Highlights from T2K

Anna Dabrowska

The H. Niewodniczanski
Institute of Nuclear Physics
Polish Academy of Sciences, Krakow

On behalf of the T2K collaboration

4th International Conference on New Frontiers in Physics

Outline:

- *The T2K experiment*
- *Oscillation analysis of electron neutrino appearance and muon neutrino disappearance*
- *First results from anti-neutrino running*
- *Other analyses (cross section)*
- *Summary*

Neutrino oscillation status

+ Majorana phases

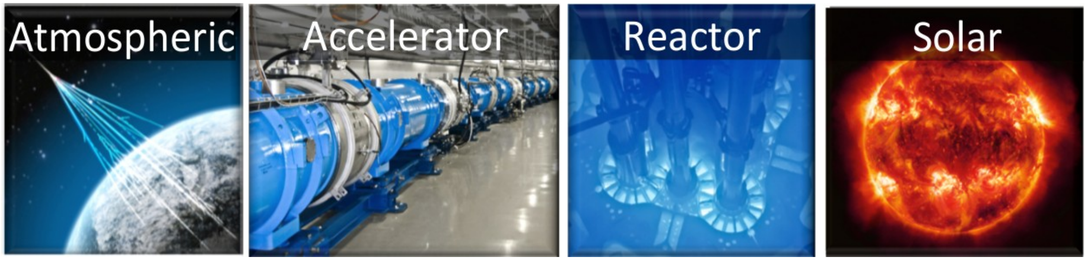
Flavour eigenstates   Mass eigenstates

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

$$U_{PMNS}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}$$

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

- **Oscillation probabilities $P(\nu_\alpha \rightarrow \nu_\beta)$ depend on:**
  - **3 mixing angles:**
  - $\Theta_{12} = (33.4 \pm 0.85)°$
  - $\Theta_{23} = (45.8 \pm 3.2)°$
  - $\Theta_{13} = (8.88 \pm 0.39)°$
  - **2 independent mass splittings:**
  - $|\Delta m^2_{32}| = (2.44 \pm 0.06) \cdot 10^{-3}\ \mathrm{eV}^2$
  - $|\Delta m^2_{12}| = (7.53 \pm 0.18) \cdot 10^{-5}\ \mathrm{eV}^2$
  - **1 complex CP phase:**
  - δ_{CP} around $-\pi/2$
  - Source-detector distance (L), neutrino energy (E)



Open questions:

CP phase (and Majorana phases) still not known

- Is δ_{CP} non-zero (CP violation in neutrino sector) ?
- Is θ_{23} 45° (maximal mixing)?
- Normal: $\mathbf{m_3>m_2}>m_1$ (N.H.) or inverted: $m_2>\mathbf{m_1>m_3}$ (I.H.) mass hierarchy?

The T2K experiment

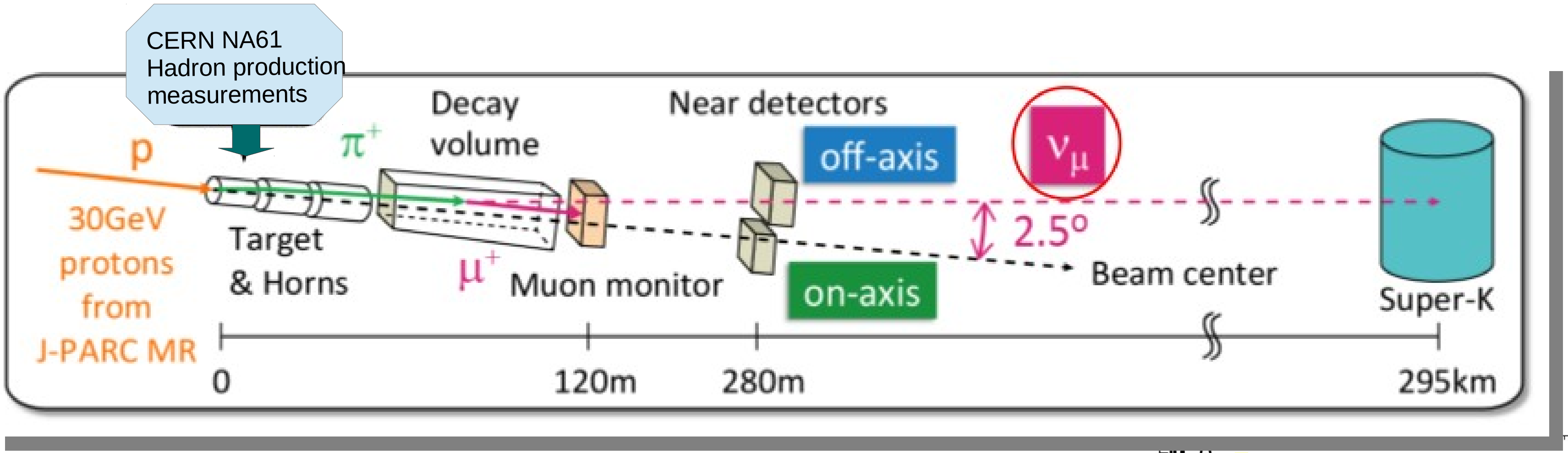
Tokai-to-Kamioka

- 11 countries,
- 59 institutions
- ~500 people

Goals:

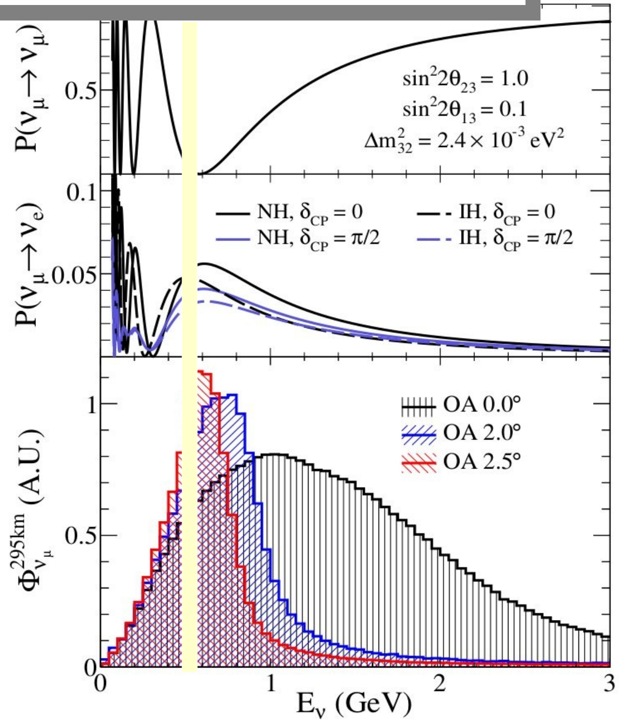
- Precision measurement of ν_μ and $\bar{\nu}_\mu$ disappearance to explore θ_{23} and Δm^2_{23}
  - test of CPT theorem or test of new non-standard ν interaction with matter
- Study and comparison of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transition to explore θ_{13}, θ_{23} and δ_{CP}, CP violation in lepton sector

T2K beam


CERN NA61
Hadron production
measurements

First use of Off-axis ν_μ Beam:

- Intense & high quality beam - beam direction stability < 1mrad
  (~1 mrad shift corresponds to ~2% energy shift at peak)
- E_ν peak around oscillation maximum (~0.6GeV)
- Small high energy tail → reduces feed-down background events
- π,K production at target was measured using CERN NA61 exp.
- $\bar{\nu}$ beam production was obtained by reversing current in magnetic horns



Processes at T2K ν spectrum

Oscillation probability depends on neutrino energy:

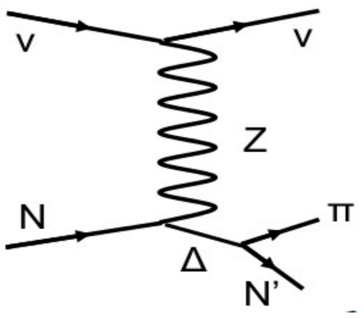
$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\,\Delta m^2_{32} L}{E}\right) + \ldots$$

$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

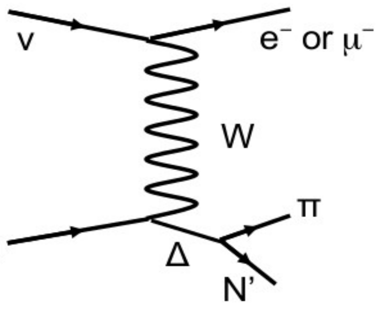
- For T2K's neutrino spectrum, **dominant process** is **C**harged **C**urrent **Q**uasi-**E**lastic
 Neutrino energy calculated from the lepton momentum and angle

- **Additional significant processes are**:
  - CCQE-like multi-nucleon interaction,
  - charged current single pion production (CCπ),
  - neutral current single pion production (NCπ)

