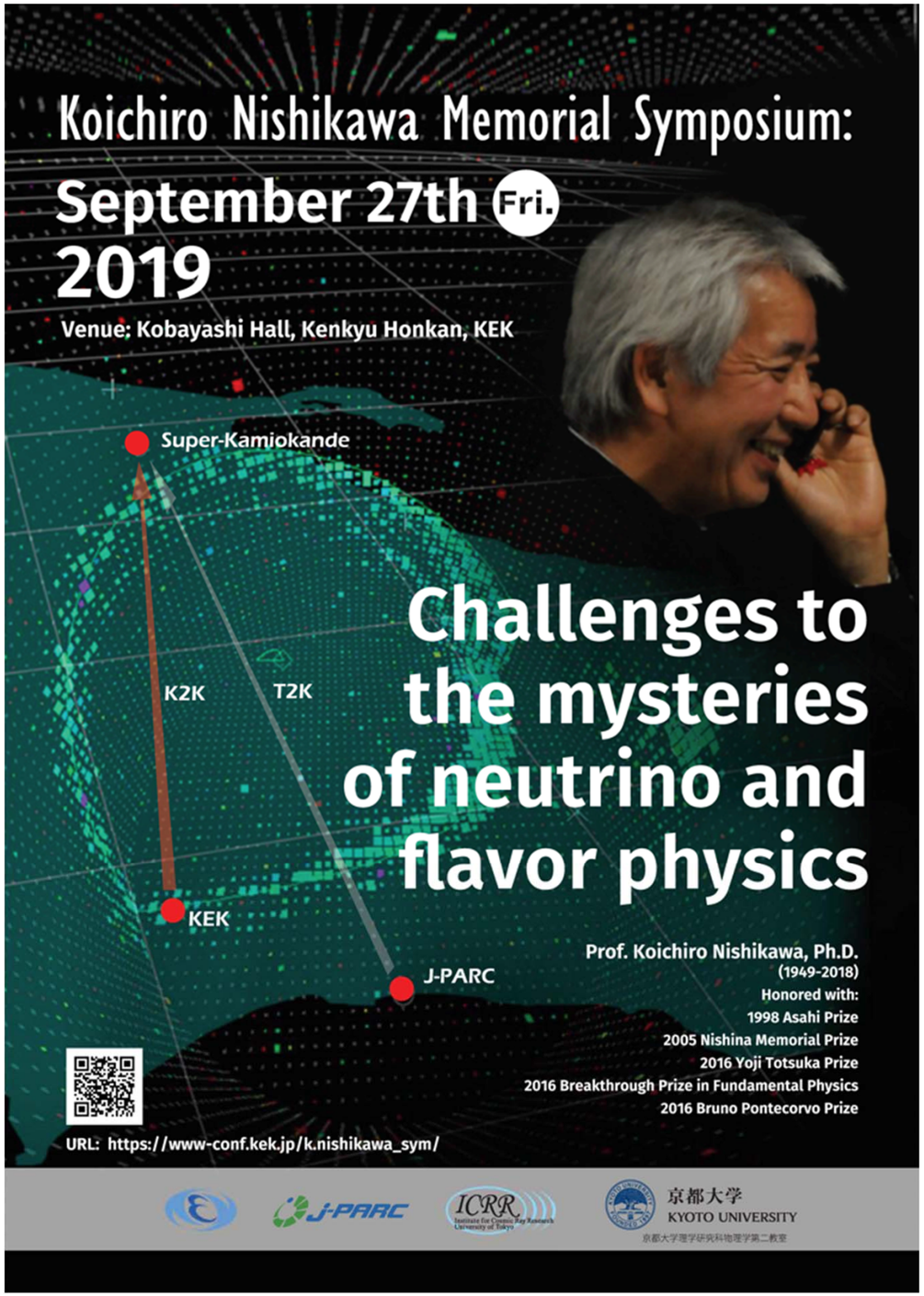
T2K and T2K-upgrade

A. K. Ichikawa (Kyoto univ.)
for the T2K collaboration



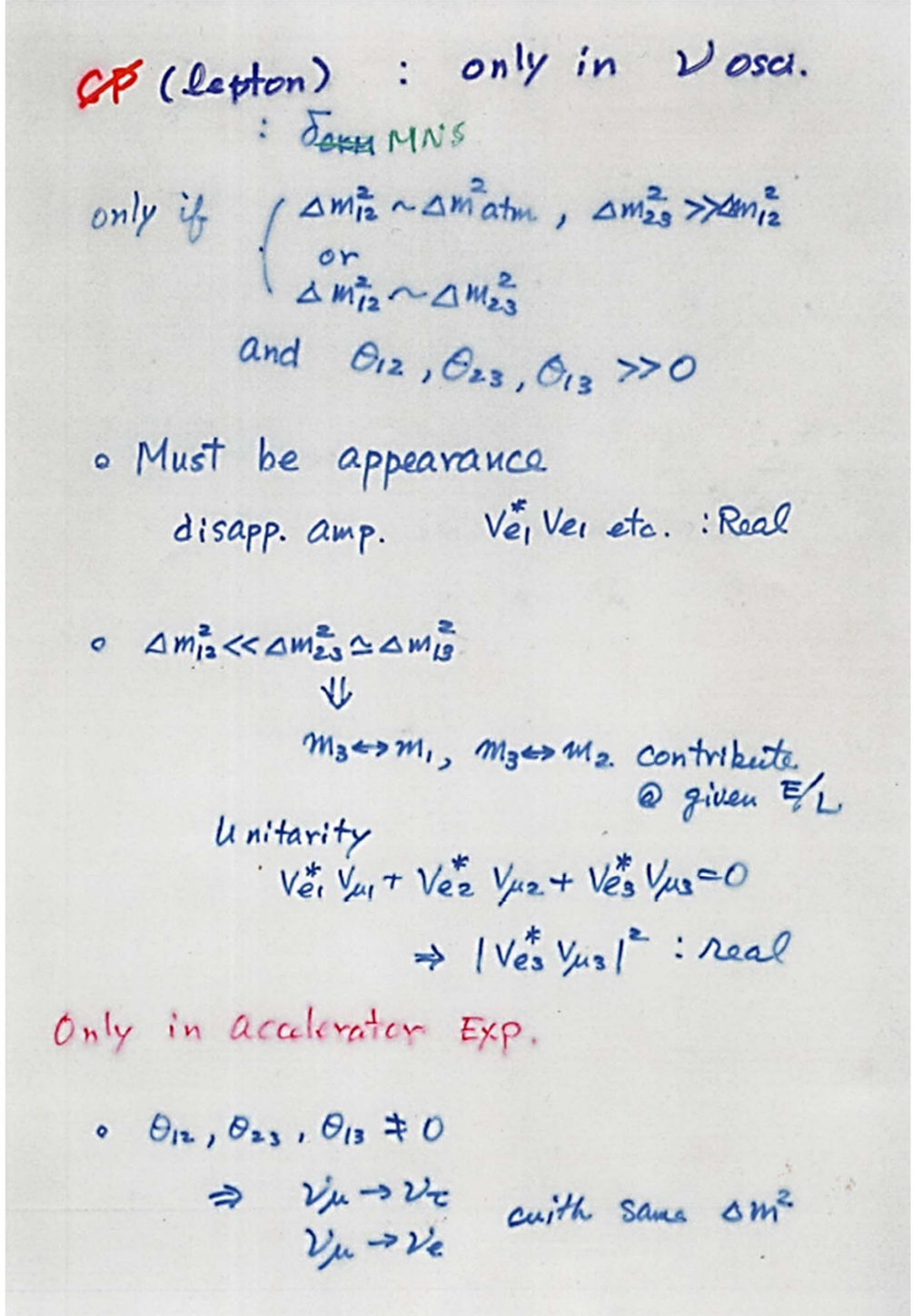
Today's slides mostly taken from my talk at "Koichiro Nishikawa Memorial Symposium" held on Sep 27th 2019

Koichiro Nishikawa (1949-2018) pioneered the long-baseline neutrino oscillation experiments as the founder of the K2K experiment and the first spokesperson of the T2K experiment.

Nishikawa-san's slide at Now1998

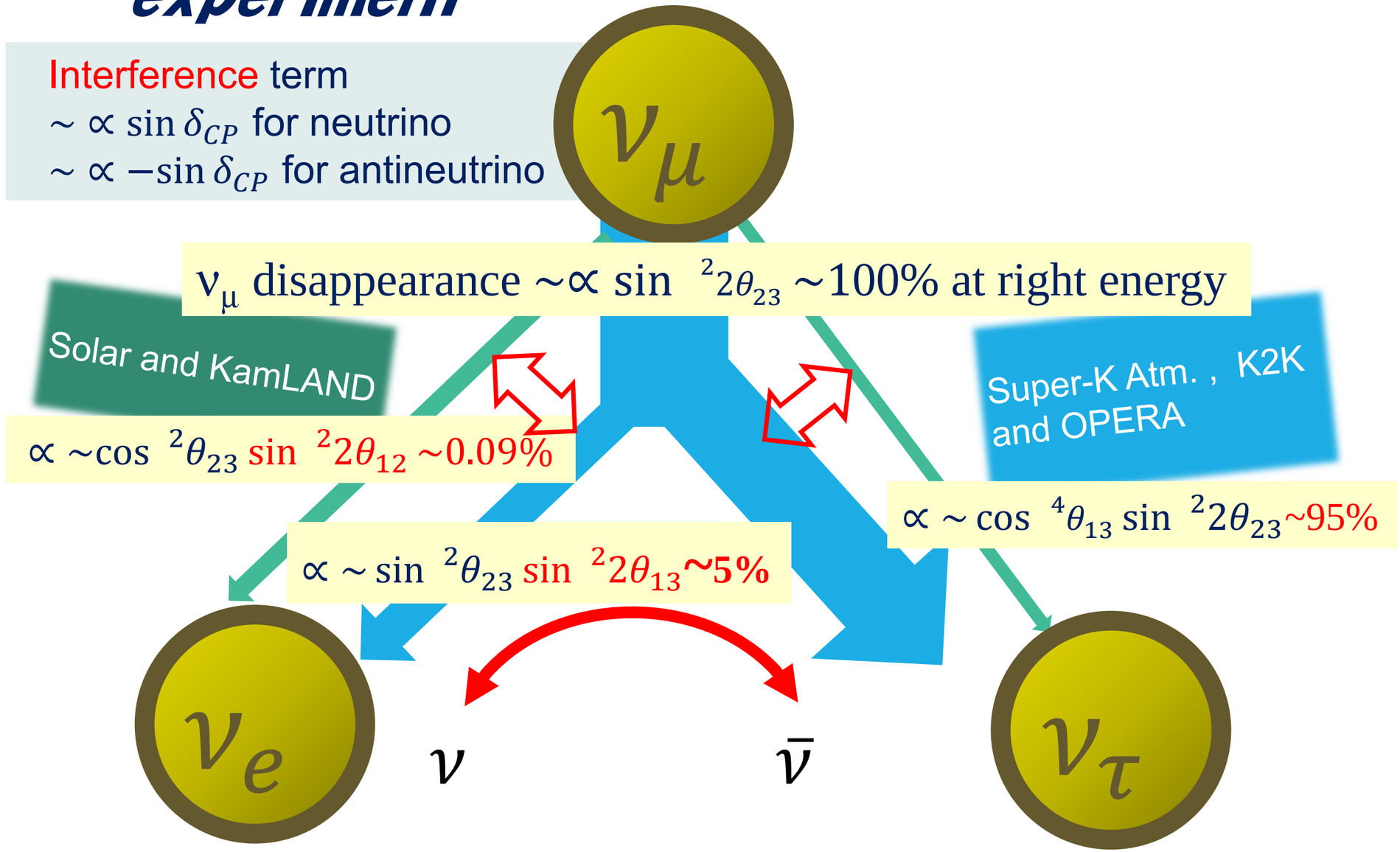
In 1999, Nishikawa-san & Totsuka-san proposed to measure ν_e appearance as a next critical step toward CP measurement.

At that time, K2K, the first accelerator-based long baseline neutrino oscillation experiment, was running.



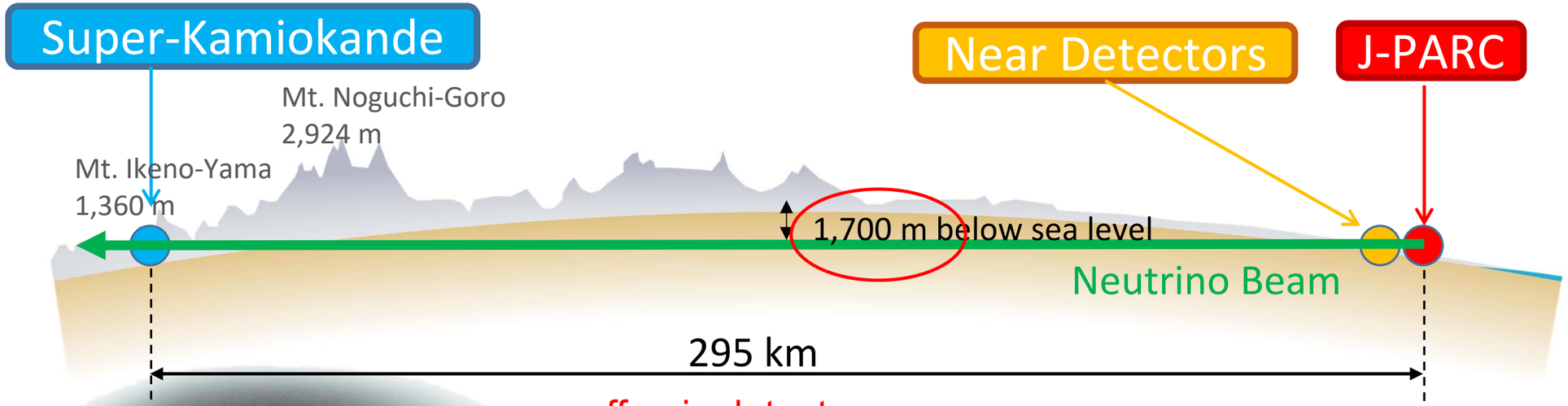
Oscillations peculiar to the Acc.-based long baseline experiment

Interference term
$\sim \propto \sin \delta_{CP}$ for neutrino
$\sim \propto -\sin \delta_{CP}$ for antineutrino

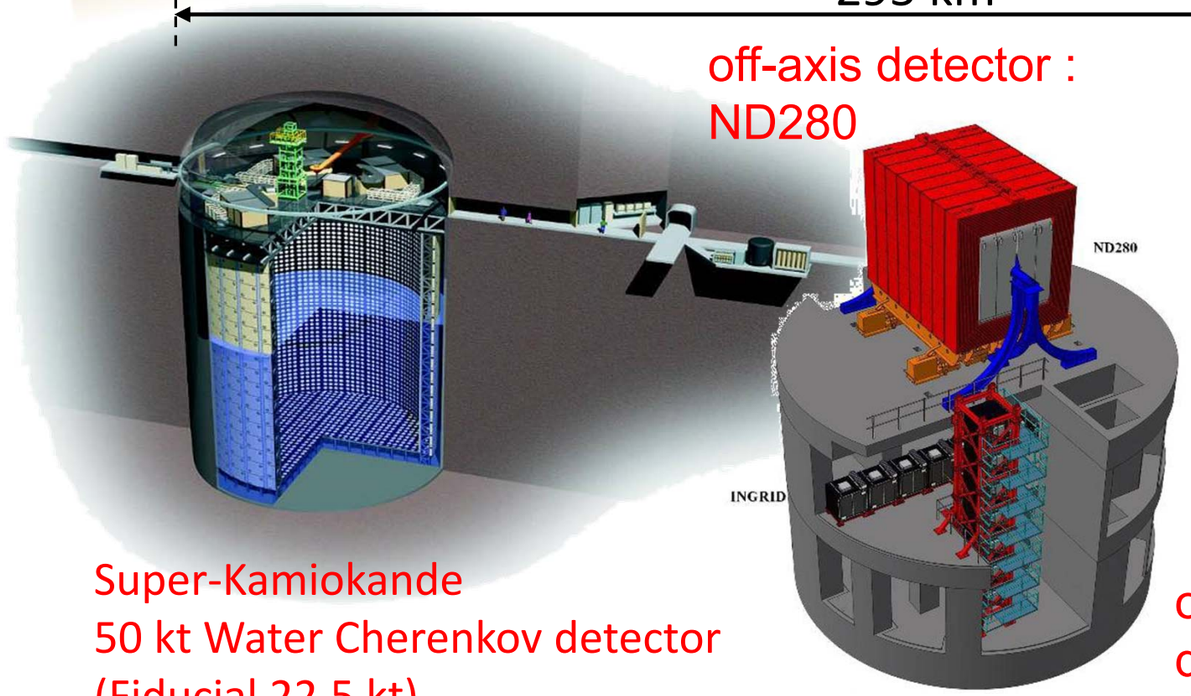


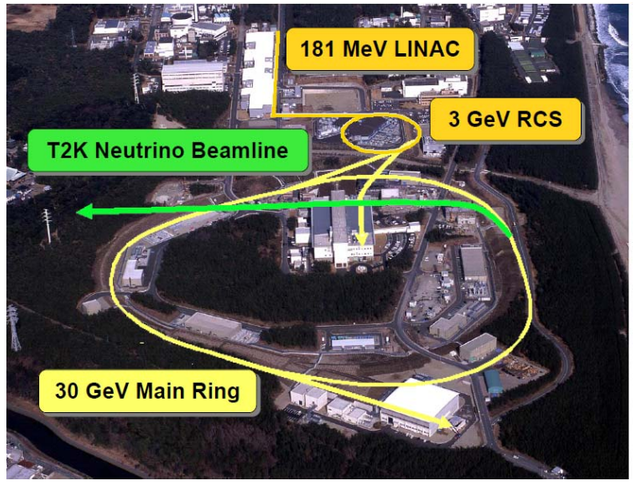
T2K Experiment, started in 2009

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



off-axis detector :
ND280





Super-Kamiokande
50 kt Water Cherenkov detector
(Fiducial 22.5 kt)

on-axis
detector
: INGRID

Evolution from K2K to T2K(-I)

- Larger and More international collaboration
- Higher intensity proton accelerator and neutrino beamline
- Narrower neutrino energy beam
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- Near detector

- Significant analysis improvement on Super-K
- Neutrino and hadronic interaction models

