
T2K NEUTRINO EXPERIMENT

HUNTING NEUTRINOS IN JAPAN



since 2010

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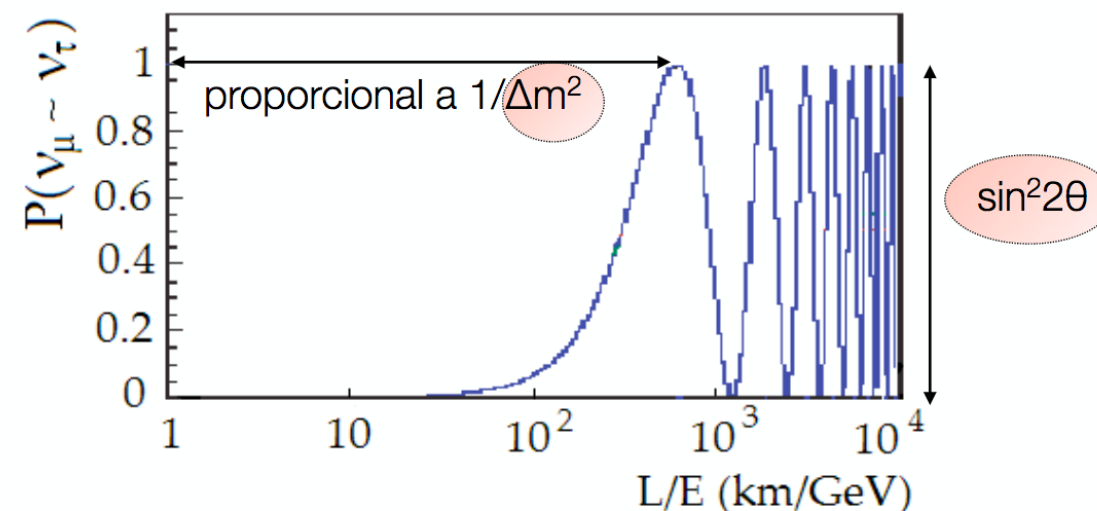
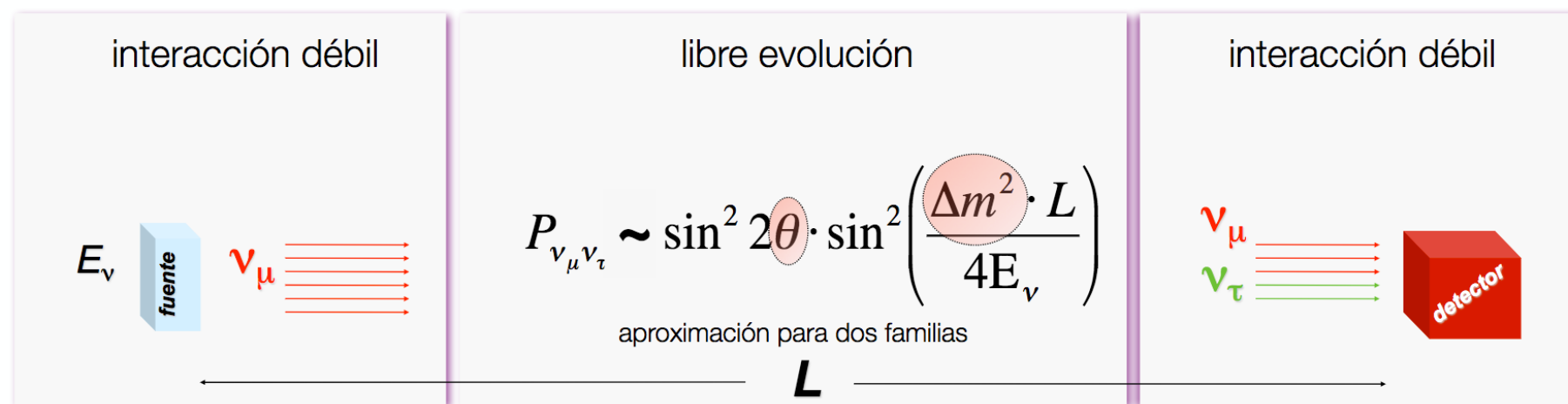
IFIC Summer School, July 2019

NEUTRINOS...

- Chargeless and the very tiny pieces of matter, tiniest!
- Neutrinos provide a test-bench to probe physics beyond the Standard Model and further open horizons of mankind knowledge
- Search for the CP (charge-conjugation and parity) symmetry violation (CPV) in the neutrino(lepton) sector
 - Considered as a mandatory condition for the matter dominance (over antimatter) in the Universe
 - What is the nature of the neutrino itself? is it its own antiparticle?
 - Does neutrino have impact on the dark matter?
 - Are there “so far hidden” effects? sterile neutrinos, heavy neutrinos?
- Beckoning neutrino quest here in IFIC-UV-CSIC Valencia

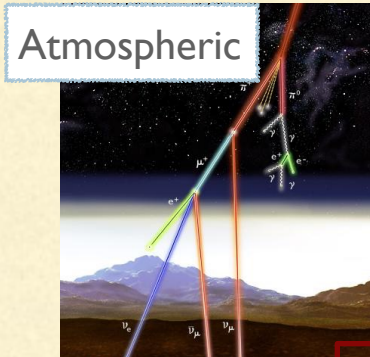
NEUTRINO OSCILLATIONS

- Neutrinos mix and can change their flavour
- Oscillations - first prove that neutrinos have masses!



NEUTRINO OSCILLATIONS - MANY DIFFERENT SOURCES

Neutrino mixing:
Pontecorvo-Maki-
Nakagawa-Sakata
(PMNS) matrix



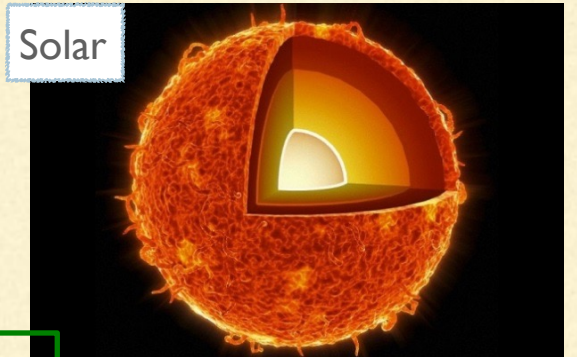
Atmospheric



Accelerator



Reactor



Solar

$$c_{ij} = \cos \theta_{ij}$$

$$s_{ij} = \sin \theta_{ij}$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

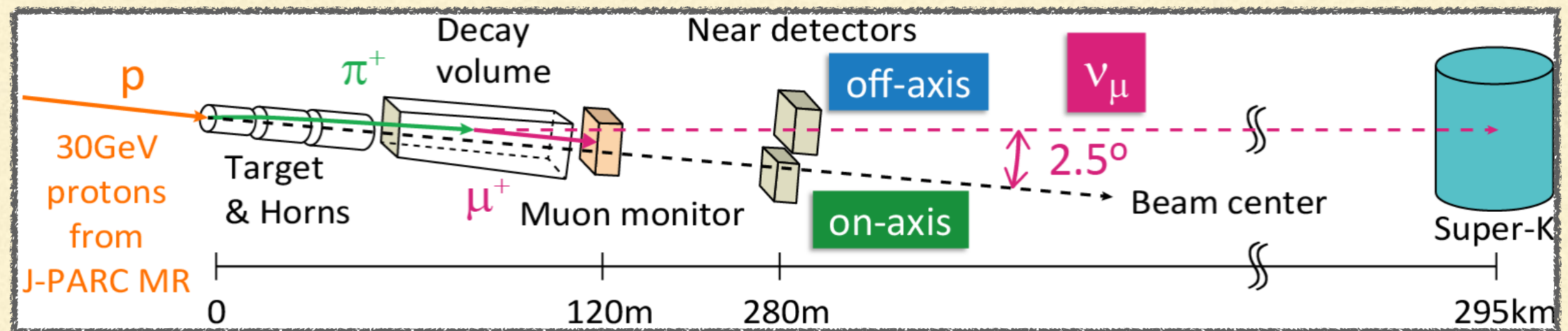
Oscillations governed by

- three mixing angles:
 - $\theta_{12} \approx 34^\circ$, $\theta_{13} \approx 9^\circ$, $\theta_{23} \approx 45^\circ$
- two mass squared differences:
 - $\Delta m_{21}^2 \approx 7.6 \times 10^{-5} \text{ eV}^2$ and $|\Delta m_{32}^2| \approx 2.4 \times 10^{-3} \text{ eV}^2$
- source-detector baseline and neutrino energy

NEUTRINOS WITH ACCELERATORS

- Neutrinos interact very rarely
- Need intense sources and big detectors
- Accelerators - a good option!
 - Neutrinos can be produced in (mostly) mesons decays
 - Powerful accelerators → intense beams
 - Does neutrino have impact on the dark matter?
 - Known energy → place a detector where expect maximum of oscillations probabilities

ACCELERATOR EXPERIMENT: DESIGN



- Near and Far detectors
- Neutrino/antineutrino beam
- Energy adjusted to maximise oscillations (E~0.6 GeV)
- Neutrino and antineutrino enhanced modes via horn polarity switching
- Many projects: K2K (Japan), MINOS (USA), T2K (Japan), NOVA (USA) ... Hyper-K (Japan), DUNE (USA)

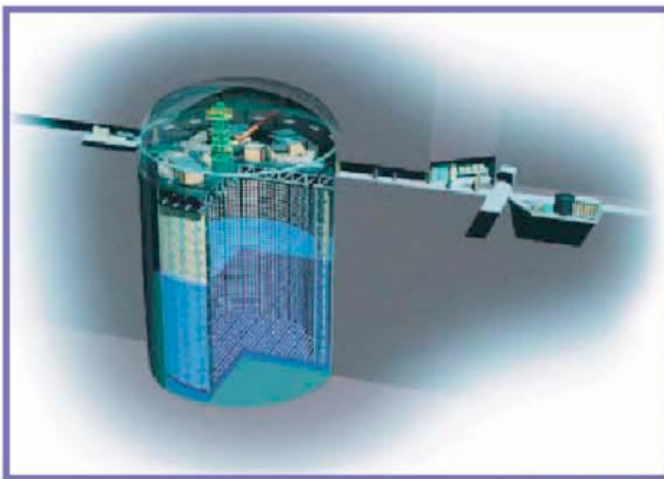
$$N_{ND} \sim \Phi_{ND} \cdot \sigma_{ND} \cdot \epsilon_{ND}$$

Observable Flux Cross section Detector response

$$N_{FD} \sim \Phi_{FD} \cdot \sigma_{FD} \cdot \epsilon_{FD} \cdot P_{Osc}$$

T2K NEUTRINO EXPERIMENT IN JAPAN

- Neutrino beam from Tokay to Kamioka across Japan



Super-Kamiokande
(ICRR, Univ. Tokyo)

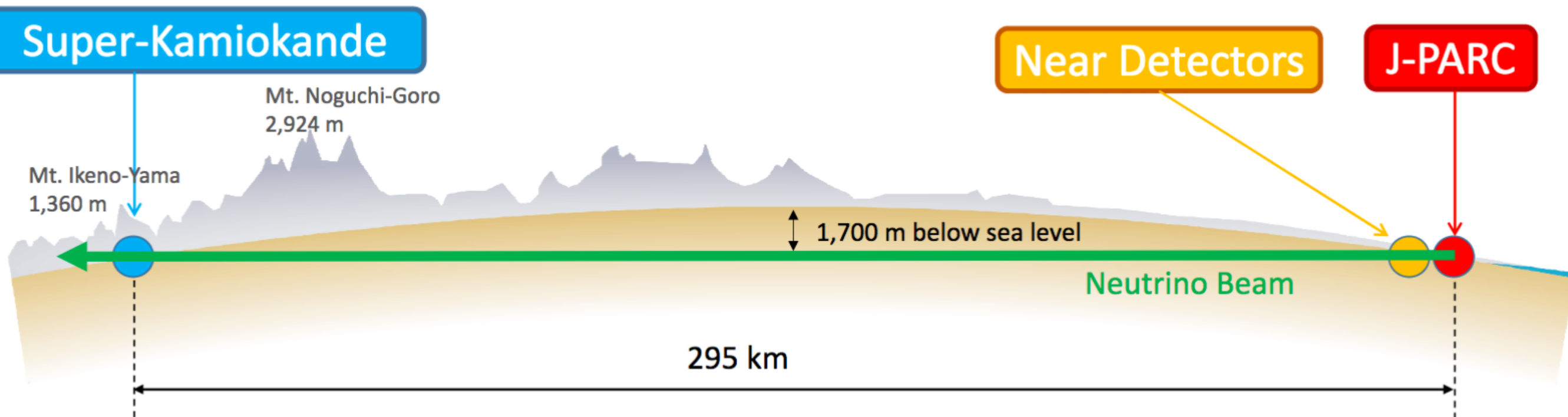


J-PARC Main Ring
(KEK-JAEA, Tokai)



T2K (TOKAI-TO-KAMIOKA) EXPERIMENT

- World-leading neutrino oscillations physics project
- T2K — long-baseline neutrino oscillation accelerator experiment in Japan
- International collaboration:
 - ~500 members, 67 institutes, 12 countries



~500 members, 67 institutes, 12 countries



T2K Experiment International Collaboration

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.

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

Poland

IFJ PAN, Cracow

NCBJ, Warsaw

U. Silesia, Katowice

U. Warsaw

Warsaw U. T.

Wroclaw U.

Russia

INR RAS

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

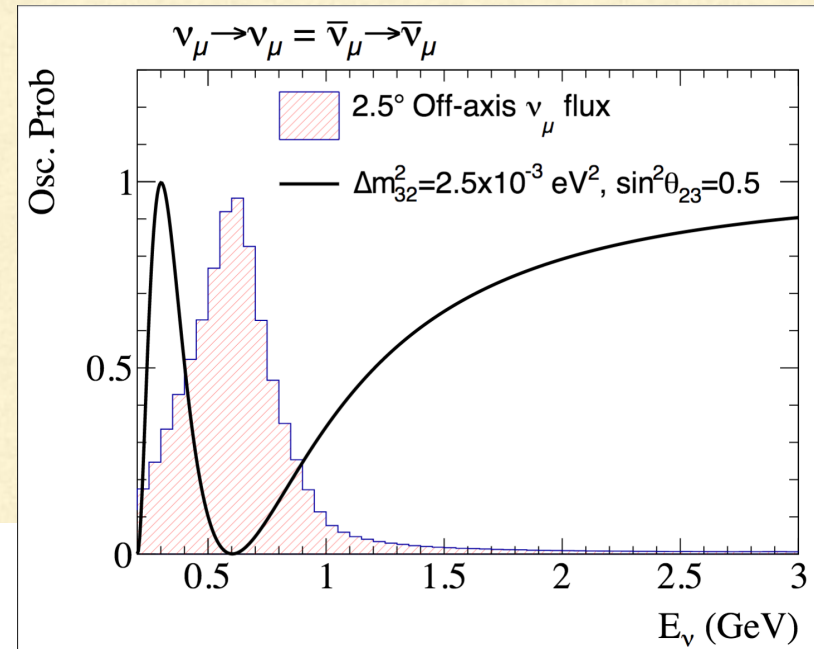
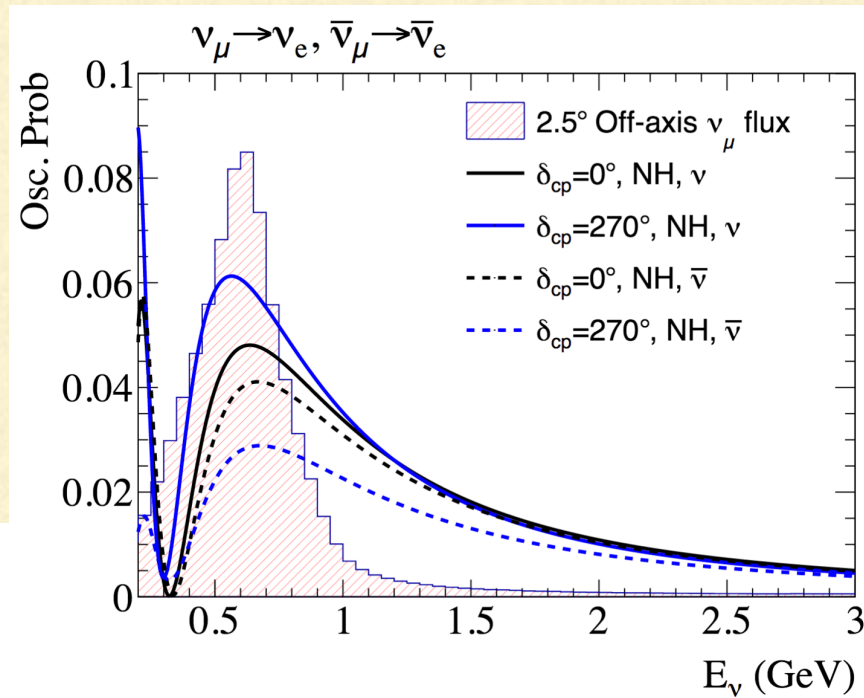
U. Washington

Vietnam

IFIRSE

IOP, VAST

T2K (TOKAI-TO-KAMIOKA) EXPERIMENT



Super-Kamiokande

Near Detectors

J-PARC

Mt. Noguchi-Goro
2,924 m

Mt. Ikeno-Yama
1,360 m

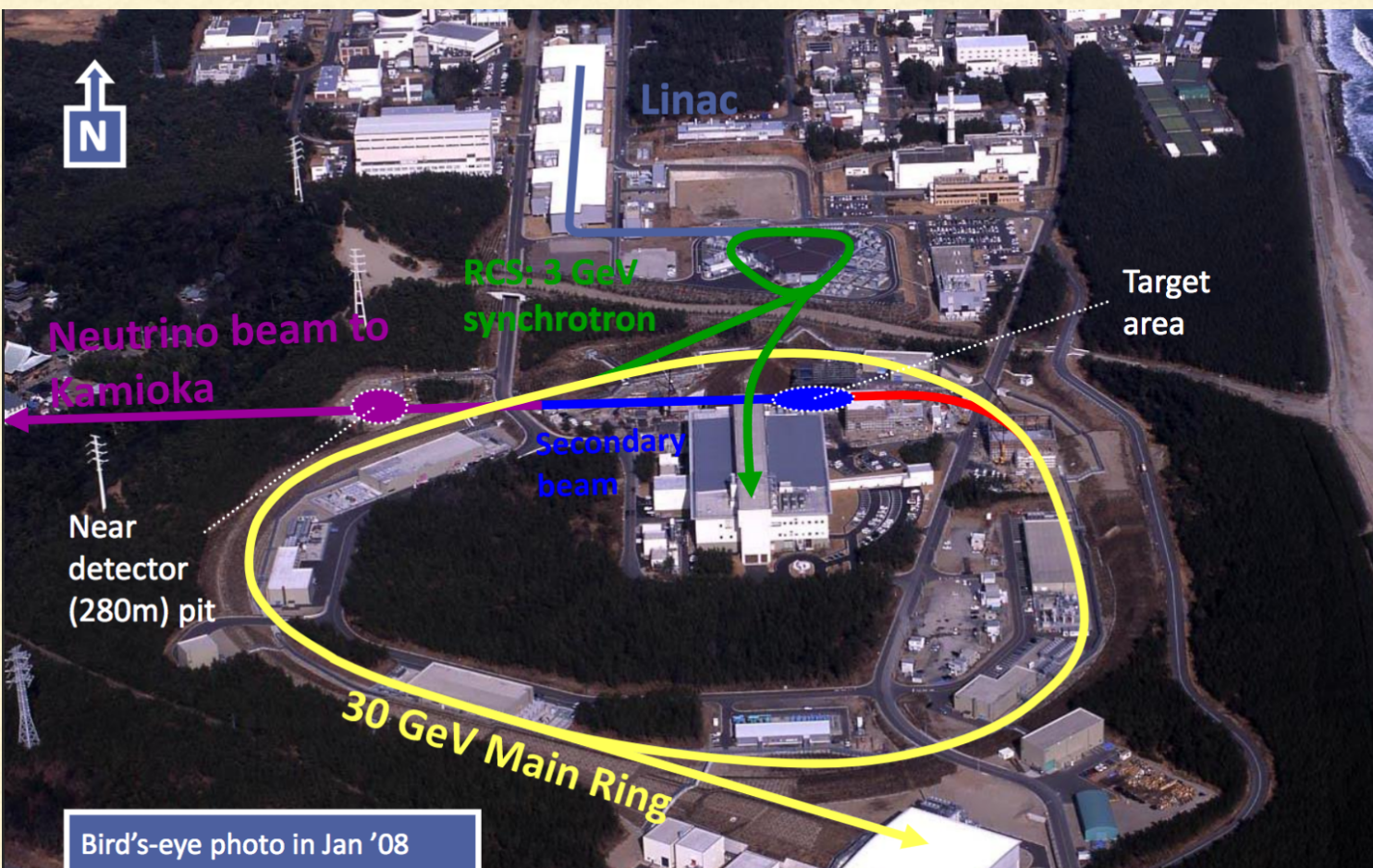
1,700 m below sea level

Neutrino Beam

295 km

T2K (TOKAI-TO-KAMIOKA) EXPERIMENT

- Collecting data since 2010
- First discovery of $\nu_\mu \rightarrow \nu_e$ oscillations
- Hints for CP-violation in neutrino/lepton sector
- Officially attacked by Godzilla in 2000



NEUTRINO OSCILLATIONS IN T2K

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23}) \sin^2 \left(\Delta m_{31}^2 \frac{L}{4E} \right)$$

“Disappearance” channel

- Precise measurement of “atmospheric” parameters θ_{23} and Δm_{32}^2 and CPT test via ν vs anti- ν analysis

From Phys. Rev. D64 (2001) 053003

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \quad \text{Leading term}$$

CP-violating “+” sign for anti- ν $-\alpha \sin \delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$

CP-conserving $+\alpha \cos \delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$

$+O(\alpha^2)$ $\alpha = \left| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right| \sim \frac{1}{30}$ $\Delta = \frac{\Delta m_{31}^2 L}{4E}$ $x = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$

“Appearance” channel: measuring θ_{13} and probing CP-violation (CPV)

