J-PARC neutrino beam and T2K/T2K-II physics

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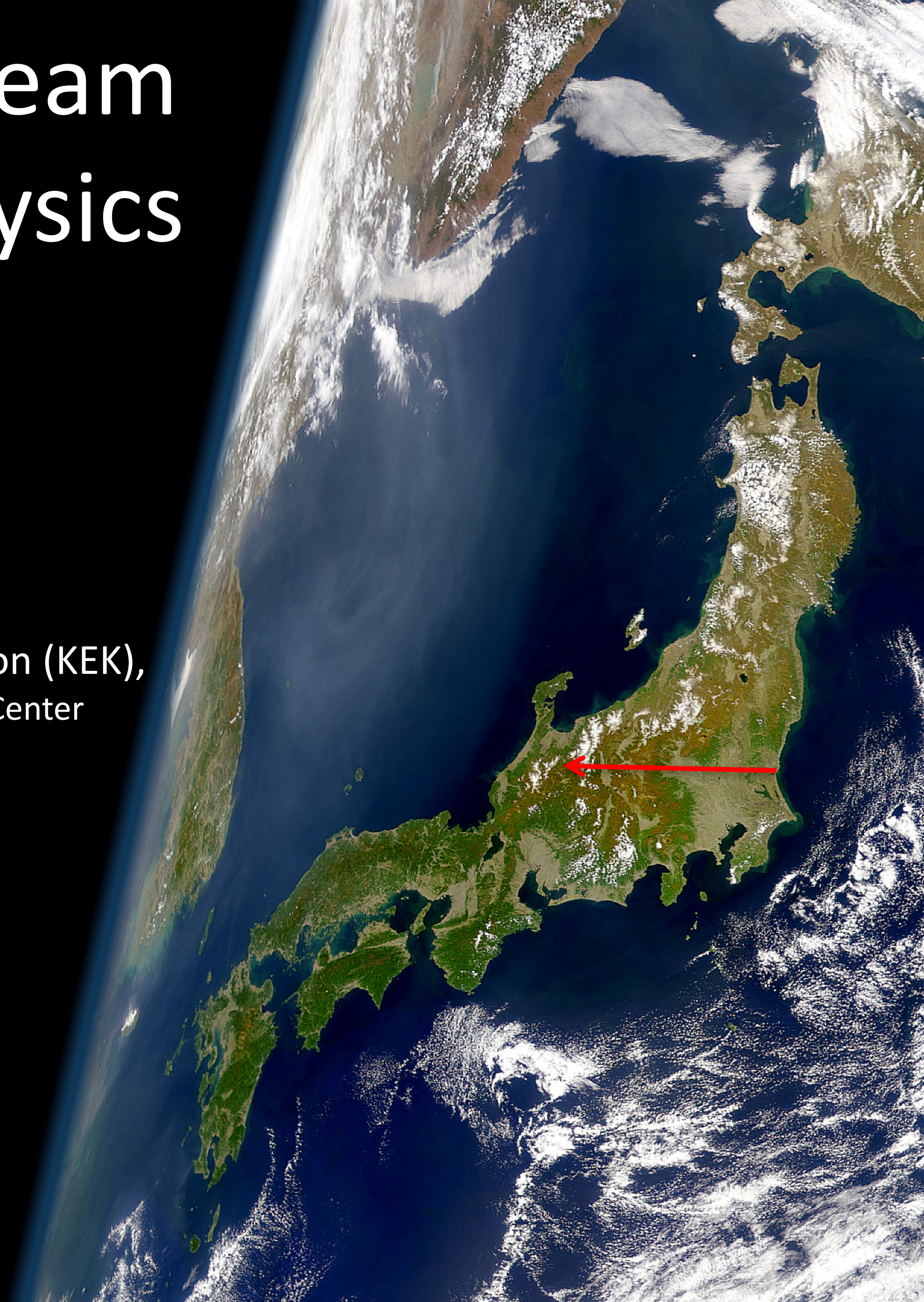
The T2K collaboration



The T2K Collaboration

～500 members, 63 Institutes, 11 countries

Canada

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

France

CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany

Aachen

Italy

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

Japan

ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Institute of Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U. of Science
Yokohama National U.

Poland

NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia

INR

Spain

IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Switzerland

U. Bern
U. Geneva

United Kingdom

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

USA

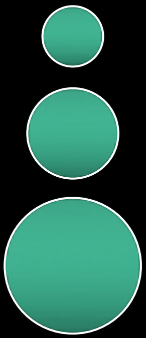
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

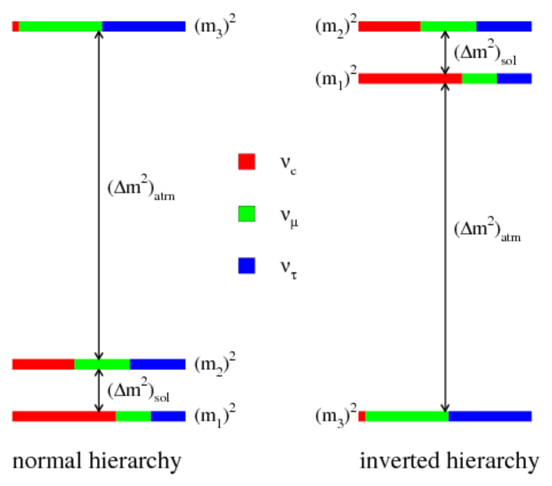
3-flavor neutrino oscillation

Weak eigenstates

Mass eigenstates

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{\text{PNMS}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \begin{matrix} m_1\\ m_2\\ m_3\end{matrix}$$





$$U_{\text{PNMS}} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{+i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix} \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

$$P(\nu_a \to \nu_b) = \delta_{ab} - 4\sum_{i>j}(U_{ai}U_{bi}U_{aj}U_{bj})\sin^2\left(\Delta m^2_{ij}L/4E\right) \qquad \Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

- 6 independent parameters in 3 mixing angles, 1 complex phases, 3 mass-squared differences.
  - Mass hierarchy (sign of $\Delta m^2{}_{32}$) and δ_{CP} are not determined yet. ← Accelerator-based Long baseline ν oscillation experiment can address.

Goal of T2K experiment

- Direct search for $\nu_\mu \rightarrow \nu_e$ oscillation: Discovered in 2013!
- Precise measurement θ_{23} of $\nu_\mu \rightarrow \nu_\mu$ disappearance
- Search for CP violation phenomena in the lepton sector
  - Difference between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \left(\cos^4\theta_{13} \cdot \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \cdot \sin^2\theta_{23}\right) \cdot \sin^2\left(\frac{\Delta m^2_{31} \cdot L}{4E_\nu}\right)$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)\left(1 + \frac{2a}{\Delta m^2_{31}}\left(1 - 2\sin^2\theta_{13}\right)\right)$$

$$- \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin\delta_{CP} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) \sin\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \cdots$$

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)\left(1 - \frac{2a}{\Delta m^2_{31}}\left(1 - 2\sin^2\theta_{13}\right)\right)$$

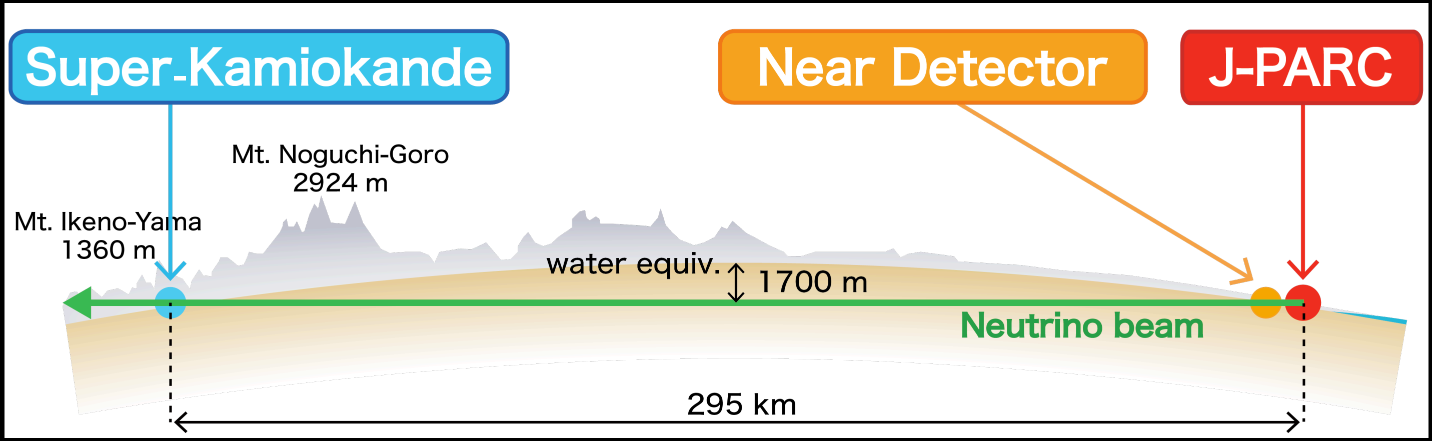
$$+ \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin\delta_{CP} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) \sin\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \cdots$$

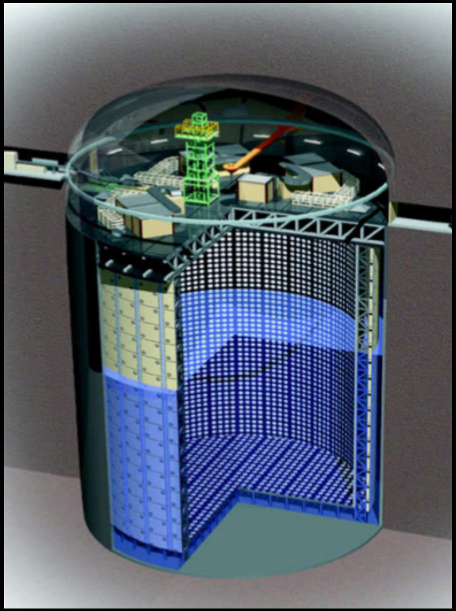
Approx. At around osci. max. L/E_ν

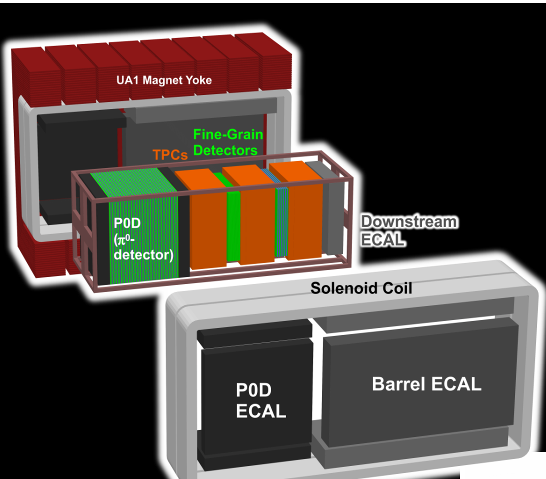
Matter effect is small for L=300km.

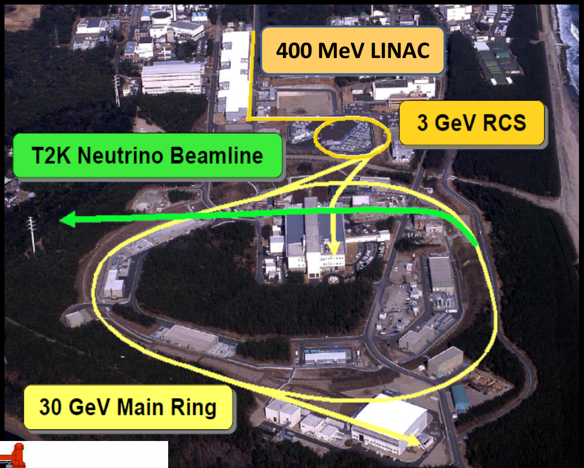
$$a \equiv 2\sqrt{2} G_F n_e E_\nu = 7.56 \times 10^{-5} \mathrm{eV}^2 \rho[g/cm^{-3}] E_\nu[\mathrm{GeV}]$$

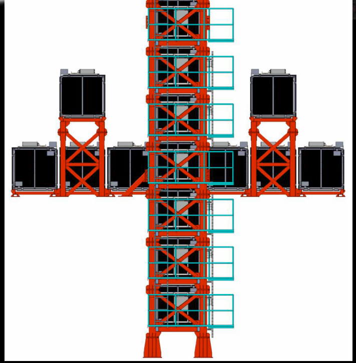
T2K experiment











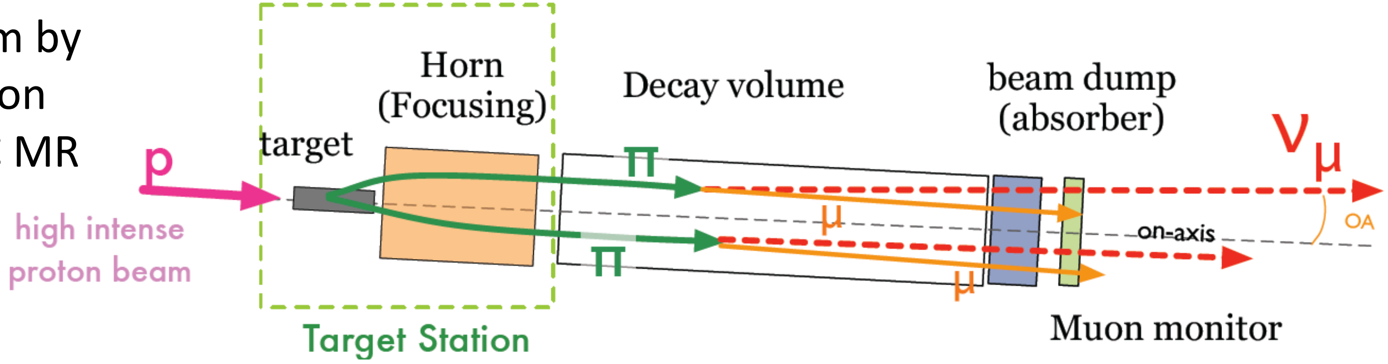
- Off-axis detector : ND280

- 50 kt Water Cherenkov detector (Fiducial 22.5 kt) @ underground (2700 m water equivalent)
- Events on the beam timing are selected using GPS.

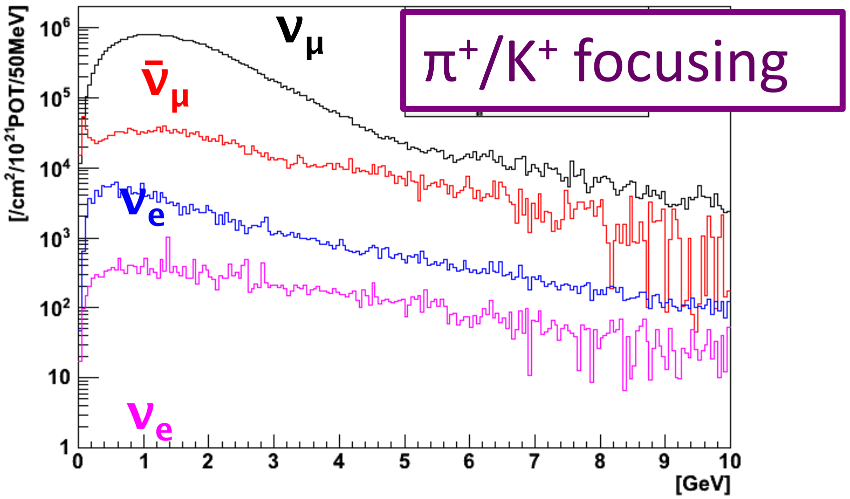
- On-axis detector : INGRID

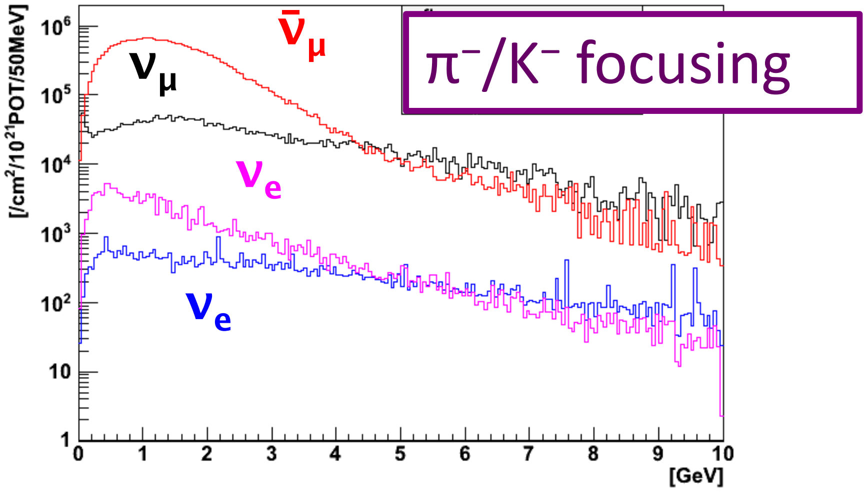
J-PARC neutrino beam-line
= conventional horn focused ν-beam

Proton beam by
Fast-extraction
From J-PARC MR



- ν beam and $\bar{\nu}$ beam can be produced by changing horn polarity.

