Precision Measurement of Muon Neutrino Disappearance by T2K

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for the T2K Collaboration

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PAINC 2014

Hamburg, Germany

Outline

- Neutrino Oscillation Introduction
- The T2K experiment
- T2K Results
- T2K Anti-Nu Run
- Summary

Neutrino Oscillation

- Neutrino production and detection is determined by their type/flavor (ν_e, ν_μ, ν_τ) eigenstates
- But propagation through space is determined by their mass (ν_1, ν_2, ν_3) eigenstates
- Flavor eigenstates are related to mass eigenstates via the *PMNS* mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The PMNS Matrix

- A unitary 3x3 matrix → 4 degrees of freedom [assume the 3-flavor paradigm]
- Commonly parameterized by 3 mixing angles (θ_{12}, θ_{23}, θ_{13}) and 1 phase (δ)

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$$U_{PMNS} = \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}_{} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{}$$

"Solar ν's"
Solar, Reactor
$\theta_{12} \approx 34^0$

Reactor, Accelerator
$\theta_{13} \approx 9^0$

"Atmospheric ν's"
Atmospheric, Accelerator
$\theta_{23} \approx 45^0$

- Note:
  Large mixing angles compare to the quark section (CKM)

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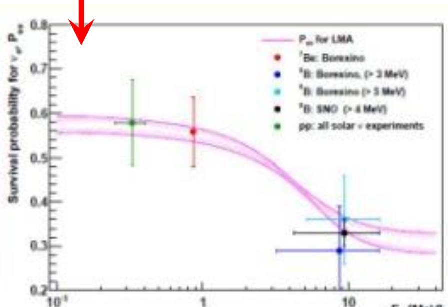
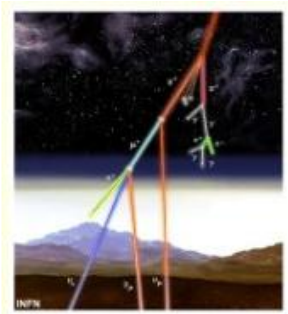
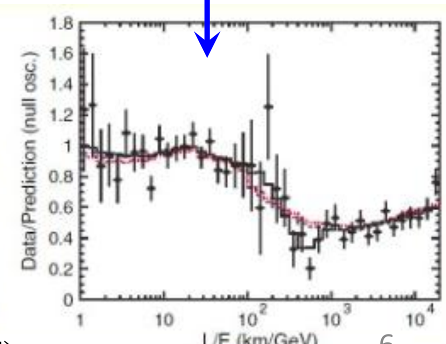


PRD 82, 033006 (2010)





PRL 93, 101801 (2004)

Oscillation Probabilities

- In general

$$P(\nu_\alpha \to \nu_\beta) = \left| \langle \nu_\alpha | \nu_\beta(t) \rangle \right|^2 = \left| \sum_i U^*_{i\alpha} U_{\beta i} e^{\frac{-i m_i^2 L}{2E}} \right|^2$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillation Probabilities

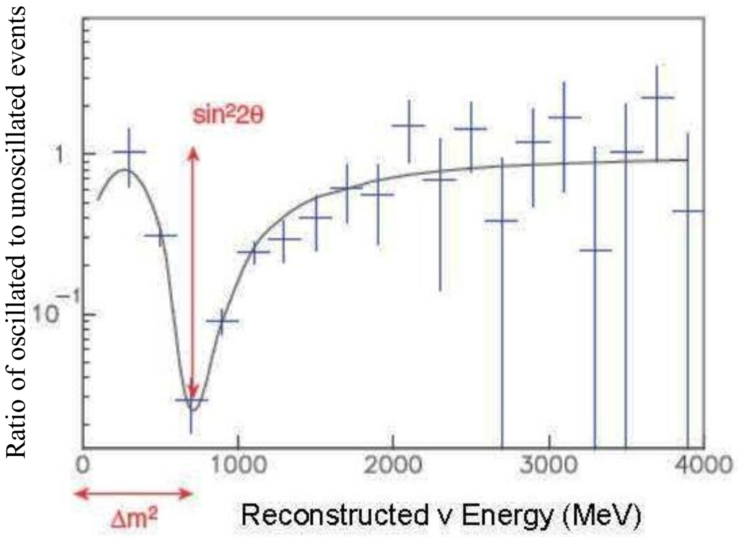
- T2K ν_μ Disappearance

$$P(\nu_\mu \to \nu_\mu) \cong 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}\left[1-\cos^2\theta_{13}\sin^2\theta_{23}\right]s^2\Delta_{32}$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

where

$$s^2\Delta_{ij} = \sin^2\left(\frac{L}{E_\nu}\frac{m_i^2 - m_j^2}{\hbar c}\right) = \sin^2\left(1.267\frac{L[km]}{E_\nu[GeV]}\Delta m_{ij}^2[eV^2]\right)$$



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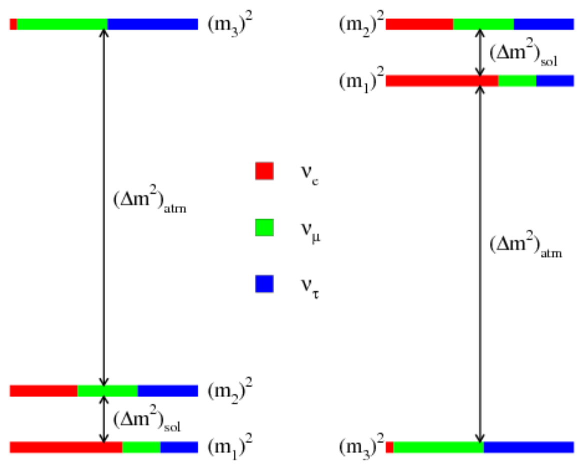
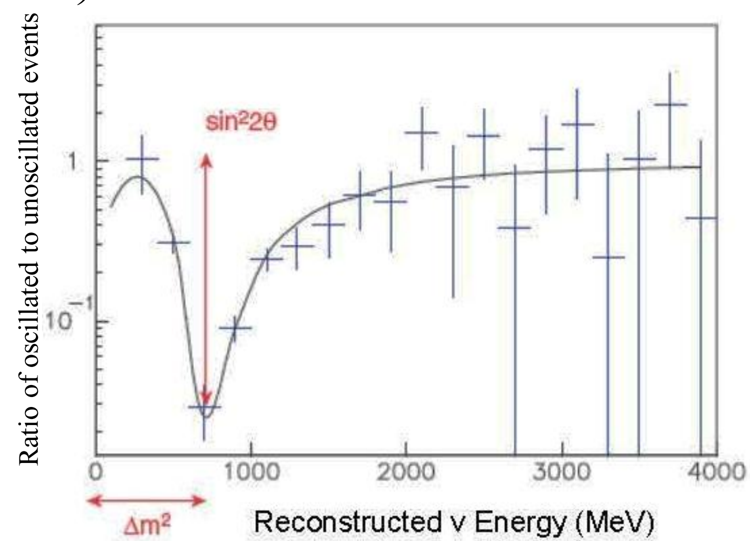


normal hierarchy   inverted hierarchy



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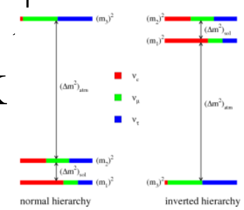
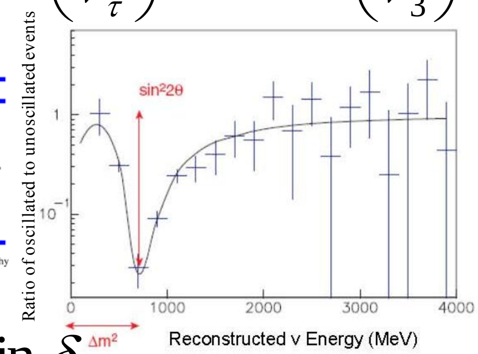
- T2K ν_e Appearance $\rightarrow$ see Helen's talk





$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{23}\sin^2\theta_{13}s^2\Delta_{32}$$

$$-\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin 2\theta_{12}s^2\Delta_{13}s^2\Delta_{12}\sin\delta_{CP}$$

$$+\text{(CPC terms, matter terms, ...)}$$

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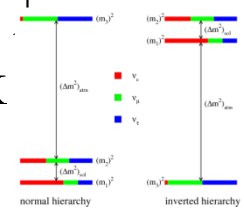

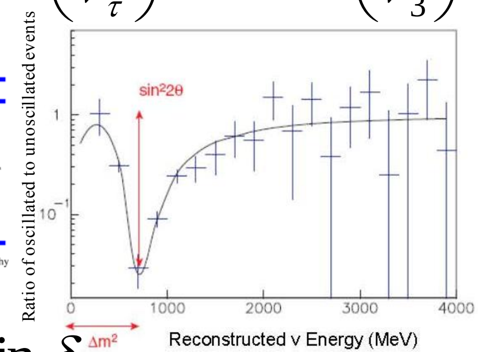

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$$+\,(\text{CPC terms, matter terms, ... })$$

- T2K is designed (and optimized) for both Appearance and Disappearance measurements

$$s^2\Delta_{23} = \sin^2\left(1.267\frac{L}{E_\nu}\Delta m_{ij}^2\right) = 1; \qquad \Delta m_{ij}^2 \approx 2.4\times10^3 eV^2; \quad L^{T2K} \cong 295\,km \quad \Rightarrow \quad E_\nu \cong 0.6\,GeV$$

