New results from T2K

A. Minamino (Kyoto Univ.)
on behalf of the T2K collaboration

KEK seminar

Feb. 18, 2014

Neutrino oscillation

Neutrino Mixing

Flavor States

Note: $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

Mass States

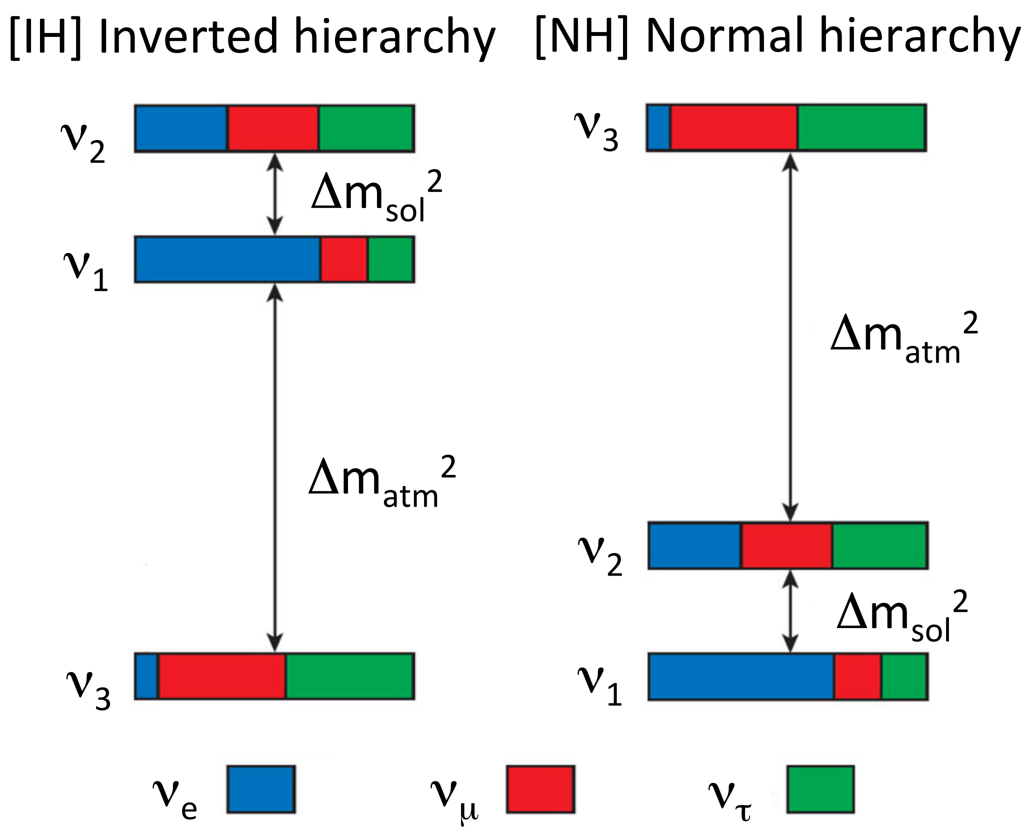
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Atmospheric ν"	"Reactor/Acc. ν"	"Solar/reactor ν"	Majorana phases;
$\sin^2 2\theta_{23} > 0.95$ (90% C.L.)	$\sin^2 2\theta_{13} = 0.098 \pm 0.013$	$\sin^2 2\theta_{12} = 0.857 \pm 0.024$	Not yet observed

- **θ_{13} is now precisely known**, and relatively large
- Long-baseline experiments (T2K & NOνA) can **constrain δ_{CP}**
- However, **the large uncertainty on θ_{23}** is limiting the information that can be extracted from ν_e appearance measurements
- Precise measurements of **all the mixing angles** will be needed to maximize sensitivity to CP violation

Unknown sign of Δm^2_{32}

- Can be determined from matter effects, as is our knowledge that $\Delta m^2_{21} > 0$ from solar neutrinos



ν_μ disappearance

- ν_μ disappearance probability

T2K: L = 295 km, E_ν peaks at ~ 0.6 GeV -> $\sin^2\Delta_{solar}$ ~ 0, $\sin 2\Delta_{atm}$ ~ 0

$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \left(\underbrace{\cos^4\theta_{13}\cdot\sin^2 2\theta_{23}}_{\text{Leading-term}} + \underbrace{\sin^2 2\theta_{13}\cdot\sin^2\theta_{23}}_{\text{Next-to-leading}}\right)\cdot\sin^2\frac{\Delta m^2_{32}\cdot L}{4E}$$

Probability depends on $\sin^2 2\theta_{13}\cdot\sin^2\theta_{23}$ to second order

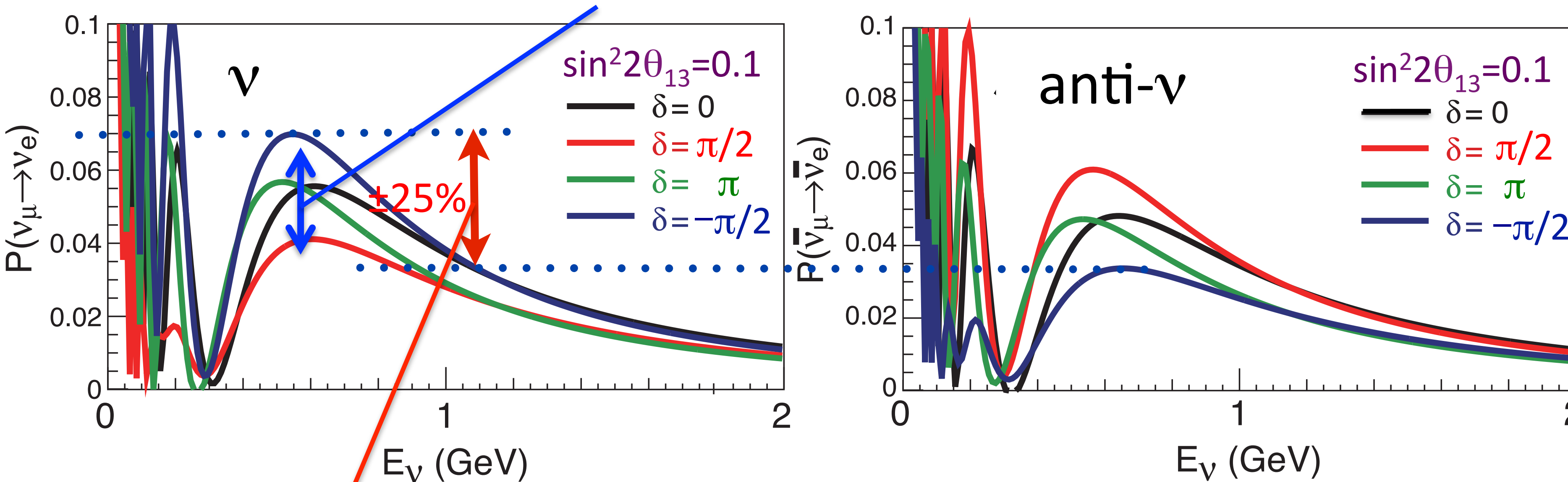
-> Therefore now fit for $\sin^2\theta_{23}$

-> Can be used to resolve the θ_{23} octant with known $\sin^2 2\theta_{13}$

ν_e appearance

- ν_e appearance probability

  δ_{CP} can be determined only from only ν run if θ_{13} is known from the reactor experiments.



Comparison of ν/anti-ν run enhances sensitivity to δ.
(T2K will have anti-ν test run in early 2014.)

- $\overline{\nu_e}$ disappearance probability (Reactor exp.: Baseline ~1km, Eν ~ 3MeV)

$$P\left[\overline{\nu_e} \rightarrow \overline{\nu_e}\right] \cong 1 - \boxed{\sin^2 2\theta_{13}} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

Simple 2 flavor oscillation formula is valid at L~1km w/ no matter effect

The T2K experiment

The T2K Collaboration

Canada
TRIUMF
U. Alberta
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 U.

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.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U. Tokyo

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

Russia
INR

~500 members, 59 Institutes, 11 countries

Spain
IFAE, Barcelona
IFIC, Valencia

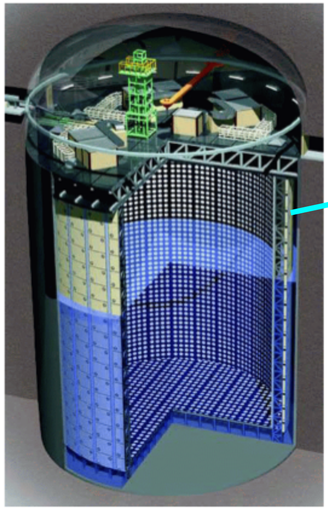
Switzerland
ETH Zurich
U. Bern
U. Geneva

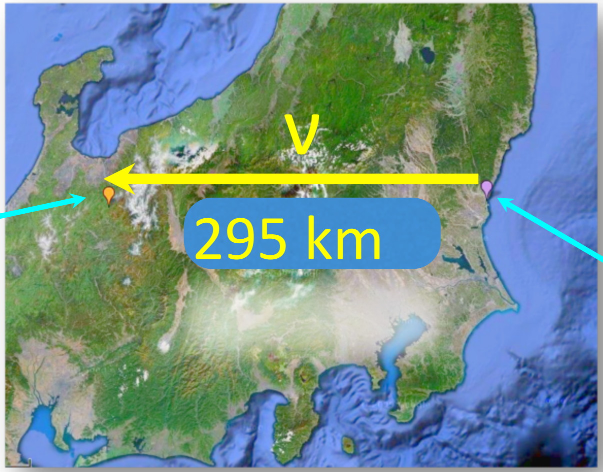
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

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

The T2K Experiment

Super-K Detector

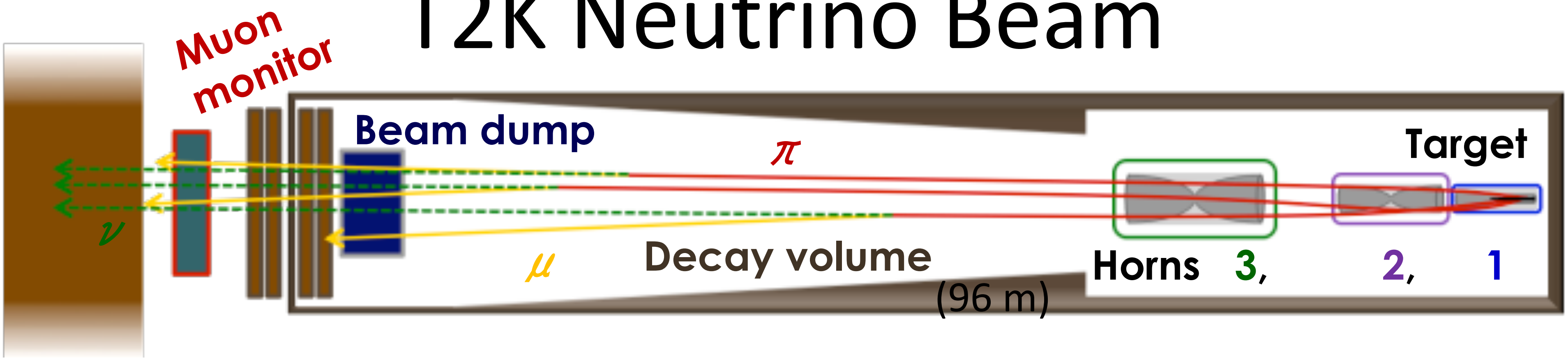




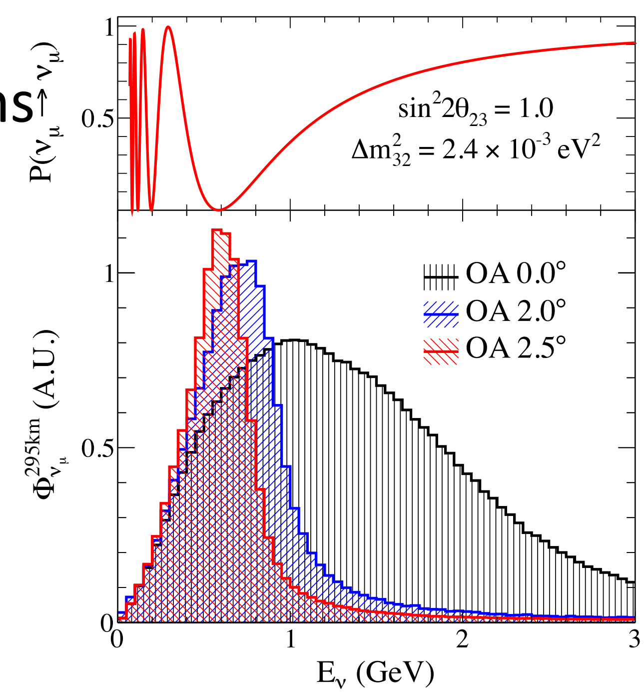
J-PARC Accelerator

- Searches for neutrino oscillations in a **high purity ν_μ beam**
  - Intrinsic beam ν_e from μ, K decays ~1%
- The neutrinos travel 295 km to the Super-K detector
  - ν_e appearance (sensitive to θ_{13} & δ_{CP})
  - ν_μ disappearance (sensitive to θ_{23} & Δm^2_{32})

T2K Neutrino Beam



- 30 GeV protons hit 90 cm graphite target
  - Profile/Intensity from SSEMs[*1]+OTR[*2]/CTs[*3]
- Three magnetic horns focus positive hadrons
  - ν_μ from π^+ decay
  - (small) ν_e contamination from μ and K decay
- 2.5 degree off-axis beam
  - Intense, low energy narrow-band beam
  - Peak E_ν tuned for oscillation max. (~0.6 GeV)
  - Reduce BG from high energy tail
  - First application to LBL experiment

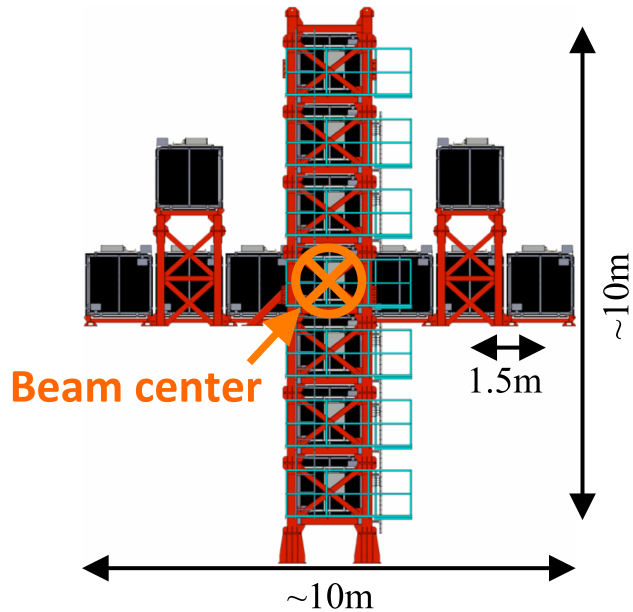


*1 SSEM: Segmented Secondary Emission Profile Monitor,
*2 OTR: Optical Transition Radiation monitor *3 CT: Current Transformer

