T2K neutrino oscillation results using 2017 data

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August 4th, 2017

Outline

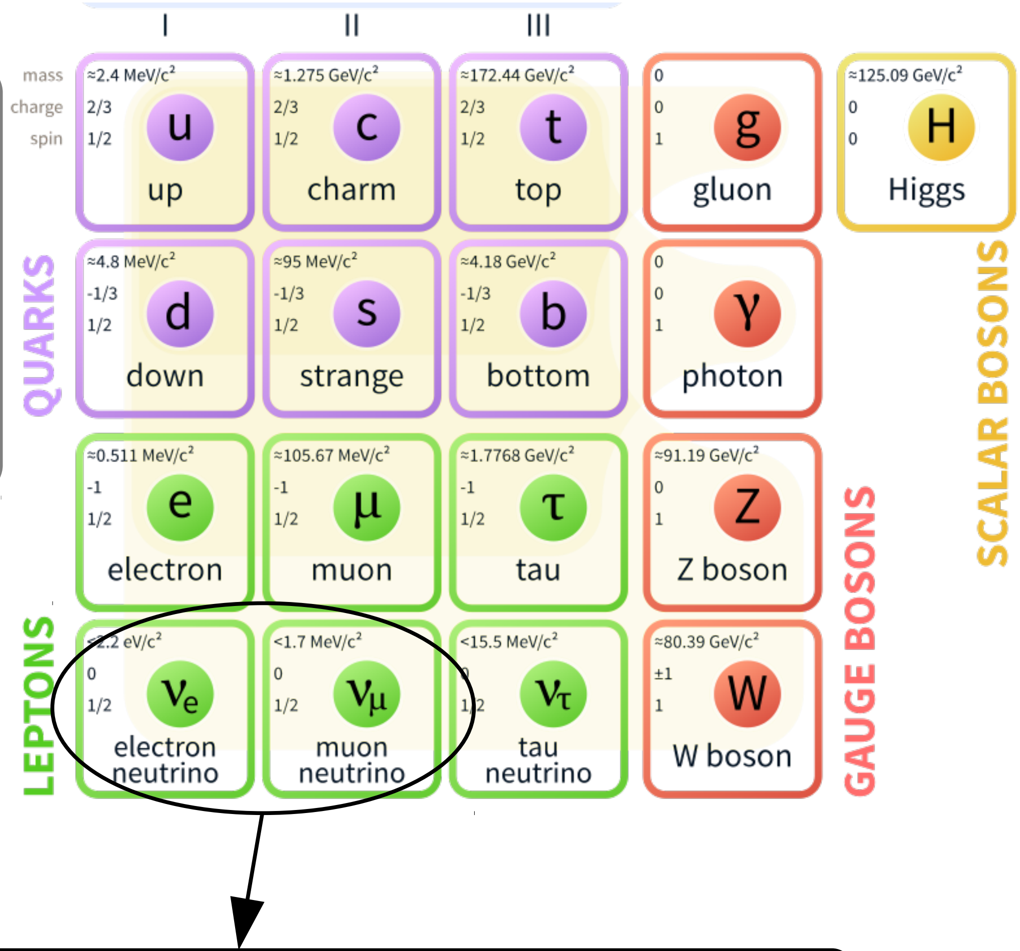
- Motivations for the study of neutrino oscillations
- The Tokai to Kamioka experiment
- Neutrino oscillation analysis
- Dataset
- Oscillation analysis results
- Perspective for the future

Open questions in the Standard Model

Highly successful theory, yet a number of unexplained facts and possible limitations

<u>Unexplained facts</u> :

- **Universe made mainly of matter and not of anti-matter**
- wide differences in the masses of particles
- 3 generations

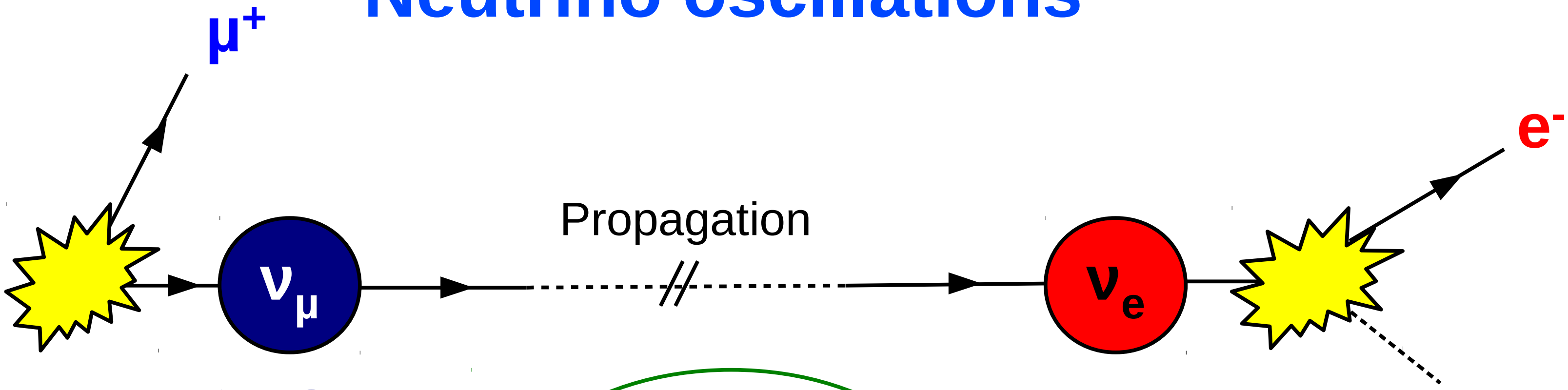


<u>Hints that the model might be incomplete</u>

- Dark matter ?
- Dark energy ?
- does not describe gravity

The study of neutrinos can shed some light on some of those questions

Neutrino oscillations



Flavor eigenstates
(interaction)

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

Mass eigenstates
(propagation)

