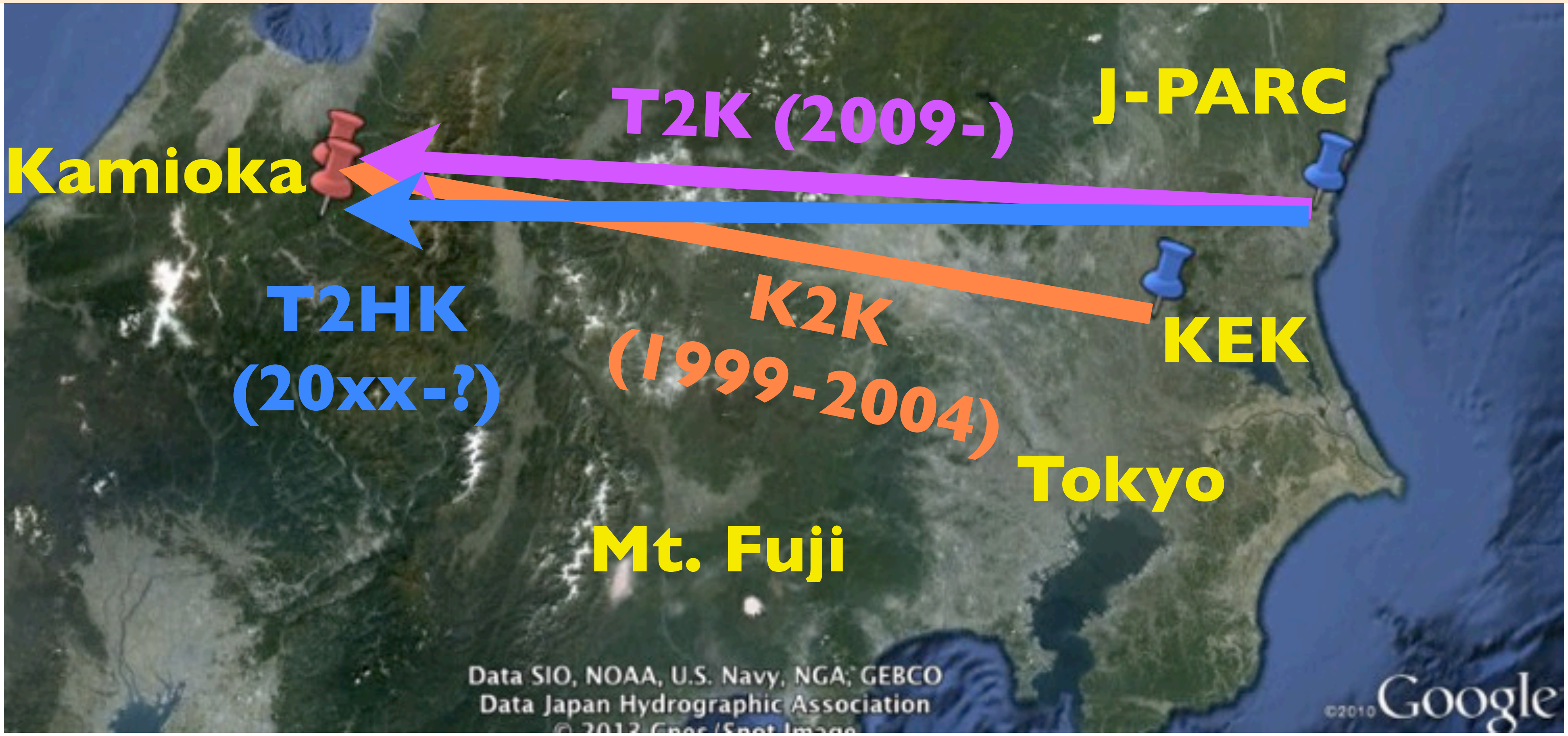
Long baseline neutrino experiments in Japan – Past, present, and future –



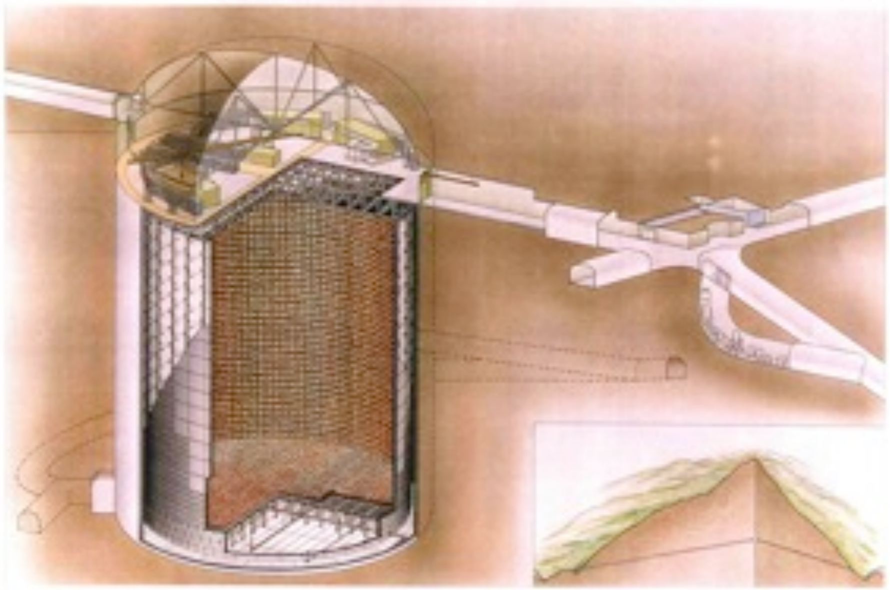
Masashi Yokoyama
Department of Physics, the University of Tokyo

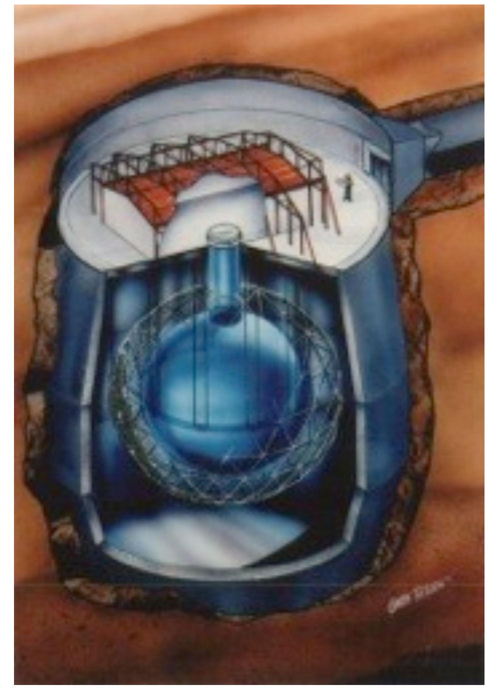
Colloquium Towards CP violation in neutrino Physics

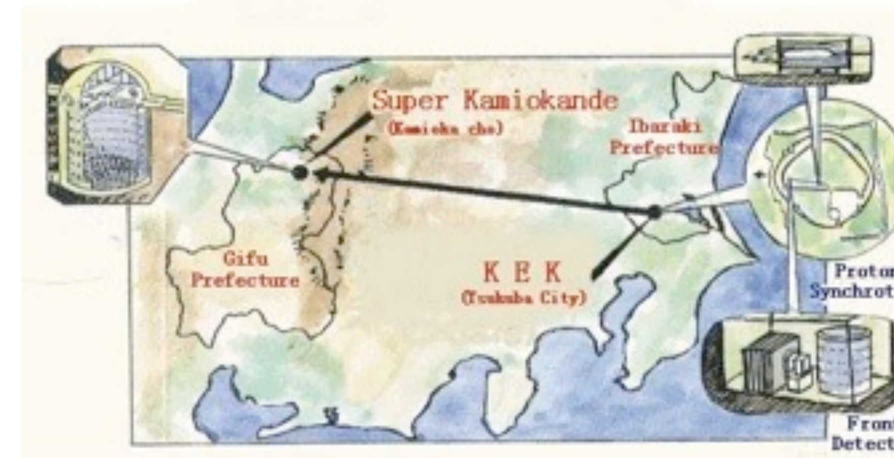
23-24 May 2013 *Faculty of Mathematics and Physics, Charles University in Prague*

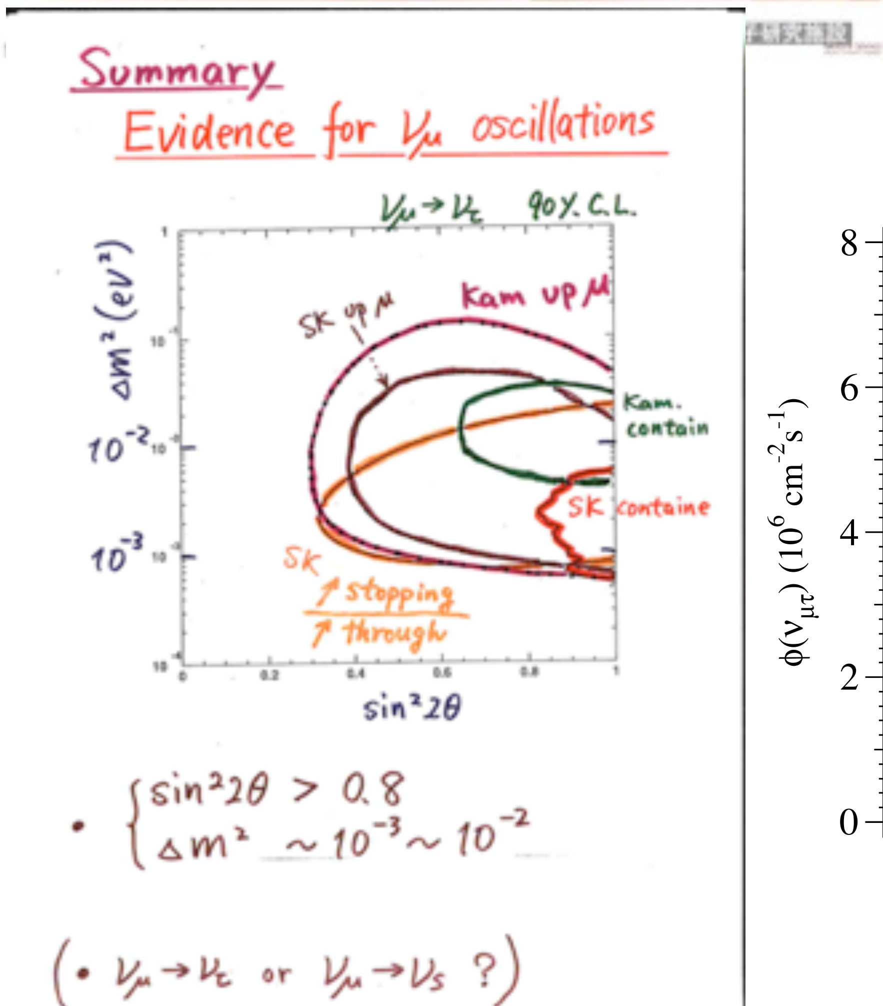
We are now in the era of second revolution in ν oscillation.

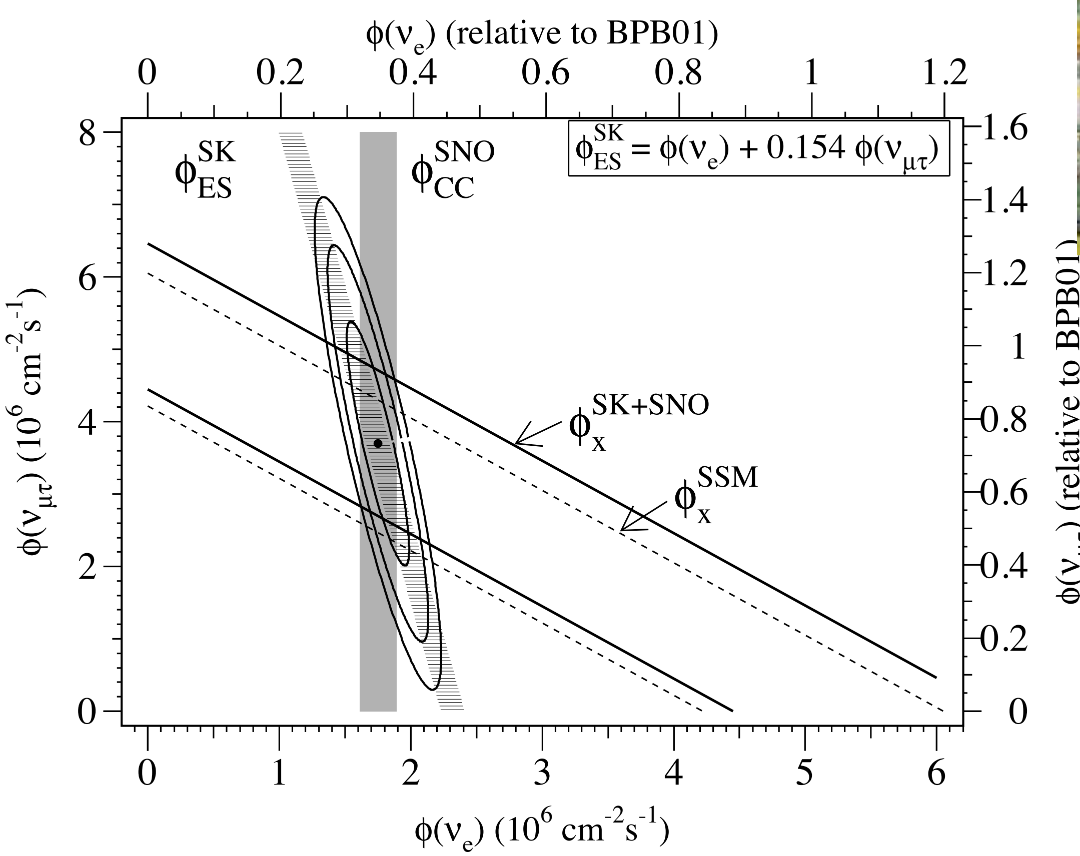
First revolution: *Discovery of ν oscillation*

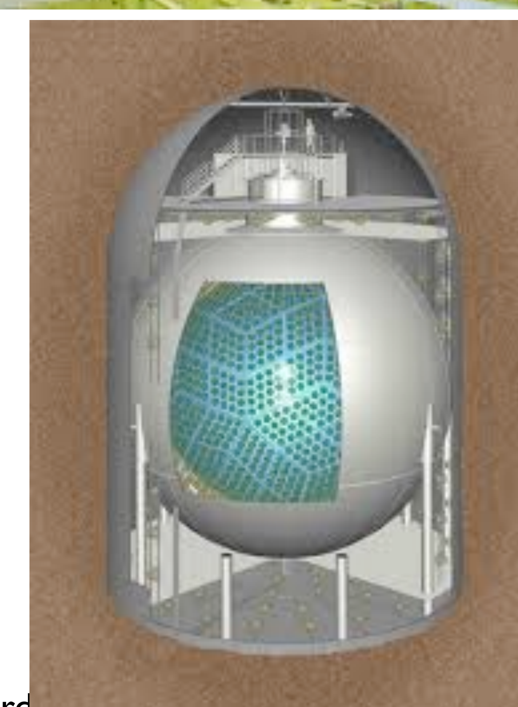












Neutrino oscillation

For two generations

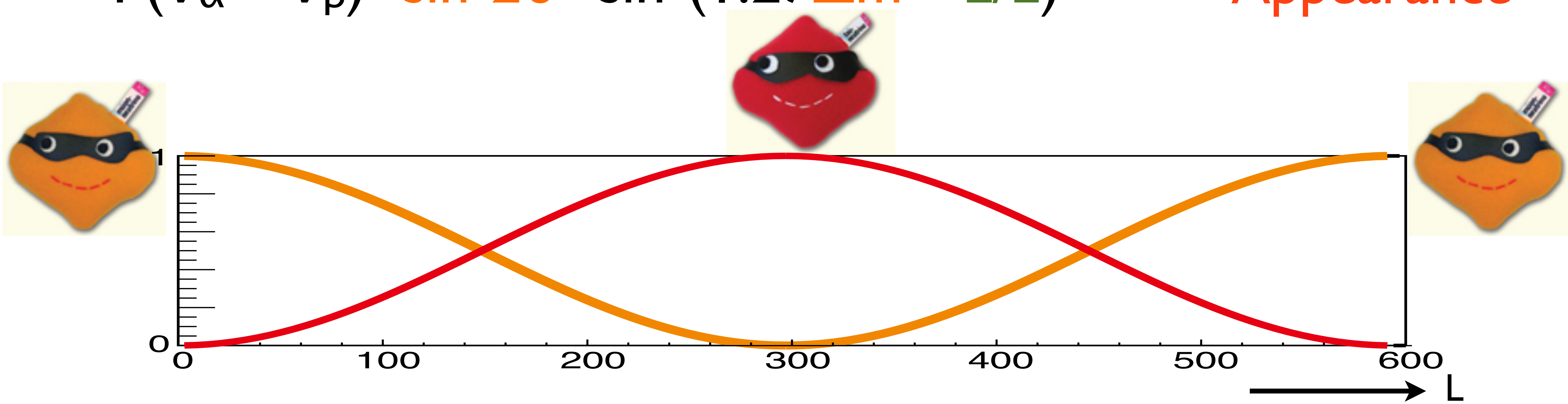
Flavor (weak) eigenstate → $|\nu_\alpha\rangle$; Mass eigenstate → $|\nu_1\rangle$, $|\nu_2\rangle$

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle+\sin\theta|\nu_2\rangle$$
$$|\nu_\beta\rangle = -\sin\theta|\nu_1\rangle+\cos\theta|\nu_2\rangle$$

θ:Mixing angle, $\Delta m^2=m_1^2-m_2^2$

$$P(\nu_\alpha\rightarrow\nu_\alpha)=1-\sin^2 2\theta\cdot\sin^2(1.27\Delta m^2_{[eV^2]}\cdot L_{[km]}/E_{[GeV]})$$ Disappearance

$$P(\nu_\alpha\rightarrow\nu_\beta)=\sin^2 2\theta\cdot\sin^2(1.27\Delta m^2\cdot L/E)$$ Appearance



Happens only if $\theta\neq0$ and $\Delta m^2\neq0$

After first generation exp'ts

Remaining questions in ν mixing

"atmospheric" region

1. maximal? → $\theta_{23} \sim 45°$

2. sign? → $|\Delta m^2_{32}| \sim 2.5\times10^{-3}\text{eV}^2$

"solar" region

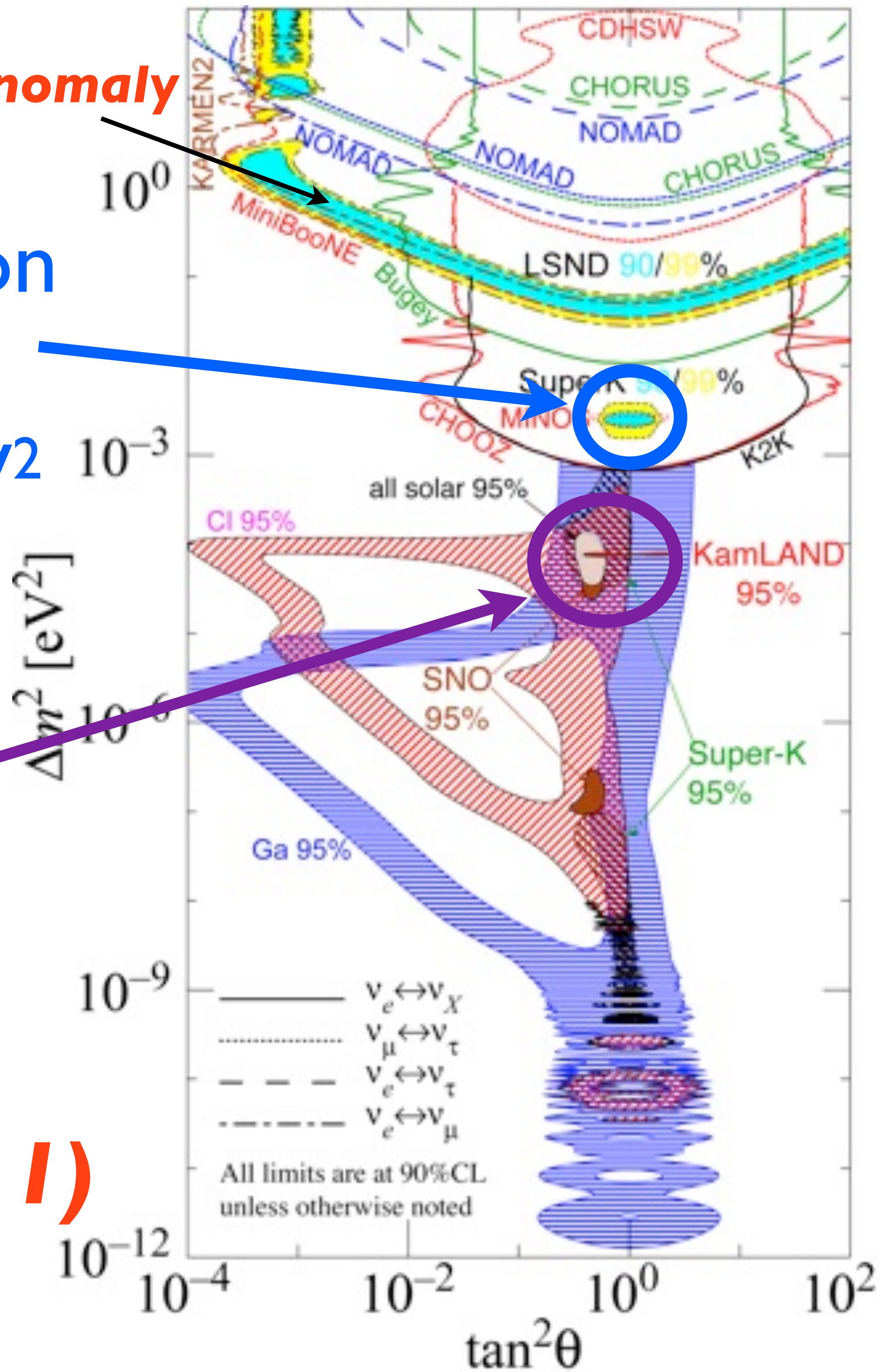
$\theta_{12} \sim 34°$

$\Delta m^2_{21} \sim 7.8\times10^{-5}\text{eV}^2$

3. θ_{13}<12° (before June 2011)

4. No information on δ

5. LSND anomaly



http://hitoshi.berkeley.edu/neutrino

After the First Age...

Three flavor mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

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

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

Leading term (θ_{13})

CP violating (flips sign for $\bar{\nu}$)

$$\begin{aligned} P(\nu_\mu \to \nu_e) \;=\; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\ & +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\ & -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\ & +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\ & -8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\ & +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31} \end{aligned}$$

Solar

Matter effect

Sensitivity to yet unknown parameters via sub-leading terms:

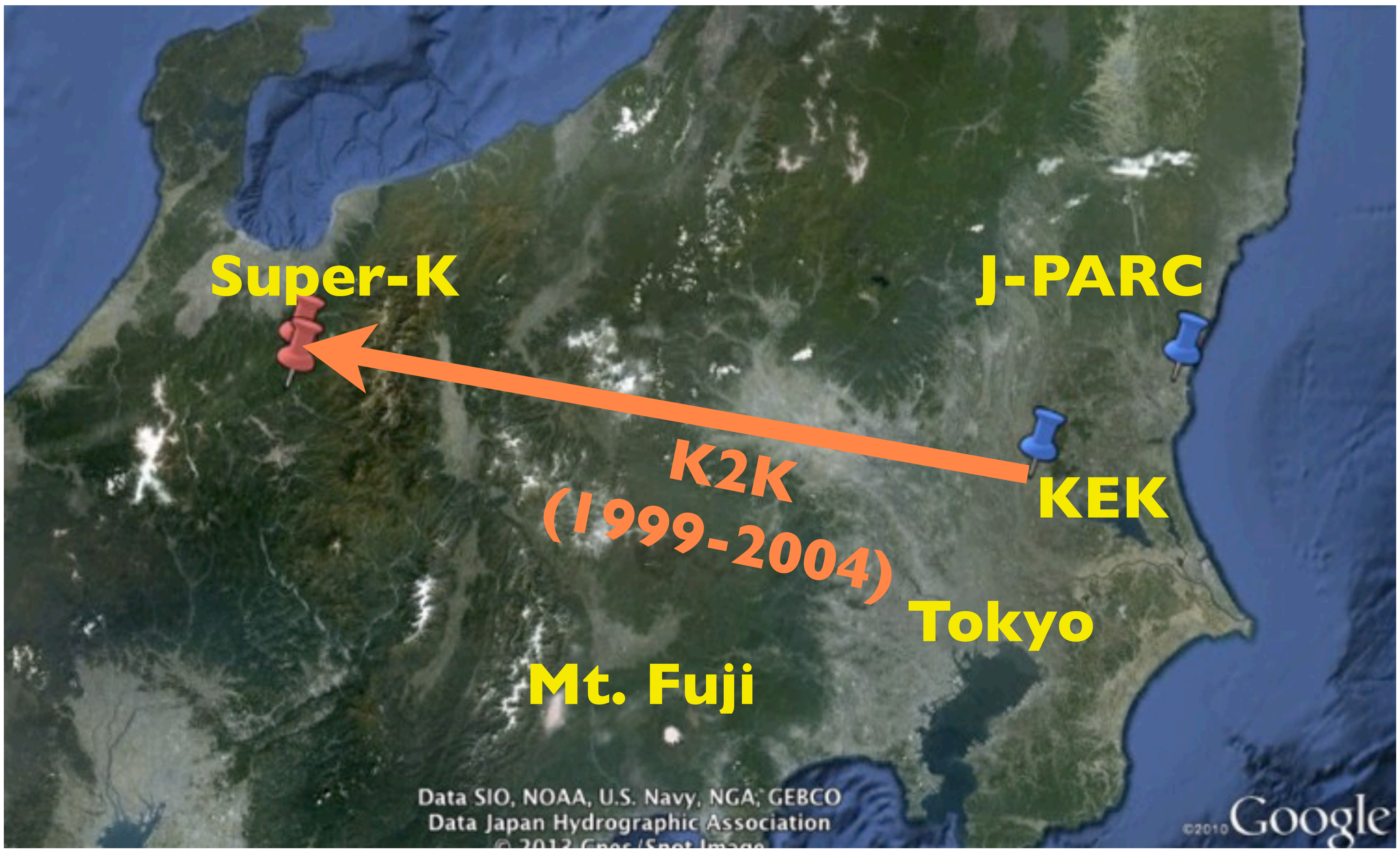
Mass hierarchy (sign of Δm^2_{32}), octant of θ_{23}(< or > 45°), and CP violating phase δ, depending on value of θ_{13}

θ_{13} was the key to determine future strategy

Second revolution: θ_{13}

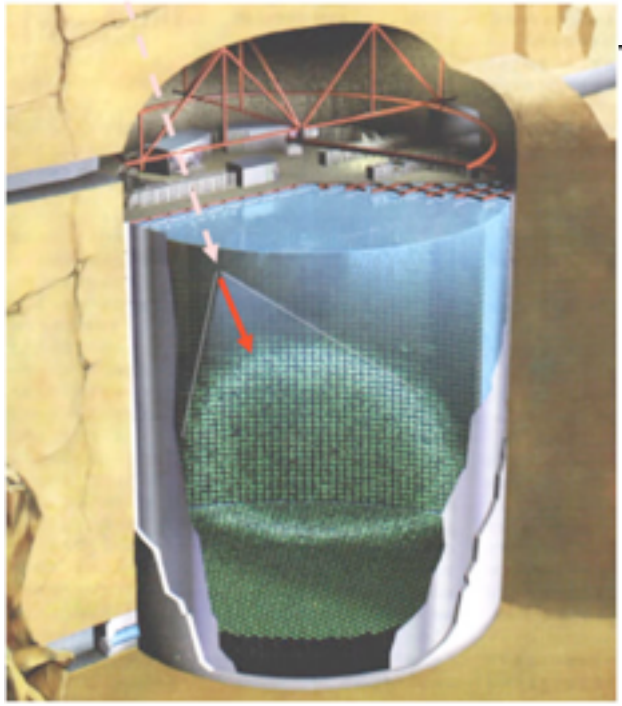
- CP asymmetry in neutrino is accessible only if
  - $\Delta m^2_{32}, \theta_{23}$ large (← atm ν, near maximal)
  - $\Delta m^2_{21}, \theta_{12}$ also large (← solar ν, LMA)
  - θ_{13} large enough (← YES YES YES !!!)
- We have just learned that these are ALL satisfied, and turning to the next goal – CP asymmetry
  - Due to 'large' value of θ_{13}, now we know that next generation experiments with conventional ν beams will have good sensitivity

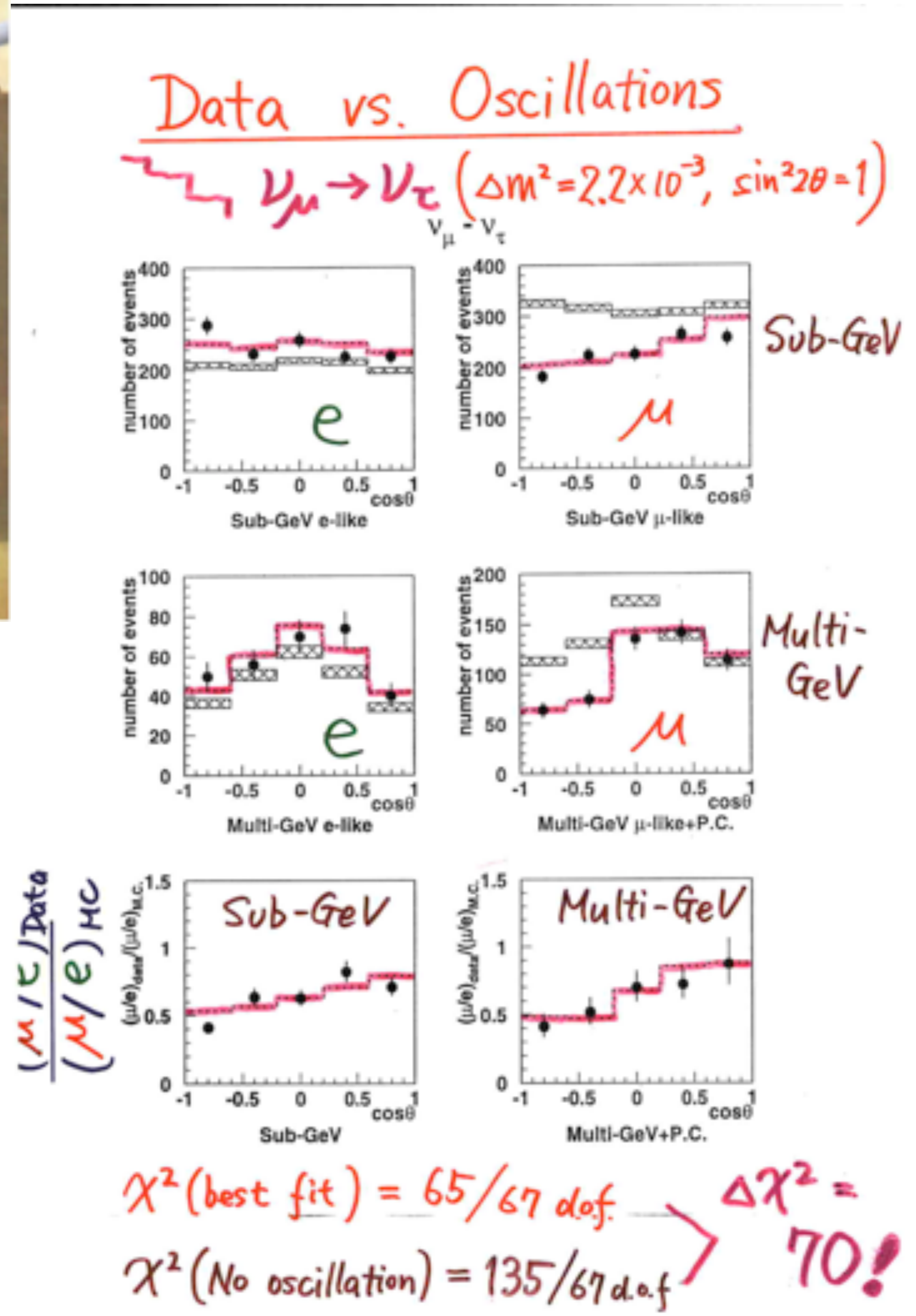
Let's start from the beginning..

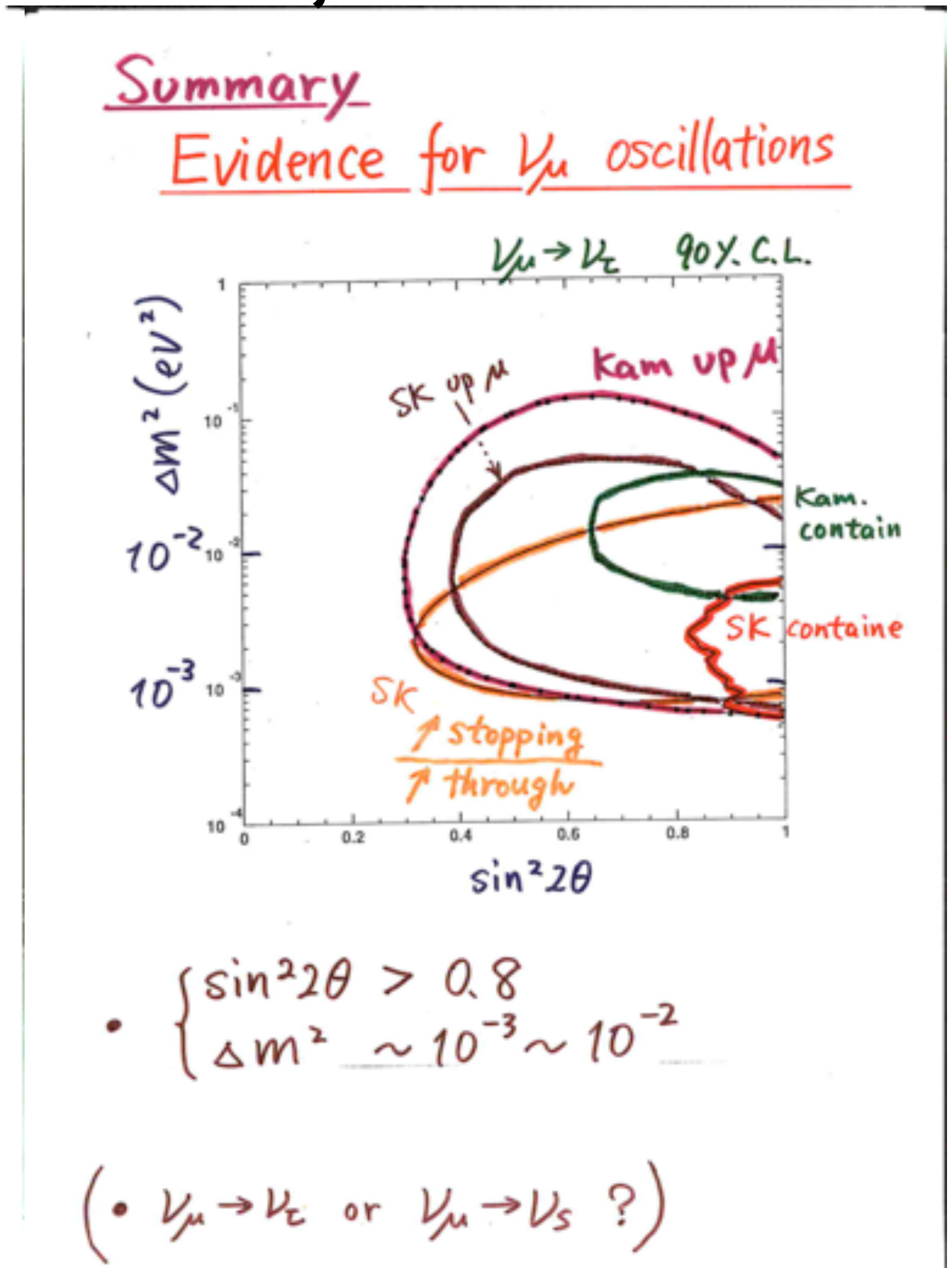


All of this started with...

