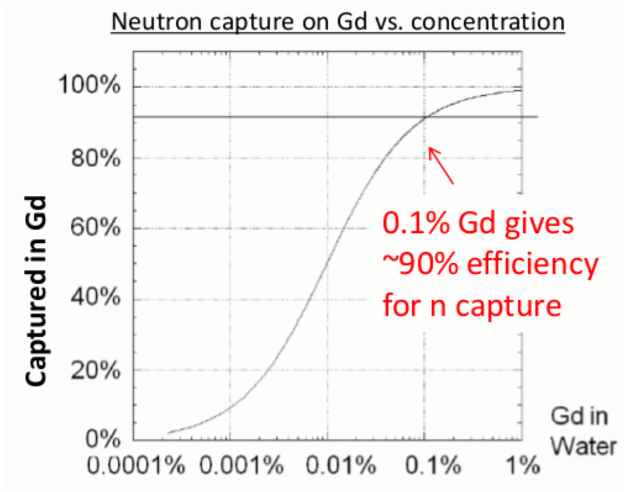
Gd-doping

- Aim to dope the experiment with Gd.

- For 0.1% concentration of Gd 90% of neutrons are captured on Gd rather than thermalized in water.

- We recently started to explore this idea. Within SK there are already studies performed with EGADS/GADZOOKS! at the Kamioka mine





- CP-related goals:
  - Use neutron tagging to reconstruct neutrino energy
  - Use to separate CC versus NC interactions. In neutrino mode, neutron multiplicity is expected to be lower for CC interactions.
  - Separation neutrinos versus anti-neutrino. More neutrons for anti-neutrinos. It's important to measure the neutrino component in an anti-neutrino beam.

Gd-doping

- Xsection physics:
  - Study nuclear models in details. A predicted effect of two-body currents is a high nucleon multeplicity in the final states.

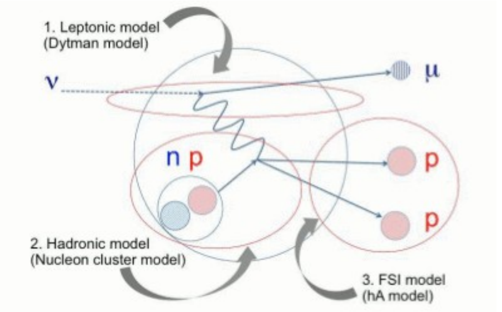


FIGURE 1. Basic strategy of modeling MEC in GENIE.

T.Katori
arXiv:1304.6014

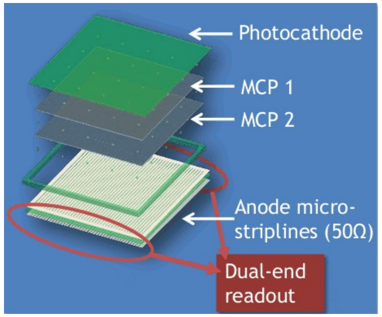
TABLE 1. Comparison of MEC models in neutrino interaction generators.

	GENIE	NuWro	GiBUU
Leptonic model	Dytman model	TEM, np-nh model, and Valencia model	Transverse projector
Hadronic model	nucleon cluster	nucleon cluster	phase space density
initial nucleon momentum	Fermi sea	Fermi sea	Fermi sea
initial nucleon momentum correlation	none	none	none
initial nucleon spatial correlation	none	none	2 nucleons are generated at the same location
initial nucleon pair	n-p:n-n=1:4 isospin ansatz	n-p:n-n=9:1 short range correlation	n-p:n-n=12:5 statistical average
FSI model	hA model	cascade model	BUU transport

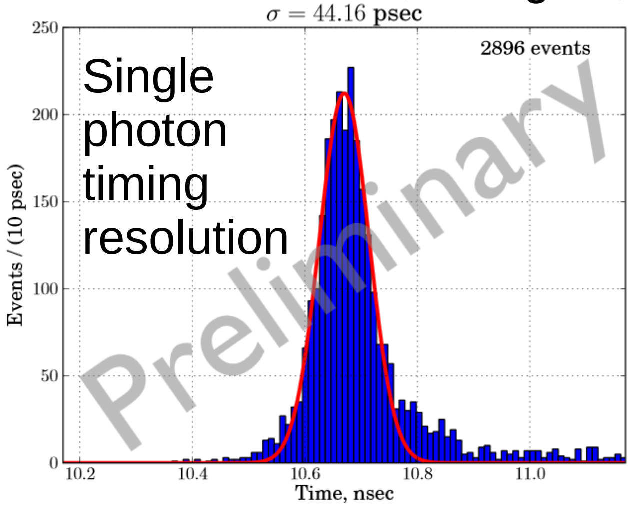
- "Other" physics:
  - Neutron interaction rate, relevant as a background for proton decay (currently will be investigated by ANNIE, but this detector has a later timescale and larger)
  - SN neutrinos → lower statistics (~500 evts?) than HK, but it is relevant to get an SN alarm in coincidence with HK.

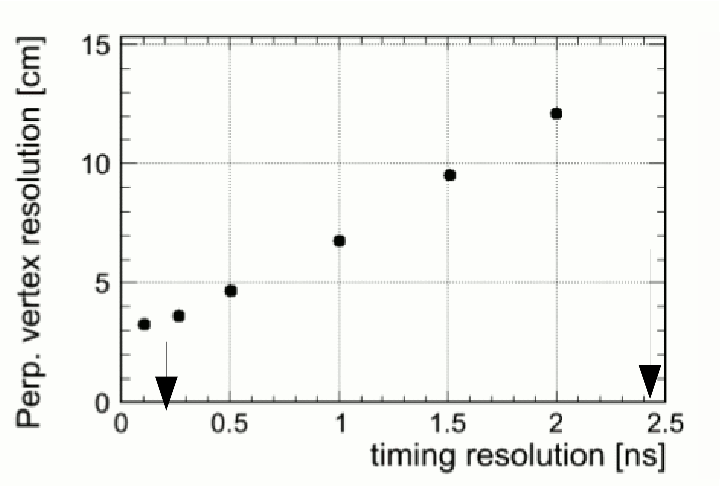
LAPPDs

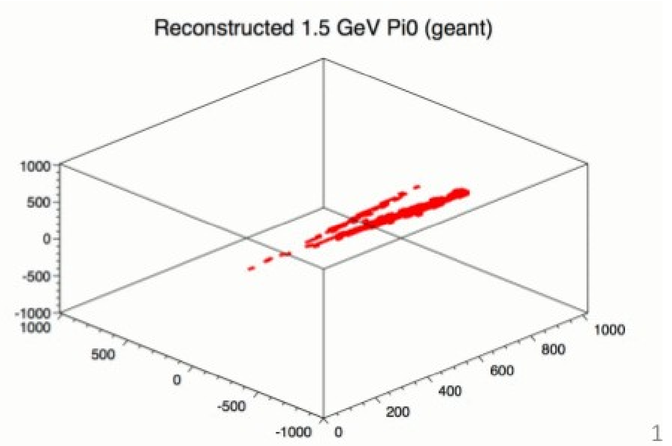
- Investigating the option of using the LAPPDs (Large Area Picosecond Photo-Detectors).
- LAPPD, developed at Argonne National Lab, is based on a micro-channel plate.
- Improved timing resolution, currently limited by PMT transit time spread (2-5ns per photon).
- LAPPDs show the benefit of excellent single timing resolution of ~50ps
  - Improved vertex resolution
  - Improved spacial resolution



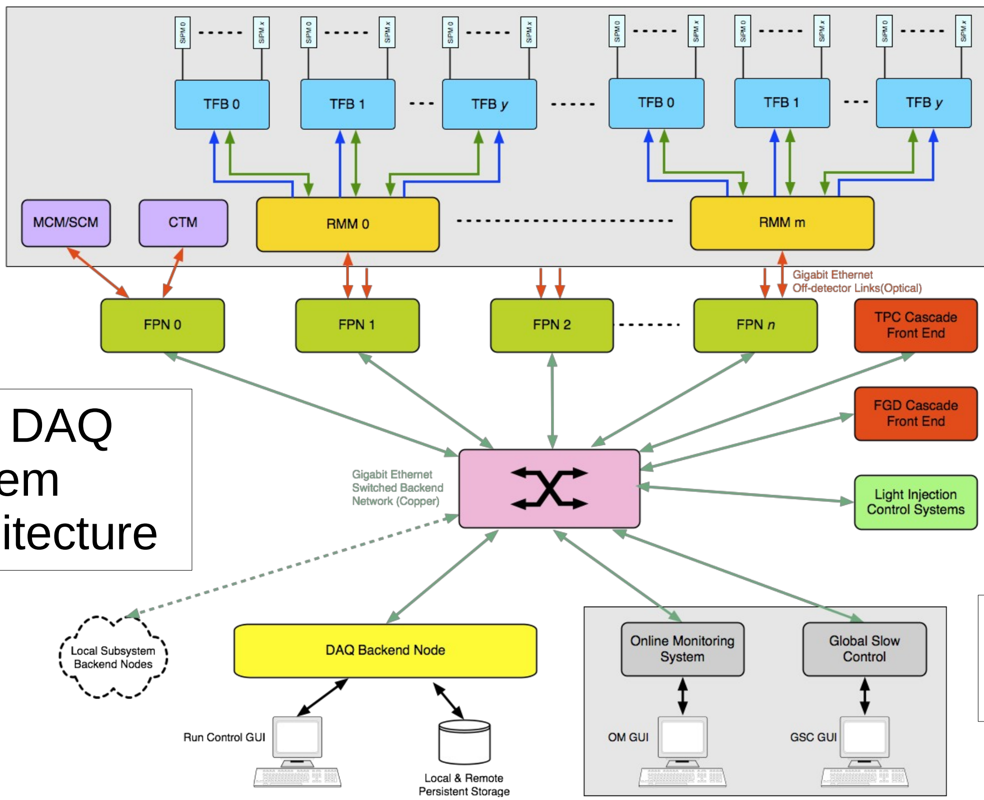
T.Xin, I. Anghel, M. Wetstein, M. Sanchez



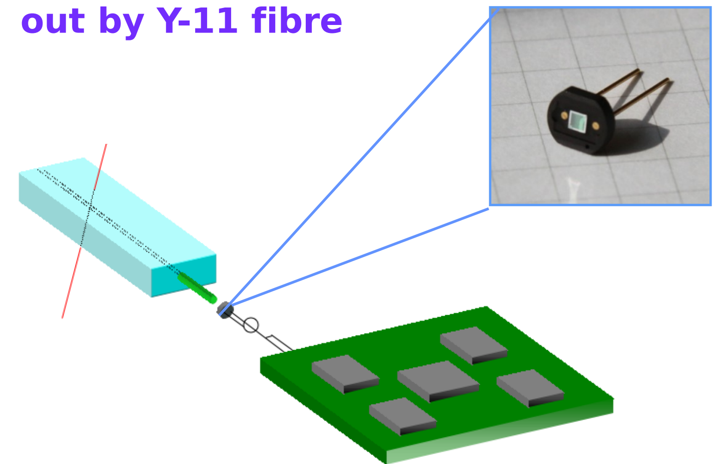




DAQ & Electronics (for Hyper-K and Interm. Det.)