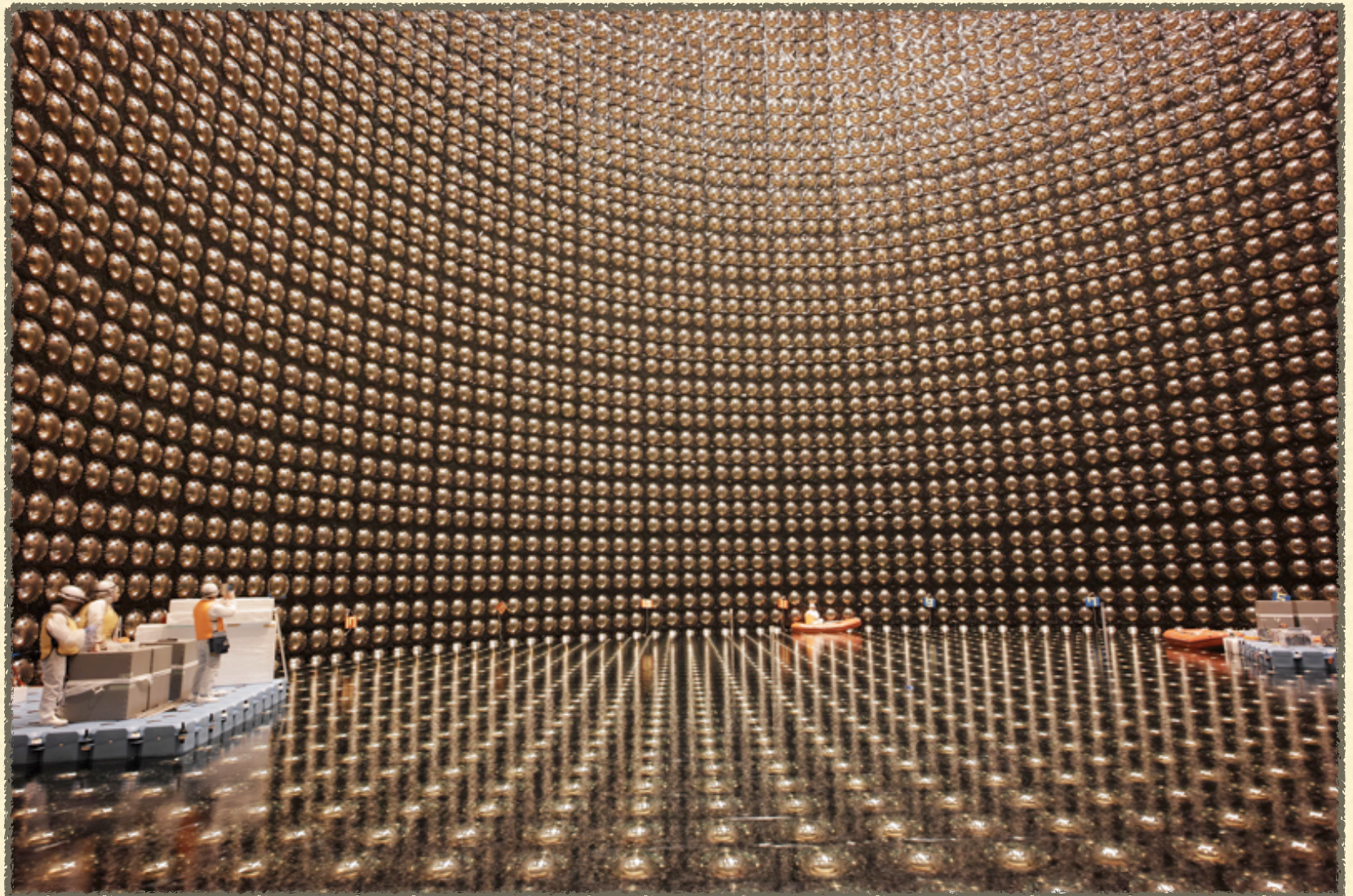
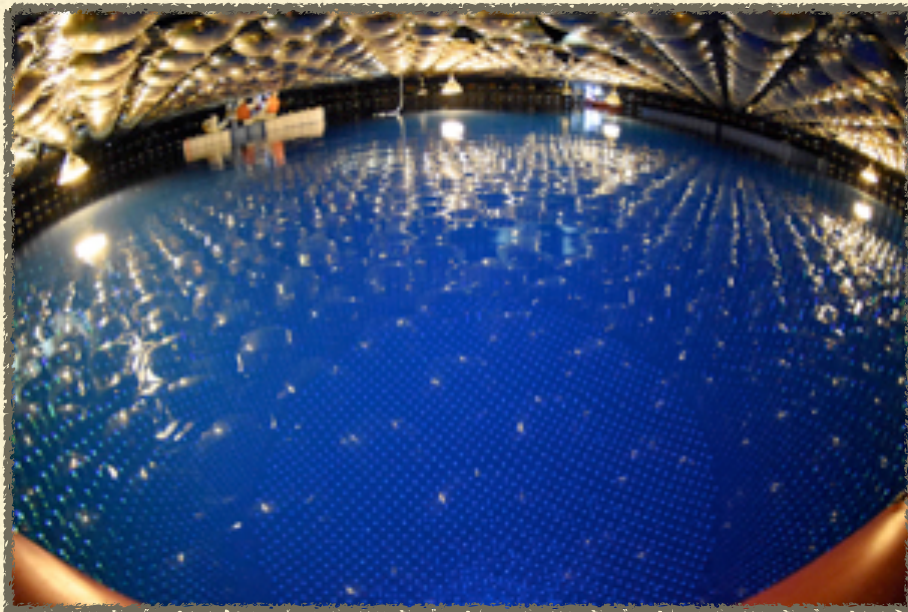
- Leading term defines the octant of θ_{23} : $<$, $>$ or $= 45^\circ$ * T2K leading efforts
- Sub-leading term accounts for CPV: enhanced effect when comparing neutrino and antineutrino data

T2K IN JAPAN

- Why Japan?
- Neutrinos require large detectors to be detected + accelerators/reactors/stars/Universe as well
 - Significant efforts of engineers, scientists, constructors ...
 - Anselmo will explain the new DUNE project tomorrow
 - Better utilise multi-purpose detectors → more physics with less cost!
- And Japan has Super-Kamiokande!

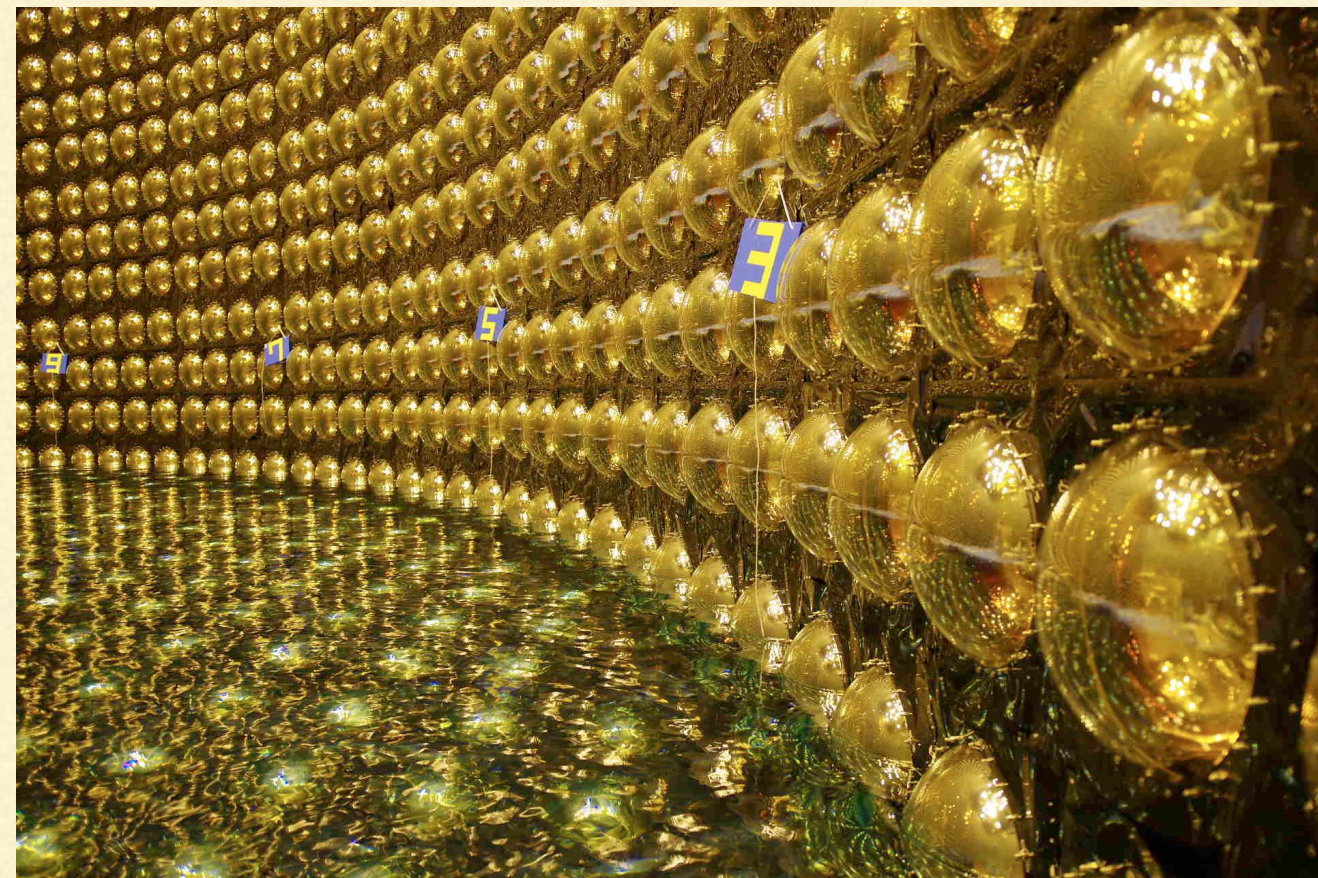
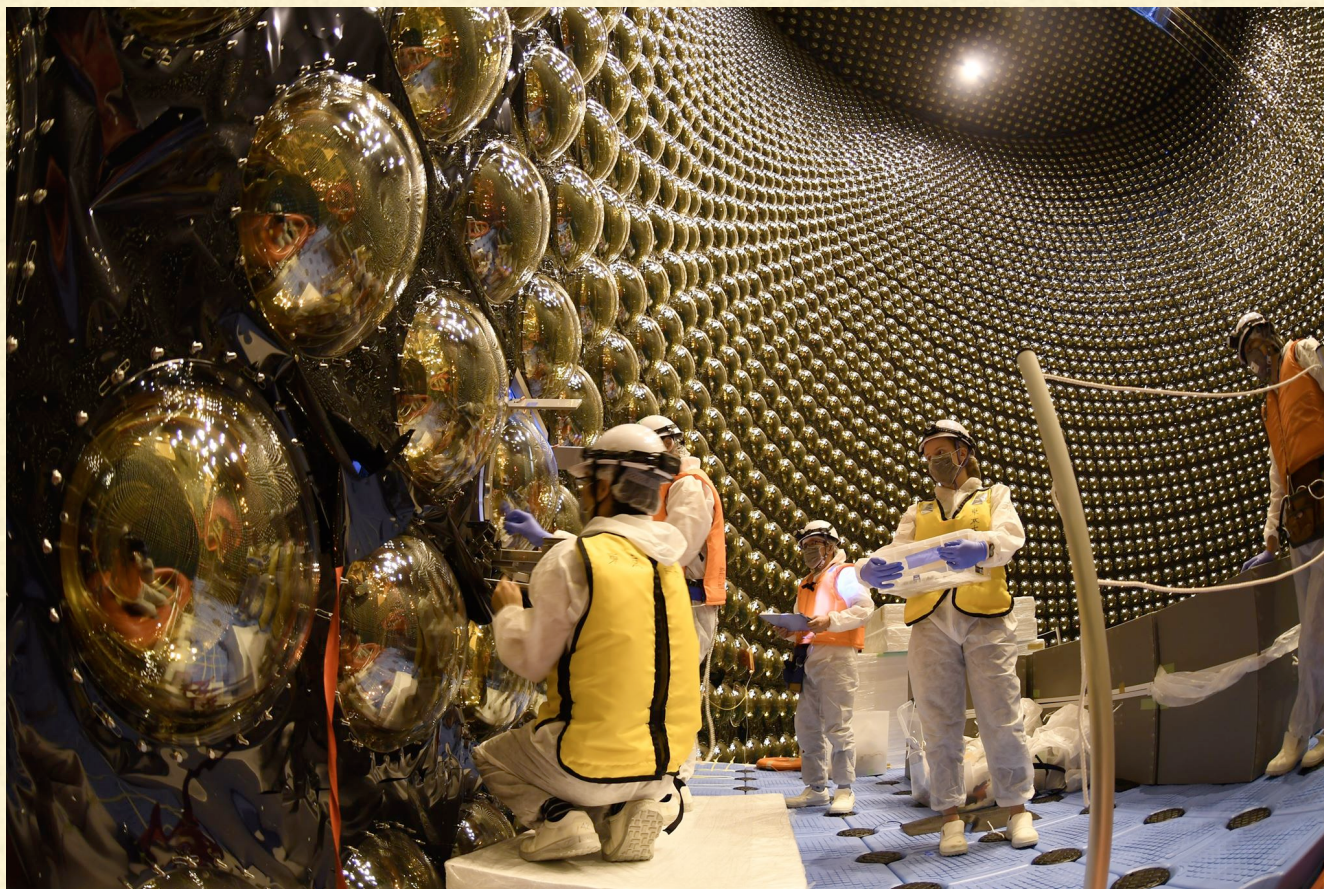
FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

- Originally started in 1980s to search for proton decays
- Then continued with solar, atmospheric and accelerator neutrinos
- KEK-to-Kamioka
- Toka-to-Kamioka



FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

- Summer 2018 - new era with a well-cleaned and renewed detector



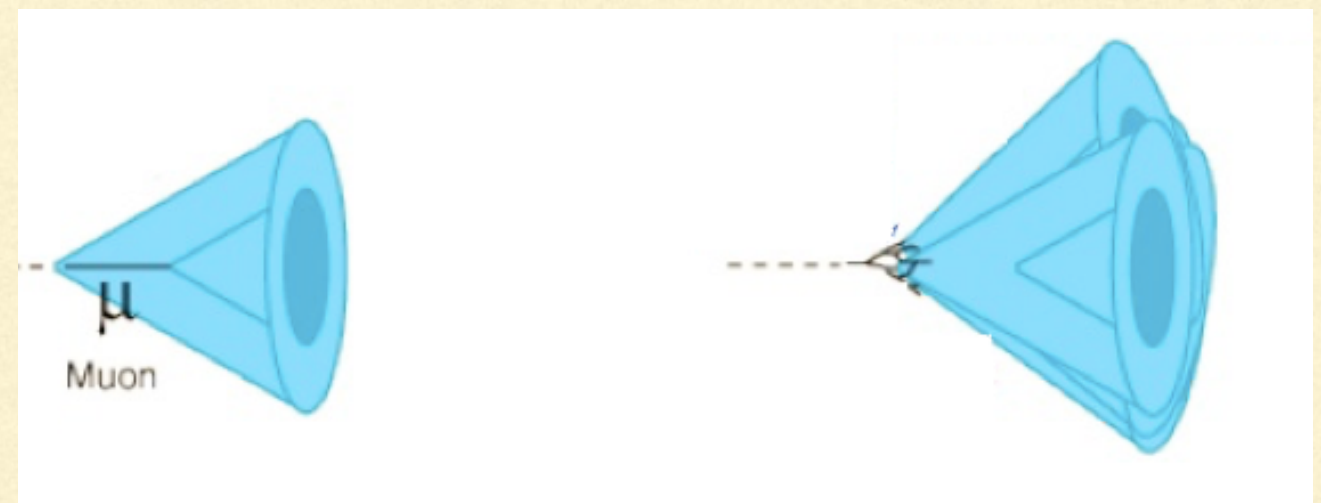
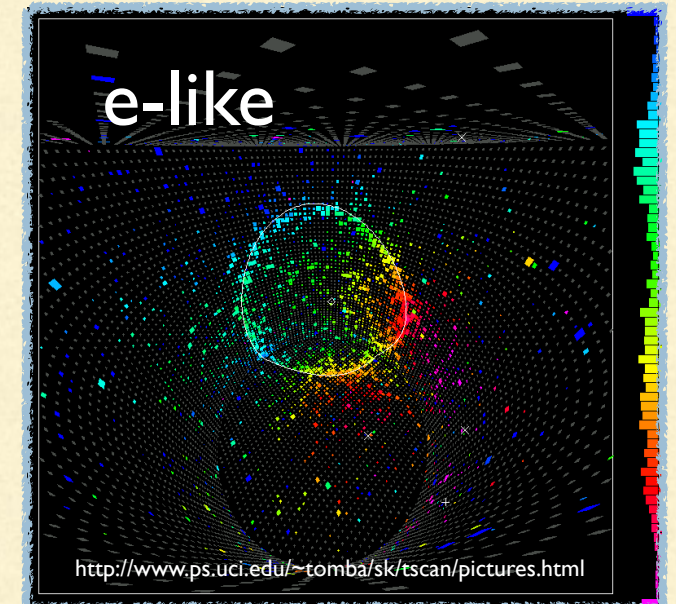
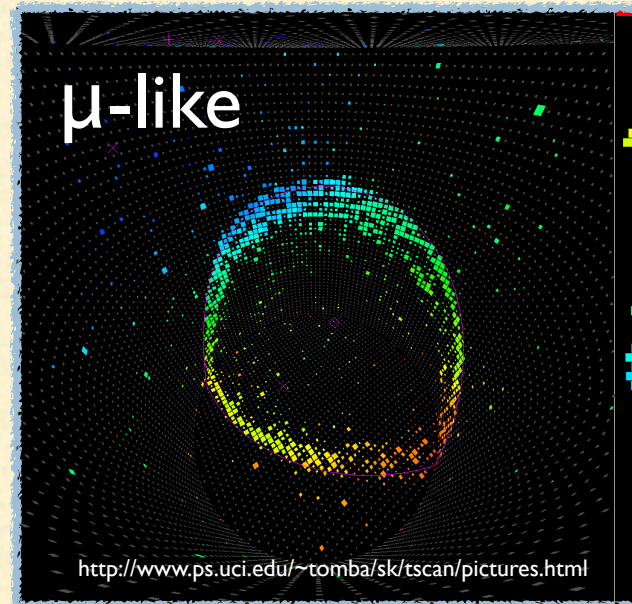
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FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

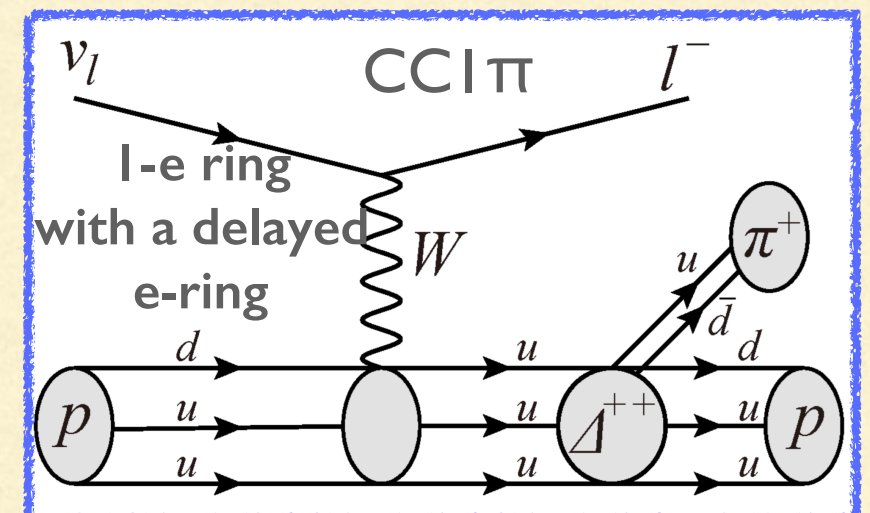
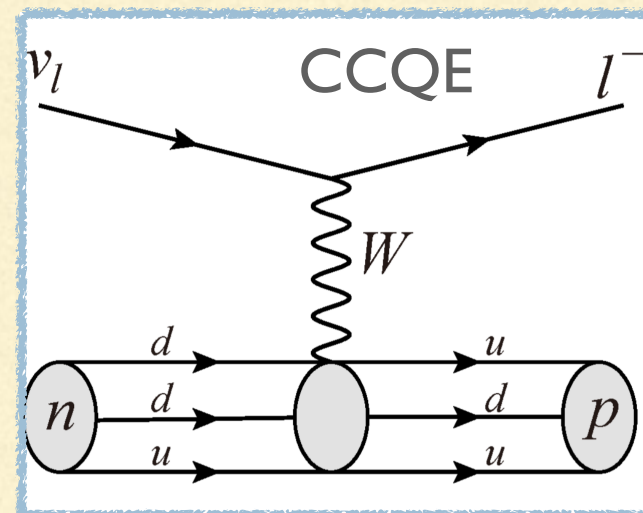
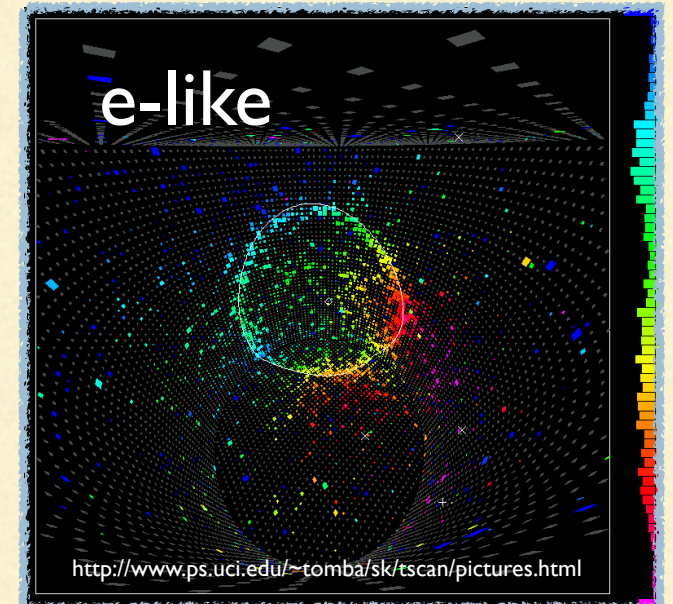
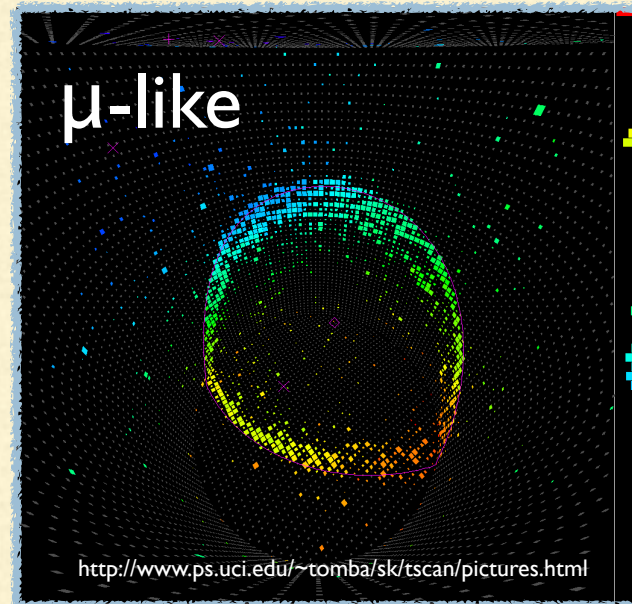
- 50 kton water-Cherenkov tank
- Separate e/ μ -like rings:
 - <1% misidentified μ as e
- π^0 rejection
- No magnetic field