Mixing (or Pontecorvo-Maki-Nagawa-Sakata) matrix
link between the two sets of eigenstates

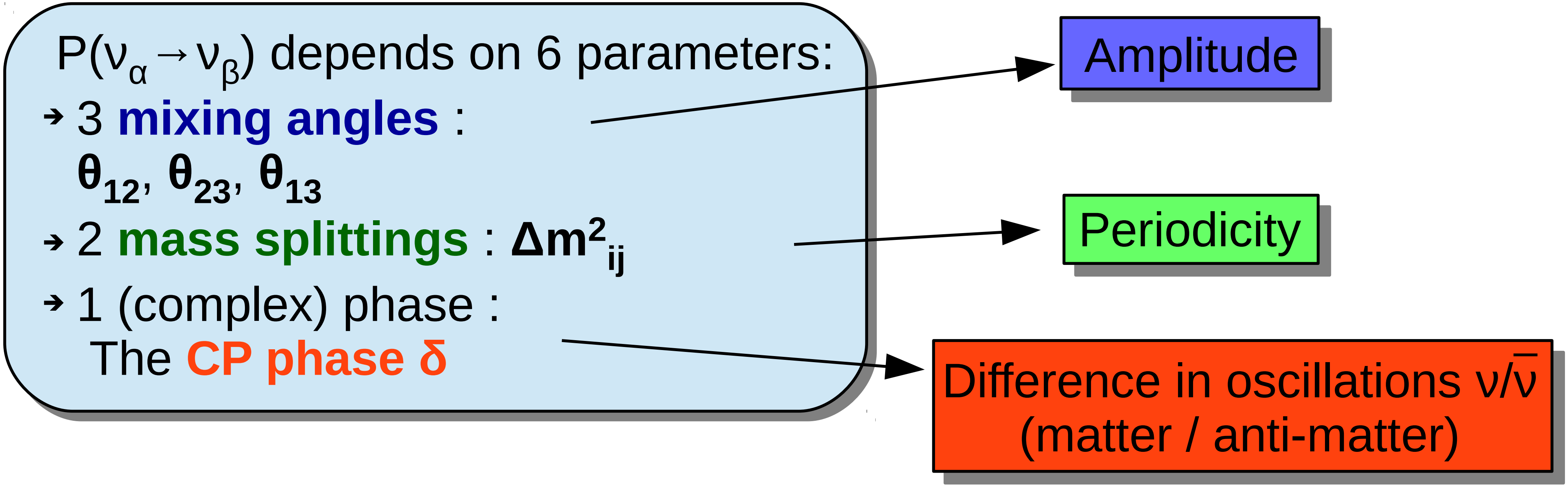
$P(\nu_\alpha \rightarrow \nu_\beta)$ oscillates as a function of distance L traveled by the neutrino with periodicity **$\Delta m^2_{ij}L/E$**

$(\Delta m^2_{ij}=m^2_i-m^2_j)$

Neutrino oscillations Parameters

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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



$P(\nu_\alpha \rightarrow \nu_\beta)$ depends on 6 parameters:

- 3 **mixing angles** : $\boldsymbol{\theta_{12}, \theta_{23}, \theta_{13}}$
- 2 **mass splittings** : $\boldsymbol{\Delta m^2_{ij}}$
- 1 (complex) phase : The **CP phase δ**

Amplitude

Periodicity

Difference in oscillations $\nu/\bar{\nu}$ (matter / anti-matter)

CP symmetry and difference matter/anti-matter
The CP phase δ

Universe mainly made of matter
Sakharov's conditions: **requires violation of CP symmetry**

3 possible sources in the Standard Model:

- Strong interaction
- Quark mixing matrix
- **Neutrino mixing matrix**

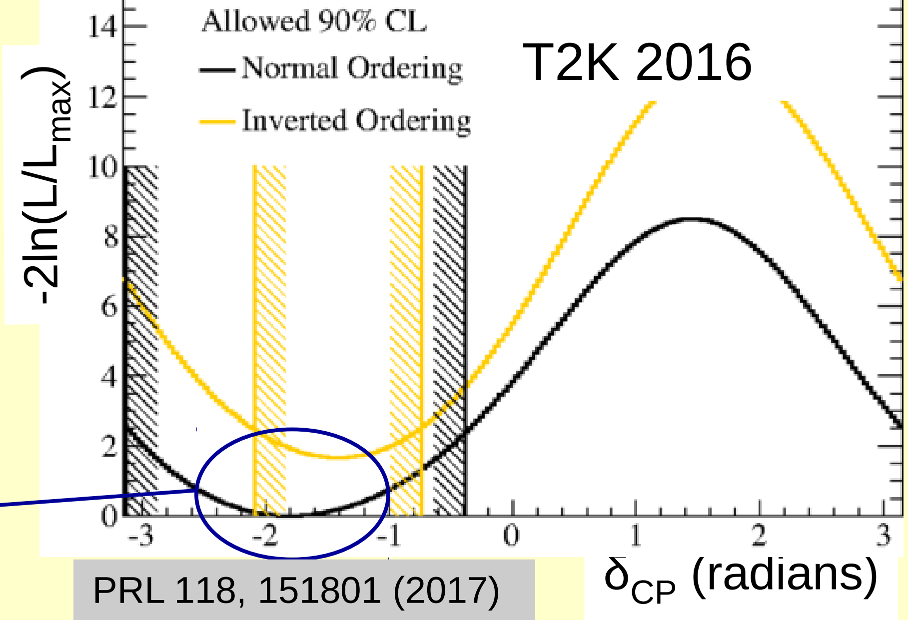
C : Charge conjugation
P : Parity (x → -x)
CP : $\nu_L \rightarrow \nu_R$

Neutrino oscillations

$$\cancel{CP} \Leftrightarrow \sin(\delta) \neq 0$$

$$\text{Amplitude} \propto |\sin(\delta)|$$

Previous results : δ ~ -π/2
(|sin(δ)|~1 : maximal)

