

NA-61/*SHINE* Meeting

平成29年 07月 28日

# T2K overview

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Imperial College London

# Outline

- Introduction
  - Oscillation analysis highlights
- Experimental Overview
  - Beam, ND, FD
  - Upgrades
  - XSEC measurements
- Summary

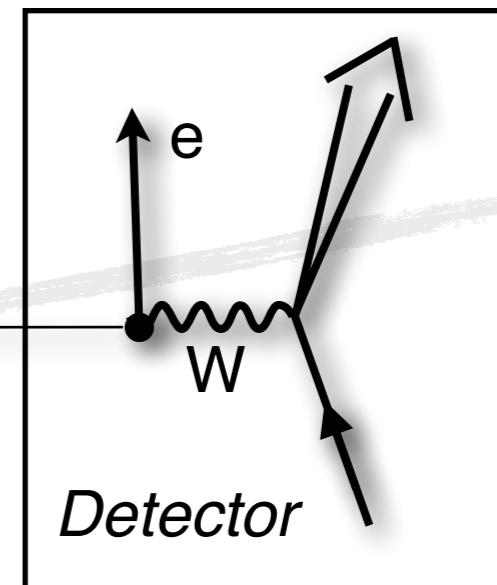
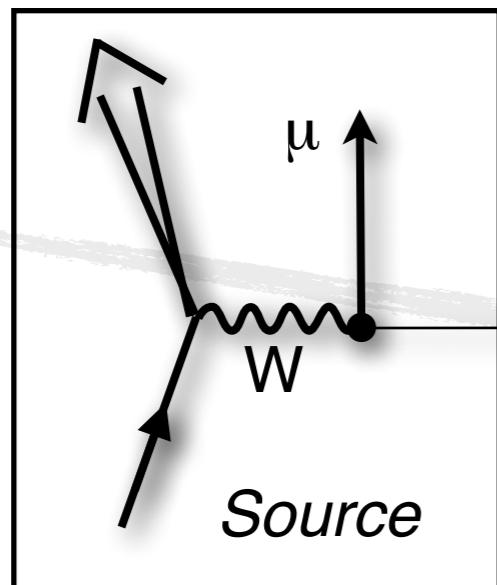
# Neutrino oscillation



*Bruno Pontecorvo*

[Sov.Phys.JETP 6:429,1957](#)

[Sov.Phys.JETP 26:984-988,1968](#)

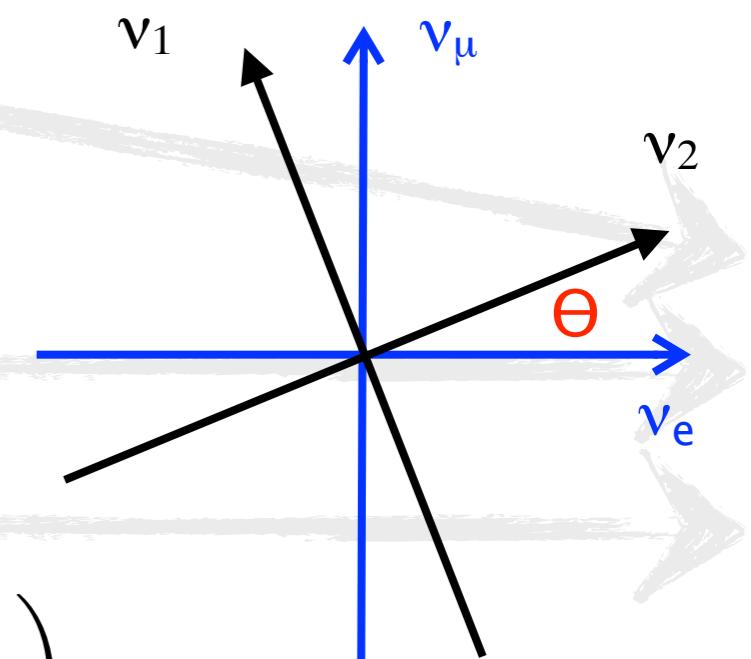


Maki,  
Nakagawa,  
Sakata

[Prog.Theor.Phys. 28, 870 \(1962\)](#)

Simple 2 neutrino example-  
if weak eigenstates ( $\nu_e, \nu_\mu$ ) differ from mass eigenstates ( $\nu_1, \nu_2$ ):

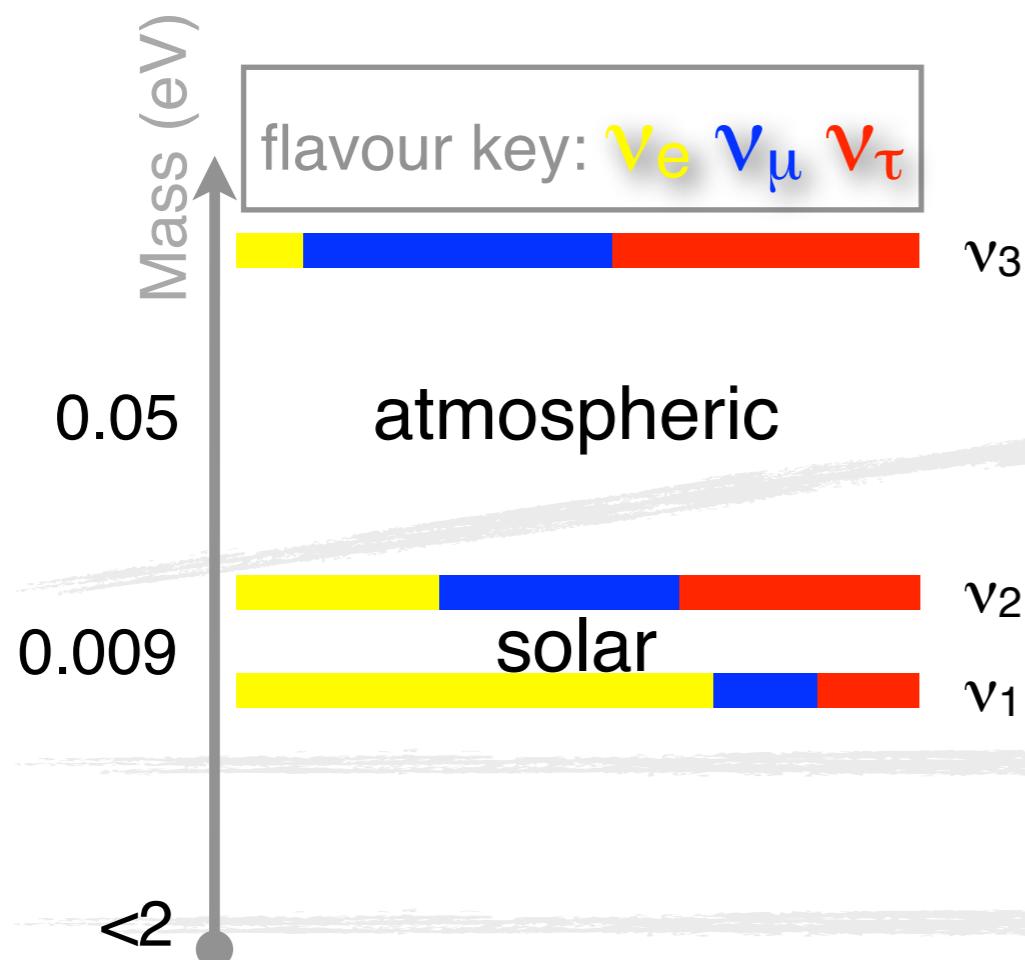
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$P_{\text{oscillation}}(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 (eV^2) L(km)}{E_\nu (GeV)} \right)$$

# Current neutrino picture

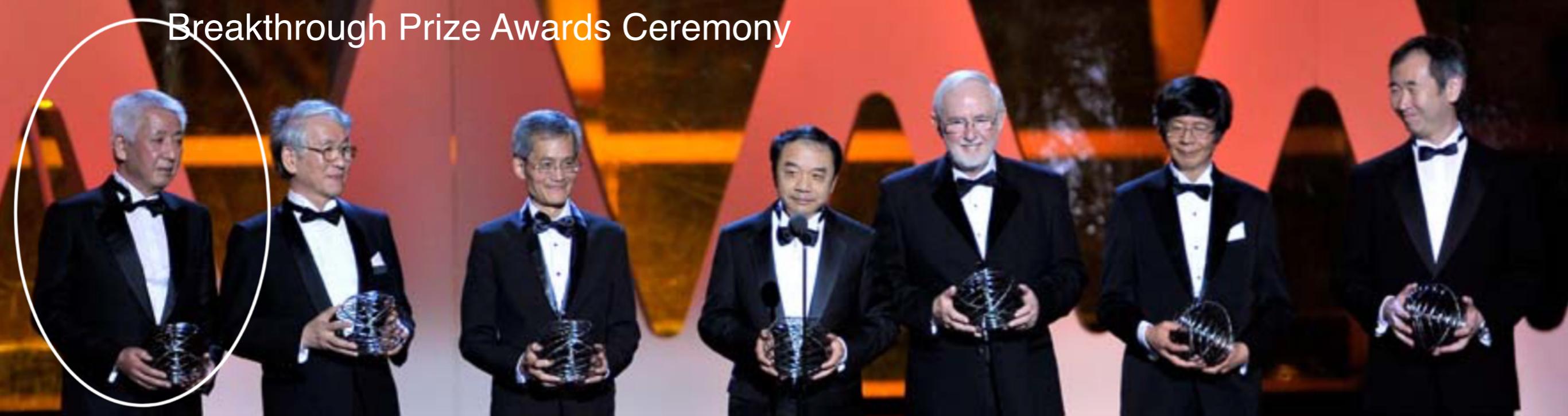
flavour	<i>atmospheric</i>	<i>accelerator</i>	<i>solar</i>	<i>Majorana</i>	mass
$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$	$\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$	$\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$	$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$



	VALUE
$ \Delta m^2_{32} $	$2.35 \pm 0.12 \text{ E-03 (eV}^2)$
$\Delta m^2_{21}$	$7.58 \pm 0.24 \text{ E-05 (eV}^2)$
$\sin^2 \theta_{12}$	$0.31 \pm 0.018$
$\sin^2 \theta_{23}$	$0.42 \pm 0.08$
$\sin^2 \theta_{13}$	$0.02 \pm 0.007$
$\delta_{CP}$	$3\pi/2?$

Accelerator experiments measure:  $\Delta m^2_{32}$  (including sign),  $\sin^2 \theta_{23}$ ,  $\sin^2 \theta_{13}$  &  $\delta_{CP}$

# Breakthrough Prize Awards Ceremony



T2K founding spokesperson Ko Nishikawa and all T2K collaboration members won the 2016 Breakthrough Prize for fundamental physics!



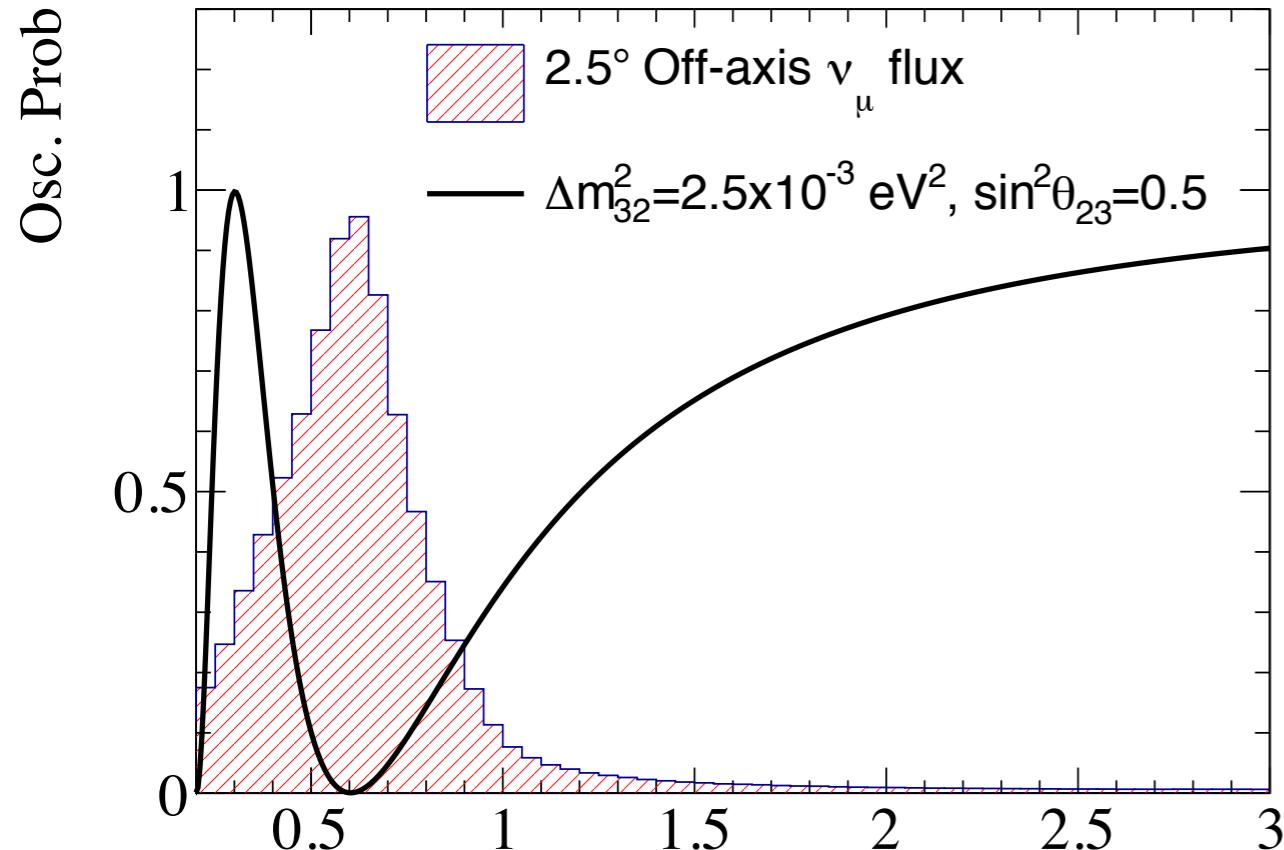
Nishikawa-san

Breakthrough Prize Partygoers

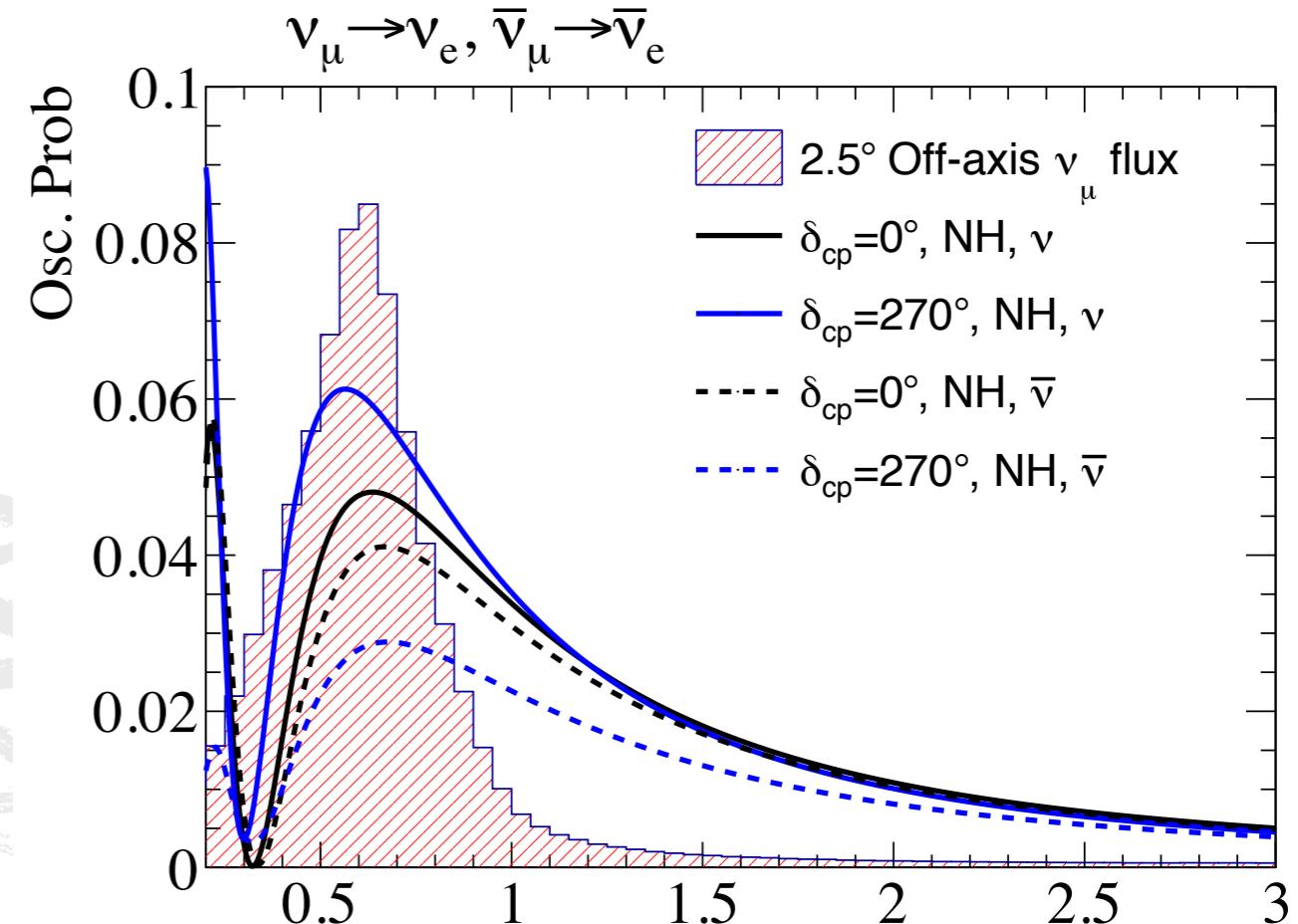
T2K Spokespersons

# Measuring CPV in T2K

$$\nu_\mu \rightarrow \nu_\mu = \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$



