Recent development in T2K Oscillation Analysis

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Stony Brook University

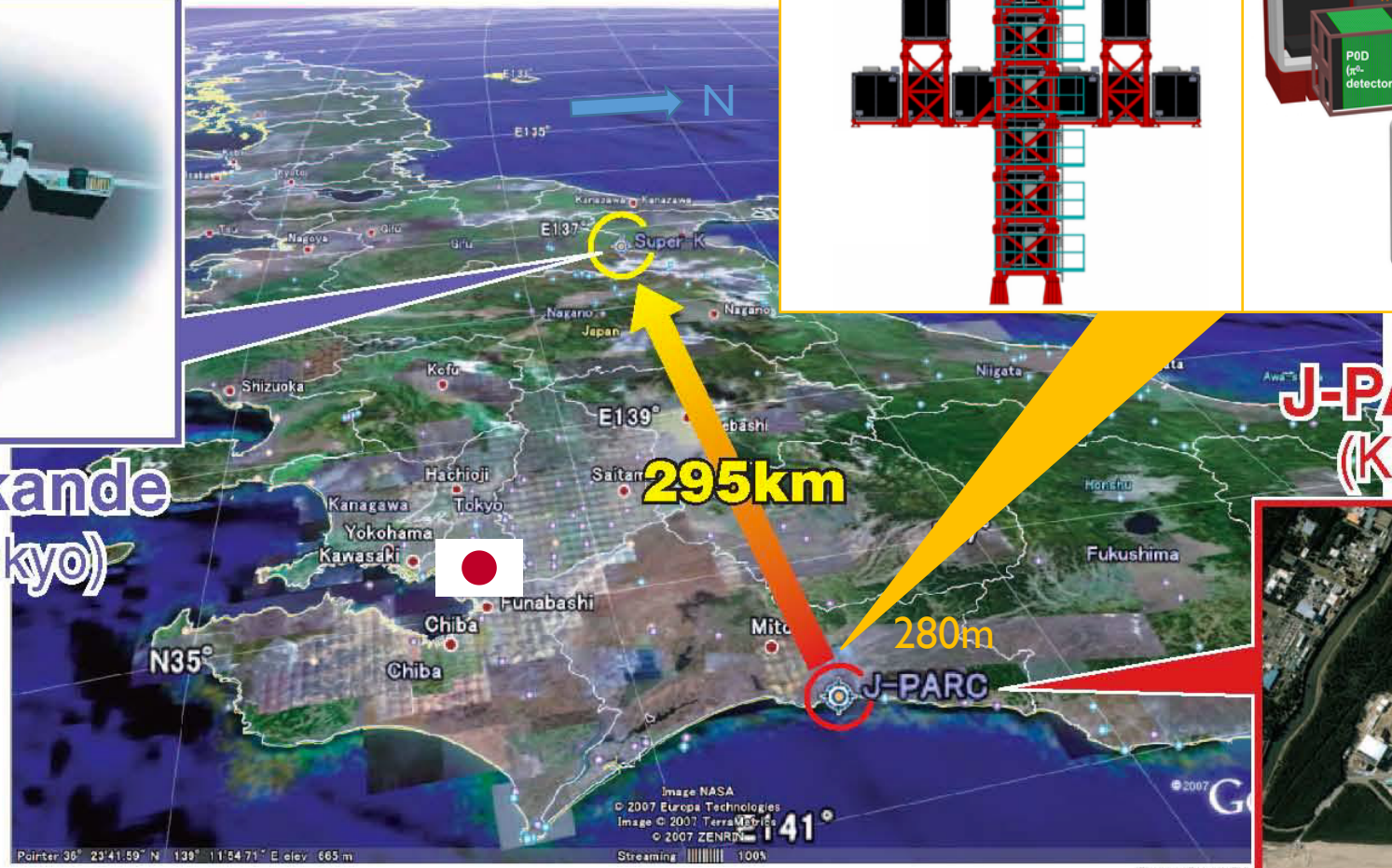
DPF – FNAL

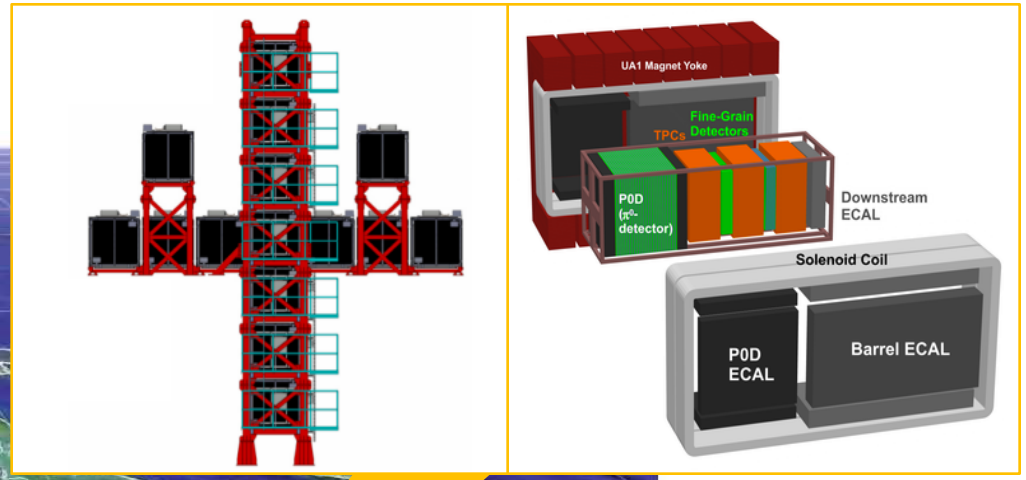
July 31st, 2017

The T2K experiment

Near detectors

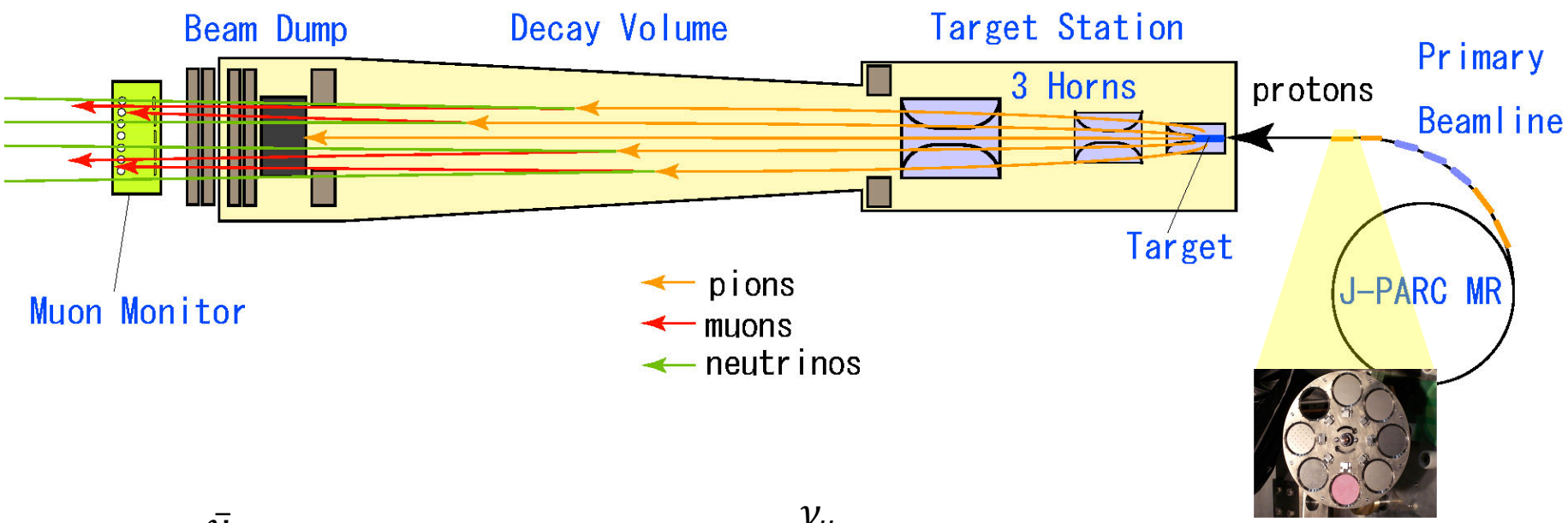
Super-Kamiokande
(ICRR, Univ. Tokyo)

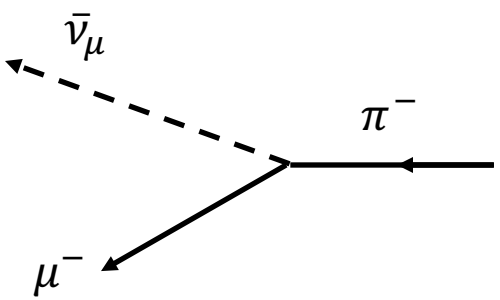


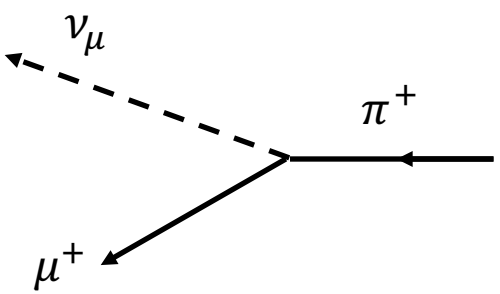


J-PARC Main Ring
(KEK-JAEA, Tokai)

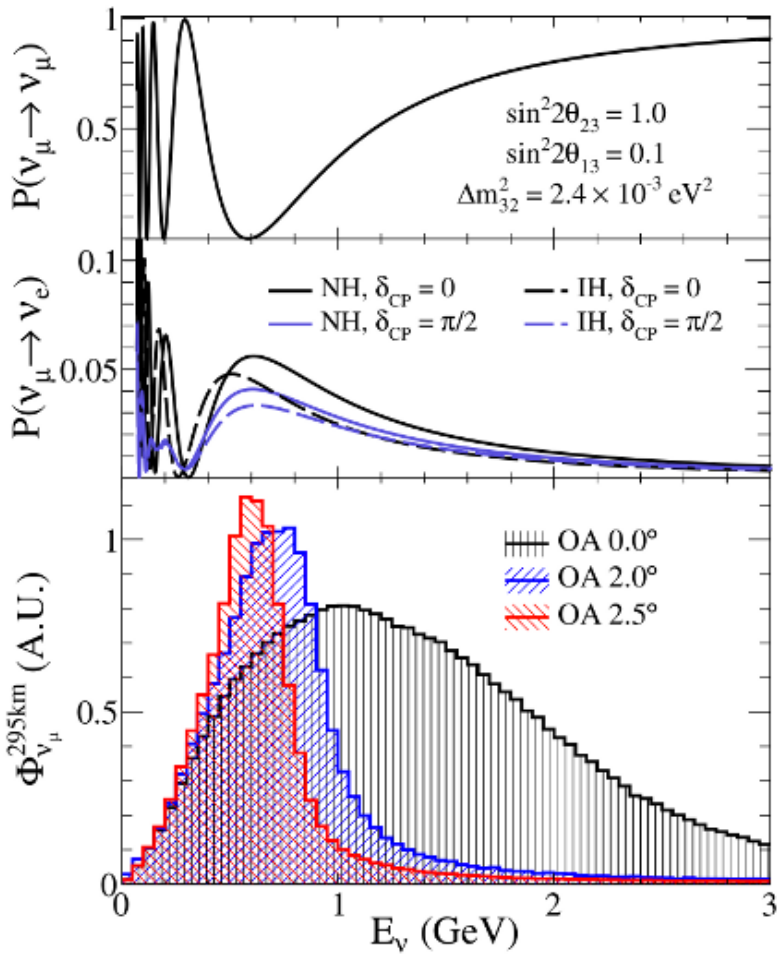
The T2K experiment – beam

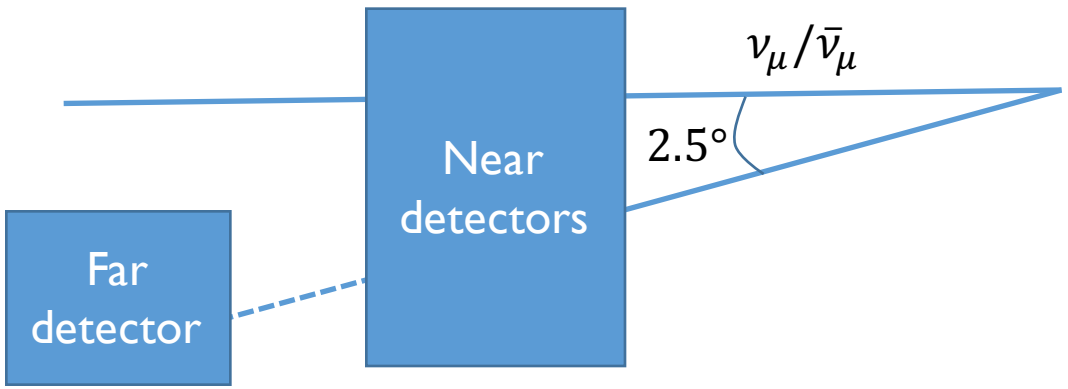






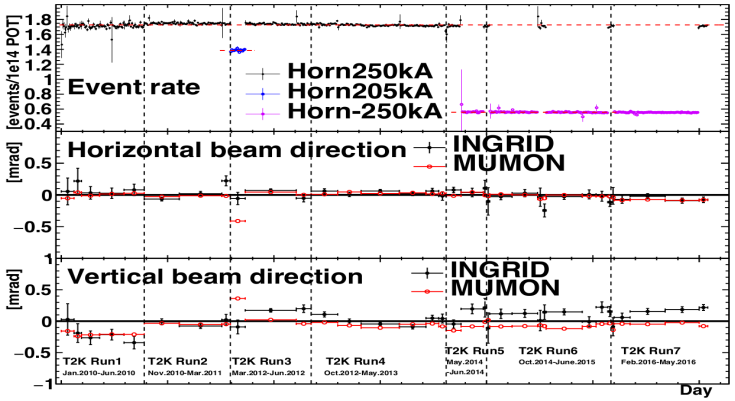
The T2K experiment – beam

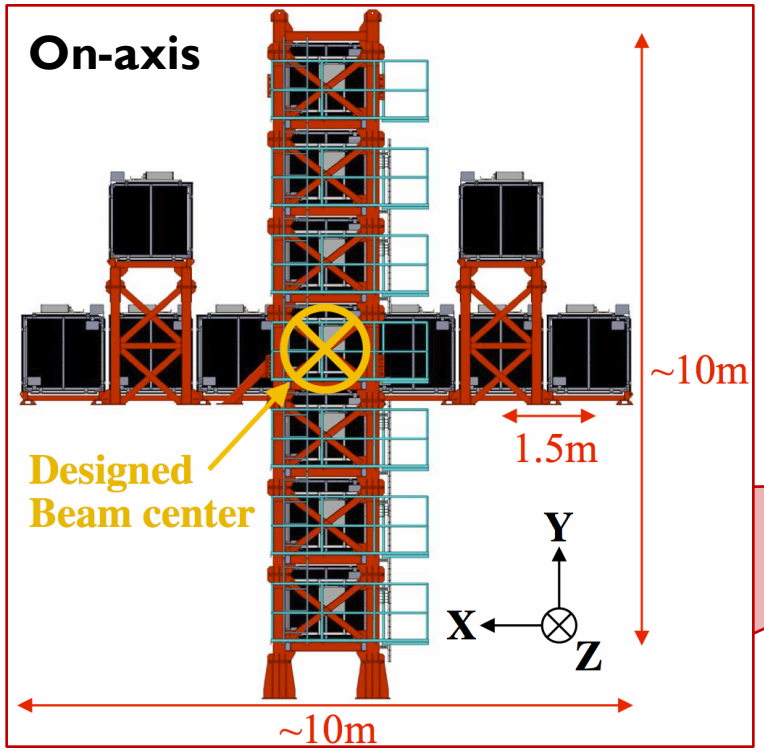


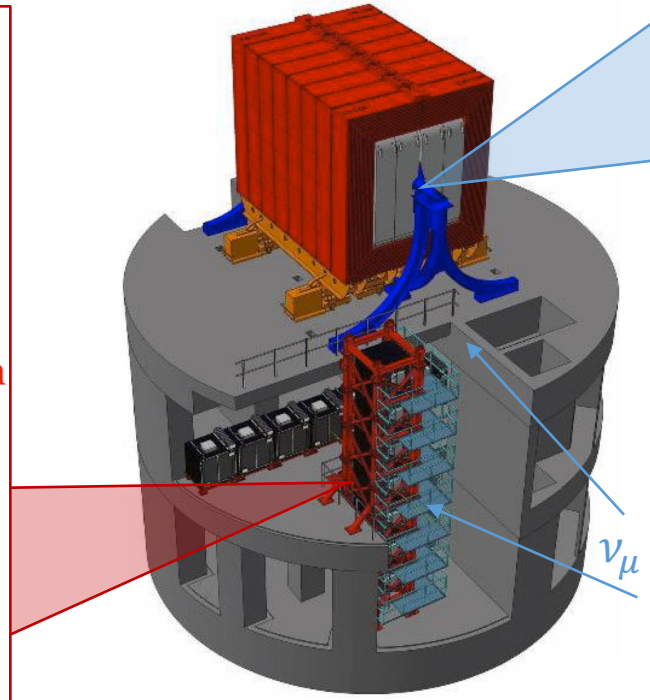


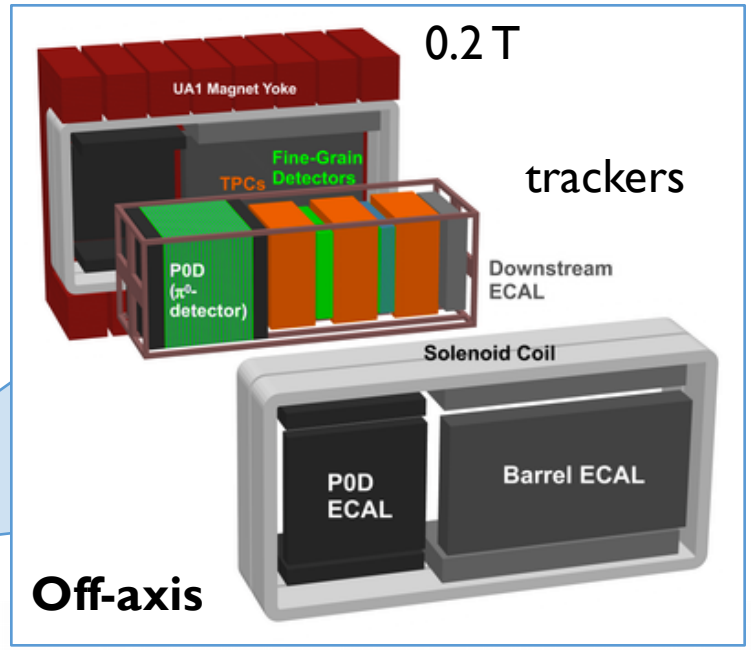
- Narrow band neutrino beam peaked at oscillation maximum (~0.6 GeV)
- Reduces intrinsic ν_e contamination
- Reduces neutrinos with higher energy; enhances CCQE mode & suppress NC mode