T.Kajita, NEUTRINO98

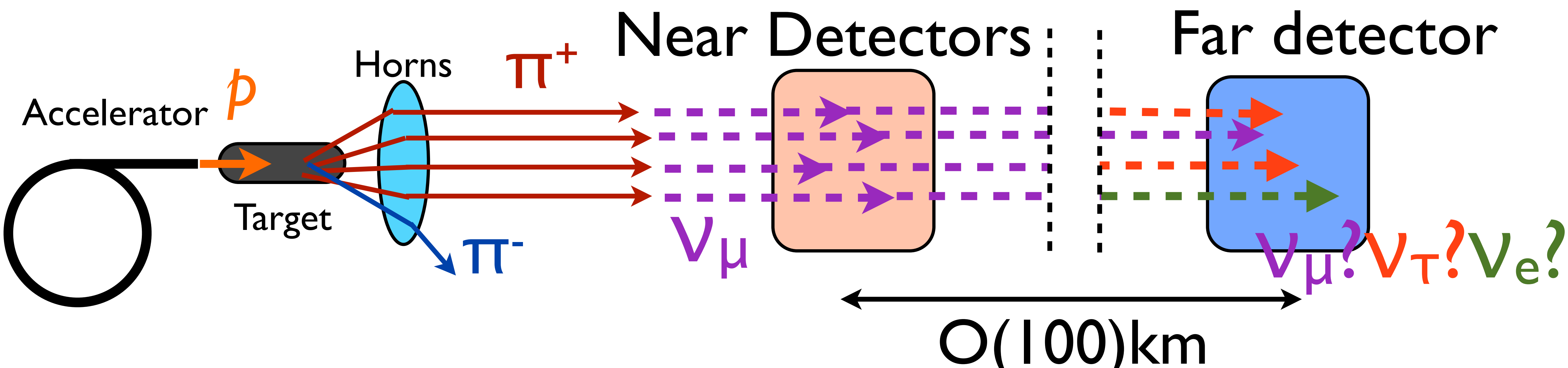






$\Delta m^2 \sim 3\times10^{-3} \to$ L~O(100km) for E~1GeV @max oscillation

Check with artificial ν beam: Long baseline experiment

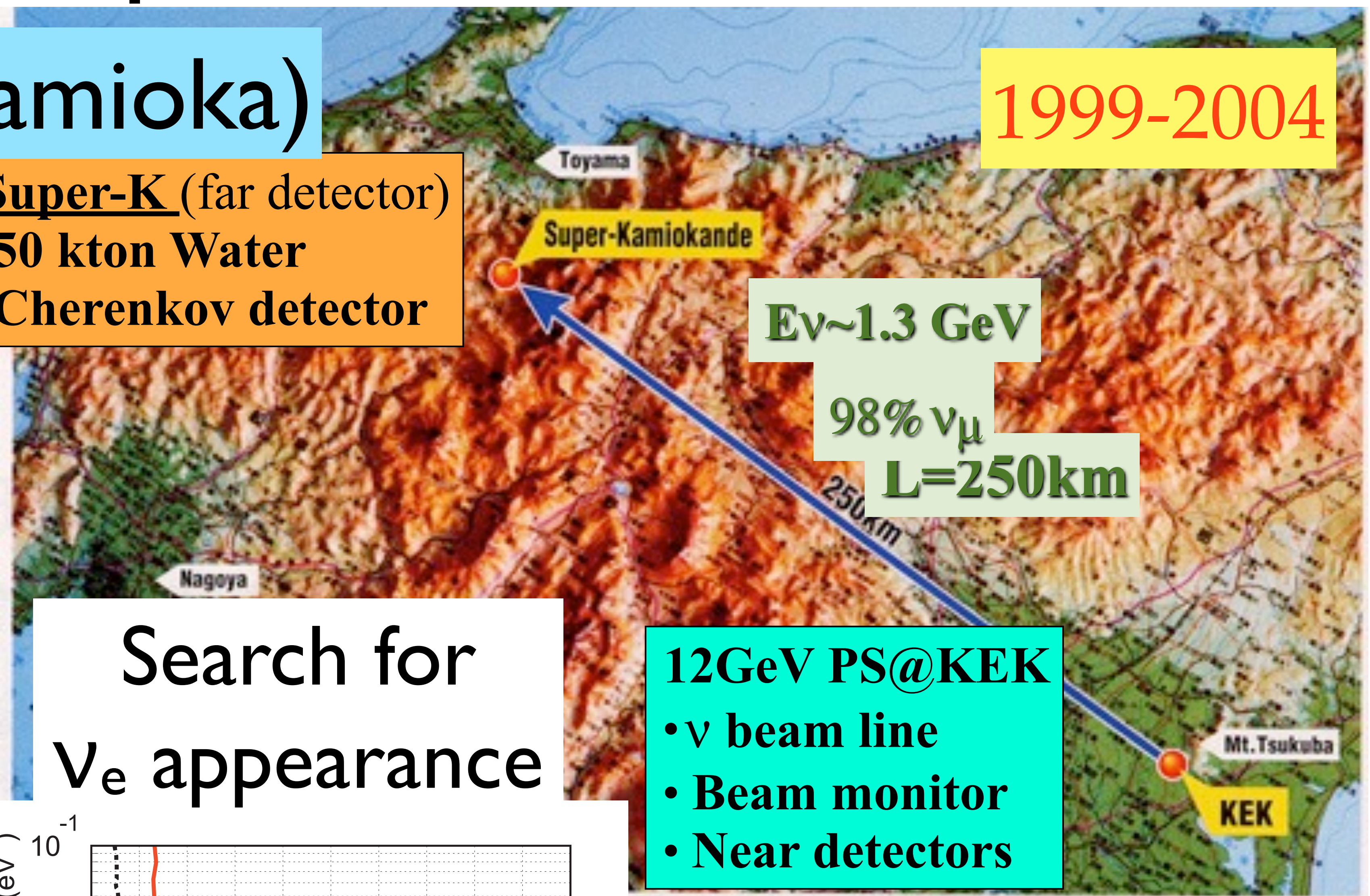


- Shooting neutrinos to a detector >100km away
  - Powerful beam + gigantic far detector
  - Synchronization with GPS system
- Control systematics by measuring neutrino beam before oscillation with *Near Detectors*
  - Flux and cross-section have large a priori uncertainties

First LBL experiment in the world

K2K (KEK-to-Kamioka)

1999-2004

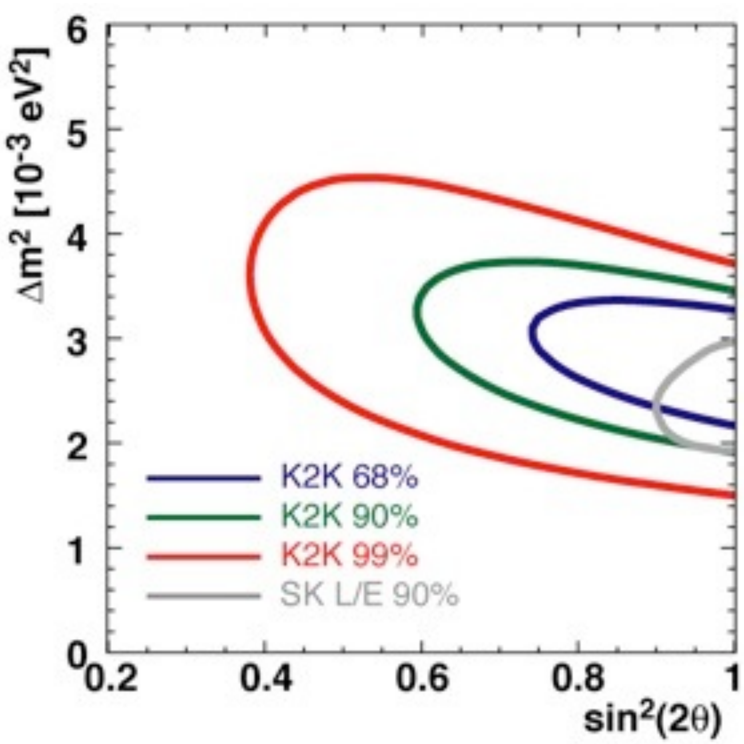


Super-K (far detector)
50 kton Water Cherenkov detector

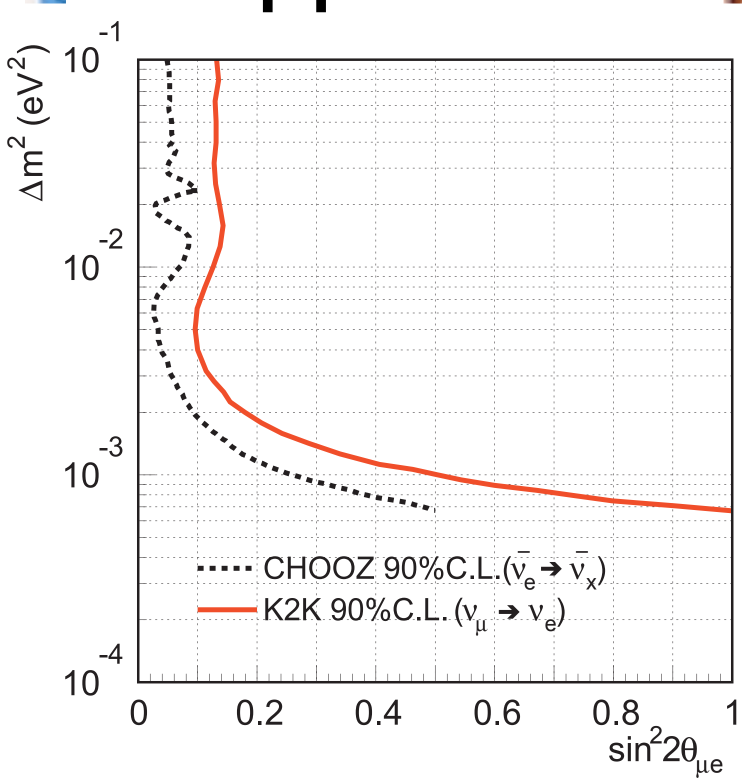
Eν~1.3 GeV
98% ν_μ
L=250km

12GeV PS@KEK
- **ν beam line**
- **Beam monitor**
- **Near detectors**

Confirmation of ν_μ disappearance



Search for ν_e appearance



Established techniques for long baseline experiments

Based on the success of K2K, the second generation LBL experiment was realized in Japan.

T2K

Tokai-to(2)-Kamioka

- Search for $\nu_\mu \rightarrow \nu_e$ (θ_{13})
- Precise meas. of $\nu_\mu \rightarrow \nu_\mu$ (θ_{23})
- Sterile ν, other surprise?

The T2K Collaboration
(~500 members, 59 institutions, 11 countries)

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
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. Education
Okayama U.
Osaka City U.
U. Tokyo
Tokyo Metropolitan U.

Poland
IFJPAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U.T.
U. Wroklaw

Russia
INR

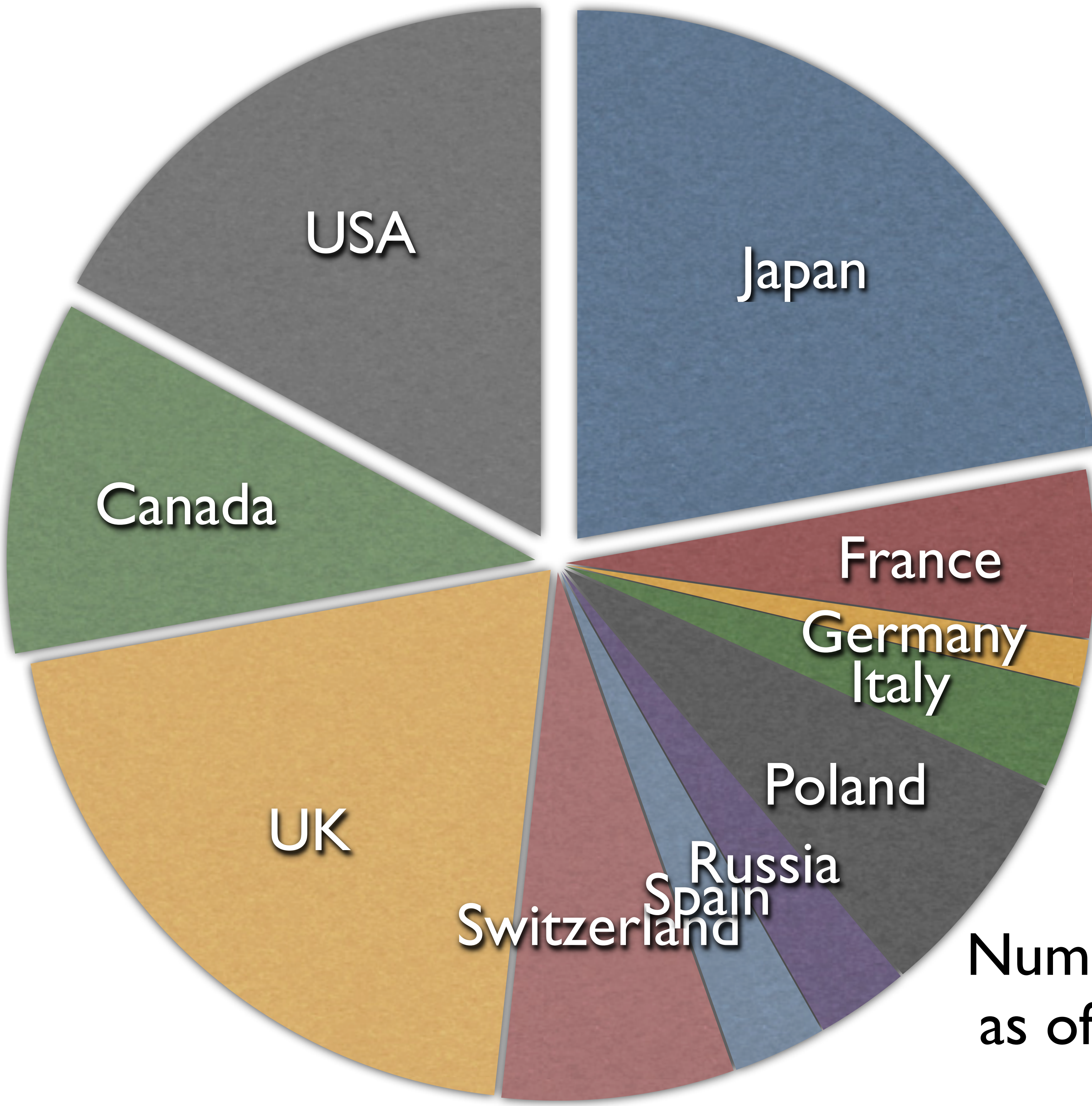
Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
U. Bern
U. Geneva
ETH Zurich

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

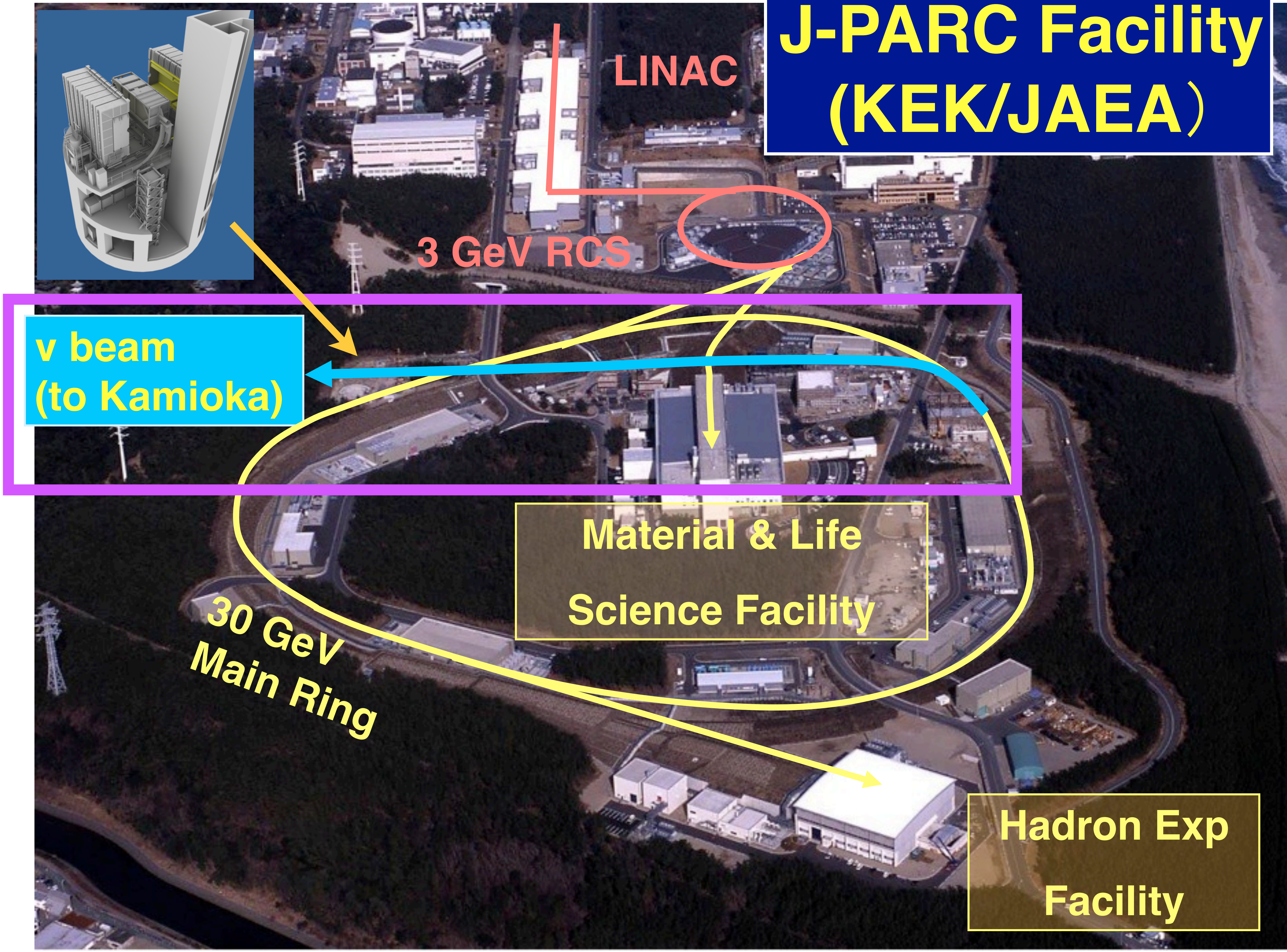
USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

T2K collaboration

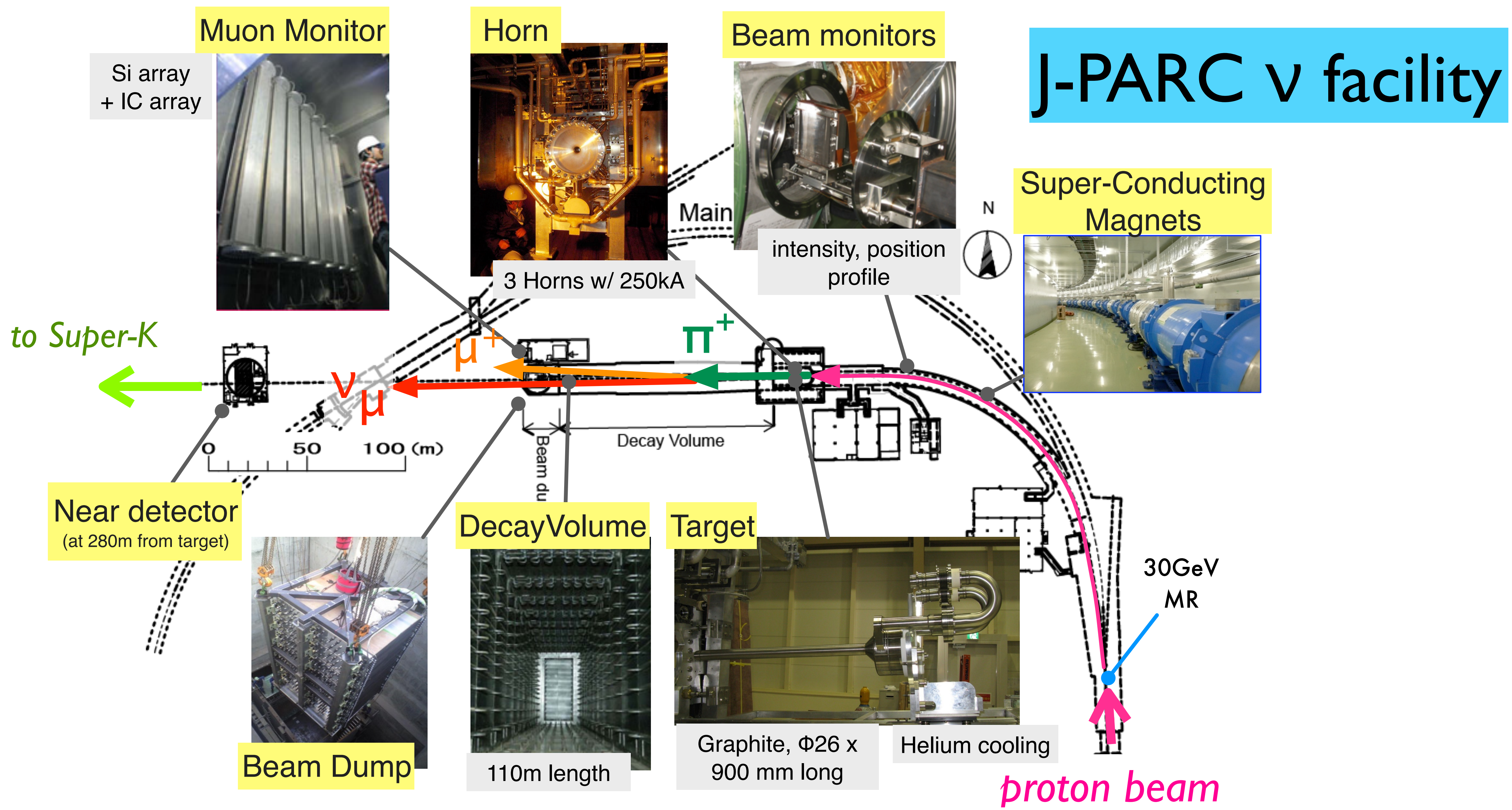


Number of authors as of May 20, 2013

J-PARC Facility (KEK/JAEA）



Producing neutrino beam

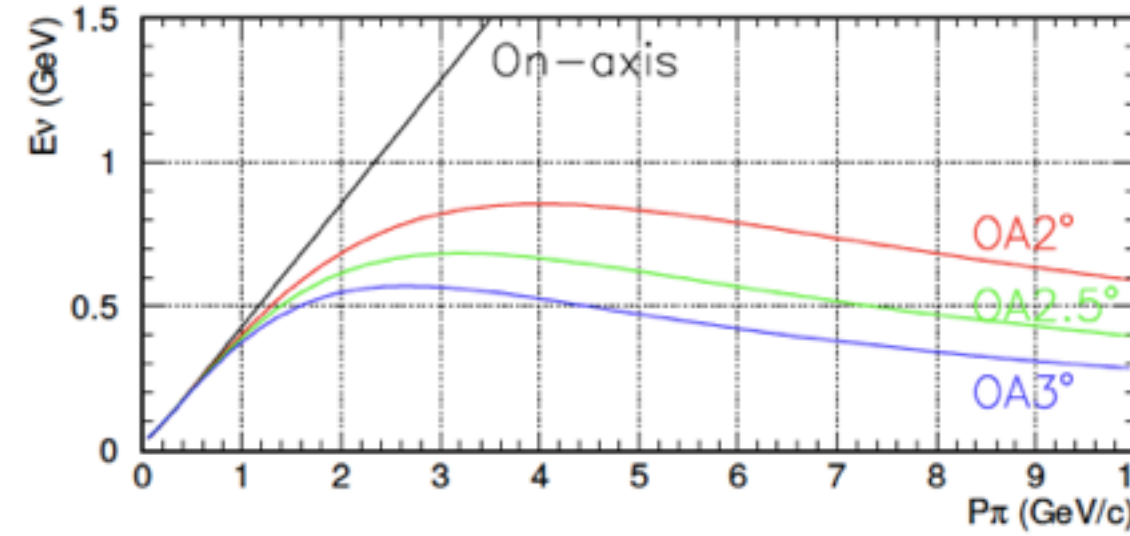


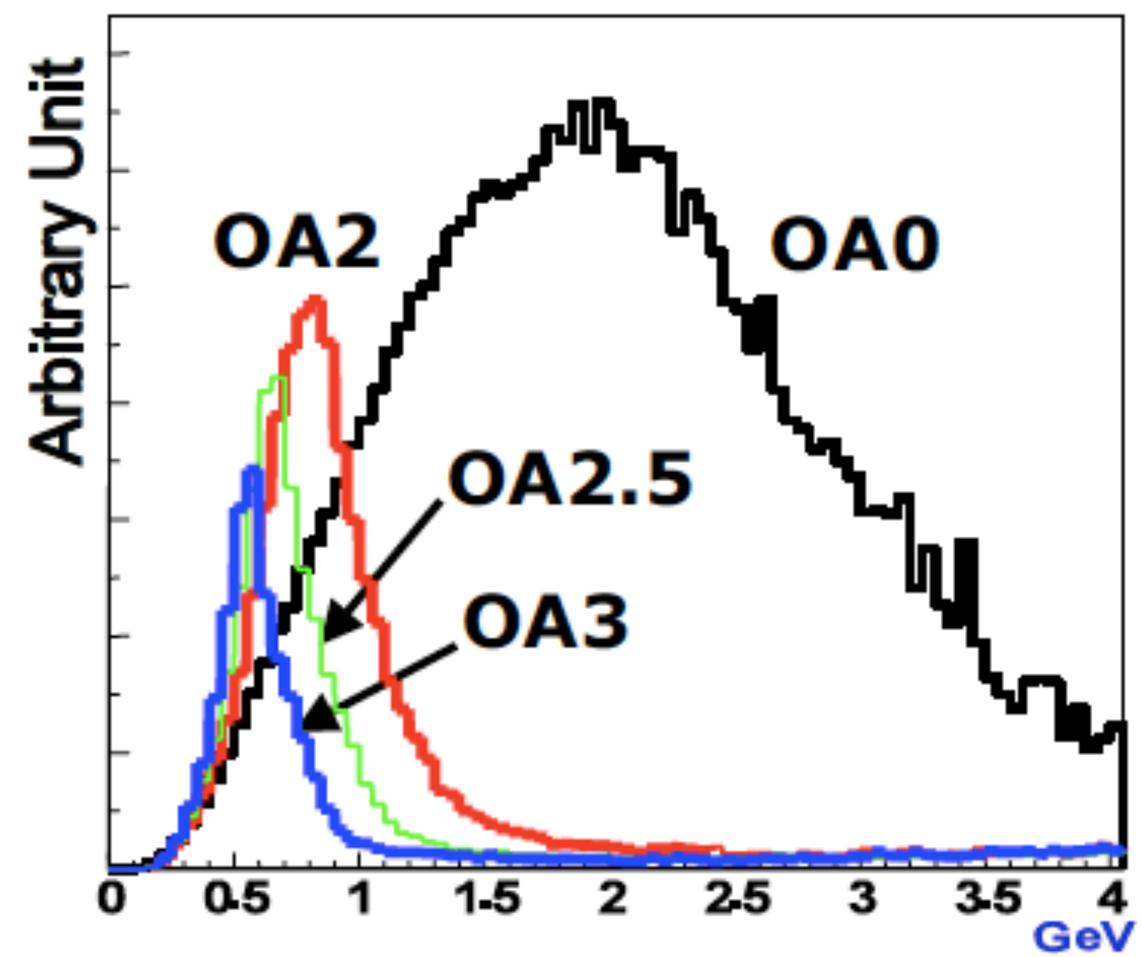
- High power operation: struggle against heat&radiation
  - Target, horns, monitors, beam dump, air, water...
- Continuous improvement for higher beam power

Off-axis beam

Idea from
BNL-E889 proposal

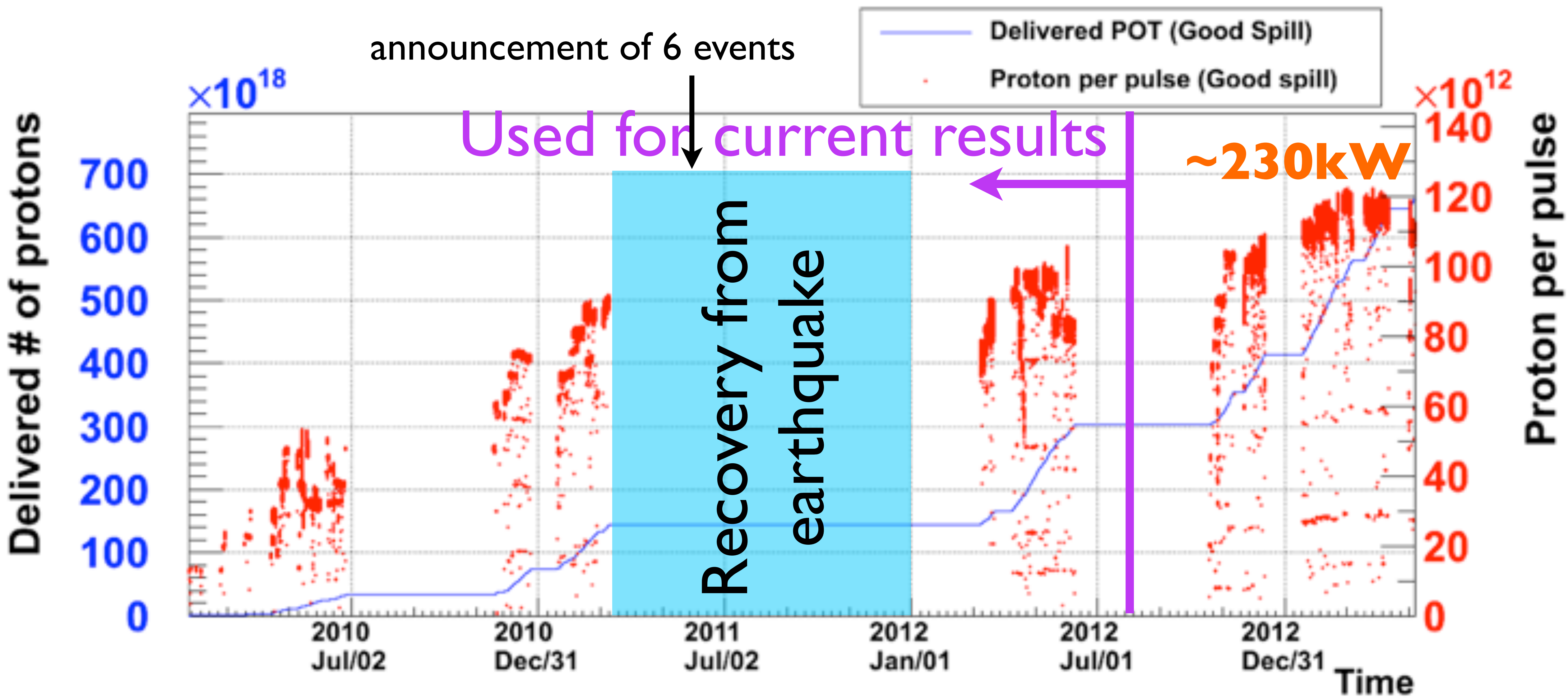
- A clever way to make ~monochromatic beam with conventional ν facility
  - Increase E_ν flux at oscillation maximum
  - Reduce high energy flux (source of background events)





T2K is the first experiment with off-axis ν beam (2.5°)

Beam operation history



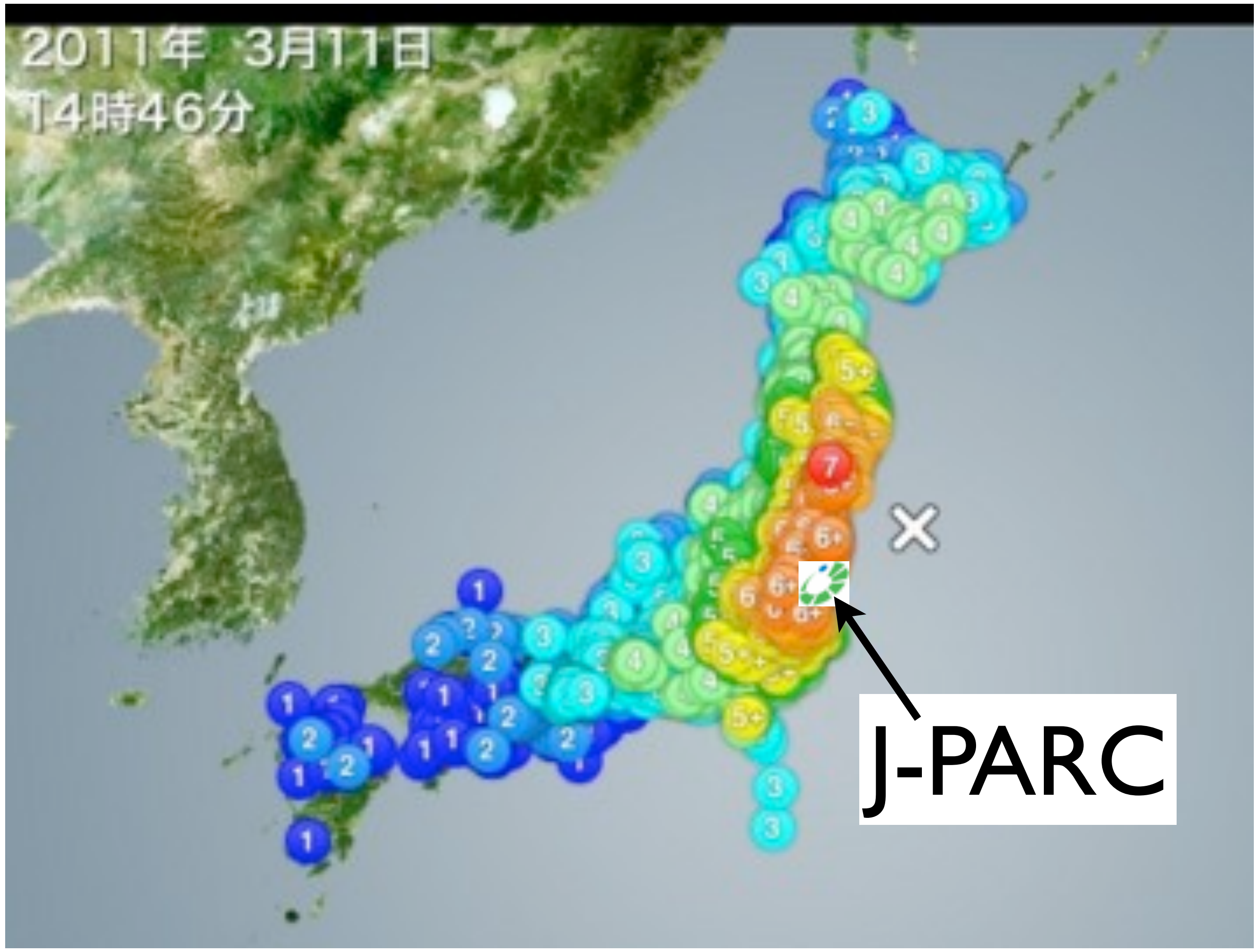
Steady increase of beam power

3.01×10^{20} protons on target (POT) for current results

6.6×10^{20} POT delivered so far (~8.5% of approved POT)

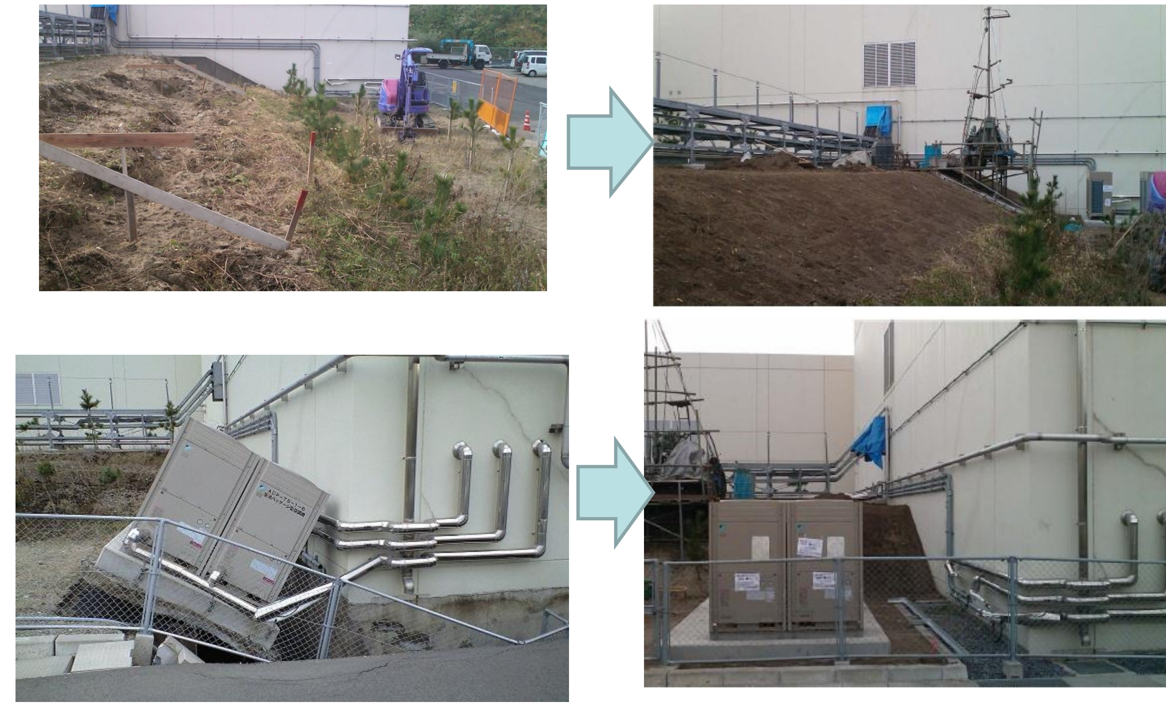
Recovery from the earthquake

Mar.11, 2011

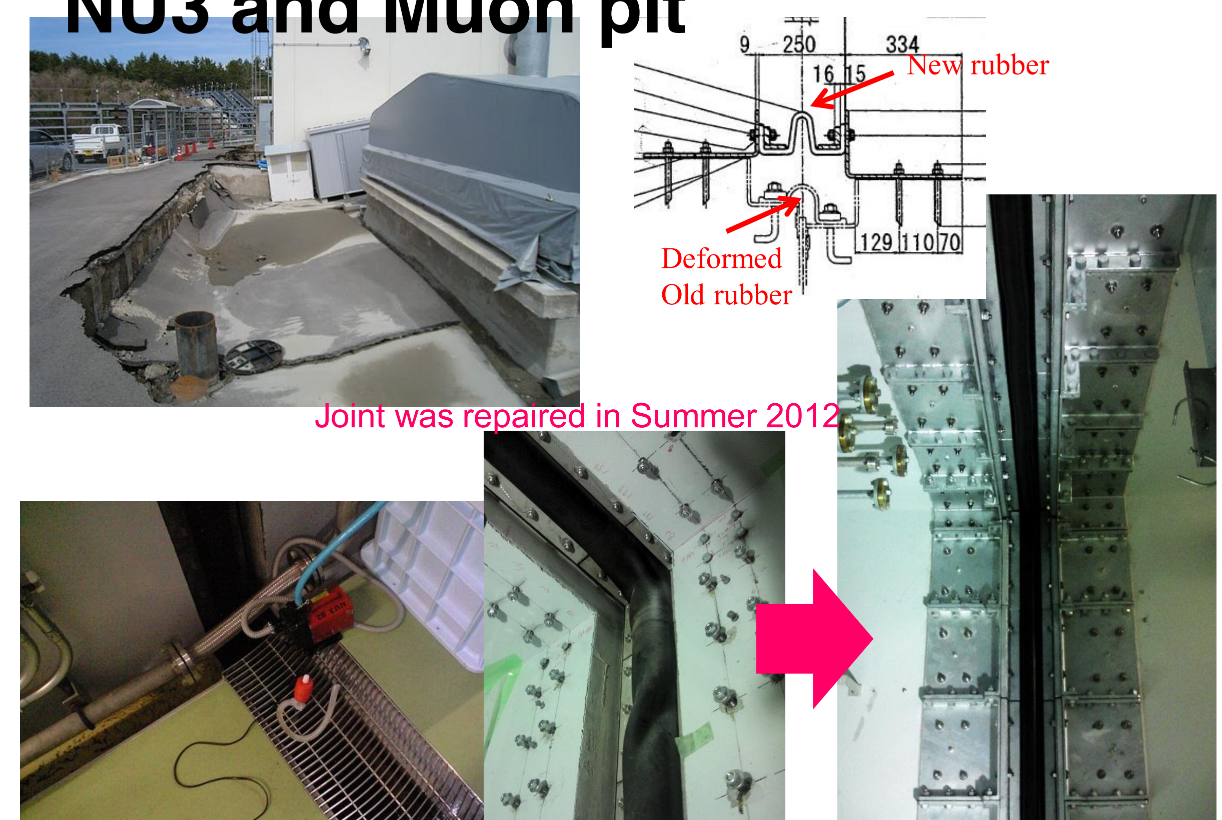


- Beam commissioning restarted in Dec. 2011.
  - T2K-ND saw events on Dec.24!

