T2K Neutrino Oscillation Results

ν_e

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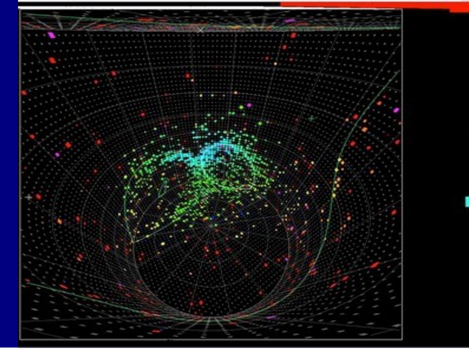
Tokai

Overview

- The T2K experiment
- Latest results
  - ν_e appearance / ν_μ disappearance joint fit
  - $\bar{\nu}_\mu$ oscillation
- Future Sensitivity for CP violation
- Summary and Conclusion

ν_μ

Neutrino Mixing

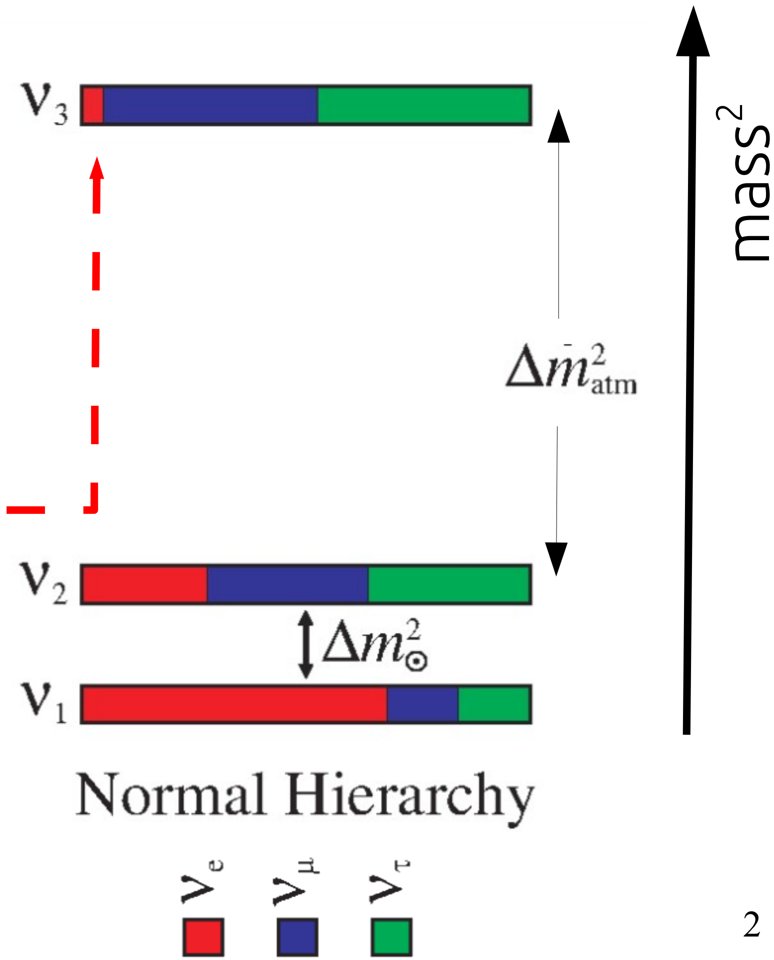


Neutrino flavour states are not the same as neutrino mass states

$$|\nu_\alpha> = \sum_{i=1}^{3} U_{\alpha i} |\nu_i>$$

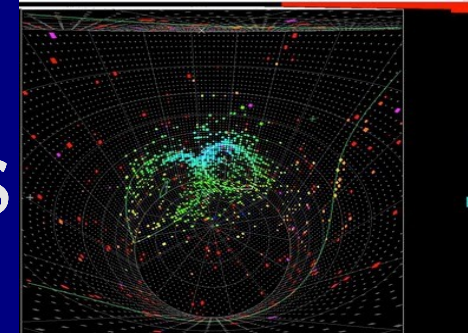
Oscillations parametrised by a complex 3x3 mixing matrix called the PMNS matrix.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



For physics motivation of neutrino oscillation measurements refer back to talk of R. Hill (T1-5)

Oscillations : Current Status



Pontecorvo – Maki – Nakagawa- Sakata matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\times\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta}\\0&1&0\\-\sin\theta_{13}e^{i\delta}&0&\cos\theta_{13}\end{pmatrix}\times\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\times\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\nu_\mu \rightarrow \nu_\tau$

$$\sin^2 2\theta_{23} = 0.999^{+0.001}_{-0.018}$$

$$\Delta m^2_{32} = (2.44 \pm 0.06)\times 10^{-3}\, eV^2$$

SK, MINOS, T2K, K2K

T2K,MINOS (App)
Daya Bay, RENO
Double CHOOZ (Dis)

$\nu_\mu \rightarrow \nu_e$

$$\sin^2(2\theta_{13}) = 0.085 \pm 0.005$$

$$\Delta m^2_{32} = (2.44 \pm 0.06)\times 10^{-3}\ \ eV^2$$

SK, SNO, Borexino

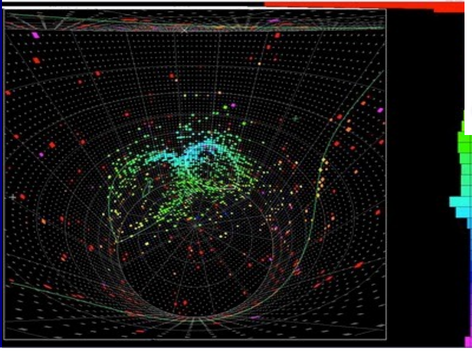
$\nu_e \rightarrow \nu_x$

$$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$$

$$\Delta m^2_{21} = (7.53 \pm 0.18)\times 10^{-5}\, eV^2$$

Values for
Normal Hierarchy
from PDG(2014)

Two flavour oscillations



Appearance Measurement

Mixing angle — Mass splitting — Baseline

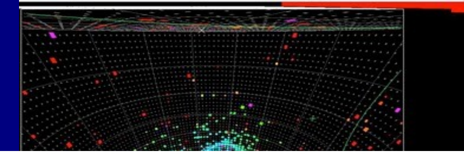
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(\Delta m^2_{31}\frac{L}{4E}\right)$$

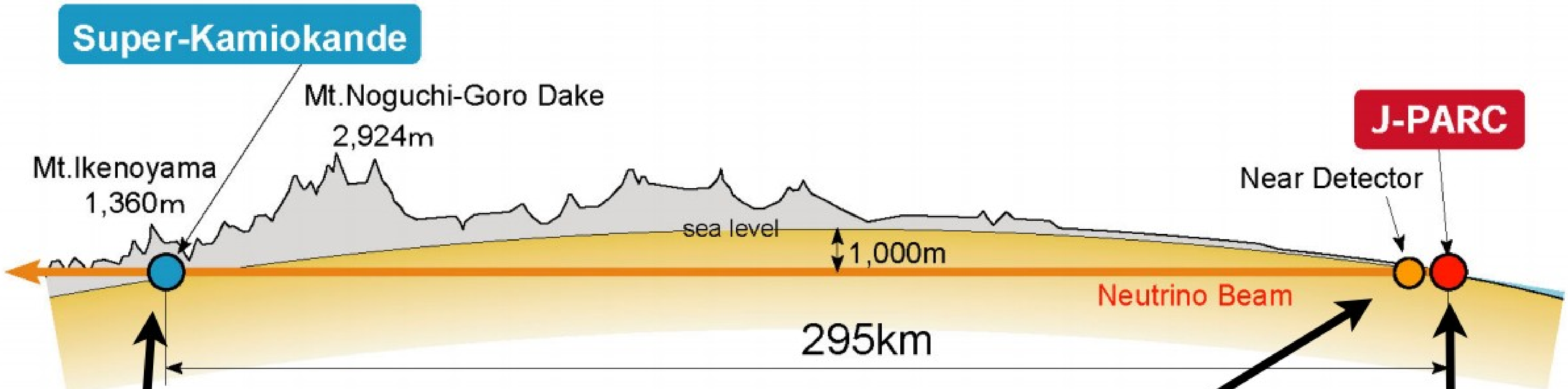
+ CPV terms + subleading terms

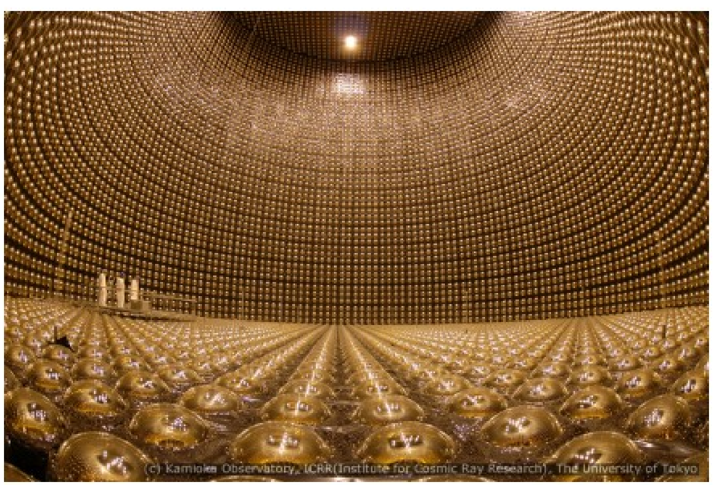
Disappearance Measurement

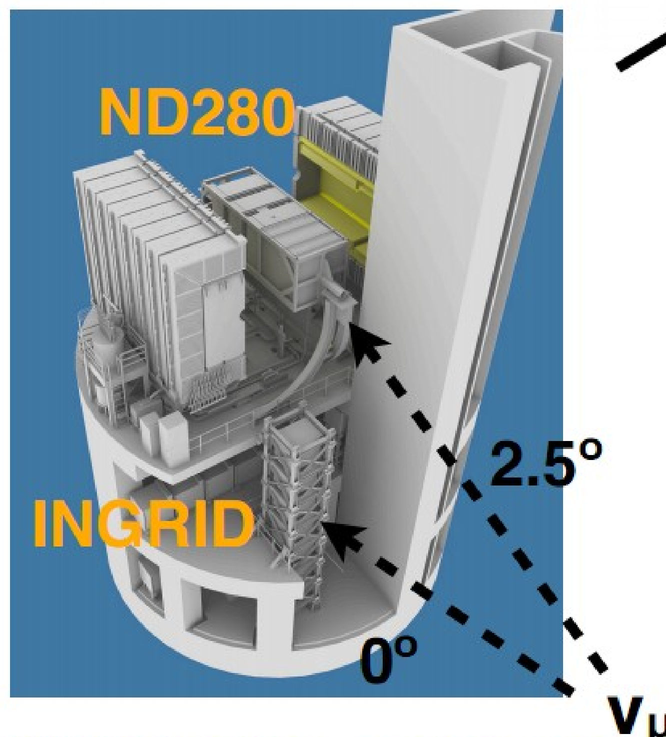
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2\left(\Delta m^2_{32}\frac{L}{4E}\right)$$

The T2K Experiment







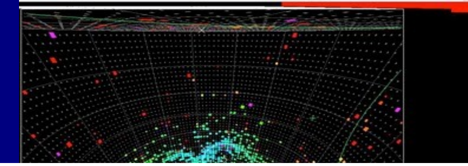


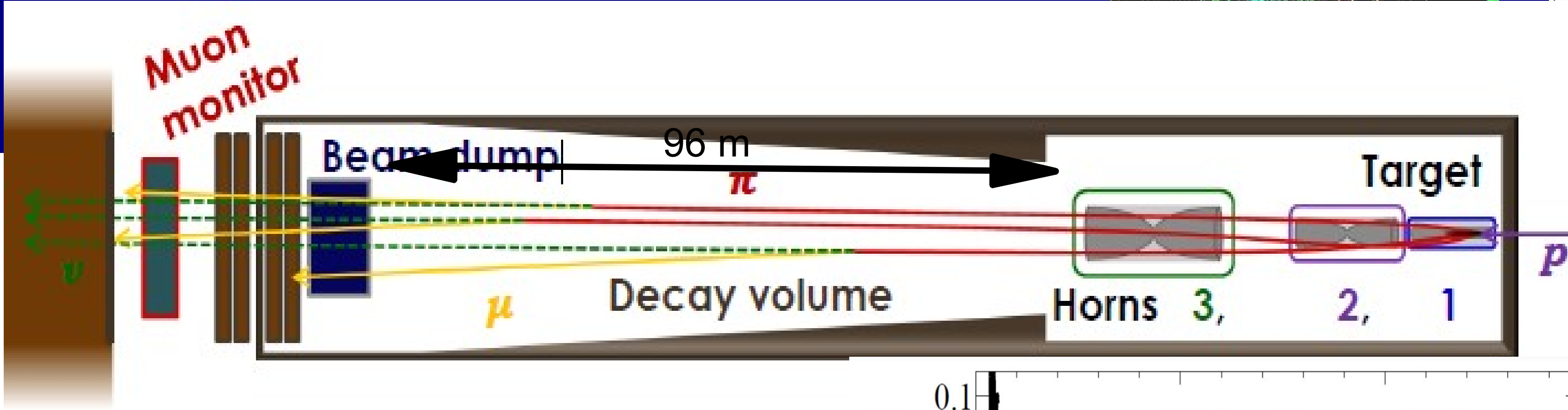
Super-Kamiokande

INGRID (on-axis) and ND280 (off-axis)

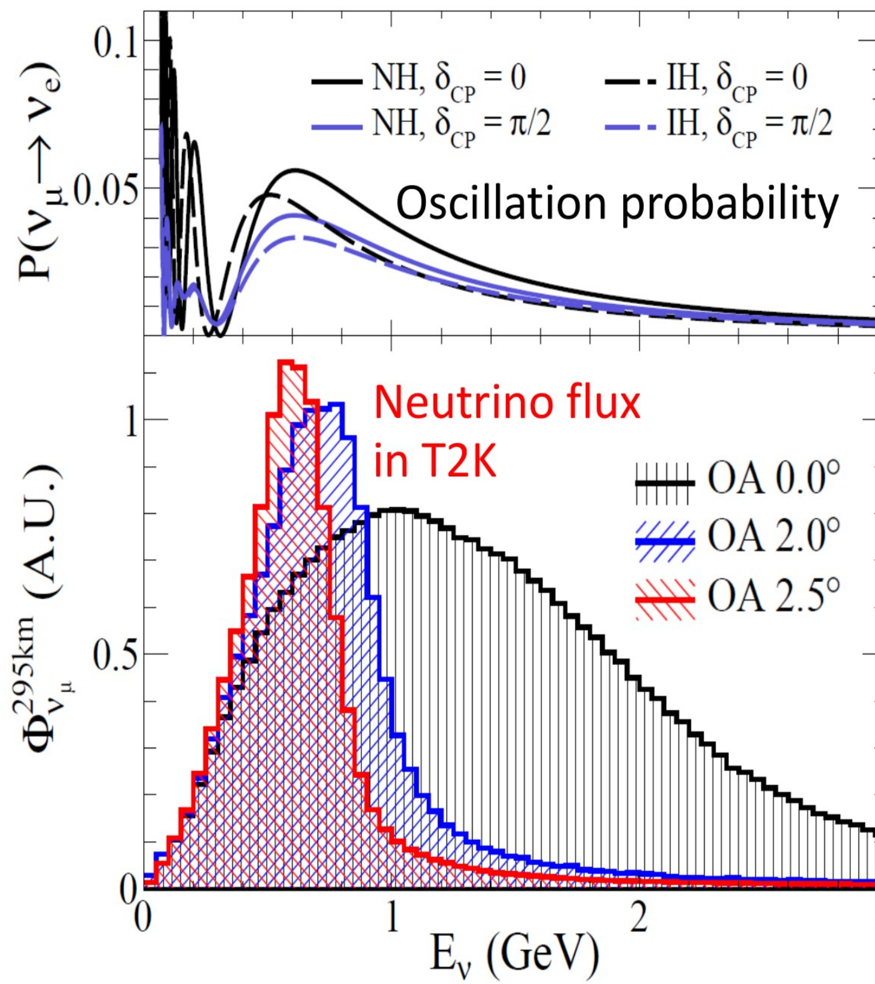
Neutrino beam created at J-PARC main ring

The T2K Beam

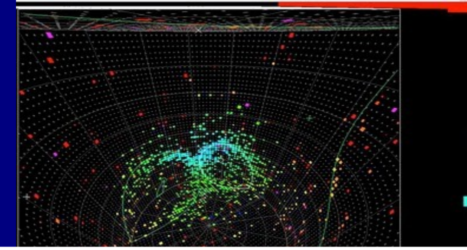




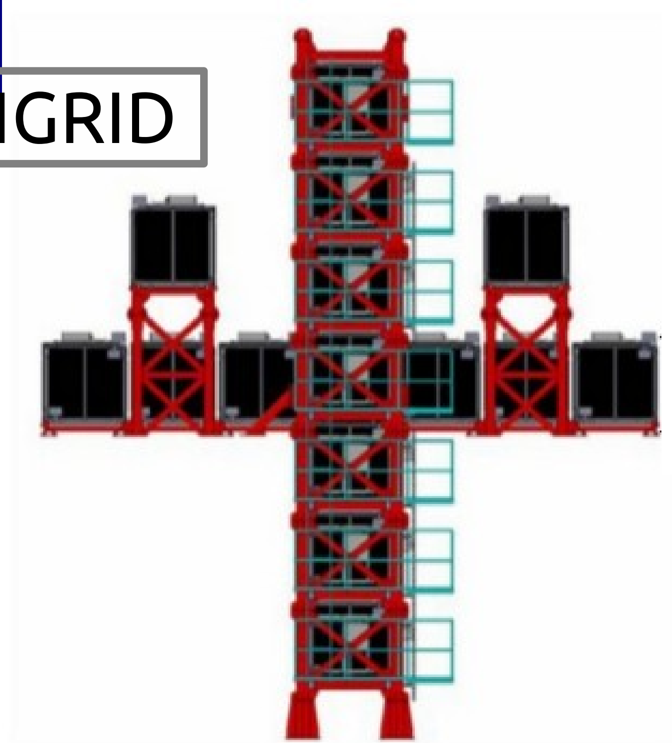
- ν_μ from pion decay
- Off-axis beam
  - concentrates flux around oscillation maximum
  - eliminates high-energy tail
  - Ideal for ν_e appearance
- Beam ν_e present at ~1.2 %



Near Detectors



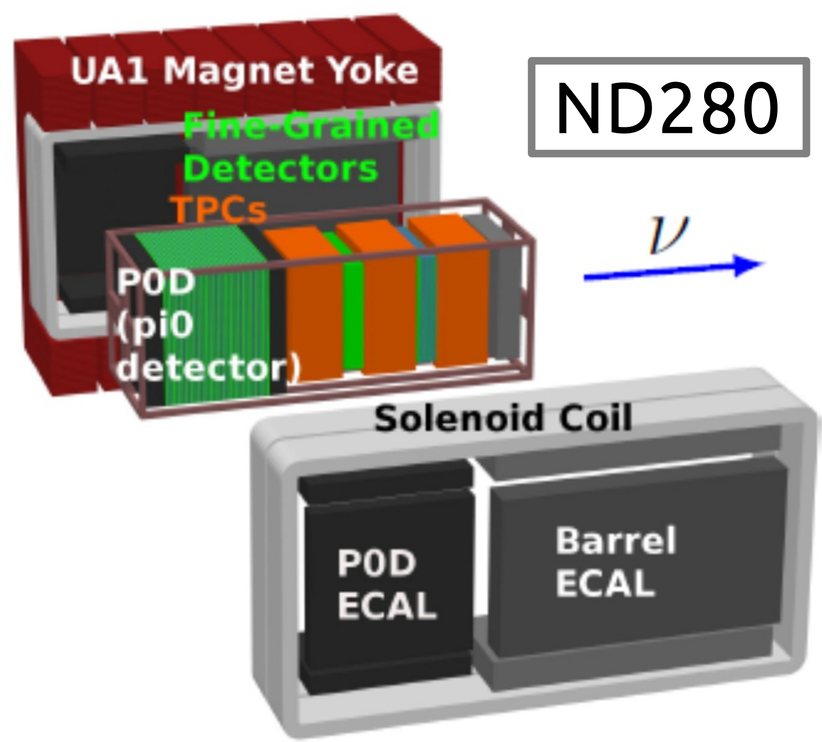
INGRID



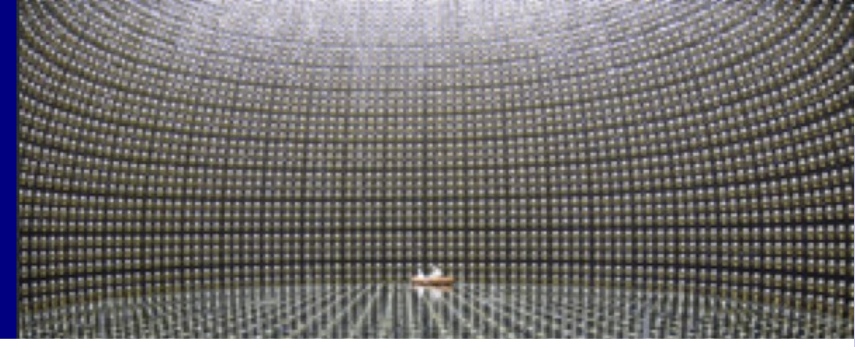
- On-axis detector 280 m from neutrino production point
- 16 iron-scintillator tracking calorimeters in cross profile
- 1 scintillator-only “proton module”
- Measures beam profile and CC inclusive rate

- Two fine grained detectors (C/H_20 target) sandwiched by
- Three gas TPCs in
- UA1/NOMAD Magnet (0.2 T) with
- Upstream pi0 detector (P0D)

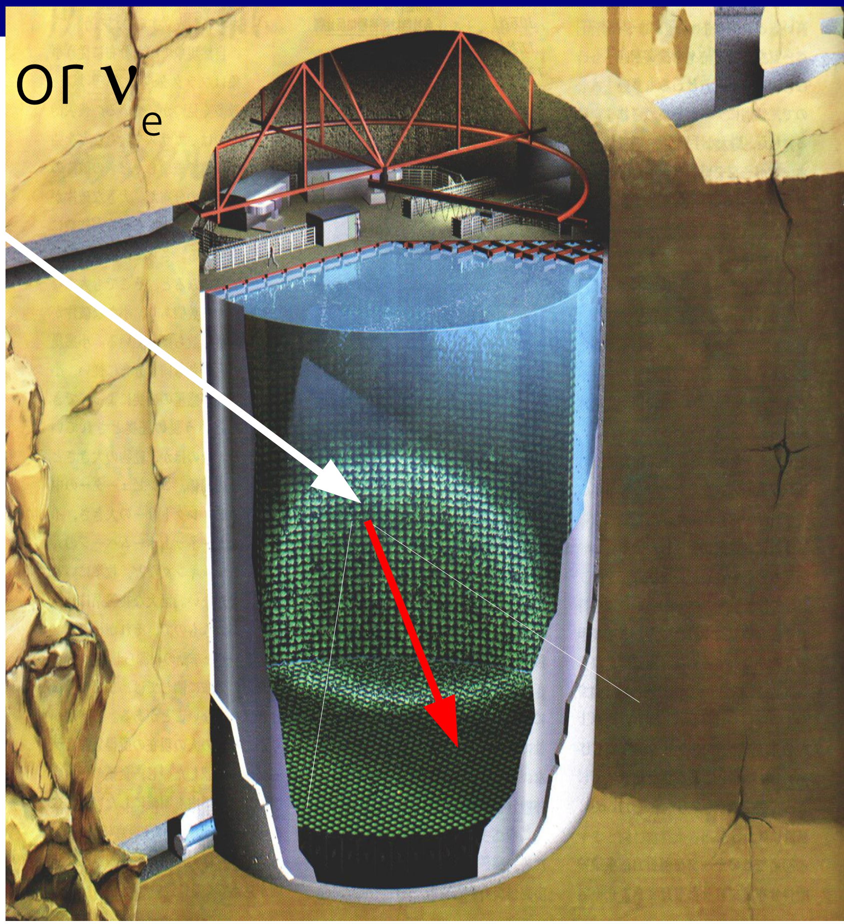
ND280

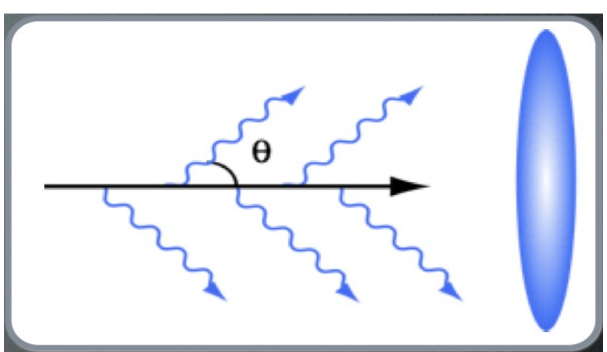


Far Detector Super-Kamiokande



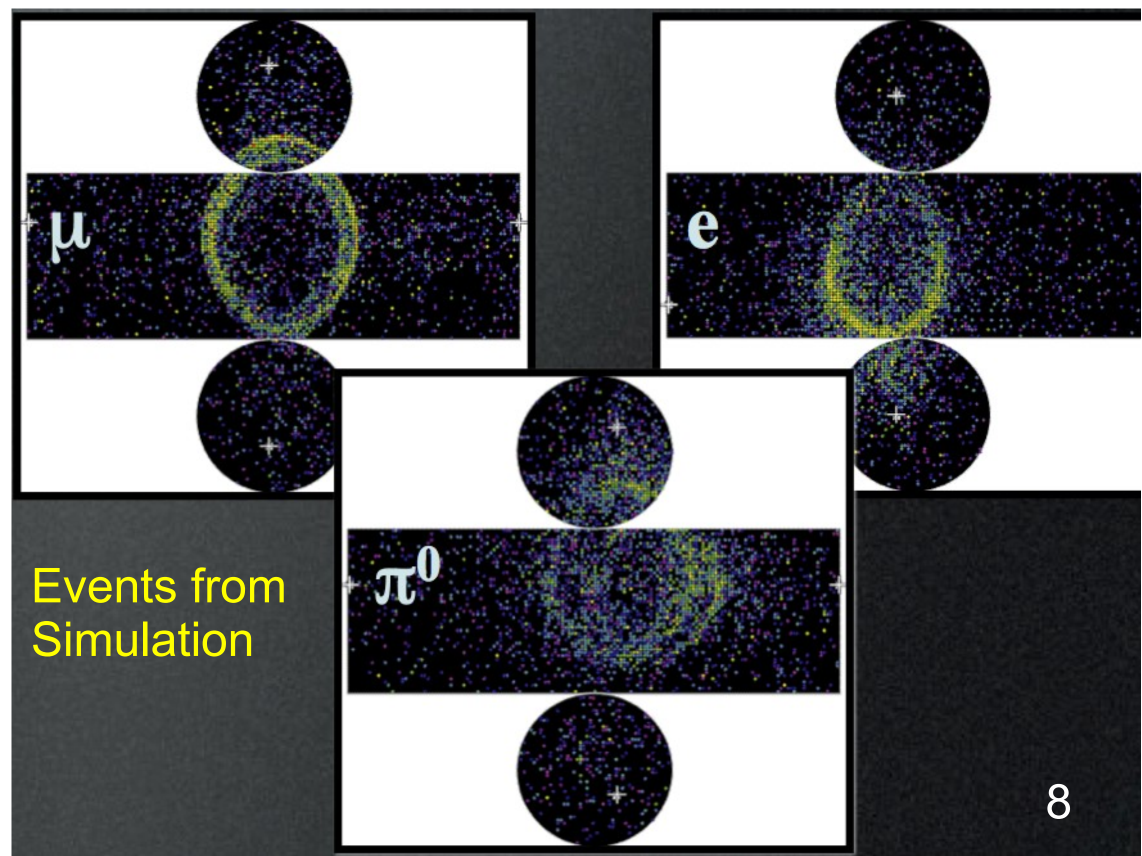
ν_μ or ν_e



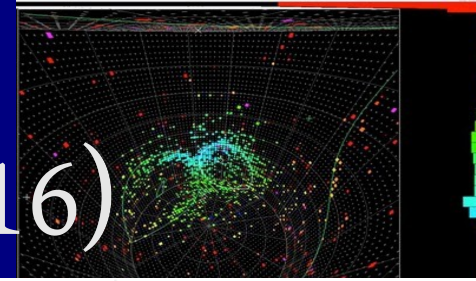


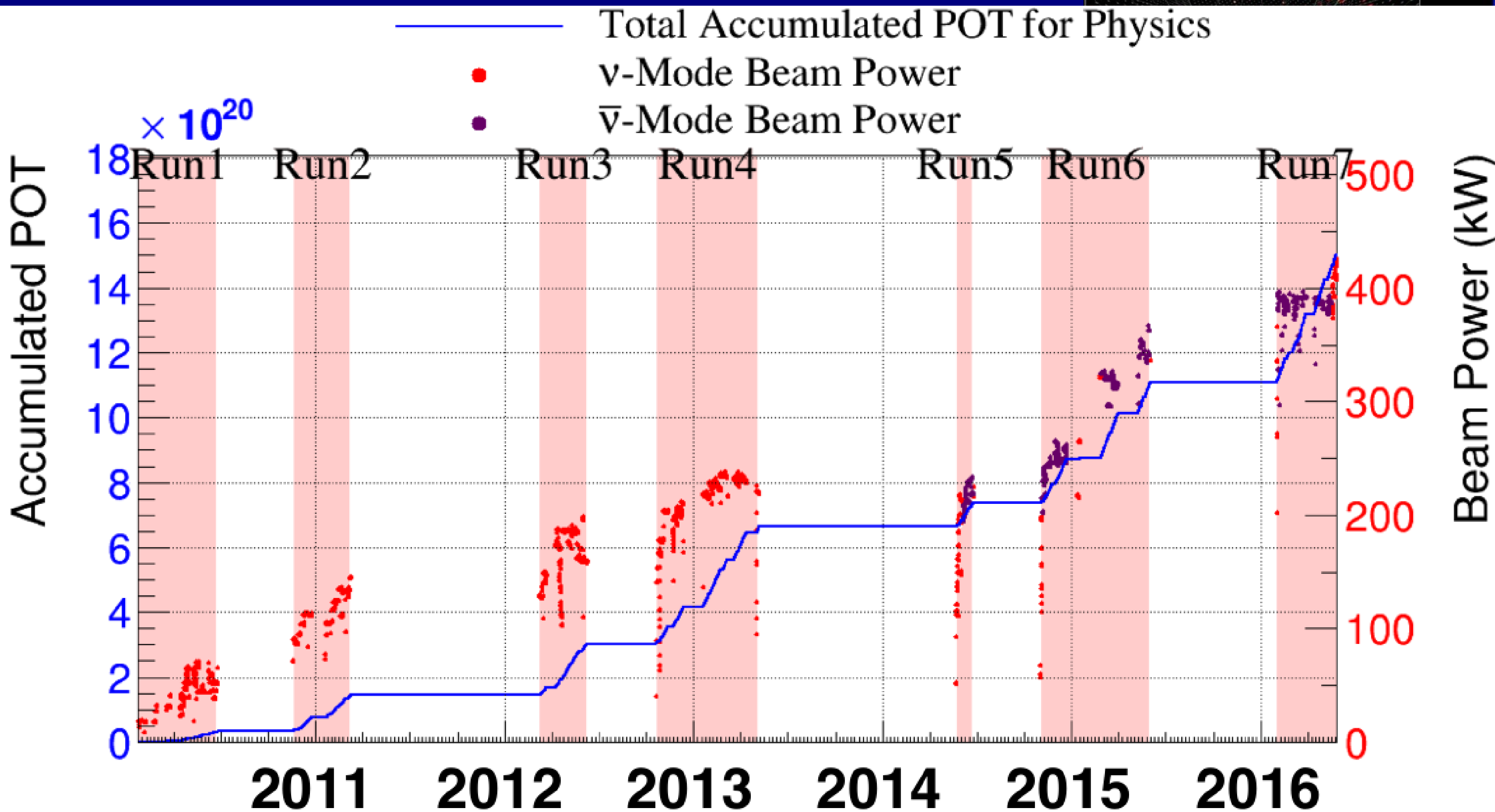
Over 10,000 PMTs

- 50 kTon water Cherenkov detector
- (22.5 kton fiducial volume)
- Cherenkov ring pattern can be used to distinguis lepton flavour
- Well-understood and stable detector