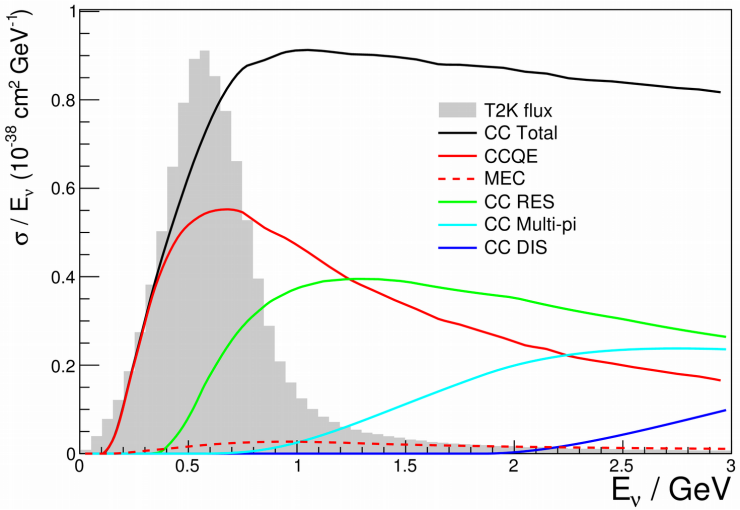
The T2K experiment – near detectors





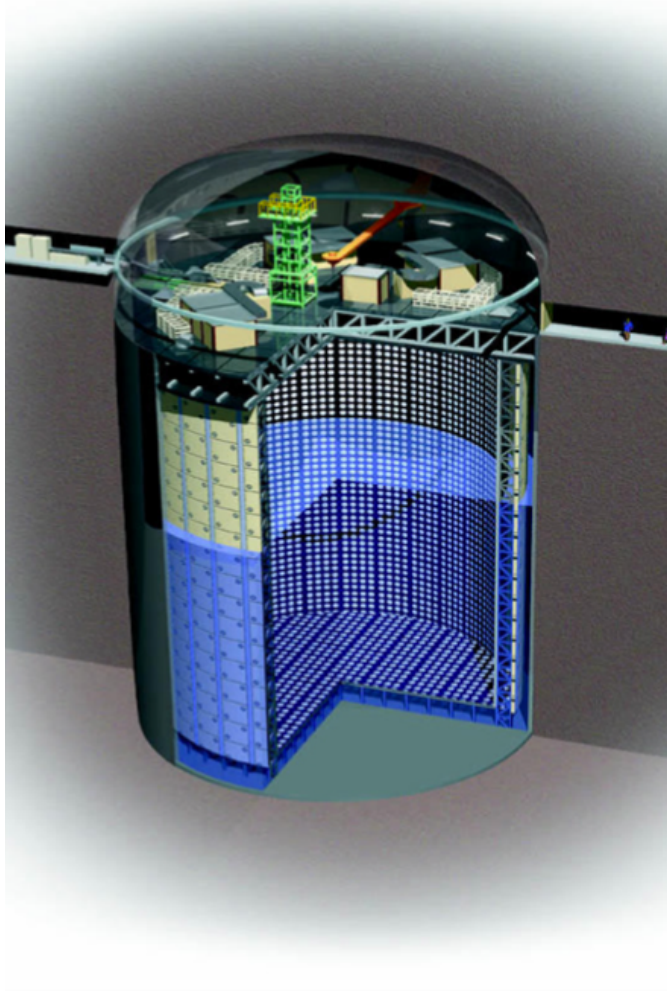




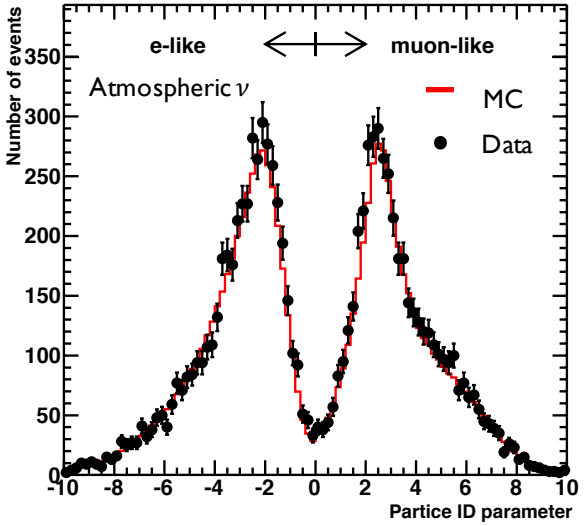


The T2K experiment – far detector

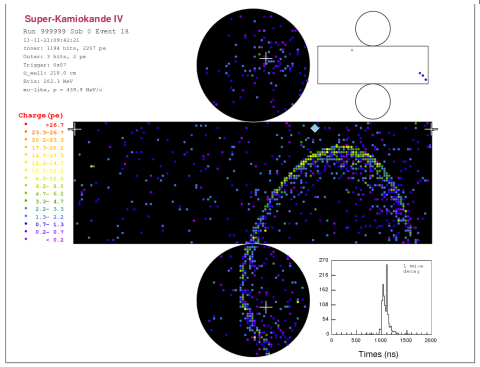
Super-Kamiokande



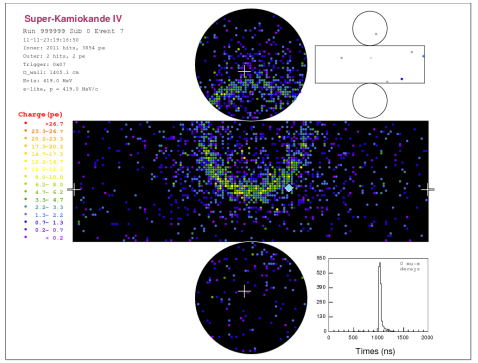
- 50 kilo-ton Water Cherenkov detector
- Outer detector to veto cosmic background
- Excellent e/μ separation
- Cannot separate $\nu/\bar{\nu}$
- Cannot detect particles below Cherenkov threshold



ν_μ CCQE



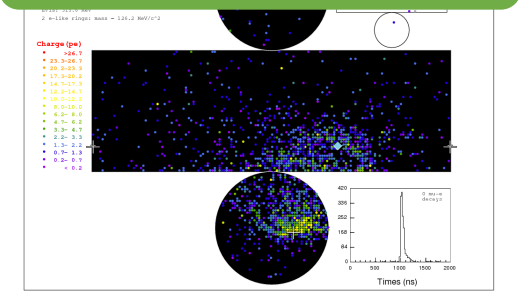
ν_e CCQE



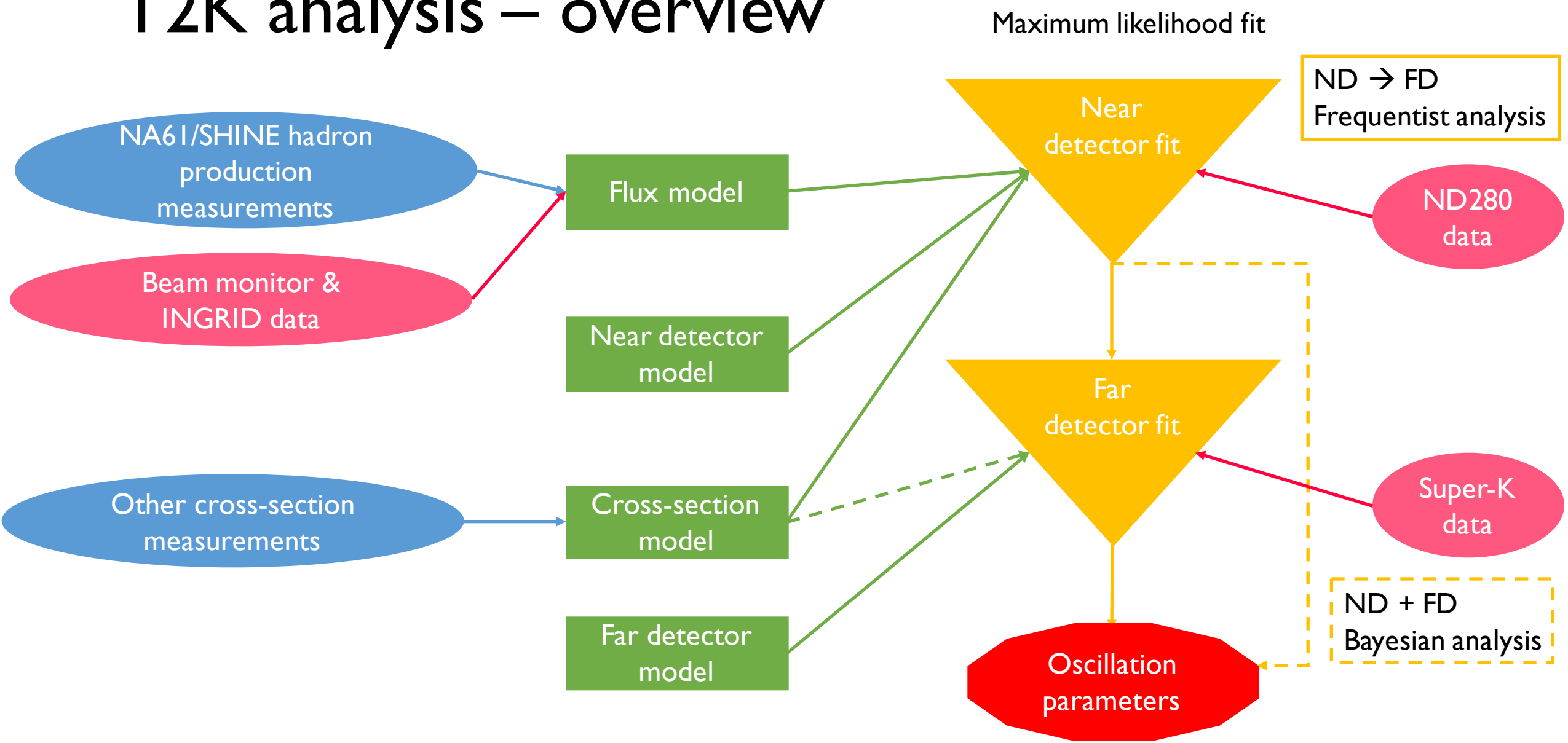
T2K Signal

- $\nu_\alpha + n \rightarrow l_\alpha^- + p$
- $\bar{\nu}_\alpha + p \rightarrow l_\alpha^+ + n$
- Energy reconstruction based on lepton kinematics → select CCQE-enriched samples

NC1π^0 background

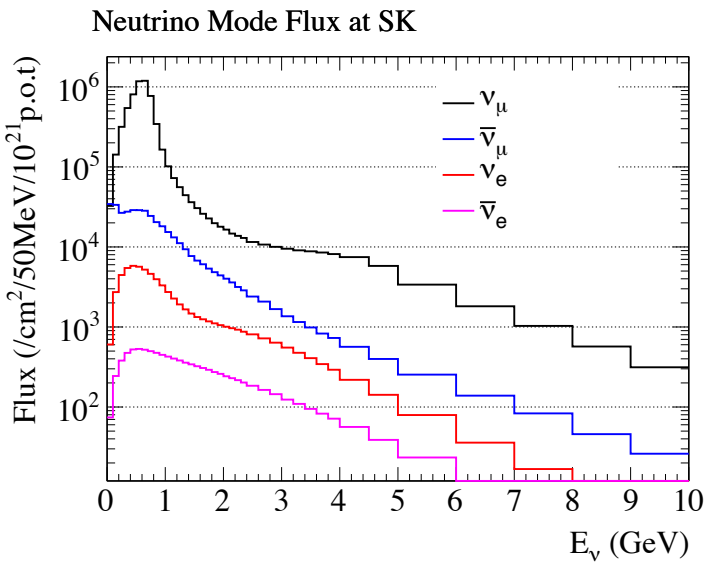


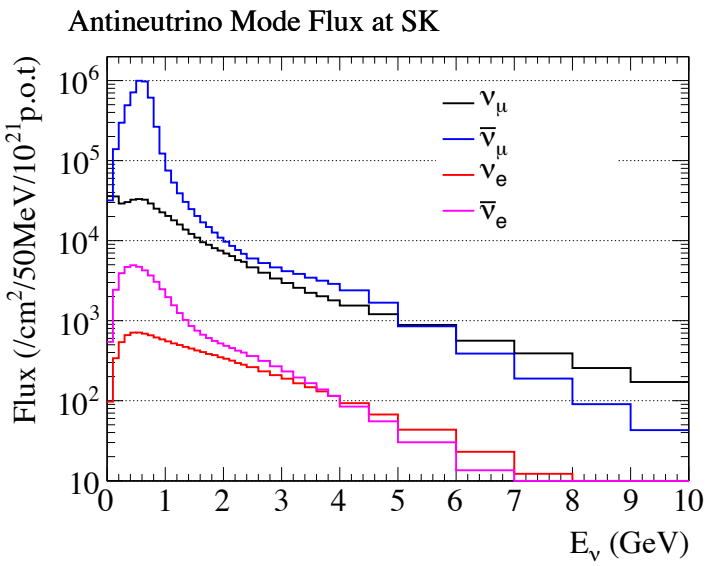
T2K analysis – overview

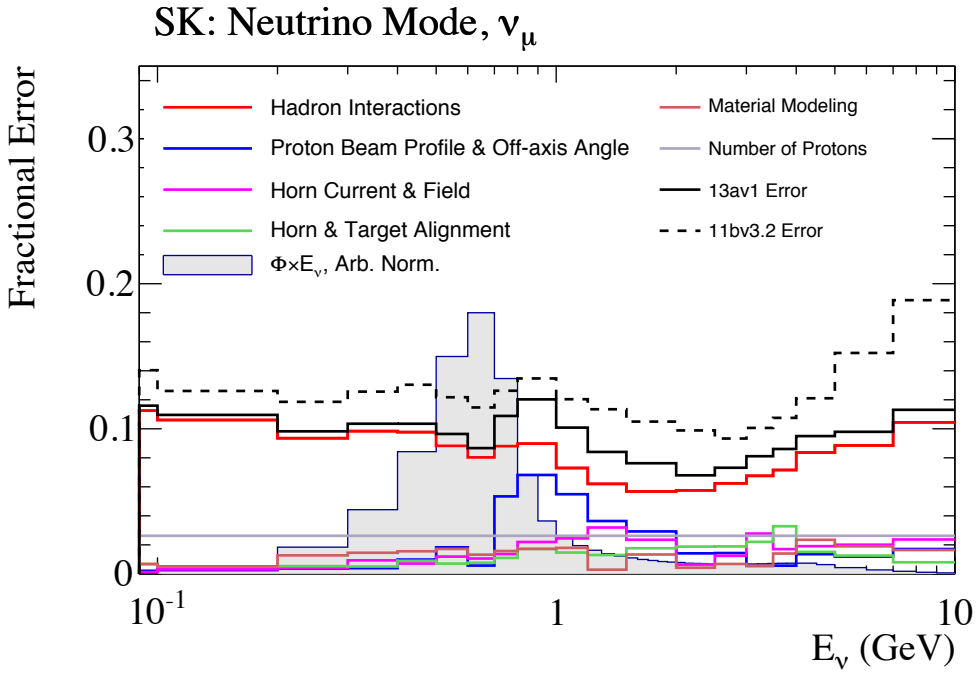


Flux prediction and uncertainties

- FLUKA/Geant3-based neutrino beam simulation
  - "Wrong-sign" component
  - Significant ν component in $\bar{\nu}$ beam
  - ~0.5% intrinsic $\nu_e(\bar{\nu}_e)$