- 5 Super-K samples used for analysis
- 1-ring μ and e-like events in ν and anti- ν modes + CC 1π e-like for ν mode

FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

- 50 kton water-Cherenkov tank
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- 5 Super-K samples used for analysis
- I-ring μ and e-like events in $\bar{\nu}$ and anti- $\bar{\nu}$ modes + CCI π e-like for $\bar{\nu}$ mode

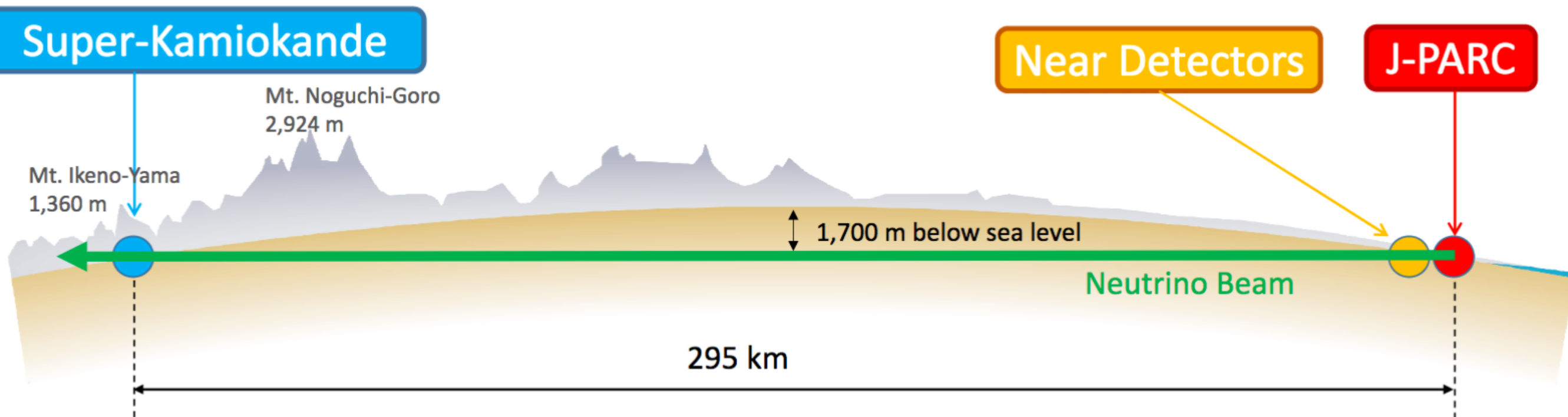
T2K IN JAPAN

- Deficiently some Japanese experiments
- <https://bit.ly/2LtrFc9>

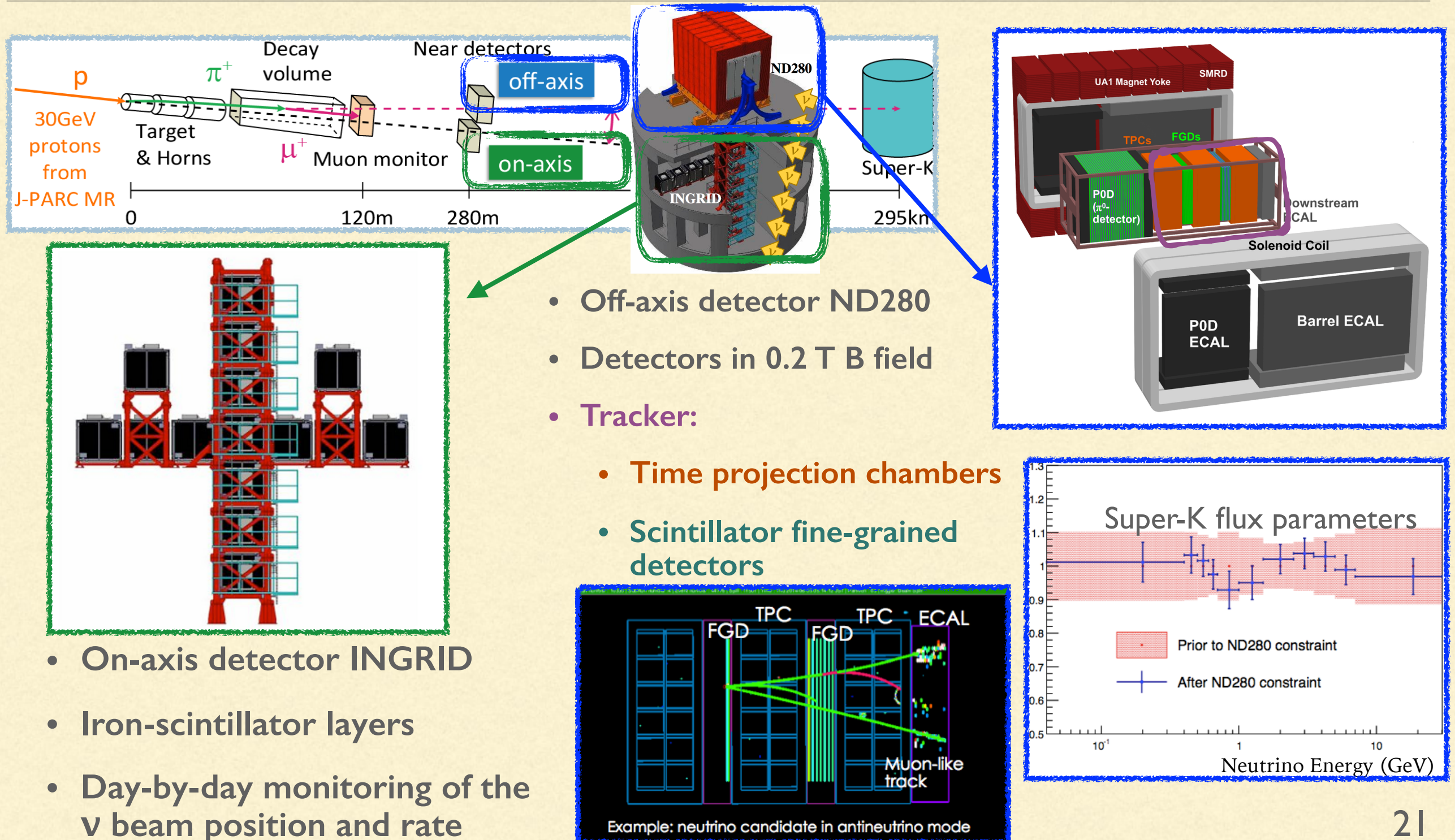


T2K (TOKAI-TO-KAMIOKA) EXPERIMENT: NEAR DETECTORS

- Why near detectors?
- We need to understand our neutrino flux before they start to oscillate!
- We need to “tune” our models of neutrinos

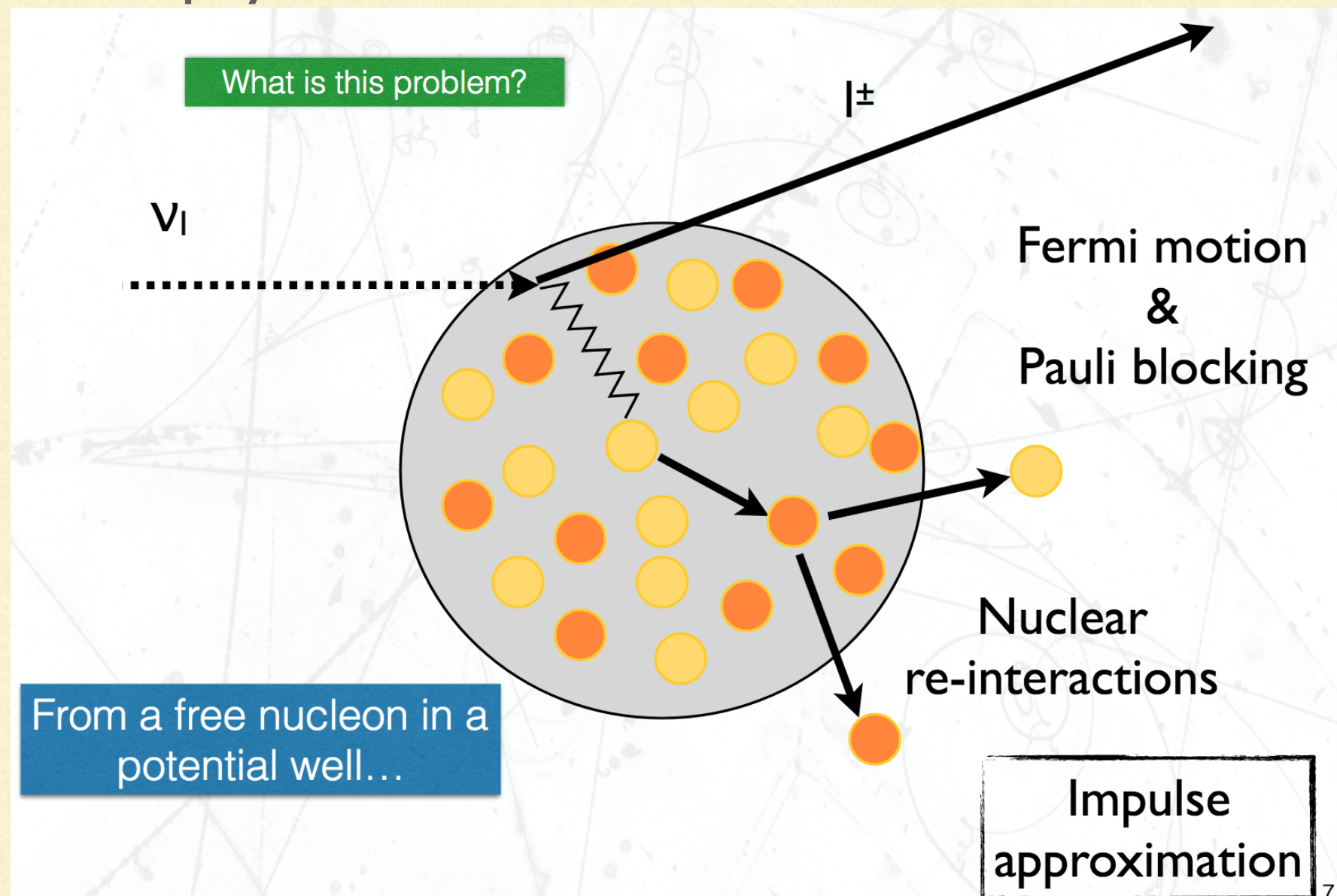


NEAR DETECTOR MEASUREMENTS



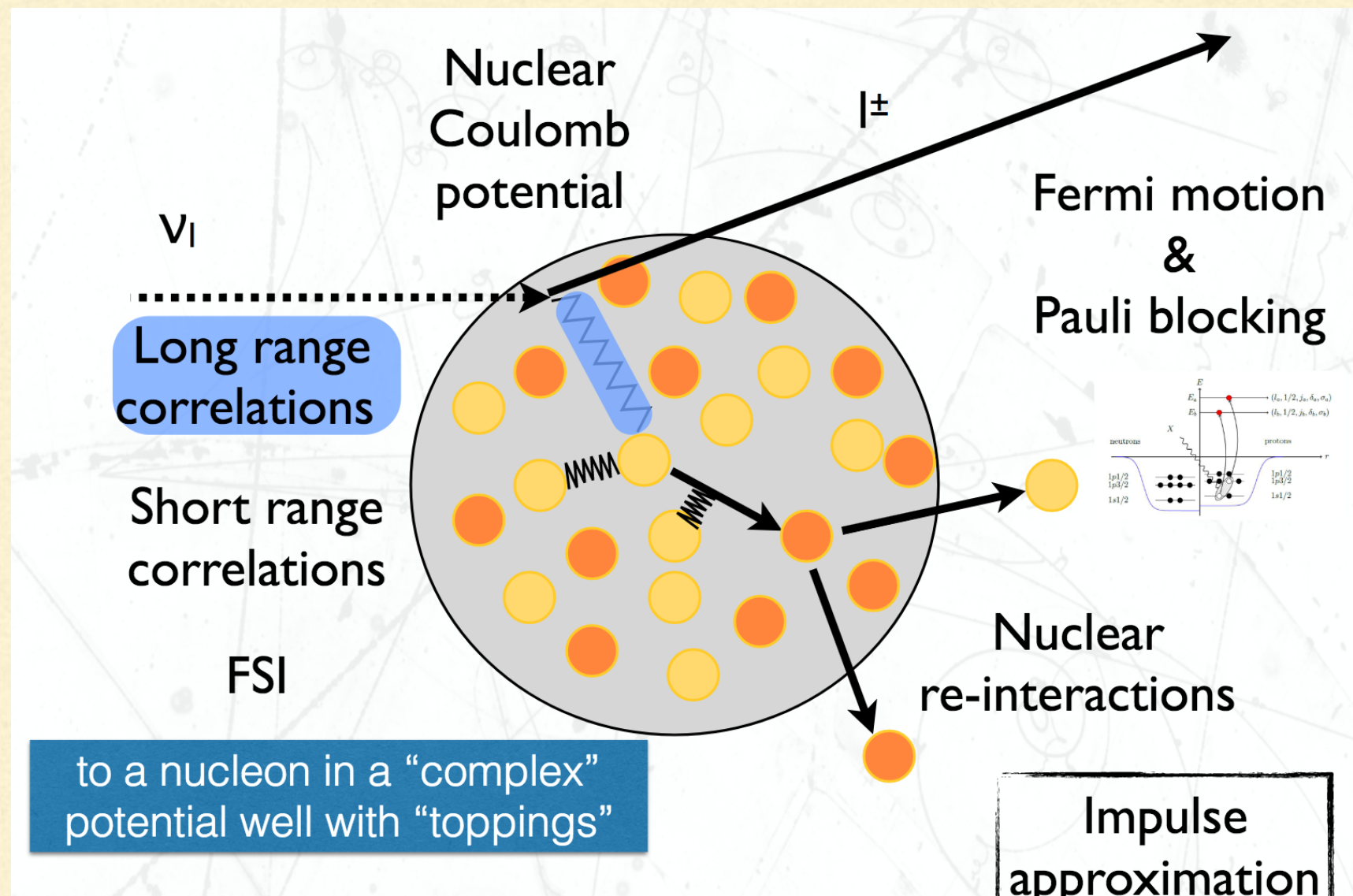
ROLE OF NEAR DETECTOR

- Neutrinos interact with nuclei!
- All nuclear physics is involved



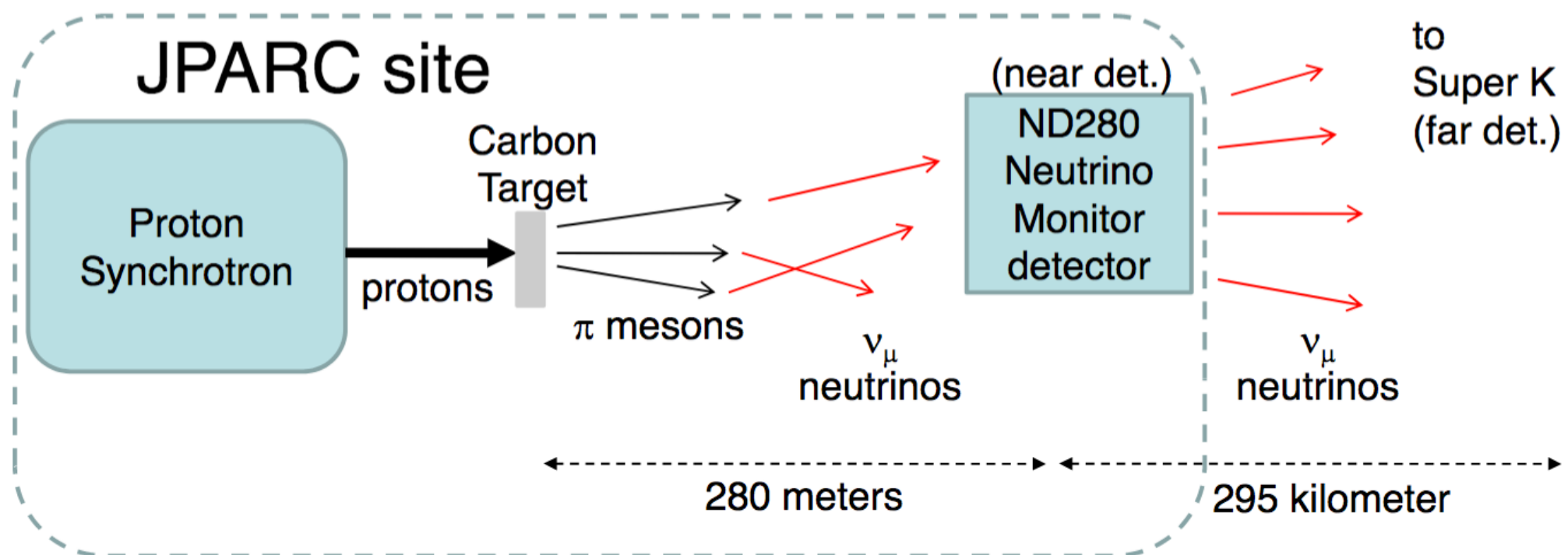
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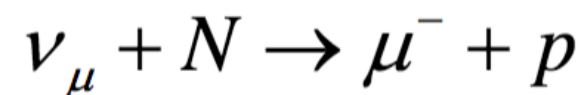
T2K NEAR DETECTOR

Simplified Schematic Diagram of the T2K Expt

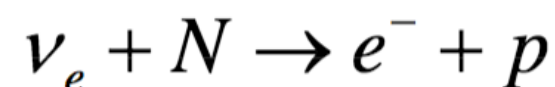


π mesons decay into neutrinos in the process; $\pi^+ \rightarrow \mu^+ + \nu_\mu$

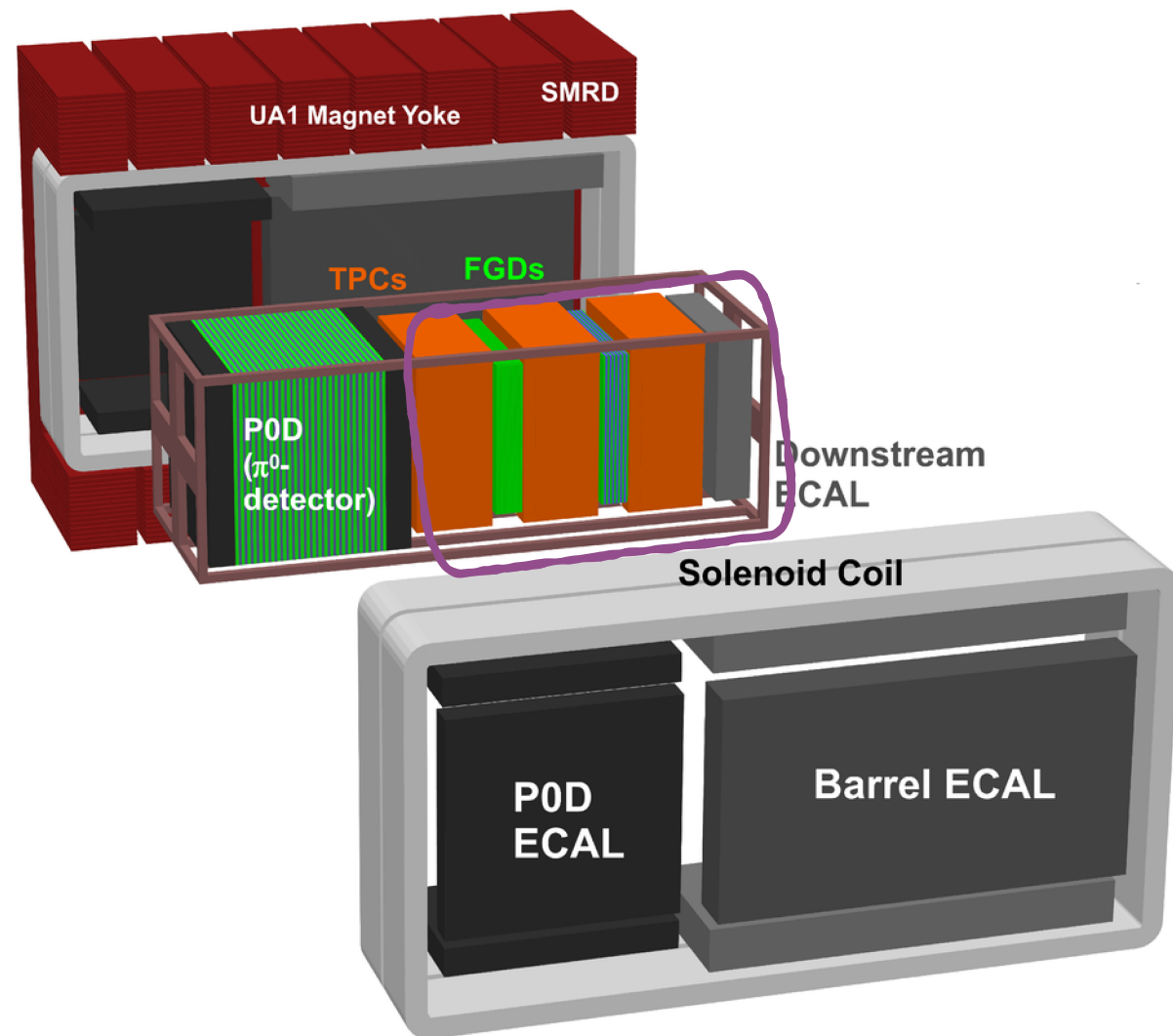
ν_μ neutrino are detected in the process ;



