Recent results from T2K

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on behalf of the T2K collaboration

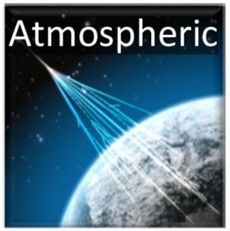
25th WIN, June 10th, 2015

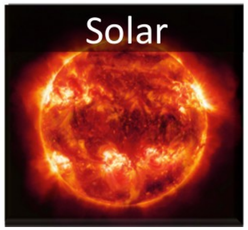
Neutrino mixing and oscillations

mixing of flavor and mass eigenstates → PMNS matrix

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

+ Majorana phases





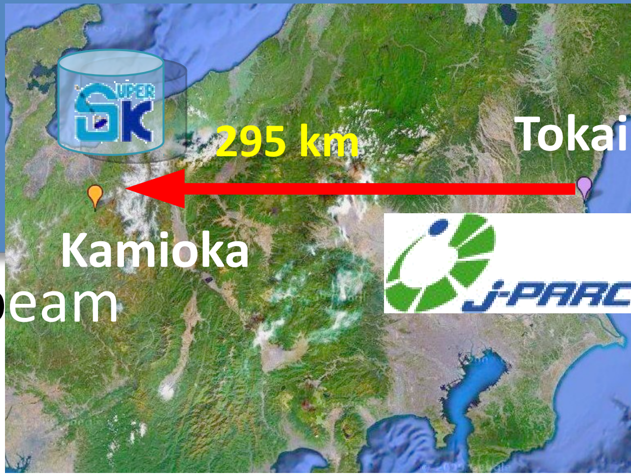
$\theta_{23} = 45.8 \pm 3.2°$
$\theta_{12} = 33.4 \pm 0.85°$
$\theta_{13} = 8.88 \pm 0.39°$

$\Delta m^2_{21} = (7.53 \pm 0.18)\cdot 10^{-5}\ \mathrm{eV}^2$
$|\Delta m^2_{32}| = (2.44 \pm 0.06)\cdot 10^{-3}\ \mathrm{eV}^2$
$\delta_{CP} = [-\pi \div 0.14\pi]$ and $[0.87\pi \div \pi]$ (90% interval)

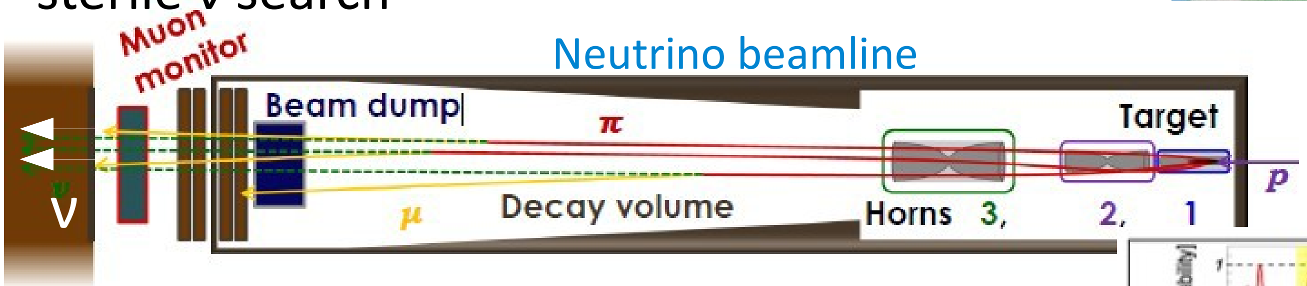
- mass hierarchy, CPV phase (and Majorana phases) still unknown

→ long-baseline experiments only

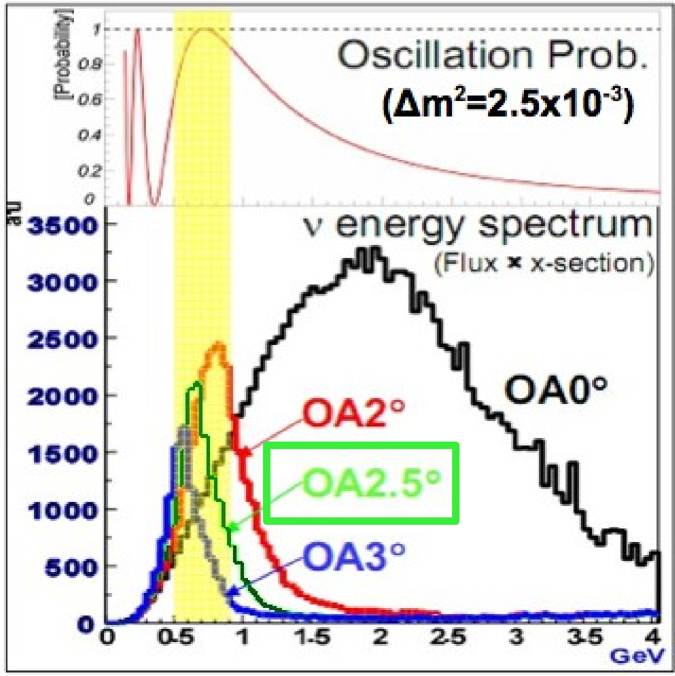
T2K experiment



- searches for ν oscillations in high purity ν_μ beam
- other measurements: cross sections, sterile ν search



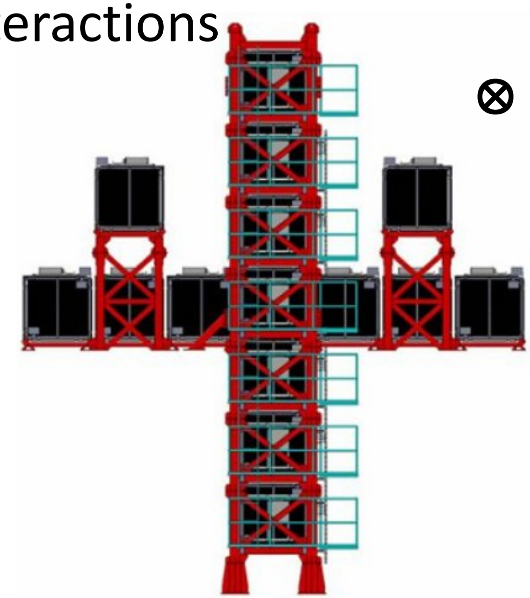
- **off-axis** technique
  - ▸ CC quasi-elastic sample enhanced
  - ▸ backgrounds reduced
    - δOA~1mrad → δE/E ~2% at far detector
- collaboration: ~500 members, 59 institutes, 11 countries



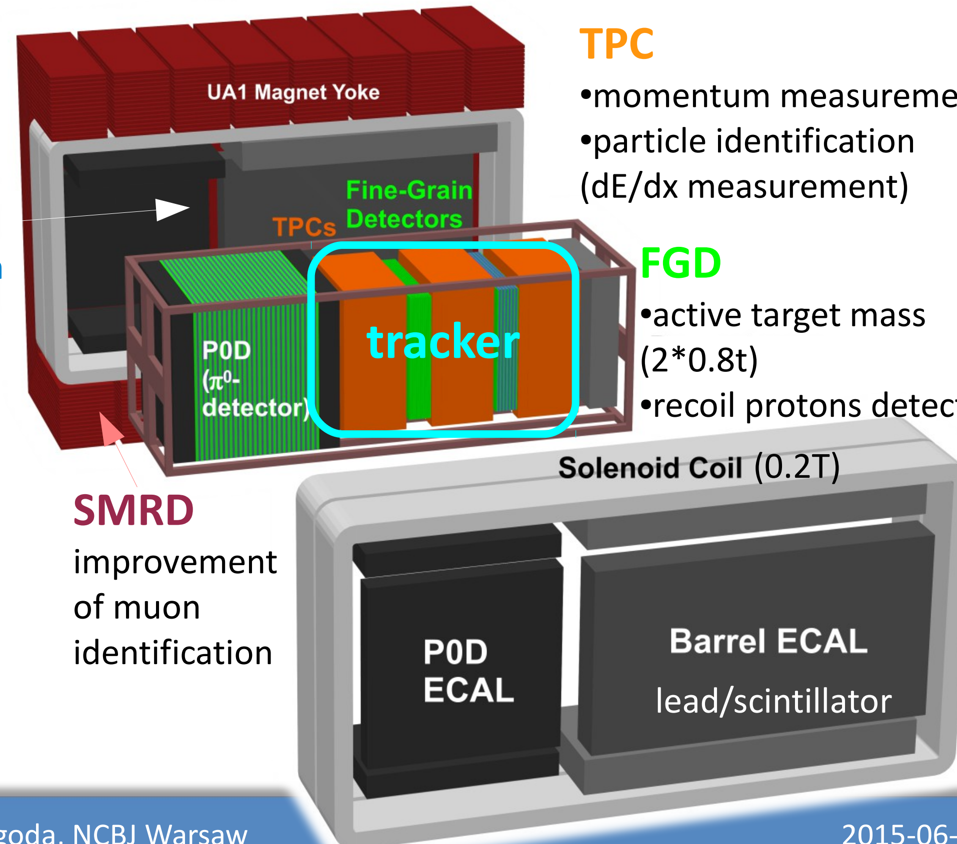
The near detectors (280m)

- INGRID (on axis)
  - iron/scintillator tracking calorimeters, 16 modules
  - 1 all-scintillator proton module
  - direction, profile, rate of CC interactions