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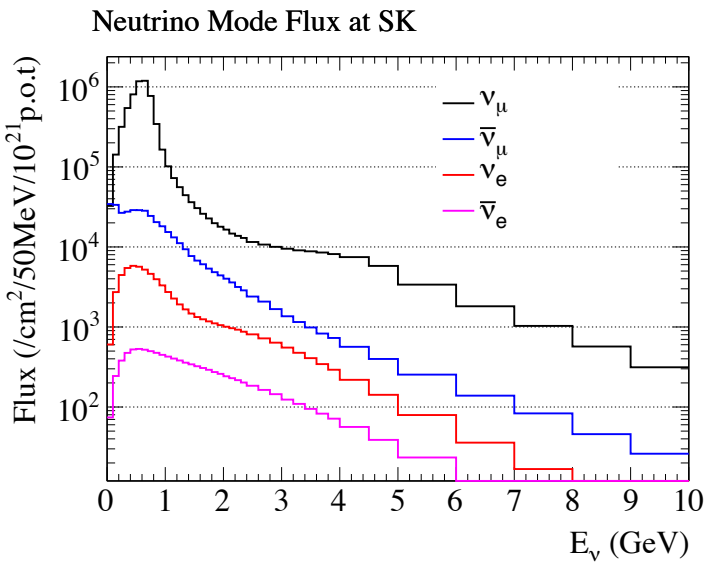
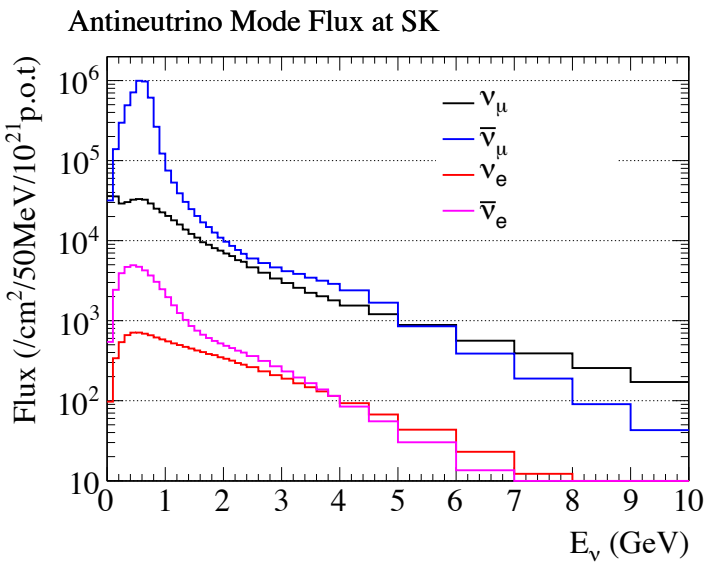
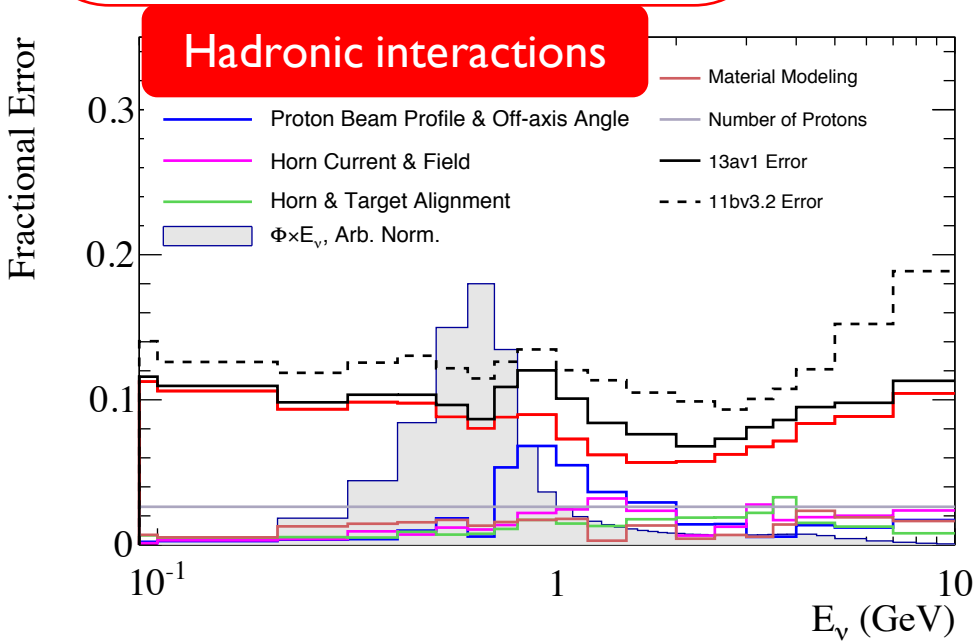
- Constrained by NA61/SHINE experiment
  - Thin carbon target and replica target
  - $\pi^{\pm}, K^{\pm}, K_S^0$ production







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- FLUKA/Geant3-based neutrino beam simulation
  - "Wrong-sign" component
  - Significant ν component in $\bar{\nu}$ beam
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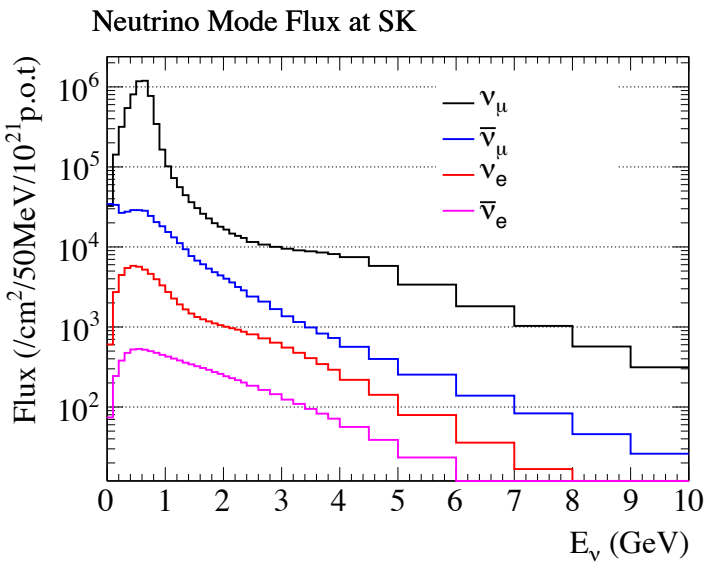
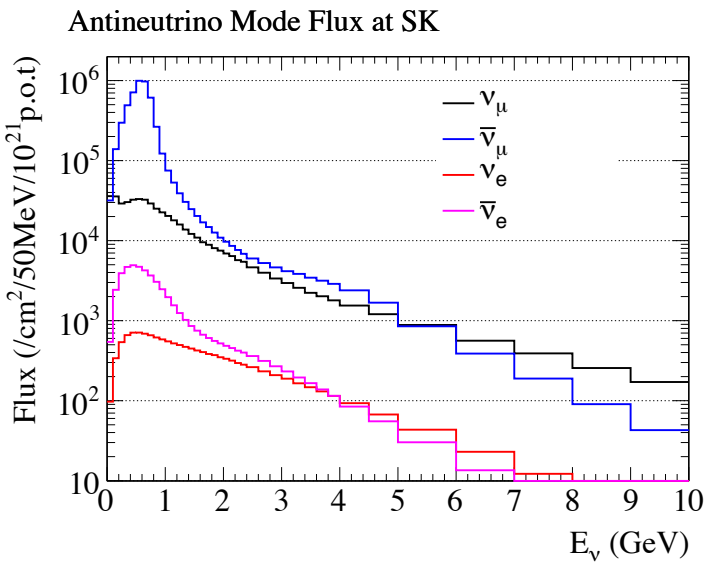
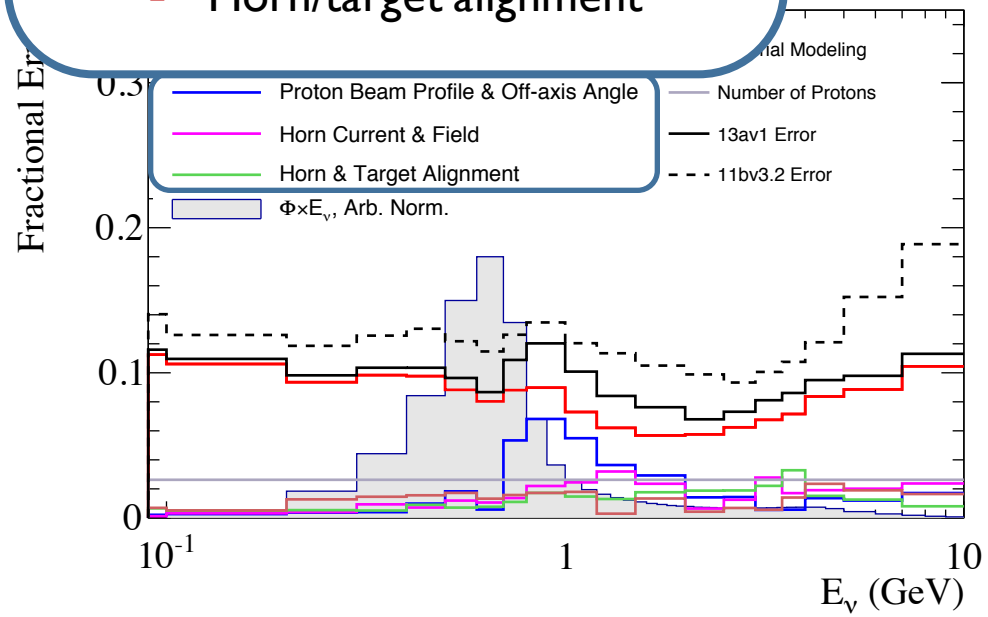
- In-situ measurements to constrain
  - Proton beam profile
  - Off-axis angle
  - Horn/target alignment







Cross-section modeling

- NEUT event generator

Y. Hayato. Acta Physica P. A neutrino interaction simulation program library neutolonica B, 40(9):2477, Sep 2009.

- CCQE
  - Global Relativistic Fermi Gas (RFG) + Random Phase Approximation (RPA)

PHYSICAL REVIEW C 70, 055503 (2004)

- Multi-nucleon interactions
  - ~10% relative to CCQE
  - 2p2h model by Nieves *et al*

Phys. Rev. C, 83:045501, Apr 2011.

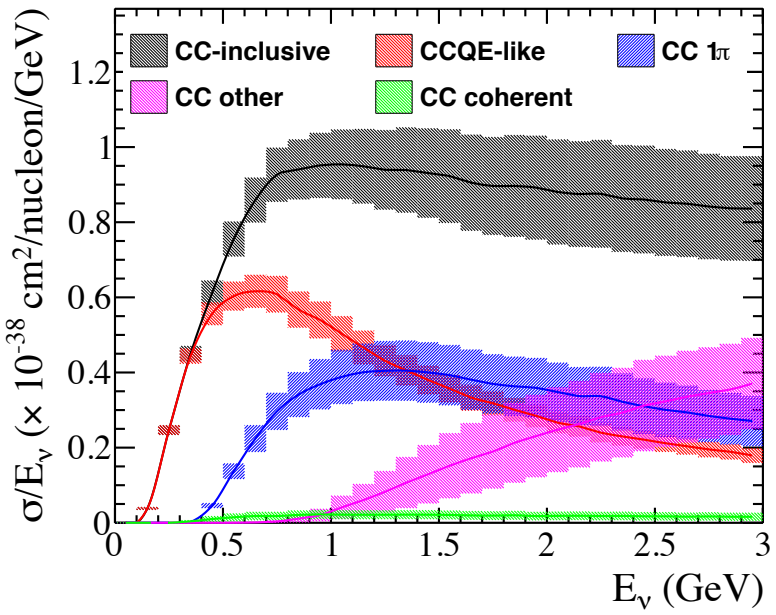
Phys. Rev., D88(11):113007, 2013

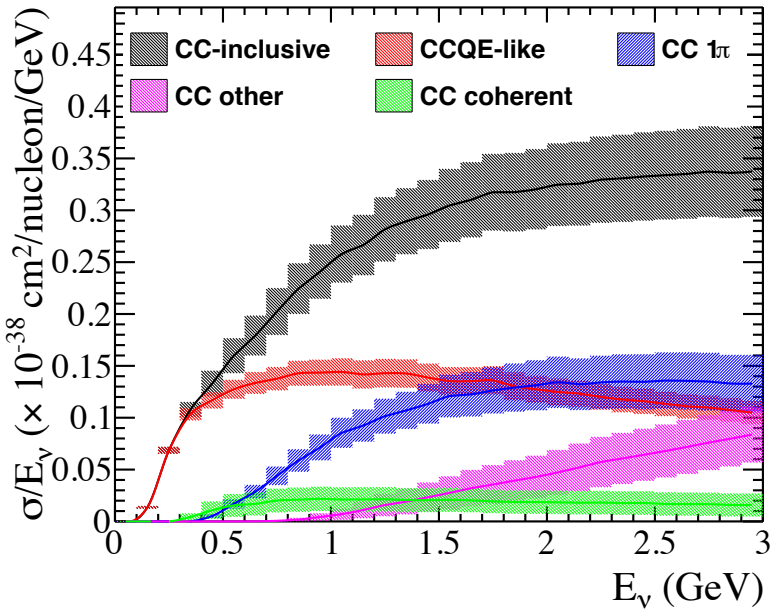
- Single resonant pion interactions
  - Rein-Sehgal model with modified Delta form factor tuned to bubble chamber data

Phys. Rev., D77:053001, 2008.

Tuned to MiniBooNE and MINERvA

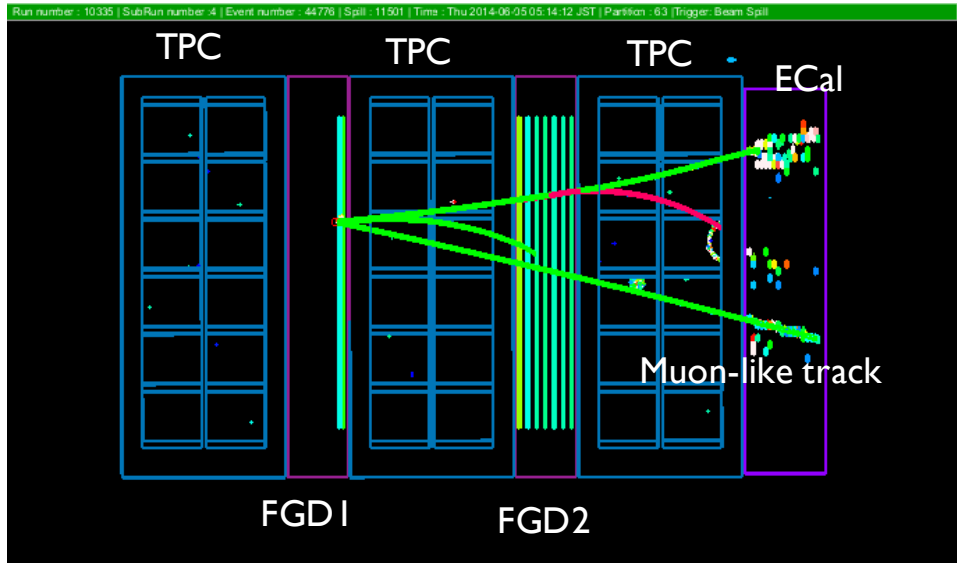
- Final state interaction (FSI) and Secondary interaction(SI)
  - Pion cascade model tuned by external pion scattering measurements
- Extensive studies of analysis sensitivity to different cross-section models



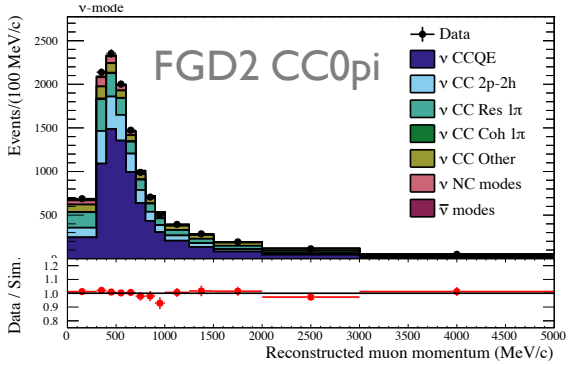


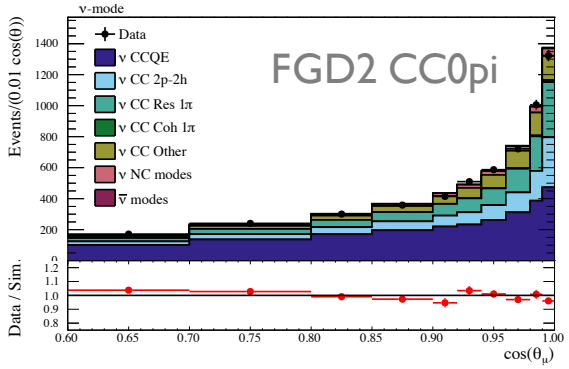
Near detector fit

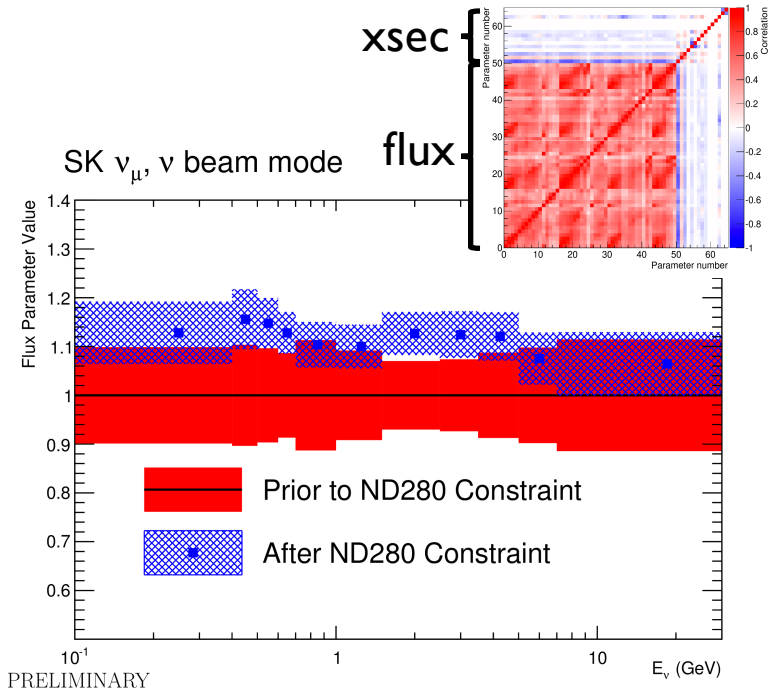
- Select CC $\nu_\mu, \bar{\nu}_\mu$ interactions with vertex in either Fine-Grained Detectors (FGD)
  - FGD1: CH target
  - FGD2: 42% water by mass
- Event samples provide information on flux and cross-section