Near Detectors

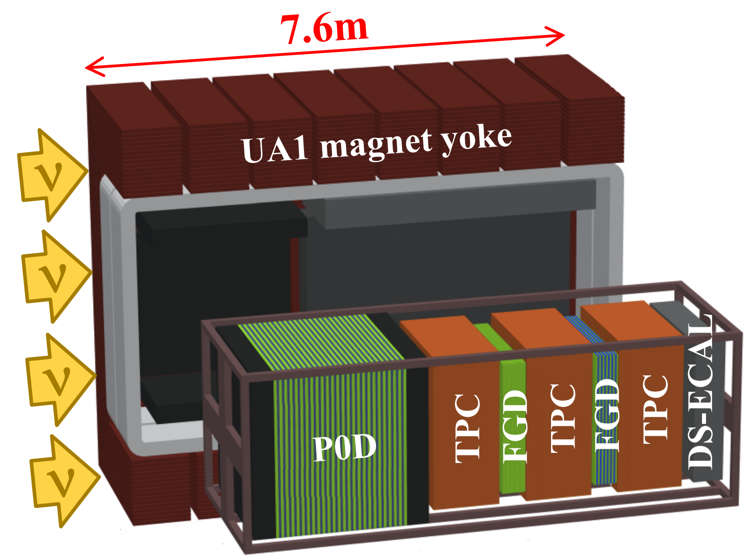
- Located 280 m downstream of the target
- Measure unoscillated neutrinos

INGRID @ on-axis (0°)



- 16 identical modules (14 in cross)
- Iron/scintillator layers
- Monitor ν beam profile/rate

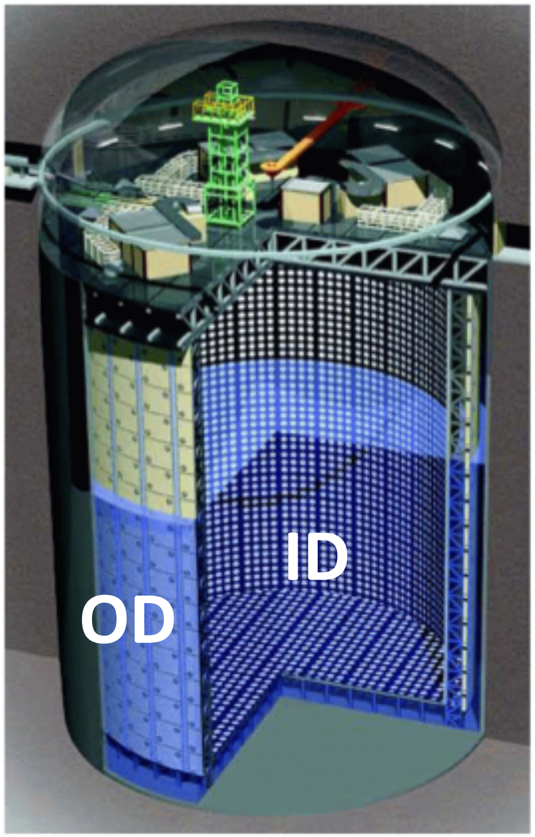
ND280 @ 2.5° off-axis



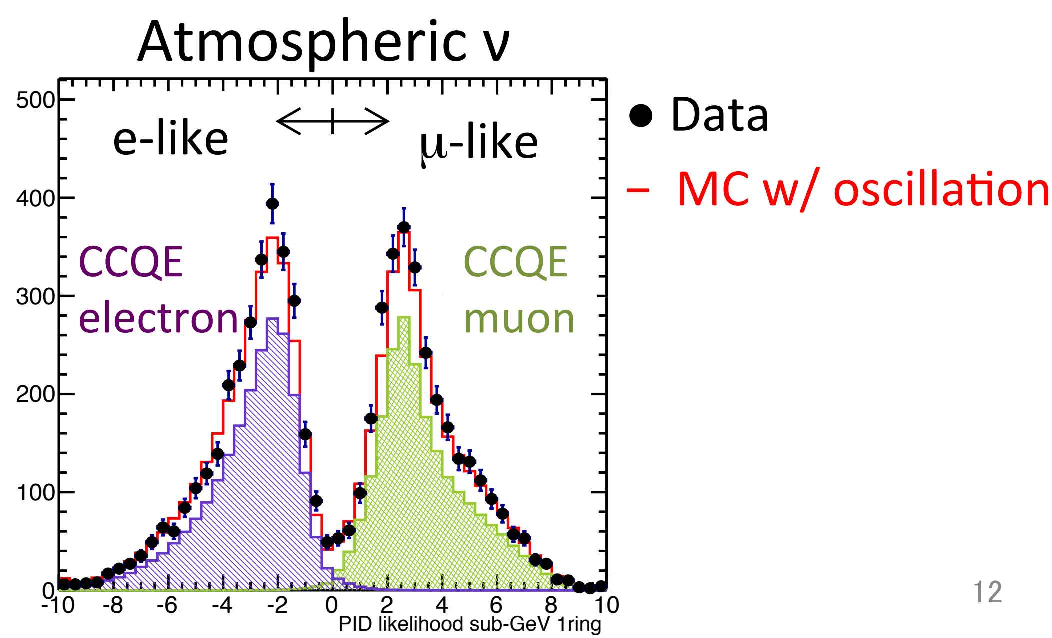
- Tracker (FGDs*1 + TPCs*2) in a 0.2 T magnet
- Principal ν target is plastic scinti. in FGDs
- Measures ν flux/spectrum

*1 FGD: Fine-Grained Detector, *2 TPC: Time Projection Chamber

Super-K (Far) Detector

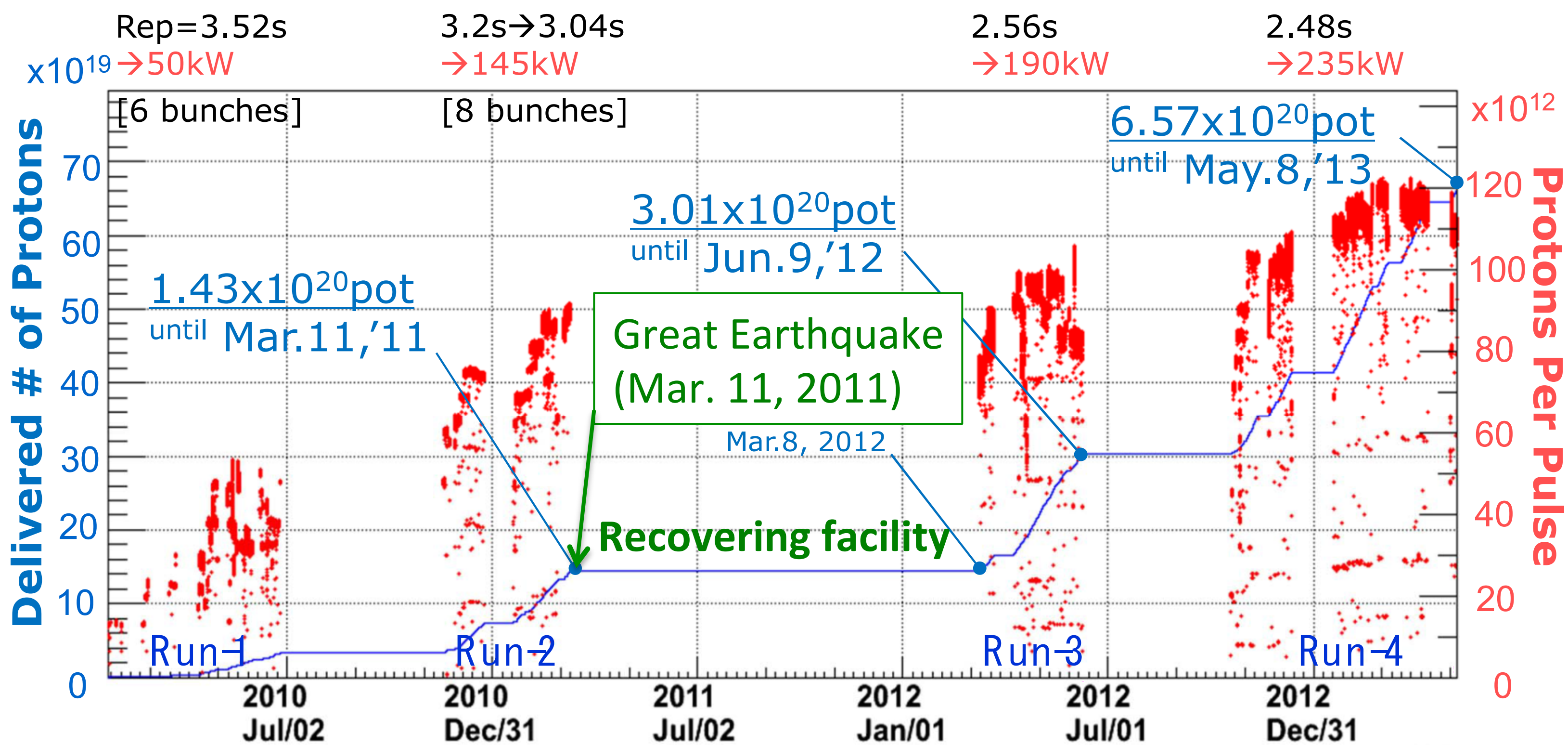


- 50 kton Water Cherenkov detector
  - 22.5 kton Fiducial volume
- Good performance for sub-GeV neutrinos
  - Good e/μ separation from ring shape topology
- T2K recorded events
  - All interactions in ±500μsec around ν arrival time



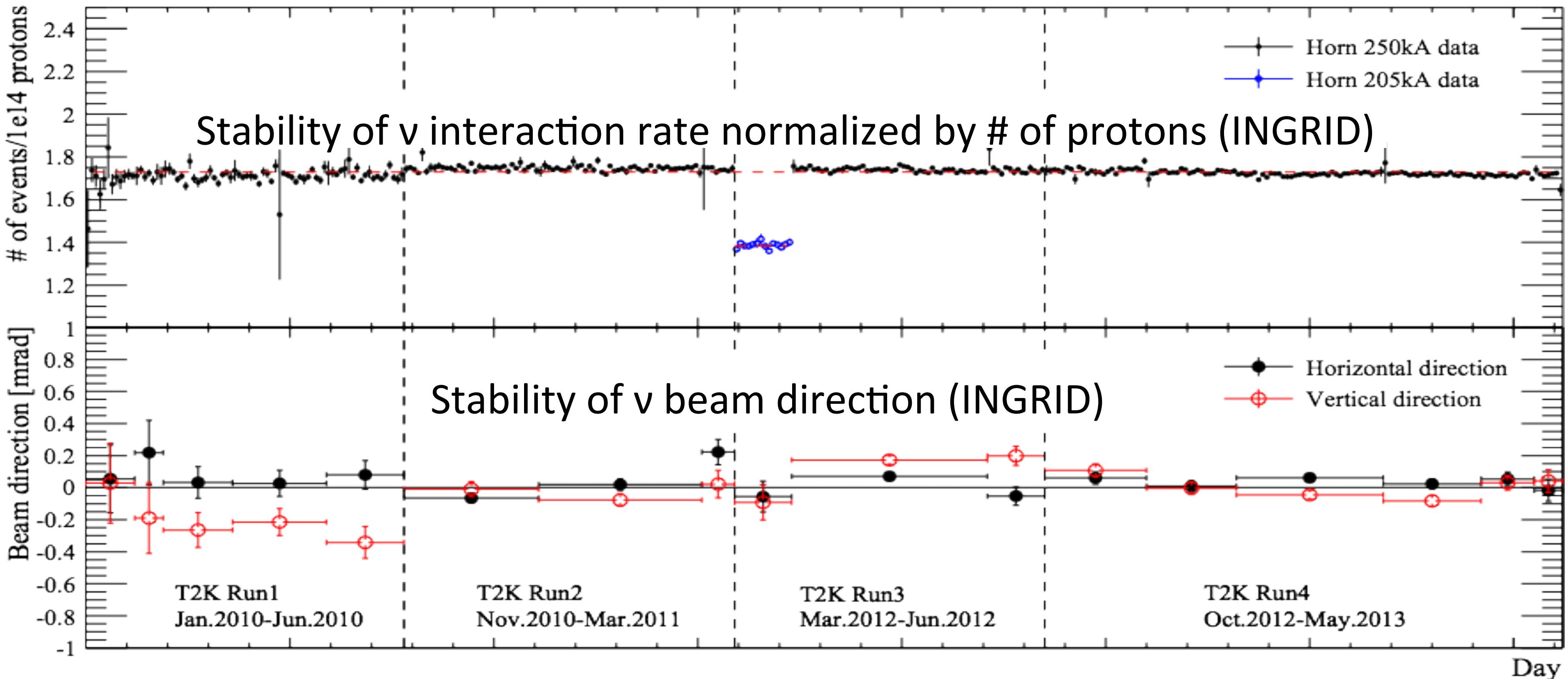
T2K measurement

T2K Data Set (until May 8, 2013)



- Total delivered beam: 6.57x10^{20} Proton on Target (POT)
  - ~8% of T2K goal
- Dead time fraction in T2K Run-4 due to T2K beam line failure ~ 3%
- Super-K running efficiency > 99% over run period

Beam stability



- Neutrino rate per POT is stable to 0.7% over run period
- Neutrino beam direction is stable < 1mrad over run period

Note: Dataset includes 0.21×10^{20} POT with 250 -> 205kA horn operation
(13% flux reduction at peak)

What's new?

- ν_μ disappearance analysis
  - Results using a data set of 6.57×10^{20} POT
- ν_e appearance analysis
  - Constraint on the CP violating phase δ_{CP} by combining our ν_e appearance results with θ_{13} measurements by reactor experiments
- T2K future sensitivity study

Neutrino oscillation analysis

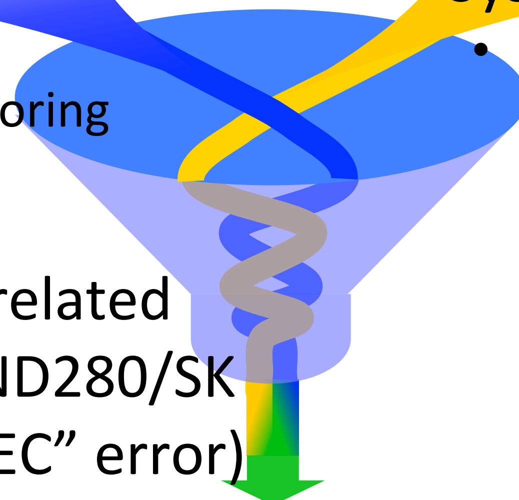
Neutrino oscillation analysis principle

ν flux prediction

- Hadron production (NA61@CERN,…)
- Systematics
  - Hadron production
  - Proton/ν beam monitoring

ν cross section

- Generator: NEUT
- Systematics
  - External data (MiniBooNE, π scattering exp., …)



ND280 measurement

- Constrain strongly-correlated systematics between ND280/SK (Reduce abs. "flux × XSEC" error)

Super-K performance

- Systematics
  - Atmospheric ν
  - Cosmic ray μ

Super-K prediction
with systematics

Compare

Super-K measurement

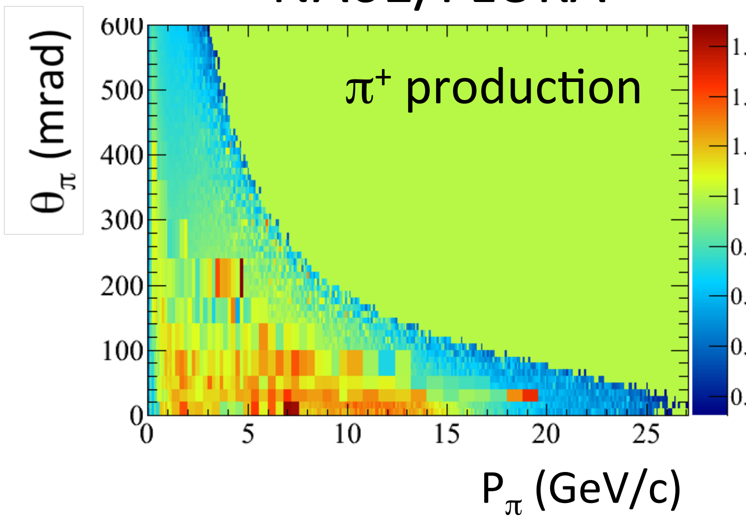
ν flux prediction

Flux prediction

- External hadron production measurement
  - CERN-NA61: Same proton beam energy/target material as T2K
- T2K
  - Proton beam monitoring
    - Profile on target from SSEMs*1, OTR*2
    - Intensity from CTs*3
  - Alignment of and current in horns
  - The neutrino beam direction
    - 1 mrad direction shift