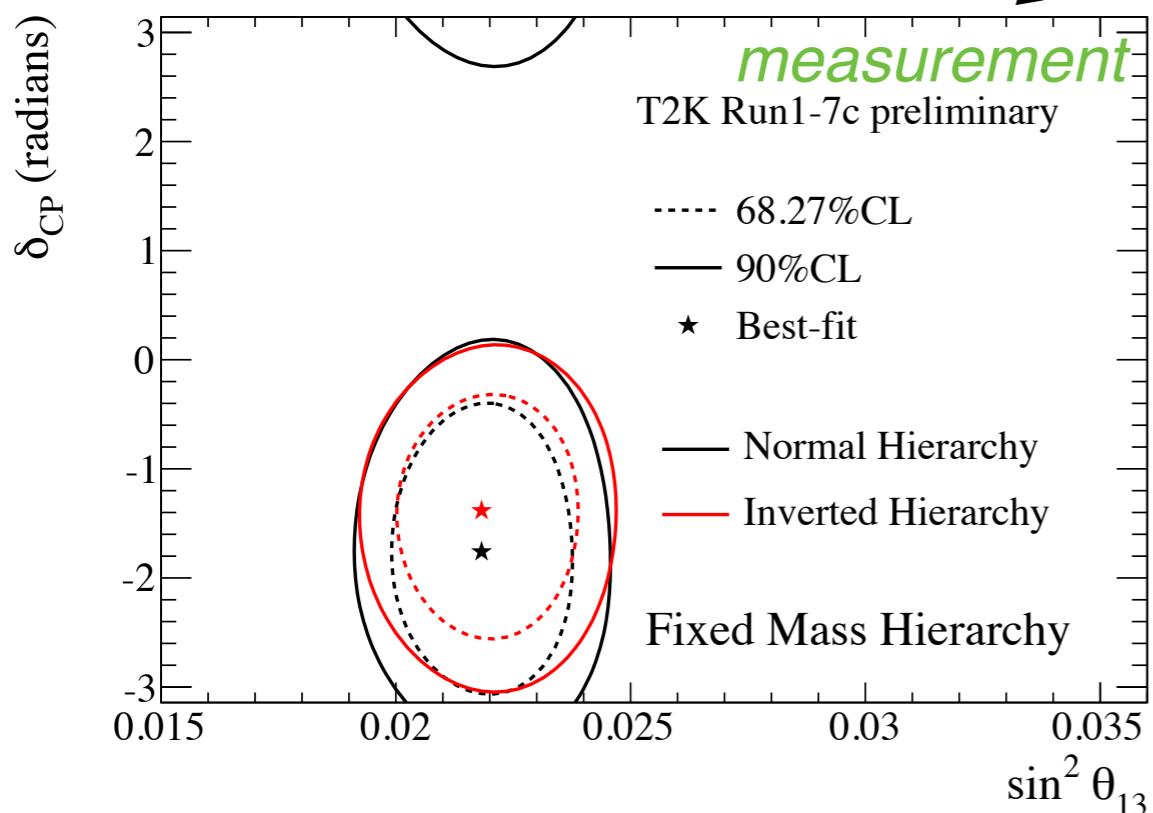
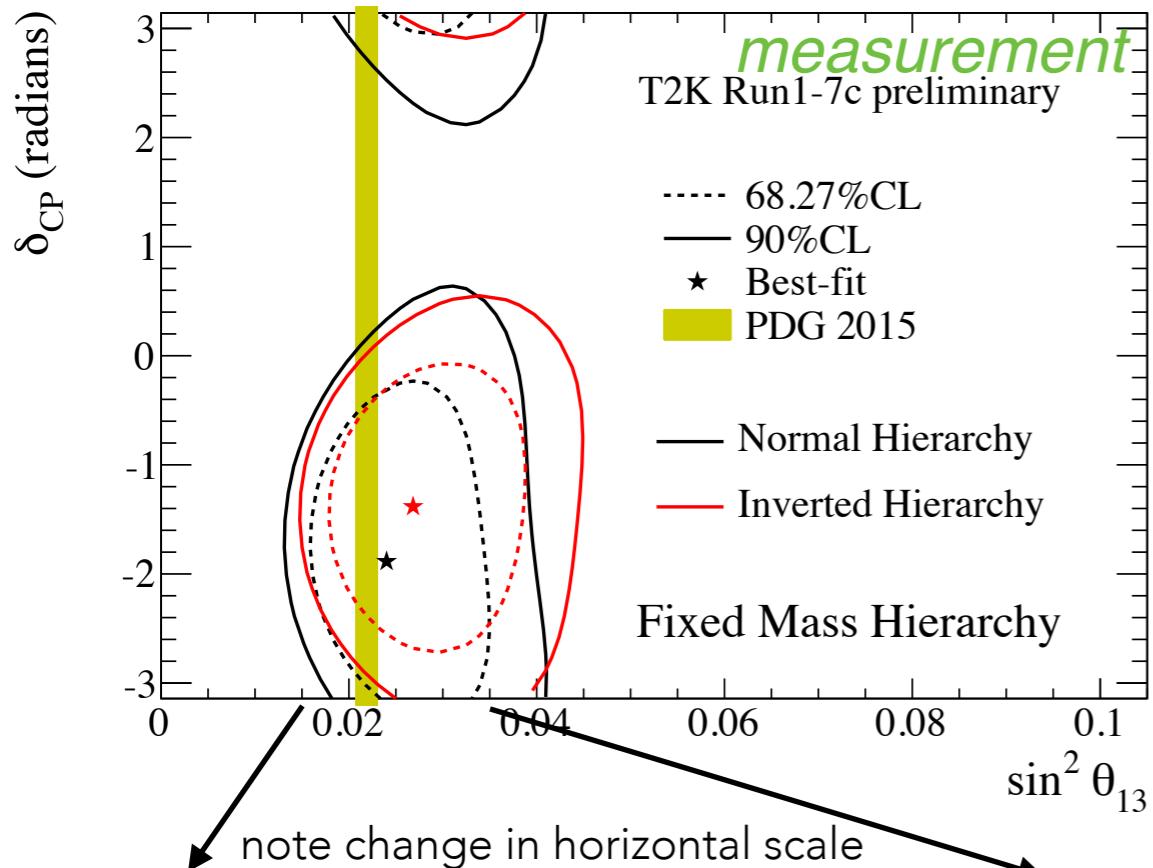
- Tests CPT symmetry  $E_\nu$  (GeV)
- Leading order dependence on  $\sin^2 2\theta_{23}$ 
  - Can't separate  $\theta_{23} > 45^\circ$  from  $\theta_{23} < 45^\circ$
- Leading order dependence on  $|\Delta m_{32}^2|$ 
  - Doesn't depend on the sign of the mass splitting (hierarchy)



- Tests CP symmetry  $E_\nu$  (GeV)
- Leading order dependence on  $\sin^2 2\theta_{13}$
- Leading order dependence on  $\sin^2 \theta_{23}$ 
  - Can separate  $\theta_{23} > 45^\circ$  from  $\theta_{23} < 45^\circ$
- Sub-leading dependence on  $\sin(\delta_{cp})$ 
  - Can detect CP violation
- Sub-leading dependence on  $\Delta m_{32}^2$  through matter effect
  - Relatively small in T2K due to baseline

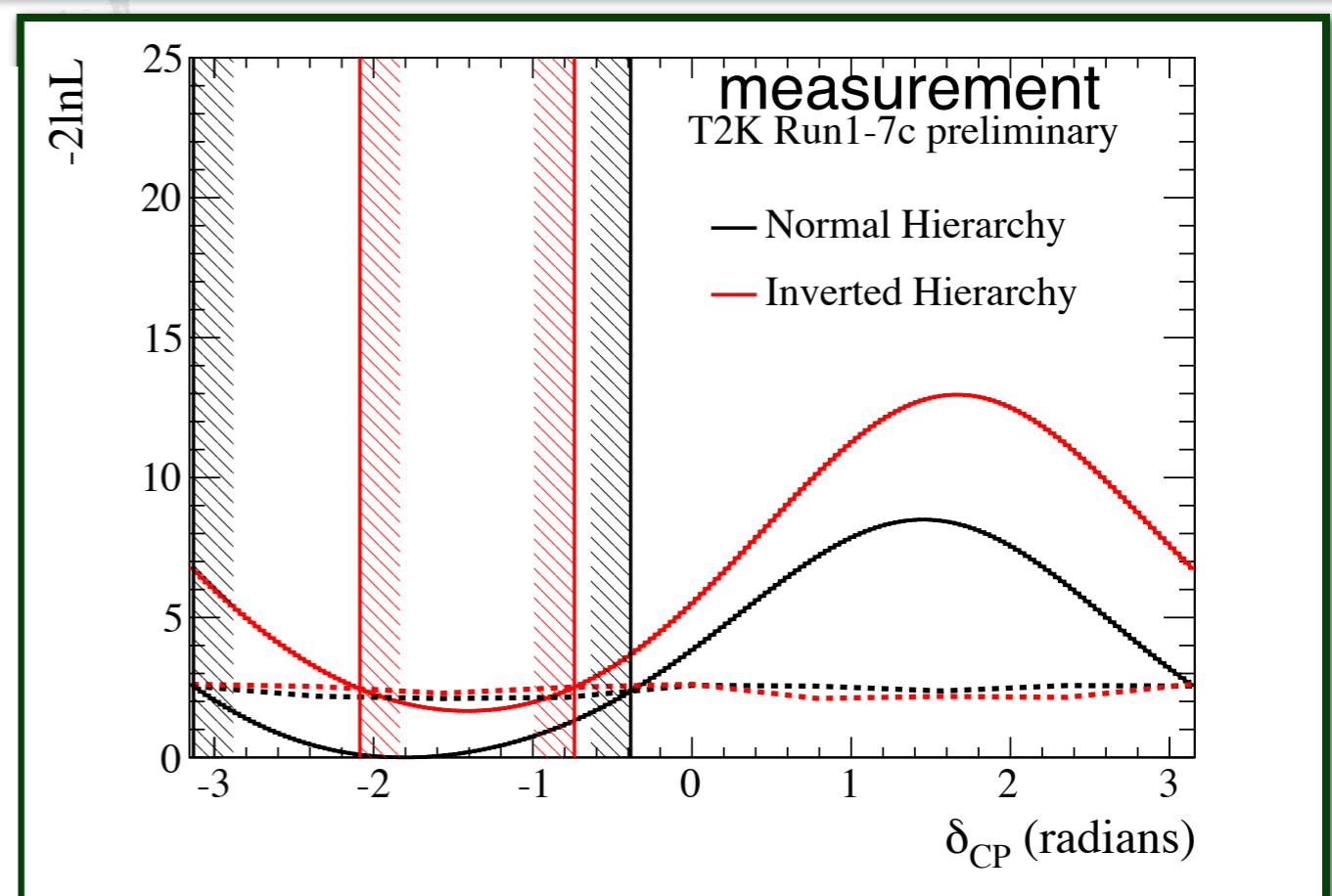
# Data

# T2K 2016: $\delta_{CP}$ vs. $\theta_{13}$



- Left:  $\delta_{CP}$  vs.  $\theta_{13}$  (fixed  $\Delta\chi^2$ , fixed hierarchy)
  - T2K-only
  - T2K with reactor  $\sin^2 2\theta_{13} = 0.085 \pm 0.005$
- Below:  $\delta_{CP}$  with Feldman-Cousins critical values and reactor  $\theta_{13}$

$$\delta_{CP} = [-3.13, -0.39] \text{ (NH)}, [-2.09, -0.74] \text{ (IH)} @ 90\% CL$$



# T2K Experiment

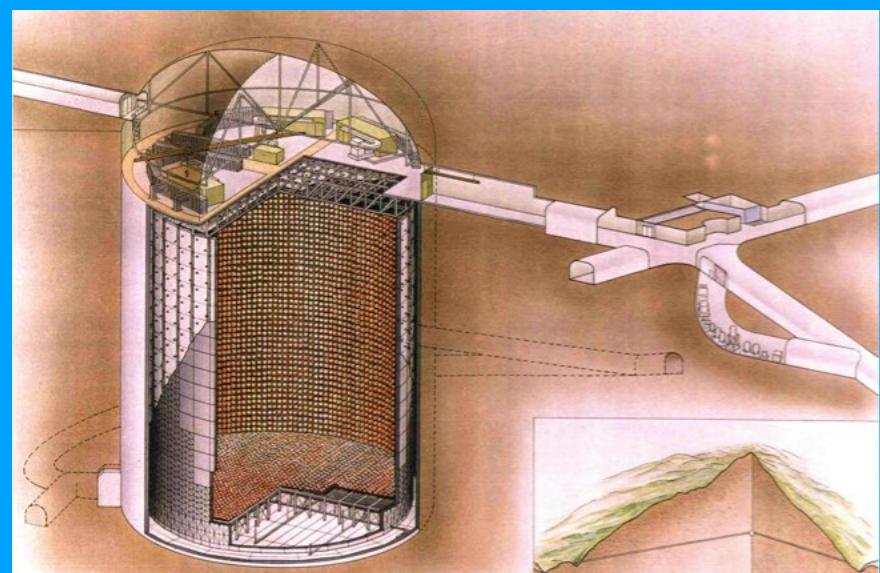




# The T2K Collaboration

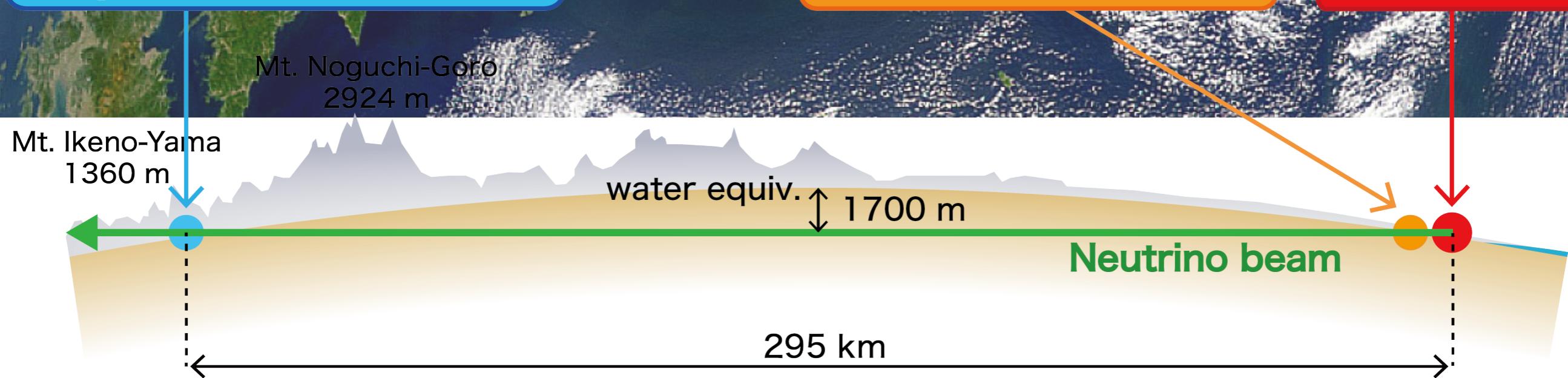


# T2K



ICRR, Univ. of Tokyo

## Super Kamiokande



KEK / JAEA

# T2K strategy

Search for  $\delta_{CP}$  by comparing  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ .