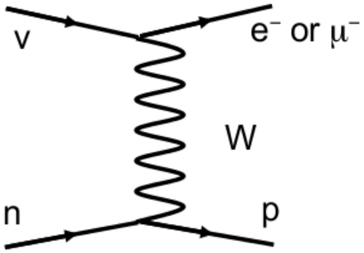
NCπ

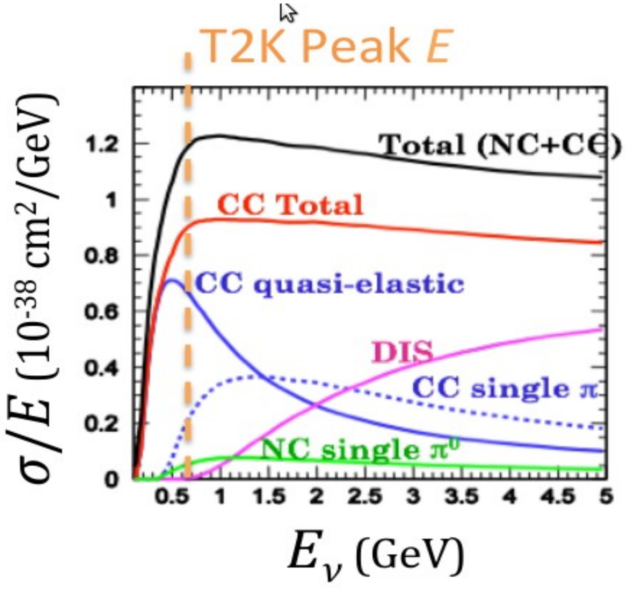


CCπ

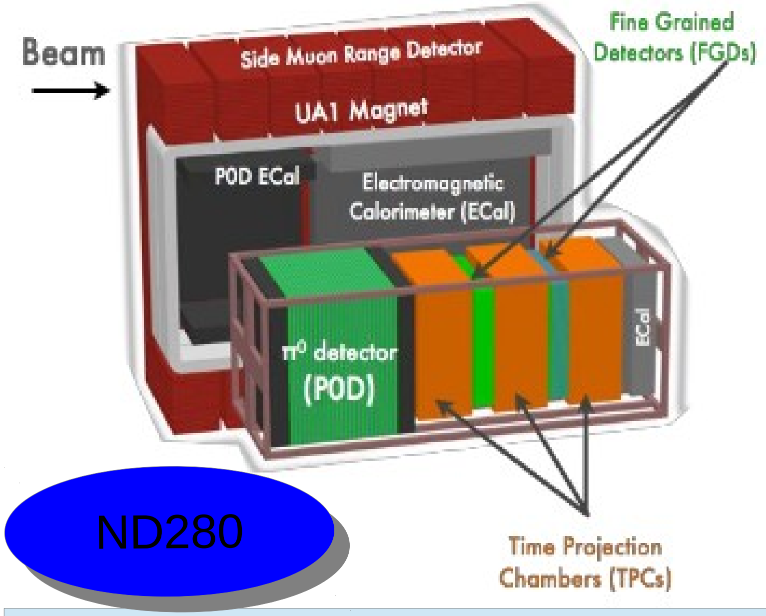


CCQE





T2K Near Detectors

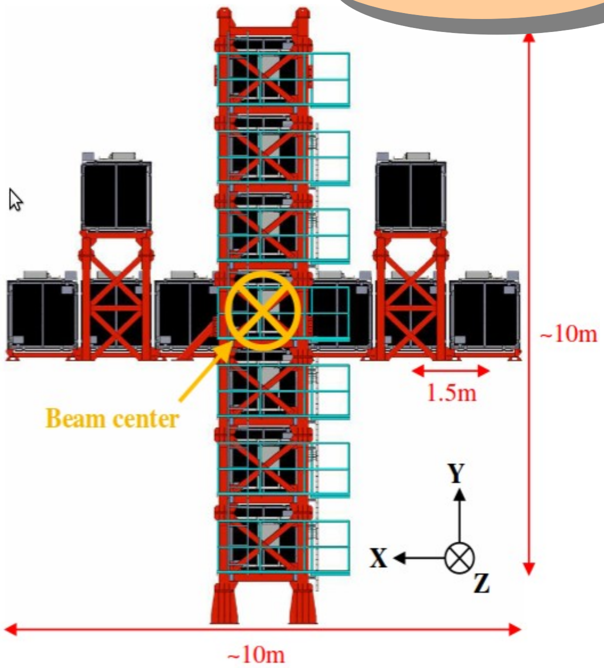


ND280

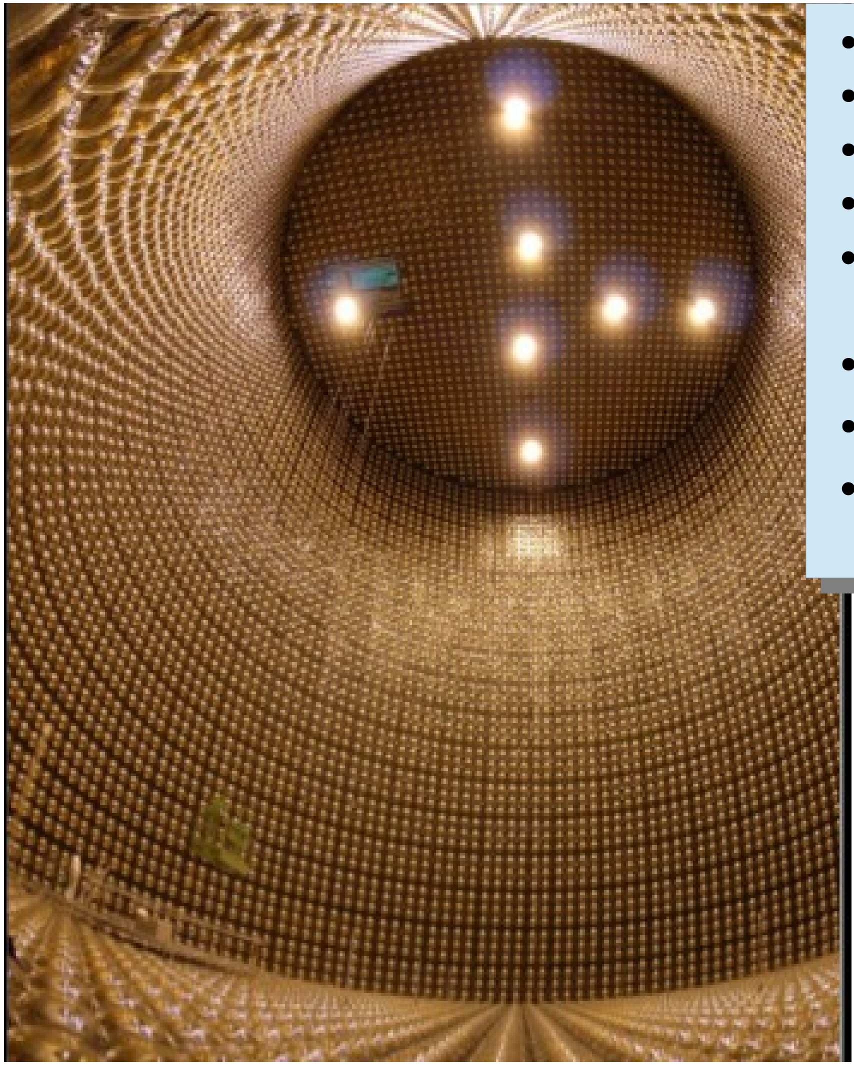
- Off-axis by 2.5° (same as far detector) near detector :
- Several sub-detectors in 0.2T magnetic field:
  - Tracker (TPCs & FGDs), Pizero Detector (P0D), Electromagnetic Calorimeter (ECAL), Side Muon Range Detector (SMRD)
- Measure flux and cross section before the oscillation occurs
- Measure intrinsic ν_e contamination in the beam
- Used to constrain flux and cross-section systematics for oscillation analysis.

- On-axis detector:
  (iron/scintillator tracking calorimeters, 16 modules + additional scintillator-only, proton module)
- Monitor beam rate, direction and stability
- Count ν's by reconstructing μ's from ν_μ interactions
- Used to constrain flux systematic errors

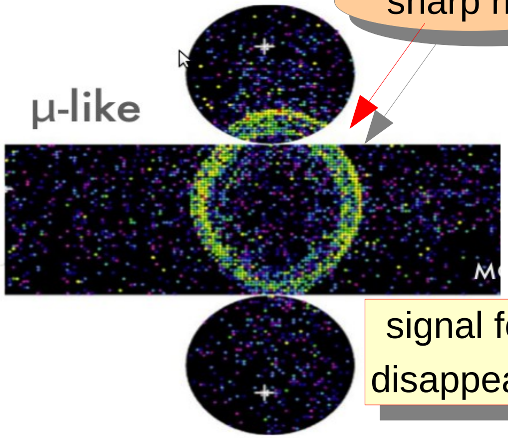
INGRID



T2K Far Detector - Super-K

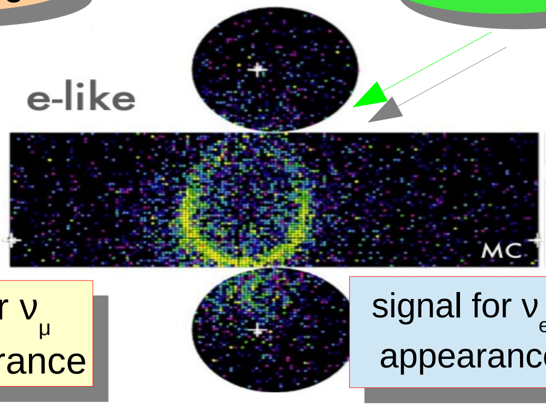


- 50 kton water Cherenkov Detector 1 km underground
- Above 11000 PMTs in the inner detector
- Efficient for CCQE like interactions
- Select single ring - only leptons above threshold
- Neutrino flavour identification based on ring topology from charged particle
- Excellent muon-electron separation
- (<1% ν_μ misidentified as ν_e)
- No magnetic field (no separation between ν and $\bar{\nu}$)



sharp ring

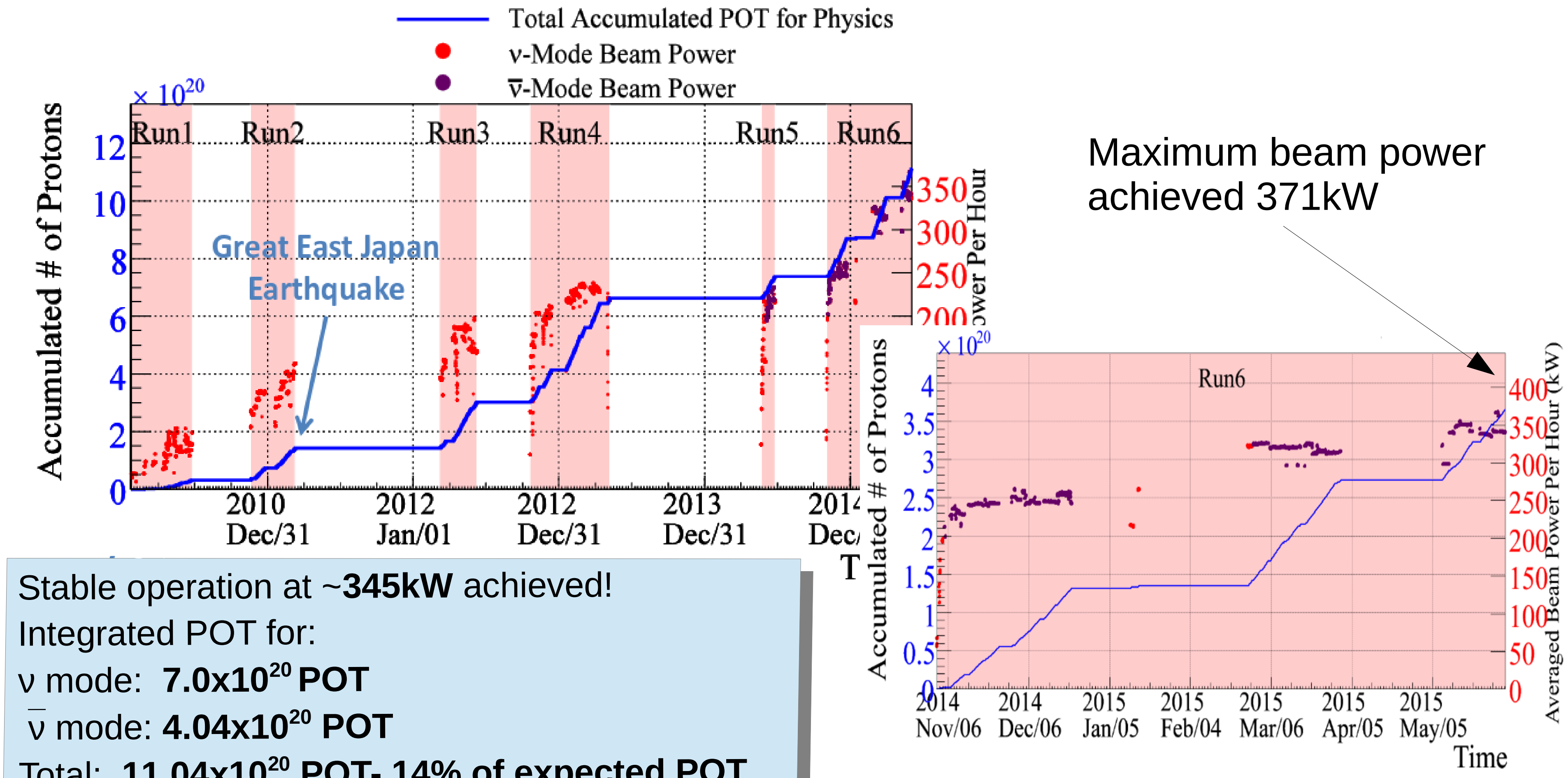
signal for ν_μ disappearance



fuzzy ring

signal for ν_e appearance

Beam operation and data taking



Maximum beam power achieved 371kW

Stable operation at ~**345kW** achieved!

Integrated POT for:

ν mode: **7.0x10^{20} POT**

ν̅ mode: **4.04x10^{20} POT**

Total: **11.04x10^{20} POT- 14% of expected POT**

where POT-> Proton On Target

accumulated Runs 1-6 (Jan 2010 ~ June 2015)

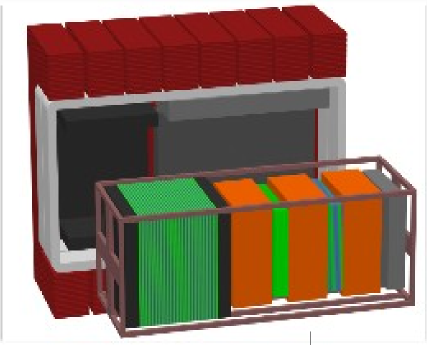
Analysis strategy

The neutrino flux is predicted by:

MC simulations of the beamline base on hadron productions measurements in NA61 exp.
+
beam monitor measurements

Neutrino interactions are simulated:

Tuned NEUT(interaction model)
+
Constrained using external data



Fit to ND280 data

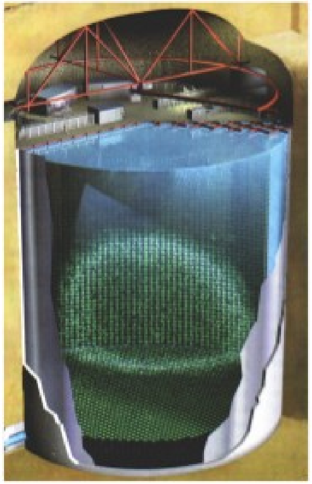
ν_μ / $\bar{\nu}_\mu$ CC samples
(CC0π, CC1π, CCother / CC1-Track, CC>1 Track)
+
Intrinsic ν_e and
$NC\pi^0$ measurements