      -> ~3% energy shift at peak

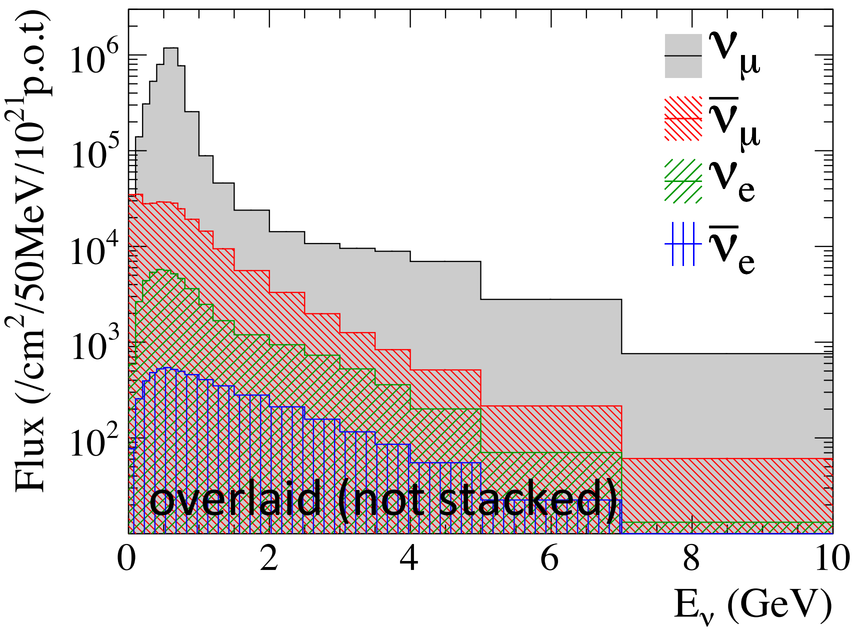
NA61/FLUKA*4



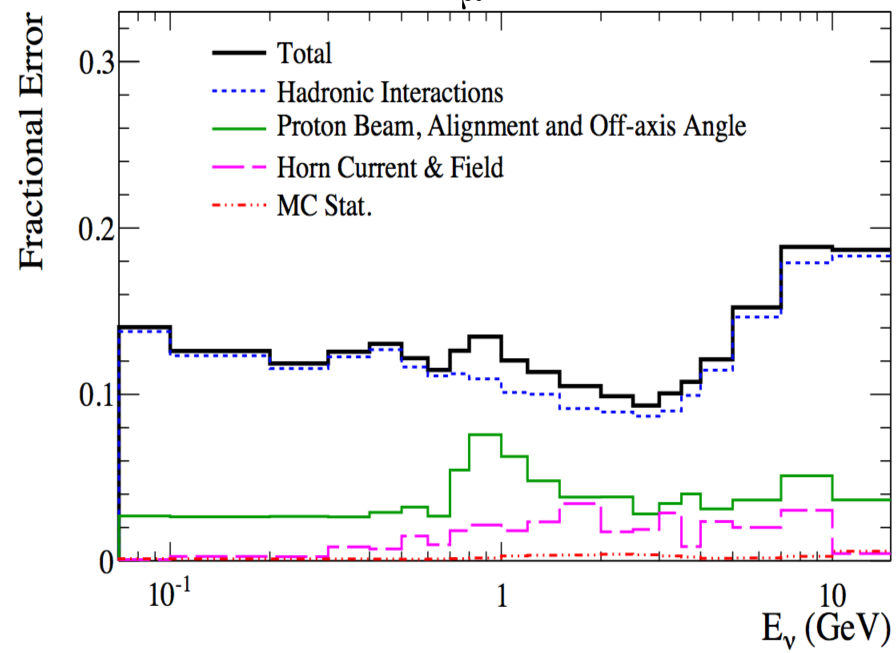
*1 SSEM: Segmented Secondary Emission Profile Monitor,
*2 OTR: Optical Transition Radiation monitor
*3 CT: Current Transformer, *4 FLUKA: Hadron production simulator

Flux and Uncertainties

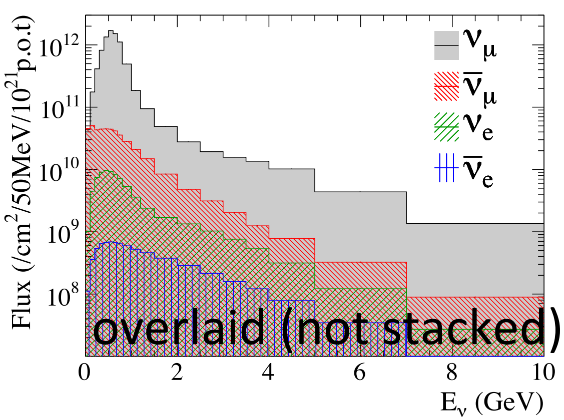
Super-K flux



Super-K ν_μ uncertainty



ND280 flux



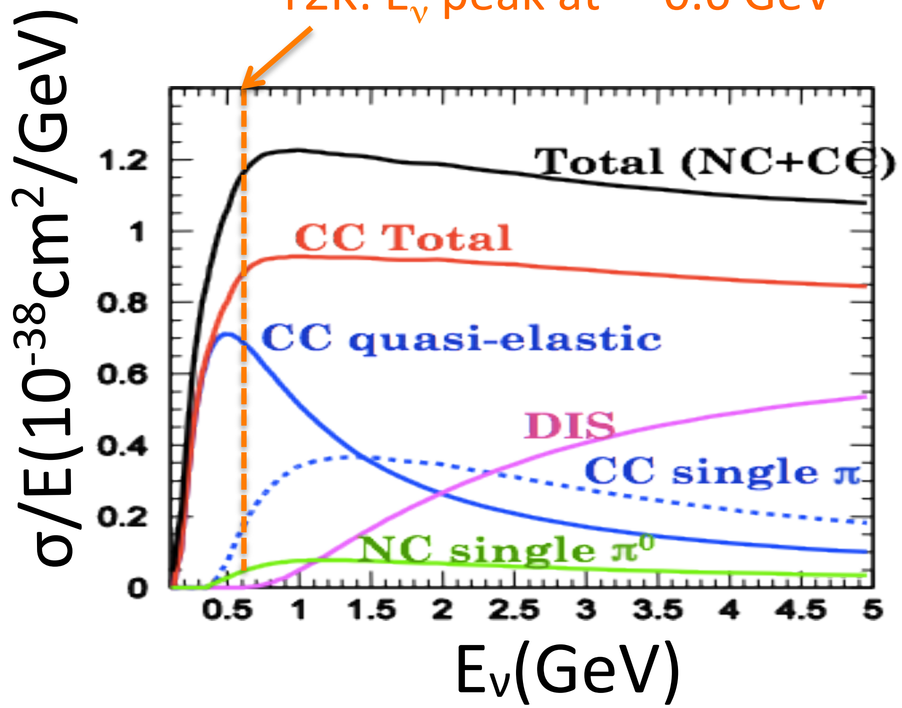
- Super-K flux has 10-15% uncertainties from 0.1 to 5 GeV
- Near (ND280) and Far (Super-K) fluxes are not identical, but highly correlated

ν cross section and its uncertainty

Neutrino Interactions in T2K

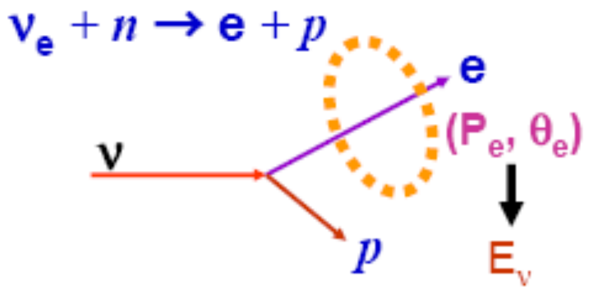
- CC(Charged-Current) quasi elastic (CCQE)
  - $\nu + n \rightarrow \mu^- + p$
- CC (resonance) single π (CC-1π)
  - $\nu + n(p) \rightarrow \mu^- + \pi^+ + n(p)$
- DIS(Deep Inelastic Scattering)
  - $\nu + N \rightarrow \mu^- + m\pi^{+/-/0} + N'$
- CC coherent π
  - $\nu + A \rightarrow \mu^- + \pi^+ + A$
- NC (Neutral-Current)
  - copious process (NC-1π^0, …)
- + Nuclear Effects

T2K: E_ν peak at ~ 0.6 GeV



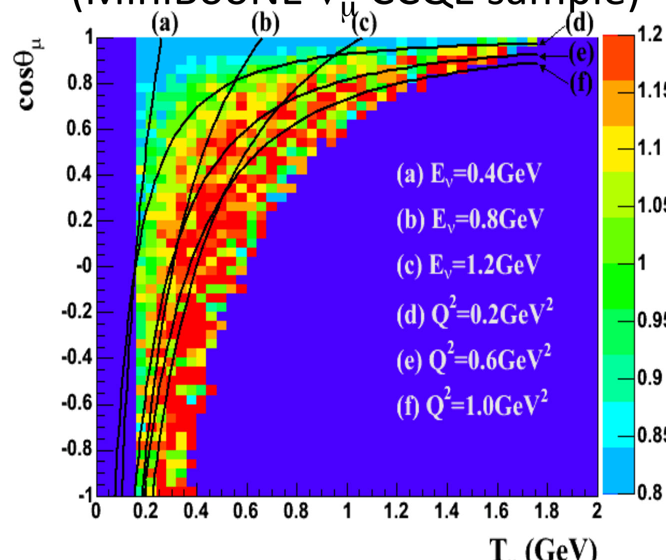
a main BG for ν_e appearance analysis

Cross-section Model: CCQE



- Signal reaction for T2K energies
  - Elastic kinematics allow us to measure neutrino energy from e/μ
- T2K is currently using a very simple model
  - Nucleon form factors from e⁻ scattering and νD scattering
  - Model of nucleus is Fermi gas
- ~20% diff. between Data/Model
  - Approach: add effective parameters (M_A, normalization) with uncertainties based on external data sets (MiniBooNE,…)

Data/Model(M_A=1.03)
(MiniBooNE ν_μ CCQE sample)



(*Phys. Rev.* ***D81*** *092005, 2010)*

ND280 measurement/fit

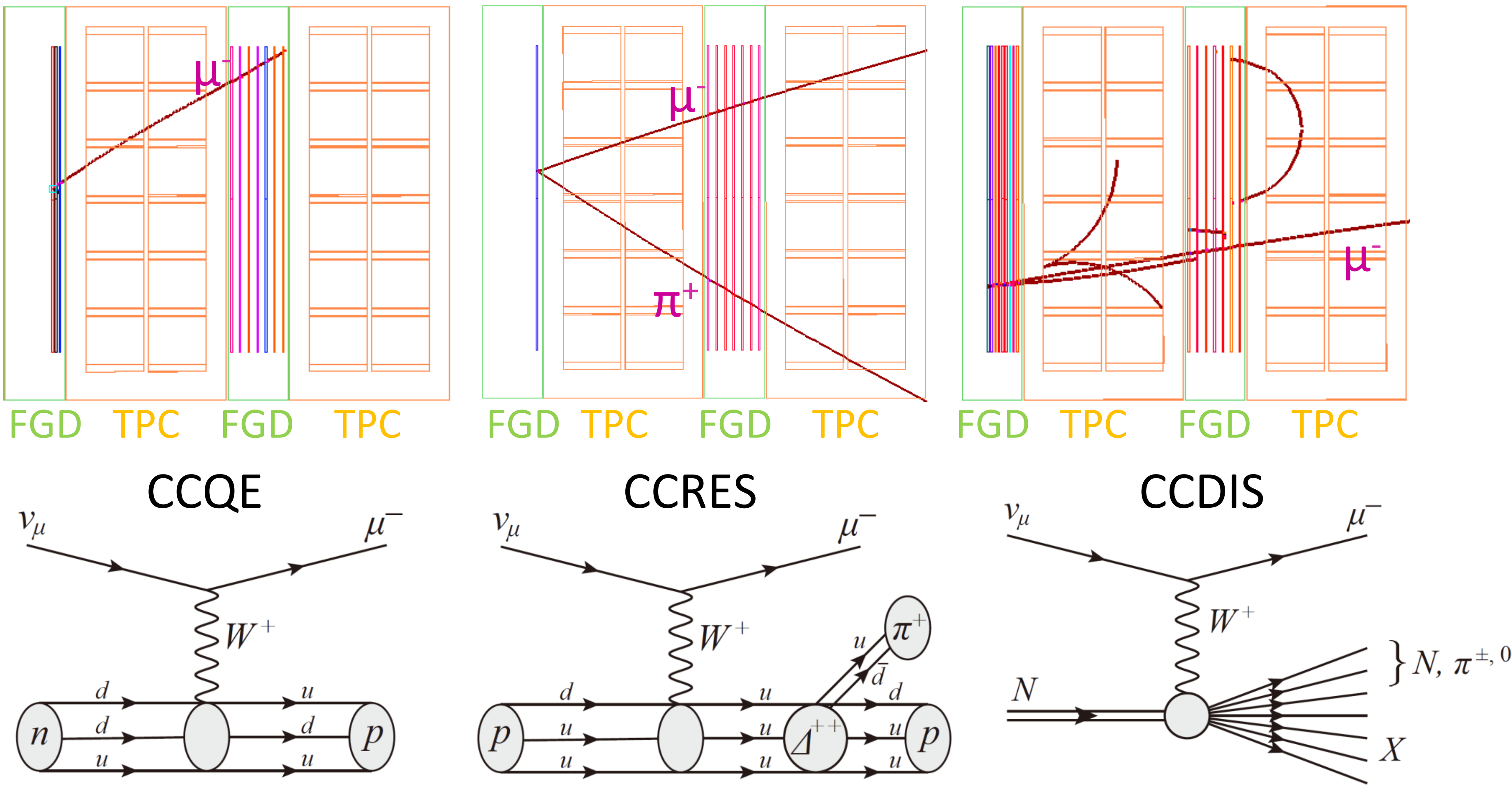
ND280 Event Categories

- Exclusive samples based on # of final state charged πs

Charged current (CC) 0π (CCQE 64%)