- A likelihood fit to all ND samples is performed; tuned flux and cross-section parameters are provided to far detector analysis



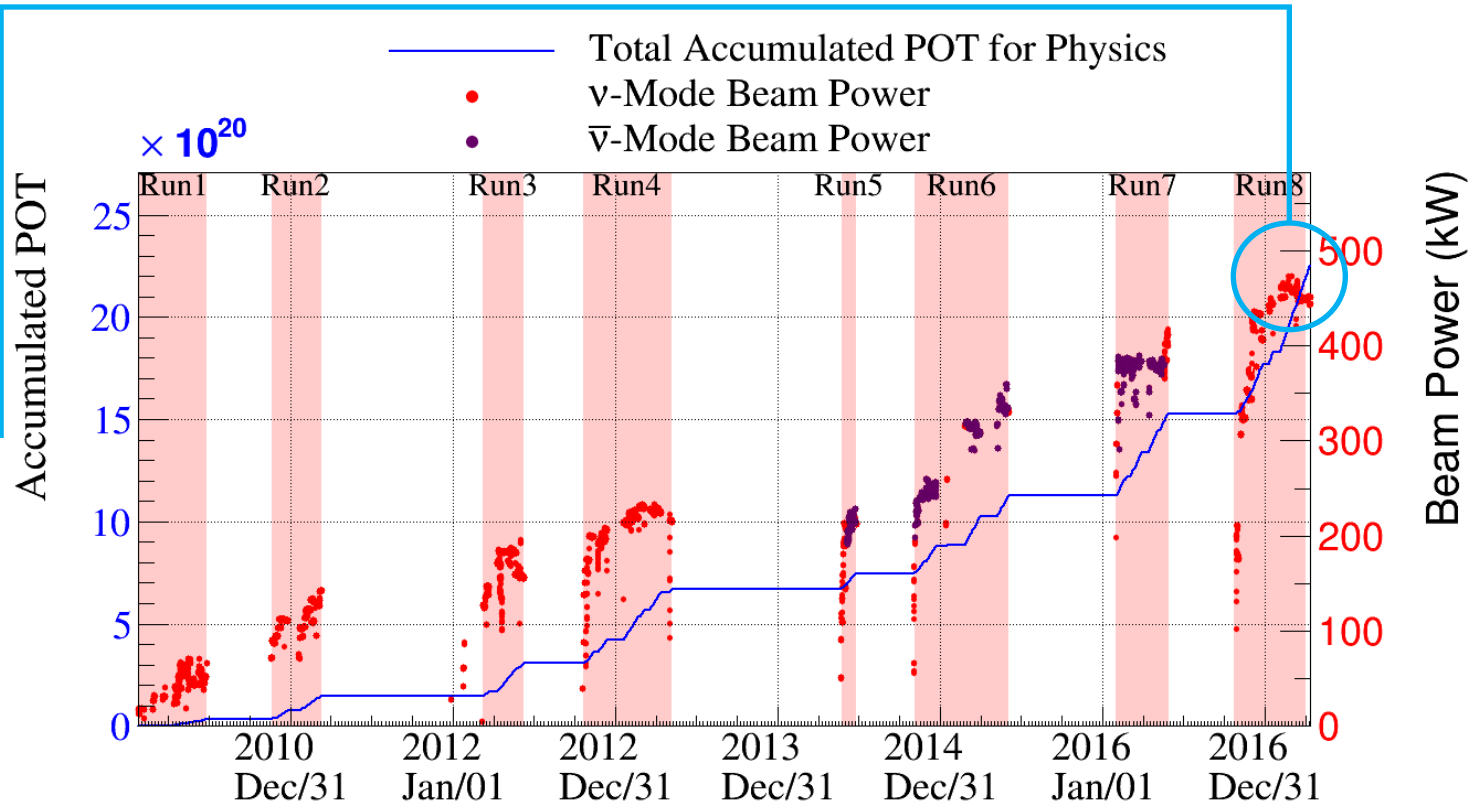




Total N_{SK} Fractional Uncertainty			
Beam mode	Sample type	w/o ND280	w/ ND280
ν	μ-like	12.3%	5.1%
ν	e-like	12.0%	5.5%
anti-ν	μ-like	12.9%	5.2%
anti-ν	e-like	14.1%	6.3%

Data sample

- Stable running at 470kW achieved during Run8
- Ongoing studies to further improve beam power



Results shown today are from T2K Run1-7 data analysis

- ν-mode: 7.48×10^{20} POT
- $\bar{\nu}$-mode: 7.47×10^{20} POT

Run8: 7.25×10^{20} POT in ν-mode
Results coming out soon!

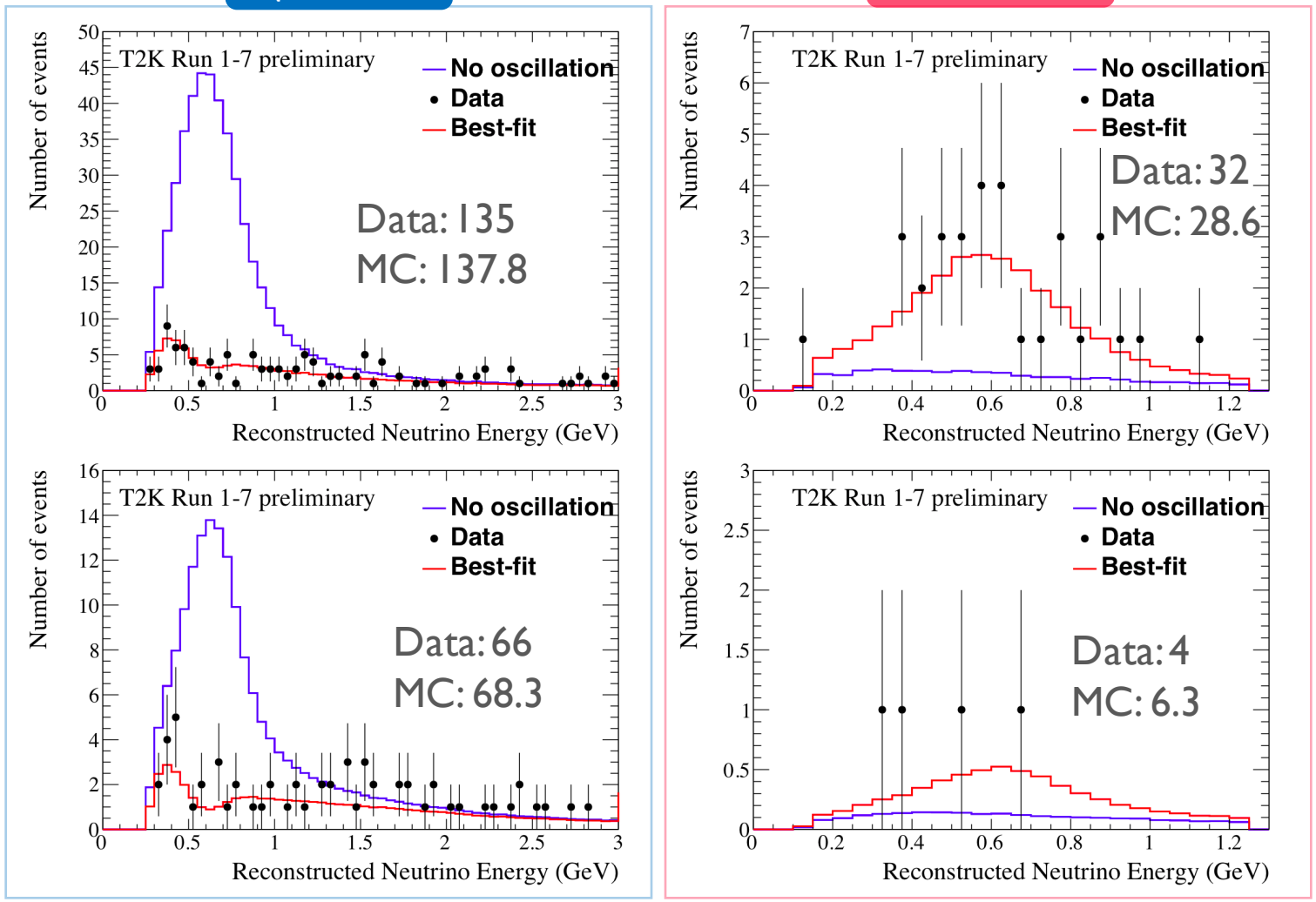
Run period	Dates	ν-mode POT ($\times10^{20}$)	$\bar{\nu}$-mode POT ($\times10^{20}$)
Run 1	Jan. 2010 - Jun. 2010	0.323	–
Run 2	Nov. 2010 - Mar. 2011	1.108	–
Run 3	Mar. 2012 - Jun. 2012	1.579	–
Run 4	Oct. 2012 - May 2013	3.560	–
Run 5	May 2014 - Jun. 2014	0.242	0.506
Run 6	Nov. 2014 - Jun. 2015	0.190	3.505
Run 7	Feb. 2016 - May 2016	0.480	3.520
Run 8	Nov. 2016 - May 2017	7.252	–
Total	Jan. 2010 - May 2017	14.734	7.531

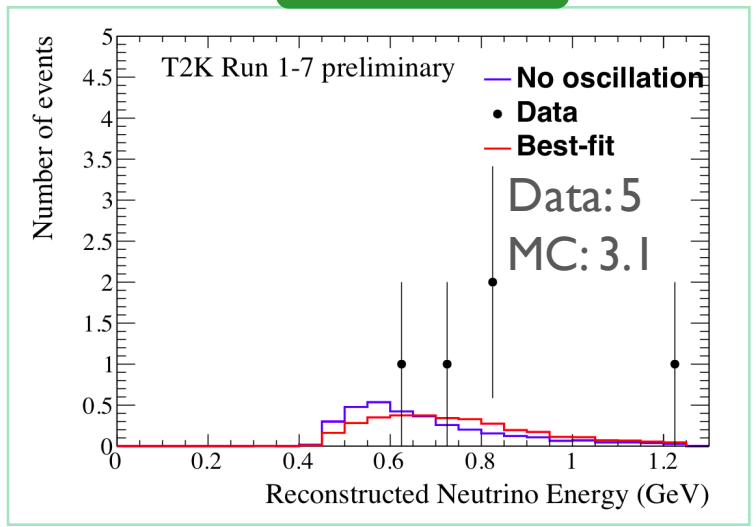
Far detector data samples

ν_μ CC0π | ν_e CC0π | ν_e CC1π^+

ν-mode

$\bar{\nu}$-mode



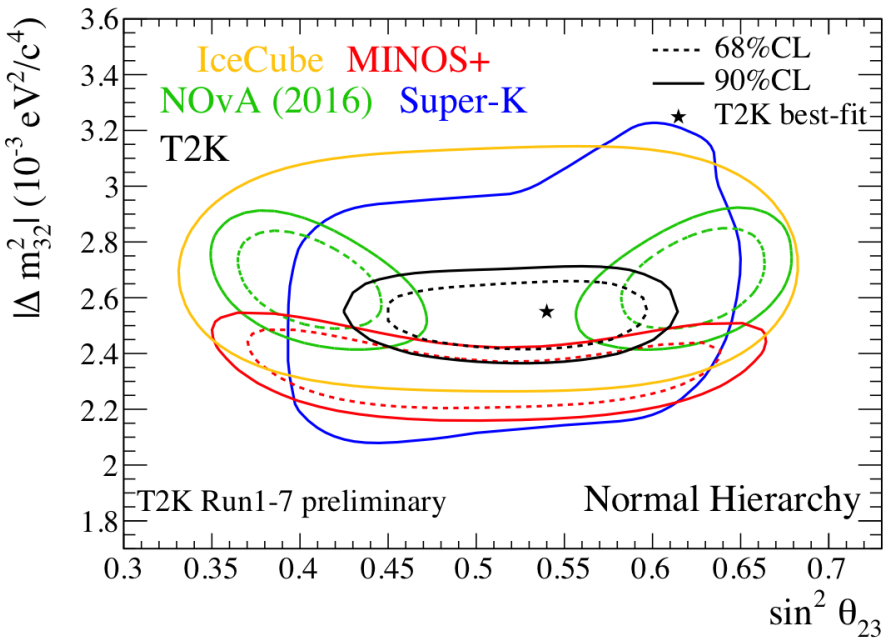


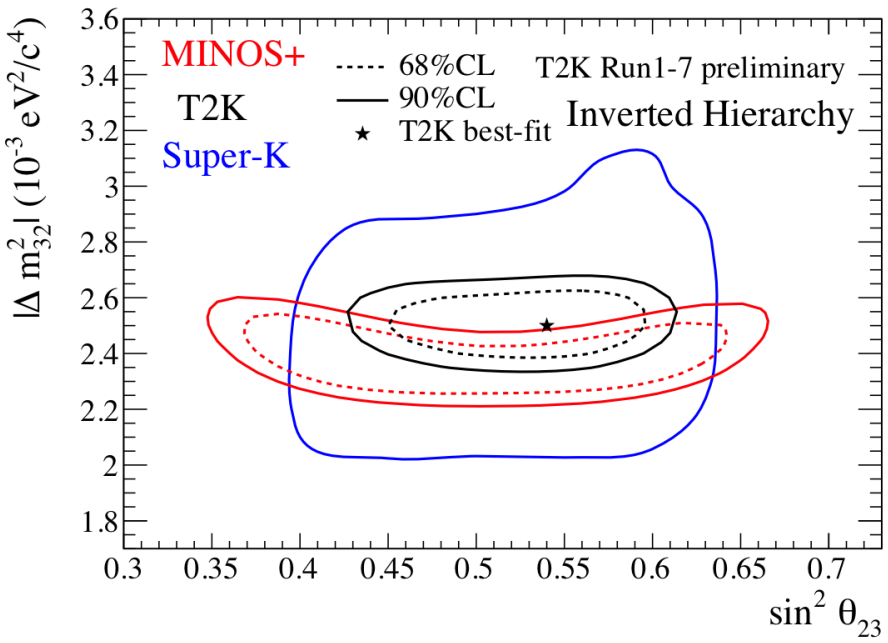
CC-0π 1R$_\mu$ rings	CC-0π 1R$_e$ rings	CC-1π^+ 1R$_e$ rings
event in SK fiducial volume		
exactly 1 Cherenkov ring		
PID is μ-like	PID is e-like	
$p_\mu^{rec} > 200$ MeV	visible energy > 100 MeV	
≥ 1 electron decay	0 electron decay	$= 1$ electron decay
	reconstructed $E_\nu < 1.25$ GeV	
	fitQun π^0 rejection	