Constraints on ν flux and ν interactions

SK predictions

Oscillation parameter fit

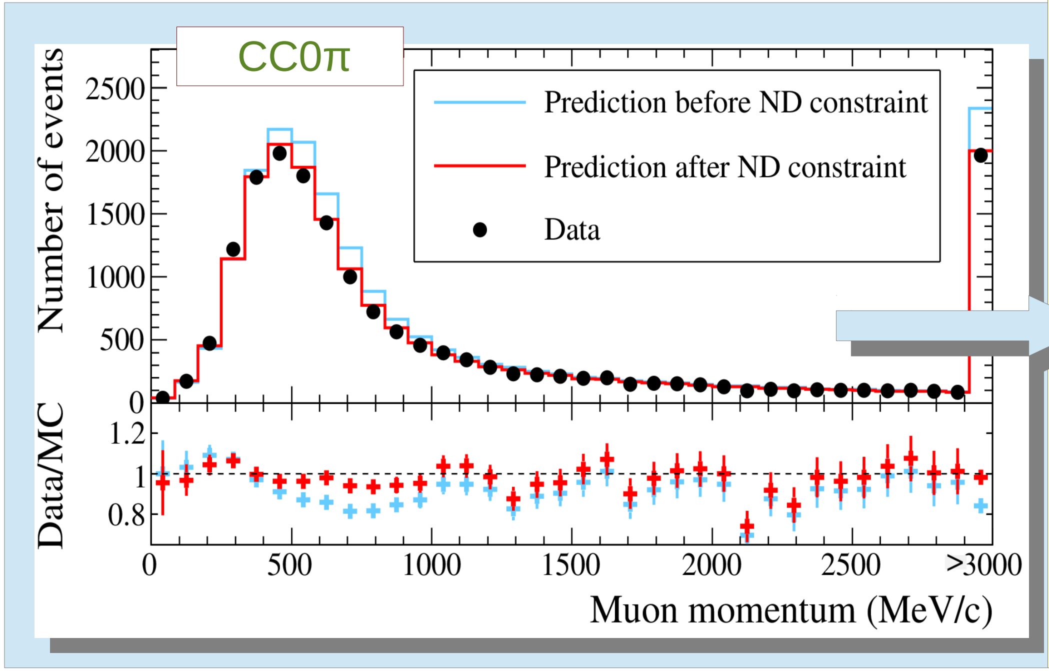
Oscillation parameters

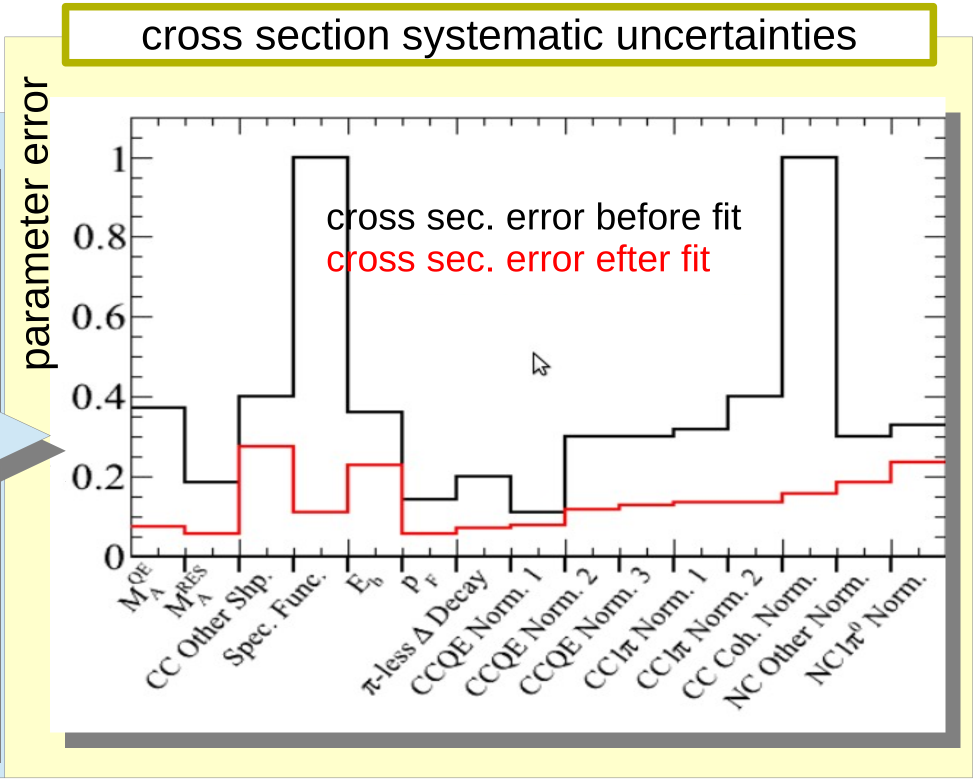


SK data:
ν_e or ν_μ interaction candidates

Near detector analysis

- Select charged-current (CC) events in ND280
- Use exclusive subsamples to isolate cross section components: CCQE (**CC0π**) , CC Resonance (**CC1π**), CC DIS (**CCother**)
- Fit for *p* and *θ* in CC ν_μ subsamples.
- Parameters used for prediction of Super-K neutrino spectrum w/o oscillation

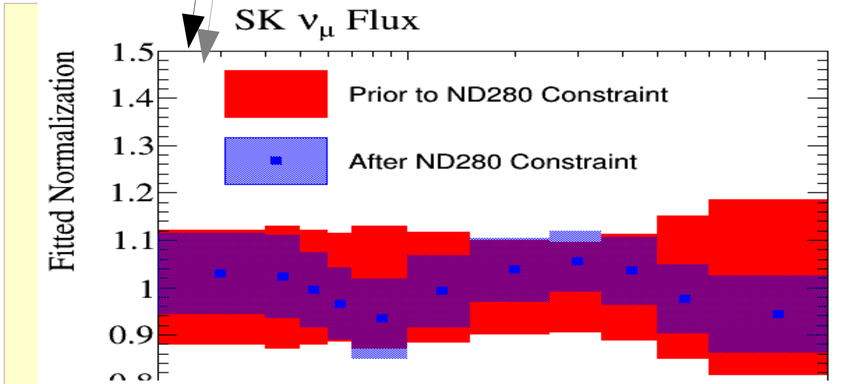


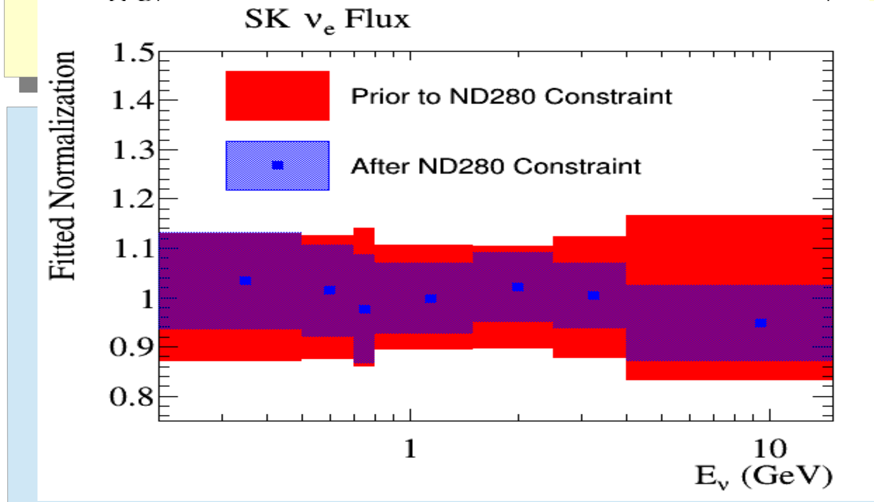

cross section systematic uncertainties

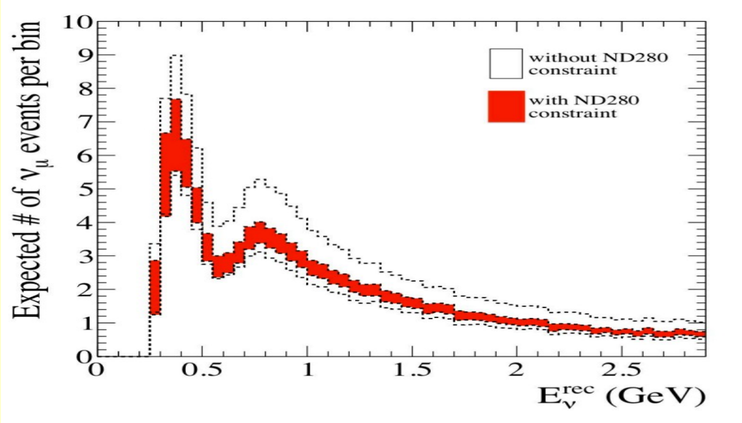
Near detector constraints (ν mode)

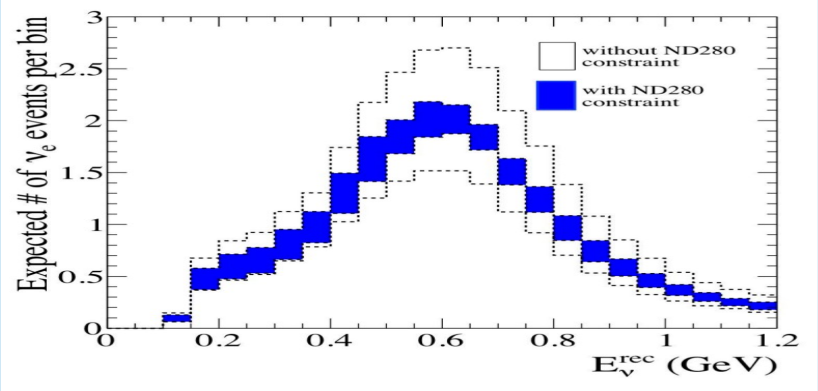
Reduction of the cross section and flux parameters uncertainties

Significant reduction of the far detector event rate errors









Long-baseline oscillation analyses in T2K

- appearance of ν_e - (**in 2013 first measurement of ν_e appearance (7.3σ)**)- measurement of **$\sin^2\theta_{13}$**

PRL 112 (2014) 061802

- disappearance of $\boldsymbol{\nu}_\mu$ - in 2014 **most precise** measurement of **$\sin^2\theta_{23}$**

PRL 112 (2014)18 181801

- joint analysis of $\boldsymbol{\nu}_\mu$ and $\boldsymbol{\nu}_e$ **– constraints on θ_{23} octant, δ_{CP}, MH**

PRD 91 (2015) 7, 072010

- disappearance of $\overline{\boldsymbol{\nu}}_\mu$ and $\overline{\boldsymbol{\nu}}_e$ appearance analyses - measurement of $\sin^2\overline{\boldsymbol{\theta}}_{23}$ and CP in neutrino sector

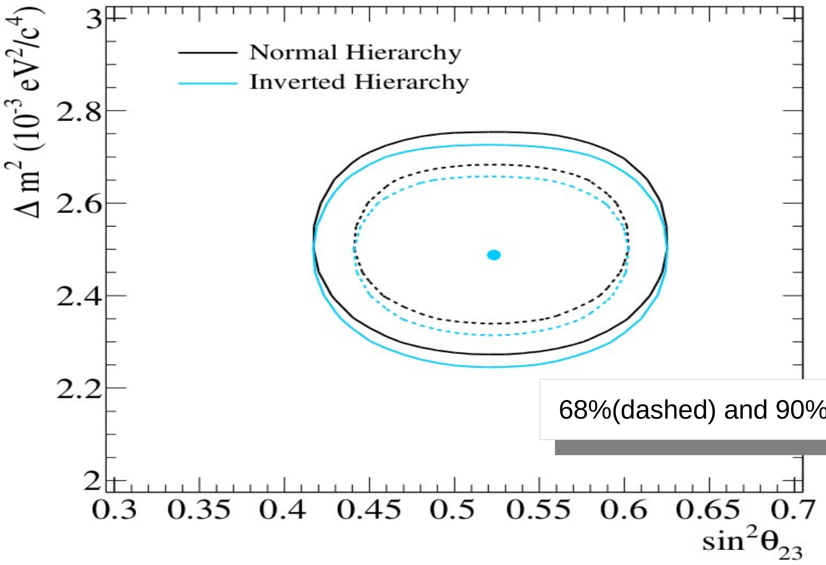
$\nu_e+\nu_\mu$ joint analysis (T2K only)