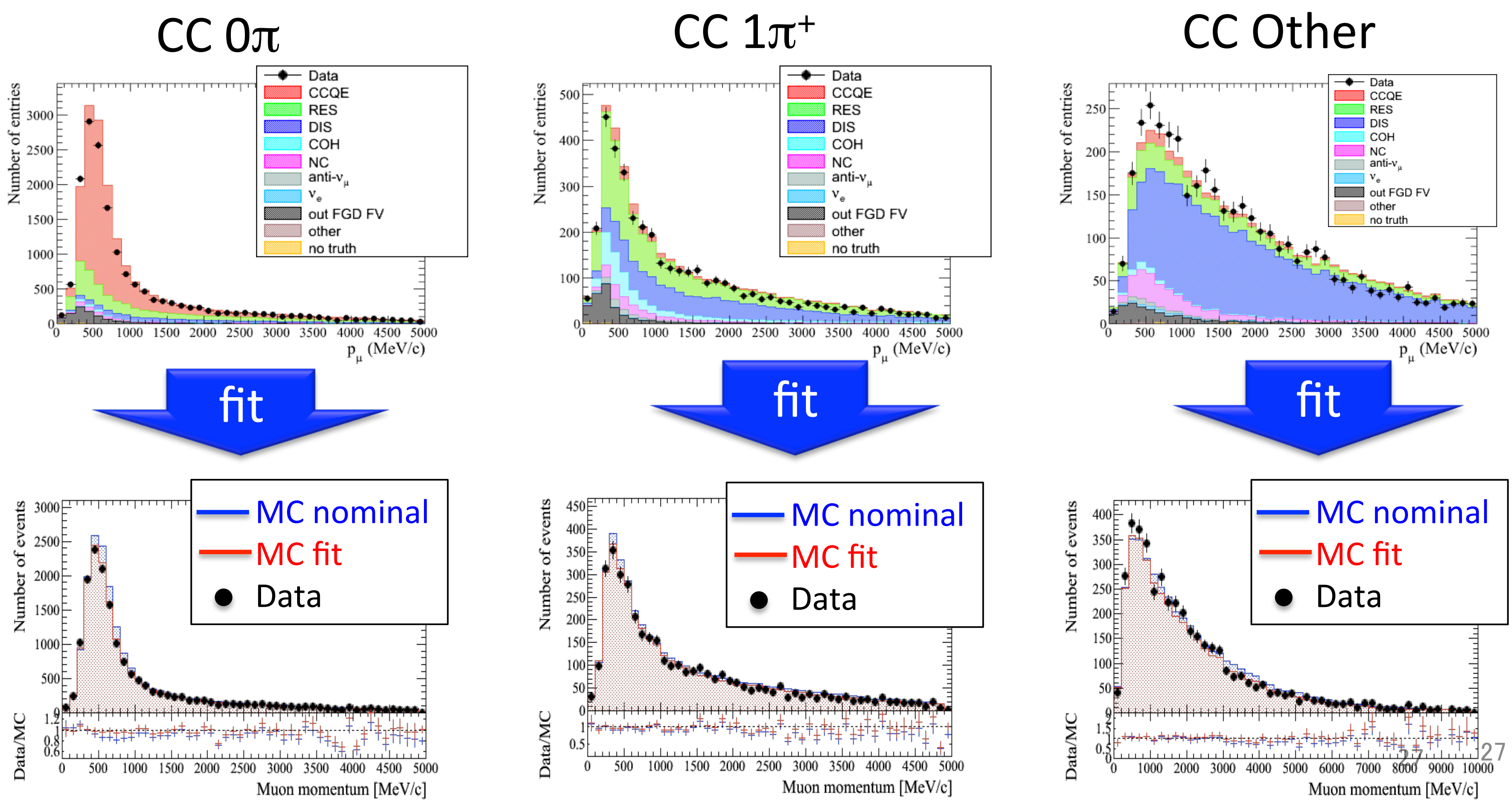
CC 1π^+ (CCRES 40%)

CC Other (CCDIS 68%)



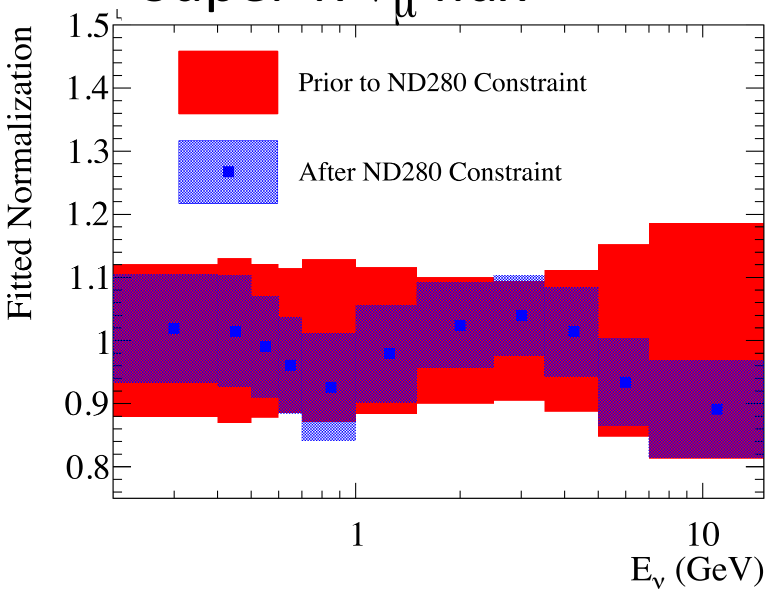
ND280 measurement/fit

- Fit p_μ-$\cos\theta_\mu$ distributions
- Constrain strongly-correlated syst. between ND280/SK



Flux/Cross-Section uncertainties after ND280 constraint

Super-K ν_μ flux



Cross-section parameters

Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.223 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.963 ± 0.063
CCQE Norm.*	1.00 ± 0.11	0.961 ± 0.076
CC1π Norm.**	1.15 ± 0.32	1.22 ± 0.16
NC1π^0 Norm.	0.96 ± 0.33	1.10 ± 0.25

*For E_ν<1.5 GeV **For E_ν<2.5 GeV

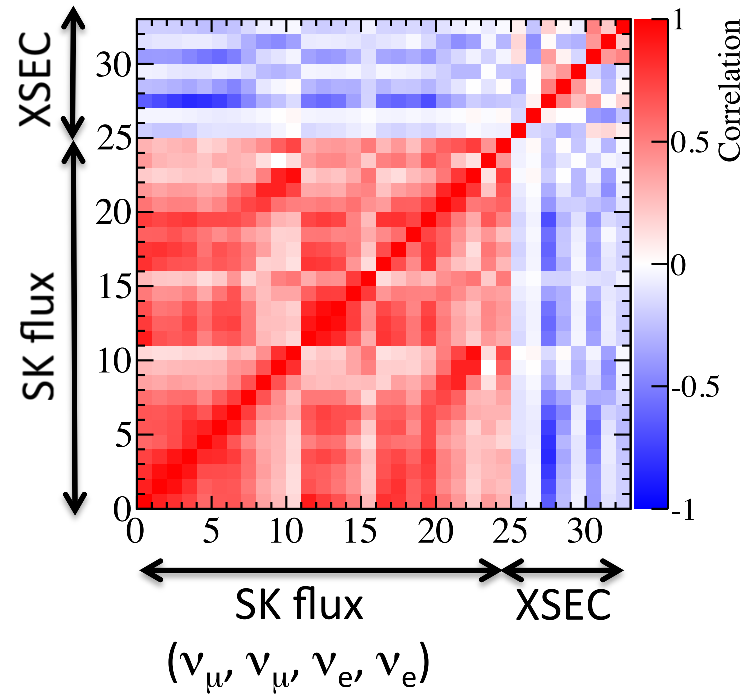
- ND280 constraint reduces both flux and cross-section model uncertainties individually

Uncertainty of # of SK ν_e events before/after ND280 constraint

Systematic uncertainties on # of ν_e candidate events

	$\sin^2 2\theta_{13} = 0.1$	
	w/o ND280 constraint	w/ ND280 constraint
Flux/XSEC (ND280 constraint)	25.9% →	2.9%
Other XSEC	7.5%	7.5%
Super-K +FSI	3.5%	3.5%
Total	27.2% →	8.8%

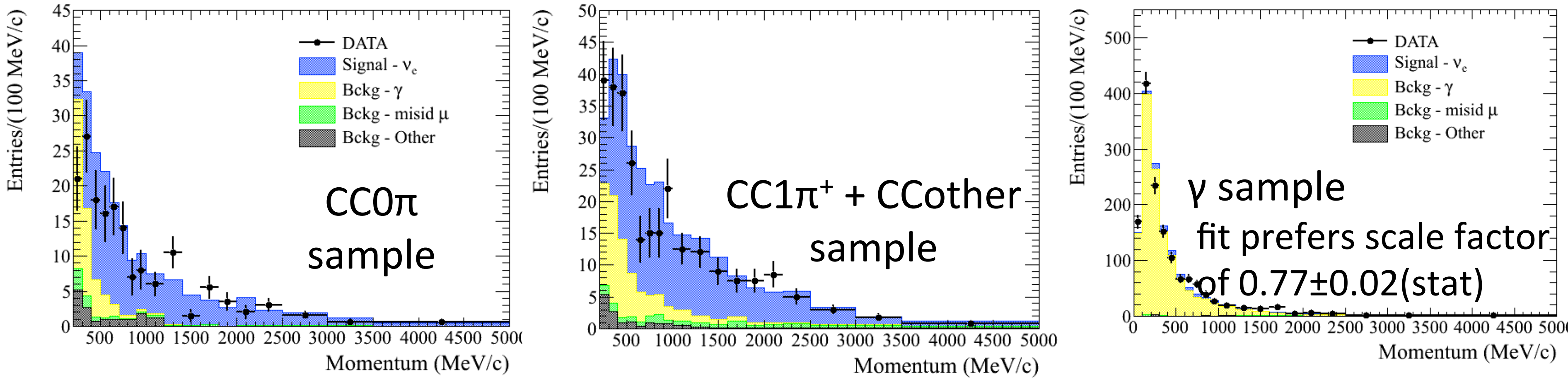
Correlation matrix of systematics



- Flux and cross-section parameters are anti-correlated after ND280 constraint becauseND280 constrains only the observable event rate

ND280 ν_e Measurement

- Interactions in FGD and particle ID in TPC
- Major background: photons from π^0 decays
- Fit CC0π, CC1π+CCother and γ sideband



$$\frac{\text{measured } \nu_e \text{ flux}}{\text{predicted } \nu_e \text{ flux}} = 1.06 \pm 0.06(\text{stat}) \pm 0.08(\text{syst})$$

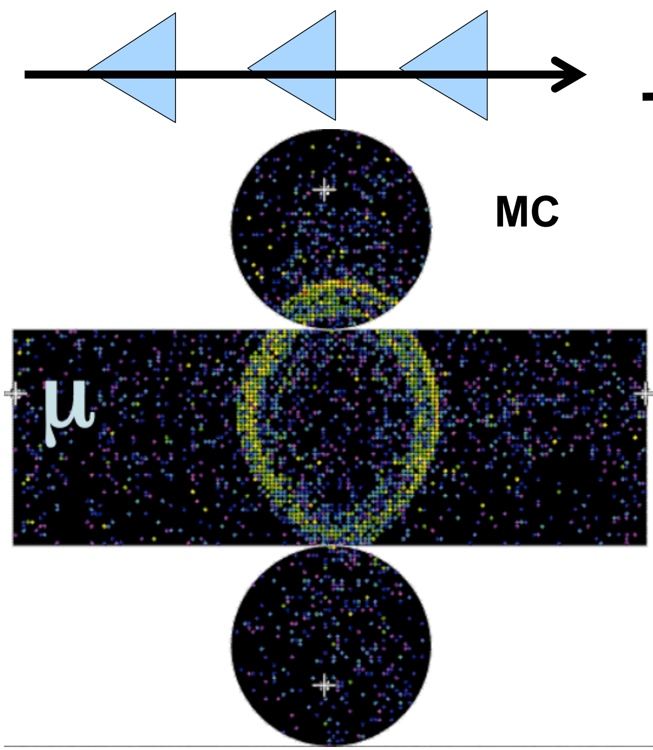
Intrinsic beam ν_e background prediction is validated!

ν_μ disappearance analysis

Particle Identification at SK

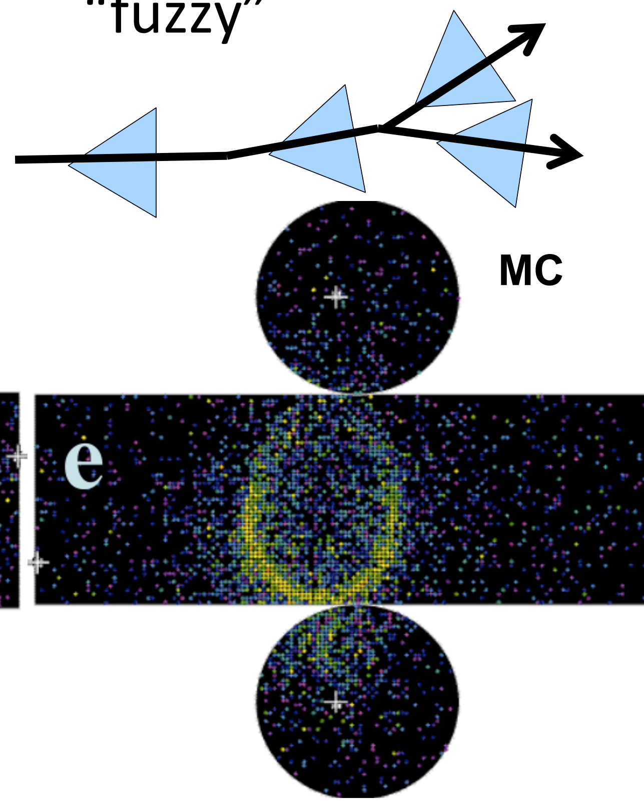
μ

- scattering is minimal
- Rings with sharp edges



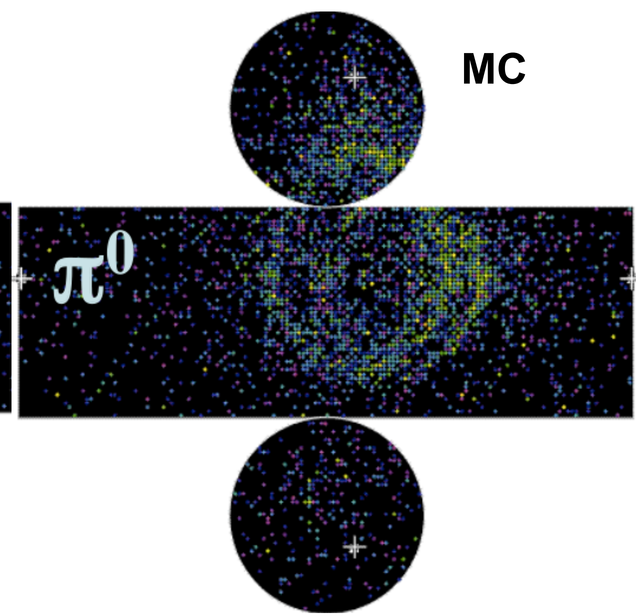
e

- Electromagnetic shower
- Rings are “fuzzy”



π^0

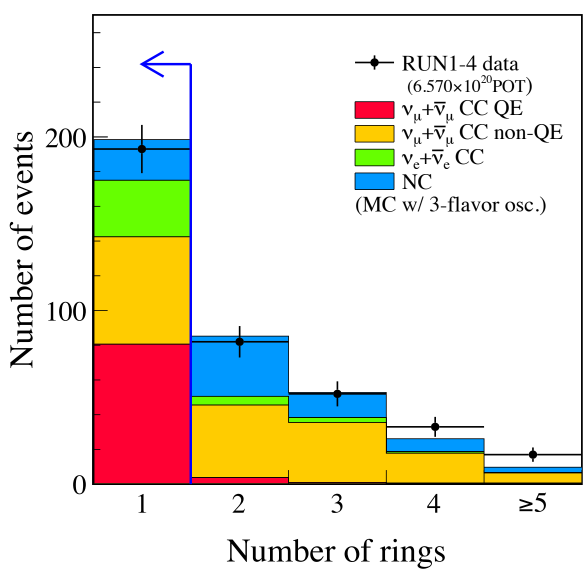
- γ from π^0 decays shower and look like electrons
- Multiple fuzzy rings