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- **The T2K experiment**
- T2K Results
- T2K Anti-Nu Run
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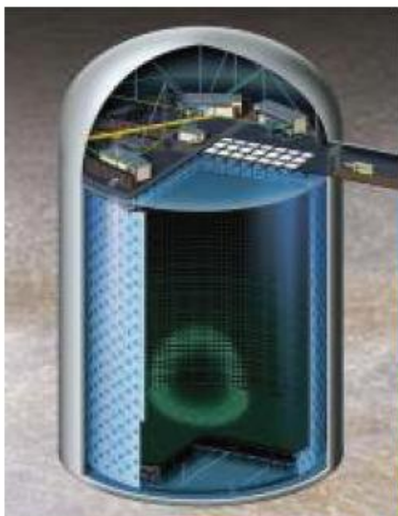
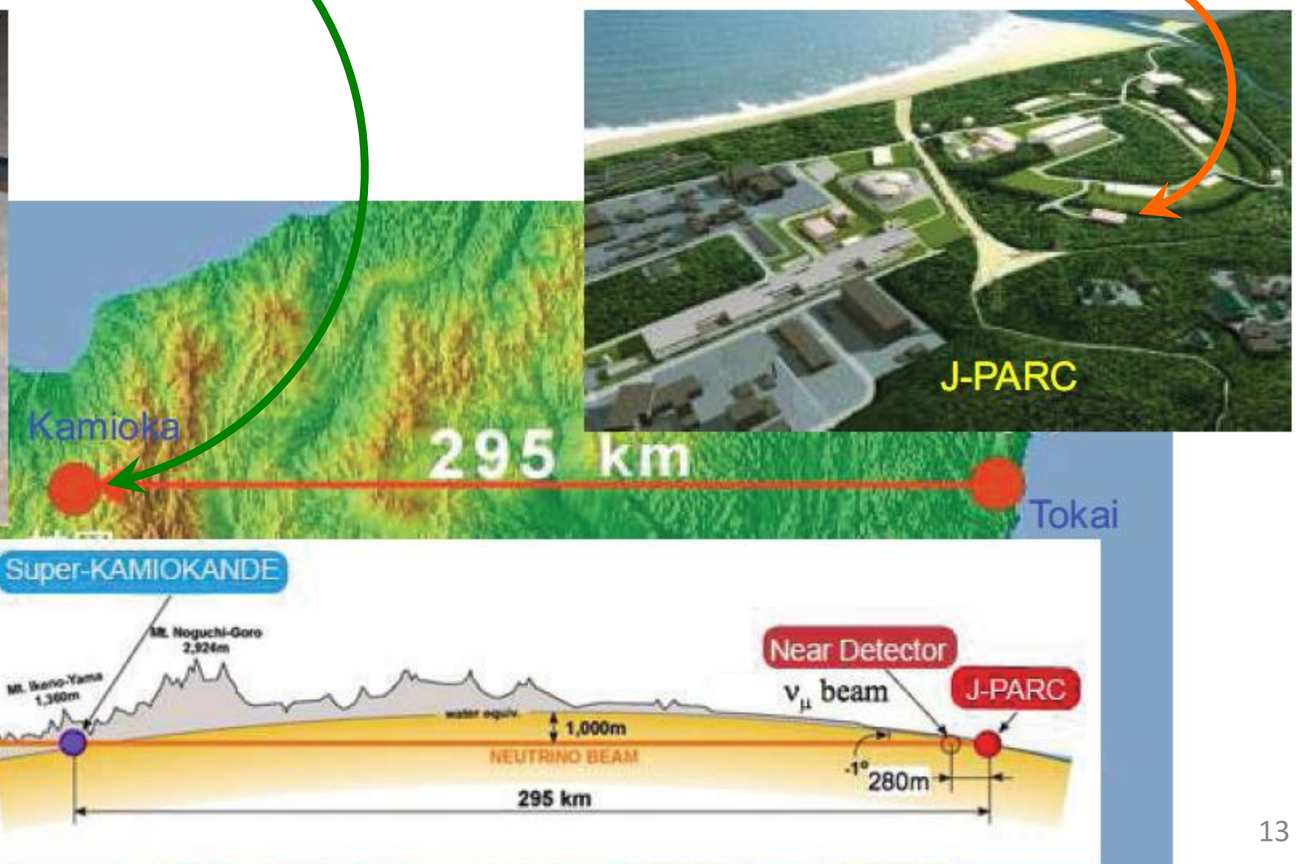
The T2K Experiment

- Tokai-to-Kamioka (T2K): Neutrino Oscillation experiment
  - Location: Japan
  - Baseline: ~295 km
  - Far Detector: Super-Kamiokande
  - Beam: J-PARC Lab 30 GeV proton beam
    Designed to produce ~0.6 GeV ν_μ
  - Near Detectors: In J-PARC campus

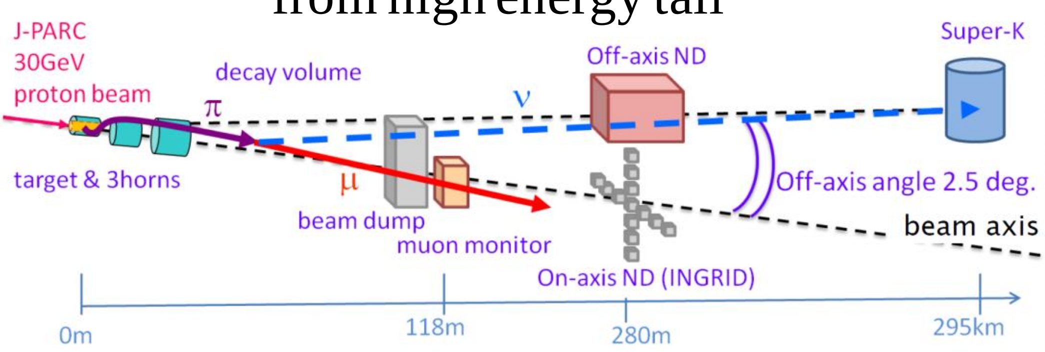


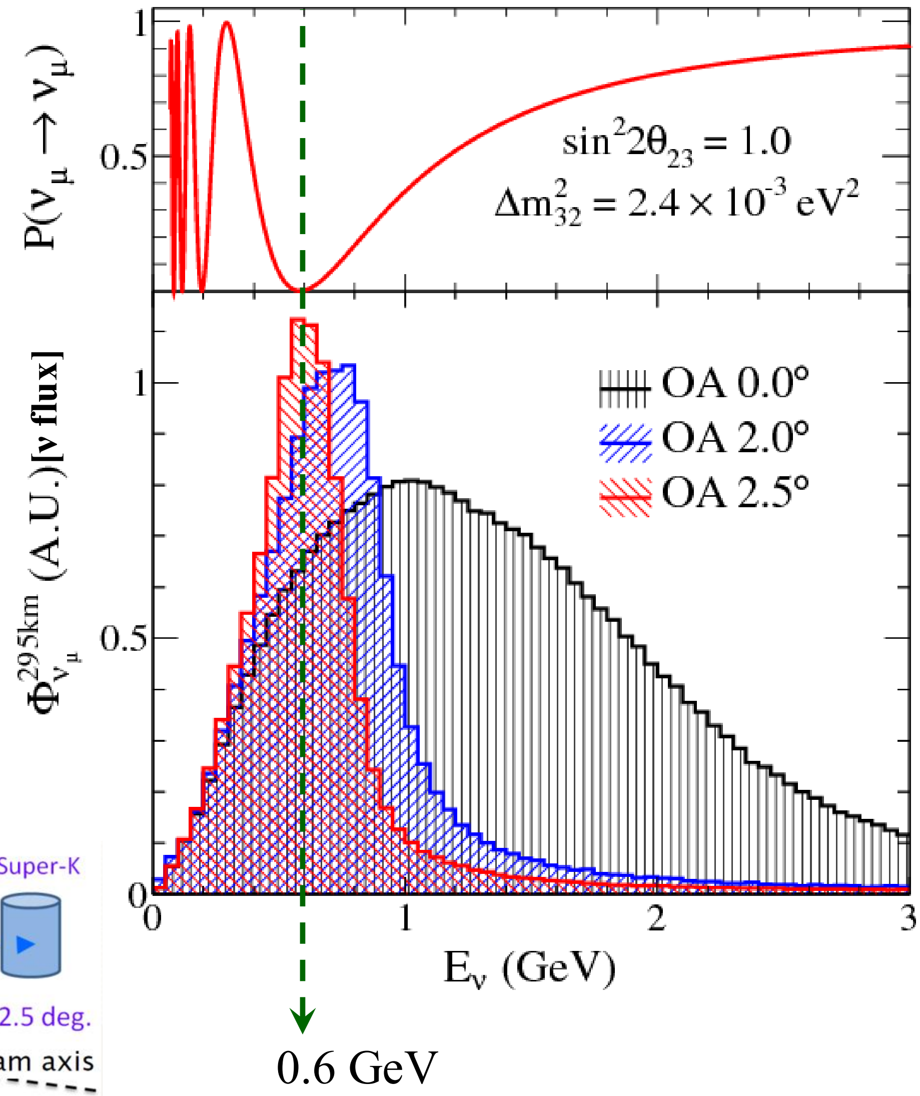


T2K Main Properties

- Survival probability at T2K Far Detector (FD)
  Maximum: $P(\nu_\mu \rightarrow \nu_e)$
  Minimum: $P(\nu_\mu \rightarrow \nu_\mu)$

- Off-axis experiment
- Beam is aimed 2.5^0 off the direction to the Super-K (FD)
  - Narrow-band ν beam
  - Reduce background from high energy tail