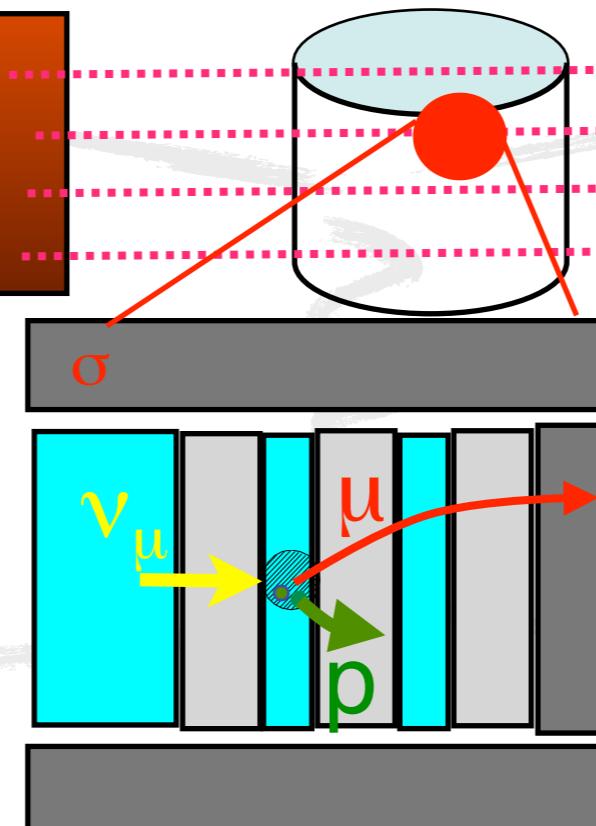
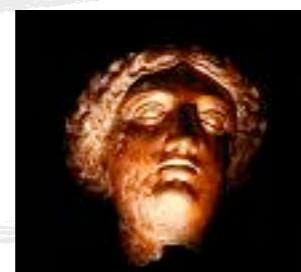
Intense beam

protons



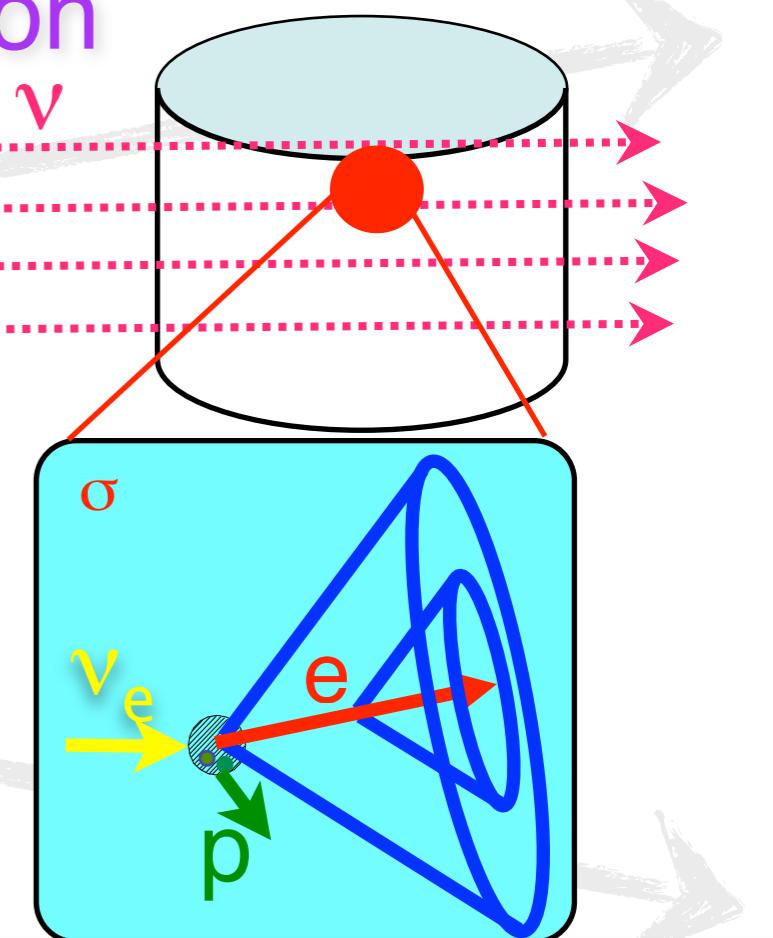
$\pi, \pi, \pi, \pi, K$

$\Phi_\nu(E)$



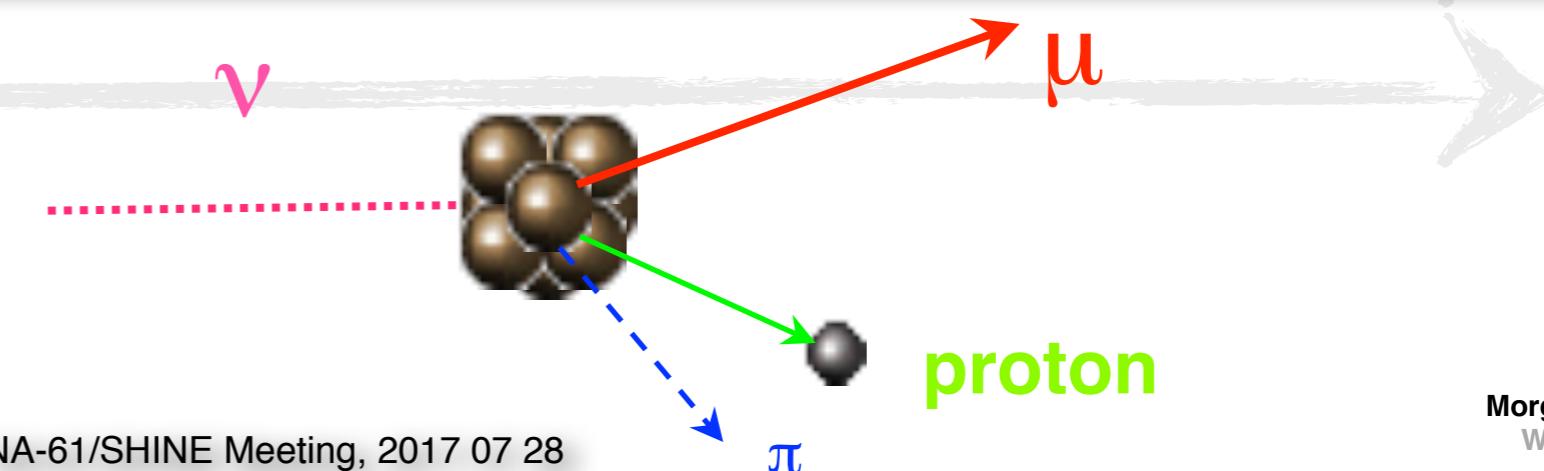
oscillation

$\nu, \nu, \nu, \nu$

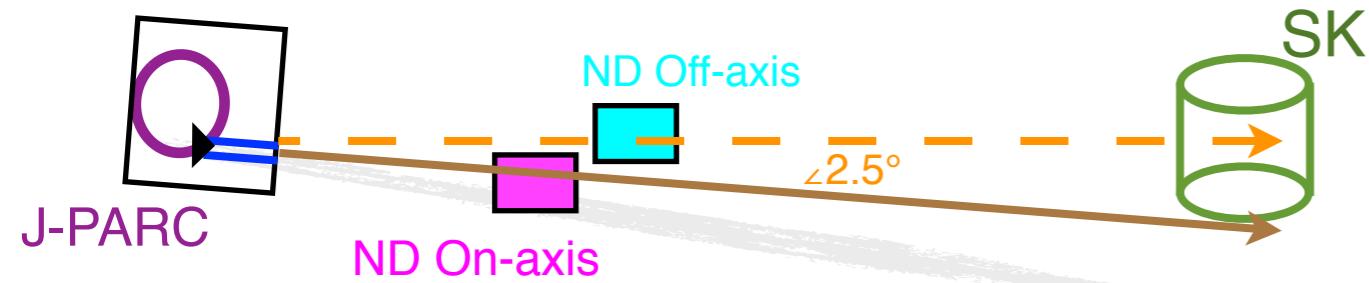


$$\Phi_{\nu\text{near}}(E) \cdot \sigma_{\text{near}}(E, Q^2) \cdot \varepsilon_{\text{near}}(E) \Leftrightarrow \Phi_{\nu\text{far}}(E, \theta, \Delta m^2, \delta) \cdot \sigma_{\text{far}}(E, Q^2) \cdot \varepsilon_{\text{far}}(E)$$