T2K DAQ system architecture



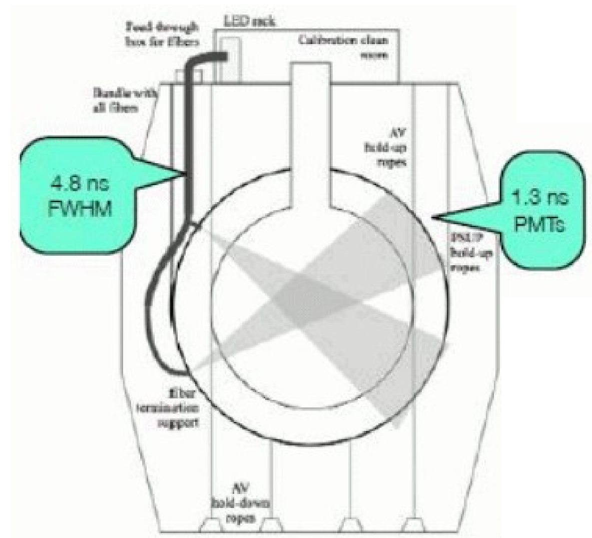
ND280 electronics for MPPC-based detectors

- DAQ & electronics ae running stably since the start of T2K.
- Based on the previous experience, we are devising the DAQ for HK and Interm. Det. – 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 Interm. Det.)

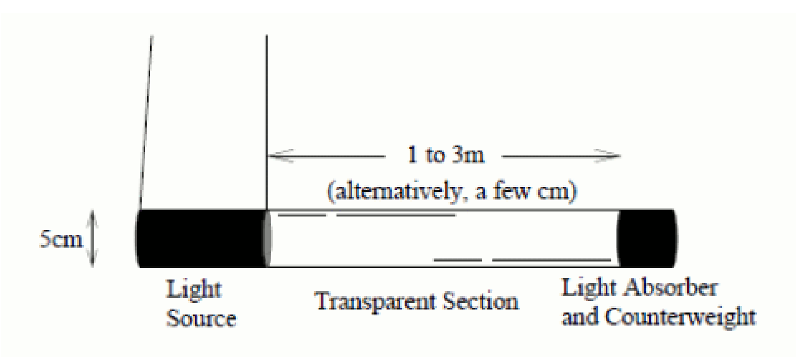
- Exploit current expertise (e.g. SNO+, ANTARES..)

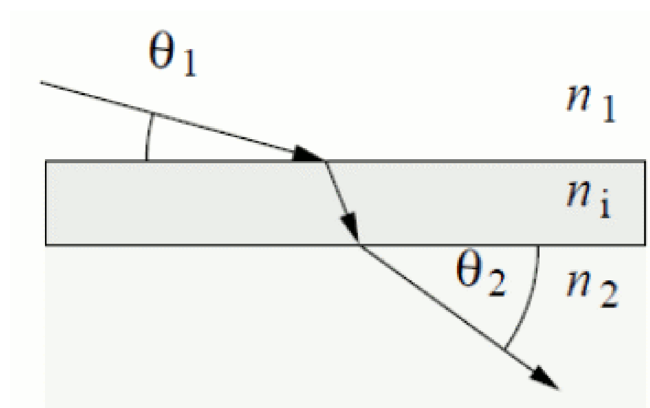
ANTARES Beacon



SNO+ Detector

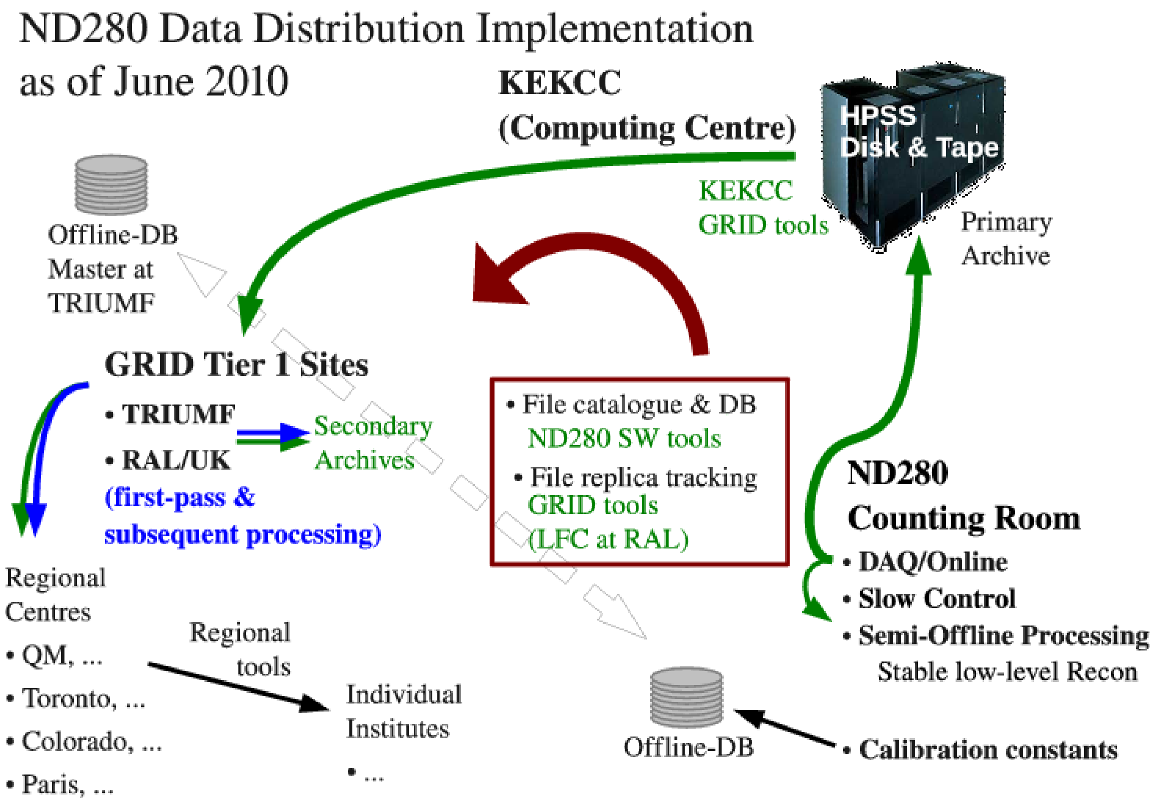
- Some initial work:
  - Development of updated LED drivers for HK
  - A source to simulate muons and test reconstruction