⊗ beam direction



- ND280 (off axis)
  - ν_μ and ν_e flux measurement
  - non-oscillation analyses

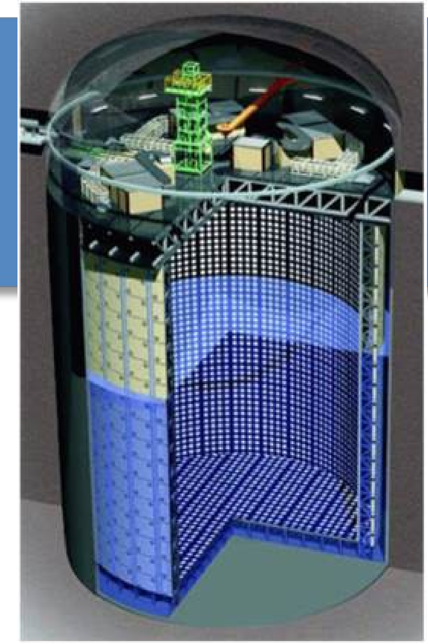


TPC
- momentum measurement
- particle identification (dE/dx measurement)

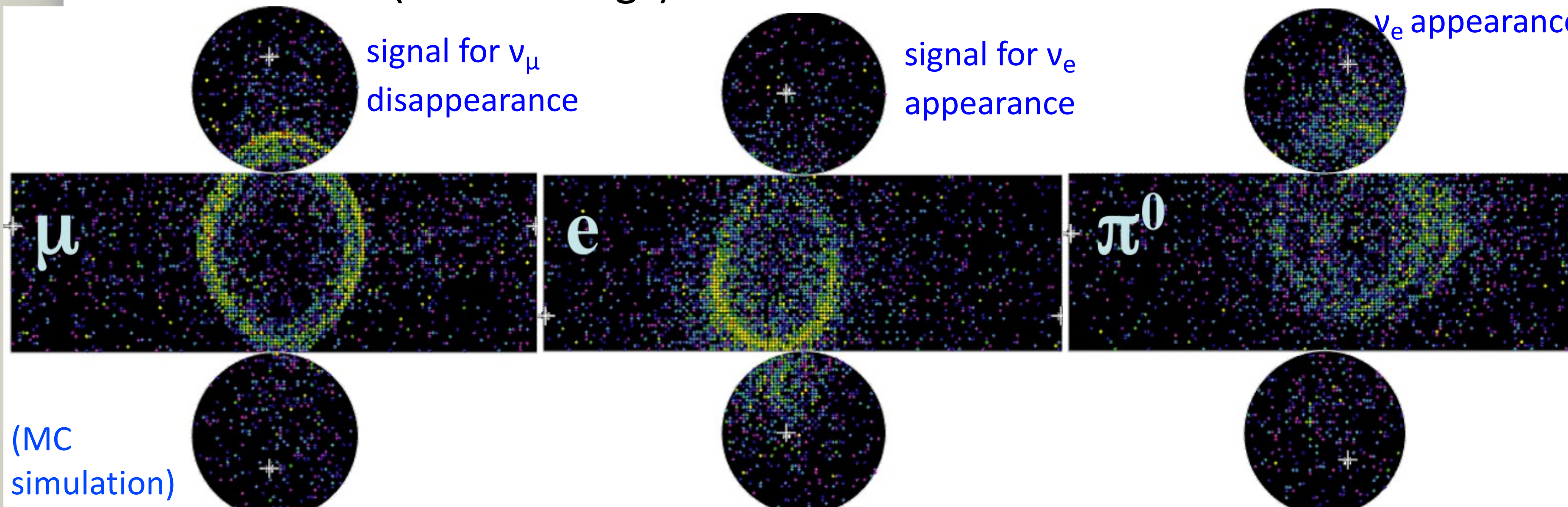
FGD
- active target mass (2*0.8t)
- recoil protons detection

SMRD
improvement of muon identification

The far detector: Super-Kamiokande



- water Cherenkov detector
  - total mass 50 kt, fiducial mass 22.5kt
  - >11000 PMTs in inner detector
- $\Delta E/E$ ~10% for 2-body kinematics
- very good μ/e separation
  - muons misidentified as electrons: <1%
- π^0 detection (2 e-like rings)



signal for ν_μ disappearance

signal for ν_e appearance

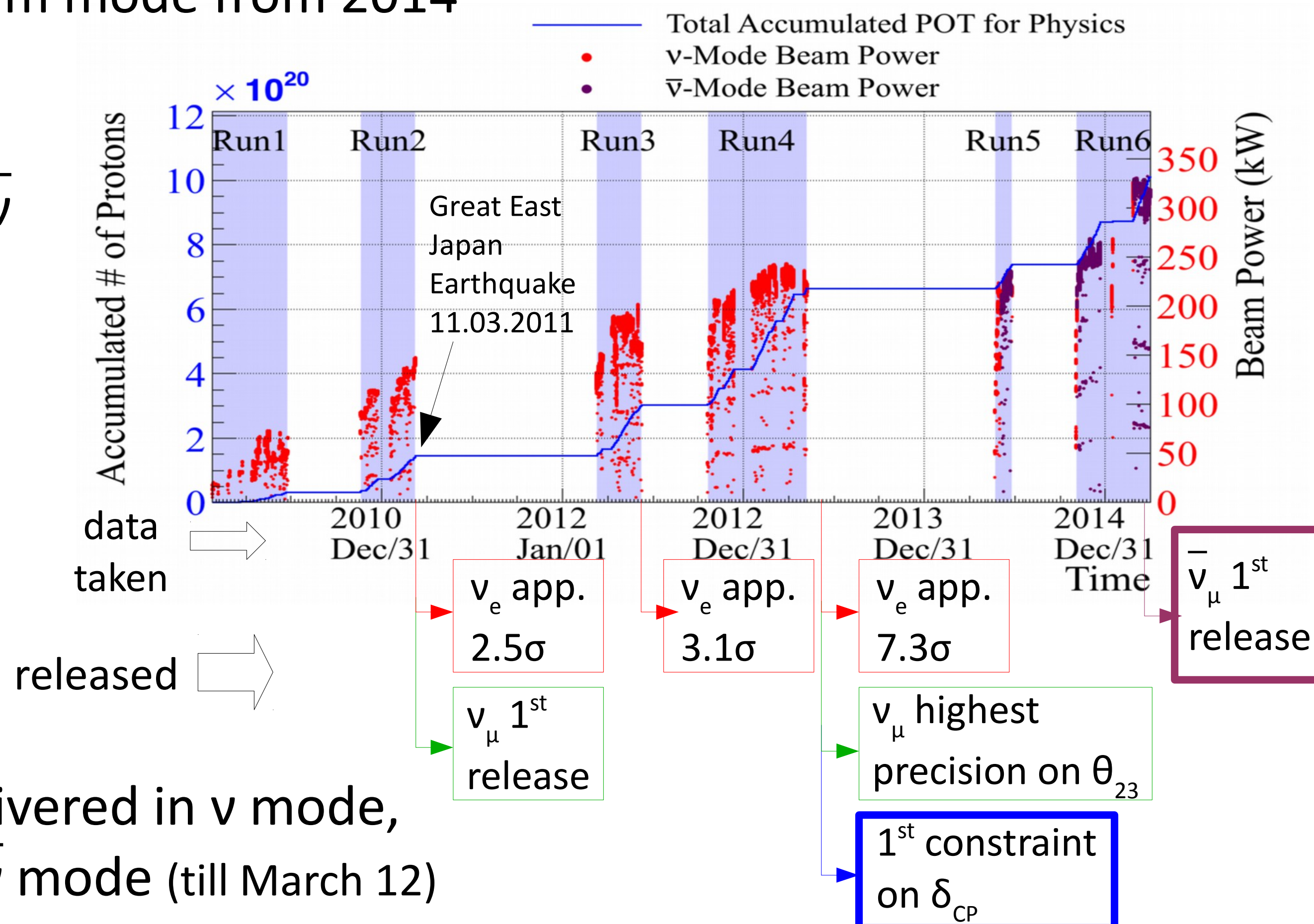
background for ν_e appearance

(MC simulation)

Data taking

- antineutrino beam mode from 2014
  - looking for any differences between ν and $\bar{\nu}$ oscillations
  - potentially measure δ_{CP} (T2K data only)

Prog. Theor. Exp. Phys. 043C01 (2015)