Current Results – Joint Analysis θ_{23} & Δm^2_{23}

T2K + Reactor
$\sin^2\theta_{13} = 0.085 \pm 0.005$

* 5 samples
frequentist analysis

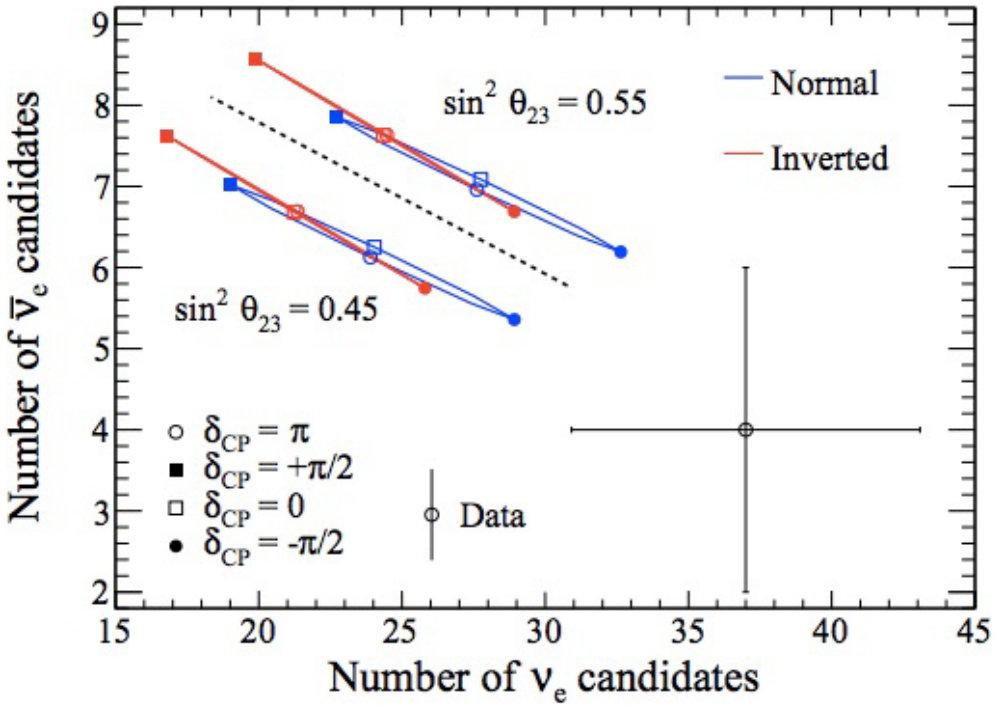




- T2K data favors maximal disappearance and are consistent with maximal mixing
- Consistent with results from other experiments

1D parameter constraints		
	NH	IH
$\sin^2\theta_{23}$	$0.550^{+0.051}_{-0.085}$	$0.552^{+0.048}_{-0.083}$
$\lvert\Delta m^2_{23}\rvert$ $(\times 10^{-3} eV)$	$2.540^{+0.080}_{-0.081}$	$2.510^{+0.078}_{-0.081}$

Current Results – Joint Analysis δ_{CP}



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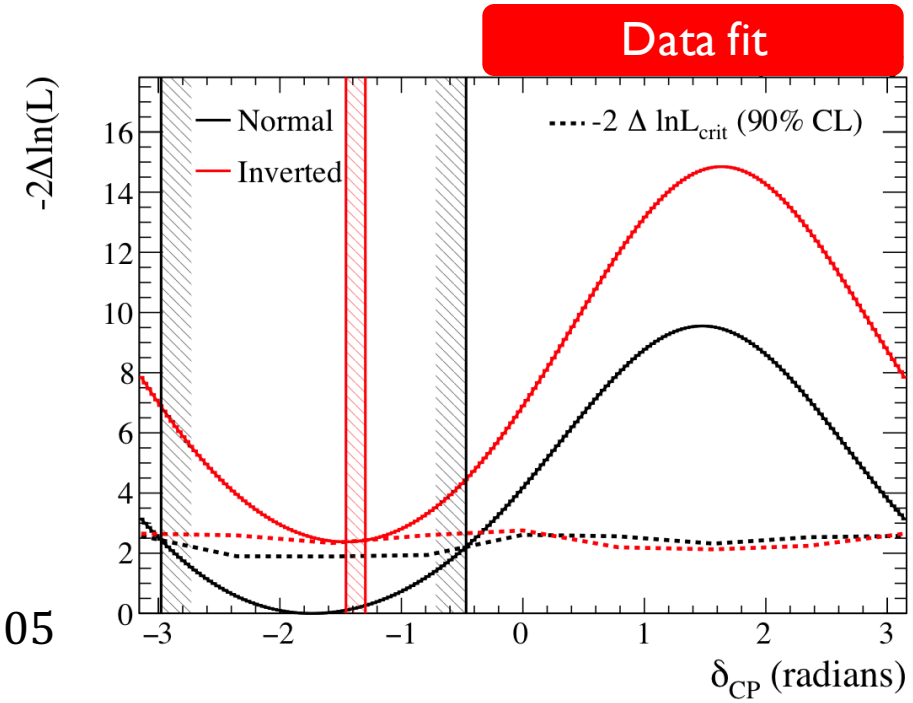
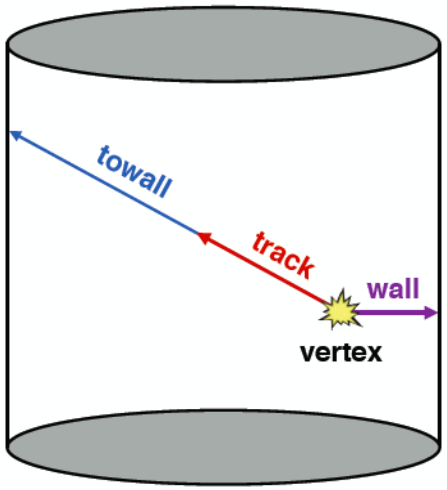


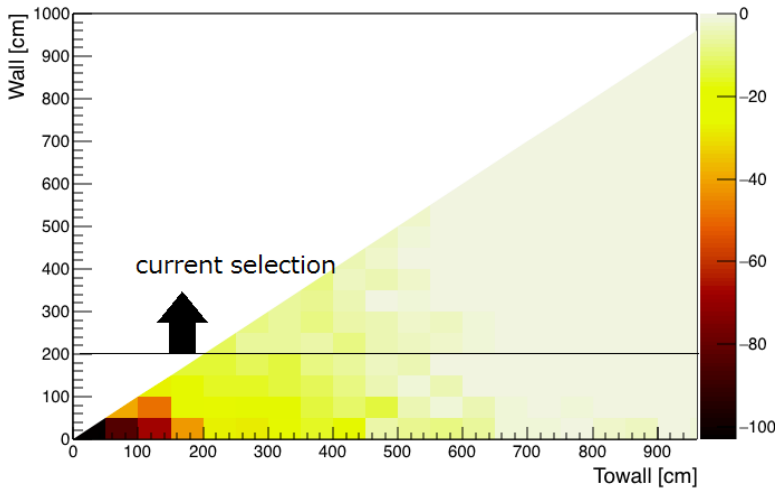
- Data prefers largest CP asymmetry $\delta_{CP} = -\pi/2$, normal hierarchy

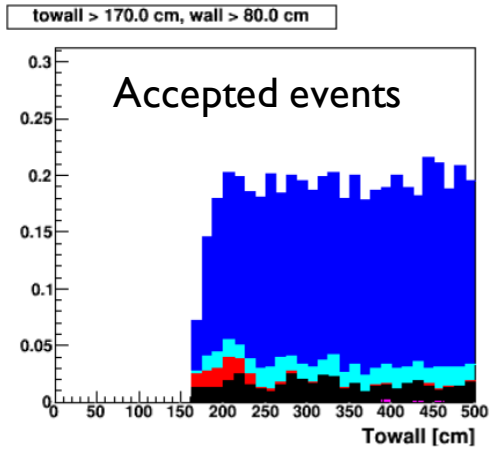
- CP conservation disfavored at 90% C. L.
- Normal hierarchy: $\delta_{CP} = [-2.978, -0.467]$ at 90% C.L.
- Inverted hierarchy: $\delta_{CP} = [-1.466, -1.272]$ at 90% C.L.

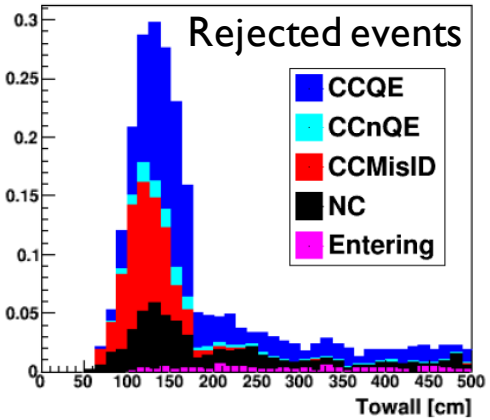
Recent developments



Reconstructed momentum bias





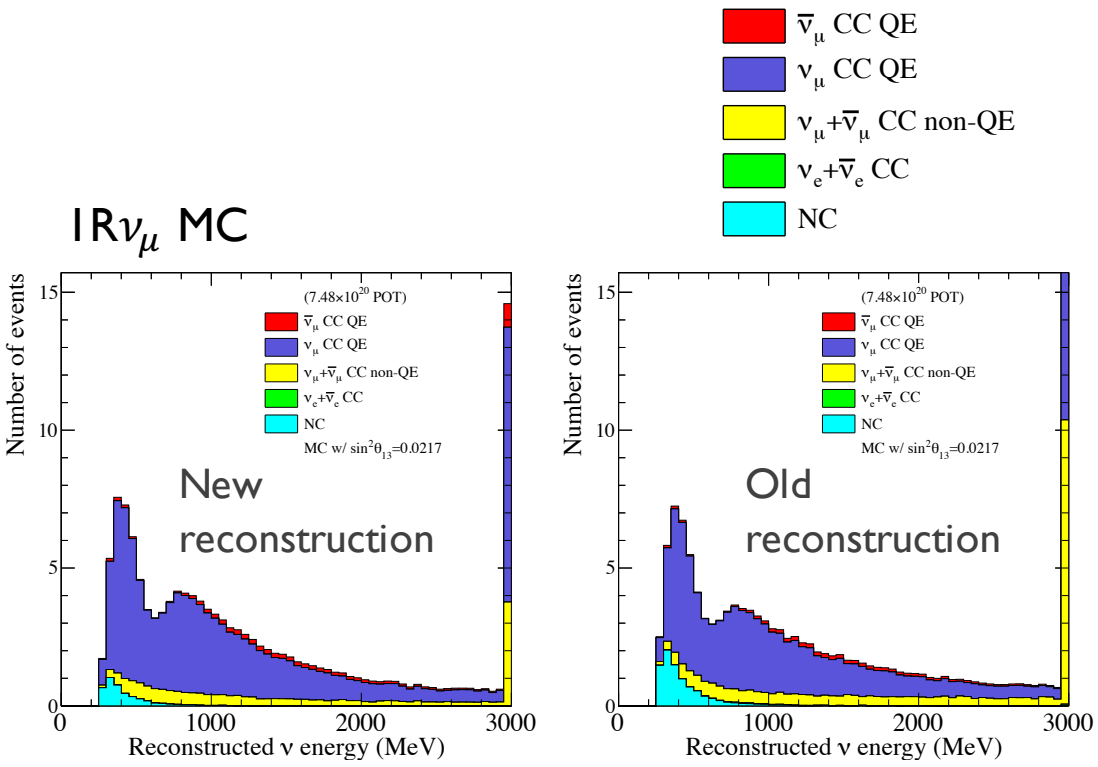


- SK fiducial volume is expanded
  - Use atmospheric neutrino data to estimate detector systematics in different detector regions
  - Optimize fiducial cut for each T2K sample for sensitivity to oscillations with systematics in different detector regions taken into account

Sample	Towall cut (cm)	Wall cut (cm)
CCQE 1-ring e-like FHC	170	80
CCQE 1-ring μ-like FHC	250	50
CC1π 1-ring e-like FHC	270	50
CCQE 1-ring e-like RHC	170	80
CCQE 1-ring μ-like RHC	250	50

Recent developments

- New reconstruction algorithm is used at SK
  - Enhanced e/μ separation
- Optimized event selection for sensitivity to oscillation parameters
  - All systematics taken into account
  - Maximize sensitivity to precision of $\sin^2\theta_{23}$ for ν_μ samples
    - Introduce μ/π separation cut in ν_μ sample for the first time
  - Maximize sensitivity to reject $\delta_{CP} = 0$ for ν_e samples
- Total effective statistical improvement is **33%**
  - ~15% signal increase and ~50% NC background reduction in ν_μ
  - ~23% statistical increase in ν_e sample
  - ~33% signal increase and background reduction in ν_e CC1π^+ sample

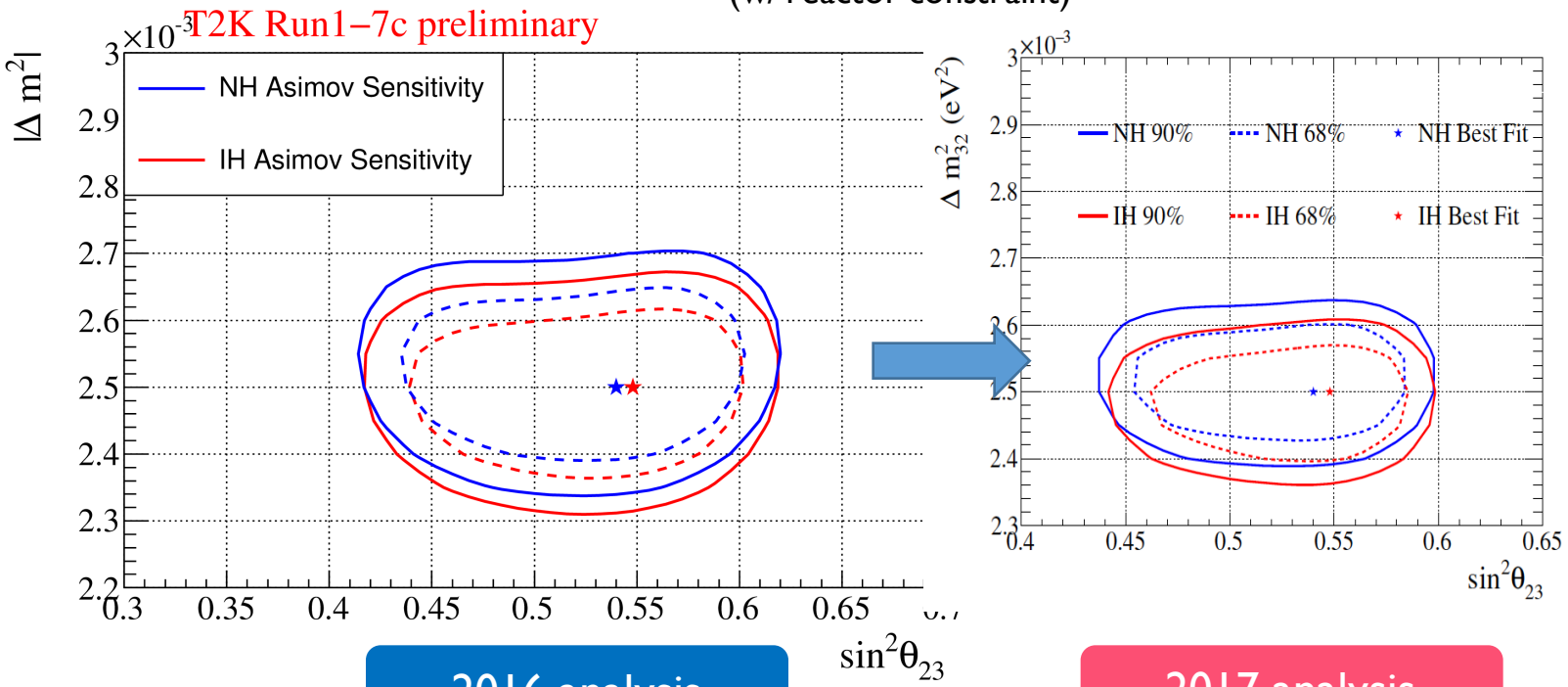


Sample	Event #		purity	
	New	Old	New	Old
CCQE 1-ring e-like FHC	69.5	56.5	81.2%	81.4%
CCQE 1-ring μ-like FHC	261.6	268.7	82.9%	71.4%
CC1π 1-ring e-like FHC	6.9	5.6	78.8%	72.0%
CCQE 1-ring e-like RHC	7.6	6.1	62.0%	63.3%
CCQE 1-ring μ-like RHC	62.0	65.4	79.7%	68.1%

Recent developments

Parameters	Set A
Δm^2_{21}	7.53×10^{-5} eV^2
Δm^2_{32}	2.509×10^{-3} eV^2
$\sin^2\theta_{23}$	0.528
$\sin^2\theta_{12}$ ($\sin^2 2\theta_{12}$)	0.304 (0.846)
$\sin^2\theta_{13}$ ($\sin^2 2\theta_{13}$)	0.0219 (0.0857)
δ_{CP}	-1.601
Earth matter density	2.6 g/cm^3
Baseline length	295 km
Mass hierarchy	Normal

T2K sensitivity
(w/ reactor constraint)



2016 analysis

Old reconstruction and Run1-7 statistics

2017 analysis

New reconstruction and Run1-8 statistics

- Run8 doubles ν-mode statistics
- Improvements in cross-section modeling
  - Inclusion of RPA uncertainty
  - 2p2h normalization + shape uncertainties
  - New tuning of the uncertainties on single resonant pion production

* 2017 analysis uses new samples

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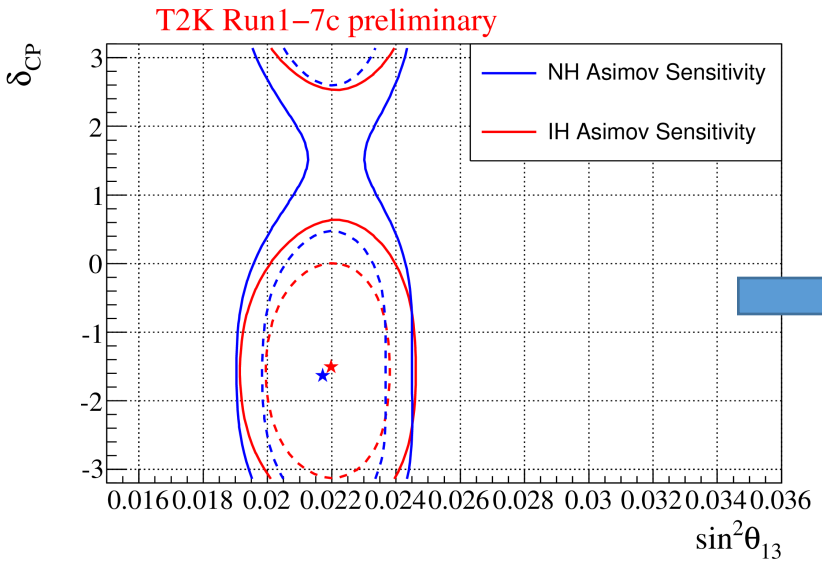