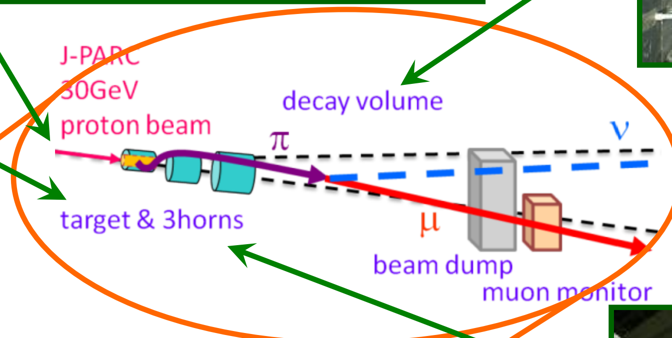
T2K Beam-Target Setup

- J-PARC Lab

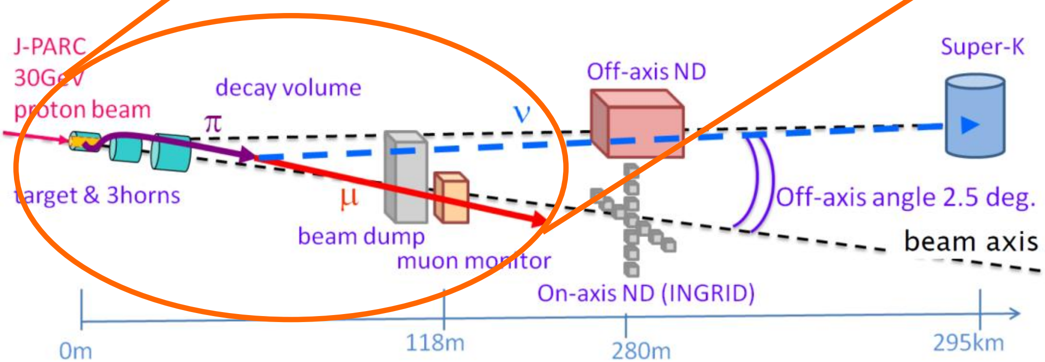
Accelerator Main Ring

Decay pipe

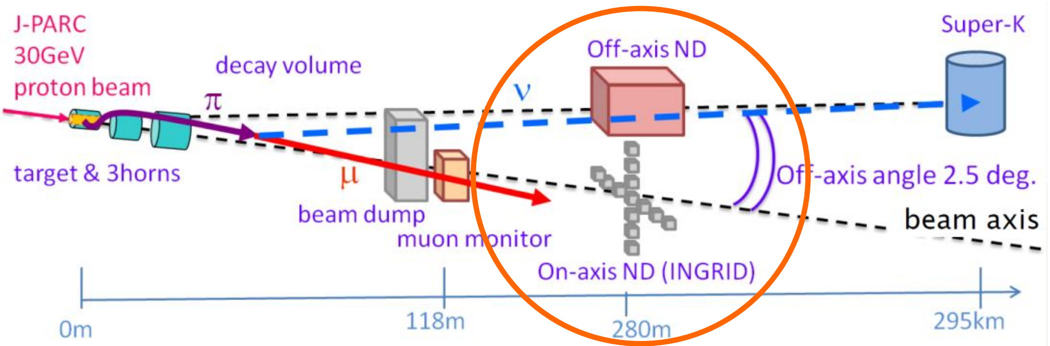
T2K graphite target



T2K horn 1

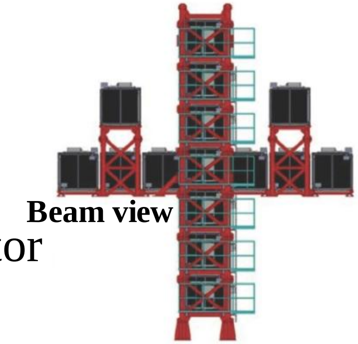


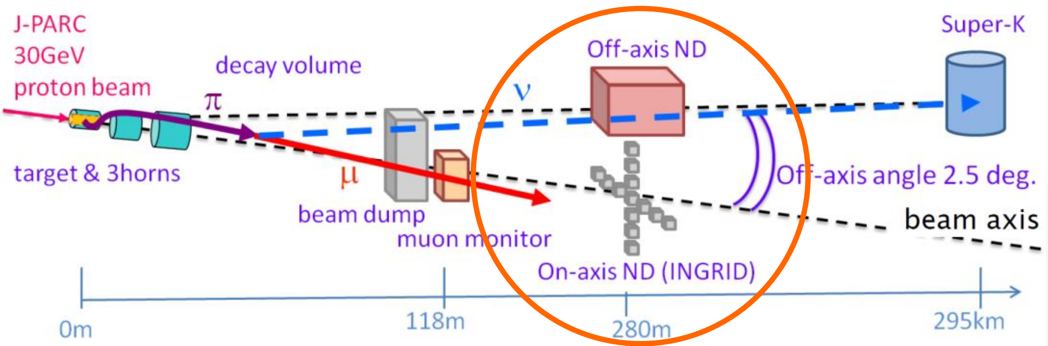
T2K Near Detectors



T2K Near Detectors

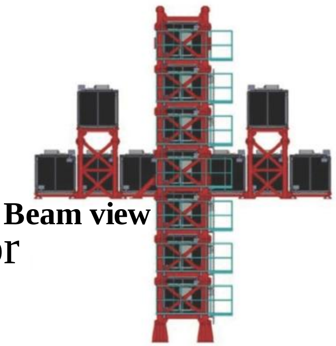
- On-Axis:
  - INGRID
    - 16 Modules of Iron and Scintillator

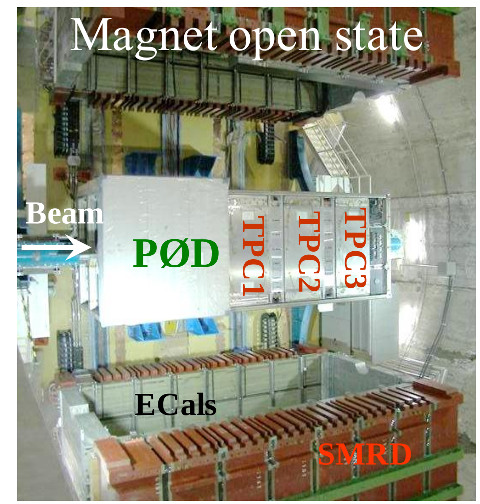


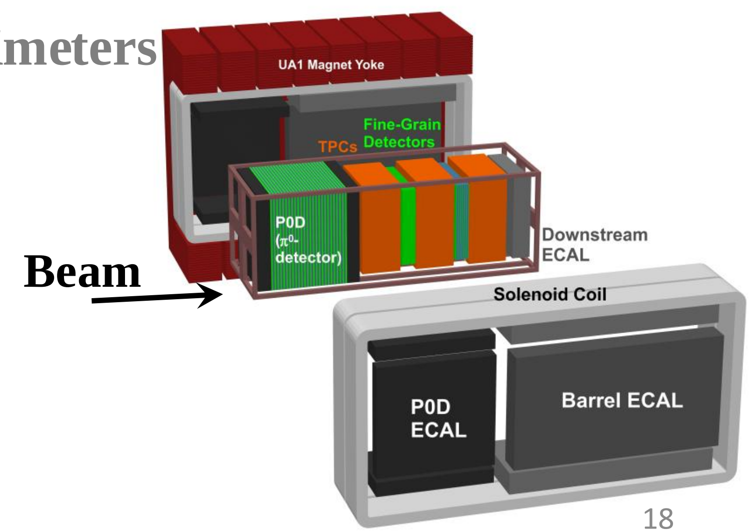


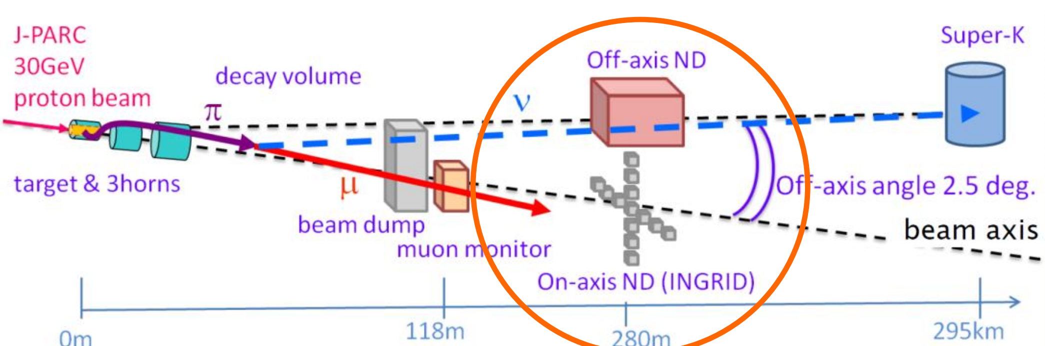
T2K Near Detectors

- On-Axis:
  - INGRID
    - 16 Modules of Iron and Scintillator
- Off-Axis (ND280):
  - Pi-Zero Detector (**PØD**)
  - Tracker
    - 3 Time Projection Chambers (**TPC**)
    - 2 Fine Grain Detectors (**FGD**)
  - Surrounded by **Electromagnetic Calorimeters**
  - Housed inside the **Magnet** of the UA1