Data collected (Jan.23, 2010 – May 27, 2016)

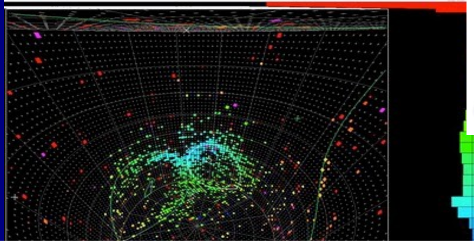




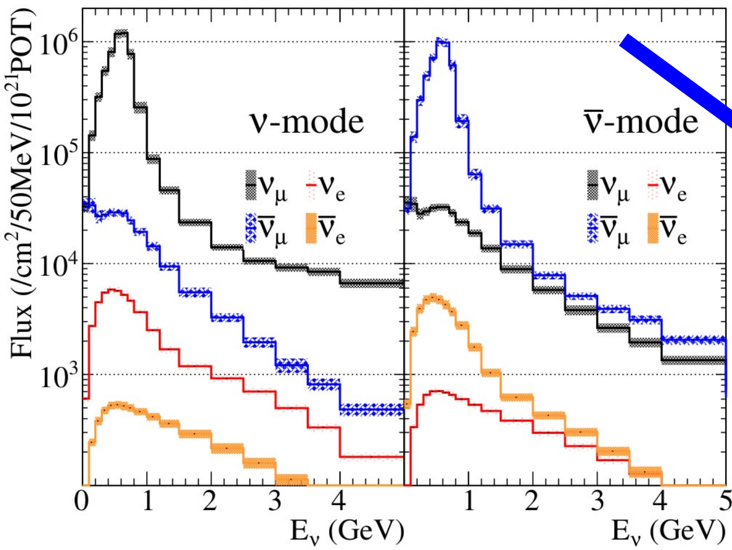
- Maximum beam power achieved: 420 kW
- Protons on target for physics:

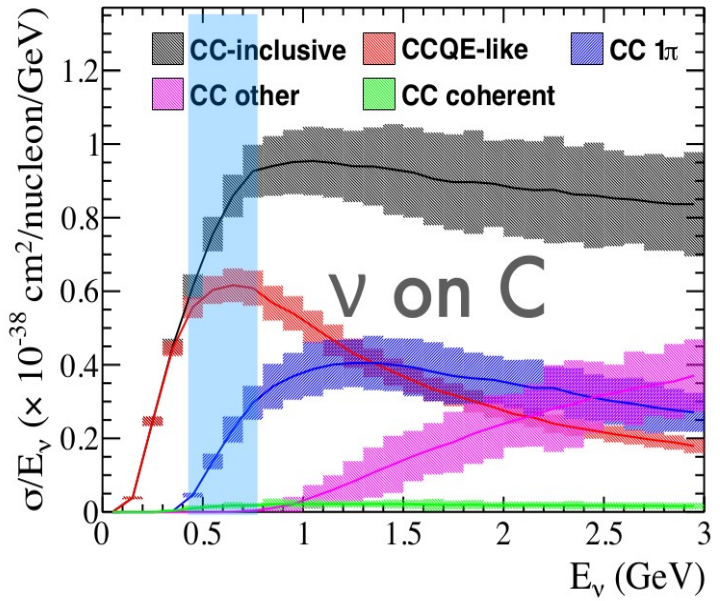
$1.510\text{x}10^{21}$ (total) = $7.57\text{x}10^{20}$ (ν) + $7.53\text{x}10^{20}$ ($\bar{\nu}$)

Oscillation analysis flow



- Neutrino flux prediction
  - Measurement of proton beam
  - Hadron production data from NA61
  - Beam direction measured with INGRID
  - Simulation with FLUKA and GEANT
- Neutrino interaction model
  - External cross-section data (MiniBooNE, SciBooNE, MINOS, etc.)
  - Simulation by NEUT





Constrain Uncertainty with ND280

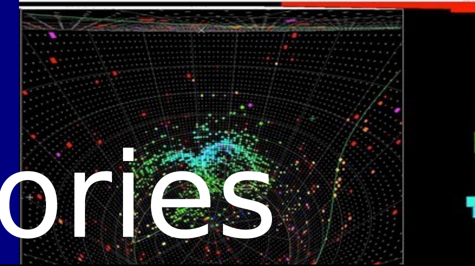
ν oscillation

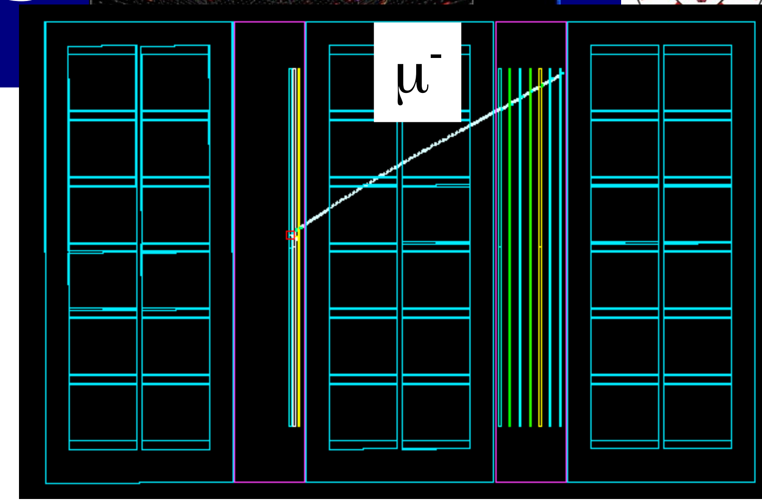
Neutrino event prediction at Super Kamiokande

Comparison

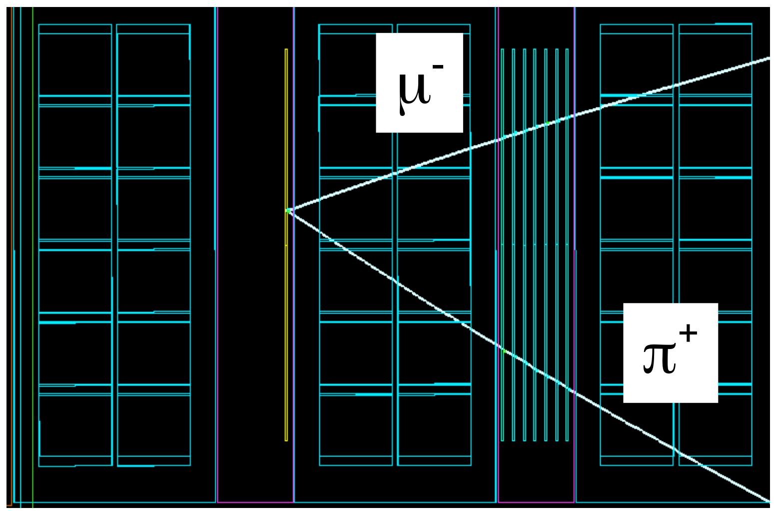
Neutrino data measured at Super Kamiokande

•ND280 Event Categories

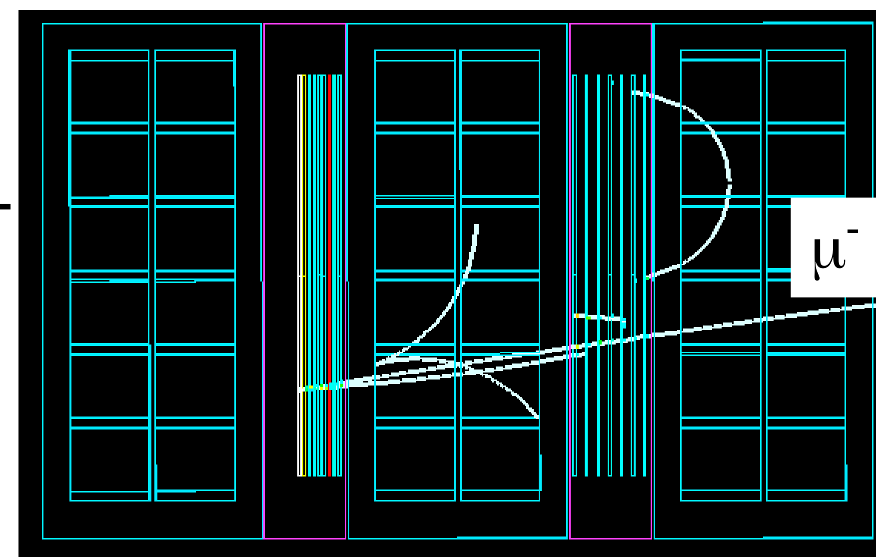




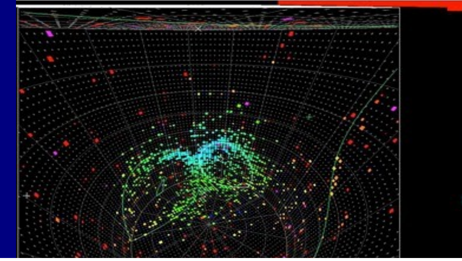
- Charged current (CC) with 0π
- CC 1π+



- CC Other (≥1π- or π0 ,or >1 π+
  - π0 candidates have identified electrons in the TPC
- Disappearance analysis joins CC 1π+ and CC other together

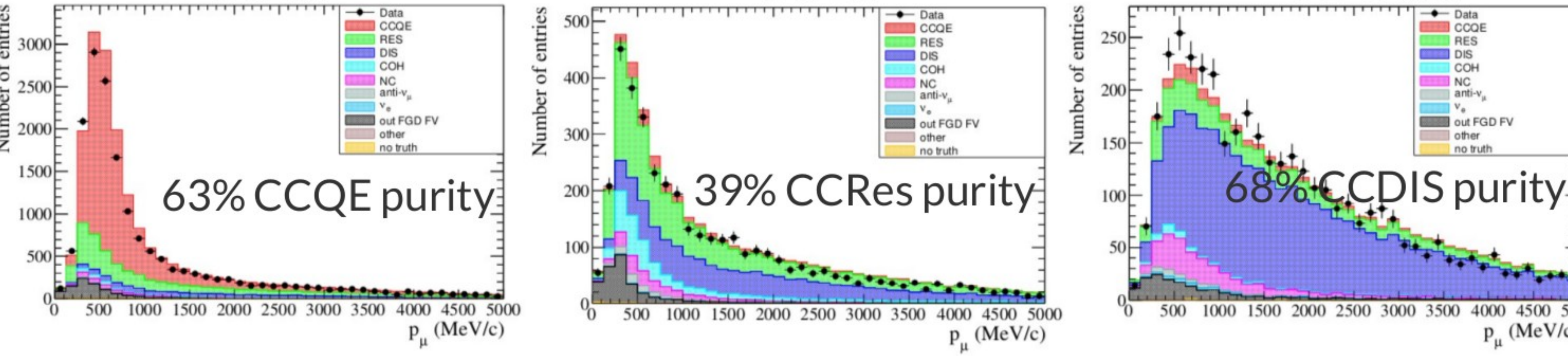


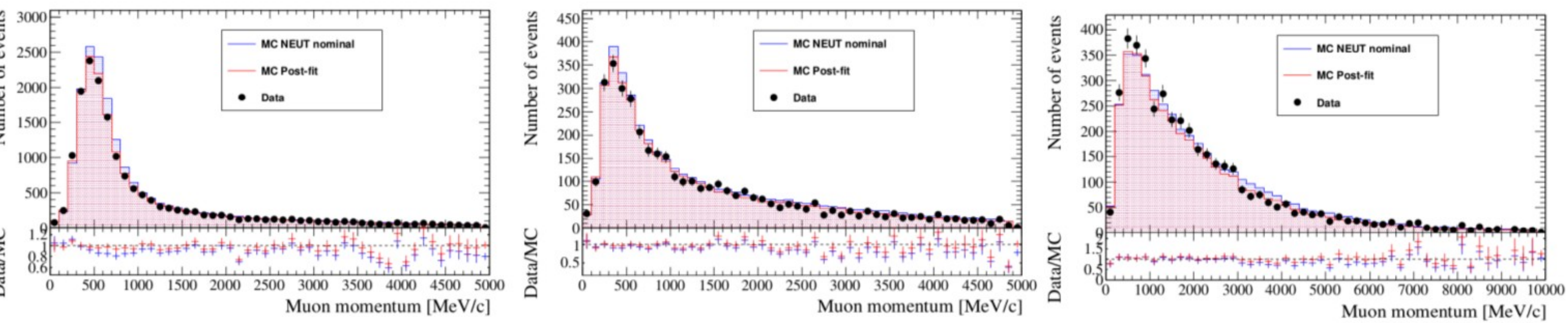
ND280 ν_μ Event Samples

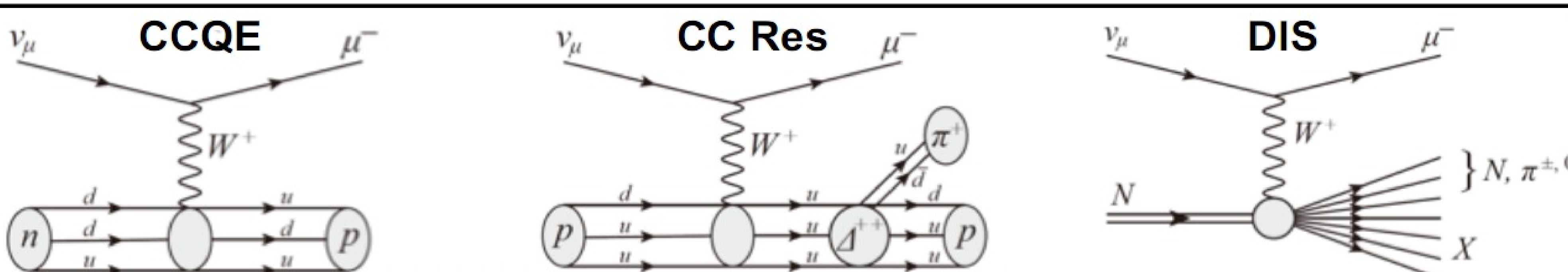


Used to constrain flux * cross section uncertainties:
25% → 3%

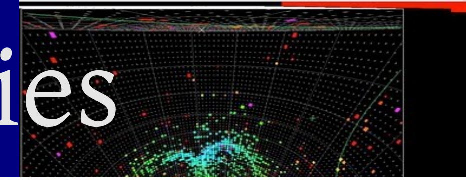
CC-0π | CC-1π+ | CC-Other







T2K Systematic Uncertainties

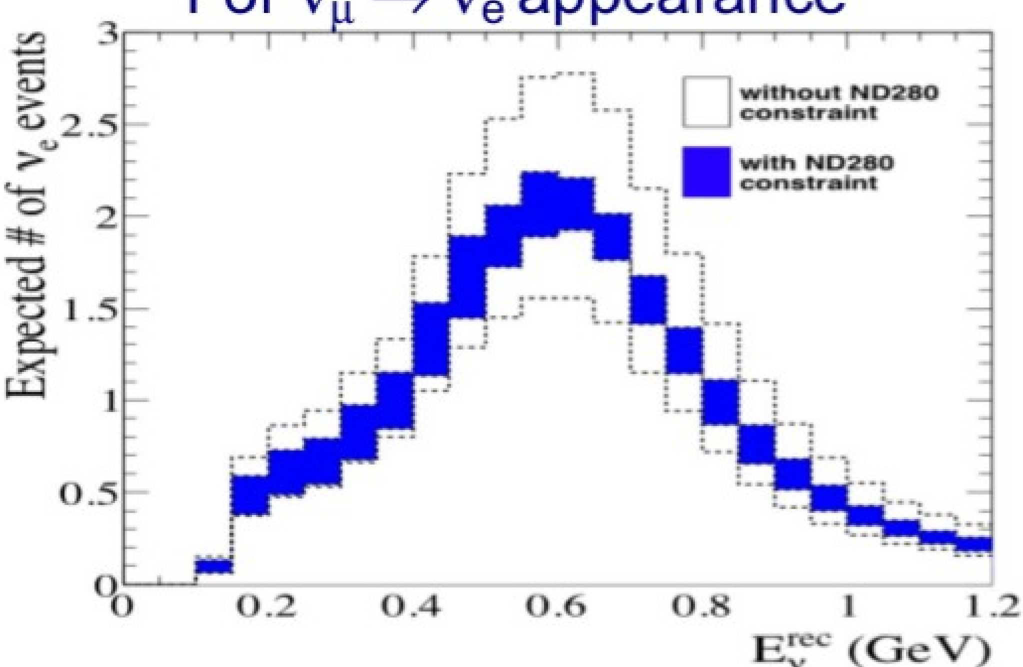


2014 → 2015

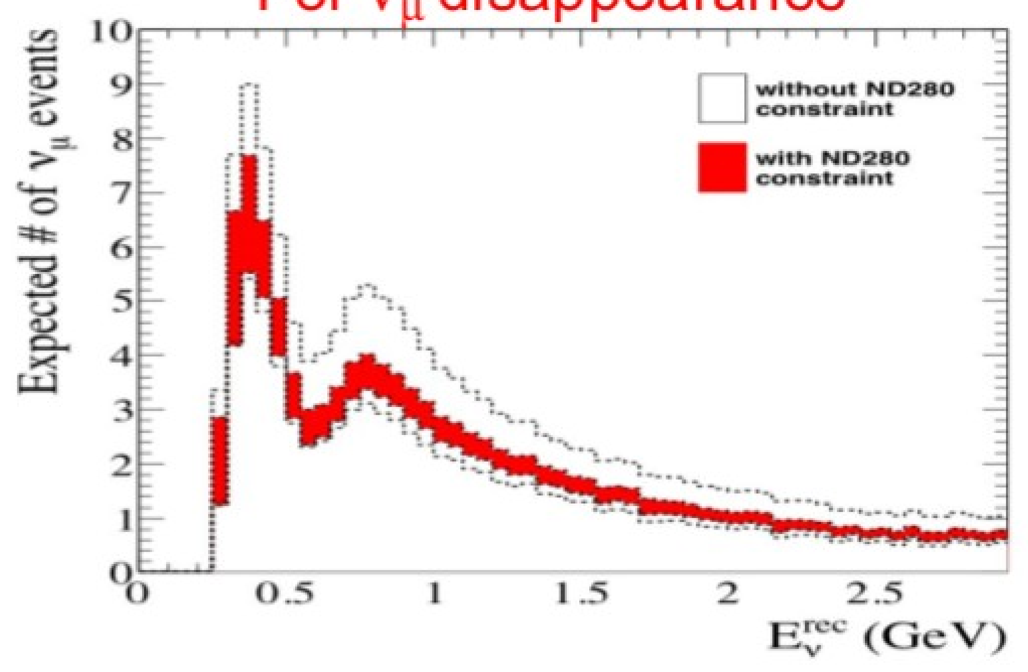
		ν_μ sample	ν_e sample	$\bar{\nu}_\mu$ sample	$\bar{\nu}_e$ sample
ν flux		16%	11%	7.1%	8%
ν flux and cross section	w/o ND measurement	21.8%	26.0%	9.2%	9.4%
	w/ ND measurement	2.7%	3.1%	3.4%	3.0%
ν cross section due to difference of nuclear target btw. near and far		5.0%	4.7%	10%	9.8%
Final or Secondary Hadronic Interaction		3.0%	2.4%	2.1%	2.2%
Super-K detector		4.0%	2.7%	3.8%	3.0%
total	w/o ND measurement	23.5%	26.8%	14.4%	13.5%
	w/ ND measurement	7.7%	6.8%	11.6%	11.0%

Examples of error reduction on the expected number of events in Super-K

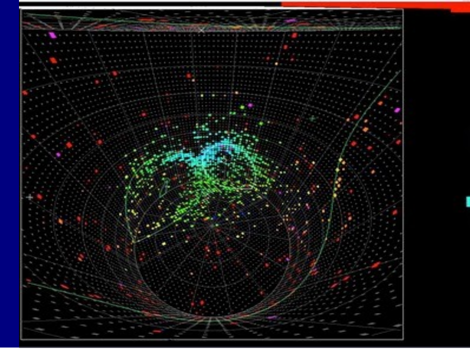
For $\nu_\mu \rightarrow \nu_e$ appearance



For ν_μ disappearance



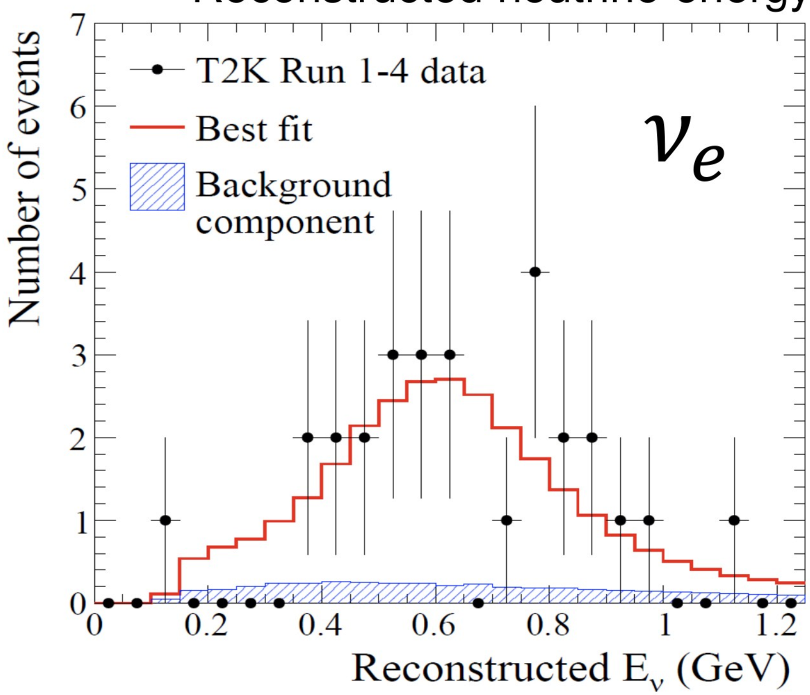
T2K Far Detector Data (Super-K)

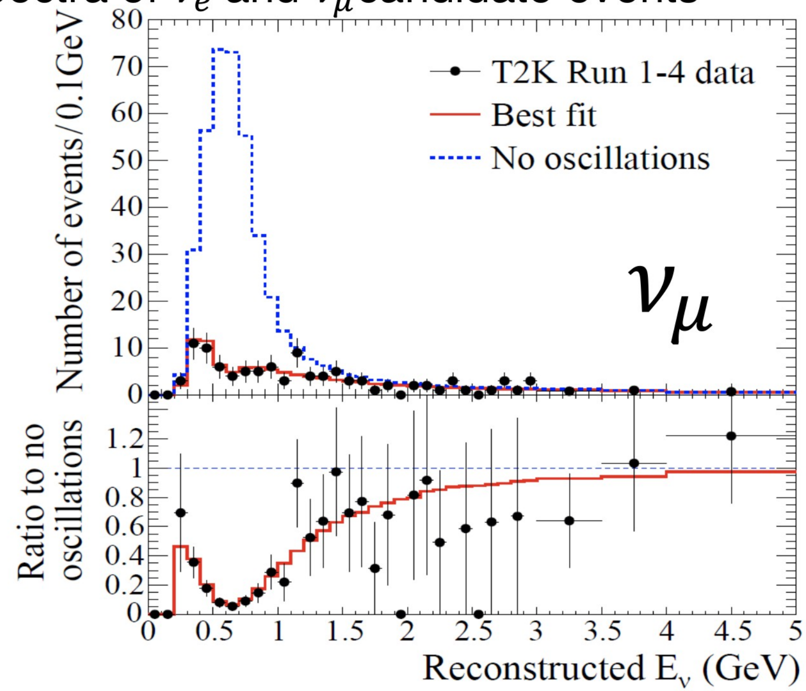


- Select ν_e and ν_μ in SK
- ν_e appearance and ν_μ disappearance clearly seen

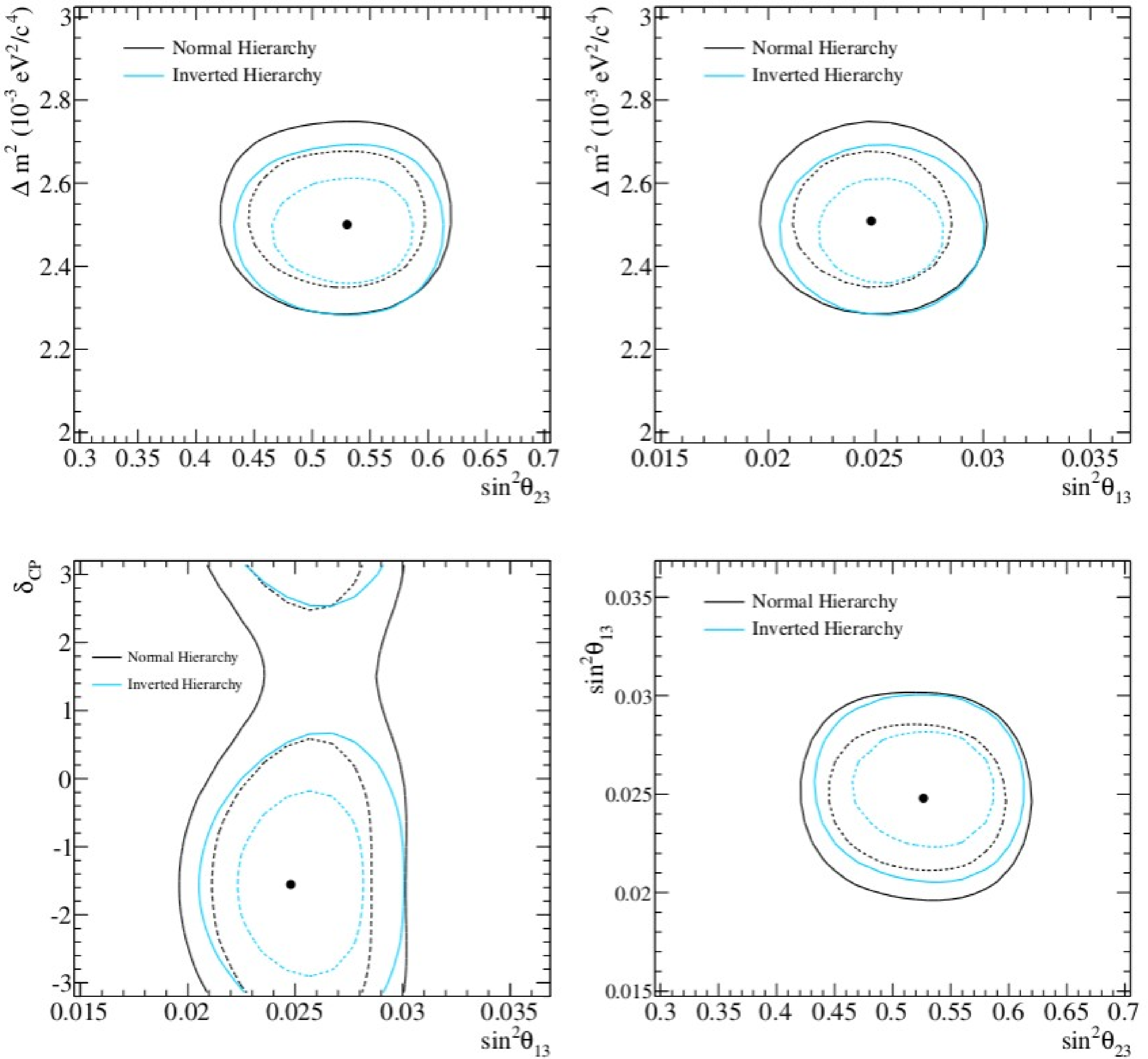
Data from Runs 1-4
Neutrino mode
6.6×10^{20} POT
Phys. Rev. D91, 072010 (2015)

Reconstructed neutrino energy spectra of ν_e and ν_μ candidate events





ν Oscillation Result w/ Reactor Constraint



90% CL excluded Region becomes:

$0.15\pi < \delta < 0.83\pi$ (NH)

$-0.08\pi < \delta < 1.09\pi$ (IH)