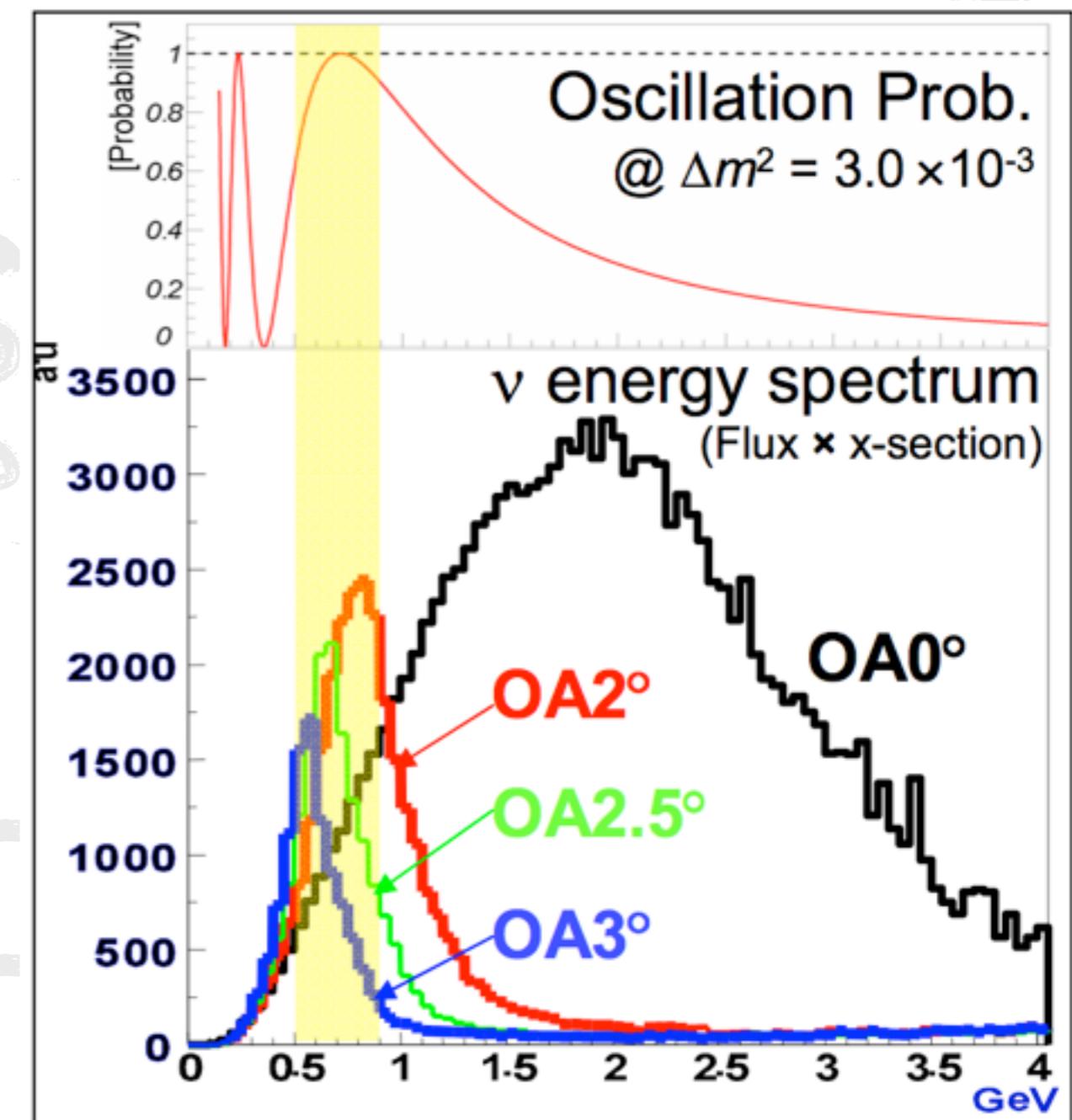
SciBooNE

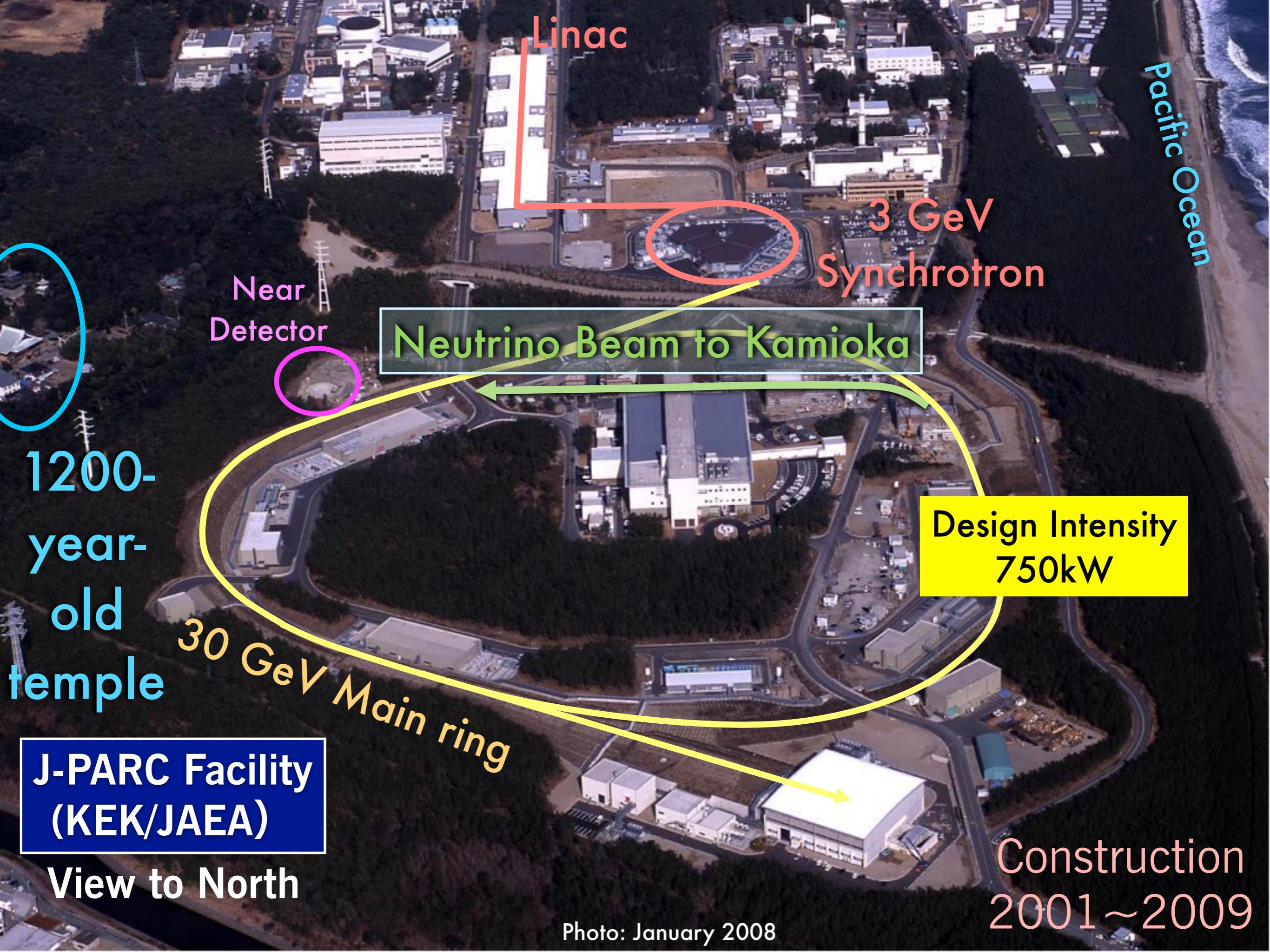


# Off-Axis Beam

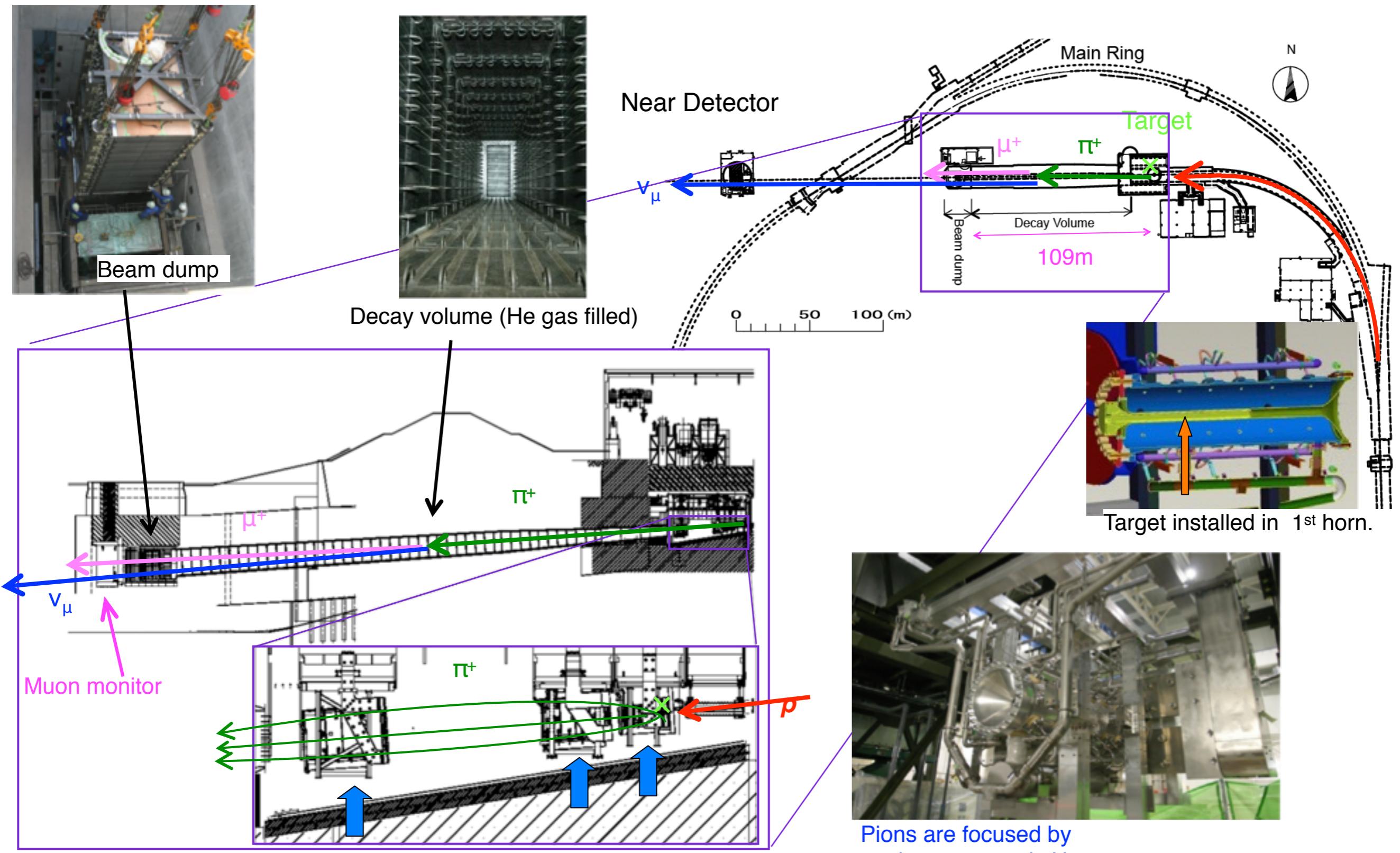


- Use kinematics of pion decay to tune the neutrino energy
- Flux peak at target energy for desired value of L/E
  - $E\nu$  well matched to Super-K

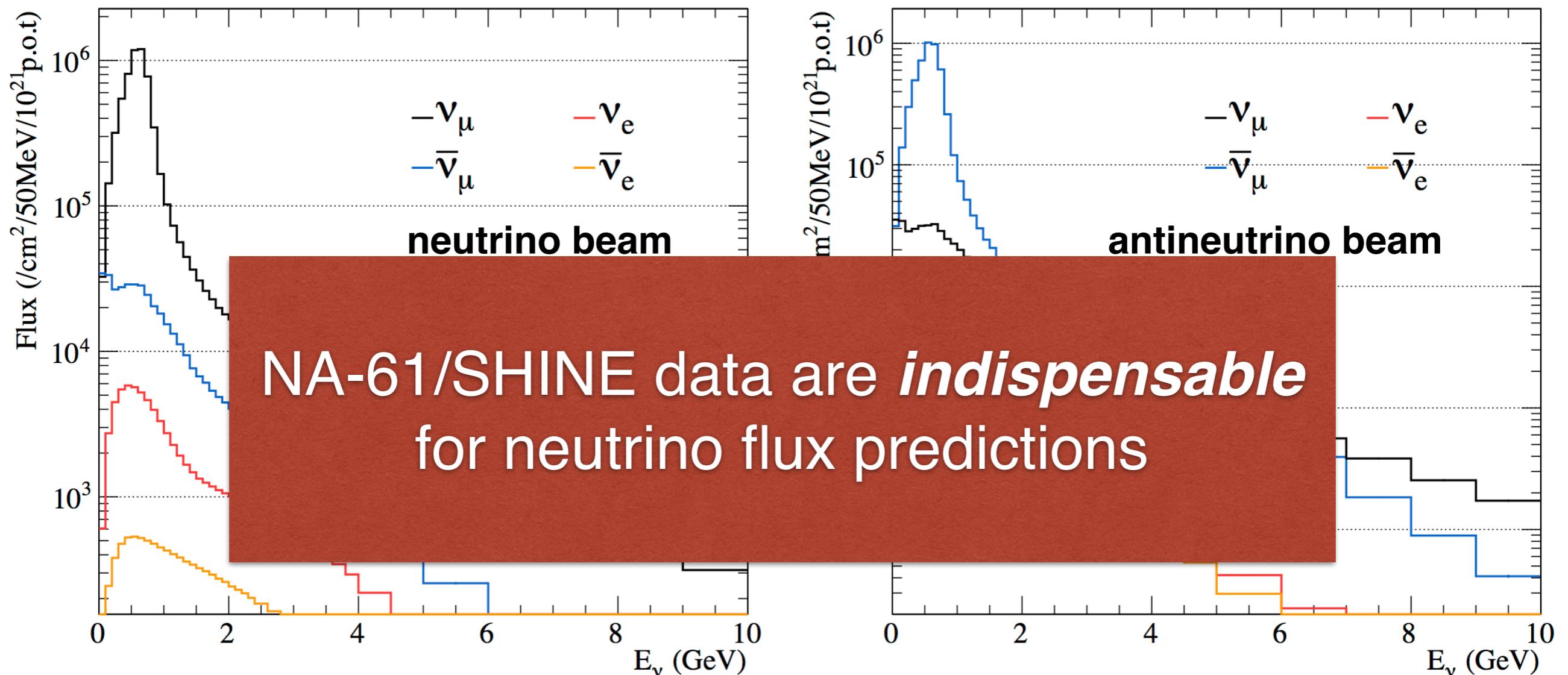




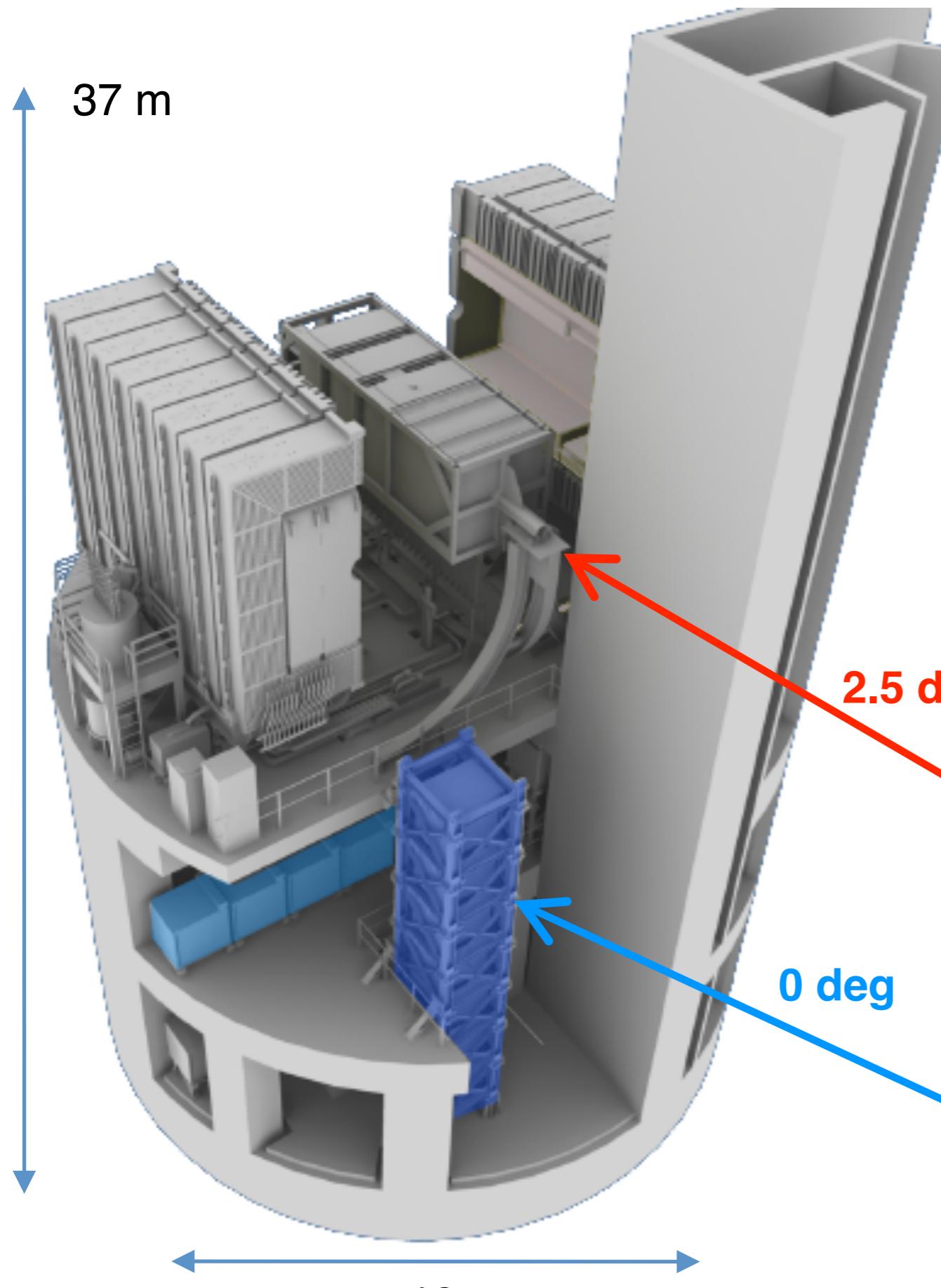
# J-PARC neutrino beamline overview



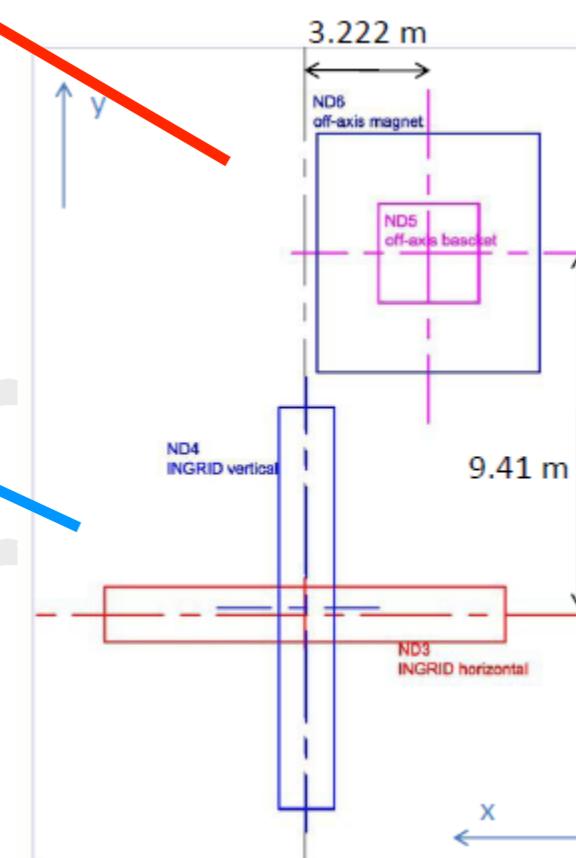
# Neutrino flux predictions



- <1% impurity from  $\nu_e(\bar{\nu}_e)$  at energy peak; important background for  $\nu_e(\bar{\nu}_e)$  appearance
- “wrong sign” component: neutrinos contaminating antineutrino beam, vice versa.