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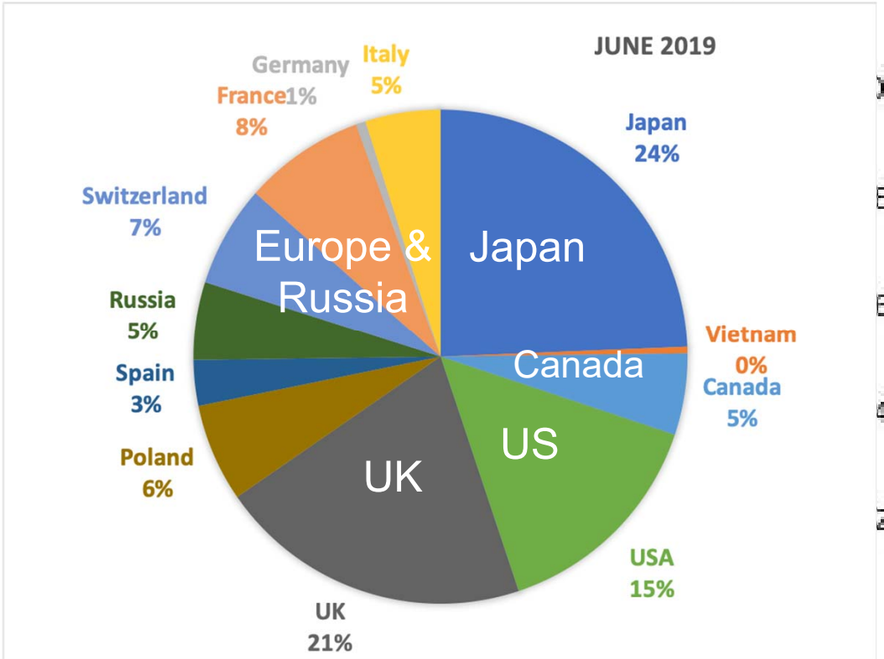
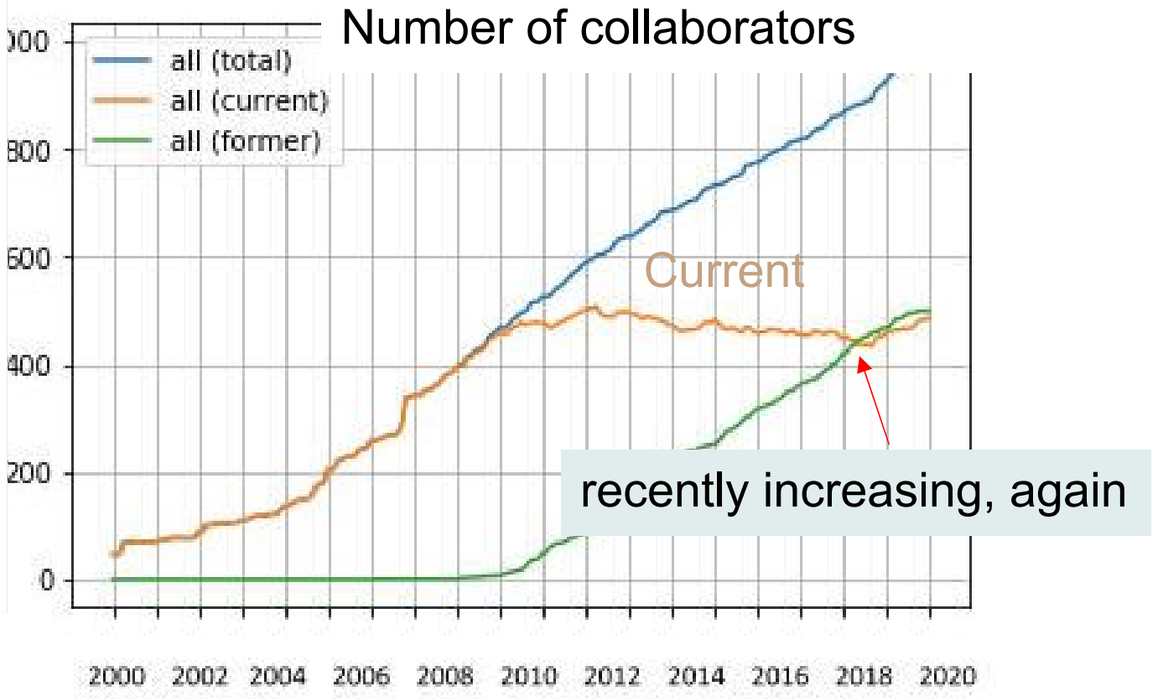
T2K collaboration

~500 members, 68 Institutes, 12 countries





As of 2018,

- ✓ 44 original articles
- ✓ Total citations of papers adds up to 5,972
- ✓ 116 Ph.D theses

Collaboration photo taken in 2019 at Paris

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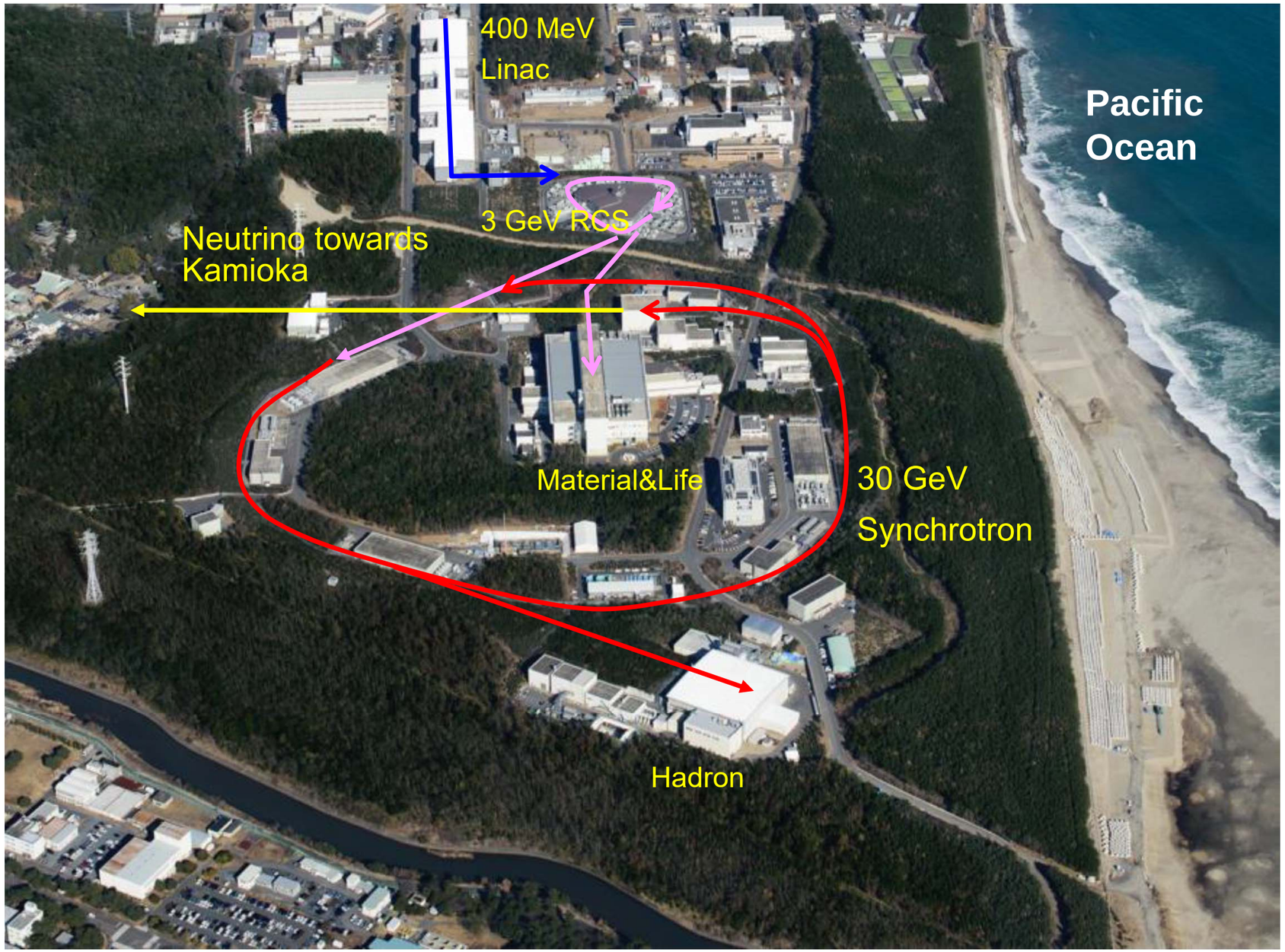
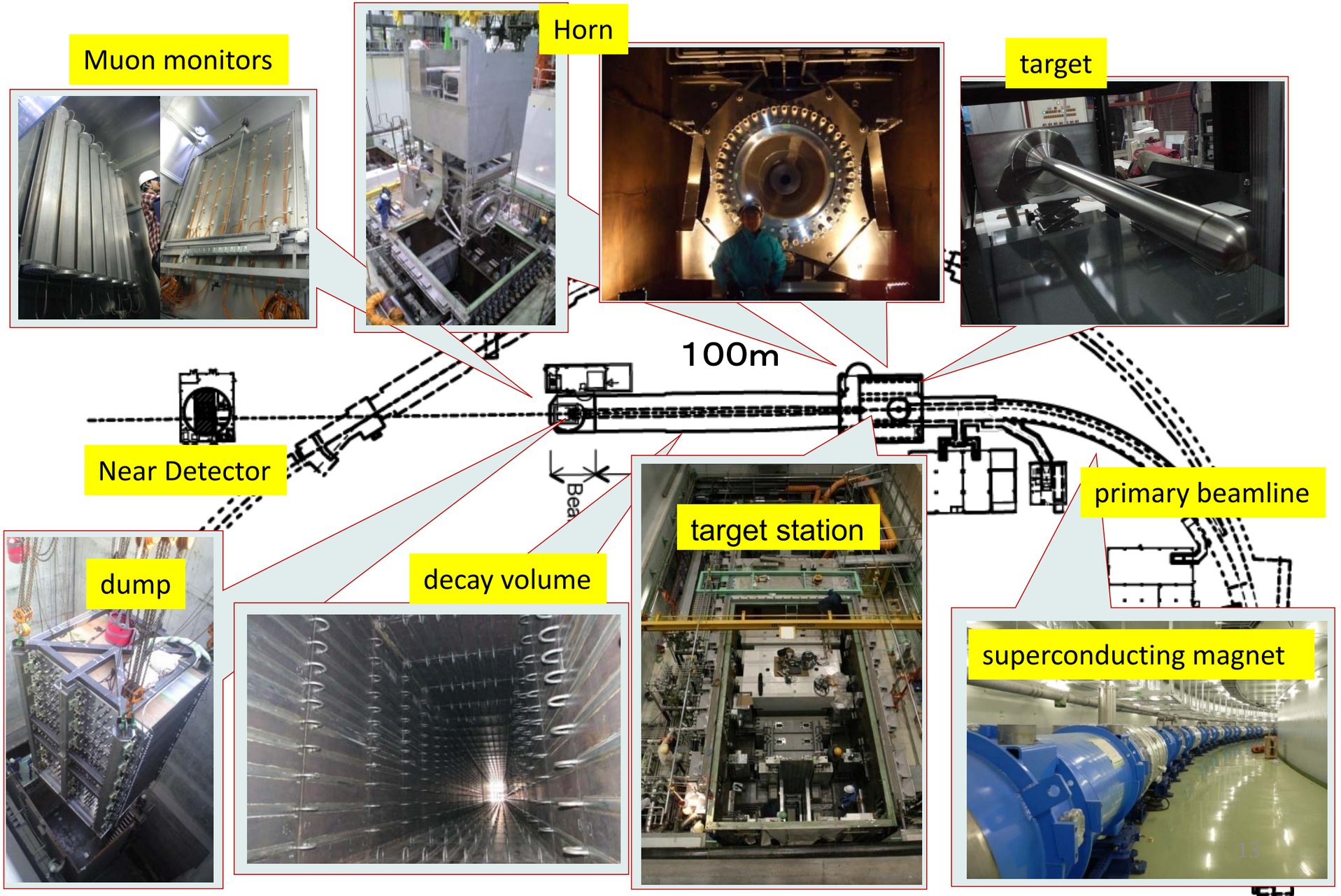
T2K J-PARC Japan Proton Accelerator Research Complex

Joint project of KEK & Japan Atomic Energy Agency

Construction from 2001 to 2008



Neutrino Beamline



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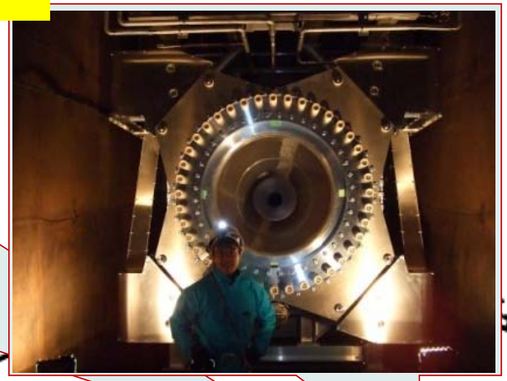
Neutrino Beamline

Muon monitors

Horn



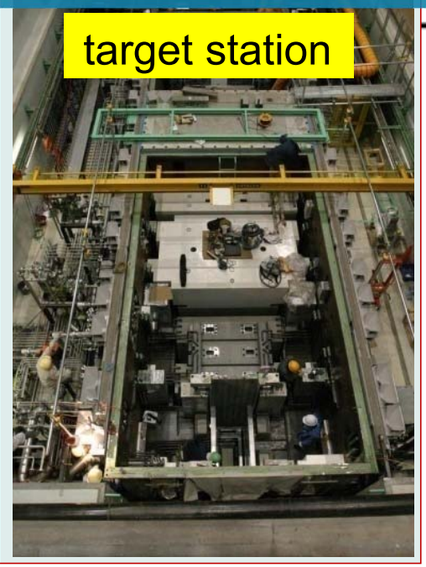
target

Designed for
- ✓ 0.75 MW for upgradable parts with a few exceptions
- ✓ 3 MW for non-upgradable parts

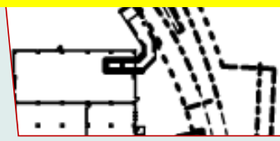
dump

decay volume

target station



primary beamline



superconducting magnet

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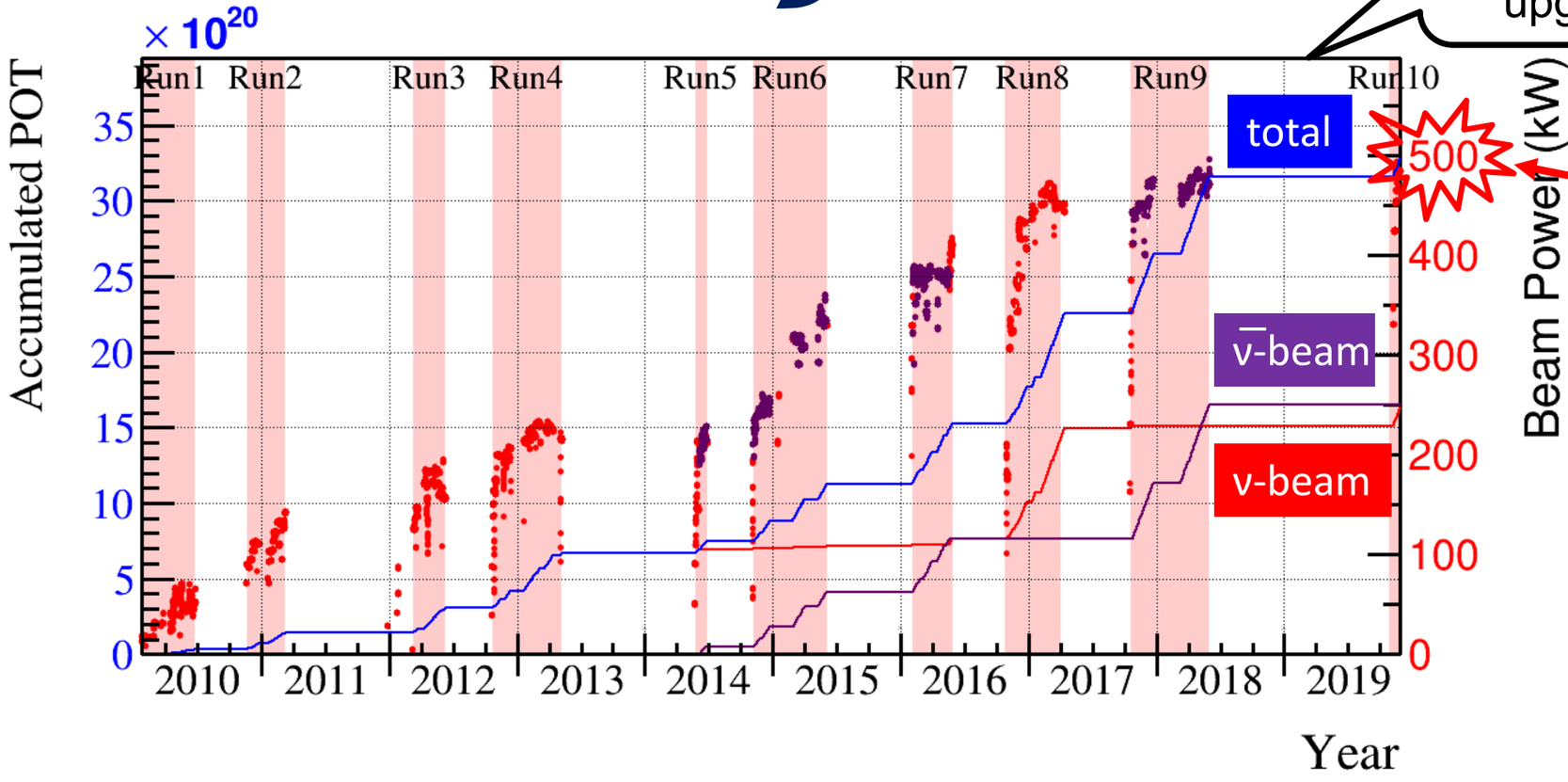
Data taking status

Beamtime limited in 2019 and 2020 to prioritize accelerator upgrade for higher intensity