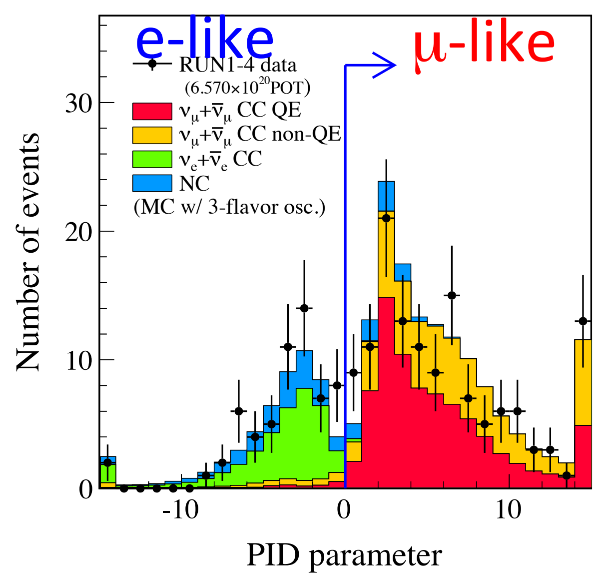


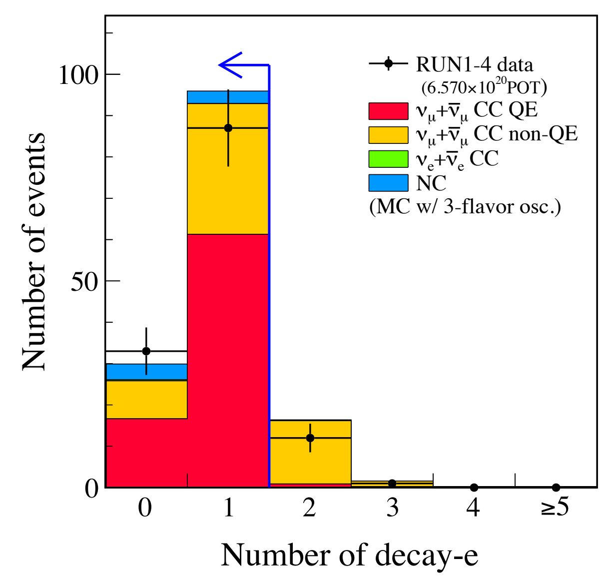
ν_μ event selection

- Fully-contained fiducial volume (FCFV) event
- Single-ring μ-like event
- Reconstructed momentum > 200 MeV/c
- # of decay electron ≤ 1

120 events
in 6.57×10^{20} POT







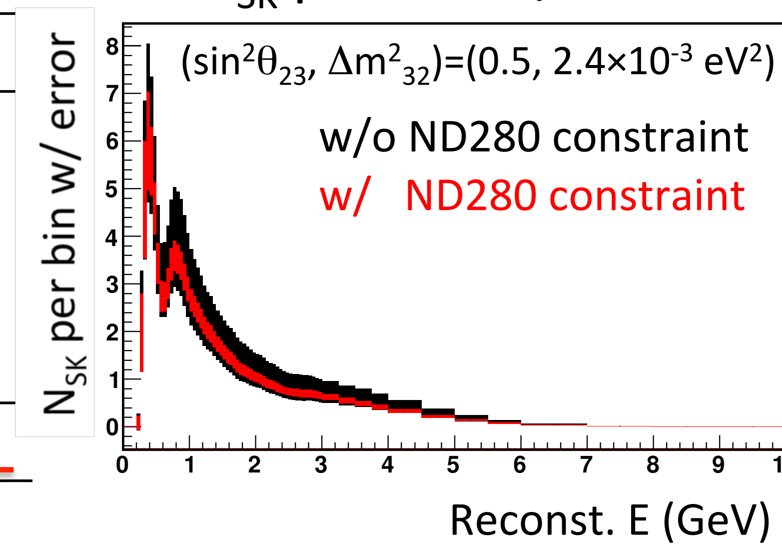
Predicted # of events & syst. errors

Predicted # of events

$(\sin^2\theta_{23}, \Delta m^2_{32})=(0.5, 2.4\times10^{-3}\ \mathrm{eV}^2)$

Event category	# of events
ν_μ CCQE	77.93
ν_μ CCnonQE	40.78
ν_e CC	0.35
NC All	6.78
Total	125.85

N_{SK} per bin w/ error



Systematic uncertainties of # of events*

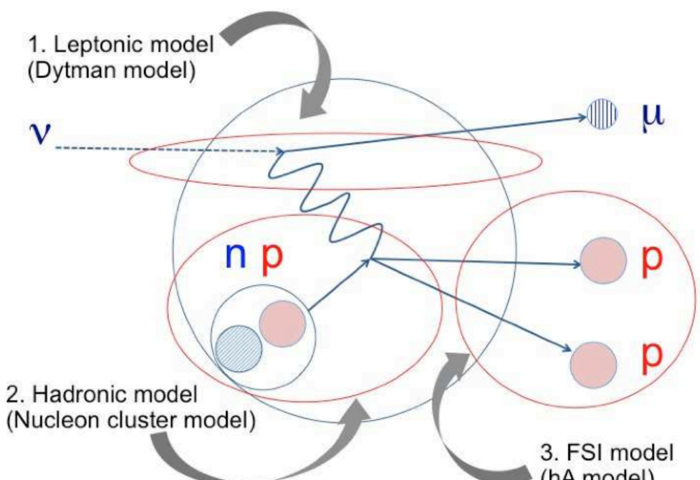
$(\sin^2\theta_{23}, \Delta m^2_{32})=(0.5, 2.4\times10^{-3}\ \mathrm{eV}^2)$

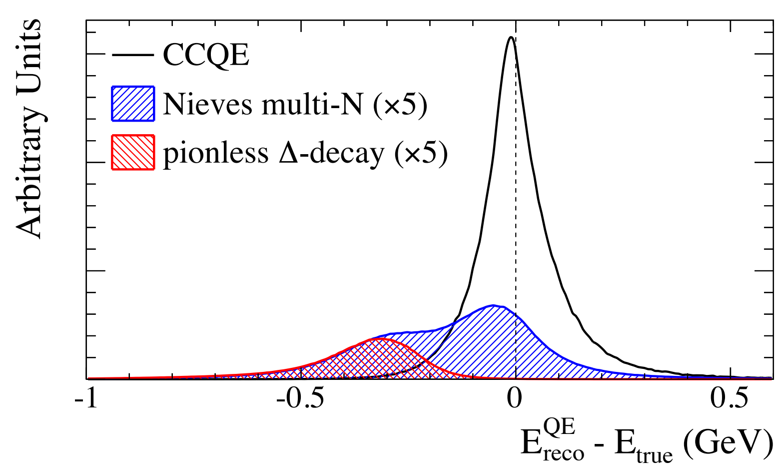
Systematics	Uncertainties
Flux/XSEC (ND280 constraint)	2.7%
Other XSEC	4.9%
Super-K +FSI	5.6%
Total	8.1%

* Binding energy/SK energy scale are some of the dominant uncertainties affecting T2K Δm^2_{32} precision, but they don't appear in the left table of # of events since they don't affect overall normalization.

Multi-Nucleon Systematic Uncertainty

- Lively discussion motivated by CCQE cross section inconsistency between MiniBooNE/other experiment
- Not incorporated directly into analysis
  - But we have a large systematic uncertainty (100%) on decays of Δ resonances w/ prompt π absorption ("π-less Δ-decay"). It has similar impact on neutrino energy reconstruction as a 100% uncertainty in the multi-nucleon interaction model (Nieves model)
  - Dedicated MC study shows the impact on oscillation analysis is small relative to our current statistical error.





Oscillation Likelihood Fits

- Search for Oscillation parameters which maximize L
  - Observables: # of events, E_ν^{rec} distribution

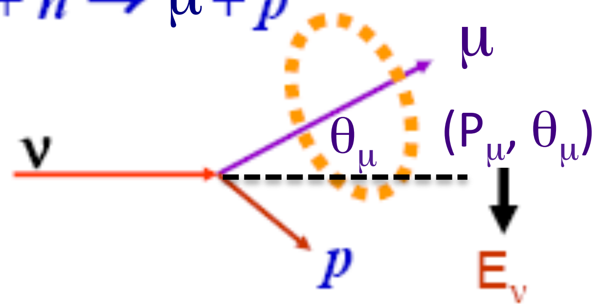
$$L = L_{norm} \times L_{shape} \times L_{syst} \times L_{osci}$$

# of events — E_ν^{rec} dist. — Syst. — Osci. param.

Neutrino energy from elastic kinematics

$$E_{\rm reco} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

$\nu_\mu + n \rightarrow \mu + p$



* E_b is mean binding energy.

Note: $\sin^2\theta_{13}$, $\sin^2\theta_{12}$, Δm^2_{21} are constrained by PDG2012. δ_{CP} is unconstrained.

[NH] Normal hierarchy, [IH] Inverted hierarchy

Results of ν_μ disappearance analysis

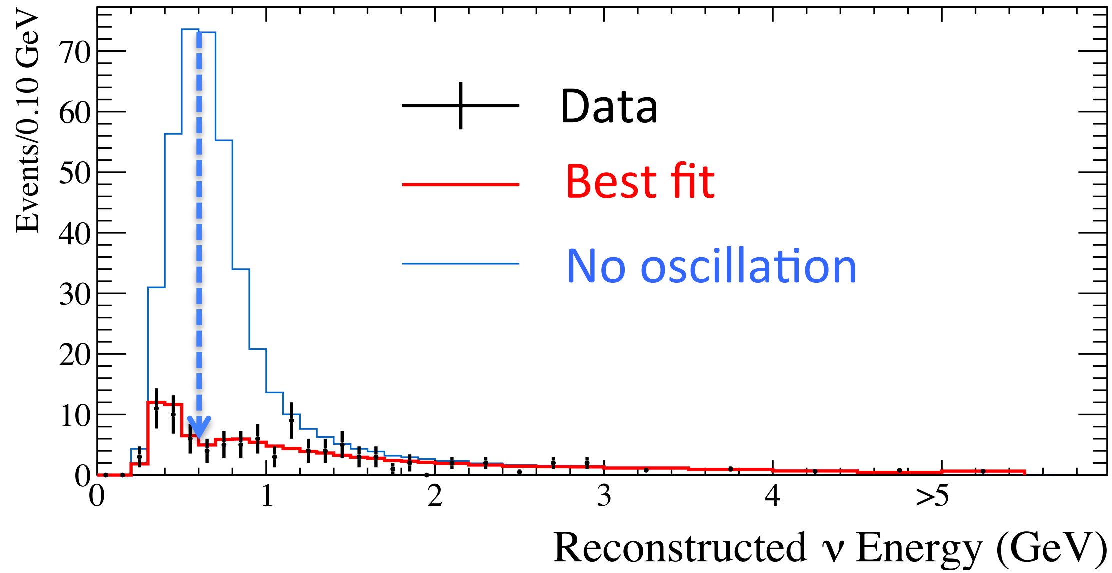
Best fit

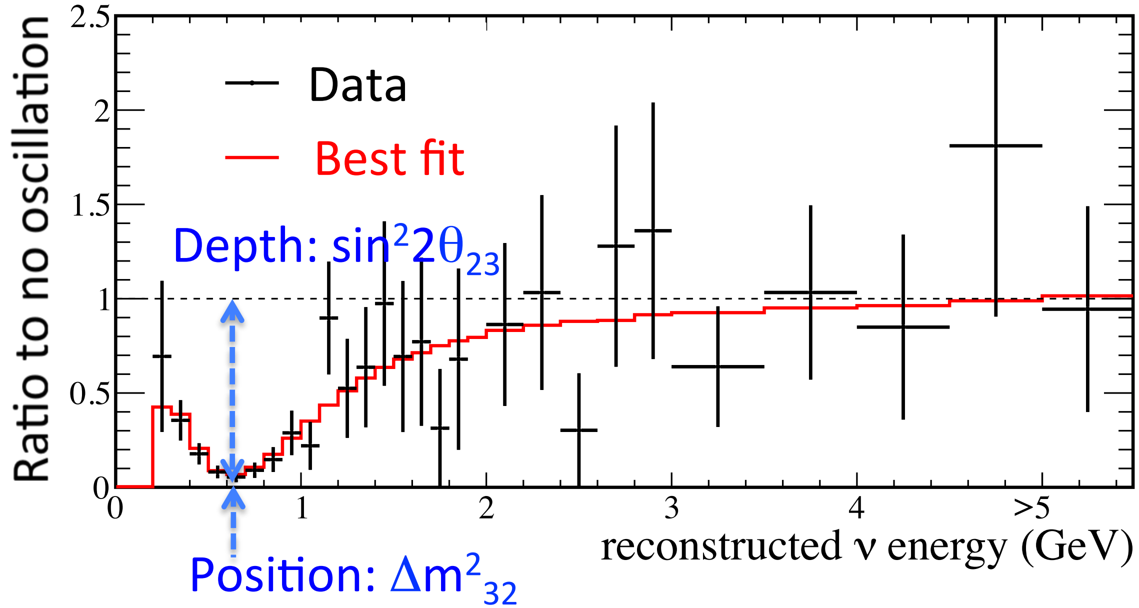
$\sin^2\theta_{23}$ [NH] ([IH])	0.514 (0.511)
Δm^2_{32} [NH] (Δm^2_{13} [IH])	2.51 (2.48) $\times 10^{-3}$
N_{exp} [NH] ([IH])	121.41 (121.39)

Note: N_{obs} = 120 events

2 flavor approximation

$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \cdot \sin^2 \frac{\Delta m^2_{32} \cdot L}{4E}$$

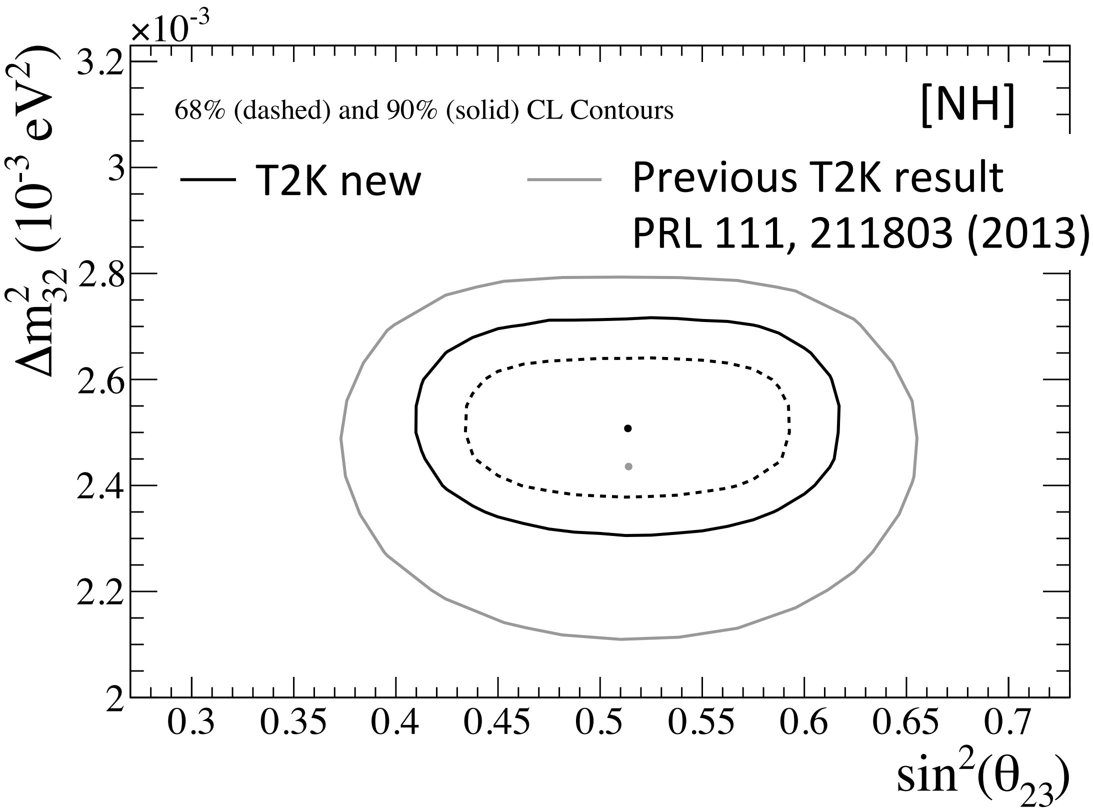




[NH] Normal hierarchy, [IH] Inverted hierarchy

Results of ν_μ disappearance analysis

Feldman-Cousins 2D confidence regions



F&C 1D intervals

	68% CL	90% CL
$\sin^2(\theta_{23})$ [NH]	[0.458,0.568]	[0.428,0.598]
Δm^2_{32} (x10^{-3}) [NH]	[2.41,2.61]	[2.34,2.68]
$\sin^2(\theta_{23})$ [IH]	[0.456,0.566]	[0.427,0.596]
Δm^2_{13} (x10^{-3}) [IH]	[2.38,2.58]	[2.31,2.64]
θ_{23} [NH]	[42.6°, 48.9°]	[40.9°, 50.7°]
θ_{23} [IH]	[42.5°, 48.8°]	[40.8°, 50.5°]