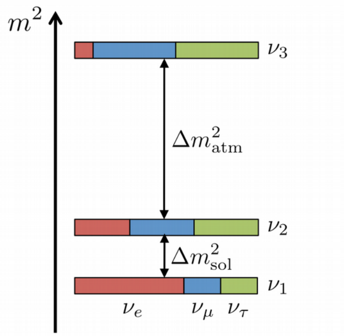


PRL 118, 151801 (2017)

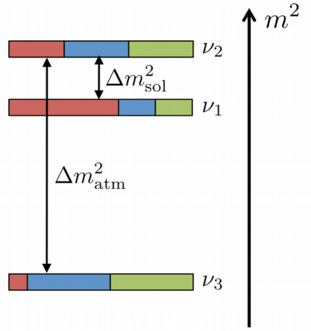
Neutrino oscillation experiments
Main current physics goals

Mass hierarchy:
$m_3 > m_2, m_1$?

normal hierarchy (NH)



inverted hierarchy (IH)



PDG 2016 summary table

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99) ((0.83 – 1.99))

Octant of θ_{23}:
$\theta_{23}>\pi/4$?
$\theta_{23}<\pi/4$?

Violation of CP symmetry in neutrino oscillations?

Degeneracies between those 3 questions

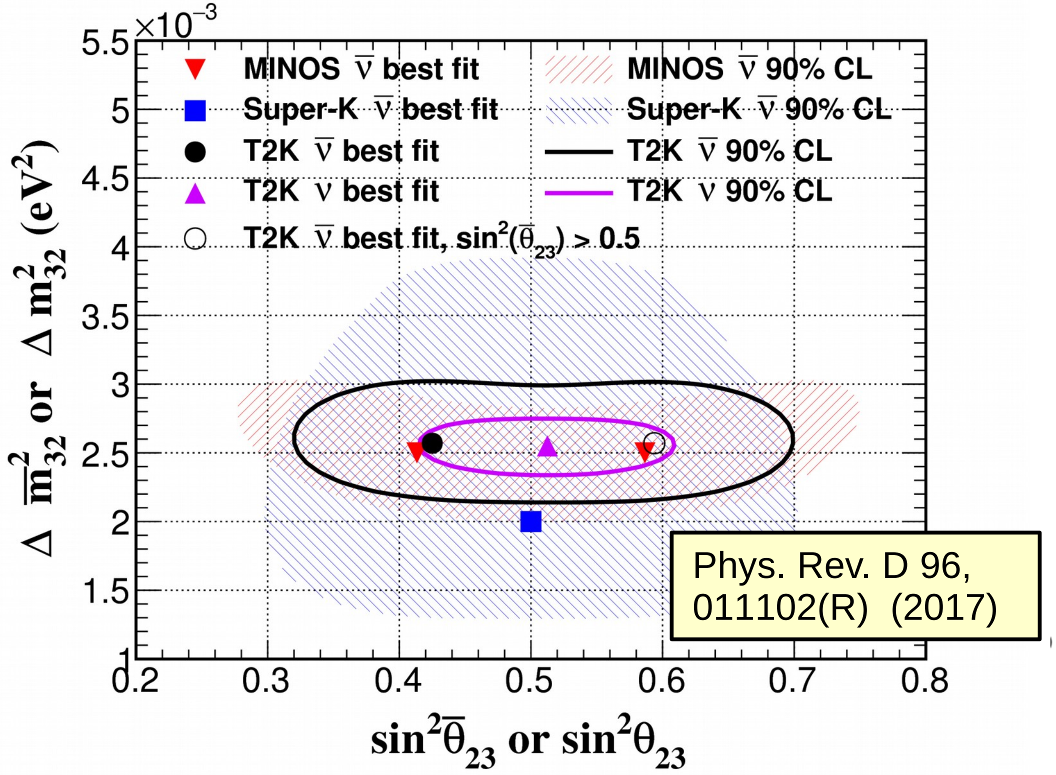
Neutrino oscillation experiments
Beyond the Standard Model

Tests of the 3 flavor oscillation model

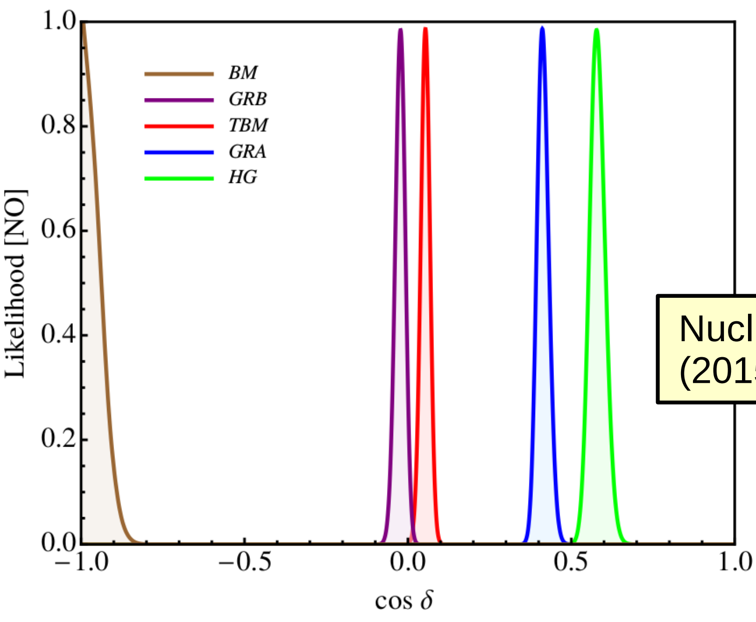
- Agreement of the measurements in the different channels ?
- Unitarity of the 3x3 PMNS matrix?

Tests of new models

- New symmetries ?
- Additional neutrino flavors ?
- New interactions between neutrinos and matter ?
- Violation of Lorentz symmetry?
- Violation of CPT symmetry ?