Now, running stably at 496 kW beam power

23 Jan. 2010 – 27 Nov. 2019
POT total: 3.29×10^{21}

		Analyzed
ν-mode	1.63×10^{21} (49.76%)	1.51×10^{21} POT
$\bar{\nu}$-mode	1.65×10^{21} (50.24%)	1.65×10^{21} POT

cf. T2K-I goal : 7.8×10^{21} POT , T2K-II goal : 20×10^{21} POT

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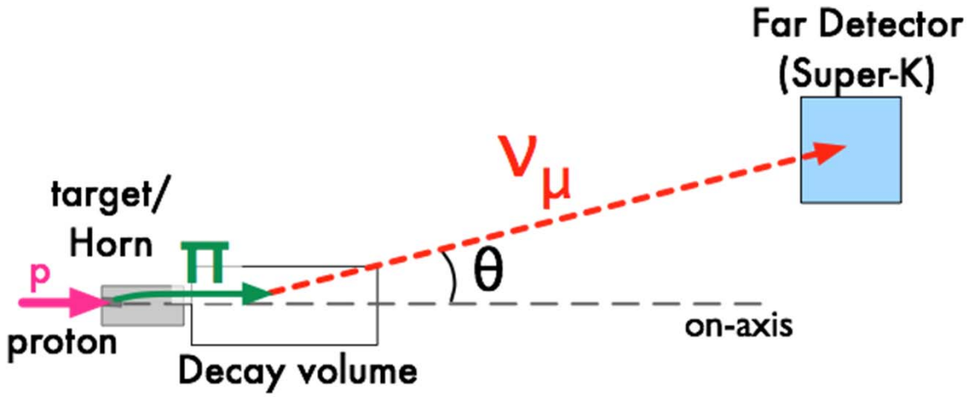
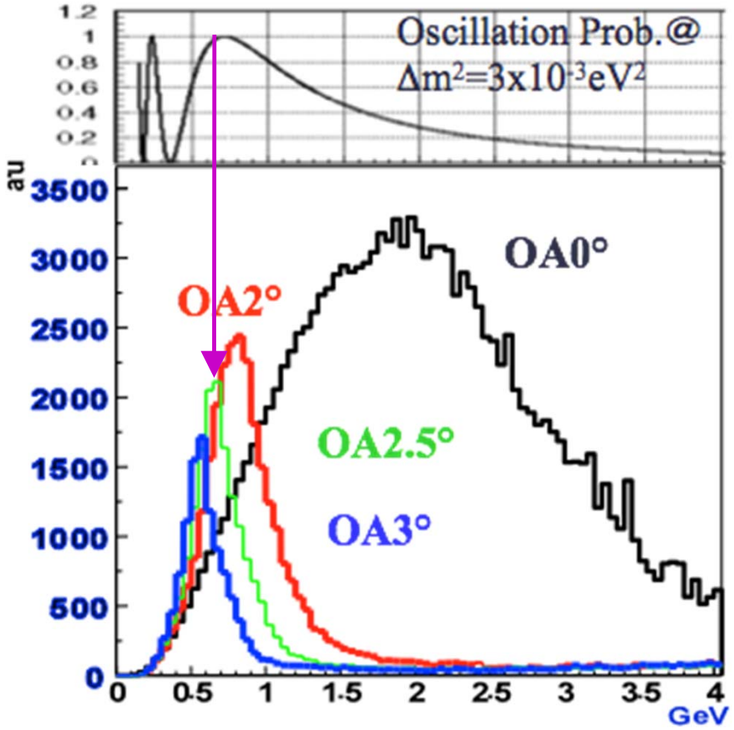
Off-axis beam : intense & narrow-band beam





- ✓ Idea in BNL-E889 Proposal
- ✓ Pseud monochromatic beam utilizing pion decay kinematics
- ✓ T2K off-axis angle is 2.5°

  peak energy at oscillation max. (~0.6GeV at L=295km)
- ✓ more signal, less background

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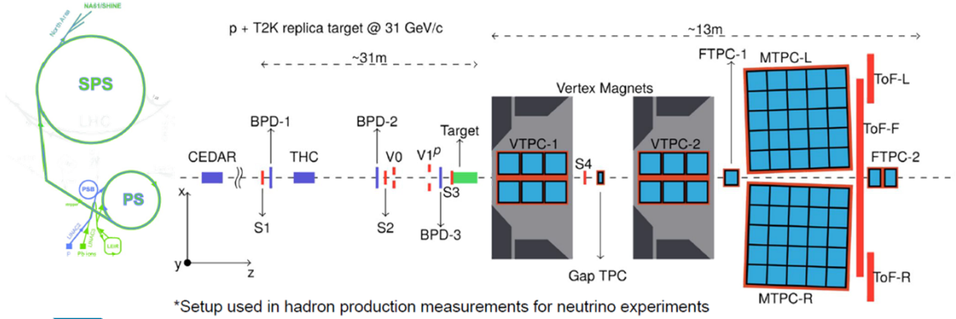
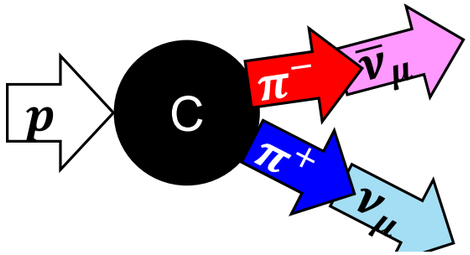
Measurement of p+C interaction at 30 GeV for precise neutrino flux prediction

North **A**rea **61** / **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
NA61 / SHINE

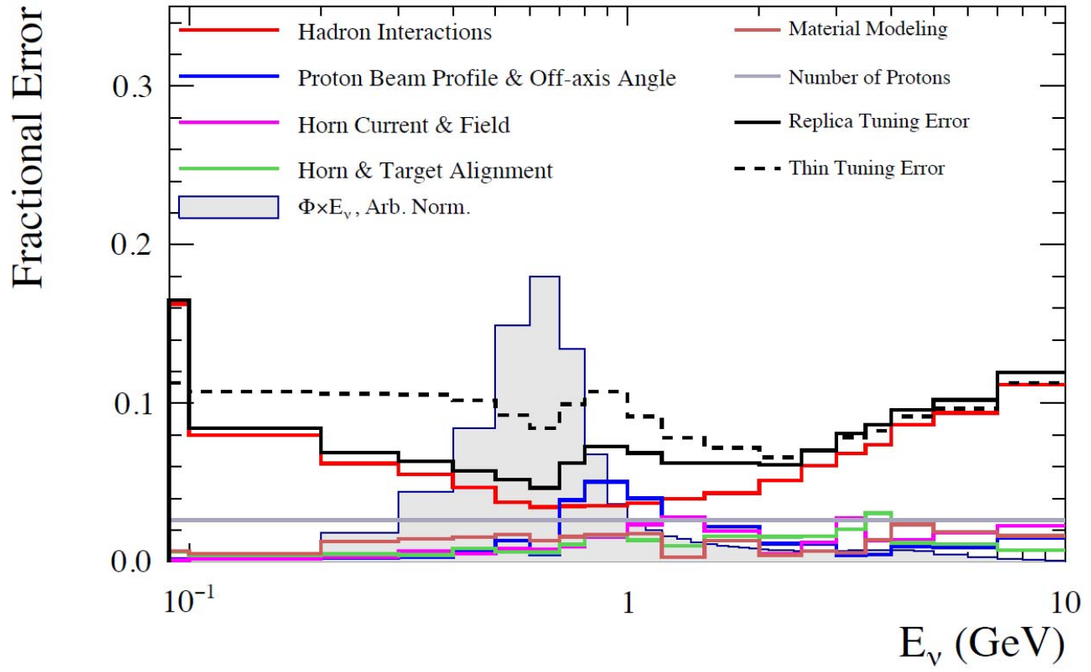


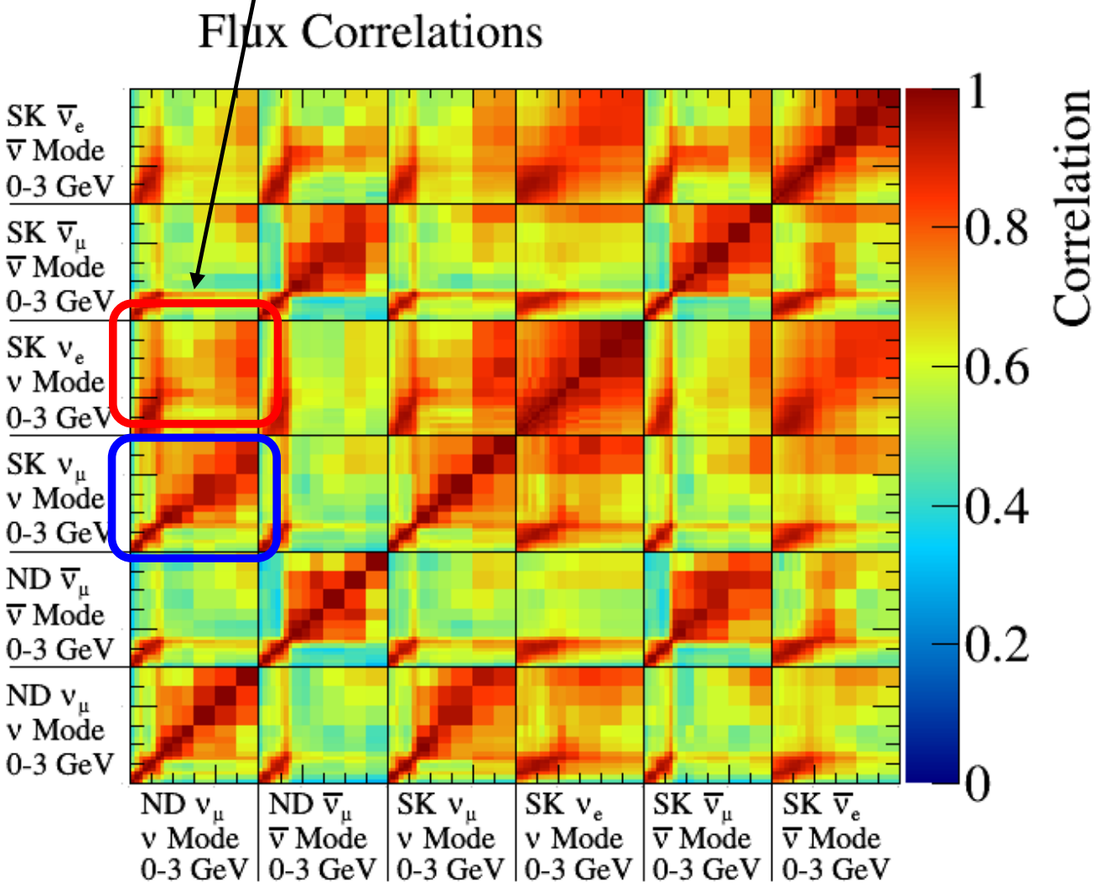
*Setup used in hadron production measurements for neutrino experiments



ND ν_μ measurement constrains
SK ν_μ
SK ν_e

Flux uncertaintynow, 5% at peak energy





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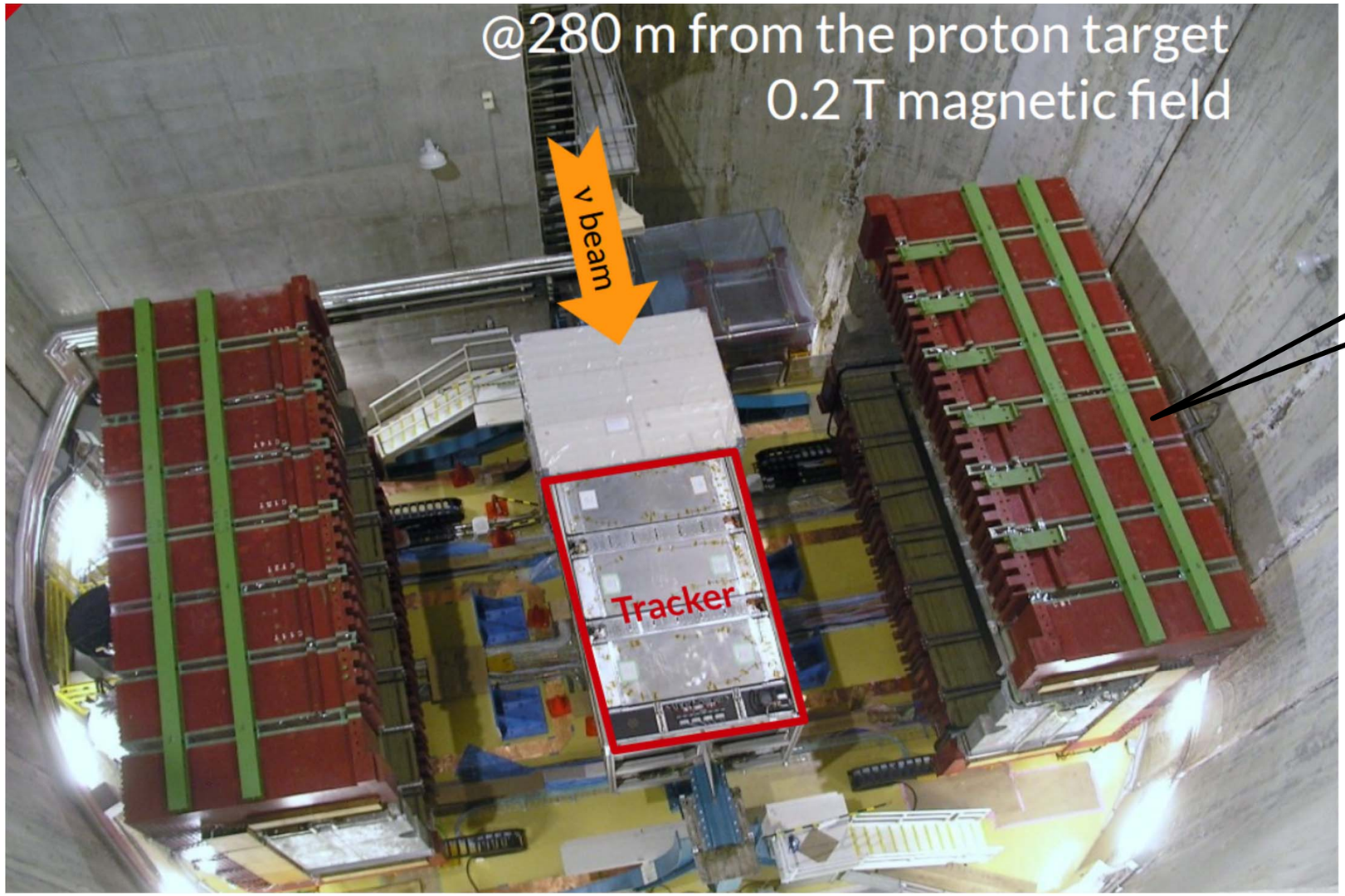
off-axis near detector: ND280



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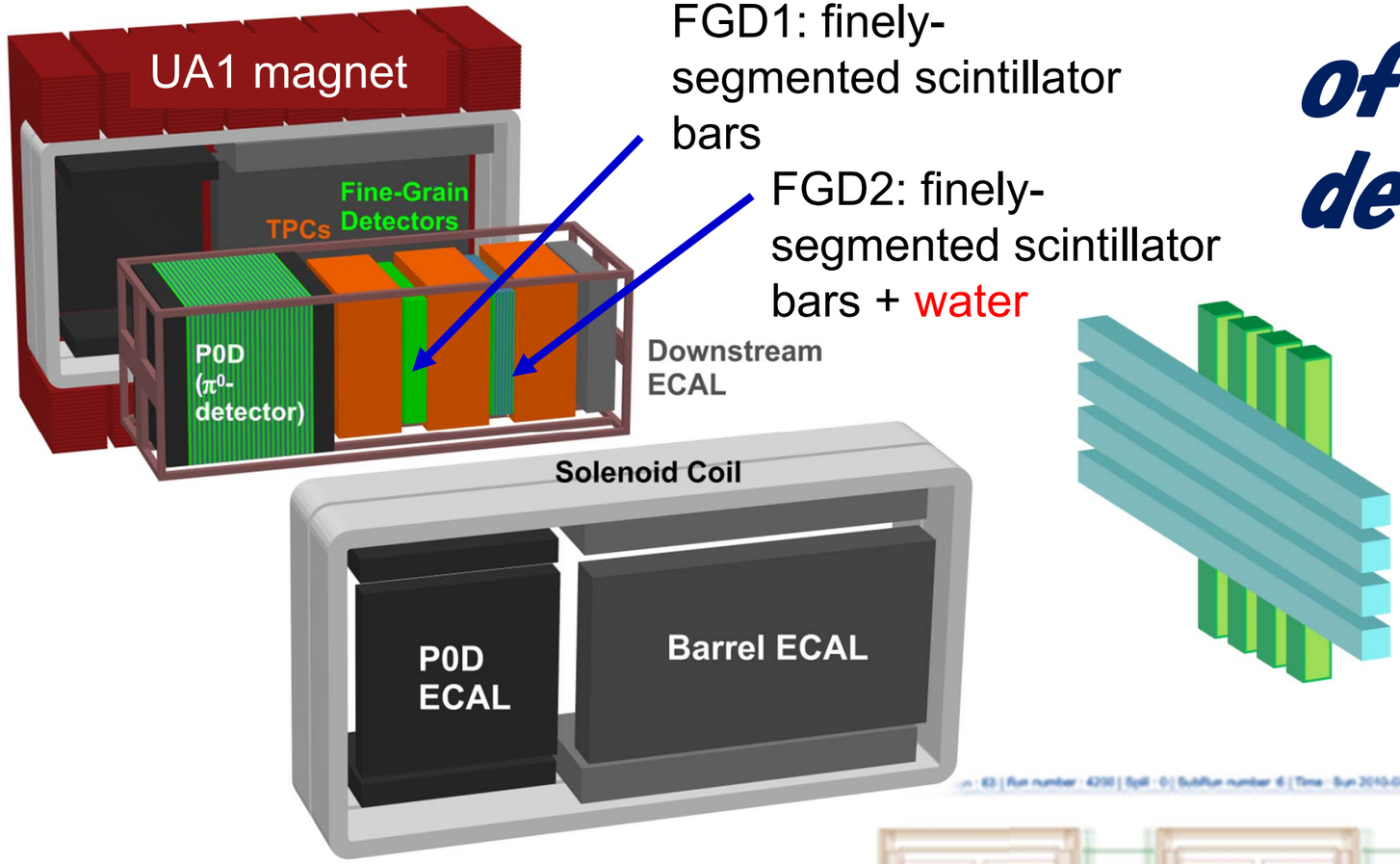
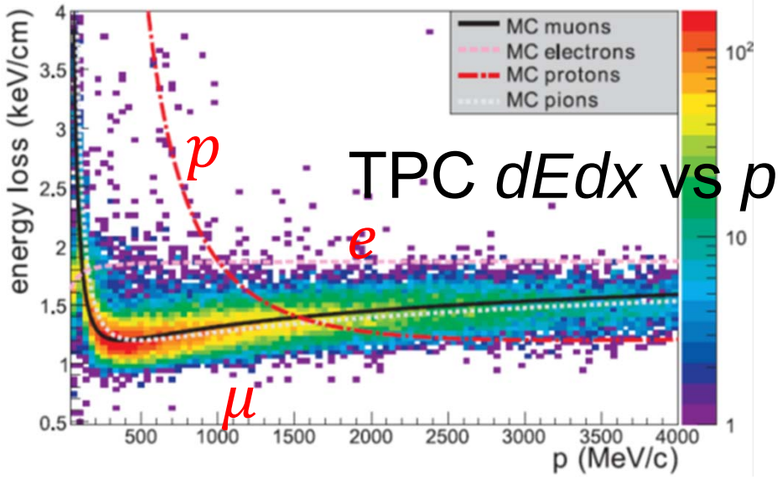
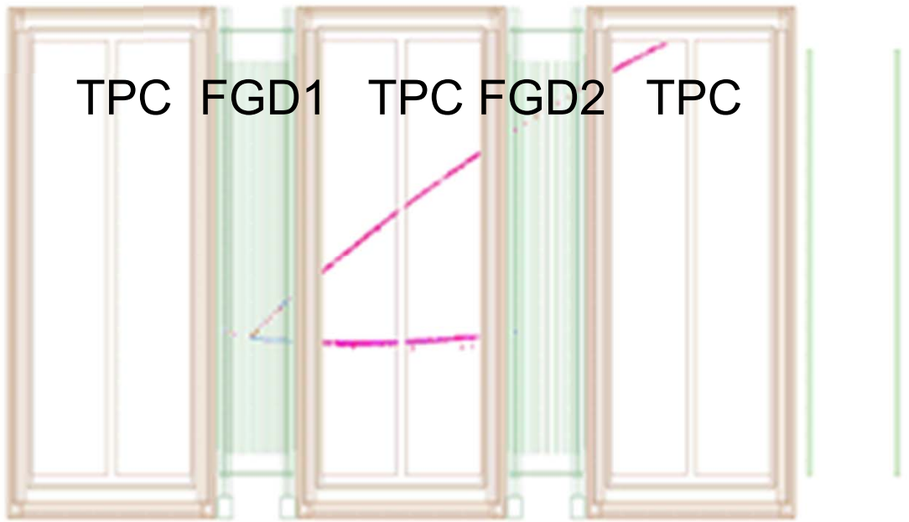