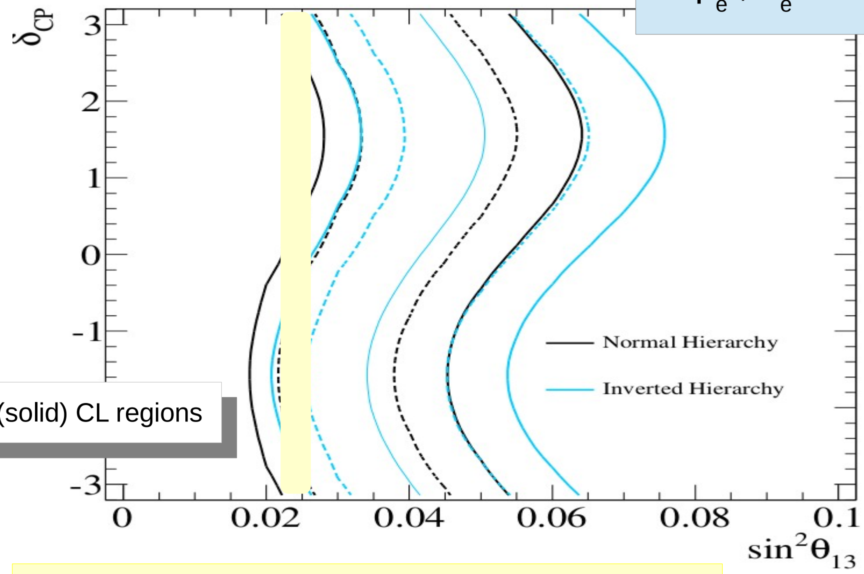
Extended maximum likelihood fit (for both T2K ν_μ and ν_e spectra simultaneously) **$L= L_{\nu_\mu} \times L_{\nu_e} \times L_{sys}$,**

where **$L_\nu = L_{norm} \times L_{shape}$**

number of events

shape of distributions:
- E_{rec} for ν_μ
- p_e , θ_e for ν_e





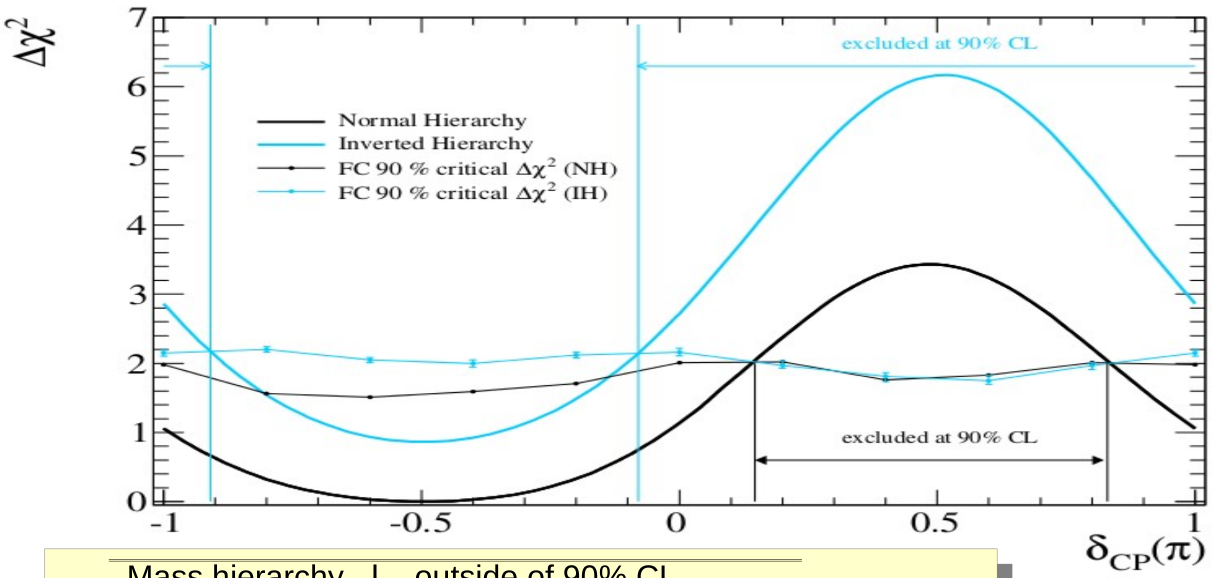
68%(dashed) and 90%(solid) CL regions

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

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

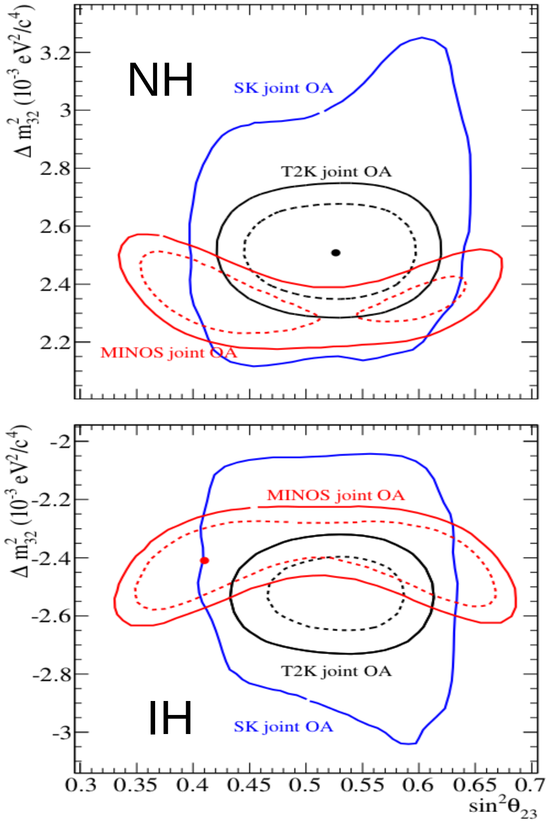
$\sin^2\theta_{23}=0.524\ ^{+0.057}_{-0.059}$ (NH), $\sin^2\theta_{23}=0.523\ ^{+0.055}_{-0.065}$ (IH)

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



Mass hierarchy	outside of 90% CL
Normal	(0.14; 0.87)π
Inverted	(-0.08; 1.09)π

hints towards CP violation



68%(dashed) and 90%(solid) CL regions

Phys. Rev. D91, 072010, (2015)

posterior probabilities (Bayesian)

	Normal hierarchy	Inverted hierarchy	Row 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
Column sum	0.684	0.311	1.000

First anti-neutrino results

Runs (5-6) - 4.04 x 10^{20} POT analysed

Changes in analysis in 2015

Flux:

new NA61 data used in the beam MC simulation
(uncertainty reduced by 4% in the energy peak)

Cross section:

- T2K neutrino MC model, NEUT includes improved CCQE and CCRES models as well as multi-nucleon interactions
- Nominal NEUT parameters are tuned to external data (MiniBooNE, Minerva and DUET)

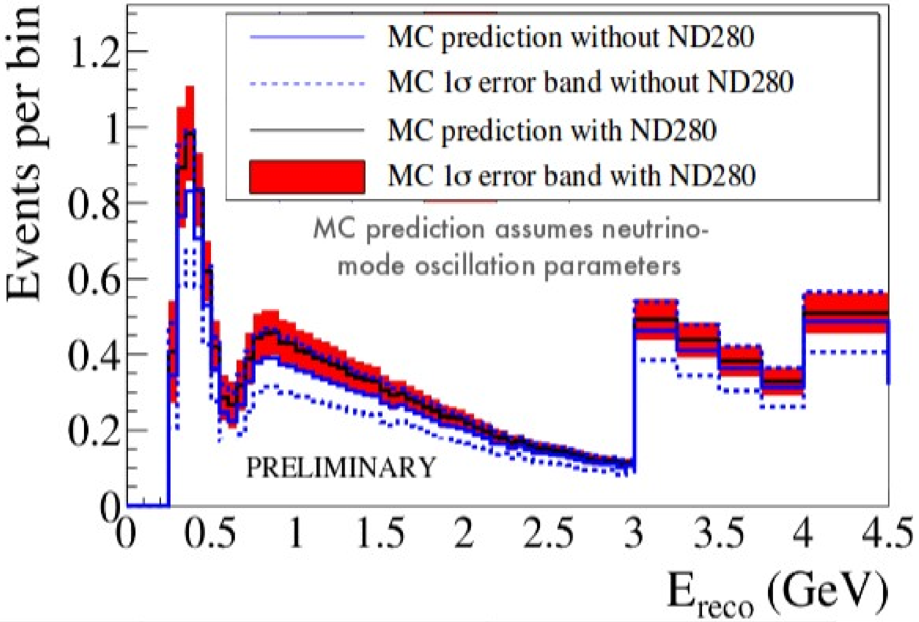
T2K near detector constraints:

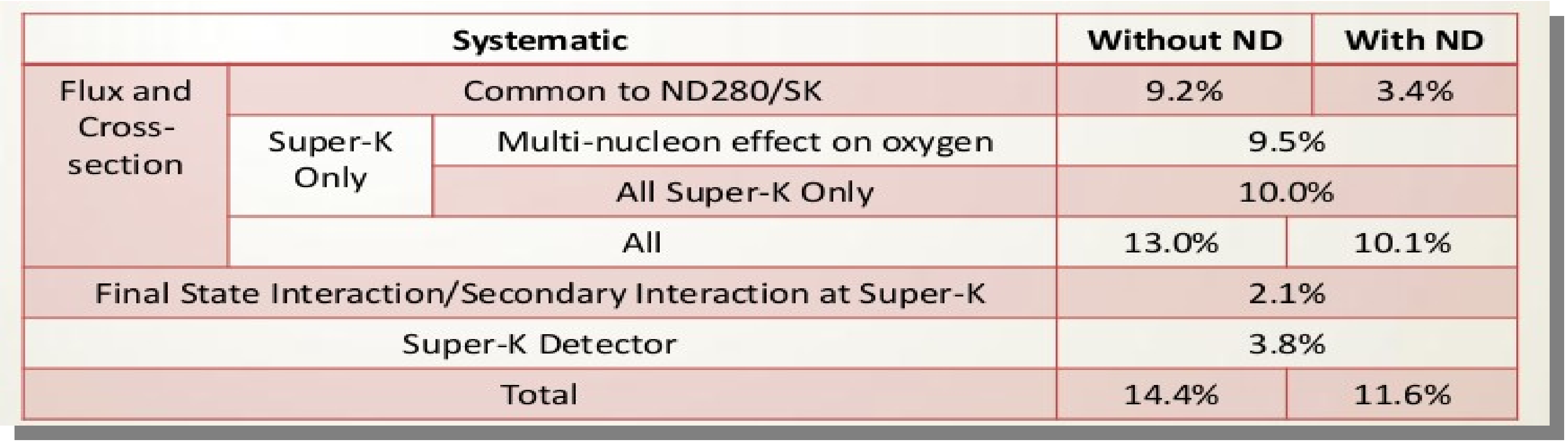
Taking all the available information, in both neutrino and anti-neutrino modes, the constraints on flux and cross section measurement uncertainties decreases to about 3%.