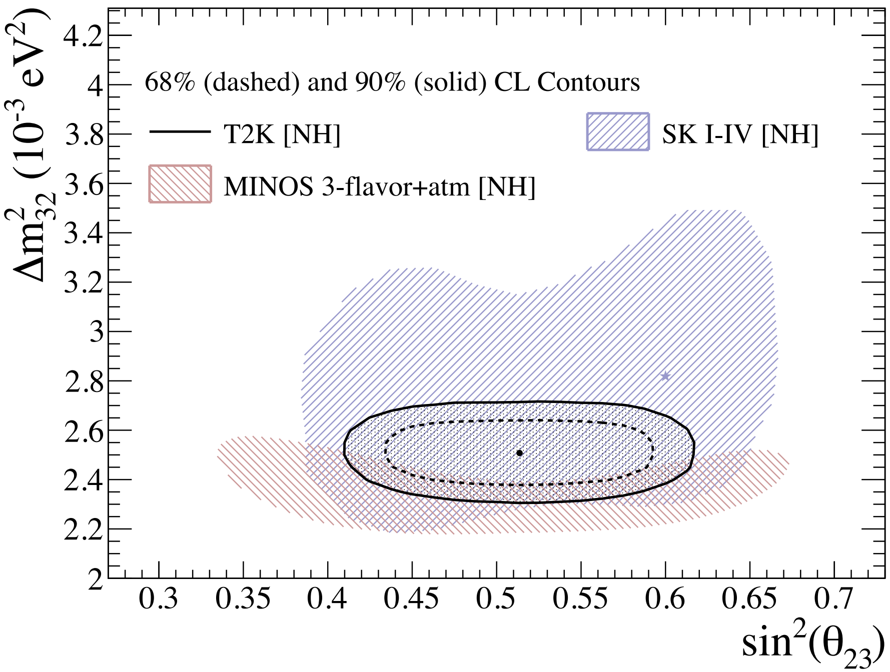
Great improvement from the previous T2K result!

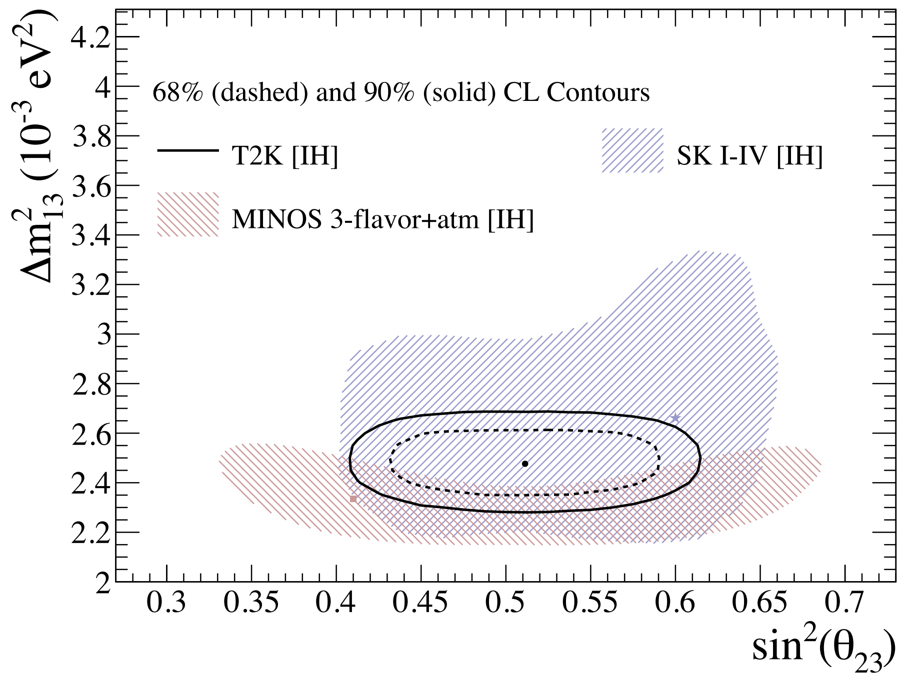
T2K favors maximal mixing

[NH] Normal hierarchy, [IH] Inverted hierarchy

Results of ν_μ disappearance analysis

Comparison w/ other experiments





T2K measures θ_{23} with the world-leading precision!

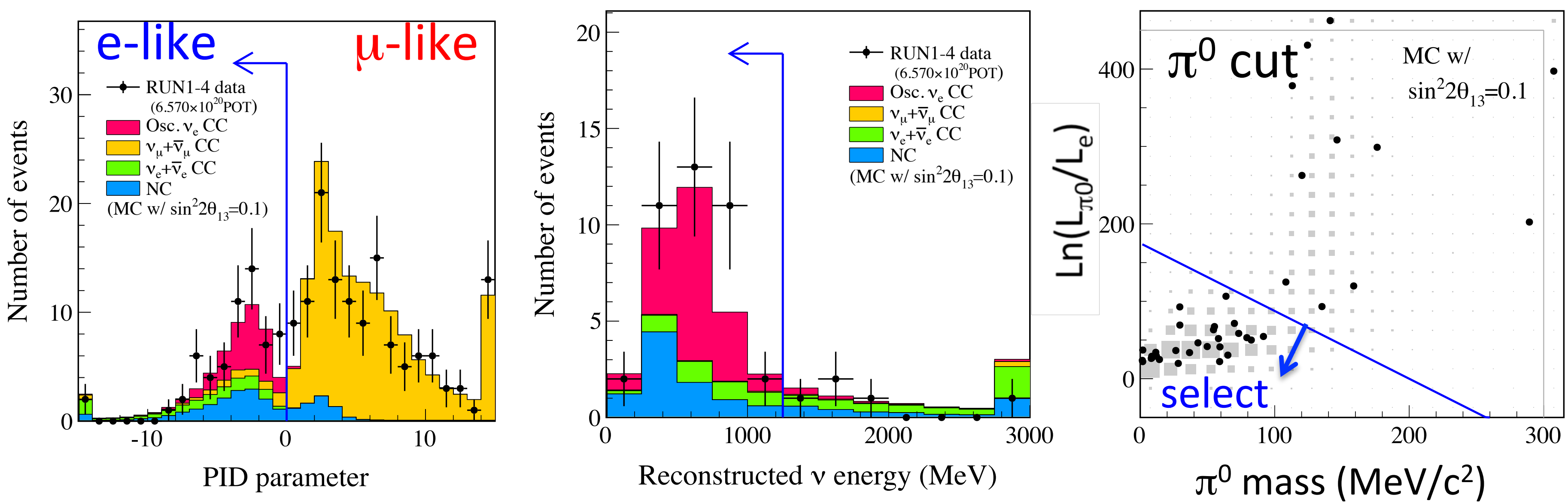
ν_e appearance analysis

T2K collaboration, PRL 112, 061802 (2014)

ν_e event selection

- Fully-contained fiducial volume (FCFV) event
- Single-ring e-like event
- $E_{visible}$ > 100 MeV
- # of decay electron = 0
- $0 < E_\nu^{rec} < 1250$ MeV
- π^0 cut

28 events in 6.57×10^{20} POT



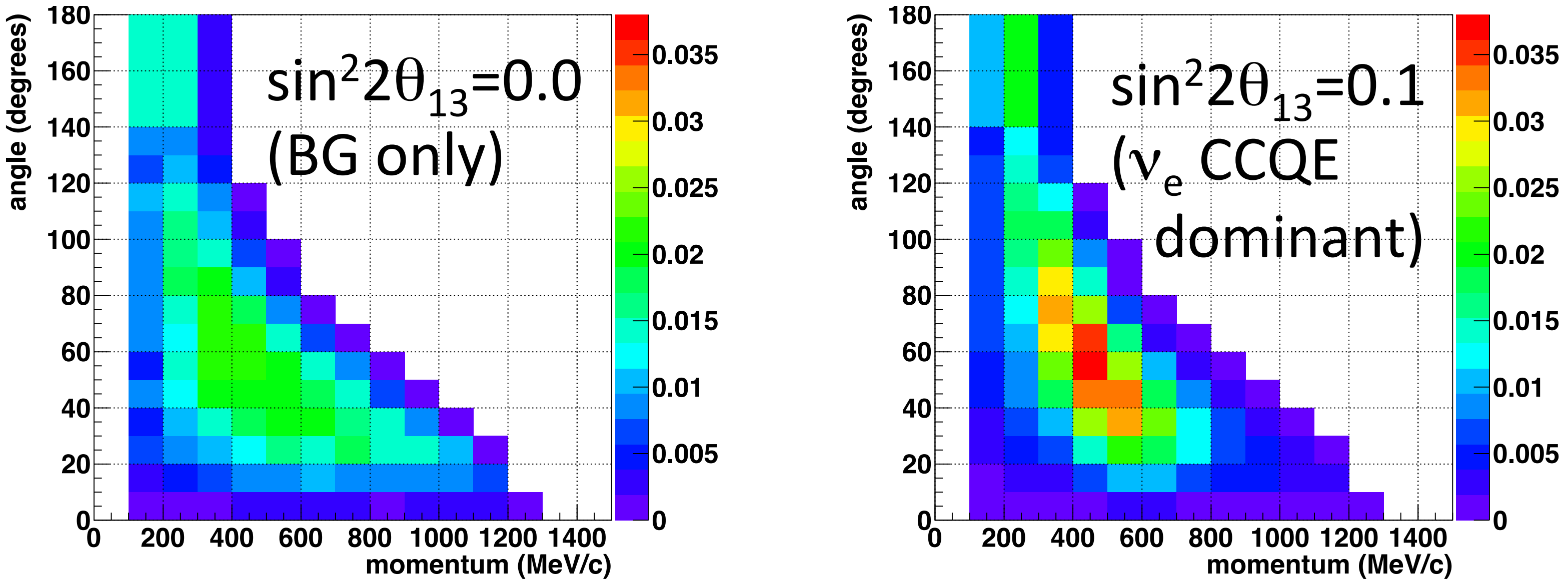
Oscillation Likelihood Fits

- Search for Oscillation parameters which maximize L
  - Observables: # of events, (p_e, θ_e) distribution

$$L = L_{norm} \times L_{shape} \times L_{syst} \times L_{osci}$$

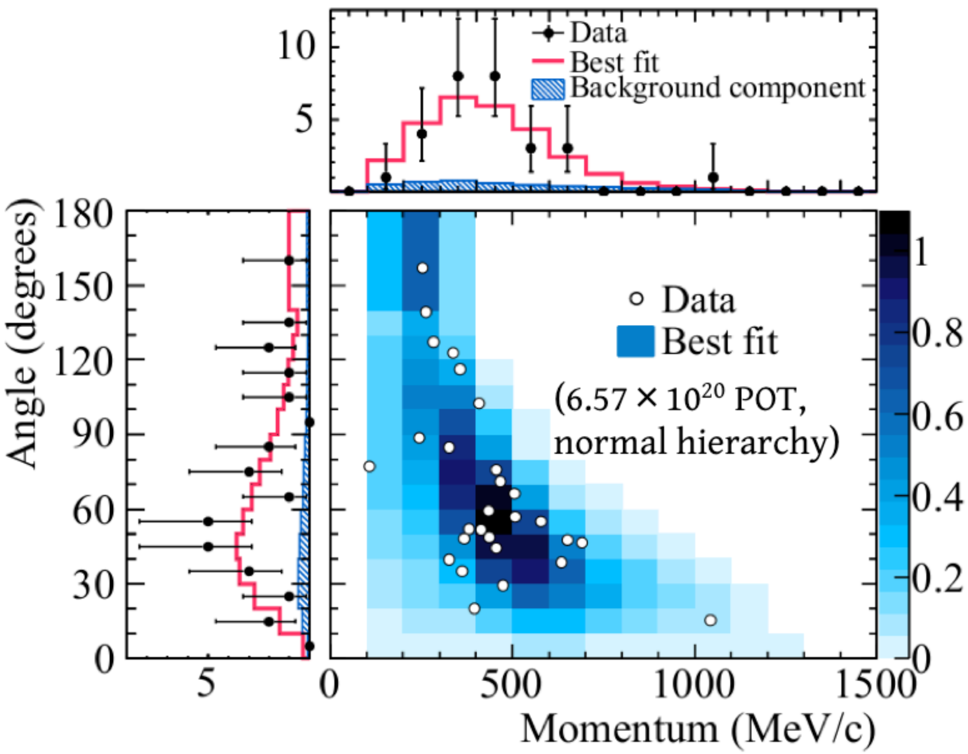
\# of events — (p_e, θ_e) dist. — Syst. — Osci. param.

(p_e, θ_e) distribution



Results of ν_e appearance analysis

Electron p-θ distribution



Best fit for [NH] ([IH])

(Assuming δ_{CP}=0)

$$\sin^2 2\theta_{13} = 0.136^{+0.044}_{-0.033}$$

$$(0.166^{+0.051}_{-0.042})$$

Significance of non-zero θ_{13} yields 7.3σ

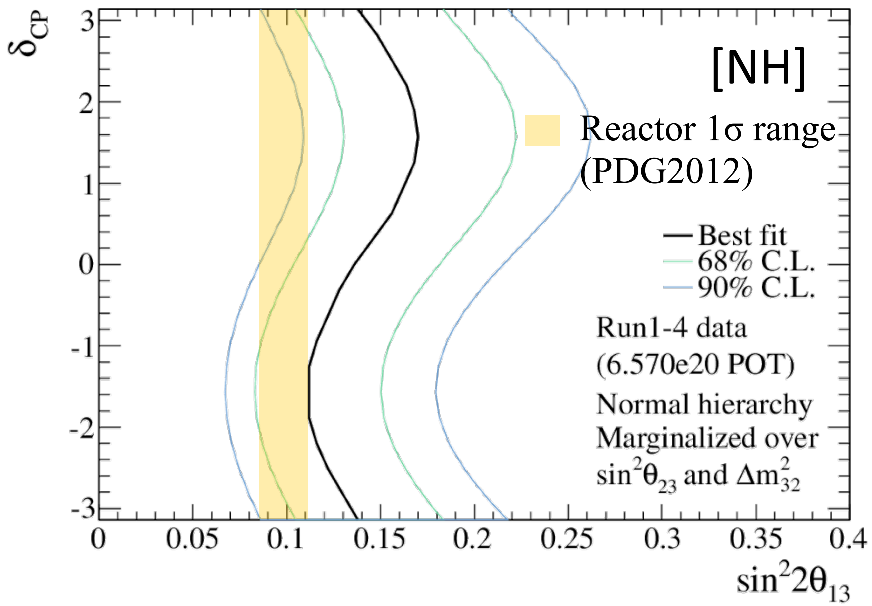
Discovery of ν_e appearance!