Hints that CP phase may be non-zero

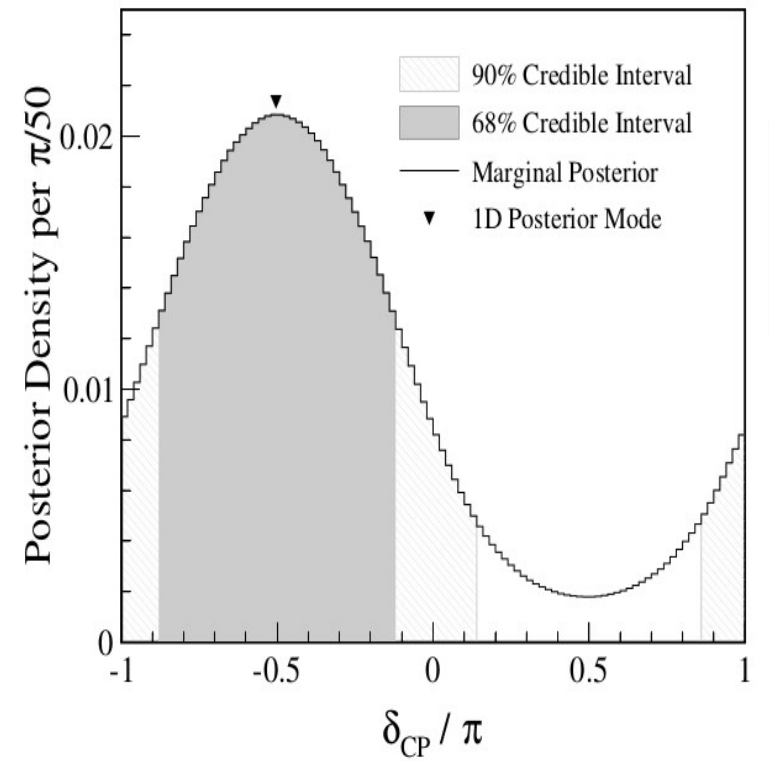
Joint Fit to both ν_e and ν_μ data

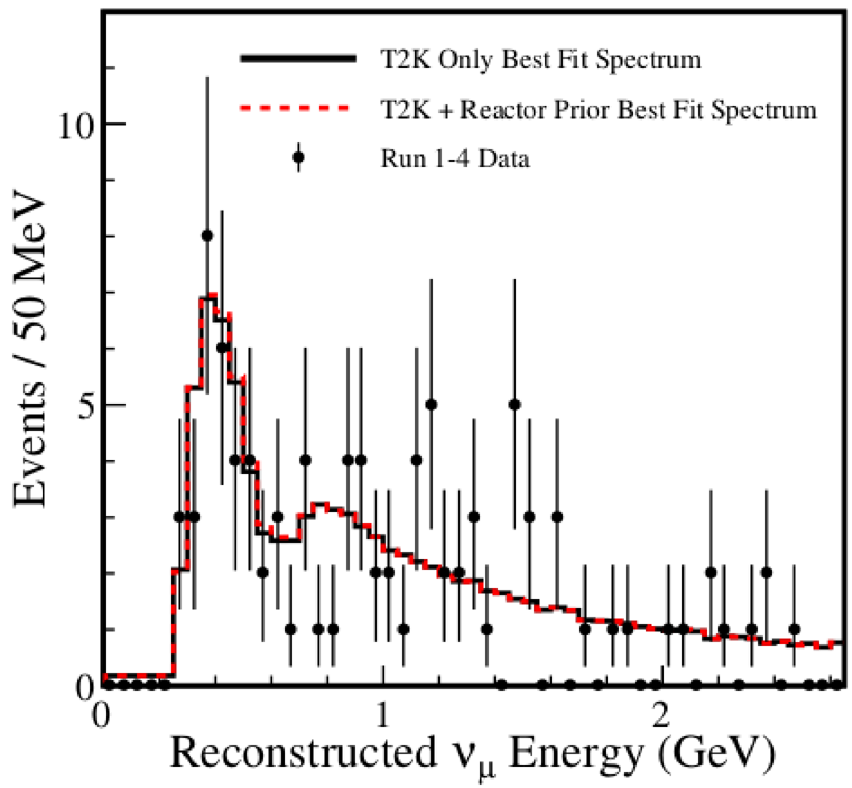
See Thesis prize talk of P. de Perio (R2-2)

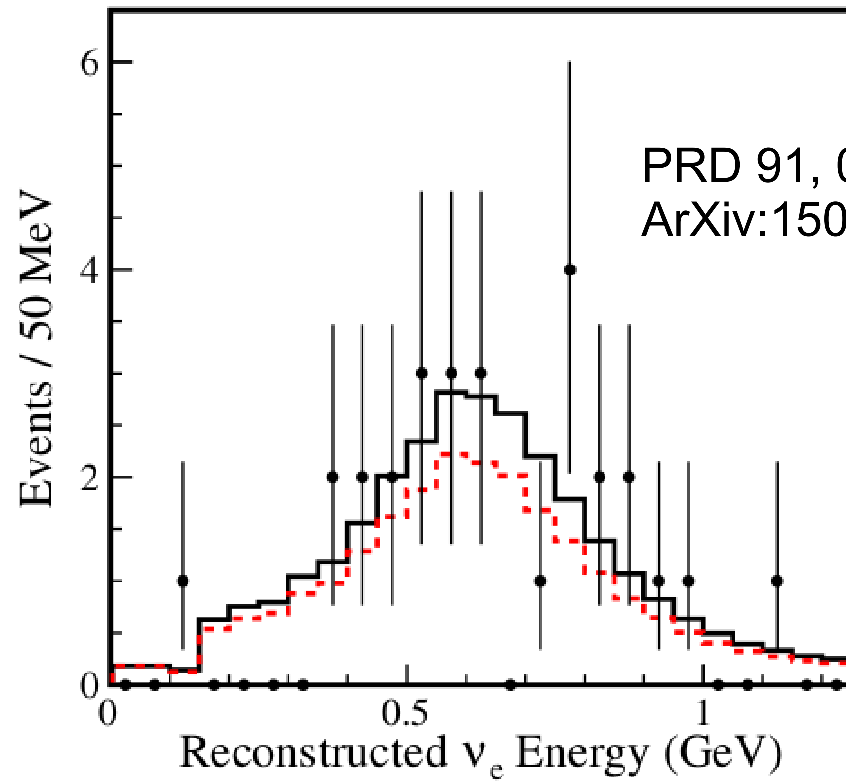
PRD 91, 072010 (2015)
ArXiv:1502.01550

T2K Far Data Compared to Best Fit Osc.

	$\lvert\Delta m^2_{32}\rvert$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$
Analysis	10^{-3} eV^2/c^4	1σ cred. intervals	
T2K-only	[2.46, 2.68]	[0.470, 0.565]	[0.0314 ,0.0664]
T2K+reactor	[2.40, 2.62]	[0.490, 0.583]	[0.0224, 0.0276]

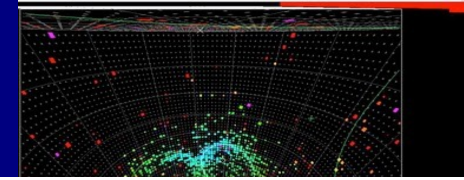




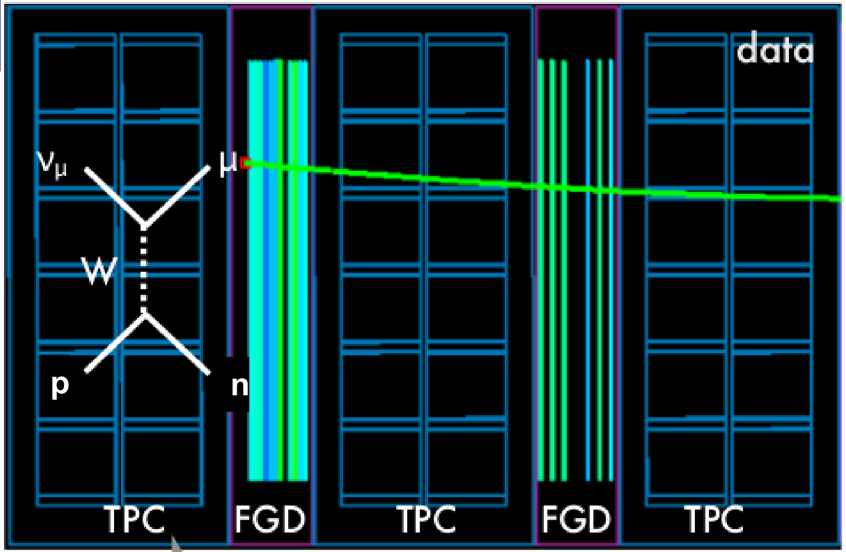


PRD 91, 072010 (2015)
ArXiv:1502.01550

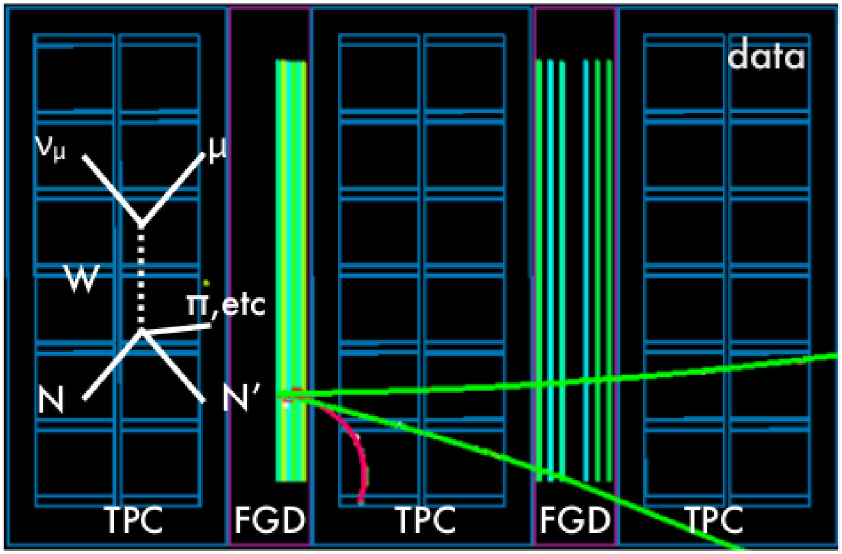
ND280 $\bar{\nu}_\mu$ Event Topologies

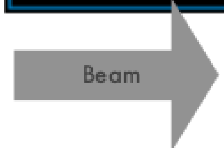


$\bar{\nu}_\mu$ CC-1Track

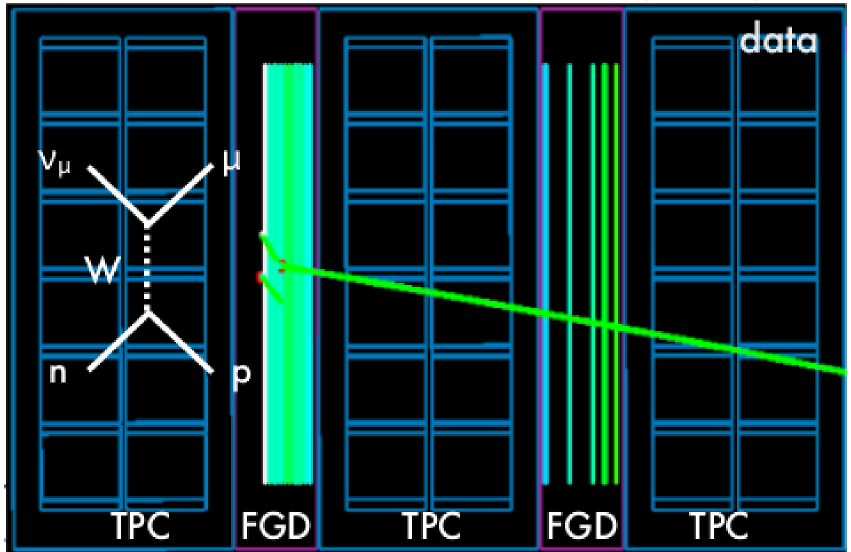


$\bar{\nu}_\mu$ CC-NTrack

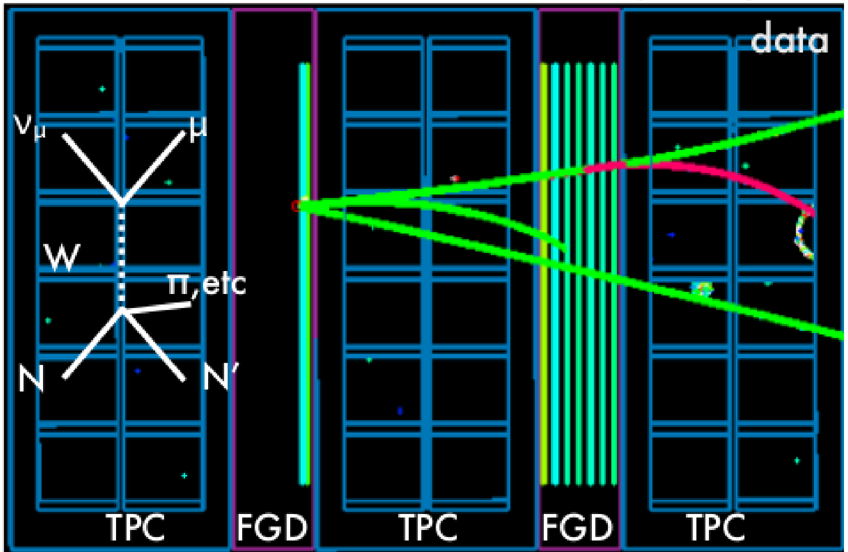




ν_μ CC-1Track (wrong sign)

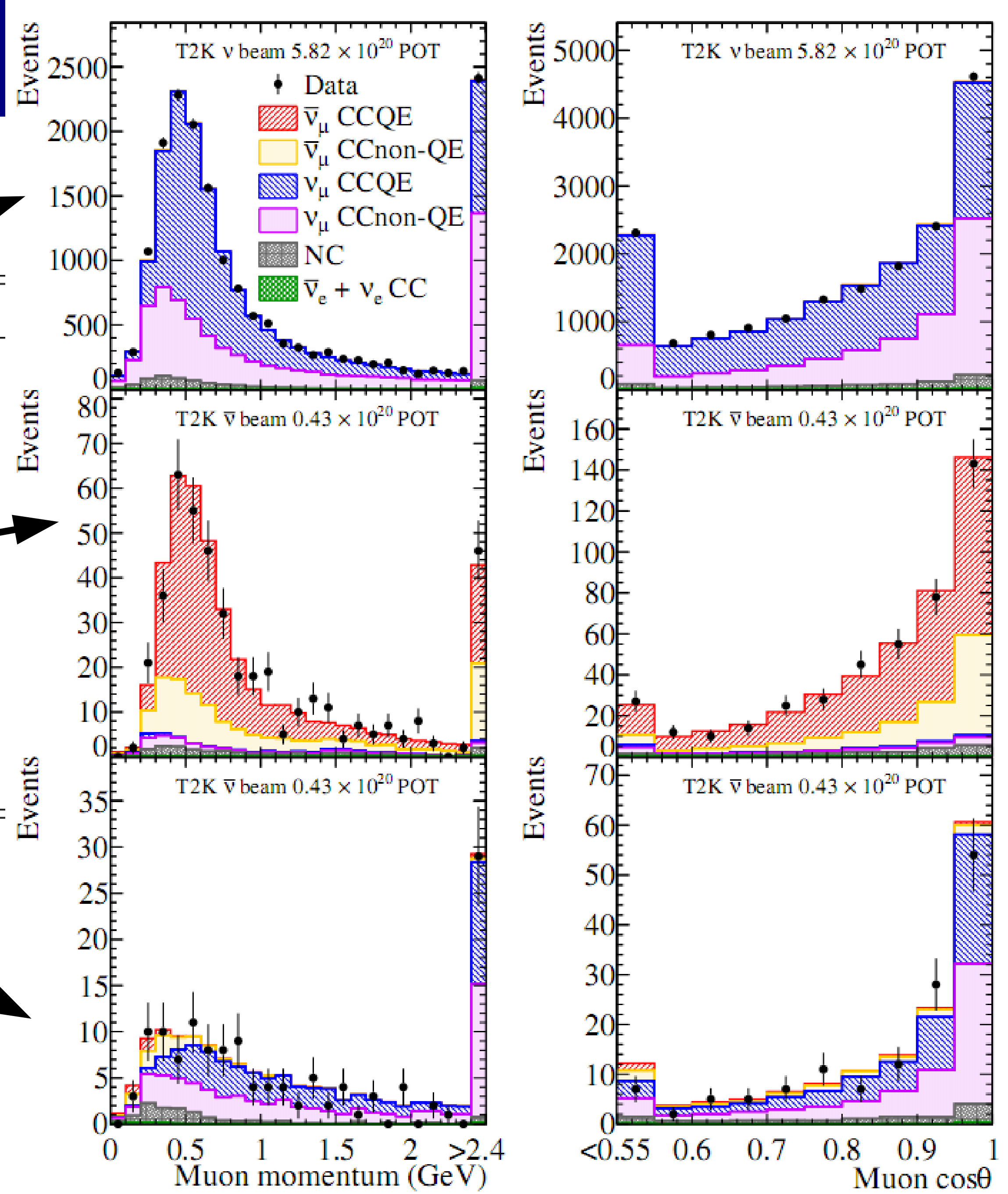


ν_μ CC-NTrack (wrong sign)



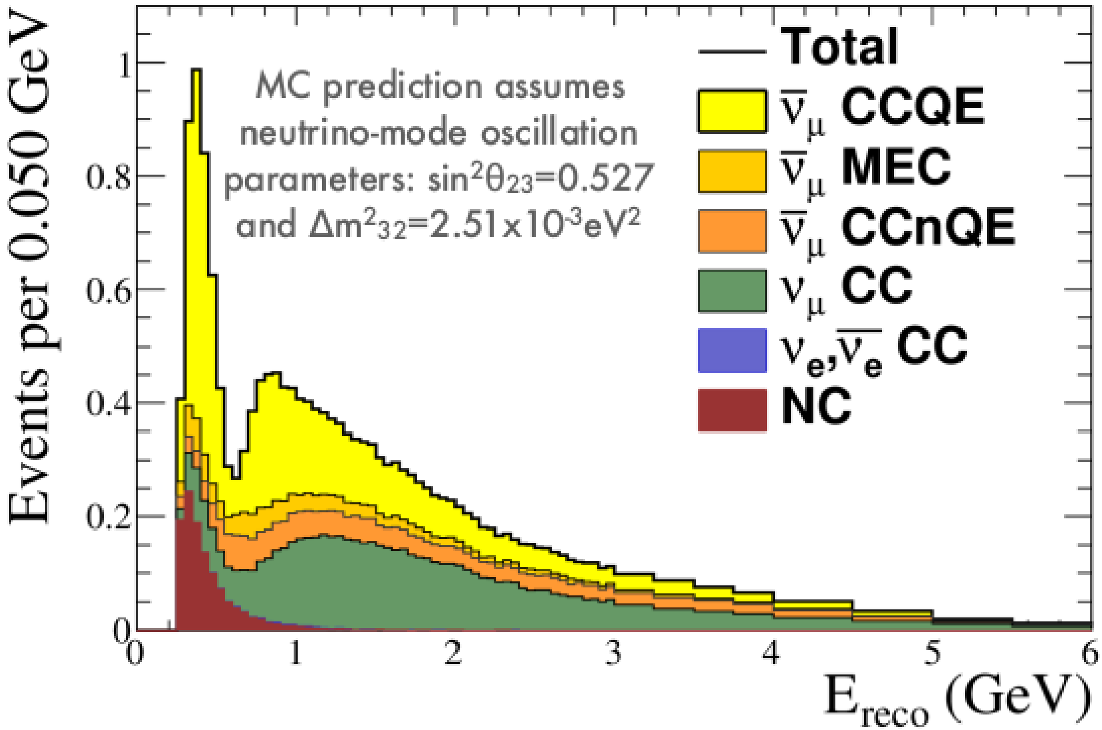
$\bar{\nu}$-mode ND280 Samples Post-Fit

Sample	Data	Prefit
	ν beam mode	
ν_μ CC 0π	17 362	15 625 $\pm$ 1663
ν_μ CC $1\pi^+$	3988	4748 $\pm$ 686
ν_μ CC other	4219	3772 $\pm$ 431
	$\bar{\nu}$ beam mode	
$\bar{\nu}_\mu$ CC 1 track	435	387 $\pm$ 41
$\bar{\nu}_\mu$ CC N tracks	136	128 $\pm$ 17
ν_μ CC 1 track	131	141 $\pm$ 15
ν_μ CC N tracks	145	147 $\pm$ 17



Phys. Rev. Lett. 116, 181801 (2016)

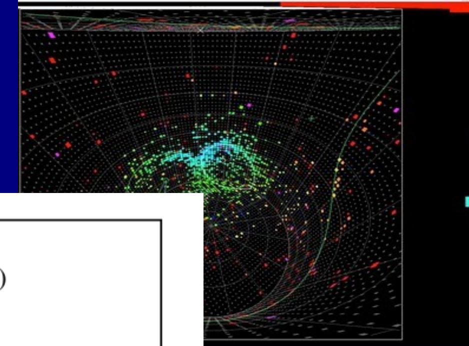
$\bar{\nu}_\mu$ Prediction at Far Detector

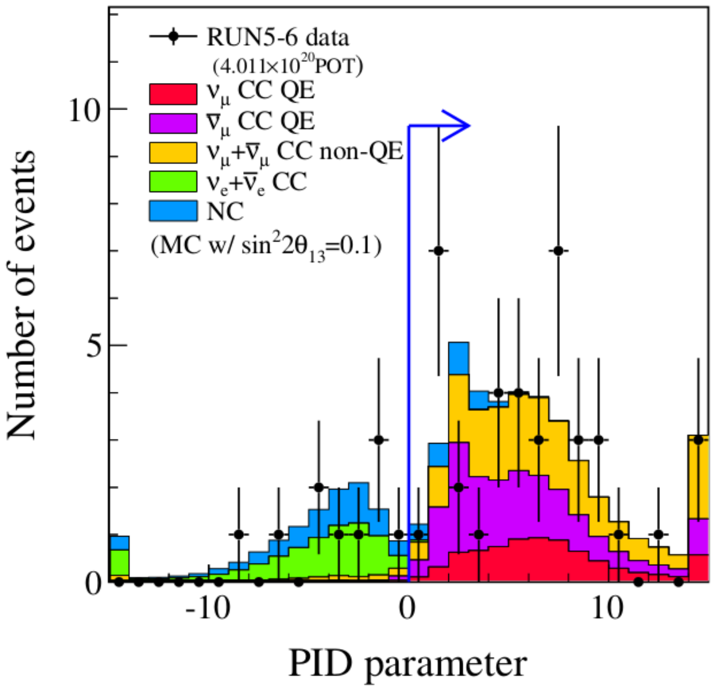


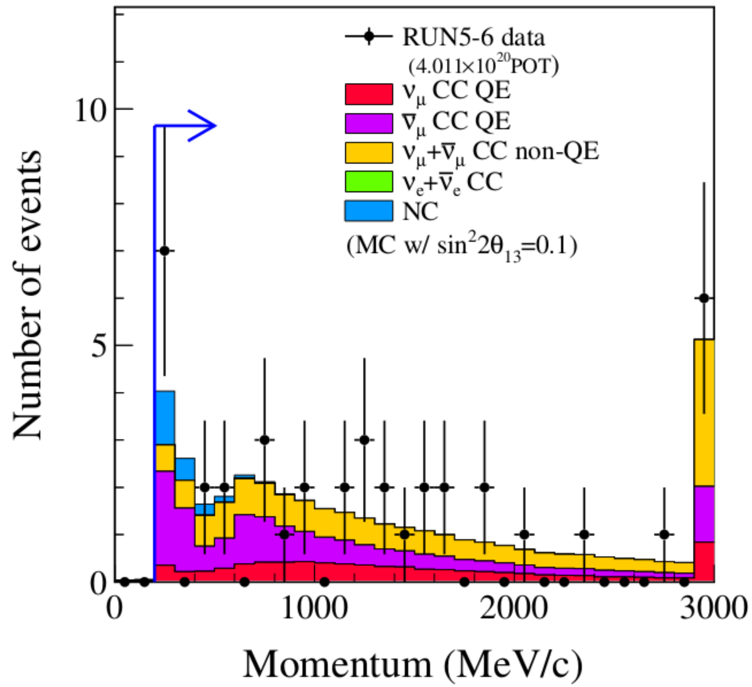
1. Fully contained within the fiducial volume of SK
2. Have one and only one reconstructed ring
3. Have μ-like PID
4. Have muon momentum >200 MeV/c
5. Have one or fewer decay electron

- Predict the expected spectrum at SK using neutrino-mode oscillation parameters
- Dominated by $\bar{\nu}$ CCQE events, but many other contributions—this is why cross section model is so important
- Predict **36.1** events with oscillation and **106.8** without oscillation

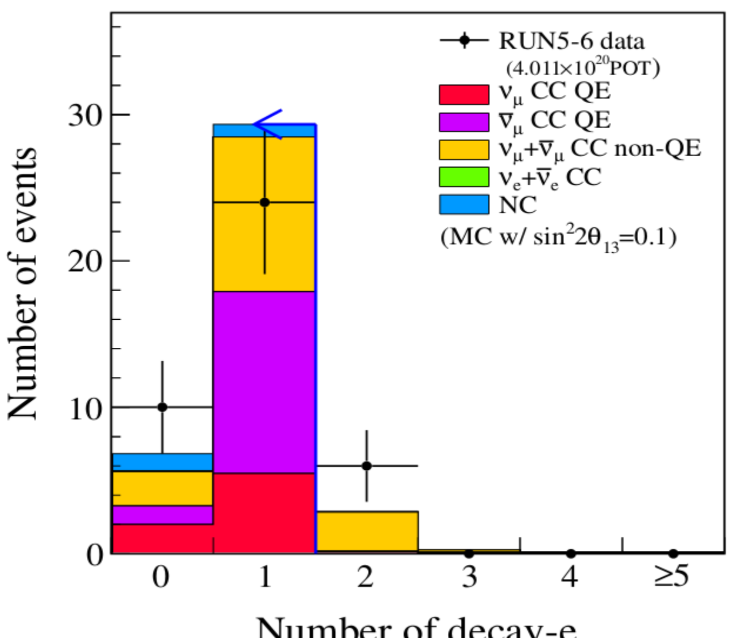
$\bar{\nu}_\mu$ Selection Far Detector







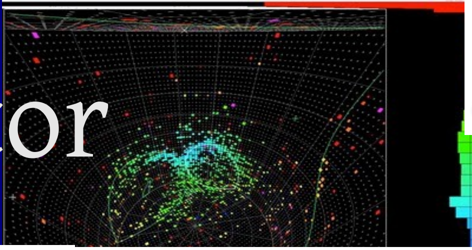
Runs 5, 6
4.0×10^{20} POT

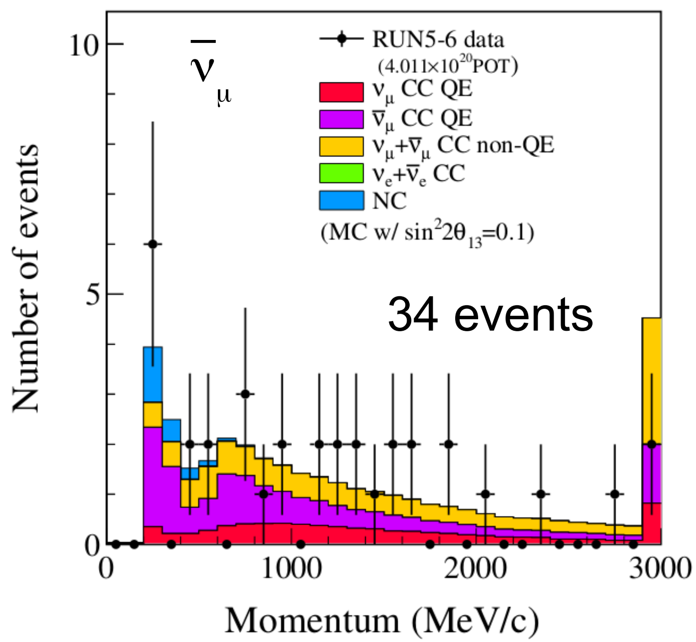


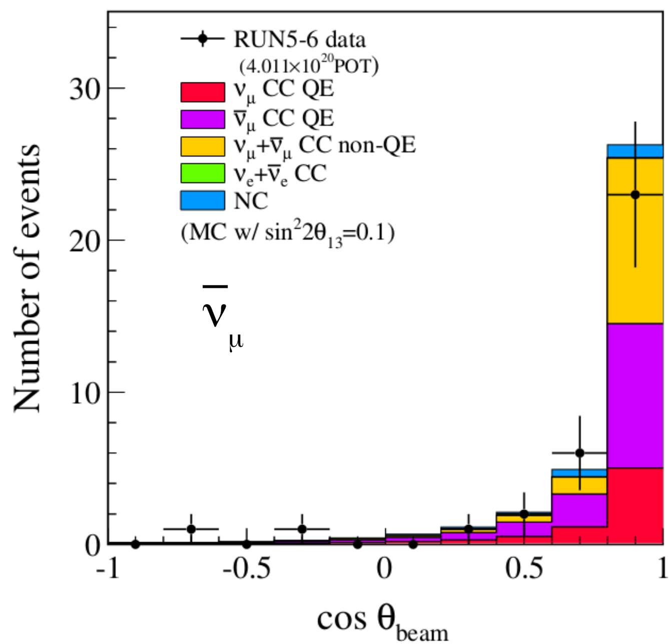
Parameter	Value
Δm^2_{21}	$7.6 \times 10^{-5}\mathrm{eV}^2$
Δm^2_{31}	$2.476 \times 10^{-3}\mathrm{eV}^2$
$(\Delta m^2_{32}$	$2.4 \times 10^{-3}\mathrm{eV}^2)$
$\sin^2 2\theta_{12}$	0.8495
$\sin^2 2\theta_{13}$	0.1
$\sin^2 2\theta_{23}$	1.0
δ_{CP}	0
Mass hierarchy	Normal
ν travel length	295 km
Earth density	$2.6\mathrm{g/cm}^3$