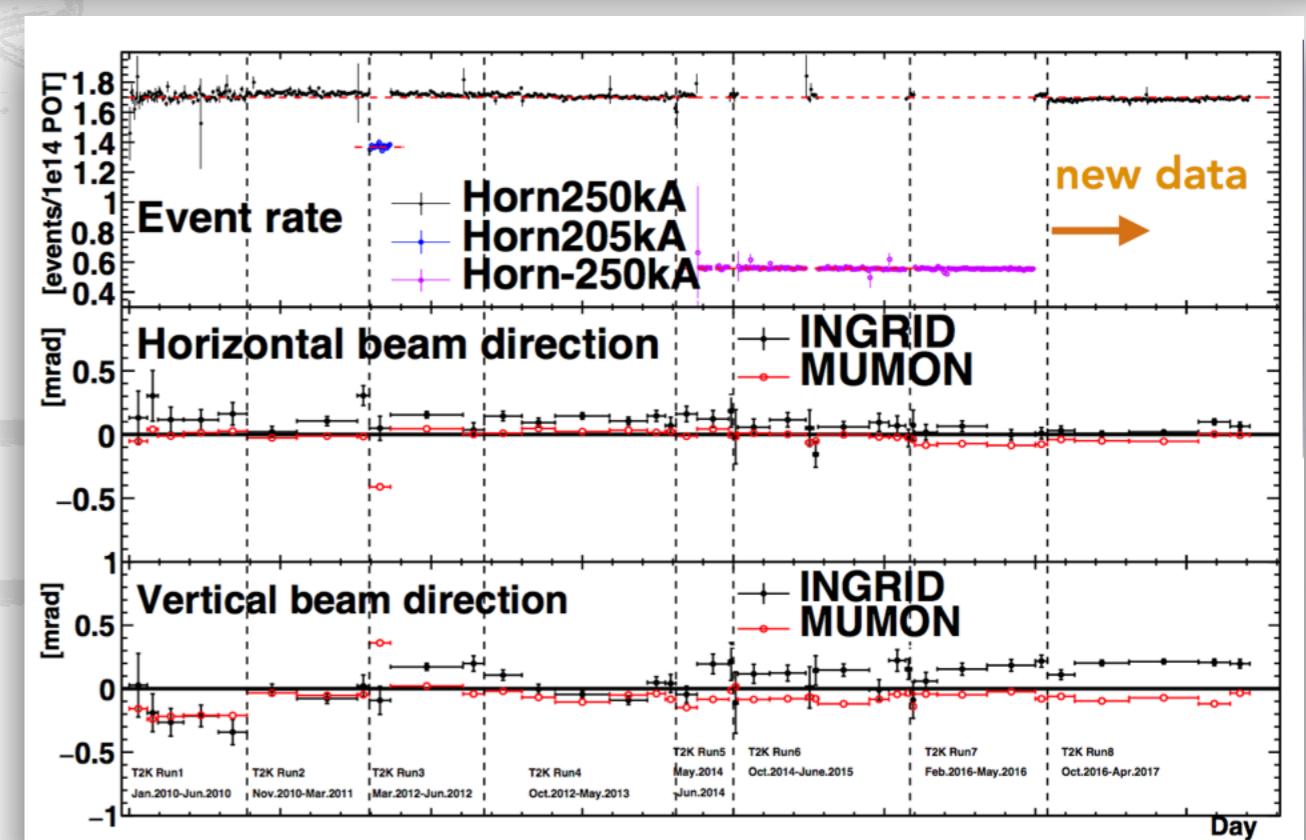
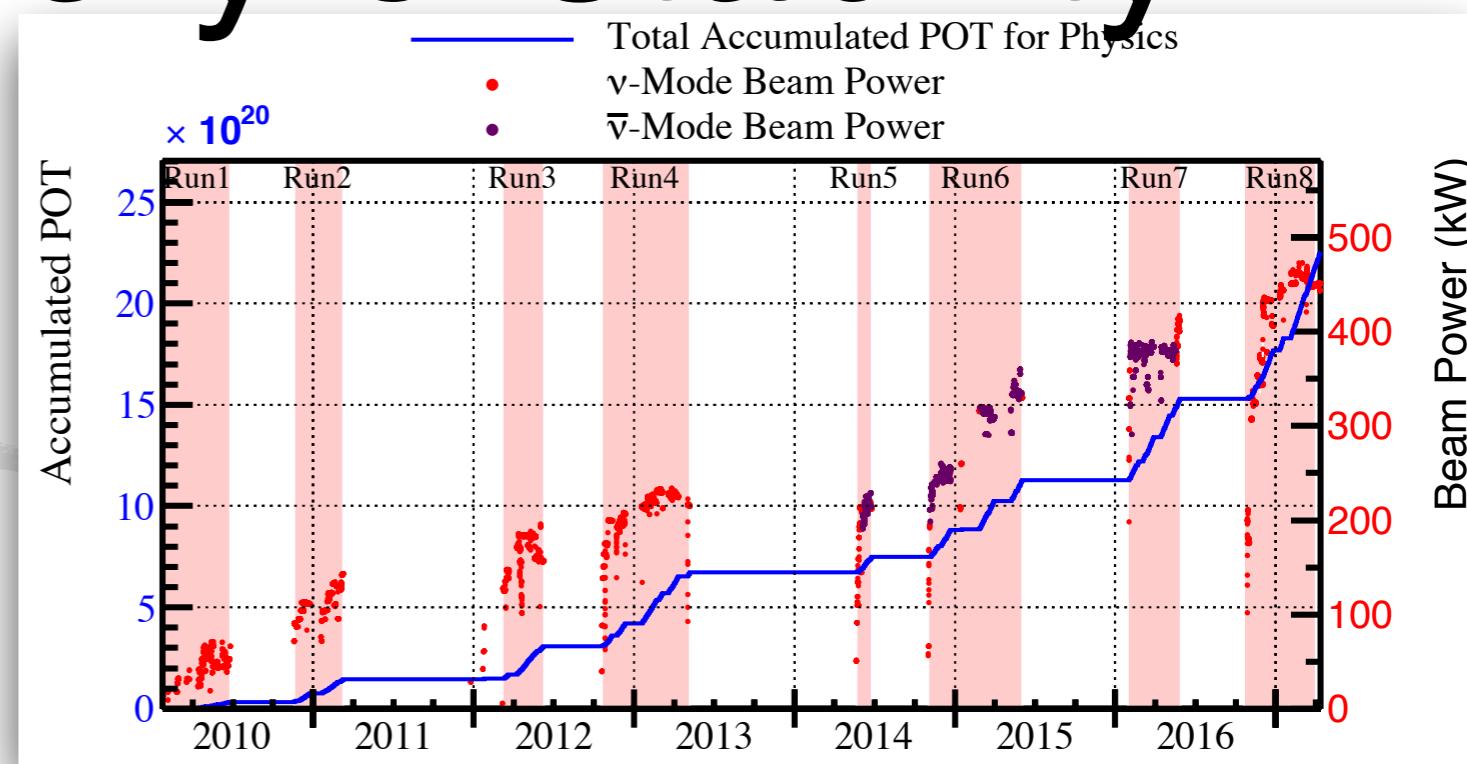


The Near Detector pit houses both the **off-axis** (ND280) and **on-axis** (**INGRID**) detectors



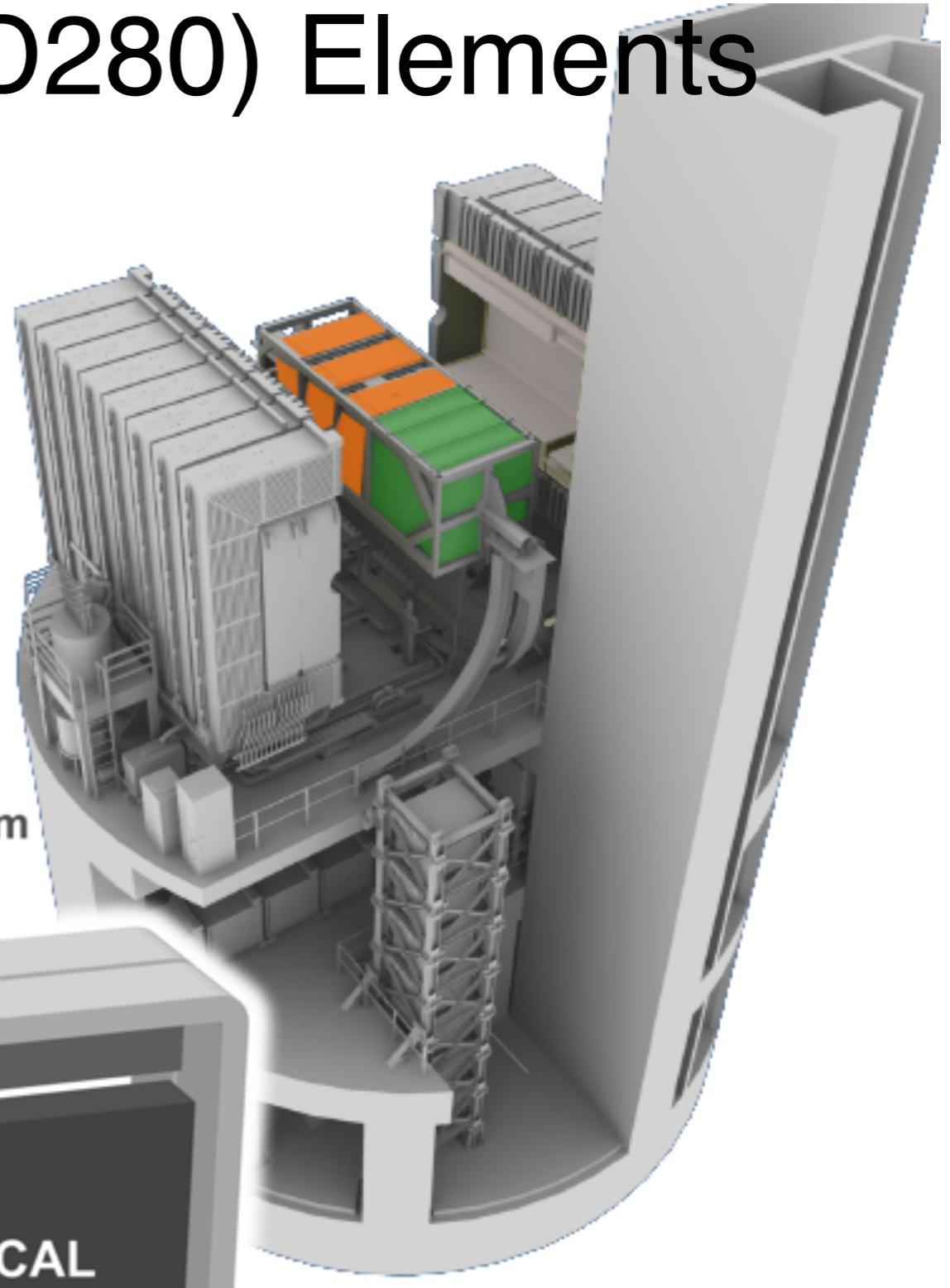
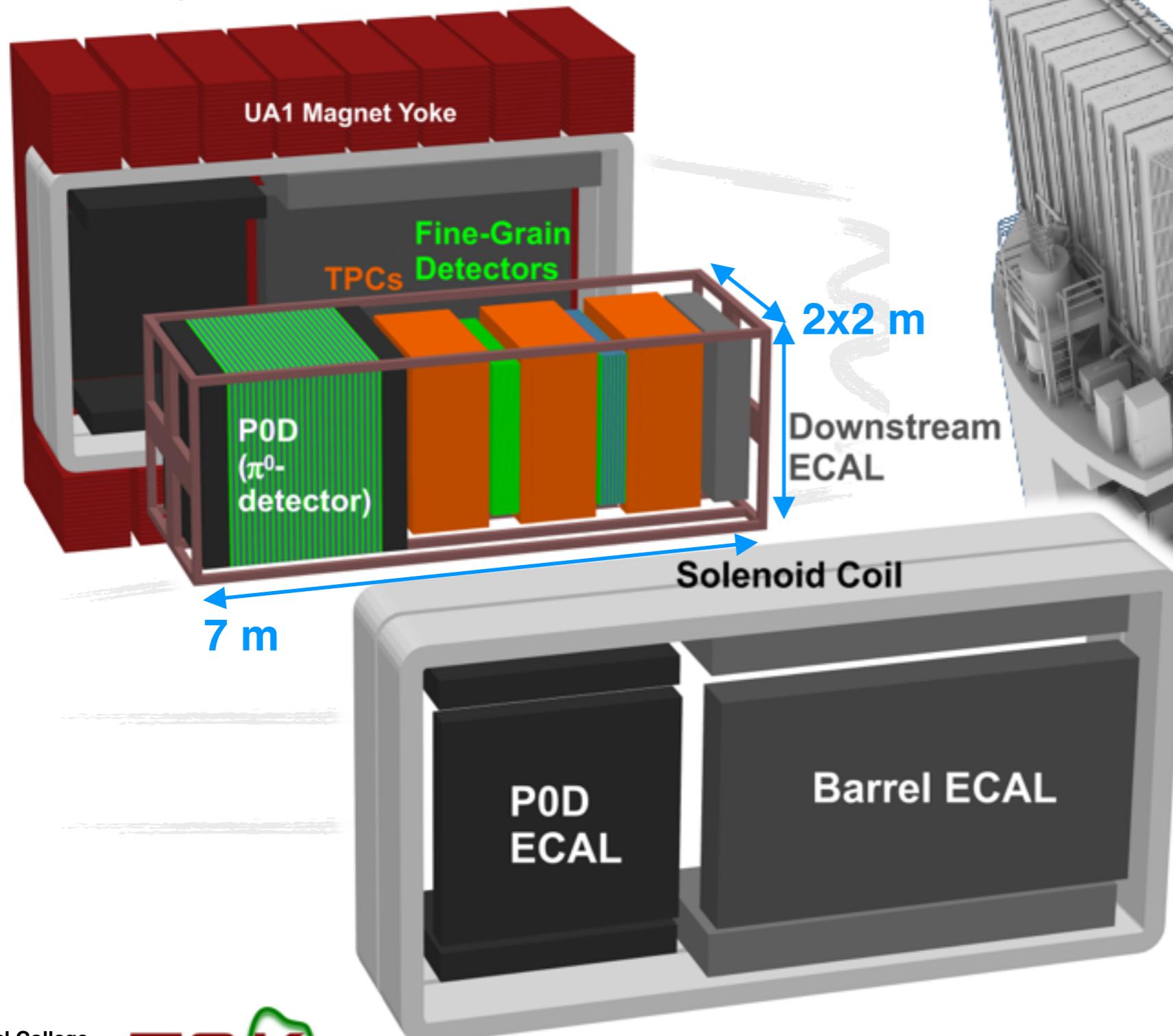
# Beam delivery & stability

- Beam delivery until Apr 2017
  - **$2.5 \times 10^{21}$  POT TOTAL**
  - $1.49 \times 10^{21}$  POT in  $\nu$ -mode
  - $0.76 \times 10^{21}$  POT in  $\bar{\nu}$ -mode
- Beam operated stably at **470 kW!**
- Expect  $0.8 \times 10^{21}$  POT in 2017-18 data run
- Main Ring power supply upgrade approved by MEXT
- Will allow operation up to and beyond 750 kW in 2019