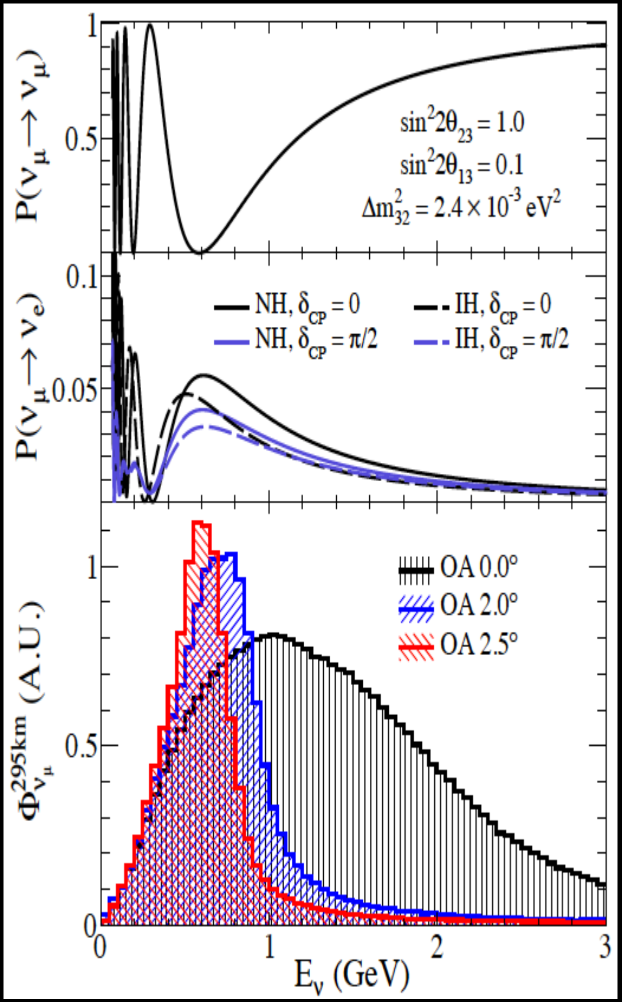


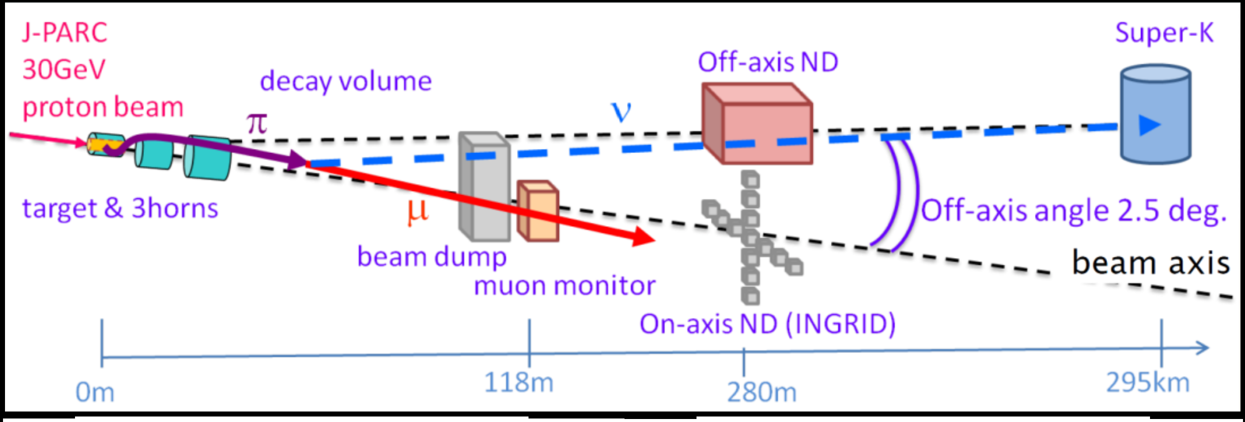


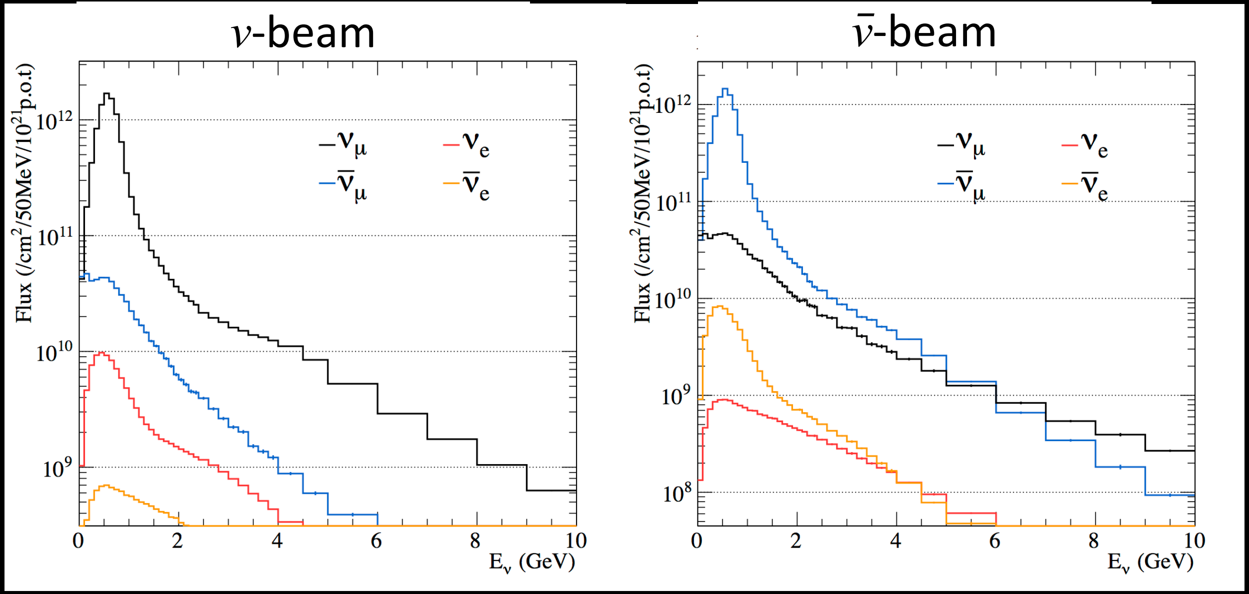
Ex. Horn(250kA) On-axis @ 295km

J-PARC neutrino beam

- Narrow band beam by off-axis method.
- ν-beam and $\bar{\nu}$-beam can be switched by changing the field polarity of horns.
- Neutrino flux is estimated from beam MC using the hadron production of 30 GeV p-C measured by CERN NA61/SHINE experiment, etc.

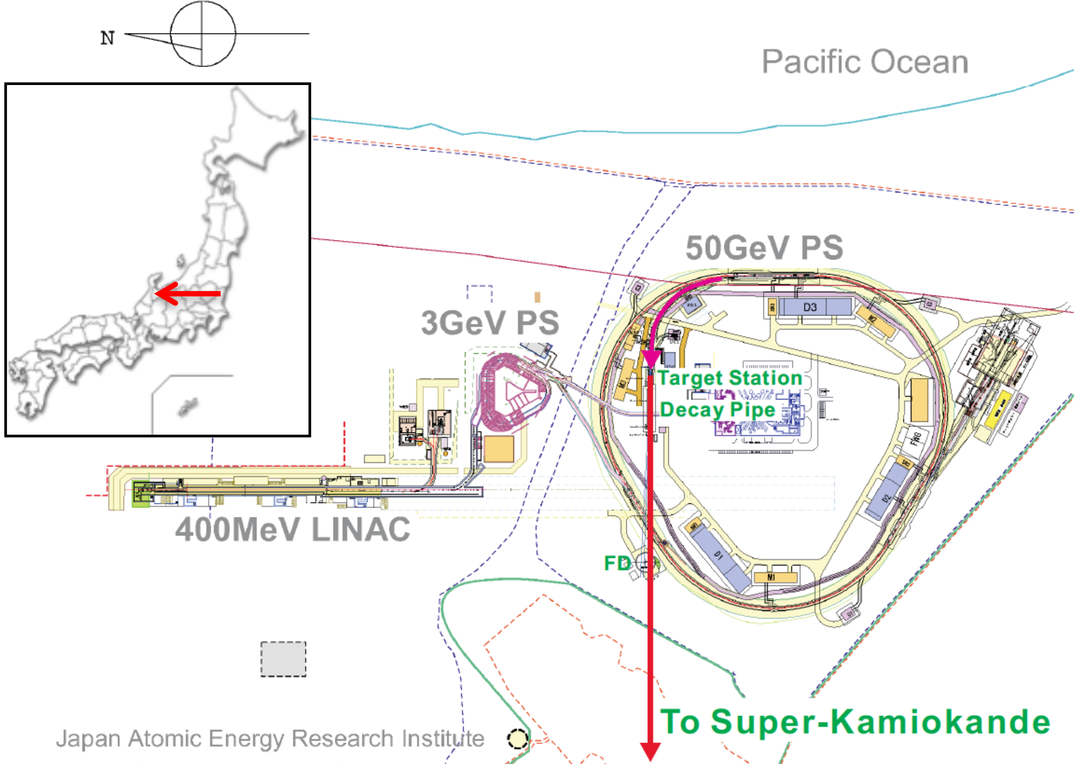


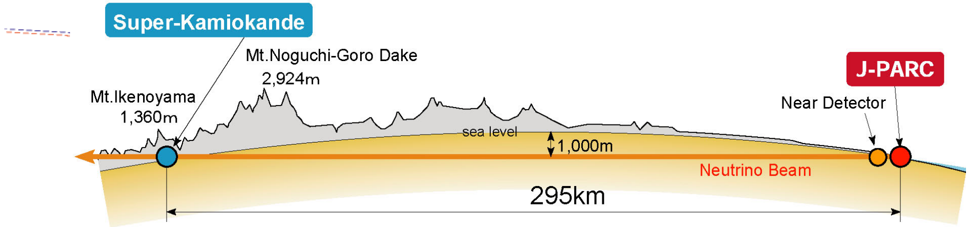


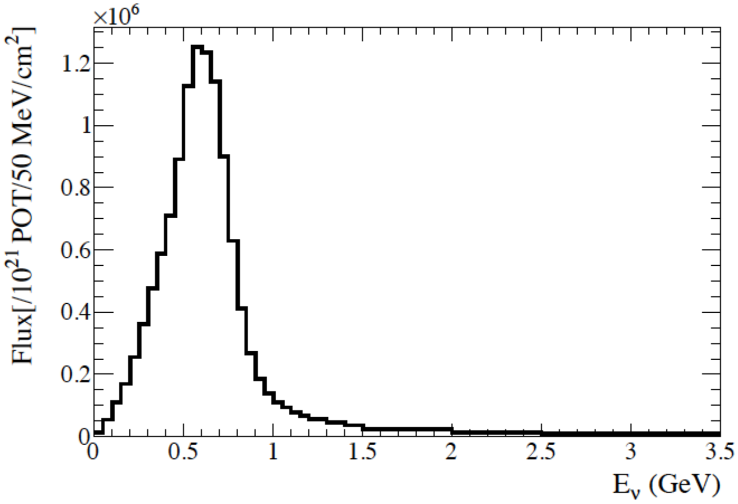


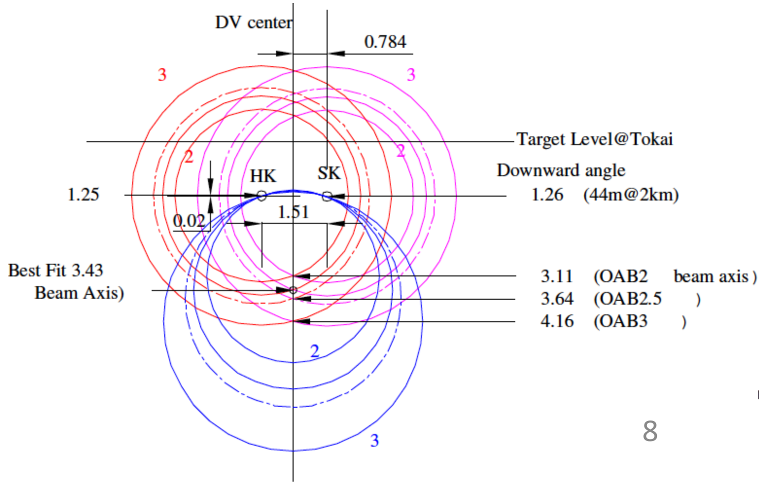
J-PARC neutrino beam

- Off-axis beam for SK-site & HK-site candidate
  - Provide narrow band beam.