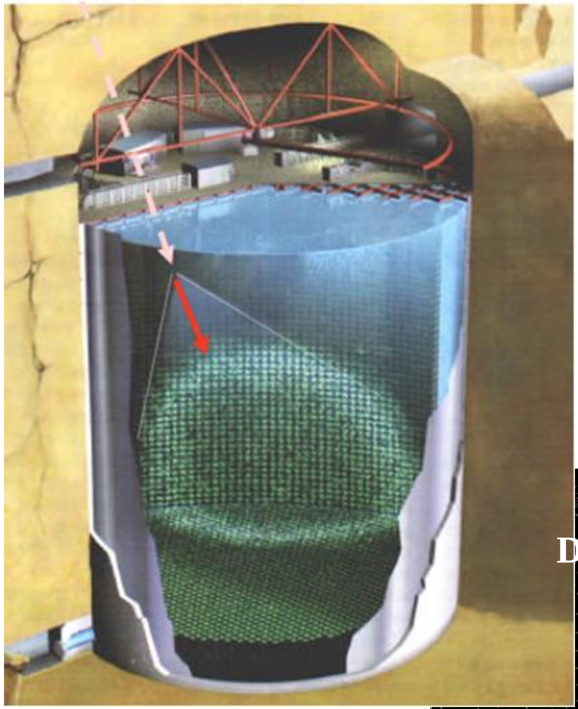


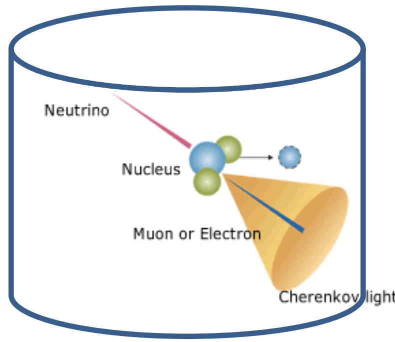


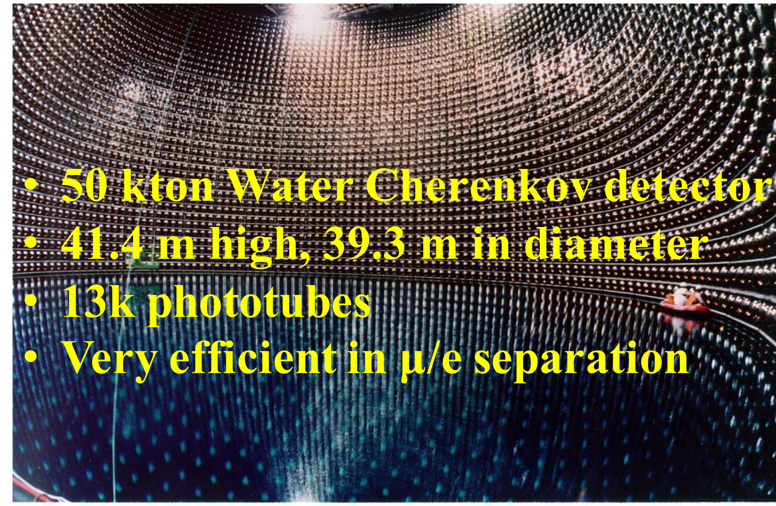


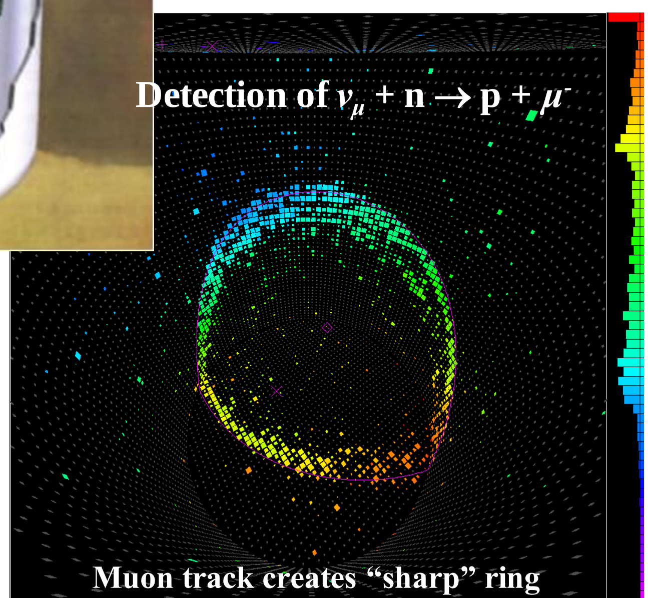
T2K Far Detector

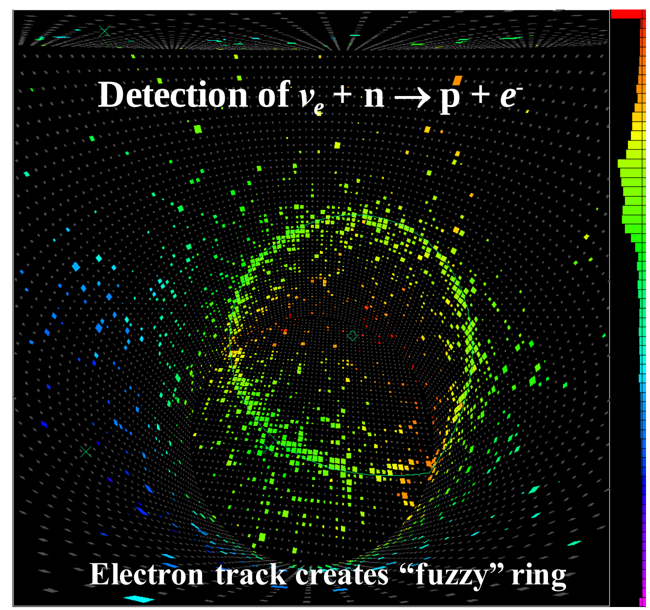
- Super-Kamiokande (SK)











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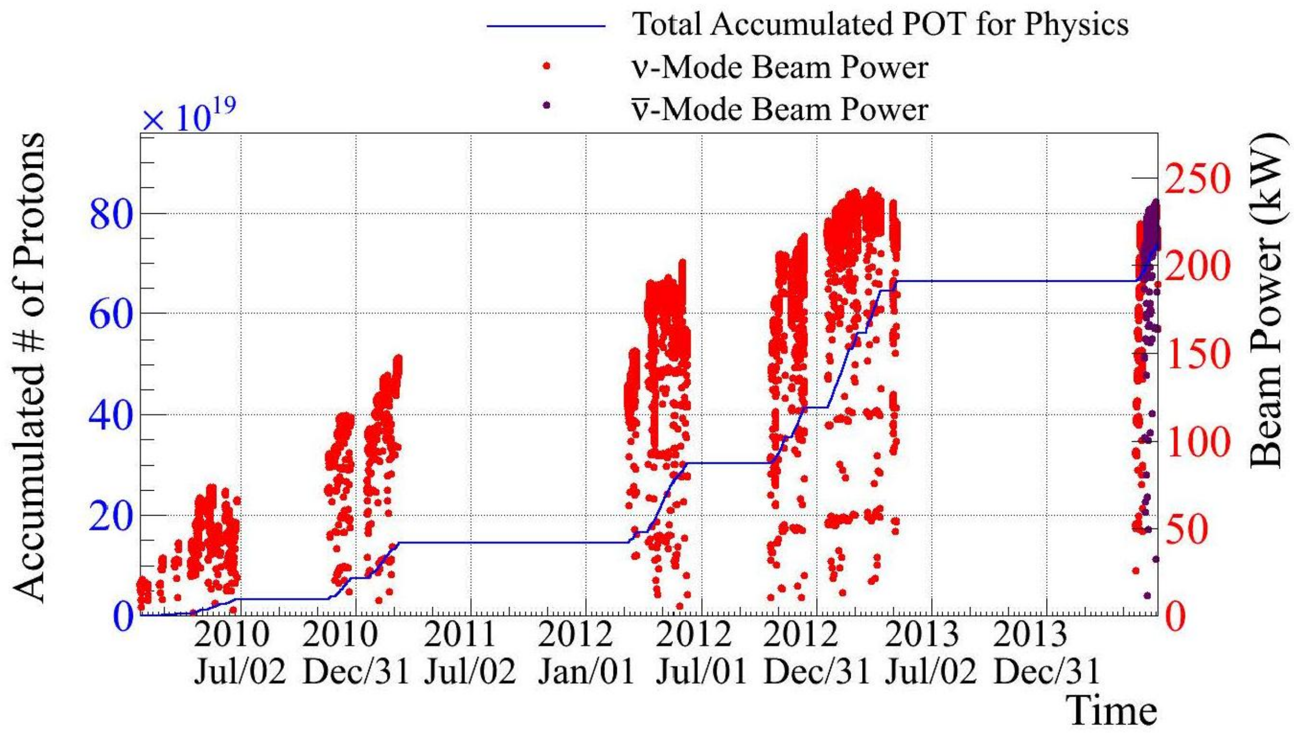
T2K Results: J-PARC/Beam

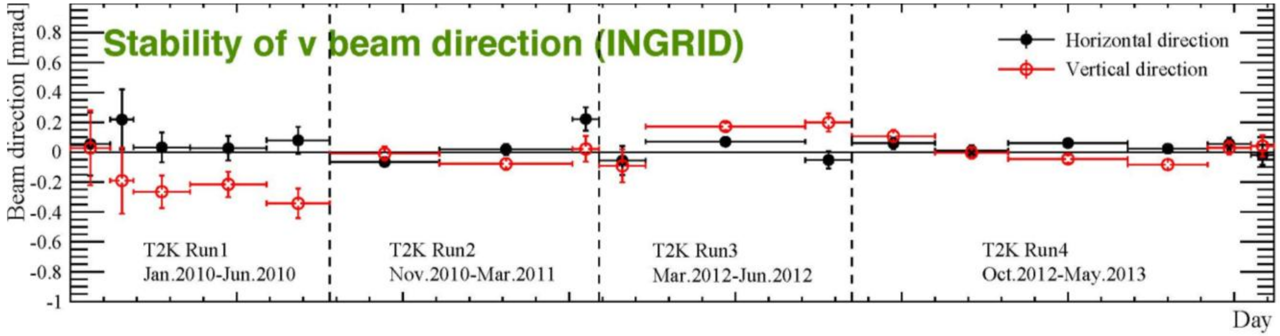
- Protons-On-Target (POT) for T2K Runs 1-5



- Integrated nu beam mode: ~6.9x10^{20} POT
- Integrated anti-nu beam mode:~0.5x10^{20} POT

T2K Results: Near Detectors

- On-Axis (INGRID):
  - Monitor beam direction stability



T2K Results: Near Detectors

- On-Axis (INGRID):
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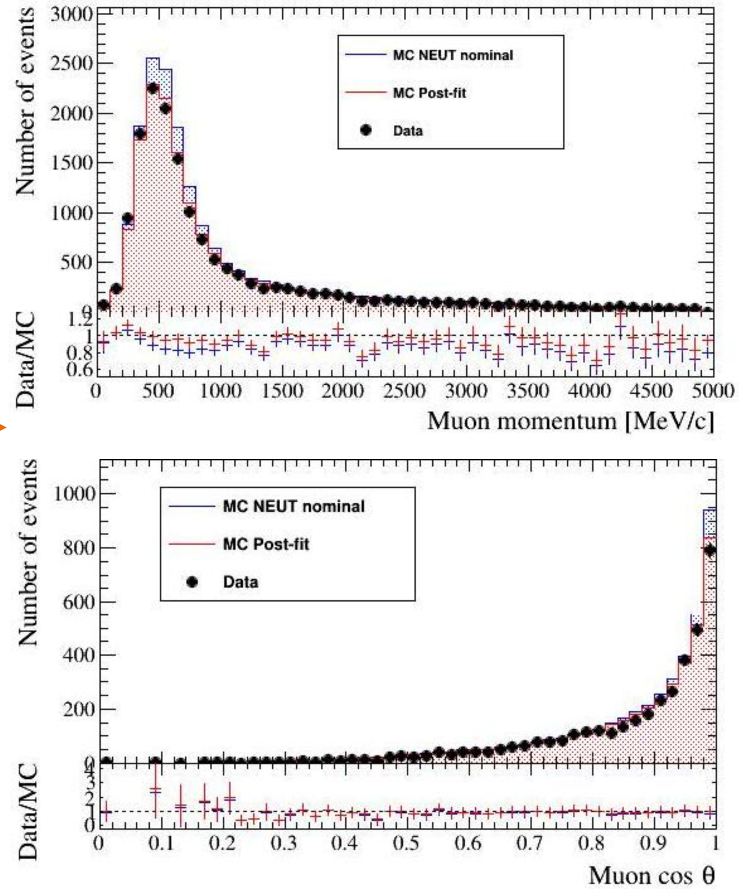
- Off-Axis (ND280):
  - Constrains Flux ⊗ Cross Section
    - Use different topology samples
      - Measure properties like momentum, angle and position which then are used to constraint our MC simulations to a better degree