FGD1: finely-segmented scintillator bars

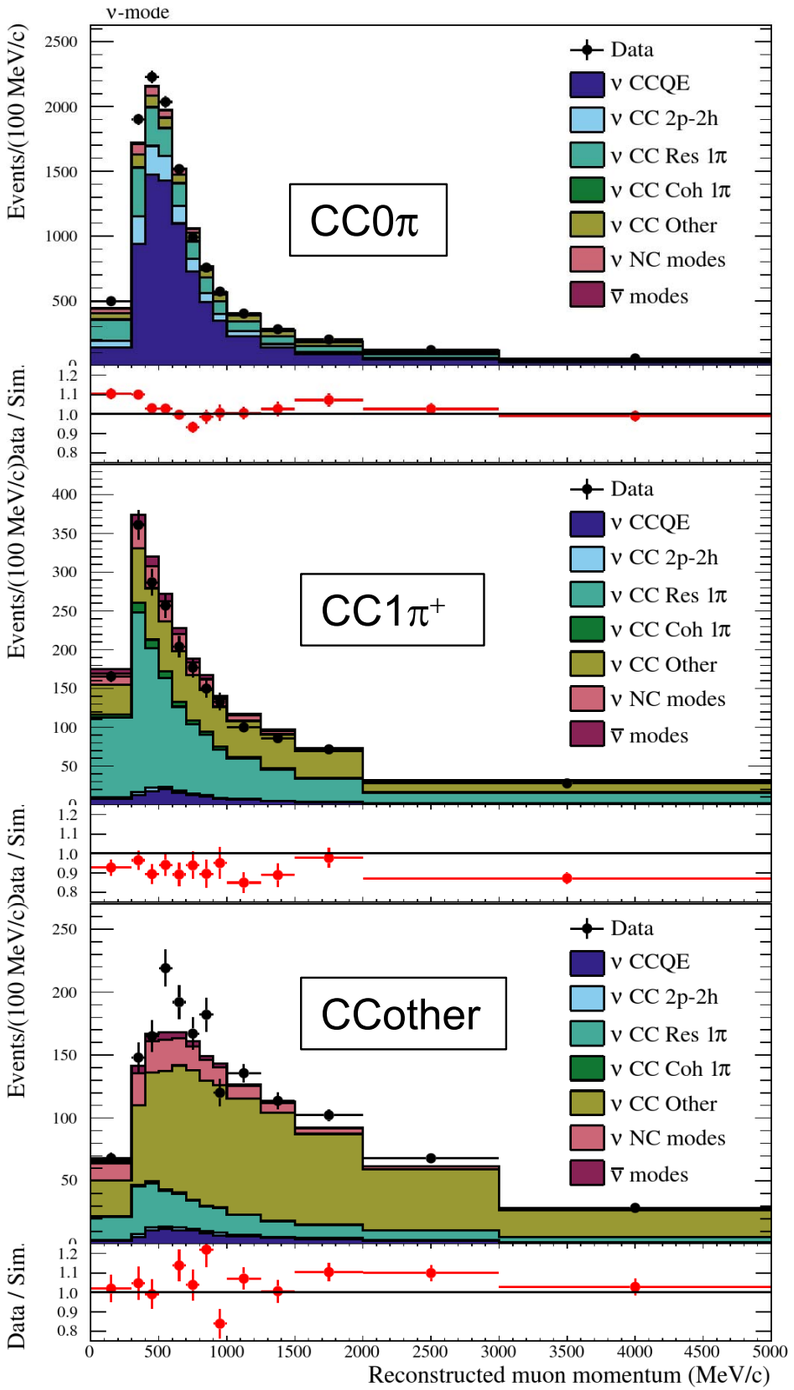
FGD2: finely-segmented scintillator bars + water



TPC *dEdx* vs *p*

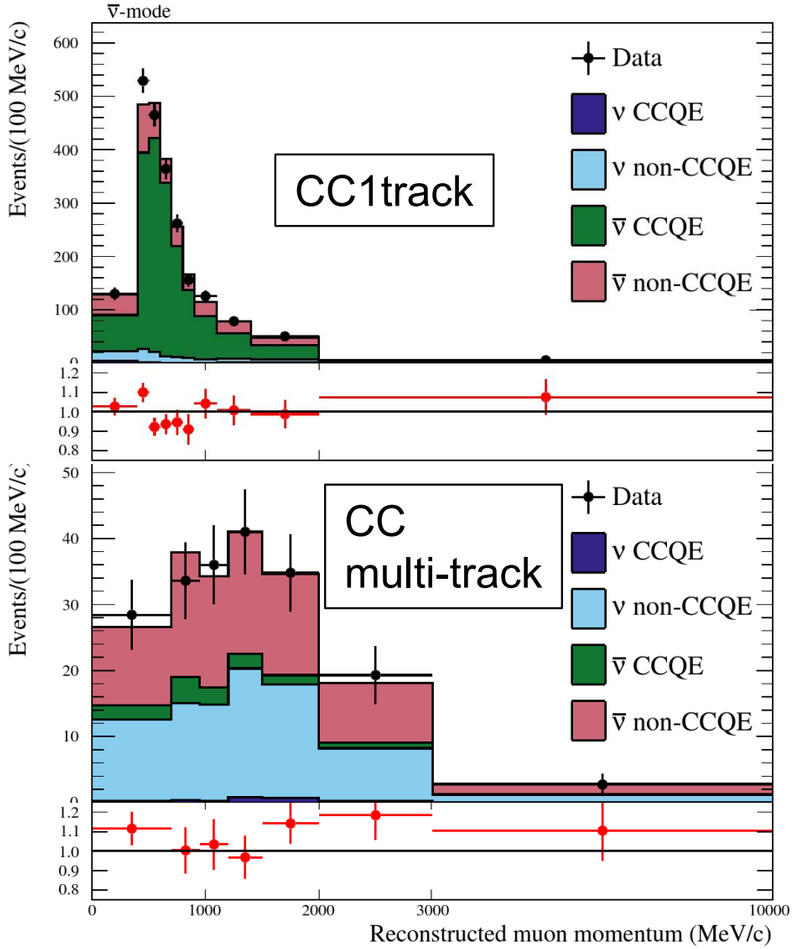


neutrino beam mode



Momentum distribution
Colors represent interaction types

anti-neutrino beam mode



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- **Near detector**
  Fine-grained active target with surrounding detectors for charge-ID, PID and momentum-ID in Magnet
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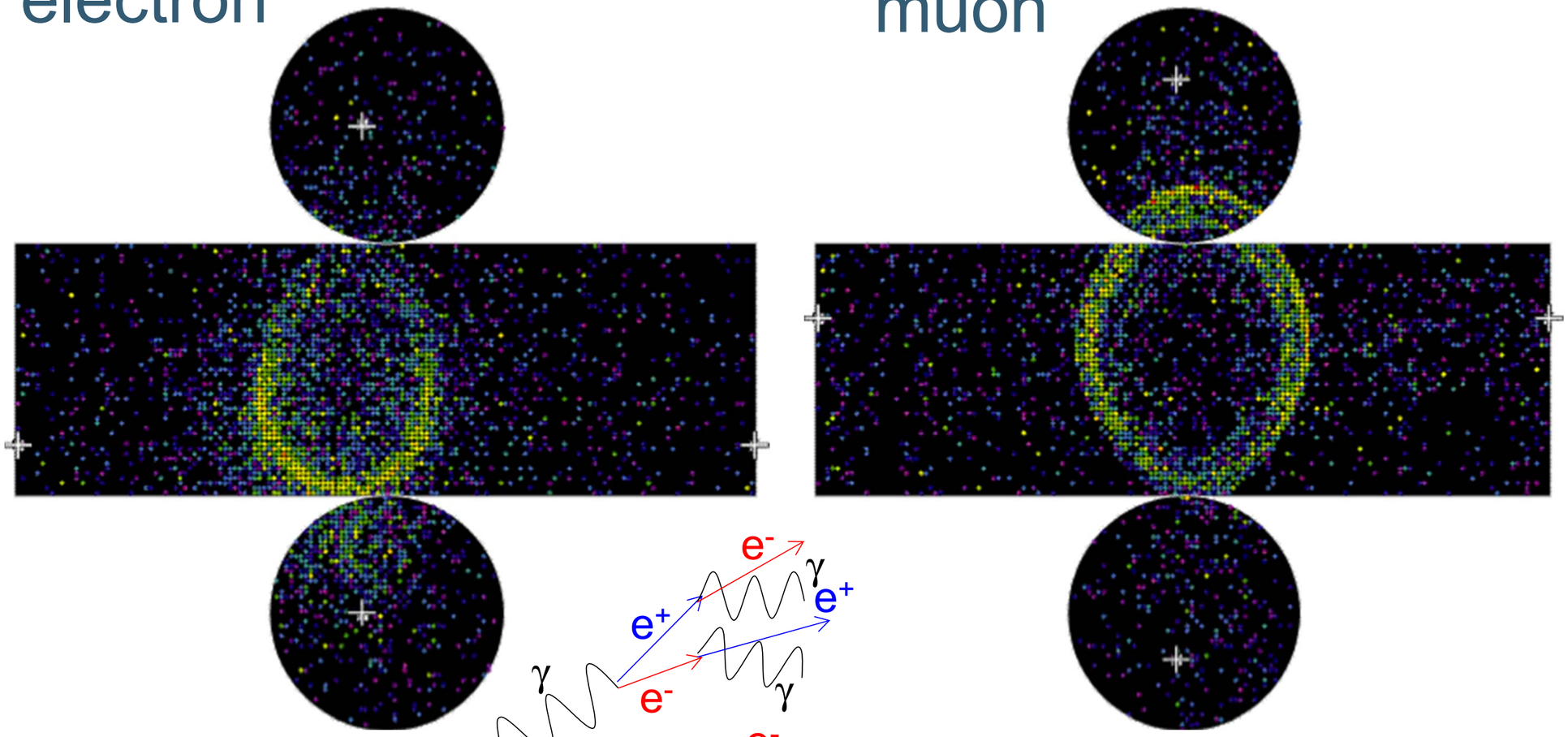
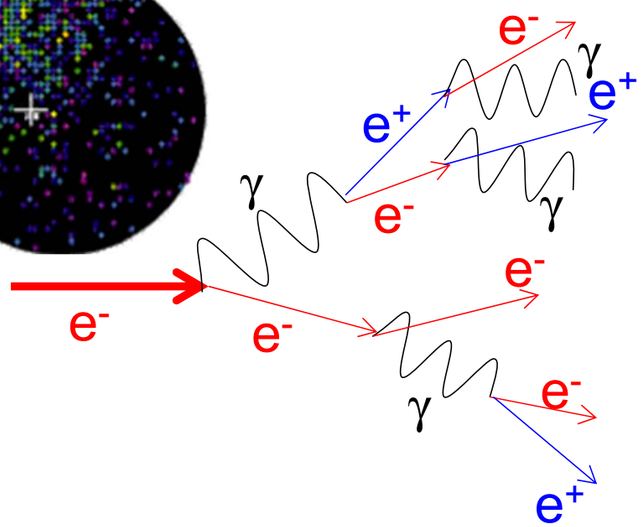
Super-KamioKande

electron

muon





SK MC event display

SK Analysis upgrade

- Reconstruction

  iterative fit with either Q or T

  ↓

  simultaneous fit with all information including no-hits

  → Better precision and ID

  ✓ vertex resolution 29 cm → 20 cm

  ✓ removes 70% more π0 background

- Fiducial optimization

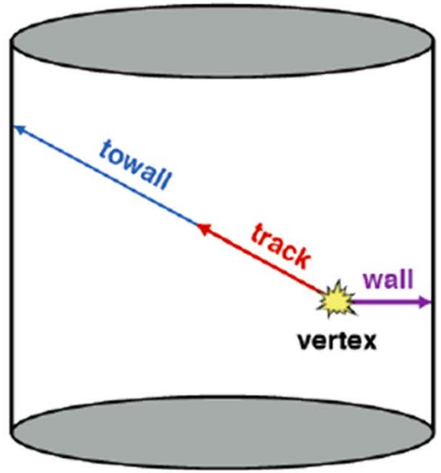
  Dist-Wall > 2 m → Dist-Wall and To-Wall cut

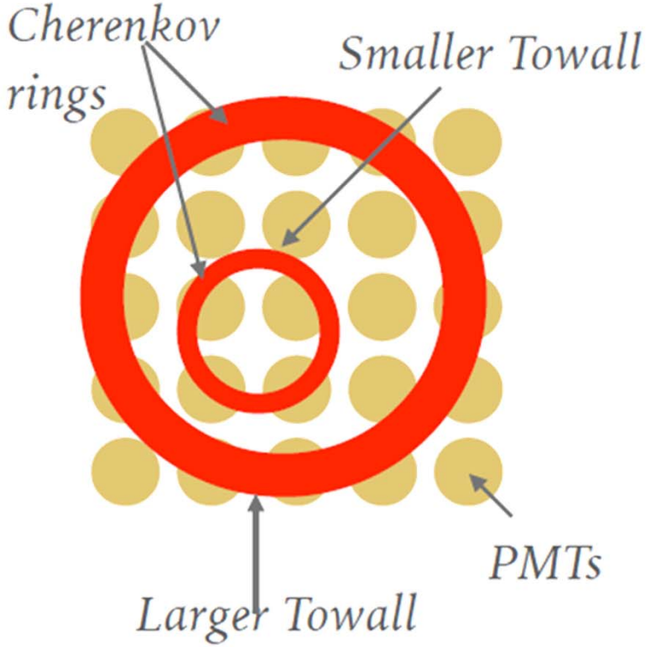
- Usage of non-CCQE samples

  – #decay-e, multi-ring

30%~50% increase in statistics!

Partially realized and partially work in progress





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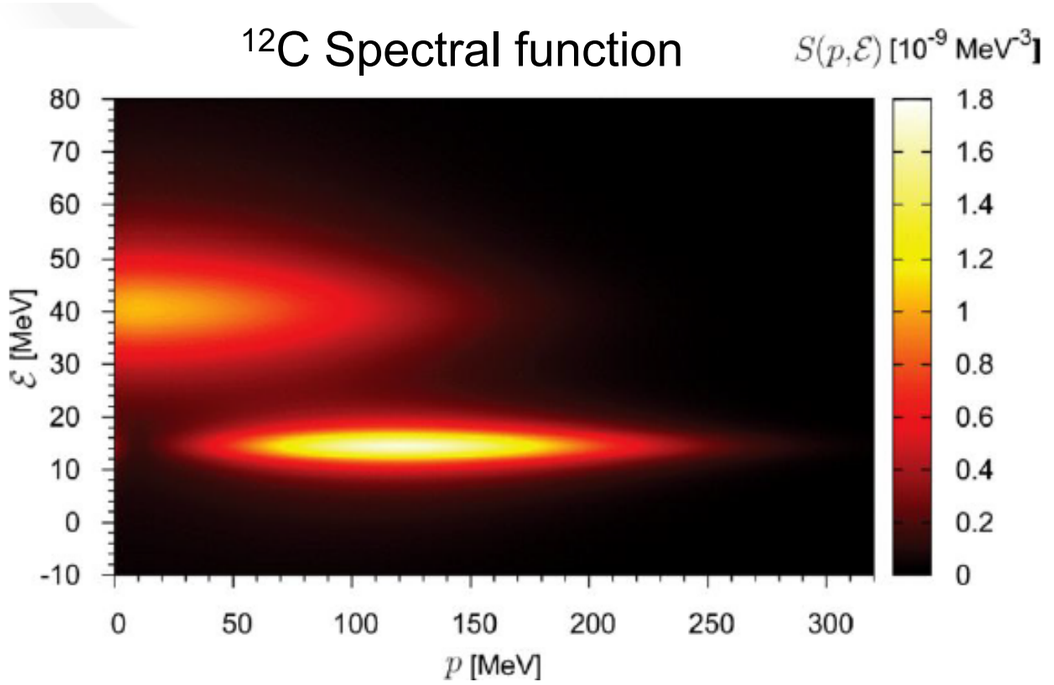
Neutrino and hadron interaction model improvement

- Neutrino interaction working group in T2K

  Many experts including theorists in collaboration

- Nuclear model
  - Global Relativistic Fermi Gas model → Local Fermi Gas, Spectral Function
  - Correlations between nucleons
- pion production model
- second-class currents and radiation correction for ν_e interaction
- Less model dependent analysis



M.V.Ivanov et al., J.Phys.Conf.Ser. 1023 (2018) no.1, 012028

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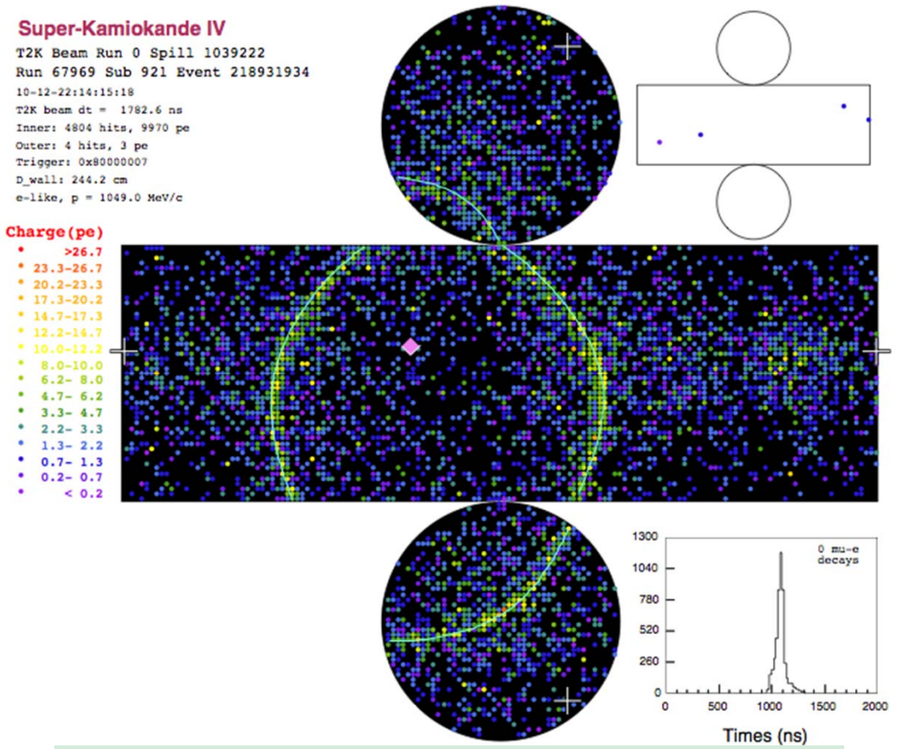
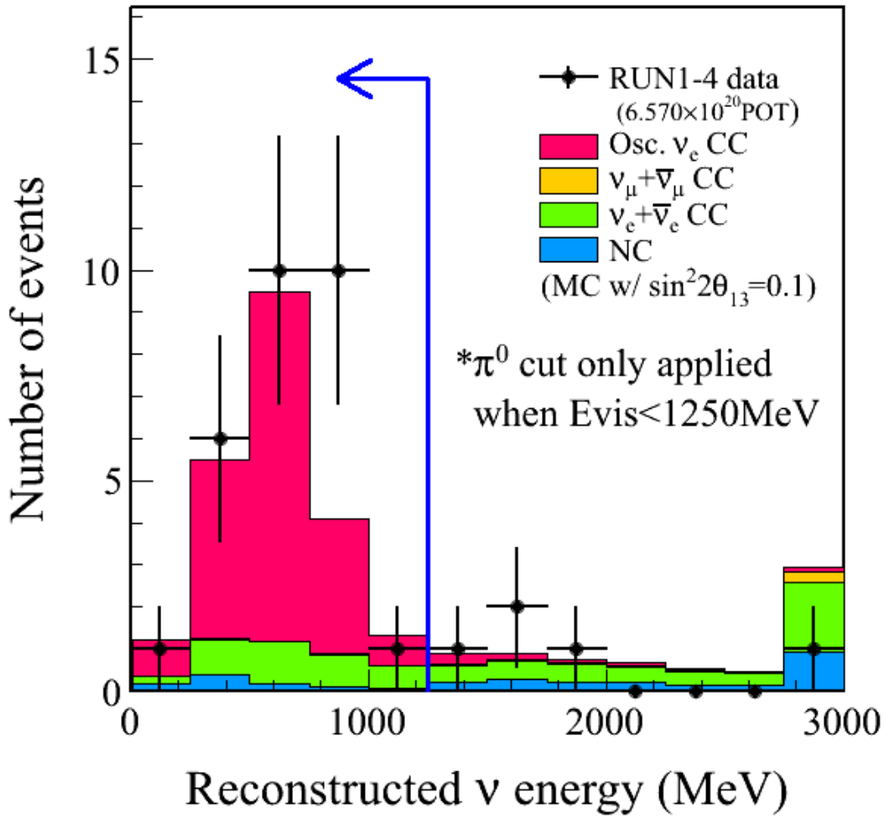
ν_e appearance