Recovery around Target Station

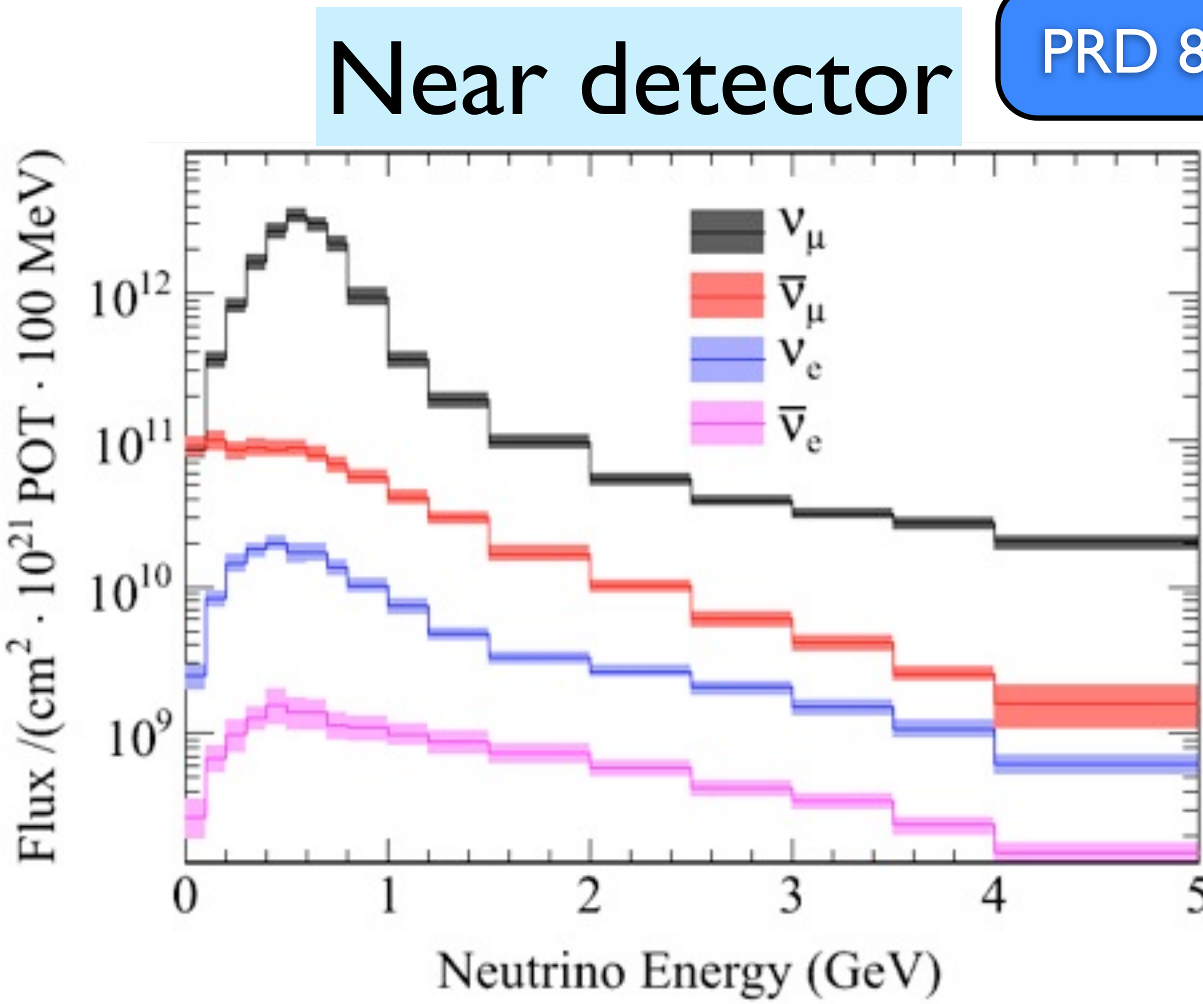


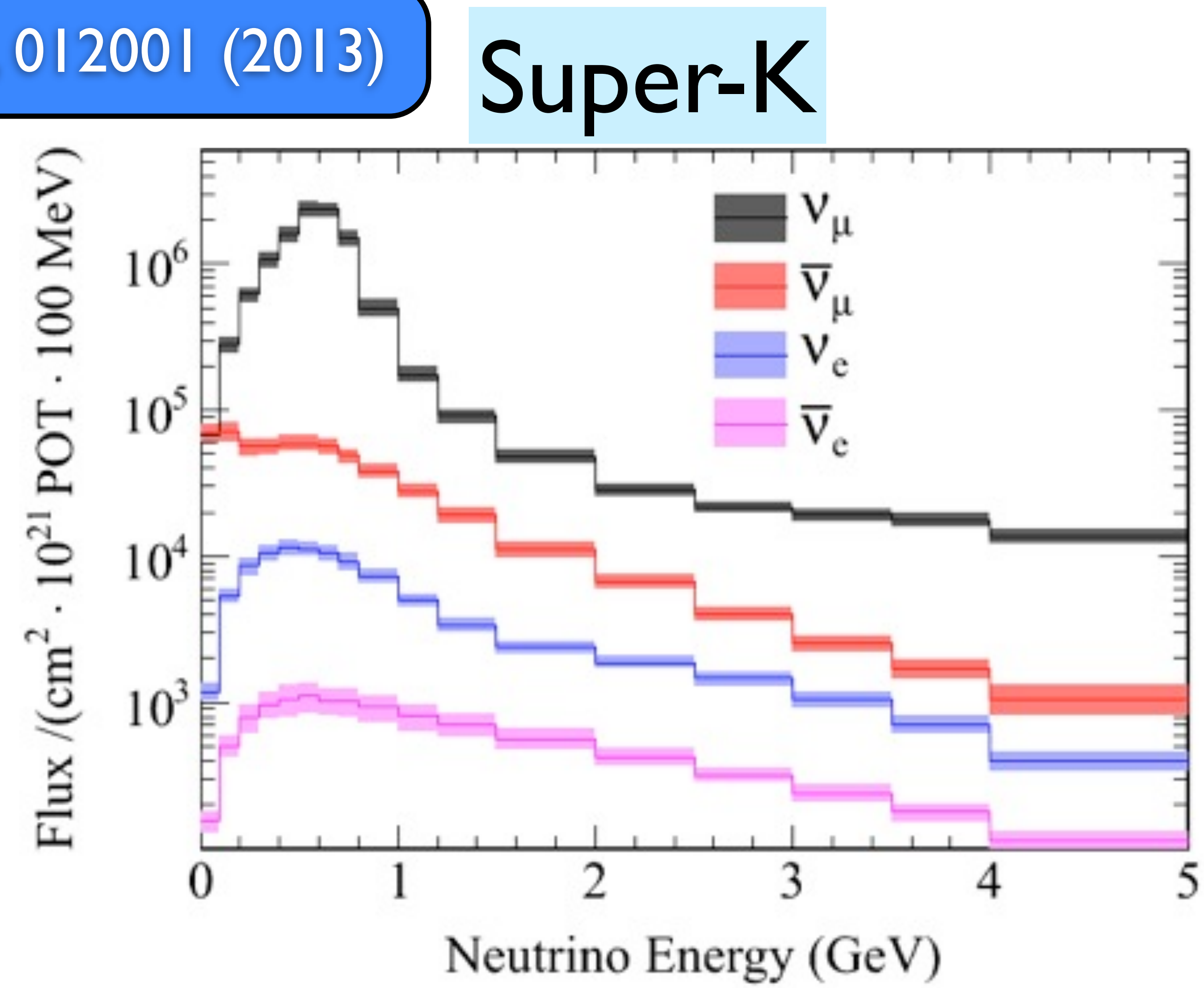
NU3 and Muon pit



Predicting neutrino flux

PRD 87, 012001 (2013)





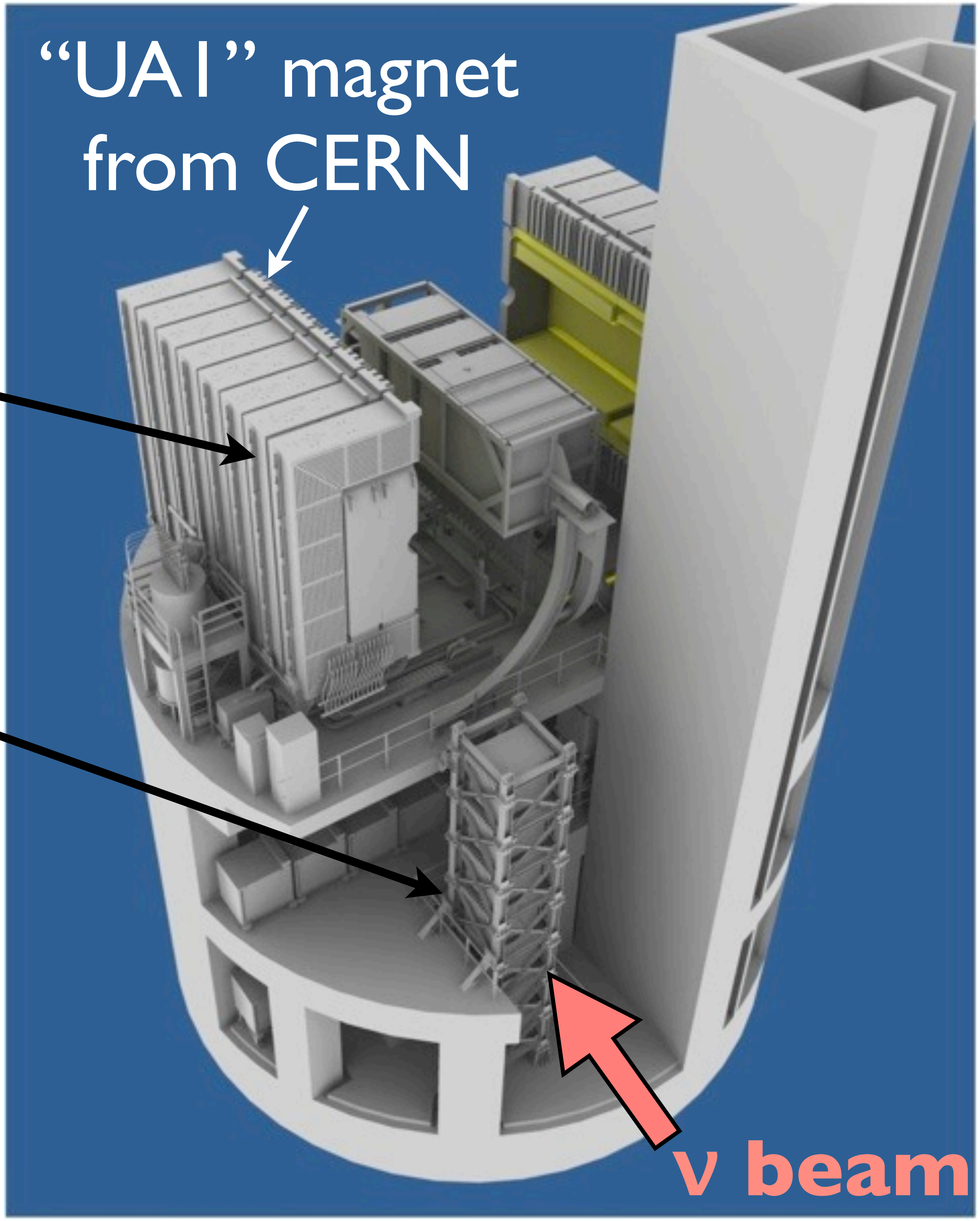
- GEANT3 based beamline MC simulation
  - \+ In situ proton beam measurements during run
  - \+ Hadron production measurements w/ NA61 @CERN
- 10-15% uncertainty (before ND280 constraints)

T2K near detectors

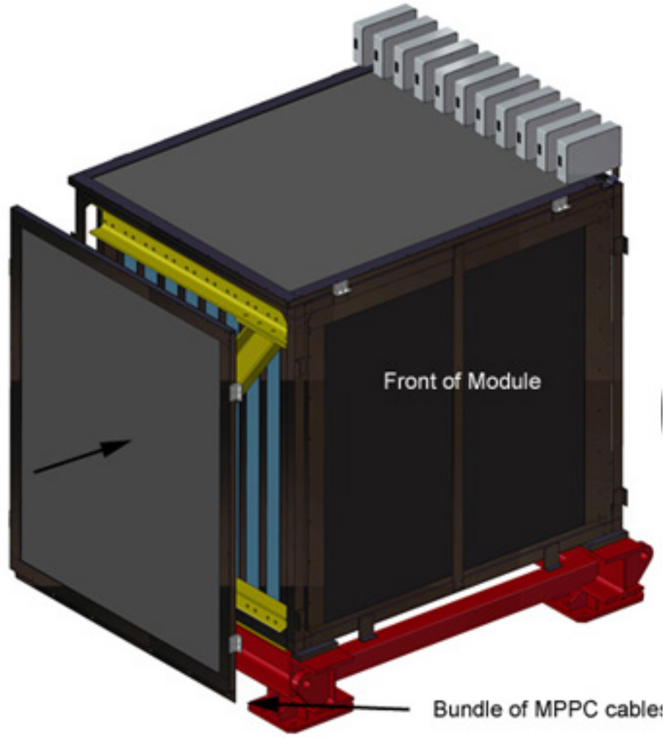
~280m from target

Off-axis detector
(ND280)
measure ν beam properties

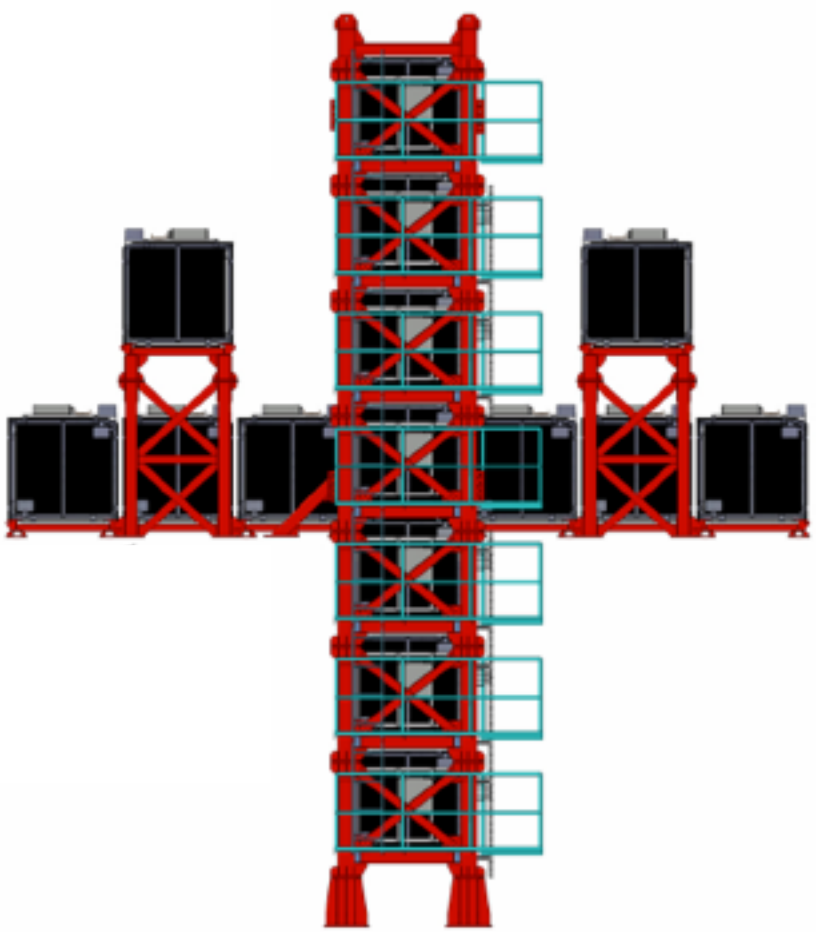
On-axis detector
(INGRID)
Monitor direction/stability
of ν beam

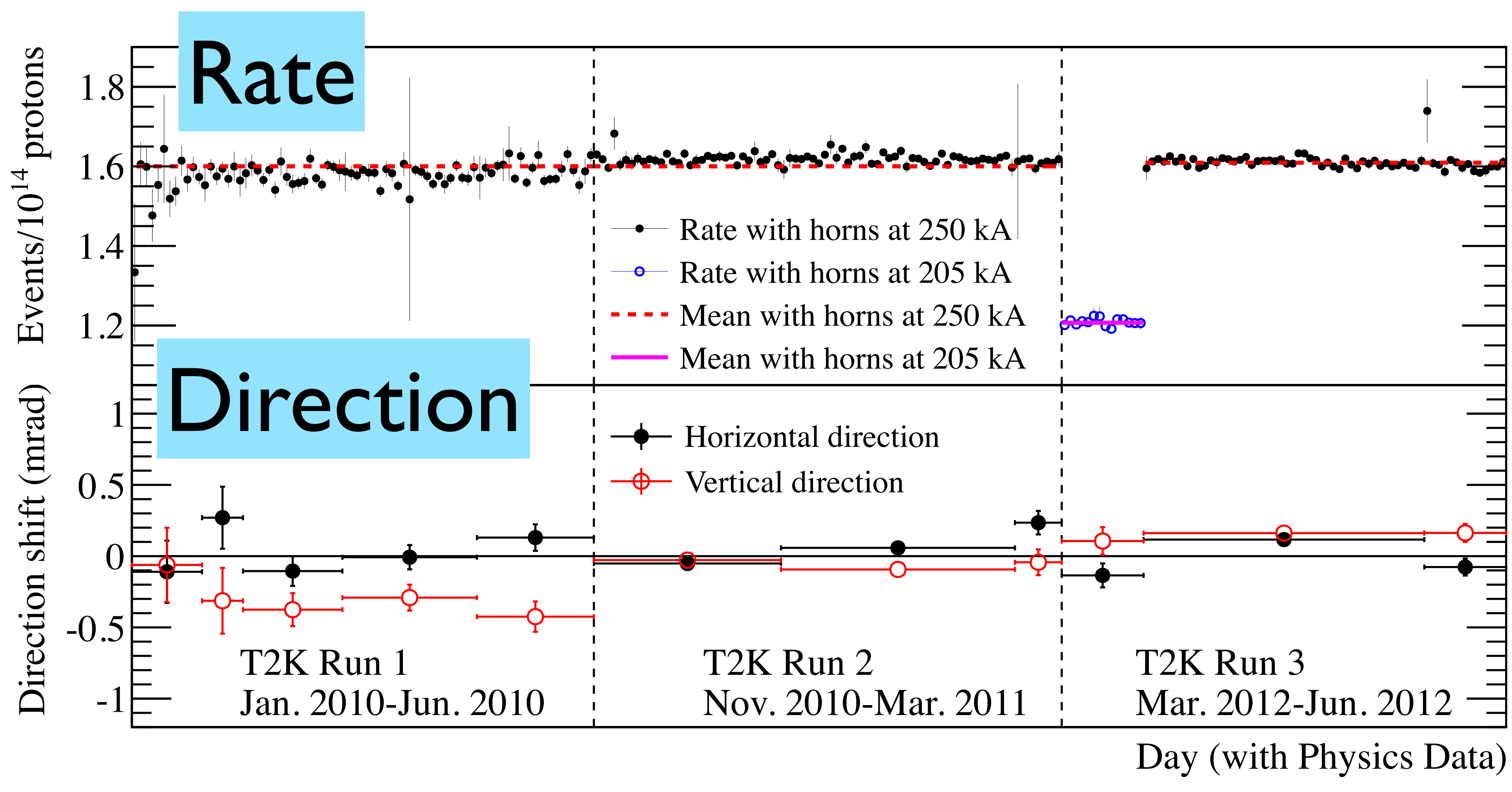


INGRID: on-axis detector



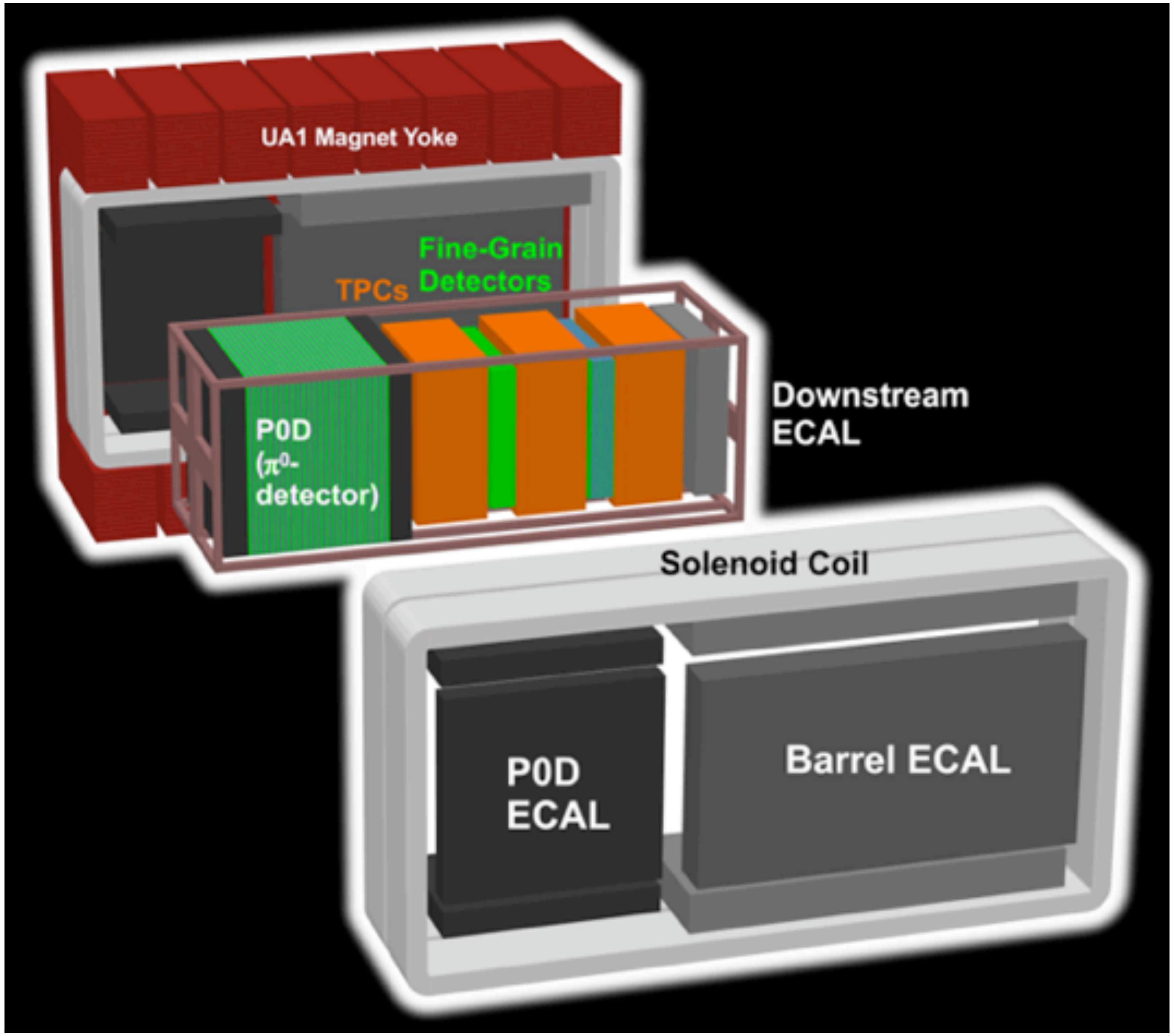
- Iron-scintillator sandwich modules
- Monitor beam intensity, direction, and their stability using ν events





Excellent stability for whole run

Off-axis ND280



- Detector suite @ 2.5degree off-axis
  - Dipole magnet (0.2T)
  - π^0 detector (P0D)
  - FGD+TPC: target+tracker
  - EM calorimeters
  - Side Muon Range detector

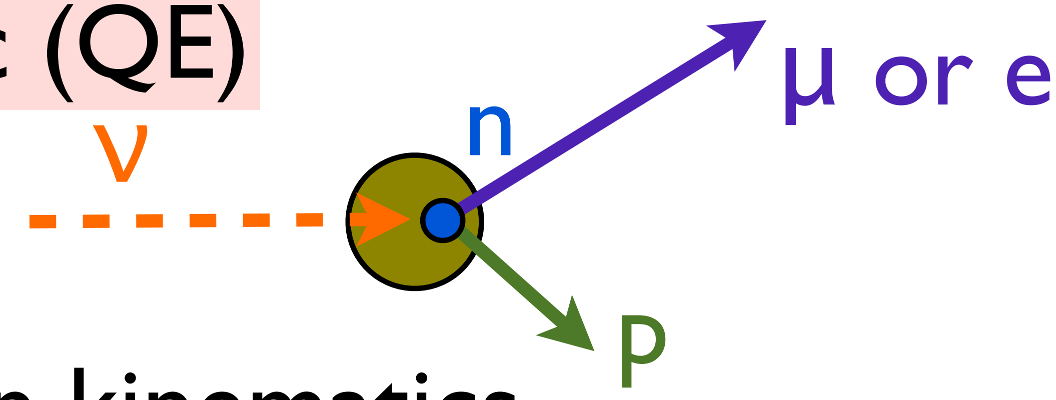
Measure neutrino beam just after production.

- Event rate (flux × cross section) normalization
- Various cross section meas.

Neutrino interaction in T2K

Charged current (CC) quasi-elastic (QE)

$\nu + n \rightarrow \mu/e + p$



- Largest cross section in ~<1GeV
- Energy reconstruction with lepton kinematics
  - E_ν reconstructed assuming CCQE in T2K

CC single pion production

$\nu + p(n) \rightarrow \mu/e + n(p) + \pi^\pm$

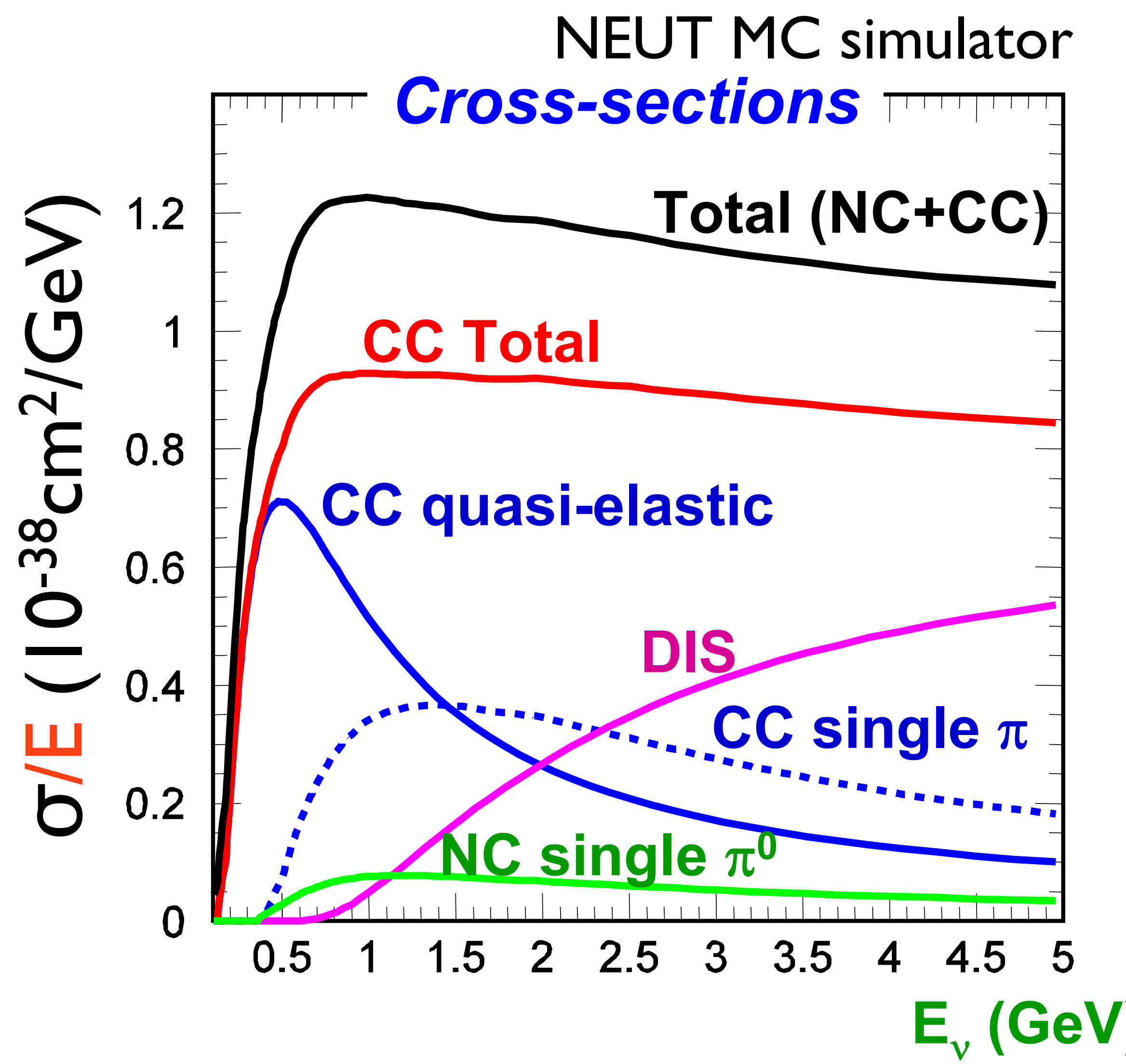
- Incorrect E_ν reconstruction

NC single pion production

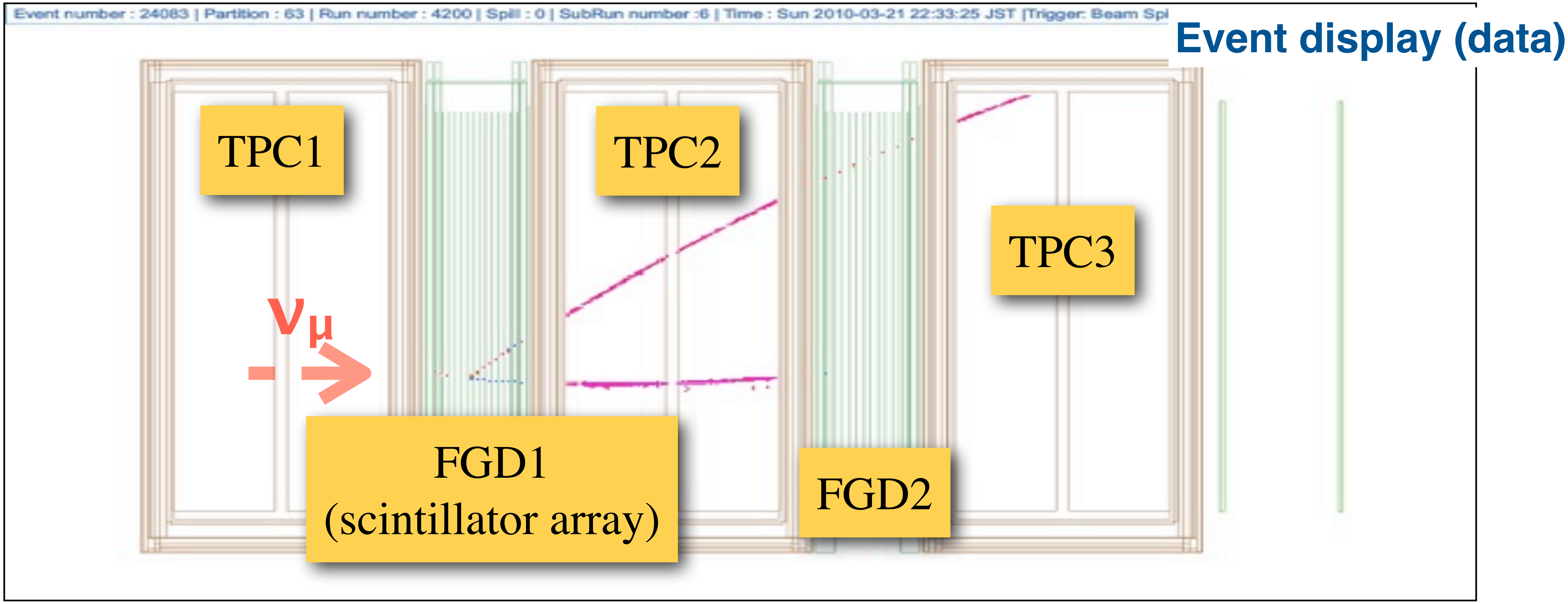
- π^+: BG in ν_μ disappearance
- π^0: BG in ν_e appearance