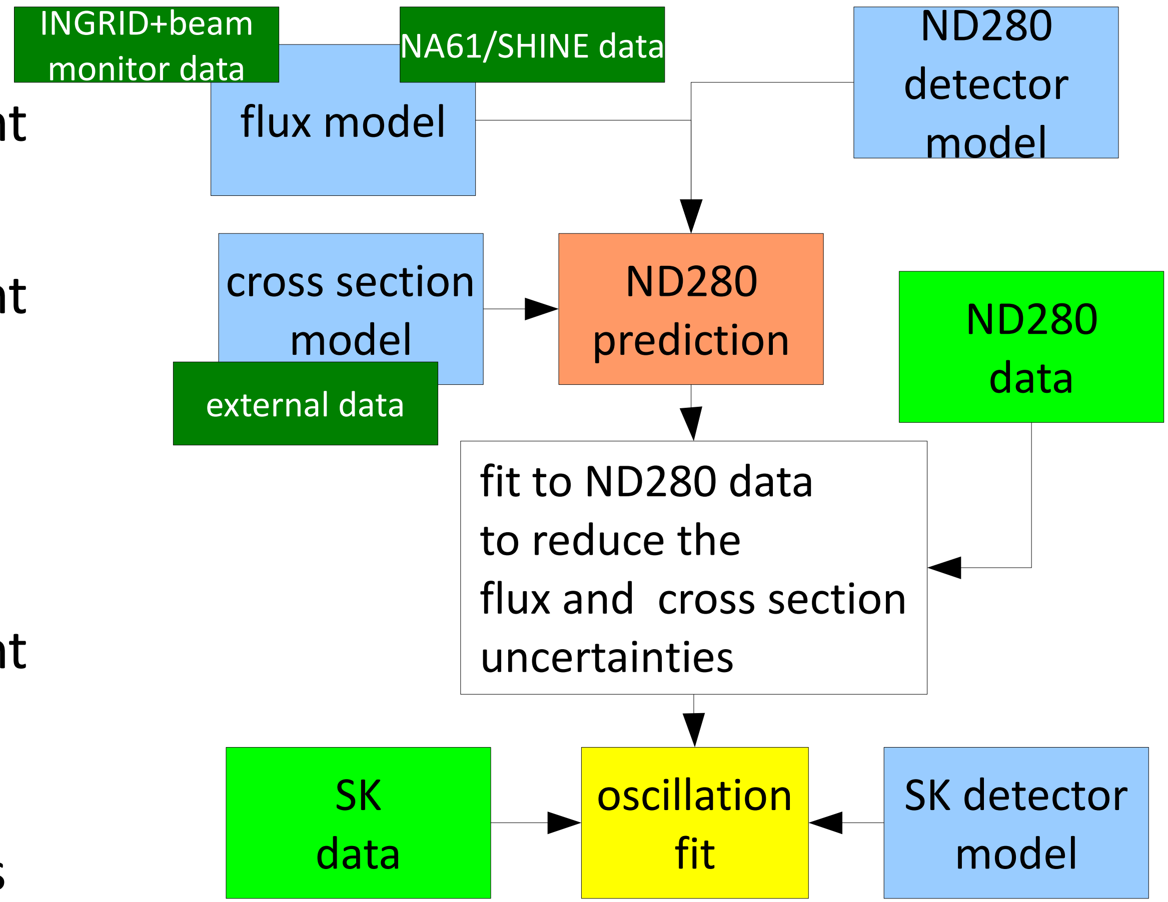
- $7.0 \cdot 10^{20}$ POT delivered in ν mode, $2.3 \cdot 10^{20}$ POT in $\bar{\nu}$ mode (till March 12)
- beam stability <1mrad

Analyses in T2K

2013
- ν_e appearance
  - $\sin^2\theta_{13}$ measurement

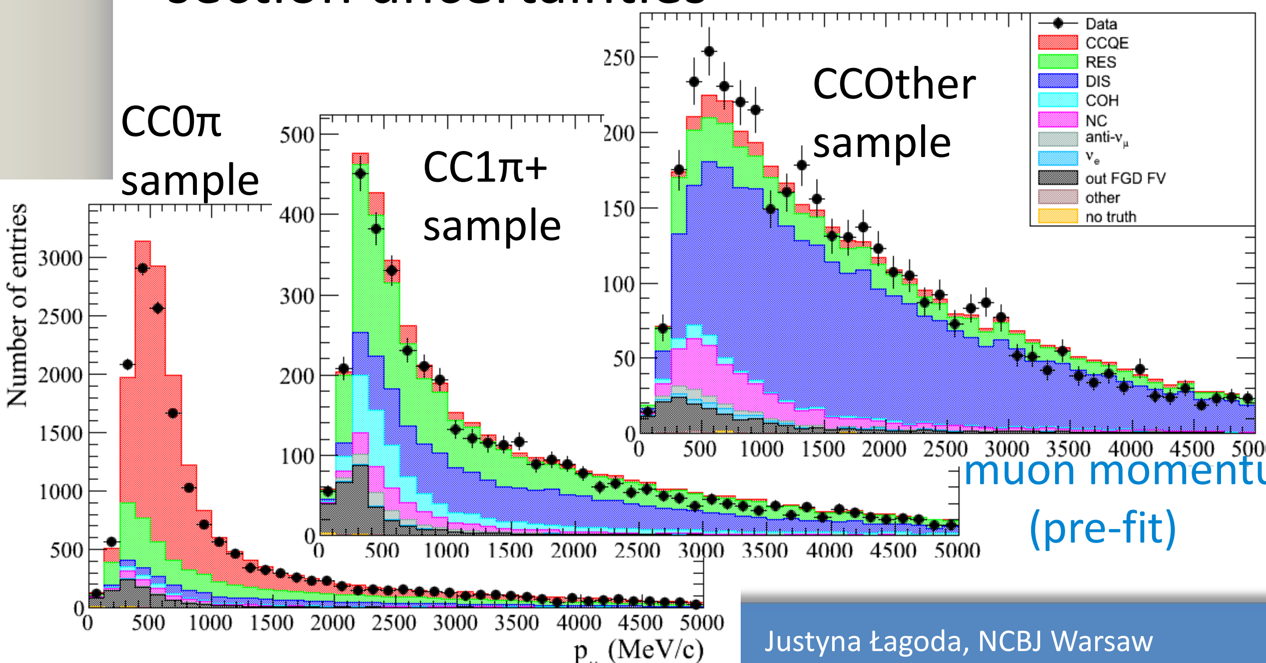
2014
- ν_μ disappearance
  - $\sin^2\theta_{23}$ measurement
- **joint $\nu_e+\nu_\mu$ analysis**
  - first δ_{CP} constraints
- **$\bar{\nu}_\mu$ disappearance**
  - $\sin^2\bar{\theta}_{23}$ measurement

- cross section and other measurements at near detector

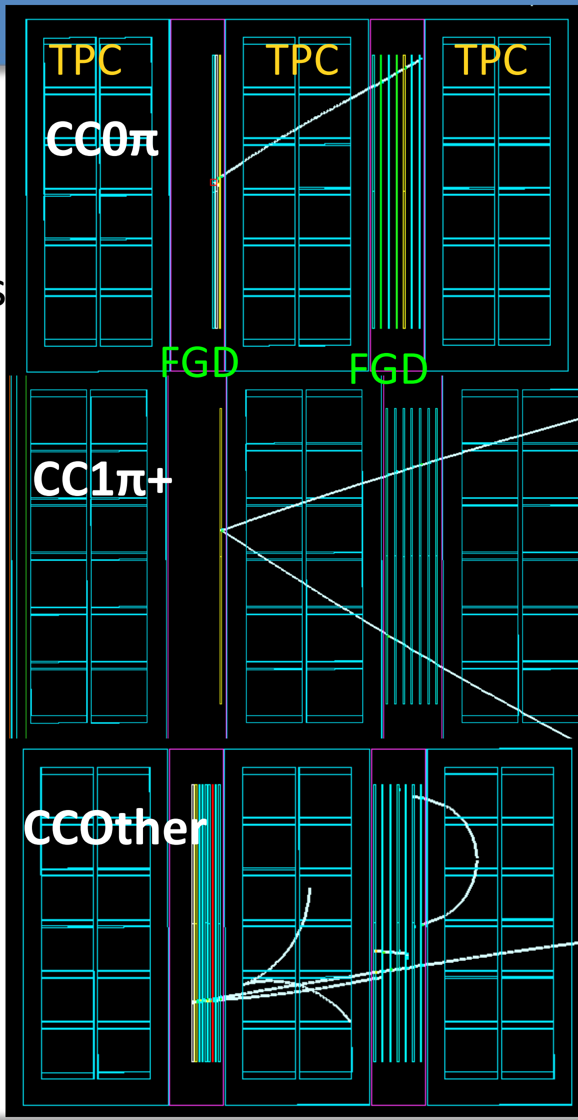


Near detector analysis

- ν_μ CC selection in tracker
  - subsamples ← presence of pions in final state
  - sensitivity to different energy ranges and interactions (CC quasi-elastic, resonant, deep inelastic scattering)
- fit of spectra to reduce flux and cross section uncertainties



muon momentum (pre-fit)

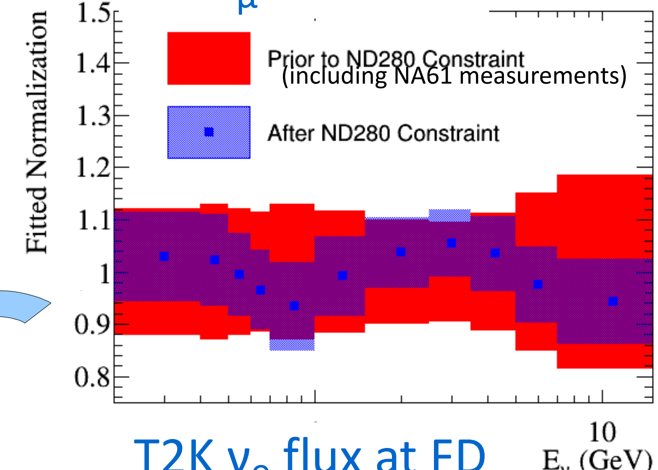


Near detector constraints

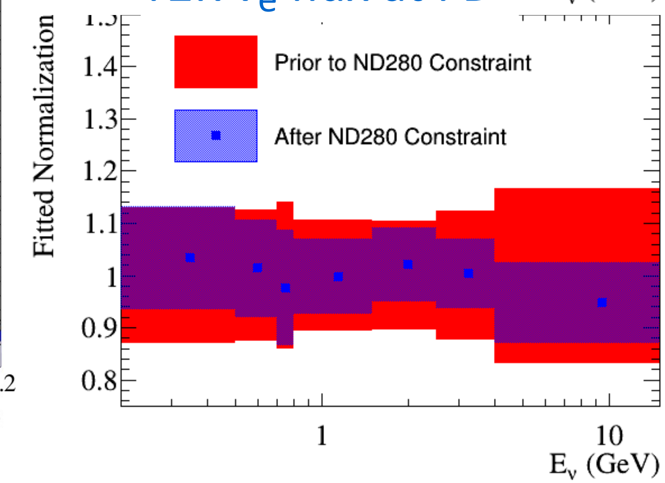
- reduced uncertainties on the cross section and flux parameters