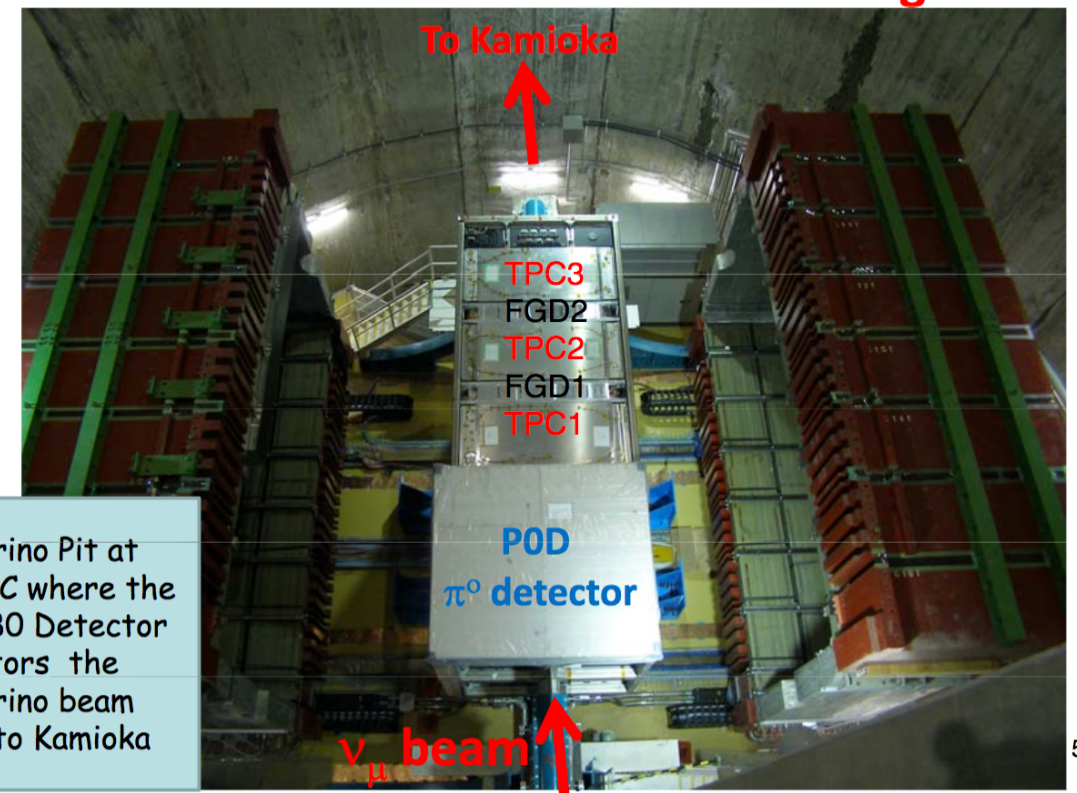
ν_e neutrino are detected in the process



T2K NEAR DETECTOR: ND280



ND280 Detector (down stream det. 280m) at JPARC in front of the neutrino beam target



Neutrino Pit at JPARC where the ND280 Detector Monitors the Neutrino beam sent to Kamioka

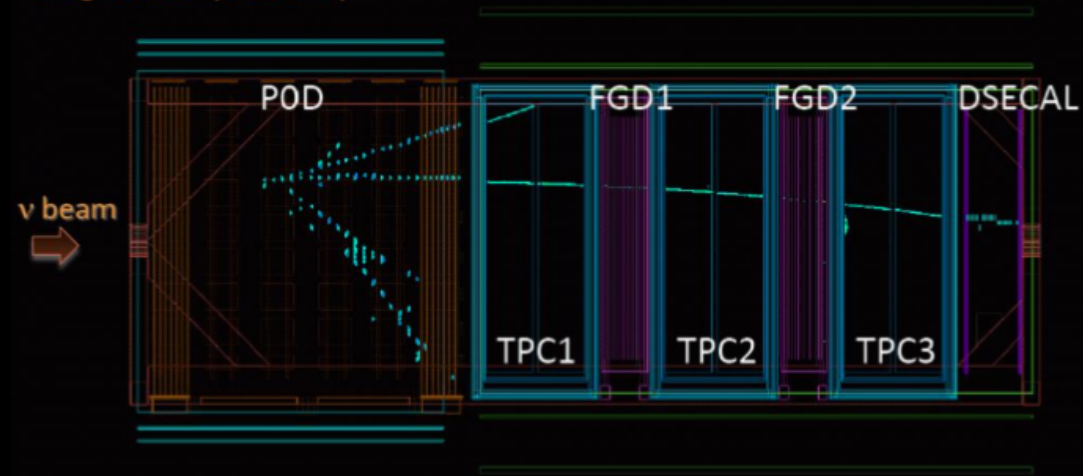
5

T2K NEAR DETECTOR

Event number : 1609 / Partition : 63 / Run number : 2553 / Spill : 7205 / SubRun number : [INVALID] / Time : Fri 2010-02-05 01:57:45 JST

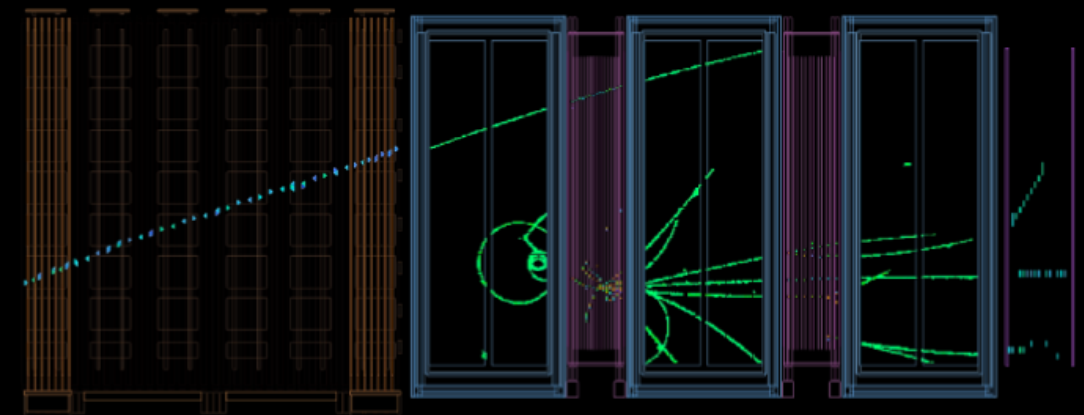
Magnet on (0.188 T)

01:57 JST, Feb. 5, 2010



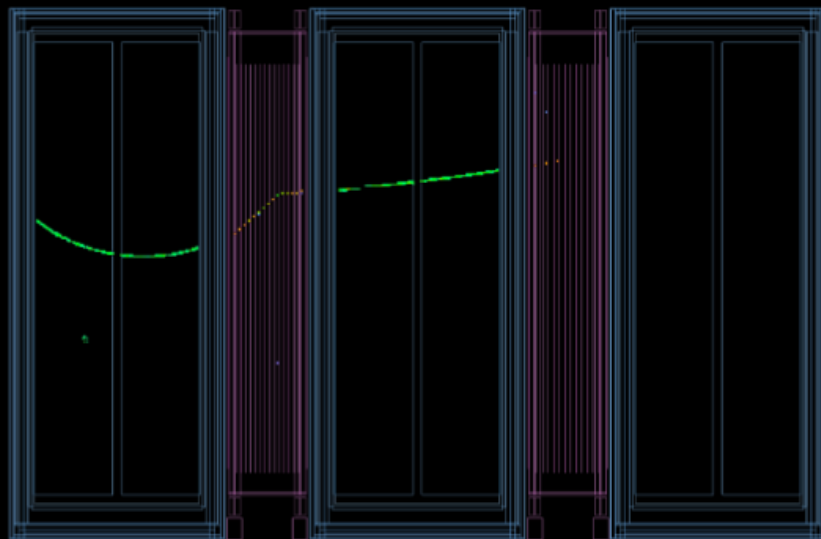
Interaction in P0D: View from (north) side

Event number : 19211 / Partition : 63 / Run number : 4200 / Spill : 0 / SubRun number : 30 / Time : Mon 2010-03-22 15:10:44 JST / Trigger : Beam Spill



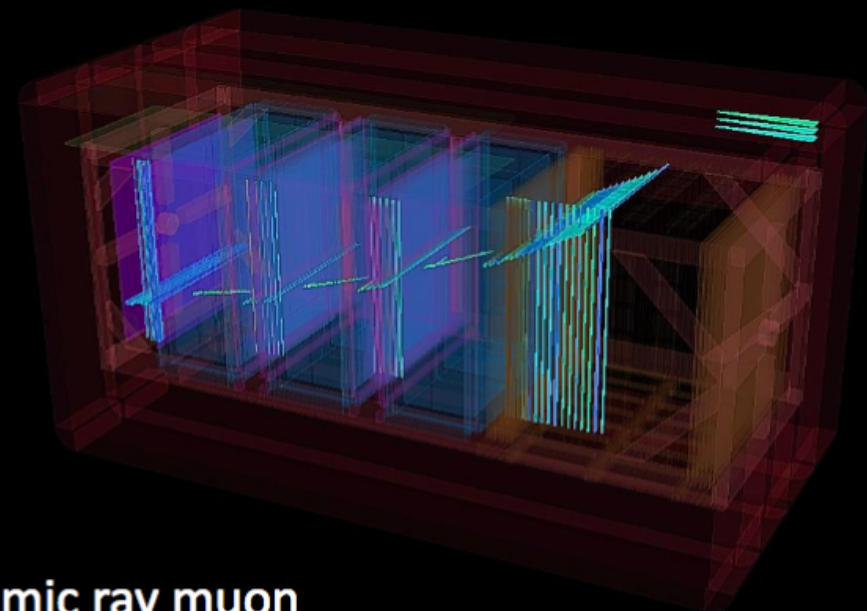
Sand Muon & FGD interaction

Event number : 19215 / Partition : 63 / Run number : 4200 / Spill : 0 / SubRun number : 15 / Time : Mon 2010-03-22 09:04:20 JST / Trigger : Beam Spill



FGD interaction with backward track

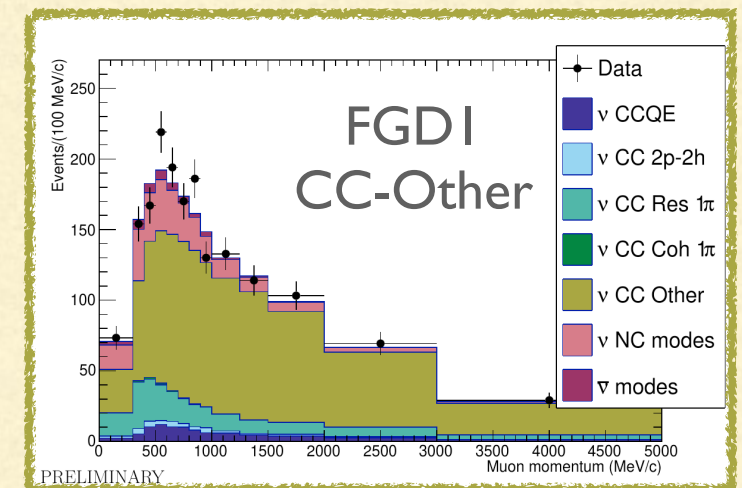
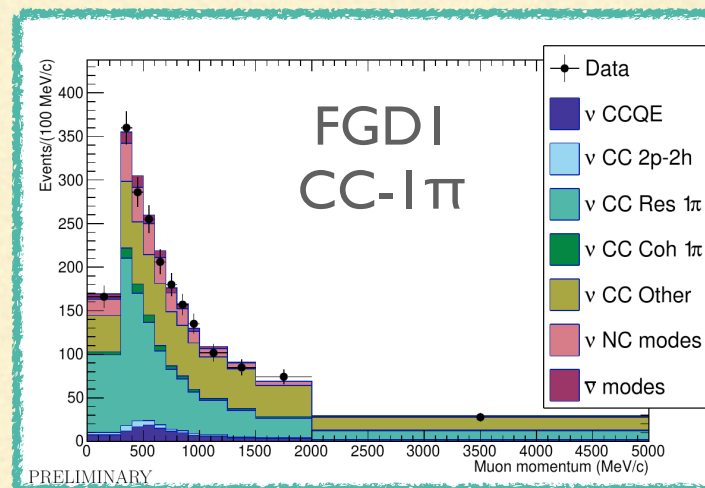
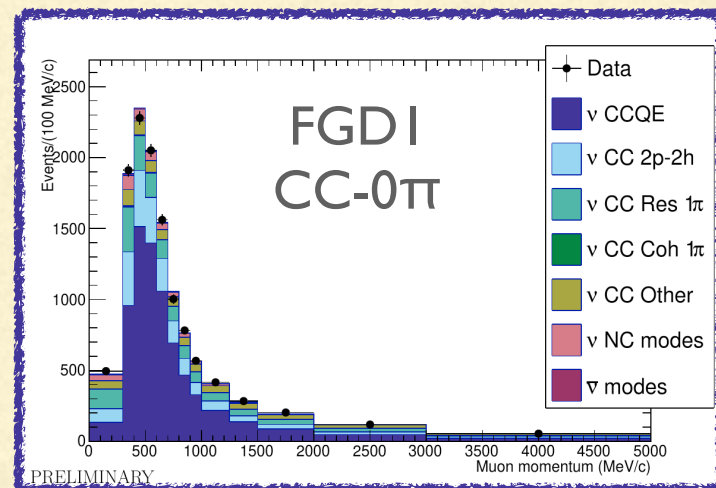
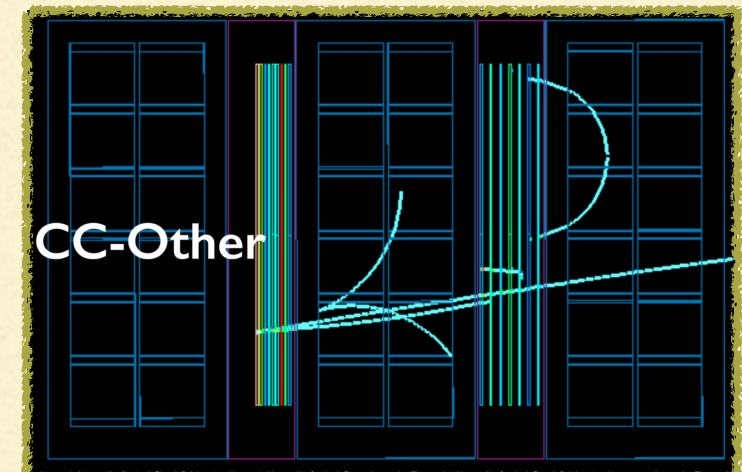
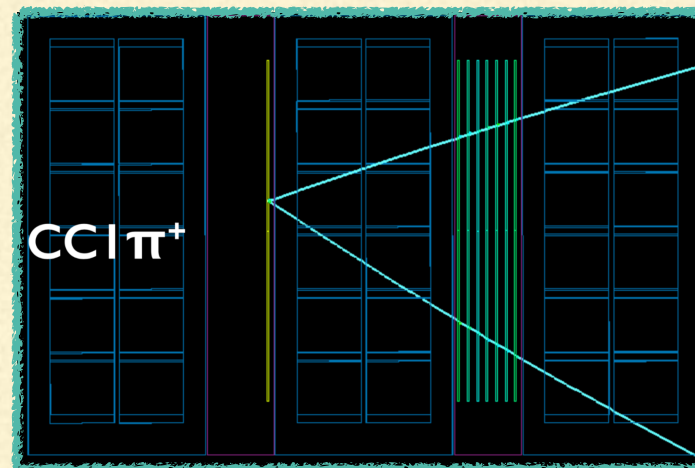
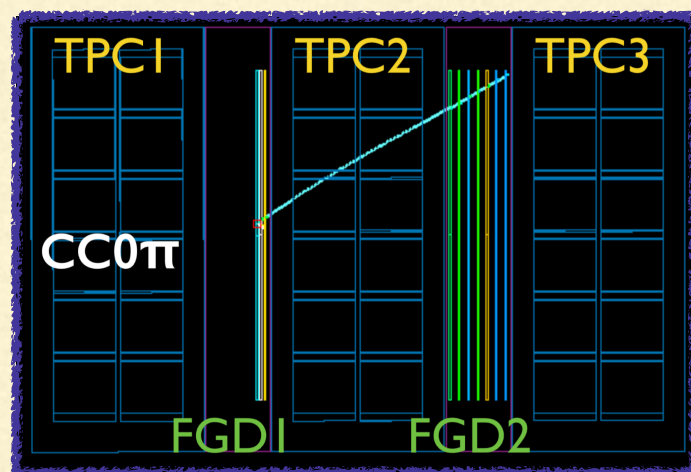
Event number : 7 / Partition : 63 / Run number : 2536 / Spill : 0 / SubRun number : 0 / Time : Wed 2010-02-24 15:47:58 JST / Trigger : TFB Cosmic



Cosmic ray muon

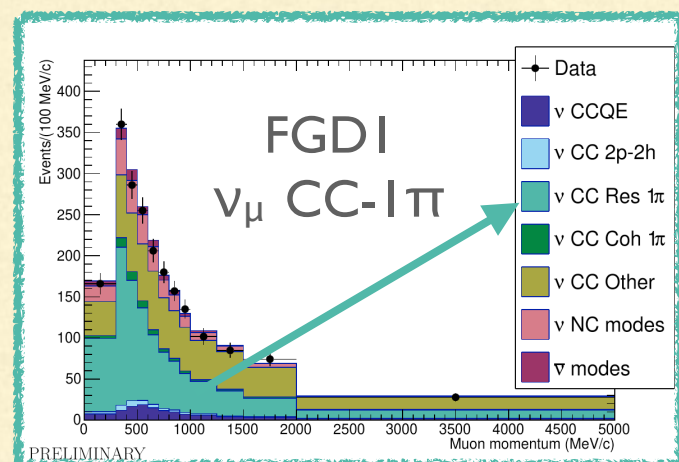
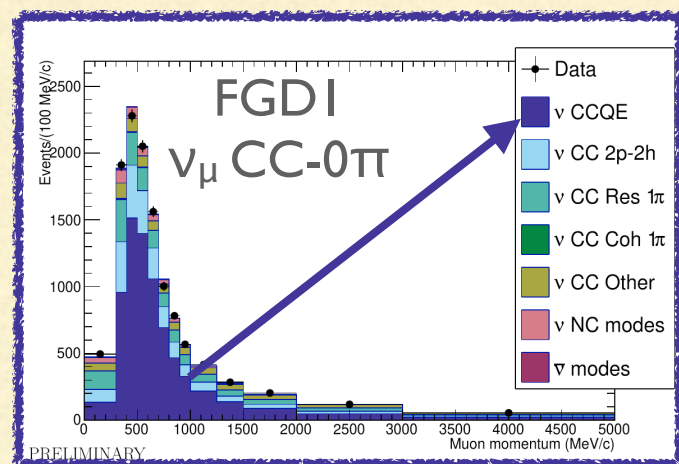
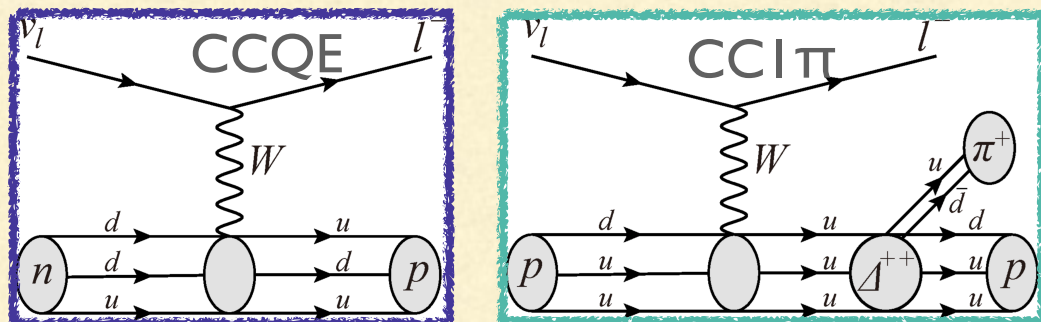
ND280 ANALYSIS: ν -MODE

- In the course will get acquainted how to select signal events
- Develop our selection of neutrino interactions in T2K ND280