2011 T2K observed 6 events(1.5 bkgs). 2.5σ significance
2012 Daya Bay observed non-zero $\sin^2 2\theta_{13}$ by reactor $\bar{\nu}_e$ disappearance
2013 T2K observed 28 events over 4.9bkgs 7.3σ significance
Also first confirmation of 'appearance' w/ >5σ significance

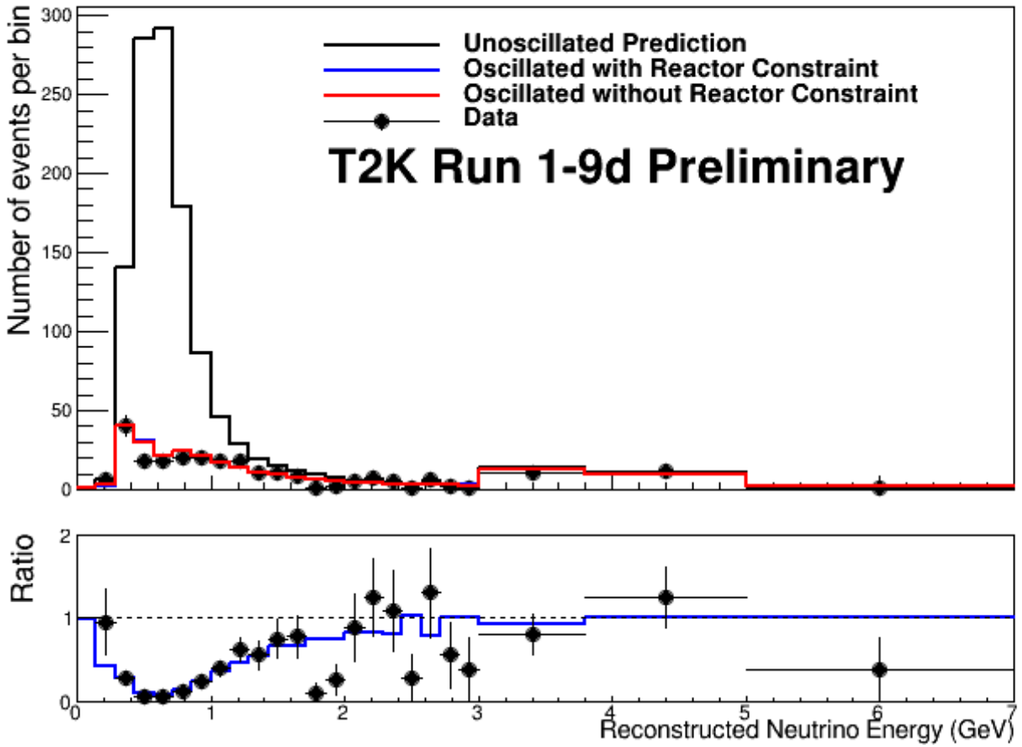


Example of ν_e candidate event



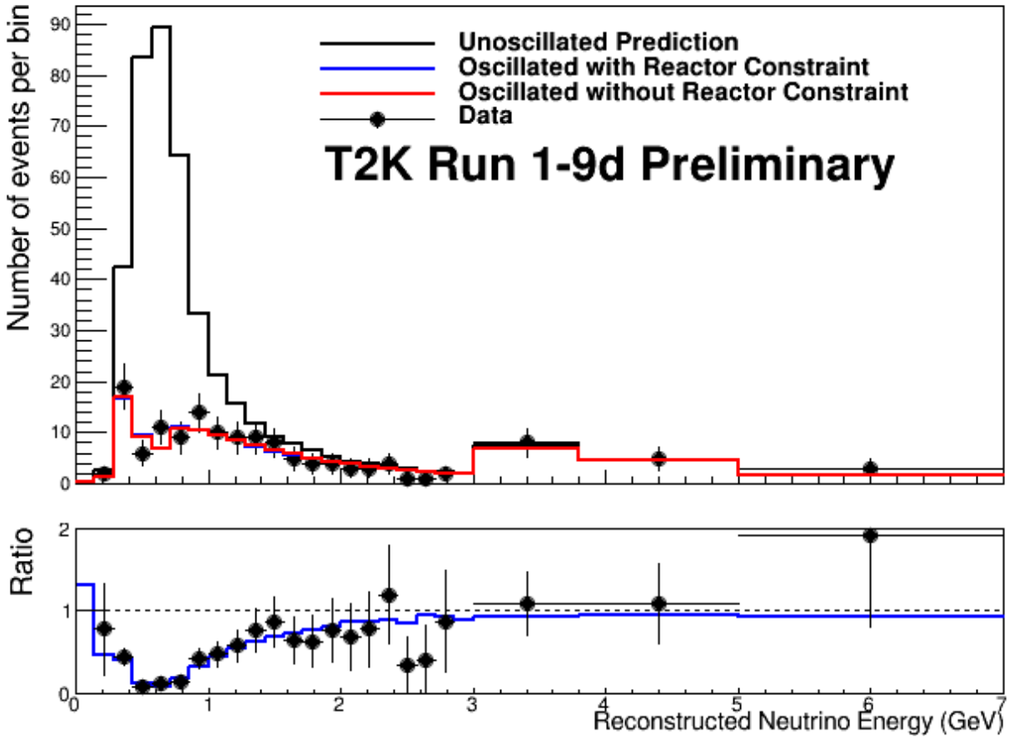
And Now,

Disappearance



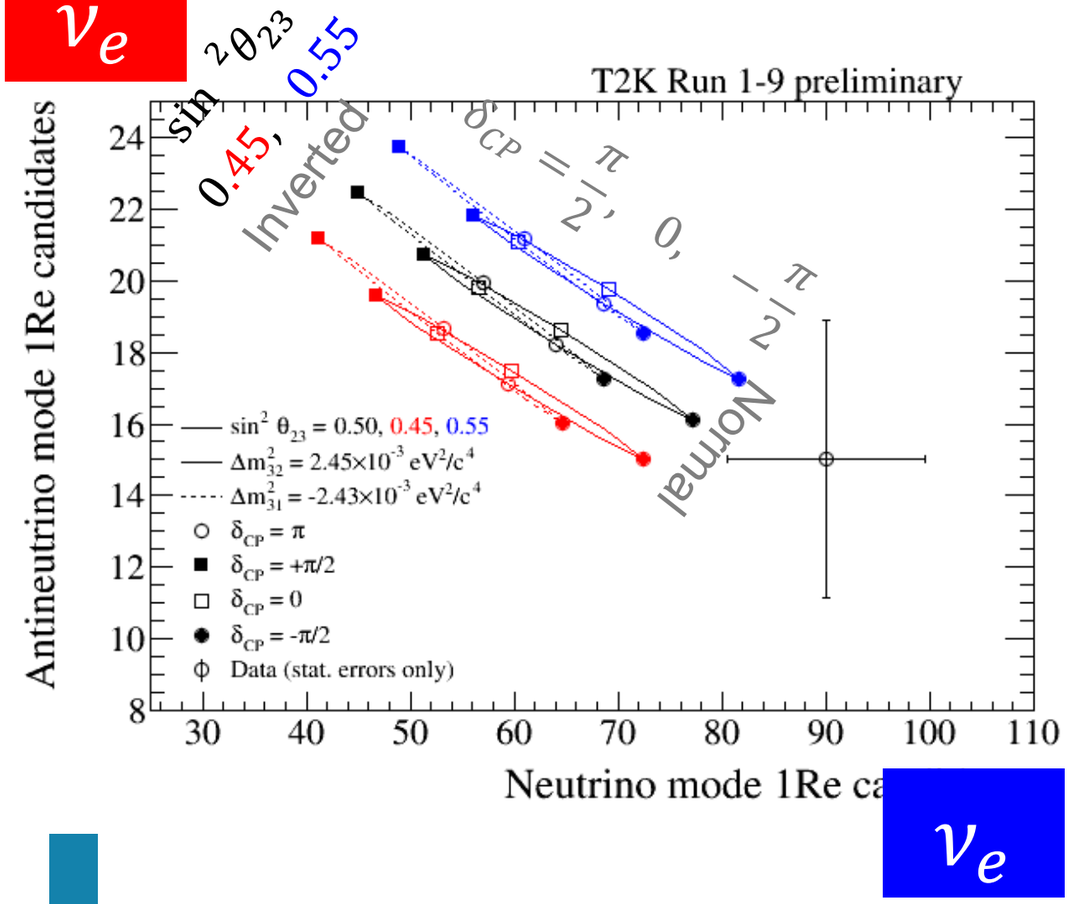
muon neutrino disappearance

muon antineutrino disappearance



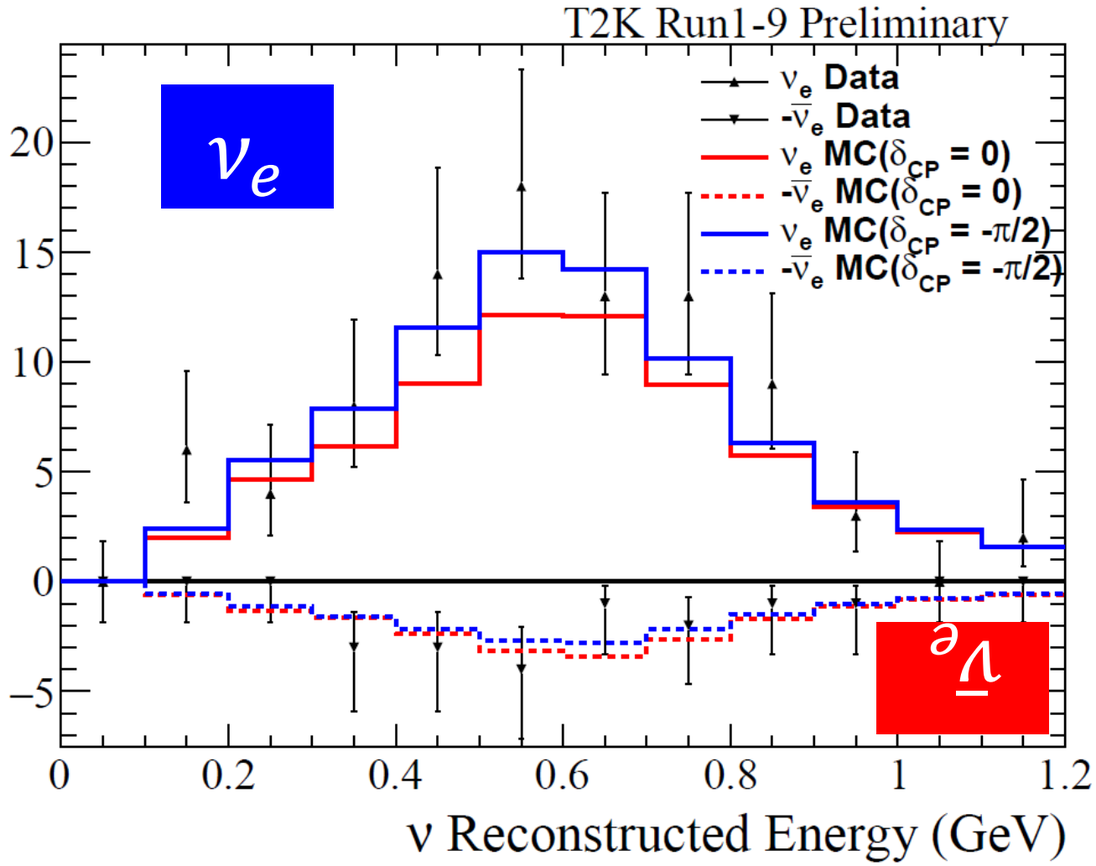
Appearance

$\bar{\nu}_e$

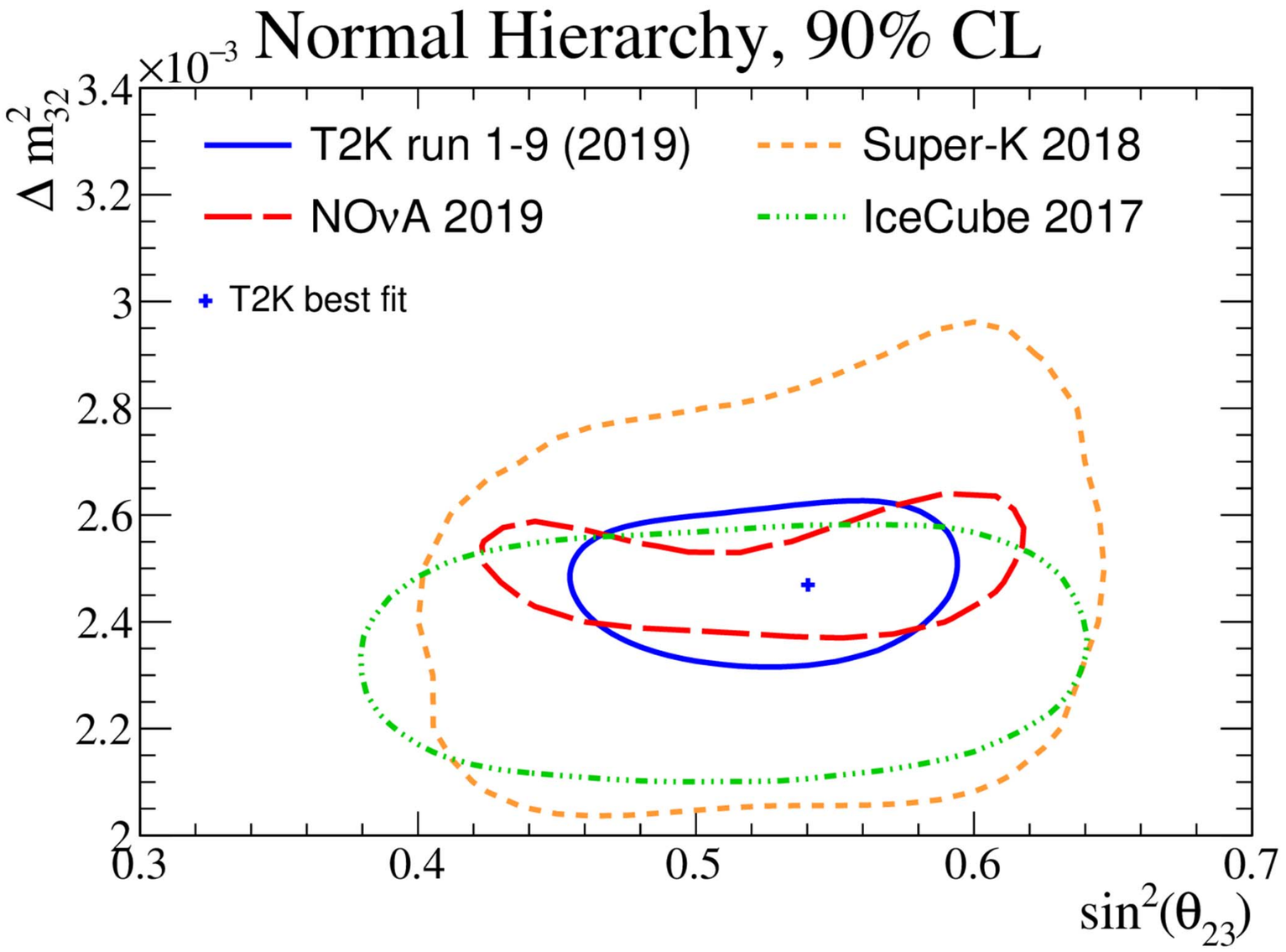


ν_e

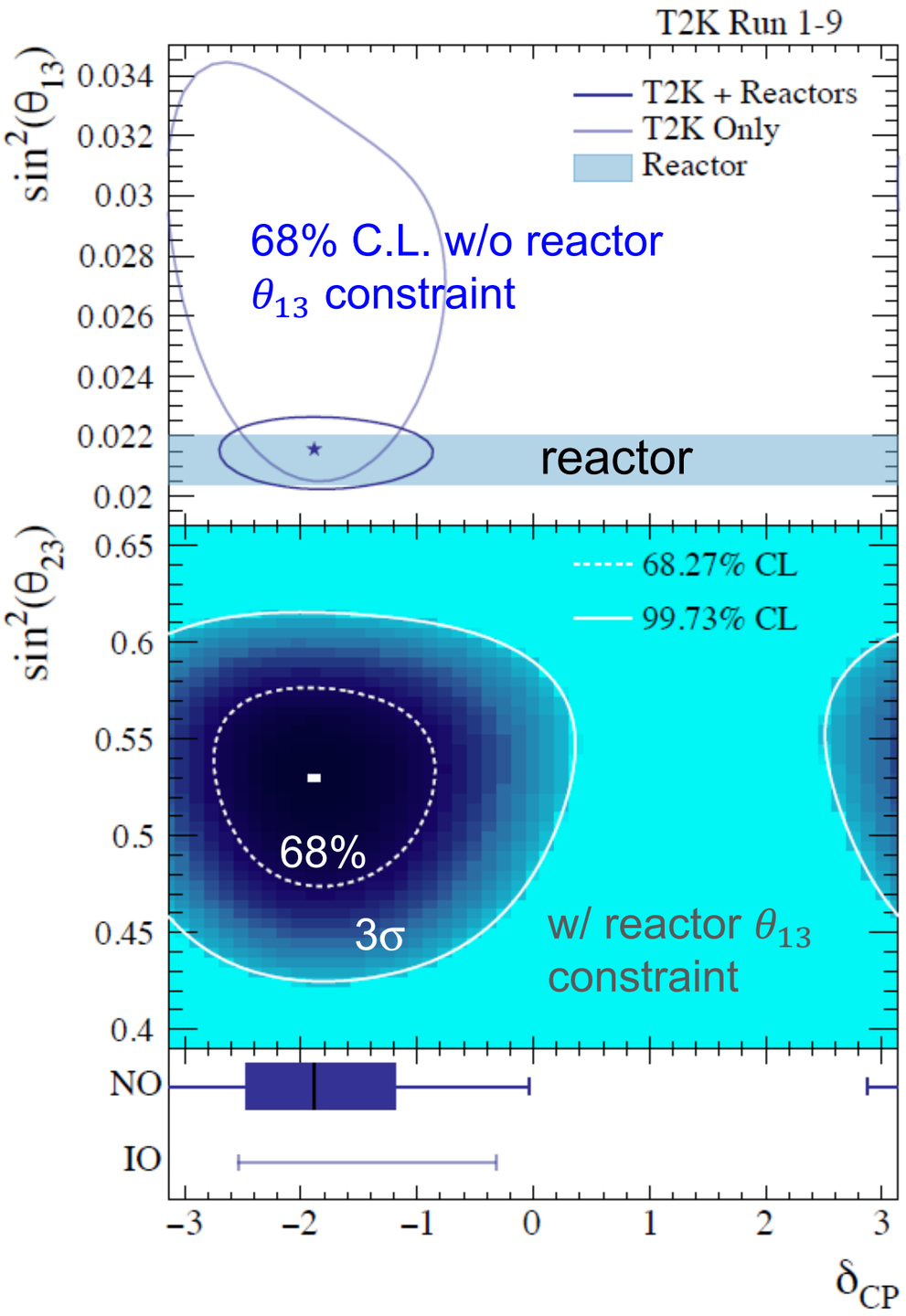
Tendency,
More electron neutrino
Less electron antineutrino