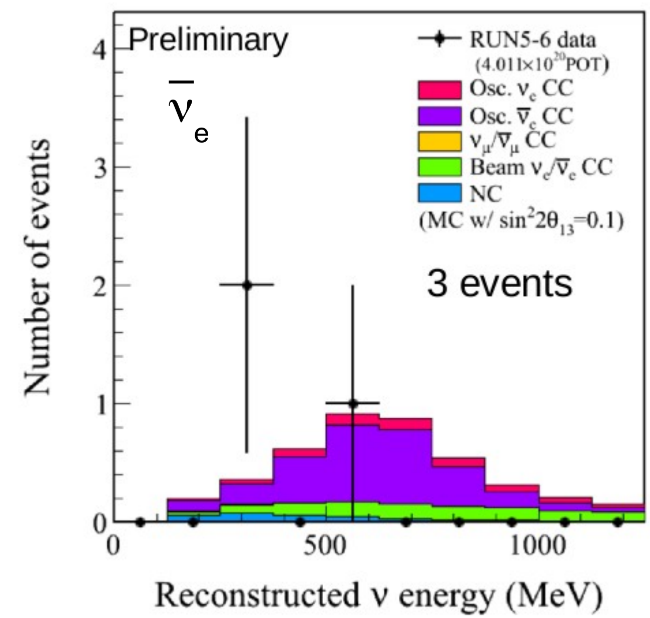
Oscillation parameters in these plots

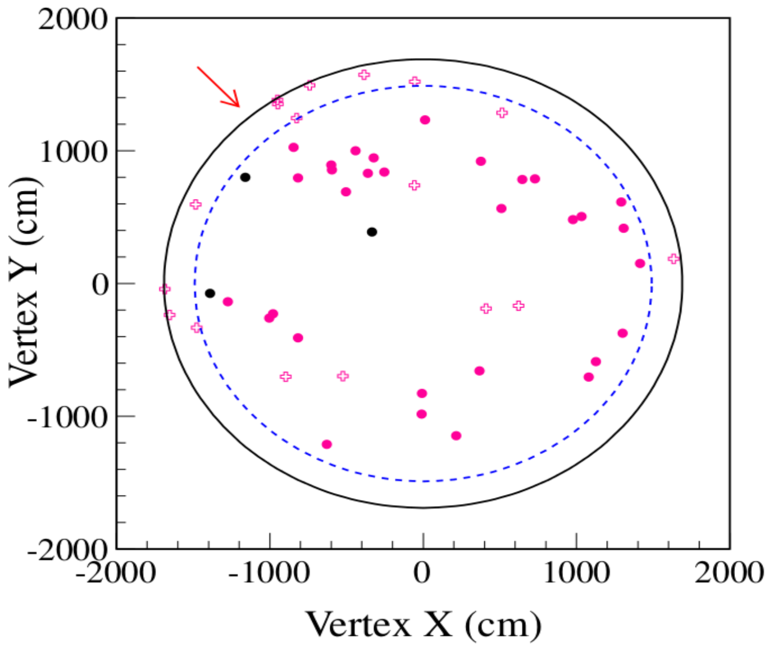
$\bar{\nu}$ Events at T2K Far Detector

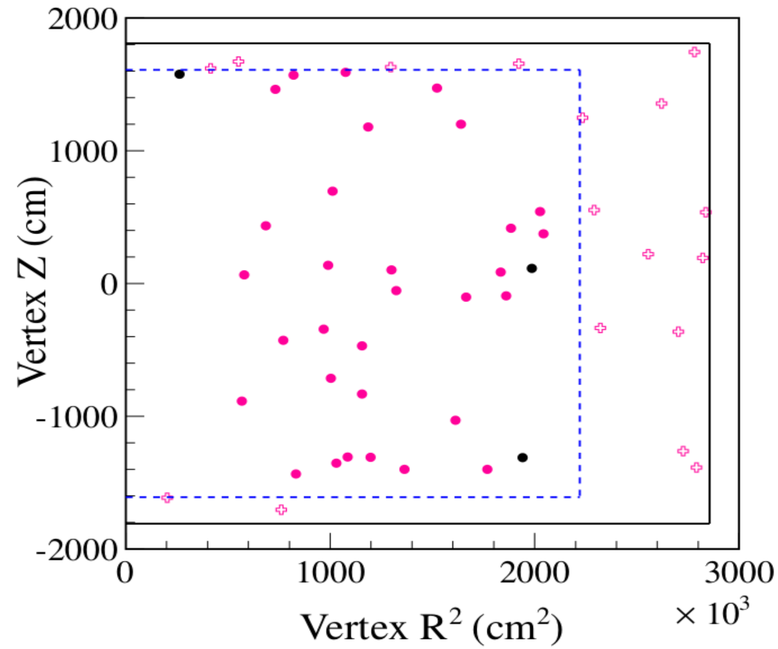






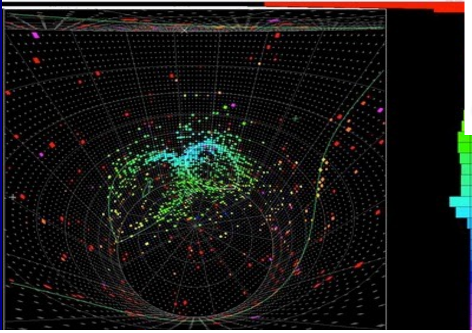




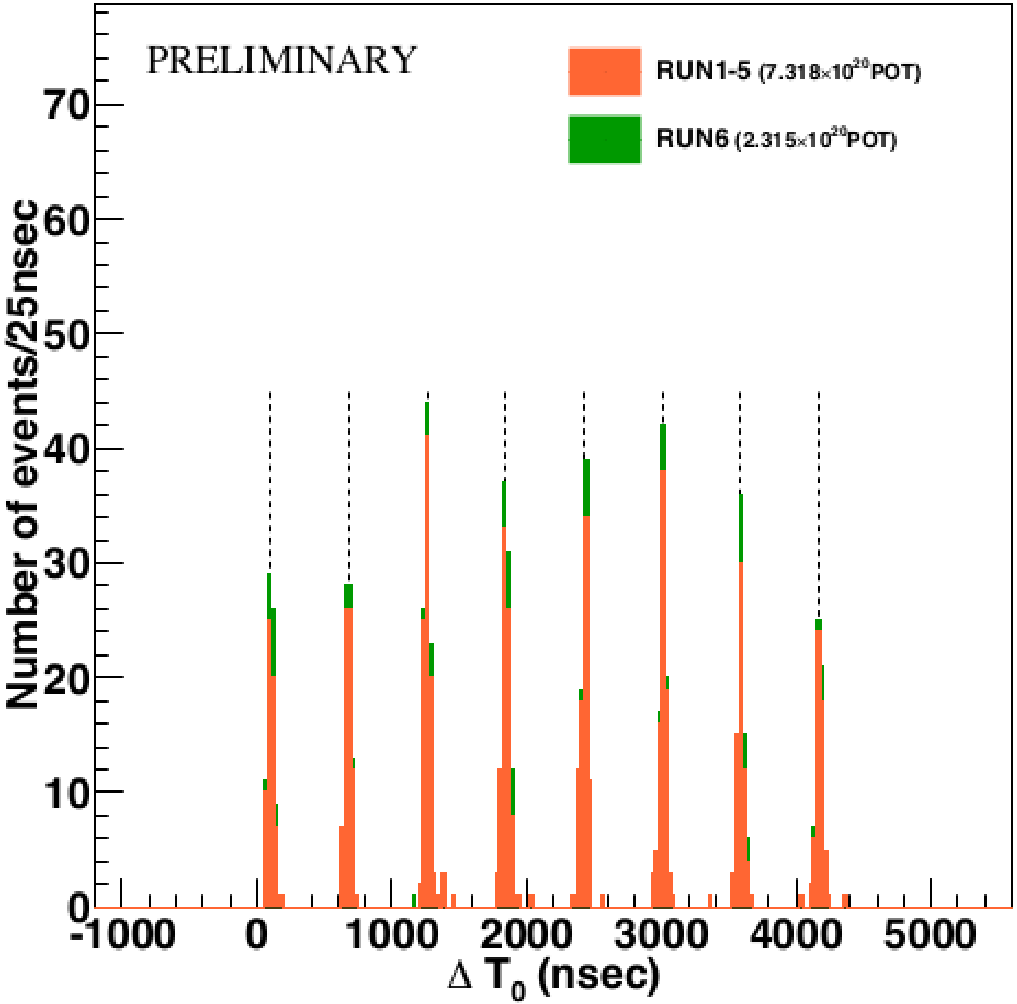


Black points are $\bar{\nu}_e$ selection

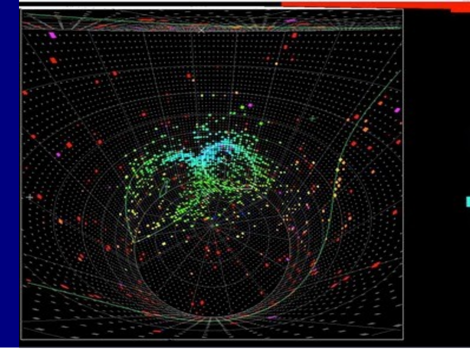
T2K Far Detector Timing



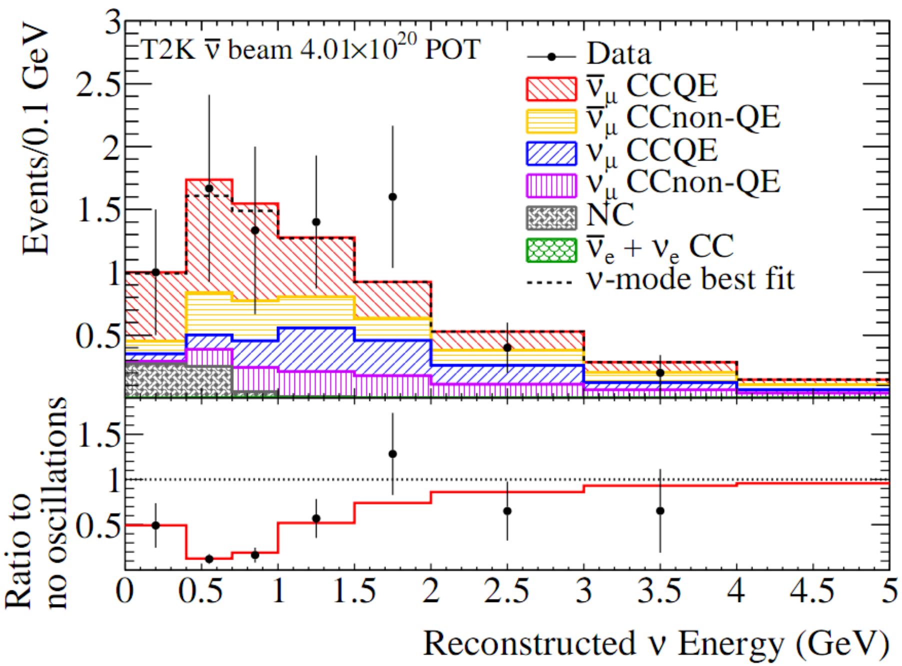
- Fully contained events in the SK fiducial volume appear in time with the T2K beam
- Both ν-mode and $\bar{\nu}$-mode events have good beam timing



$\bar{\nu}_\mu$ disappearance analysis method



T2K Run 5 and 6
4×10^{20} POT of anti-neutrino data

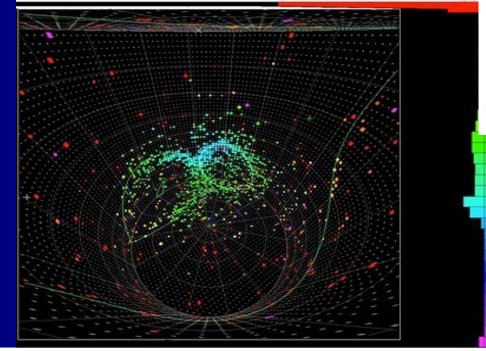


Data show clear evidence of Oscillation

- Maximize likelihood which is a product of Poisson term and systematics uncertainty terms
- Three separate analyses including Frequentist and Bayesian, all agree
- Fix all oscillation parameters except $\sin^2\bar{\theta}_{23}$ and $\Delta\bar{m}^2_{32}$ using T2K neutrino data and PDG2014 as in table below

$\sin^2\theta_{23}$	0.527	$\sin^2\bar{\theta}_{23}$	0–1
Δm^2_{32}	2.51×10^{-3} eV^2	$\Delta\bar{m}^2_{32}$	0–0.02 eV^2
$\sin^2\theta_{13}$	0.0248	$\sin^2\bar{\theta}_{13}$	0.0248
$\sin^2\theta_{12}$	0.304	$\sin^2\bar{\theta}_{12}$	0.304
Δm^2_{21}	7.53×10^{-5} eV^2	$\Delta\bar{m}^2_{21}$	7.53×10^{-5} eV^2
δ	−1.55 rad	$\bar{\delta}$	−1.55 rad

T2K $\bar{\nu}_\mu$ oscillation

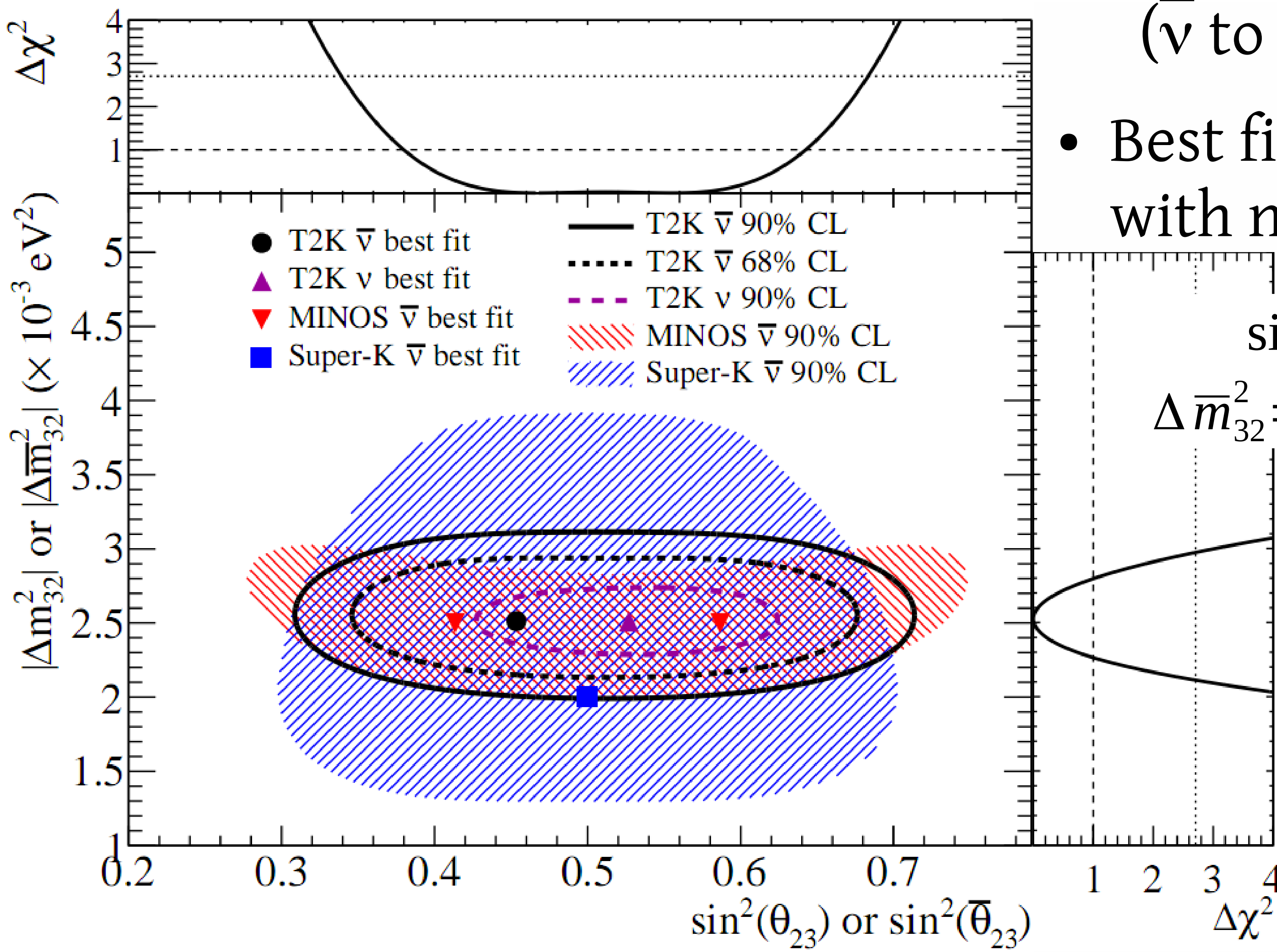


Phys. Rev. Lett. 116, 181801 (2016)

- Using 4.01×10^{20} POT ($\bar{\nu}$ to end of Run 6)
- Best fit values consistent with neutrino mode:

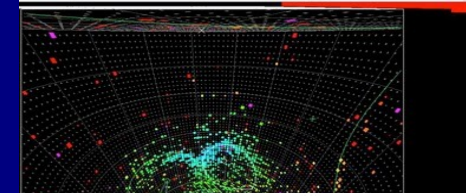
$$\sin^2\bar{\theta}_{23} = 0.45^{+0.11}_{-0.07}$$

$$\Delta\bar{m}^2_{32} = 2.51^{+0.29}_{-0.25}\times10^{-3}\,eV^2$$



MINOS result from PRL 110 (2013) 25, 251801

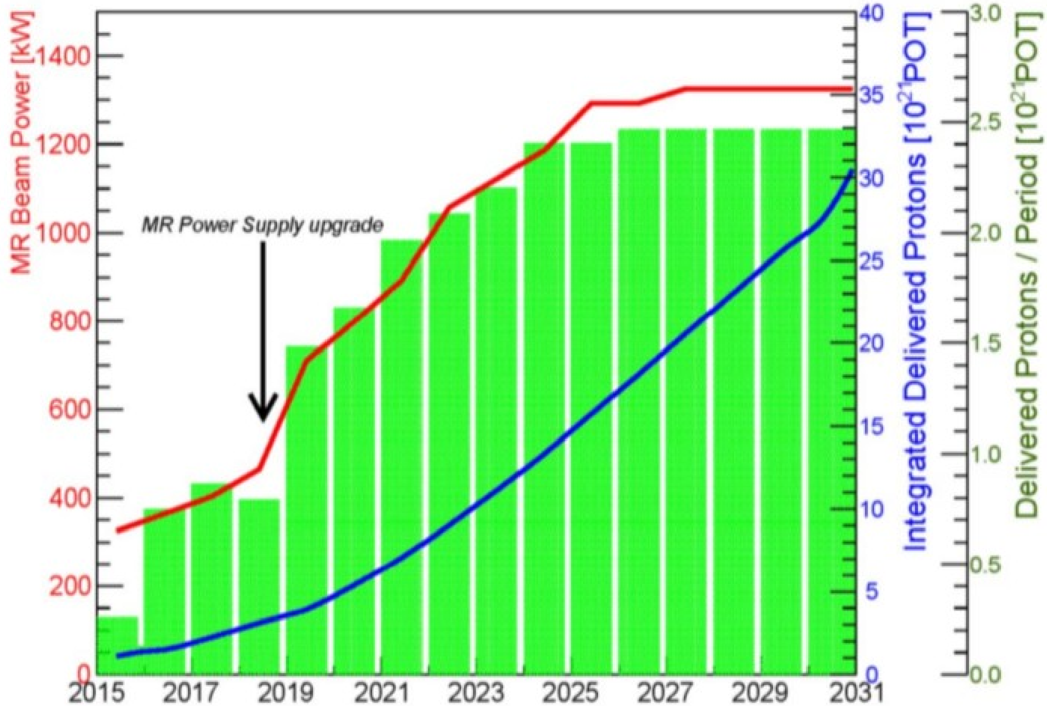
T2K-II



750 kW budget approved
(2.48s → 1.3s by 2019)

- Target Beam power 1.3 MW
- 20E21 POT by 2025~2026
- Increase effective statistics by up to 50%
  - horn current, SK fiducial volume, new event samples
- Reduce systematic error ~6% → ~4%

J-PARC MR expected performance and T2K-2 POT accumulation scenario



KEK Project Implementation Plan (PIP plan) → Given highest priority by review panel

Includes intermediate detectors (νPRISM)

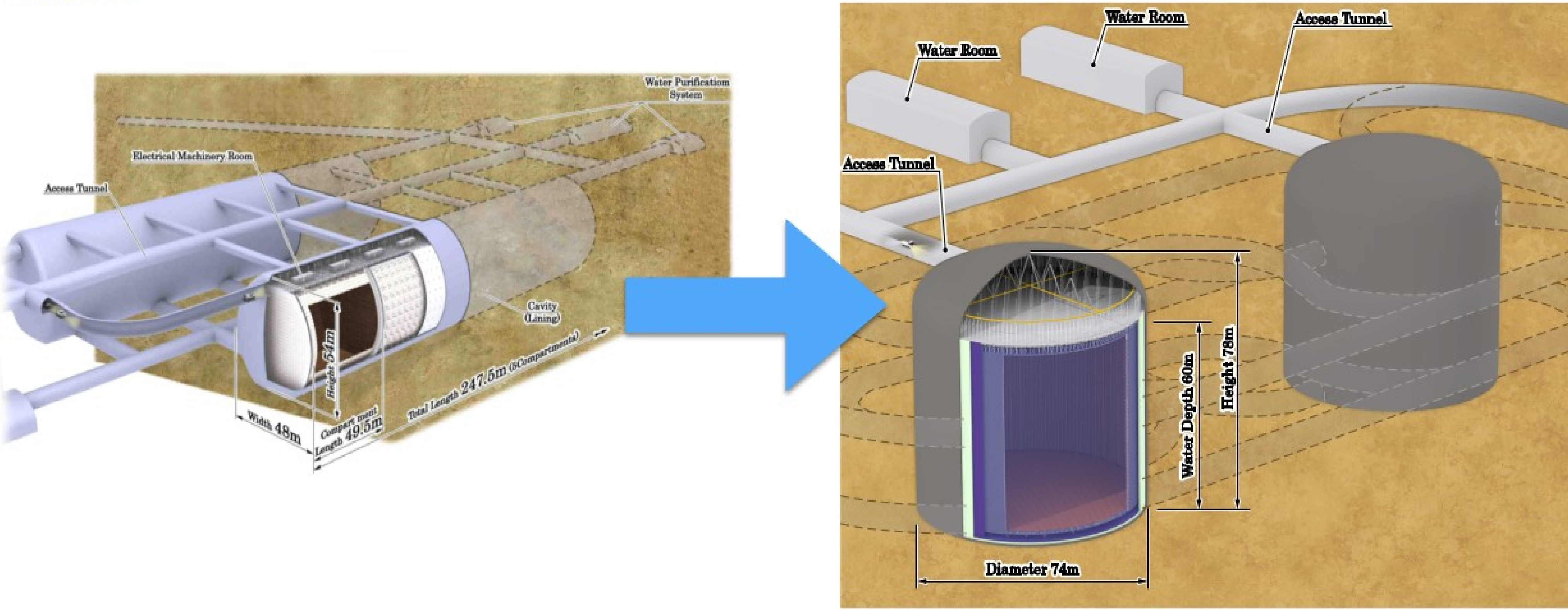
Expected number of events (1:1 $\nu : \bar{\nu}$ running case)

ν_e sample : 455 evts ±20% change depending on δ_{CP}

$\bar{\nu}_e$ sample : 129 evts ±13% change depending on δ_{CP}

*** More details on T2K-II in talk of Tom Feusels
νPRISM in talk of Mark Scott ***

Hyper-Kamiokande : Design Updated



- SK-like cylindrical vertical tank: Φ74m x H60m
  - Total volume: 260kton/tank, Fiducial volume: 190kton/tank
- Photo-coverage = 40% → 40k ID PMTs/6.7k OD PMT
- 2 tanks with staging (1 tank at day1)

- Each 10x Vol. Super-Kamiokande
- First tank by ~2026

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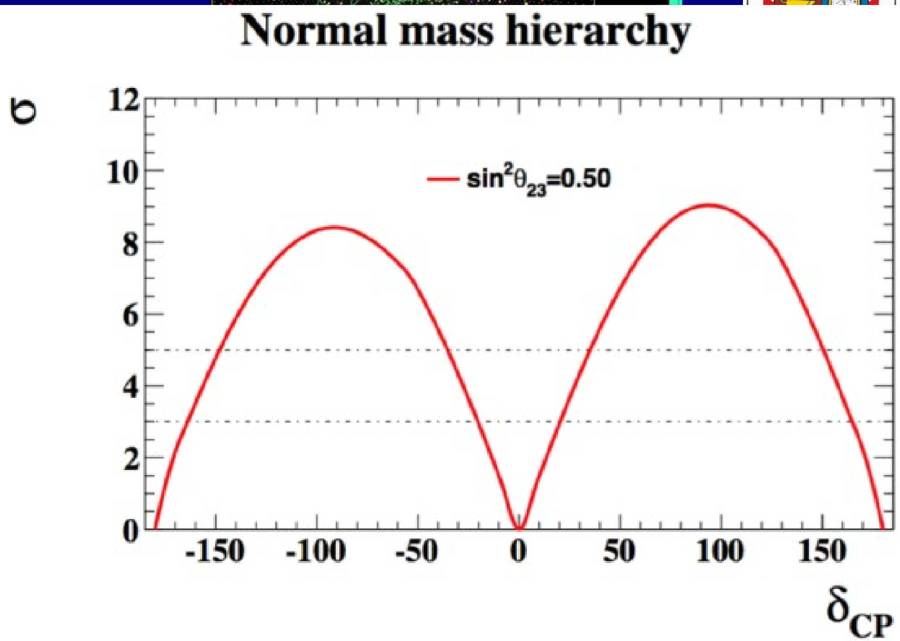
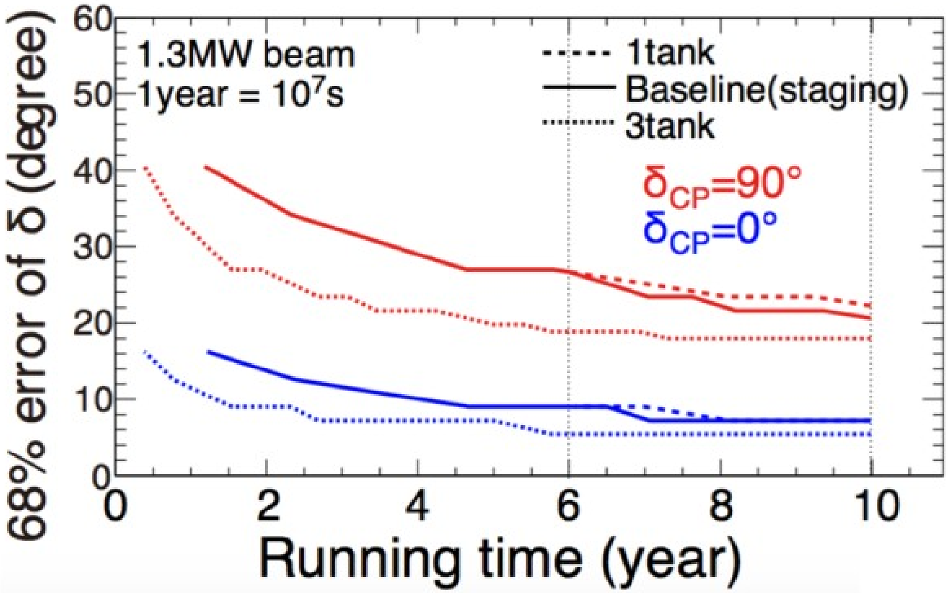
J-Parc to Hyper-K CP Violation

- Exclusion of sin δ_{CP}=0
  - >8σ (6σ) for δ=-90°(-45°)
  - ~80% coverage of δ parameter space with >3σ
- δ_{CP} measurement precision
  - 7~21° precision



		sinδ=0 exclusion		68% error	
		>3σ	>5σ	δ=0°	δ=90°
Old	7.5MWy	76%	58%	7.5°	19°
2tank (staging)	13MWy	78%	62%	7.2°	21°



Prog. Theor. Exp. Phys (2015) 053C02

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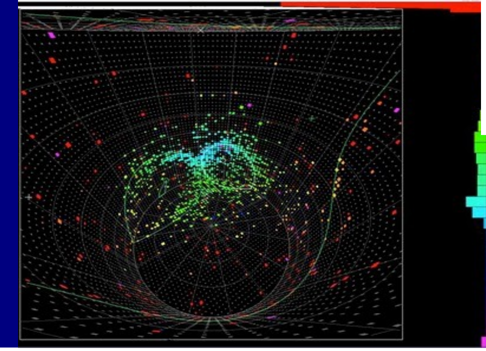
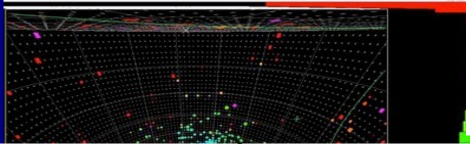
Summary and conclusions



- Data samples analyzed by T2K so far correspond to
  - 7×10^{20} POT in ν-mode
  - 4×10^{20} POT in $\bar{\nu}$-mode (additional 3×10^{20} to be analyzed)

  *** Approved to exposure is 7.8×10^{21}
- T2K reported observation of neutrino appearance ($\nu_\mu \rightarrow \nu_e$)
- Muon anti-neutrino disappearance results consistent with our world leading ν_μ disappearance measurements.
- J-PARC accelerator has achieved stable >400kW running
- Proposal for T2K-II with a goal of 20×10^{21} POT is formulated to reach a 3σ significance for maximum CP violation

The T2K Collaboration



~ 500 members, 61 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 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.
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Okayama U.
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Michigan S.U.
Stony Brook U.
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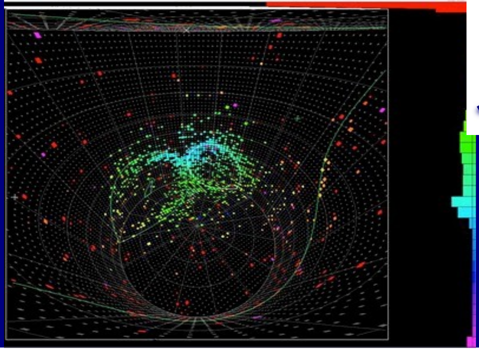
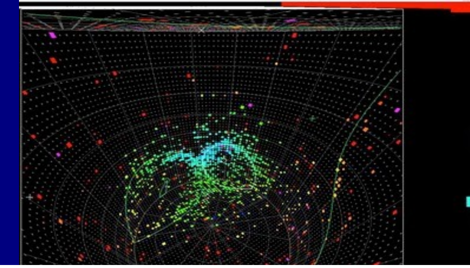


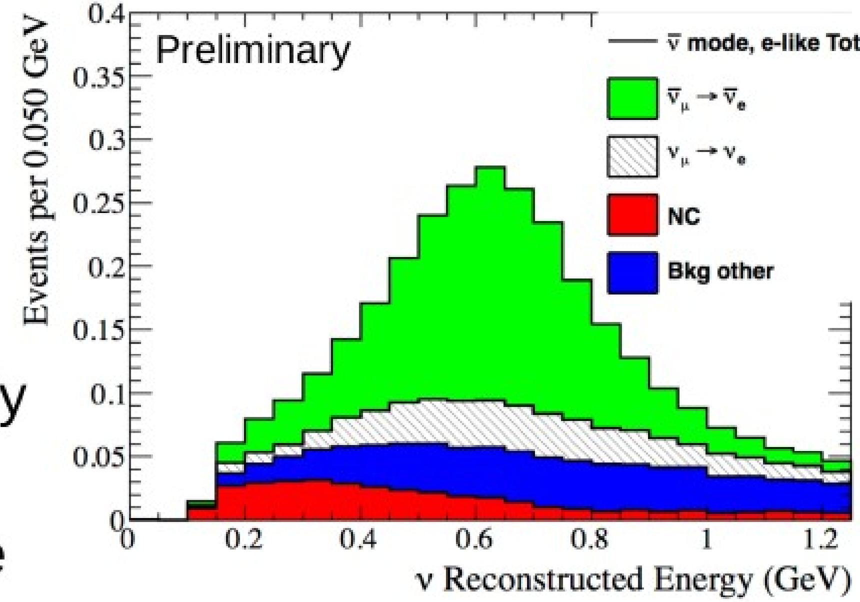
Backups

$\bar{\nu}_e$ Appearance



Why?

- Observe anti-neutrino appearance
- Compare to ν_e – constrain δ_{CP}



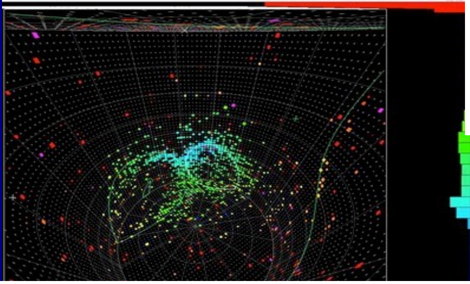
How?