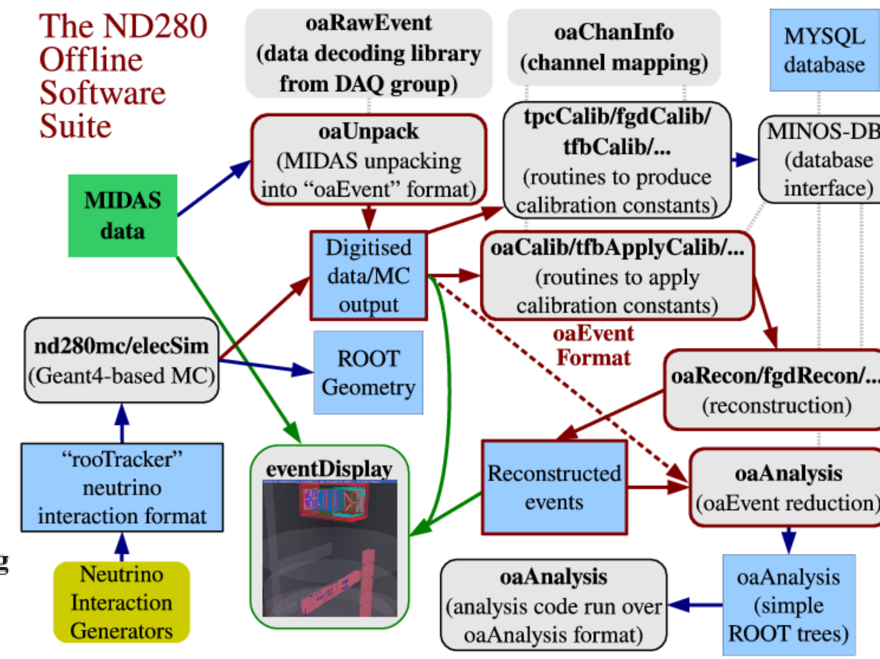




Muon Source Design

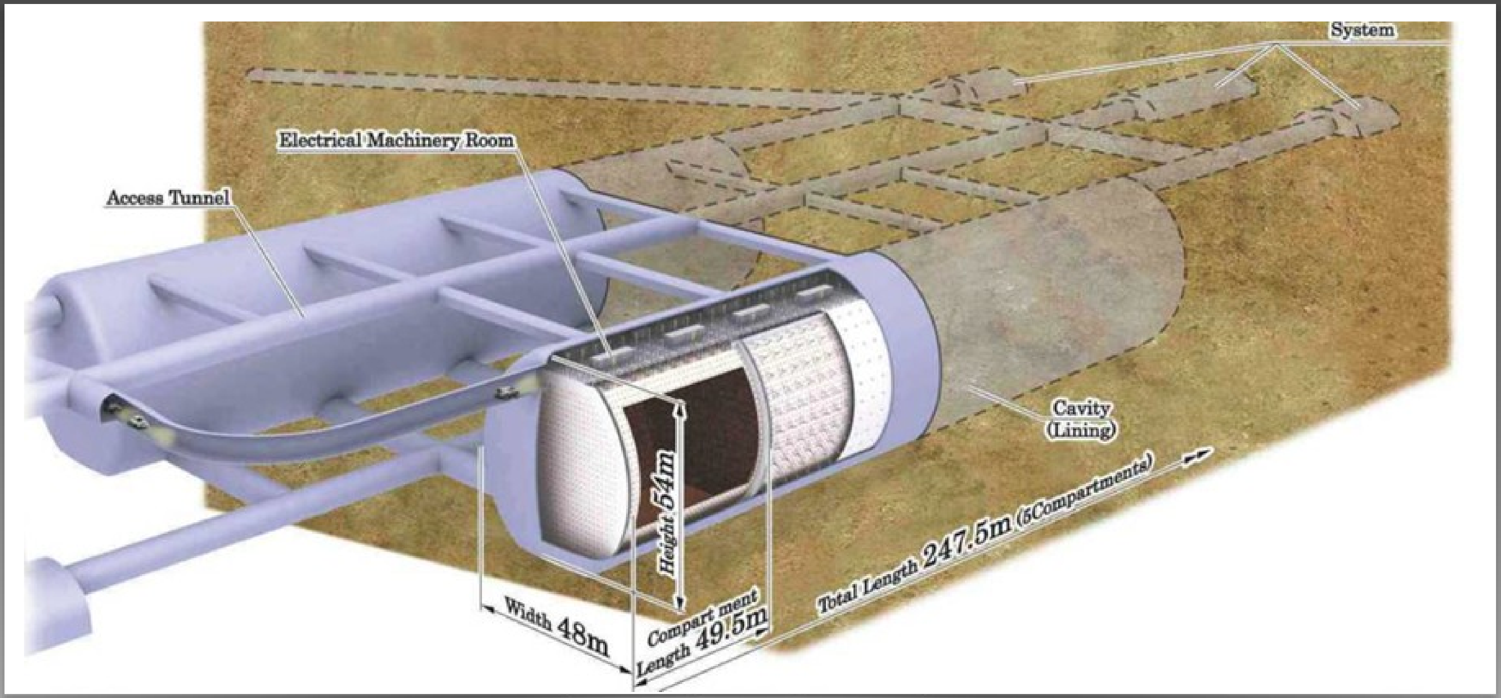
Software/Computing





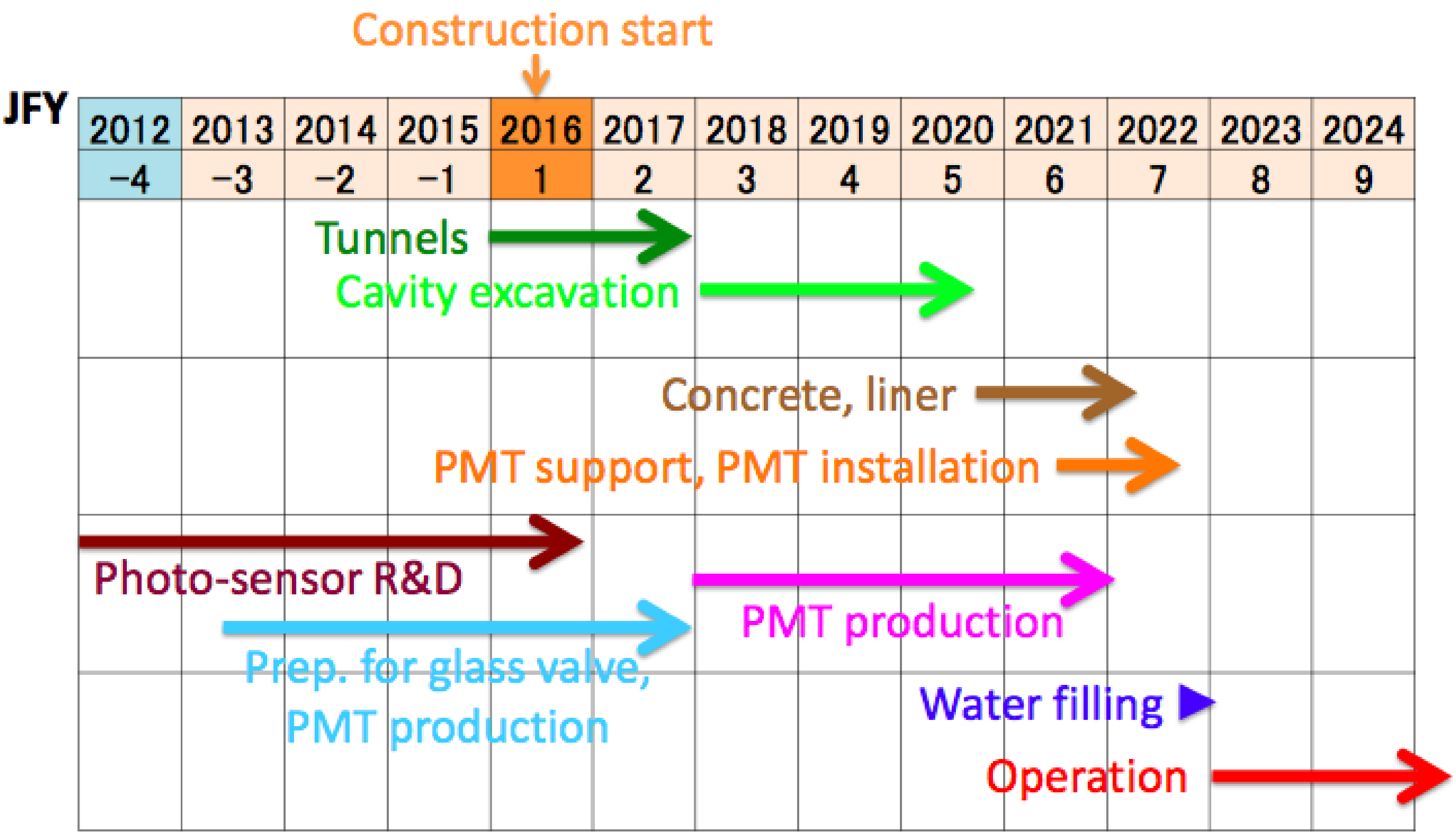
- Central role in software/computing for T2K.
- Already working on Hyper-K computing model.
- Currently producing Hyper-K simulated events.

Schedule & Summary



Overall Project Schedule

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



Overall Project Schedule

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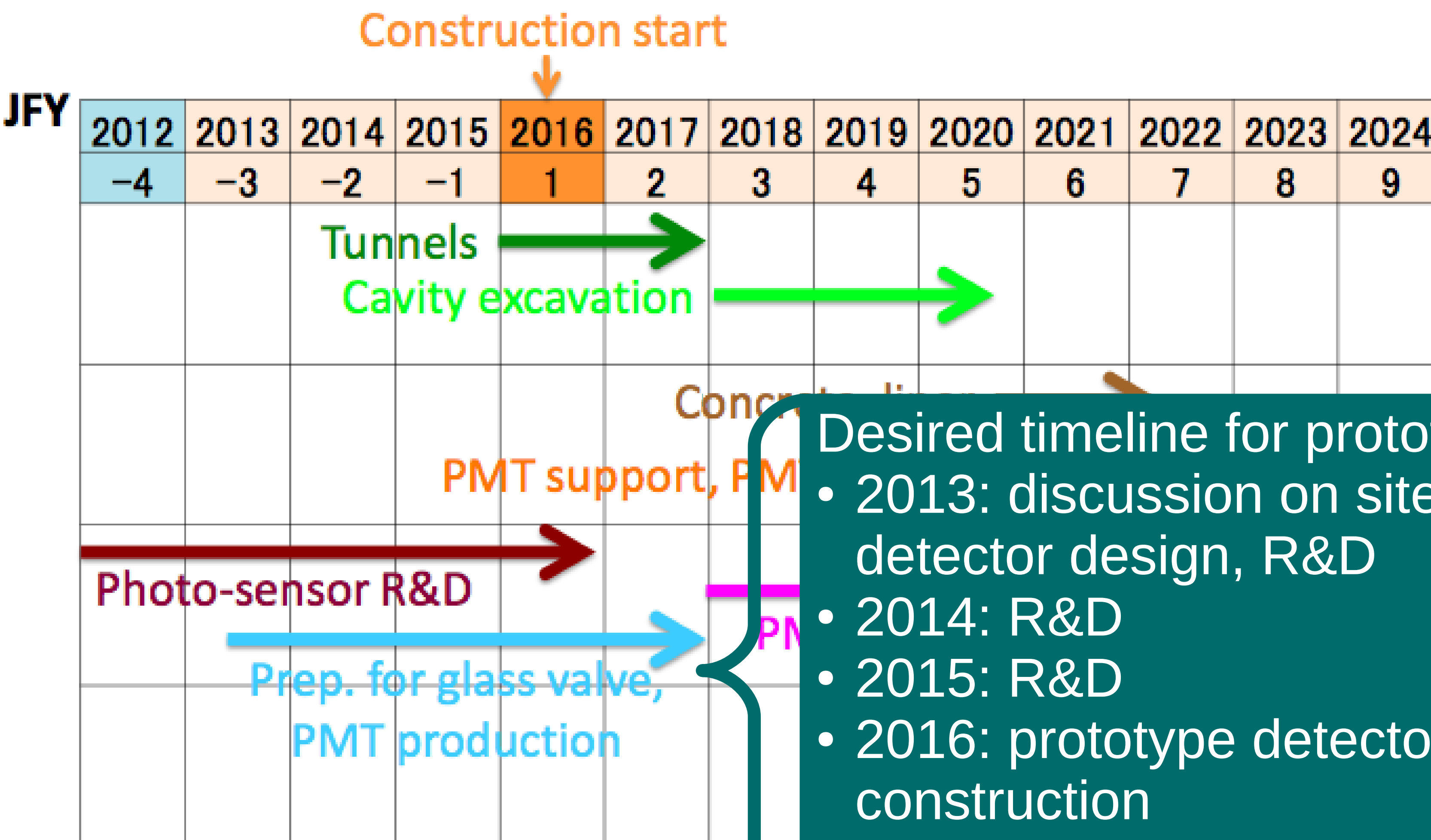


Desired timeline for prototype
- 2013: discussion on site, detector design, R&D
- 2014: R&D
- 2015: R&D
- 2016: prototype detector construction
- 2017: operation and conclusion on components

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 (2013). 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, ...)

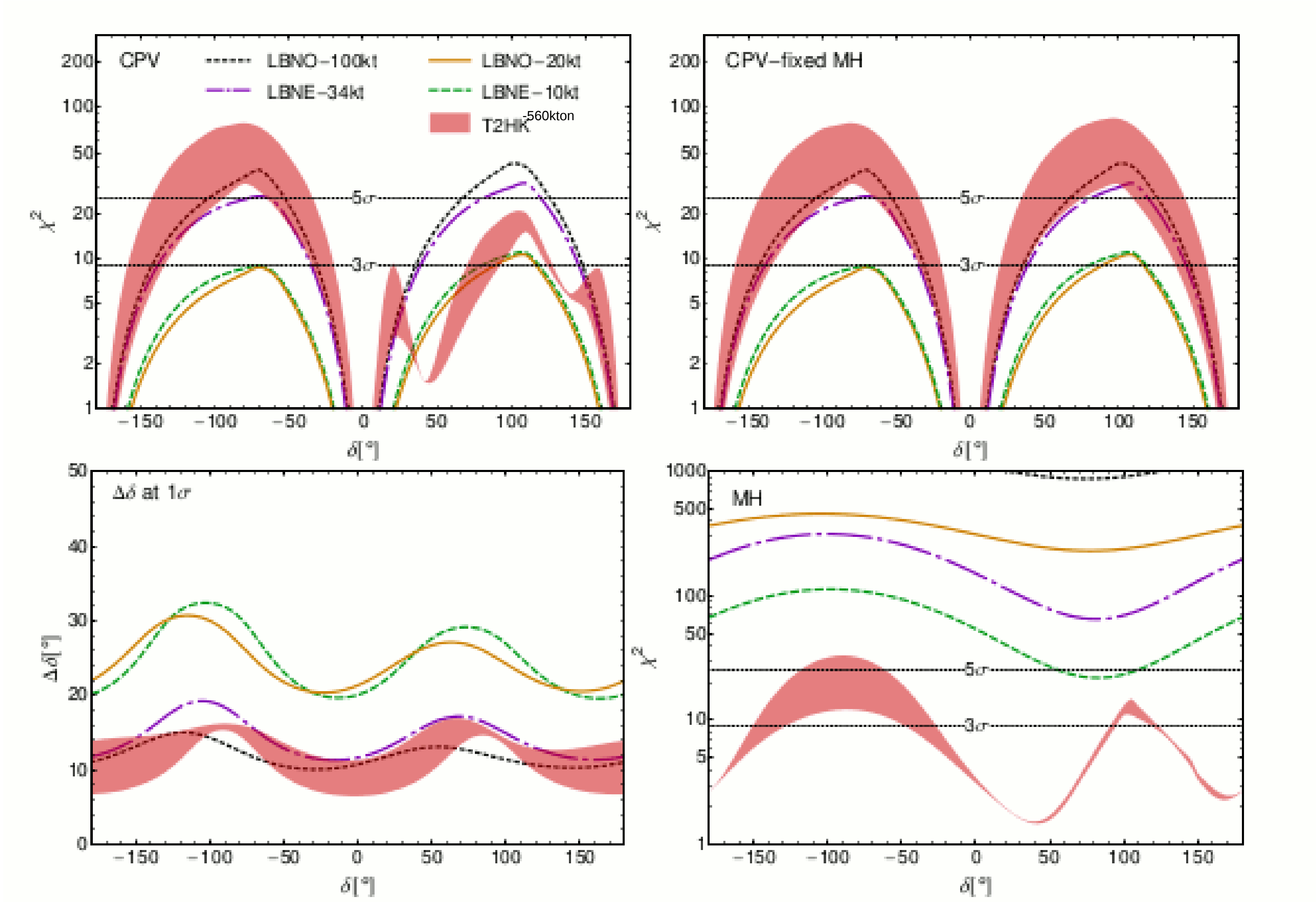
Overall Cost Estimate

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

- T2K measured non-zero θ_{13} with 7σ significance by observation of $\nu_\mu \rightarrow \nu_e$
  - Major analyses improvements: ND280 selection and SK reconstruction
- Also measurement of $\nu_\mu \rightarrow \nu_\mu$ which favors maximal mixing
  - Run4 will be added soon
- Hyper-K covers wide range of physics:
  - Neutrino oscillation with beam-ν & atmospheric-ν
    - ➔Main goal: CP violation
  - Nucleon decay search and astrophysical neutrinos
- R&D started in all areas and progressing
- Japan HEP community: HK at highest priority. Strongly growing international community.