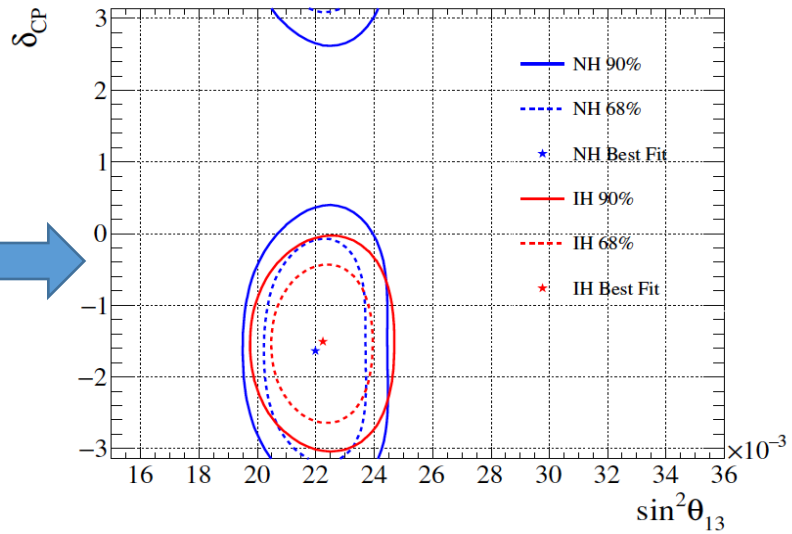

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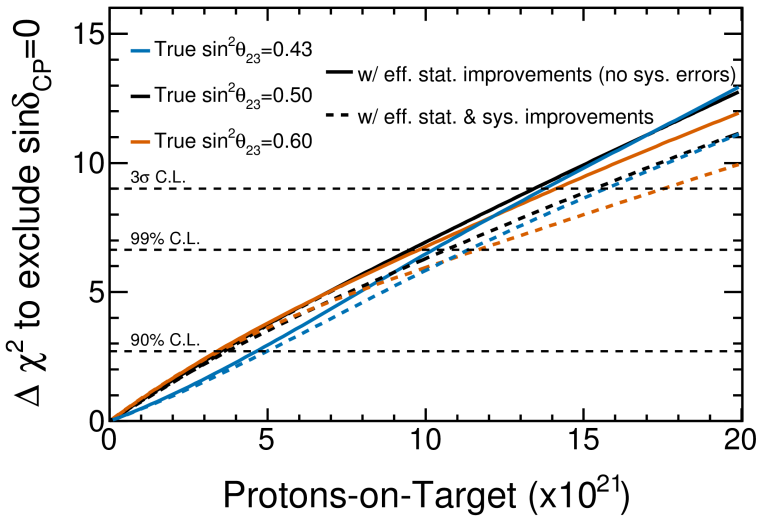
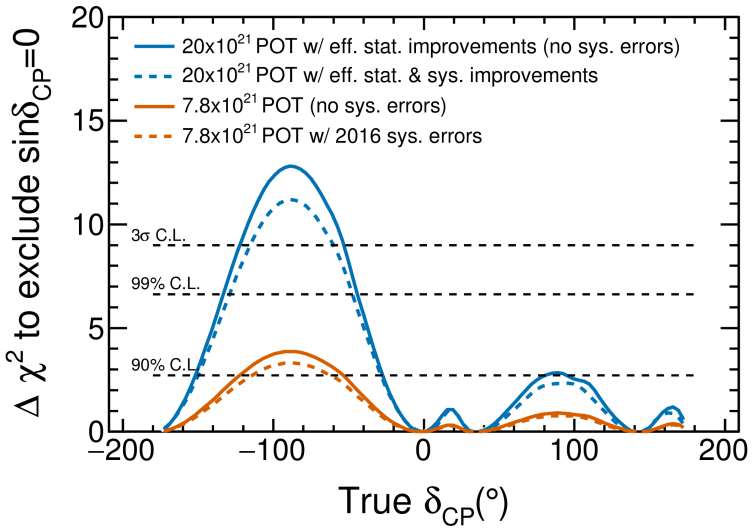
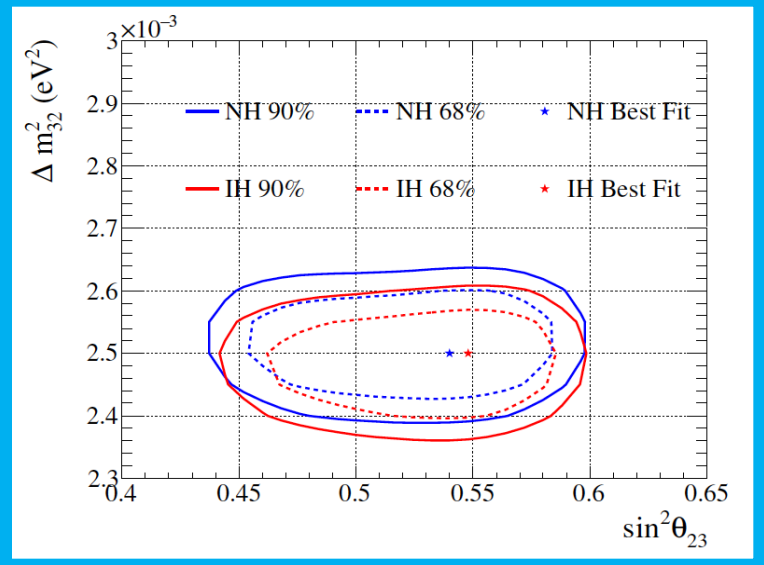
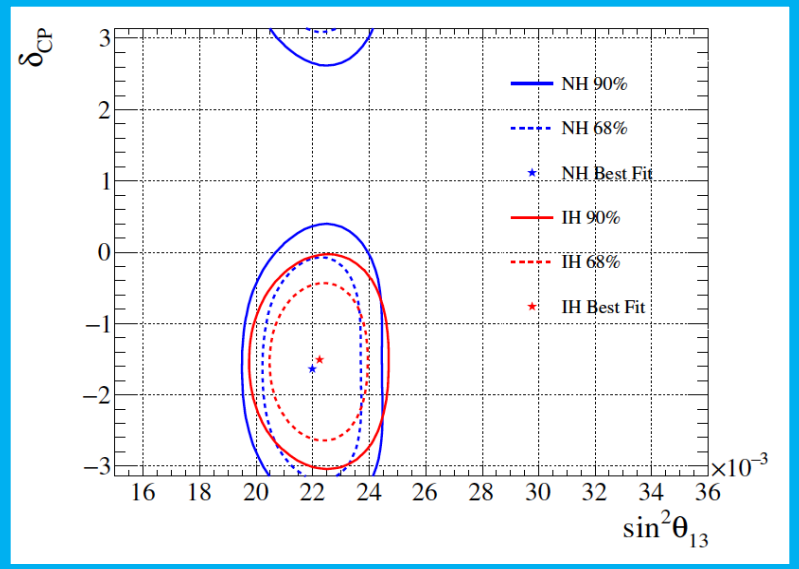
Summary and future prospect

- So far T2K has analyzed data
  - ν-mode: 7.48×10^{20} POT
  - $\bar{\nu}$-mode: 7.47×10^{20} POT
- **New results to be released soon**
  - ν-mode: 14.75×10^{20} POT
  - New reconstruction algorithm and expanded fiducial volume
- Short term target: 9×10^{20} POT in $\bar{\nu}$-mode next year
- Beam power improvements
  - MR power supply upgrade etc. scheduled in 2019
  - To 750kW – repetition rate 2.48 sec → 1.3 sec
- T2K phase II
  - 7.8×10^{21} POT → 20×10^{21} POT
  - Near detector upgrade
  - 1.3MW beam









Data and Results will be shown at KEK seminar

August 4th 10:00 am JST

"New T2K Neutrino Oscillation Results", C.K. Jung, DPF plenary Aug. 4th, 8:30am

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

IFJ PAN, Cracow
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

Supplemental

Oscillation probabilities

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (cos^4\theta_{13} sin^2 2\theta_{23} + sin^2 2\theta_{13} sin^2\theta_{23}) \cdot sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

$$P(\nu_\mu \to \nu_e) \approx 4c_{13}{}^2 s_{13}{}^2 s_{23}{}^2 \sin^2 \Delta_{31}\left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2s_{13}^2\right)\right)$$

Leading including matter effect

$$+8c_{13}{}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CP conserving

$$-8c_{13}{}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CP violating

$$+4s_{12}{}^2 c_{13}{}^2(c_{12}{}^2 c_{23}{}^2 + s_{12}{}^2 s_{23}{}^2 s_{13}{}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$

Solar

$$-8c_{13}{}^2 s_{13}{}^2 s_{23}{}^2(1 - 2s_{13}{}^2)\frac{aL}{4E}\cos\Delta_{32}\sin\Delta_{31}$$

Matter effect (small)

$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

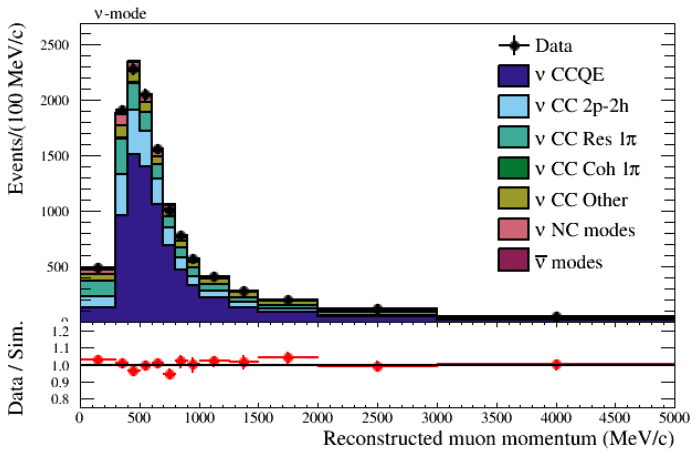
$$a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\,\mathrm{eV}^2 \frac{\rho}{\mathrm{gcm}^{-3}}\frac{E}{GeV}$$

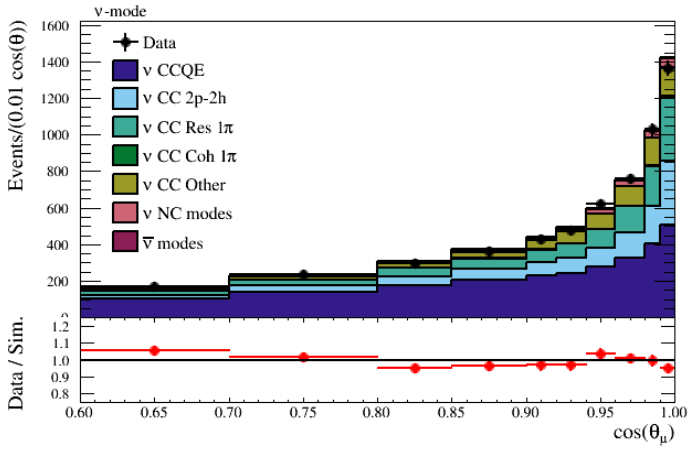
replace δ by $-\delta$ and a by $-a$ for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

Near Detector samples -- ν-mode

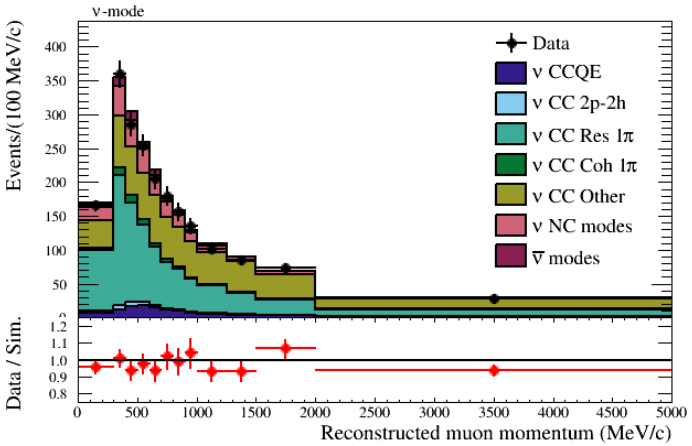
FGD1

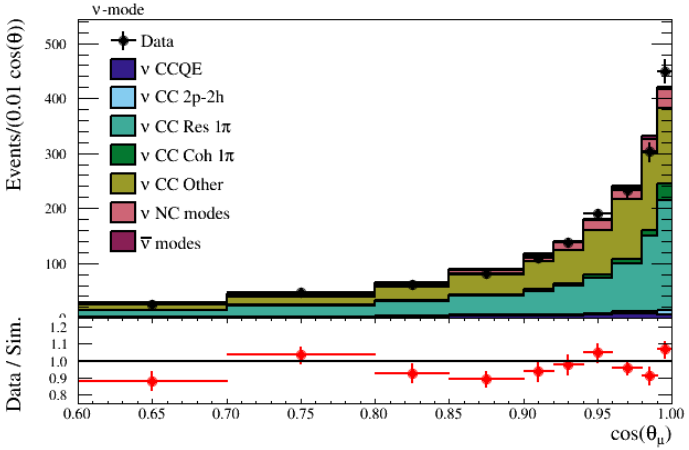
CC0pi



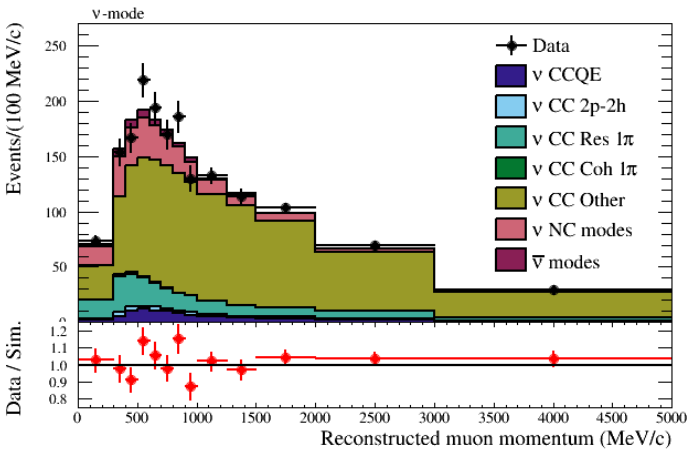


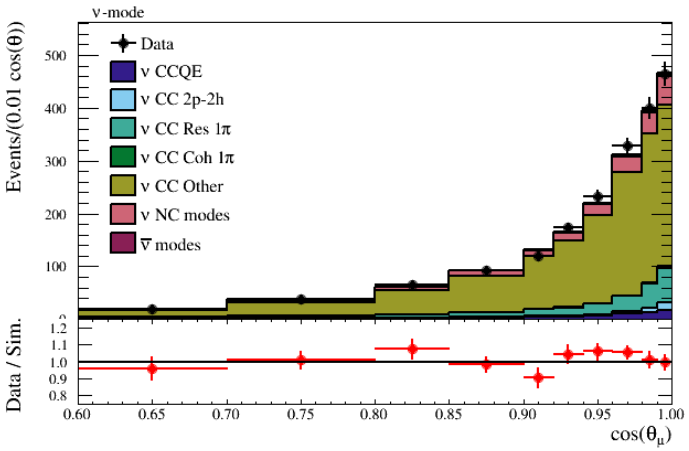
CC1pi





CCother

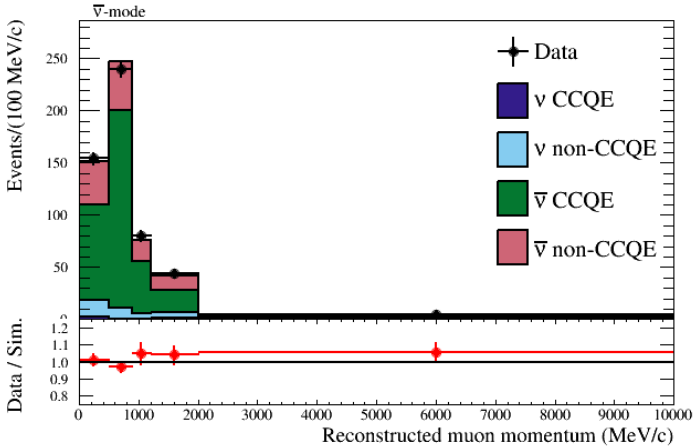




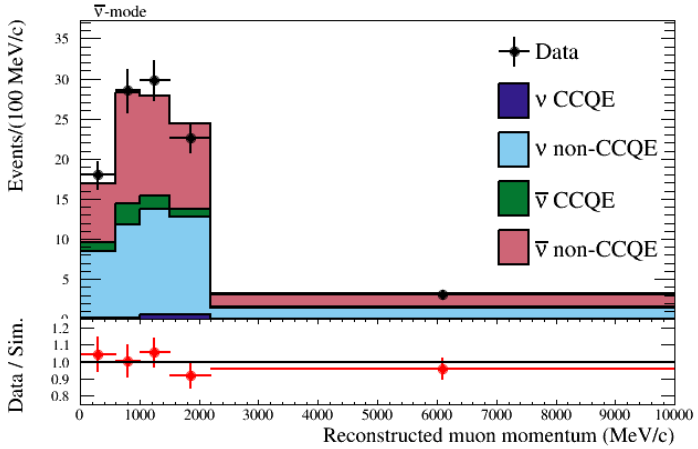
Near Detector samples -- $\bar{\nu}$-mode