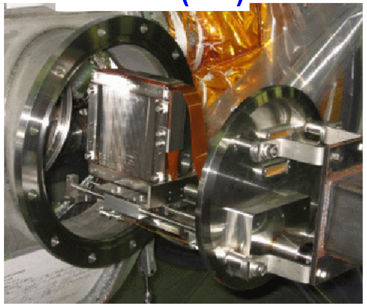




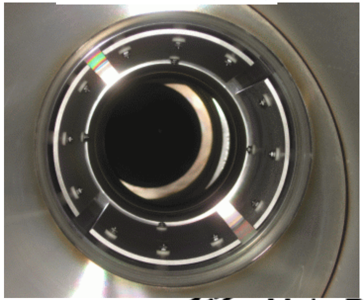
J-PARC ν beam line :Primary-line

Beam monitors are install along the proton beam transport

Profile (19)

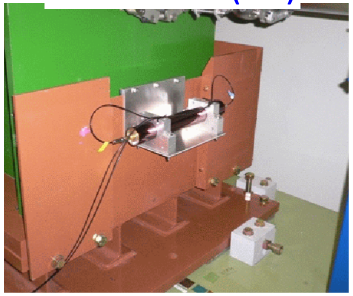


Position (21)



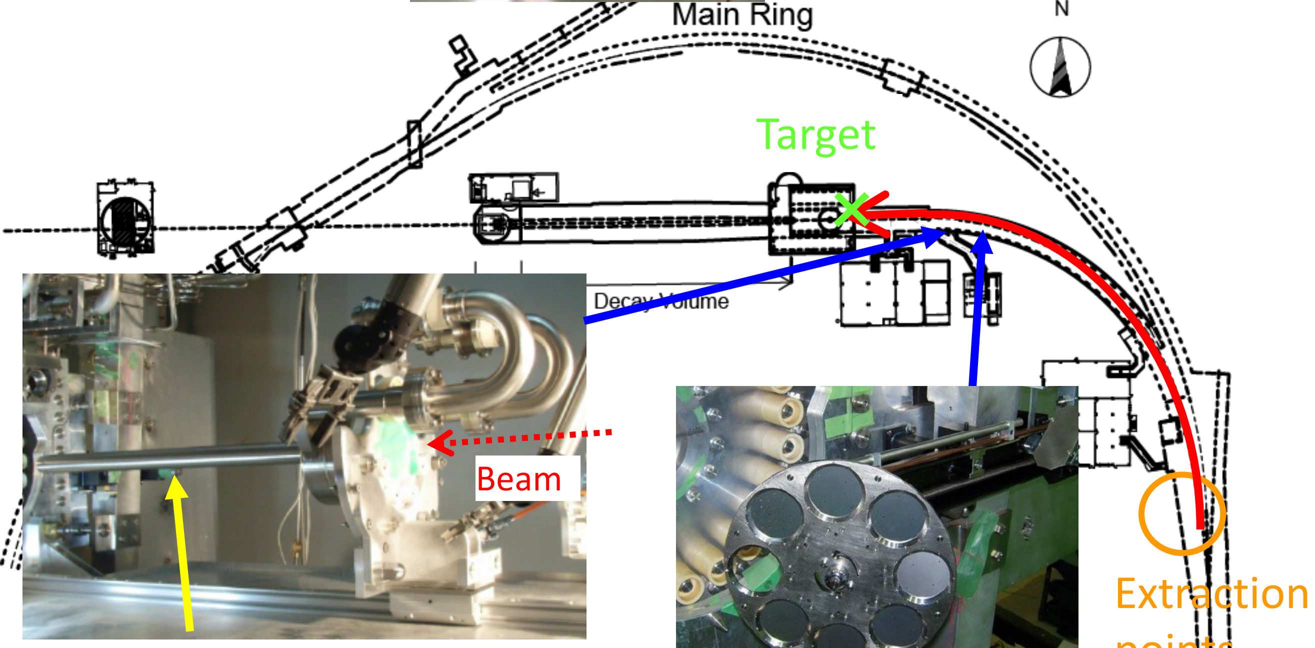
Intensity (5)

Beam loss (50)



Primary proton transport line

Super-conducting combined-function magnets

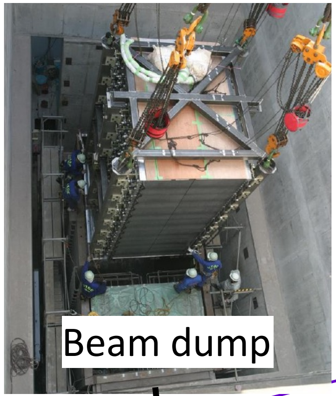


Target :graphite rod
ϕ26mm,L=900mm

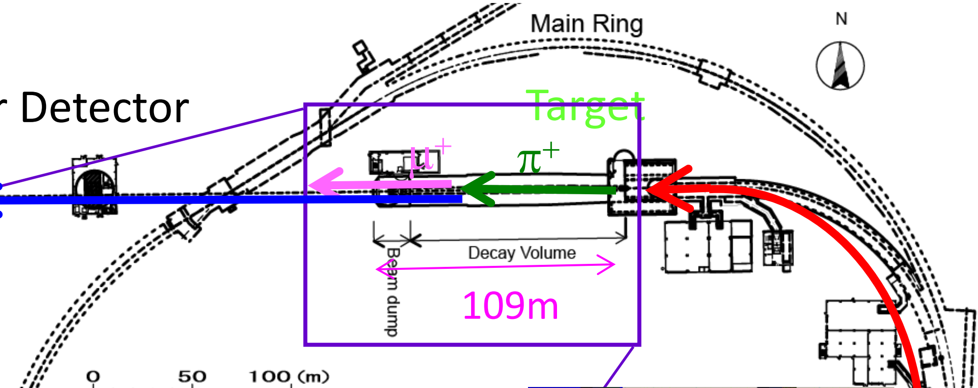
Optical Transition Radiation (OTR) Profile monitor

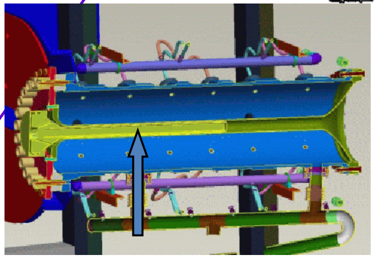
Normal-conducting magnets

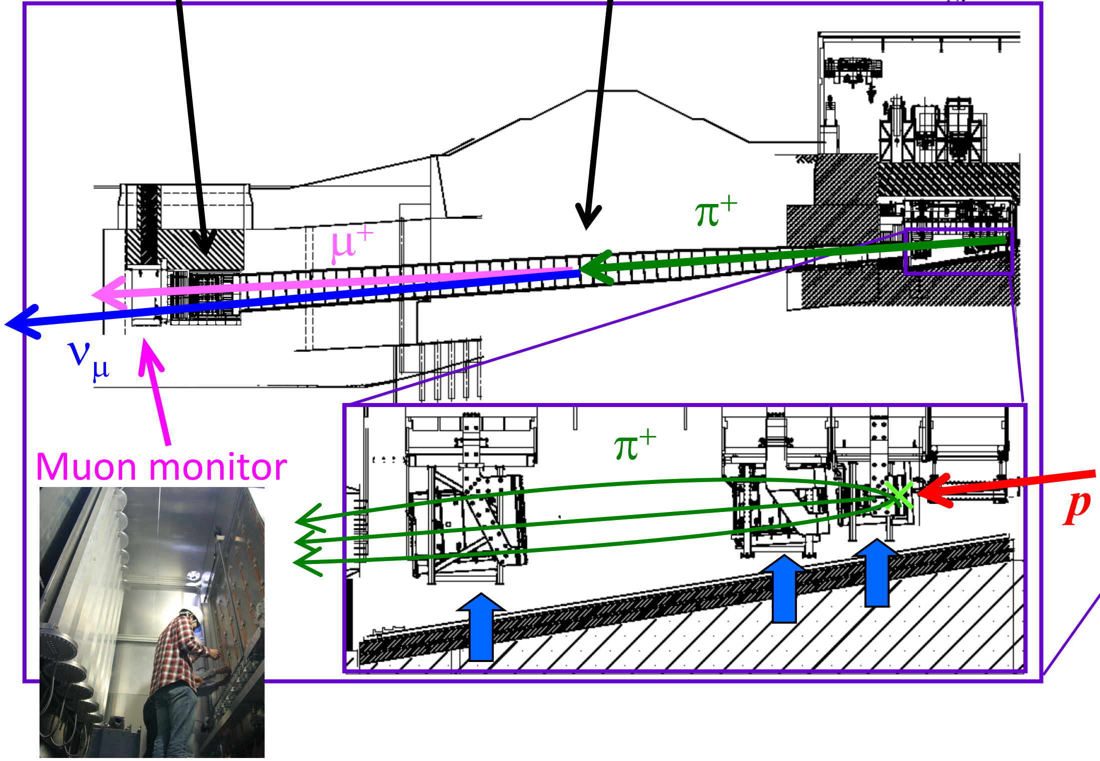
J-PARC ν beam line: secondary line


Beam dump


Decay volume (He gas filled)



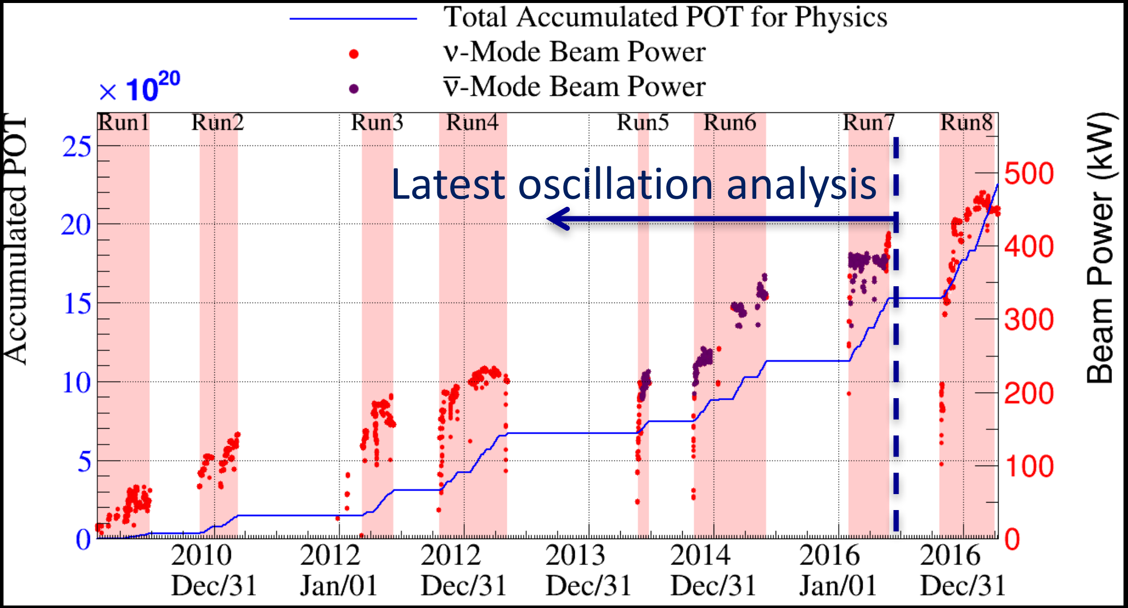

Target installed in 1^{st} horn.

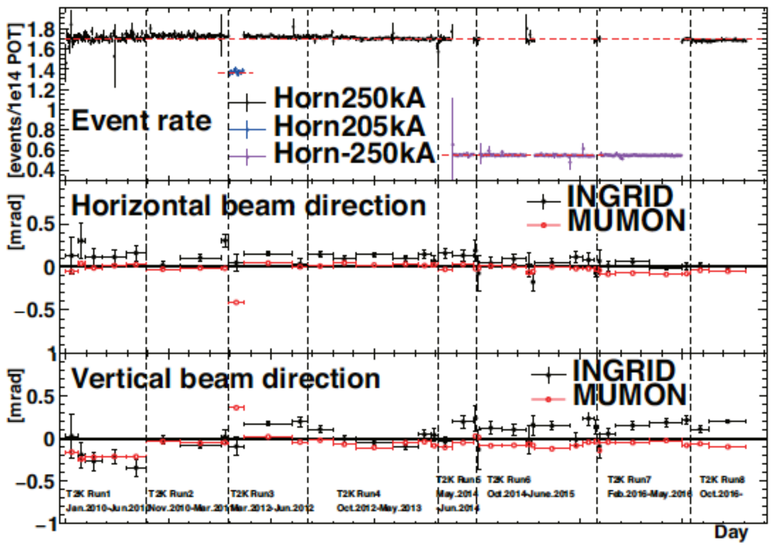



Pions are focused by
3 electromagnetic Horns.

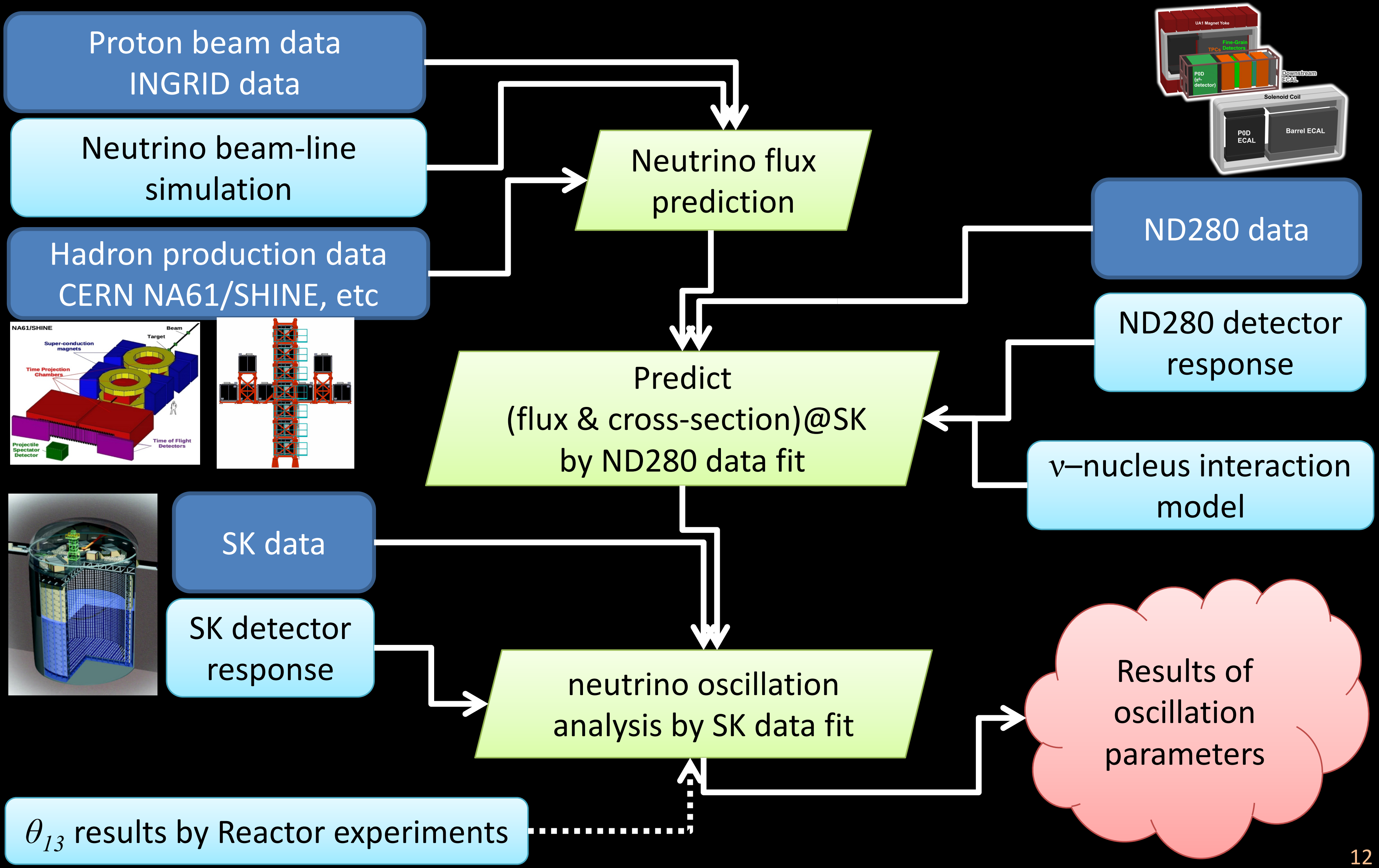
T2K data-taking status

- T2K has been taking physics data from Jan. 2010.
- From 2014, $\bar{\nu}$-beam data are also produced.
- Beam quality is stable for entire run period.
- Latest oscillation analysis result is based on data up to May, 2016.
  - ν-beam data: 7.482×10^{20} POT (Protons-On-Target)
    $\bar{\nu}$-beam data: 7.471×10^{20} POT
- As of Mar 8th, beam power for physics run is ~470kW.
  Accumulated POT for T2K exceeds 2×10^{21} POT.





T2K oscillation analysis strategy



Proton beam data
INGRID data

Neutrino beam-line simulation

Hadron production data
CERN NA61/SHINE, etc

Neutrino flux prediction

ND280 data

ND280 detector response

ν–nucleus interaction model

Predict
(flux & cross-section)@SK
by ND280 data fit

SK data

SK detector response

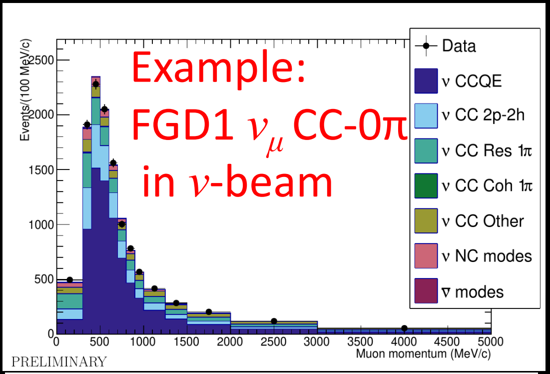
neutrino oscillation analysis by SK data fit

θ_{13} results by Reactor experiments

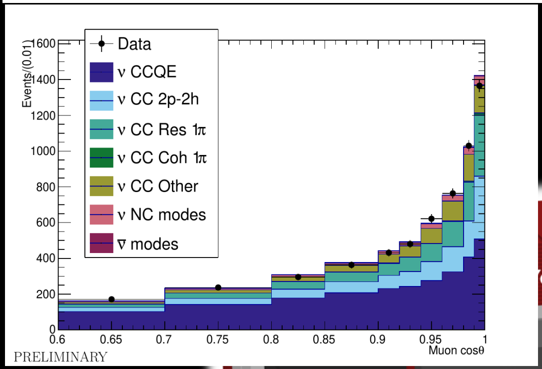
Results of oscillation parameters

Near detector data fit

- Charged-current ν_μ / $\bar{\nu}_\mu$ interaction event sub-samples in FGD1(CH target) and FGD2(CH+$H_2 0$ target) that are categorized by final-state and beam-mode (ν/ $\bar{\nu}$) are fitted simultaneously.