- Introduce discrete β parameter to modify appearance probability
- β = 0, null hypothesis, no $\bar{\nu}_e$ appearance
- β = 1, $\bar{\nu}_e$ appearance with same parameters as ν_e appearance

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{\mathrm{PMNS}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Parameter(s)	Treatment	Nominal value
$\sin^2\theta_{23}$	marginalized	0.528
$\sin^2\theta_{13}$	marginalized	0.025
$\sin^2\theta_{12}$	fixed	0.306
$\lvert\Delta m^2_{32}\rvert$ (NH) / $\lvert\Delta m^2_{31}\rvert$ (IH)	marginalized	2.509×10^{-3} eV^2/c^4
Δm^2_{21}	fixed	7.5×10^{-5} eV^2/c^4
δ_{CP}	marginalized	-1.601
Mass Hierarchy	marginalized	NH

$\bar{\nu}_e$ Appearance



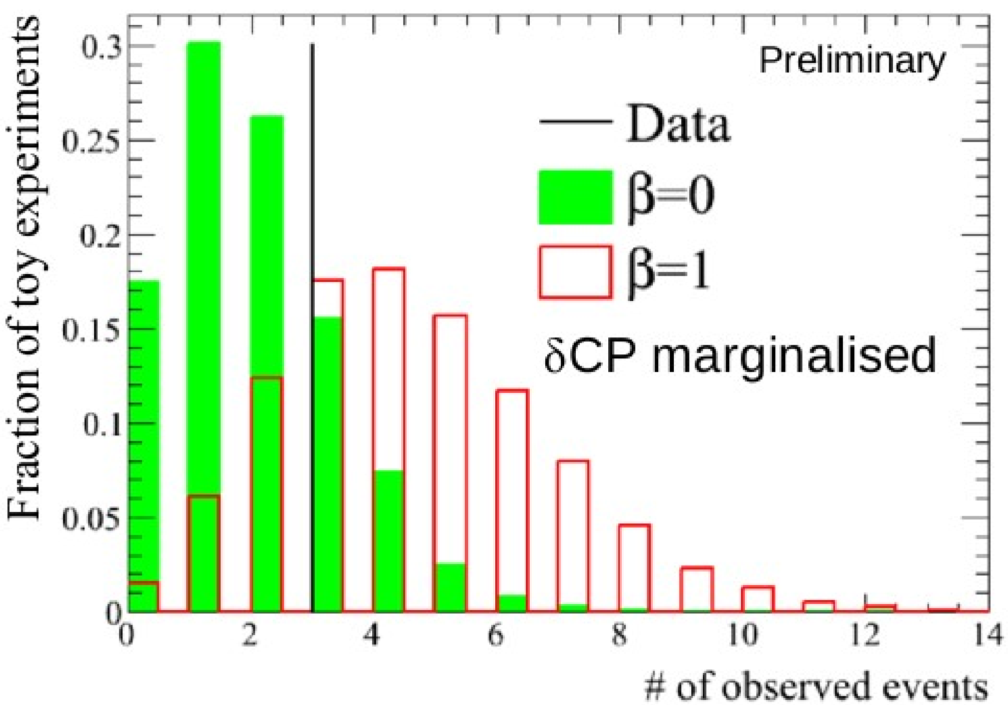
Expected event rates for given oscillation parameters

- ~4 if $\beta = 1$
- ~1.6 if $\beta = 0$
- Observed 3 events in the data

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Sig $\bar{\nu}_\mu \to \bar{\nu}_e$	1.961	2.636	3.288
Bkg $\nu_\mu \to \nu_e$	0.592	0.505	0.389
Bkg NC	0.349	0.349	0.349
Bkg other	0.826	0.826	0.826
Total	3.729	4.315	4.851

Observed $\beta = 0$ p-value	$\beta = 1$ / $\beta = 0$ Marginalised likelihood ratio
0.26	1.09

Data do not show evidence for or against $\bar{\nu}_e$ appearance



$\nu_{\mu,e}$ Cross Section Analyses at ND

Target	CC0π (π⁰) NC0π	2p2h	CC1π (π⁰, K) NC1π	CCcoher.	CCinclusive
Scintillator (CH)	FGD1 FGD1 FGD1 INGRID	FGD1	FGD1 FGD1	FGD1 INGRID	FGD1 FGD1
iron					INGRID
Water (H_2O)	FGD2 P0D		FGD2 P0D	FGD2	FGD2

There are also CCQE results for ND280 and INGRID

Published | Paper on arXiv

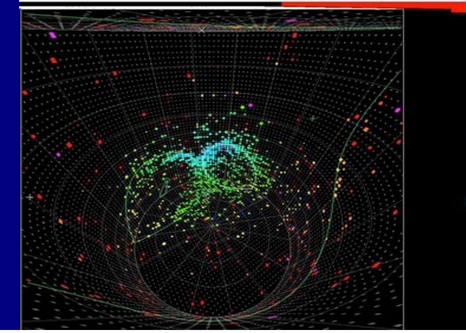
$\nu_{\mu,e}$ CC, NC

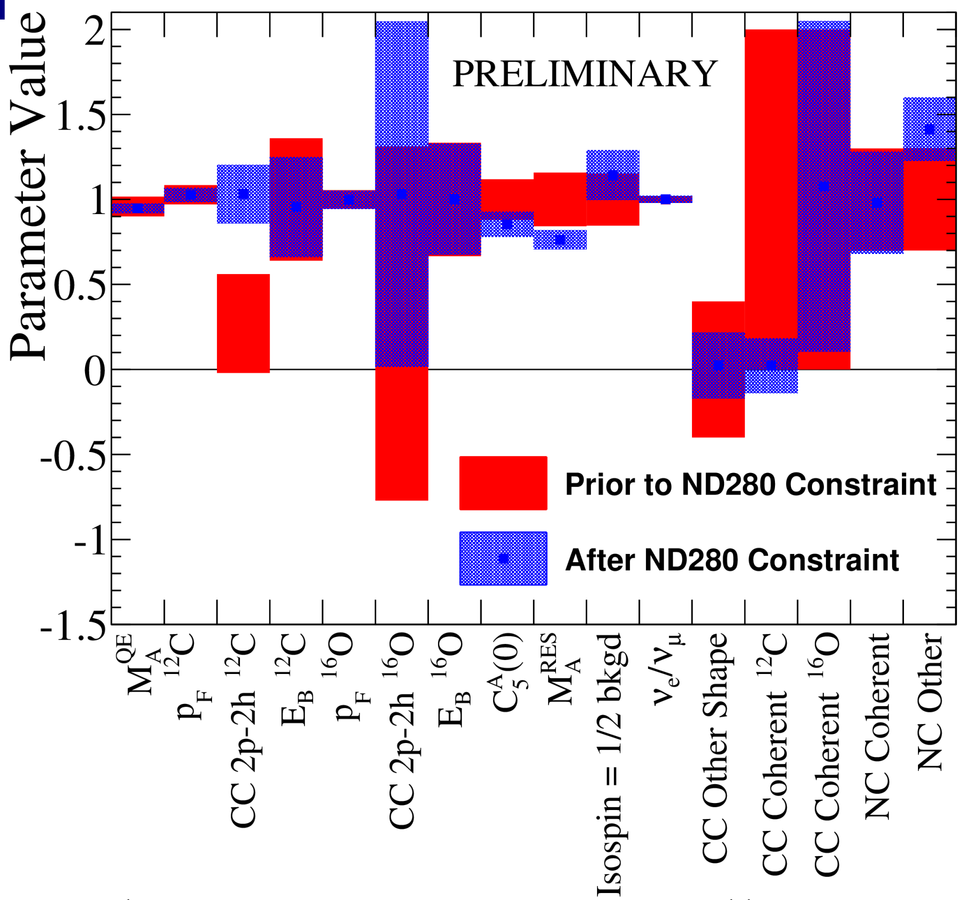
Strategy:

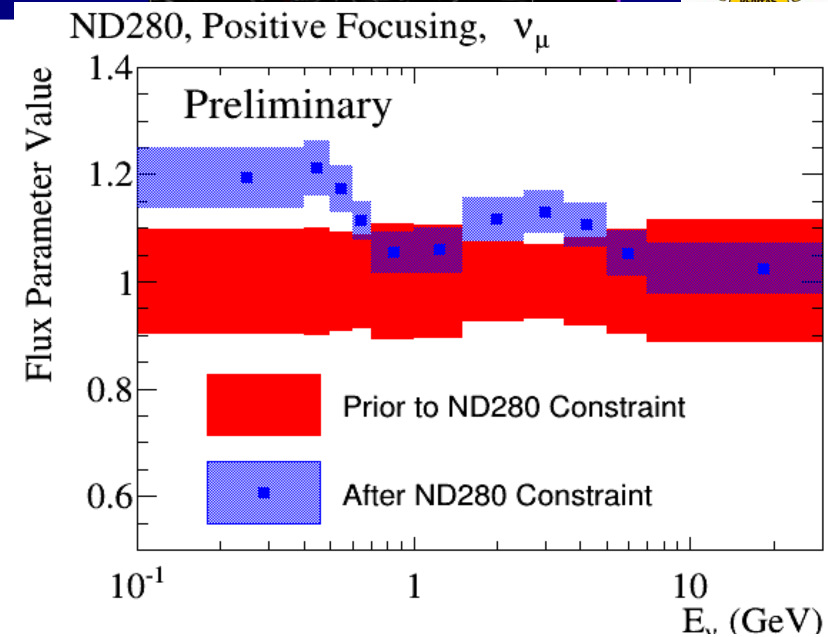
- Cross section on carbon (FGD1, INGRID)
- Cross section on water (FGD2 and P0D)
- Cross sections on ν versus $\bar{\nu}$
- Cross sections vs proton kinematic and multiplicity, and transverse variable.
- Other analyses (CCkaon, NCγ, NCEL etc.)

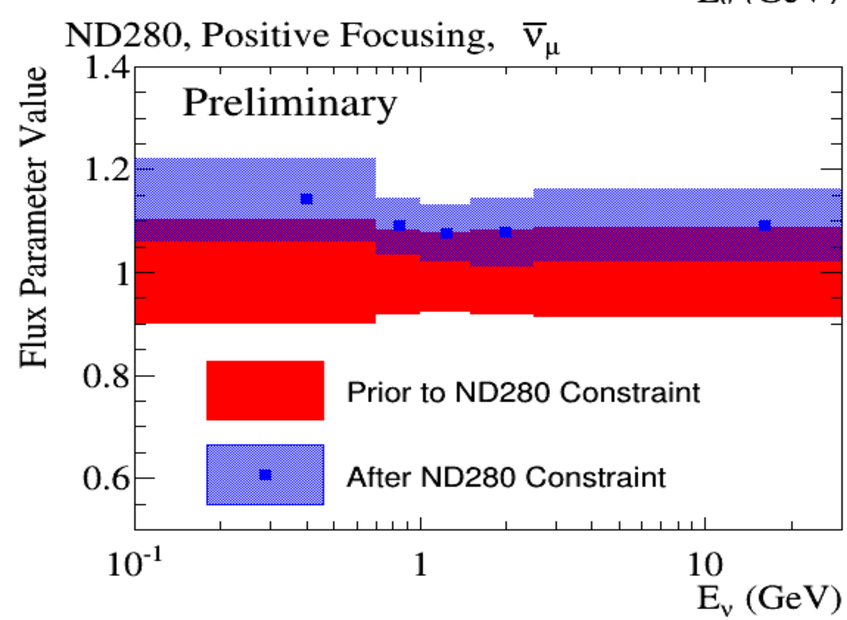
Accepted as PRD: “Measurement of double-differential muon nueutrino charged-current interactions on C_8H_8 without pions in the final state,” arXiv:1602.03652.

Near Detector Constraints on Flux and Cross-Section



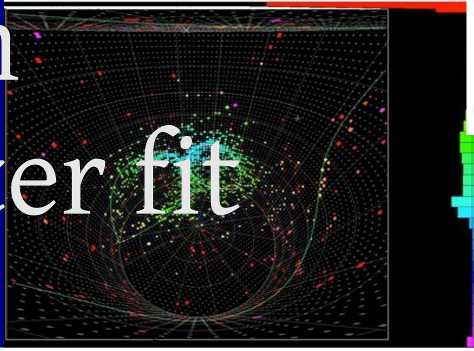


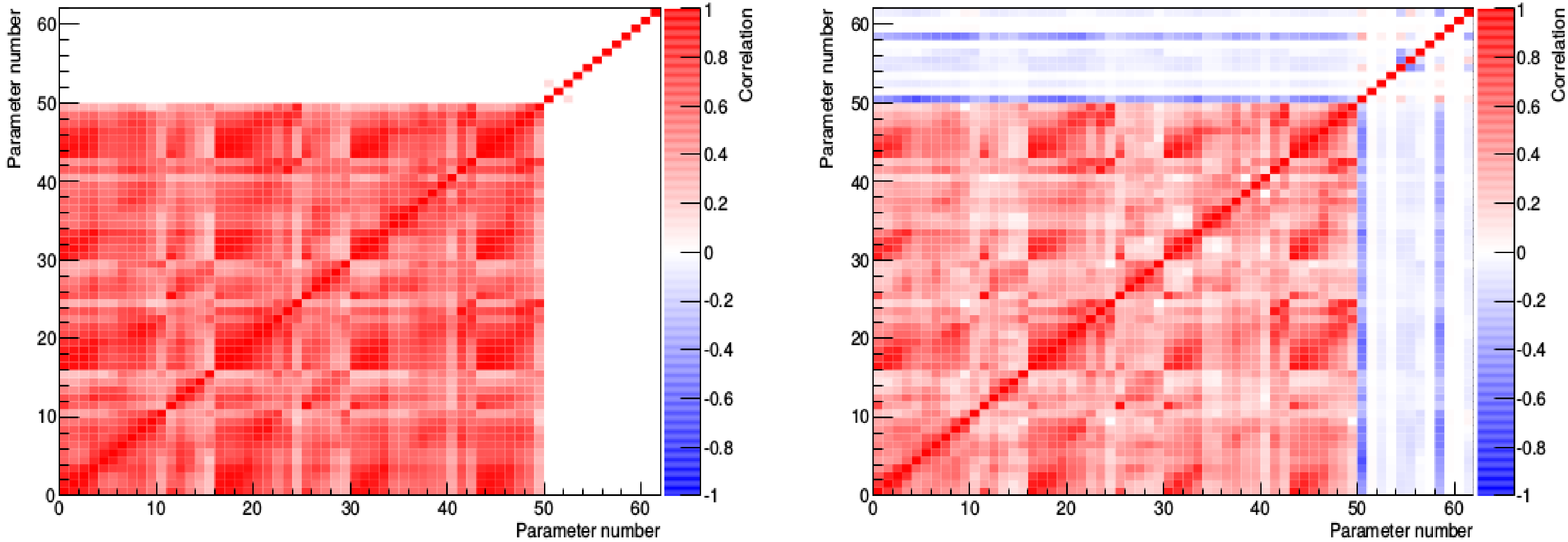




- Flux parameters generally increased
- Some cross section parameters moved from nominal (eg. carbon multi-nucleon CC 2p-2h)

Flux and Cross Section Correlations before and after fit to Near Detector Data



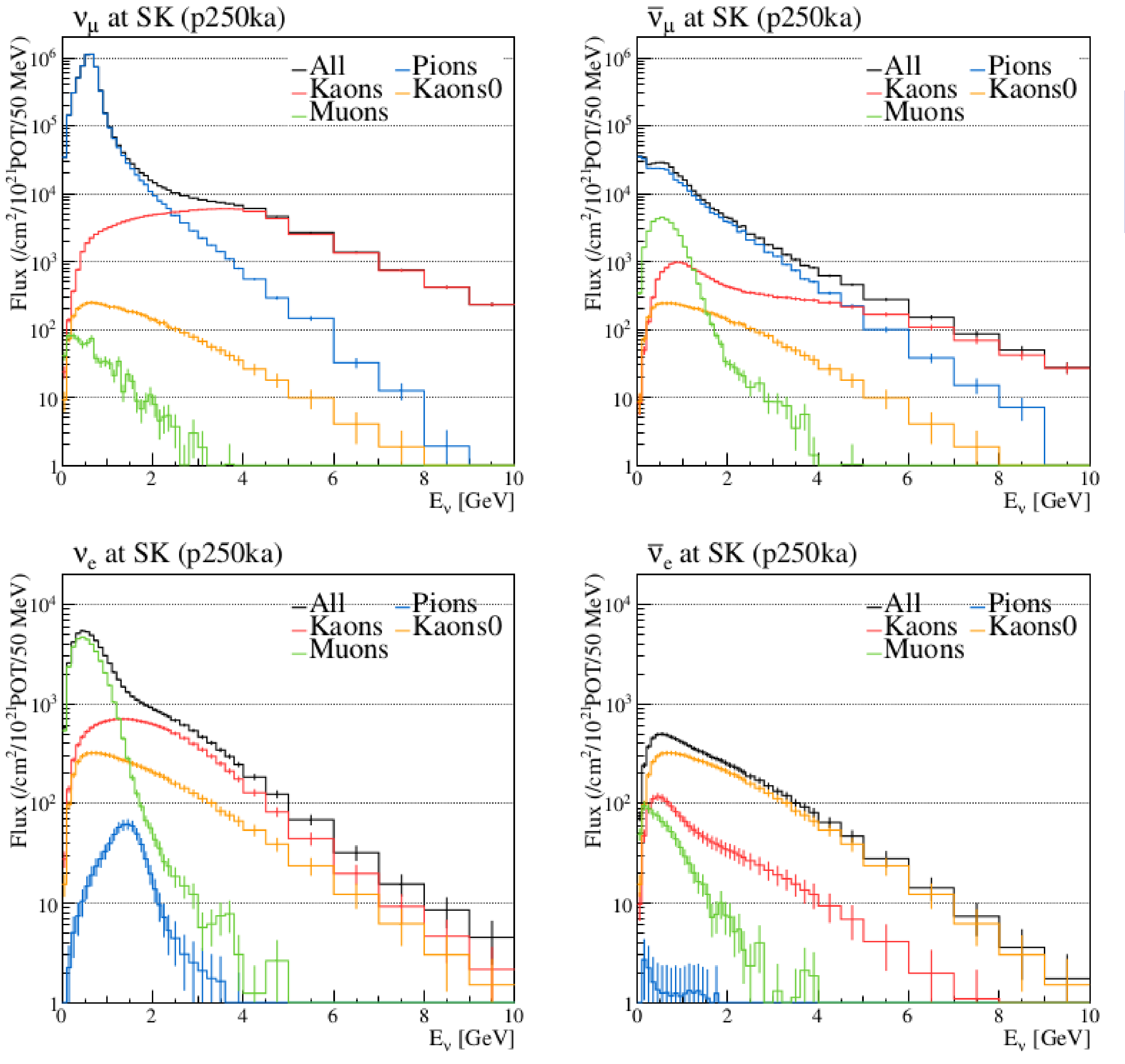


(a) Prefit

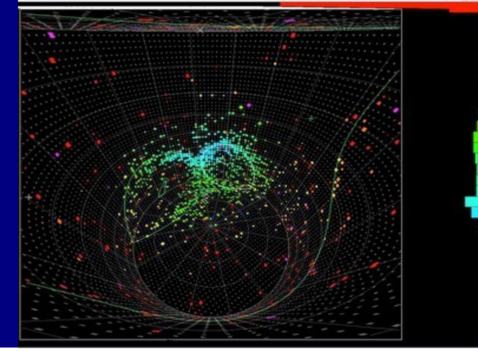
(b) Postfit

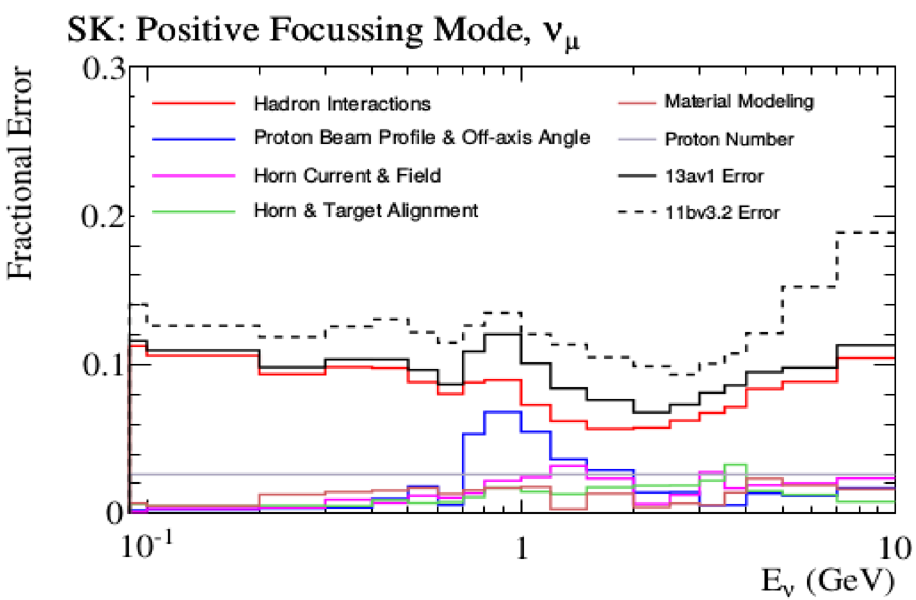
Figure 49: The parameter correlations prior to and after the BANFFv3 fit. The parameters are 0-24 SK PF flux, 25-49 SK NF flux, 50 M_A^{QE}, 51 p_F ^{16}O, 52 MEC ^{16}O, 53 E_B ^{16}O, 54 $CA5^{RES}$, 55 M_A^{RES}, 56 Isospin=$\frac{1}{2}$ Background, 57 ν_e/ν_μ, 58 CC Other Shape, 59 CC Coh ^{16}O, 60 NC Coh, 61 NC Other

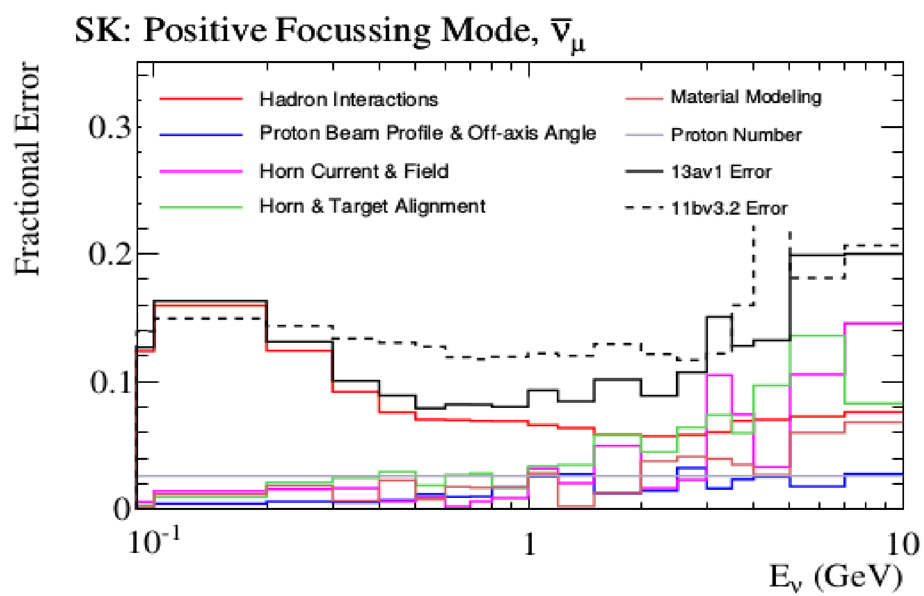
Flux prediction Positive focusing (neutrino-mode)

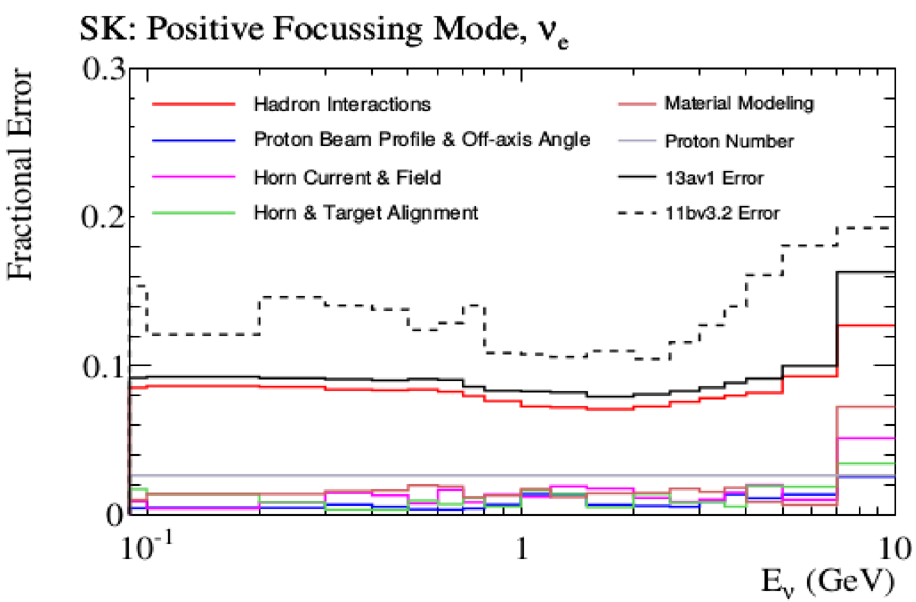


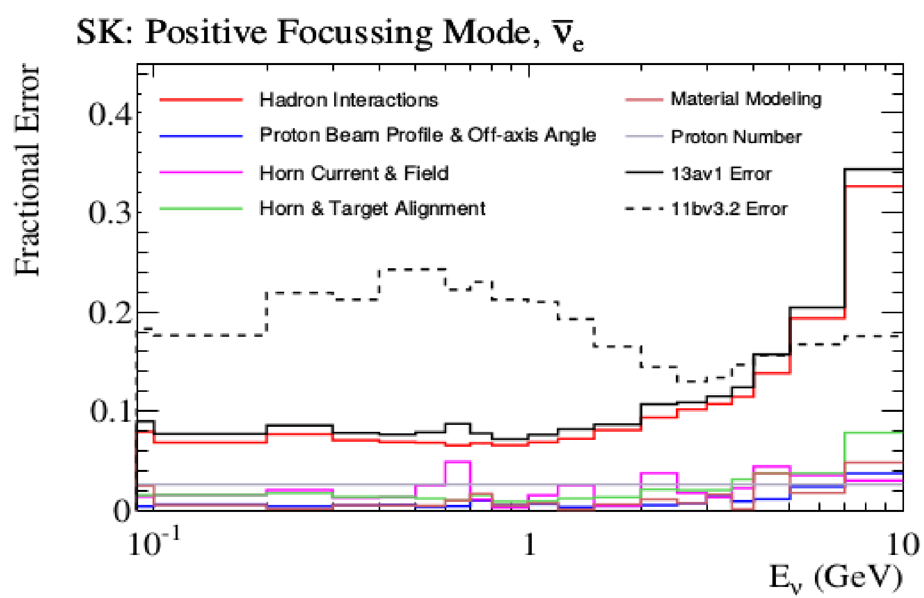
T2K beam flux uncertainty Positive Focusing



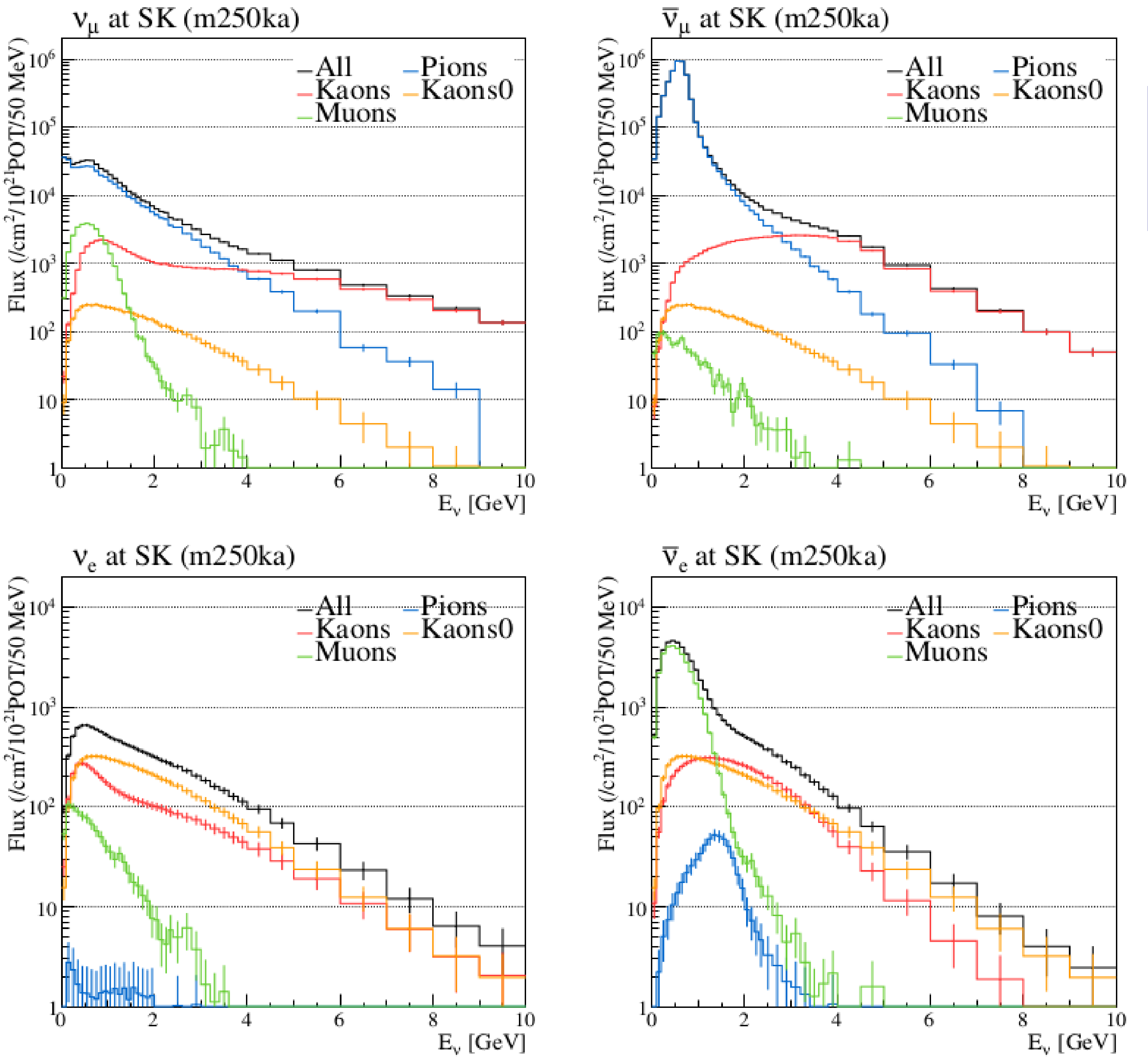




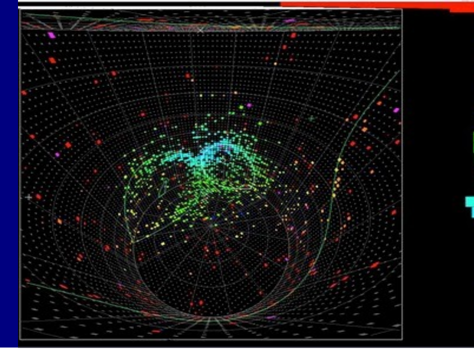


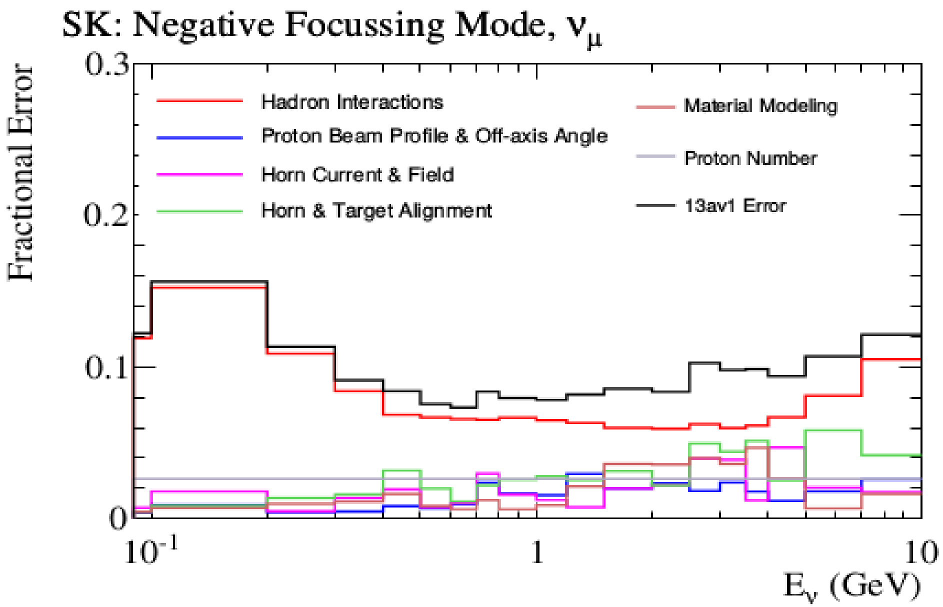


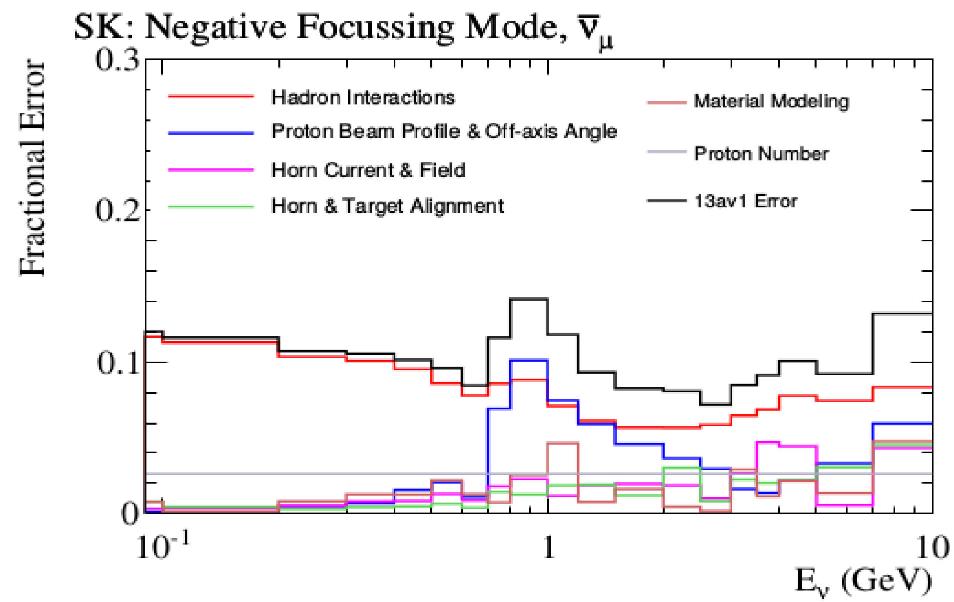
Flux prediction Negative focusing (anti-neutrino-mode)