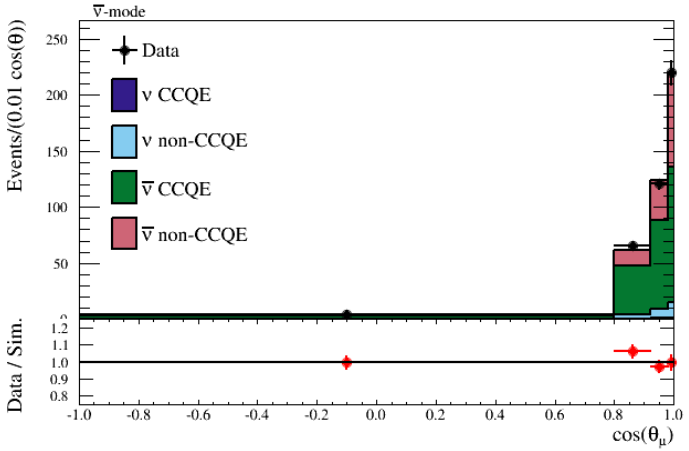
FGD1

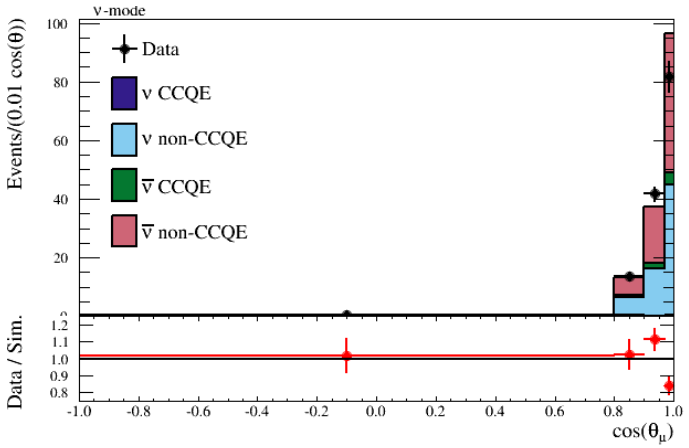
$\bar{\nu}$ CC1track



$\bar{\nu}$ CCNtrack



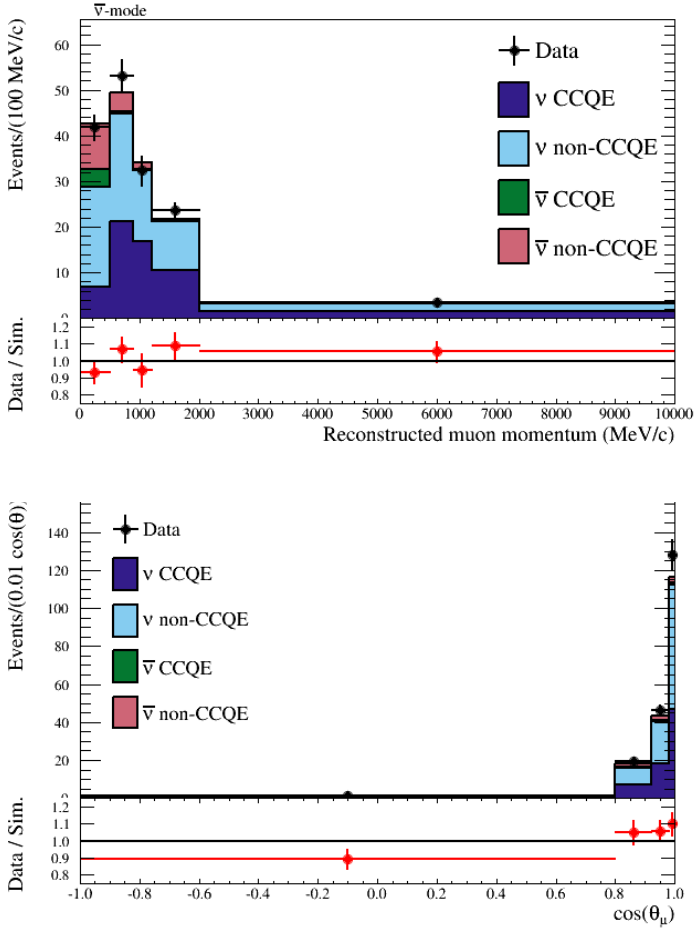




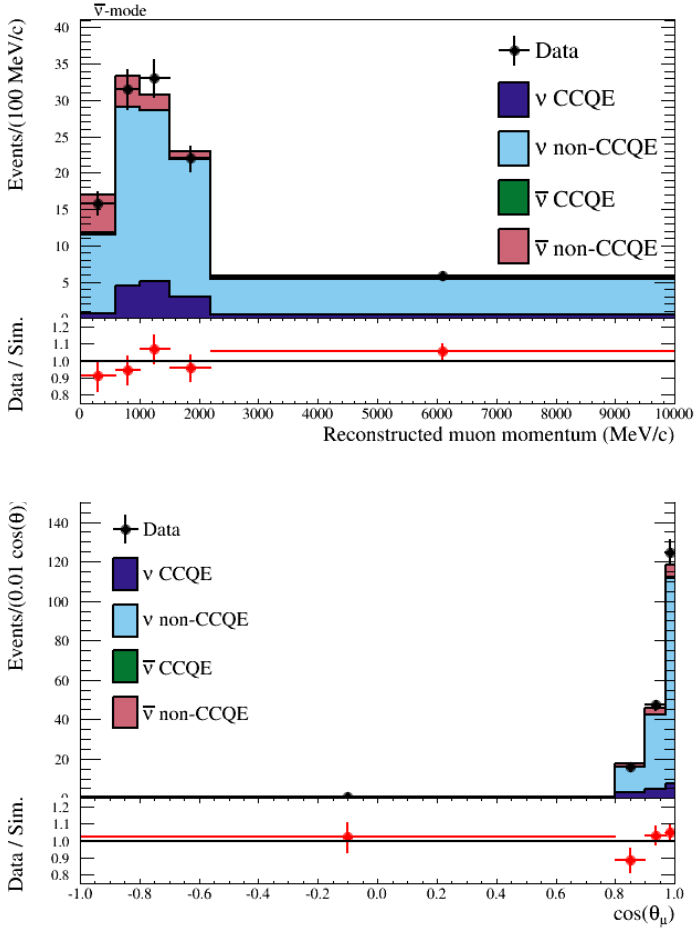
Near Detector samples -- $\bar{\nu}$-mode

FGD1

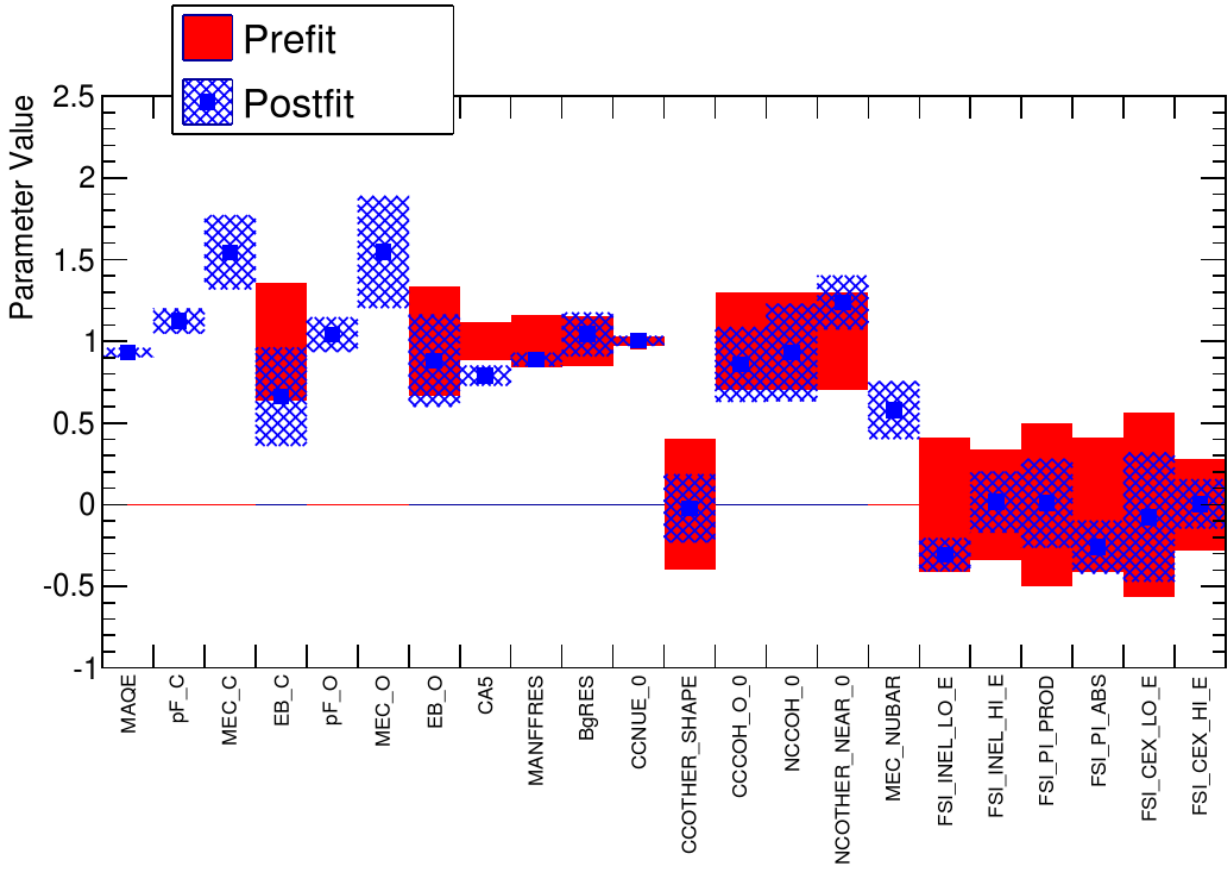
ν CC1track



ν CCNtrack

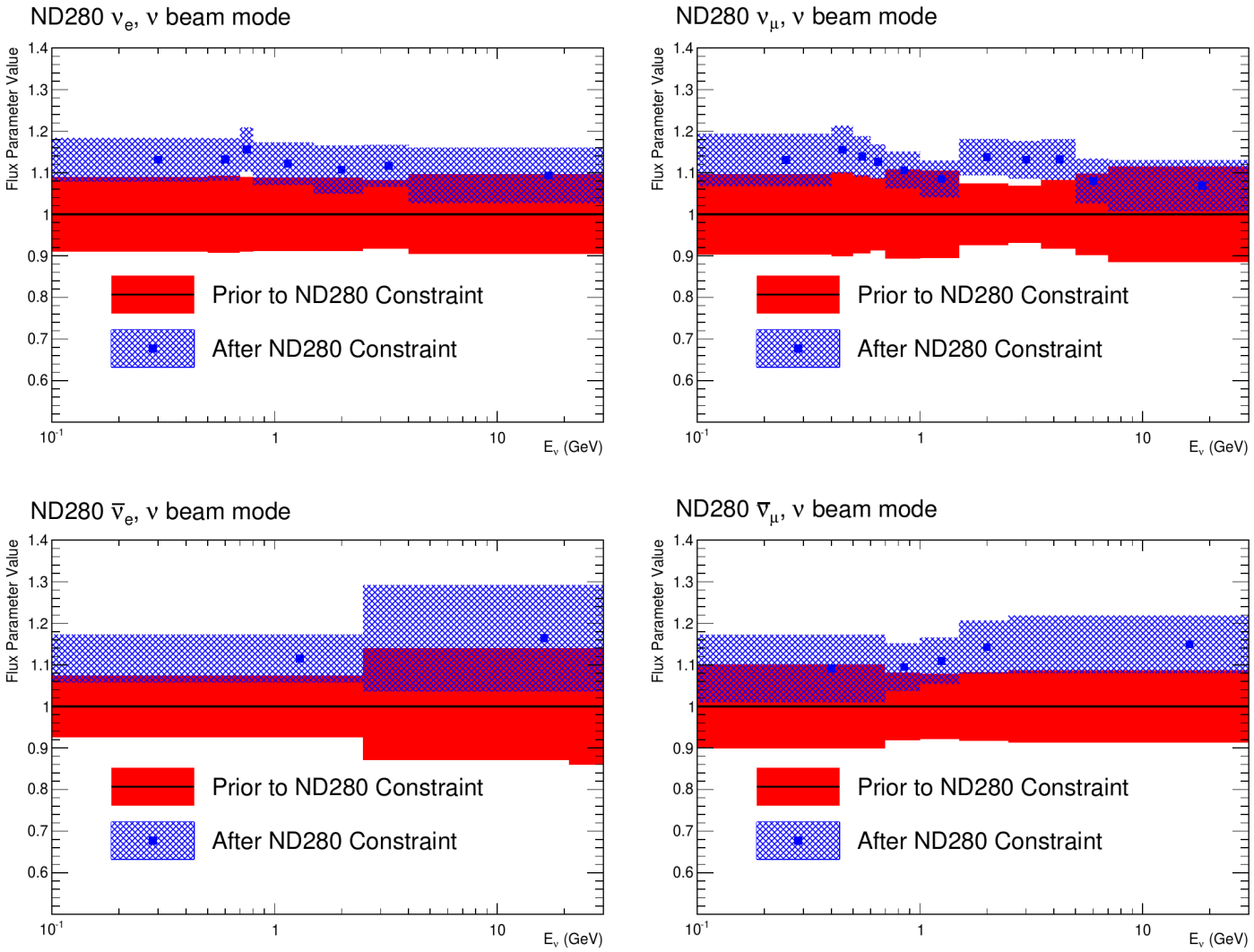


Near Detector fit



Cross section parameter	Prefit	ND280 postfit
M_A^{QE} (GeV/c^2)	1.20	1.12 ± 0.03
p_F ^{12}C (MeV/c)	217.0	243.9 ± 16.6
2p2h ^{12}C	100.0	154.5 ± 22.7
E_b ^{12}C (MeV)	25.0 ± 9.00	16.5 ± 7.53
p_F ^{16}O (MeV/c)	225.0	234.2 ± 23.7
2p2h ^{16}O	100.0	154.6 ± 34.3
E_b ^{16}O (MeV)	27.0 ± 9.00	23.8 ± 7.61
C_A^5	1.01 ± 0.12	0.80 ± 0.06
M_A^{RES} (GeV/c^2)	0.95 ± 0.15	0.84 ± 0.04
$I_{\frac{1}{2}}$ background	1.30 ± 0.20	1.36 ± 0.17
CC other shape	0.00 ± 0.40	-0.02 ± 0.21
CC coherent	1.00 ± 0.30	0.86 ± 0.23
NC coherent	1.00 ± 0.30	0.93 ± 0.30
2p2h $\bar{\nu}$	1.00	0.58 ± 0.18
NC other	1.00 ± 0.30	Not constrained
NC 1-γ	1.00 ± 1.00	Not constrained
ν_e/ν_μ ratio	1.00 ± 0.02	Not constrained
$\bar{\nu}_e/\bar{\nu}_\mu$ ratio	1.00 ± 0.02	Not constrained
FSI elastic low-E	1.00 ± 0.41	Not constrained
FSI elastic high-E	1.00 ± 0.34	Not constrained
FSI pion production	1.00 ± 0.50	Not constrained
FSI pion absorption	1.00 ± 0.41	Not constrained
FSI charge exchange low-E	1.00 ± 0.57	Not constrained
FSI charge exchange high-E	1.00 ± 0.28	Not constrained