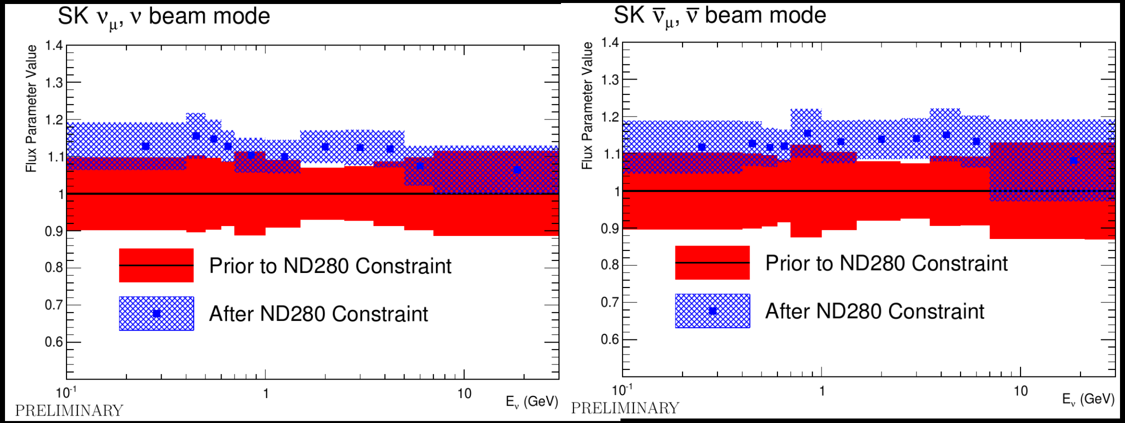


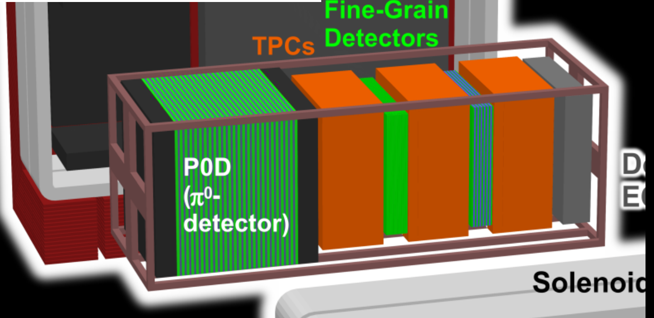
Example:
FGD1 ν_μ CC-0π
in ν-beam



+ Other event samples

Estimated SK event normalization parameter / nominal flux parameters





Total systematic uncertainty of SK event rate prediction.

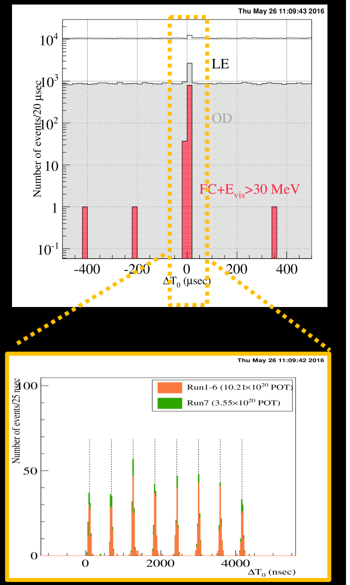
SK event sample		w/o ND280	ND280 constrained
ν-beam	1-ring μ-like	12.0 %	5.1 %
	1-ring e-like	12.7 %	6.8 %
	CC-1π^+ like	21.9 %	15.3 %
$\bar{\nu}$-beam	1-ring μ-like	17.9 %	11.7 %
	1-ring e-like	14.5 %	7.4%

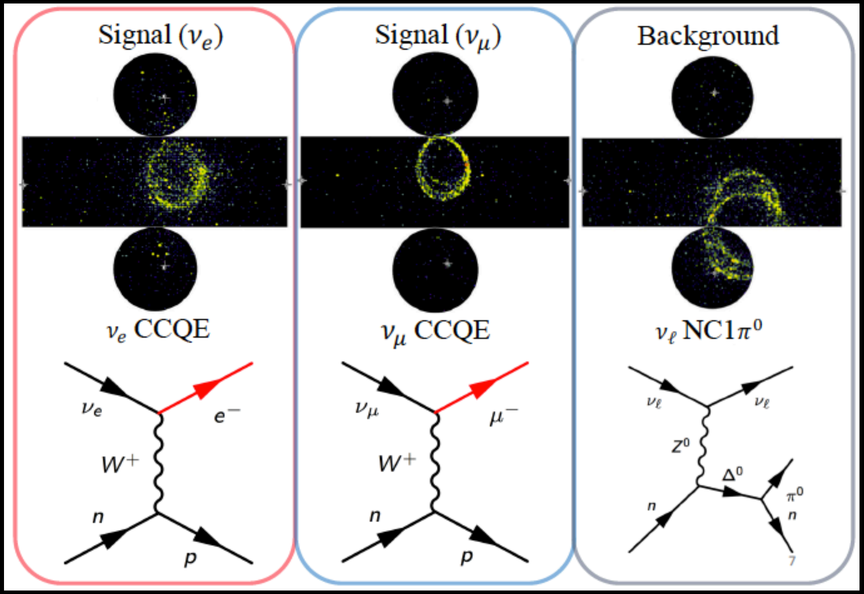
Far detector (SK) event selection

Fully contained at beam-timing + vertex inside fiducial volume

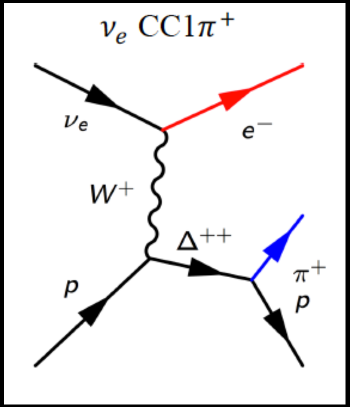
Only one-ring reconstructed

- PID: μ-like
  - μ momentum p_μ > 200MeV
  - # of decay-e ≦ 1
  - $\nu_\mu/\bar{\nu}_\mu$ CC-QE candidate
- PID: e-like
  - Visible energy E_{vis} > 100MeV
  - No decay-e
    - Reconstructed E_ν < 1250MeV
    - NC-π^0 rejection
    - $\nu_e/\bar{\nu}_e$ CC-QE candidate
  - Only 1 decay-e
    - Reconstructed E_ν < 1250MeV
    - NC-π^0 rejection
    - $\nu_e/\bar{\nu}_e$ CC-1π candidate





A new event sample become available for oscillation analysis!



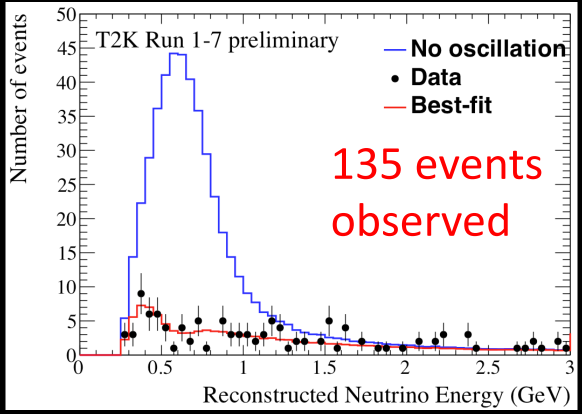
Neutrino energy is reconstructed assuming π-production via Δ-resonance

Observed SK neutrino event candidates

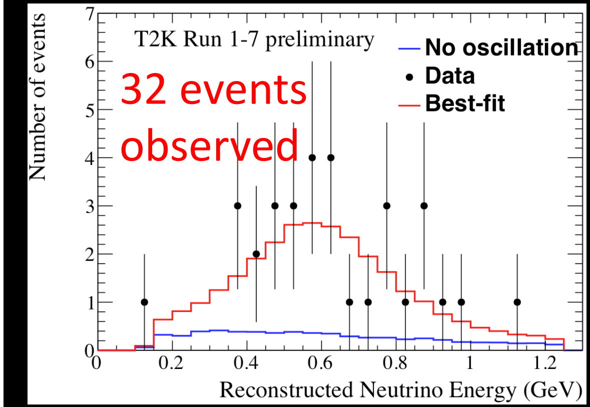
- Oscillation parameter is determined by fitting 5 event categories simultaneously.

New event sample

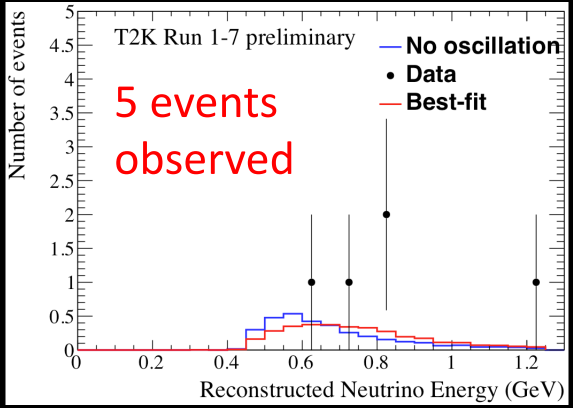
$\nu_\mu/\bar{\nu}_\mu$ CC-QE in ν-beam



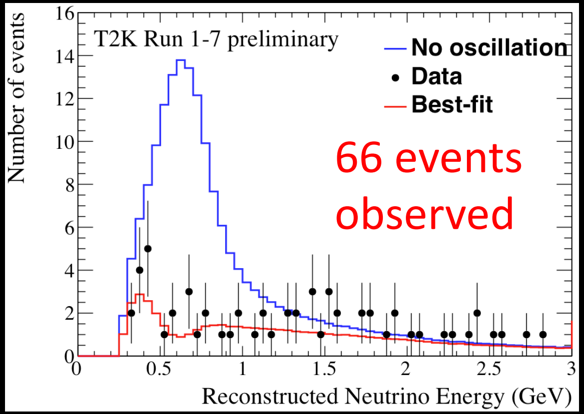
$\nu_e/\bar{\nu}_e$ CC-QE in ν-beam



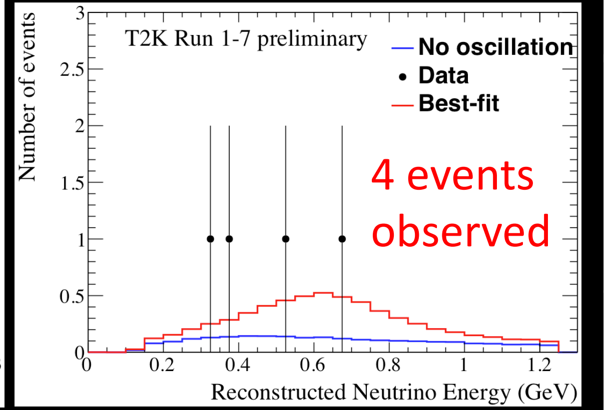
$\nu_e/\bar{\nu}_e$ CC-1π in ν-beam



$\nu_\mu/\bar{\nu}_\mu$ CC-QE in $\bar{\nu}$-beam



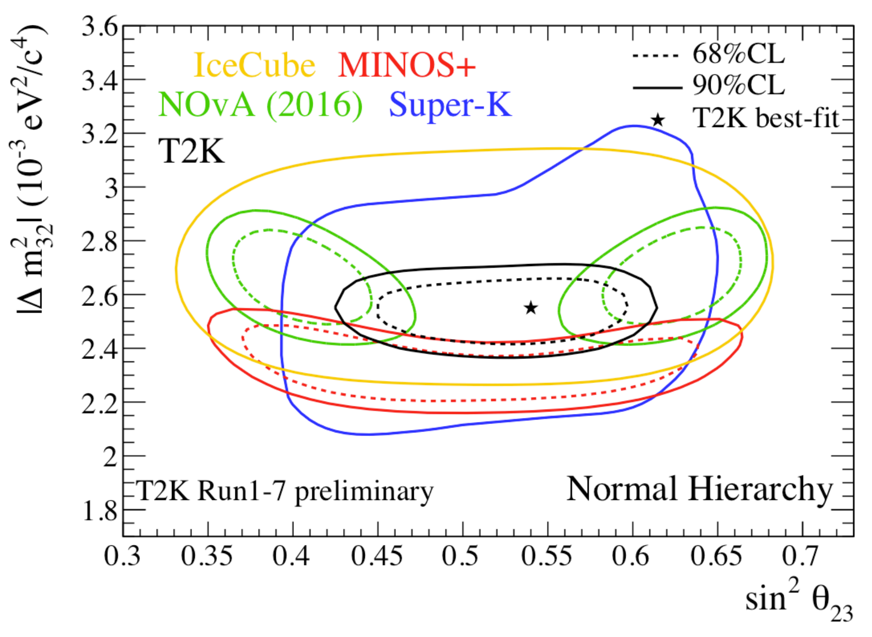
$\nu_e/\bar{\nu}_e$ CC-QE in $\bar{\nu}$-beam

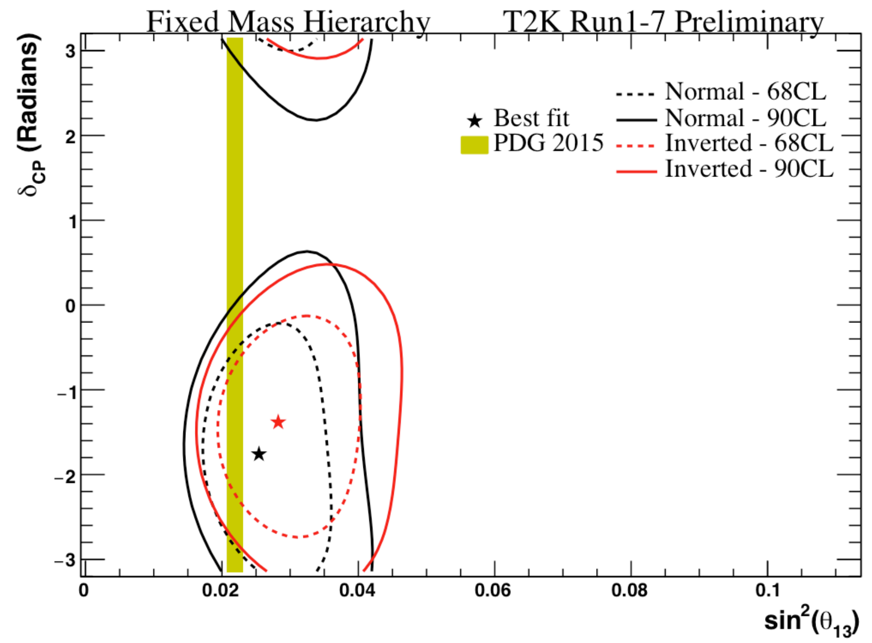


Expected # of events		δ_{CP}	
		-1.6	0
ν-beam	$\nu_\mu/\bar{\nu}_\mu$ CC-QE	135.8	135.5
	$\nu_e/\bar{\nu}_e$ CC-QE	28.7	24.2
	$\nu_e/\bar{\nu}_e$ CC-1π	3.1	2.7
$\bar{\nu}$-beam	$\nu_\mu/\bar{\nu}_\mu$ CC-QE	64.2	64.1
	$\nu_e/\bar{\nu}_e$ CC-QE	6.0	6.9

Latest results on oscillation parameters

- T2K results consistent with the max. oscillation ($\sin^2\theta_{23}$=0.5).