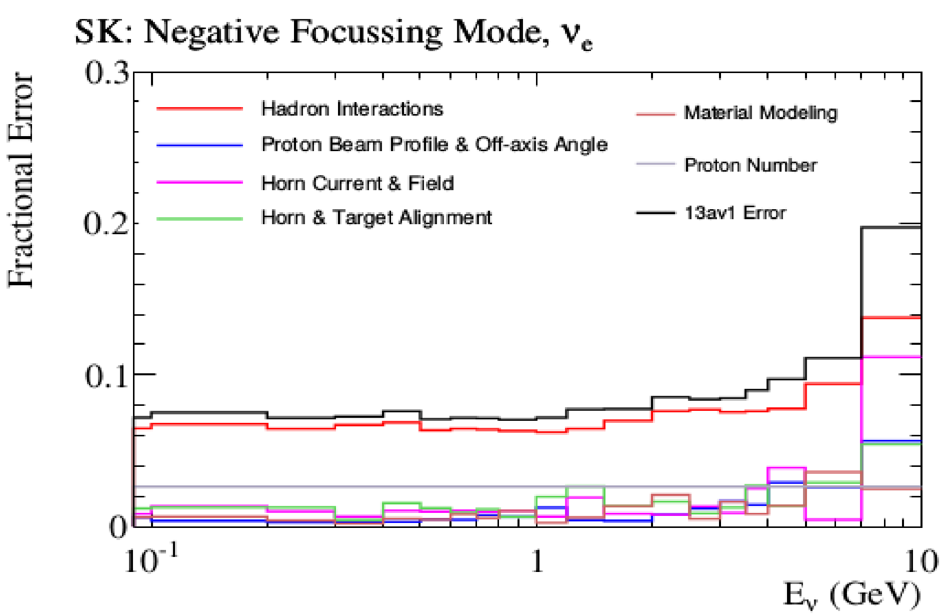


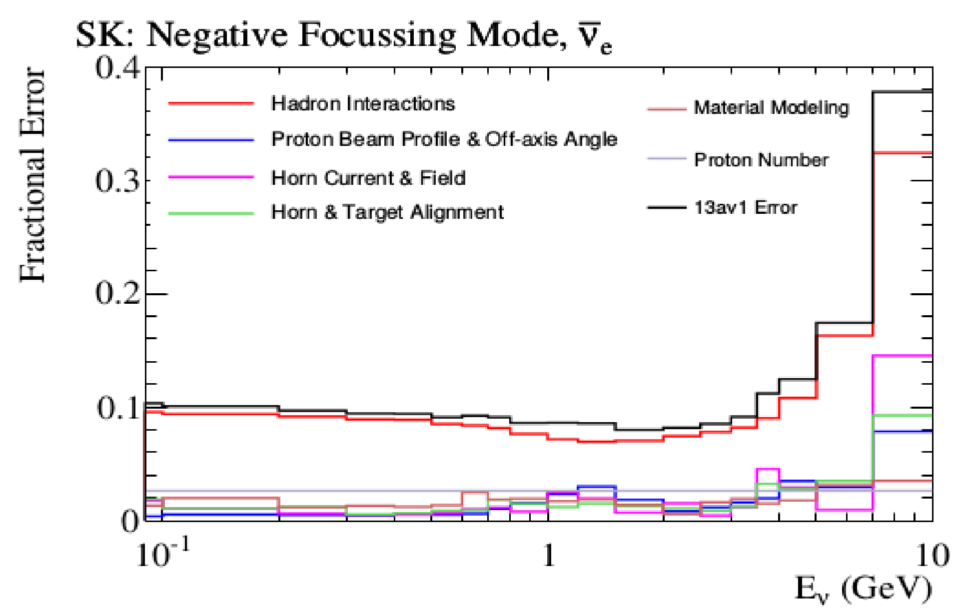
T2K beam flux uncertainty Negative Focusing



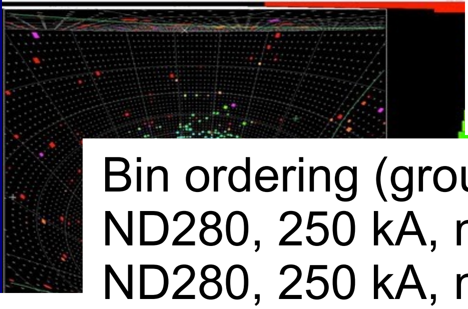


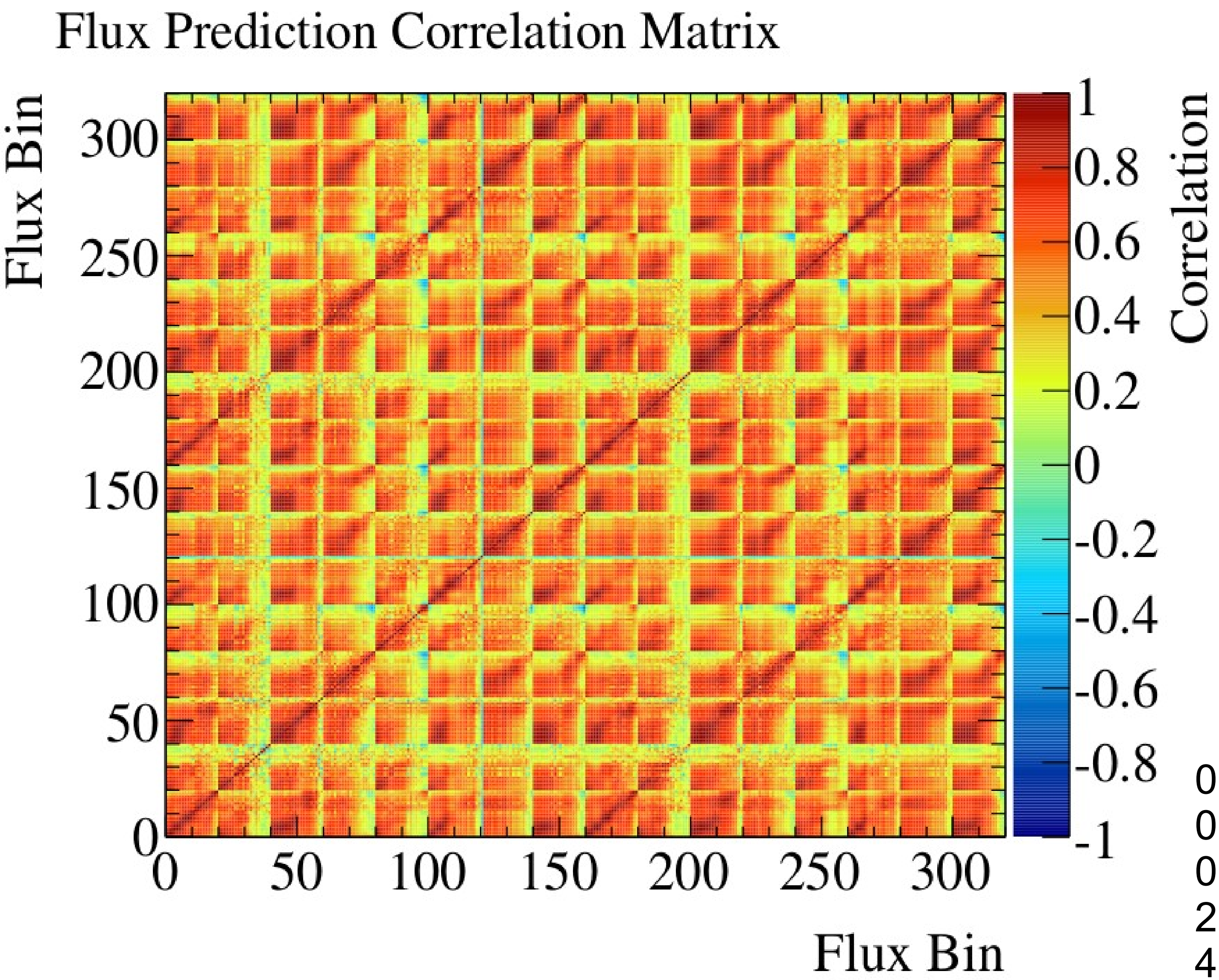






Flux prediction SK/ND280 correlation matrix

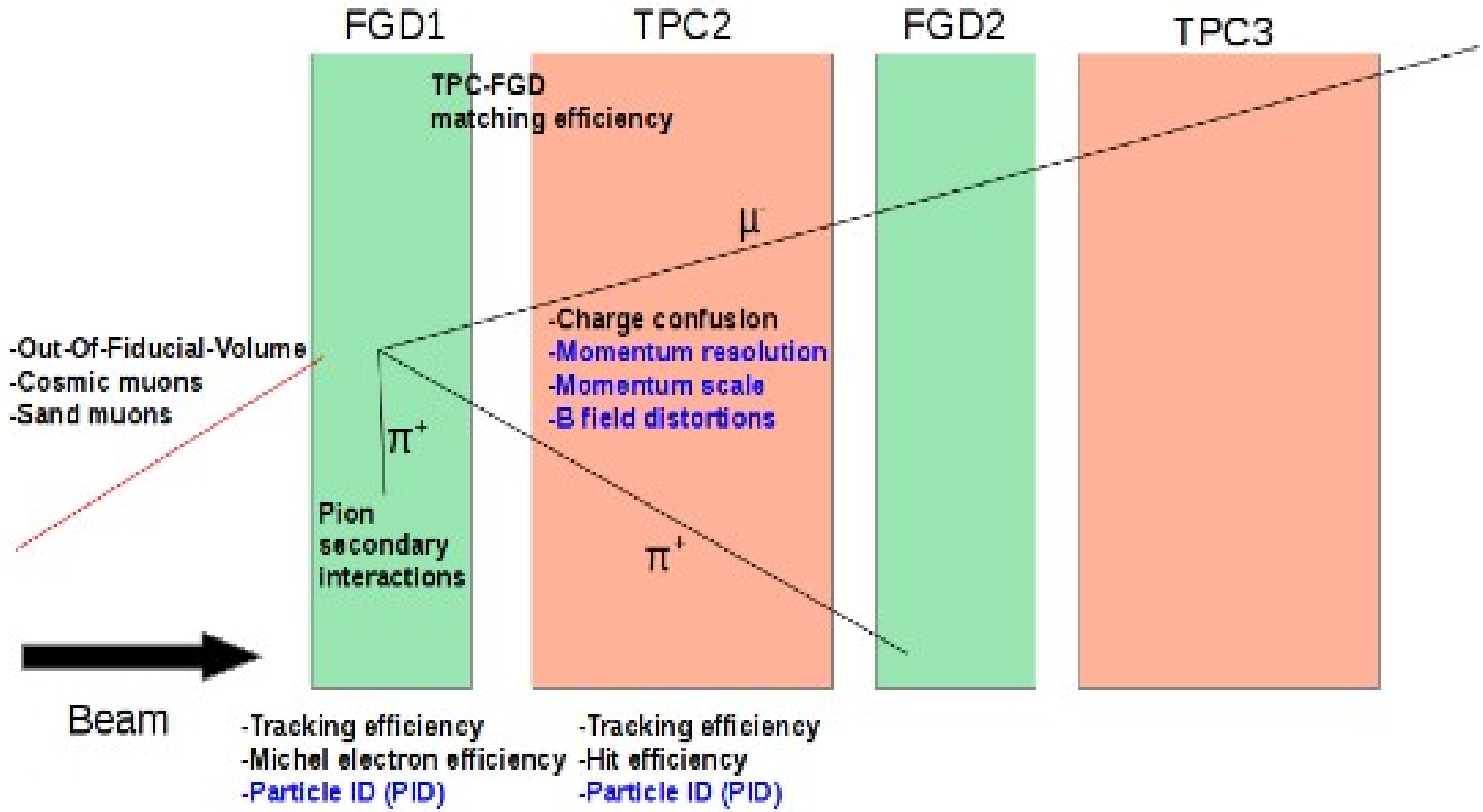




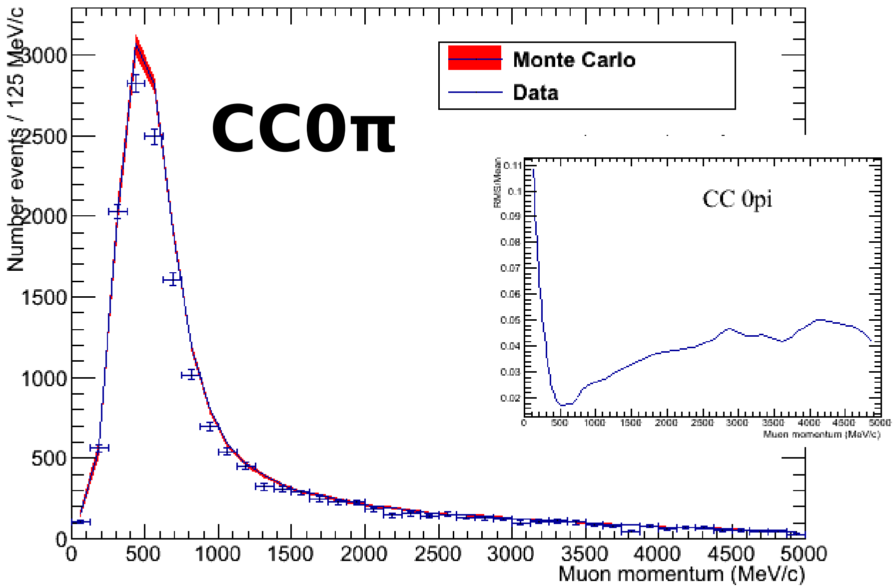
Bin ordering (groups):
ND280, 250 kA, nu_mu
ND280, 250 kA, nu_mu-bar
ND280, 250 kA, nu_e
ND280, 250 kA, nu_e-bar
ND280, -250 kA, nu_mu
ND280, -250 kA, nu_mu-bar
ND280, -250 kA, nu_e
ND280, -250 kA, nu_e-bar
SK, 250 kA, nu_mu
SK, 250 kA, nu_mu-bar
SK, 250 kA, nu_e
SK, 250 kA, nu_e-bar
SK, -250 kA, nu_mu
SK, -250 kA, nu_mu-bar
SK, -250 kA, nu_e
SK, -250 kA, nu_e-bar

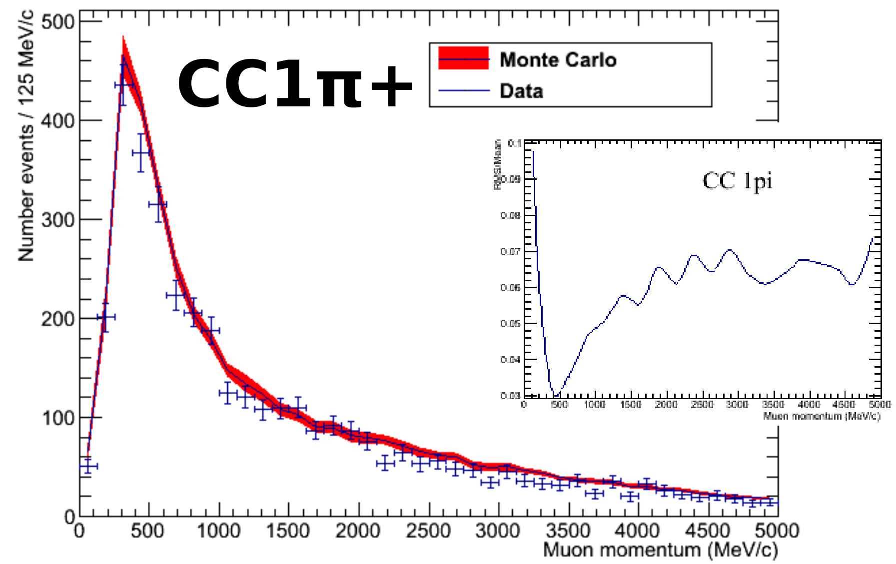
Each group energy binning:
0.0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7, 0.7-0.8, 0.8-1.0, 1.0-1.2, 1.2-1.5, 1.5-2.0, 2.0-2.5, 2.5-3.0, 3.0-3.5, 3.5-4.0, 4.0-5.0, 5.0-7.0, 7.0-10.0, 10.0-30.0 GeV

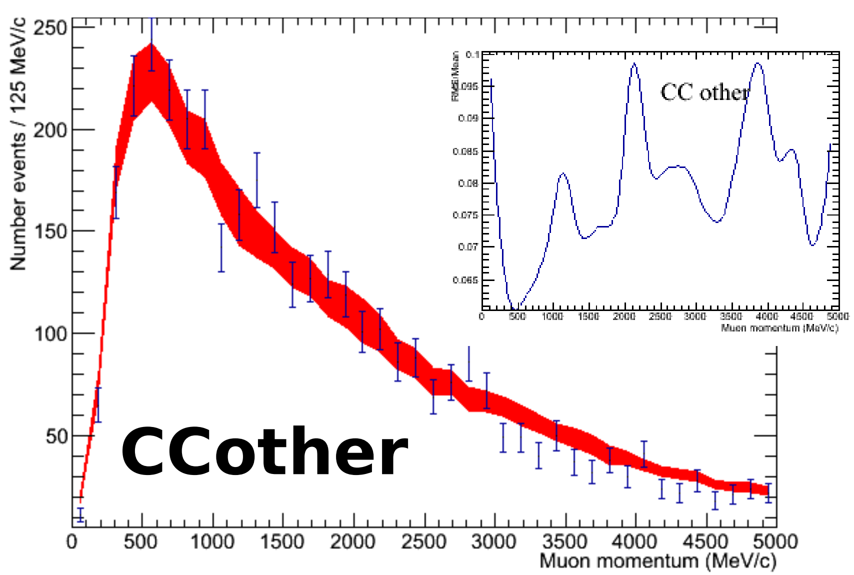
ND280 Systematic Errors



ND280 Detector systematics







Largest relative error in all momentum bins in all categories

B Field distortion (0.3%)

TPC Tracking efficiency (0.6%)

TPC-FGD matching efficiency (1%)

TPC Charge confusion (2.2%)

TPC Momentum scale (2%)

TPC Momentum resolution (5%)

TPC Quality cut (0.7%)

Michel electron efficiency(0.7%)

FGD Mass(0.65%)

Out of Fiducial Volume (10%)

Pile-up (0.07%)

Sand muon (0.02%)

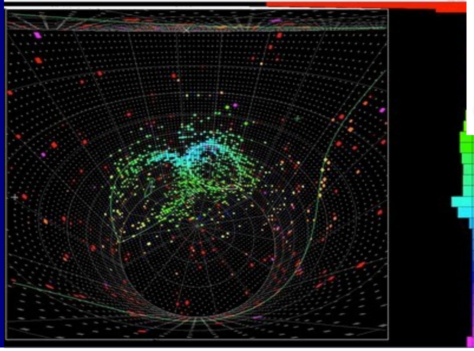
TPC PID (3.5%)

FGD PID (0.3%)

FGD tracking efficiency (1.4%)

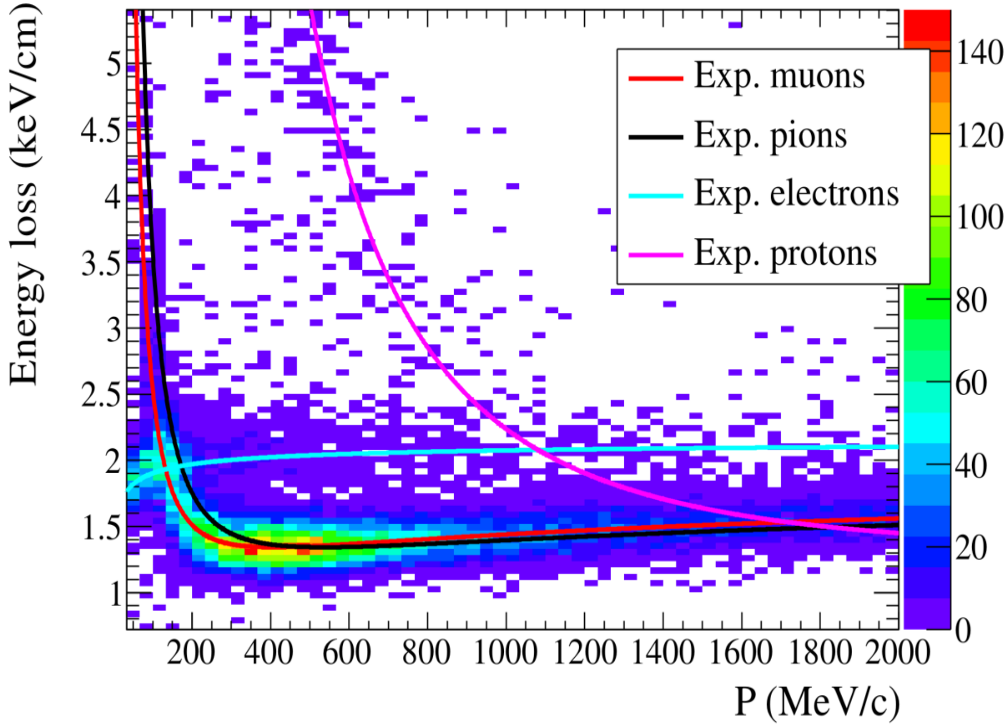
Pion secondary interaction (8%)

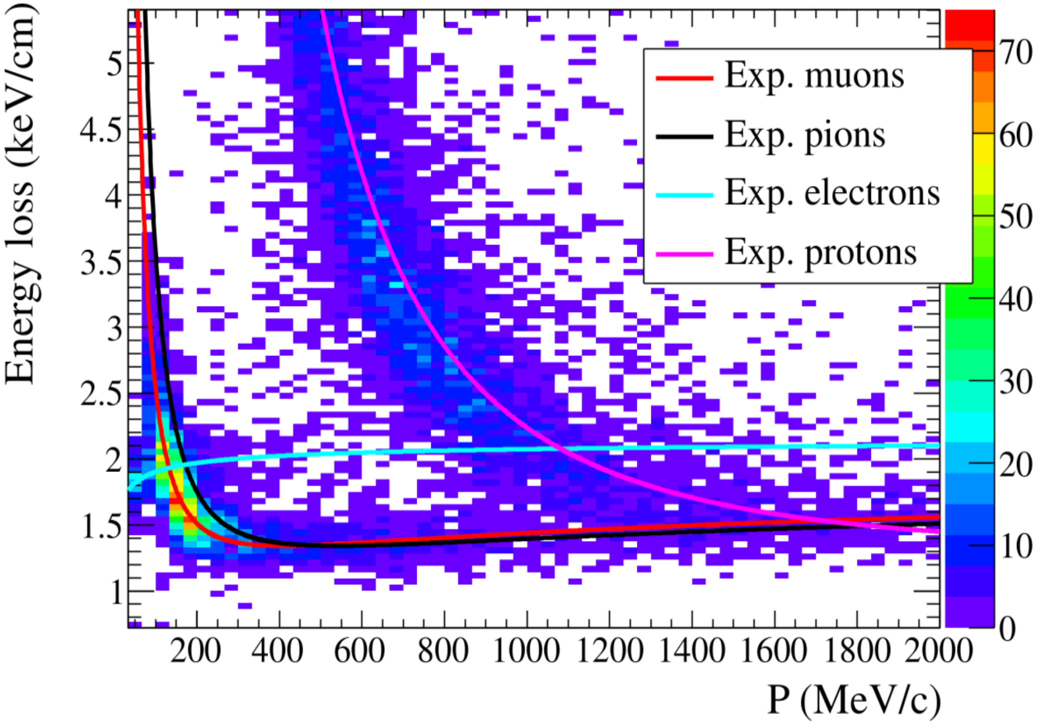
ND280 TPC Particle ID by dE/dx



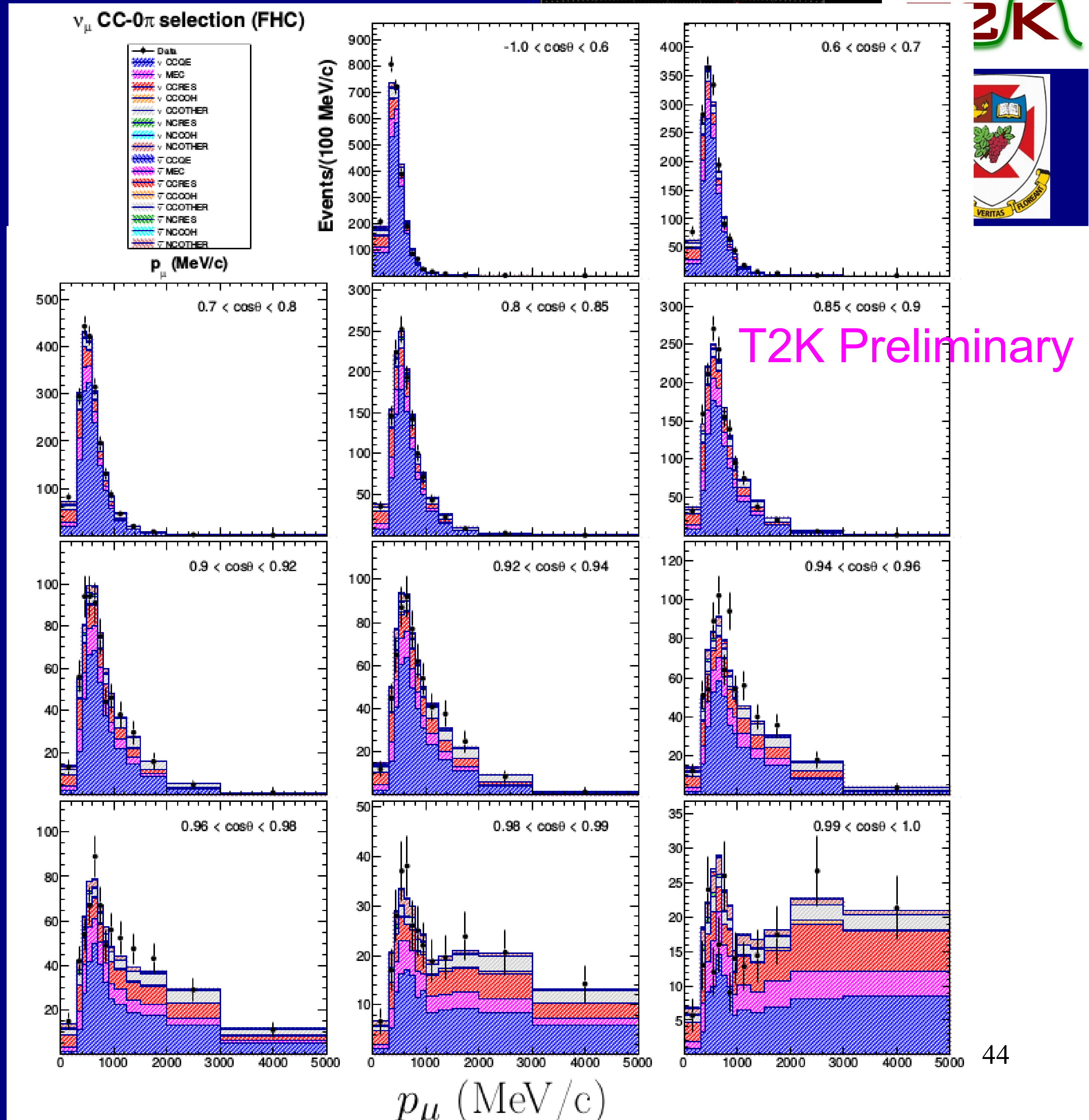
Negative tracks in the TPC.