Near Detector fit



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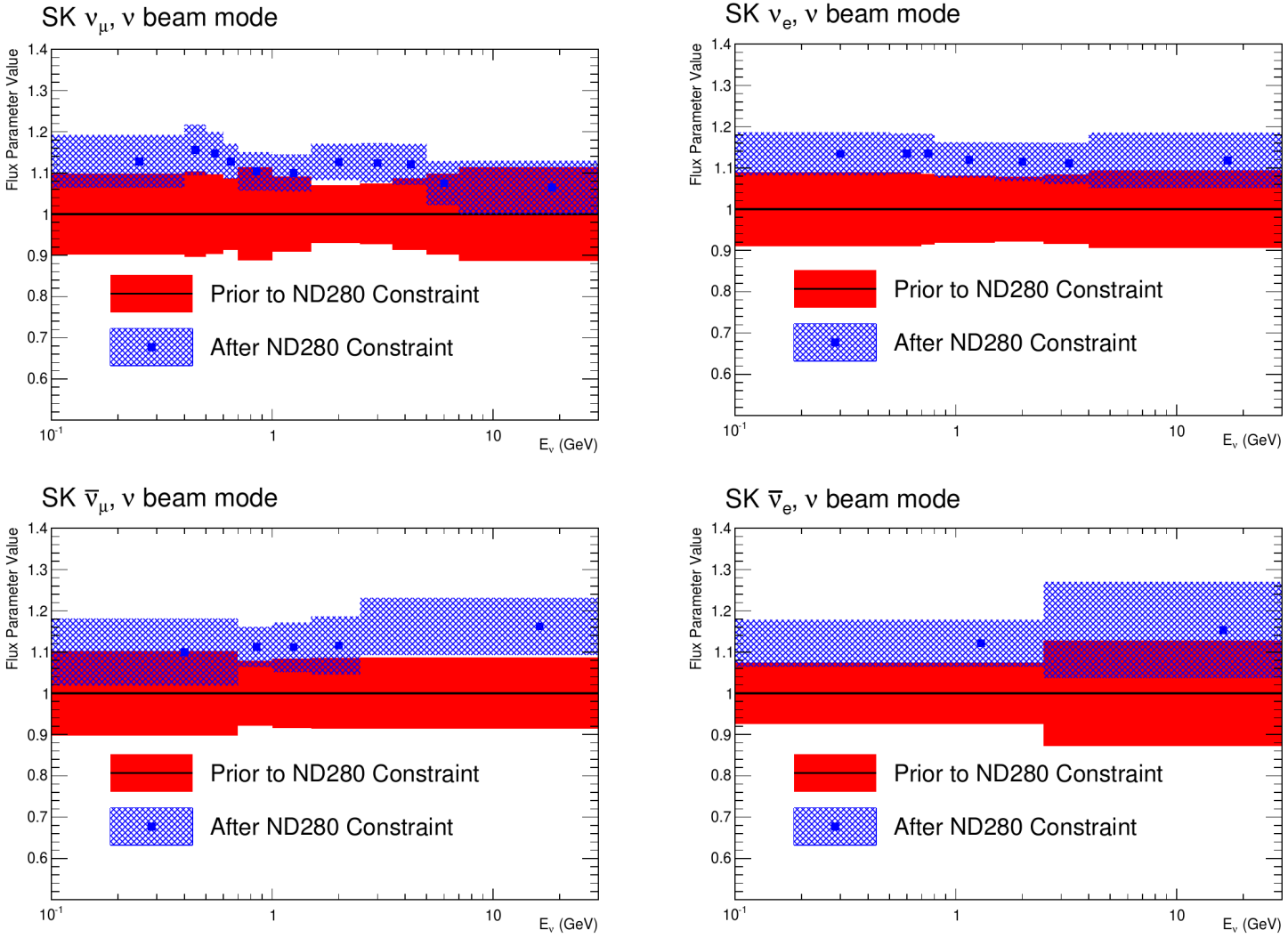
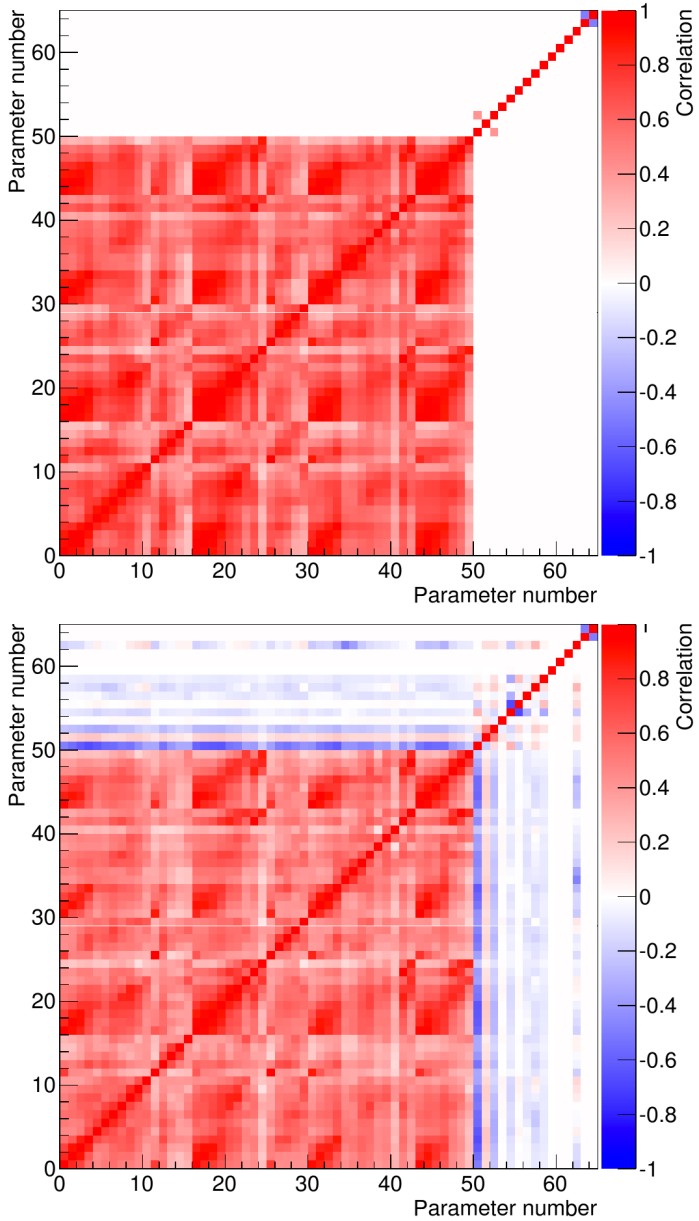
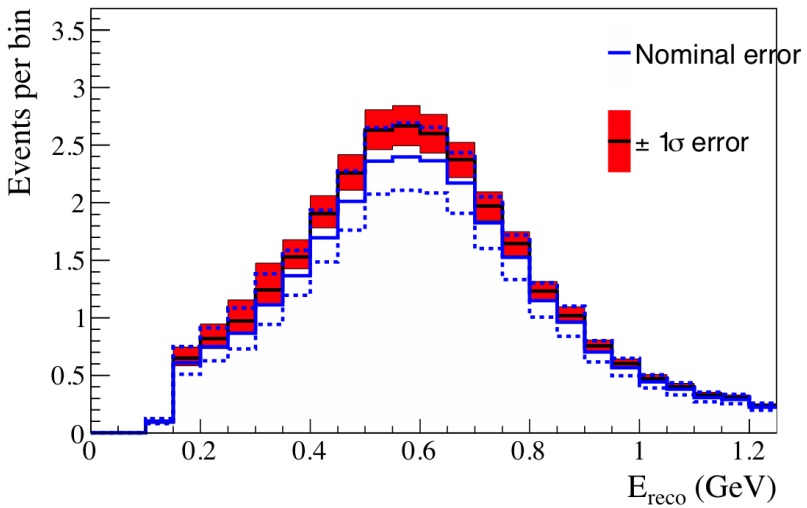


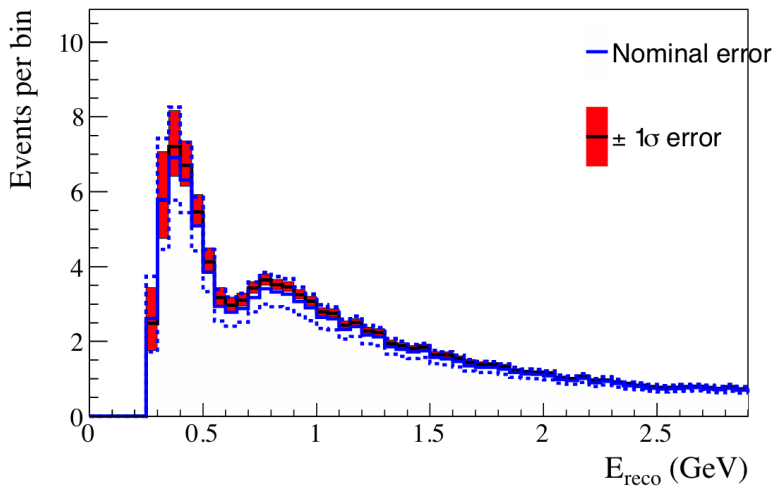


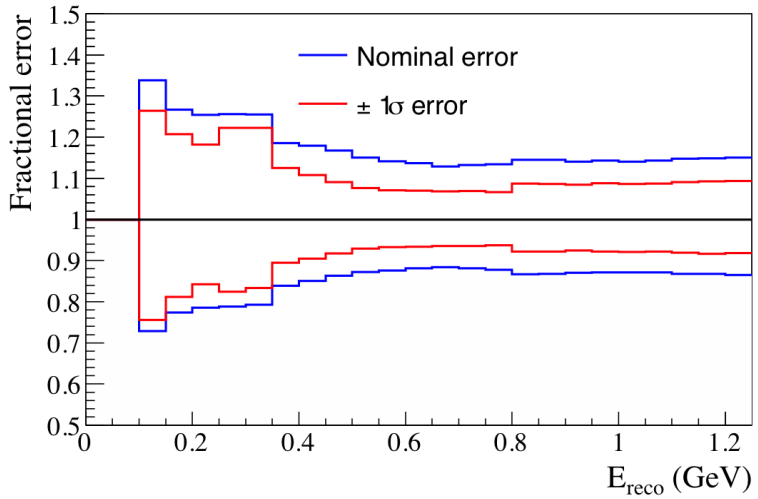
Pre-fit

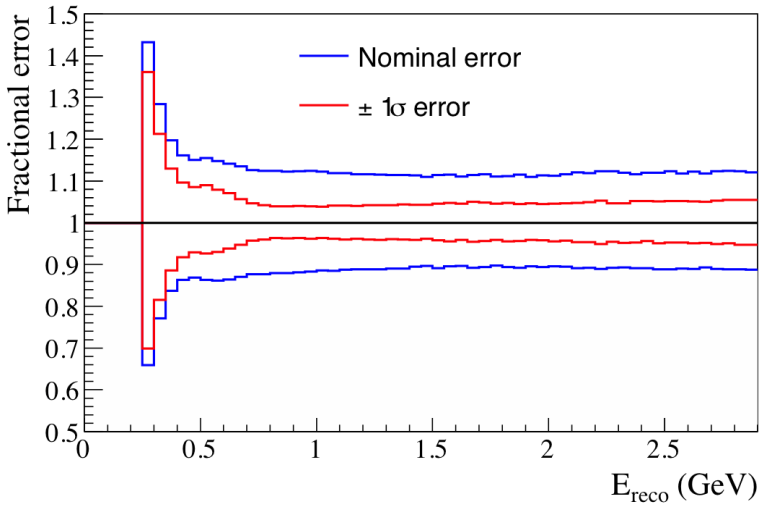
Post-fit

Effect of systematics uncertainties



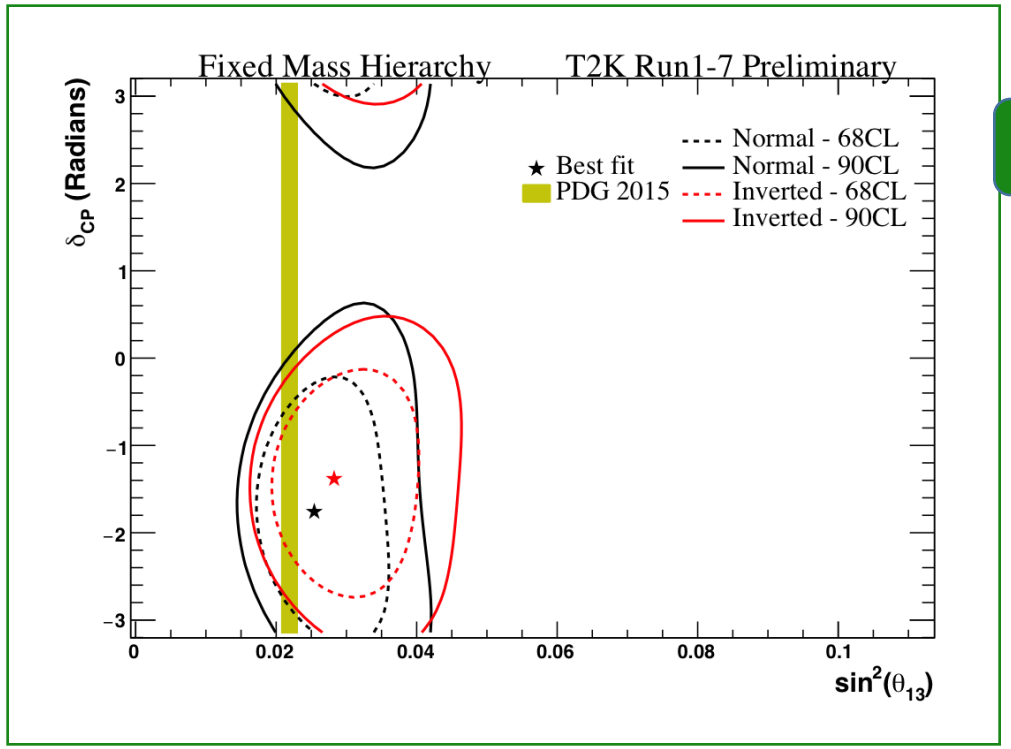






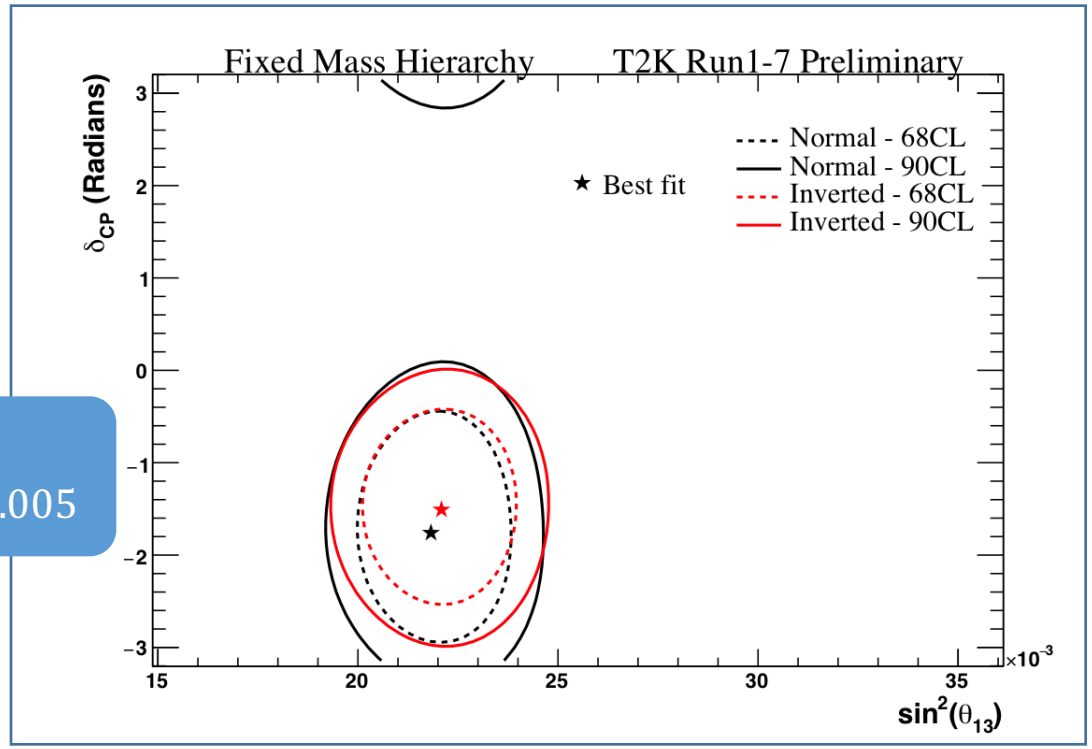
Source of uncertainty	numu $\delta N_{SK}/N_{SK}$ Asimov A	nue $\delta N_{SK}/N_{SK}$ Asimov A	numubar $\delta N_{SK}/N_{SK}$ Asimov A	nuebar $\delta N_{SK}/N_{SK}$ Asimov A	Nue CC1pi+ $\delta N_{SK}/N_{SK}$ Asimov A
SKDet+FSI+SI	4.13%	3.47%	3.91%	3.47%	14.10%
FSI+SI	1.47%	2.50%	2.05%	2.50%	10.39%
SKDet	3.89%	2.45%	3.34%	2.45%	9.22%
Flux	3.54%	3.66%	3.79%	3.66%	3.58%
MEC (corr)	3.52%	3.90%	2.96%	3.90%	0.48%
MECbar (corr)	0.21%	0.05%	1.82%	0.05%	0.01%
NC 1gamma (uncorr)	0.00%	1.46%	0.00%	1.46%	0.44%
XSec nue/numu	0.01%	2.63%	0.00%	2.63%	2.43%
XSec Tot	4.07%	5.14%	4.16%	5.14%	4.80%
Flux+XSec	2.90%	4.12%	3.39%	4.12%	5.03%
Flux+XSec (Pre ND280)	10.90%	11.47%	11.84%	11.47%	16.26%
Oscillations	0.02%	0.49%	0.03%	0.49%	0.42%
All	5.08%	5.53%	5.19%	5.53%	14.84%
All (Pre ND280)	12.25%	12.06%	12.88%	12.06%	21.84%

Current Results – Joint Analysis θ_{13}



T2K only

T2K + Reactor
$\sin^2\theta_{13} = 0.085 \pm 0.005$



- T2K-only measurement consistent with reactor results
- Favors "small" $\sin^2\theta_{13}$ and large CPV