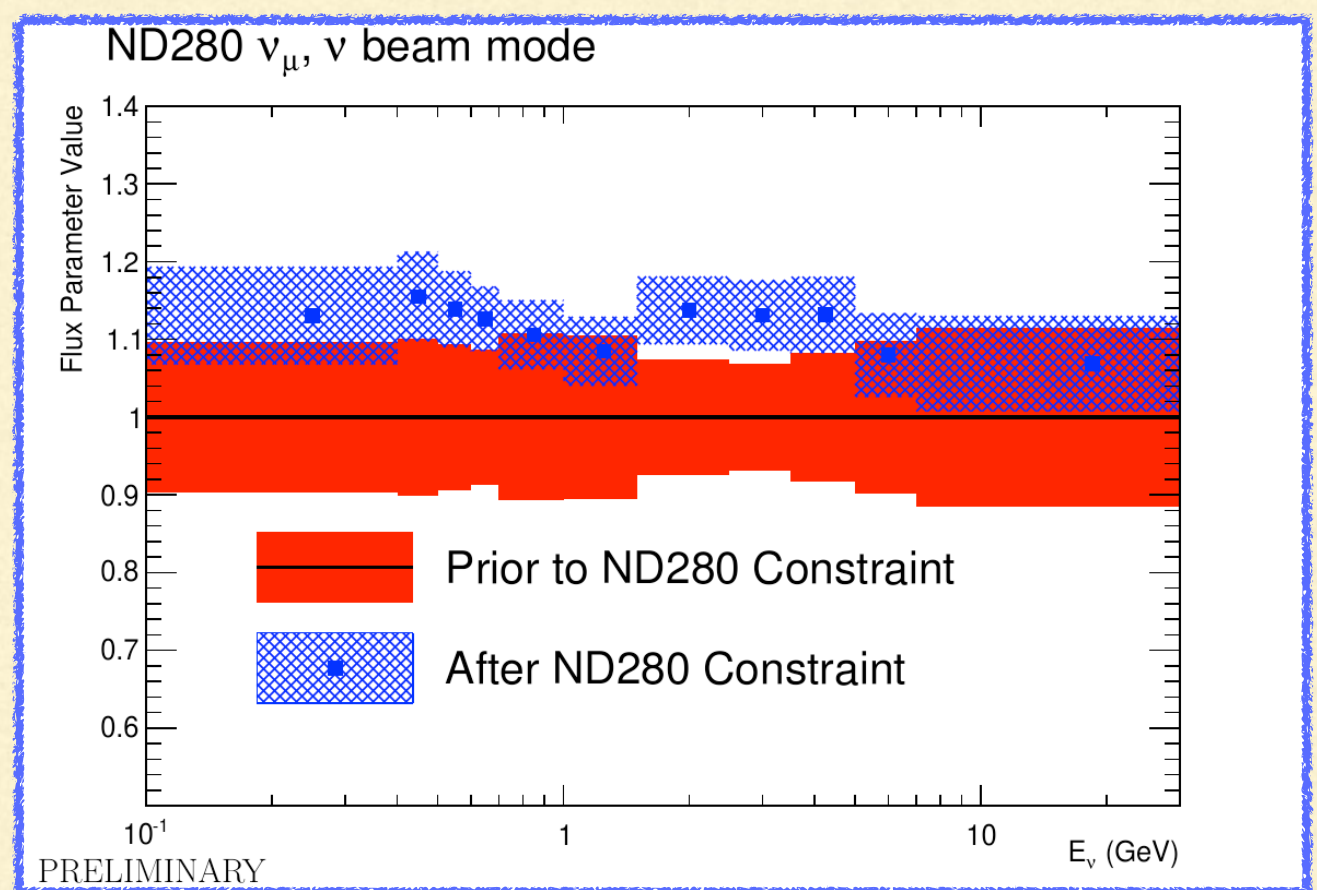


ND280 ANALYSIS

Example samples

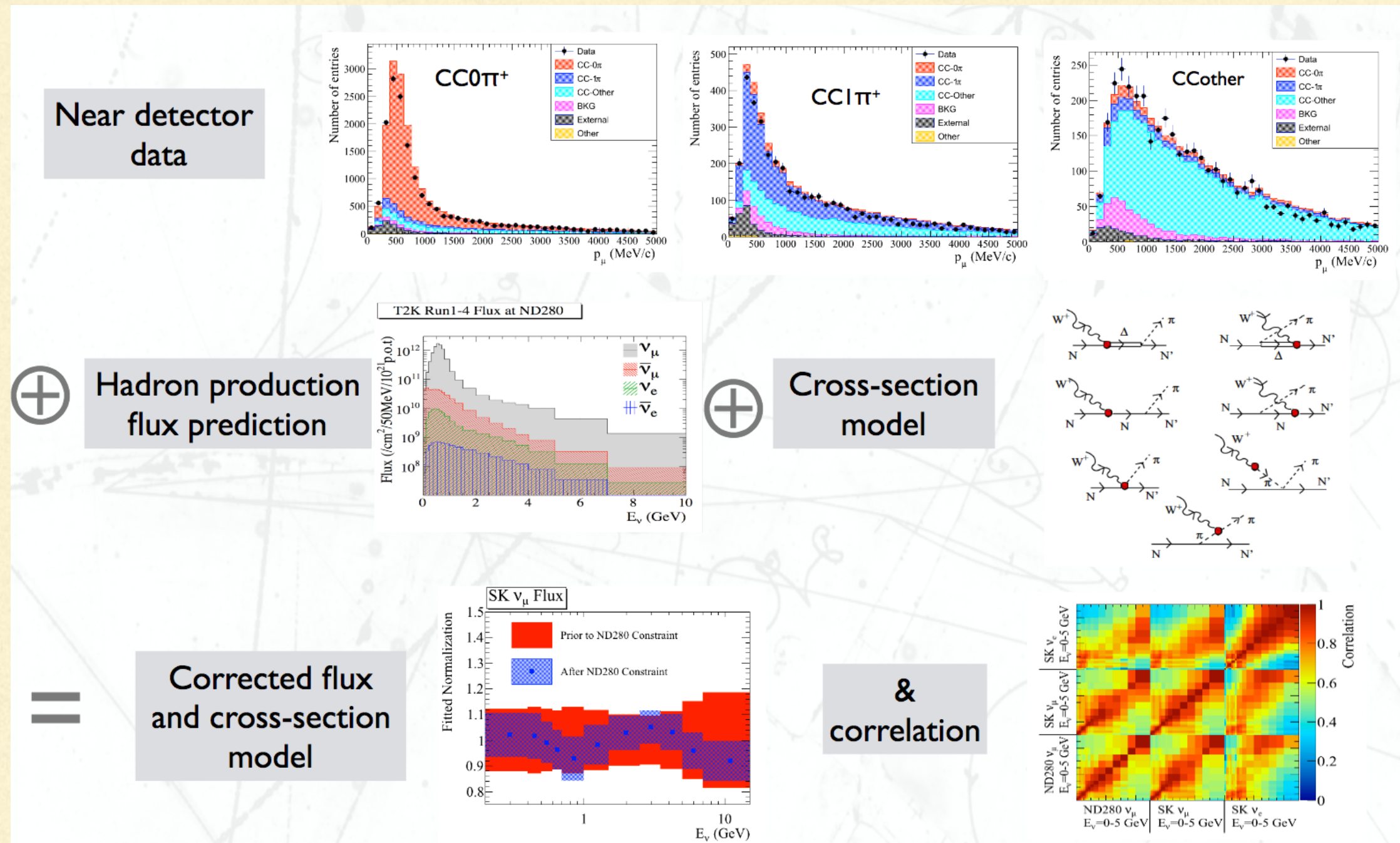


- Fit to ND280 samples constrains neutrino flux and cross-section model
- Reduce systematic uncertainty for oscillation analysis: $\approx 12\% \rightarrow \approx 6\%$
- +Many cross-section results with ND280 data

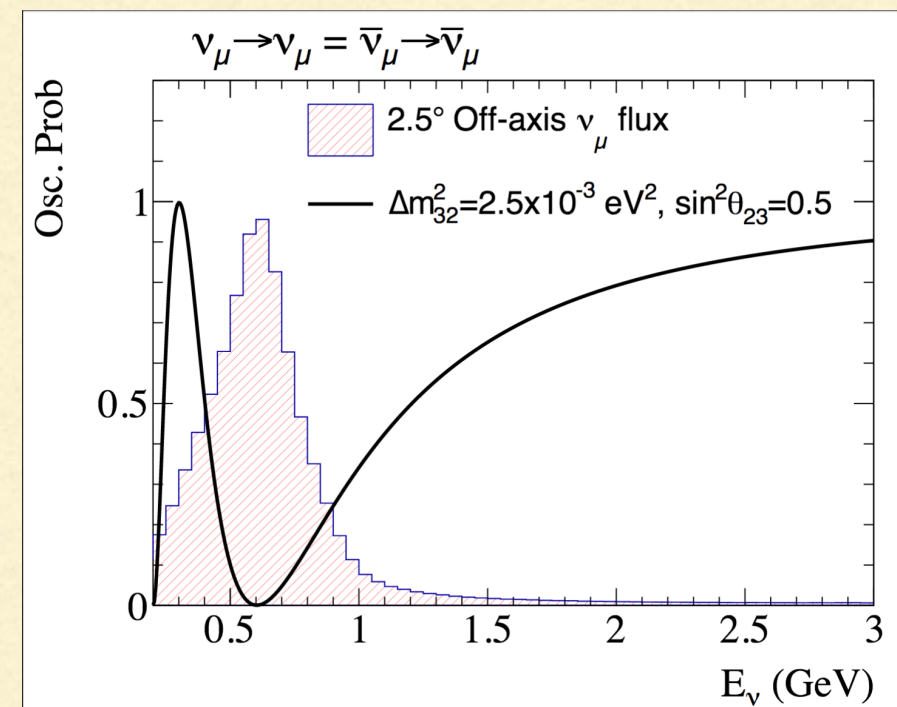
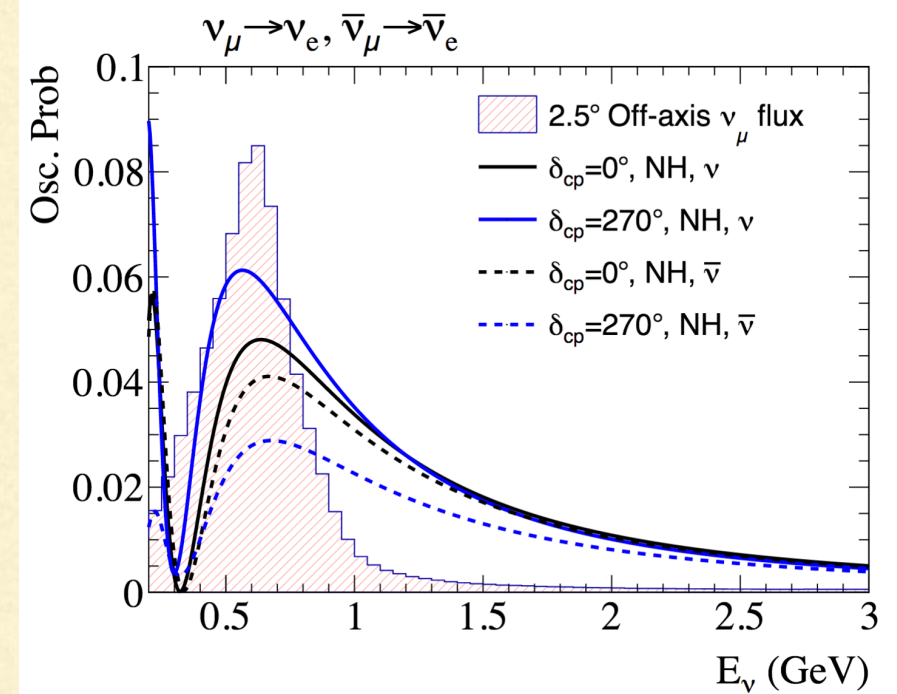
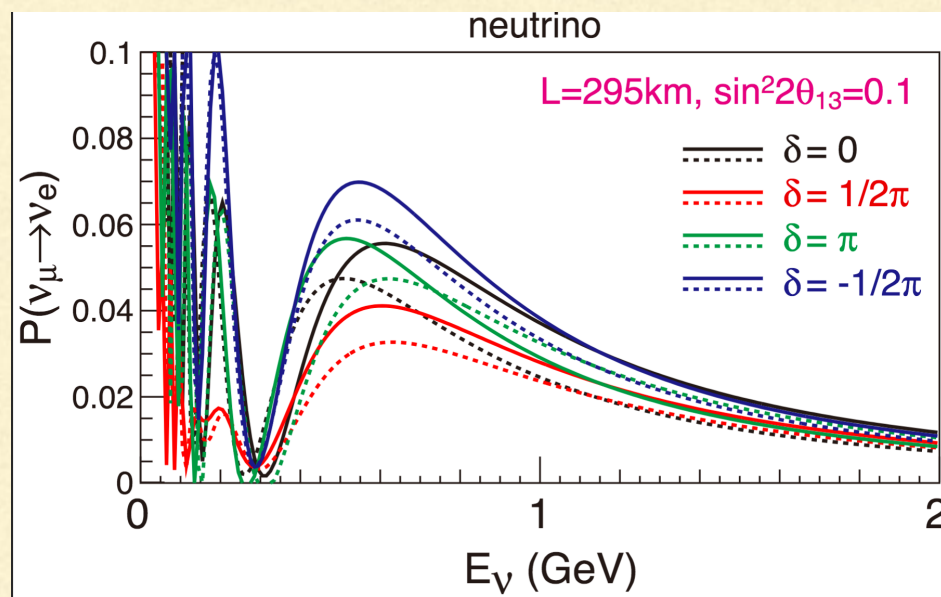
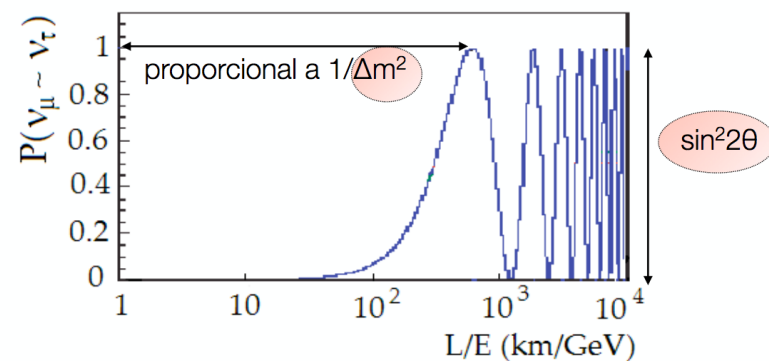
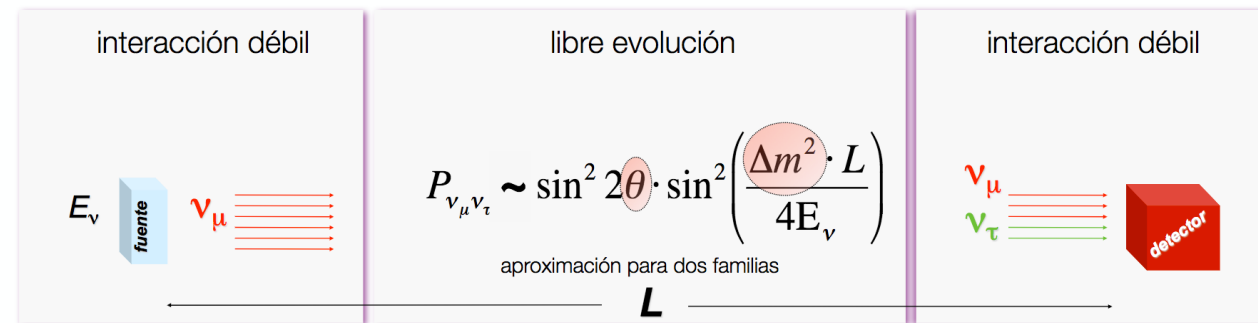


ROLE OF NEAR DETECTOR

- Understand neutrinos prior to as they travel and oscillate

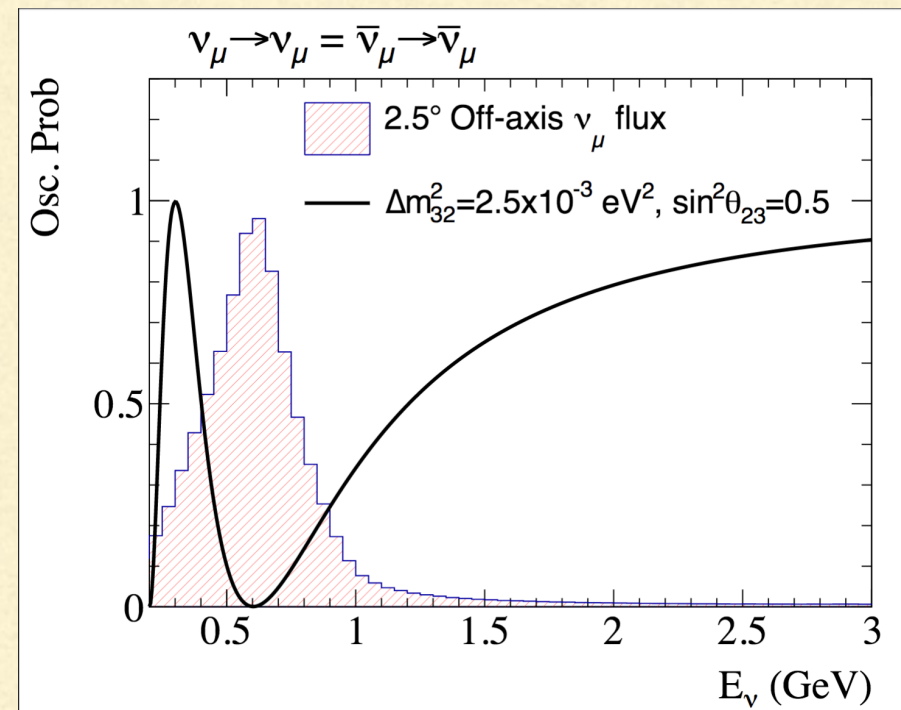
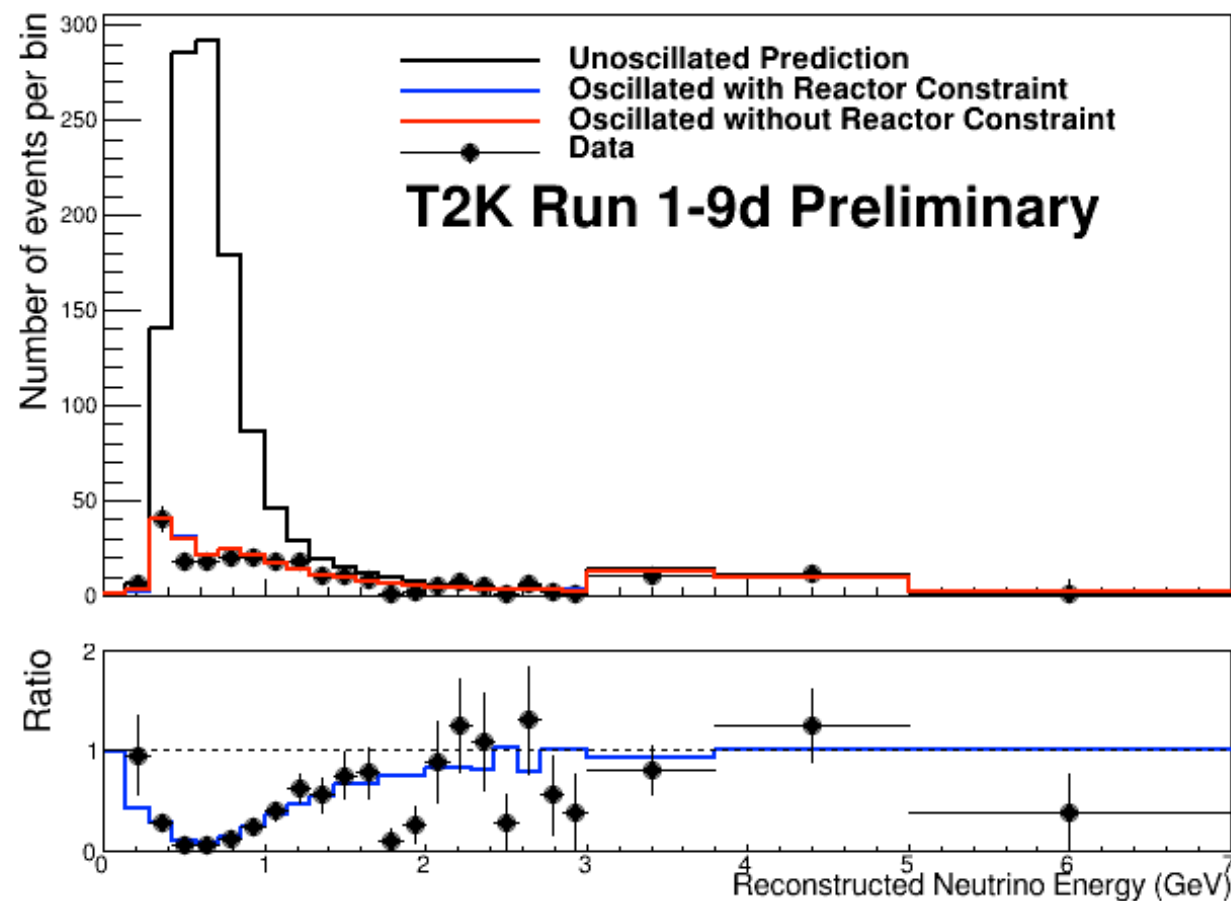


SEARCH FOR OSCILLATIONS



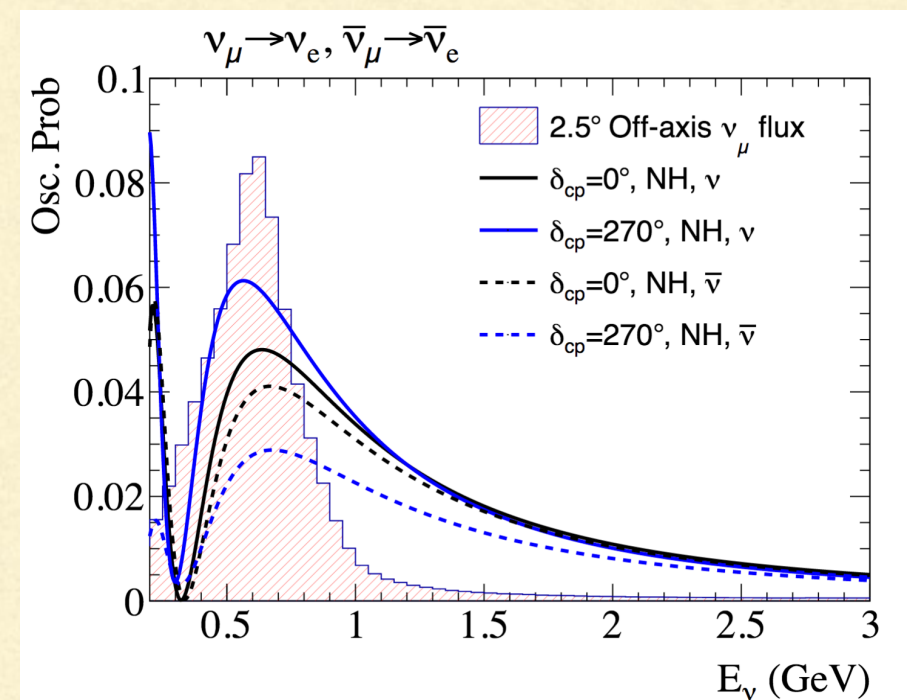
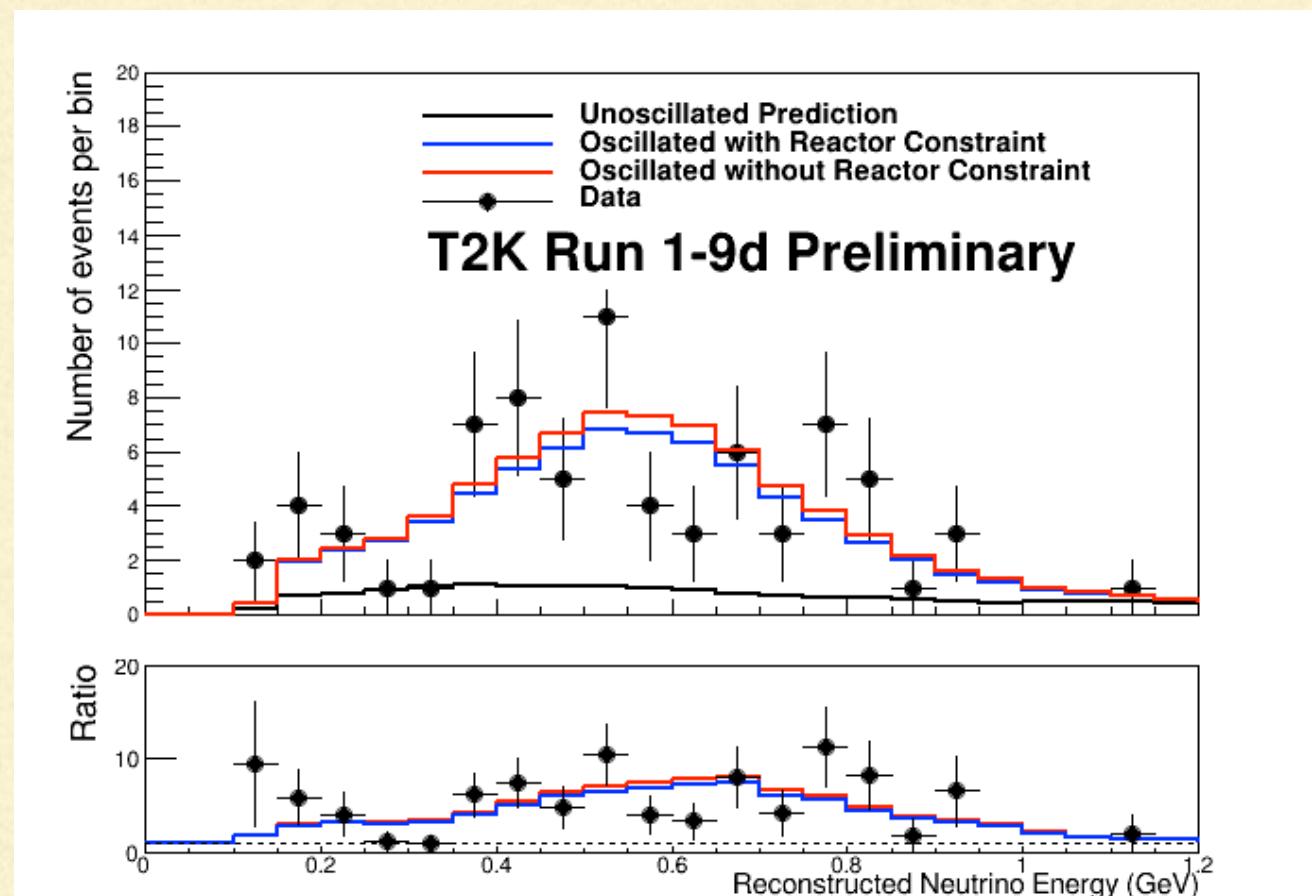
SEARCH FOR OSCILLATIONS