Total systematic uncertainties

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

- Constraining the flux and cross-section parameters at the near detector significantly reduces the uncertainty due to systematic error at the far detector (14.4% → 11.6%)
- Flux and cross section uncertainties are dominated by uncertainties on the difference between interactions on C and O

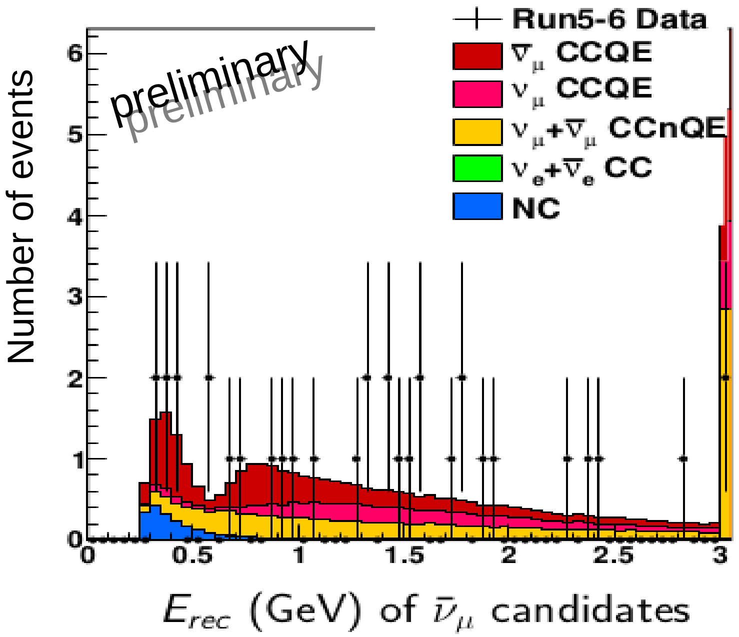




Systematic			Without ND	With ND
Flux and Cross-section	Common to ND280/SK		9.2%	3.4%
	Super-K Only	Multi-nucleon effect on oxygen	9.5%	
		All Super-K Only	10.0%	
	All		13.0%	10.1%
Final State Interaction/Secondary Interaction at Super-K			2.1%	
Super-K Detector			3.8%	
Total			14.4%	11.6%

Disappearance of $\bar{\nu}_{\mu}$ – SK detector measurement and selection

Selection:
- Inside the FV
- Fully contained
- Only one reconstructed ring, muon-like ($p_{\mu} > 200$ MeV/c, no of decay electrons ≤ 1)



Selected 34 $\bar{\nu}_{\mu}$ cadidates

Predict the expected SK spectra using neutrino-mode oscillation parameters

Expectation:

34.6 w/ oscillation

103.6 w/o oscillation

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

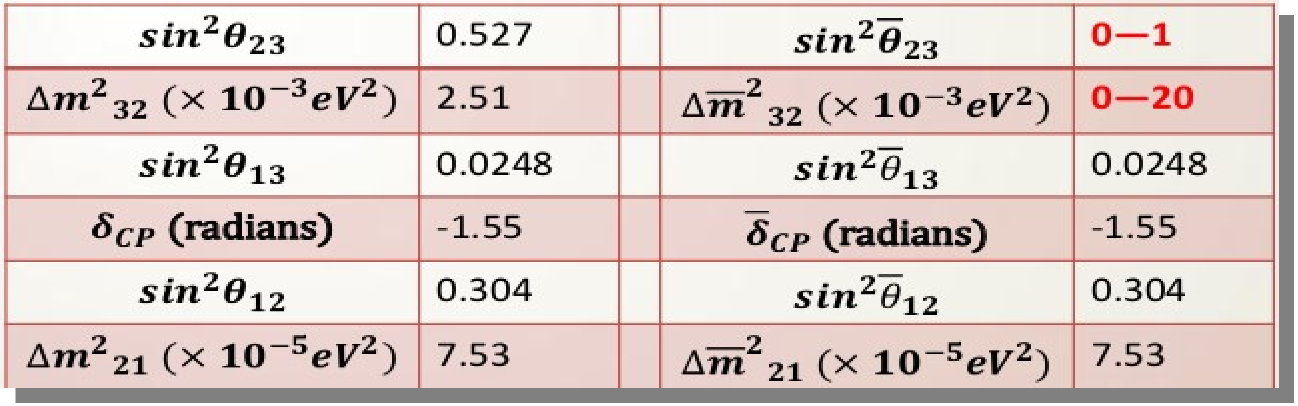
Oscillation param.

Systematic param.

Fit maximizes a likelihood: $\mathcal{L} = \mathcal{L}_{Poisson}(\vec{o}, \vec{f}) \times \mathcal{L}_{Syst.}(\vec{f})$

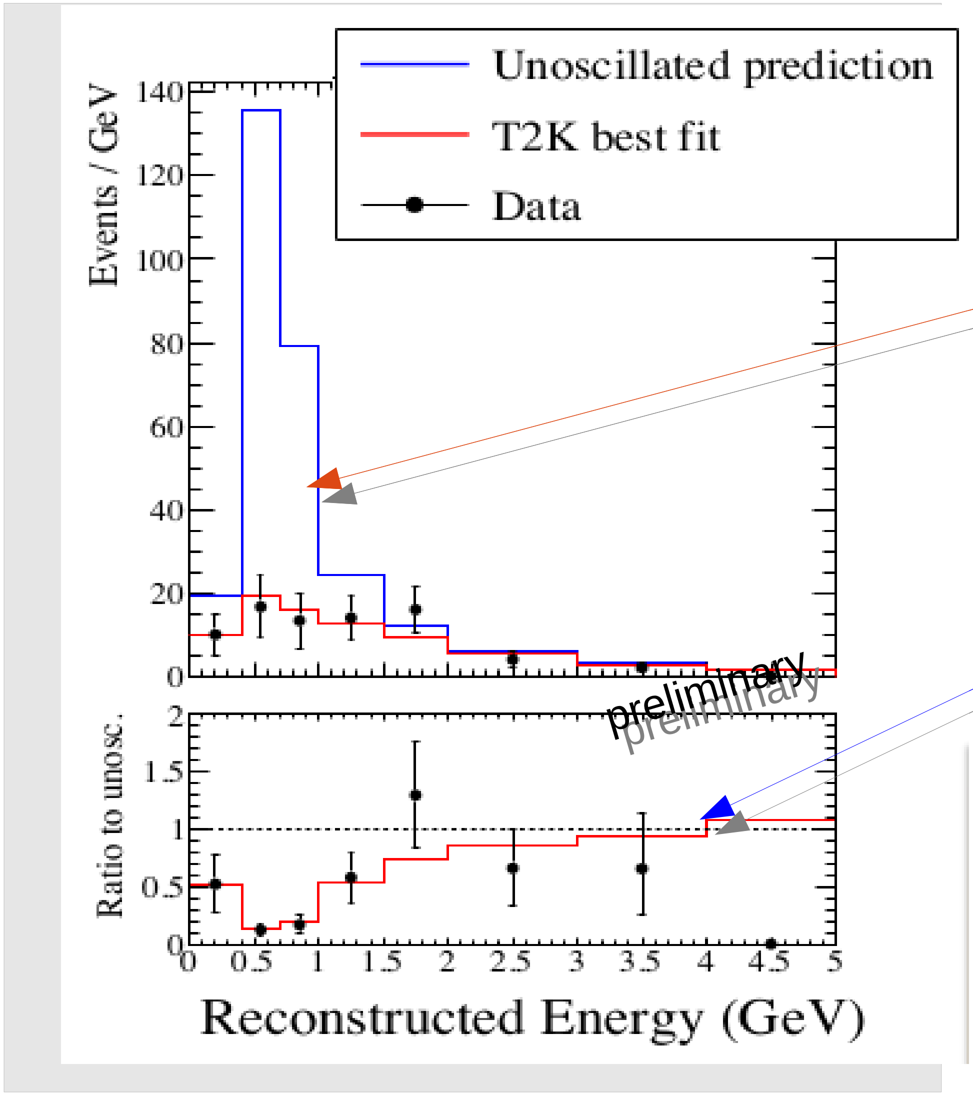
which is the product of a Poisson term comparing the predicted spectrum to the data and a term incorporating the systematics.

Fix all oscillation parameters except $sin^2\bar{\theta}_{23}$ and $\Delta\bar{m}^2{}_{32}$ using T2K data and PDG 2014



$sin^2\theta_{23}$	0.527		$sin^2\bar{\theta}_{23}$	0—1
$\Delta m^2{}_{32}$ ($\times 10^{-3} eV^2$)	2.51		$\Delta\bar{m}^2{}_{32}$ ($\times 10^{-3} eV^2$)	0—20
$sin^2\theta_{13}$	0.0248		$sin^2\bar{\theta}_{13}$	0.0248
δ_{CP} (radians)	-1.55		$\bar{\delta}_{CP}$ (radians)	-1.55
$sin^2\theta_{12}$	0.304		$sin^2\bar{\theta}_{12}$	0.304
$\Delta m^2{}_{21}$ ($\times 10^{-5} eV^2$)	7.53		$\Delta\bar{m}^2{}_{21}$ ($\times 10^{-5} eV^2$)	7.53

Best fit spectrum ($\bar{\nu}_\mu$)



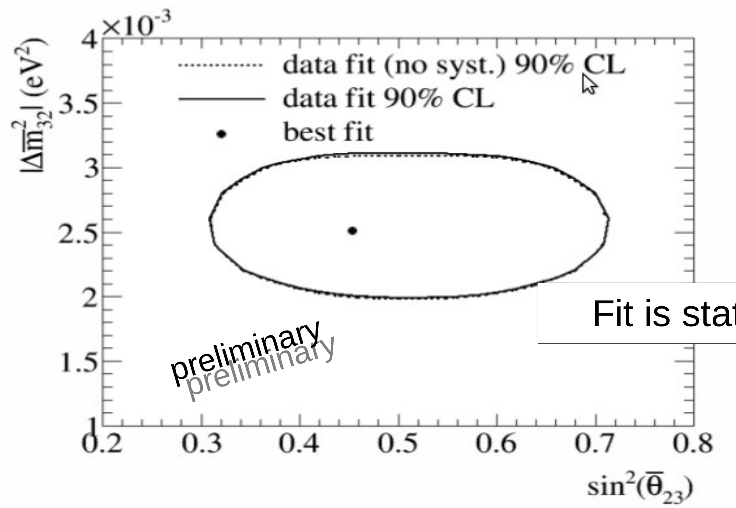
Data show clear evidence of oscillation

Clear, visible oscillation “dip” in the data

Location of dip in energy: $\Delta\overline{m}^2_{32}$

Depth of dip: $\sin^2\overline{\theta}_{23}$

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



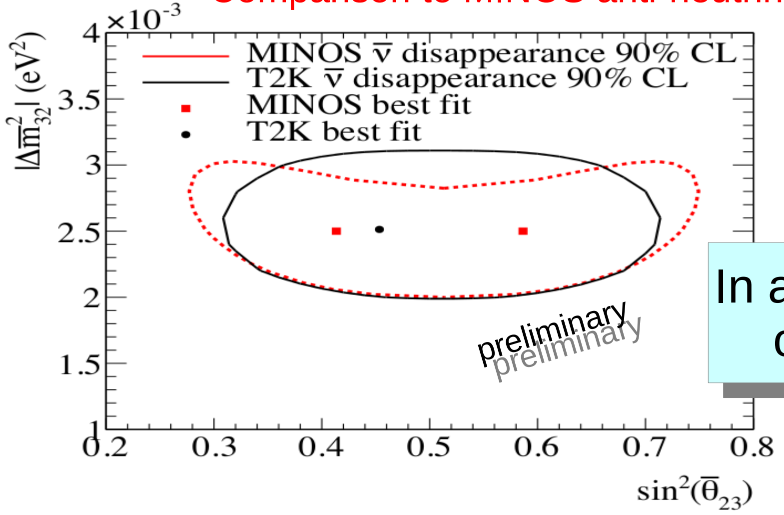
Fit is statistically limited

Best fit values

$$\sin^2\bar{\theta}_{23} = 0.46^{+0.14}_{-0.06}$$

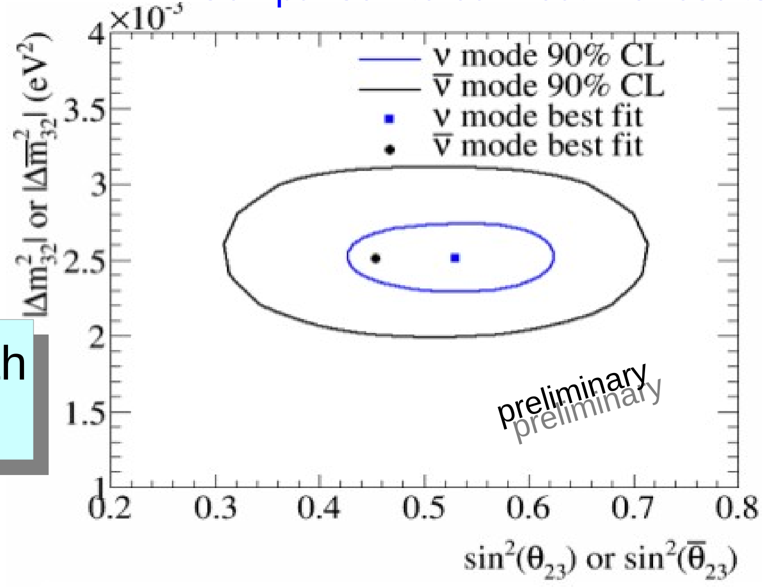
$$\Delta\bar{m}^2_{32} = 2.50^{+0.3}_{-0.2} \times 10^{-3}\,eV^2$$