Phys. Rev. D 96, 011102(R) (2017)

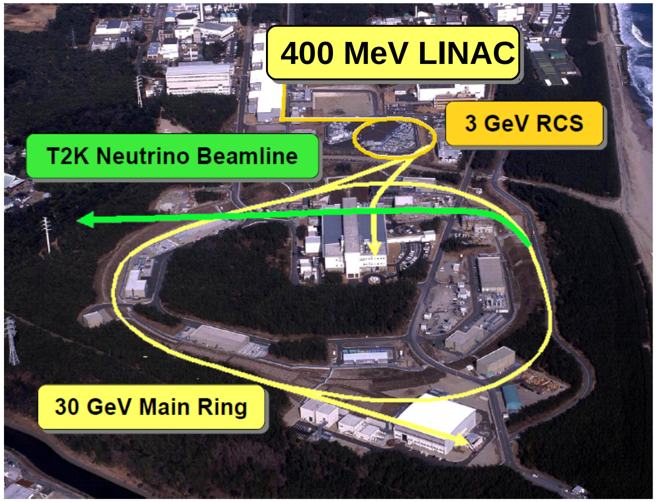


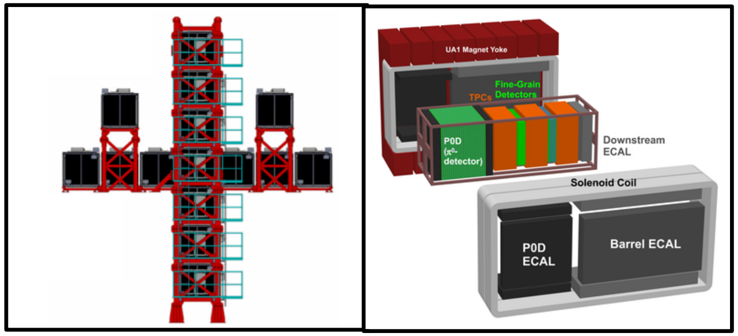
Nucl. Phys. B 894 (2015) 733-768

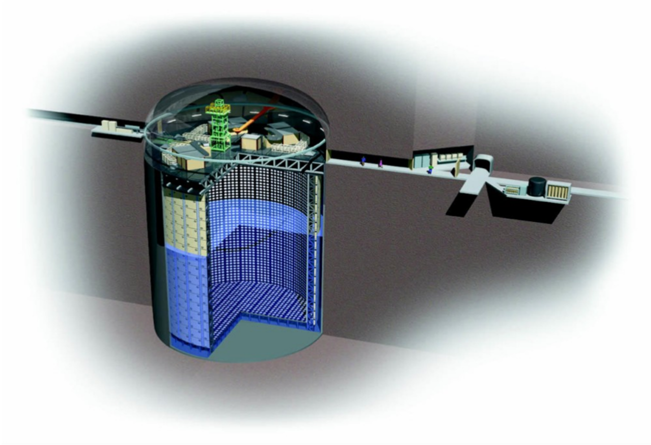
The Tokai to Kamioka experiment

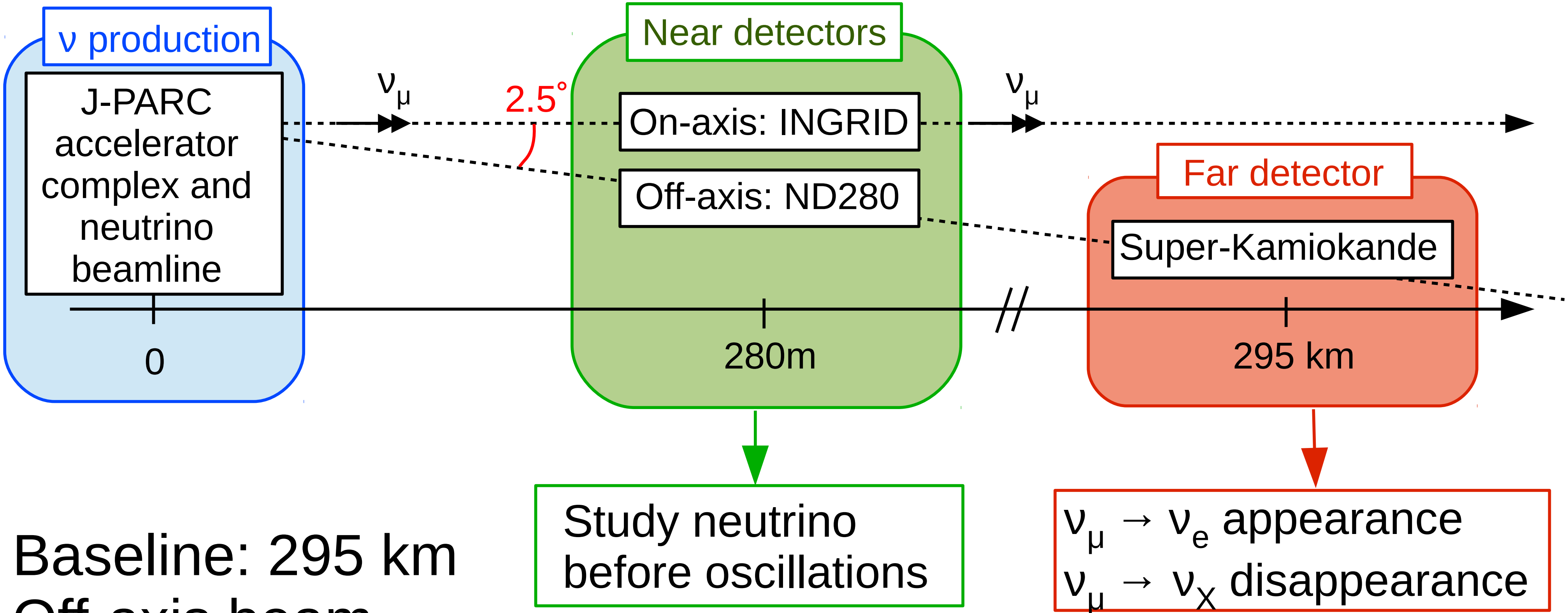
～500 members
62 Institutes
11 countries

The T2K experiment Overview









ν production

J-PARC accelerator complex and neutrino beamline

0

ν_μ

2.5°