See Jon's talk for more details

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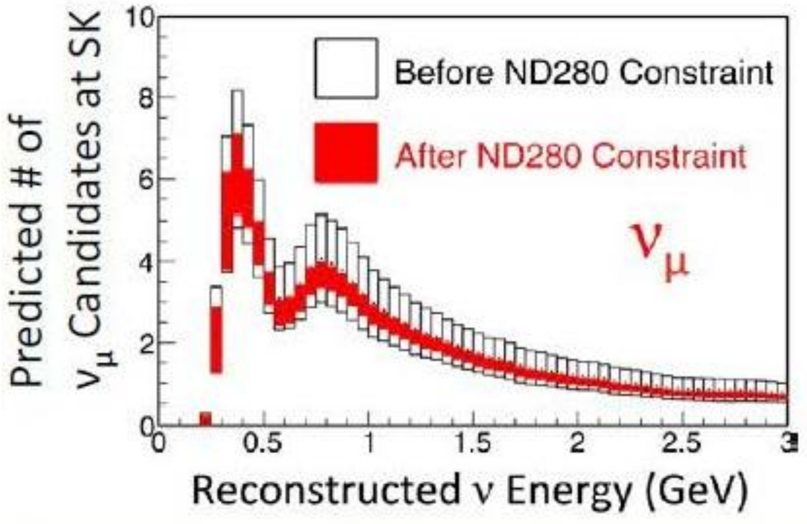
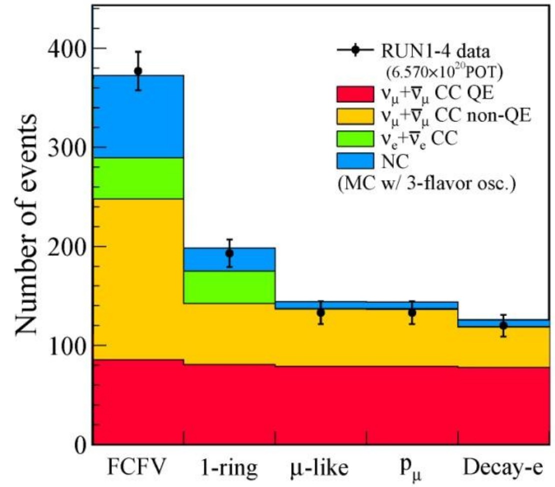
    - Total uncertainty reduction @ the FD

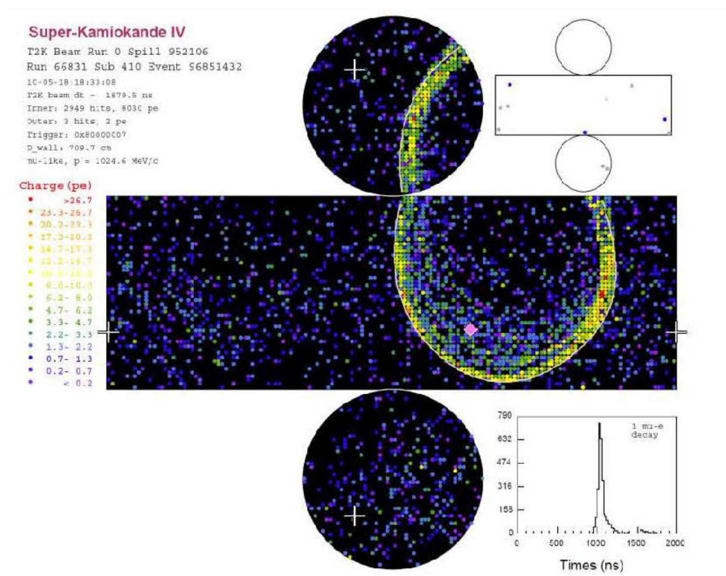
ν_μ Disappearance



T2K Results: ν_μ Disappearance

- SK Event Selection:
  - Fully Contained in Fiducial Volume (FCFV) and in-time with beam
  - 1-Ring
  - Muon-like PID
  - $p_\mu > 200$ MeV
  - ≤ 1 Decay electron
- <u>Observed</u>: 120 muon-like events





Phys. Rev. Lett. 112, 181801 (2014)

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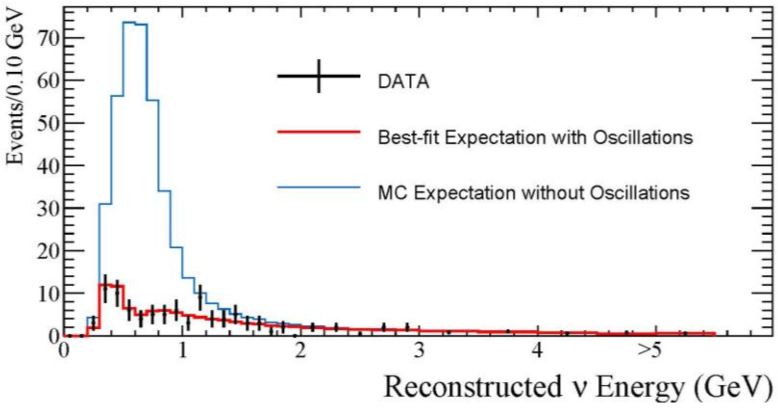
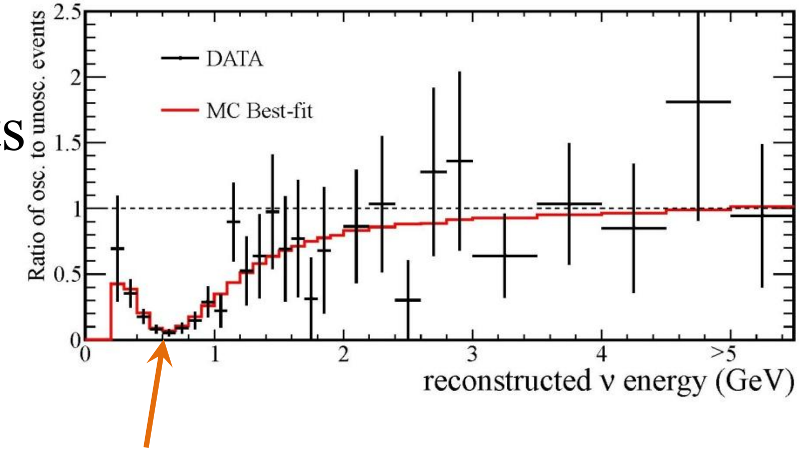
- Observed: 120 muon-like events
- MC expectation: 446.0 ± 22.5 events (without oscillations)



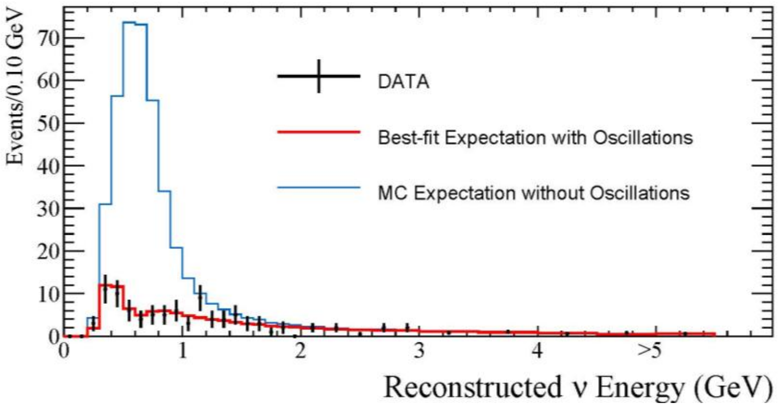


- Shows the power of the off-axis technique, $P(\nu_\mu \rightarrow \nu_\mu) \approx 0$@E$\nu$=0.6GeV

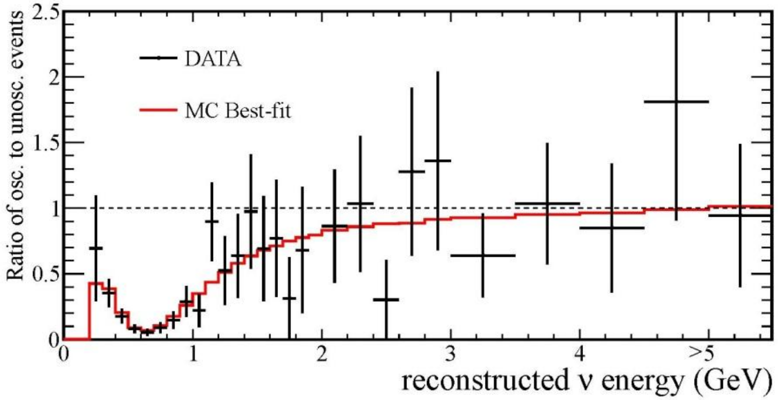
Phys. Rev. Lett. 112, 181801 (2014)

T2K Results: ν_μ Disappearance

- The Oscillation fit
  - Full three-flavor oscillation framework
  - Parameters constrained by 2012-2013 PDG values and errors
    - $\sin^2\theta_{13} = 0.0251 \pm 0.0035$
    - $\sin^2\theta_{12} = 0.312 \pm 0.016$
    - $\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}\,\mathrm{eV}^2$
  - 45 nuisance fit parameters, uncertainties 0.2%-5.6%



Source of uncertainty (number of parameters)	$\delta n_{\mathrm{SK}}^{\mathrm{exp}}/n_{\mathrm{SK}}^{\mathrm{exp}}$
ND280-independent cross section (11)	4.9%
Flux and ND280-common cross section (23)	2.7%
SK detector and FSI + SI systematics (7)	5.6%
$\sin^2(\theta_{13})$, $\sin^2(\theta_{12})$, Δm^2_{21}, δ_{CP} (4)	0.2%
Total (45)	8.1%