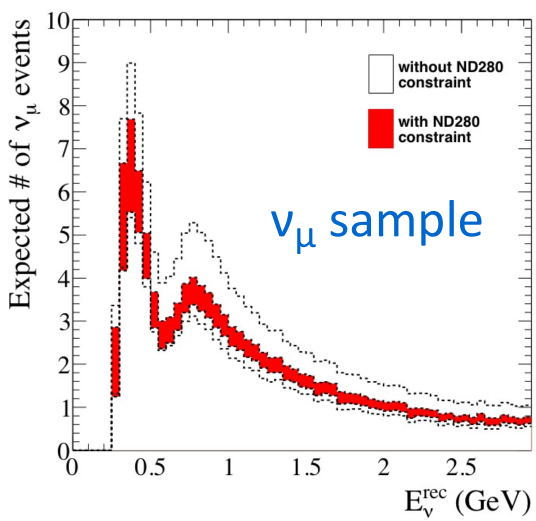
  significant reduction of the far detector event rate errors

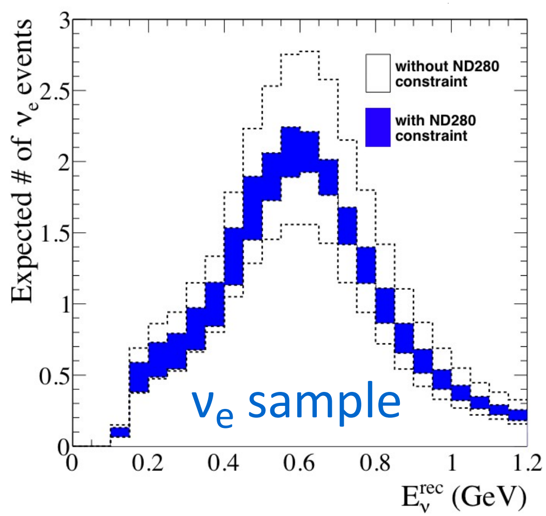
T2K ν_μ flux at FD



T2K ν_e flux at FD







$\nu_\mu + \nu_e$ joint analysis (T2K only)

- we consider both T2K ν_μ and ν_e spectra simultaneously
- extended maximum likelihood fit:

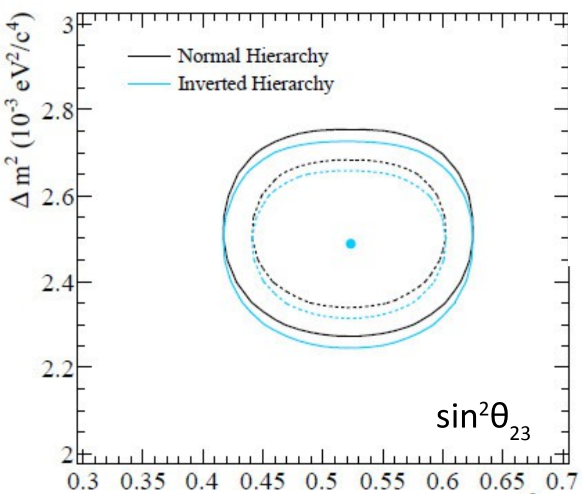
$$L = L_{nue} \times L_{numu} \times L_{sys}$$

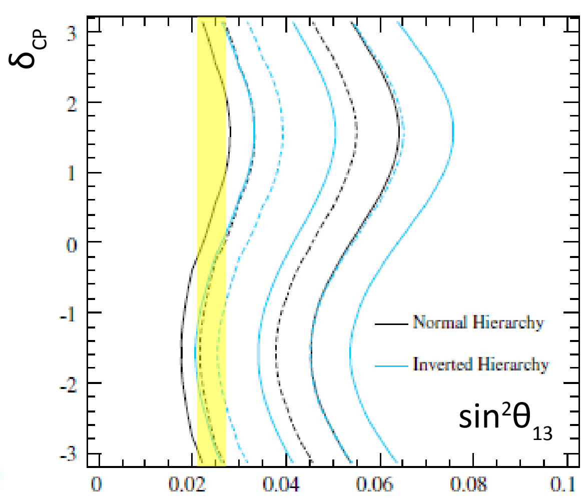
$$L_{nux} = L_{norm} \times L_{shape}$$

number of events → L_{norm}

shape of distribution E_{rec} for ν_μ, p_e,θ_e for ν_e → L_{shape}

$\sin^2\theta_{23}$ favours maximal mixing – world best precision





$\sin^2\theta_{13}$ compatible with reactor measurements

$$\sin^2\theta_{23} = 0.524^{+0.057}_{-0.059}\ \text{(NH)}\quad 0.523^{+0.055}_{-0.065}\ \text{(IH)}$$

$$\sin^2\theta_{13} = 0.042^{+0.013}_{-0.021}\ \text{(NH)}\quad 0.049^{+0.015}_{-0.021}\ \text{(IH)}$$

$\nu_\mu + \nu_e$ joint analysis (+reactor)

- include results from reactor experiments: extra constraint term in the likelihood
  - improves precision on $\sin^2\theta_{23}$ and Δm^2_{23}
  - frequentist and Bayesian approaches

Hints towards CP violation

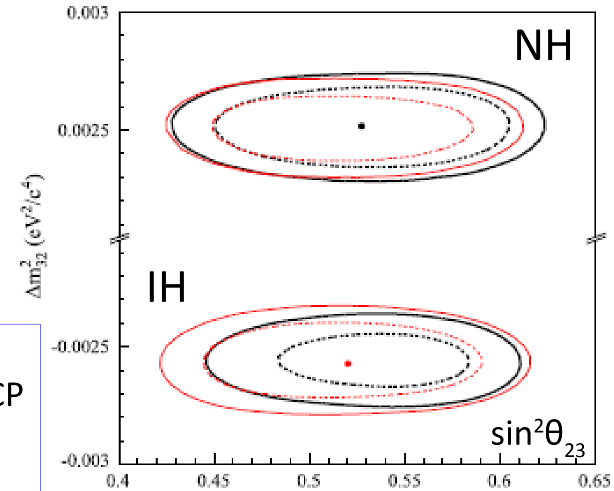
90% C.L. excluded region of δ_{CP}

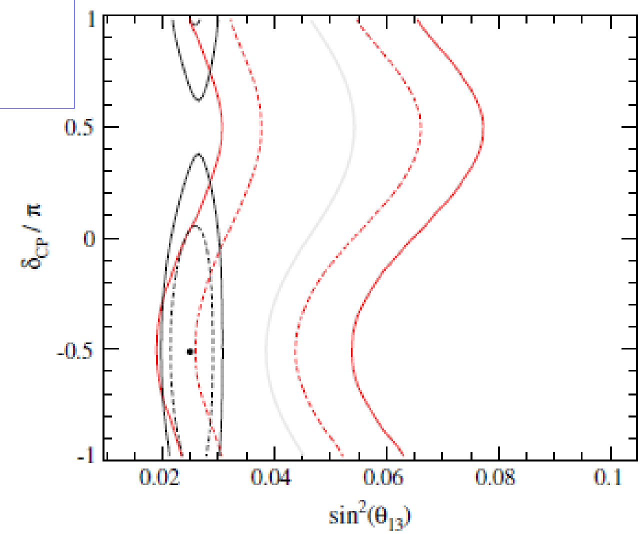
$0.15\pi < \delta_{CP} < 0.83\pi$ (NH)

$-0.08\pi < \delta_{CP} < 1.09\pi$ (IH)

posterior probabilities (Bayesian)

	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	0.179	0.078	0.257
$\sin^2\theta_{23} > 0.5$	0.505	0.238	0.743
Sum	0.684	0.316	1.0



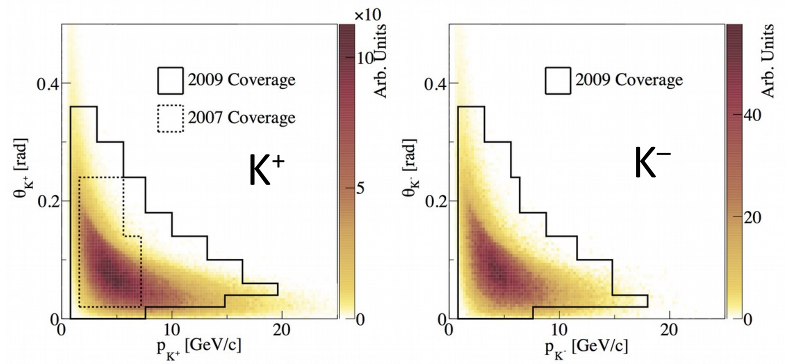


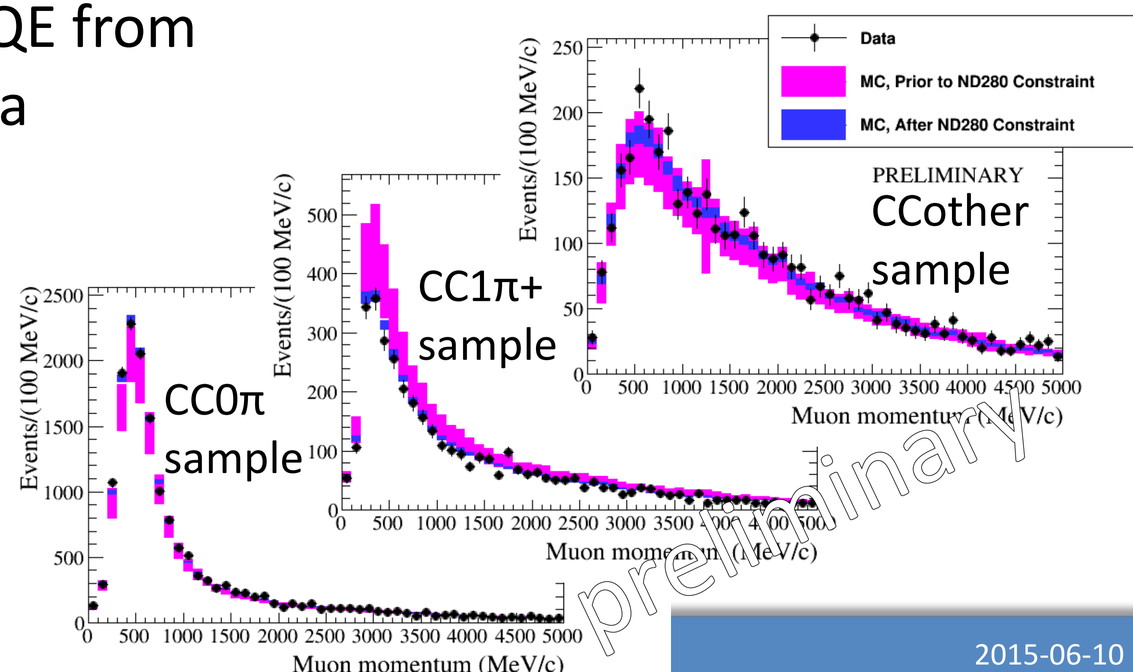
Phys. Rev. D 91, 072010 – Published 29 April 2015