Near detectors

On-axis: INGRID

Off-axis: ND280

280m

ν_μ

Far detector

Super-Kamiokande

295 km

Study neutrino before oscillations

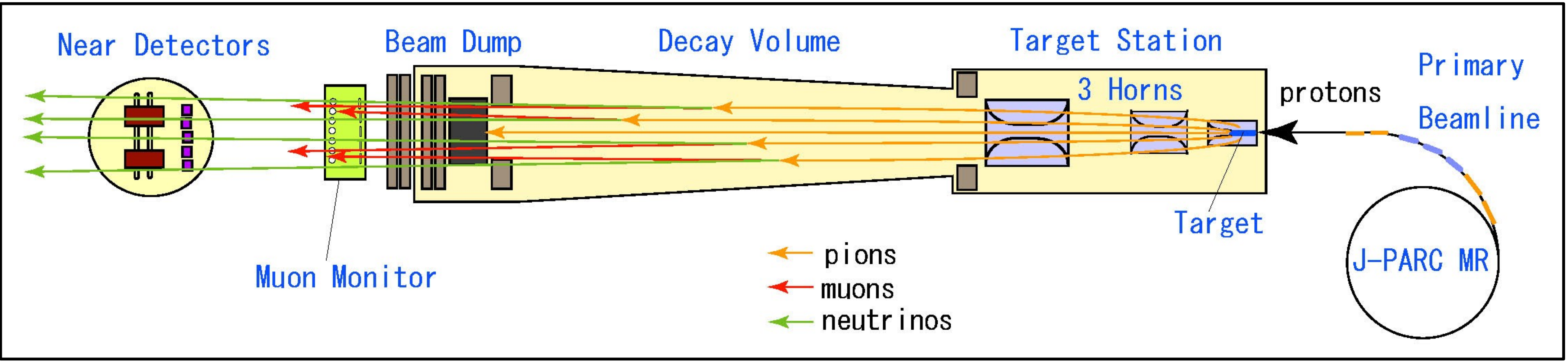
$\nu_\mu \to \nu_e$ appearance

$\nu_\mu \to \nu_x$ disappearance

- Baseline: 295 km
- Off-axis beam

The T2K experiment
Neutrino production

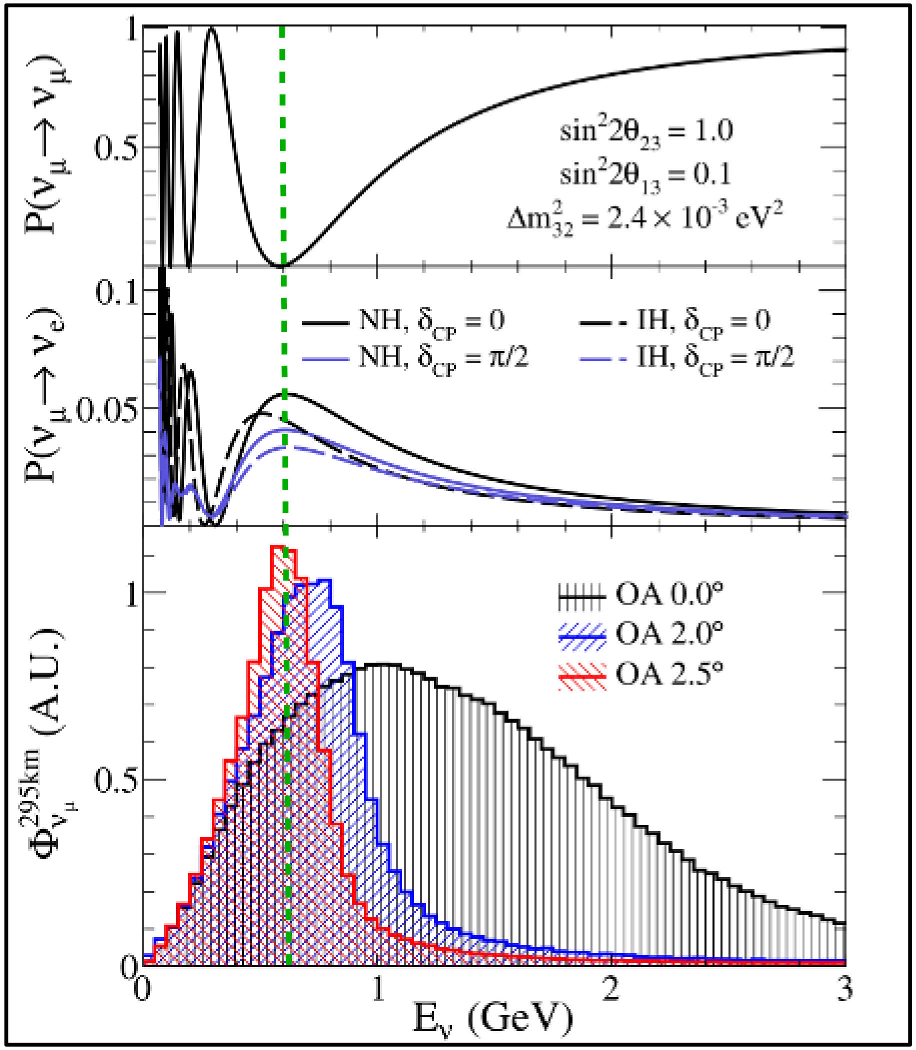
Conventional neutrino beam produced from 30 GeV protons