Comparison to MINOS anti-neutrino results



In agreement with other results

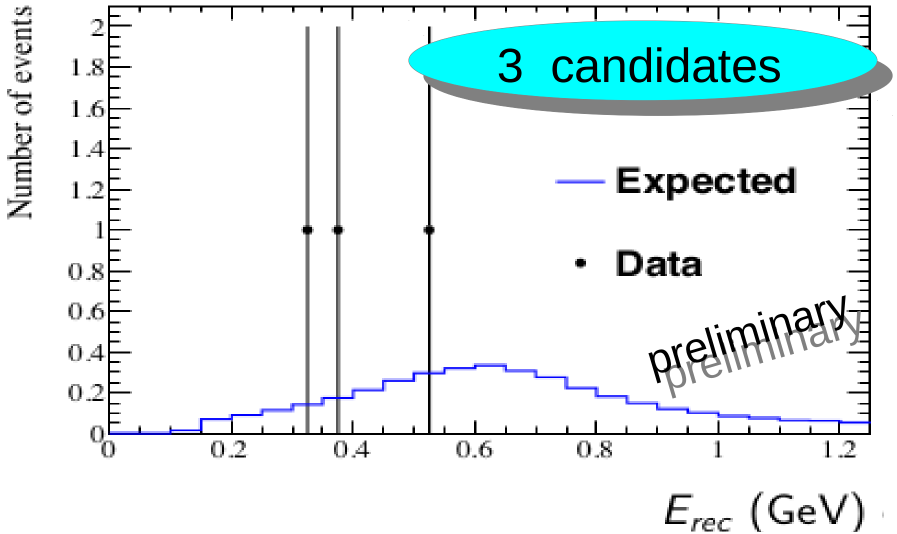
Comparison to our neutrino results

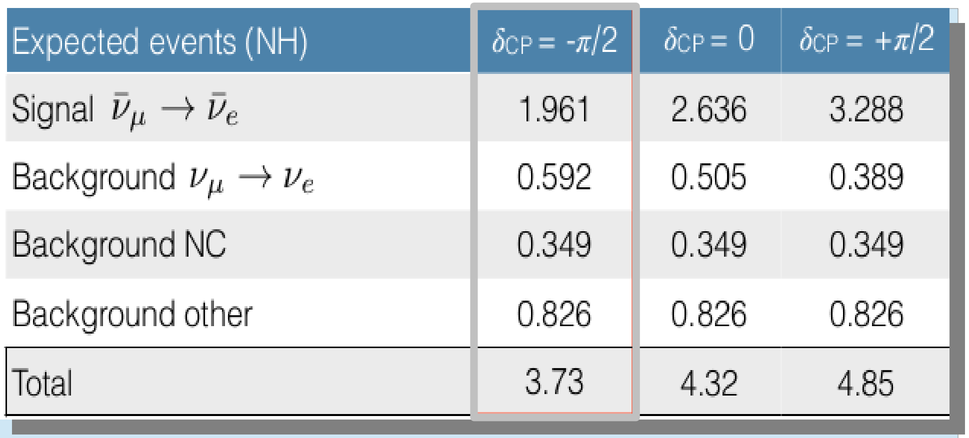


Search for $\bar{\nu}_e$ appearance

Selection:
Inside the fiducial volume

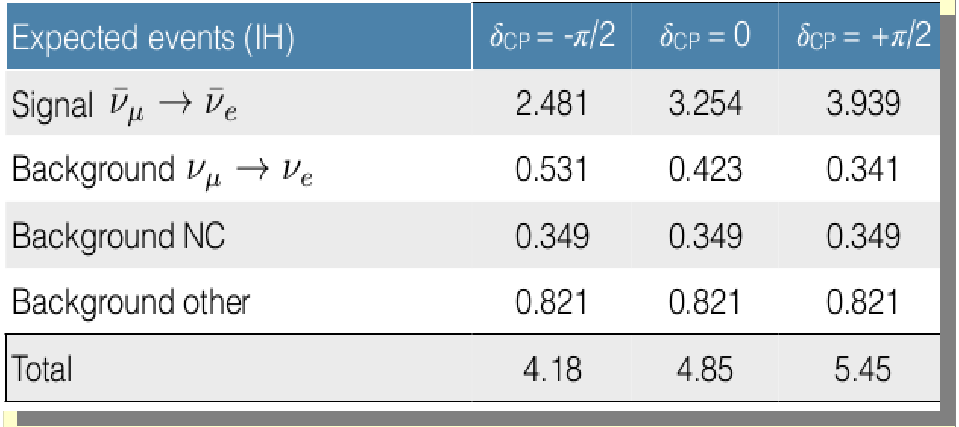
- Fully contained events in $\bar{\nu}$ mode
- Only one reconstructed ring electron-like
- $p_e > 100$ MeV/c
- No decay electron
- π^0 rejection
- $E_{rec} < 1250$ MeV





Expected events (NH)	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	1.961	2.636	3.288
Background $\nu_\mu \to \nu_e$	0.592	0.505	0.389
Background NC	0.349	0.349	0.349
Background other	0.826	0.826	0.826
Total	3.73	4.32	4.85

normal hierarchy



Expected events (IH)	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	2.481	3.254	3.939
Background $\nu_\mu \to \nu_e$	0.531	0.423	0.341
Background NC	0.349	0.349	0.349
Background other	0.821	0.821	0.821
Total	4.18	4.85	5.45

inverted hierarchy

The expected background and signal number of events depending on δ_{CP} value and MH.
Statistics collected is insufficient to confirm or exclude appearance.

Other analyses - cross section measurements

no	Cross section measurement	Detector	Target	Reported in
1.	ν_μ CC inclusive	Tracker of ND280	CH	PRD 87 092003 (2013)
2.	ν_e CC inclusive	Tracker of ND280	CH	PRL 113,241803(2014)
3.	ν_μ NC elastic	Super-K	Water	PRD 90 072012 (2014)
4.	ν_μ CC inclusive	INGRID	CH/Fe	PRD 90 052010 (2014)
5.	ν_μ CCQE	INGRID	CH	PRD 91 112002 (2015)
6.	ν_μ CCQE	Tracker of ND280	CH	Accepted by PRD
7.	ν_μ NC π^0	P0D of ND280	CH/ Water	Publication in progress
8.	ν_μ CC coherent	INGRID	CH	Publication in progress
9.	ν_μ CC coherent	Tracker of ND280	CH	Publication in progress
10.	ν_μ CCπ^+	Tracker of ND280	Water	Publication in progress
11.	ν_μ CC0π^+	Tracker of ND280	CH	Publication in progress

Summary

The $\nu_\mu + \nu_e$ joint analysis with reactor constraint :

- prefer the value of δ_{CP} around $-\pi/2$
- a weakly-favored normal hierarchy and octant $\sin^2\theta_{23} > 0.5$

T2K presents first results with anti-neutrino data (4.04 x 10^{20} POT):

anti-ν_e appearance:

- 3 candidate events observed
- data does not favor or disfavor the $\bar{\nu}_e$ appearance hypothesis

anti-ν_μ disappearance

- data - 34 events used for world leading determination of $\bar{\theta}_{23}$
- results consistent with T2K ν_μ disappearance and MINOS $\bar{\nu}_\mu$ disappearance
- both analyses are still statistics limited

Next step: joint neutrino+anti-neutrino beam analysis

Additional physics on T2K: cross section measurement

Backup slides

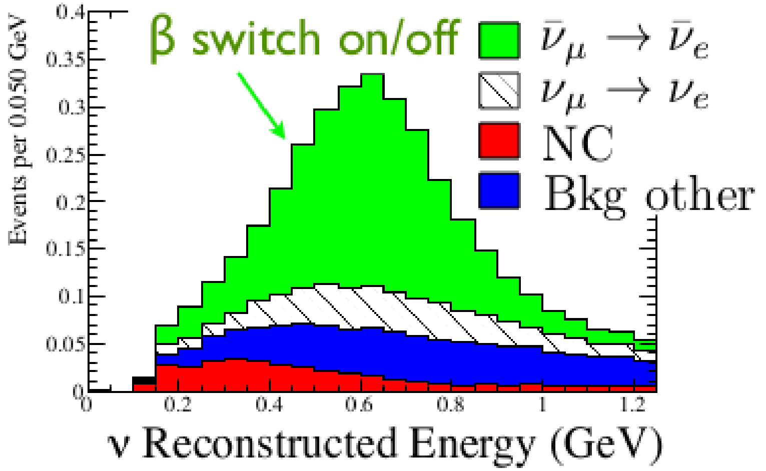
$\bar{\nu}_e$ appearance analysis

Test the null appearance hypothesis:

Introduce a discrete parameter β to modify the $\bar{\nu}_e$ appearance probability:

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

Assume oscillation parameter the same for neutrinos and anti neutrinos (assume CPT symmetry).



β = 1: $\bar{\nu}_e$ appearance in accordance with the PMNS prediction (including CP violation)

β = 0: no $\bar{\nu}_e$ appearance (new physics!)

Report of significance for β = 1 in two ways:
- a p-value to characterise how anomalous data is with respect to the β = 0 hypothesis

- a Bayes factor (B_{10}) to characterise how data favours β = 1 over β=0

Rate and shape likelihood definition

-A likelihood that depends on the number of measured and expected events at the far detector is created.
-The likelihood includes the information from the systematic and oscillation parameters (and β).
-The number of events is split in reconstructed energy bins or momentum-angle bins.

Oscillations parameters

Systematic parameters

$$\mathcal{L}(\beta,\vec{o},\vec{f}) = \prod_{i}^{N\ bins} \mathcal{L}(N_i^{obs}, N_i^{exp}(\beta,\vec{o},\vec{f})) \times \mathcal{L}_{syst}(\vec{f})$$

E_{rec} or p-θ binning

number of 1-Ring e-like events at SK
or test experiments for a β hypothesis

Erec: reconstructed energy for e-like ring
p-θ: reconstructed momentum and angle of the e-like ring

The analysis is based on the marginal likelihood, with all parameters other than β integrated out.

p-value characterise data “excess” with respect to null appearance hypothesis (β=0)

p- value calculated for :(test statistic)

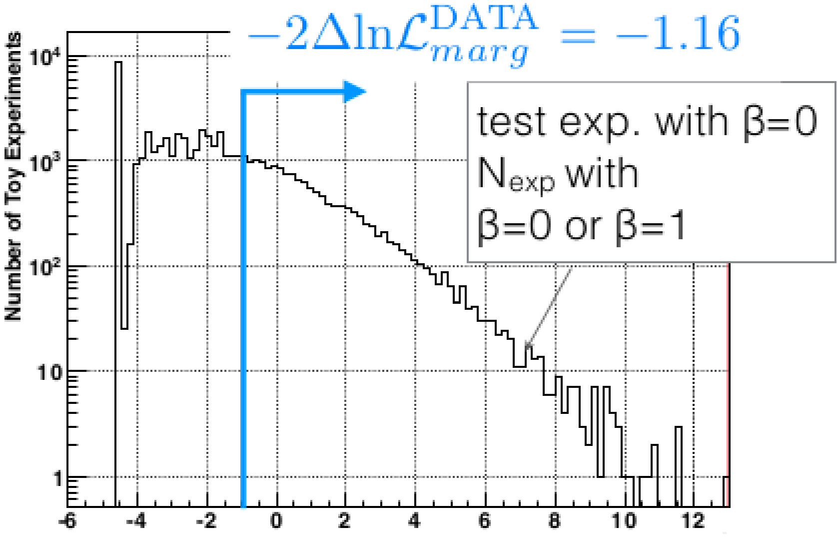
$$-2(ln\mathcal{L}(\beta=0) - ln\mathcal{L}(\beta=1))$$

The Bayes factor (B_{10}) to characterise how the data favours the β =1 hypothesis compared to the β=0 hypthesis.