$\sin^2 2\theta_{23}$, Δm^2



CP-violation phase δ_{CP}



CP-conserving case ($\delta_{CP} = 0, 180°$) is out side 2σ (95%) region

$[-2°, 165°]$ is outside 3σ region

(arXiv:1910.03887)

Mass Ordering

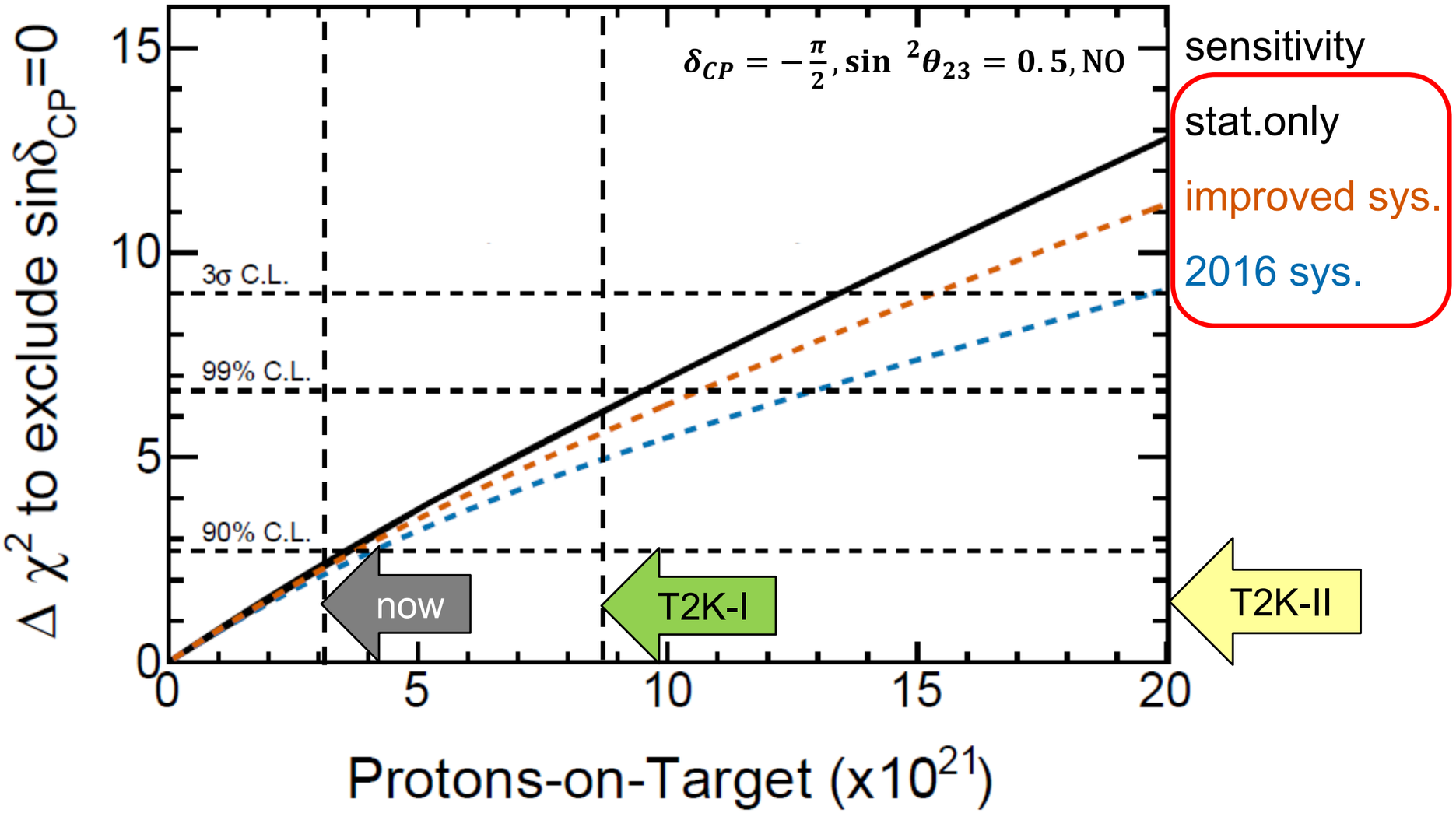
- Some sensitivity to mass ordering by the matter effect
- Posterior probability (Run1-9)

Normal order ($m_3 > m_2 > m_1$): 88.9%

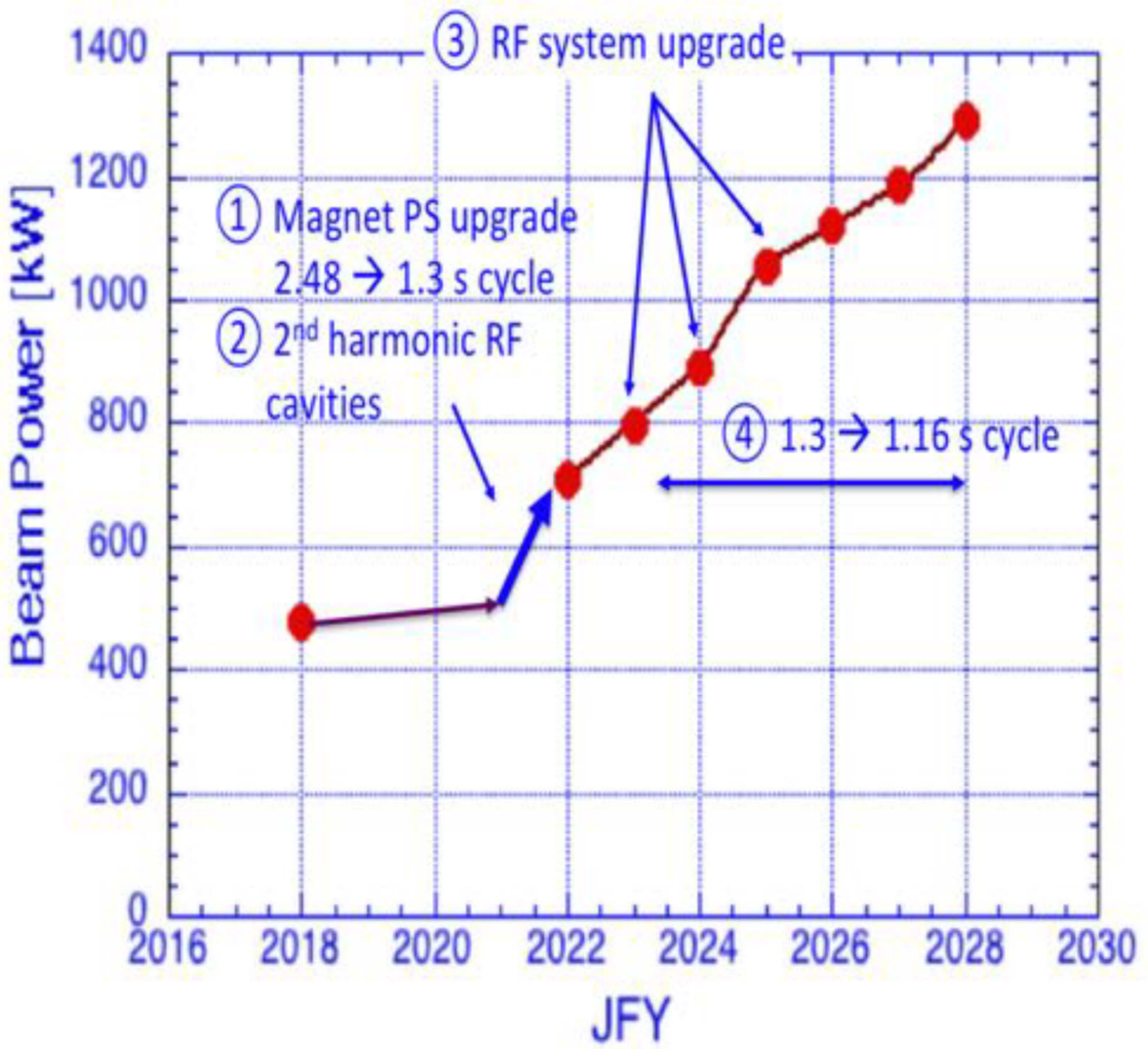
vs

Inverted order ($m_2 > m_1 > m_3$): 11.1%

Evolution from T2K-I to T2K-II- CPV sensitivity



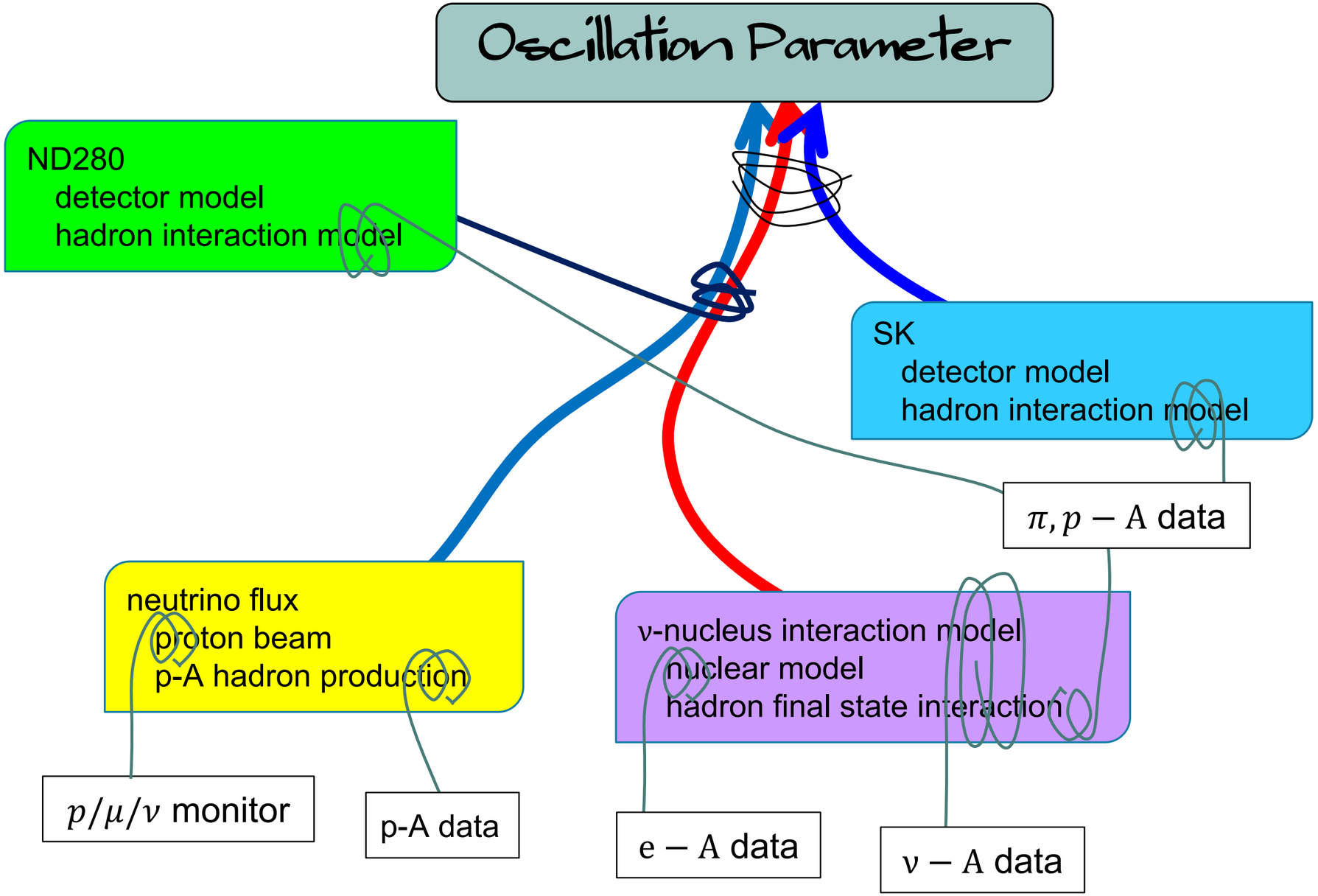
Evolution from T2K-I to T2K-II- Intensity upgrade -



N. Saito, Director of J-PARC Center, at 27th J-PARC PAC

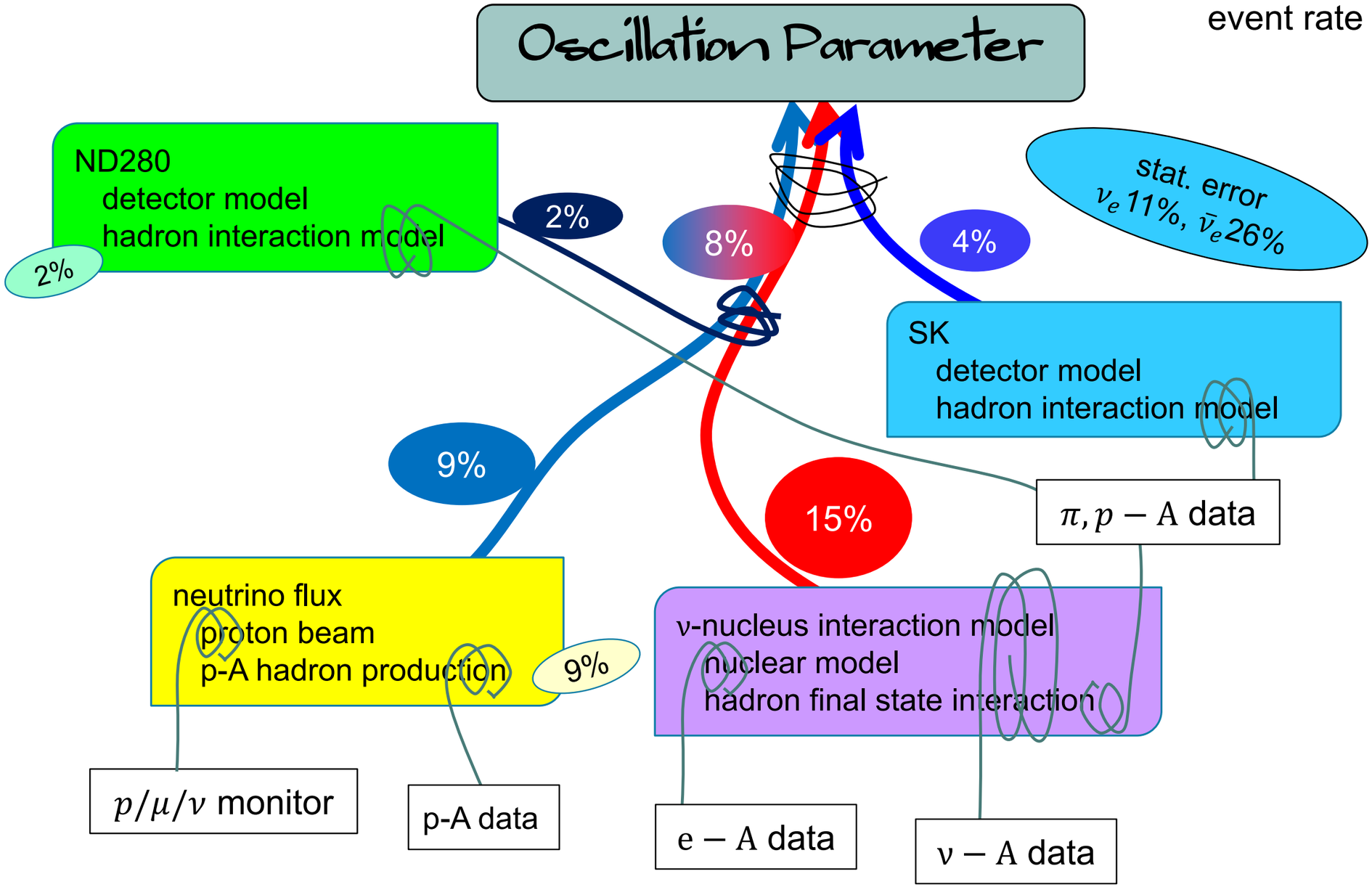
- ✓ Aim 1.3 MW by upgrading the main ring accelerator and neutrino beamline.
- ✓ Further ~7% increase by horn current 250 kA → 320 kA