Multi-pion production

++ Nuclear effects

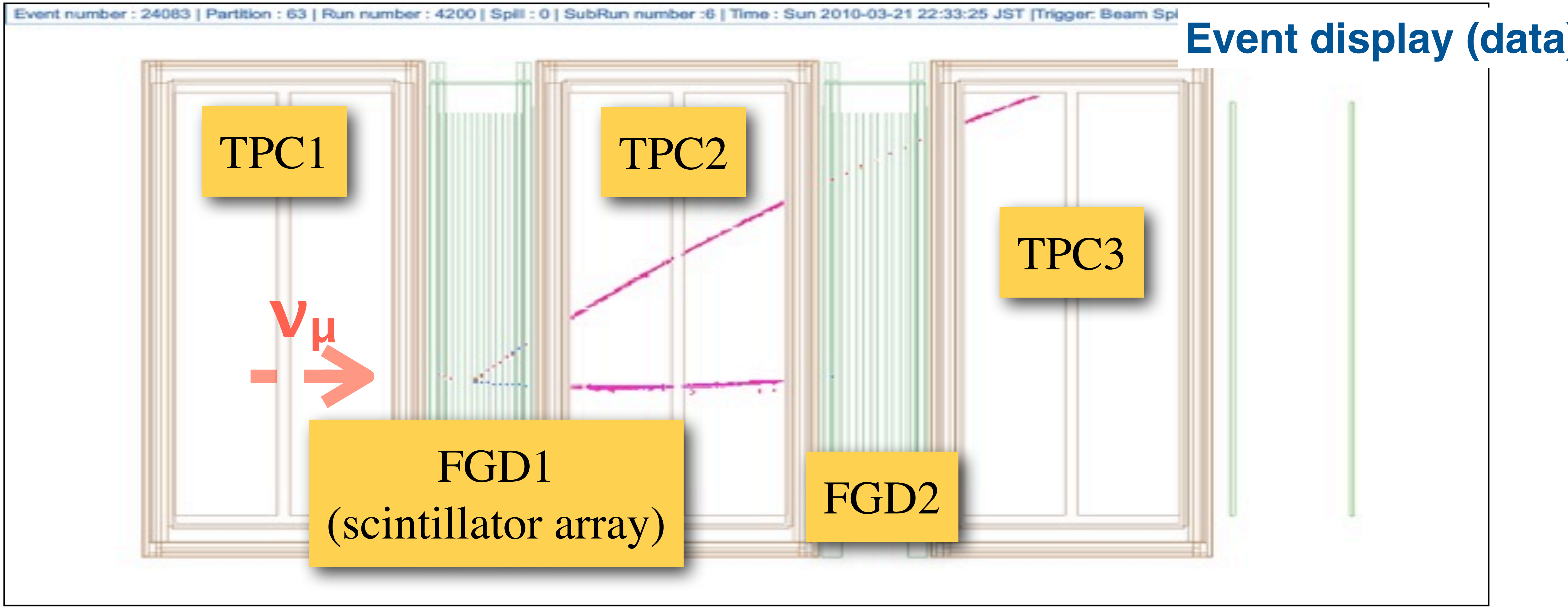


ND280 ν_μ event selection (1)



- CC event selection
  1. At least one negative track
     - Highest momentum selected as μ candidate
  2. Originating from FGD1 fiducial volume
  3. No track in TPC1 (veto incoming particles)
  4. TPC dE/dx consistent with μ

ND280 ν_μ event selection (2)

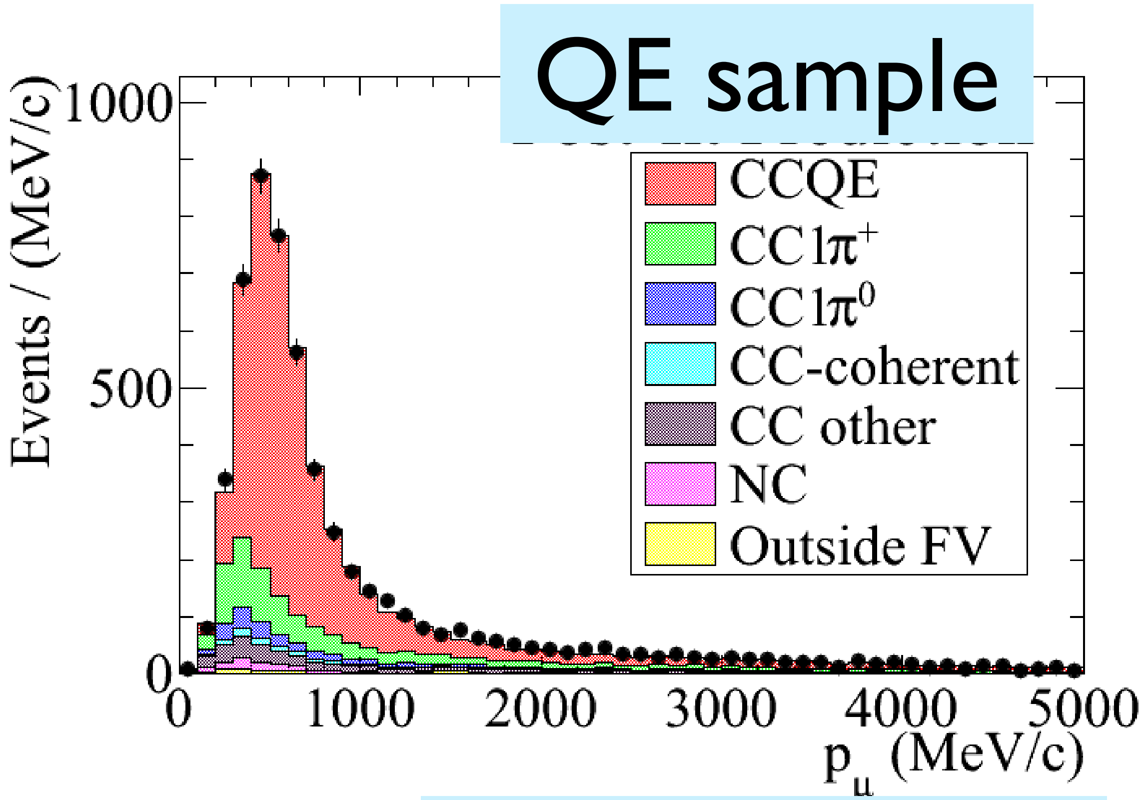


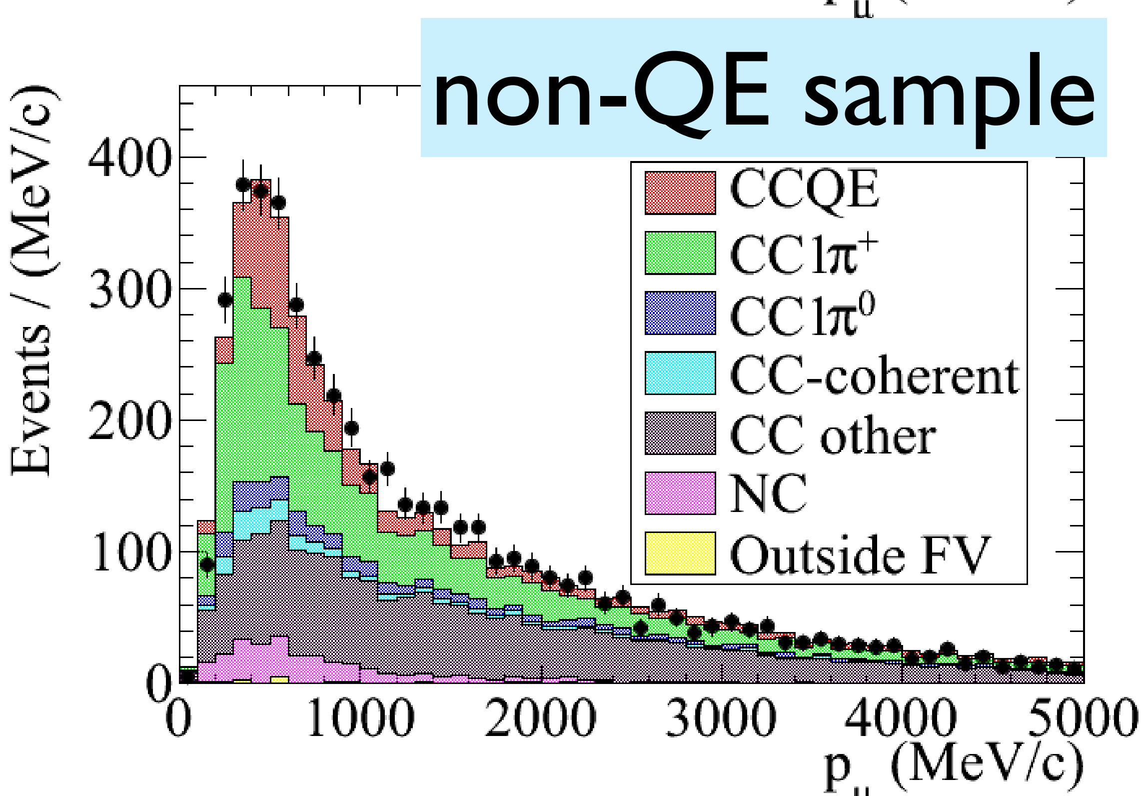
- Additional requirements to select QE events
  1. Only one FGD-TPC track
  2. No Michel electron in FGD1 (from $\pi \rightarrow \mu \rightarrow e$)

Two samples: CCQE and CC non-QE

Constraints from ND280

Reconstructed μ momentum





- Use (p_{μ}, θ_{μ}) distributions of two samples to constrain flux and cross-sections.
- Flux at ND280 and SK highly correlated because they are from same parent particles in beam
- CCQE/nQE separation allows constraints on cross section models

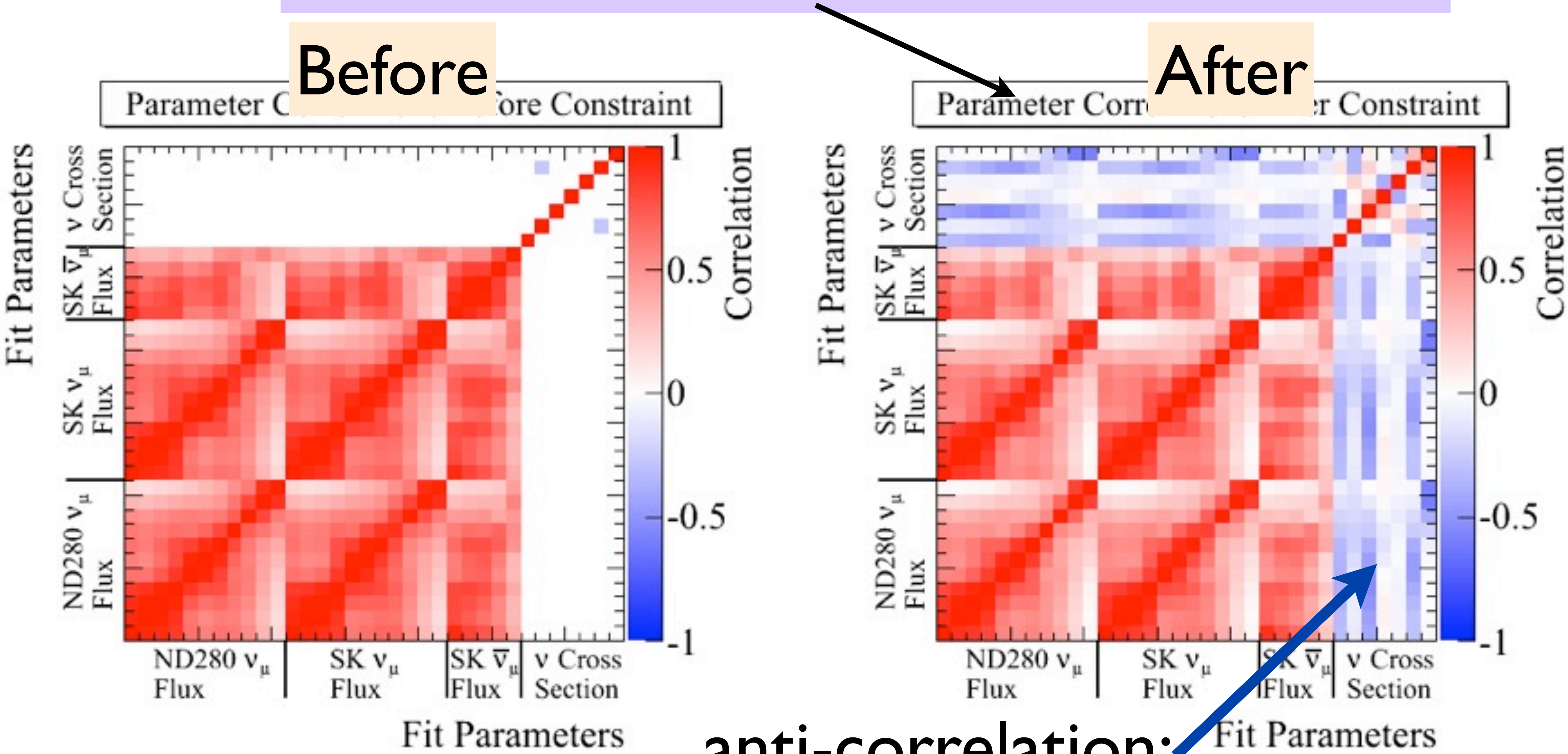
Constraining flux × cross section

Flux prediction (NA61, beamline meas.)

ND280 measurements (p_μ, θ_μ)

Cross-sec. uncertainties (external meas., models)

Fit with correlations taken into account



anti-correlation:
reduced rate (flux × cross section) uncertainty

Prediction at Super-K (ν_e)

The predicted # of events w/ 3.01 x 10^{20} p.o.t.

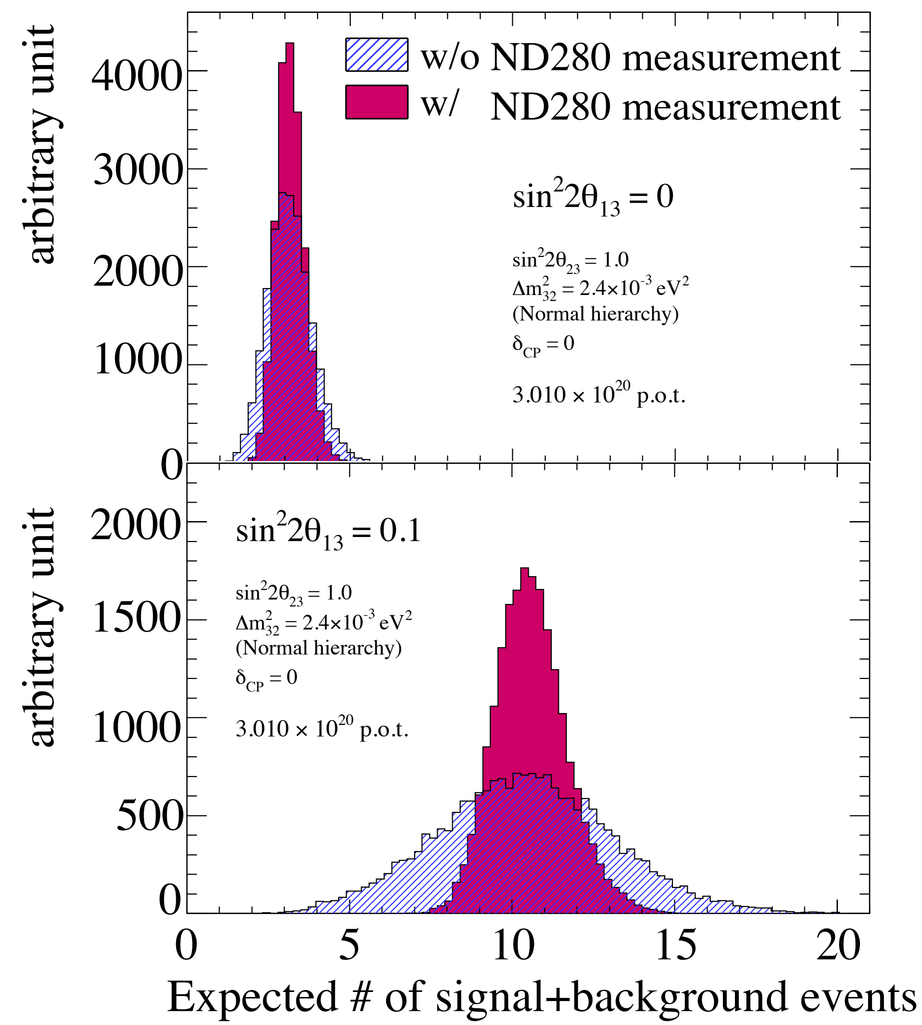
Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background (mainly NCπ^0)	1.21	1.21
$\bar{\nu}_\mu + \bar{\nu}_e$ background	0.16	0.16

Systematic uncertainties

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %
(T2K 2011 results:	~23%	~18%)

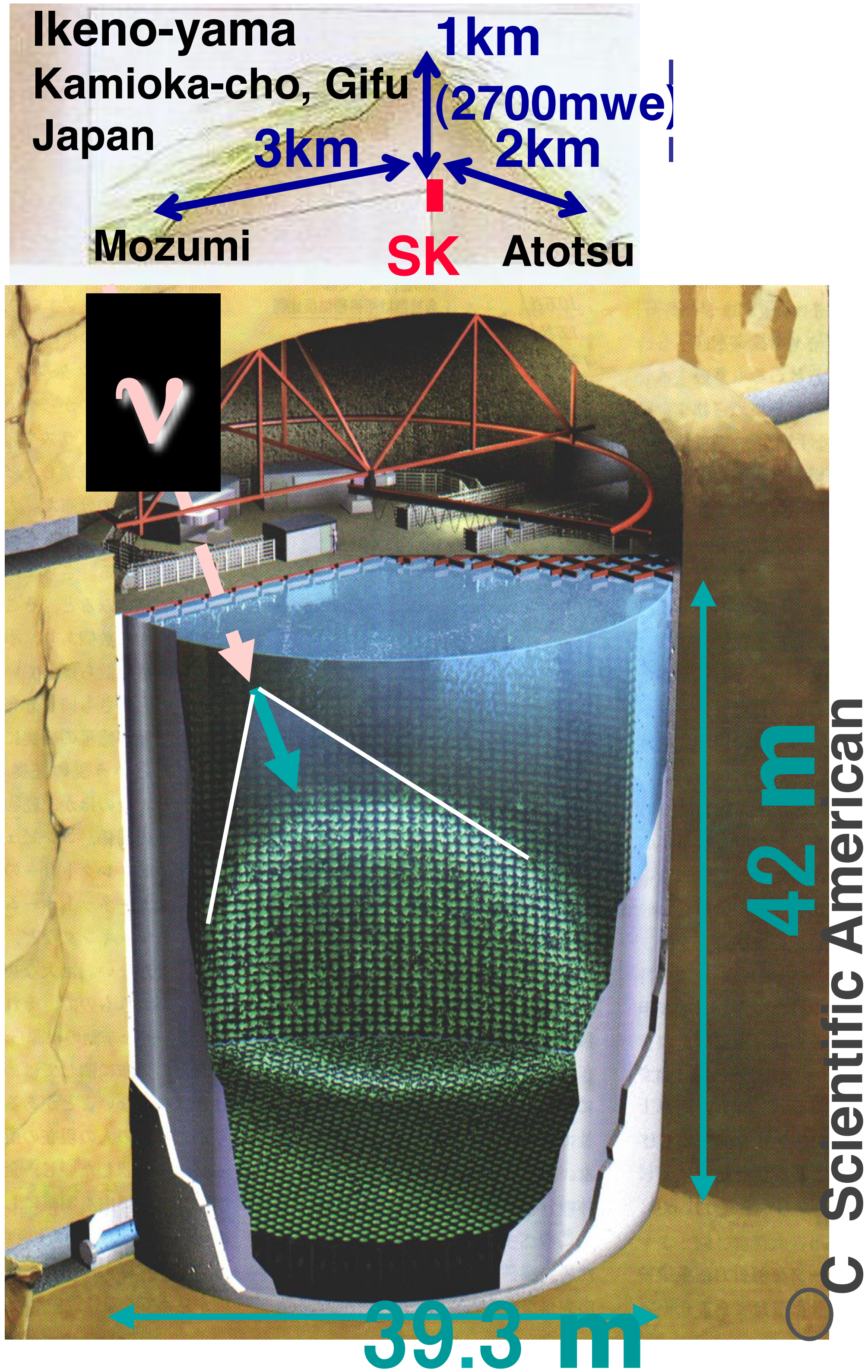
big improvement from the T2K 2011 results

the predicted # of event distribution

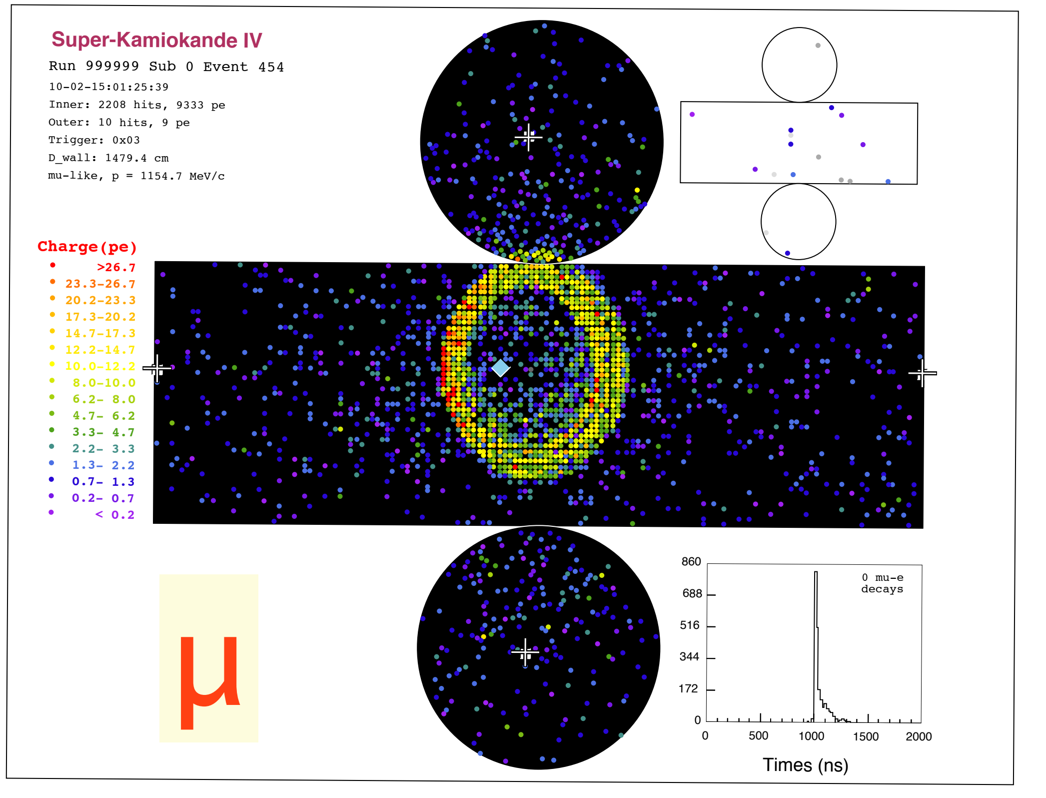


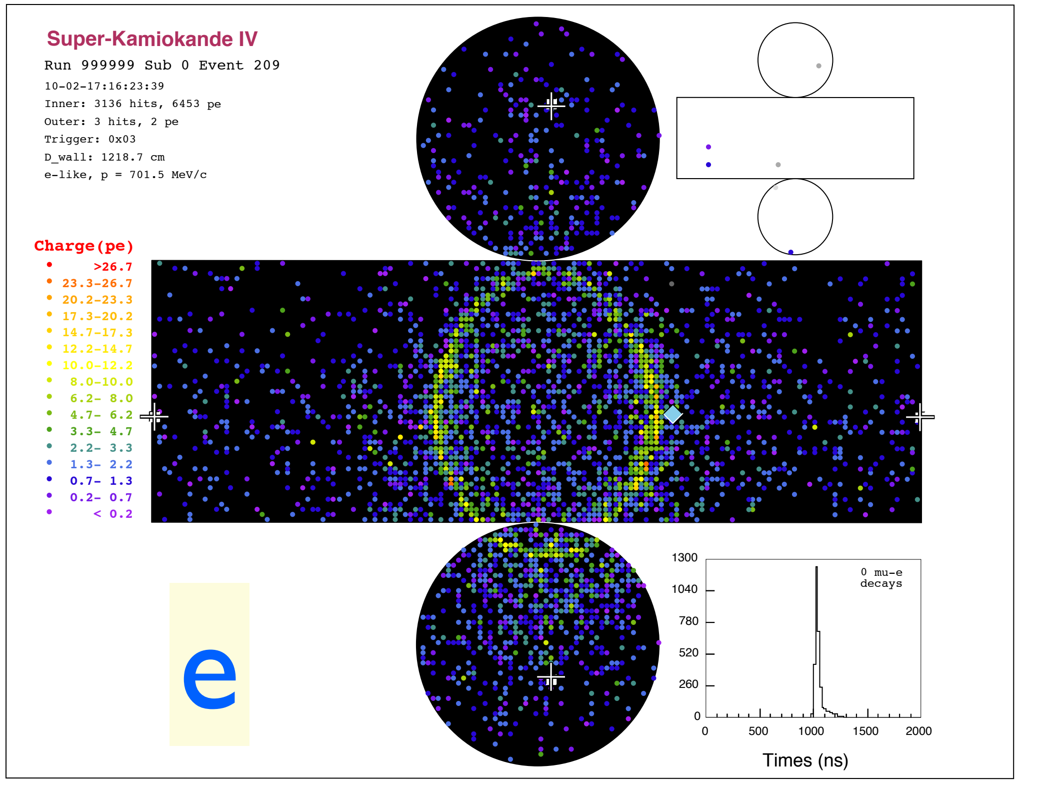
Uncertainties are reduced using ND280 measurement

Super-Kamiokande detector

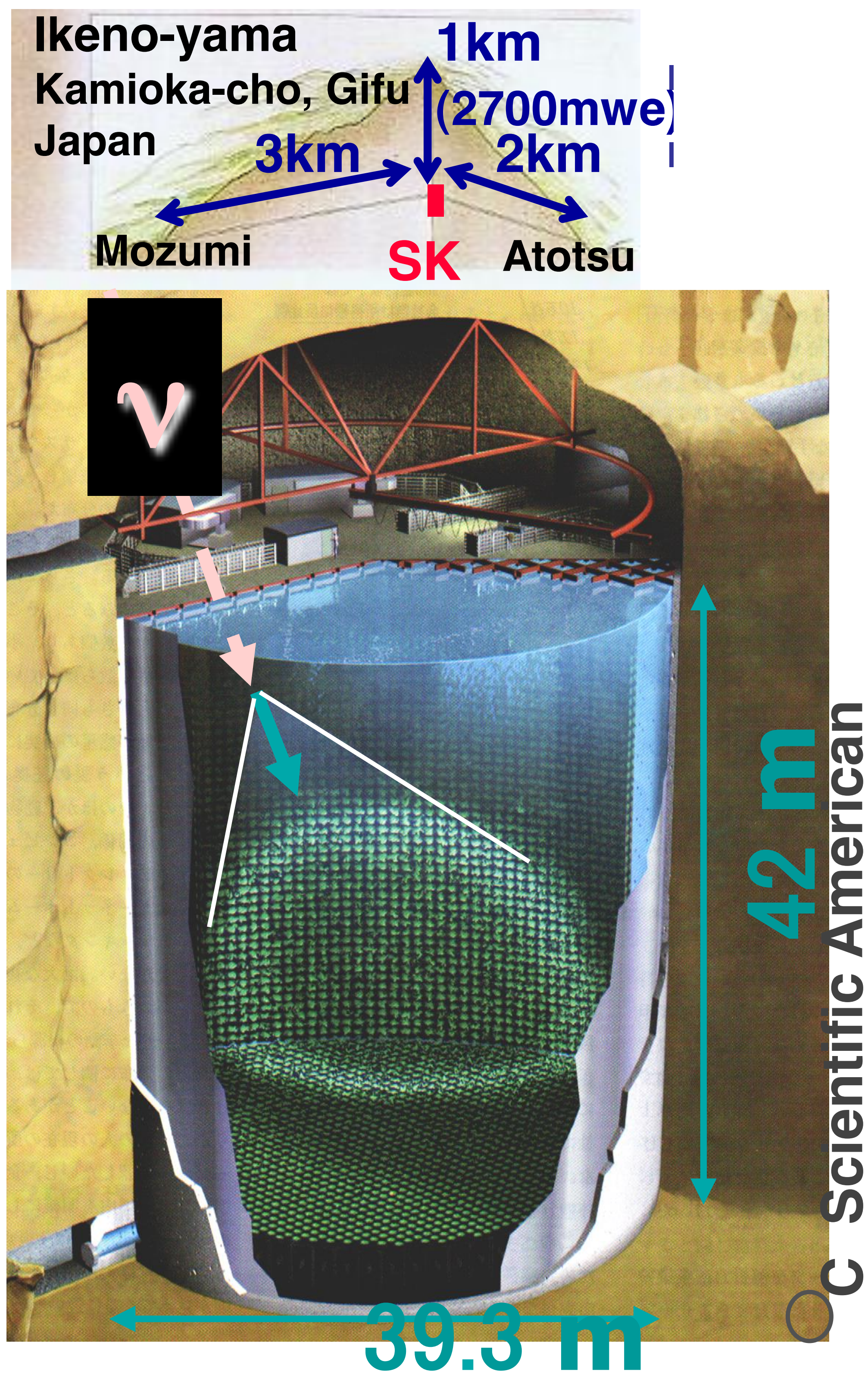


>11,000 50cm PMTs



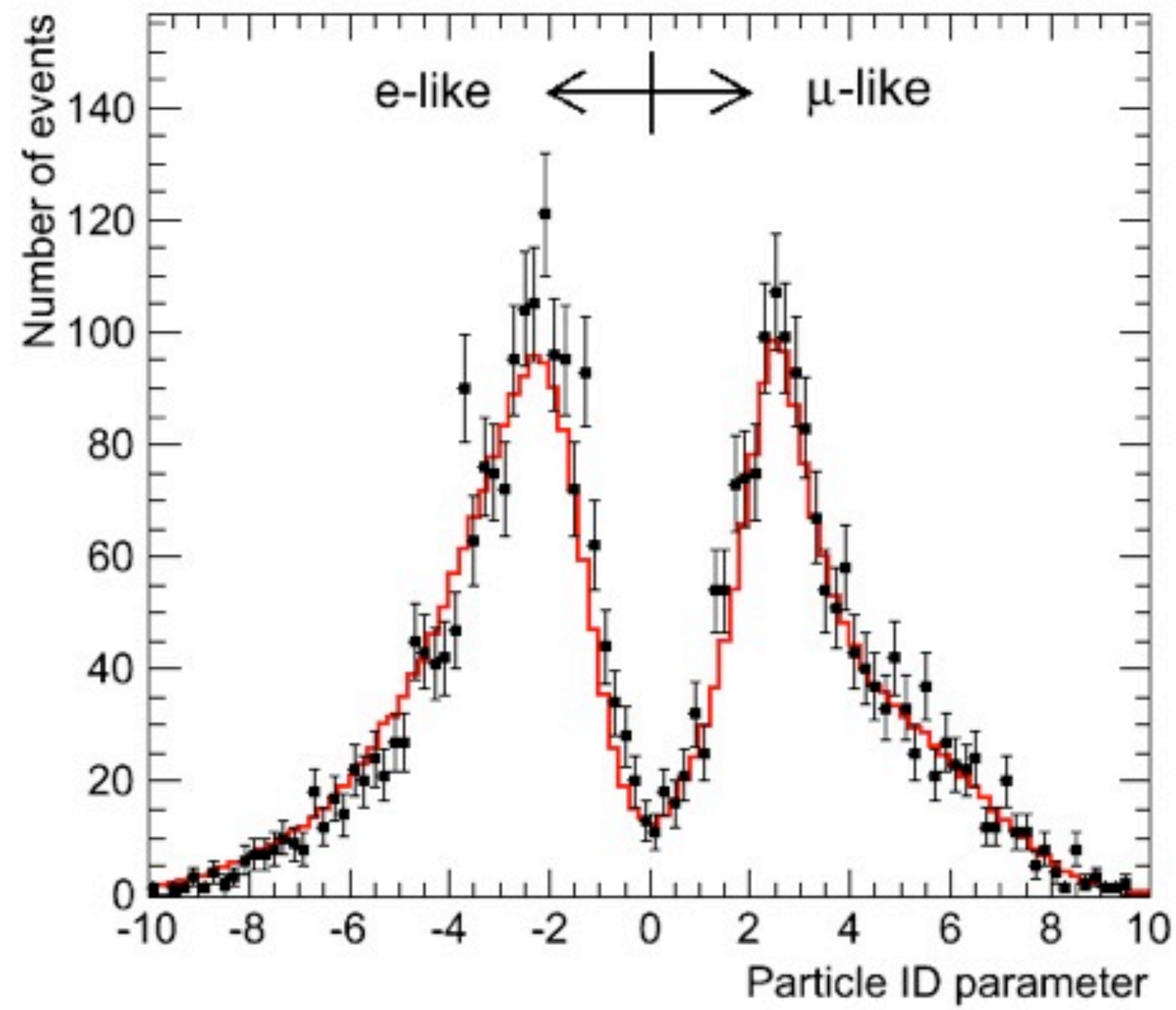


Super-Kamiokande detector



>11,000 50cm PMTs

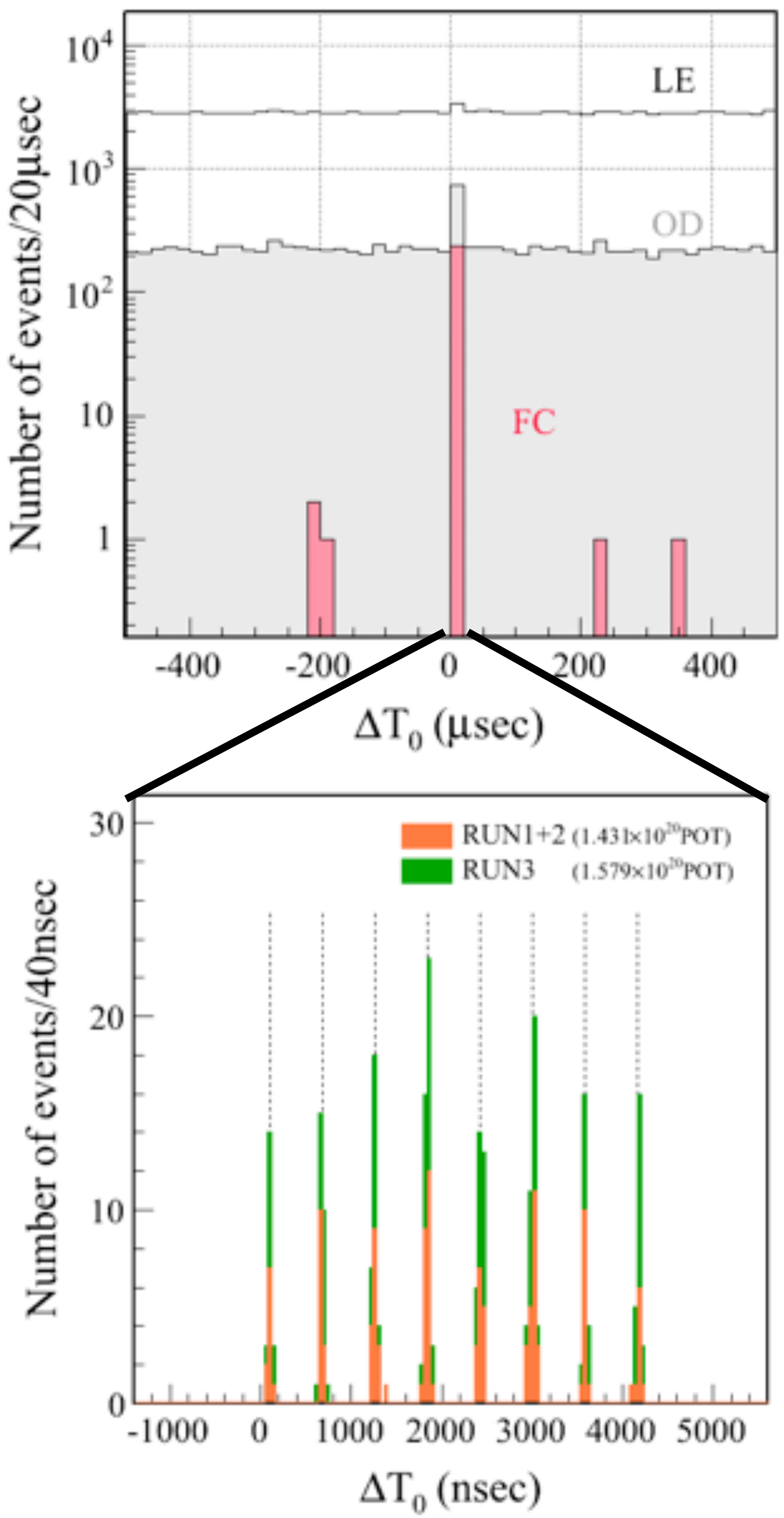
Particle identification using ring shape & opening angle