Bayes factor: calculated as likelihood ratio

$$B_{10} = \frac{\mathcal{L}(Data|\beta=1)}{\mathcal{L}(Data|\beta=0)}$$

Rate and shape analysis



$$-2\Delta\ln\mathcal{L} = -2[\ln\mathcal{L}_{marg}(\beta=0) - \ln\mathcal{L}_{marg}(\beta=1)]$$

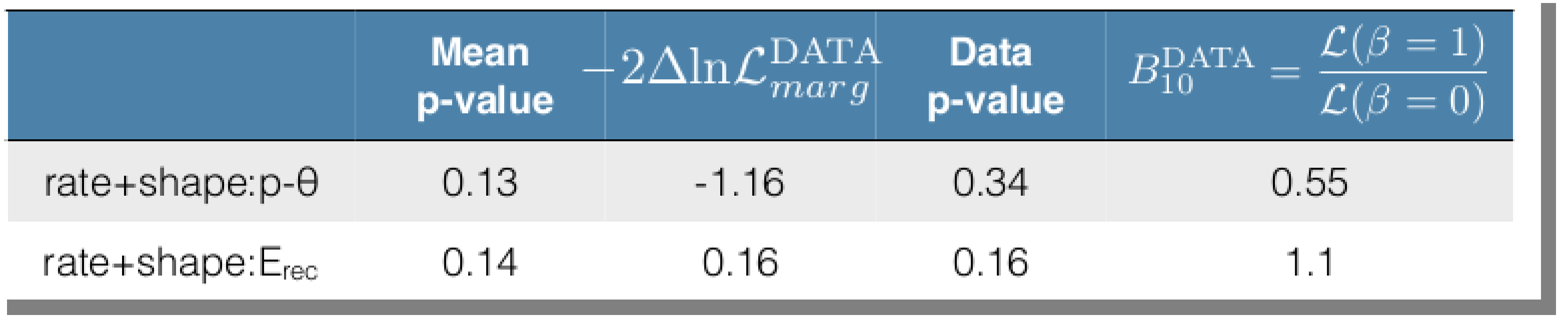
Marginal likelihood L_{marg} (β)

Test data against the no appearance hypothesis

➡ p-value calculated for: $-2\Delta\ln L_{marg}$

➡ B_{10} = Bayes factor which is the likelihood ratio

if $3 < B_{10} < 10$, preference for β=1 is substantial



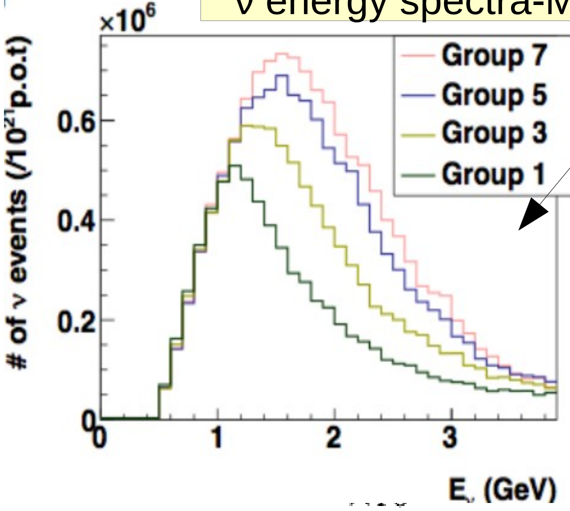
	Mean p-value	$-2\Delta\ln\mathcal{L}^{\mathrm{DATA}}_{marg}$	Data p-value	$B^{\mathrm{DATA}}_{10} = \frac{\mathcal{L}(\beta=1)}{\mathcal{L}(\beta=0)}$
rate+shape:p-θ	0.13	-1.16	0.34	0.55
rate+shape:E_{rec}	0.14	0.16	0.16	1.1

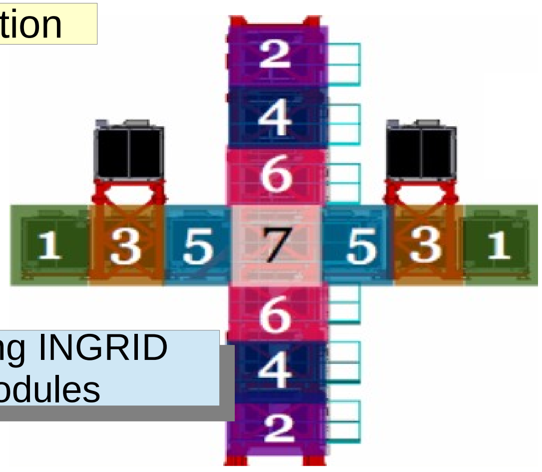
Current data does not strongly favor either of the two hypotheses (β =1 or β=0)

CC inclusive cross section on Fe

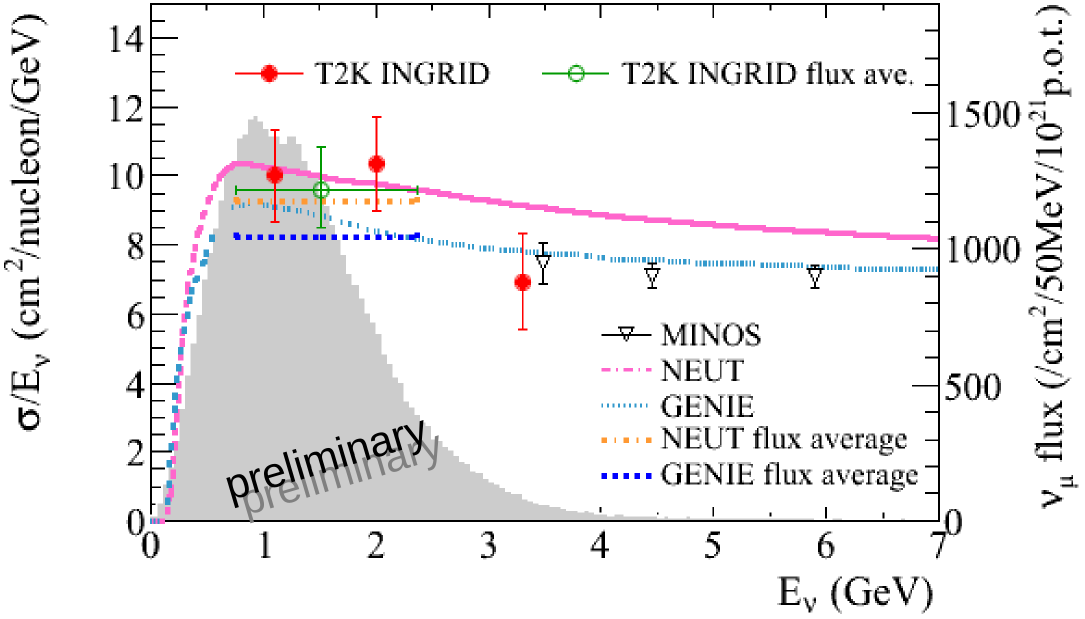
- Different energy spectra at different modules according to off-axis angles (0°-0.9°)
- Analyse events in grouped modules to minimize effects from the ν beam
- direction variation

ν energy spectra-MC prediction





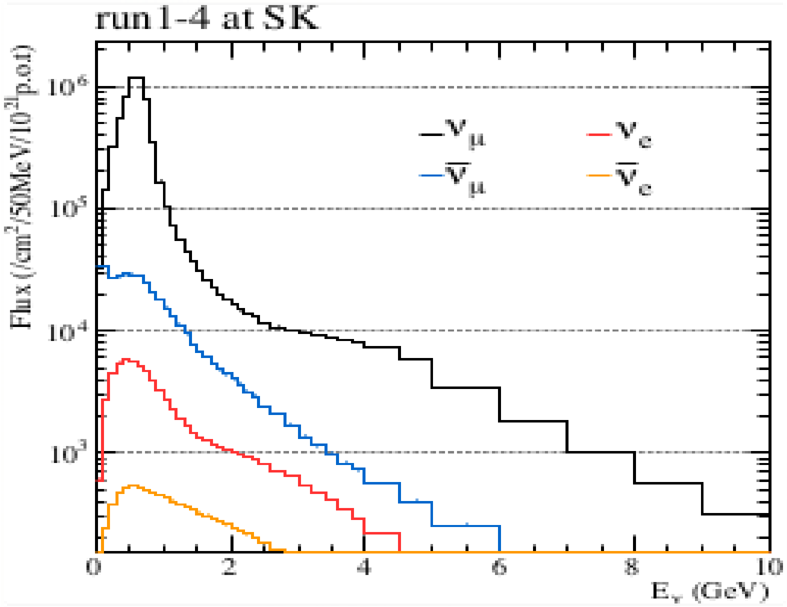
grouping INGRID modules



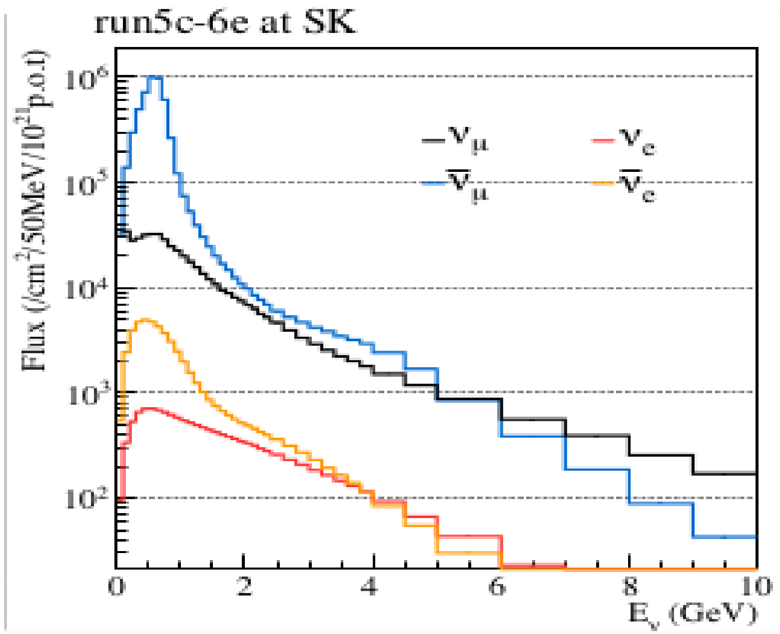
Results:
The difference of neutrino spectra at different modules and distribution of event topology enabled to extract the cross section at three different energies

Beam configurations

ν-beam mode flux at SK

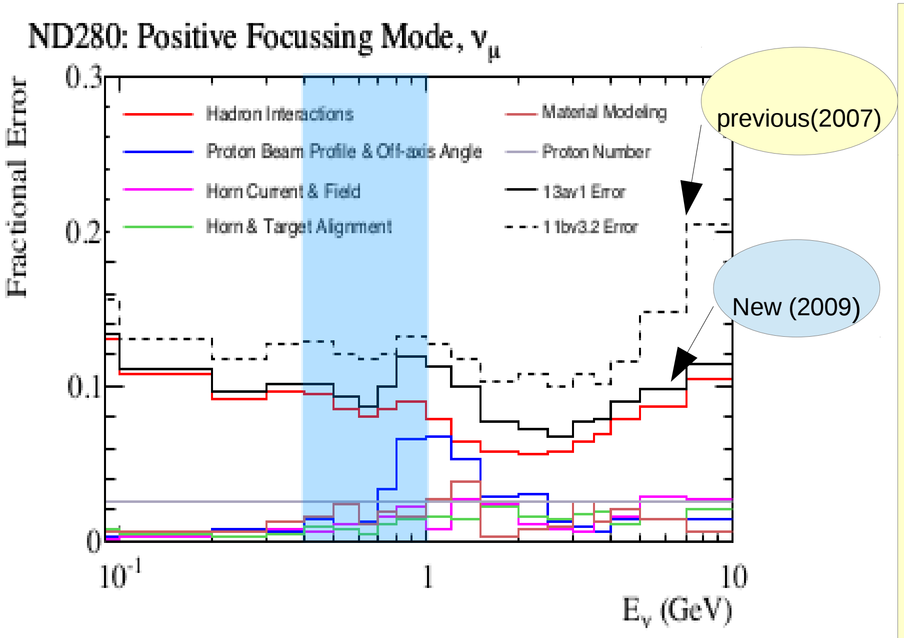


$\bar{\nu}$-beam mode flux at SK



Neutrino flux

Beam uncertainties



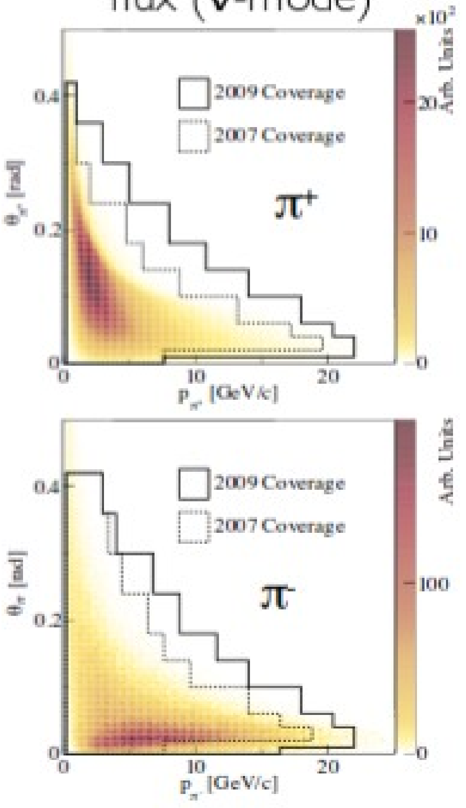
In T2K neutrino energy region the greatest contribution to the flux error come from:

- hadron interactions
- proton beam profile and off- axis angle

Hadron uncertainties

- NA61/SHINE recently released the production of $\pi\pm$, $K\pm$, K^0s and Λ from the 2009 thin graphite,target dataset.
- The new data has both improved the beam rediction and reduced the uncertainty by 4% in the pik energy.
- Implementation of NA61 replica target is ongoing and will contribute to a significant reduction of the T2K systematic uncertainties

p-θ phase space of hadrons contributing to T2K far detector flux (ν-mode)



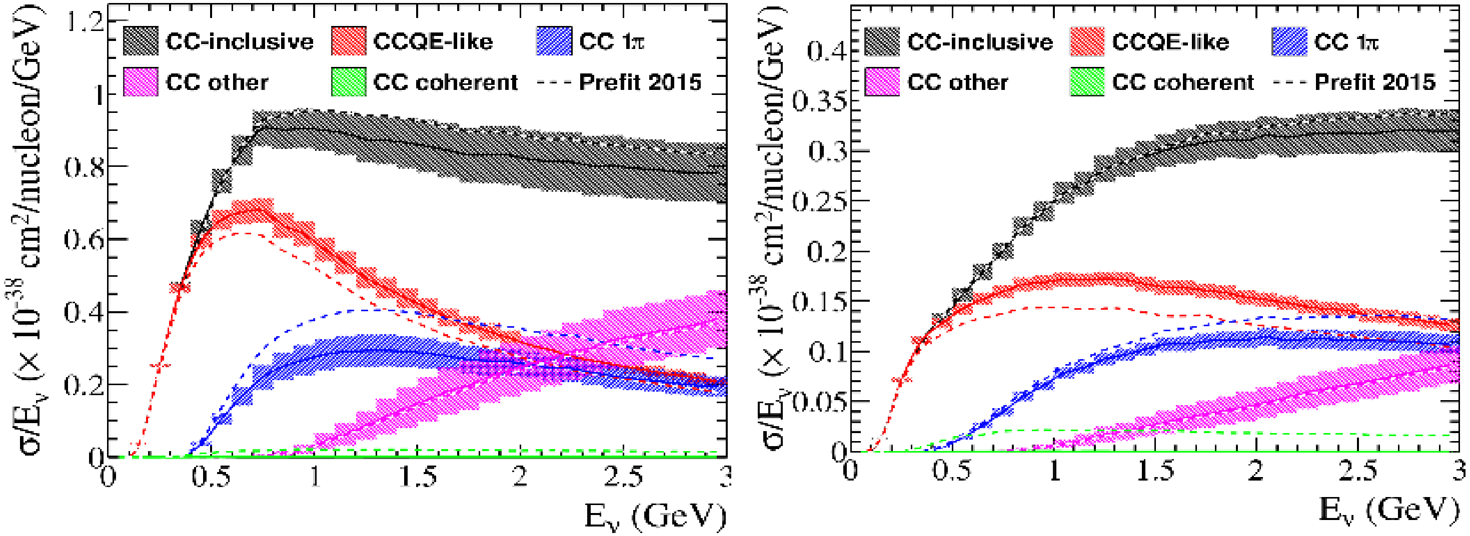
Cross section

Improvements:

NEUT model (5.3.2+) for 2015 (antineutrino, neutrino+antineutrino) analyses:

- Two new CCQE models implemented for consideration in the analysis: CCQE: Spectral function model (Benhar et al.) MAQE= 1.2 GeV and CCQE: Relativistic Fermi Gas (RFG)+Random Phase Approximation (RPA). New: “Meson exchange current” (MEC) CCQE like scattering from Nieves et. al

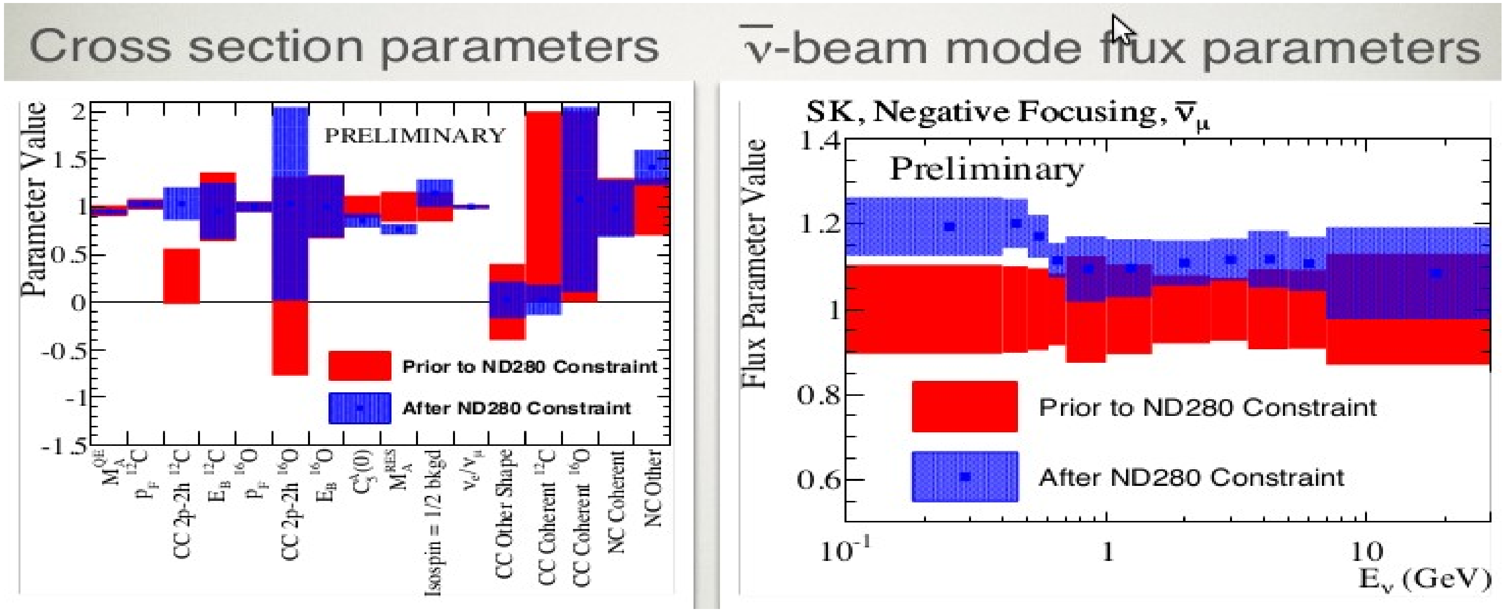
- 1π (NC and CC) production model: Rein-Sehgal with modified form factor for Delta. No pion-less delta decay.



Tuned NEUT
(dashed- prefit 2015)
RPA+RFG+MEC model based on, from fits to external cross section measurements by MINERvA, MiniBooNE, bubble chamber data **compared to**
NEUT with near detector data tuning (solid with associated errors)

Near detector constraints

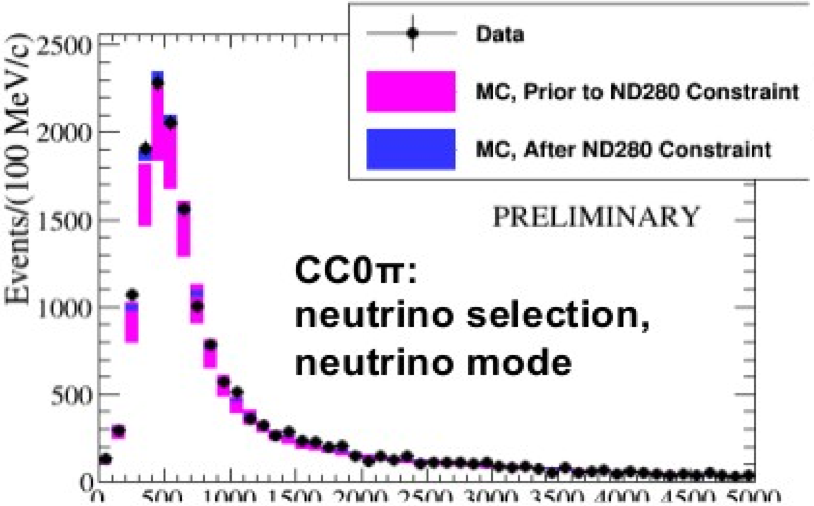
Constraints done for both neutrino and anti-neutrino mode



Flux and cross section parameters after fit to ND280 data

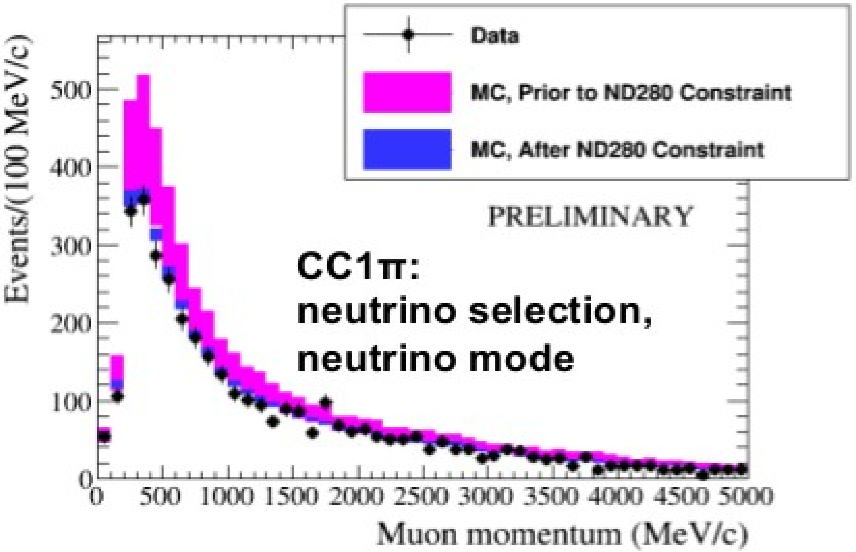
- Flux parameters are generally increased
- Some cross section parameters especially the carbon multi-nucleon parameter-are changed significantly from prior values

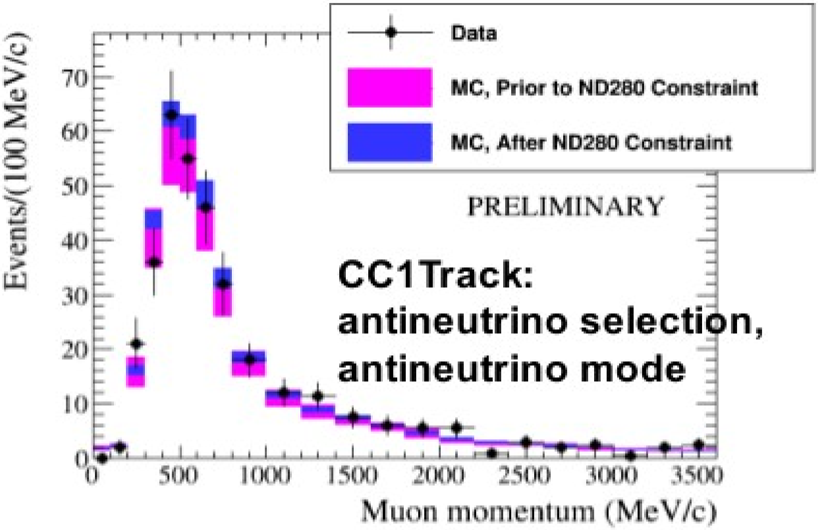
Near detector rate measurement



Expected number of events at the far detector is tuned using a likelihood fit to the near detector samples

- Neutrino, antineutrino fluxes are highly correlated between near and far detectors
- Cross sections are also correlated
- Significant reduction to overall uncertainties





Neutrino oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j} \Re(U_{\alpha i}^{*} U_{\beta j} U_{\alpha j} U_{\beta j}^{*}) \cdot \sin^2 \Phi_{ij}$$

$$\pm 2\sum_{i<j} \Im(U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*}) \cdot \sin^2 \Phi_{ij}$$

$$\Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu} = 1.27 \cdot \Delta m_{ij}^2 [eV^2] \cdot \frac{L[km]}{E_\nu [GeV]}$$

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

$$- \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2\sin\theta_{13}} \sin\left(\frac{\Delta m_{21}^2}{4E}\right) \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\delta_{CP} + \ldots$$

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4\cos^2\theta_{13} \sin^2\theta_{23} [1 - \cos^2\theta_{13} \sin^2\theta_{23}] \sin^2\left(\frac{1.27 \Delta m^2 L}{E}\right)$$