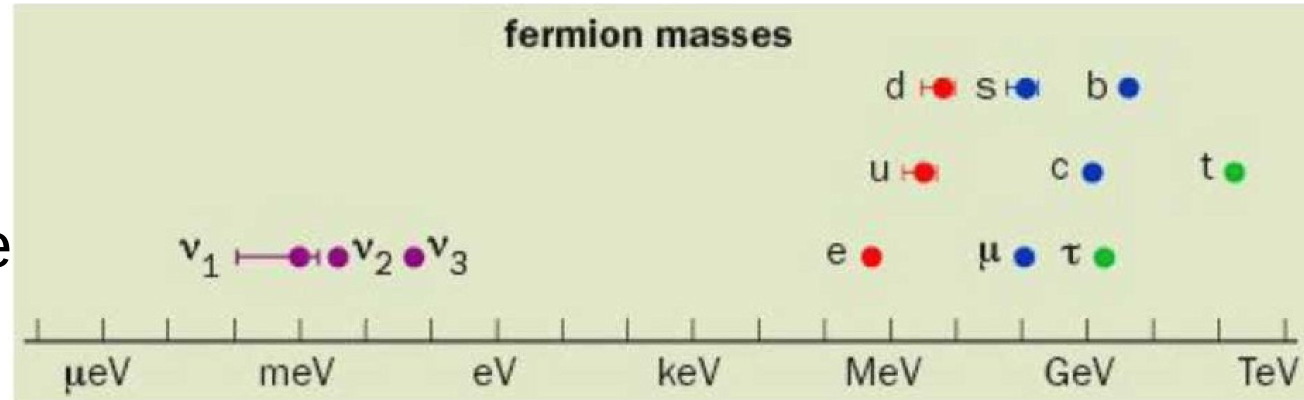


Input to strategy group for the update of the EU strategy http://cds.cern.ch/record/1628377/files/Briefing_book.pdf(2013). Beam power: LBNE 700kW 10years, T2HK 1.66 MW 5 years, LBNO 800kW 10 years).

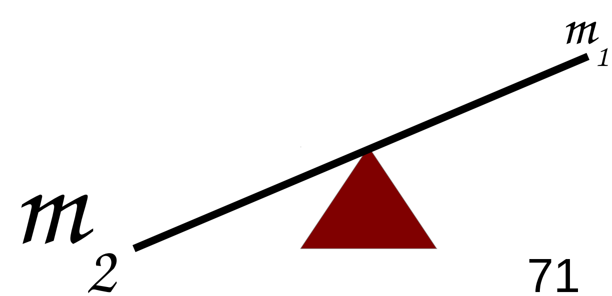
Backup Slides

What we Know about Neutrinos

- Three flavours: ν_e, ν_μ, ν_τ
- Neutral
- Interact via the weak force
- Abundant
- Massive

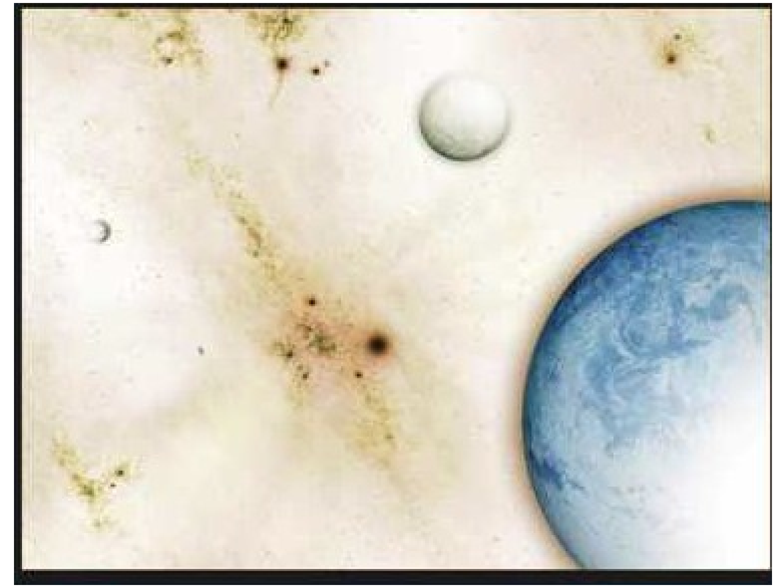


- In the Lagrangian, charged leptons have Dirac mass terms which couple left and right chiral components: $-m_D\,(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$
- Neutrinos are massless in the SM, only interact with the left handed left force
- The see-saw mechanism explains the lightness of the neutrino mass by adding a very heavy right handed neutrino, N_R



ν and the Matter-Antimatter Asymmetry

≠



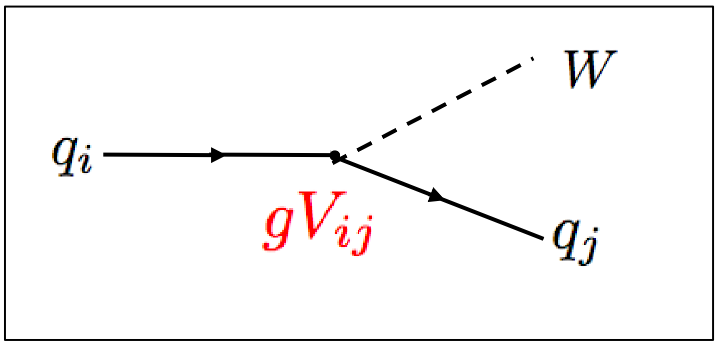
- Leptogenesis: CP violation in the decay of N_R can create a lepton number asymmetry which can be converted to a lepton number asymmetry (M. Fukugita and Y. Yanagita, PLB 174, 45 (1986).

- For the matter-antimatter asymmetry to be generated, we require: non-thermal equilibrium , CP Violation, and baryon number violation (A.D. Sakharov, JEPT Lett. 5, 24 (1967)).

Neutrino Oscillations

- Similar mechanism as in the quark oscillation (CKM matrix).
- Free parameters: 3 angles, 1 phase

CKM matrix



$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$

- PMNS (Pontecorvo, Maki, Nagakawa, Sakata) matrix for ν:

Flavour eigenstates
(coupling to the W)

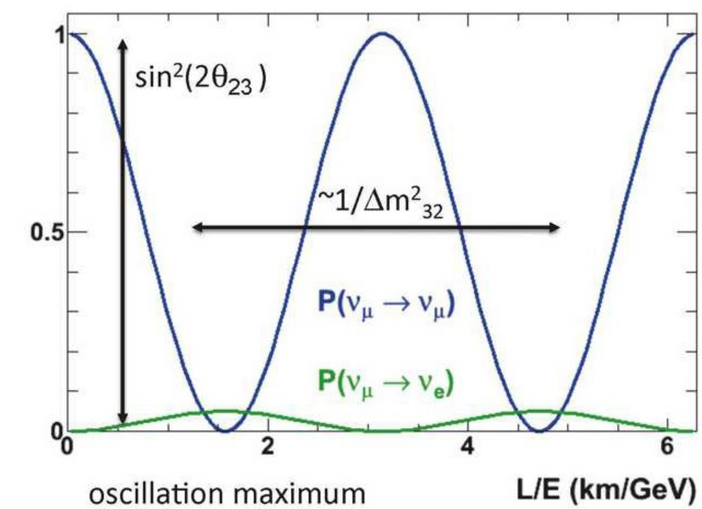
Mass eigenstates
(definite mass)

Neutrino Oscillation Revisited

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

- $\Delta m^2_{32} >> \Delta m^2_{21}$, producing high frequency and low frequency oscillation terms in the probability formula.
- If choose L,E such that $\sin^2(\Delta m^2_{32}\, L/E) \sim 1$, then Δm^2_{21} terms will be small.
- ν_μ "disappear" in ν_e, ν_τ:

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



- A small fraction of ν_e will appear:

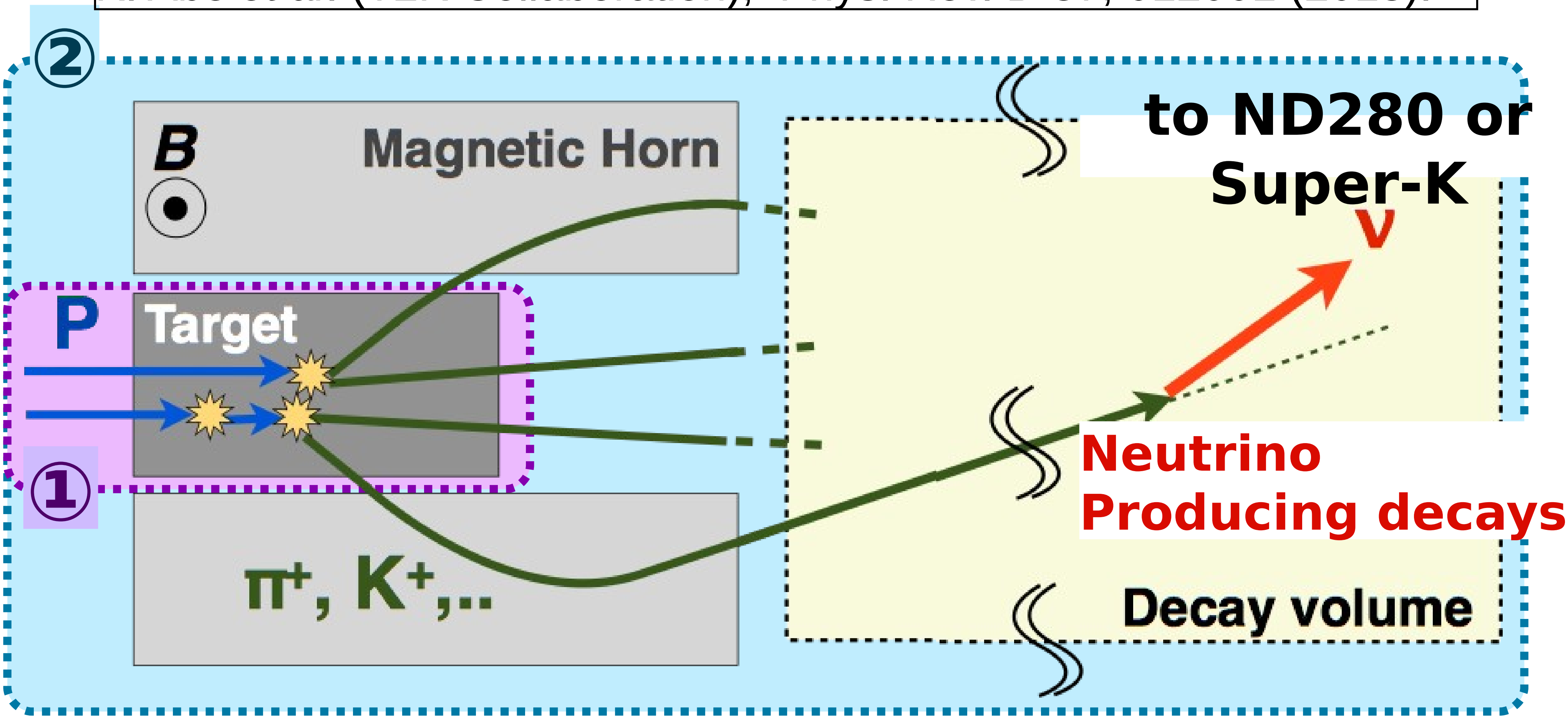
$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$\Delta m^2_{31} \sim \Delta m^2_{32}$