Overview of T2K analysis

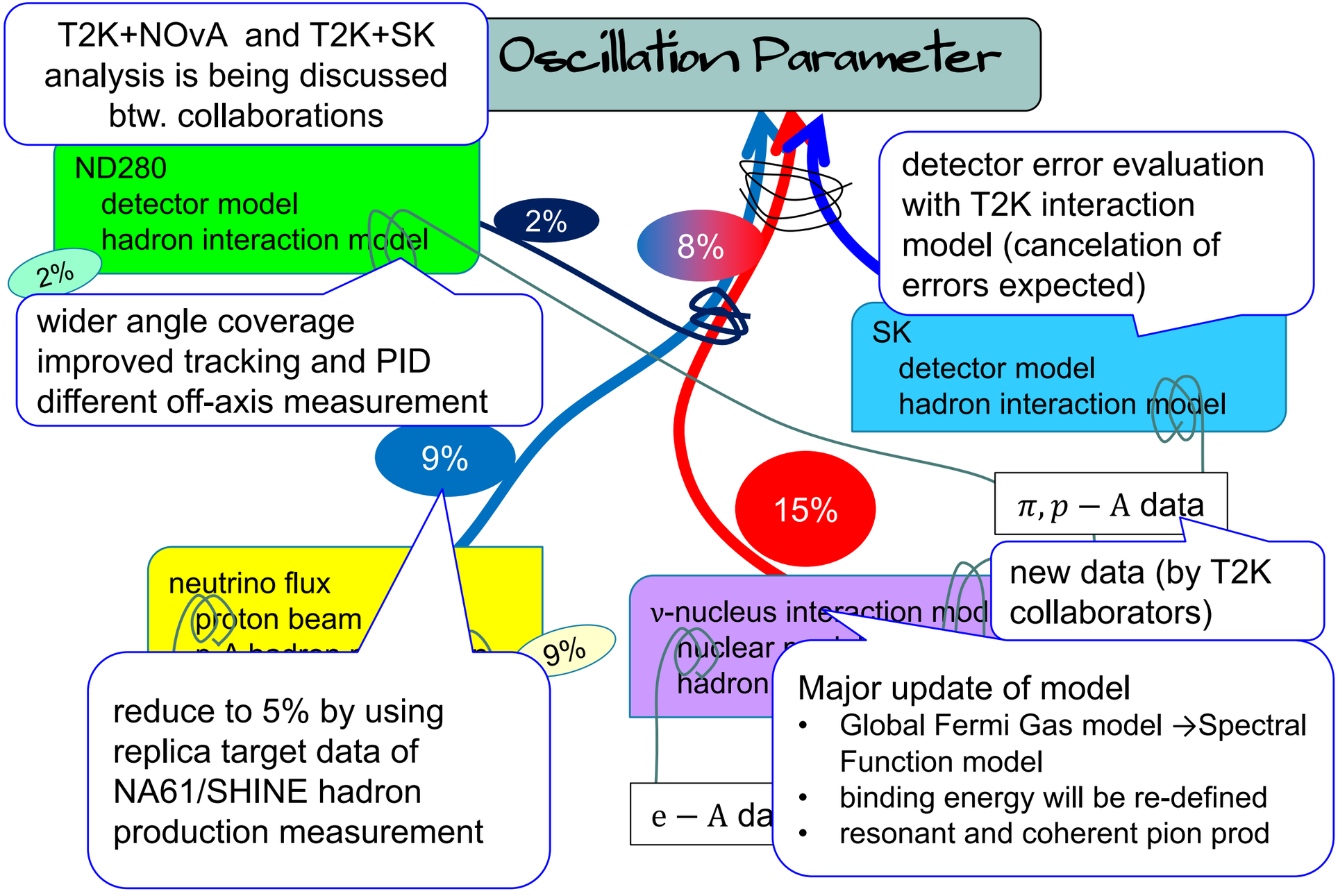


Overview of T2K analysis

numbers: error on event rate prediction



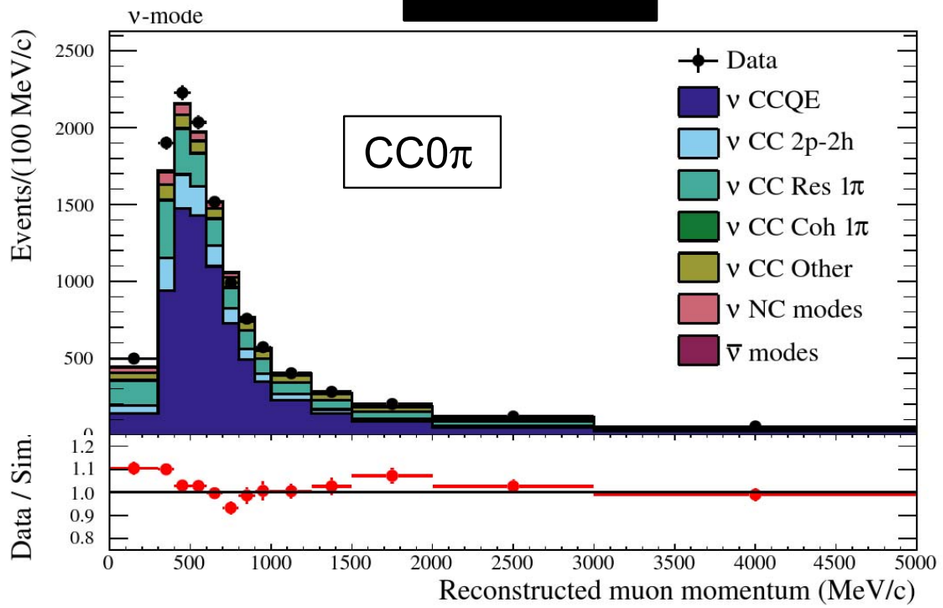
Improvements expected in 2019

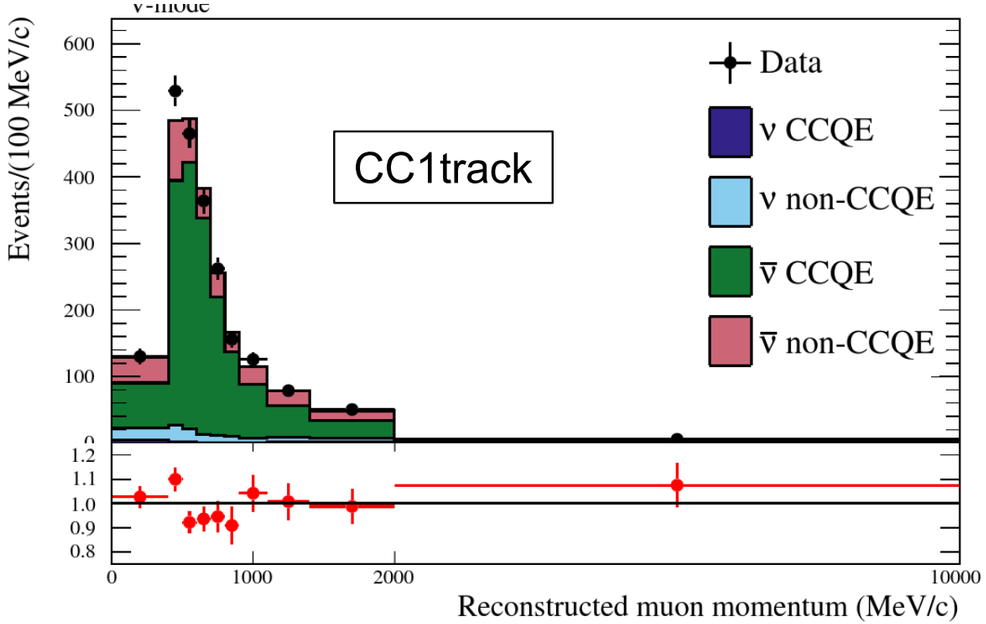


neutrino beam mode

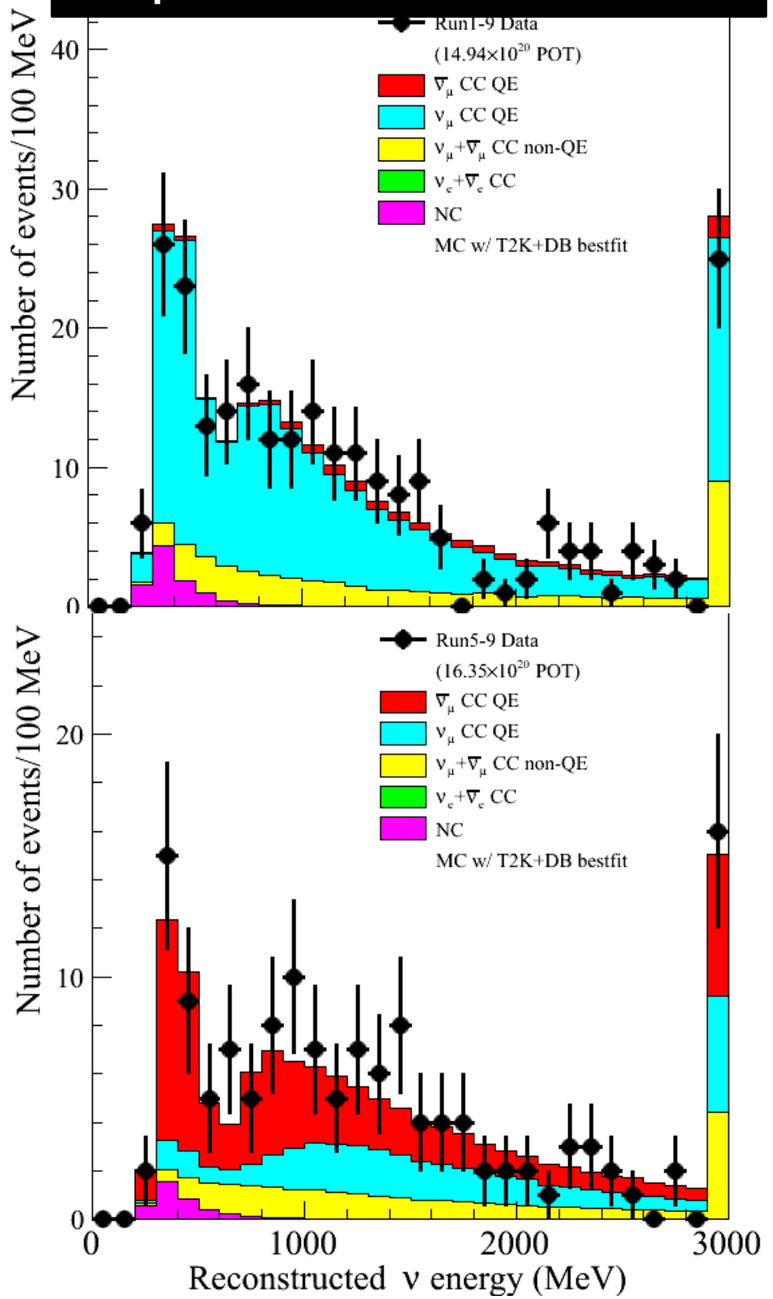
antineutrino beam mode

ND280





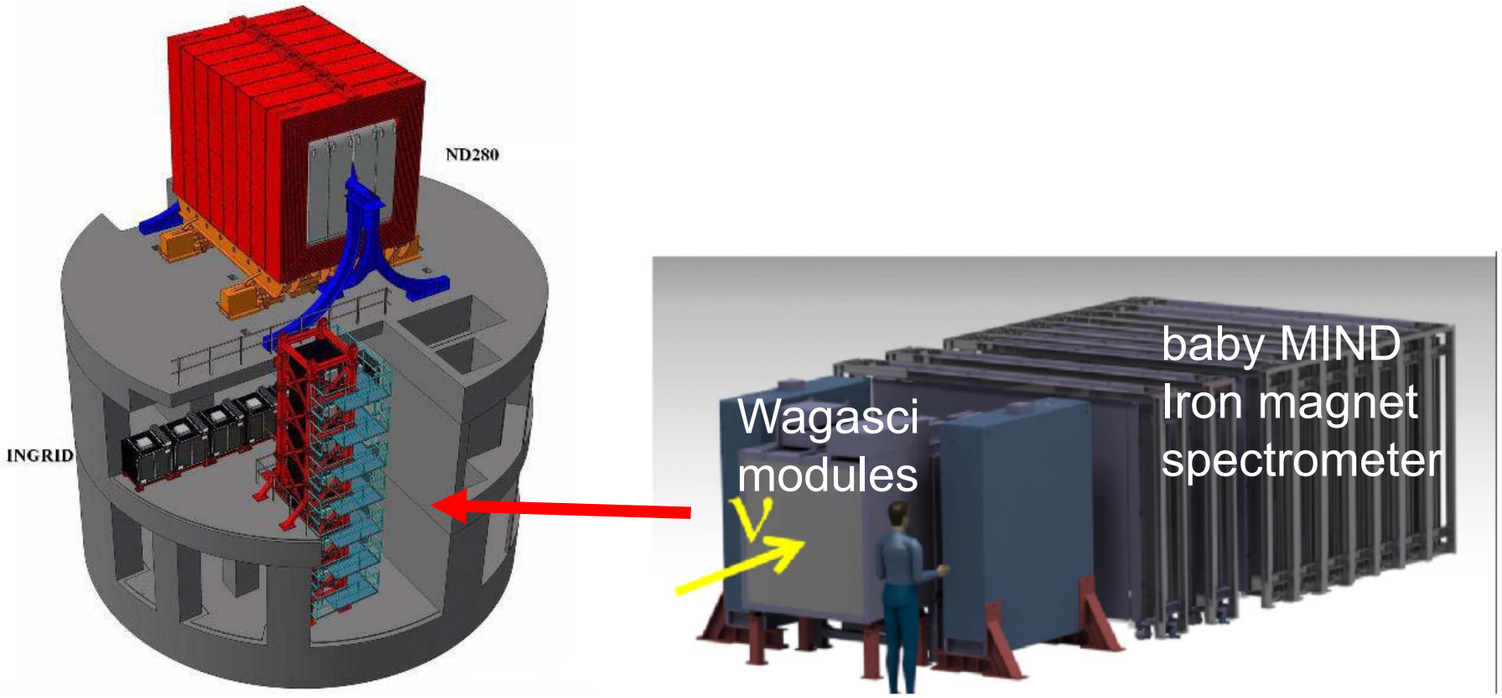
Super-K muon neutrino

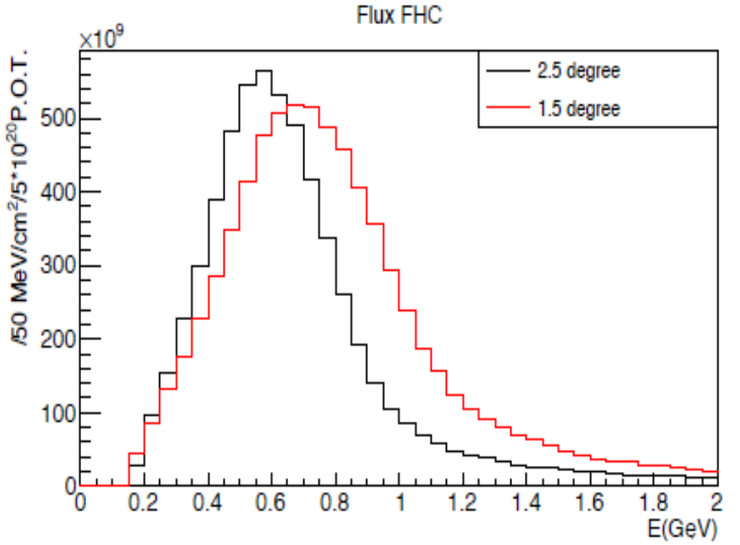


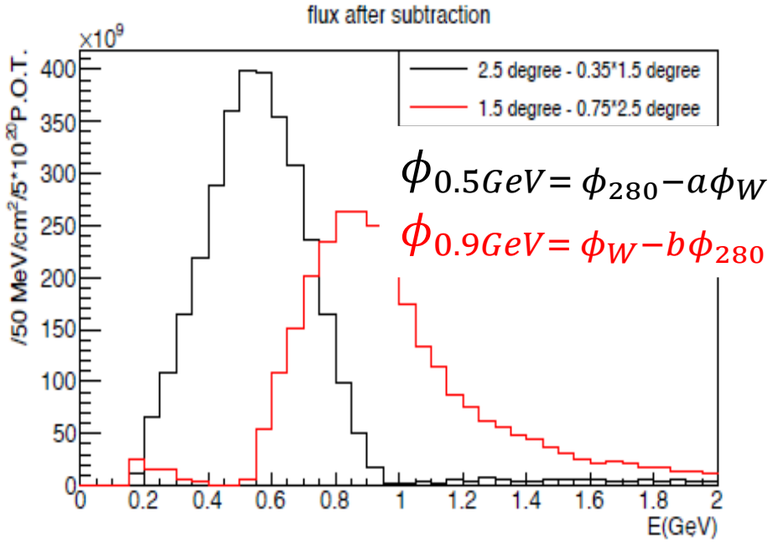
PRELIMINARY

Evolution from T2K-I to T2K-II
- Near Detector upgrade, Wagasci/baby MIND -

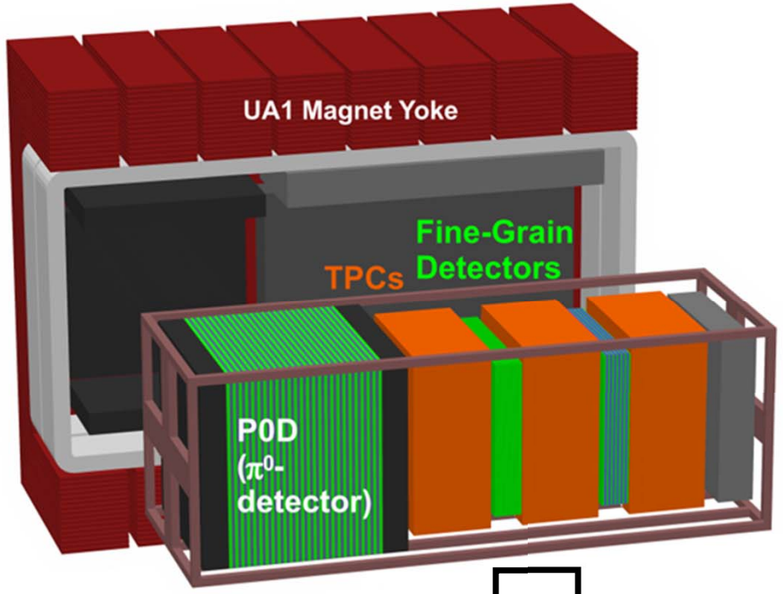
- ✓measurement at different off-axis
- ✓Data taking has started in this November.