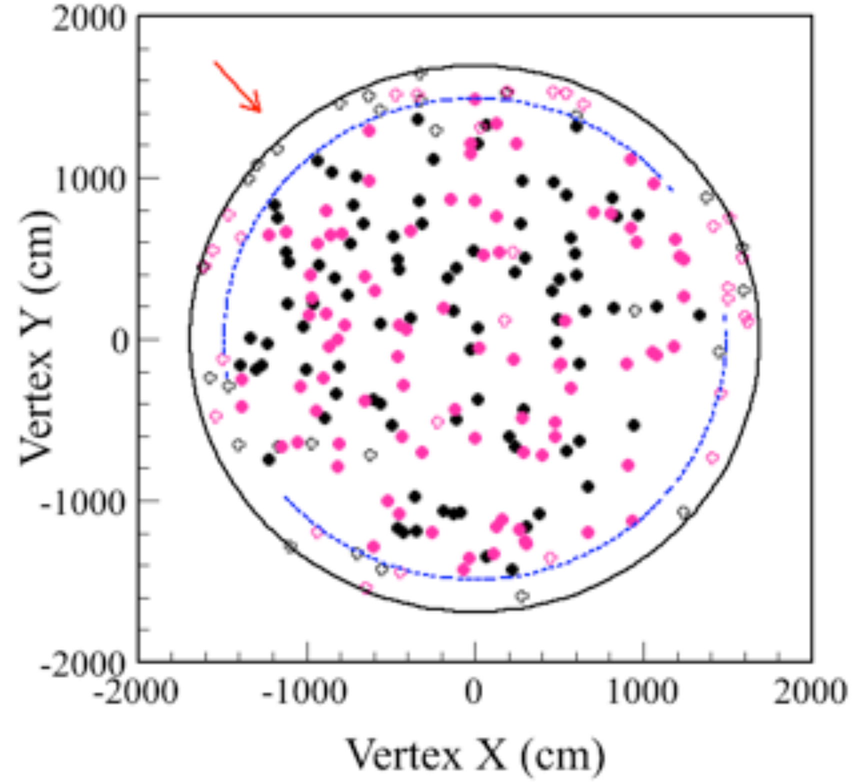


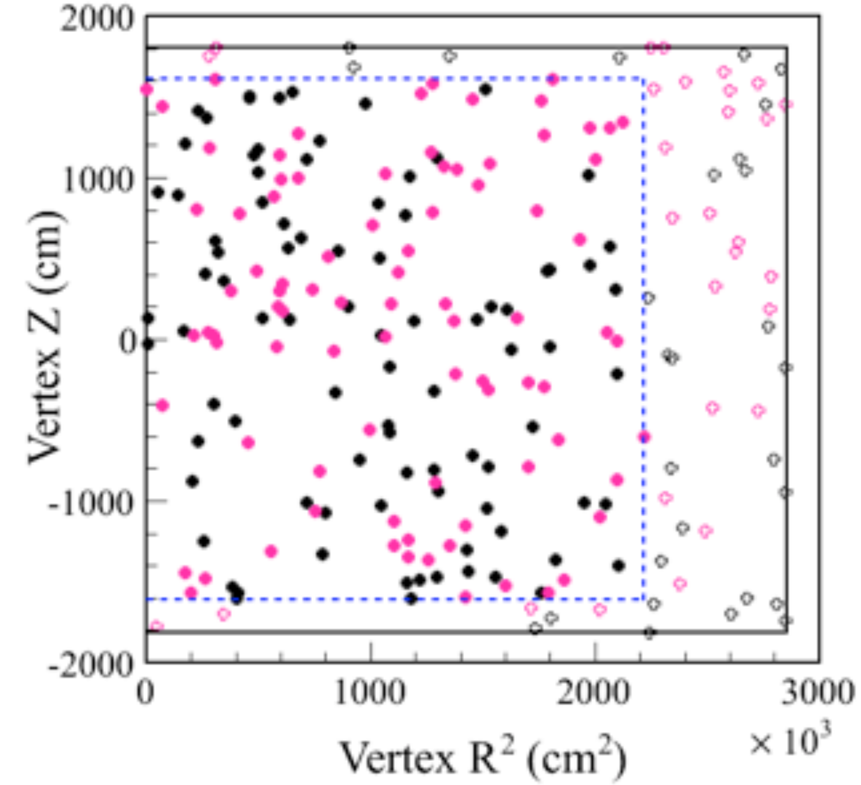
● atmospheric ν data

▯ MC

Event selection at far detector

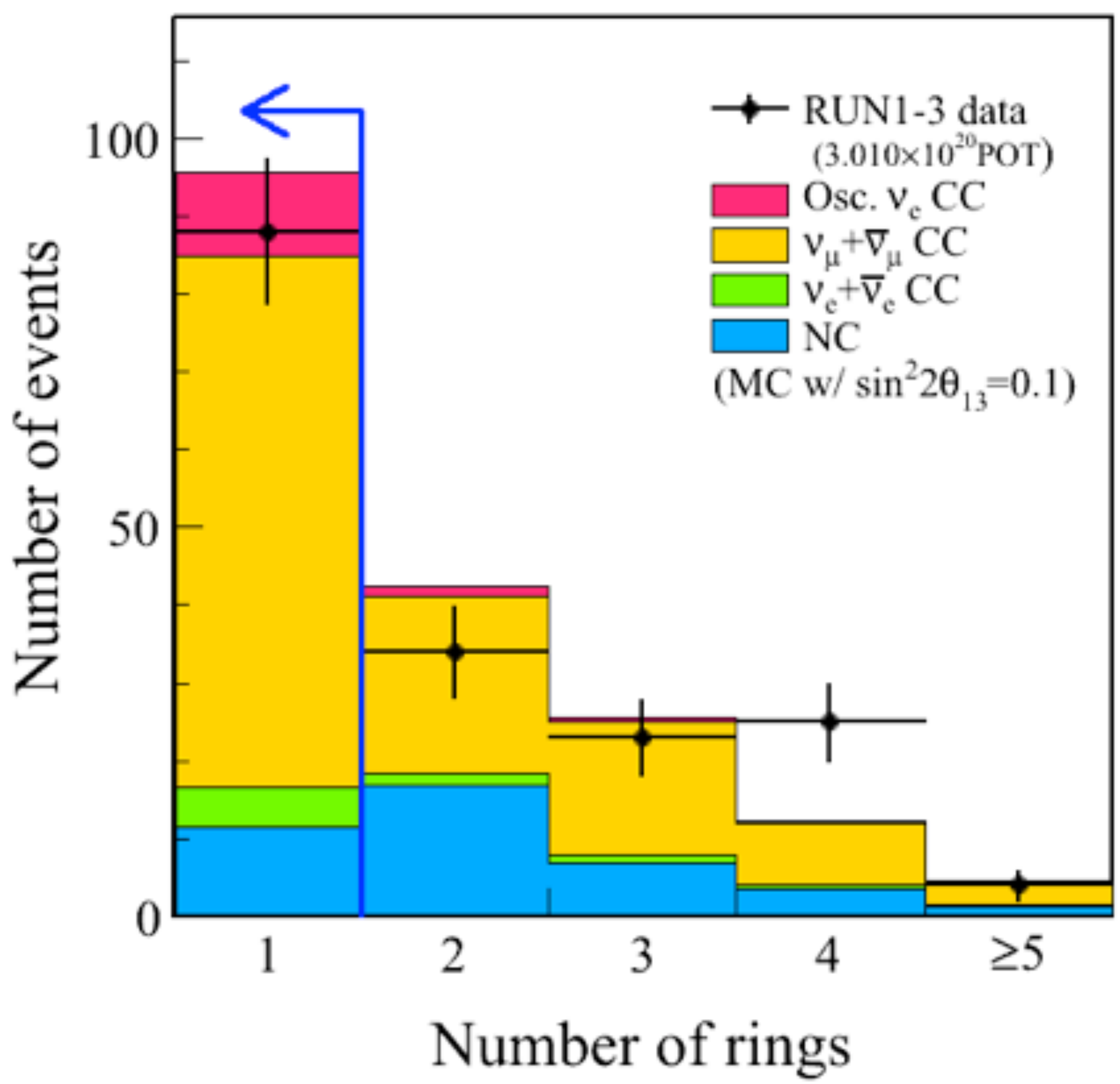




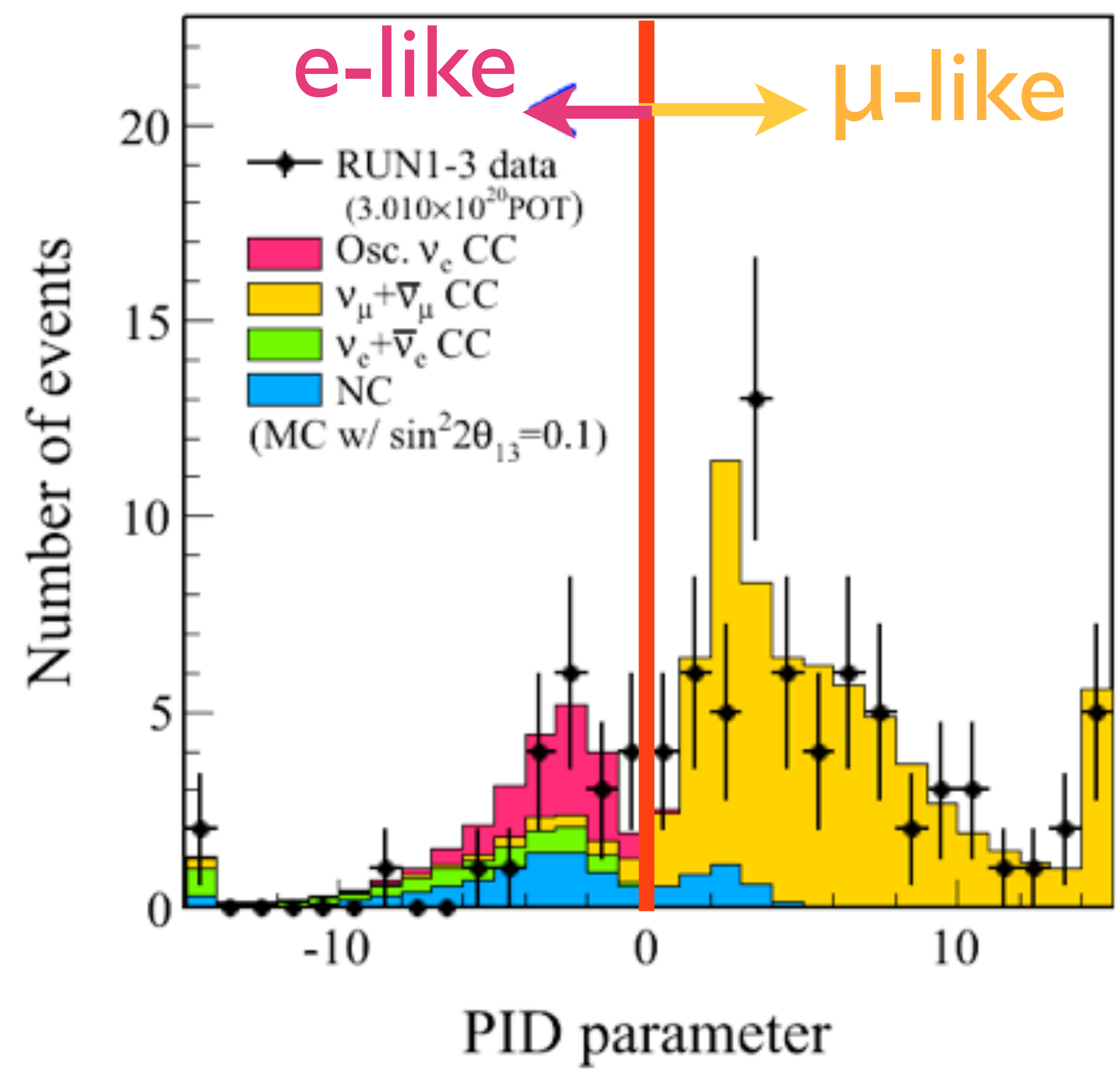


- Event timing compatible with beam timing (synch by GPS)
- Event must be fully contained in inner detector (ID)
- vertex must be inside the fiducial volume (2m from ID wall)

Single ring



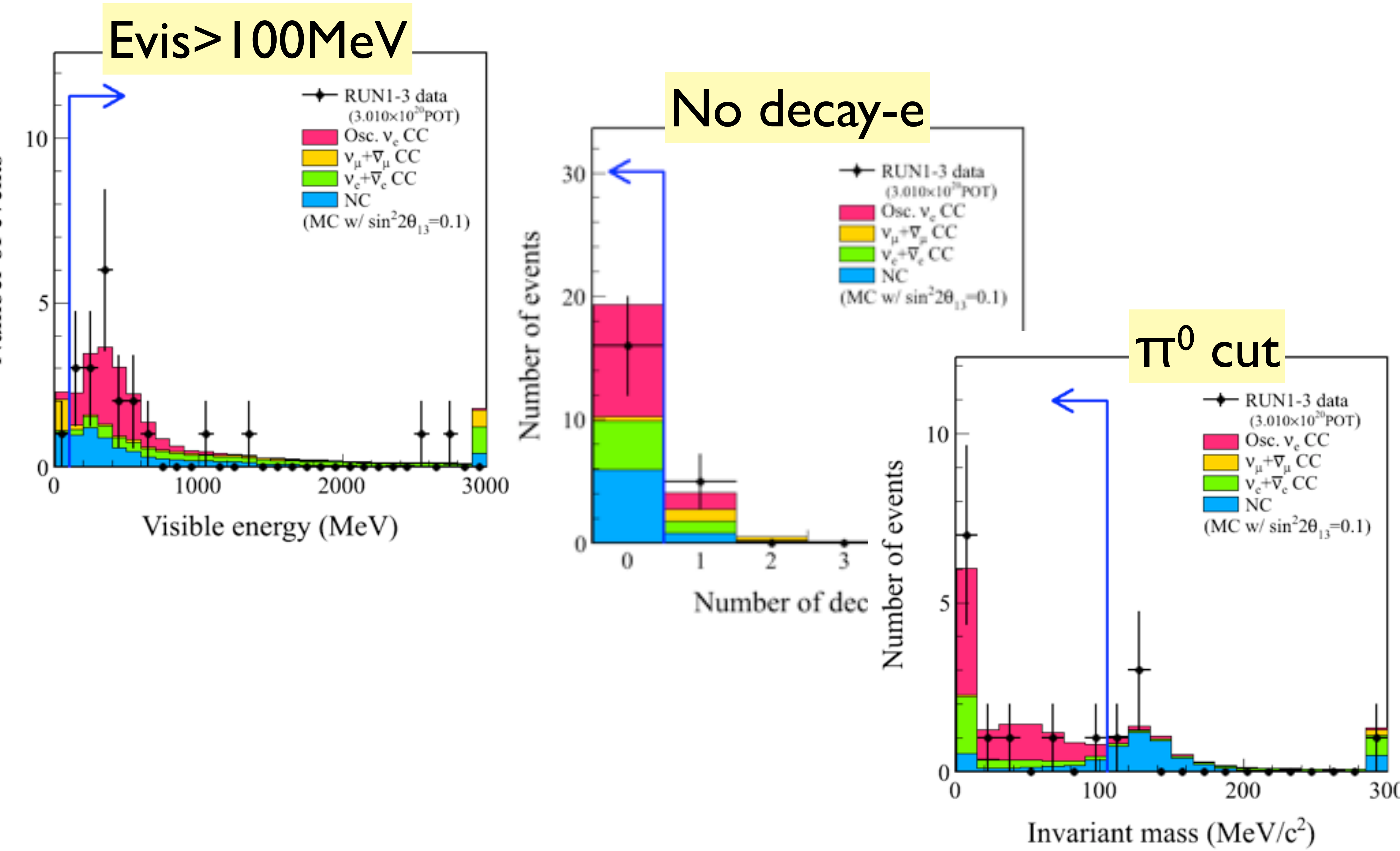
Particle ID



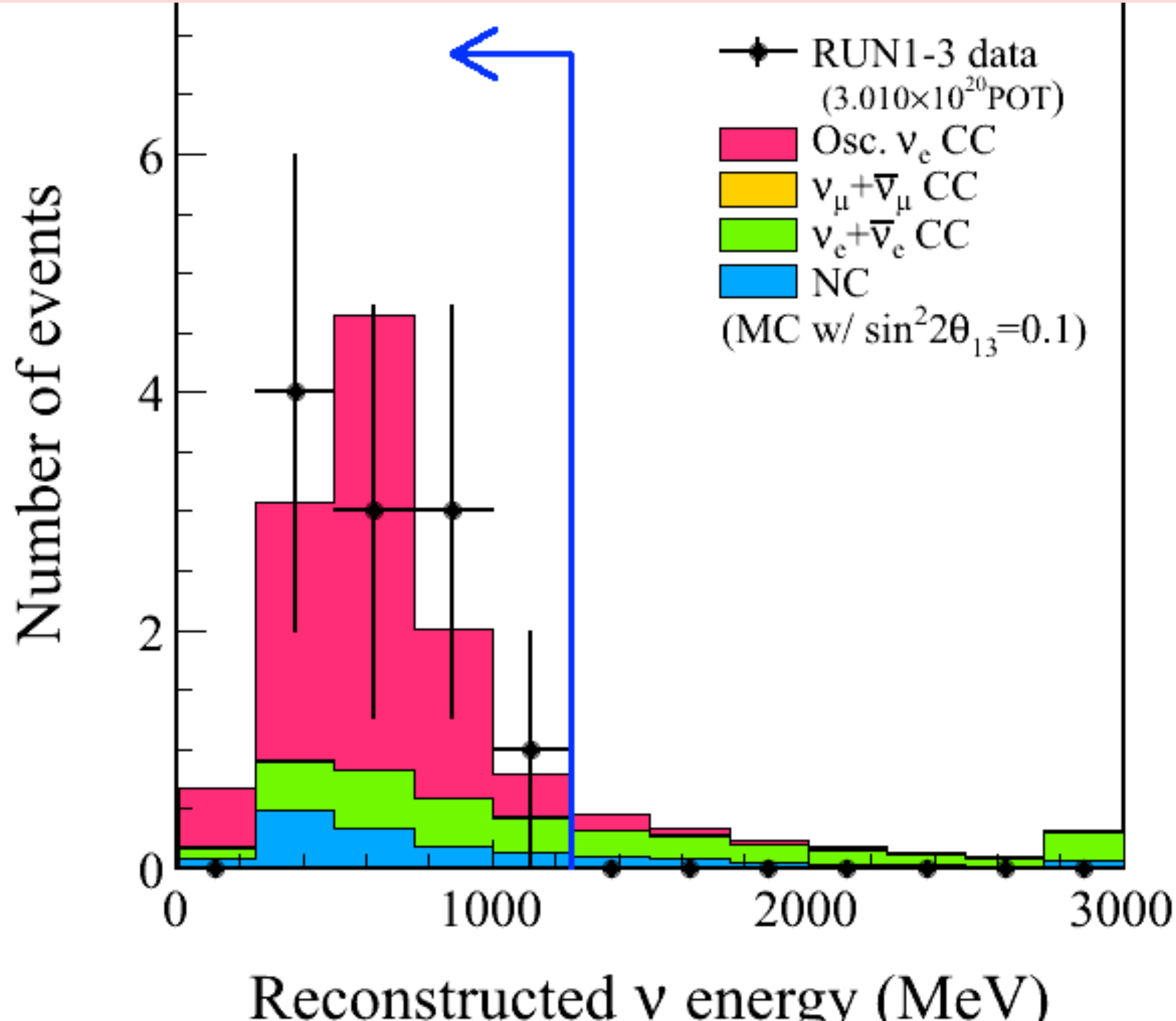
Basic event selection (not final sample!)

RUN1+2+3 3.010×10^{20} POT	Data	MC Expectations			BG (12μs window)
		$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0$	No osc.	
FC	240	231.6	216.4	465.8	0.039
FCFV	174	163.4	152.7	322.0	0.0048
Single-ring	88	85.6	76.5	222.7	
μ-like (p_μ>200MeV/c)	66 (65)	61.8 (61.4)	61.8 (61.4)	201.4 (200.1)	
e-like (p_e>100MeV/c)	22 (21)	23.8 (21.7)	14.7 (12.8)	21.4 (14.8)	
Multi-ring	86	77.8	76.2	99.2	

ν_e selection



11 νe candidates observed!! (3.3±0.4 if $\sin^2 2\theta_{13}=0$ → 3.1σ)



ν_e oscillation parameter fit

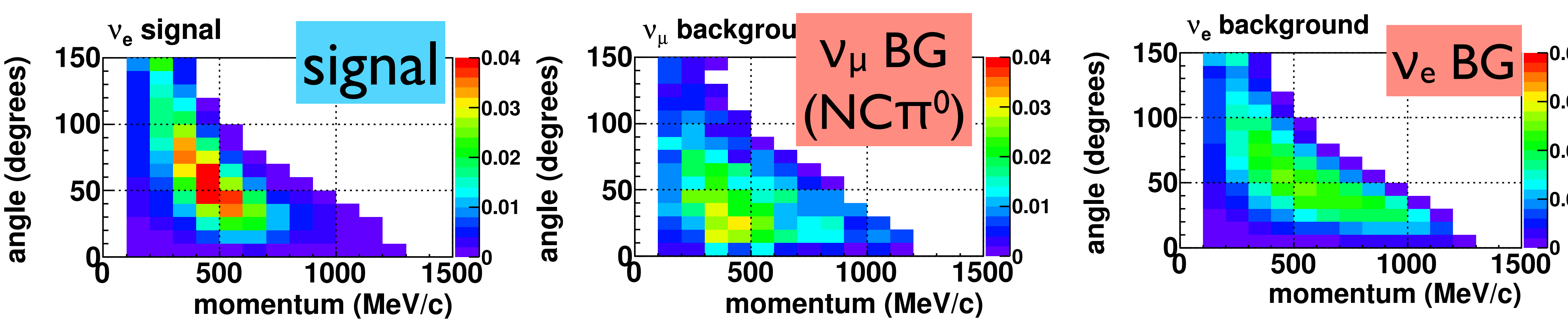
Extended maximum likelihood fit

$$L(N_{obs},\vec{x};\vec{o},\vec{f}) = L_{norm}(N_{obs};\vec{o},\vec{f}) \times L_{shape}(\vec{x};\vec{o},\vec{f}) \times L_{syst}(\vec{f})$$

Measured variables   Oscillation parameters   Systematic parameters (ND fit result as prior)

Fit data with rate + (p_e, θ_e) shape

- Difference in (p_e, θ_e) distribution allows better discrimination of signal and BG

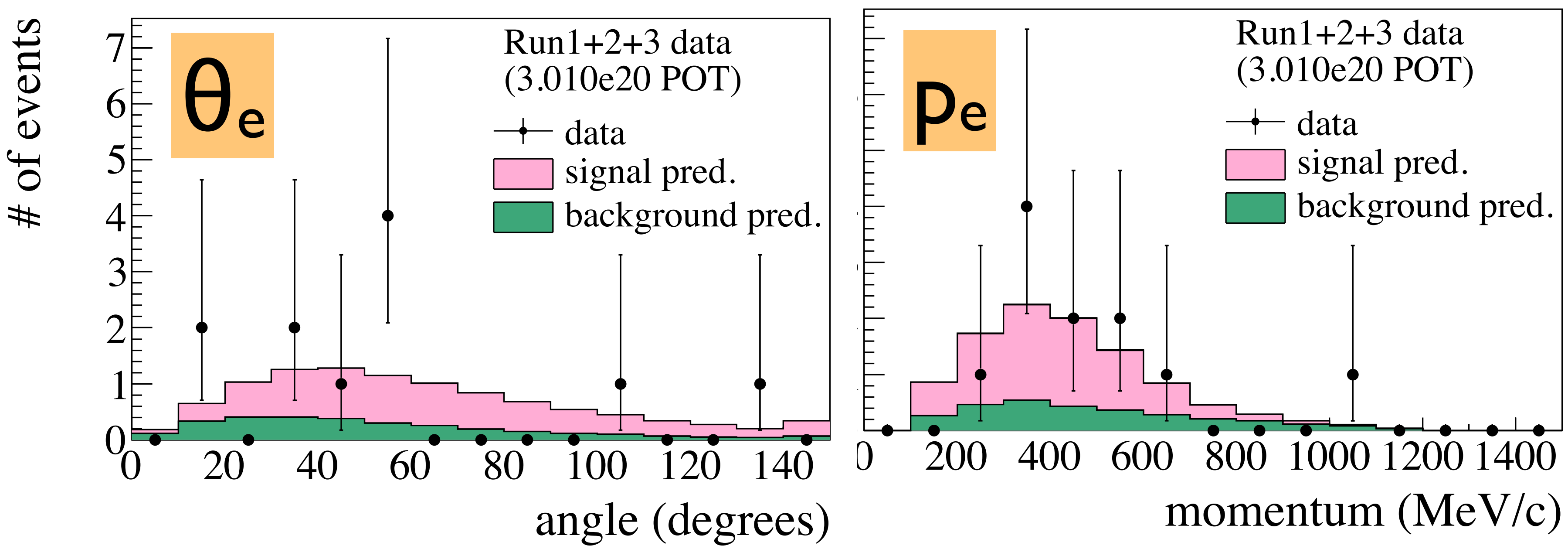


Other independent methods give consistent results:

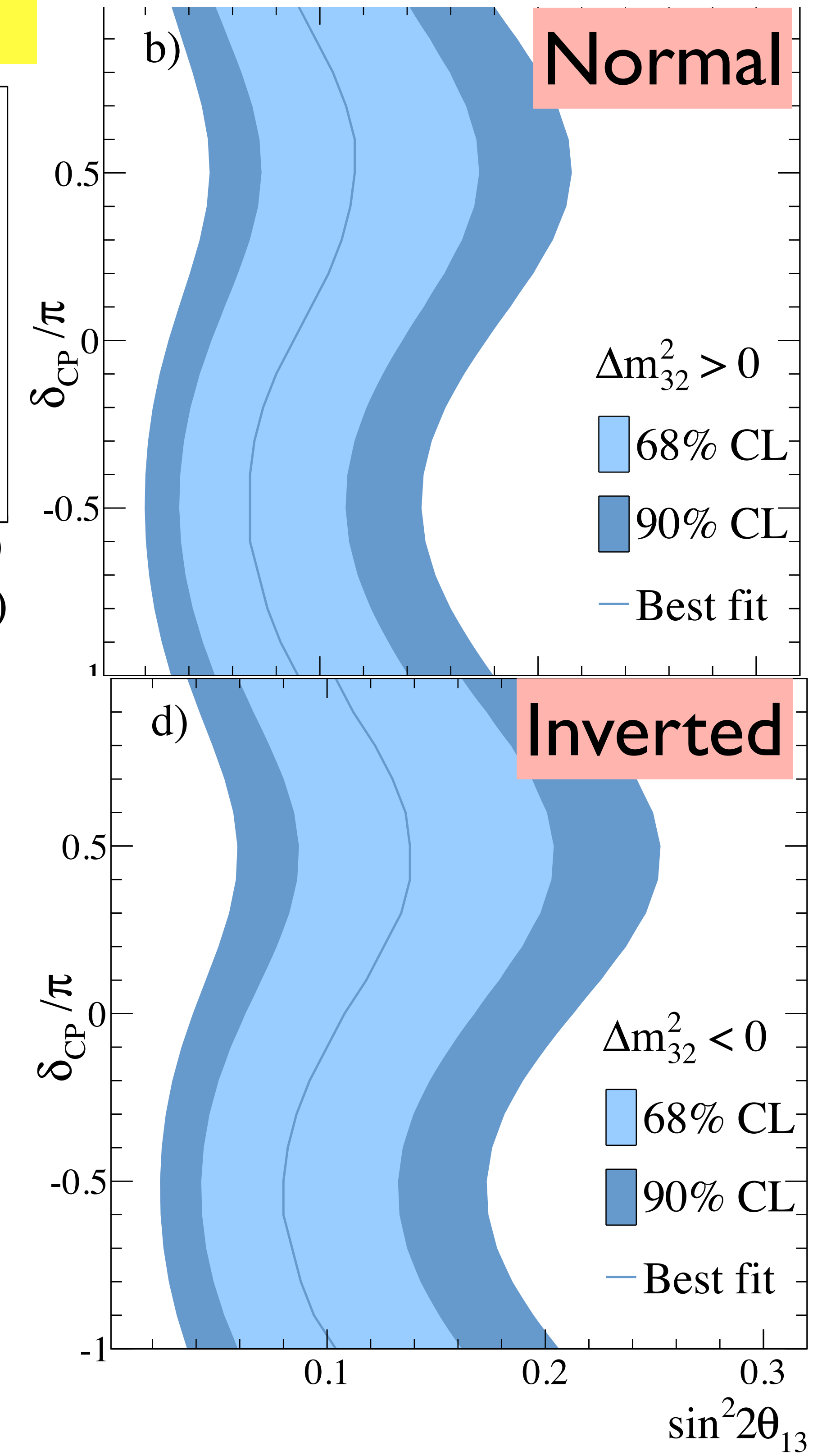
- Rate + rec. $E\nu$
- Rate only

ν_e appearance result

3.1σ evidence for ν_e appearance



arXiv:1304.0841

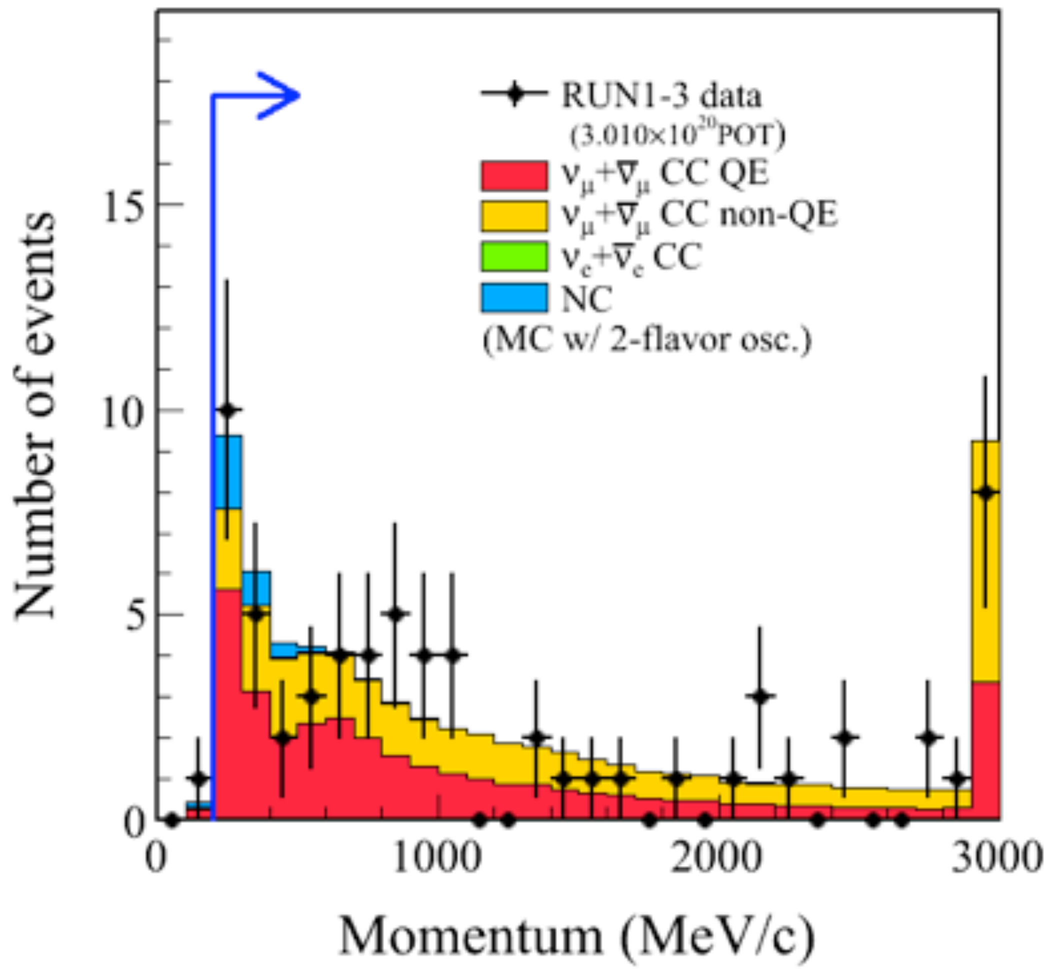


Best fit values & 1σ of $\sin 2^2\theta_{13}$	
Normal hierarchy	$0.088^{+0.049}_{-0.039}$
Inverted hierarchy	$0.108^{+0.059}_{-0.046}$

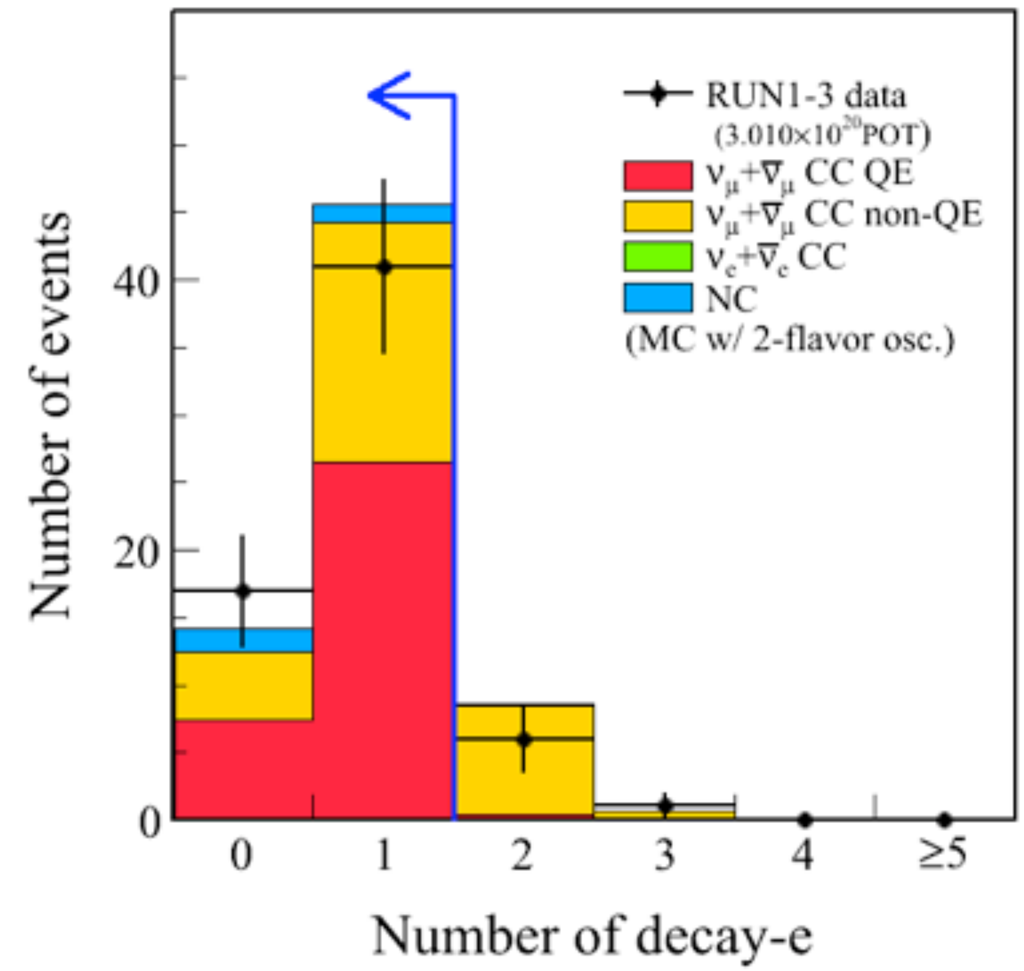
for $\sin^2 2\theta_{23}=1.0$, $\delta=0$

ν_μ selection

Momentum>200MeV/c

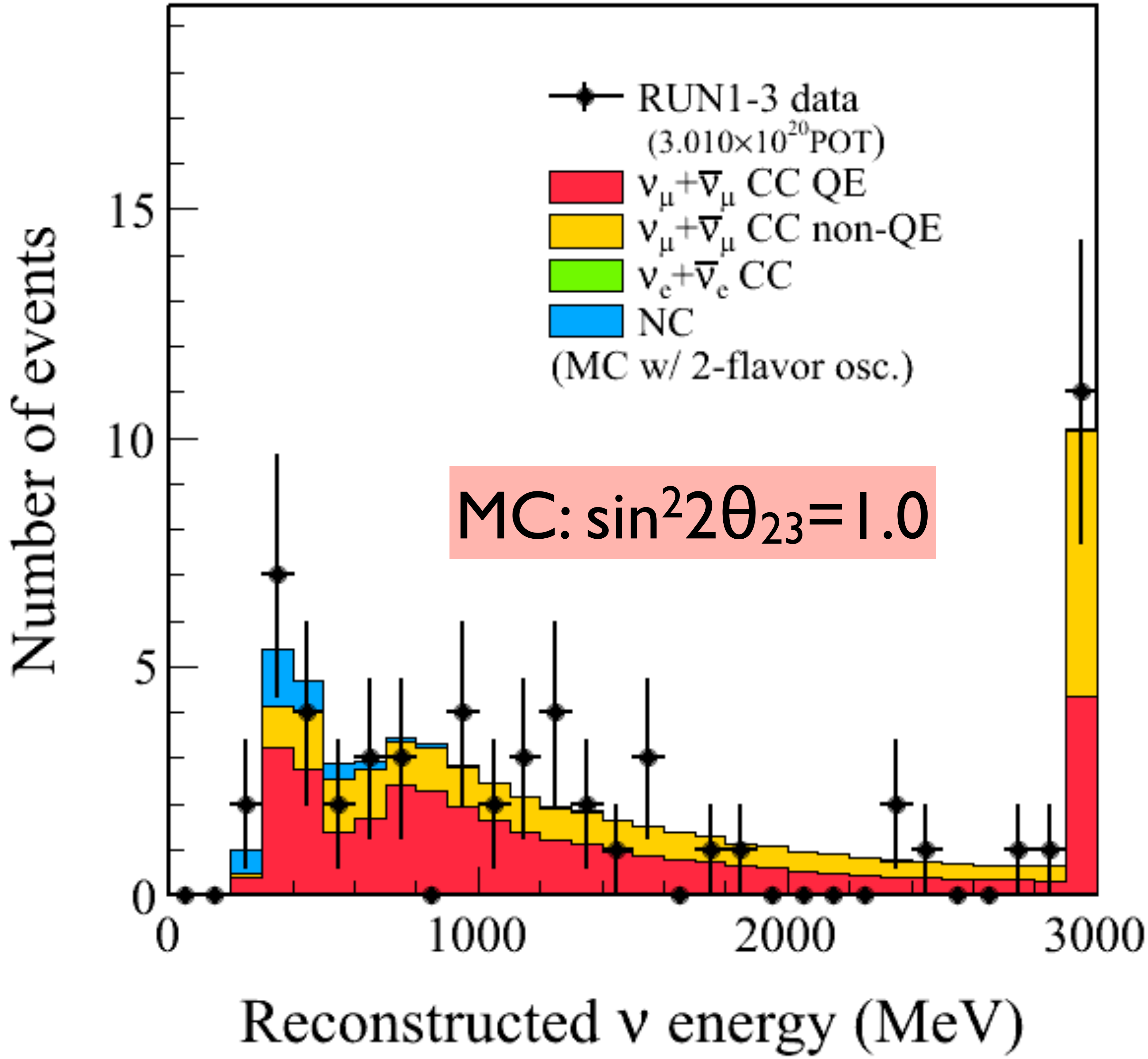


Decay-e≤1



58 events observed
(205±17 if no osc.)