Only leading order terms shown

Simulating neutrino flux

K. Abe *et al*. (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).



1. p interaction inside the carbon target with FLUKA2008.3d
2. Tracking through horn fields and decay volume using GEANT3 with GCALOR

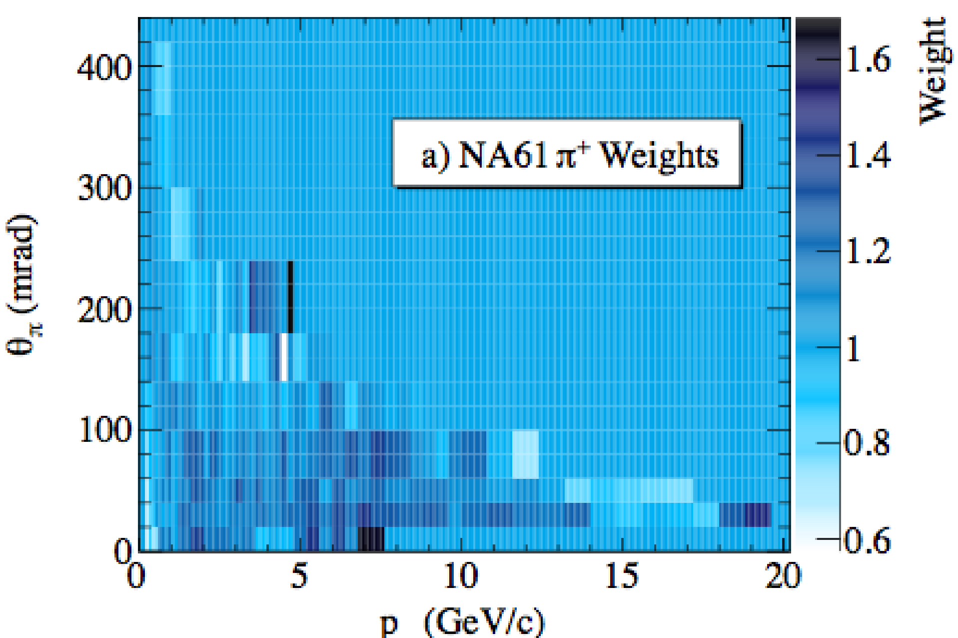
Calculate neutrino producing decays

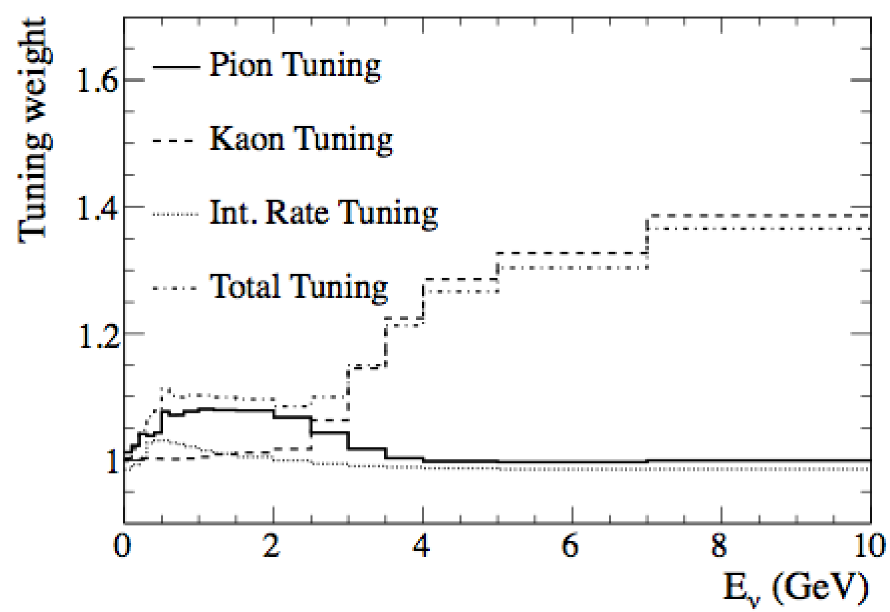
Estimate the flux at the near/far detector

External Data and Flux

- Hadro-production simulated with FLUKA2008.3d, weighted so that interactions match external data **[1]**
  - NA61/SHINE (CERN) **[2][3]**, Eitchen *et al.* **[4]**, and Allaby *et al.* **[5]**

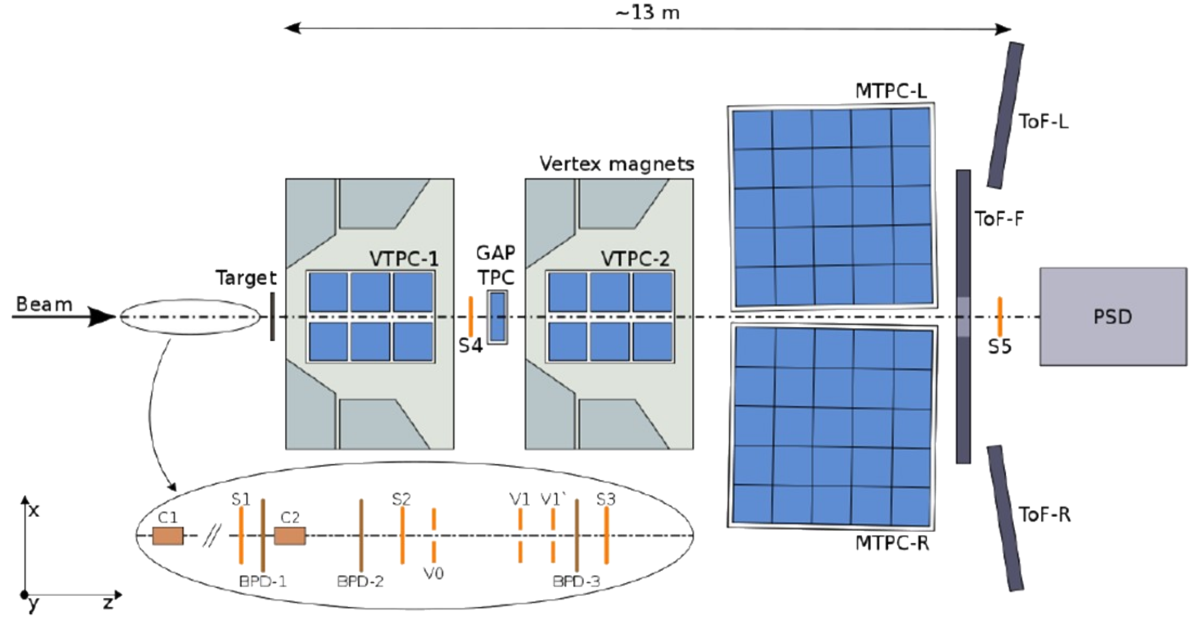
[1] K. Abe et al. (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).
[2] N. Abgrall *et al*. (NA61/SHINE Collaboration), Phys. Rev. C 84, 034604 (2011)
[3] N. Abgrall *et al*. (NA61/SHINE Collaboration), Phys. Rev. C 85, 035210 (2012)
[4] T. Eichten *et al*., Nucl. Phys. B 44 (1972)
[5] J. V. Allaby *et al*., Tech. Rep. 70-12 (CERN,1970)





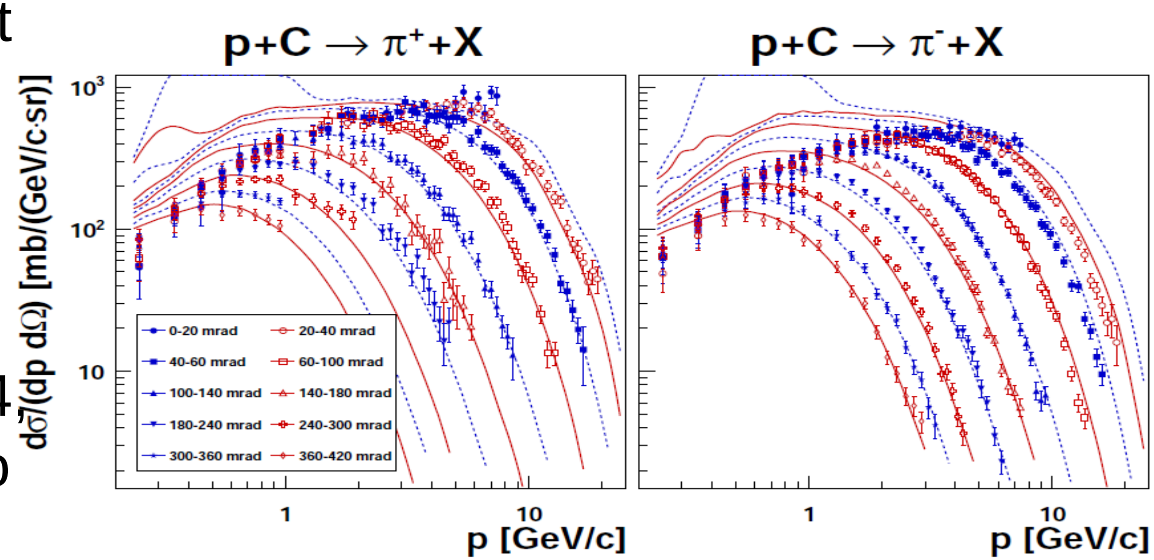
NA61/SHINE

- Located at the CERN SPS (North Area, H2 beam line)
- Fixed target experiment on primary (ions) and secondary (ions, hadrons) beams



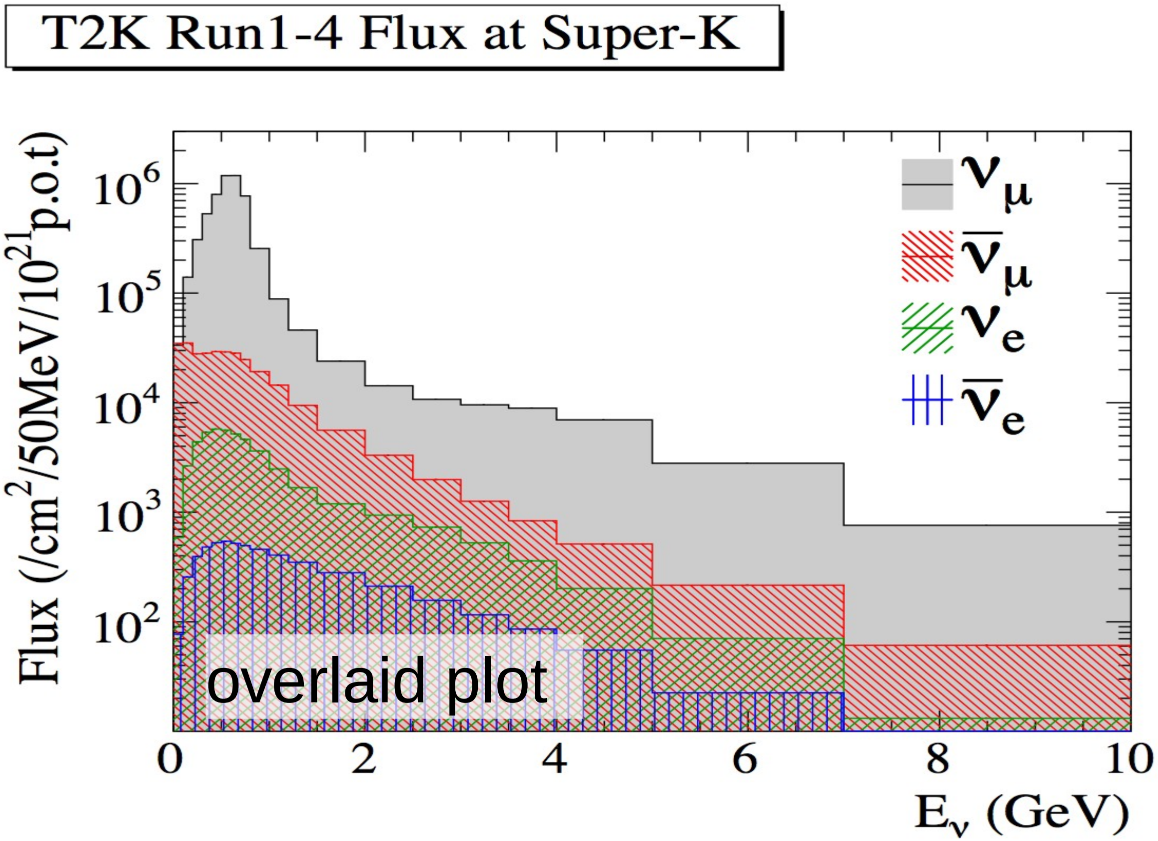
- Pion spectra in p+C interactions at 31 GeV/c are published:
  Phys. Rev. C84 (2011) 034604
- They are used to improve beam neutrino flux predictions
- Adjust models (UrQMD 1107.0374 Fritiof 1109.6768) used in neutrino and cosmic-ray experiments