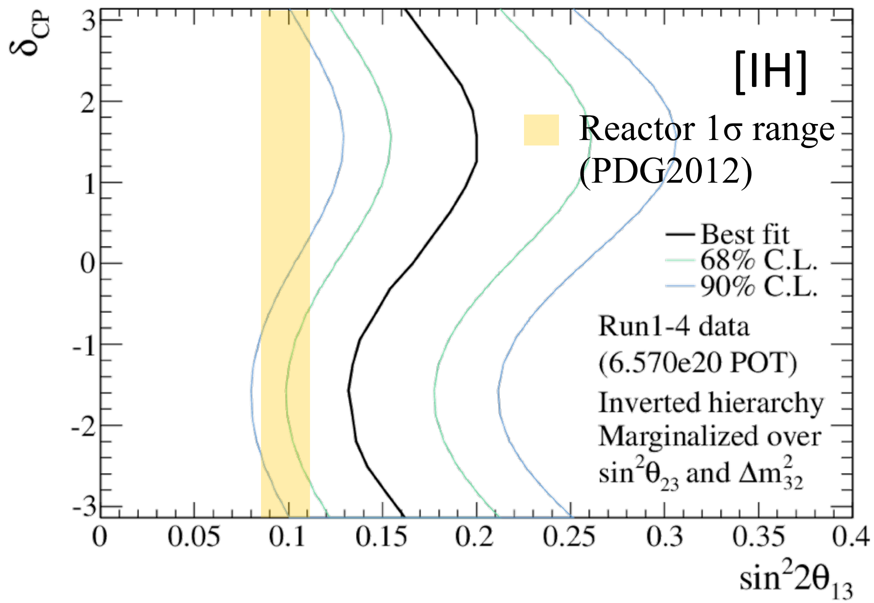
Note: $\sin^2\theta_{23}$, Δm^2_{32} are constrained by previous T2KRun 1-3 ν_μ result (PRL 111, 211803 (2013))

[NH] Normal hierarchy, [IH] Inverted hierarchy

Results of ν_e appearance analysis

Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}





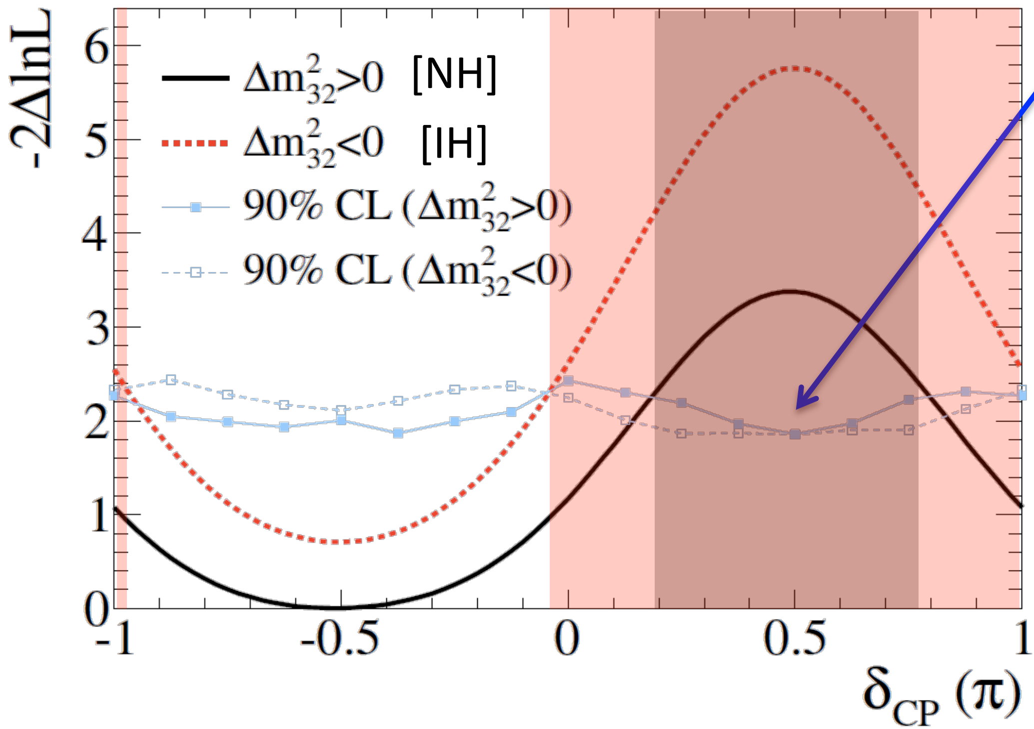
Note

- These are 1D contours for values of δ_{CP}, not 2D contours in δ_{CP}-θ_{13} space

[NH] Normal hierarchy, [IH] Inverted hierarchy

Results of ν_e appearance analysis

Combination of T2K + Reactor ($\sin^2 2\theta_{13}$=0.098±0.013 from PDG2012)



90% C.L. limits by Feldman-Cousins

90% C.L. excluded region

[NH]: 0.19π ~ 0.80π

[IH]: -0.04π ~ 1.03π

- Best fit is found at very interesting point, δ_{CP} ~ -π/2.
- If it is true, severe competition w/ NOνA.

Very important to increase statistics ASAP.

Physics
spotlighting exceptional research

American Physical Society APS physics

Log in | Create Account (what's this?)

Home | About | Browse | APS Journals | SEARCH

Viewpoint: Neutrino Experiments Come Closer to Seeing *CP* Violation

Joseph A. Formaggio, *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

Published February 10, 2014 | Physics **7**, 15 (2014) | DOI: 10.1103/Physics.7.15

The T2K experiment has measured the largest number of events associated with muon neutrinos oscillating into electron neutrinos, an important step toward seeing *CP* violation in neutrino interactions.

Charge-parity (*CP*) violation—evidence that the laws of physics are different for particles and antiparticles—is often invoked as a "must" to explain why we observe more matter than antimatter in the universe. But the *CP* violation observed in interactions involving quarks is insufficient to explain this asymmetry. As a result, many theorists are looking toward leptons—and, specifically, neutrinos—for additional sources of *CP* violation. Researchers running the Tokai to Kamioka (T2K) experiment —a particle physics experiment at the Japan Proton Accelerator Research Complex (J-PARC)—have now made an important contribution toward the search for *CP* violation in neutrinos. Writing in *Physical Review Letters*, the T2K collaboration reports the strongest evidence to date for the appearance of electron neutrinos from a pure muon neutrino beam [1]. Their measurement allows them to determine a fundamental parameter of the standard model of particle physics, called θ_{13}, which can in turn be used to make an early estimate of *CP* violation in neutrinos. Although this estimate has a large uncertainty, it will serve as a guide to future, more definitive neutrino experiments that are directly sensitive to *CP* violation.

Observation of Electron Neutrino Appearance in a Muon Neutrino Beam
K. Abe *et al.* (T2K Collaboration)
Phys. Rev. Lett. 112, 061802 (2014)
Published February 10, 2014 | PDF (free)

+Enlarge image

Article Options

- Printable Version
- Share/Email This
- Download PDF
- Export Citation (BibTeX)
- Export Citation (RIS)

Subject Areas

- **Particles and Fields**

Related Articles

More Particles and Fields

Looking for the Invisible at Colliders
Synopsis | Jan 29, 2014

Catching Z's in Particle Colliders
Synopsis | Jan 15, 2014

All Particles and Fields »

Our paper on the ν_e appearance analyses (PRL 112, 061802 (2014)) was selected for a "Viewpoint in Physics" of APS.

Future sensitivity study

- ν_e appearance and ν_μ disappearance combined fit
- Realistic (shape-dependent) systematic errors
  - Errors are assumed to be fully correlated between ν/anti-ν

Koseki-san’s slides @ T2K collaboration meeting, Sep, 2013

Mid-term plan of MR

FX：We adopt the high repetition rate scheme to achieve the design beam intensity, 750 kW.
Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS’s and RF cavities.

JFY	2011	2012	2013	2014	2015	2016	2017
			Li. upgrade				
FX power [kW] SX power ：User op.（study）[kW]	150 3 (10)	200 10 (20)	240 ~ (300) 25 (30)	~ 400 50 (100)	→		750 100
Cycle time of main magnet PS **New magnet PS for high rep.**	3.04 s	2.56 s R&D	2.4 s		Manufacture installation/test		1.3 s
Present RF system **New high gradient rf system**	Install. #7,8	Install. #9 R&D			Manufacture installation/test		
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW)				
Injection system **FX system**	New injection kicker	Kicker PS improvement、Septum 2 manufacture /test LF septum, PS for HF septa manufacture /test					

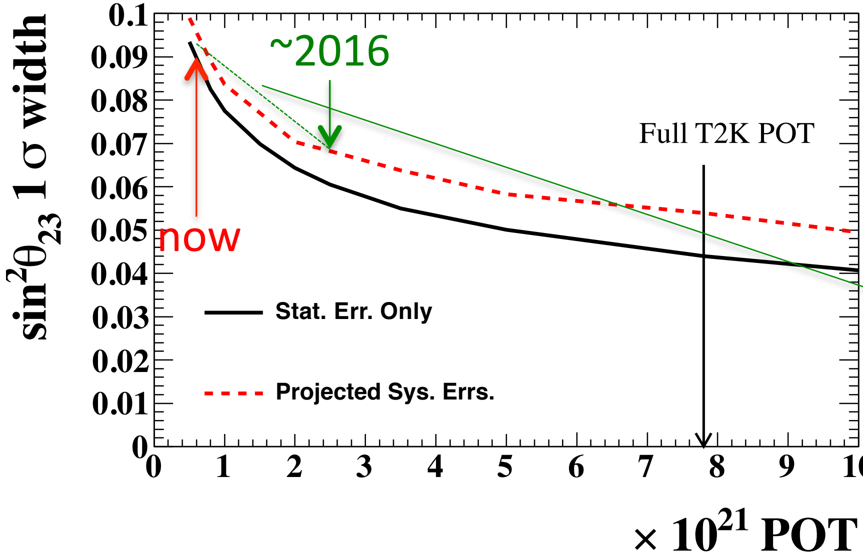
Expected POT is estimated based on the information.

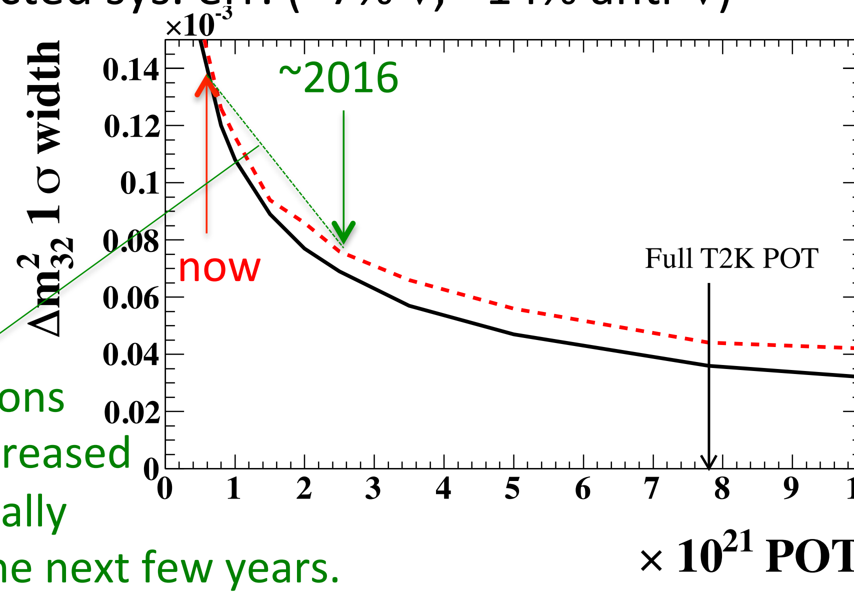
$\sin^2\theta_{23}/\Delta m^2_{32}$ 1σ Precision vs. POT

50% POT ν + 50% POT anti-ν

Solid Lines: no sys. err.

Red Dashed: with conservative projected sys. err. (~7% ν, ~14% anti-ν)





Precisions are increased drastically over the next few years.

Statistical limit of 1σ precision at full POT

- $\sin^2\theta_{23}$ (θ_{23}): ~0.045 (~2.6°)
- Δm^2_{32}: ~4×10^{-5} eV^2

Assuming true: $\sin^2 2\theta_{13}=0.1$, $\delta_{CP}=0°$, $\sin^2\theta_{23}=0.5$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2, [NH]

θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

[NH] Normal hierarchy, [IH] Inverted hierarchy

Appearance 90% C.L. Sensitivity

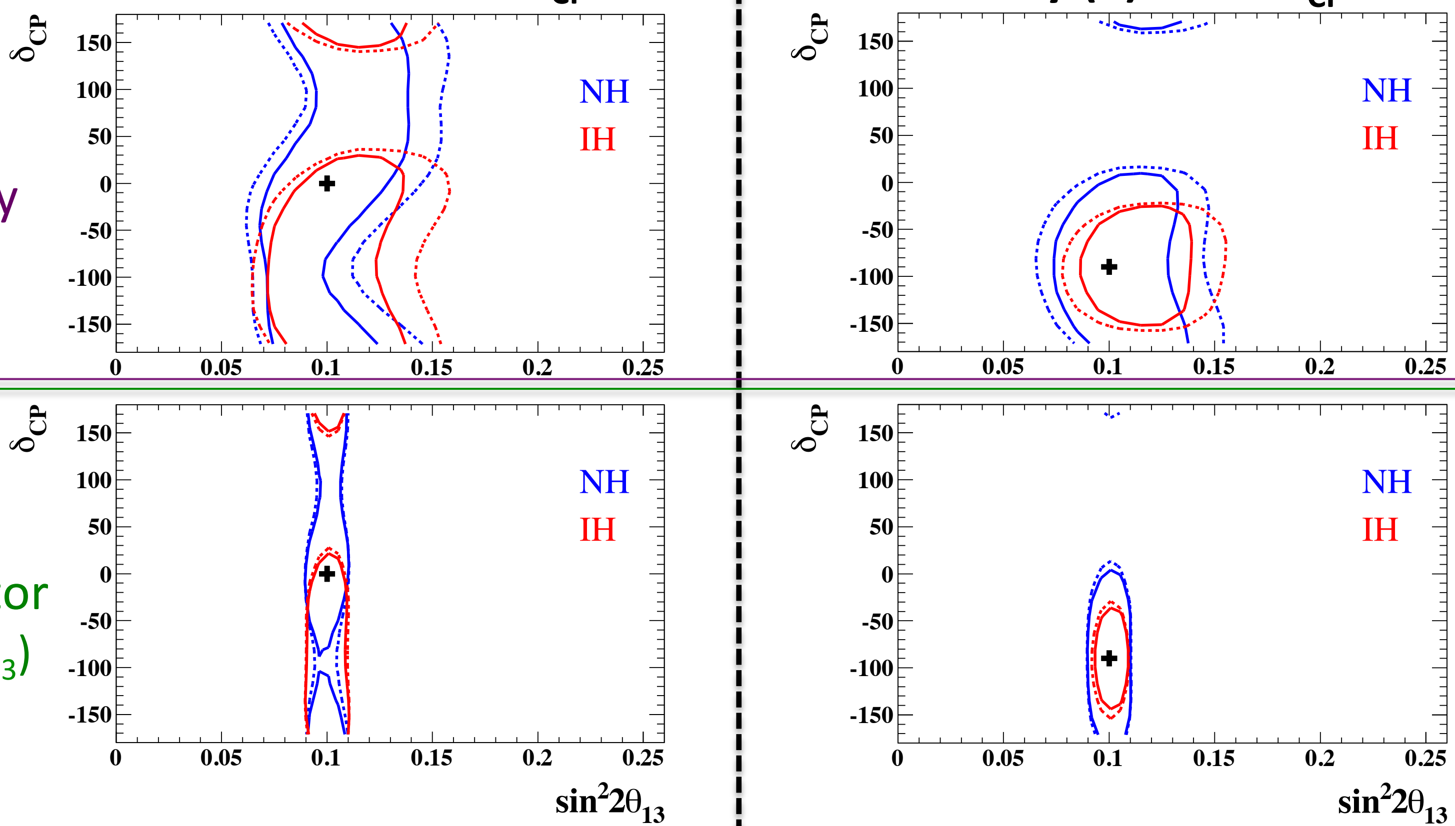
7.8×10^{21} POT (50% POT ν + 50% POT anti-ν)