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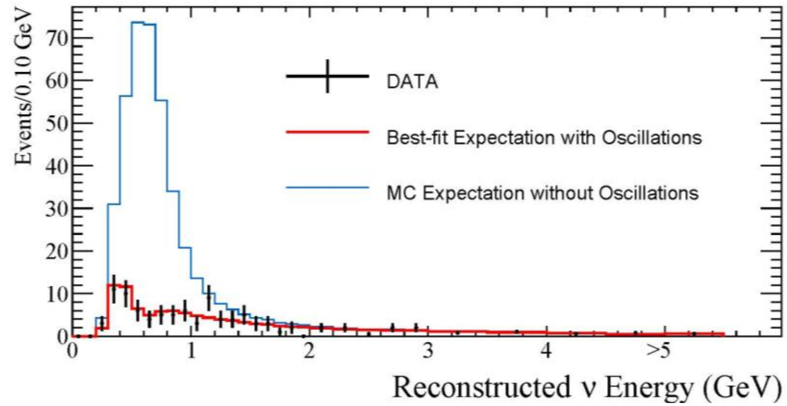

- The best-fit

	Oscillation Parameters	Value ± 68% CL
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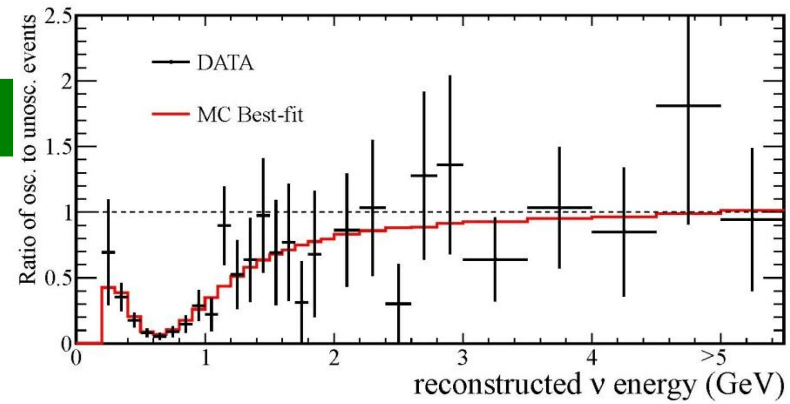
	$\Delta m^2_{23}\,[\times 10^{-3}\,\mathrm{eV}^2]$	2.51 ± 0.10



- Currently most precise measurement of θ_{23}!

Phys. Rev. Lett. 112, 181801 (2014)

T2K Results: ν_μ Disappearance

- The Oscillation fit
  - Full three-flavor oscillation framework
  - Parameters constrained by 2012-2013 PDG values and errors
    - $\sin^2\theta_{13} = 0.0251 \pm 0.0035$
    - $\sin^2\theta_{12} = 0.312 \pm 0.016$
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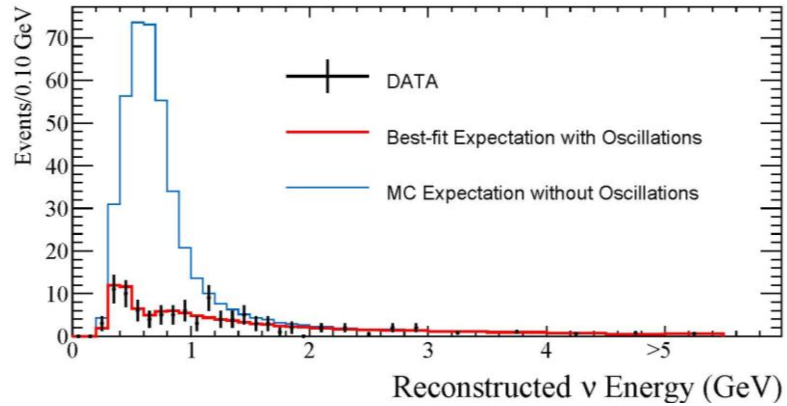

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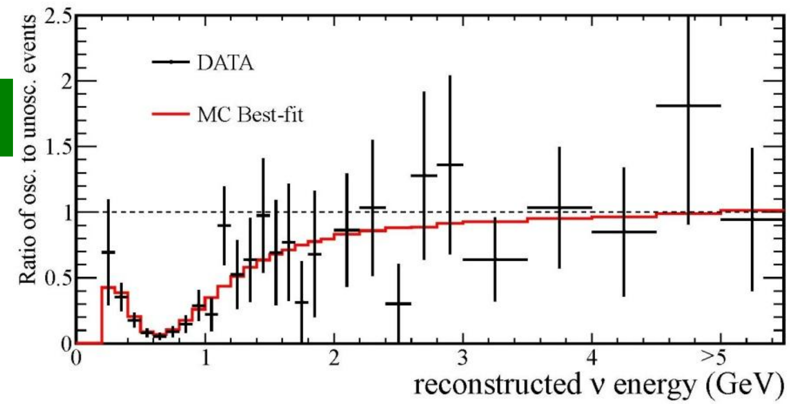

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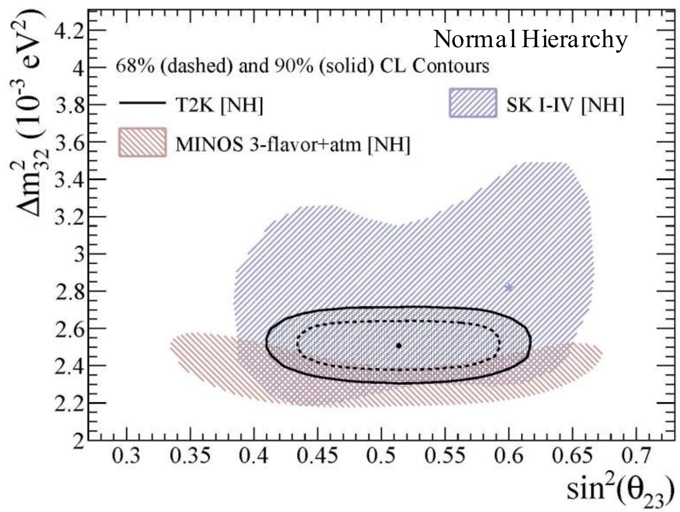
Phys. Rev. Lett. 112, 181801 (2014)

T2K Results: ν_μ Disappearance

- Comparison with other disappearance results
  - SK Atmospheric Runs I-IV
  - MINOS 3-flavor+Atm
  - T2K is more sensitive to ϑ_{23} while MINOS is more sensitive to Δm^2
  - Consistent with maximal mixing
    - Is it equal or not to maximal?



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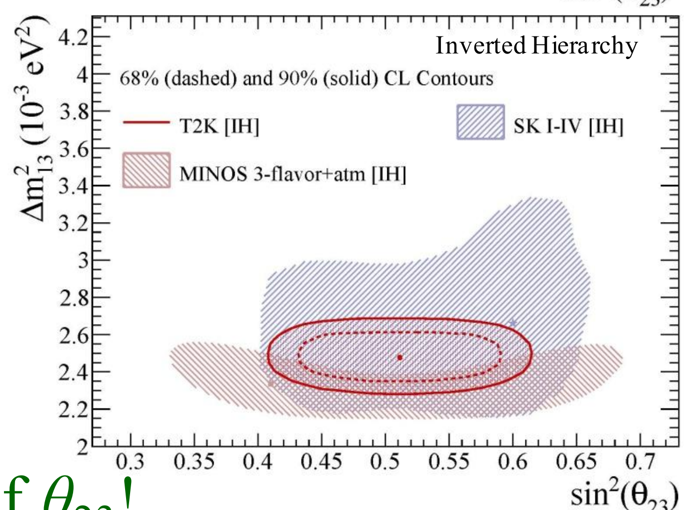

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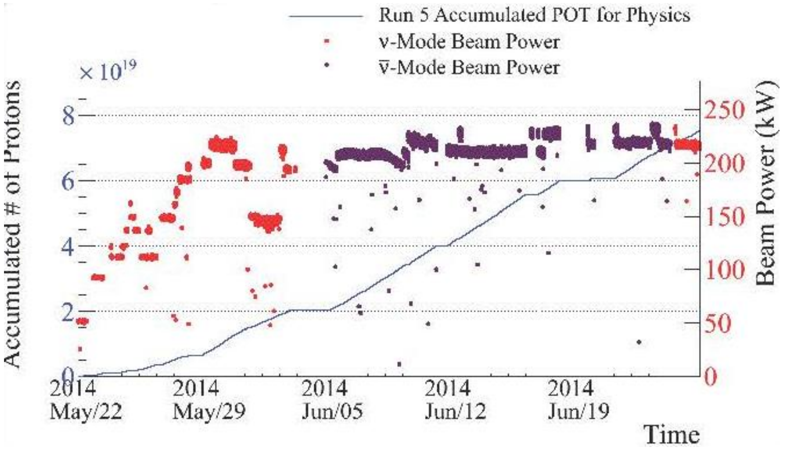
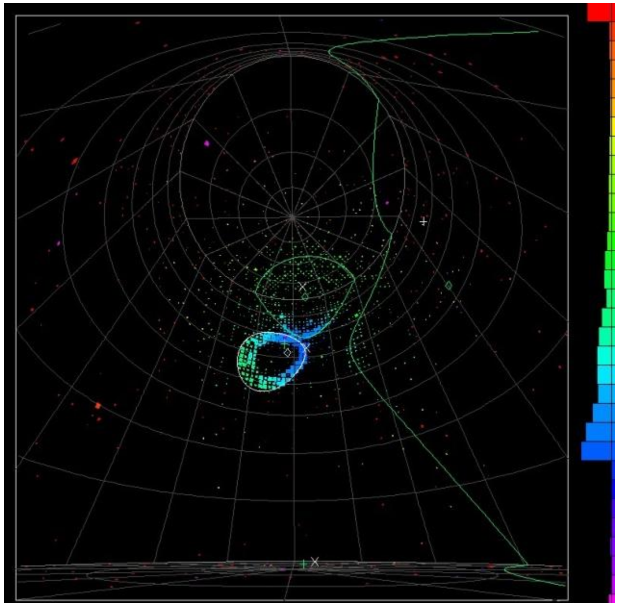
Phys. Rev. Lett. 112, 181801 (2014)