Reconstructed E_ν



ν_μ oscillation parameter fit

- Two methods
  - Both use reconstructed E_ν shape

(a) Binned likelihood-ratio

$$\chi^2 = 2\sum_i \left(N_i^{obs} \ln \frac{N_i^{obs}}{N_i^{\exp}} + (N_i^{\exp} - N_i^{obs}) \right) + (\mathbf{a} - \mathbf{a_0})^T \mathbf{C}^{-1} (\mathbf{a} - \mathbf{a_0})$$

Rate + shape

systematic parameters (48 params)

(b) Maximum likelihood fit

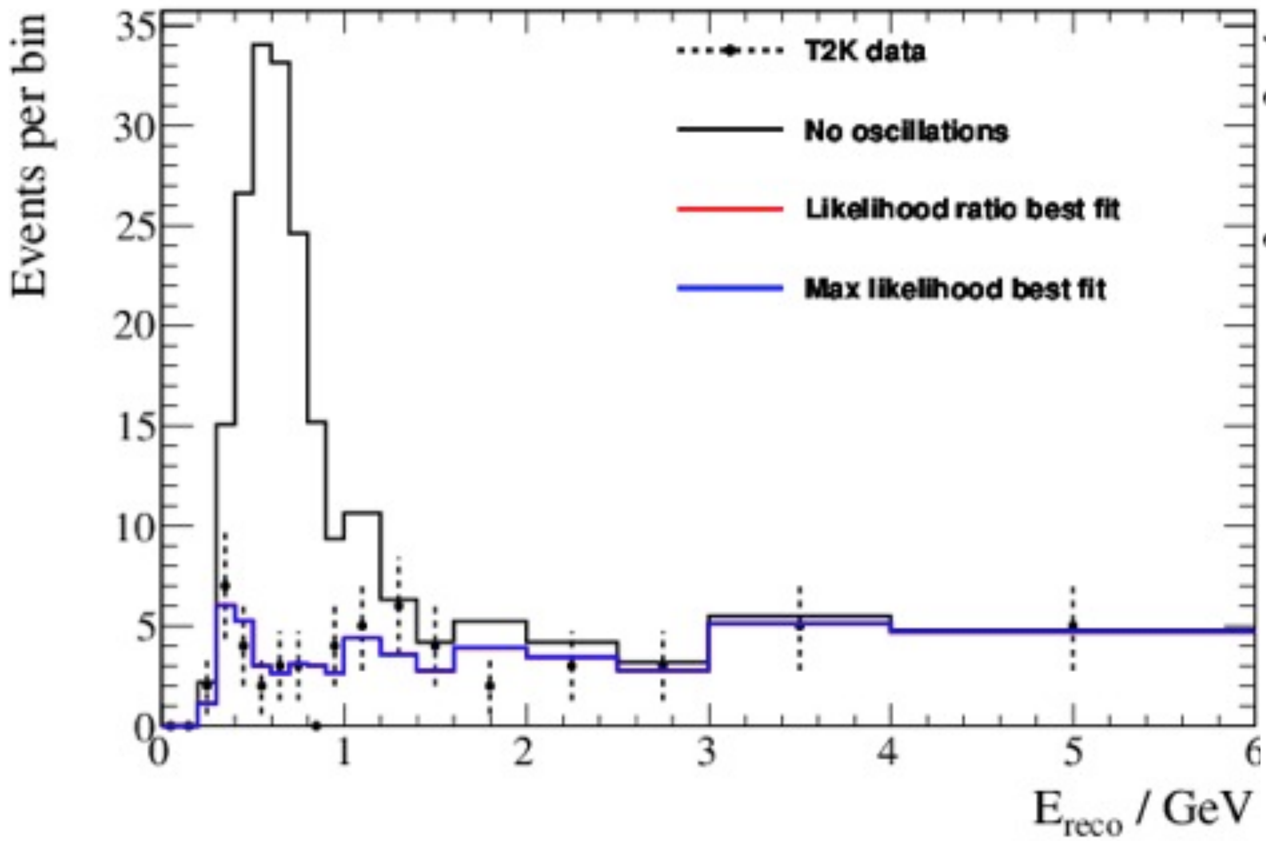
$$L(\vec{o}, \vec{f}) = L_{norm}(\vec{o}, \vec{f}) \times L_{shape}(\vec{o}, \vec{f}) \times L_{syst}(\vec{f})$$

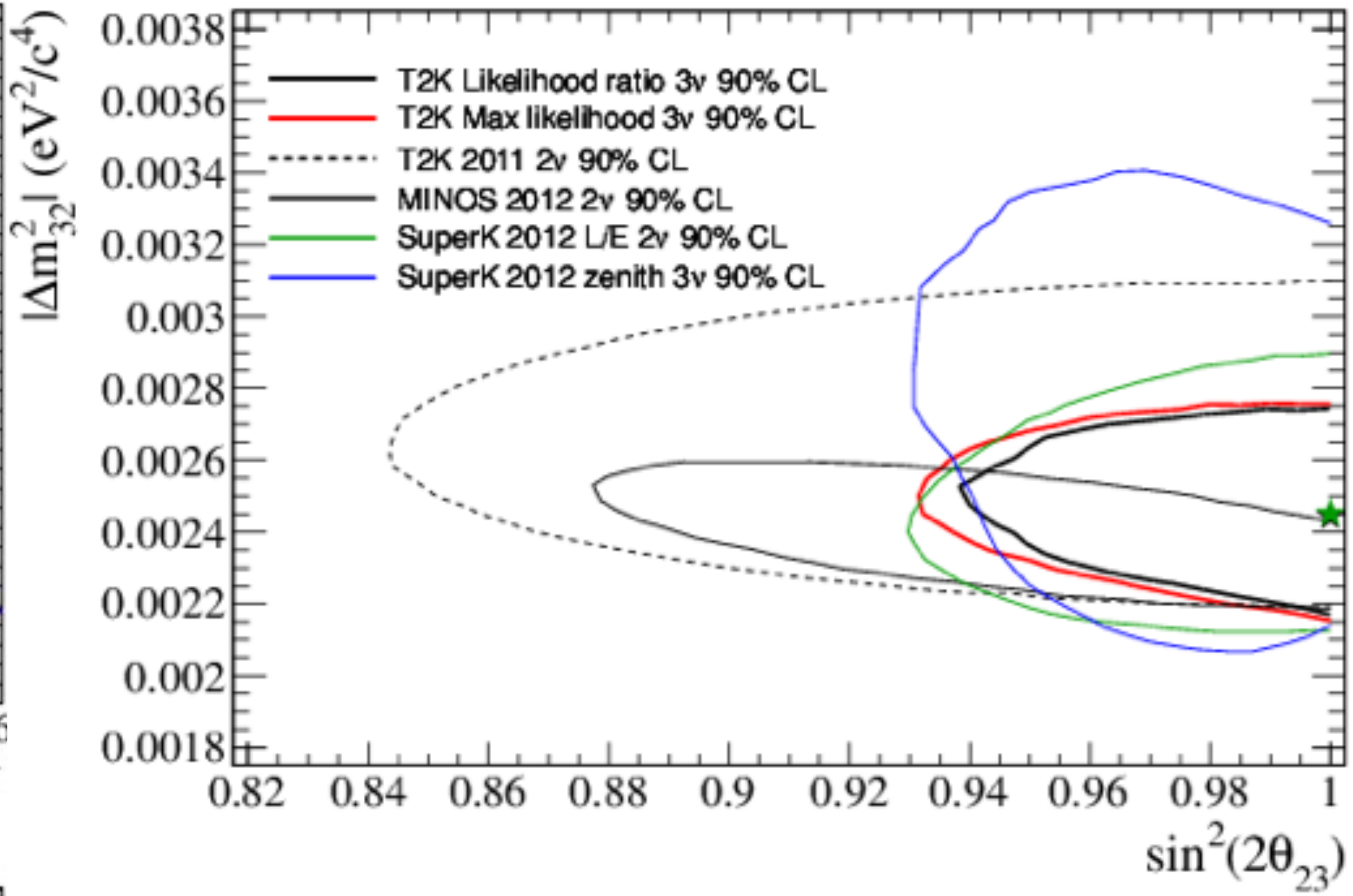
Rate

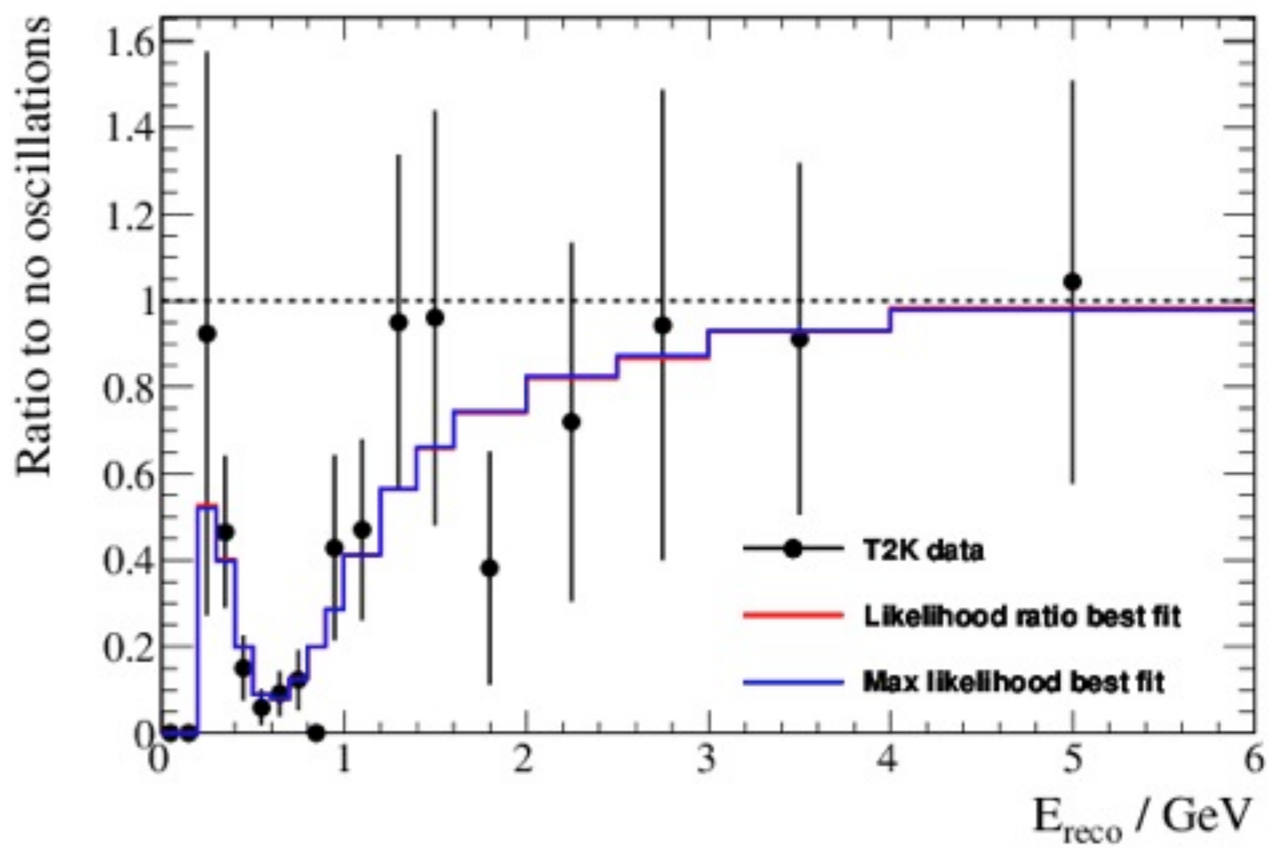
Shape

systematic parameters (41 params)

ν_μ disappearance







Best fit point:

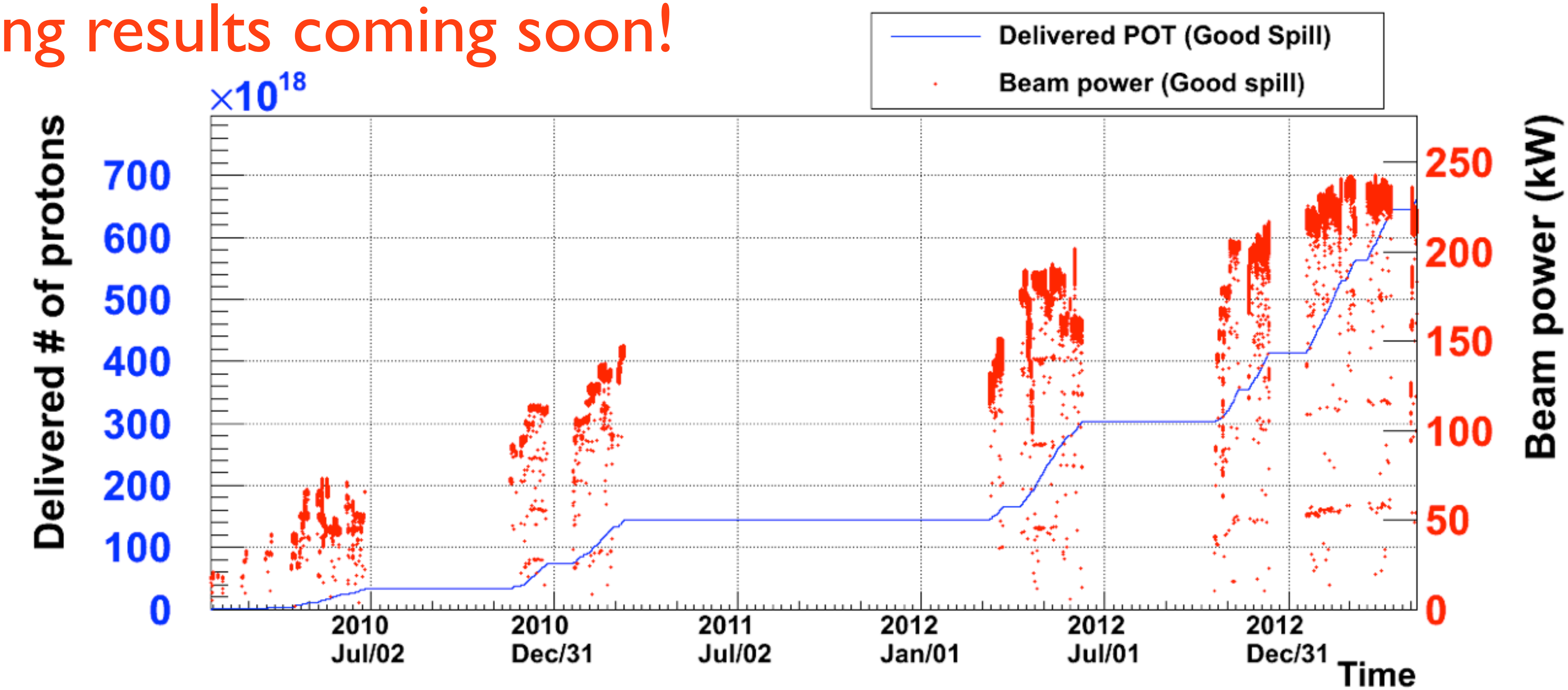
$\sin^2 2\theta_{23}=1.0$

$|\Delta m^2_{32}|=2.44\times10^{-2}\text{eV}^2$

Start to lead θ_{23} measurement

T2K future prospect

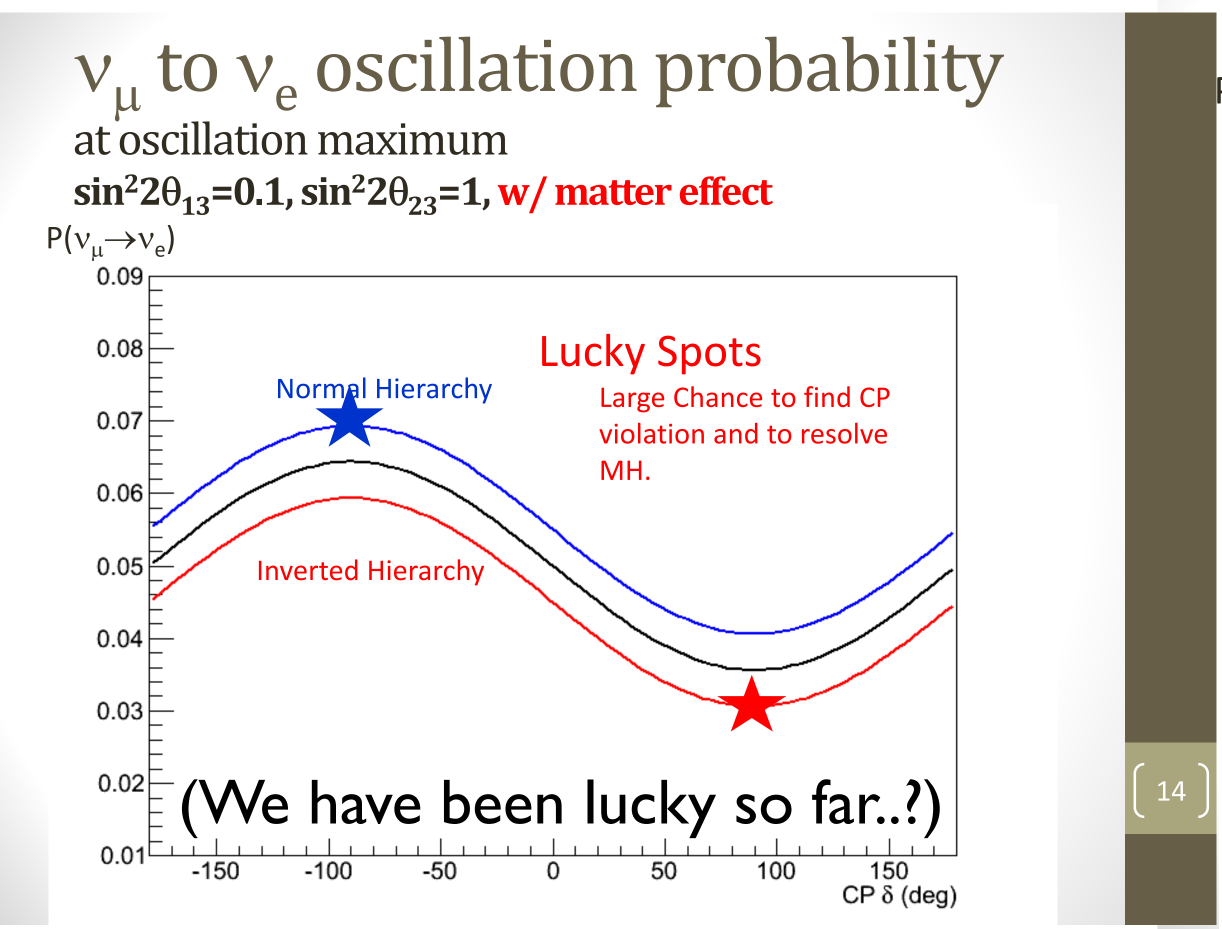
- More than ×2 data already in hand, aiming to collect sufficient data for >5σ ν_e signal before summer
  - Analysis improvement in all aspects to gain sensitivity
    - Improved reconstruction, more sub-sample in ND, ...
  - Many cross section measurements from ND
  - Exciting results coming soon!

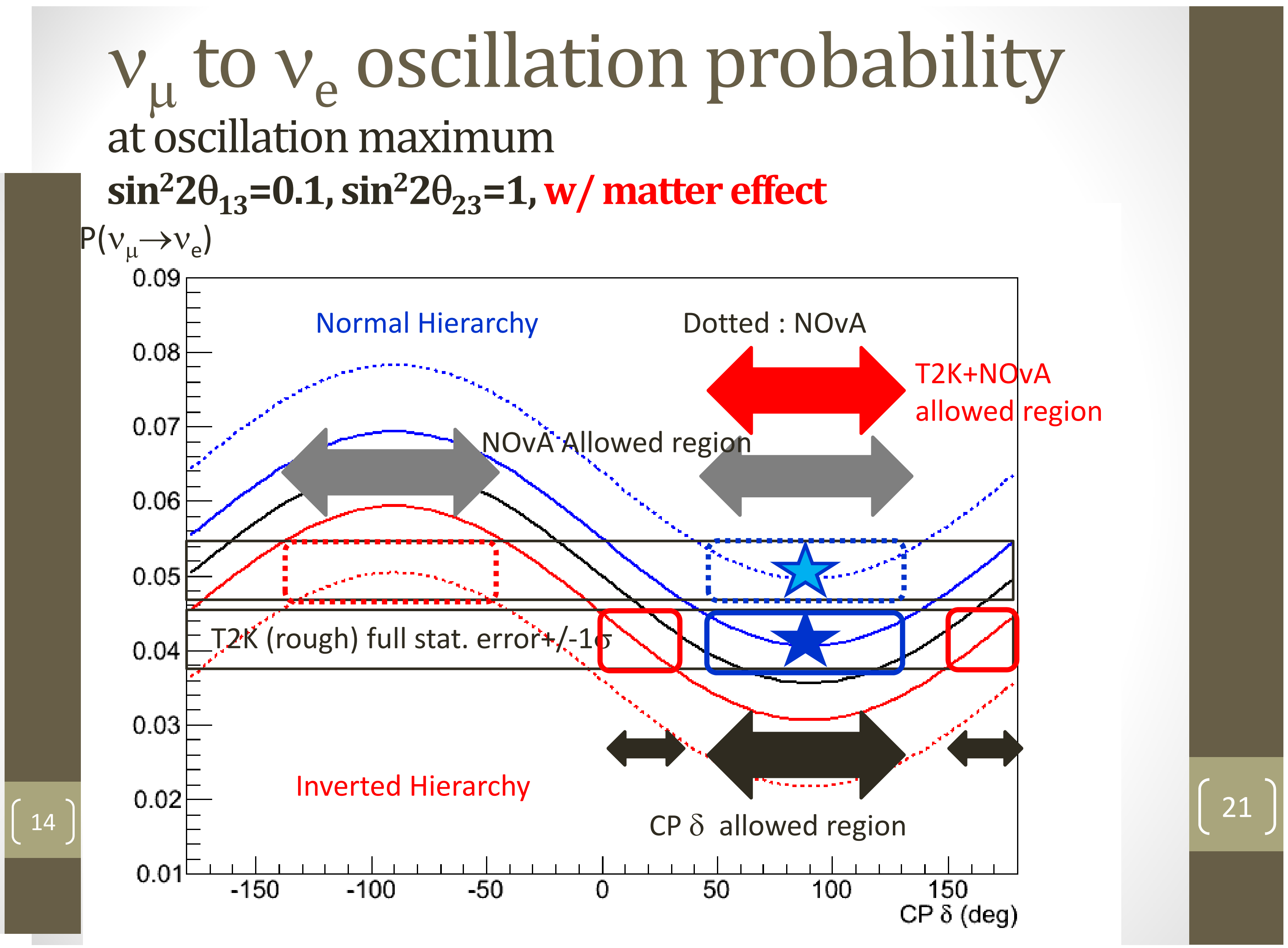


T2K future prospect

- Our data is still <1/10 of what was approved
- Long term plan after ν_e appearance discovery under study
  - Possible sensitivity to CP violation
  - Anti-neutrino running
- Have more fun!

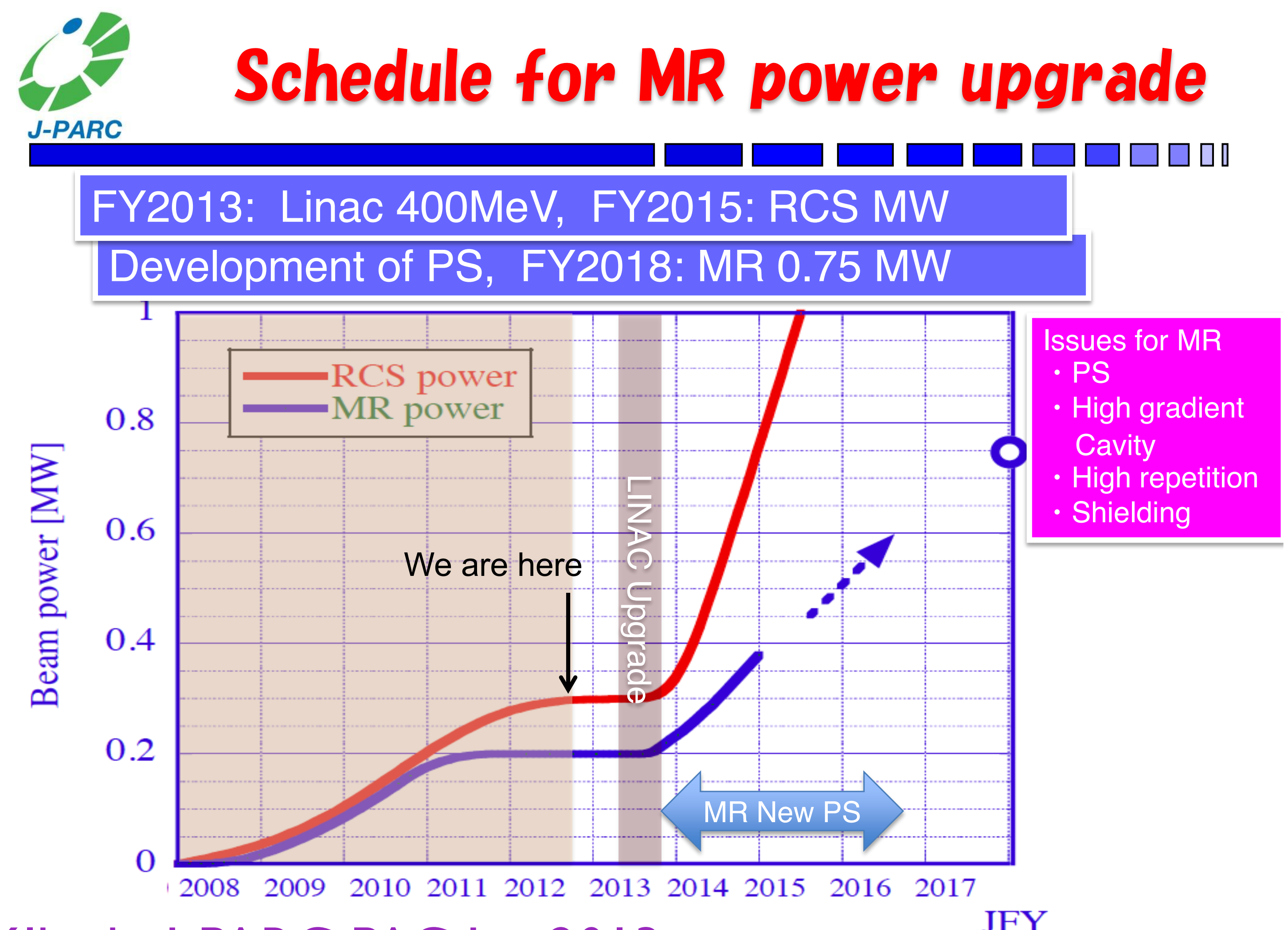
A.K.Ichikawa, J-PARC PAC Jan 2013





J-PARC future prospects

- LINAC upgrade (to 400MeV) this year
- MR power for T2K: aim to reach 750kW in ~5 years
  - Replacement of PS's and RF cavities scheduled to increase rep. rate to ~1Hz

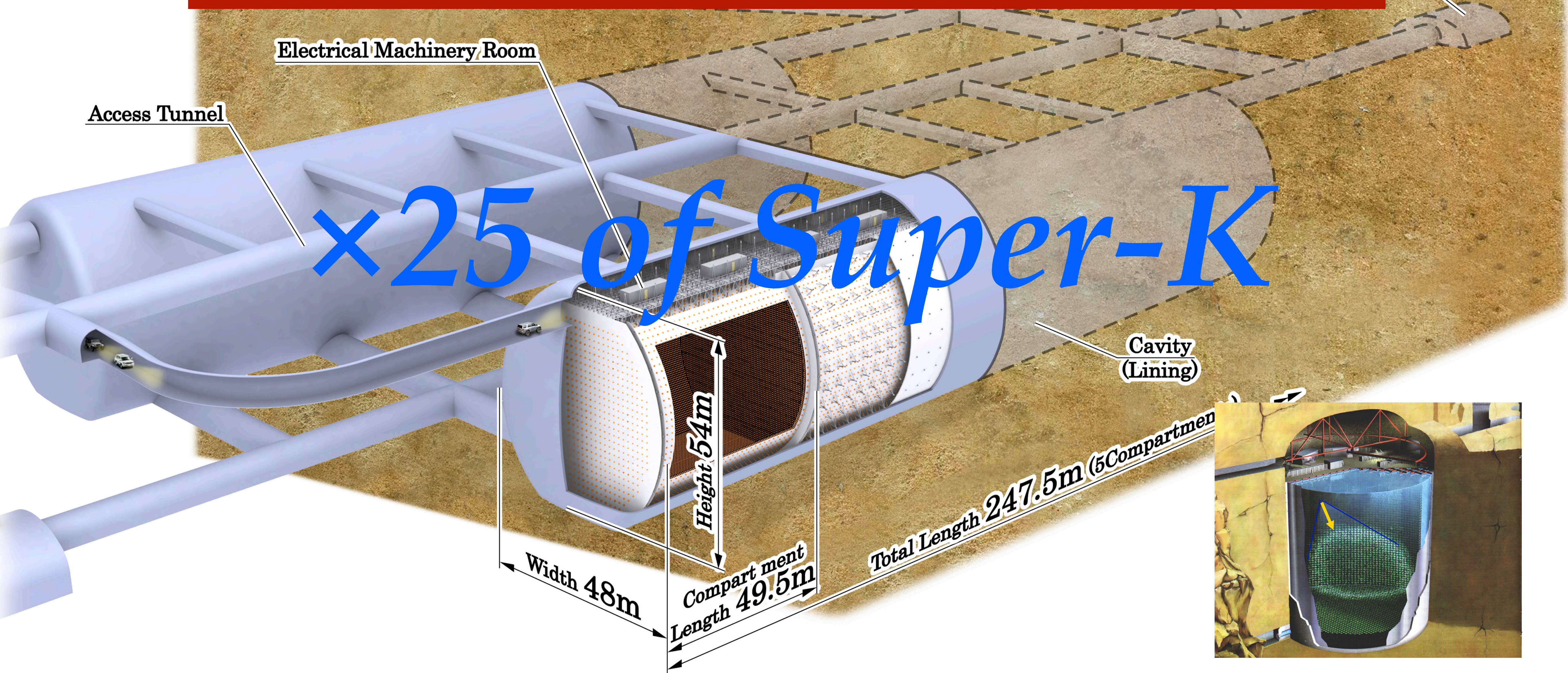


Y.Ikeda, J-PARC PAC Jan 2013

Based on the success of T2K,
the third generation LBL
experiment in Japan
is being proposed..

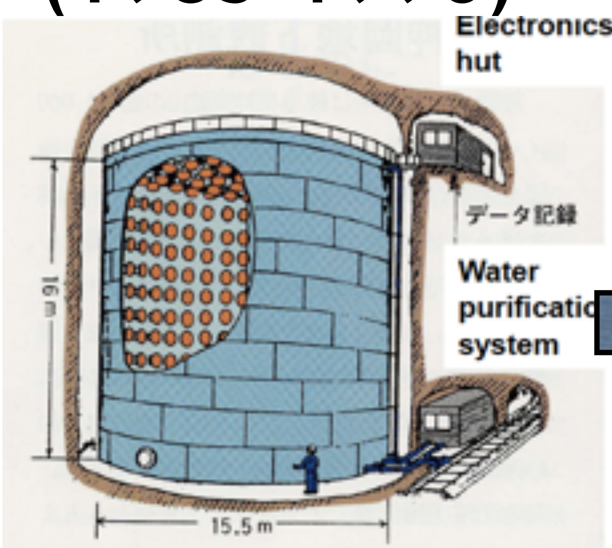
Hyper-Kamiokande

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 Det. (20% photo-coverage) 25,000 8”Φ PMTs for Outer Det.