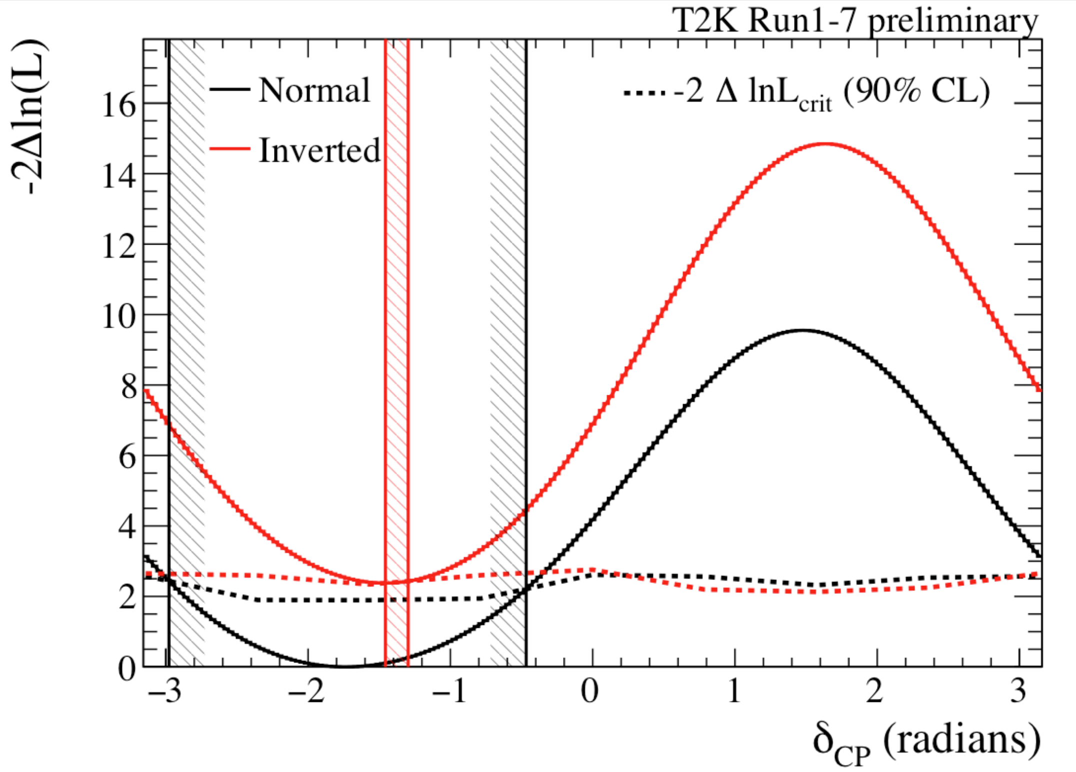




Super-K: PoS ICRC2015 (2015) 1062
Minos+: Neutrino 2014
NOvA : ICHEP2016
IceCube DeepCore: Phys.Rev. D91 (2015) 072004

Obtained results on CP

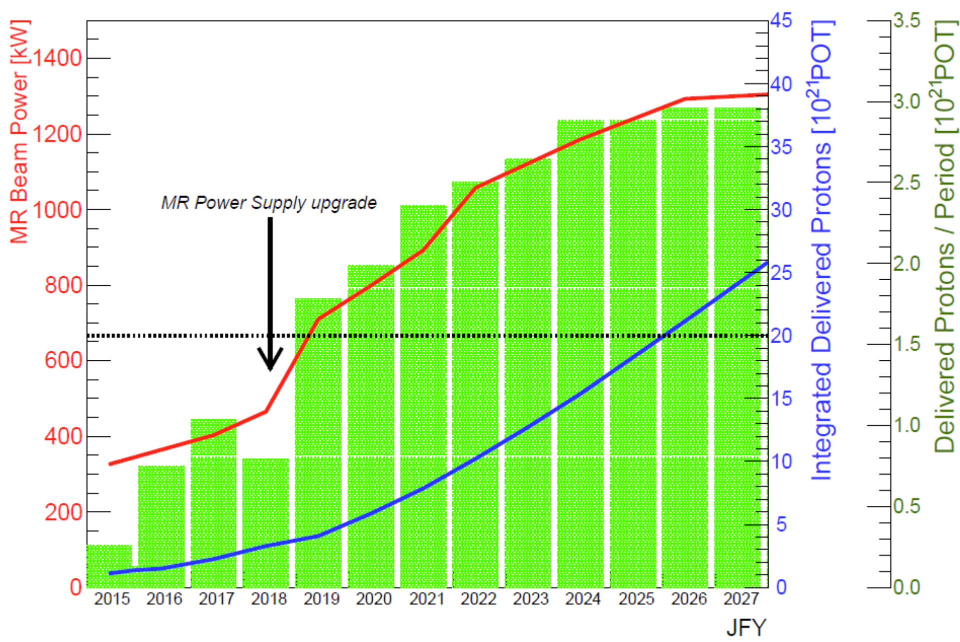
- Constrain θ_{13} with the results by reactor exp.
- CP-conservation hypothesis ($\sin\delta_{CP}=0$) is excluded with 90% CL.
- Confidence interval (90 %CL): NH -2.978 ~ -0.467 [rad]
  IH -1.466 ~ -1.272 [rad]

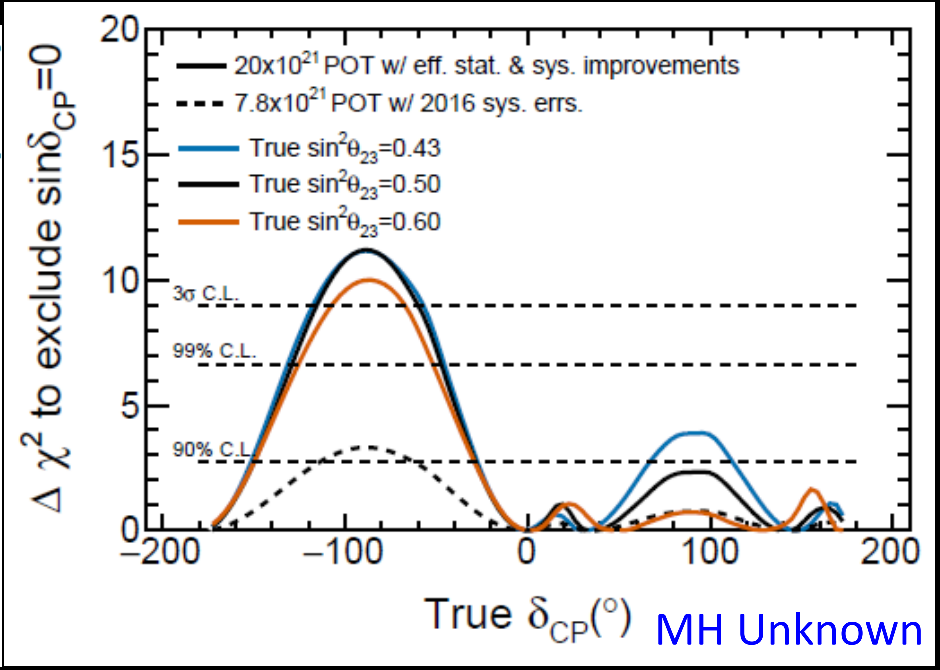


Future prospects

T2K-II (Running time extension)

- T2K proposes to collect 20 × 10^{21} POT data to search for evidence of CP violation in the lepton sector with 3σ sensitivity. (arXiv:1609.04111 [hep-ex])
  - J-PARC PAC recognizes the scientific merit and gave stage-1 status in 2016.

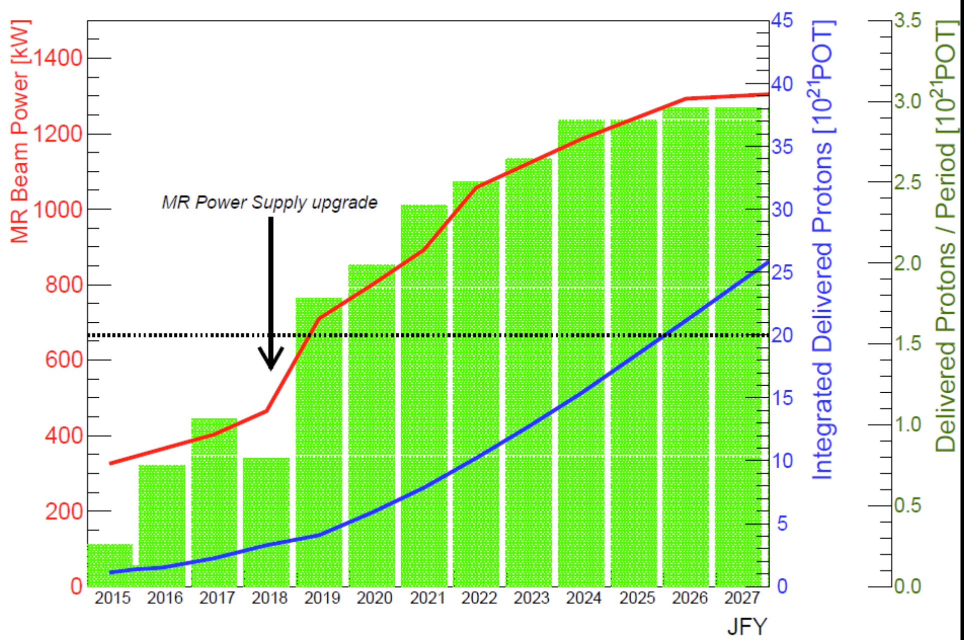


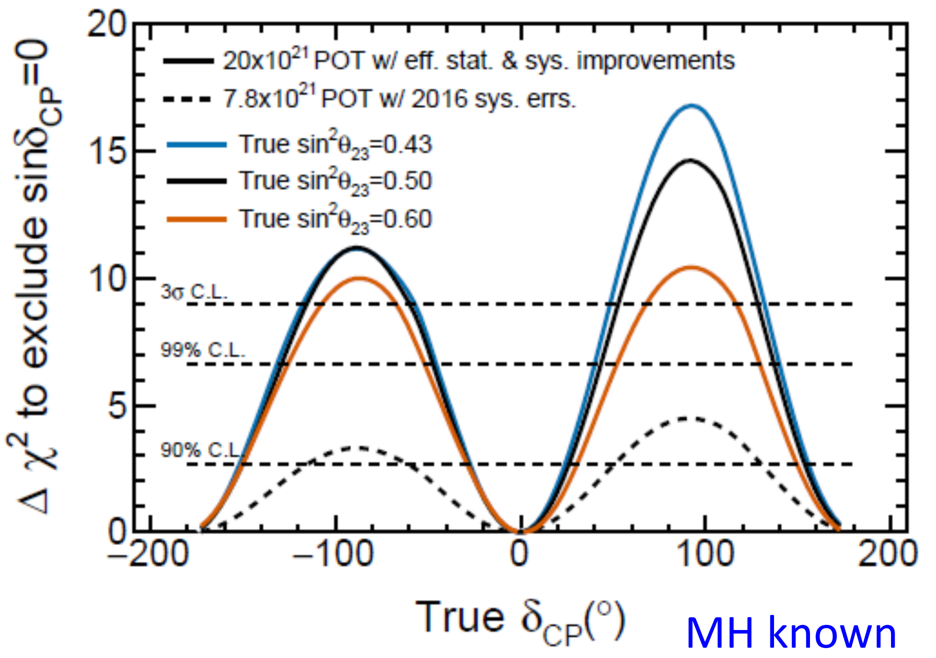


MH Unknown

T2K-II (Running time extension)

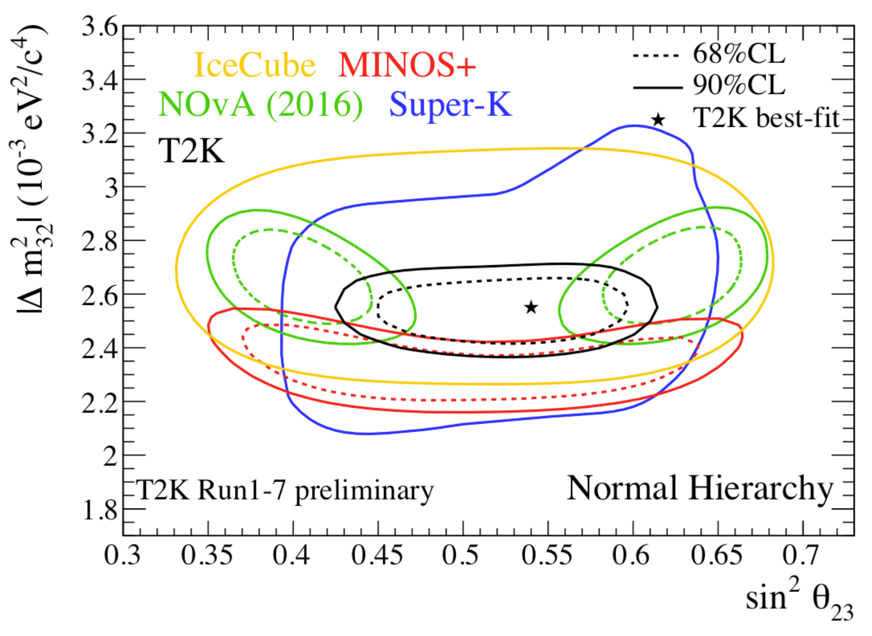
- T2K proposes to collect 20×10^{21} POT data to search for evidence of CP violation in the lepton sector with 3σ sensitivity. (arXiv:1609.04111 [hep-ex])
  - J-PARC PAC recognizes the scientific merit and gave stage-1 status in 2016.





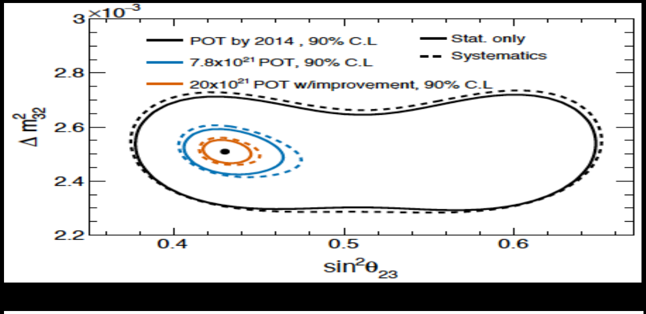
Near Term prospects on θ_{23}

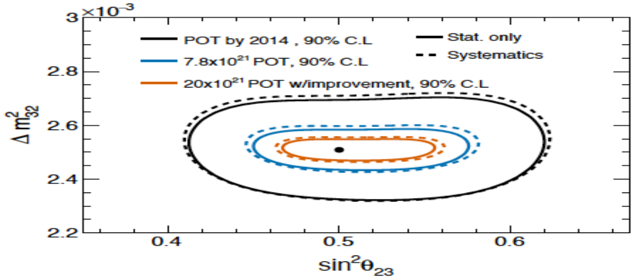
- Current results

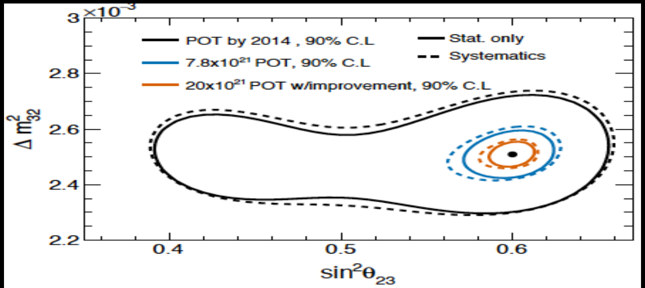


Super-K: PoS ICRC2015 (2015) 1062
Minos+: Neutrino 2014
NOvA : ICHEP2016
IceCube DeepCore: Phys.Rev. D91 (2015) 072004