Positive tracks in the TPC.

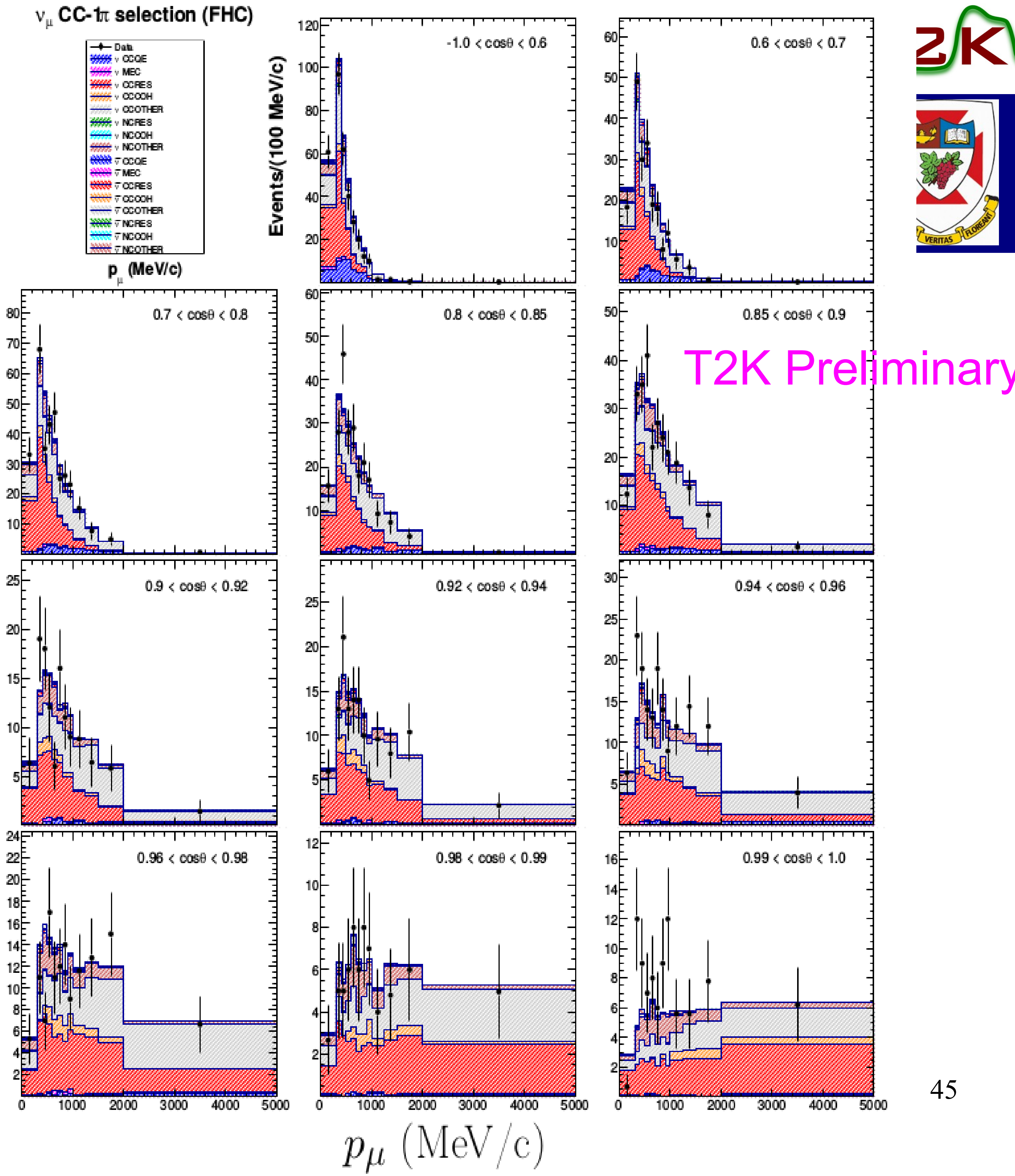




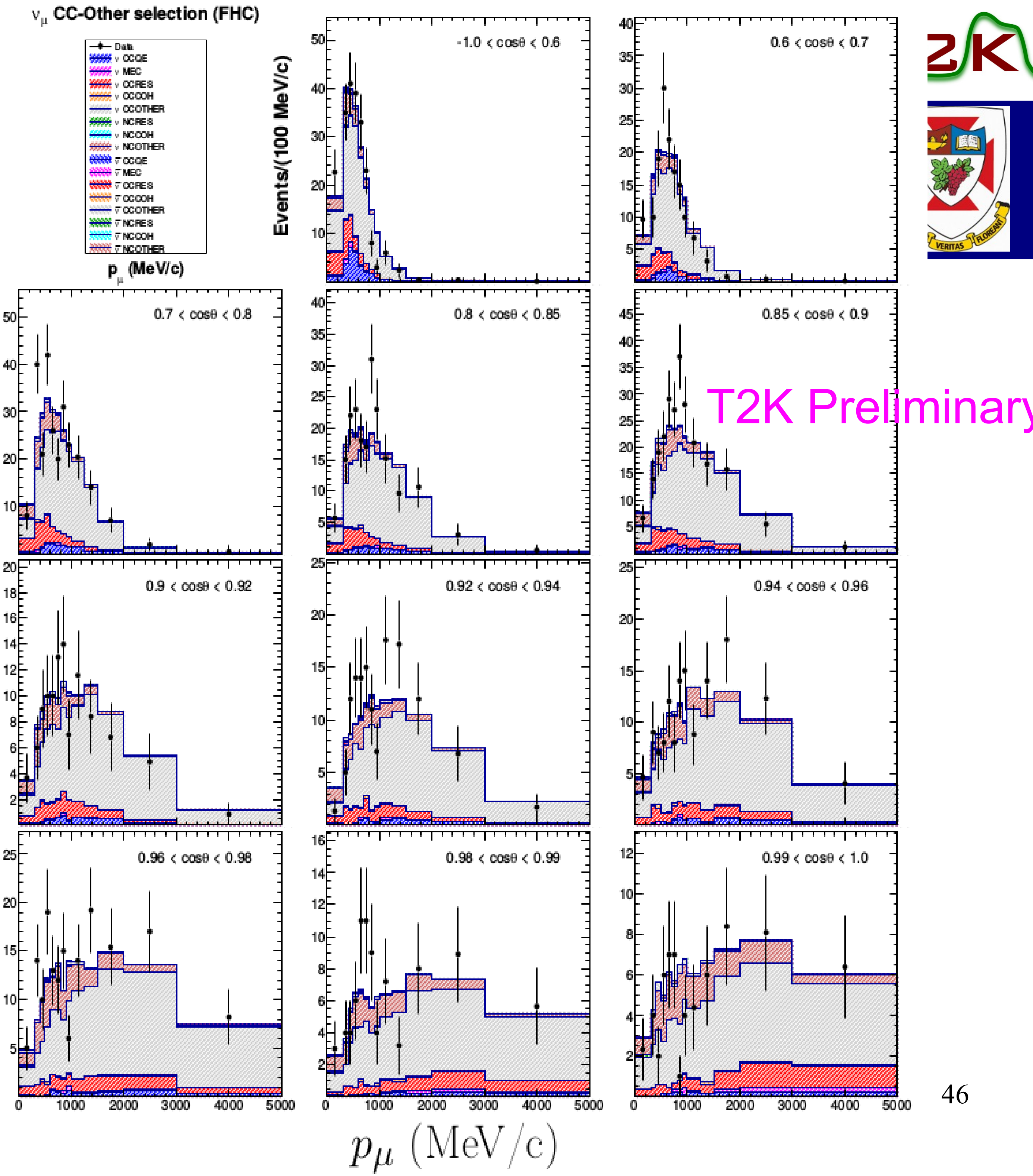
Near Detector ν_μ CC0π Data compared to BANFF fit



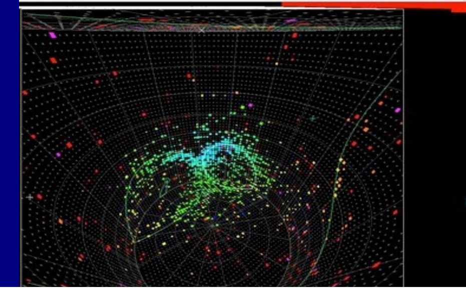
Near Detector ν_μ CC1π Data compared to BANFF fit

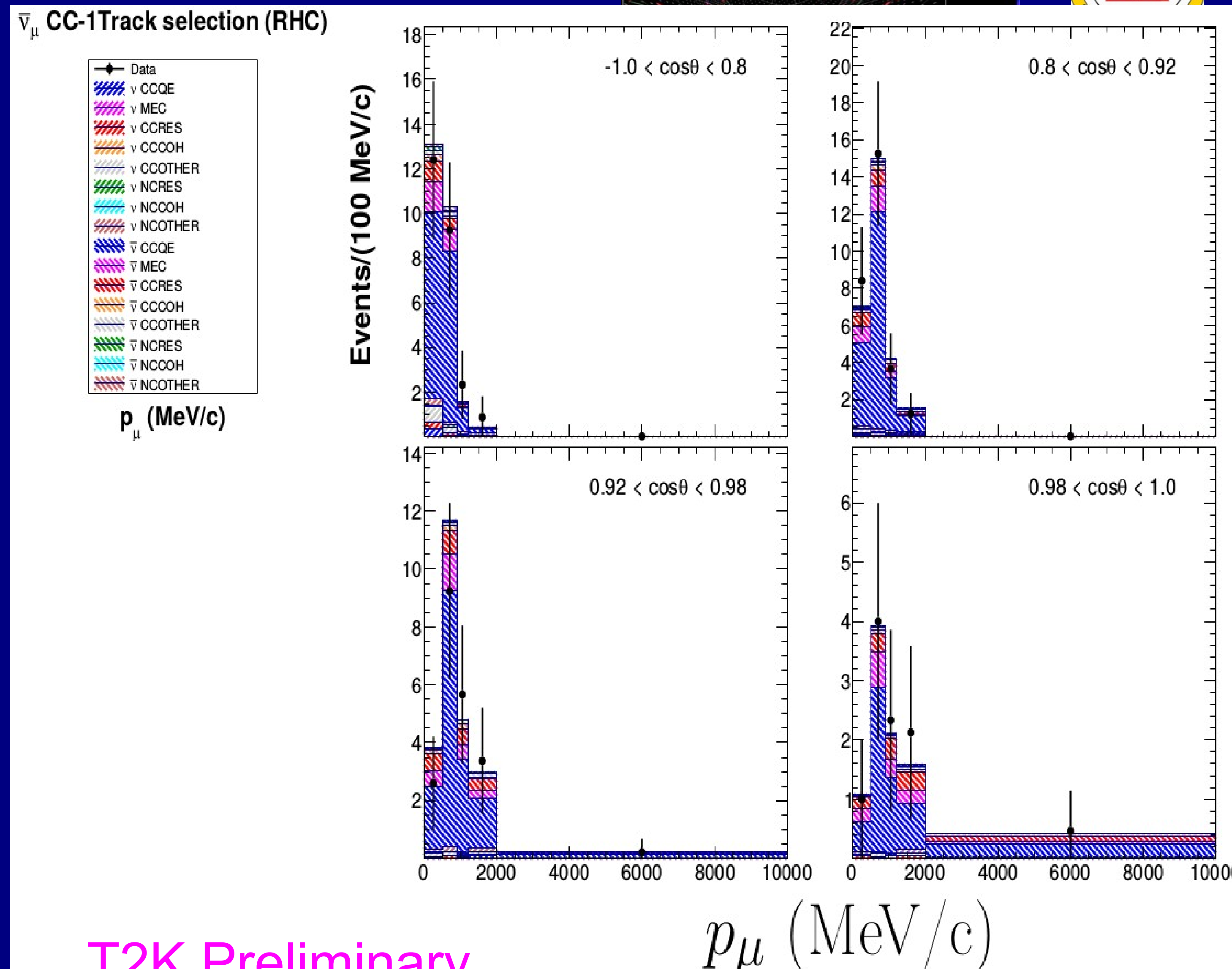


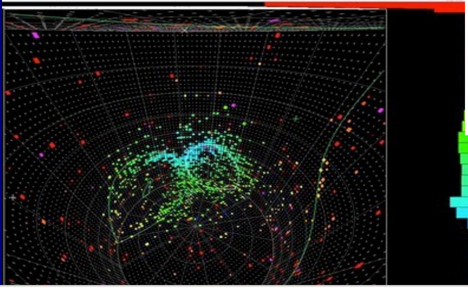
Near Detector ν_μ CCother Data compared to BANFF fit



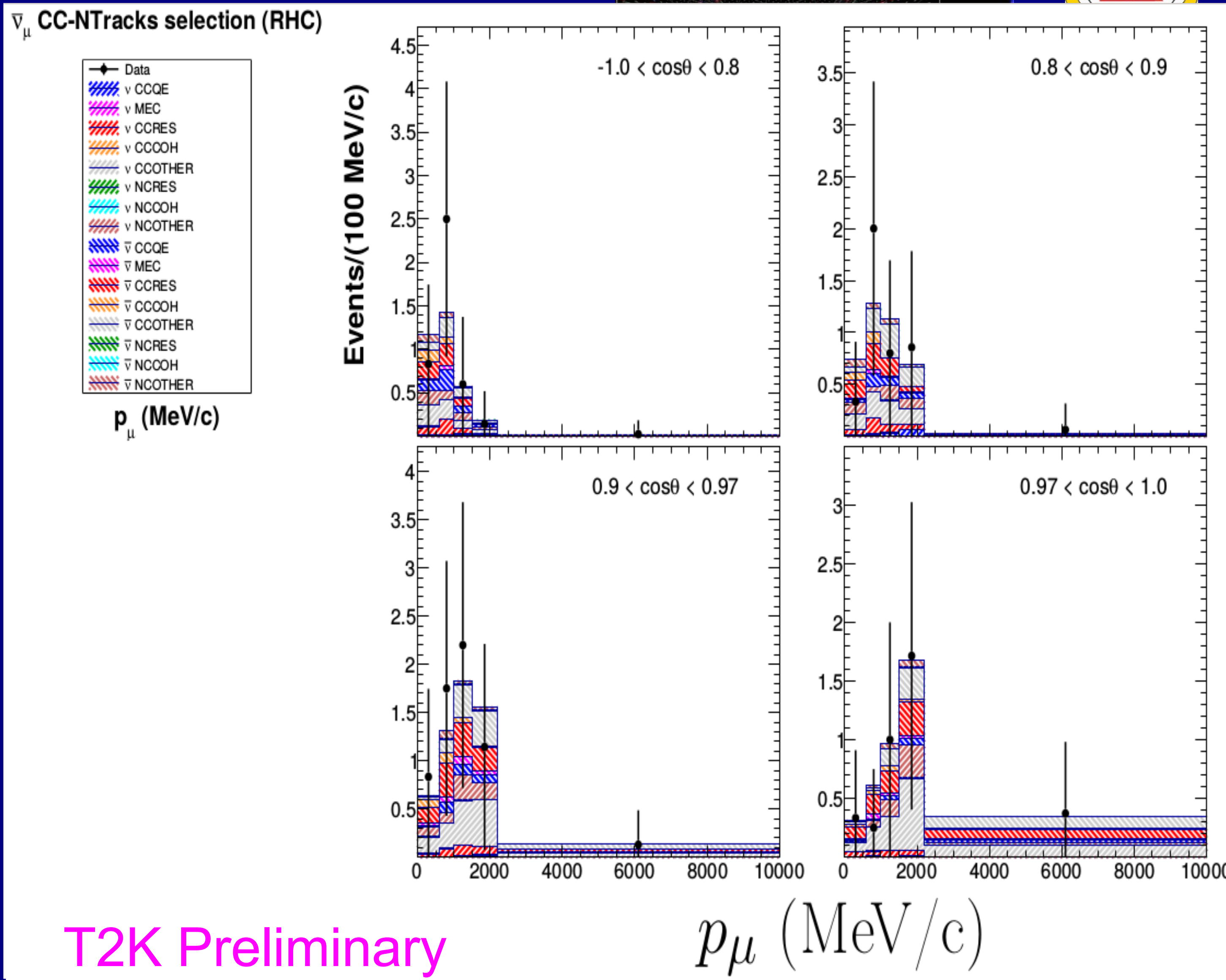
Near Detector $\bar{\nu}_\mu$ CC(1 track) Data compared to BANFF fit

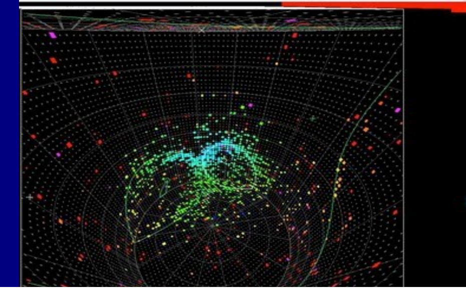




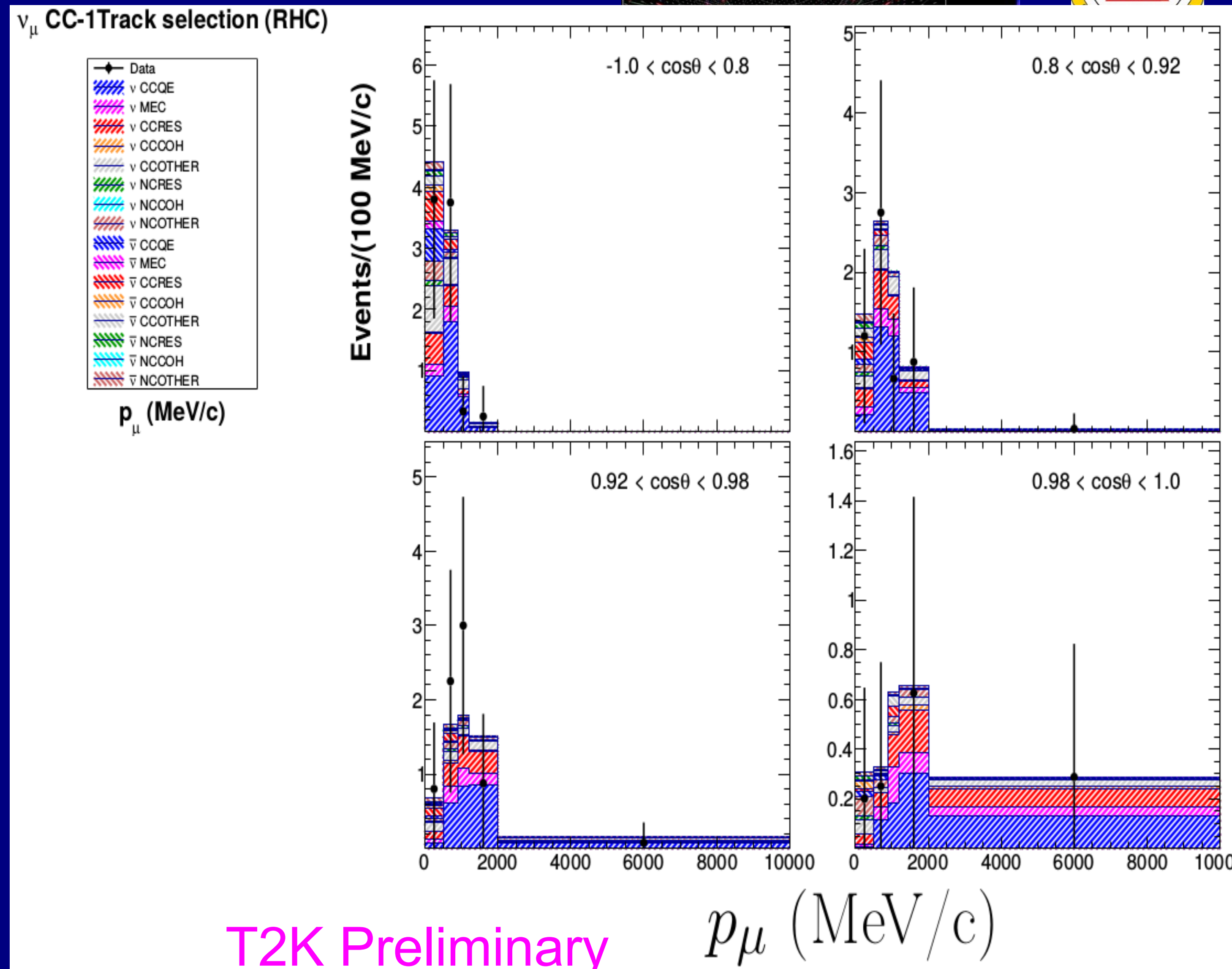


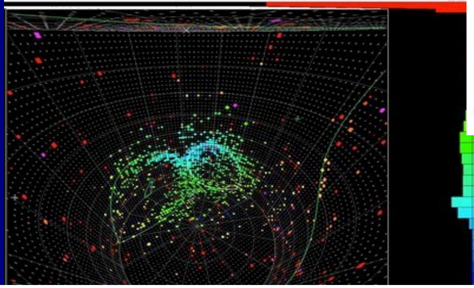
Near Detector $\bar{\nu}_\mu$ CC(N track) Data compared to BANFF fit



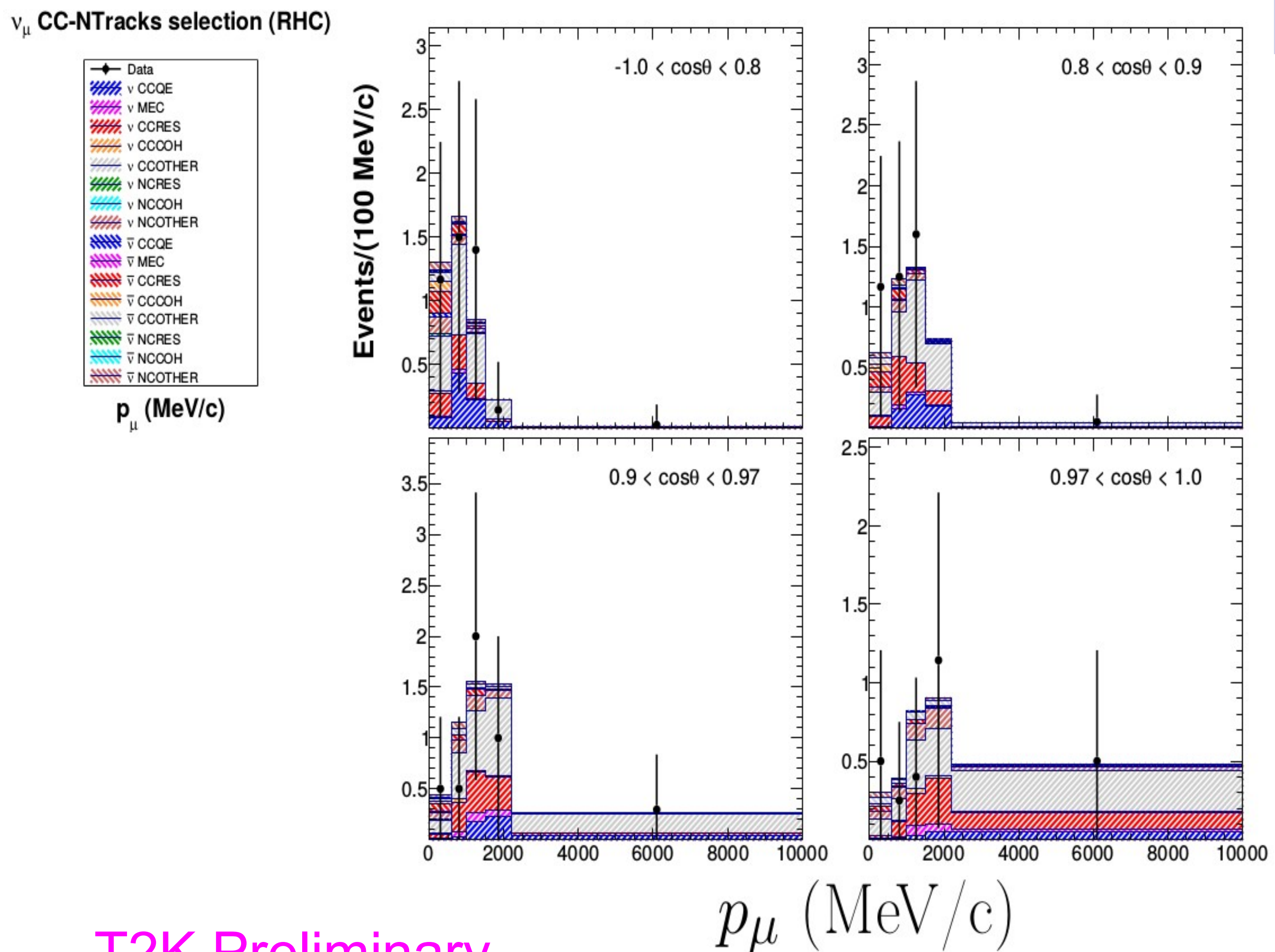


Near Detector ν_μ CC(1 track) Data compared to BANFF fit



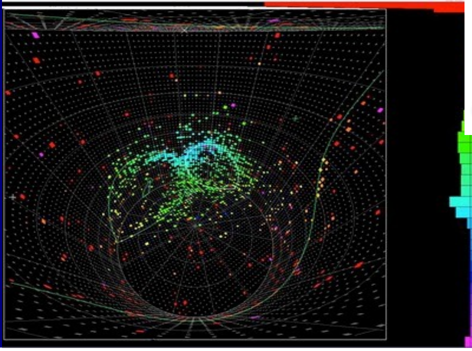


Near Detector ν_μ CC(N track) Data compared to BANFF fit

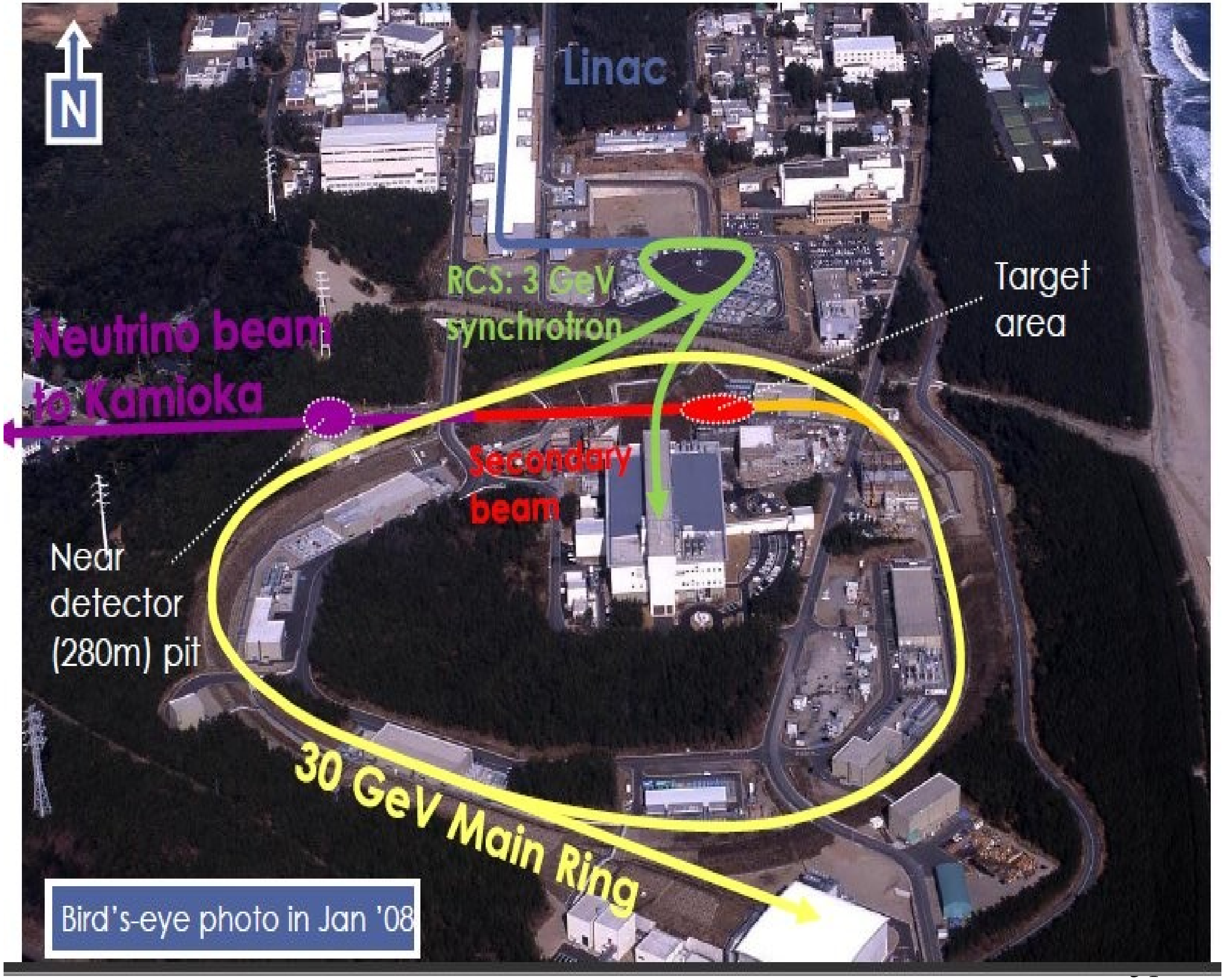


T2K Preliminary

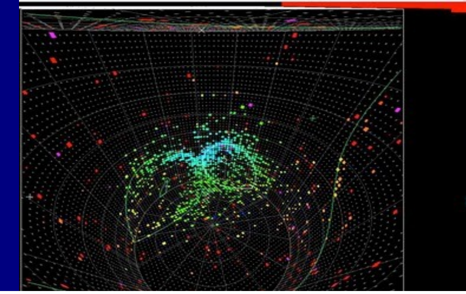
JPARC Beamline

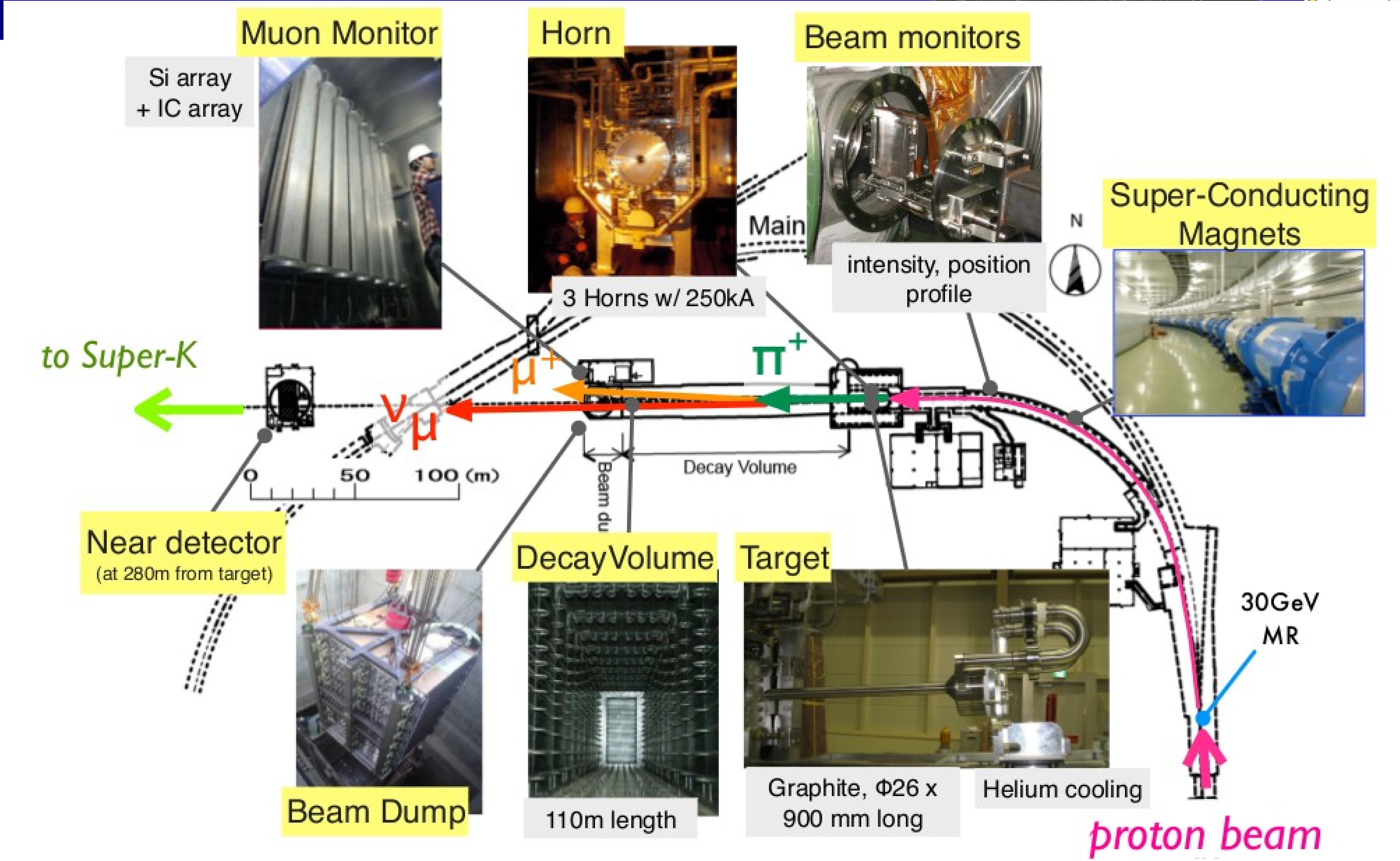


- Located in Tokai-village, 60km N.E. of KEK
- Completed in 2009
- MR
  - 1567.5 m circum.
  - Tp = 30GeV
  - 8 bunch
  - Rep cycle: 2.48sec (now)
- Design goal
  - RCS: 1MW
  - MR: 750kW
- MR achieved 220kW stable operation for neutrino experiment