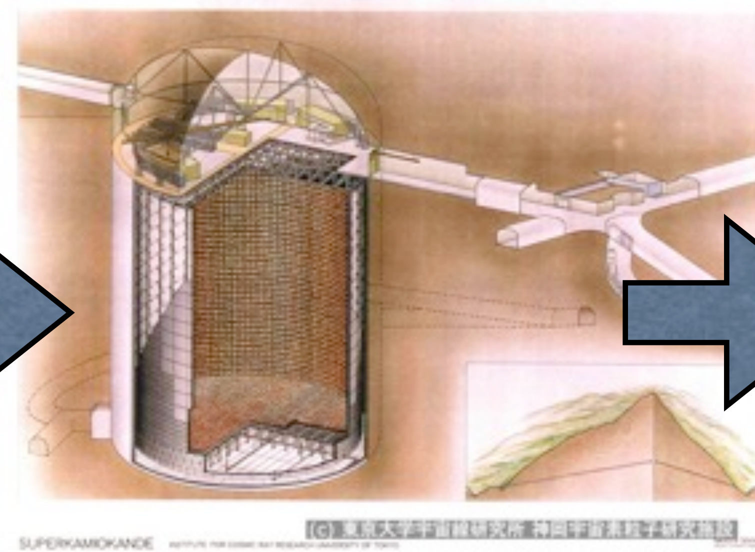


Three generations of Water Cherenkov Detectors at Kamioka

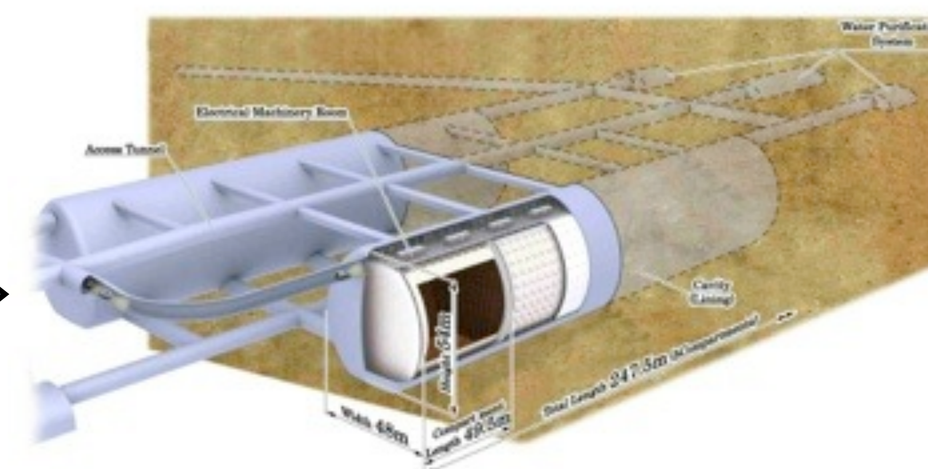
Kamiokande (1983-1996)



Super-Kamiokande (1996-)



Hyper-Kamiokande (20??-)



3kton → 50kton → 1Mton=1000kton

x17

x20
(x25 fid.)

Hyper-K WG,
arXiv:1109.3262 [hep-ex]

Sep. 2011

Letter of Intent:

The Hyper-Kamiokande Experiment

— Detector Design and Physics Potential —

K. Abe,[12,14] T. Abe,[10] H. Aihara,[10,14] Y. Fukuda,[5] Y. Hayato,[12,14] K. Huang,[4] A. K. Ichikawa,[4] M. Ikeda,[4] K. Inoue,[8,14] H. Ishino,[7] Y. Itow,[6] T. Kajita,[13,14] J. Kameda,[12,14] Y. Kishimoto,[12,14] M. Koga,[8,14] Y. Koshio,[12,14] K. P. Lee,[13] A. Minamino,[4] M. Miura,[12,14] S. Moriyama,[12,14] M. Nakahata,[12,14] K. Nakamura,[2,14] T. Nakaya,[4,14] S. Nakayama,[12,14] K. Nishijima,[9] Y. Nishimura,[12] Y. Obayashi,[12,14] K. Okumura,[13] M. Sakuda,[7] H. Sekiya,[12,14] M. Shiozawa,[12,14,*] A. T. Suzuki,[3] Y. Suzuki,[12,14] A. Takeda,[12,14] Y. Takeuchi,[3,14] H. K. M. Tanaka,[11] S. Tasaka,[1] T. Tomura,[12] M. R. Vagins,[14] J. Wang,[10] and M. Yokoyama[10,14]

(Hyper-Kamiokande working group)

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[3] *Kobe University, Department of Physics, Kobe, Hyogo 657-8501, Japan*

[4] *Kyoto University, Department of Physics, Kyoto, Kyoto 606-8502, Japan*

[5] *Miyagi University of Education, Department of Physics, Sendai, Miyagi 980-0845, Japan*

Contribution to Krakow symposium last year (ID:86)

https://indico.cern.ch/contributionDisplay.py?contribId=86&confId=175067

Also contributing to US Snowmass process

The Hyper-Kamiokande Experiment

Hyper-Kamiokande working group

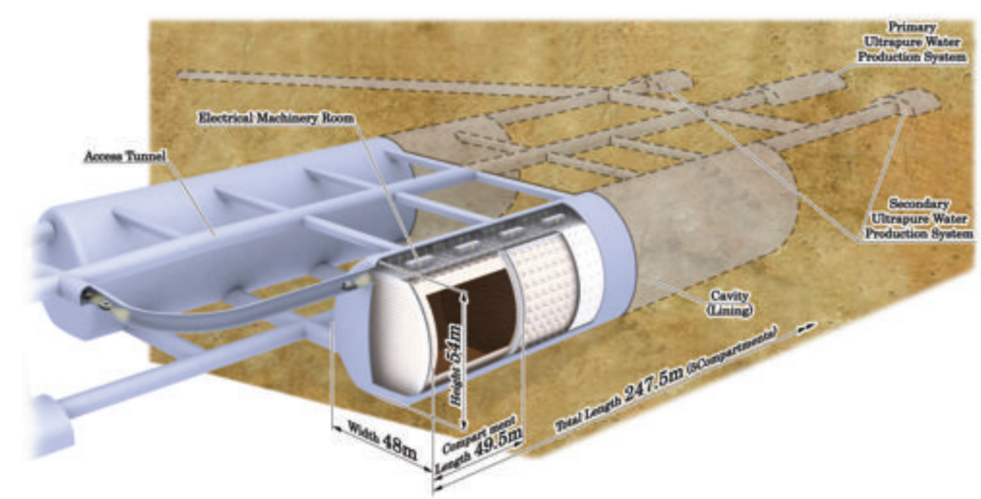
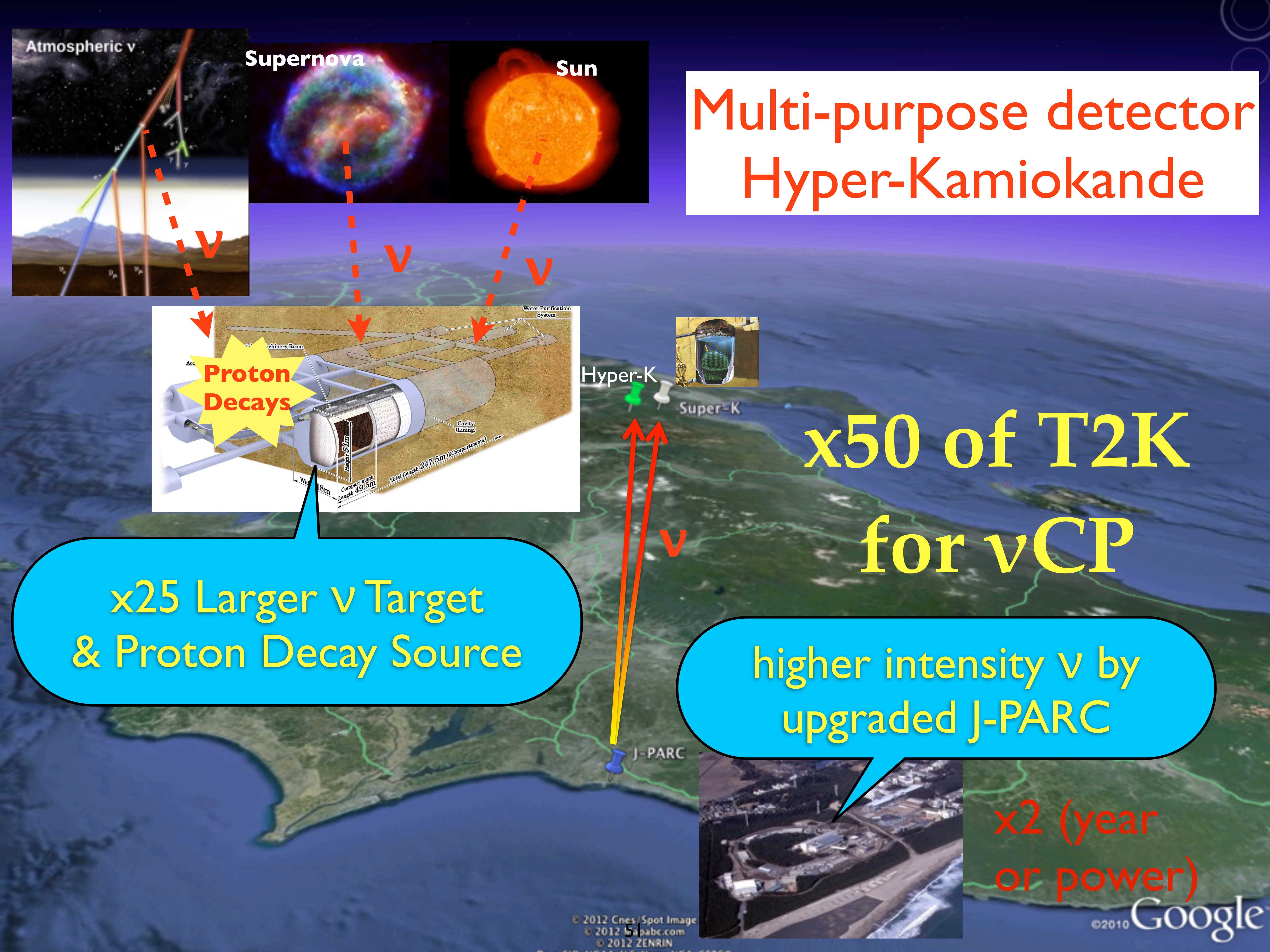


FIG. 1: Schematic view of the Hyper-Kamiokande detector.

We propose the Hyper-Kamiokande (Hyper-K) experiment as a next generation neutrino and nucleon decay experiment with an underground one Megaton water Cherenkov detector. The Hyper-K detector serves as a far detector of a long baseline neutrino oscillation experiment for the J-PARC neutrino beam and is capable of observing proton decays, atmospheric and solar neutrinos, and neutrinos from other astrophysical origins. The baseline design of Hyper-K is based on the well-proven technologies employed and tested at Super-Kamiokande (Super-K or SK). Hyper-K consists of two cylindrical tanks lying side-by-side, the outer dimensions of each tank being 48 (W) $\times$ 54 (H) $\times$ 250 (L) m^3. The total (fiducial) mass of the detector is 0.99 (0.56) million metric tons, which is about 20 (25) times larger than that of Super-K. A proposed location for Hyper-K is about 8 km south of Super-K (and 295 km away from J-PARC) and 1,750 meters water equivalent (or 648 m of rock) deep. The inner detector region is viewed by 99,000 20-inch PMTs, corresponding to the PMT density of 20% photo-cathode coverage (one half of that of Super-K). The schematic view of the Hyper-K detector is illustrated in Fig. 1. Table I summarizes the baseline design parameters of the Hyper-K detector.

Hyper-K provides rich neutrino physics programs. In particular, it has unprecedented potential for precision measurements of neutrino oscillation parameters and discovery reach for CP violation in the lepton sector. With a total exposure of 10 years (1 year being equal to 10^7 sec) to a 2.5-degree off-axis neutrino beam produced by the 750 kW J-PARC proton synchrotron, it is expected that the CP phase δ can be determined to better than 18 degrees for all values of δ and that CP violation can be established with a statistical significance of 3σ for 74% of the δ parameter space for $\sin^2 2\theta_{13} > 0.03$ assuming that the mass hierarchy is known. It is also possible to determine the mass hierarchy for some of δ with this program alone. For $\sin^2 2\theta_{13} \simeq 0.1$ obtained by the T2K, Daya-Bay,



Multi-purpose detector
Hyper-Kamiokande
Atmospheric ν
Supernova
Sun
ν
ν
ν
Proton
Decays
Water Purification System
Machinery Room
Cavity (Lining)
Height 64m
Width 48m
Compartment Length 49.5m
Total Length 247.5m (5Compartments)
Hyper-K
Super-K
x50 of T2K
for νCP
ν
x25 Larger ν Target
& Proton Decay Source
J-PARC
higher intensity ν by
upgraded J-PARC
x2 (year
or power)
© 2012 Cnes/Spot Image
© 2012 ZENRIN
©2010 Google

CP measurement strategy with Hyper-K

J-PARC ν beam + Hyper-K will be an excellent option in Japan

natural extension of technique proved by T2K

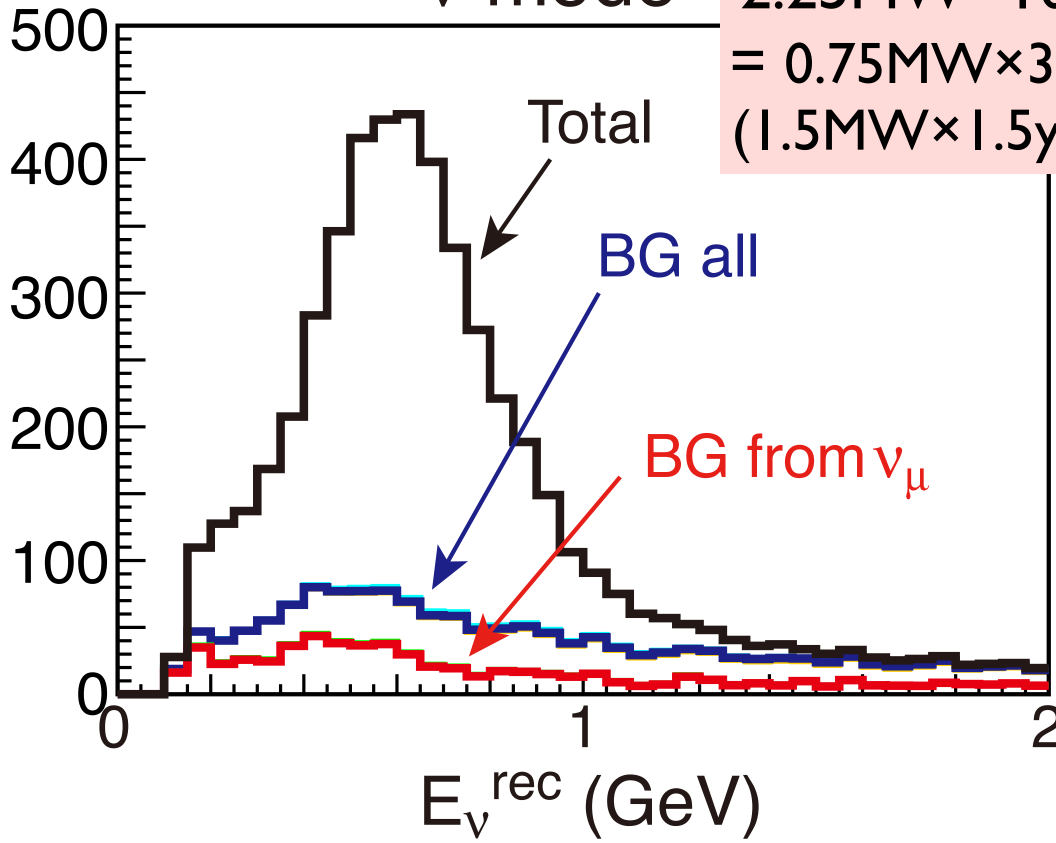
- Strength of water Cherenkov detector
  - Huge mass – statistics is always critical for ν!
  - Excellent reconstruction/PID performance especially in sub-GeV region (quasielastic→single ring)
- Best matched with low energy, narrow band beam
  - Off-axis beam with relatively short baseline
    - CP asymmetry measurement with less matter effect
- Complementary to >1000km baseline experiments planned in other regions – world wide strategy
  - Sensitivity, (CP/MH), technology (WC/LAr)

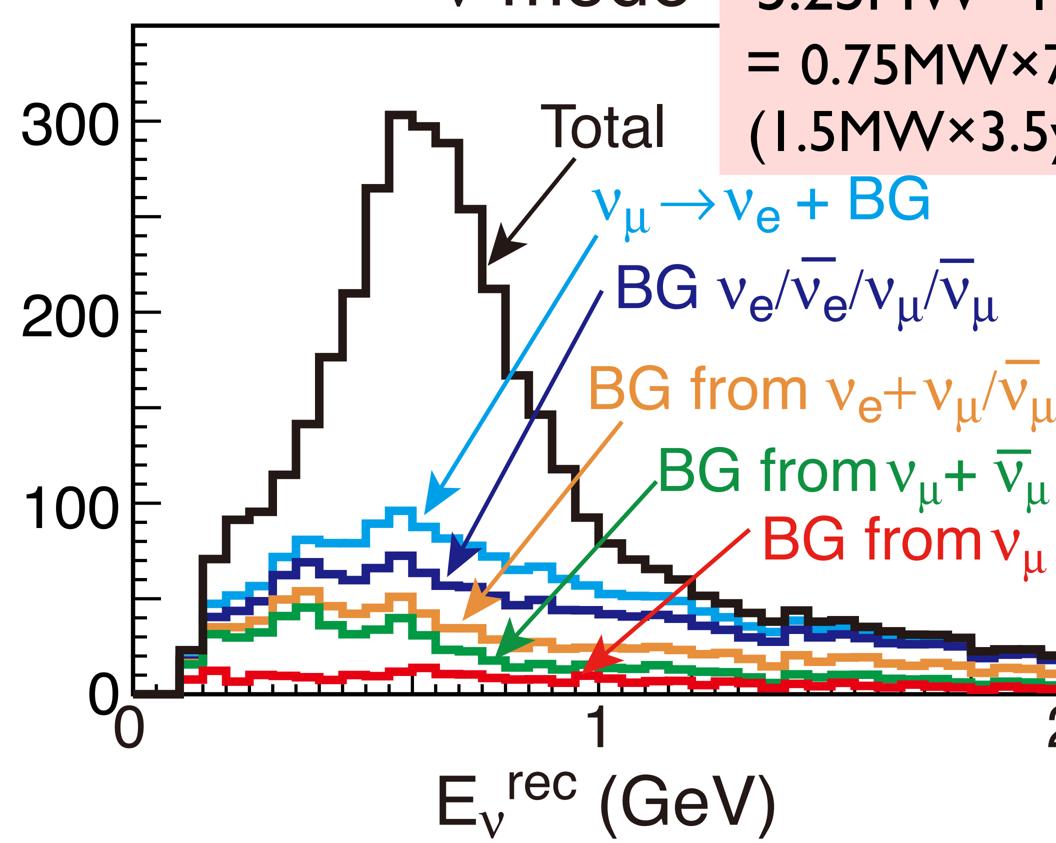
acc. ν

J-PARC to Hyper-K LBL experiment: ν_e candidate reconstructed energy distributions

7.5MW・years

$\sin^2 2\theta_{13}=0.1, \delta=0$, normal MH





	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

2000-4000 signal events for each of ν and $\bar{\nu}$

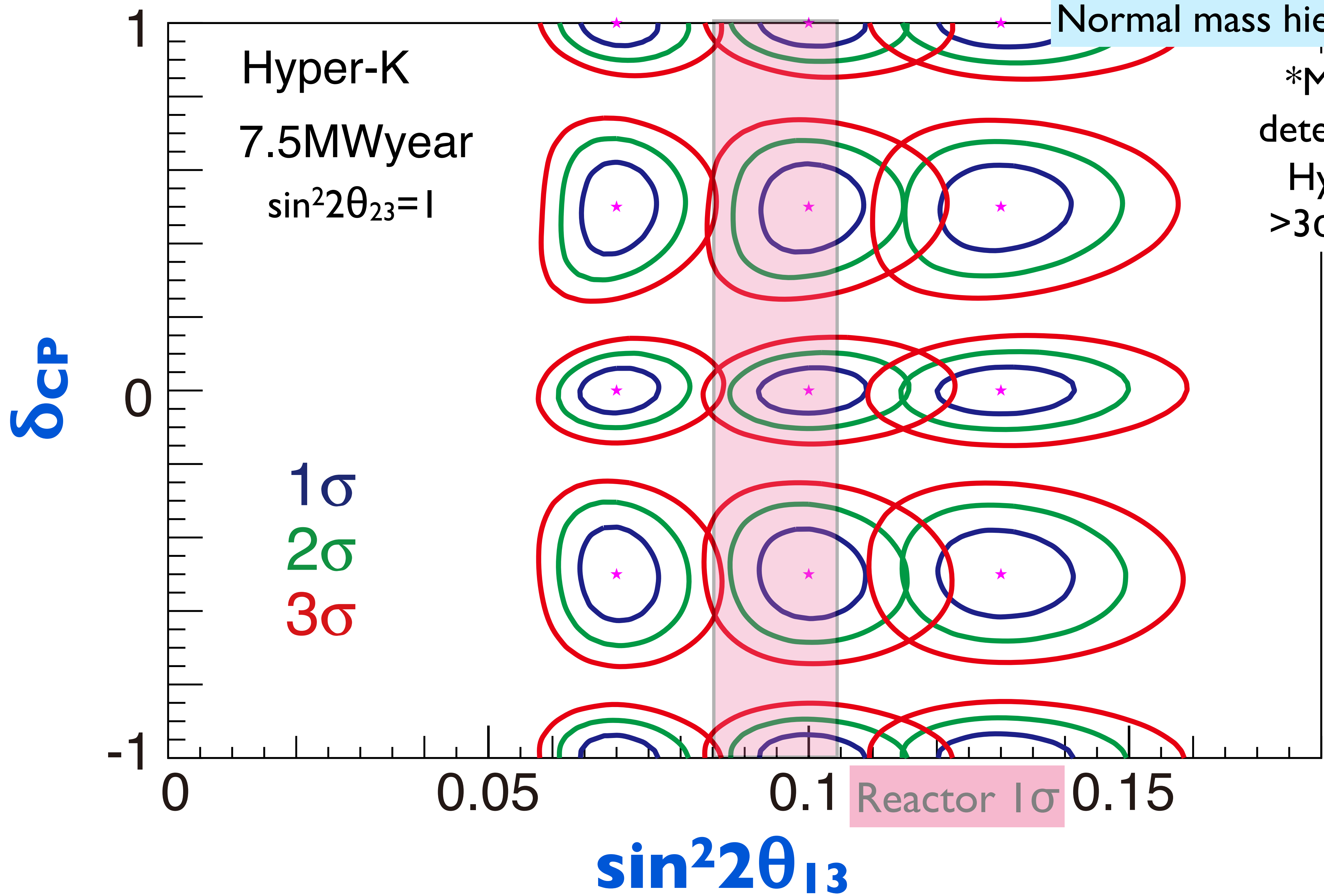
acc. ν

Expected sensitivity to CP asymmetry

7.5MW・years

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$

Normal mass hierarchy (known*)



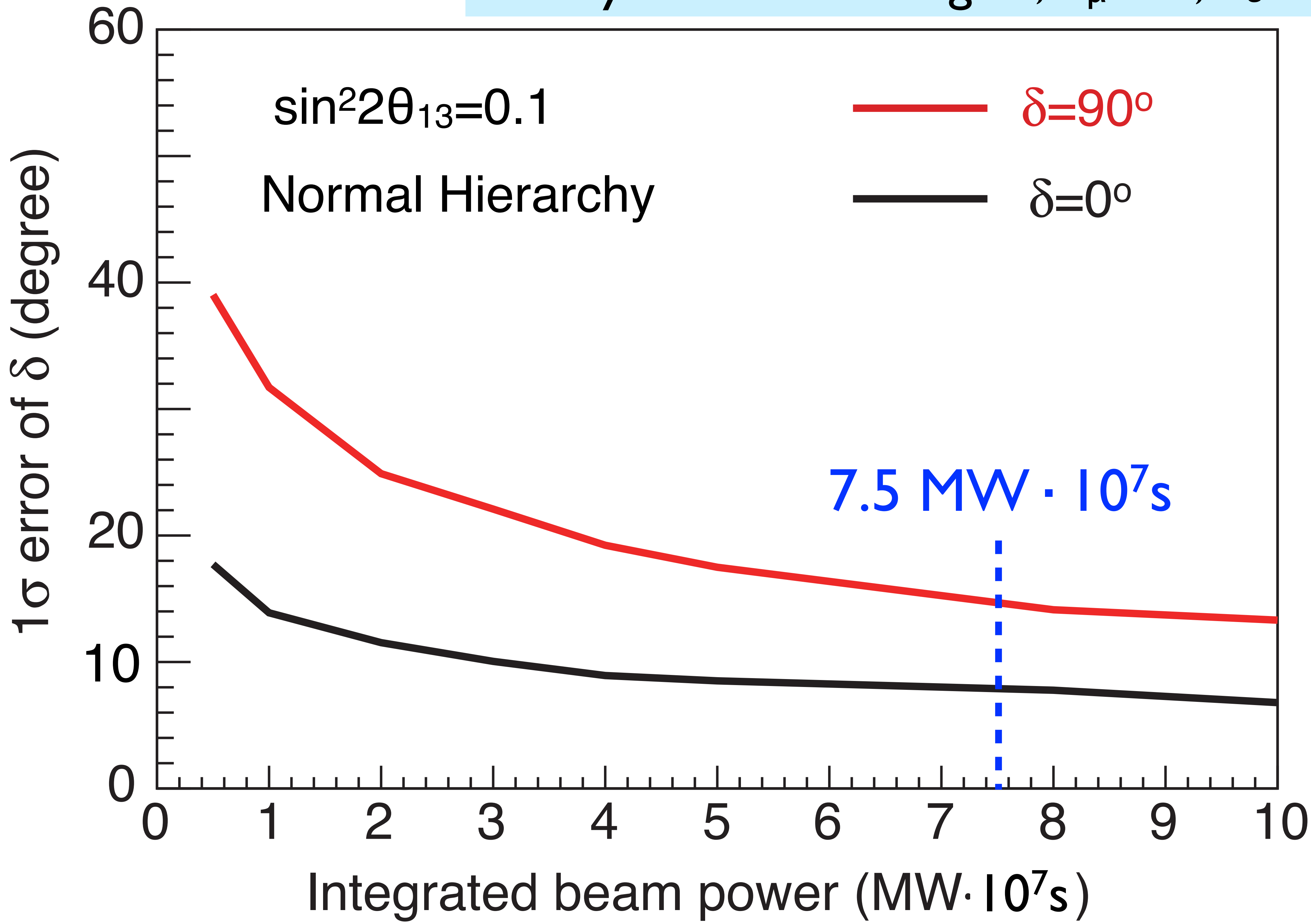
*Mass hierarchy determination with Hyper-K atm. ν: >3σ in 5-10 years

Good sensitivity for currently allowed values

acc. ν

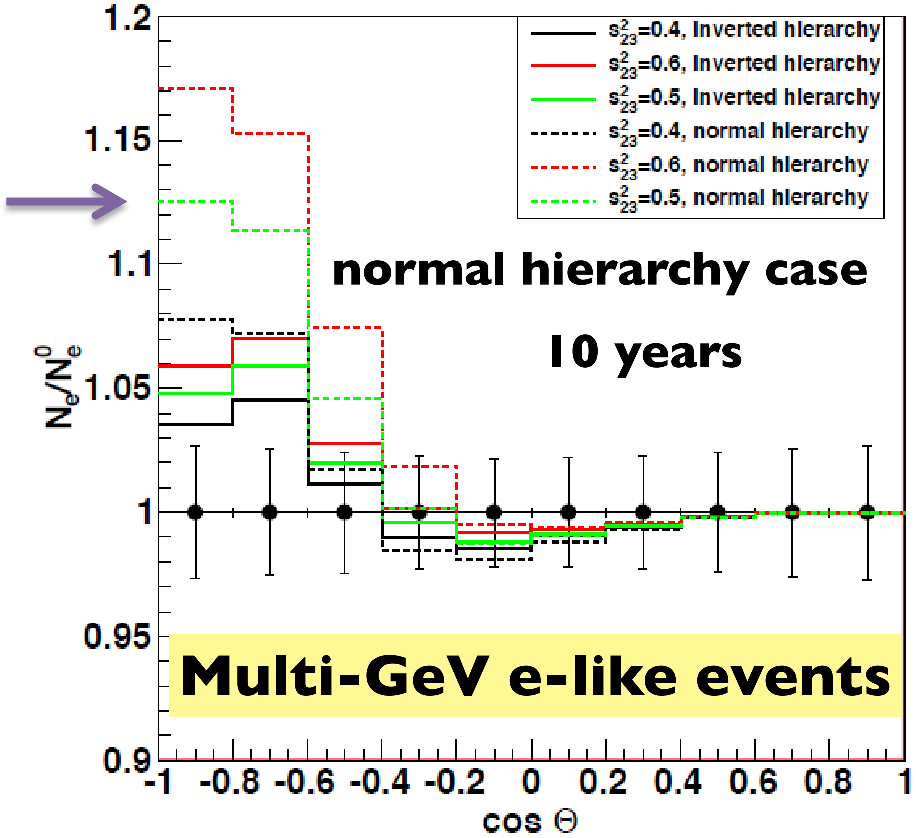
Expected uncertainty of δ (1σ)

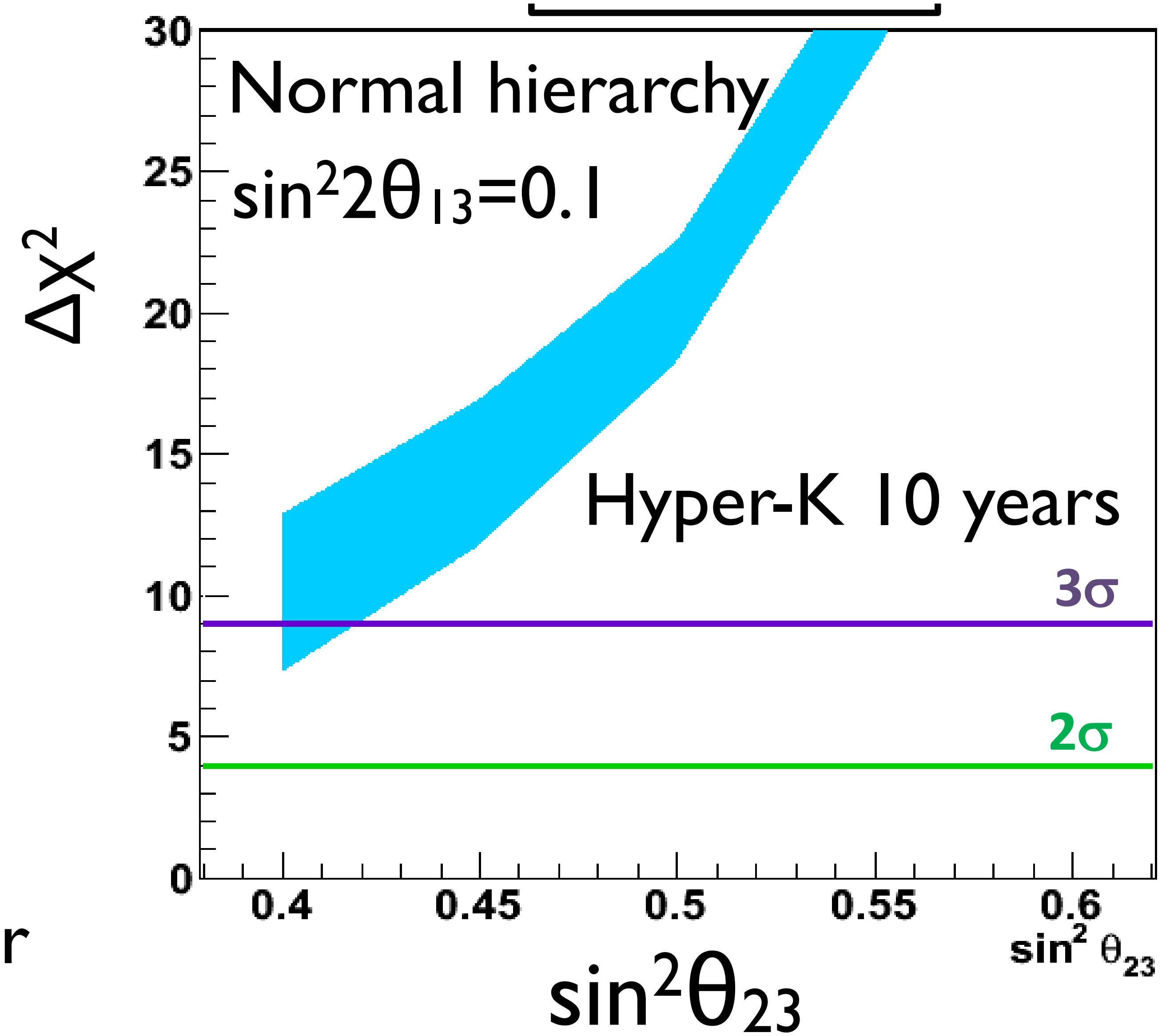
5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



<20° (δ=90°), <10° (δ=0°)

Mass hierarchy determination with atmospheric neutrinos





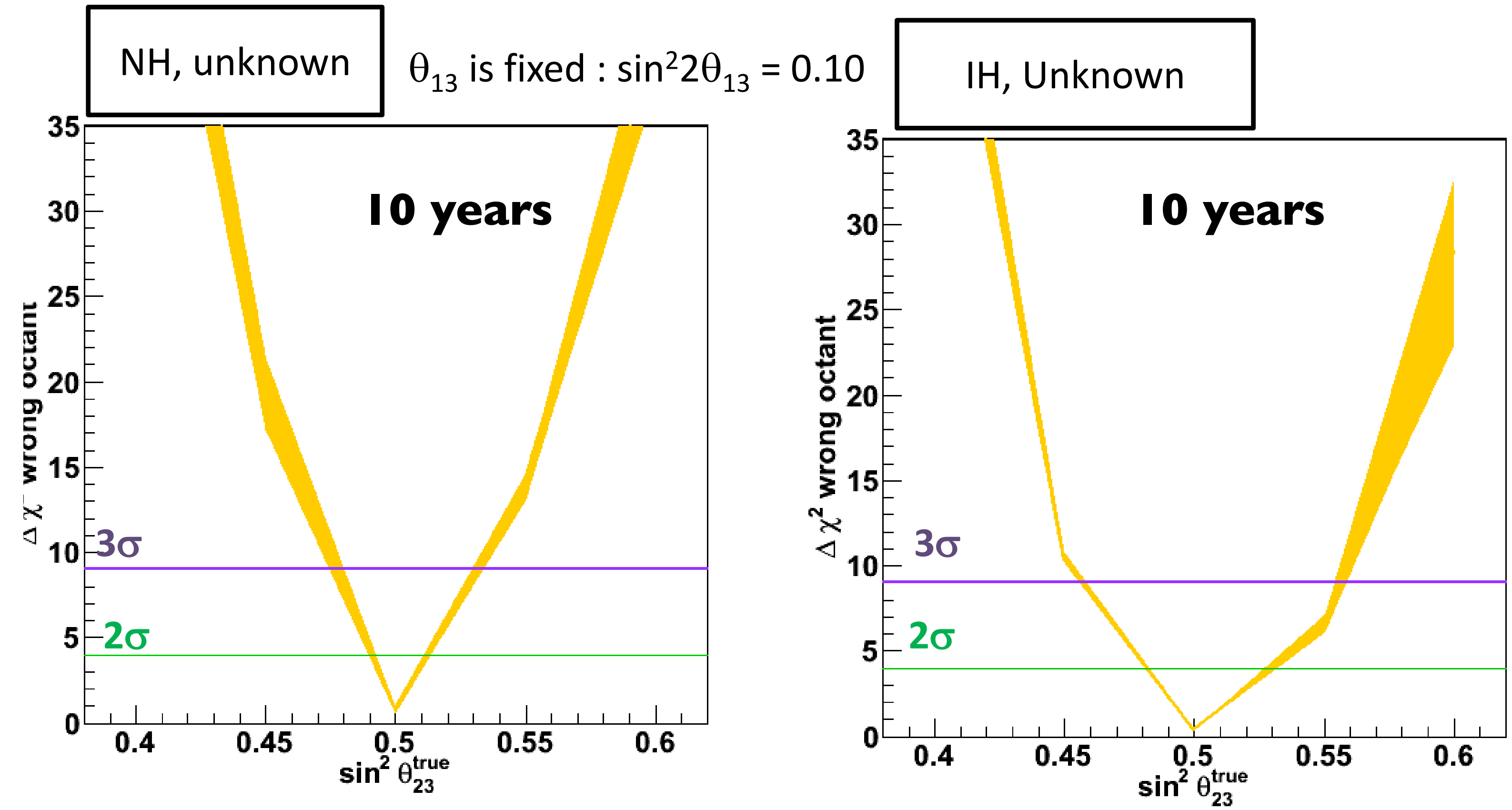
MSW effect in Earth's core
→ resonance effect on either ν or anti-ν

3σ determination with <10 year observation
(better sensitivity depending on the value of θ_{23})