T2K: Anti-Nu Run

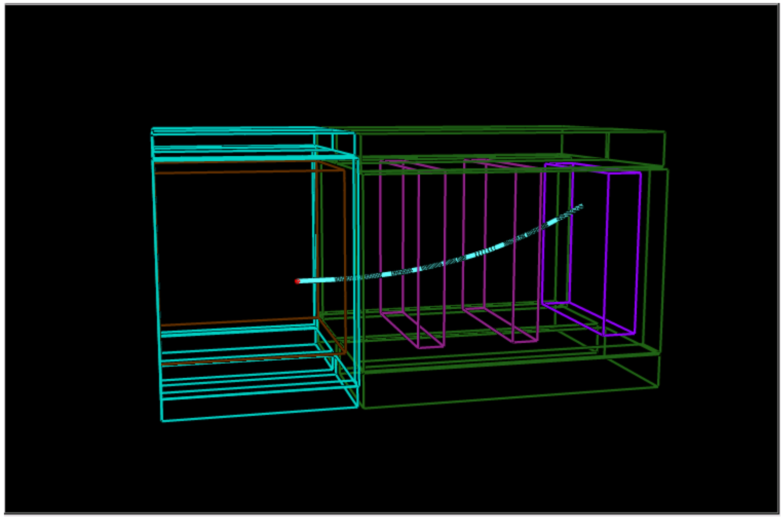
- T2K Run 5: 1st Anti-Nu run
  - Anti-nu beam mode ~0.5x10^{20} POT
  - Nu beam mode ~0.2x10^{20} POT
- Event displays



T2K Far Detector



T2K Near Detector



- T2K aims to make an anti-nu disappearance measurement

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  - Utilized the full three-flavor framework

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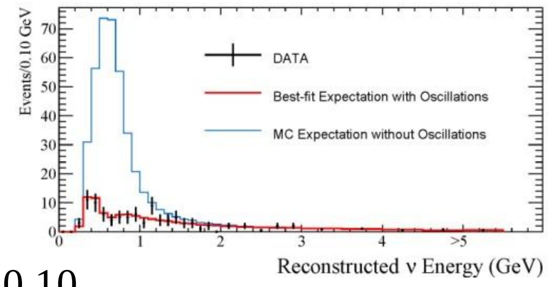

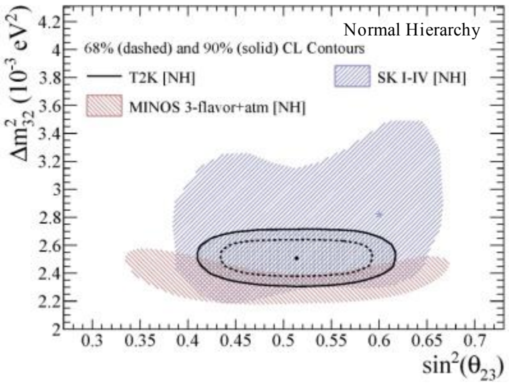

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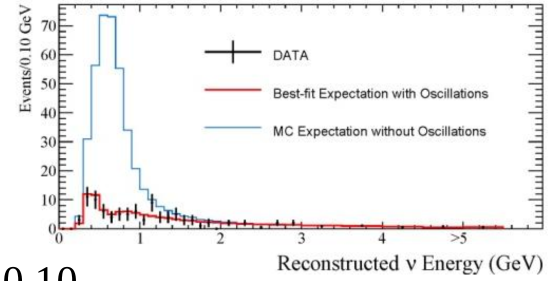

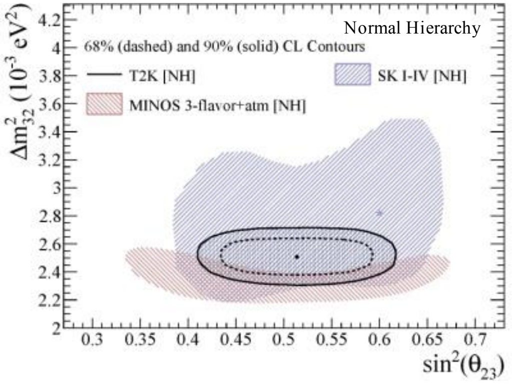

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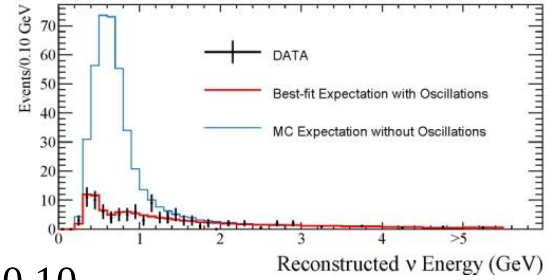

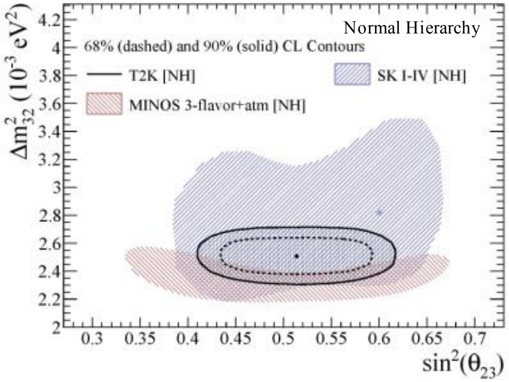

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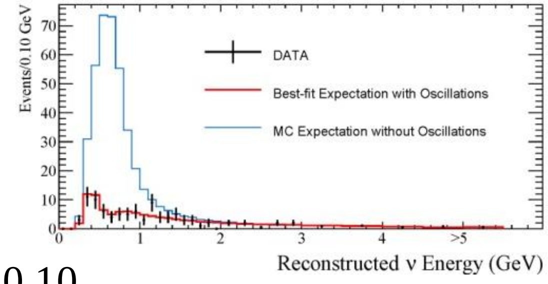
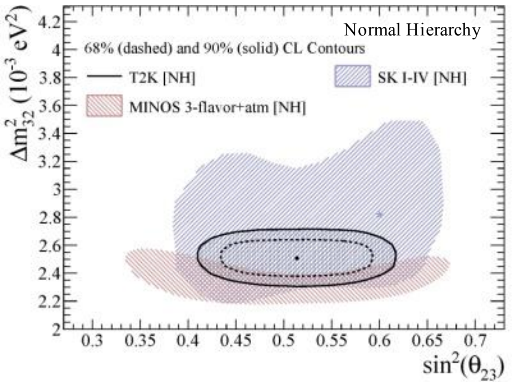
  - Goal: Anti-nu disappearance measurement





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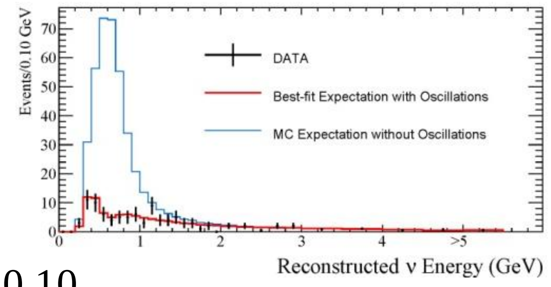

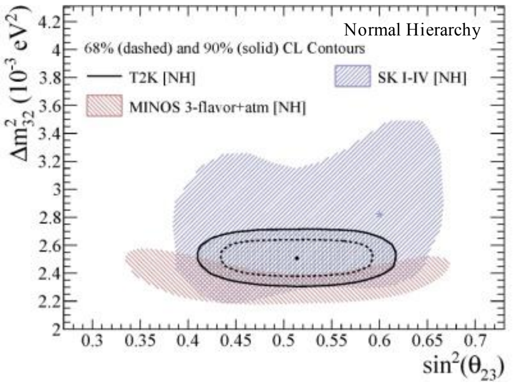

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- More T2K interesting results:
  - ν_e Appearance and joint fits - next talk by Helen
  - Near Detectors measurements - later talk by Jon

Precision Measurement of Muon Neutrino Disappearance by T2K

Erez Reinherz-Aronis

for the T2K Collaboration

Colorado State University

PAINC 2014

Hamburg, Germany

Additional material

Additional material

- From where do we have 1.267 in $\sin^2(1.267\Delta m^2 L/E_\nu)$?
  - The full version of the term is $\sin^2(\Delta m^2 L/(4E_\nu))$
  - To make the sin unitless one needs to add $1/\hbar c$ to the sin: $\sin(\Delta m^2 L/(4E_\nu \hbar c)) \rightarrow \sin(1.267\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]/E_\nu[\mathrm{GeV}])$

T2K Collaboration

~500 members (337 authers), 59 institutes, 11 counters

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

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
U. Aachen

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Metro U.
U. Tokyo

Spain
IFIC, Valencia
IFAE, Barcelona

Poland
NCBJ, Warsaw
IFJ PAN, Cracow
T. U. Warsaw
U. Silesia, Katowice
U. Warsaw
U. Wroklaw

Switzerland
ETH Zurich
U. Bern
U. Geneva

Russia
INR

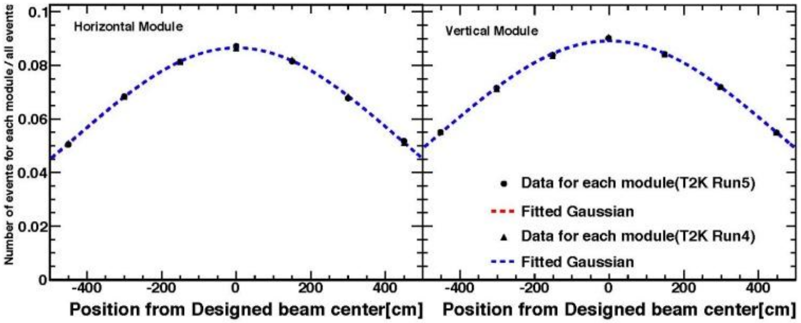
USA
Boston U.
Colorado S. U.
U. Colorado
Duke U.
U. C. Irvine
Louisiana S. U.
U. Pittsburgh
U. Rochester
Stony Brook U.
U. Washington