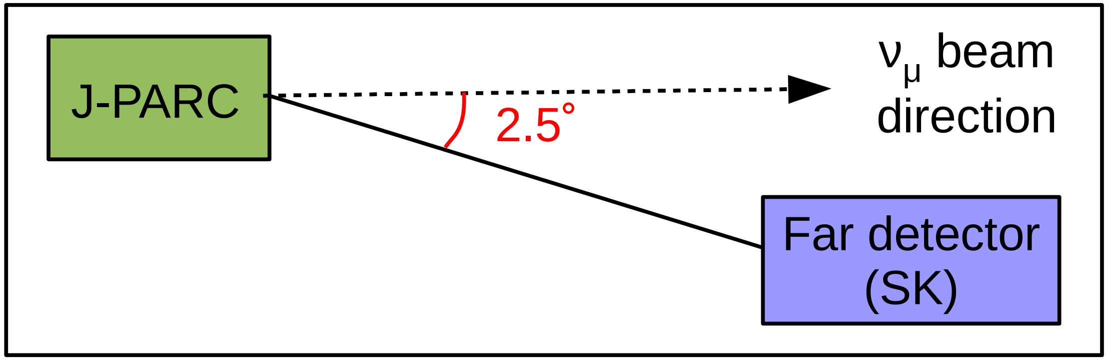


Almost pure $\nu_\mu/\bar{\nu}_\mu$ beam, with an intrinsic $\nu_e/\bar{\nu}_e$ component (<1% at peak)

Can switch from ν_μ beam to $\bar{\nu}_\mu$ beam by inverting the horn polarities

The T2K experiment
Off-axis beam





J-PARC

ν_μ beam direction

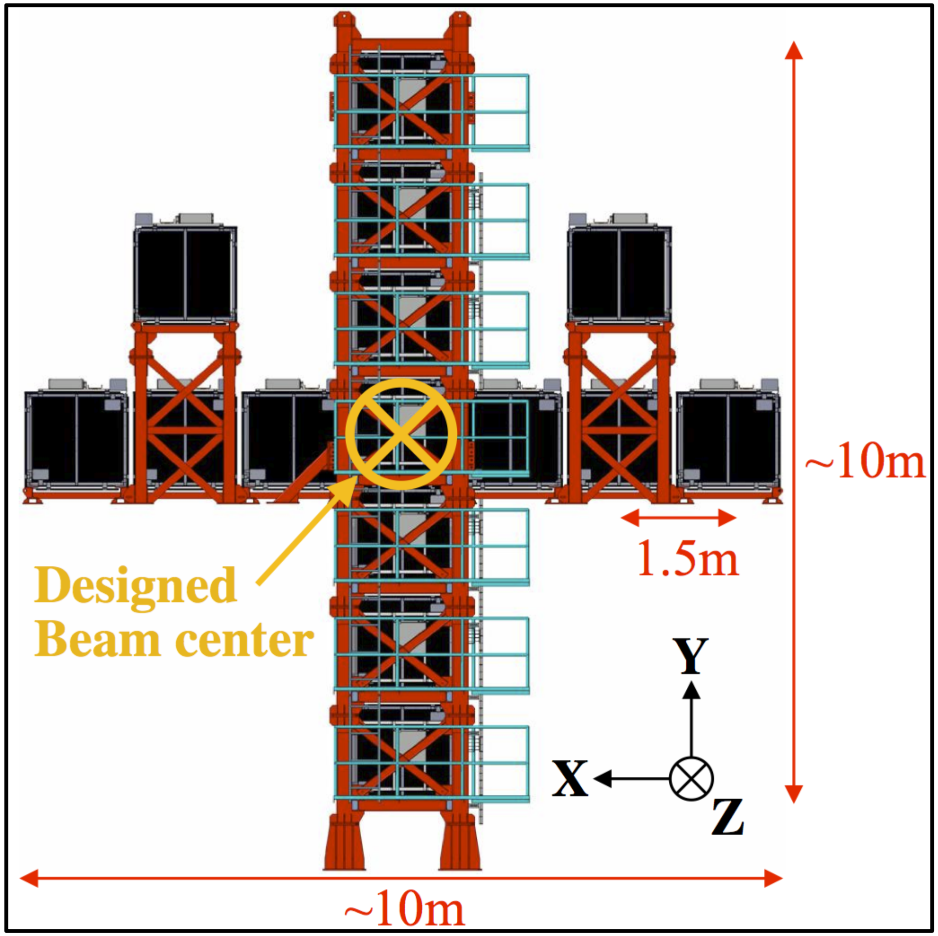
2.5°

Far detector (SK)

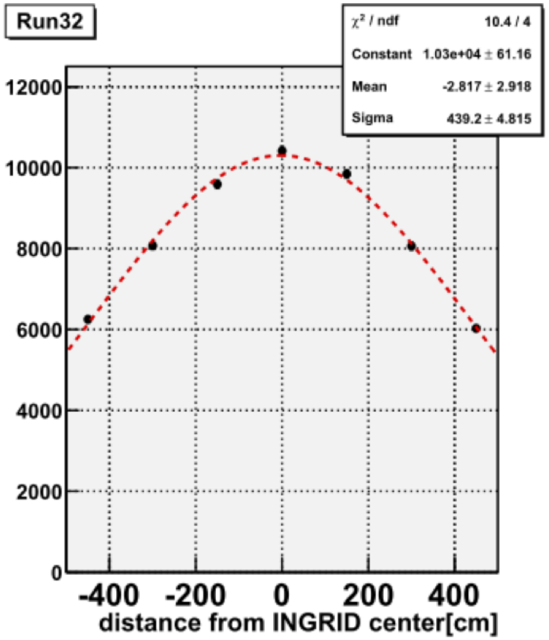
- Narrow band neutrino beam, peaked at oscillation maximum (0.6 GeV)
- Reduces high energy tail
- Reduces intrinsic ν_e contamination of the beam at peak energy
- Interactions dominated by CCQE mode