- Calculate observed μ -like and electron-like events
- And also profit from the change in the shape of the energy spectrum

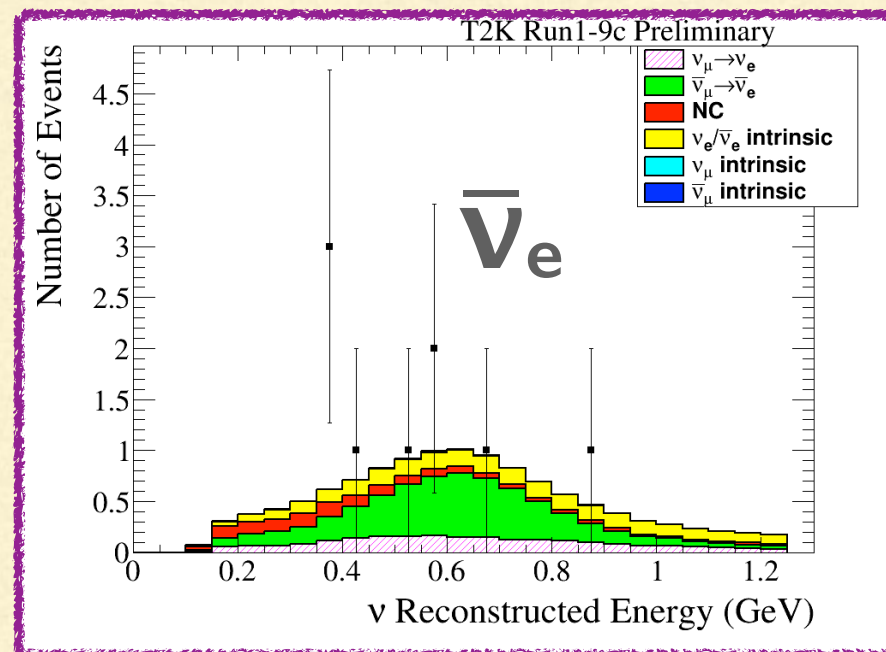
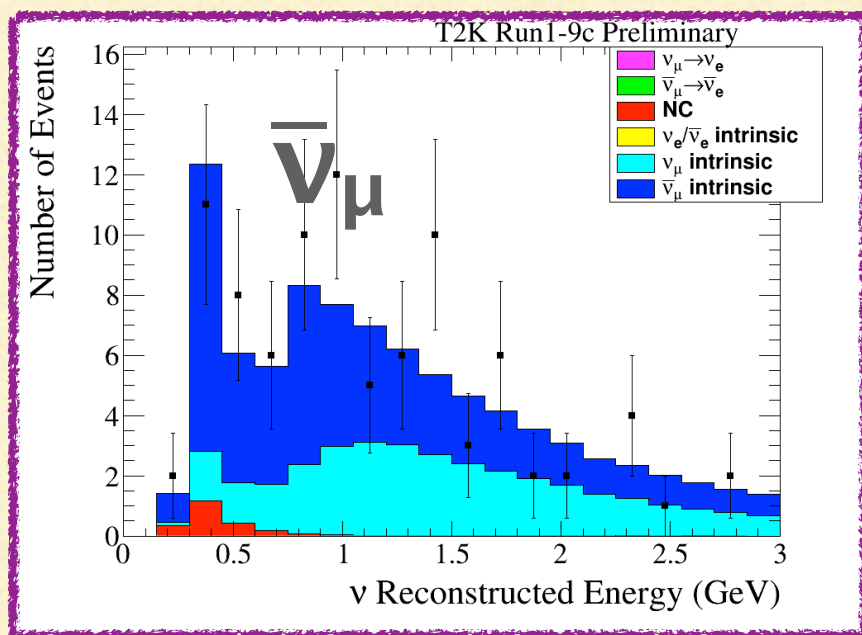
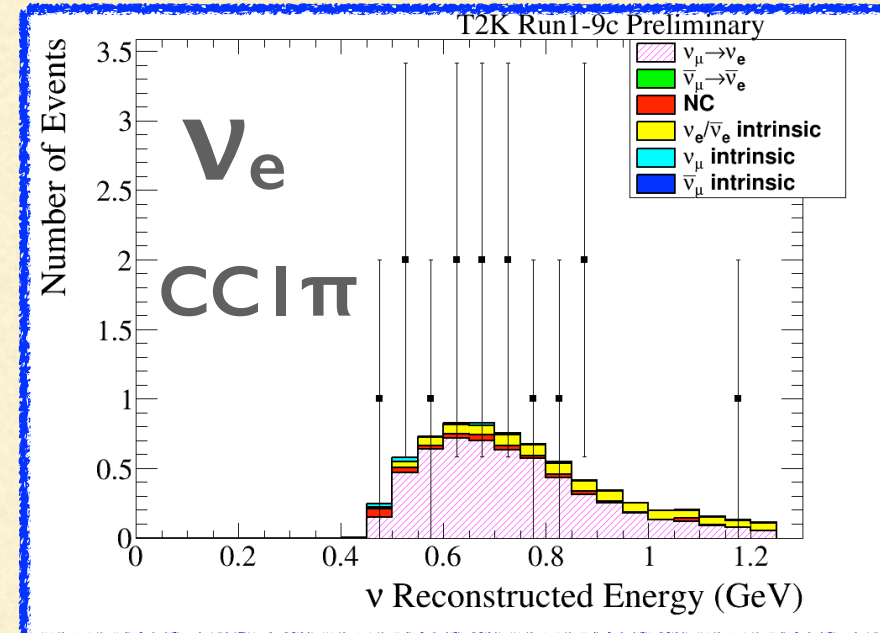
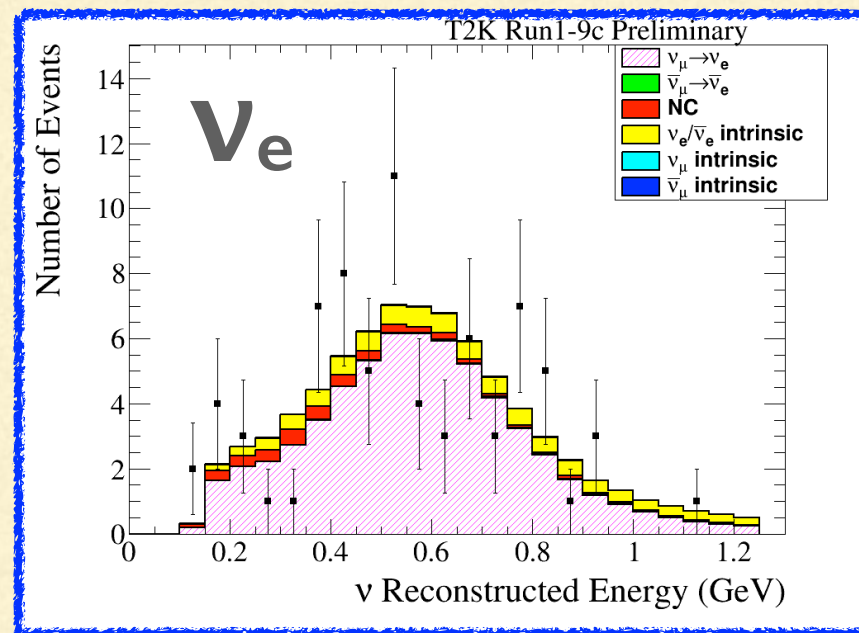
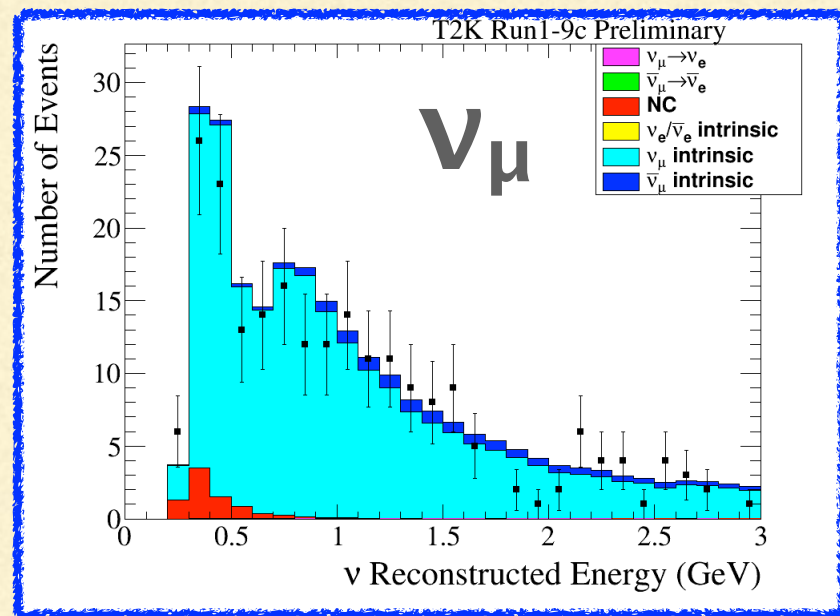


SEARCH FOR OSCILLATIONS

- Calculate observed μ -like and electron-like events
- And also profit from the change in the shape of the energy spectrum



T2K FAR DETECTOR SAMPLES



Energy distribution

ν -mode

anti- ν -mode

* T2K Preliminary

EVENT RATES

- Largely in line with the prediction for $\delta_{CP} = -\pi/2$

Sample	Predicted Rates				Observed
	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1 π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ -like FHC	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ -like RHC	63.1	62.9	63.1	63.1	68

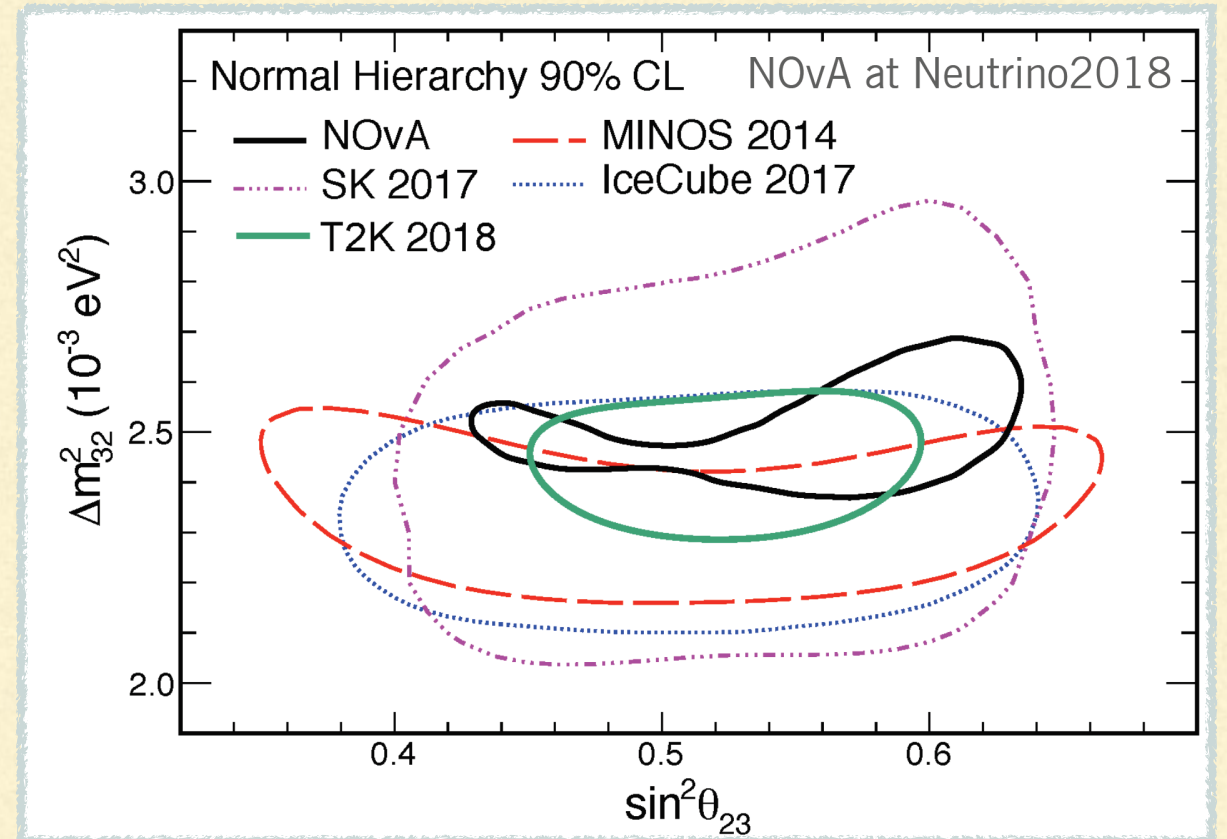
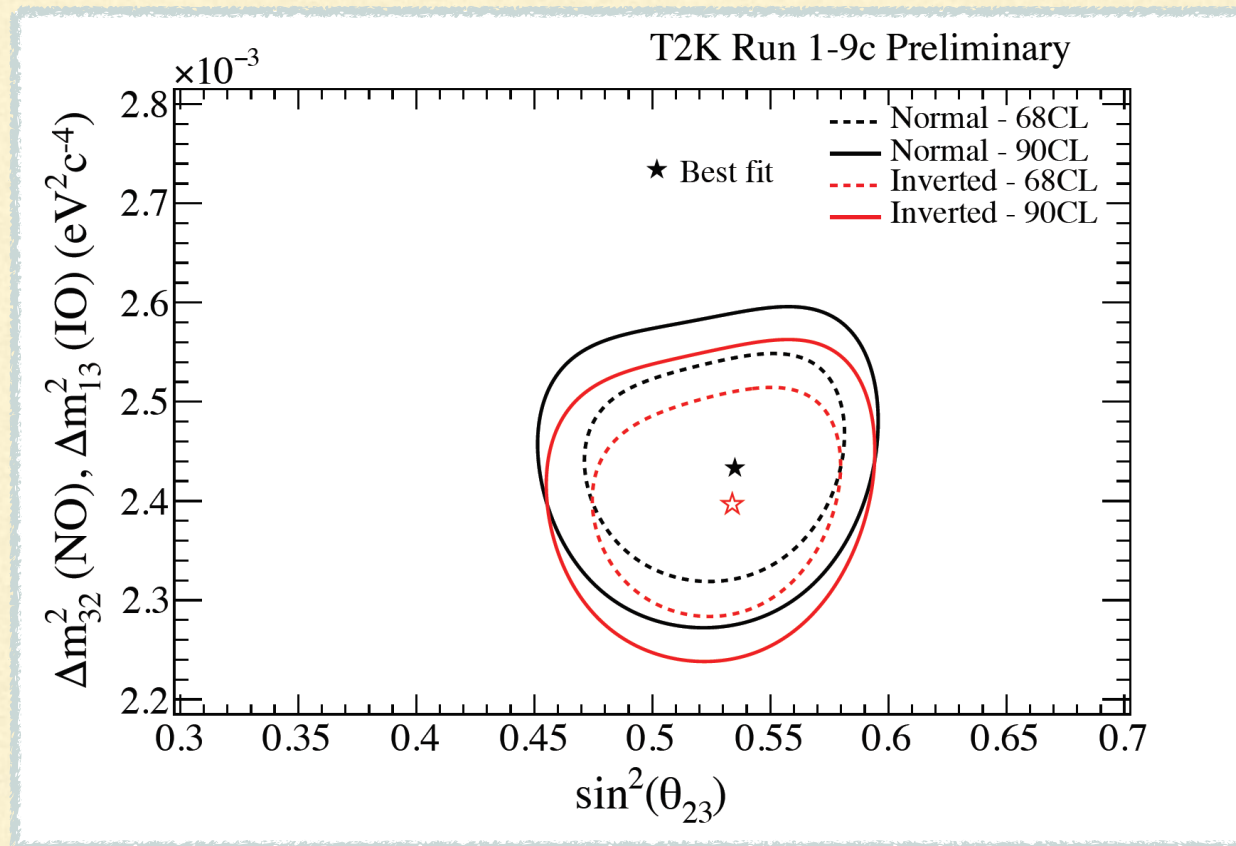
- Generally within statistical and systematic uncertainties
 - p-value: ~ 0.42
- More observed e-like CC1 π events **15** than maximum expectation **6.92₃₄**

T2K:VIDEOS

- Some nice T2K videos as well
- <https://youtu.be/u-UH3EwIEls>
- <http://scientific.ch/project/t2k/>

ANALYSIS RESULTS: ATMOSPHERIC PARAMETERS

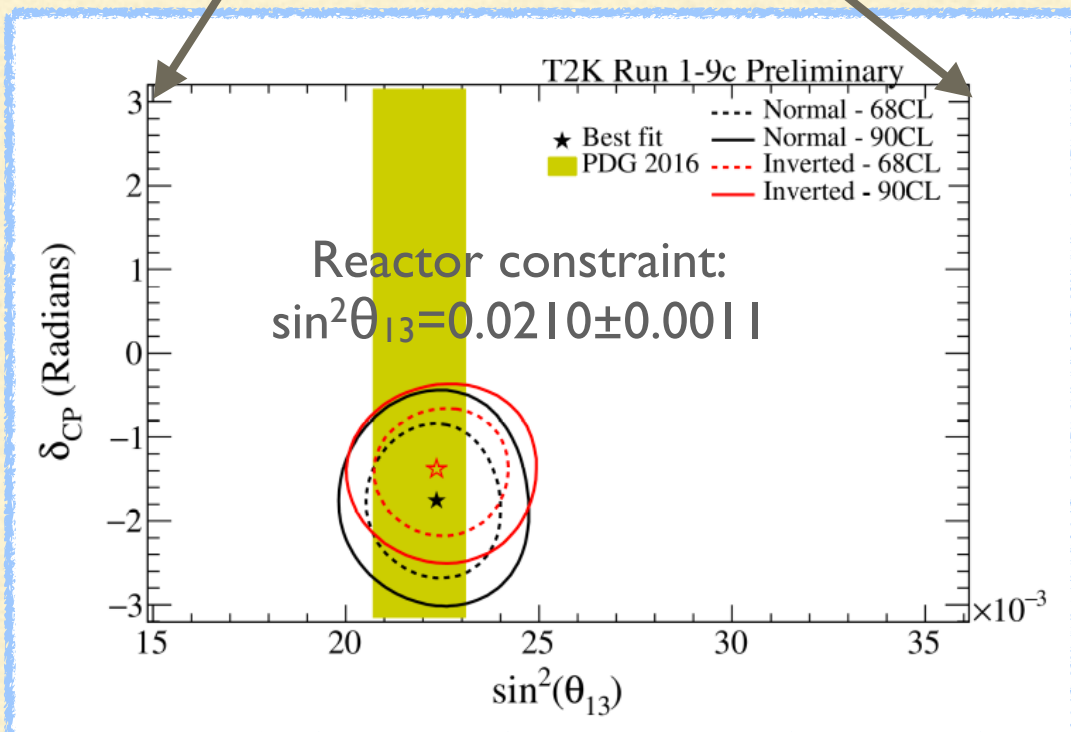
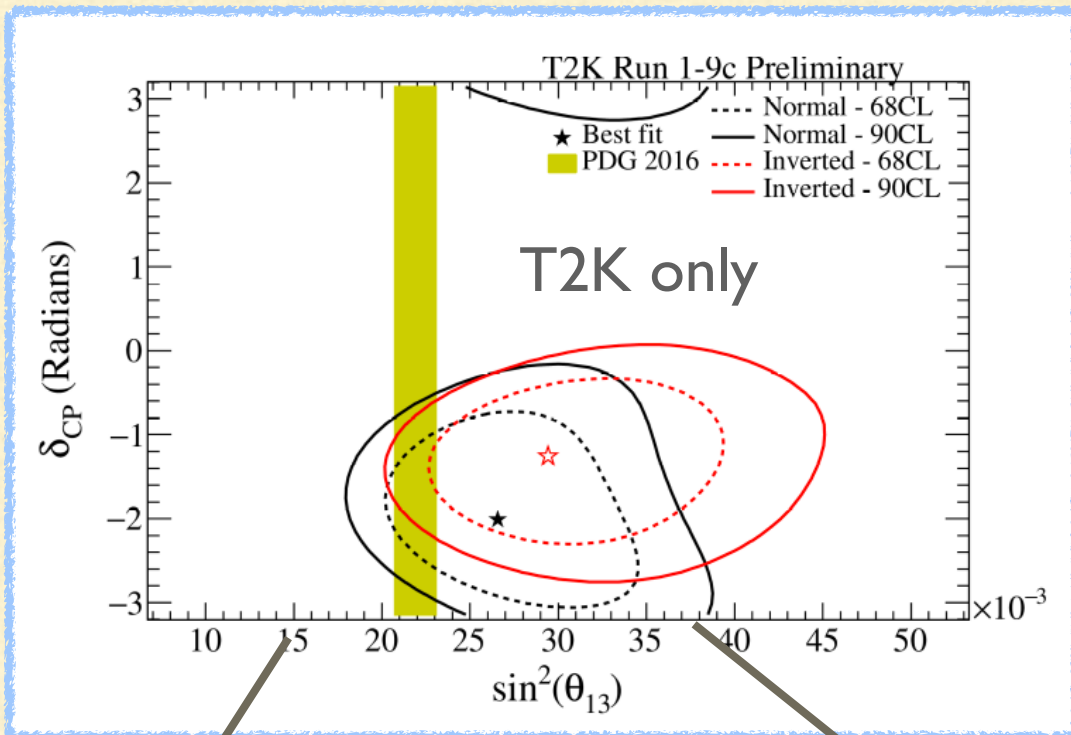
θ_{23} AND Δm_{32}^2



- T2K continues to favour maximal mixing
- Interesting tensions with NOvA
- More data needed to improve the results

	Normal	Inverted
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$ \Delta m^2 $ (10^{-3} eV^2)	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$