Antineutrino beam mode

Changes in 2015 analysis

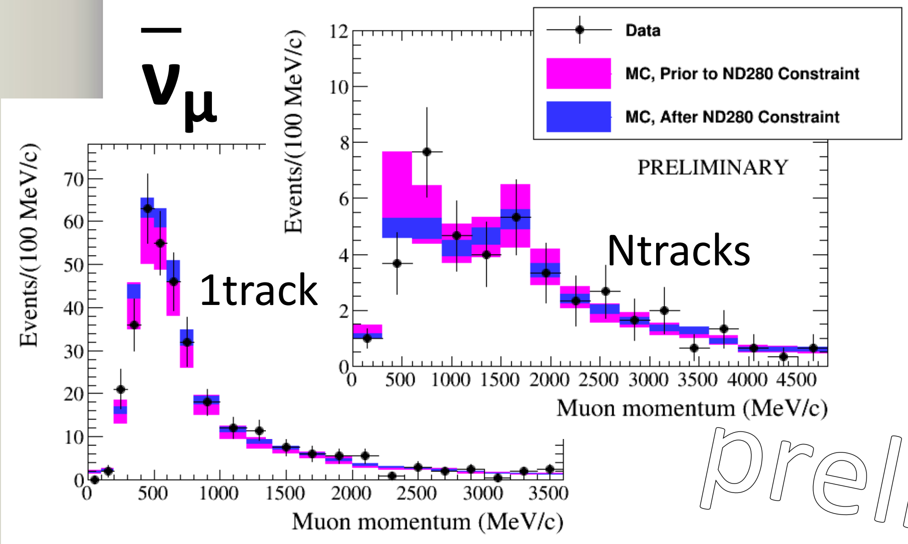
- new NA61 data used in the beam MC simulation (uncertainty reduced by 4% in the energy peak)
- new neutrino MC model with multinucleon interactions
- new constraints on CC QE from MiniBooNE and Minerva
- before ND fit the MC underestimates CC0π and CCother samples, overestimates CC1π+ sample

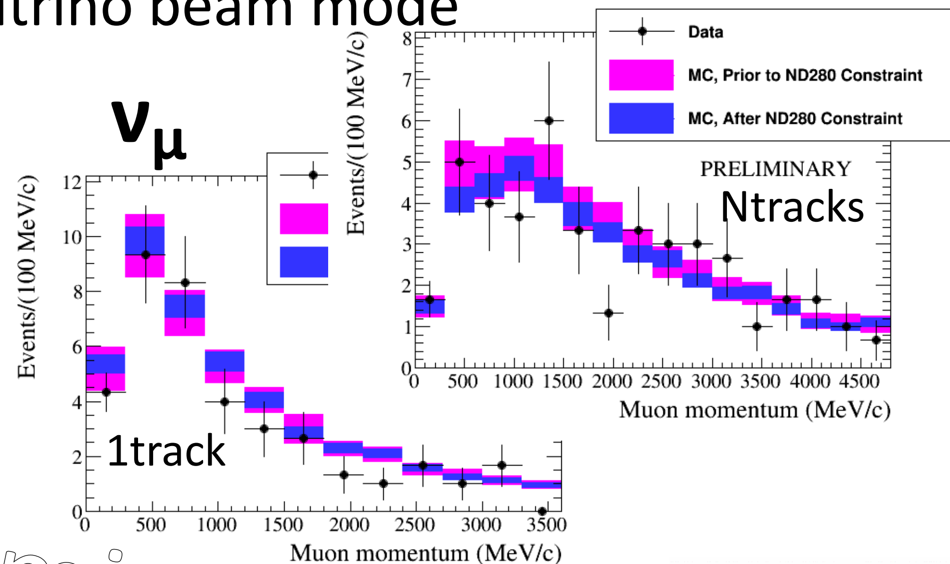




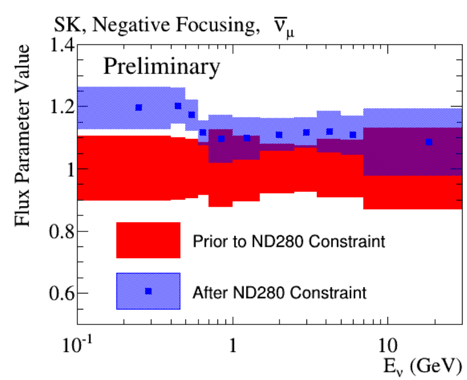
Near detector constraints for $\bar{\nu}$ beam mode

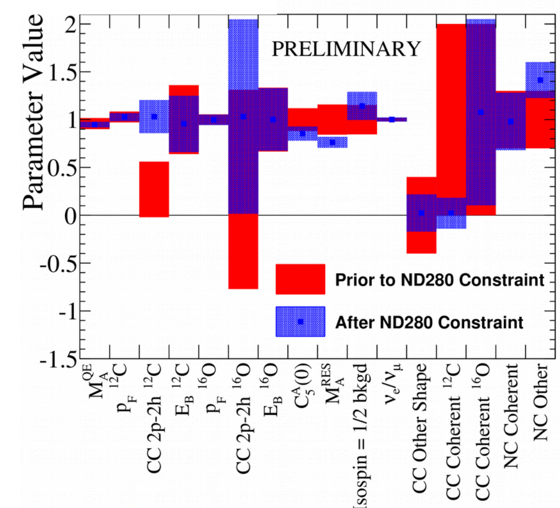
- additional samples for antineutrino beam mode





- flux and cross section parameters after fit to ND280 data

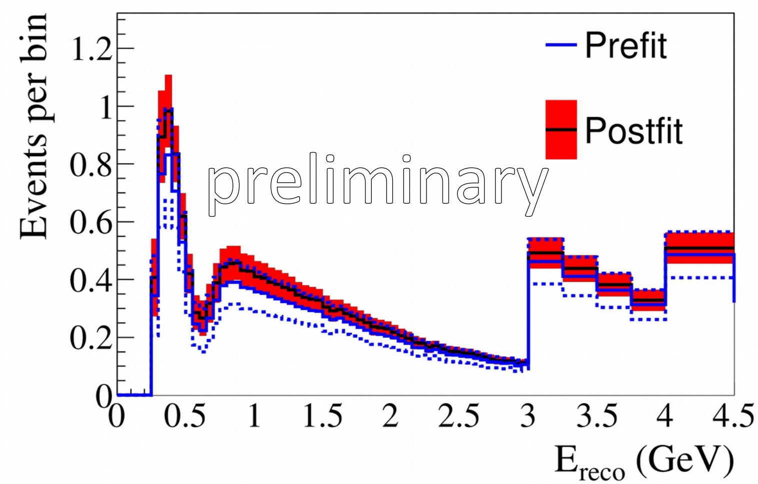




Predicted $\bar{\nu}_\mu$ spectrum at SK

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

- expected spectrum obtained using the oscillation parameters from neutrino beam results
- 19.9 events expected with oscillation and 59.8 without oscillation
  - dominated by CCQE events



- systematic errors dominated by uncertainties on the difference between interactions on C (ND280) and O (Super-K)

Systematic		without ND280	with ND280
Flux and cross section	common to SK/ND280	9.2%	3.4%
	SK only	**10%**	
	all	13%	10.1%
FSI/SI		2.1%	
SK detector		3.8%	
total		14.4%	**11.6%**