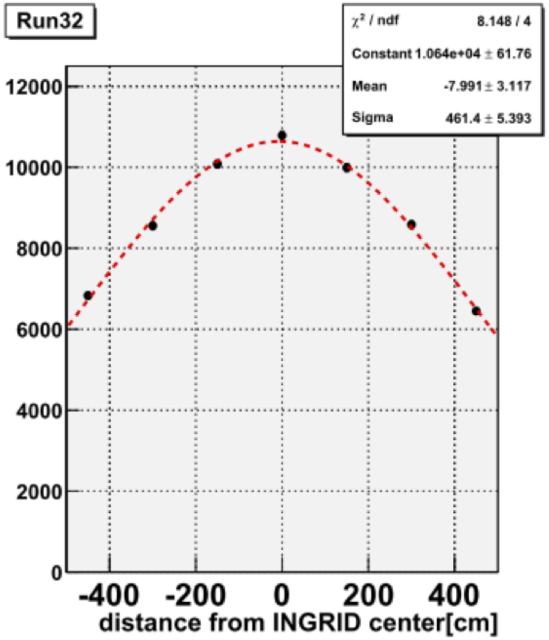
The T2K experiment
Near detectors

On-axis detector INGRID (Interactive Neutrino GRID)
Located 280m from the target



- 16 identical modules made of iron and scintillators
- 'counting neutrinos' by reconstructing muon tracks from ν_μ interactions
- Monitors neutrino beam: rate, direction and stability

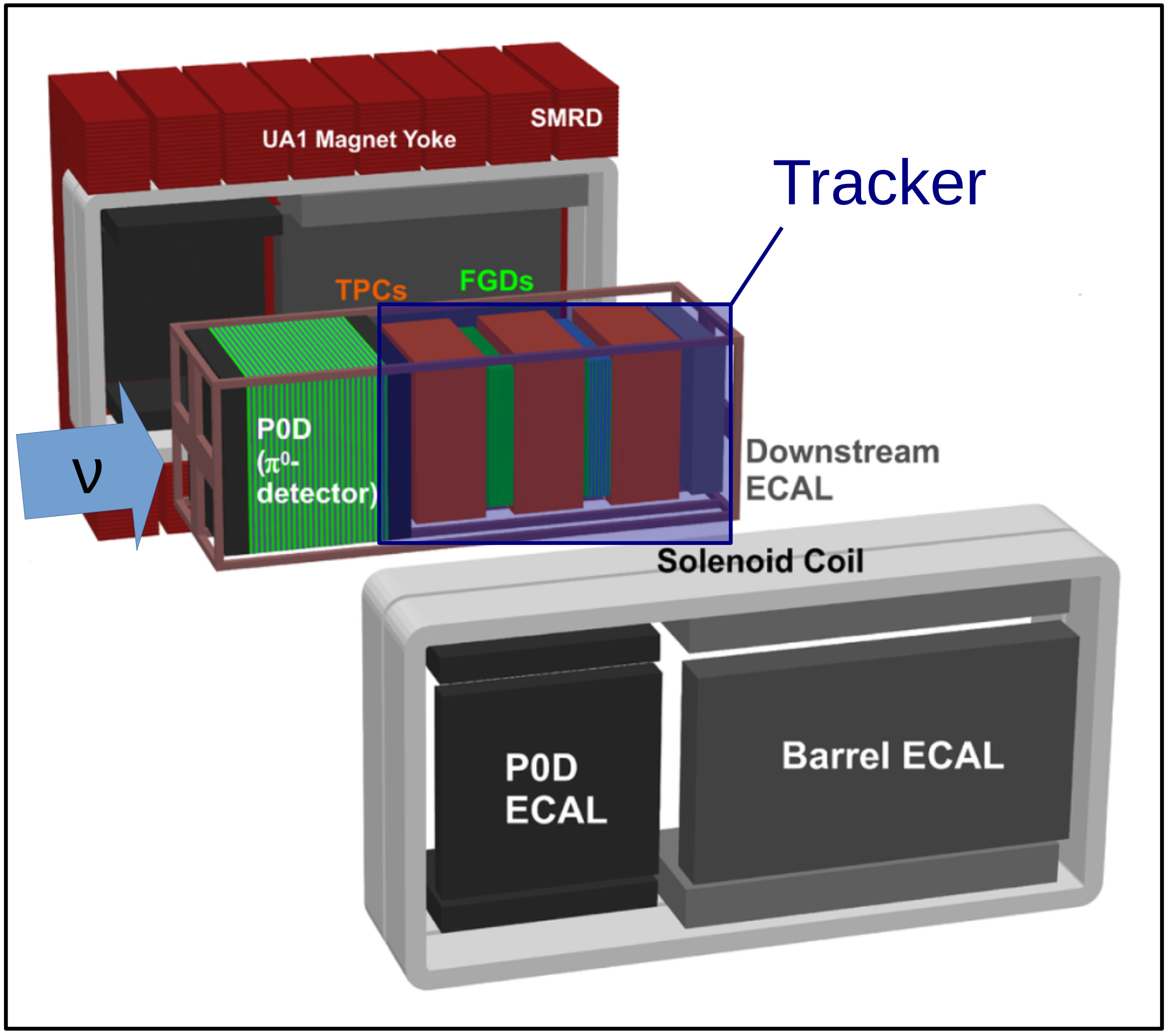


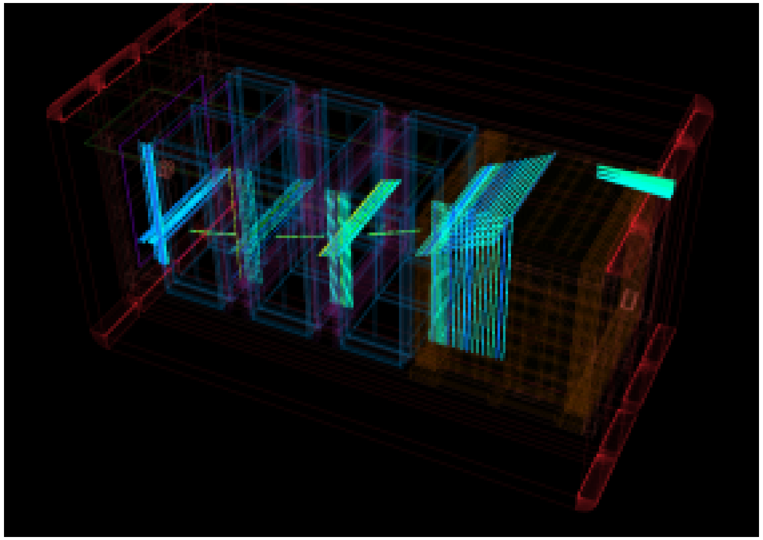


The T2K experiment
Off-axis near detectors

Off-axis near detector ND280
Located 280m from the target

- Several detectors inside a 0.2 T magnetic field
- Good tracking capabilities
- 'Tracker' used to constrain flux and interaction uncertainties for oscillation analysis
- Rich cross-section measurement program