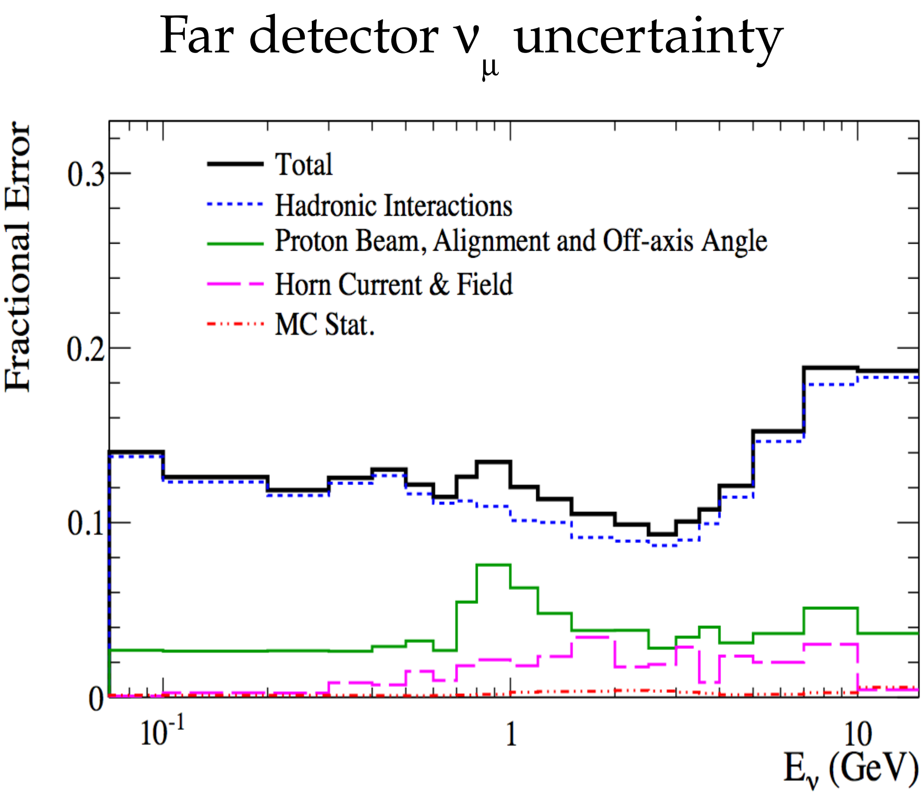
Inclusive π^+ spectra in p+C at 31 GeV/c

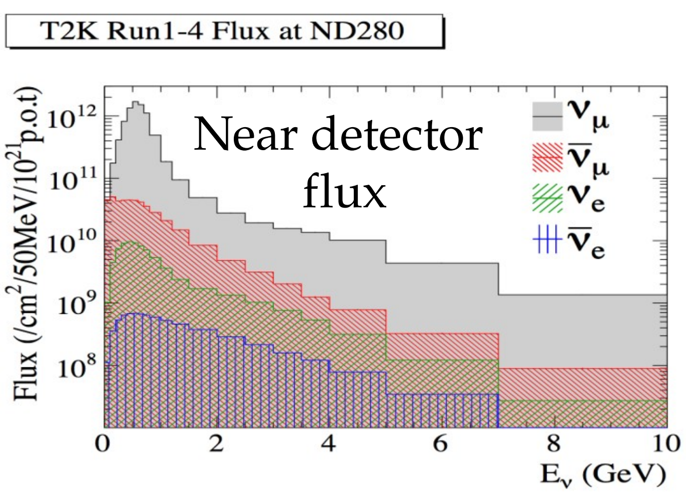


comparison to UrQMD1.3.1

Flux and Uncertainties







- A priori prediction of flux at Super-K has 10-15% uncertainties from 0.1 to 5 GeV
- Off-axis near (ND280) and Far (Super-K) fluxes are not identical, but highly correlated

fiTQun: Improved SK Reconstruction Algorithm

- Each hit PMT gives charge and time information
- For a given event topology hypothesis, it is possible to produce a charge and time PDF for each PMT
- Based on MiniBooNE likelihood model (NIM A608, 206 (2009))
- Event hypotheses are distinguished by best-fit likelihoods, e.g., electron vs muon or π^0

Cerenkov light emission profile

$$\mu^{\mathrm{dir}} = \Phi(p) \int ds g(s, \cos\theta) \Omega(R) T(R) \epsilon(\eta)$$

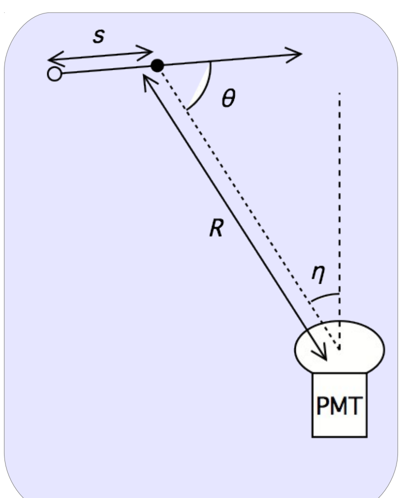
Light Yield

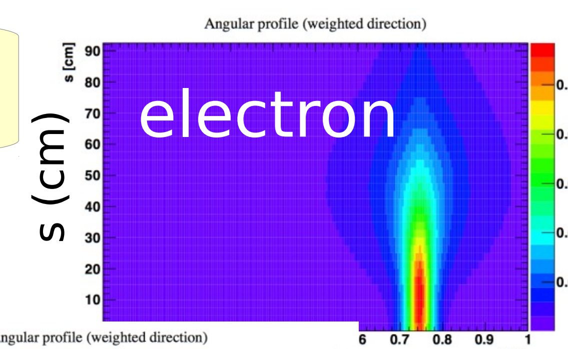
Integral over track length

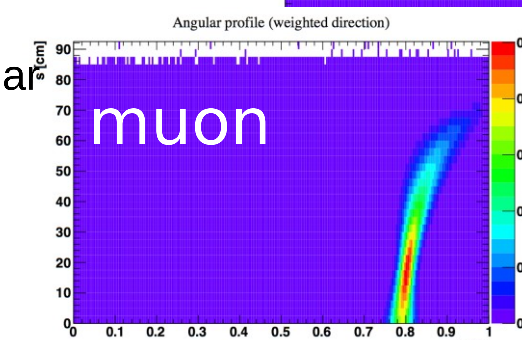
PMT solid angle

Water attenuation

PMT angular response

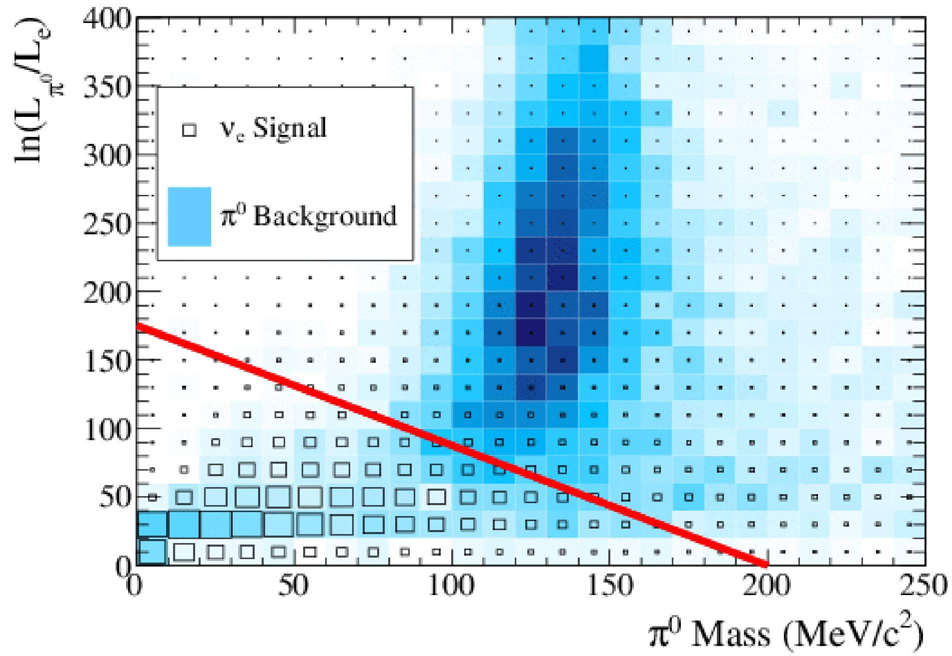






Enhanced π^0 Rejection

Likelihood Ratio vs π^0 Mass



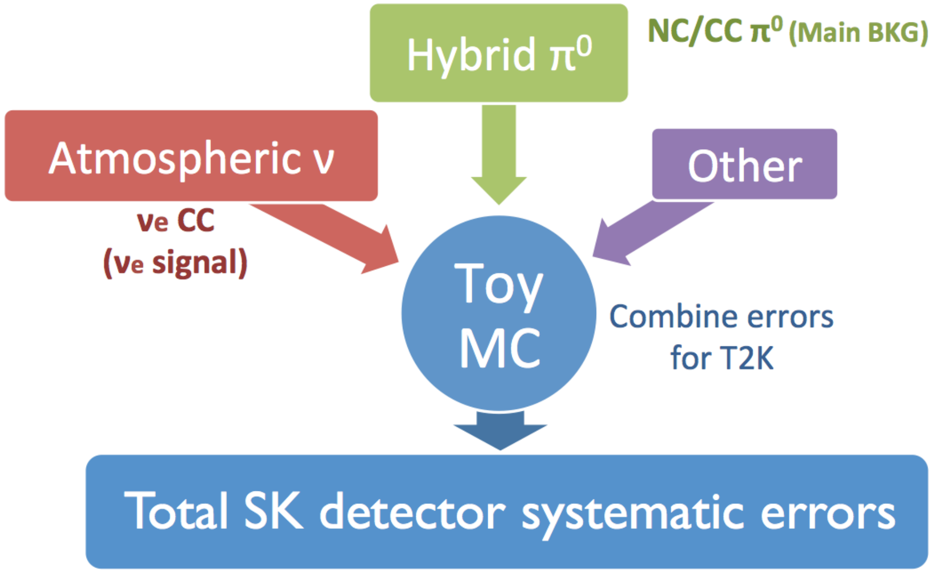
- fiTQun can use the mass of the π^0 hypothesis and best-fit likelihood ratio of e^- and π^0
- Cut removes 70% more π^0 background than previous§ method for a 2% added loss of signal efficiency.