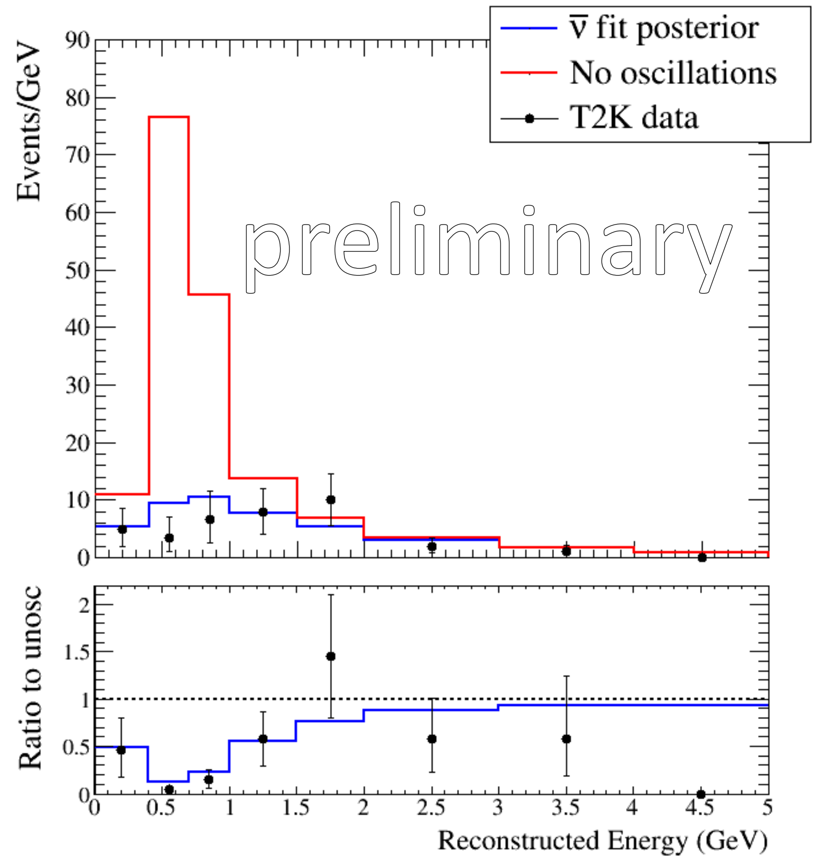
The best-fit $\bar{\nu}_\mu$ spectrum

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

- expectation:
  - 19.9 events with oscillation
  - 59.8 without oscillation
- 17 events observed
  - clear evidence of oscillation in data
- maximize the likelihood:

$$\mathcal{L} = \mathcal{L}_{\text{Poisson}} \times \mathcal{L}_{\text{Syst}}$$

  - all oscillation parameters except $\sin^2\bar{\theta}_{23}$ and $\Delta\bar{m}_{32}^2$ fixed, based on T2K neutrino data and PDG 2014

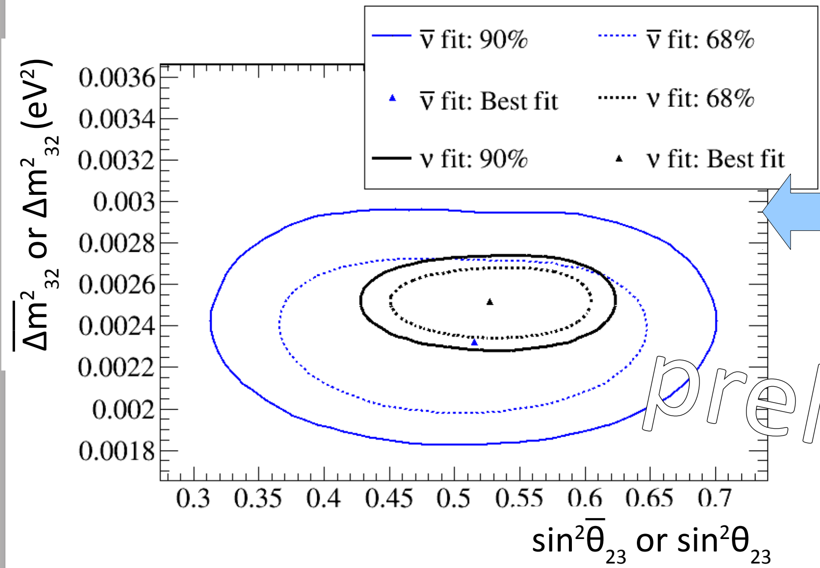


The oscillation parameters

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

best-fit point near maximal disappearance

$\lvert\Delta\bar{m}^2_{32}\rvert$	$\sin^2(\bar{\theta}_{23})$
$2.33^{+0.27}_{-0.23} \times 10^{-3}$ eV^2	$0.515^{+0.085}_{-0.095}$



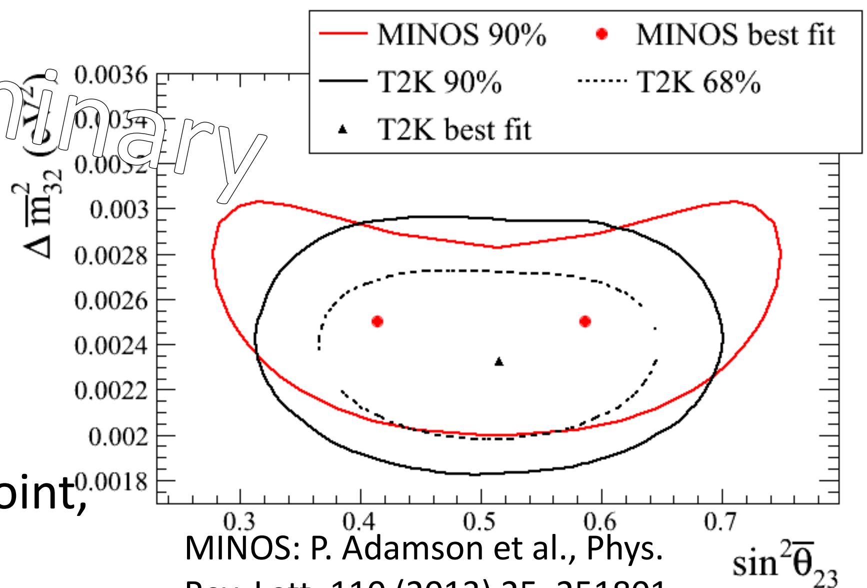
comparison to T2K neutrino data

- still much larger contours
- results consistent with no difference between neutrinos and antineutrinos

comparison to MINOS

(beam and cosmic combined)

- T2K contours smaller in $\sin^2\bar{\theta}_{23}$
- MINOS saw non-maximal best-fit point, but results compatible



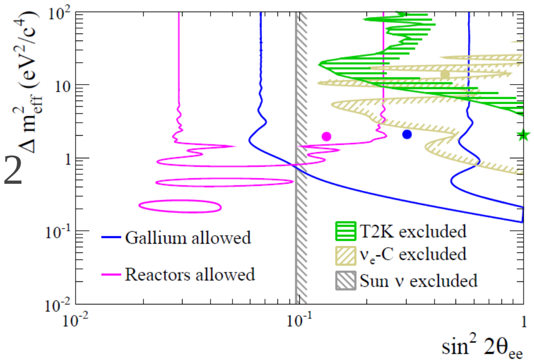
MINOS: P. Adamson et al., Phys. Rev. Lett. 110 (2013) 25, 251801

Other results: cross sections and sterile neutrino search

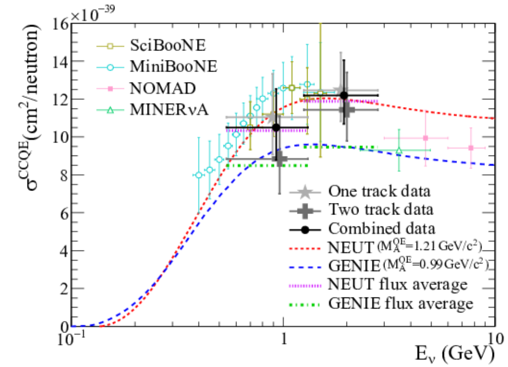
near detector

Search for short-baseline ν_e disappearance with the T2K near detector

Phys. Rev. D 91 051102 (2015)



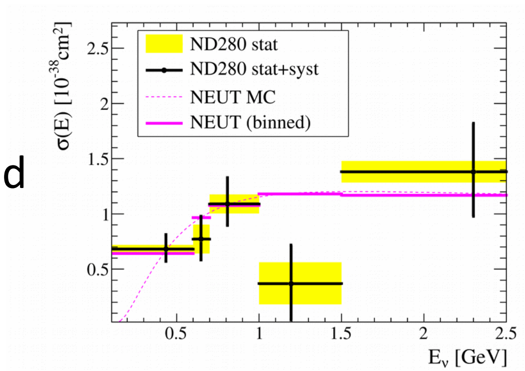
Measurement of the ν_μ CC QE cross section on carbon with T2K on-axis neutrino beam



submitted to PRD

Measurement of the ν_μ CC QE cross section on carbon with the ND280 detector at T2K

submitted to PRD



- 4 papers on cross-section published before 2015
- Measurement of the ν_e CC Interaction Rate on water with the T2K ND280 π^0 Detector (Accepted in PRD)
- more will come!

Conclusions

- recent T2K oscillation analyses:
  - combined $\nu_\mu + \nu_e$ analysis with reactor constraint
    - preference for values of δ_{CP} around $-\pi/2$
    - weakly favored normal hierarchy and octant $\sin^2\theta_{23} > 0.5$
  - first $\bar{\nu}_\mu$ disappearance result
    - consistent with T2K ν_μ disappearance measurements and MINOS $\bar{\nu}_\mu$ disappearance result
  - analysis of $\bar{\nu}_e$ appearance is underway

- many cross section measurements at the near detector
- T2K continued to take data till end of May (statistics with antineutrino beam mode doubled)

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
- U. 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.
- Osaka City U.
- Okayama U.
- Tokyo Metro U.