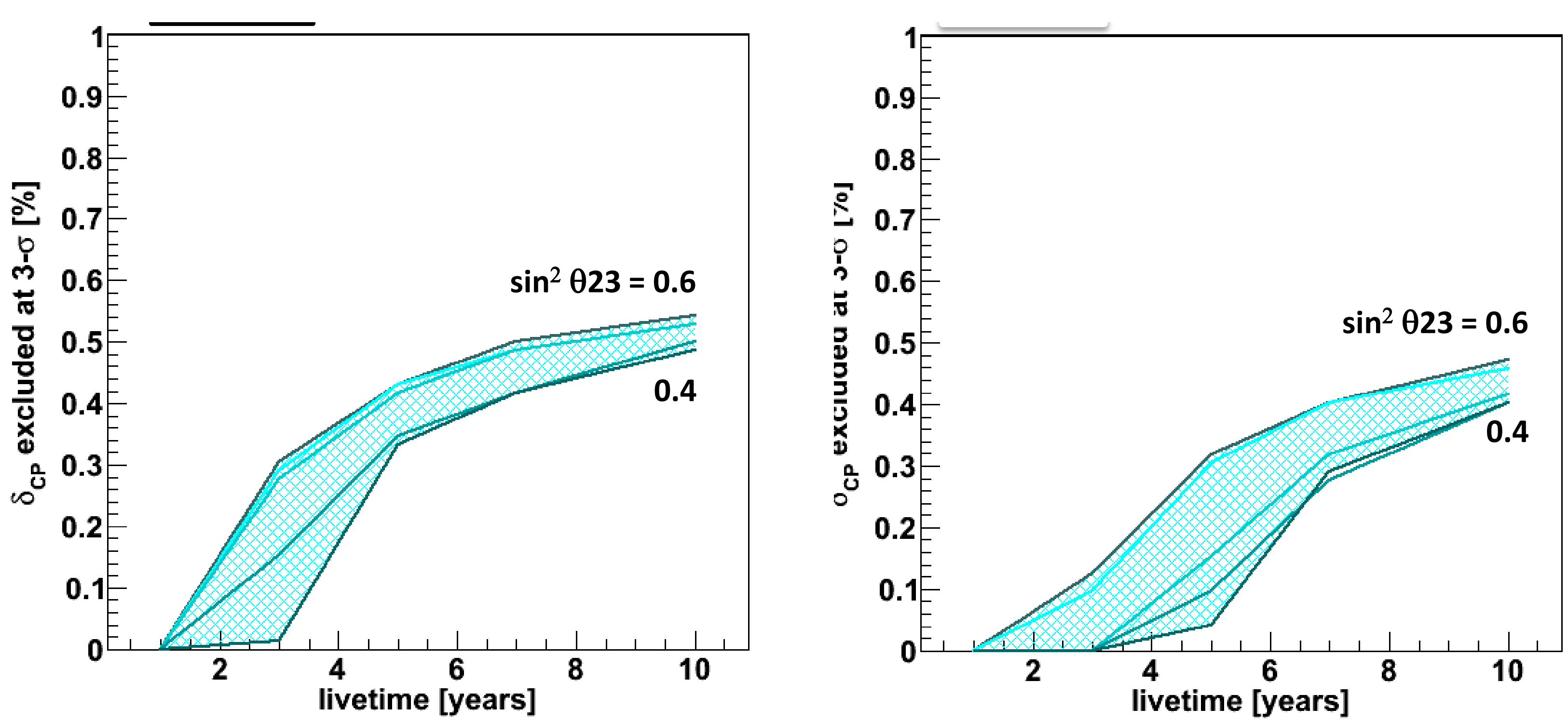
atm ν: θ_{23} octant and CPV

θ_{23} octant sensitivity

(band depends on δ)



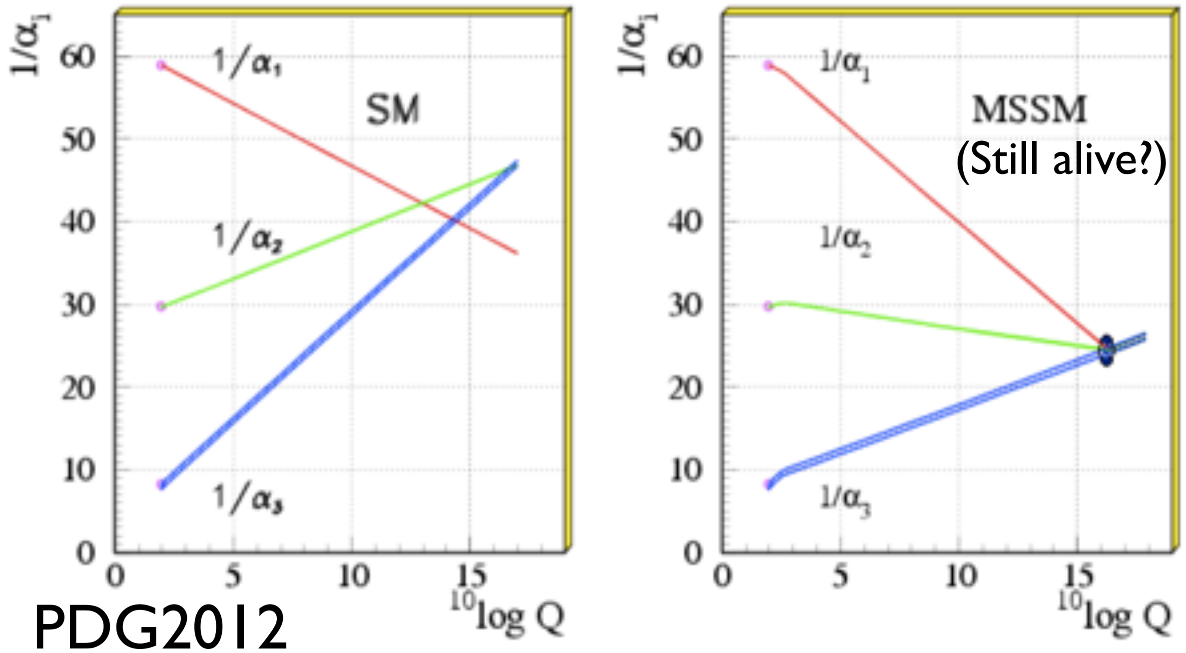
Fraction of δ_{CP} excluded (3 σ)



Complementary measurements to accelerator ν

Nucleon decays

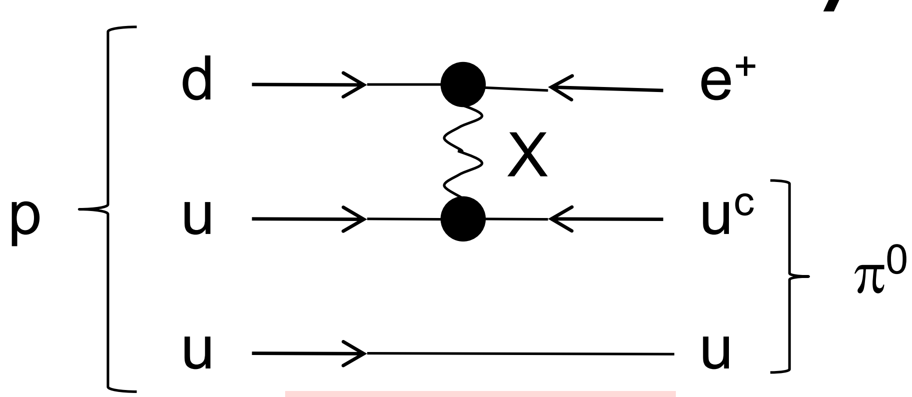
- Direct probe of Grand Unified Theory



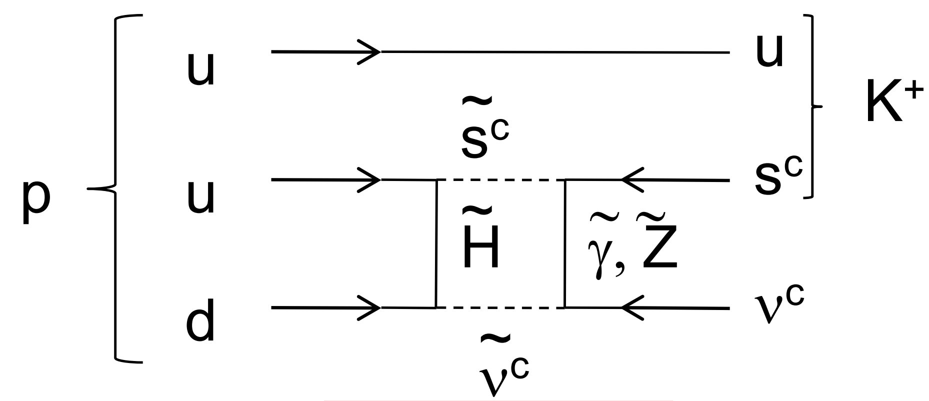
PDG2012

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

- Two modes favored by many models:



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

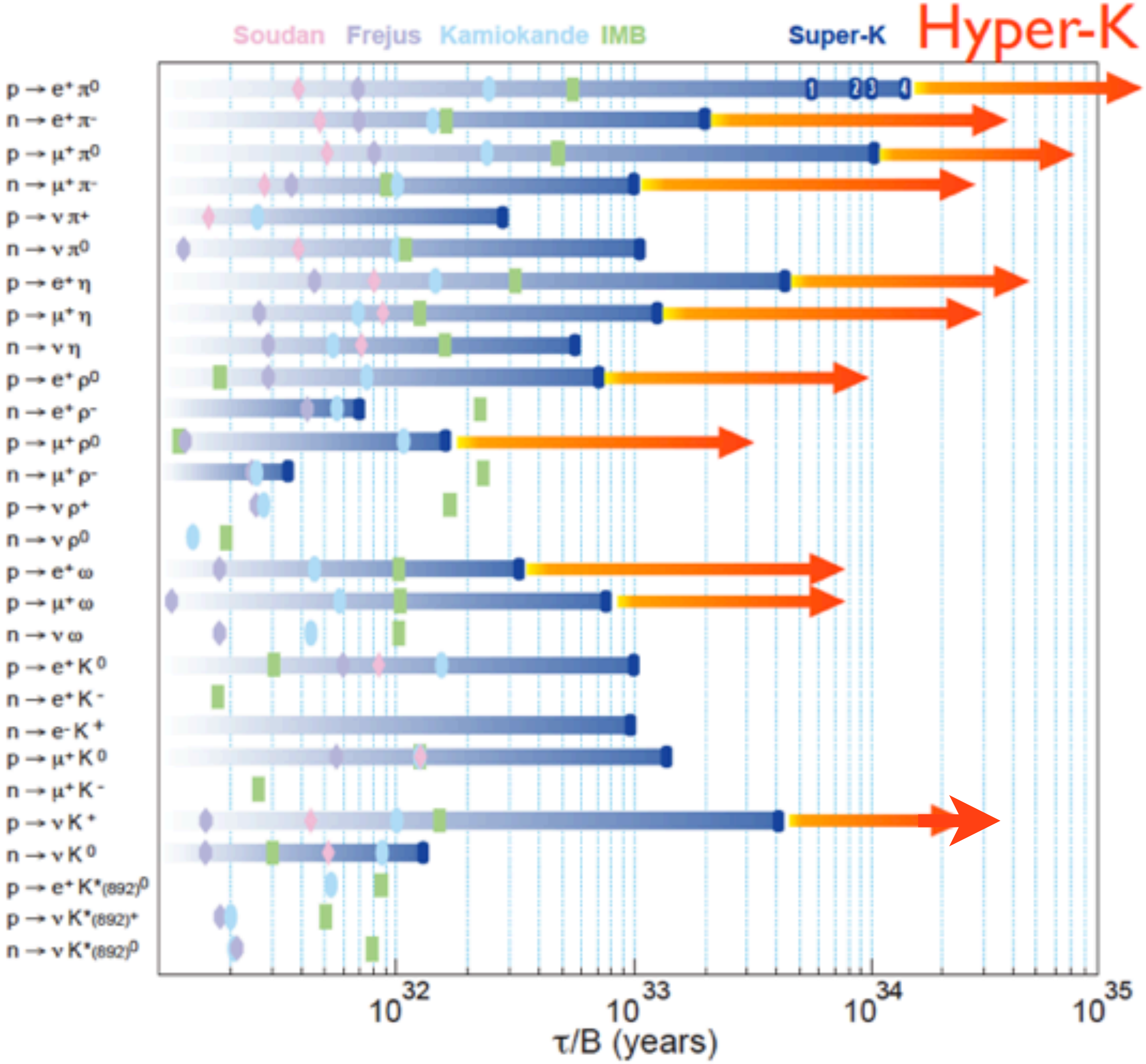


$p \rightarrow \nu K^+$

Other modes are also important (we don't know correct model!)

Search for nucleon decays

~10 times better sensitivity than current Super-K limits!



- $p \to e^+\pi^0$:
  - 1.3×10^{35}yrs (90%CL)
  - 5.7×10^{34}yrs (3σ)

$p \to \bar{\nu}K^+$:
  - 3.2×10^{34}yrs (90%CL)
  - 1.2×10^{34}yrs (3σ)

- And many other modes:
  - $(p,n) \to (e,\mu)+(\pi, \rho, \omega, \eta)$
  - K^0 modes
  - $\nu\pi^0, \nu\pi^+$
  - n-nbar oscillation
  - dinucleon decays

>3σ possible for lifetime above current SK limits

Neutrino astrophysics

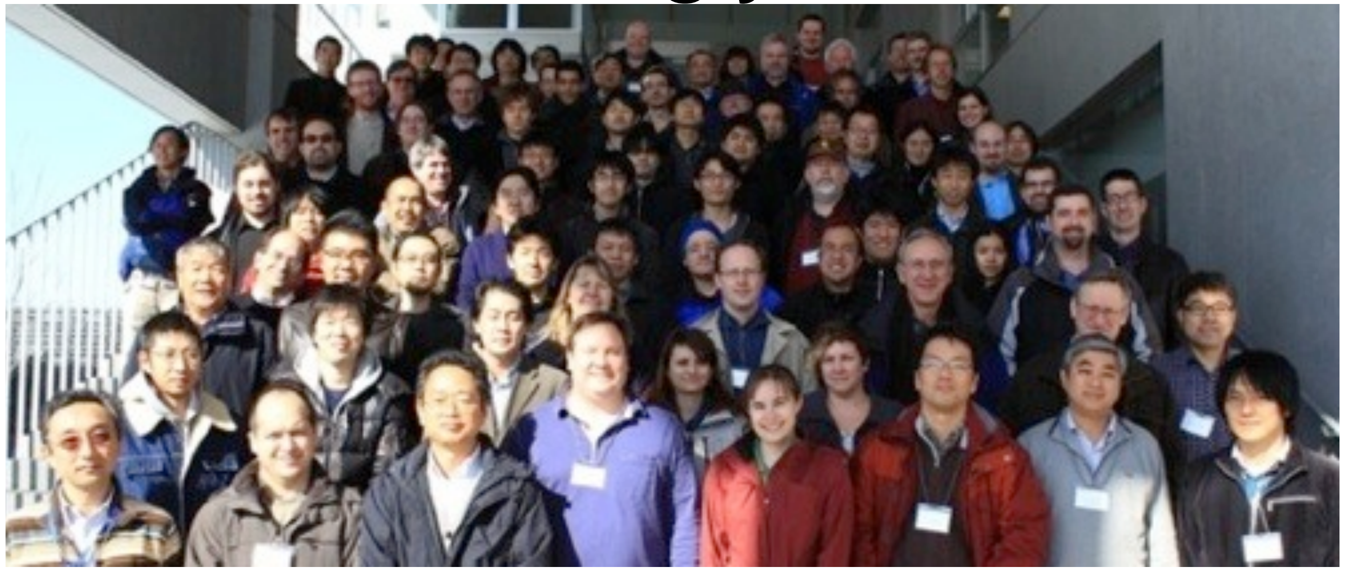
- **Supernova burst neutrino**
  - ~250k events (Garactic center) /
    ~25 events (Andromeda)
  - Reveal the detailed mechanism of supernova explosions with very large statistics sample
- **Supernova relic neutrino**
  - Study the history of heavy element synthesis in the universe
- Precision measurements of solar neutrino
- Indirect WIMP Search

International open Hyper-K meetings

First meeting: Aug. 23-24, 2012

http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=7

Second meeting: Jan. 14-15, 2013



http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=10

Next meeting: Jun. 21-22

http://indico.ipmu.jp/indico/conferenceDisplay.py?&confId=23

Hyper-K is completely open to the international community

~100 participants for each of two open meetings (~half from abroad)

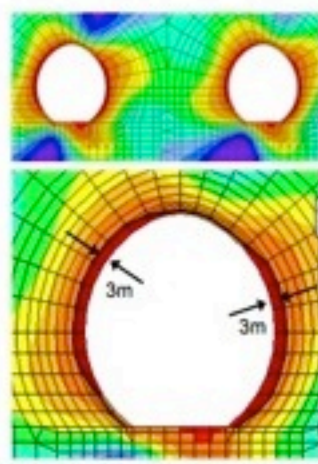
International working group was formed!

Current members are from Japan, Canada, Korea, Spain, Switzerland, Russia, UK, US

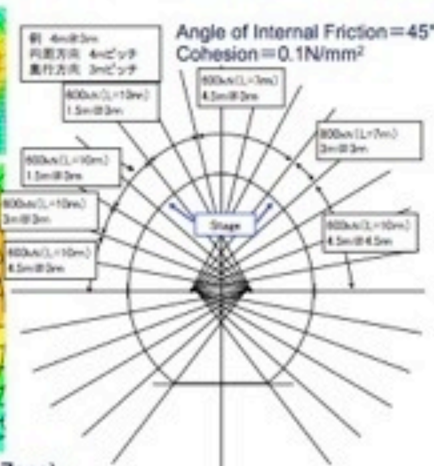
Meetings are open to anyone interested in the project – you are welcome!

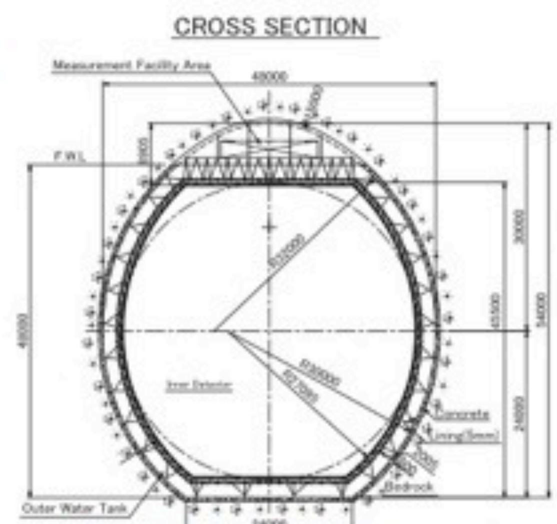
Detector design

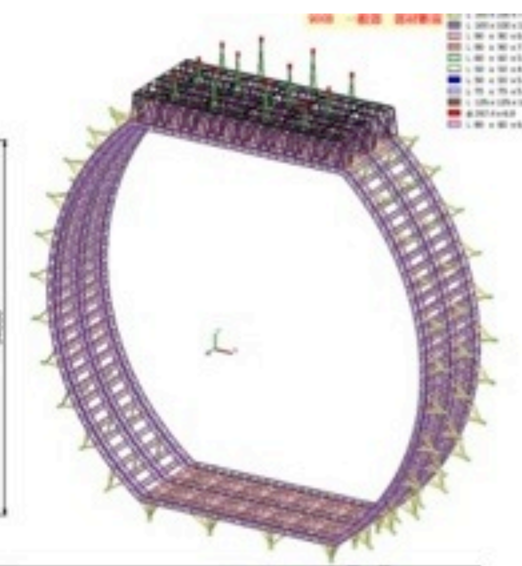
- Cavity design based on the in situ measurements of rock quality and stress
  - Feasible design established
- Optimization of cavity shape, segmentation walls, sensor support etc. ongoing

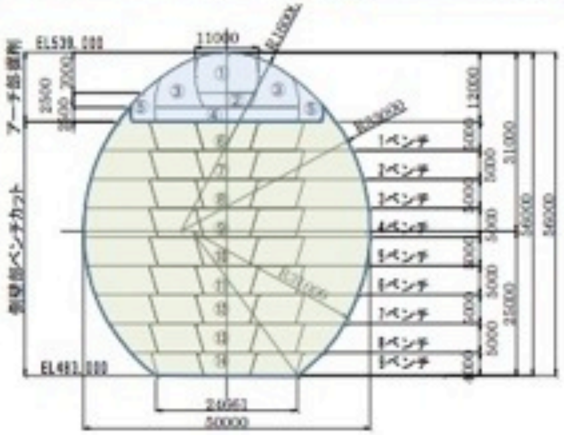


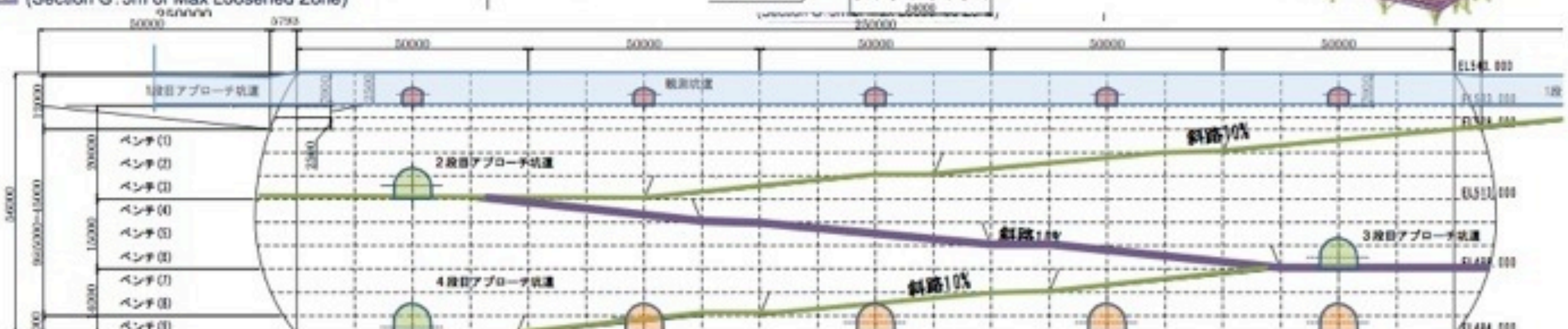
(Section G : 3m of Max Loosened Zone)









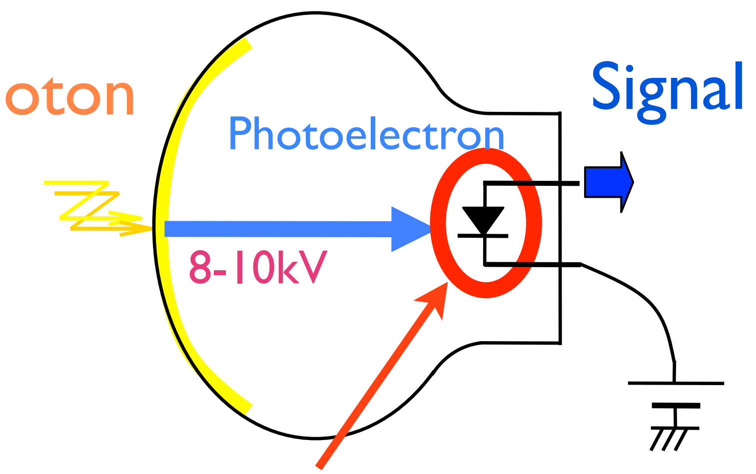


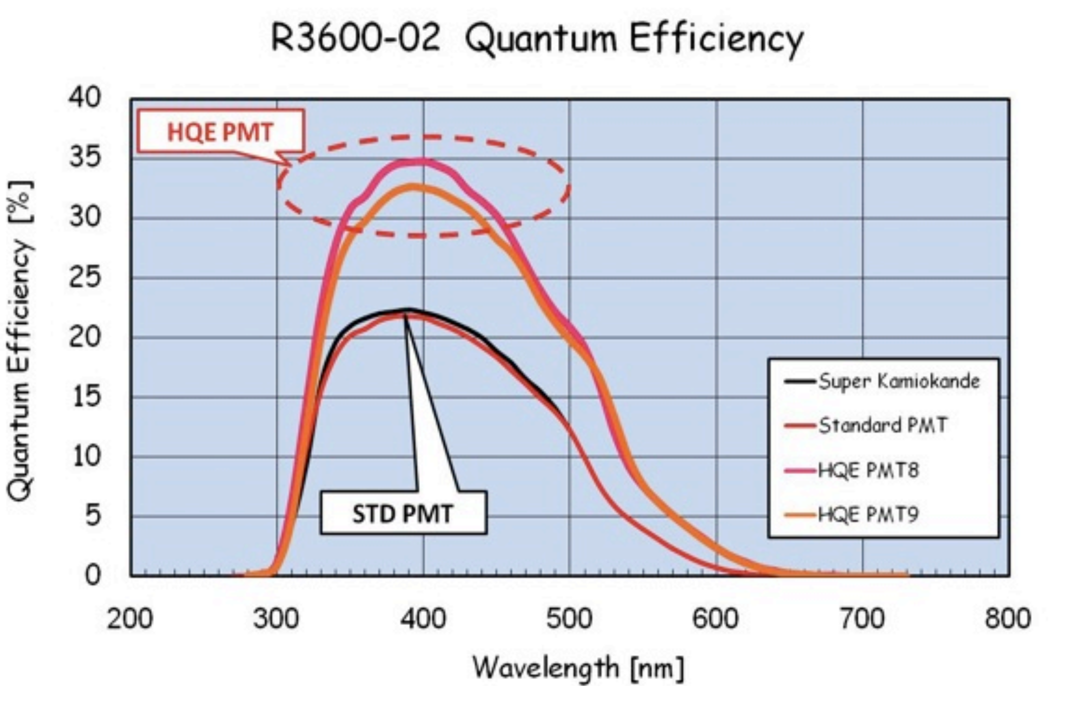
R&D of photo sensor

Developing several candidates:

- Hybrid Photodetector (HPD)
  - Photo cathode + avalanche diode
  - 8-in prototype under evaluation
  - 20-in prototype to be available soon
- 20-in PMT with improved dynode being developed in parallel
- Higher QE 20" photocathode under development
- Finish R&D and be ready for mass production in a few years

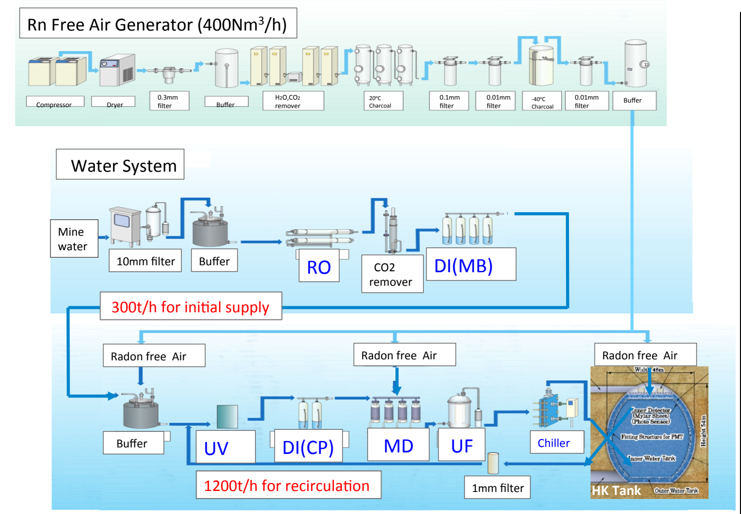
HPD

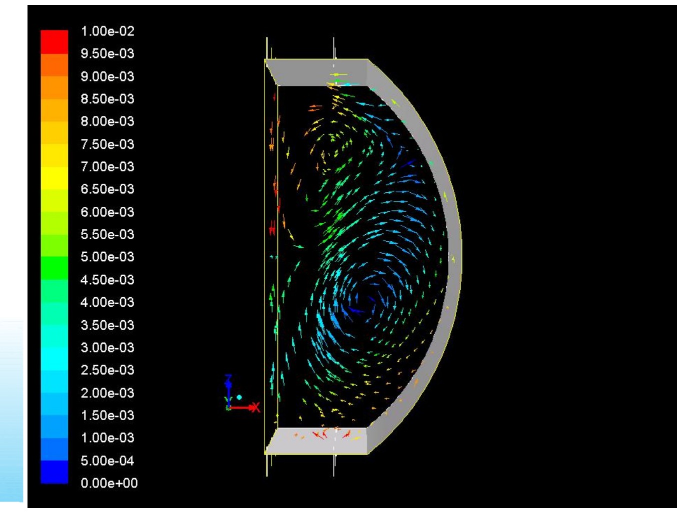




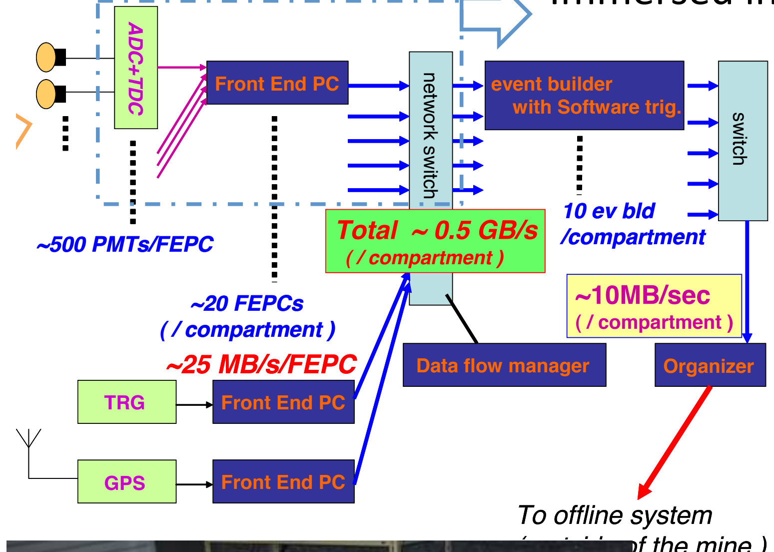
Other R&D topics

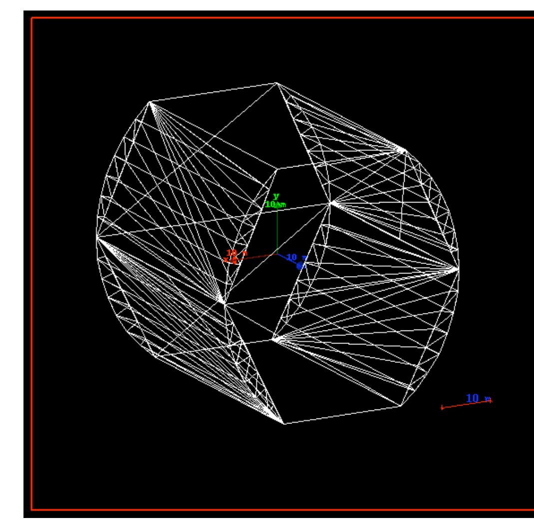
- Readout electronics
- Calibration system
- Software development
- Physics potential
- Design of near detector(s)
- Water system
- ...





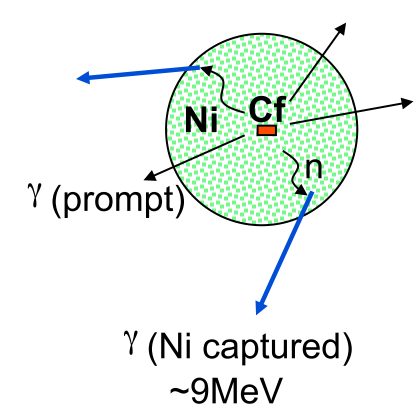
Immersed in water?





- R&D ongoing within international working group
- YOU ARE VERY WELCOME TO JOIN!

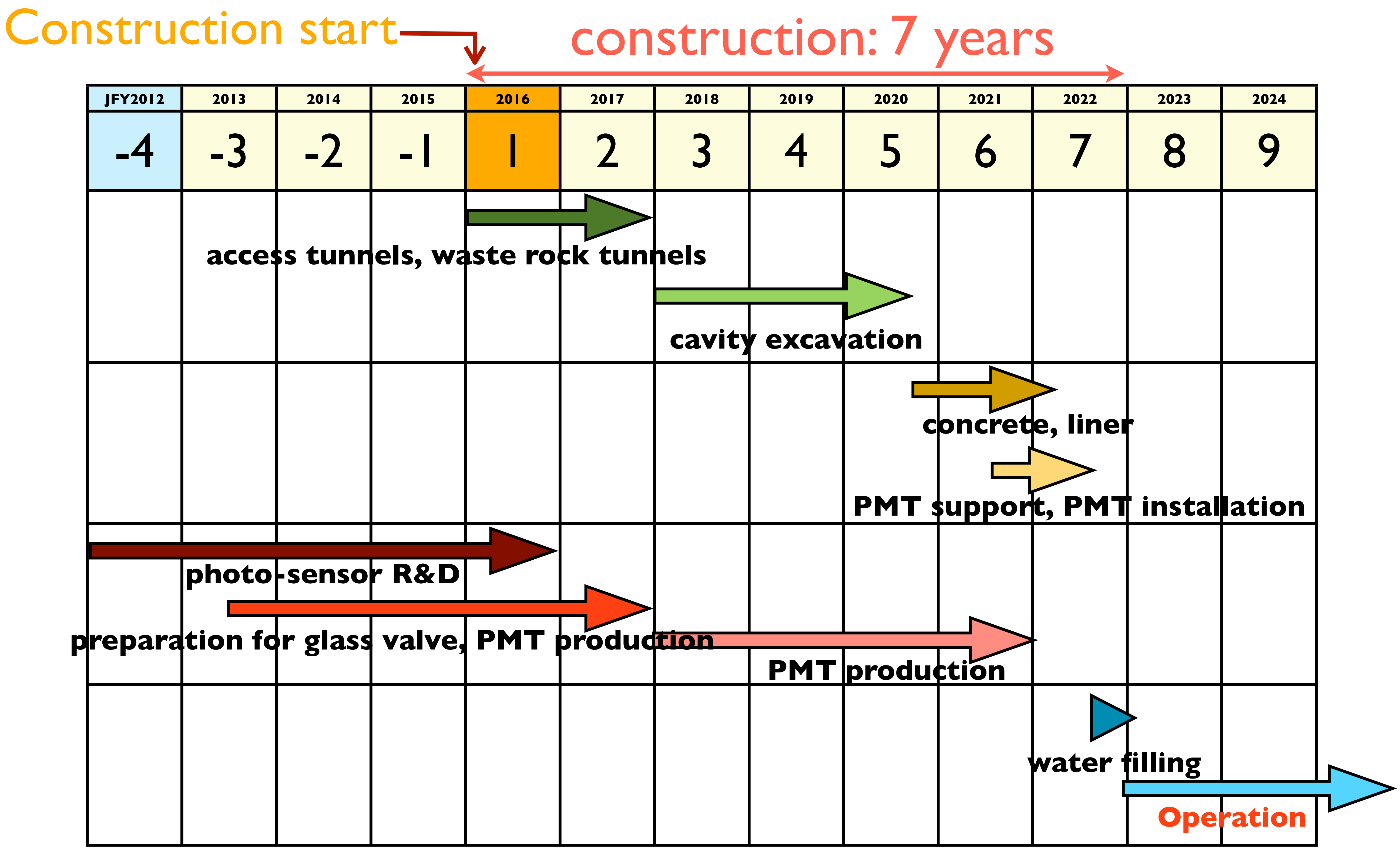
SK Nickel source



Hyper-K in Japanese roadmap

- One of two large-scale future projects recommended by HEP future projects committee.
- Final draft of KEK roadmap includes Hyper-K
- Cosmic ray physics community also endorses Hyper-K as a next large-scale project
- In 2013-14, the Japanese *Master Plan* for large scale projects (for all fields of science) is being updated by Science Council of Japan.
  - Hyper-K is one of proposed projects.
  - The *Master Plan* is expected to be an important input to the Japanese government.

Target Schedule



assuming budget being approved from JPY2016

NNN13 workshop

Nov.11-13, 2013

http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=17

Let's discuss future!!

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TODIAS 東京大学国際高等研究所 TODAI INSTITUTES FOR ADVANCED STUDY

THE KAVLI FOUNDATION

Summary

- T2K results with 3×10^{20}POT (~4% of approved run)
  - Evidence for νe appearance
  - One of most stringent limits on θ_{23}
  - Will continue to produce exciting results with more data – stay tuned!
- Large θ_{13} opened a way for *CP* measurements in future ν experiments
  - Hyper-K in Japan will have a good sensitivity
    - Also for proton decay!

1998-2002

discovery and confirmation of ν oscillation

2011-2012

large θ_{13}

202x?

neutrino CP violation?

or, more unexpected surprise??