ANALYSIS RESULTS: θ_{13} and δ_{CP} MEASUREMENTS



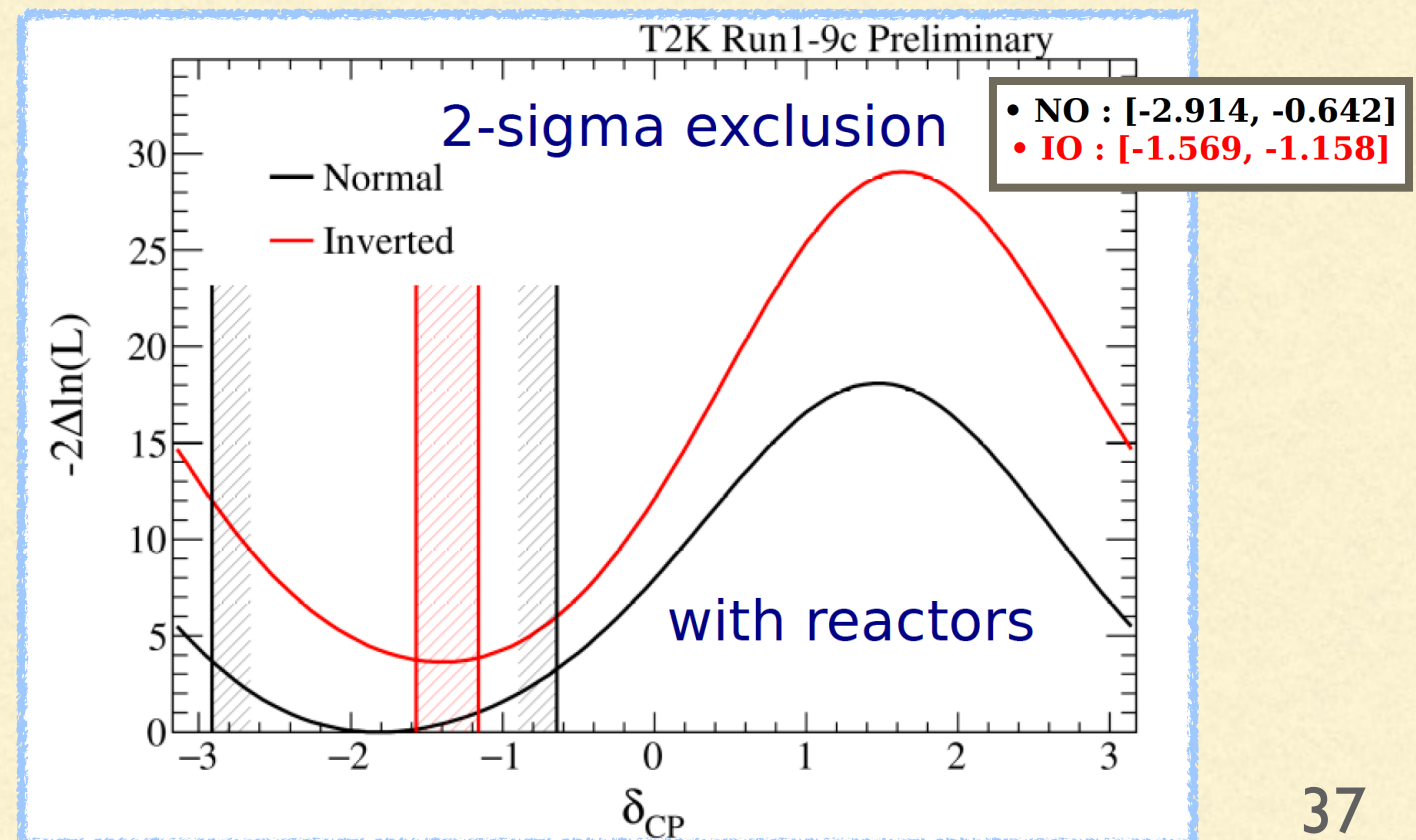
- Good agreement with reactor experiments

- T2K best fit (NH): $\sin^2\theta_{13} = 0.0277^{+0.0054}_{-0.0047}$

- PDG 2016: $\sin^2\theta_{13} = 0.0210\pm0.0011$

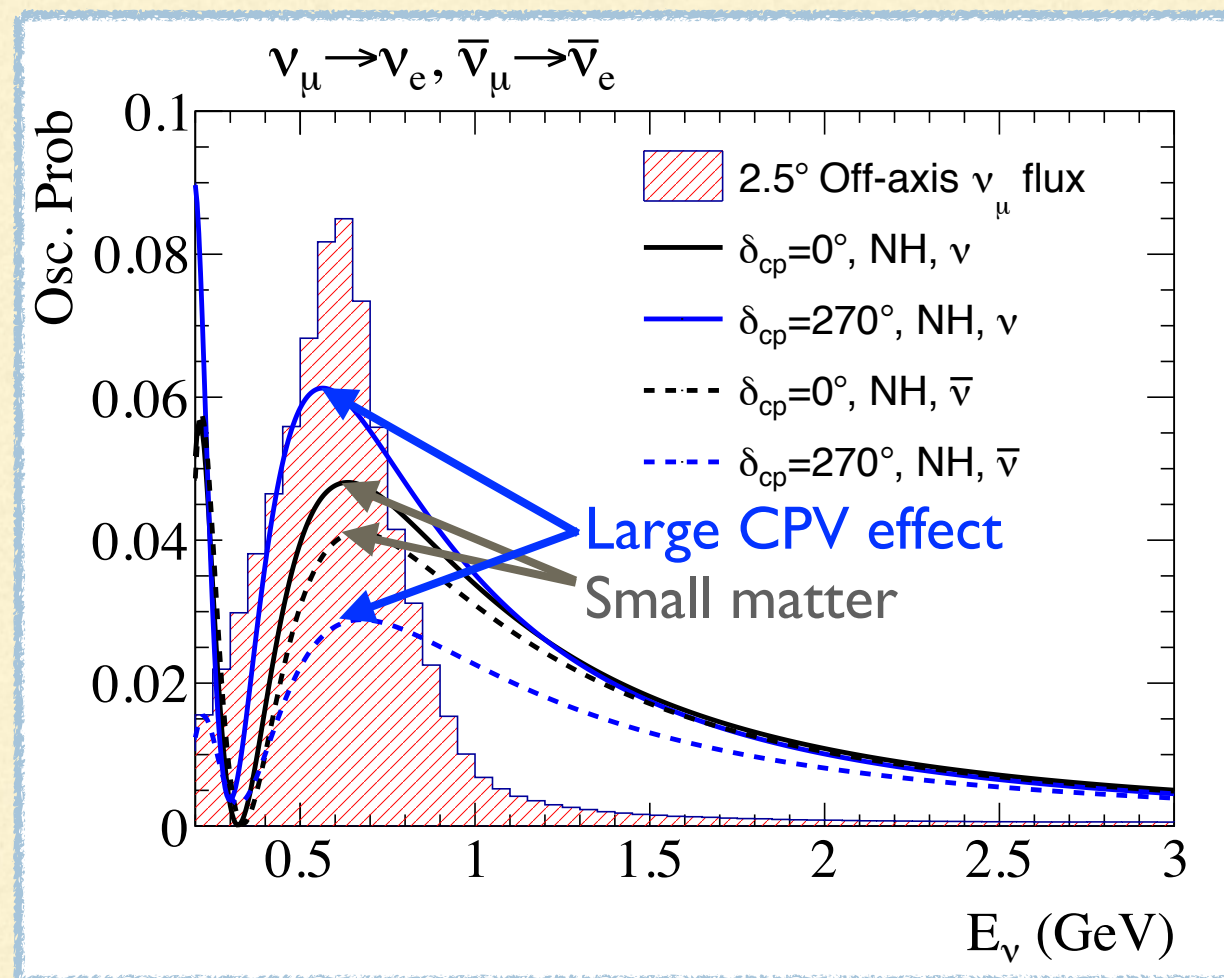
- 2σ exclusion for CP-conservation independent of OA

- Large CPV favoured



NEUTRINO OSCILLATIONS IN T2K

δ_{CP} and mass hierarchy (MH) both cause differences in ν and anti- ν oscillations



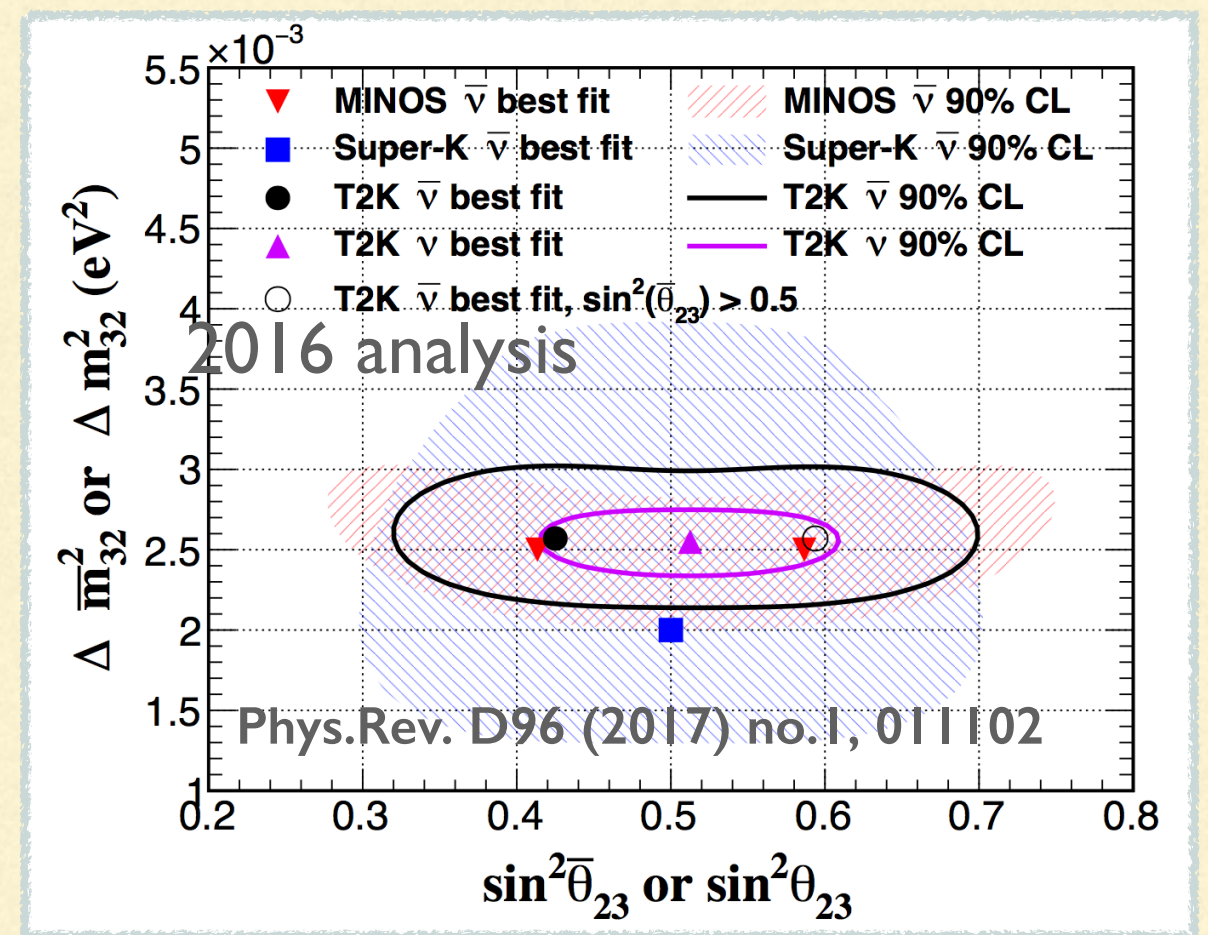
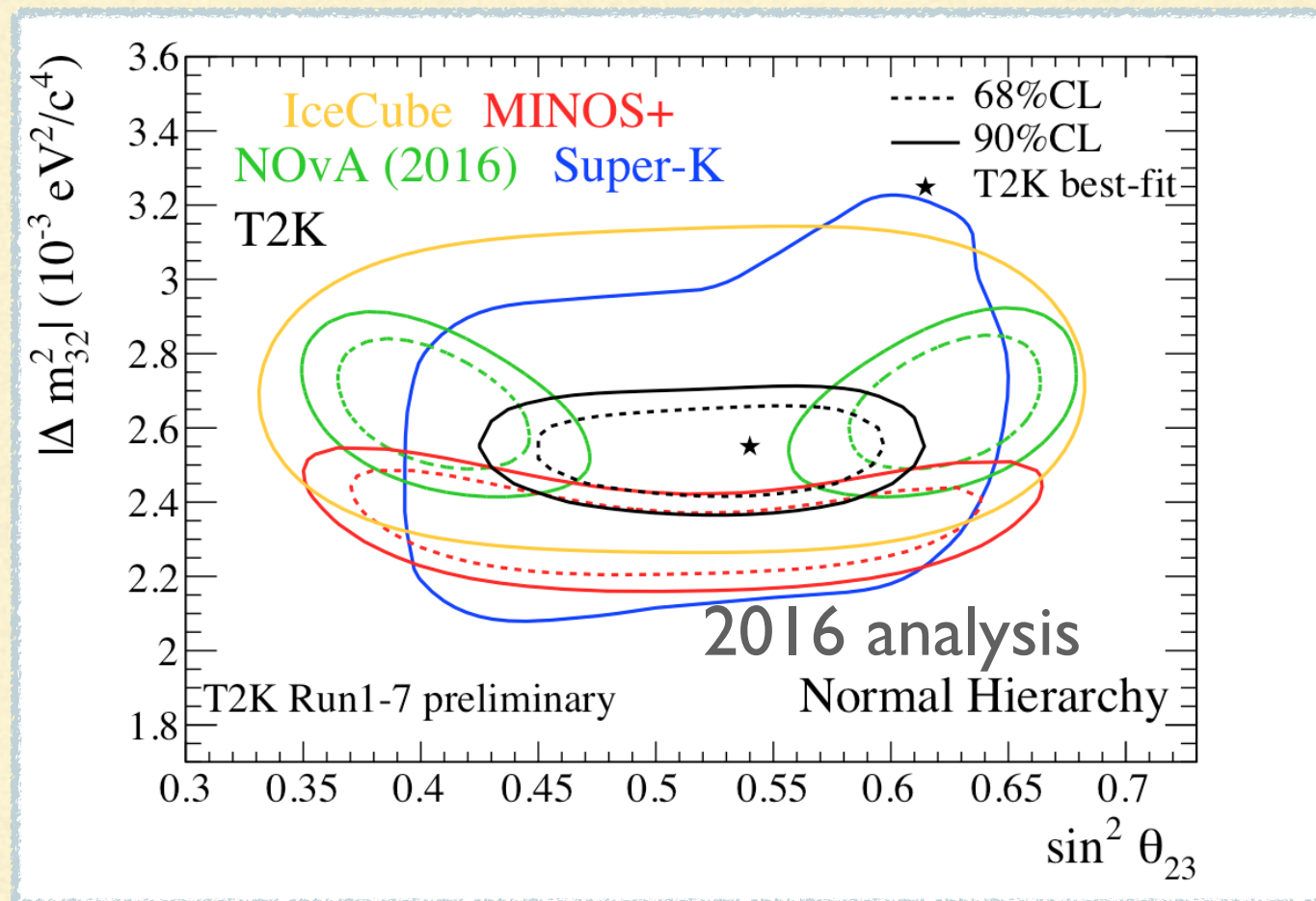
CP PHASE/ CHANNEL	$P(\nu_\mu \rightarrow \nu_e)$	$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
$\delta_{CP}=-\pi/2$	Enhance	Suppress
$\delta_{CP}=\pi/2$	Suppress	Enhance

At T2K baseline ($L \sim 295\text{km}$, $E \sim 0.6\text{GeV}$):

- CPV: $\approx \pm 30\%$ effect
- Mass hierarchy: $\approx \pm 10\%$ effect

ANALYSIS RESULTS: ATMOSPHERIC PARAMETERS

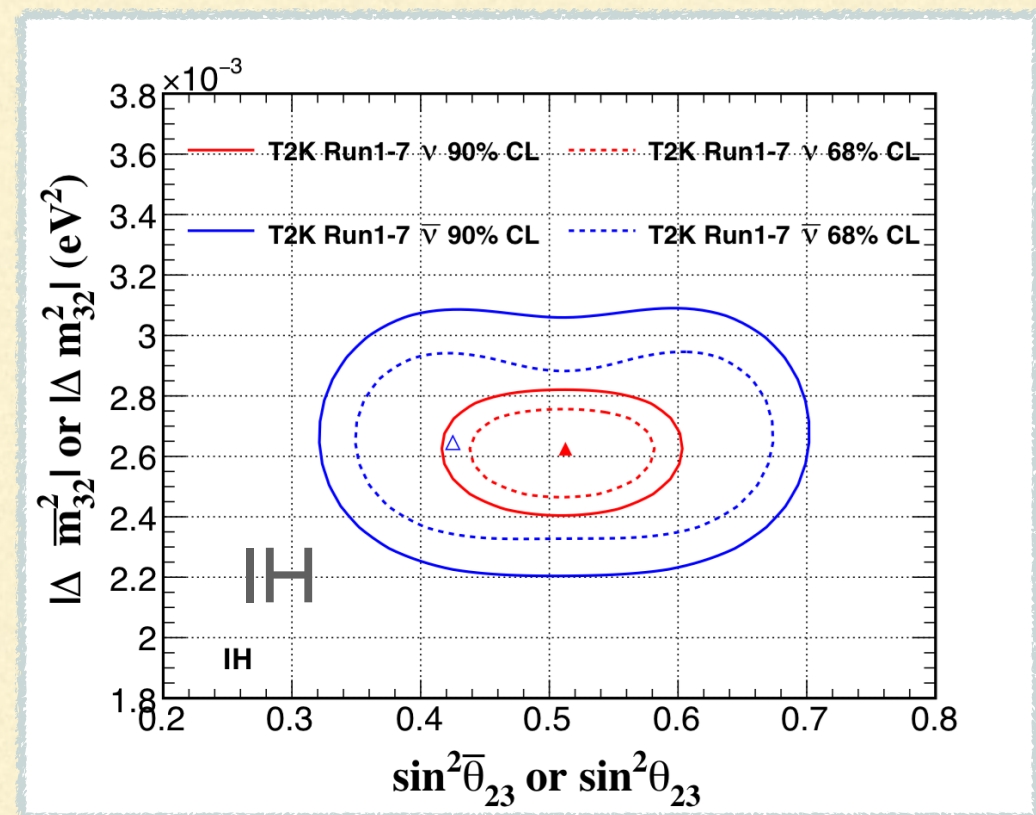
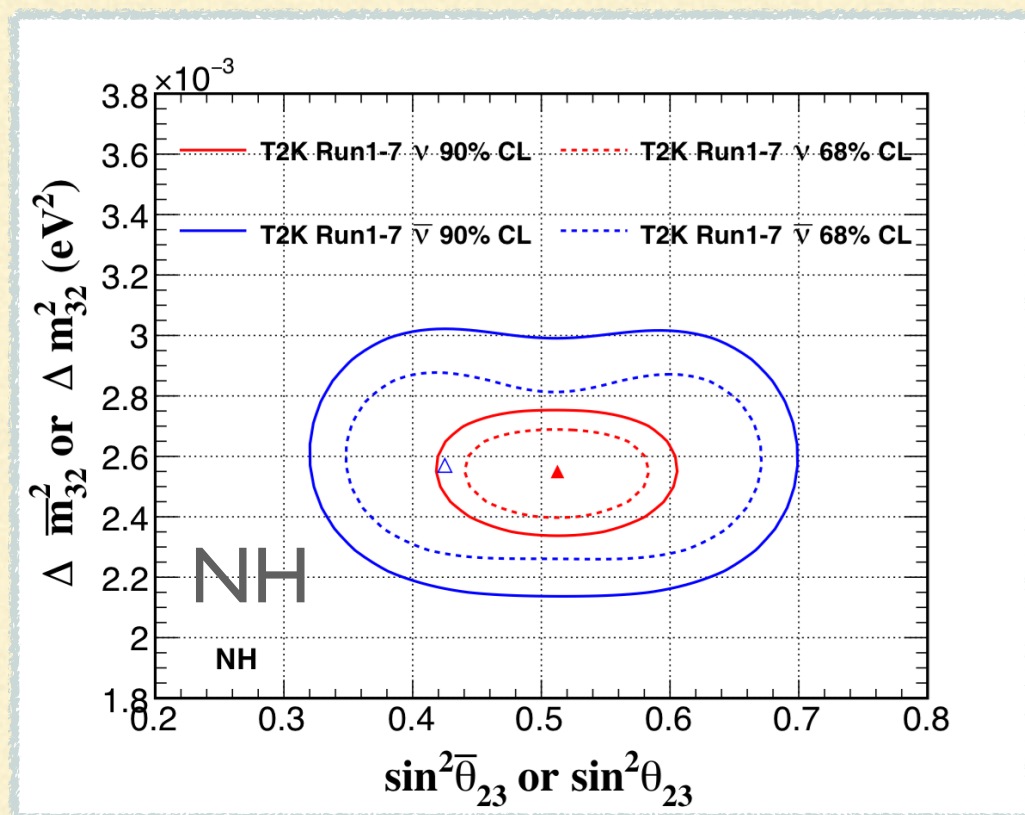
θ_{23} AND Δm_{32}^2



- 2016 analysis (joint fit of 5 samples with reactor constraint for θ_{13}):
 - Compatible and consistent results with other experiments
 - Consistent results for $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$: CPT conserved

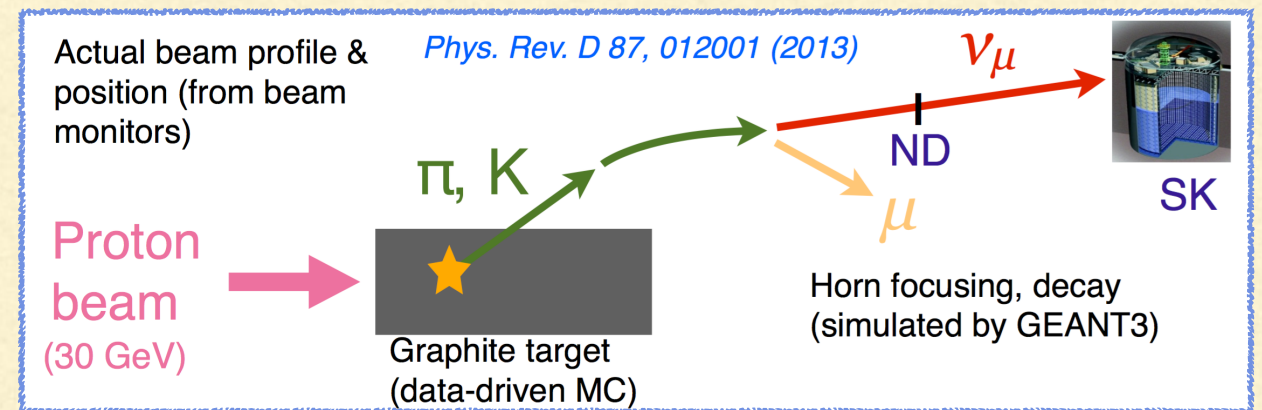
2016 CPT INVARIANCE TEST: ν_μ AND anti- ν_μ DISAPPEARANCE

- Strategy
 - Assign independent oscillation parameters for antineutrinos
 - Neutrino samples constrain “wrong-sign” background
 - Test CPT: $\theta_{23} \neq \bar{\theta}_{23}$ and $\Delta m_{32}^2 \neq \Delta \bar{m}_{32}^2$
- Consistent results for $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$: CPT conserved