- T2K-II expected 90%CL

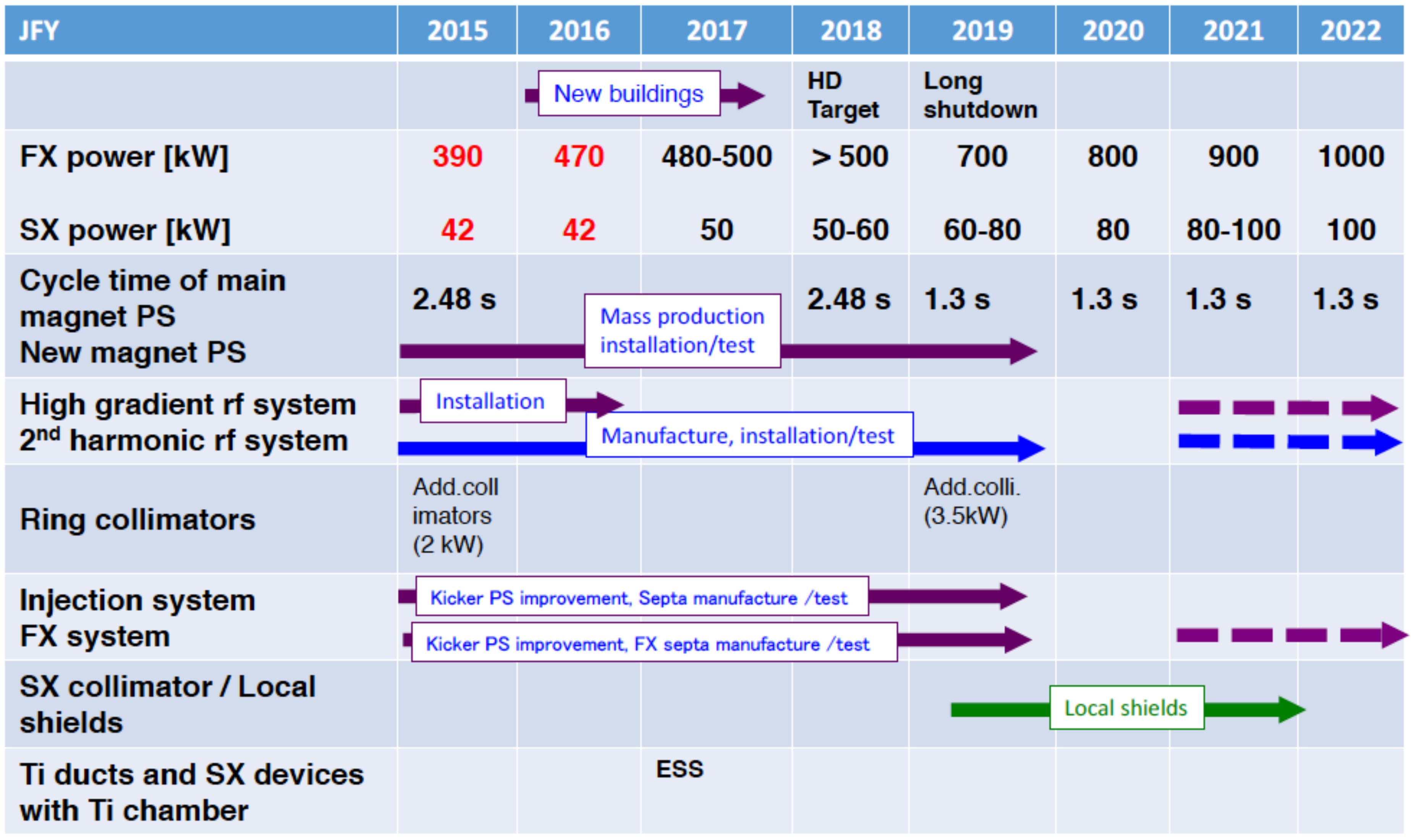






Need more neutrino for T2K-II

Mid Term Plan of J-PARC MR



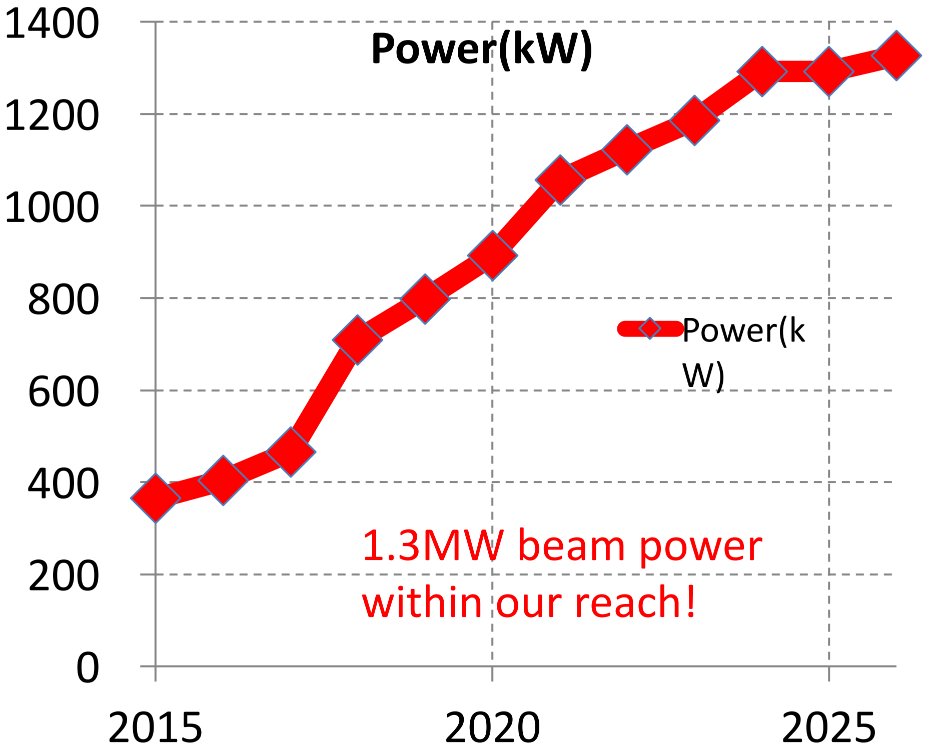
JFY	2015	2016	2017	2018	2019	2020	2021	2022
		New buildings		HD Target	Long shutdown			
FX power [kW]	390	470	480-500	> 500	700	800	900	1000
SX power [kW]	42	42	50	50-60	60-80	80	80-100	100
Cycle time of main magnet PS	2.48 s			2.48 s	1.3 s	1.3 s	1.3 s	1.3 s
New magnet PS		Mass production installation/test						
High gradient rf system	Installation							
2nd harmonic rf system		Manufacture, installation/test						
Ring collimators	Add.collimators (2 kW)				Add.colli. (3.5kW)			
Injection system	Kicker PS improvement, Septa manufacture /test							
FX system	Kicker PS improvement, FX septa manufacture /test							
SX collimator / Local shields					Local shields			
Ti ducts and SX devices with Ti chamber			ESS					

Beam power upgrade beyond 750kW

- By increasing, the instantaneous beam intensity up to original design level.

Method

- RF upgrade
- Beam monitor upgrade
  - Precise beam control for Higher proton / bunch.
- Fast Extraction Kicker upgrade



1.3MW beam power within our reach!

Beam Power	Achieved 470kW	Trial in Apr. 2017 510kW	Design 750 kW	Long time goal 1326 kW
#p/p(10^{12})	240	**270**	**200**	**320**
Rep cycle (s)	2.48	***(single shot trial)***	**1.3**	1.16

Prospects for >=750kW operation of J-PARC neutrino beam-line

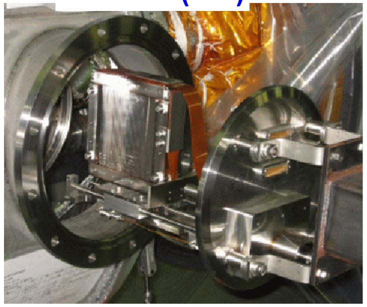
- Factors to limit the acceptable beam power.
  - Thermal shock resistance of the equipment which is exposed with beam directly. (Target, etc)
    → It depends on instantaneous beam intensity (protons/pulse).
    In current MR improve strategy to aim ~1.3MW, it is not larger than the original design value = 3.3×10^{14} protons/pules.
  - Cooling capability to deal with head generated by beam.
  - Radiation protection :
    - Beam-loss control
    - Radiation shields
    - Treatment of radioactive waste
    - Radiation damage of the beam-line equipment.
    - Reliability of the beam handling

- The equipment that can not be replaced/upgraded after the beam operation started once, such as beam-dump, Decay volume, has been designed for 3~4MW beam power.

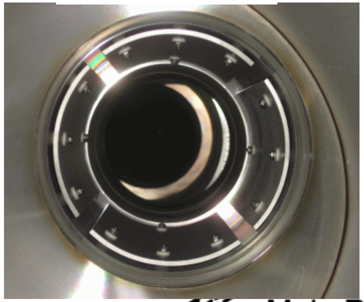
J-PARC ν beam line :Primary-line

Beam monitors are install along the proton beam transport

Profile (19)

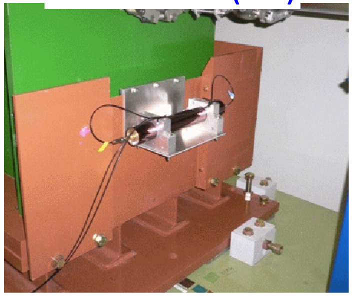


Position (21)



Intensity (5)

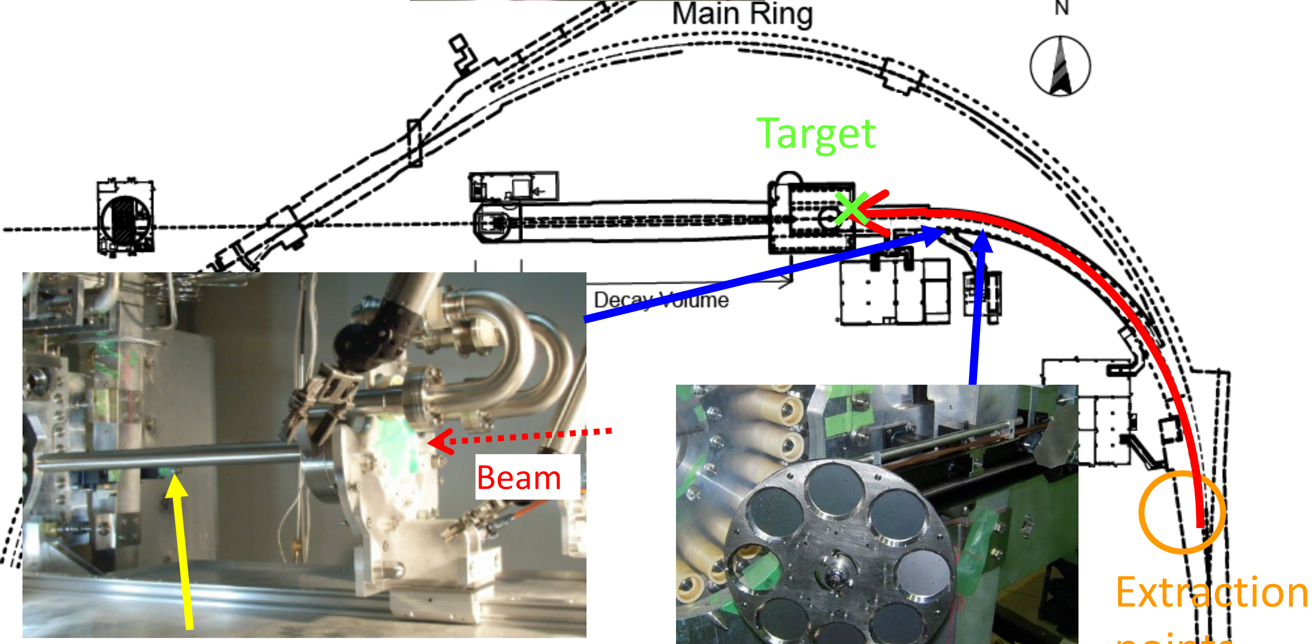
Beam loss (50)



Primary proton transport line

Super-conducting combined-function magnets

Normal-conducting magnets



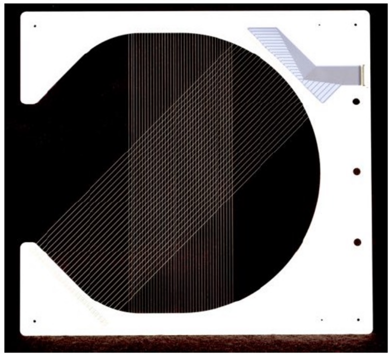
Target :graphite rod
ϕ26mm,L=900mm

Optical Transition Radiation (OTR) Profile monitor

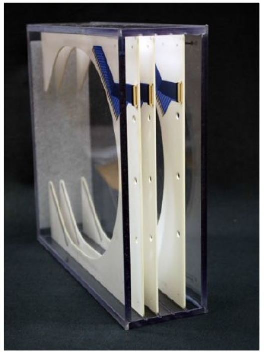
ν Beam-line upgrade (1)

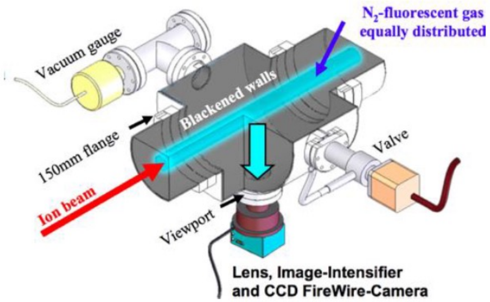
- Primary beam-line:
  - The beam monitor for lower beam loss
    - Profile monitor by graphite/Ti wires
    - Beam induced fluorescence monitor
  - Beam-data DAQ for high-repetition
    - Fast FADC should be developed.
  - Hardware beam-interlock based on the beam monitor measurement.

Finished Plane

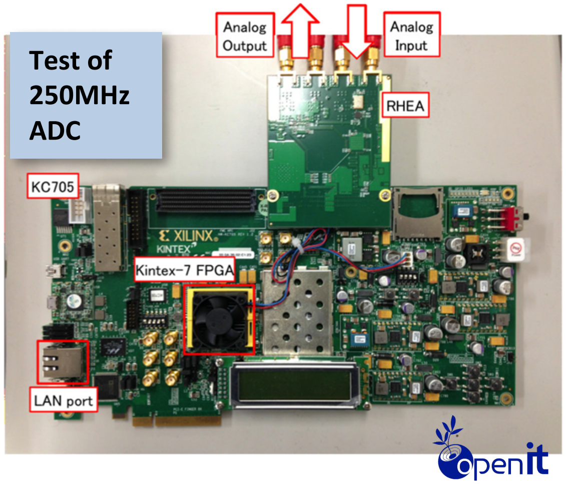


In Shipping Container



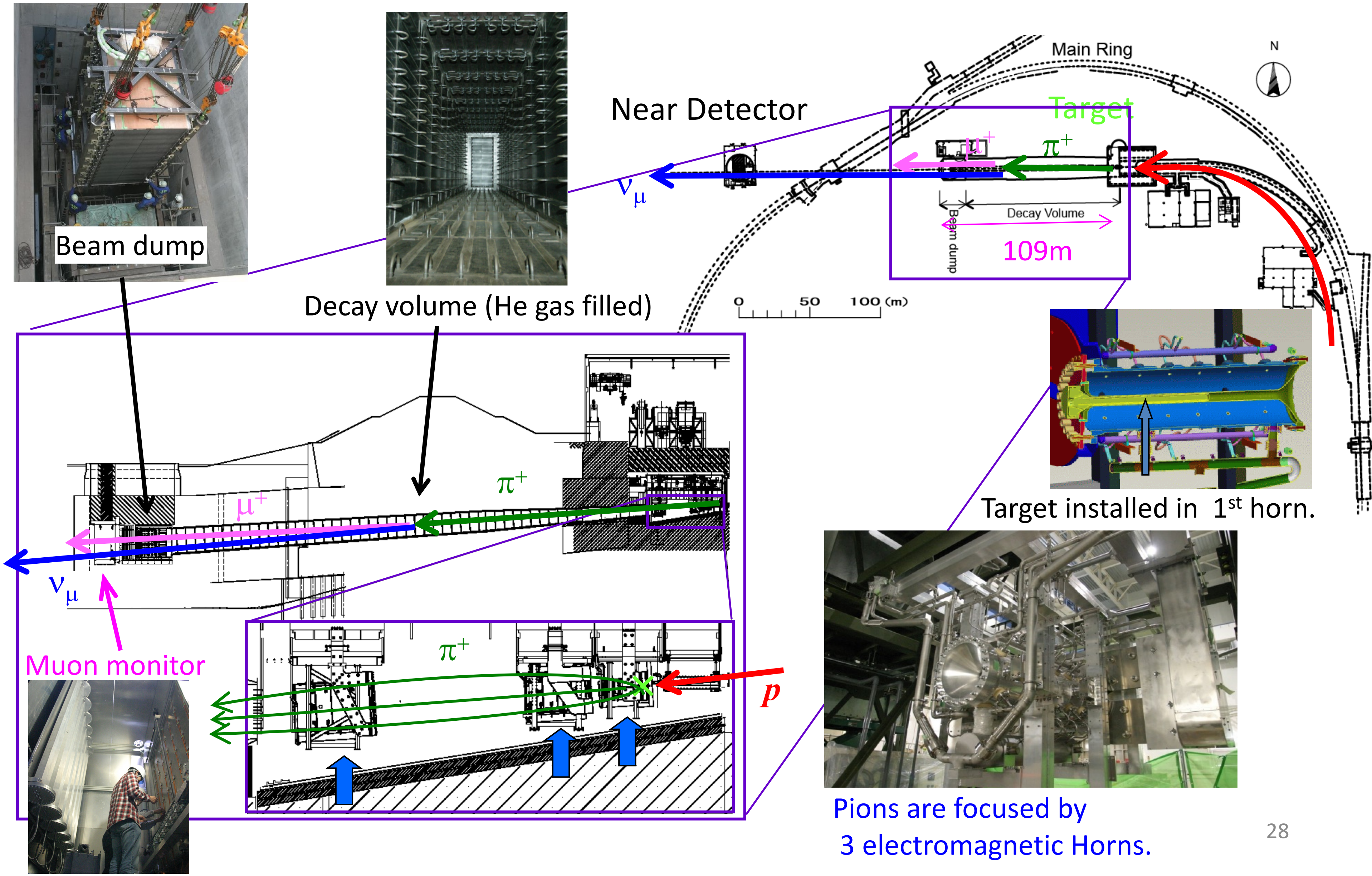


Have been used in CERN SPS (NIMA 492 (2002) 7490), GSI (Proceedings of DIPAC 2007), etc.