§ Previous approach (P0LFit) forced the reconstruction to find two rings and then formed a π^0 mass under the two-photon hypothesis

Selection Results

RUN1-4 6.570x10^{20}POT	MC Expectations w/ $\sin^2 2\theta_{13}=0.1$					Data
	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC	NC	BG total	Signal	
True FV	325.67	15.97	288.11	629.75	27.07	-
FCFV	247.75	15.36	83.02	346.13	26.22	377
One-ring	142.44	9.82	23.46	175.72	22.72	193
e-like	5.63	9.74	16.35	31.72	22.45	60
E_{vis}>100MeV	3.66	9.68	13.99	27.32	22.04	57
No decay-e	0.69	7.87	11.84	20.40	19.63	44
E_ν^{rec}<1250MeV	0.21	3.73	8.99	12.94	18.82	39
fiTQun π^0	0.07	3.24	0.96	4.27	17.32	28
Efficiency [%]	0.0	20.3	0.3	0.7	64.0	-

SK Detector Systematic Uncertainties



- Evaluation of Super-K detector systematic uncertainties uses control samples from the data
  - Atmospheric ν_e
  - Hybrid π^0 (electron from ν_e CC and MC photon)
  - Cosmic ray muon samples
- Combine errors with Toy MC method

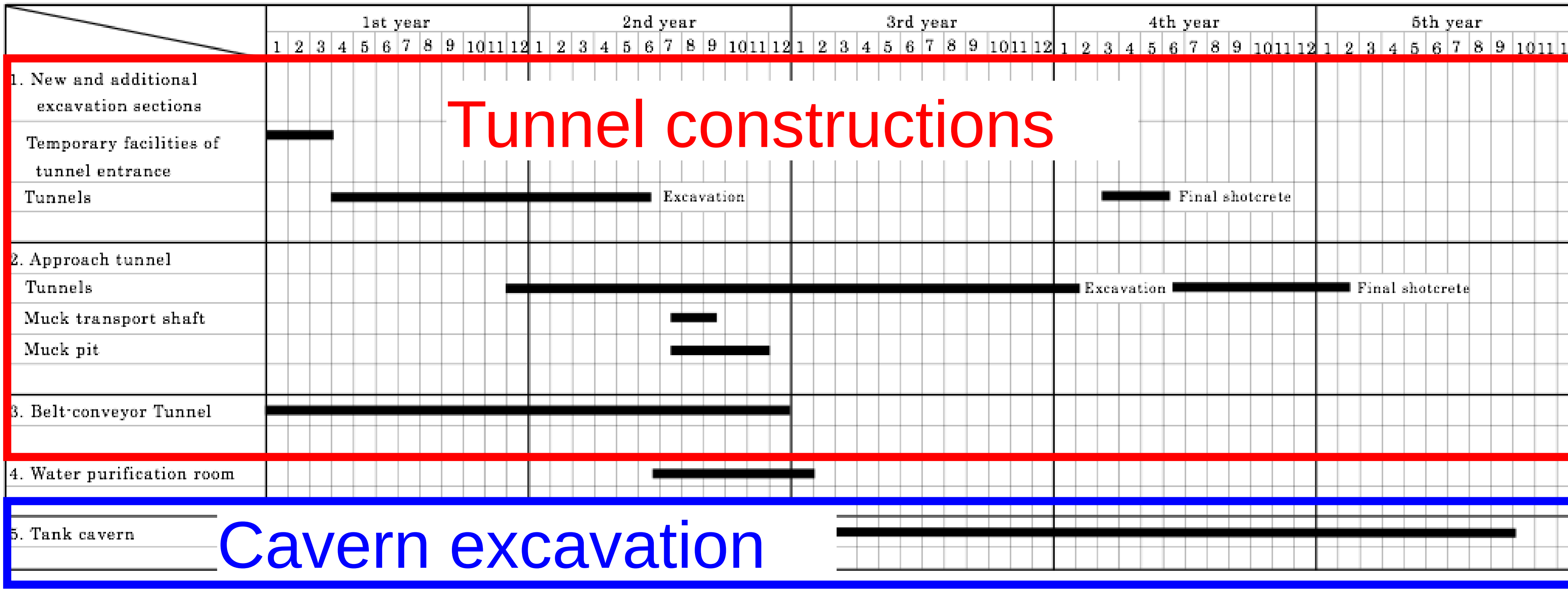
T2K and J-PARC Run Plans

- T2K's oscillation analyses still statistics limited
  - So far, we have been able to steadily decrease systematics
- T2K will continue to run and benefit from planned J-PARC Main Ring (MR) power improvements:
  - 220 kW operation in CY2013. Integrated 6.7E20 POT to date.
  - Linac upgrade to be completed with a year. Expect range of steady MR operation for neutrino between 200-400 kW
  - Planned MR upgrade by 2018 (depends on funding). Up to 750 kW
  - Possible scenario:
    - Double current protons on target by early 2015
    - Next-to-next doubling by early 2017
    - If MR upgrade done in 2018, reach full planned statistics (78E20 POT), roughly 12x the current exposure, roughly end of 2020
- T2K beamline designed to easily switch from neutrino to anti-neutrino beams
  - T2K has made no firm plans for anti-neutrino running

Summary of J-PARC/Neutrino Facility Upgrade Plan

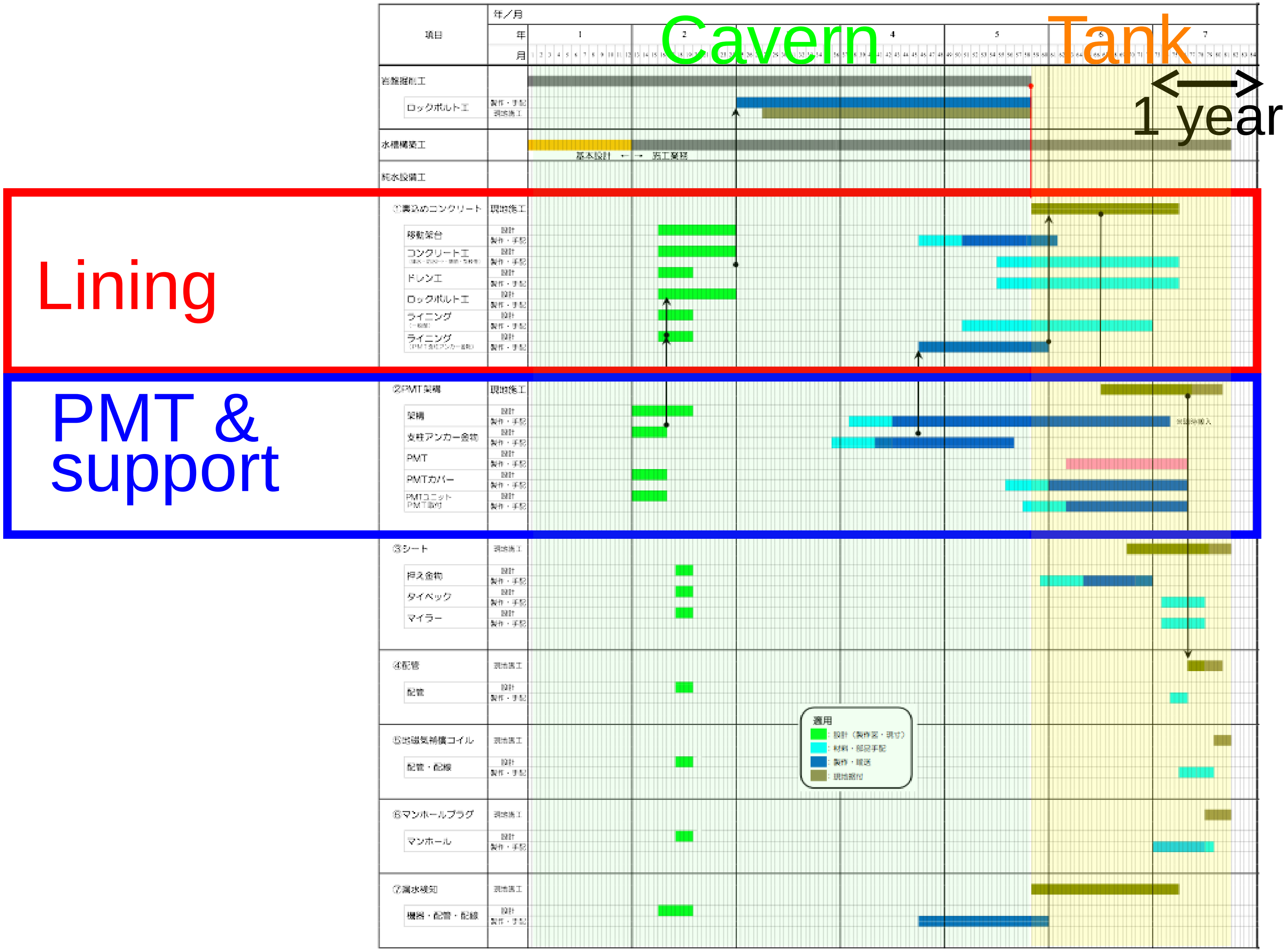
- Achieved beam power for user operation:
  - 350kW max. for T2K
- To increase #p/bunch
  - MR collimator capability 3.5kW
  - LINAC energy upgrade to 400MeV, frontend upgrade in 2014
- MR 750kW operation → to double replication rate operation
  - R&D for MR magnet power supplied well in progress
  - Higher gradient RF core to be ready for installation in 2015
- Neutrino beam-line
  - No problems for critical components so far
  - Works ongoing to replace all 3 horns/target
  - Replacement of Horn-3 completed, radiation well under control.
- Upgrade of neutrino beam-line
  - Double rep.rate: less thermal shock for target/beam window
  - Horn: triple PS operation is necessary for 1Hz *320kA) operation

Excavation Schedule



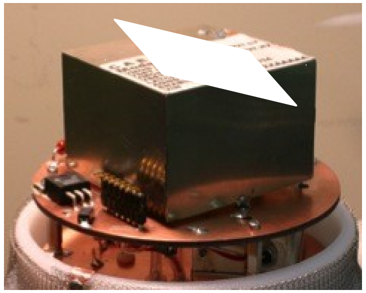
- Cavern construction period: ~5 years
- Transport / approach tunnels: ~3 years
- Excavation of caverns: ~3 years

Tank construction schedule



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

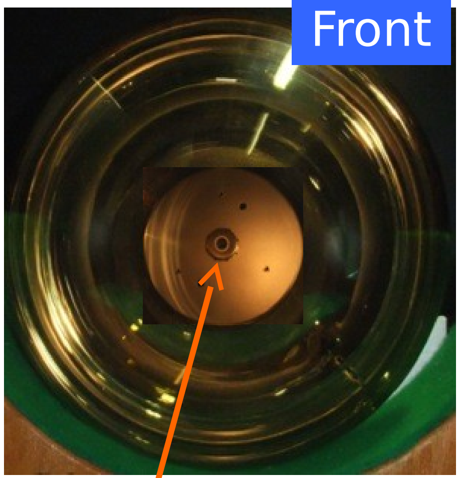
8" HPD Prototype

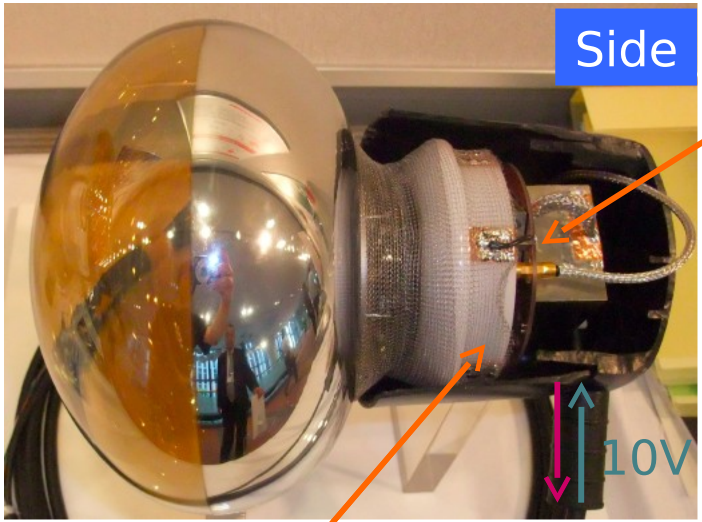


High voltage module
(2ch 10kV/500V Max.)