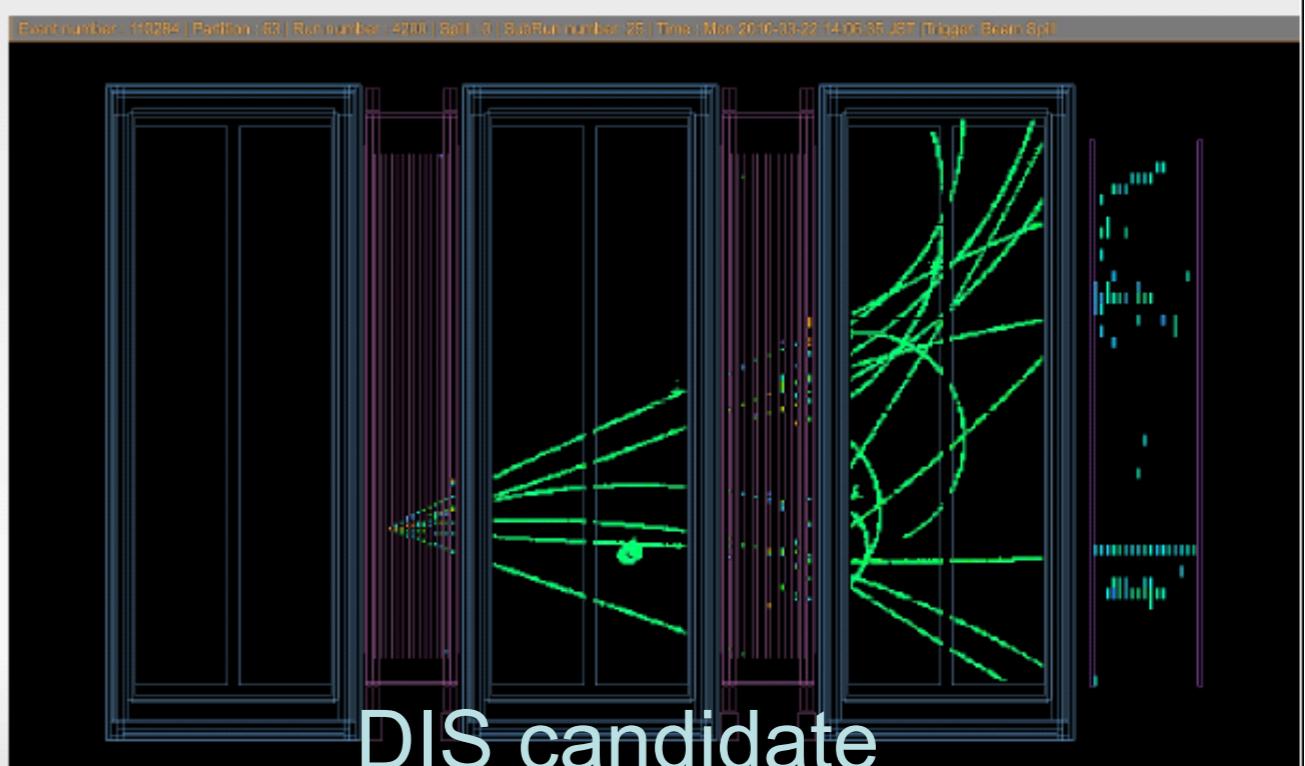
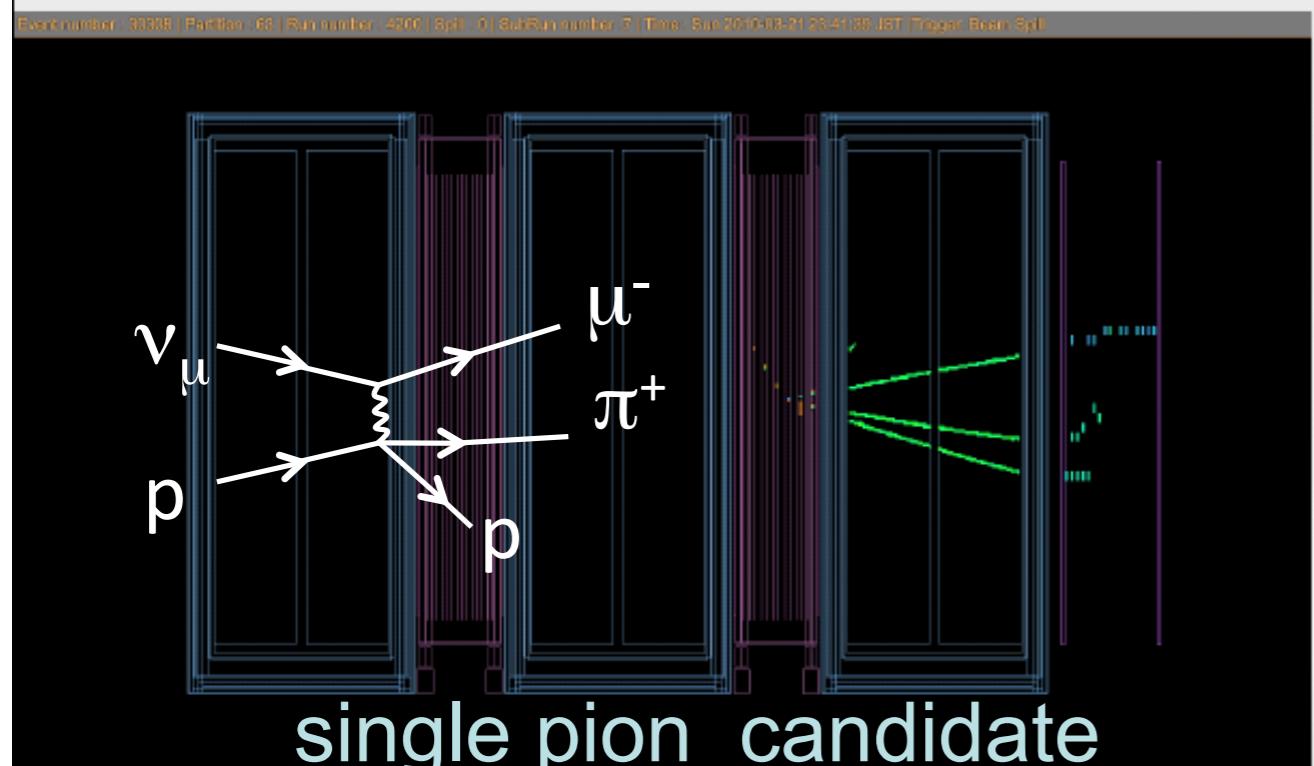
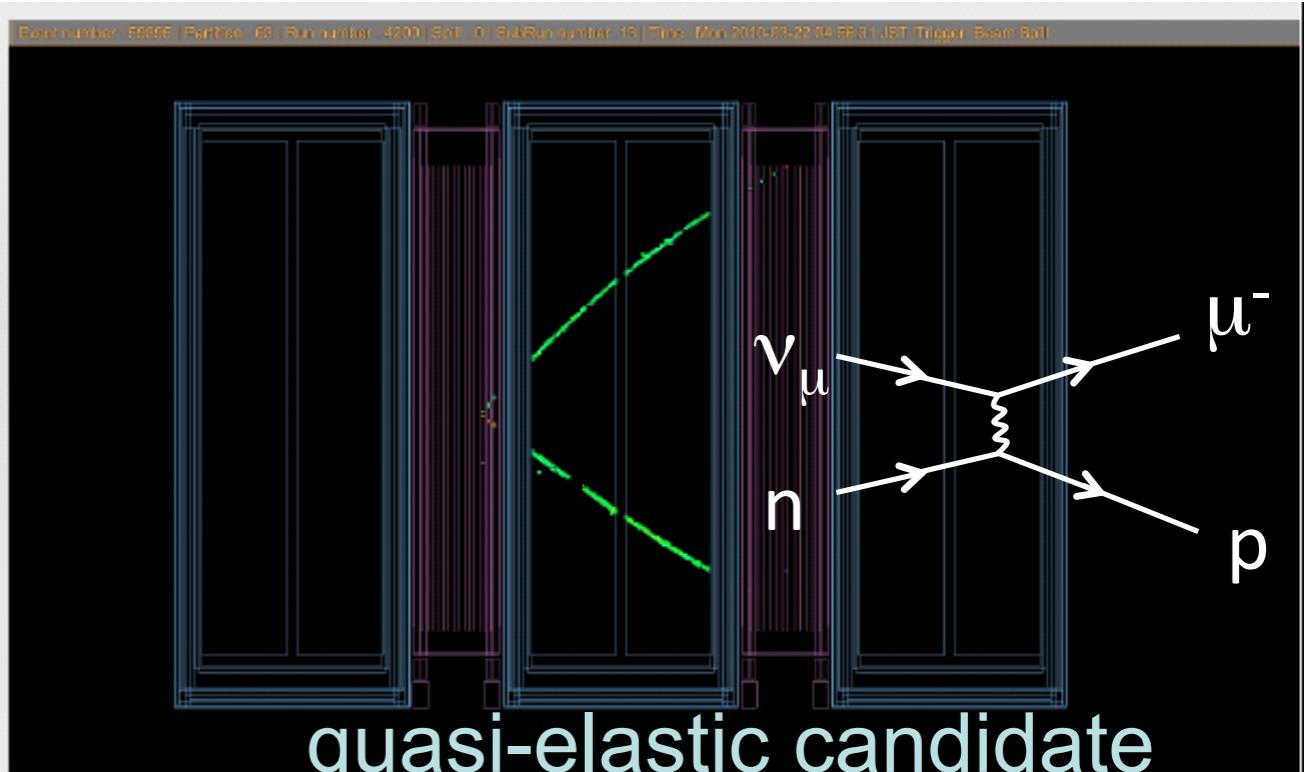
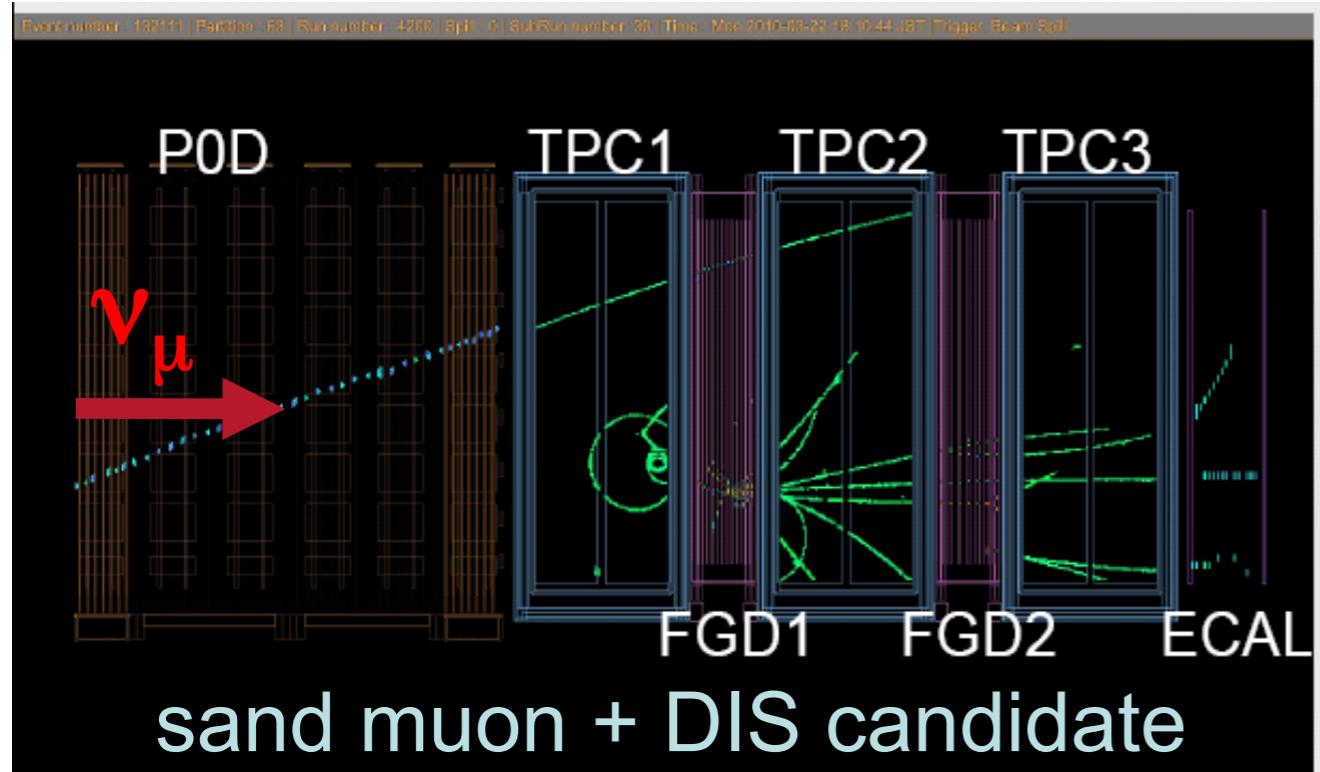


# Off-Axis Detector (ND280) Elements

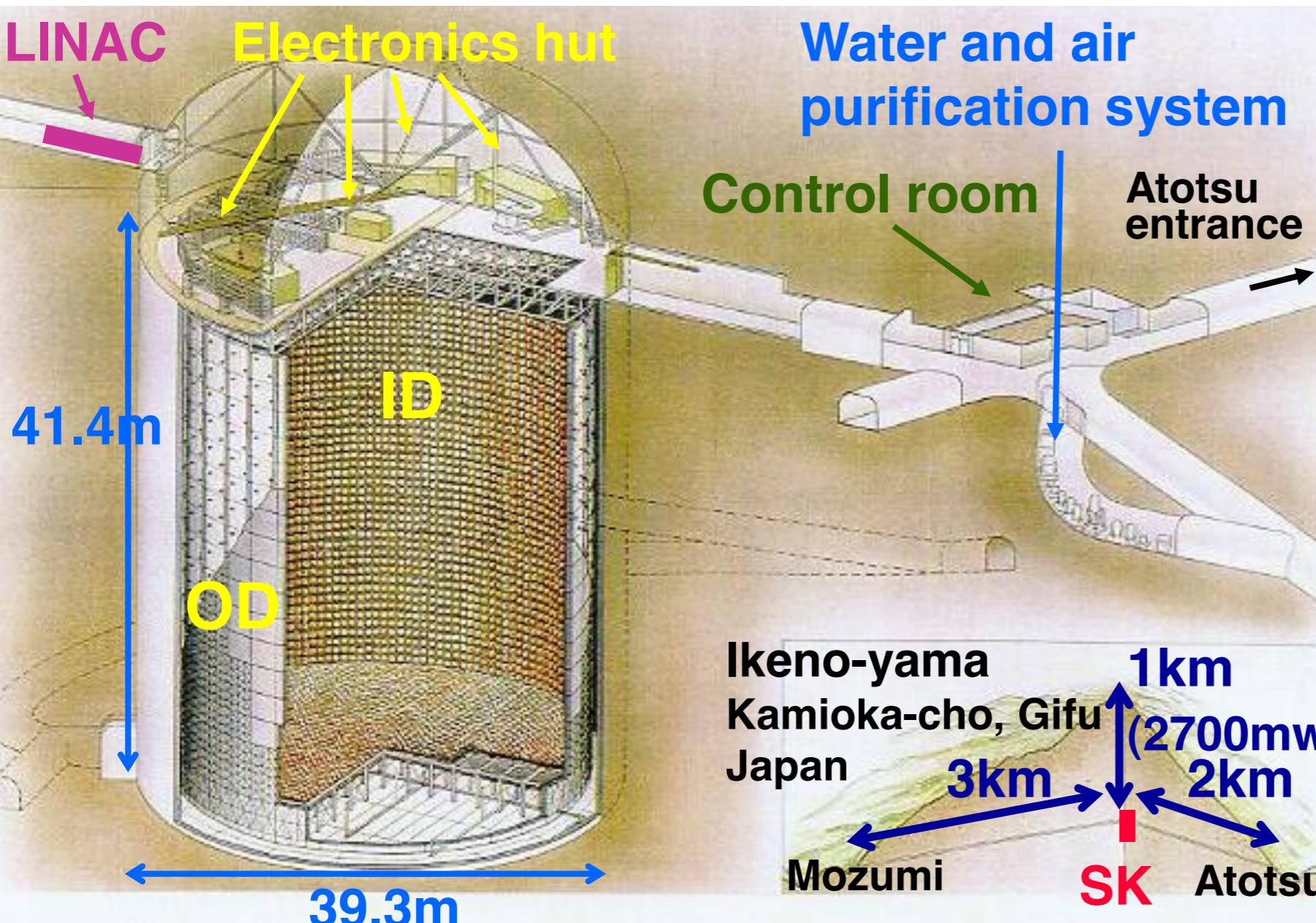
SMRD in Magnet  
Yoke air gaps



# ND280 neutrino events



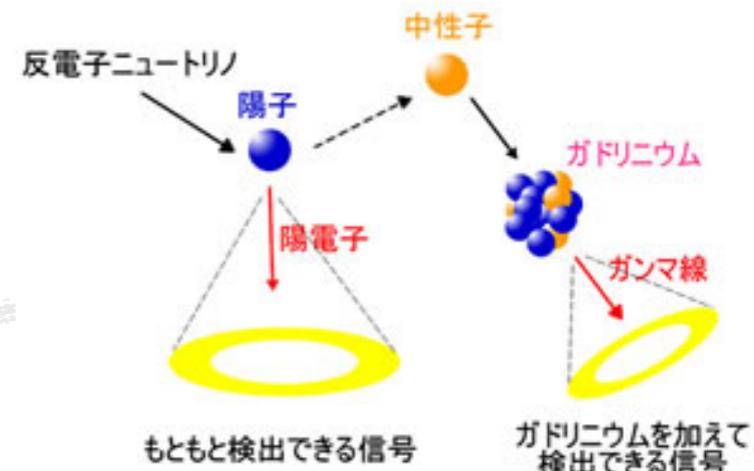
# Super-K (far) detector



- 50 kton (22.5 kton fiducial volume) water Cherenkov detector
- ~11,000 20" PMT for inner detector (ID) (40% photo coverage)
- ~2,000 outward facing 8" PMT for outer detector (OD): veto cosmics, radioactivity, exiting events
- Good reconstruction for T2K energy range
- Threshold 4 MeV