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

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

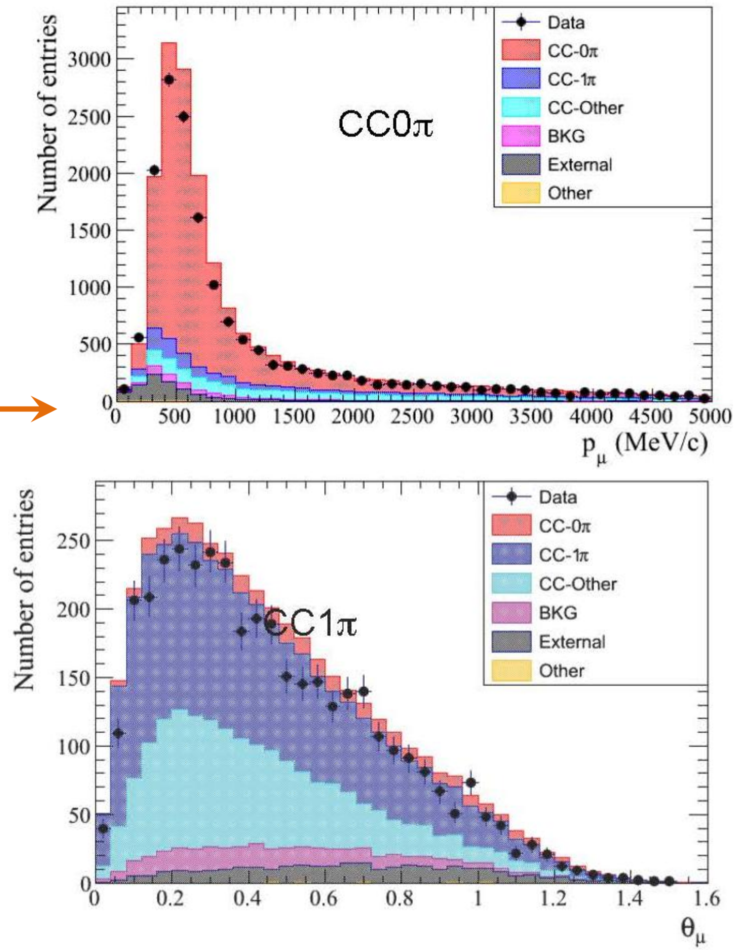
T2K Results: Near Detectors

- On-Axis:
  - Monitor beam direction stability



T2K Results: Near Detectors

- On-Axis:
  - Monitor beam direction stability
- Off-Axis (ND280):
  - Constrains on Flux ⊗ Cross Section
    - Use different topology samples
      - Measure parameters like momentum, angle and position which then are used to constrain our MC simulations to a better degree



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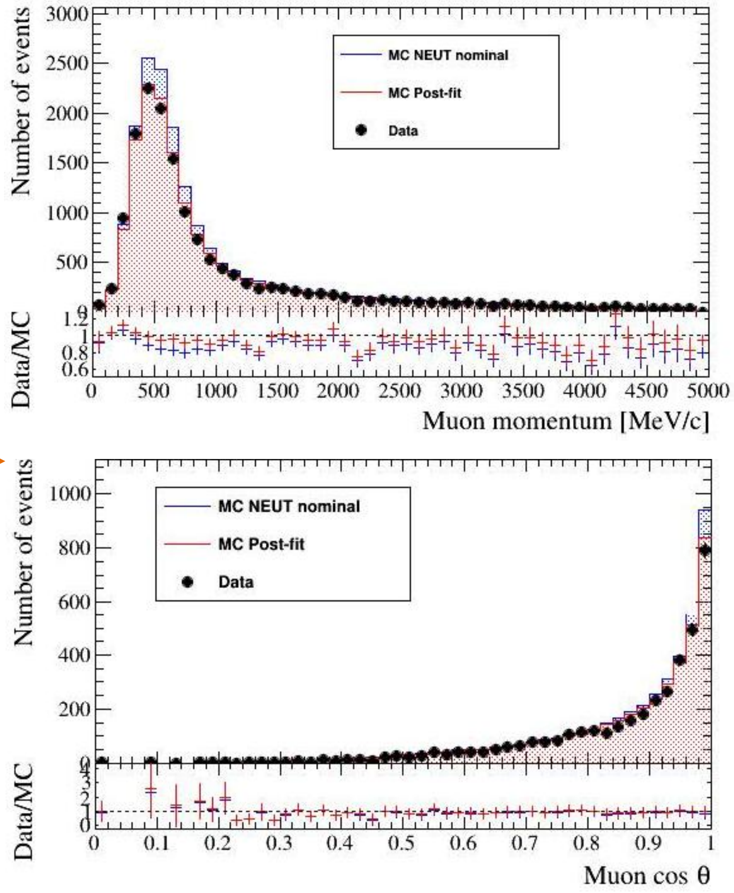

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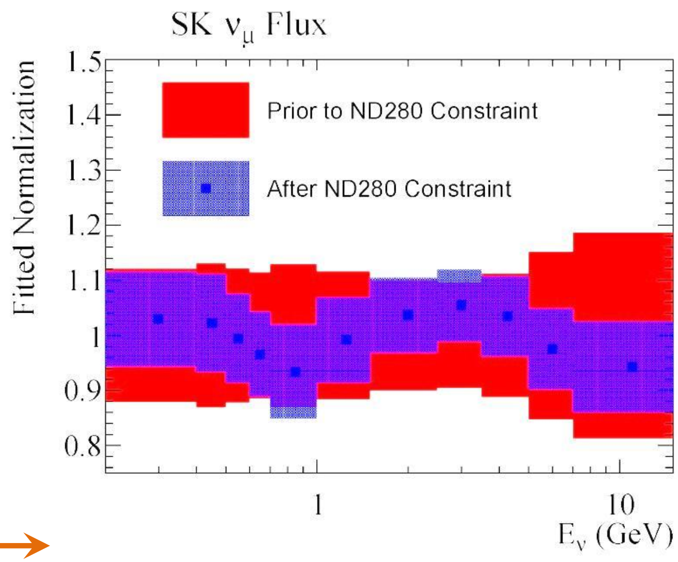

Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.240 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.965 ± 0.068
CCQE Norm. E_ν<1.5 GeV	1.00 ± 0.11	0.966 ± 0.076
CCQE Norm. 1.5<E_ν<3.5 GeV	1.00 ± 0.30	0.93 ± 0.10
CCQE Norm. E_ν>3.5 GeV	1.00 ± 0.30	0.85 ± 0.11
CC1π Norm. E_ν<2.5 GeV	1.15 ± 0.32	1.26 ± 0.16
CC1π Norm. E_ν>2.5 GeV	1.00 ± 0.40	1.12 ± 0.17
NC1π^0 Norm.	0.96 ± 0.33	1.14 ± 0.25

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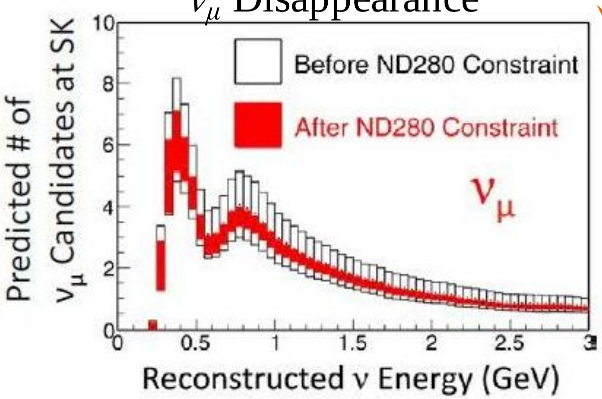
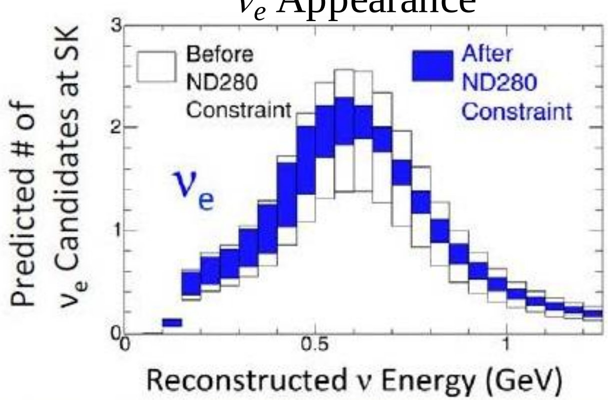
    - Total uncertainty reduction @ the FD

ν_μ Disappearance



ν_e Appearance

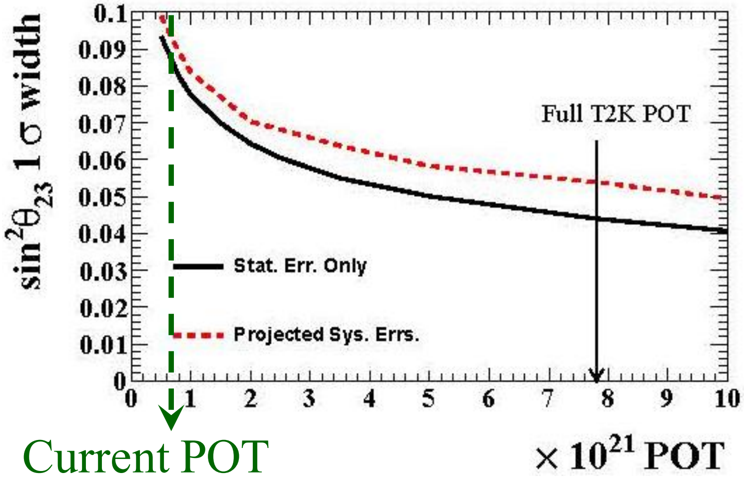


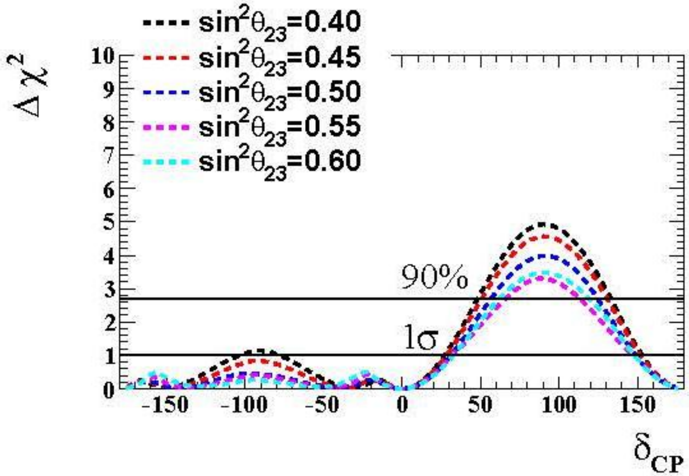
θ_{23} Outlook for T2K

- Reminder: T2K ν_e Appearance

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{23} \sin^2 \theta_{13} s^2\Delta_{32}$$
$$-\sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{12} s^2\Delta_{13} s^2\Delta_{12} \sin\delta_{CP}$$
$$+ (\text{CPC terms, matter terms, ... })$$

- T2K expected sensitivity for θ_{23}





- Effect on future δ_{CP} measurement
- For more details and results please see Helen's talk