Solid Lines: no sys. err., Dashed: with 2012 sys. err. (~10% ν_e, ~13% ν_μ)

Case study (1): True δ_{CP} = 0° | **Case study (2): True δ_{CP} = -90°**

T2K only

T2K w/ Reactor $\delta(\sin^2 2\theta_{13})$ = 0.005



Assuming true: $\sin^2 2\theta_{13}$=0.1, $\sin^2\theta_{23}$=0.5, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2, [NH]

[NH] Normal hierarchy, [IH] Inverted hierarchy

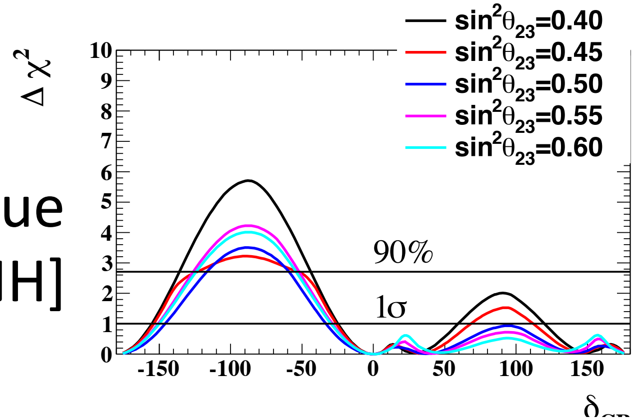
Sensitivity for Resolving $\sin\delta_{CP} \neq 0$

7.8×10^{21} POT (50% POT ν + 50% POT anti-ν)

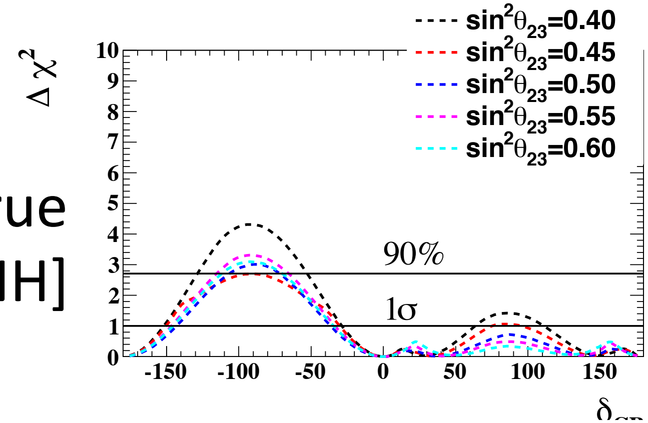
No sys. err.

w/ 2012 sys. err. (~10% ν_e, ~13% ν_μ)

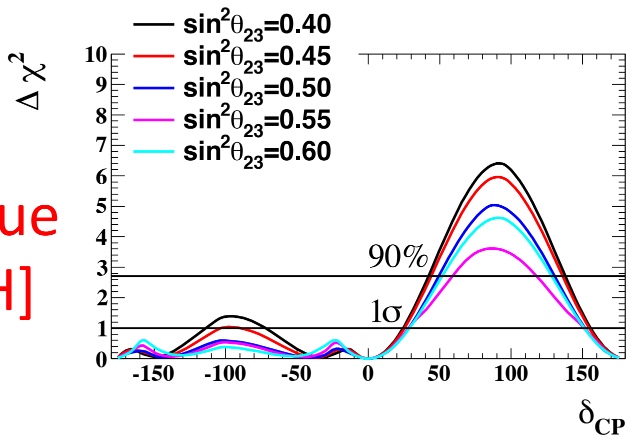
True [NH]



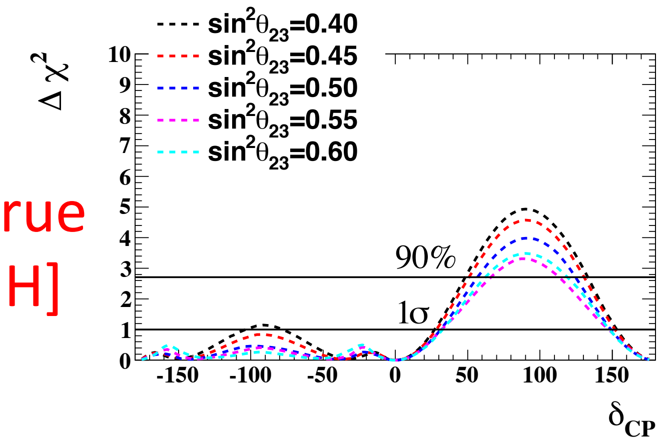
True [NH]



True [IH]



True [IH]



Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2
θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

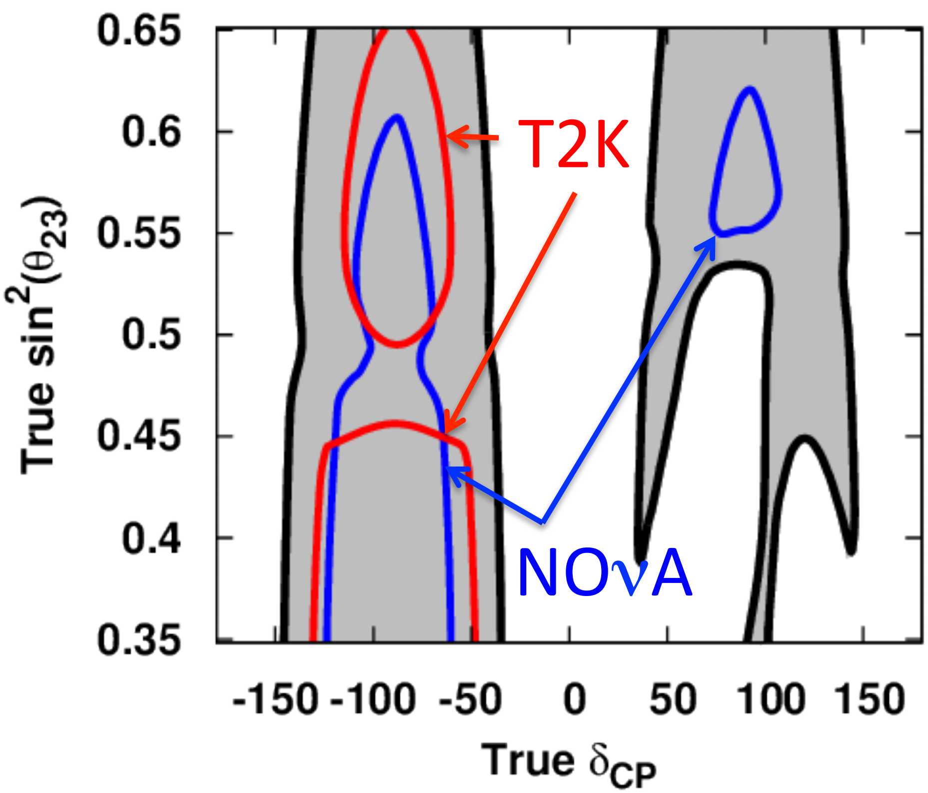
[NH] Normal hierarchy, [IH] Inverted hierarchy

T2K + NOνA Sensitivity for Resolving $\sin\delta_{CP} \neq 0$

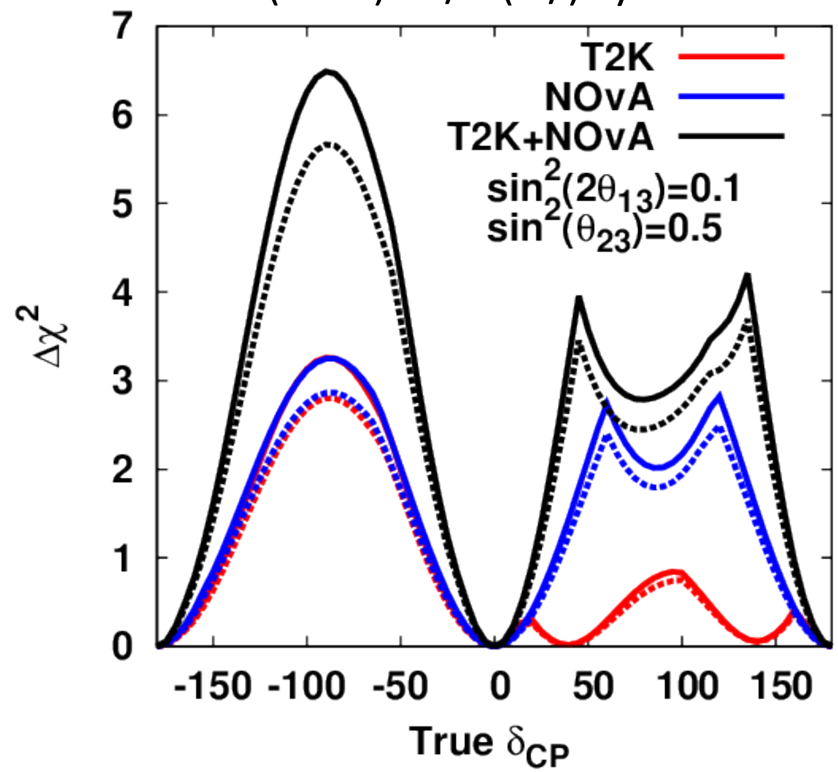
Both T2K/NOνA -> full POT (50% POT ν + 50% POT anti-ν)

Shown in [NH] case.

solid(dash): w/o (w/) systematics



Region where sinδ=0 can be excluded by 90% C.L.



Sensitivity to resolve sinδ=0

Assuming 5% (10%) normalization uncertainty on signal (background)

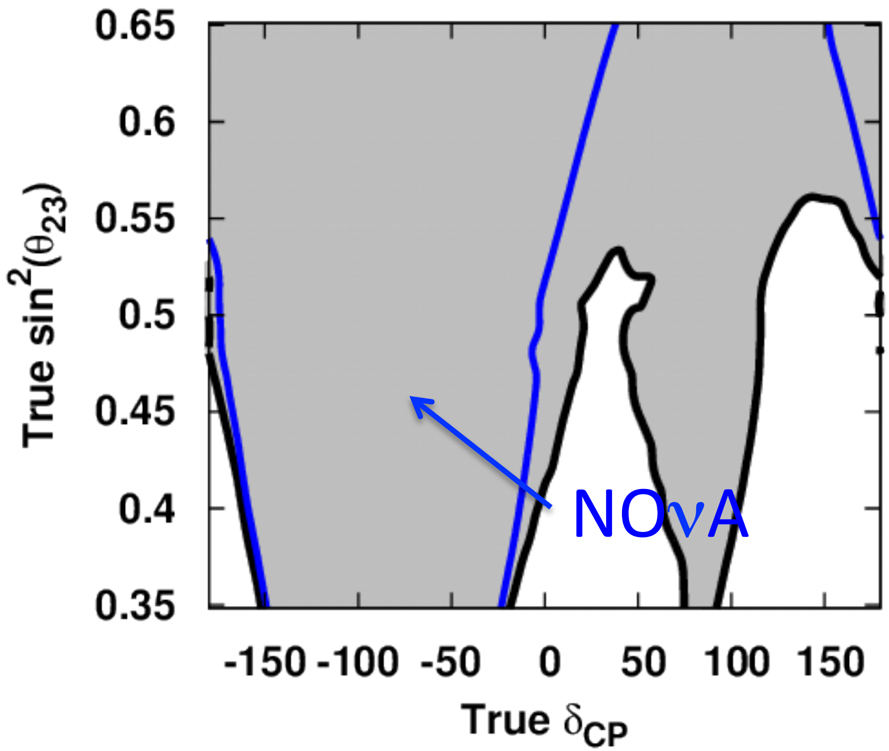
Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2, θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

[NH] Normal hierarchy, [IH] Inverted hierarchy

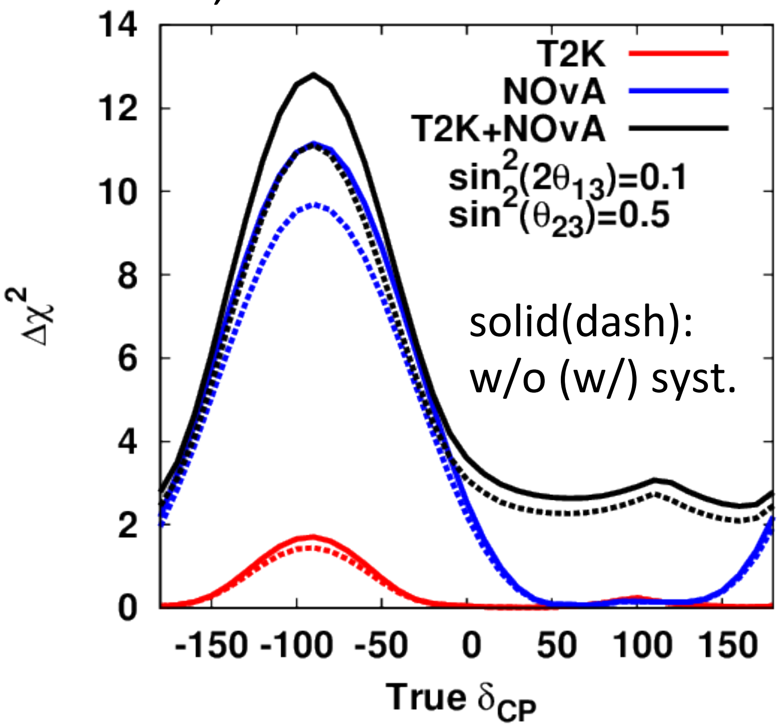
T2K + NOνA Sensitivity to Mass Hierarchy

Both T2K/NOνA -> full POT (50% POT ν + 50% POT anti-ν)
Shown in [NH] case.

Red: T2K alone, Blue: NOνA alone, Black: T2K + NOνA



Region where MH can be distinguished by 90% C.L.



Sensitivity to resolve MH

Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2, θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

Summary

- ν_μ disappearance results
  - We have measured θ_{23} with the world-leading precision
  - New result favors maximal mixing
- ν_e appearance results
  - We have constrain the CP violating phase δ_{CP} by combining our ν_e appearance results with the reactor measurements
  - Best fit is found at very interesting point, $\delta_{CP} \sim -\pi/2$. If it is true, severe competition w/ NOνA. Very important to increase statistics ASAP.
- Future sensitivity study
  - T2K can constrain δ_{CP}
  - Combined analysis w/ NOνA enhances the sensitivities to δ_{CP} and the mass hierarchy
  - Achievement of 750 kW beam operation is essential