Test of 250MHz ADC

J-PARC ν beam line: secondary line



Near Detector

Beam dump

Decay volume (He gas filled)

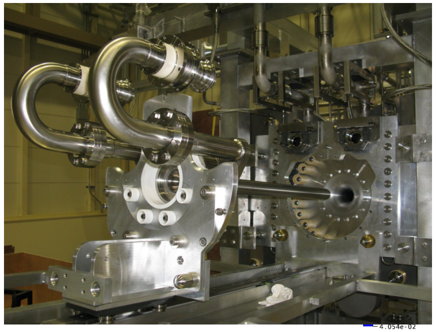
Target installed in 1st horn.

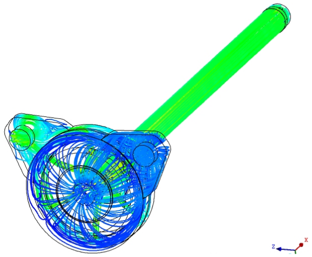
Muon monitor

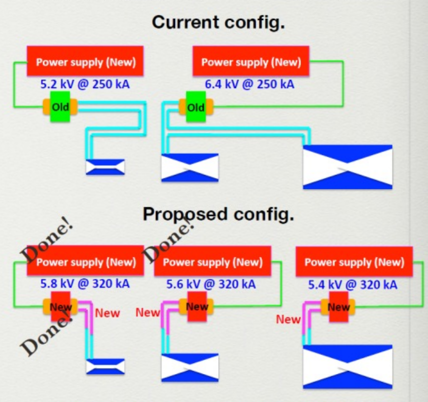
Pions are focused by
3 electromagnetic Horns.

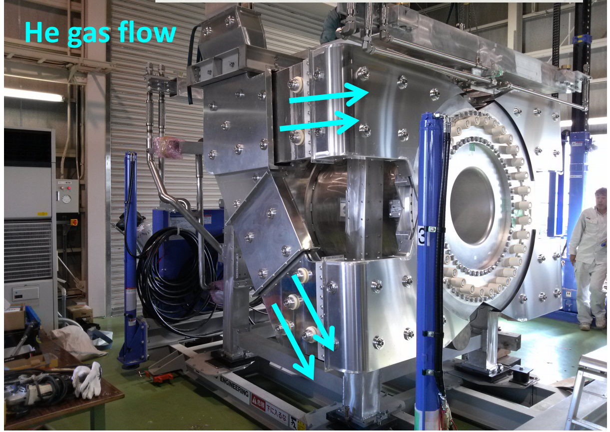
ν Beam-line upgrade (2)

- Secondary beam-line
  - Target with reinforced He-gas cooling system should be prepared.
  - Horn for >750kW beam:
    - The power supply for ~1Hz operation.
    - Reinforced strip-line cooling. (Increasing He flow, Introduce the water-cooled strip-line.)
  - Reinforcement of the cooling water facility for He-vessel/DV/Beam-dump cooling.
  - Increase the capability of the radio-activated water disposal.
    - Enlarge the disposal tanks, etc.
  - Adding the concrete radiation shields at Target Station ground floor.
- In the technical aspects, the upgrade strategy of the neutrino beam-line for >1MW beam by current MR improvement scenario is straightforward.



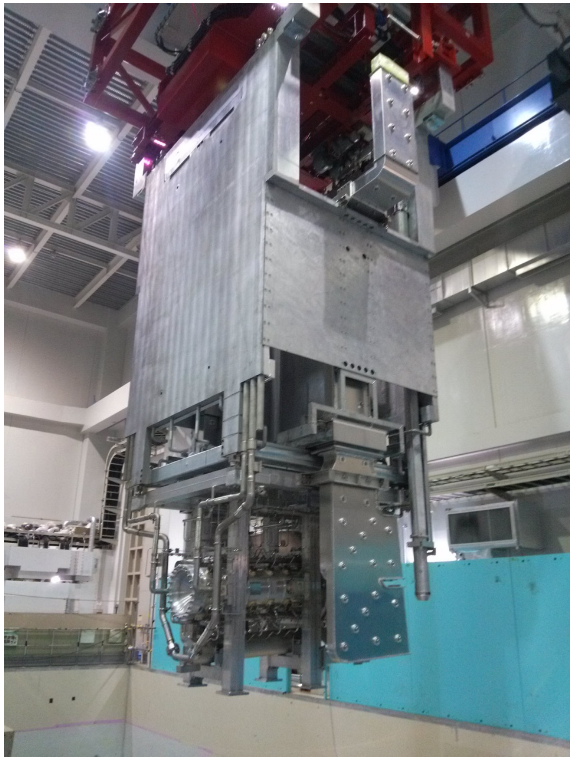




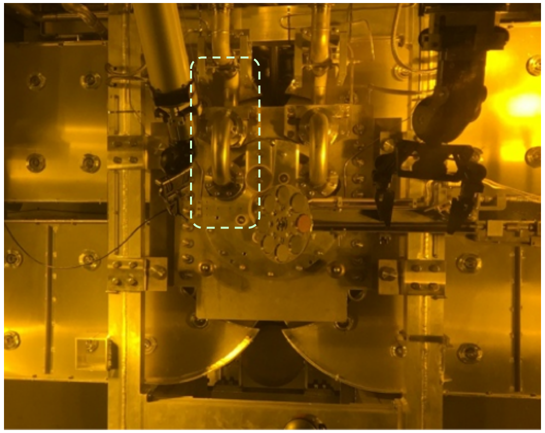


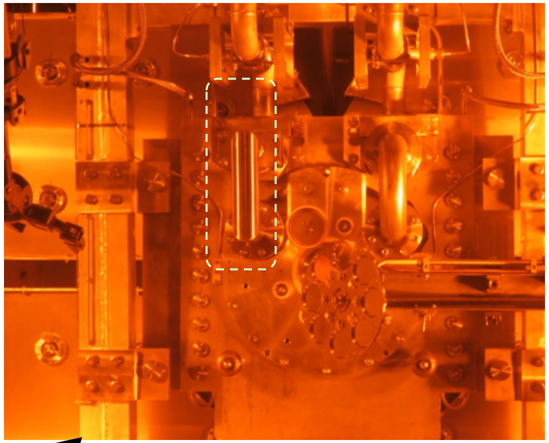
Technical challenges: One example

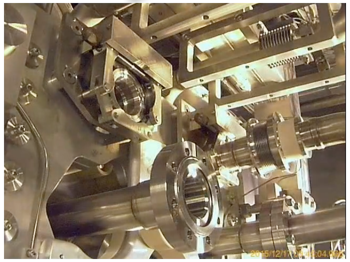
- Equipment is highly activated, thus Remote maintenance is necessary!
 (It may requires several month.)
  - Design, mechanical engineering, production, test for various equipment are to be done.
- Clever idea to minimize the maintenance period, Improvement of the robustness of essential components will directly increase the number of neutrino that will mainly determine the physics sensitivity of the T2K-II experiment.

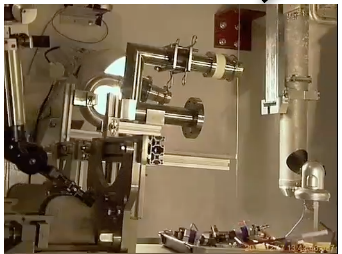


Horn system transportation by remote controlled crane)









Replaced by manipulators at the maintenance area (KEK, RAL, TRIUMF)

Summary

- Latest T2K results on neutrino oscillation by adding new event sample (ν_e CC1π) shows,
  - CP conservation hypothesis ($\sin\delta_{\mathrm{CP}}$ = 0) is disfavored with 90% CL.
  - Neutrino oscillation via mixing angle θ_{23} is consistent with Max. oscillation ($\sin^2\theta_{23}=0.5$).
- T2K propose to collect 2×10^{22} POT with aim to search for CPV with 3σ sensitivity.
  - Scientific merit is recognized by J-PARC PAC (stage-1 status)
  - Near detector upgrade has been started.
  - Effort to beam-power improvement is also on-going.
    - There are many room to new collaborator join.

Backup

Upgrade: T2K → T2K-II

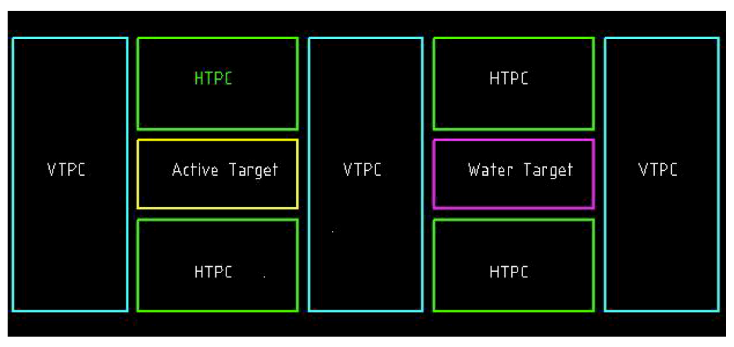
- Beam Improvement:
  - 750 kW → 1.3 MW by HW upgrade of J-PARC MR accelerator and ν-beamline
  - Improve ν-flux/POT by horn current 250 kA→320 kA
- Far detector (SK) analysis improvement:
  - Enlarge fiducial volume, etc

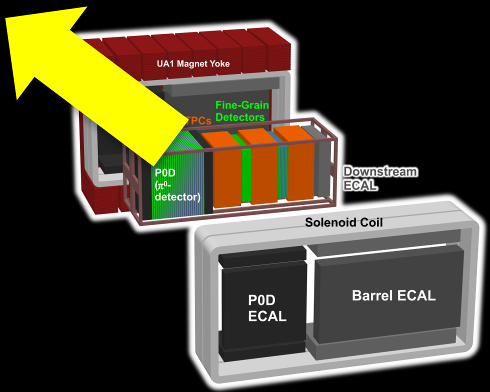
→Aiming ×1.5 signal/POT

- 356.3 $\nu_\mu \rightarrow \nu_e$ sig. expected in ν-beam
- 73.6 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal expected in $\bar{\nu}$-beam (ν-beam:$\bar{\nu}$-beam=50:50, NH, δ_{CP}=0 is assumed)

- Near detector upgrade
  - Covering more phase space, etc
  - LOI was submitted to CERN SPSC.

→ Aiming to improve syst. error: ~6% → ~4%





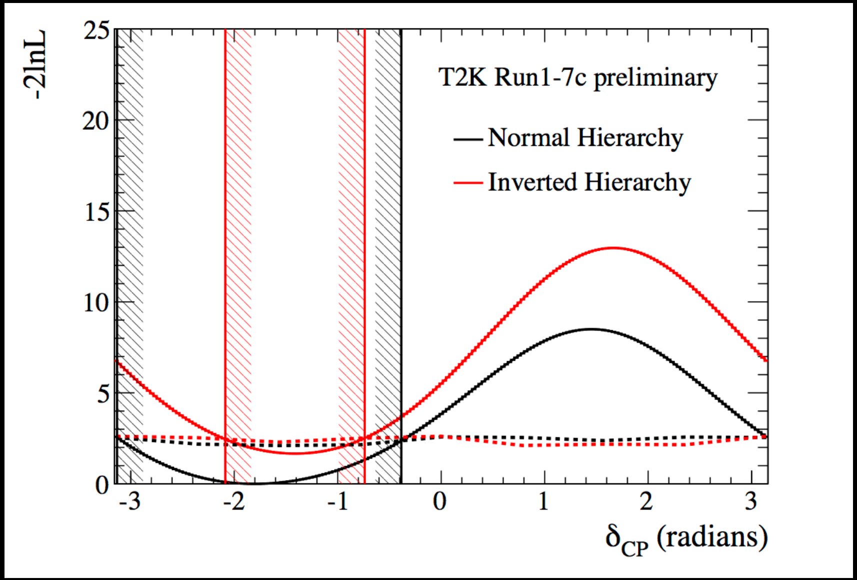
New collaborators are very welcome!