# SK status

- Recent analysis improvements enhance S/B
  - Moving to new reconstruction algorithm (fitQun)
  - Expanding fiducial volume
- SK-Gd project aims to enhance neutron detection capability with addition of Gd to water
- SK tank leak repair work will be done in summer 2018

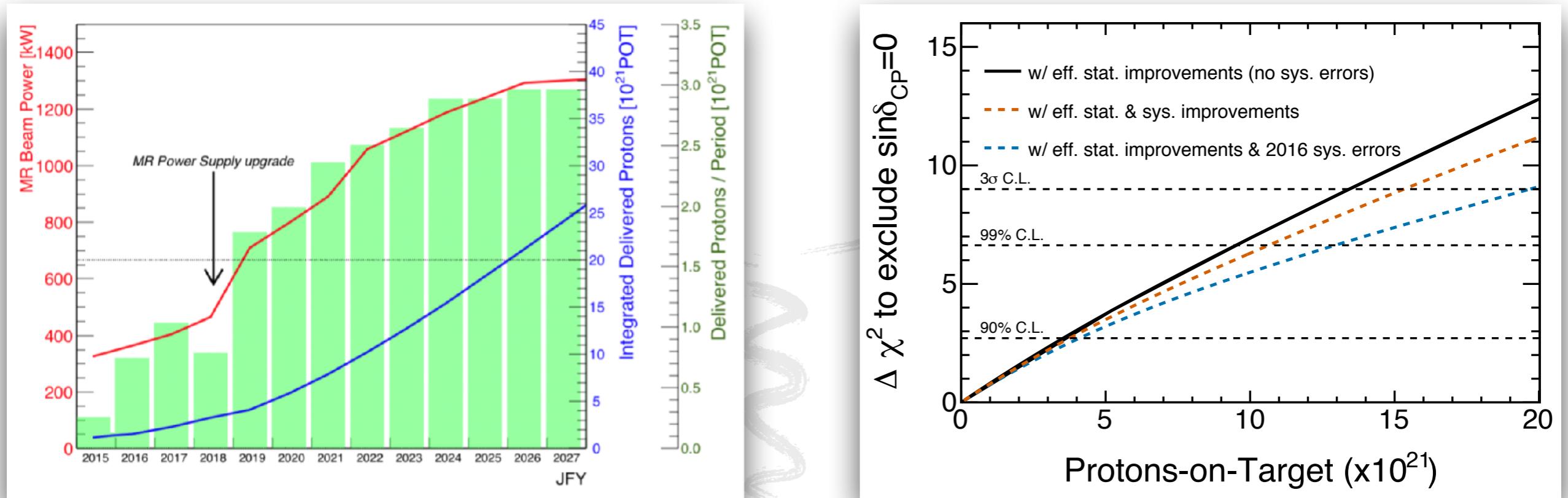


## SK-Gd project plan

STEP #		1st year	20XX	20XX	20XX	20XX
1	Leak repair work (~4 months)	—	—	—	—	—
2, 3	Fill pure water (~2.5 months)	—	—	—	—	—
4	Circulate pure water until get good water transparency (~2months)	—	—	—	—	—
5, 6	Load to 0.002% $\text{Gd}_2(\text{SO}_4)_3$ (1ton) (~1 month)	—	—	—	—	—
7	Load to 0.02% $\text{Gd}_2(\text{SO}_4)_3$ (10ton) (~1 month)	—	—	—	—	—
7	Water transparency stabilized (~4 months)	—	—	—	—	—
7	Observation with 0.02 % $\text{Gd}_2(\text{SO}_4)_3$ ?	—	—	—	—	—
8	Load to 0.2% $\text{Gd}_2(\text{SO}_4)_3$ (100 ton) (~2 months)	—	—	—	—	—
9	Observation with full loading	—	—	—	—	—

T<sub>0</sub>: Tank open work for leak repair  
T<sub>1</sub>: Loading to 0.02%  $\text{Gd}_2(\text{SO}_4)_3$   
T<sub>2</sub>: Loading to 0.2%  $\text{Gd}_2(\text{SO}_4)_3$

# T2K run extension



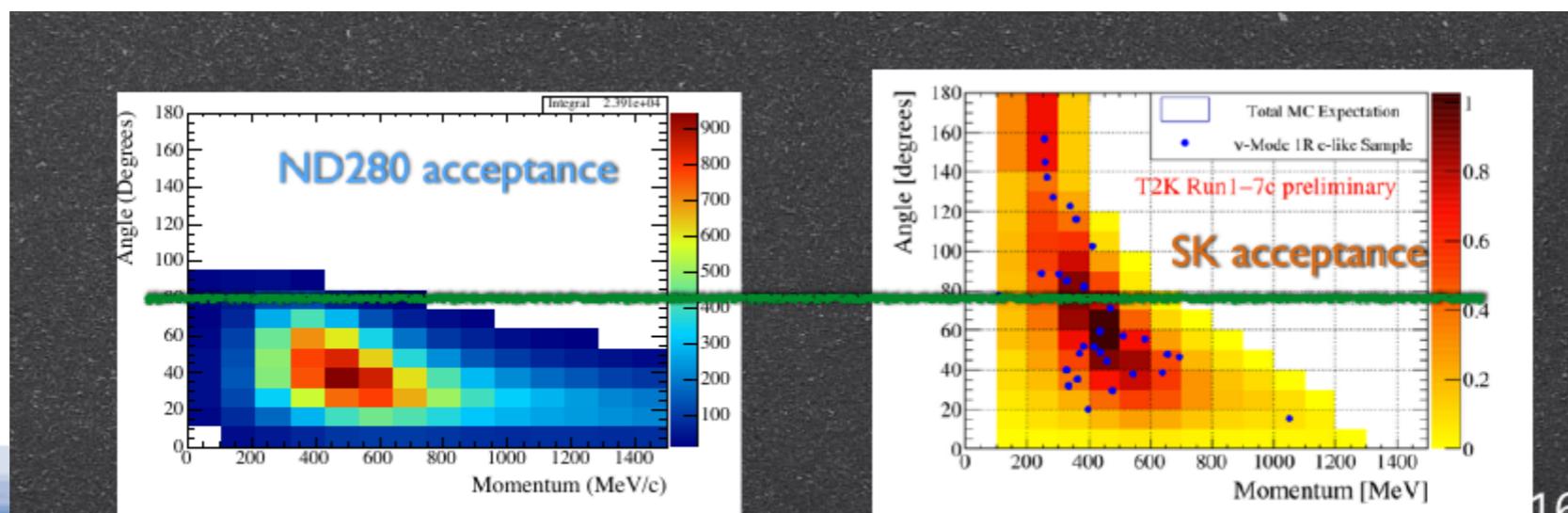
- T2K's long term goal is the pursuit CP Violation in the neutrino sector.
- In 2016, T2K run extension given Stage-1 status by KEK/J-PARC.
- Proposal to collect  $20 \times 10^{21}$  POT by ~2025 ([arXiv:1609.04111 \[hep-ex\]](https://arxiv.org/abs/1609.04111)).
- With  $20 \times 10^{21}$  POT, T2K has up to 3 $\sigma$  CPV sensitivity:
  - Sensitivity improves beyond 3 $\sigma$  with reduced systematic errors;
  - Beam, ND upgrades motivated by systematic error goals.

# ND280 upgrade project

M. Zito

## ND280 limitations

- One of the main limitations of the ND280 data used for the oscillation analyses is that they mainly cover the forward region while SK has a  $4\pi$  acceptance
- Model dependence when extrapolating to the full phase space
- The neutrino-nucleus cross-section is not well known, an upgrade is necessary to reduce the systematic errors for T2K-II



7

16

# Timeline of progress so far

- 2013–2015: ND280 upgrade R&D WG
- 2015–2016 ND280 Upgrade Task Force
  - November 2016 Open Workshop at CERN
- January 2017 Expression of Interest submitted to CERN SPSC (towards a project in the framework of the CERN Neutrino Platform)
- February 2017: the ND280 project formally approved by T2K
- March & May 2017: workshops at CERN and Tokai
- Aug 1–2 2017: 4th workshop, at CERN

## Expression of Interest SPSC-EOI-015

- Signed by ~190 physicists
- From Bulgaria, Canada, France, Italy, Japan, Germany, Poland, Spain, Sweden, Switzerland, UK, USA
- And CERN
- Aims to be part of the CERN neutrino platform
- Proposal by the end of 2017

Near Detectors based on gas TPCs for neutrino long baseline experiments<sup>1</sup>

P. Hamacher-Baumann, L. Koch, T. Radermacher, S. Roth, J. Steinmann  
RWTH Aachen University, III. Physikalisches Institut, Aachen, Germany

V. Berardi, M.G. Catanesi, R.A. Intonti, L. Magaletti, E. Radicioni  
INFN and Dipartimento Interateneo di Fisica, Bari, Italy

S. Bordoni, A. De Roeck, D. Mladenov, M. Nessi, F. Resnati  
CERN, Geneva, Switzerland

Z. Liptak, J. Lopez, A. Marino, Y. Nagai, E. D. Zimmerman  
University of Colorado at Boulder, Department of Physics, Boulder, Colorado, U.S.A.

Y. Hayato, M. Ikeda, M. Nakahata, Y. Nakajima, Y. Nishimura  
University of Tokyo, Institute for Cosmic Ray Research, Kamioka Obs., Kamioka, Japan

M. Antonova, A. Izmaylov, A. Kostin, M. Khabibullin, A. Khotjantsev, Y. Kudenko, A. Mefodiev, O. Minnev, T. Ovsiannikova, S. Suvorov, N. Yershov  
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

F. Sanchez, M. Cavalli-Sforza, T. Lux, B. Bourguille, M. Leyton  
Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, Bellaterra (Barcelona) Spain

J. Arney, P.J. Dunne, P. Jonsson, R.P. Litchfield, W. Ma, L. Pickering, M. A. Uchida, Y. Uchida, M.O. Wascko, C.V.C. Wret  
Imperial College, London, United Kingdom

C. Bronner, M. Hartz, M. Vagins  
Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa, Chiba, Japan

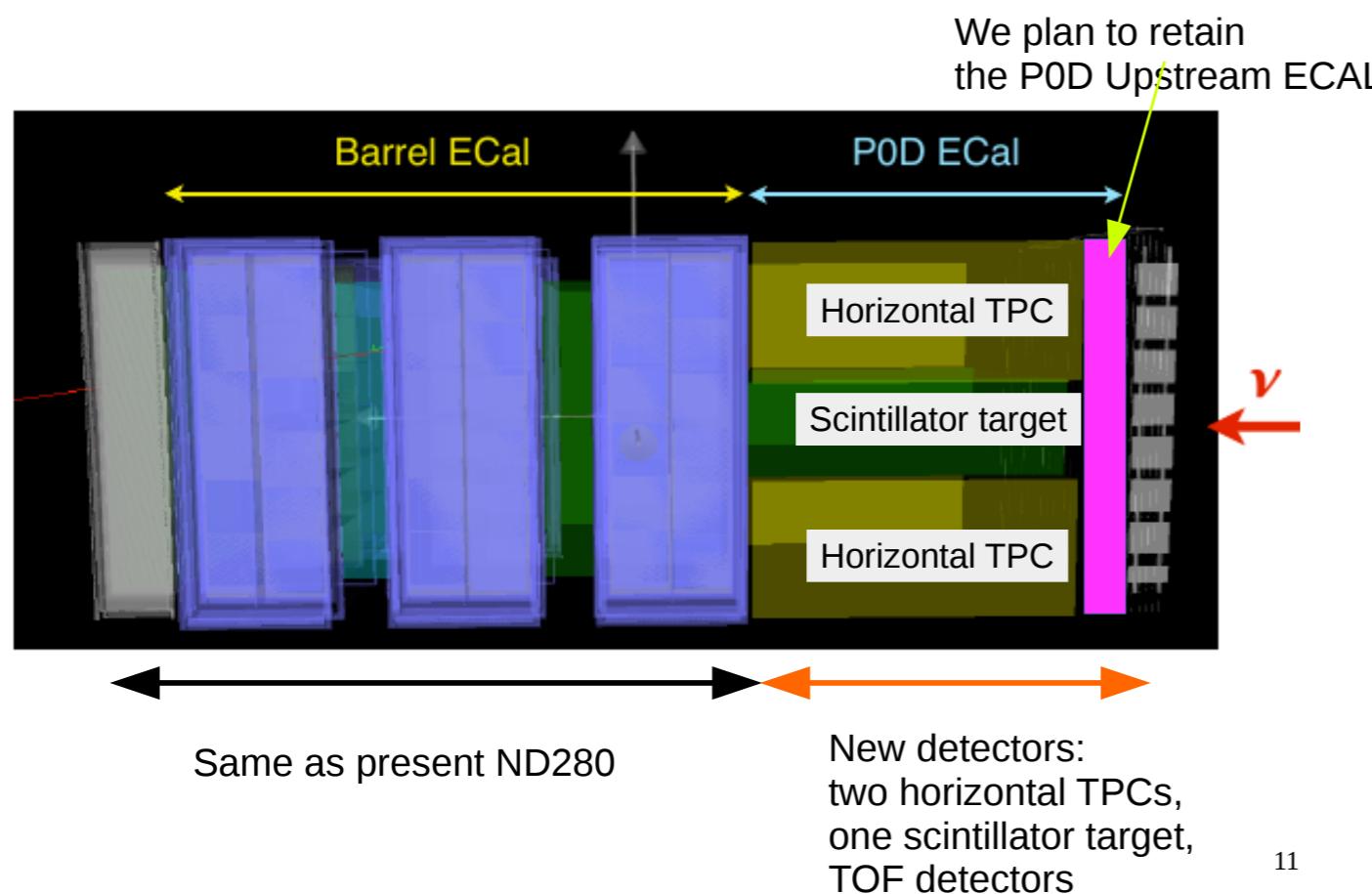
S. Bolognesi, D. Calvet, P. Colas, A. Delbart, S. Emery, F. Gizzarelli, M. Lamoureux, M. Martini, E. Mazzucato, G. Vasseur, M. Zito  
IRFU, CEA Saclay, Gif-sur-Yvette, France

<sup>1</sup> Corresponding authors: Alain Blondel (alain.blondel@cern.ch), Marco Zito (marco.zito@cea.fr)

## Statement by T2K

On February 11, 2017, the T2K Collaboration launched its Near Detector Upgrade project. The upgrade is targeted at reducing systematic errors in T2K's search for CP violation in the neutrino sector. The current conceptual design will be developed into a technical design, leading to a full proposal, by the end of 2017. The collaboration aims to install the upgraded near detector around 2020, to fully benefit from the foreseen increase of the J-PARC MR beam power.