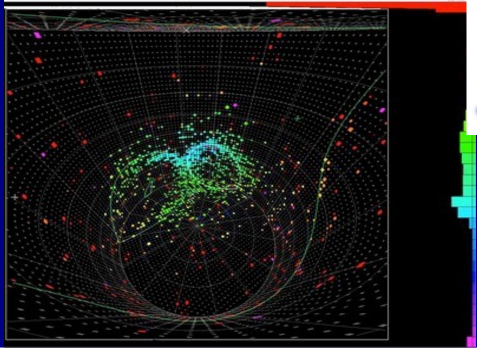


JPARC Neutrino Beamline





Three flavour joint oscillation analysis



- Use both ν_e and ν_μ datasets from SK to do a joint fit for oscillation parameters: θ_{13}, θ_{23}, Δm^2_{32} and δ_{CP}

$$P(\nu_\mu \to \nu_e) \approx 4 C_{13}^2 S_{13}^2 S_{23}^2 \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \times \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2 S_{13}^2)\right)$$ Dominant vacuum term

$$+8 C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\left(\frac{\Delta m_{32}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$ CP conserving term

$$-8 C_{13}^2 S_{13}^2 S_{23}^2 \cos\left(\frac{\Delta m_{32}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \frac{aL}{4E} (1 - 2 S_{13}^2)$$ Matter effect terms

$$-8 C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\left(\frac{\Delta m_{32}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$ CP sinδ term

$$+4 S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2 C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$ Solar term

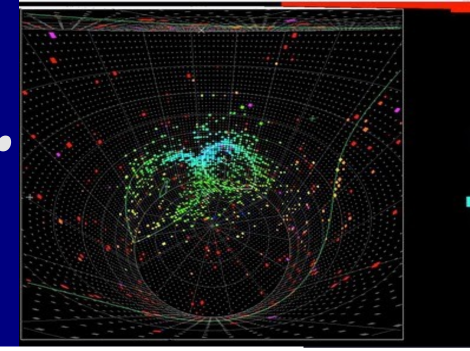
$$P(\nu_\mu \to \nu_\mu) \approx 1 - (C_{13}^4 \sin^2 2\theta_{23} + \sin^2 2\theta_{13} S_{23}^2) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

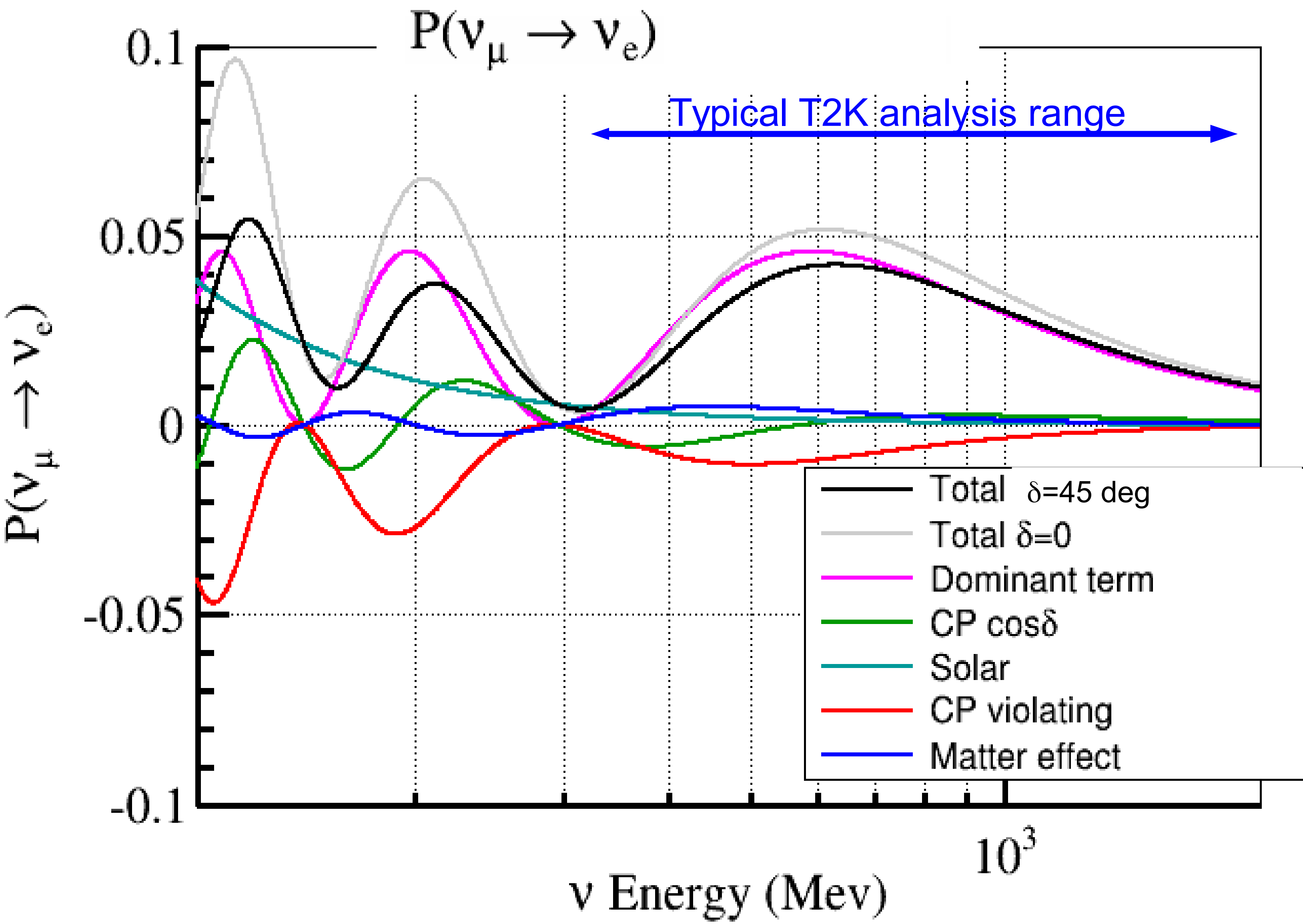
Notes: Cij = cosθij, Sij = sinθij

$$a = 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} \rho (g/cm^3) E(GeV)$$

J. Arafune, M. Koike and J. Sato, Phys. Rev.D56, 3093 (1997).

3 flavour oscillation approx. w/ matter effects





Plot for:

L = 295 km

ρ = 2.6 g/cm^3

Δm_{21} = 7.6x10^{-5} eV^2

Δm_{32} = 2.4x10^{-3} eV^2

θ_{12} = 34°

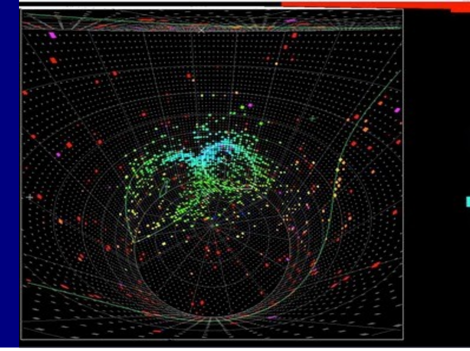
θ_{23} = 45°

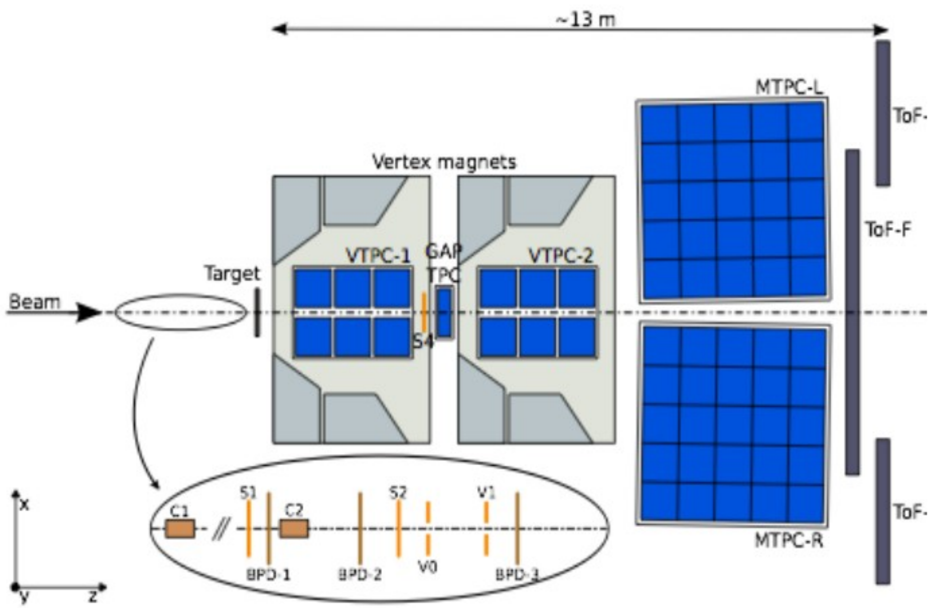
θ_{13} = 8.8°

δ = 45°

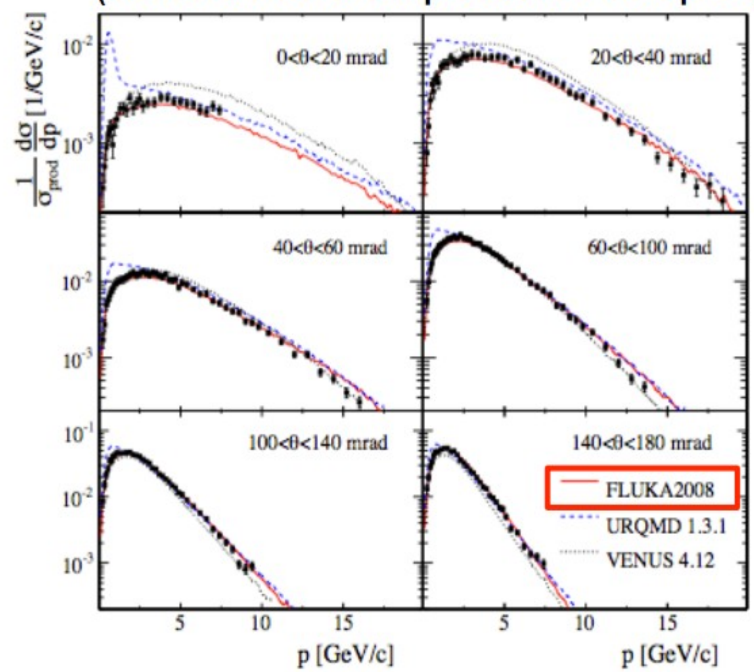
nb. Same colour Scheme as Previous page

NA61/Shine hadron production



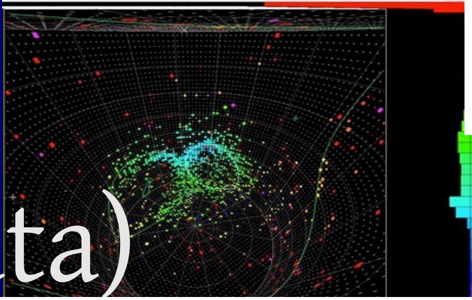


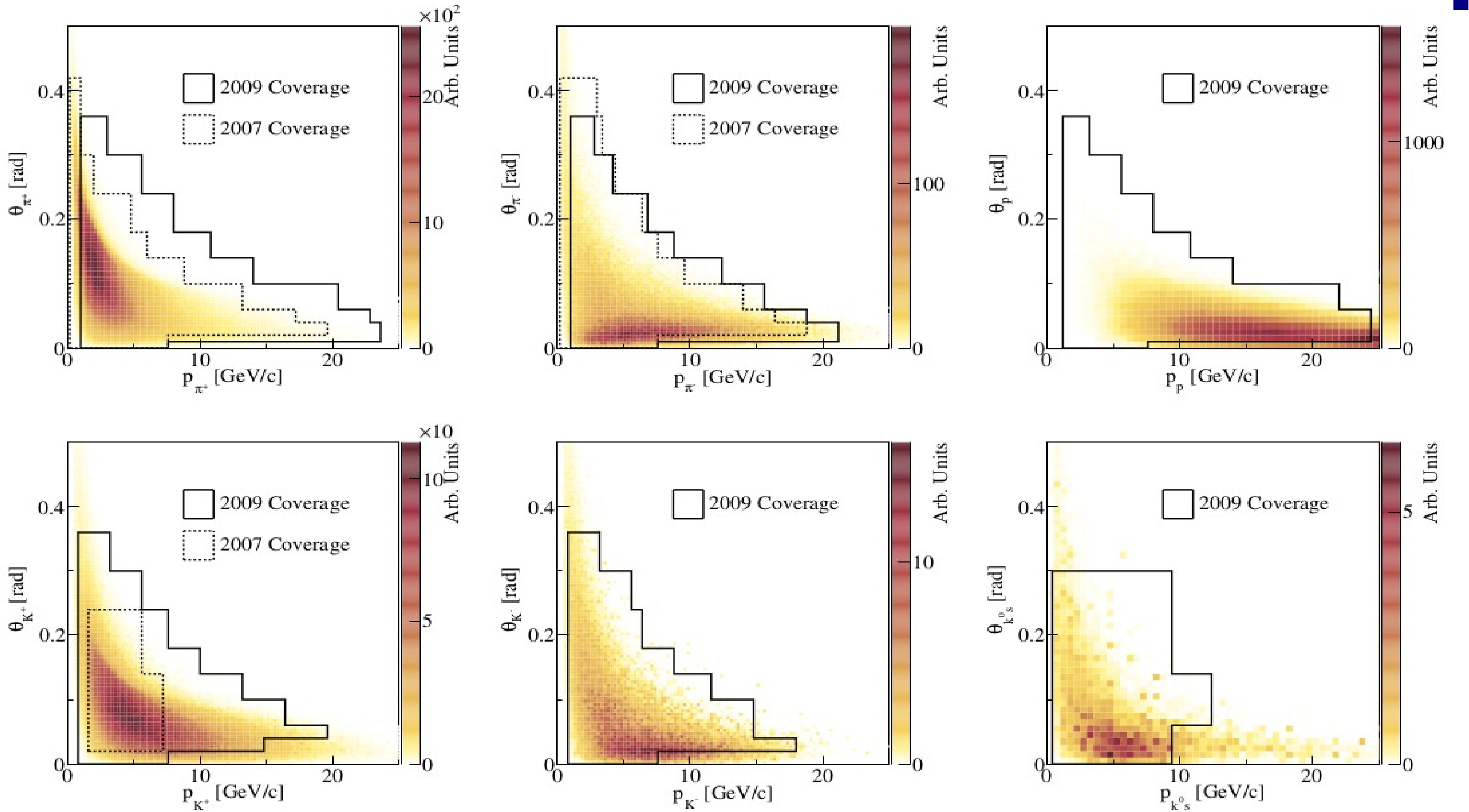
30GeV proton cross-sec on C^{12}
(measure differential production multiplicity)



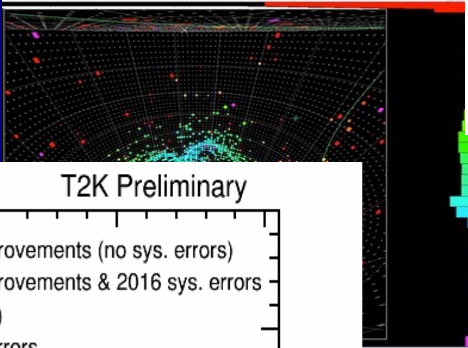
- Large acceptance spectrometer with dE/dx and TOF counters
- 30 GeV proton beam matches T2K.
- Both a "**thin**" .04λtarget and a replica of the T2K target
- Can measure **pion** and kaon production

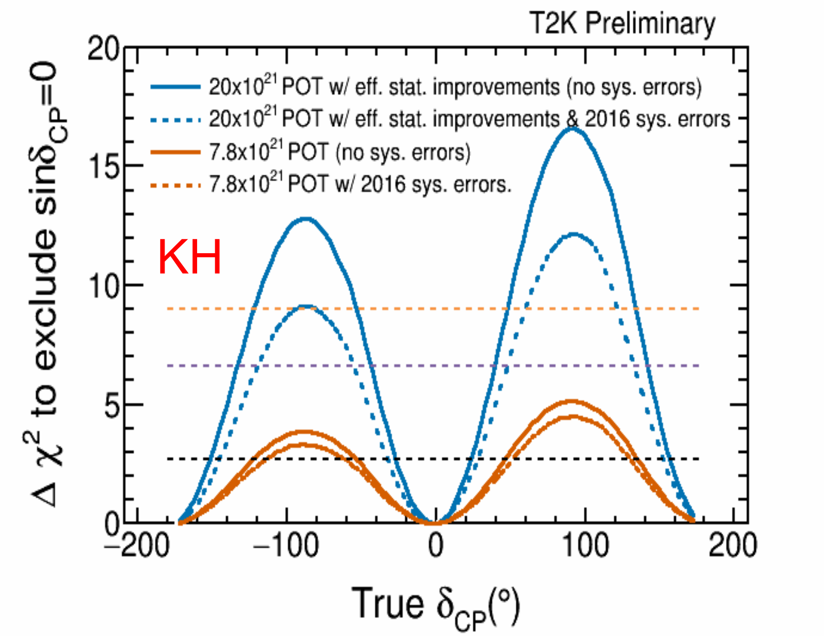
NA61/Shine
Increased coverage (2009 data)

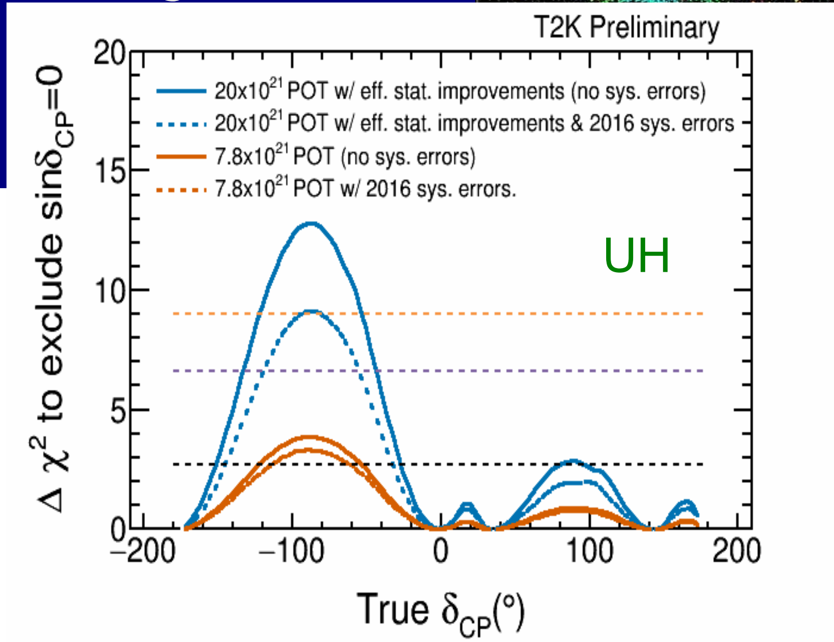




T2K-II Sensitivity



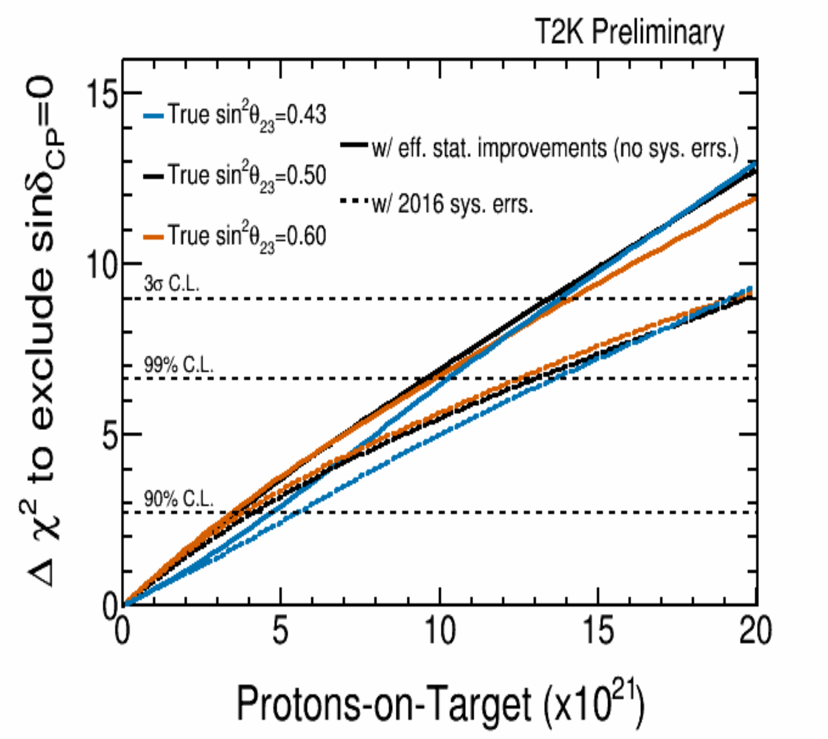


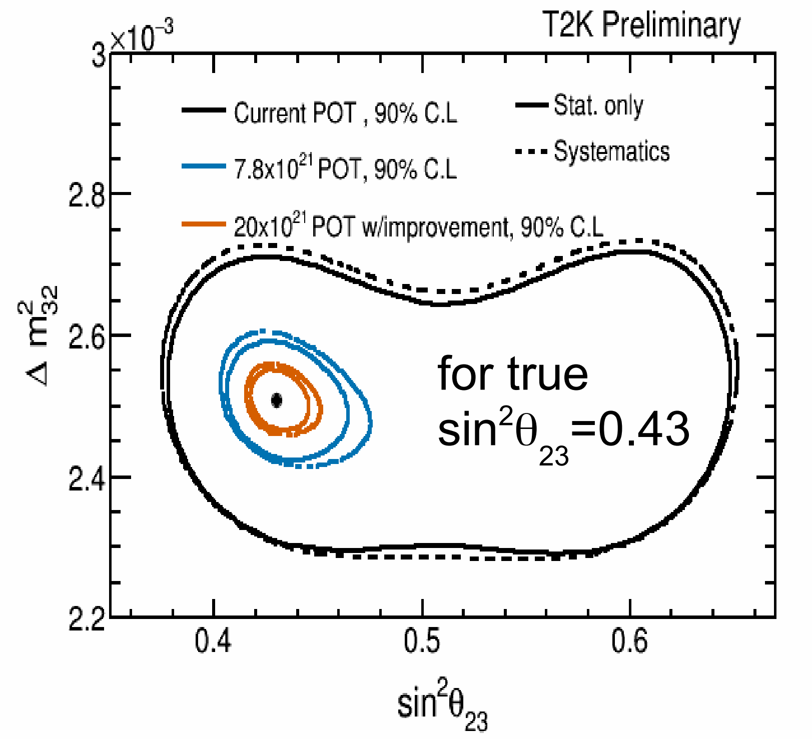


Hierarchy assumed known

KH Known Hierarchy (Normal)

UH Unknown Hierarchy (Normal)



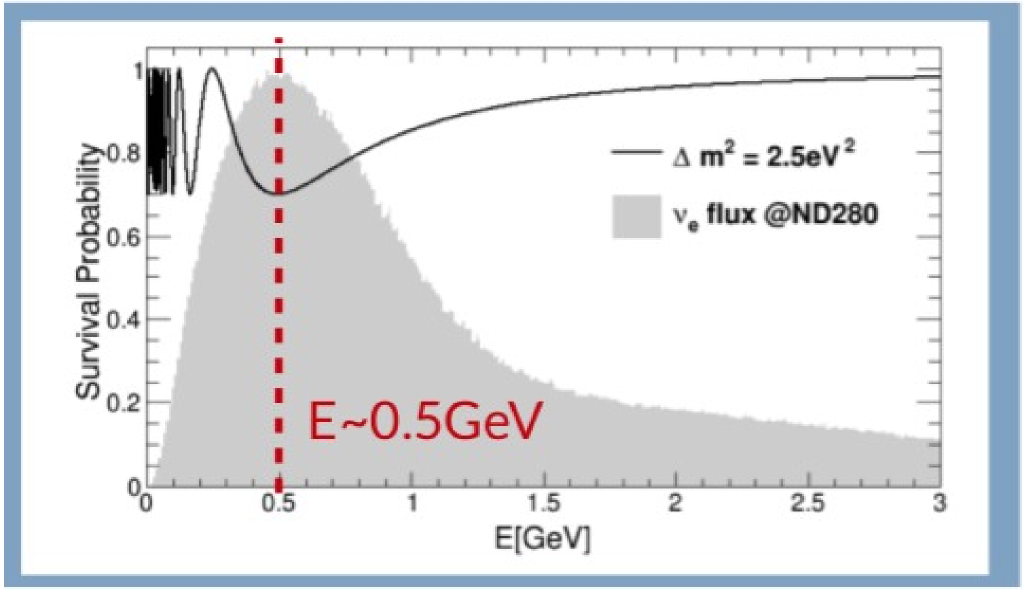


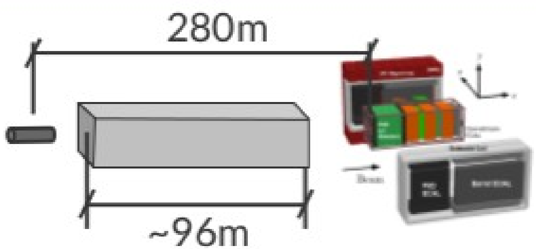
More details In talk by Tom Feusels at 2pm

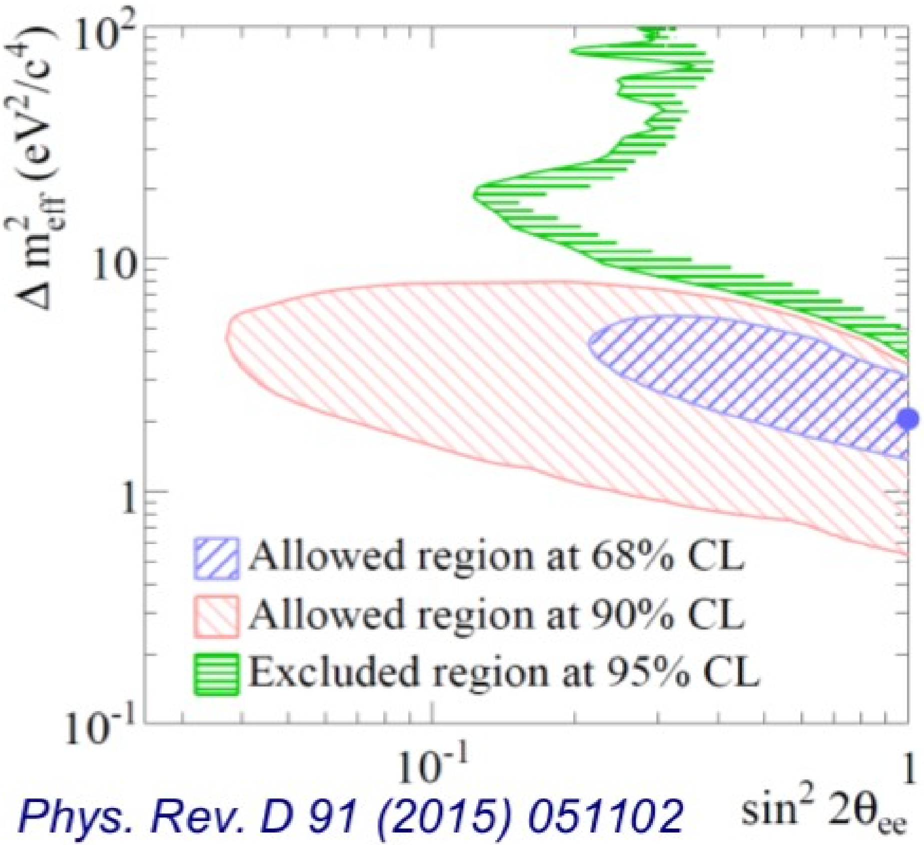
ν_e disappearance search with ND280

due to sterile neutrinos

$$P_{ee} = P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{ee})\sin^2\left(1.27\,\Delta m^2_{41}[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$







Phys. Rev. D 91 (2015) 051102

Based on 5.9×10^{20} p.o.t.

To test with ND280 the *reactor and gallium anomalies* in a ~ 1 GeV ν_e beam