Systematic uncertainty of expected # events at SK

Source of Uncertainties			**SK event sample: $\Delta N_{SK}/N_{SK}$ (1σ error)**				
			ν-beam			$\bar{\nu}$-beam	
			1-ring μ-like	1-ring e-like	CC-$1\pi^+$ e-like	1-ring μ-like	1-ring e-like
SK: Detector + Final State Int. + 2ndary int.			4.2%	3.5%	14.0%	11.1%	4.0%
Beam + Near detector	Neutrino Beam flux		3.6%	3.7%	3.6%	3.8%	3.8%
	ν-interaction cross-section	*MEC (corr)*	*3.5%*	*3.9%*	*0.5%*	*3.0%*	*3.0%*
		MEC bar (corr)	*0.2%*	*0.1%*	*0.0%*	*1.8%*	*2.3%*
		NC 1γ (uncorr)	*0.0%*	*1.5%*	*0.4%*	*0.0%*	*3.0%*
		$\sigma(\nu_e) / \sigma(\nu_\mu)$	*0.0%*	*2.6%*	*2.4%*	*0.0%*	*1.5%*
		(Cross-section: sub total)	4.0%	5.1%	4.8%	4.2%	5.5%
	(Flux + Cross-section Sub total)		2.9%	4.2%	5.0%	3.5%	4.7%
Oscillation parameters: $\sin^2\theta_{13}$, $\sin^2\theta_{12}$, Δm^2_{21}			0.0%	4.2%	3.8%	0.0%	4.0%
Total			5.1%	6.8%	15.3%	11.7%	7.4%

Improvement by SK ν_e CC-1π sample

Previous results, arXiv:1701.00432 (Accepted by PRL)

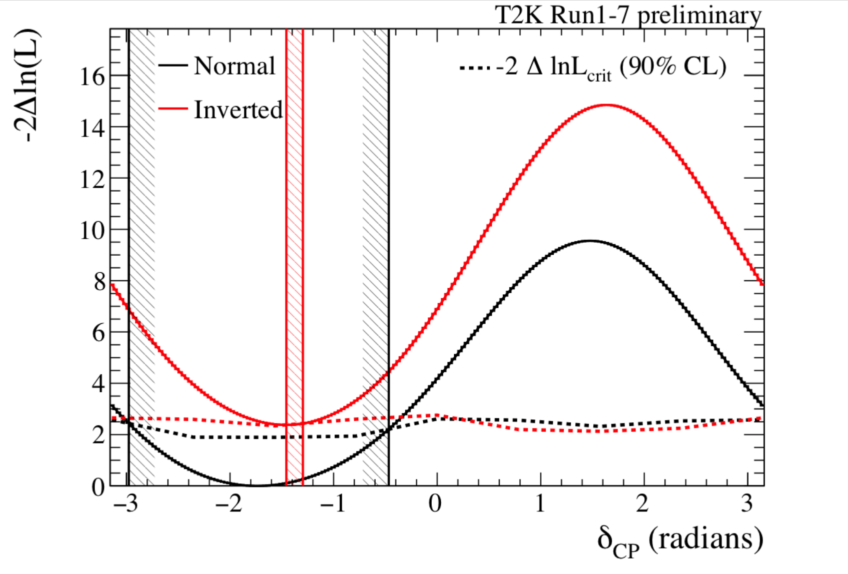


90%CL Confidence intervals

NH: -3.13 ~ -0.39

IH: -2.09 ~ -0.74

With SK ν_e CC-1π e sample

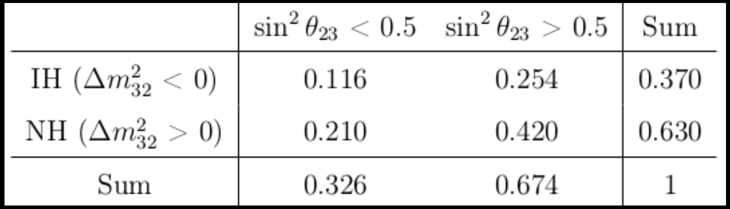


90%CL Confidence intervals

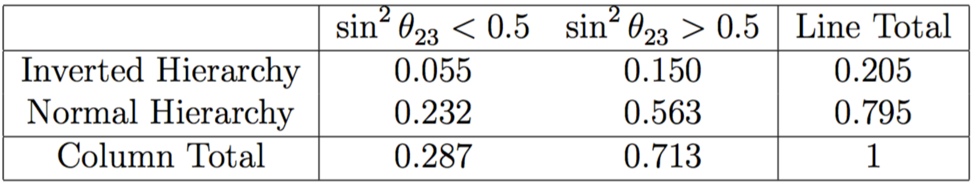
NH: -2.98 ~ -0.47

IH: -1.47 ~ -1.27

Bayesian analysis :Posterior probability for different mass hierarchies and octants.



	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
IH ($\Delta m^2_{32} < 0$)	0.116	0.254	0.370
NH ($\Delta m^2_{32} > 0$)	0.210	0.420	0.630
Sum	0.326	0.674	1

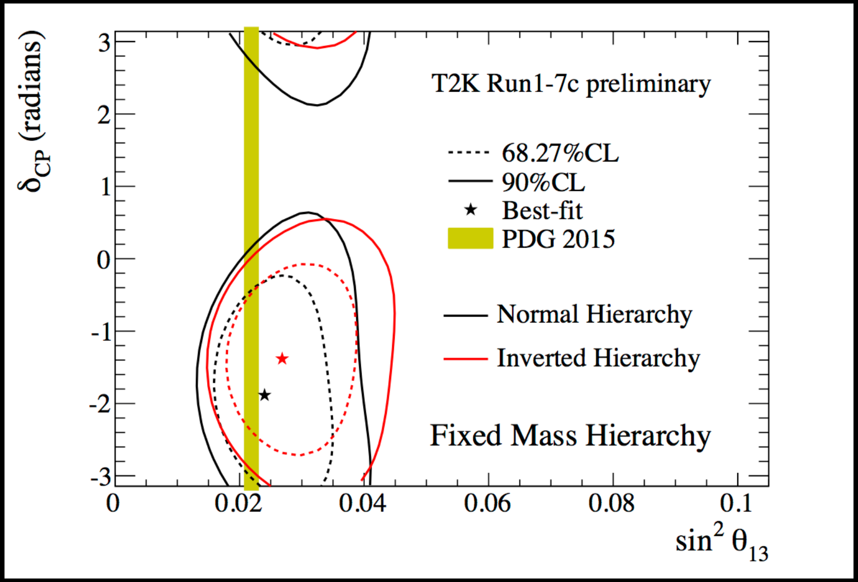


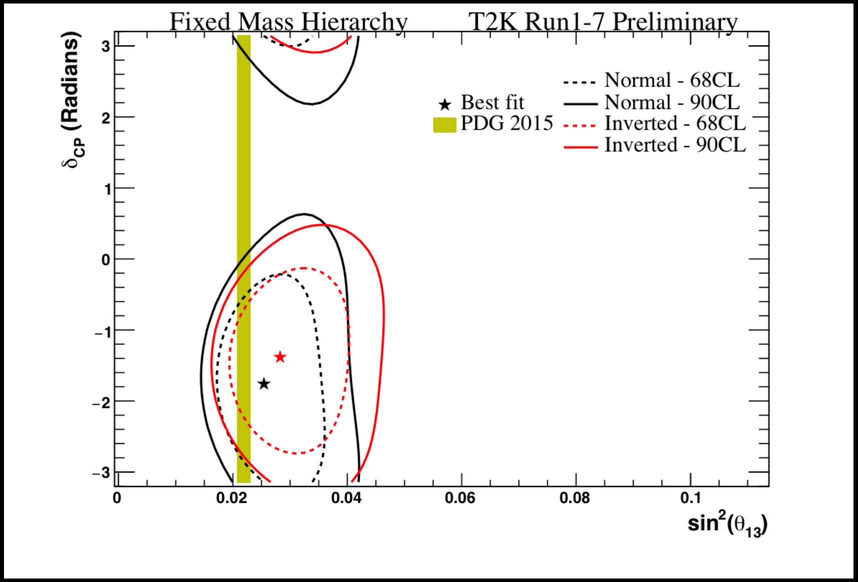
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line Total
Inverted Hierarchy	0.055	0.150	0.205
Normal Hierarchy	0.232	0.563	0.795
Column Total	0.287	0.713	1

Improvement by SK ν_e CC-1π sample

Previous results, arXiv:1701.00432 (Accepted by PRL)

With SK ν_e CC-1π e sample





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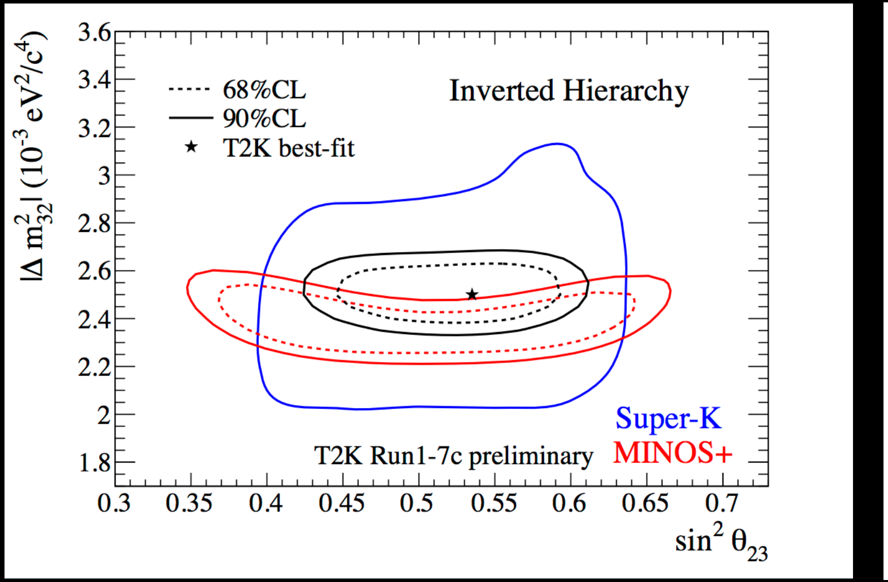
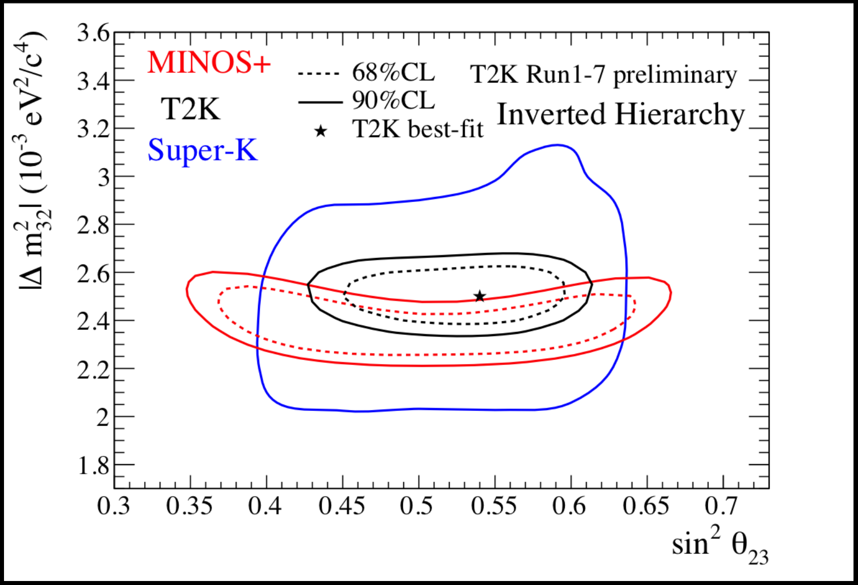


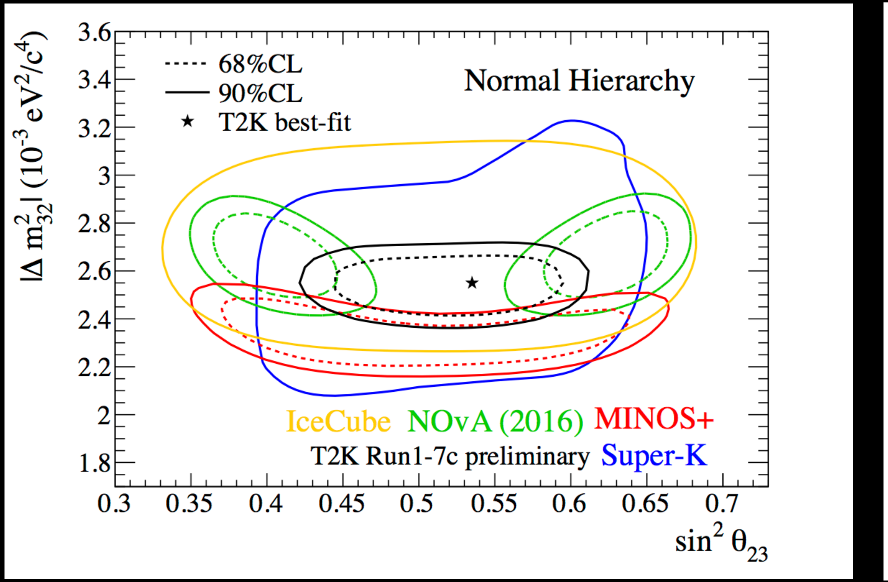
With SK ν_e CC-1π e sample

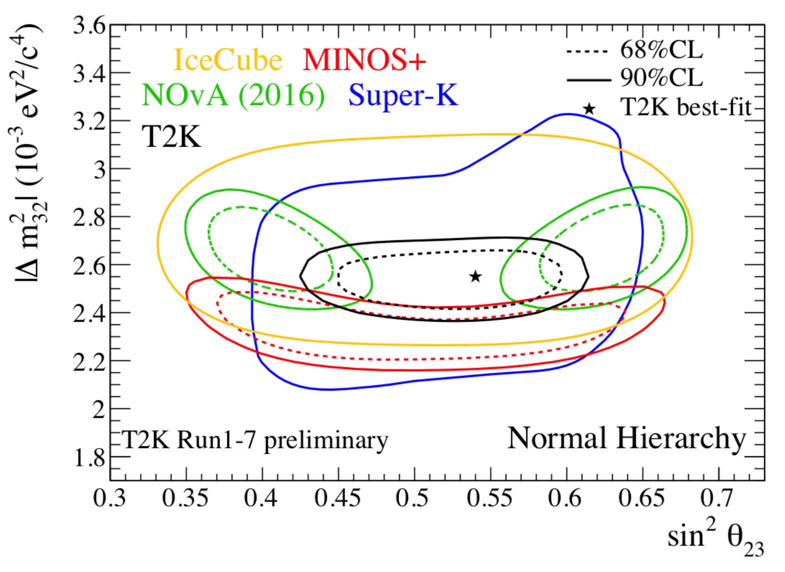


Improvement by SK ν_e CC-1π sample

Previous results, arXiv:1701.00432
(Accepted by PRL)

With SK ν_e CC-1π e sample





Near detector upgrade project

- CERN-SPSC-2017-002 ; SPSC-EOI-015
  “Near Detectors based on gas TPCs for neutrino long baseline experiments”
  - T2K plans to establish the detector design and prepare the Technical Design Report (TDR) by the end of 2017.

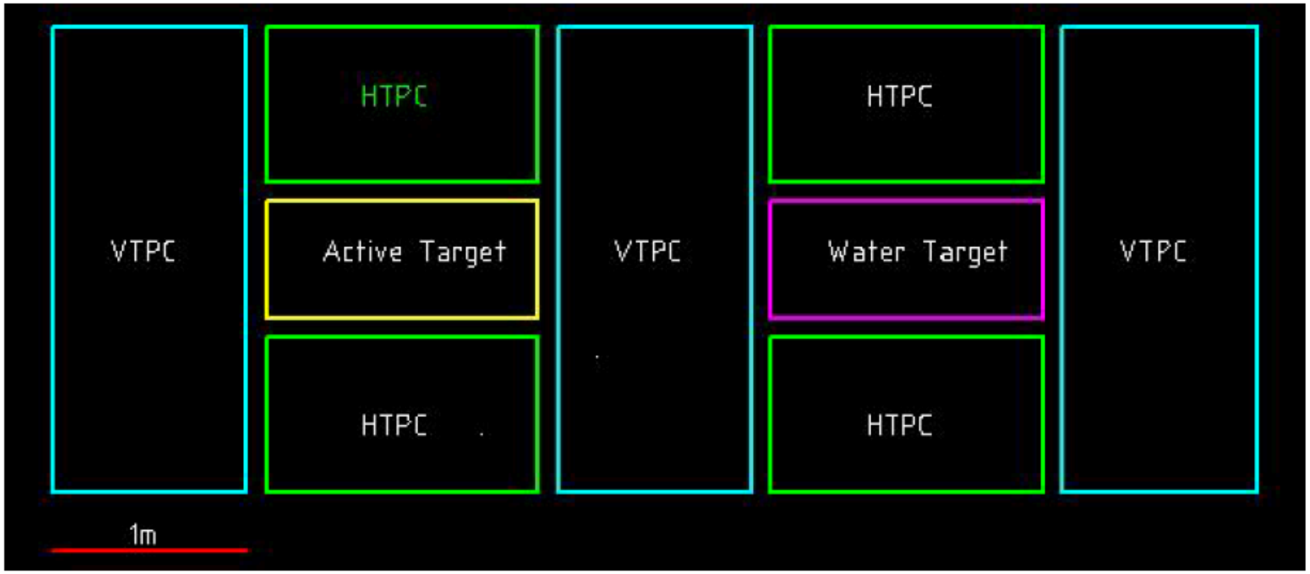


Figure 3. Schematic cross-section view of the proposed upgraded T2K ND280 detector. The new detectors are two scintillator trackers (labelled “Active Target” and “Water Target”) and the four new TPCs (labelled “HTPC). The three VTPC are the existing T2K TPCs.