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

Russia
- INR

Spain
- IFIC, Valencia
- U. A. Barcelona

Switzerland
- ETH Zurich
- U. Bern
- U. Geneva

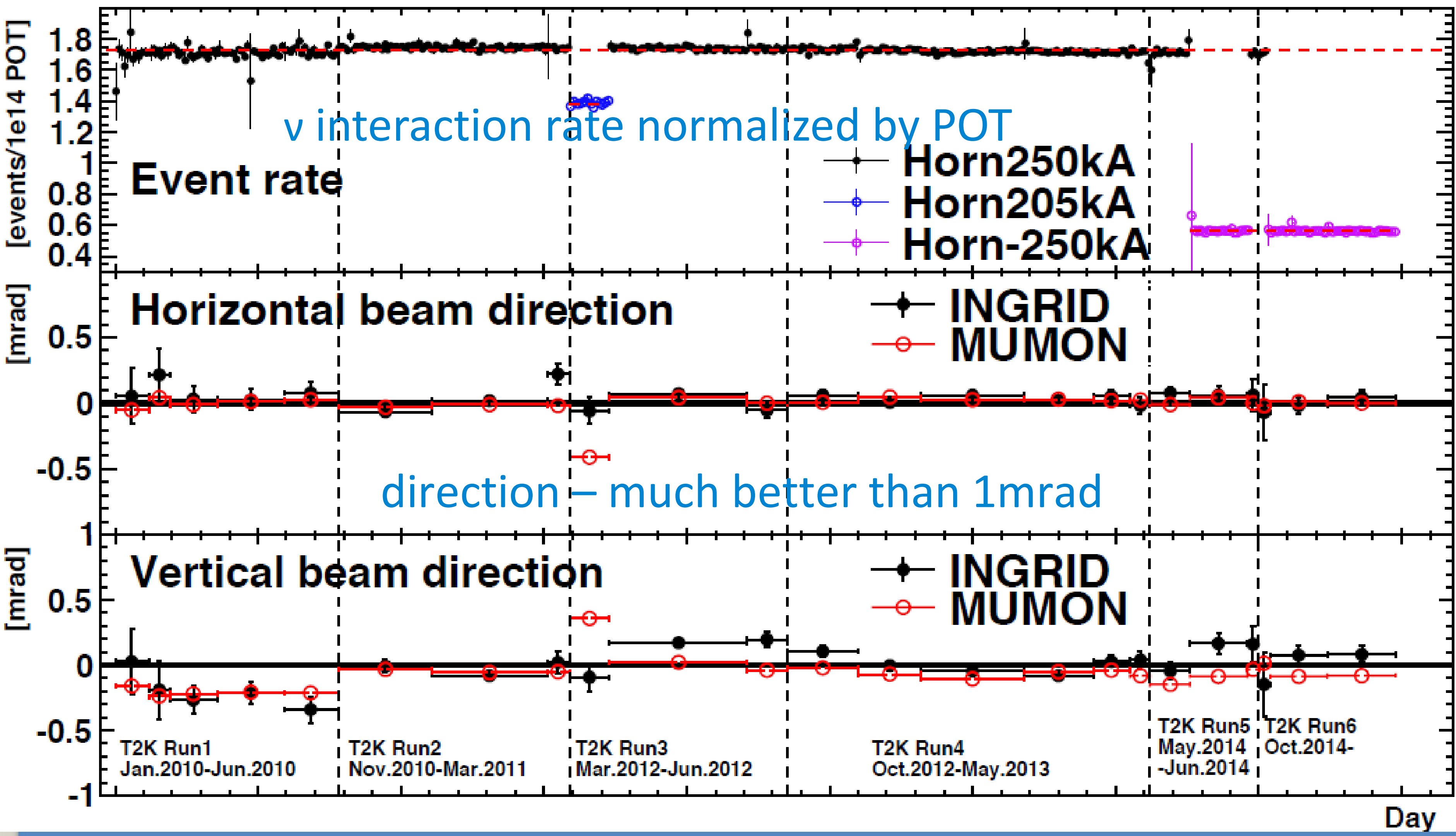
UK
- Imperial C. L.
- Lancaster U.
- Oxforf U.
- Queen Mary U. L.
- STFC/Daresbury
- STFC/RAL
- U. Liverpool
- U. Sheffield
- U. Warwick

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

Near & Far sites: KEK/JAEA ICRR

Additional slides

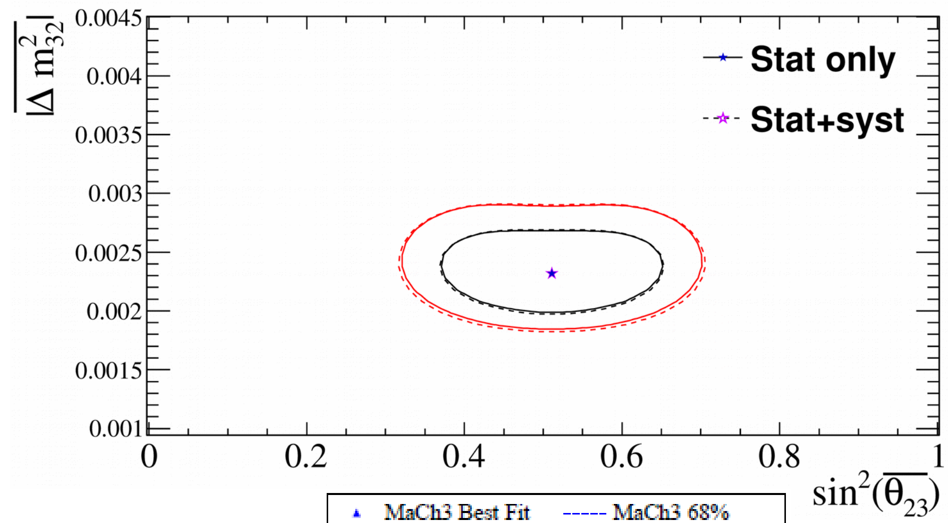
Beam stability



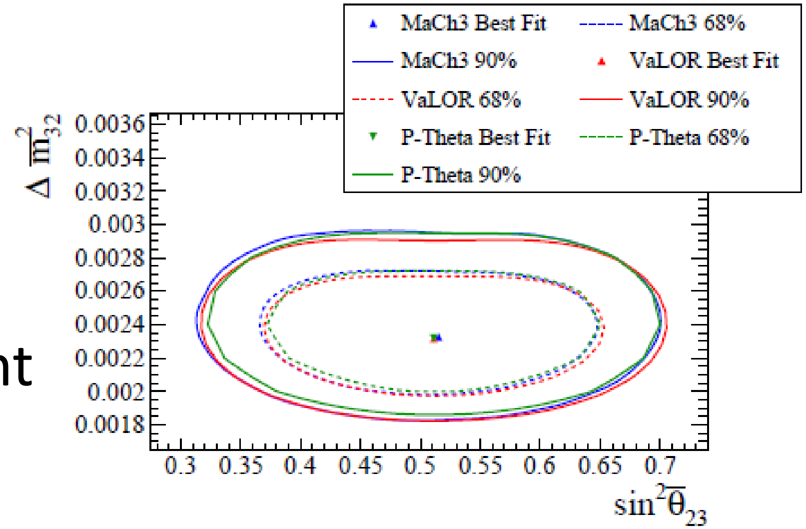
$\bar{\nu}_\mu$ disappearance

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

- effect of systematic uncertainties: nearly identical contours
- the analysis is dominated by statistical errors

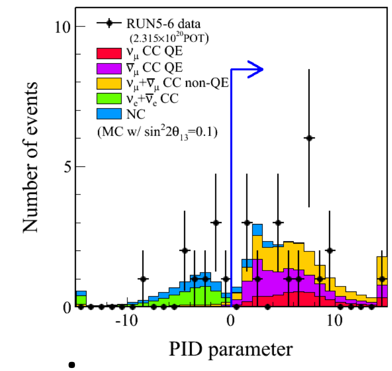


- three different analyses: different methods of maximizing likelihood
- all are in very good agreement

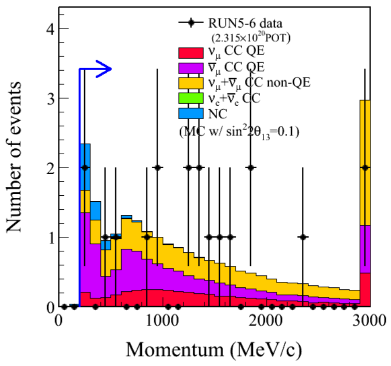


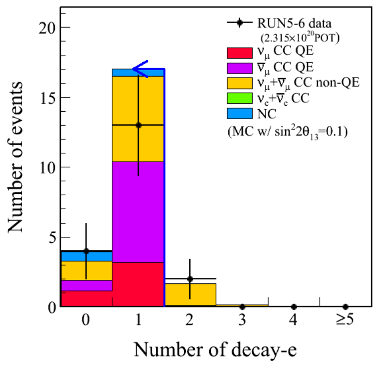
Event selection in SuperK

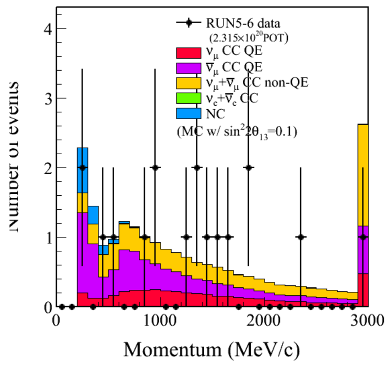
- beam timing and minimal activity in outer detector
- fully contained in fiducial volume (>200cm from wall)
- one reconstructed ring (QE-like)