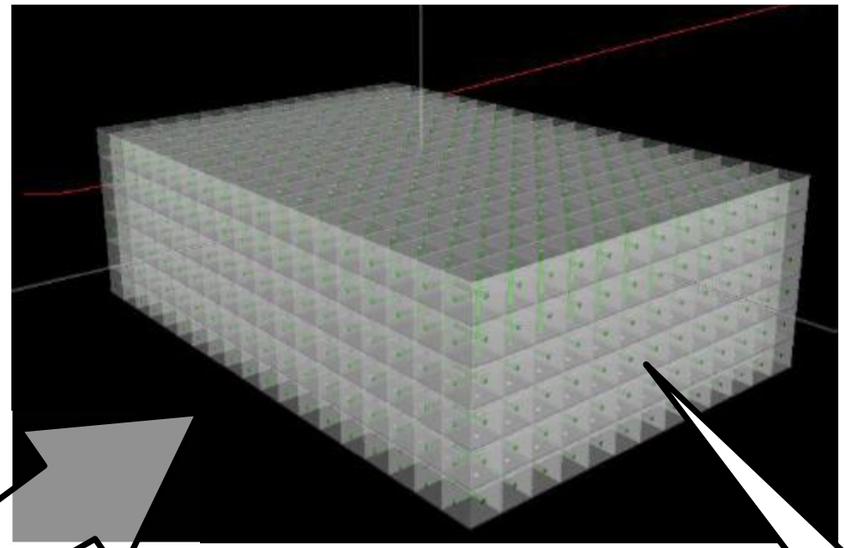


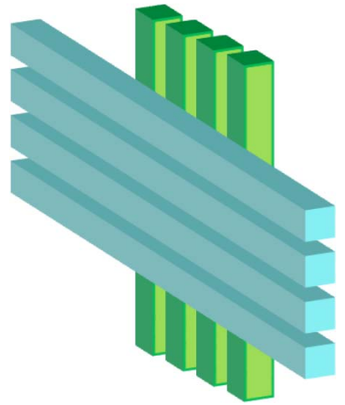


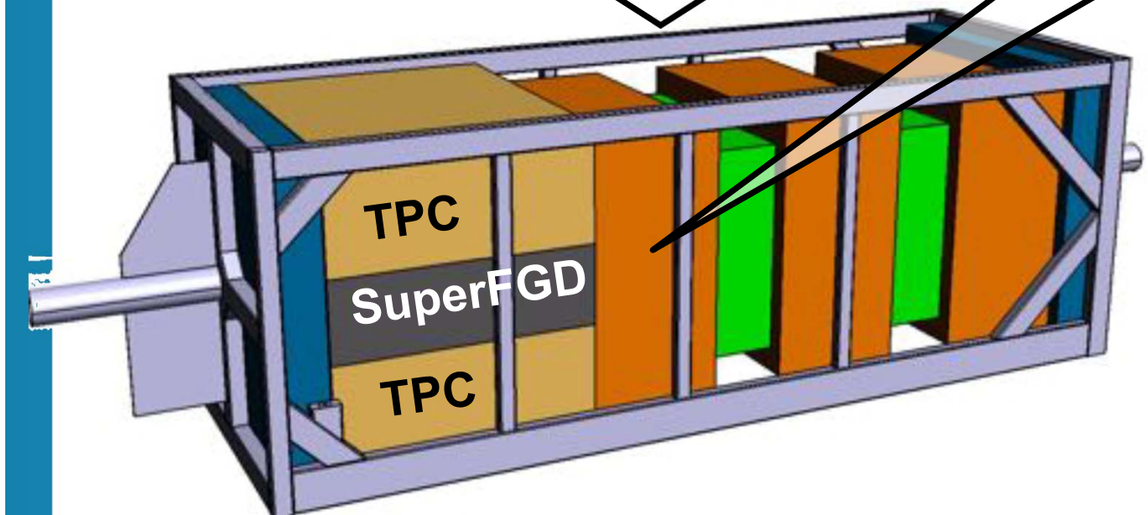


Evolution from T2K-I to T2K-II
- Near Detector upgrade, ND280-





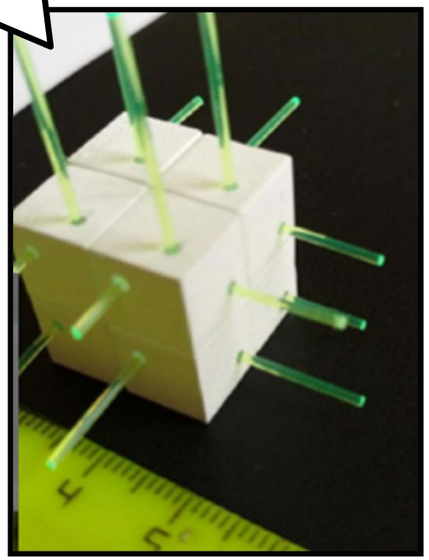




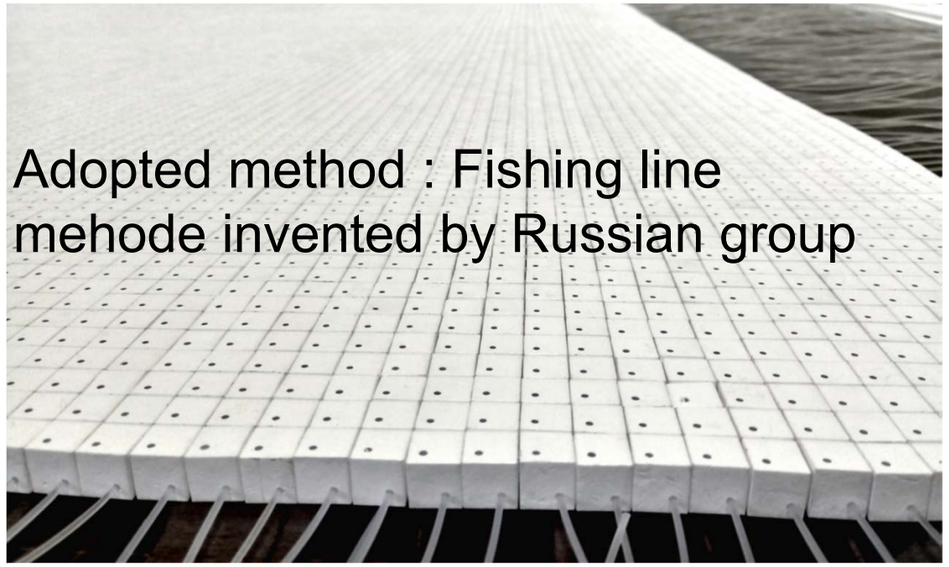
- Cover larger phase space
- higher graduality around vertex

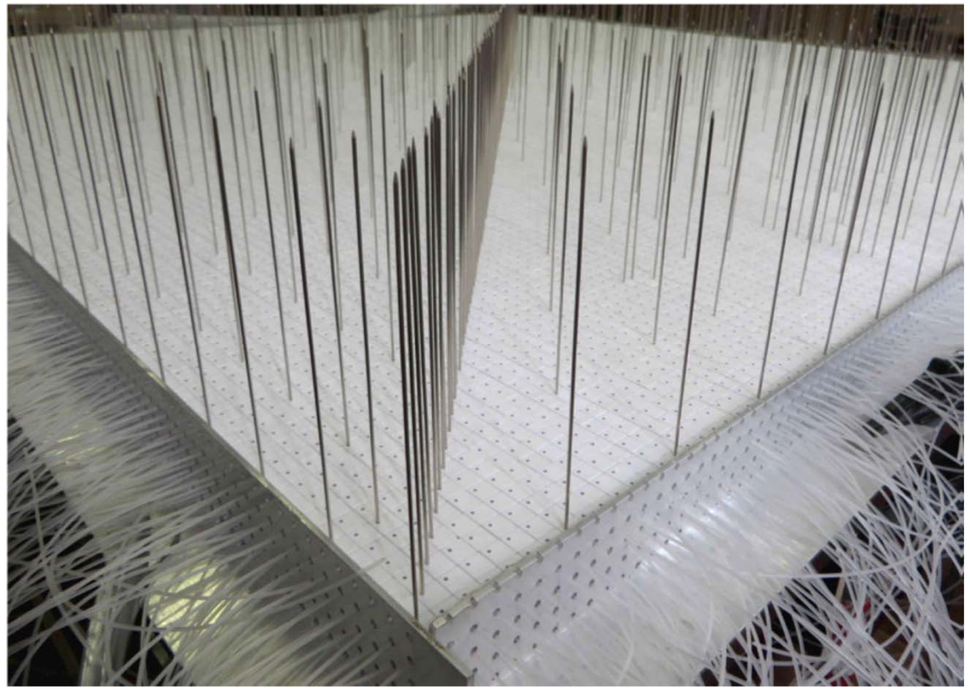
To improve the understanding of the neutrino-nucleus interaction

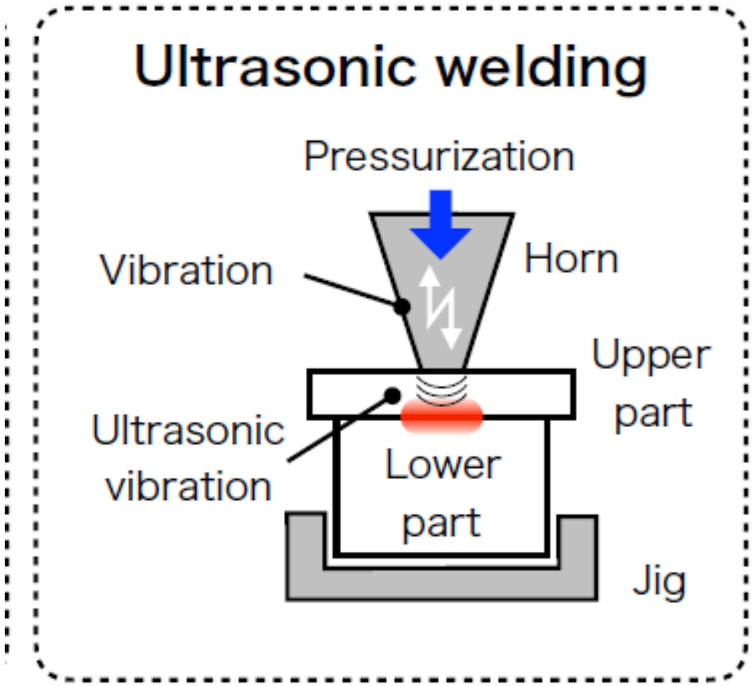
To be installed in 2021

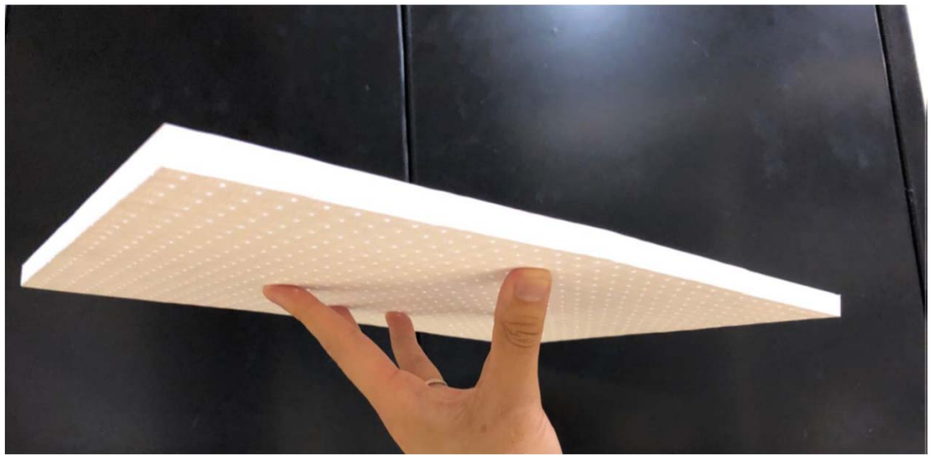


Assembling of Super-FGD



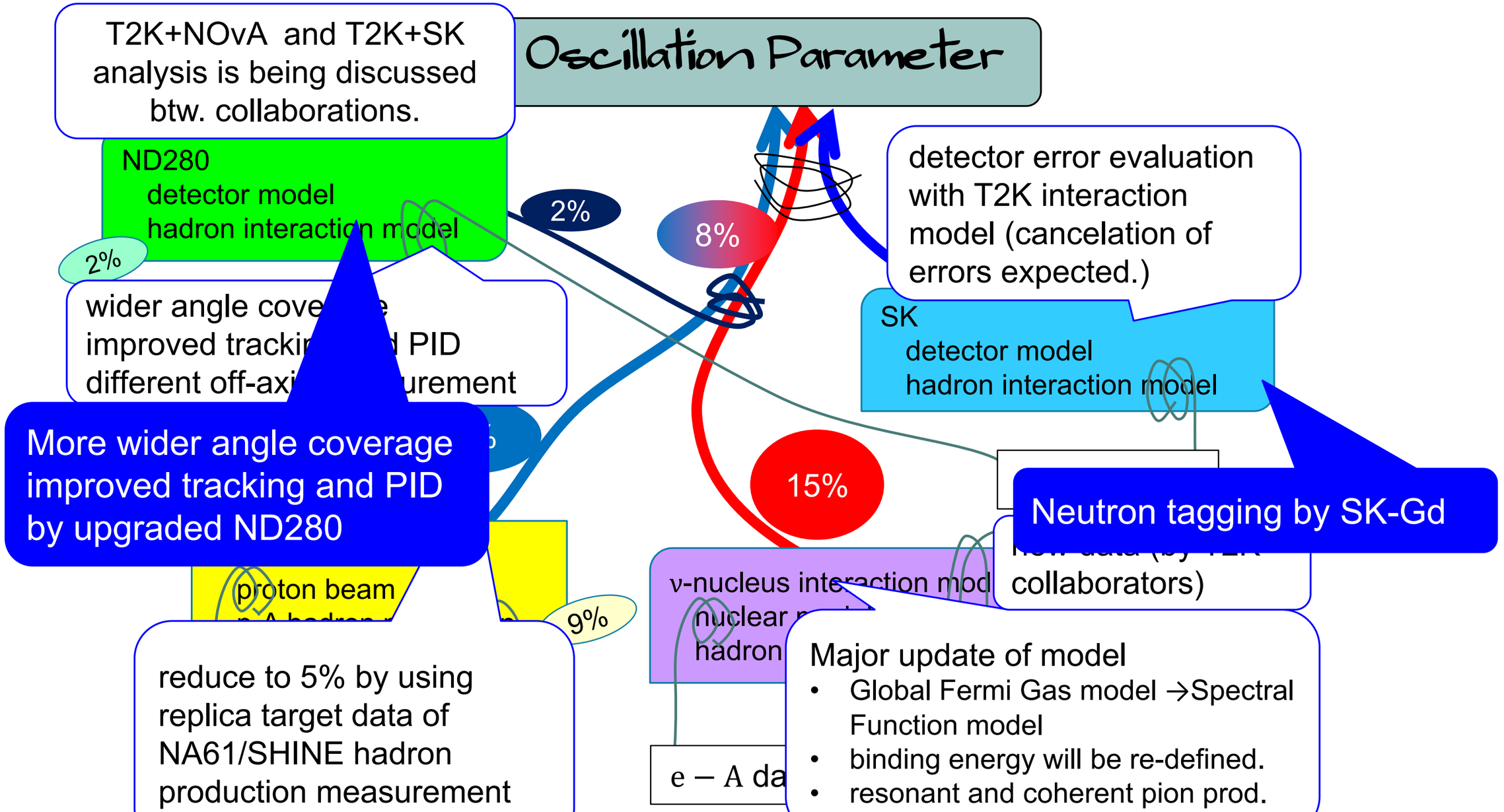




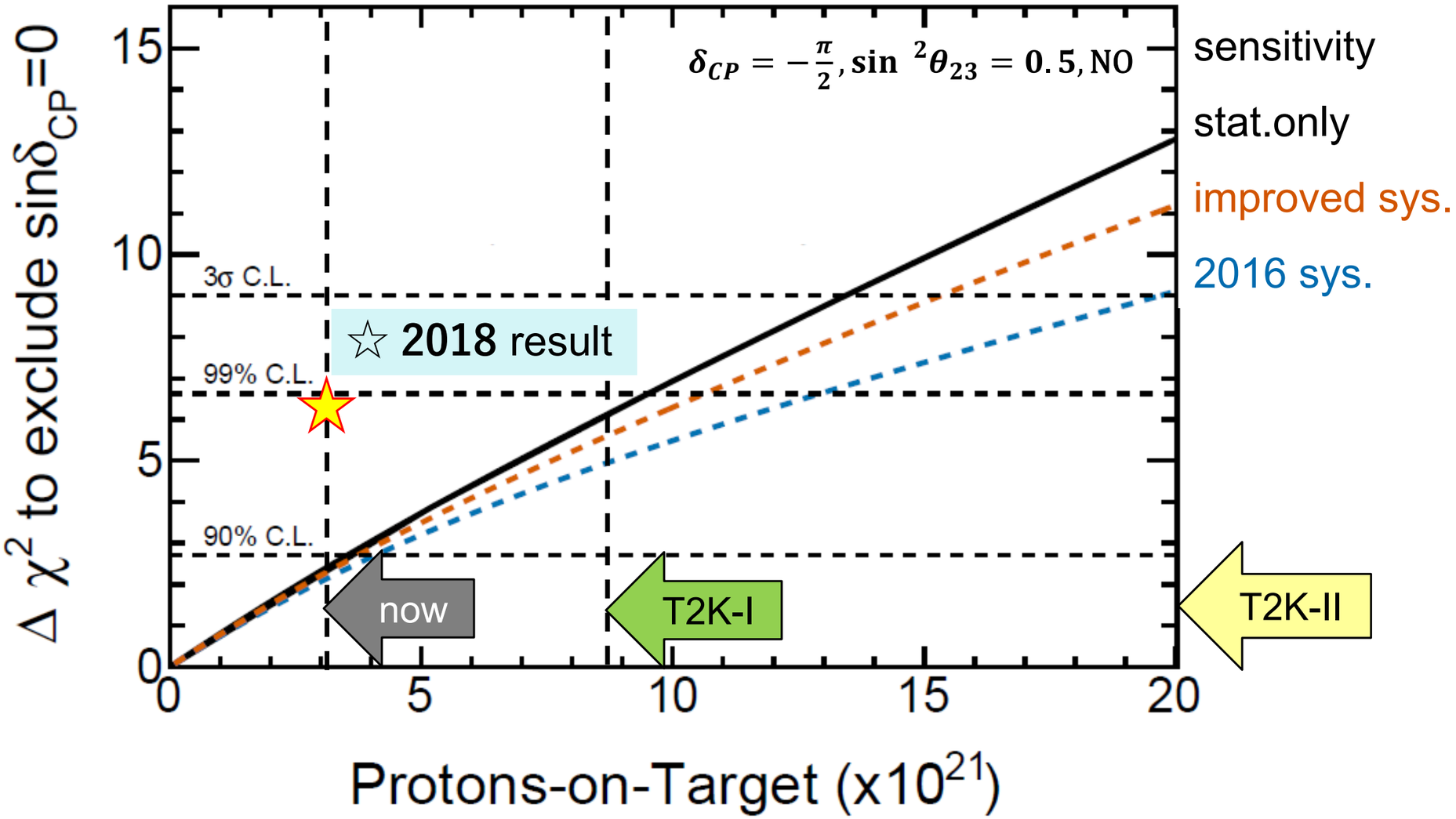


Backup method invented by Japanese group

Improvements expected after 2021



CPV, where are we now?



Summary

- The accelerator-based neutrino oscillation program in Japan, founded by Koichiro Nishikawa, is continuing evolution K2K → T2K → T2HK
- δ_{CP} 2σ confidence interval[−3.966, −0.628] (NO) [−1.799, −0.979] (IH)

  CP-conserving case ($\delta_{CP} = 0, \pi$) is outside 2σ (95%) region

  $[-2°, 165°]$ is outside 3σ region

  Normal ($m_3 > m_2 > m_1$): 88.9% vs. Inverted ($m_2 > m_1 > m_3$): 11.1%
- Timeline from now

  2020 Super-Kamiokande upgrade by dissolving Gd to 0.01% concentration

  2021 Upgrade of beam intensity(750 kW) & ND280

  2023~2025 Second beam upgrade to reach 1.3 MW

  Aiming to collect 1~2x 10^{22} POT with 3σ sensitivity to CPV <u>if CPV is ~maximal</u>