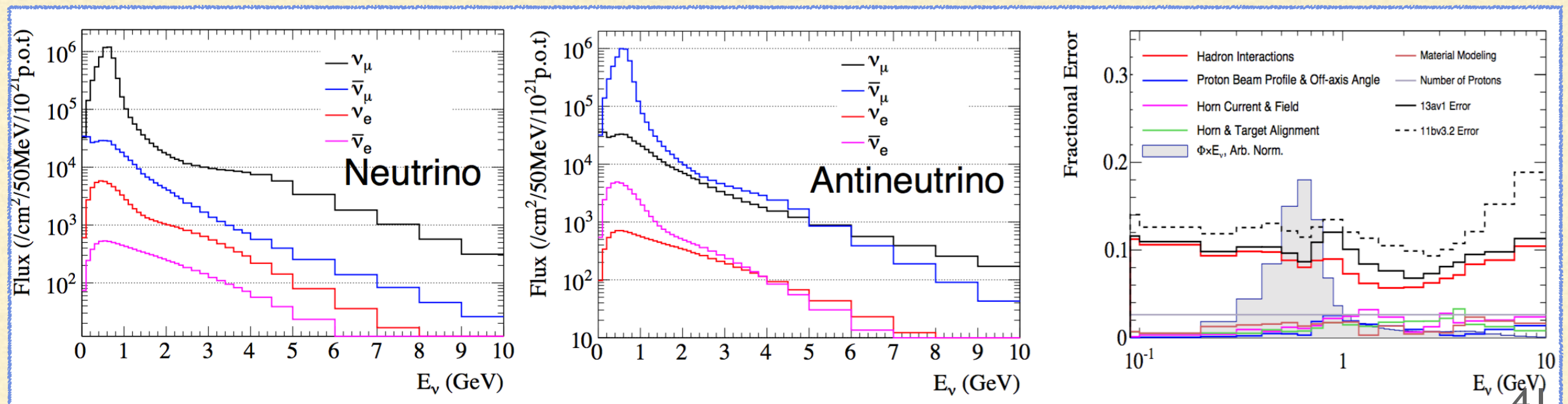


T2K NEUTRINO FLUX PREDICTION

- Simulation: FLUKA, GCALOR and GEANT3
- Tuned to external data: NA61/SHINE (CERN)
 - Measurement of pion/kaon production of 31 GeV/c proton beam with carbon target
 - Thin target (4λ) and T2K replica target
 - Reduction of uncertainties: $\sim 30\%$ to $\sim 10\%$
- Intrinsic ν_e background at $\sim 0.5\%$ level

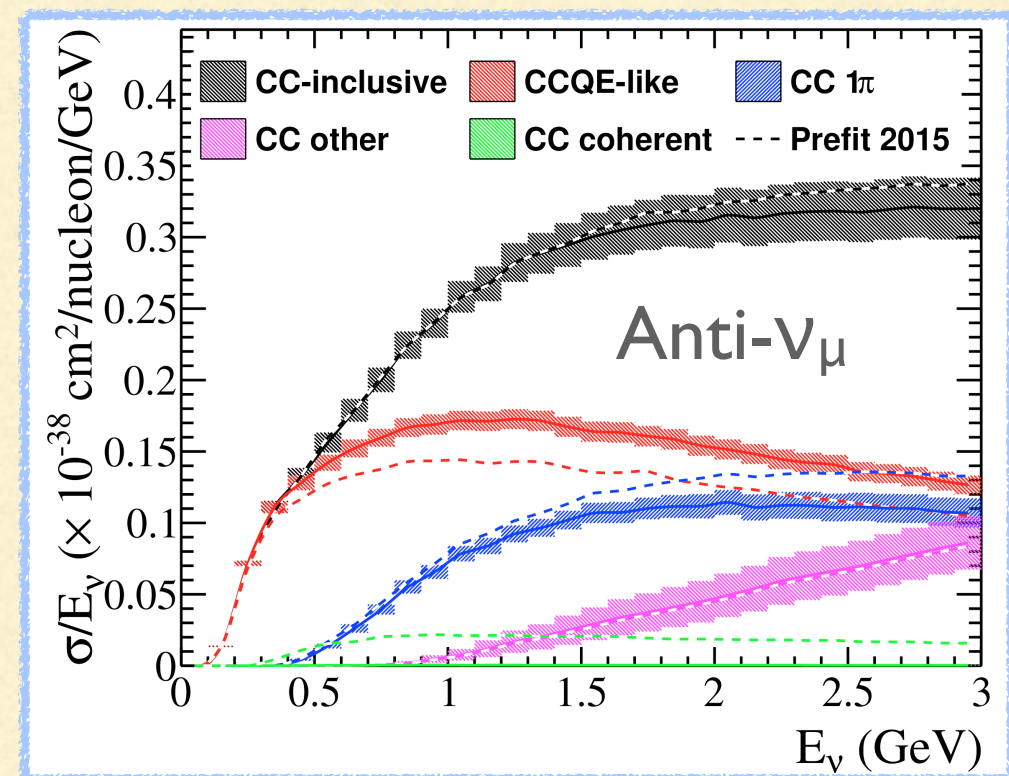
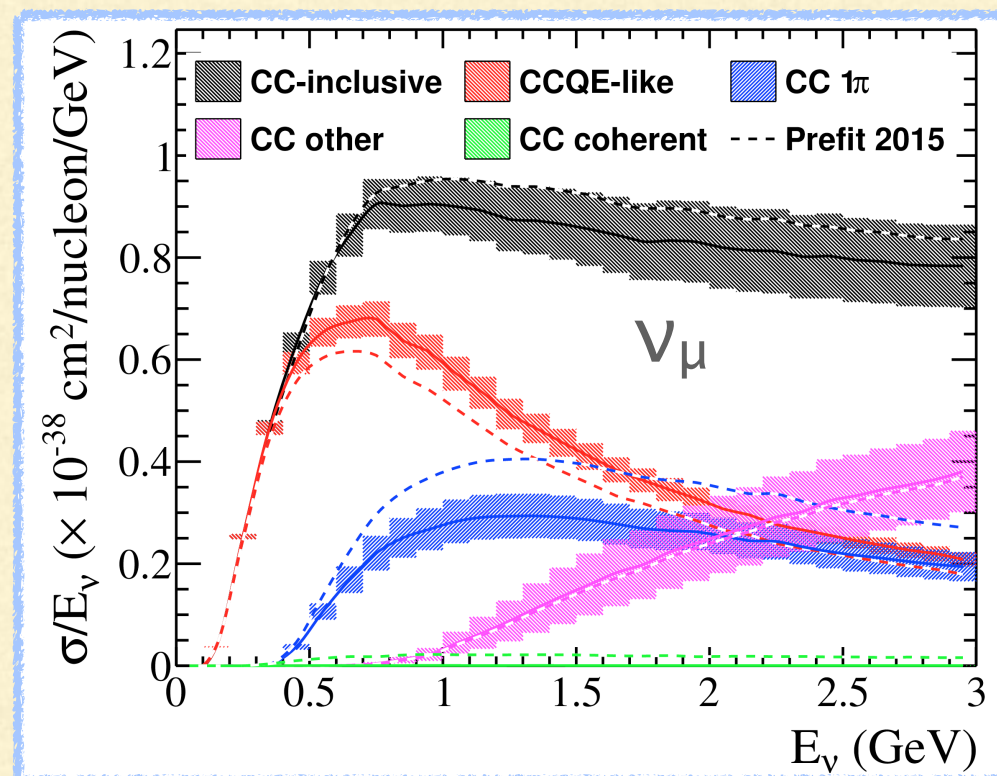


Replica target results are being incorporated into analysis

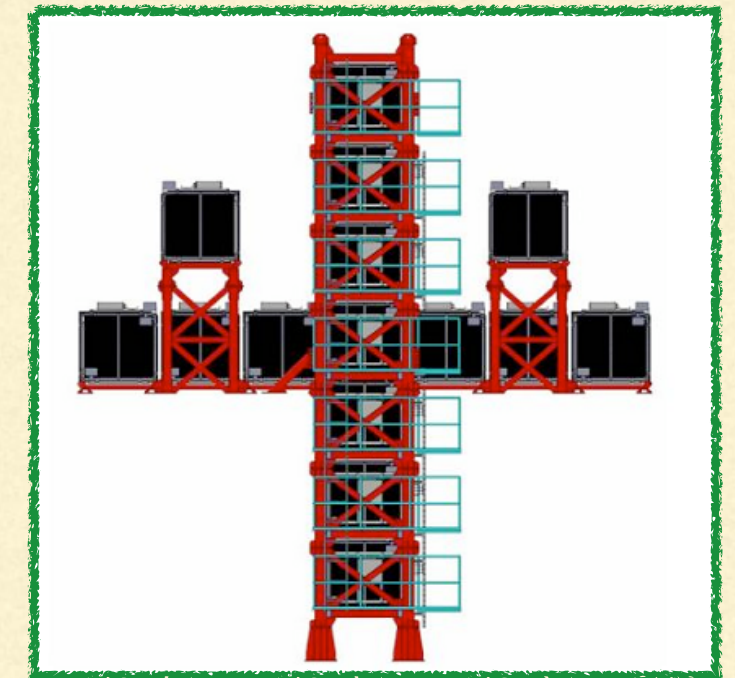
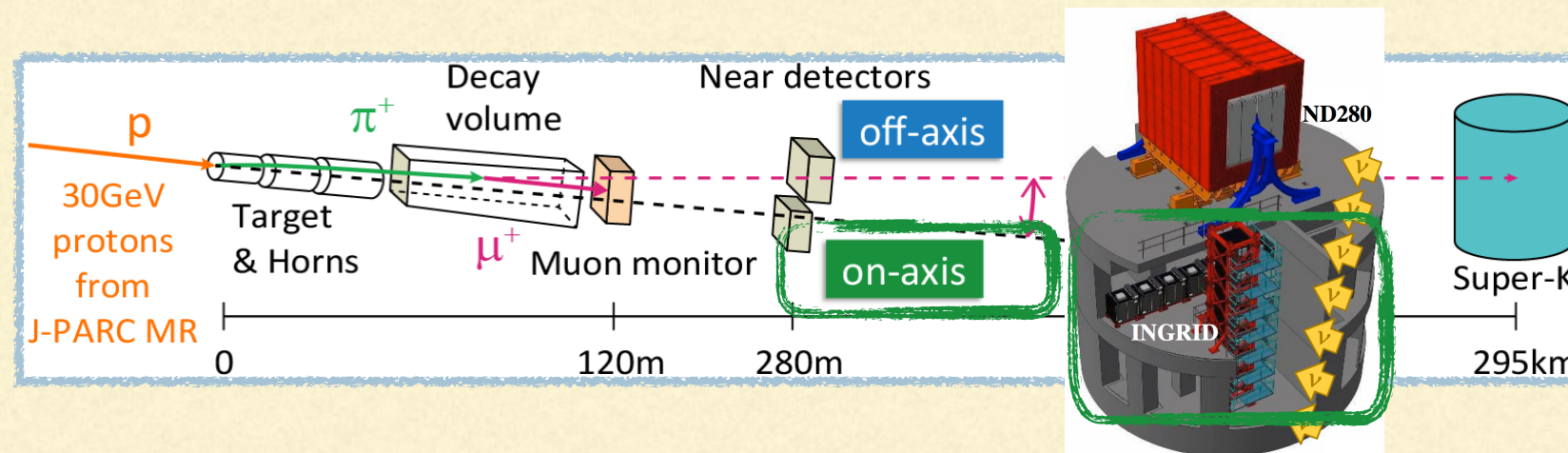


T2K NEUTRINO INTERACTIONS MODEL

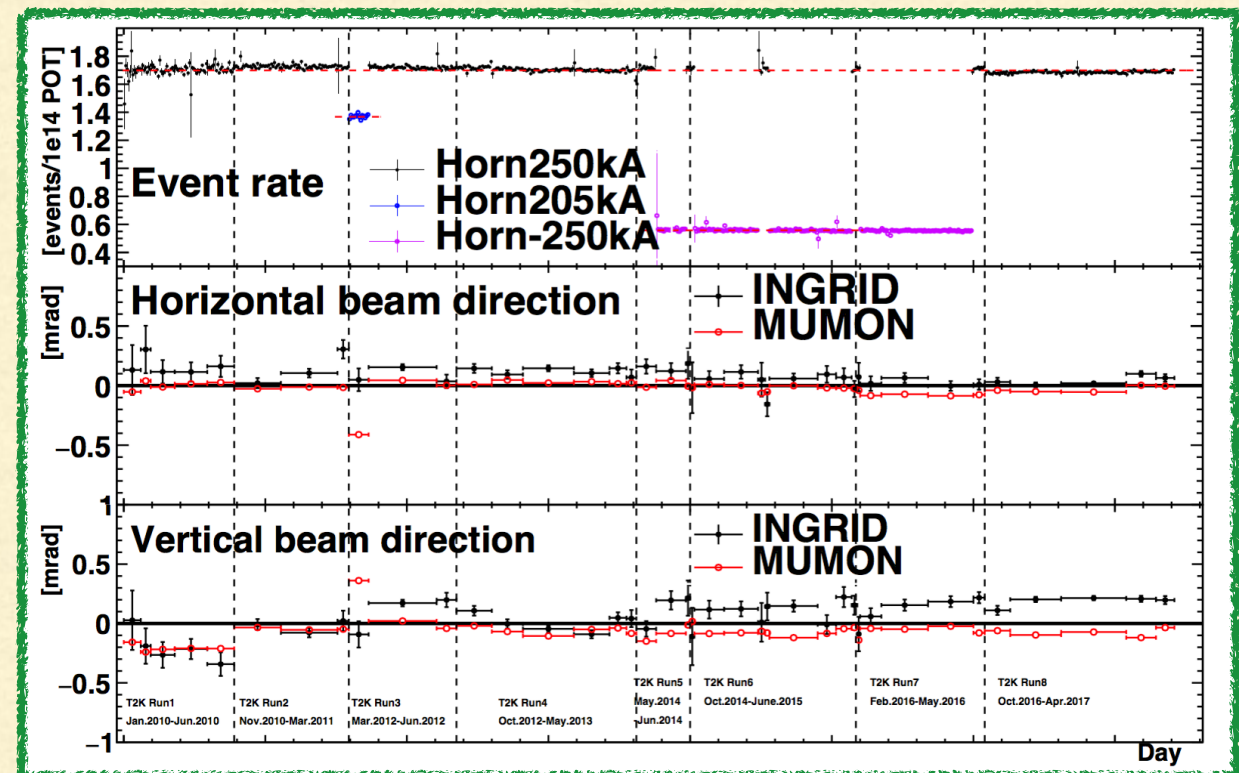
- NEUT neutrino generator
- Model tuned to external data: MiniBooNE, MINERvA, bubble chambers`
- CCQE: Relativistic Fermi Gas (weighted from Spectral Function) + relativistic Random Phase Approximation for nuclear system
- Multinucleon processes (2p2h) included based on J.Nieves model, Phys. Lett. B 707, 72 (2012)
- Pre-(ND280)fit uncertainty for Super-K: $\sim 7.5\%$



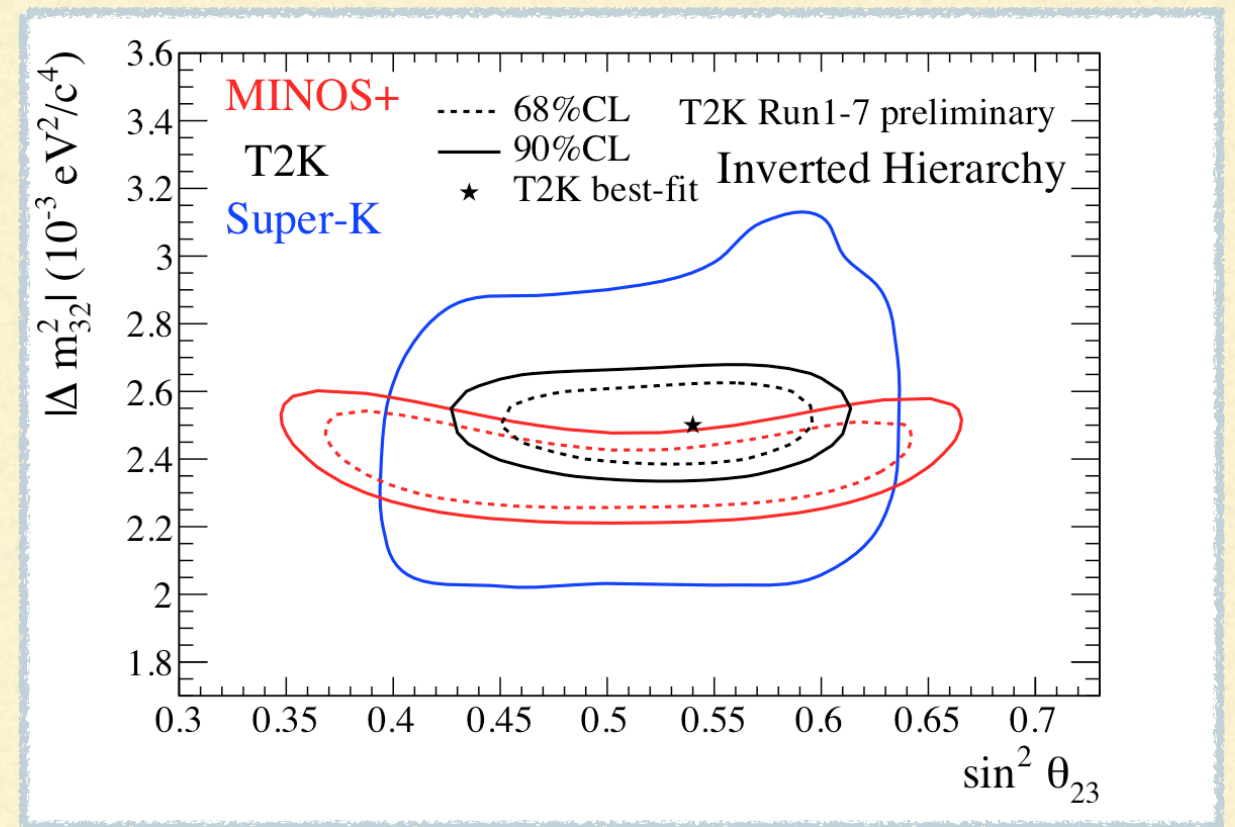
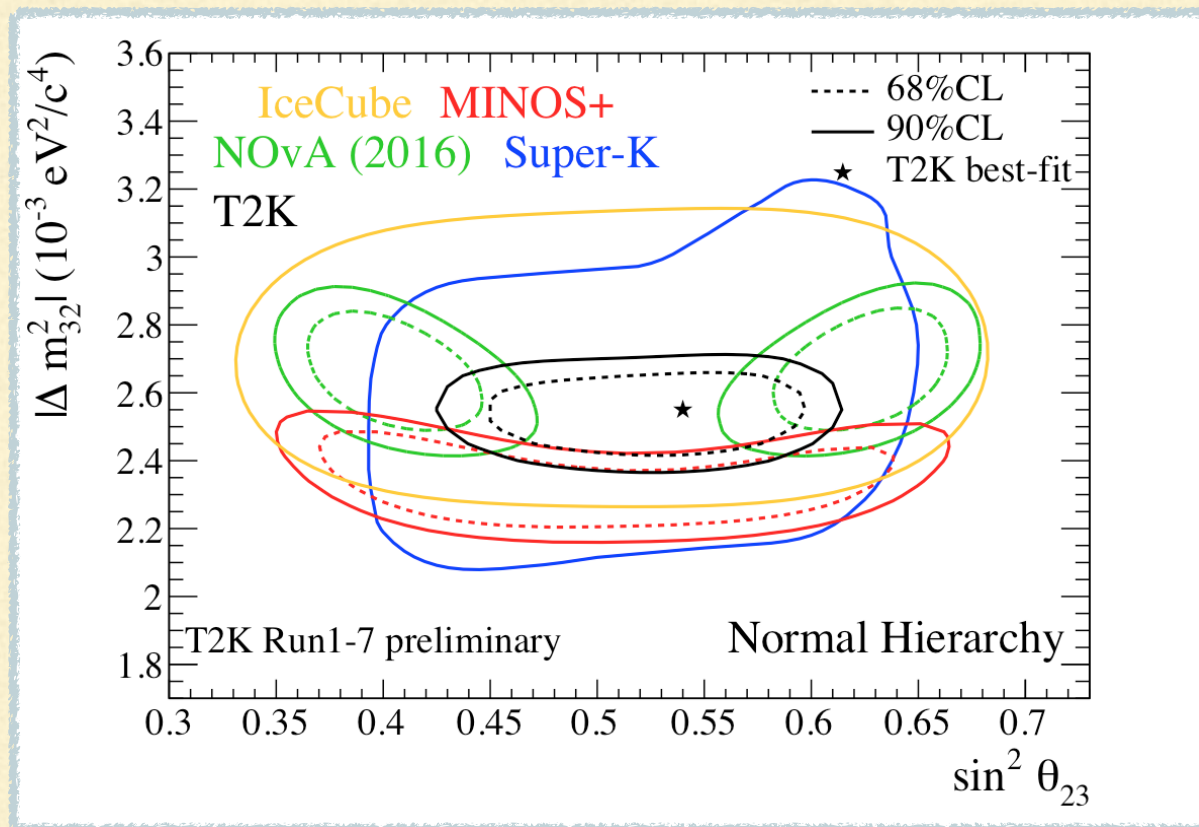
ON-AXIS NEAR DETECTOR INGRID



- T2K utilises off-axis neutrino beam:
 - Important to monitor beam intensity and direction
- Iron/scintillator detector to measure beam profile and rate
- Day-by-day monitoring
- Direction stable within 1 mrad (~2% shift in peak energy)



2016 ANALYSIS RESULTS: θ_{23} AND Δm^2_{32}



- Joint analysis with reactor constraint:
 $\sin^2 2\theta_{13} = 0.085 \pm 0.05$
- T2K data consistent with maximal mixing
- Compatible with other experiments
(intervals for fixed mass hierarchy)

PARAMETER/MASS HIERARCHY	NORMAL MASS HIERARCHY	INVERTED MASS HIERARCHY
$\sin^2 2\theta_{32}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.07}$
$ \Delta m^2_{32} $ ($\times 10^{-3} \text{ eV}^2/\text{c}^4$)	$2.545^{+0.081}_{-0.084}$	$2.51^{+0.081}_{-0.083}$

T2K: SPANISH GROUPS IMPACT

- Spanish groups provide important and in many ways crucial contributions to the T2K experiment
- Near Detector:
 - Magnet operations (IFAE), TPCs (IFAE and IFIC), near detector calibration, reconstruction and analysis
 - Conveners of the groups responsible of the data-taking coordination, neutrino interactions modelling, tracking, analysis framework development, “exotics” physics searches
- UAM actively participates in the Super-Kamiokande calibrations + work on Gd addition
- Further work beyond current activities:
 - T2K+SK+reactors global fit (IFIC+UAM with T2K-UK/Japan groups)
 - T2K ND280 analysis software for DUNE(-SP) analyses