30cm

20cm





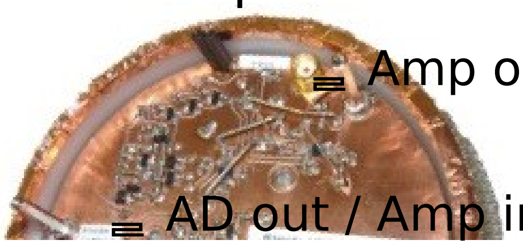
Signal

HV module and preamplifier are packed and waterproofed

→ No HV line in water

5mmφ AD

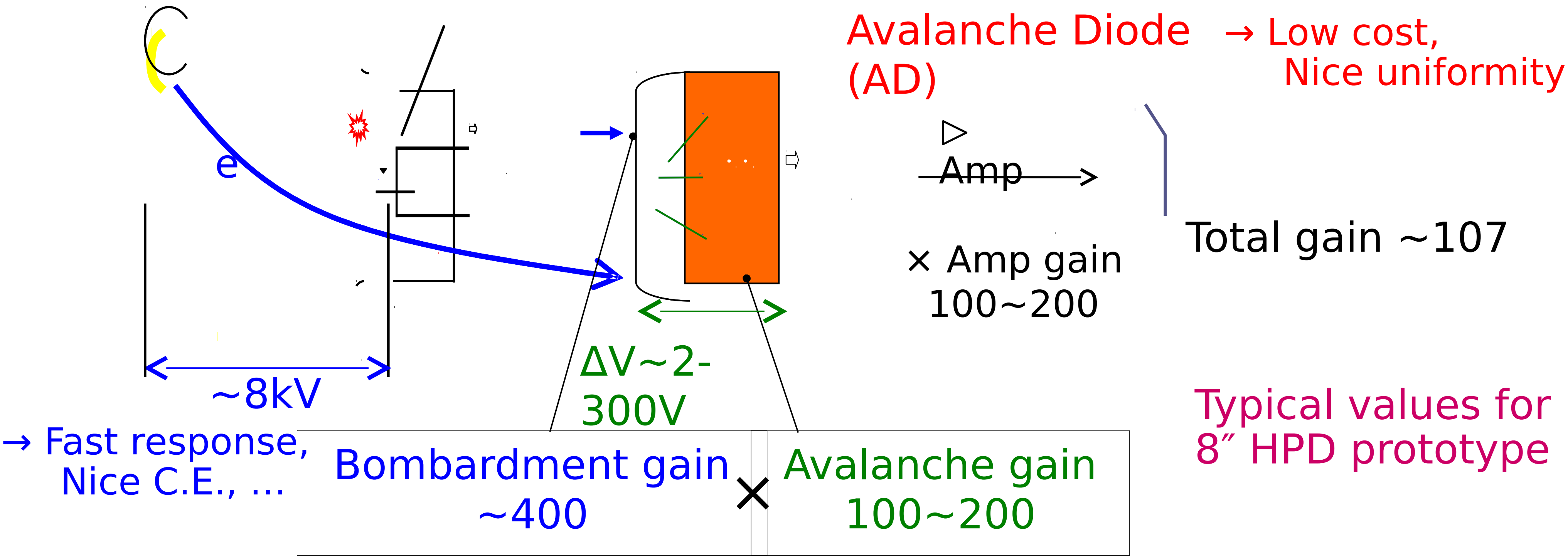
Preamp board



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.)

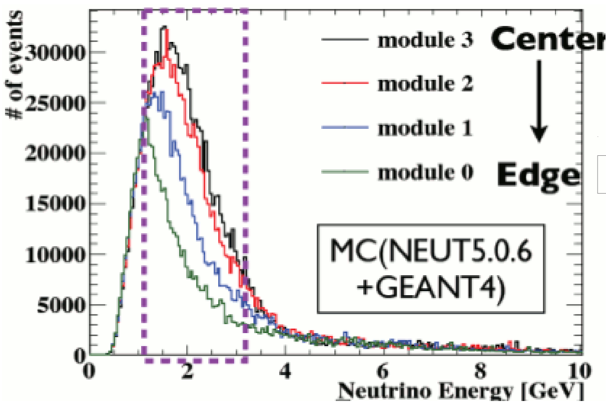
Ten 8″ HPDs were made for long-term testing

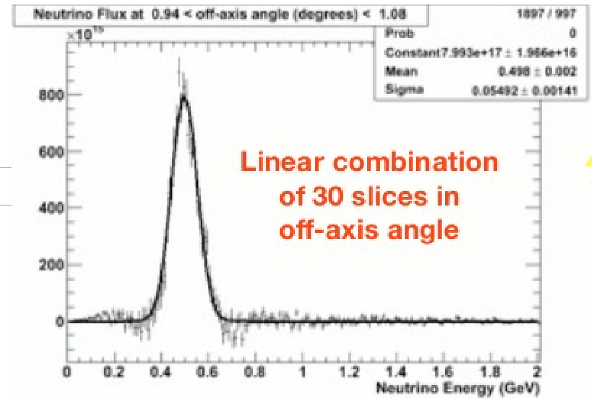
Hybrid Photodetector (HPD)



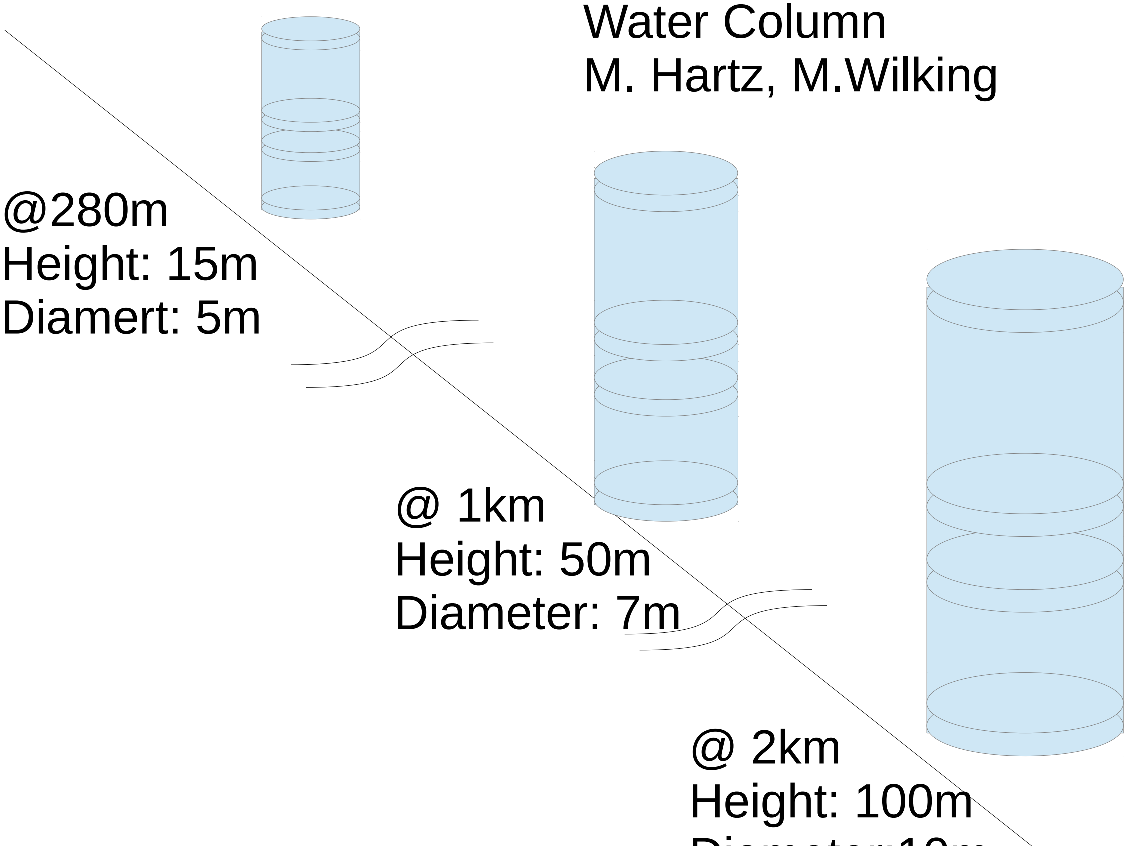
- ~8kV supply voltage + Avalanche diode multiplication
  - High voltage to focus photoelectrons into the small AD (5-20mmφ)
  - Better 1p.e. measurement capability
  - Better timing resolution, faster response
- Simple mechanical structure
  - Axial symmetric response
  - Lower production cost, shorter production period

Water Column





Water Column
M. Hartz, M.Wilking

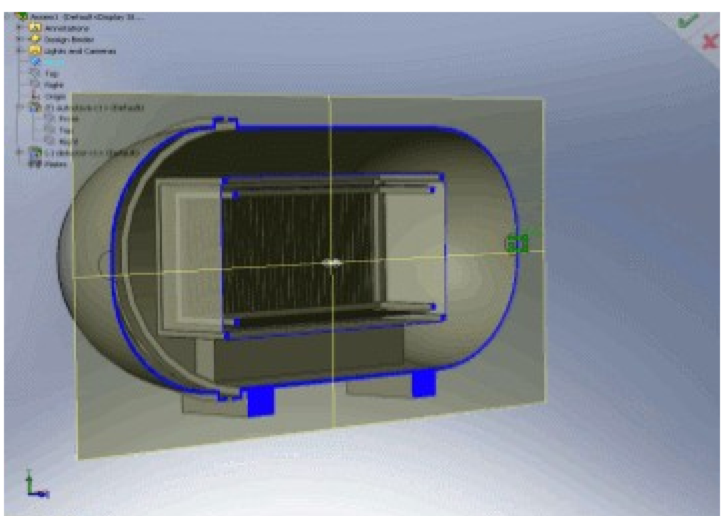


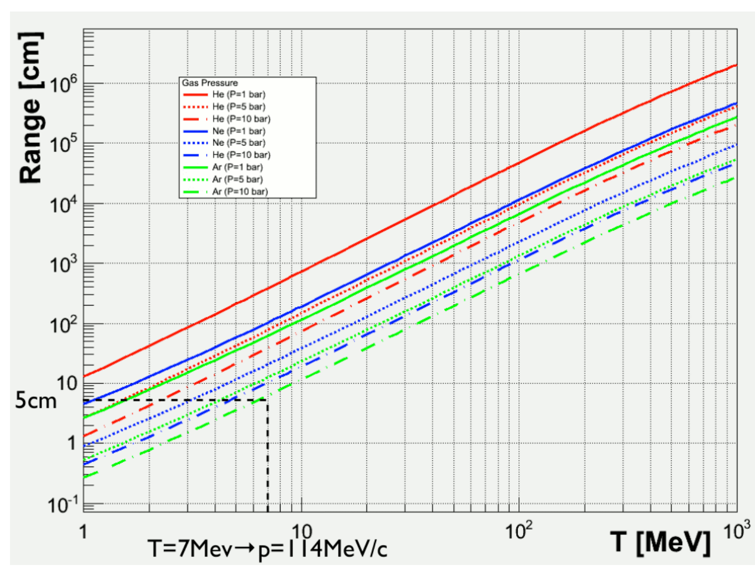
- Minimize dependence on neutrino interaction sampling the beam at several off-axis angles.
- Favoured <1km baseline from engineering point of view.
- Possibly add brine (Konaka) around detector to stop muons.

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)