# Baseline configuration

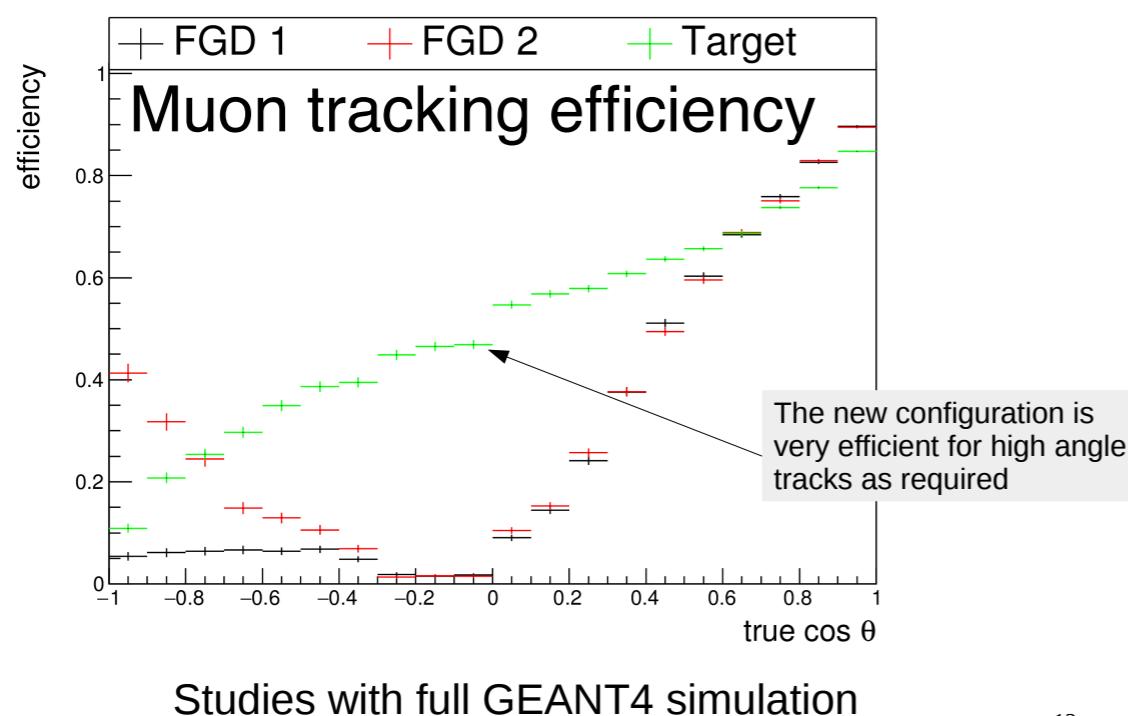


- Replace most of volume occupied by P0D with horizontally oriented detectors

- Active scintillator target
- Several options being studied based on scintillator strips and cubes

- Horizontal gas TPCs
  - Use resistive micromegas detectors

- TOF detectors surrounding new modules
- Improves high angle efficiency

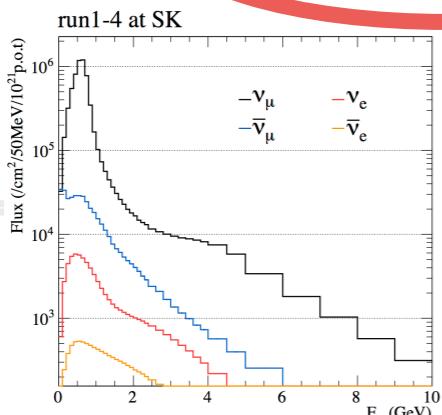


Studies with full GEANT4 simulation

12

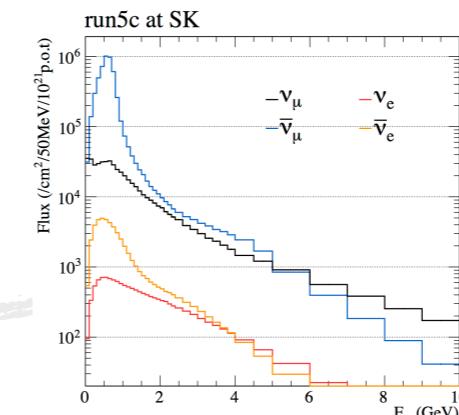
# Many possible XSEC measurements

- Four neutrino fluxes



$\nu$  mode ("FHC")

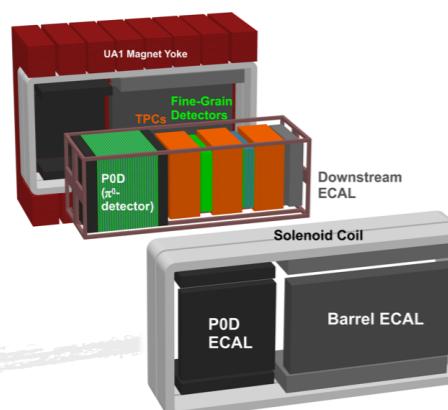
- $\nu_\mu$
- $\nu_e$



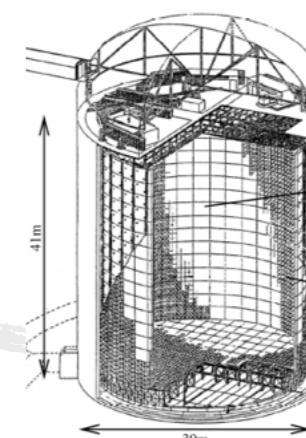
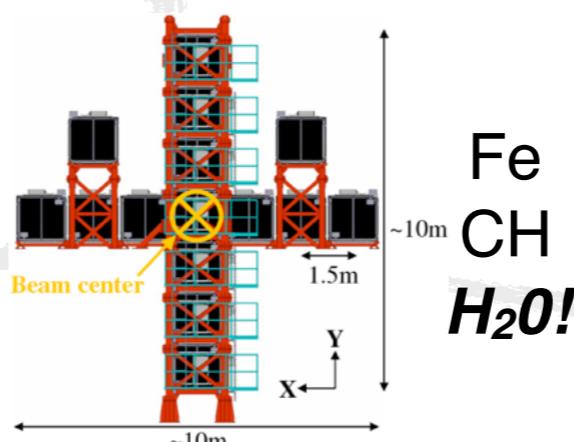
$\bar{\nu}$  mode ("RHC")

- $\bar{\nu}_\mu$
- $\bar{\nu}_e$

- Multiple detectors and target nuclei

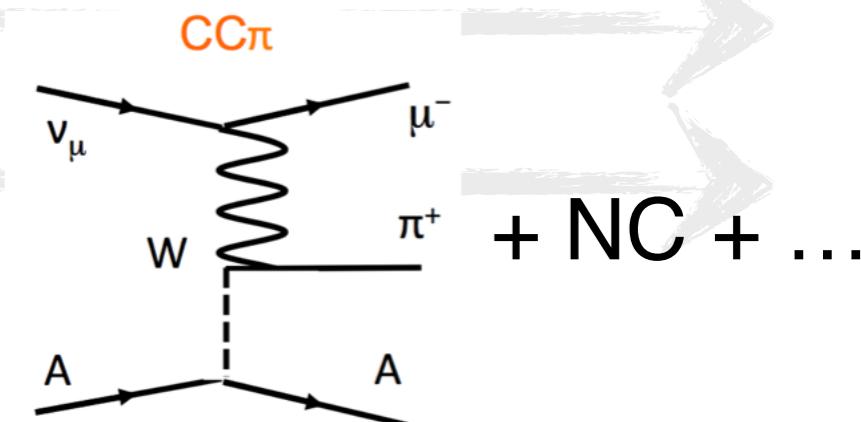
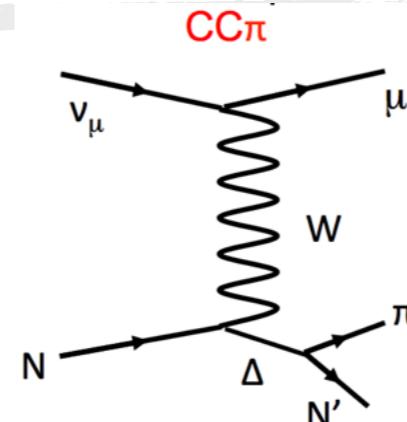
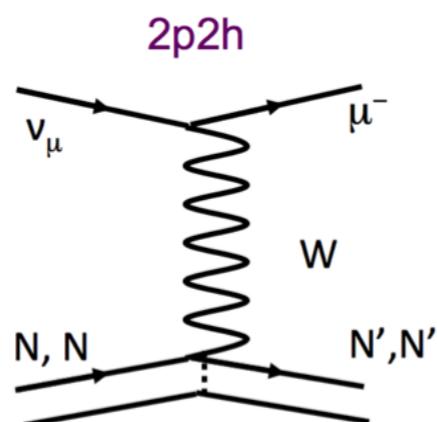
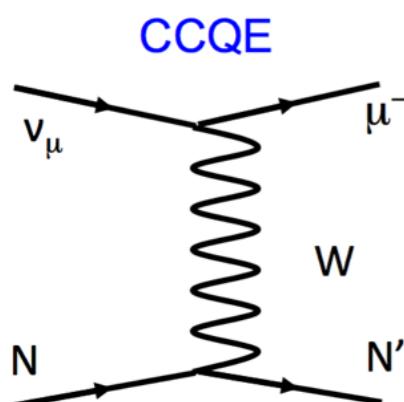


CH  
H<sub>2</sub>O  
Cu/Sn  
Pb  
Ar



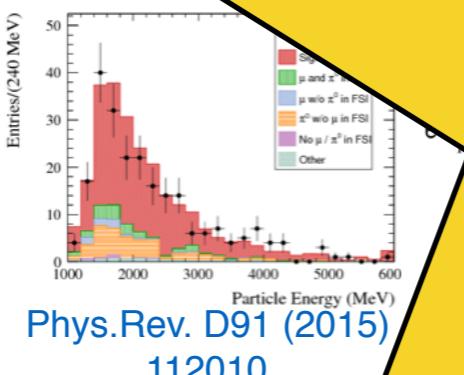
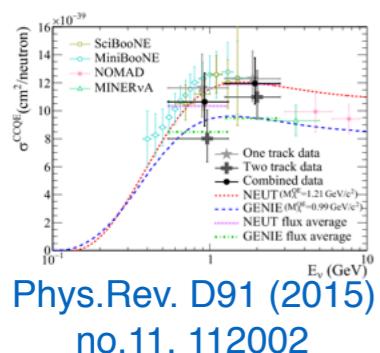
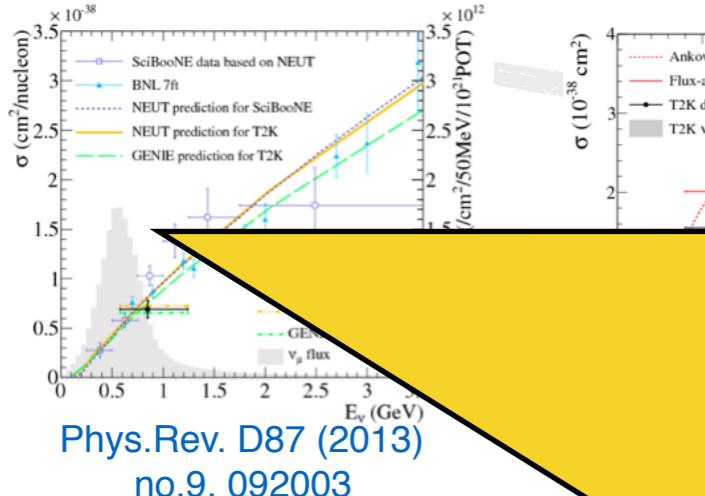
H<sub>2</sub>O

- Multiple interaction processes

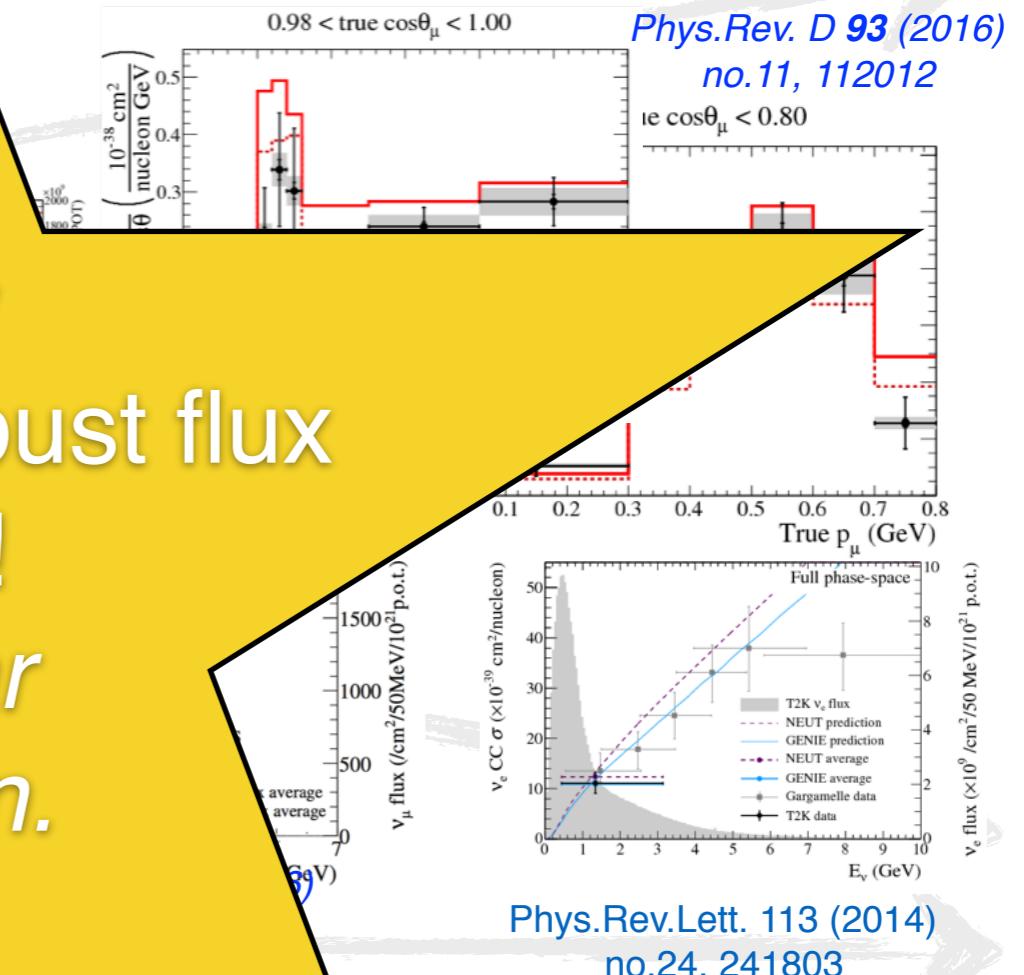


# T2K $\nu$ -nucleus interaction measurements

- Vibrant program of XSEC measurements
  - C, O, Fe targets;  $\nu_\mu$  and  $\nu_e$  fluxes
- Complementary to MINERvA accelerator neutrino experiments



Extremely  
dependent on robust flux  
prediction!  
No near-far  
cancellation.



- Upcoming measurements
  - improve resolution
  - Wider range of neutrino energies
  - More complex event topologies
  - Beginning to look at new kinematic variables for nuclear model testing
  - Antineutrino measurements!

# Summary

- T2K is making strides toward goal of studying lepton CPV.
    - Until Hyper-K/DUNE era, T2K is most sensitive experiment for lepton CPV, competing with, and complementary to, NOvA.
  - T2K has a vibrant neutrino-nucleus interaction measurement program.
- **Entire physics program of T2K needs precise flux predictions!**
- ND280 & beam line upgrade work upgrade is proceeding well.
  - NA-61/SHINE data have played a crucial role in the success of T2K!



Thank you for your attention!

ご清聴ありがとうございました