- muon-like ring
  - muon momentum >200MeV
  - one or fewer decay electrons



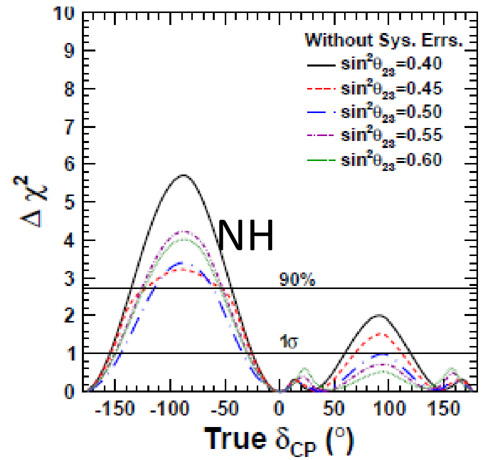


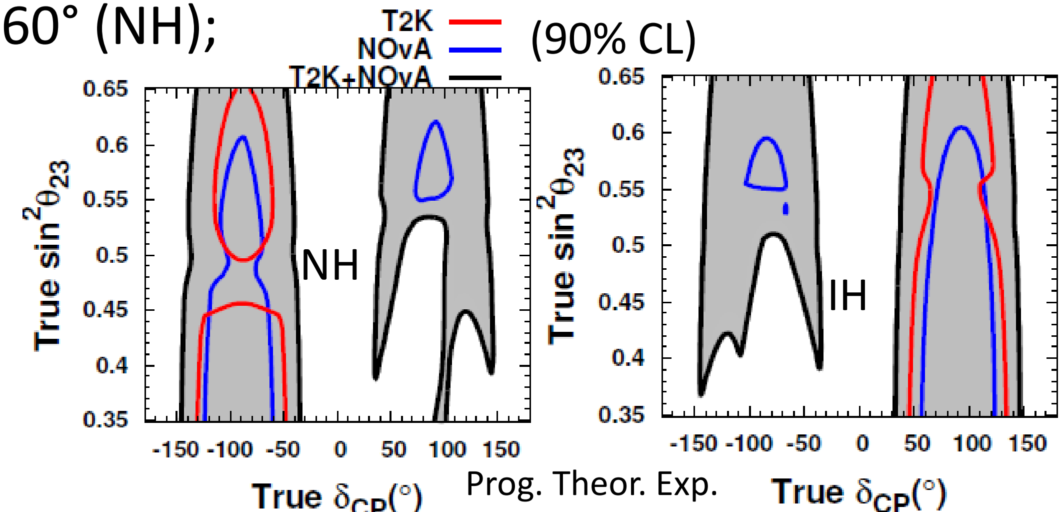


- electron-like ring
  - visible energy>100 MeV
  - no Michel (delayed) electrons
  - cut on π^0 invariant mass and likelihood ratio
  - reconstructed neutrino energy <1.25 GeV

Future sensitivity

- $7.8 \cdot 10^{21}$ POT → resolution of 0.050(0.054) on $\sin^2\theta_{23}$ and $0.040(0.045) \cdot 10^{-3}$ eV^2 on Δm^2_{32}
  - for 100%(50%) neutrino beam mode running
  - assuming $\sin^2\theta_{23}=0.5$ and $\Delta m^2_{32}=2.40 \cdot 10^{-3}$ eV^2
- sensitivity to δ_{CP} at 90% C.L. or better over a significant range.
  - if $\sin^2\theta_{23}=0.5$ → $-115° < \delta_{CP} < -60°$ (NH); $+50° < \delta_{CP} < +130°$ (IH)
- combination of results from two experiments at different baselines (T2K + NOvA) will further improve the sensitivity





Prog. Theor. Exp. Phys. 043C01 (2015)

ν_μ disappearance

ν_μ disappearance

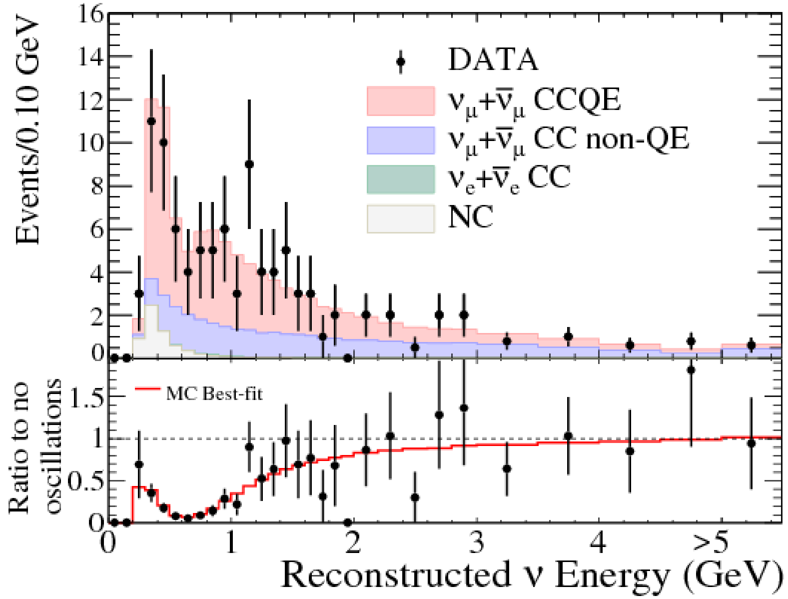
full 3-ν oscillation framework

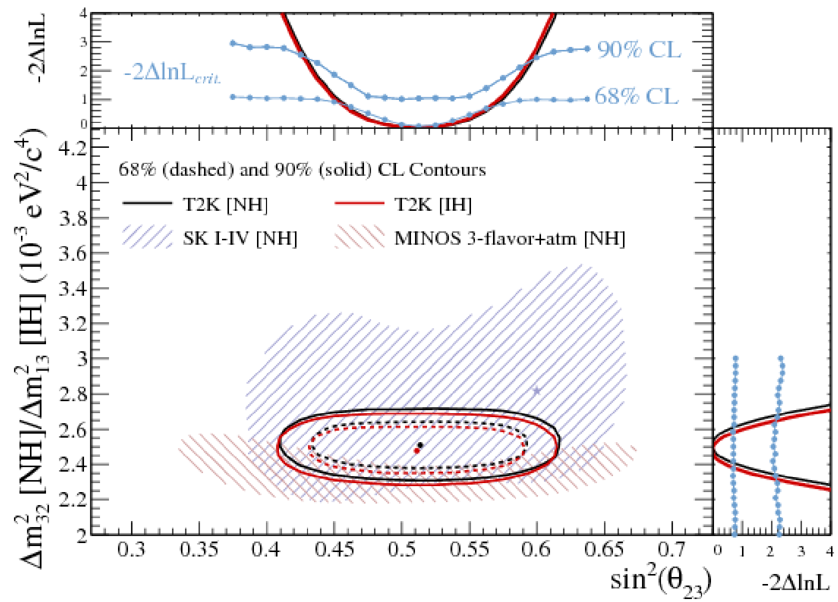
Phys. Rev. Lett. 112, 181801 (2014)

- with ND280 constraint

$$0.514^{+0.055}_{-0.056}\,(0.511 \pm 0.055)$$

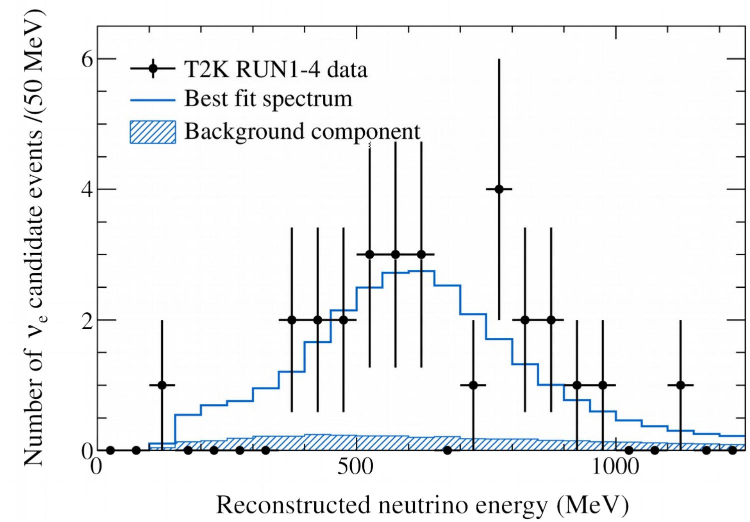
Source of uncertainty (number of parameters)	$\delta n^{exp}_{SK} / n^{exp}_{SK}$
ND280-independent cross section (11)	4.9%
Flux and ND280-common cross section (23)	2.7%
SK detector and FSI+SI systematics (7)	5.6%
$\sin^2(\theta_{13})$, $\sin^2(\theta_{12})$, Δm^2_{21}, δ_{CP} (4)	0.2%
Total (45)	8.1%

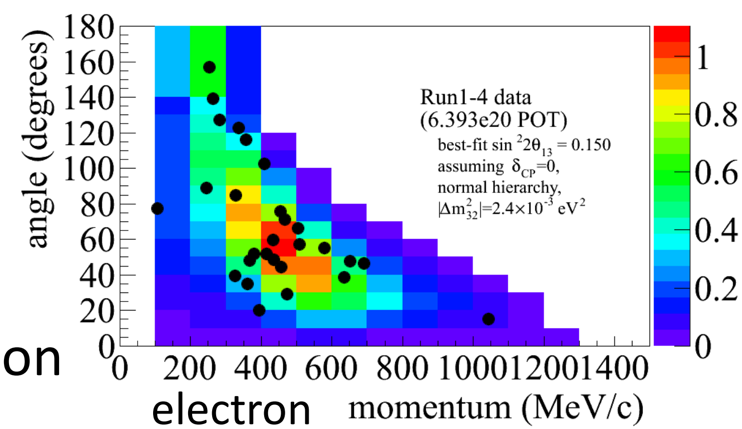




ν_e appearance

- expected number of events in T2K FD: **20.4 ± 1.8**
  - for $\sin^2 2\theta_{13}$=0.1, $\sin^2 2\theta_{23}$=1.0, δ_{CP}=0, normal mass hierarchy
- expected background: **4.64 ± 0.53**
  - 0.4 – ν_e signal (solar term)
  - 0.9 – ν_μ background
  - 3.2 – ν_e background
  - 0.3 – anti-ν background
- 5.5σ sensitivity to exclude θ_{13}=0
- 2 independent analyses:
  - neutrino energy spectrum
  - electron momentum and angle distribution





ν_e appearance result

ν_e appearance

- **28** events observed
- **7.3σ** significance for non-zero θ_{13}

First ever observation (>5σ) of ν appearance

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NOTE: These are 1D contours for various value of δ_{CP}, not 2D contours