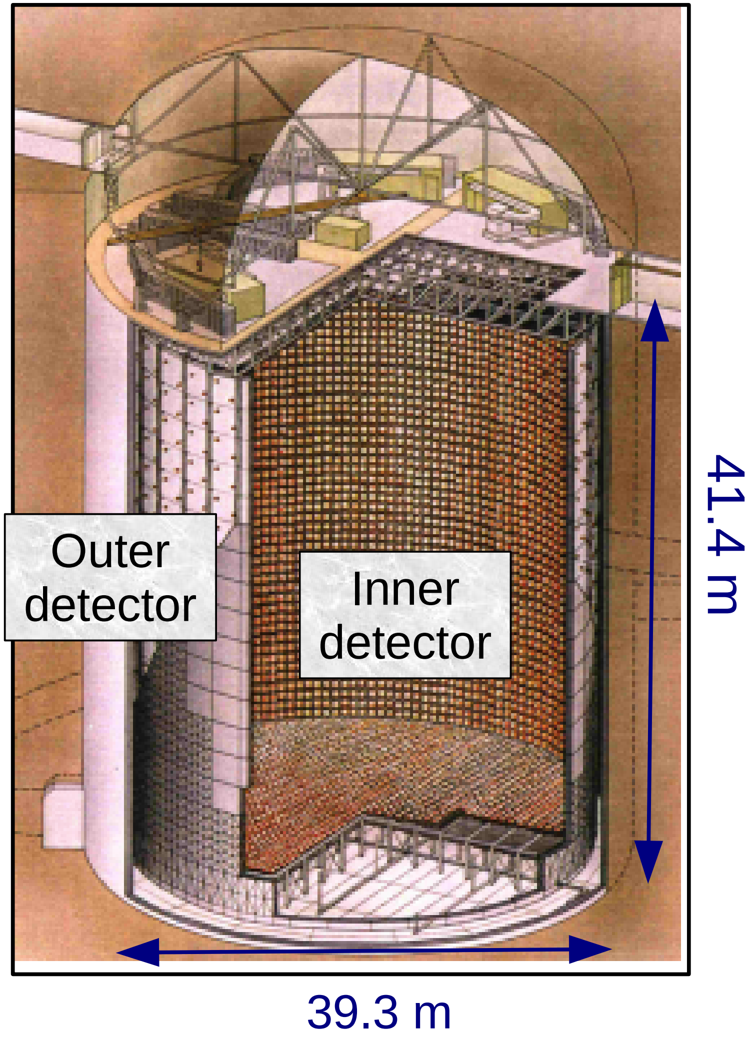




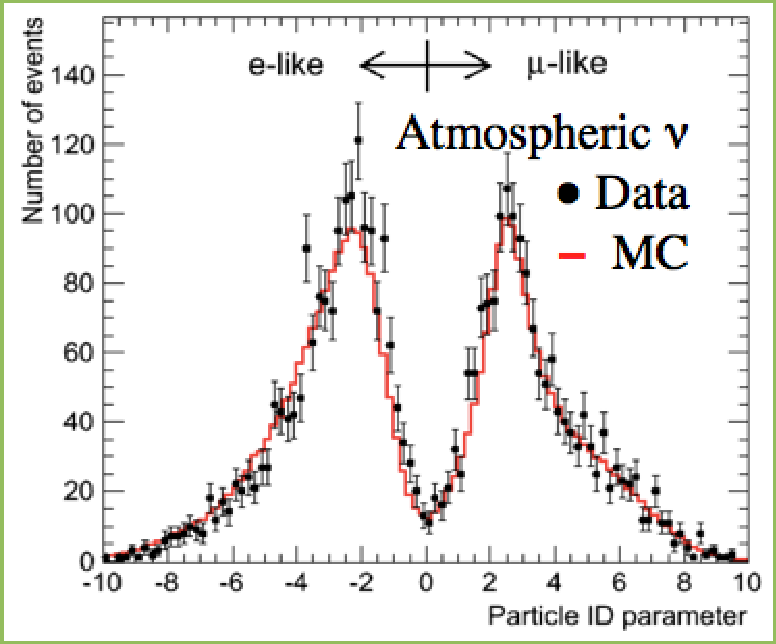
The T2K experiment
Far detector: Super-Kamiokande

Located 295 km from the target
Synchronized with beamline via GPS

- 50 kt water Cherenkov detector
- Operational since 1996



Good separation between $\mu^{\pm}$ and $e^{\pm}$ (separate ν_{μ} and ν_{e} CC interactions)



No magnetic field: cannot **separate ν and $\bar{\nu}$ on an event by event basis**

Neutrino oscillation analysis

How can we measure δ ?

Look for violation of CP symmetry by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Full probability in vacuum:

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) = & \, 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\ & + 8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\ & - 8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \boxed{\sin\delta} \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\ & + 4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta) \sin^2 \Delta_{21} \end{aligned}$$

$\sin^2 \Delta_{ij} = \sin^2 (1.27 \, \Delta m_{ij}^2 \times L / E)$

$\nu \rightarrow \bar{\nu}$

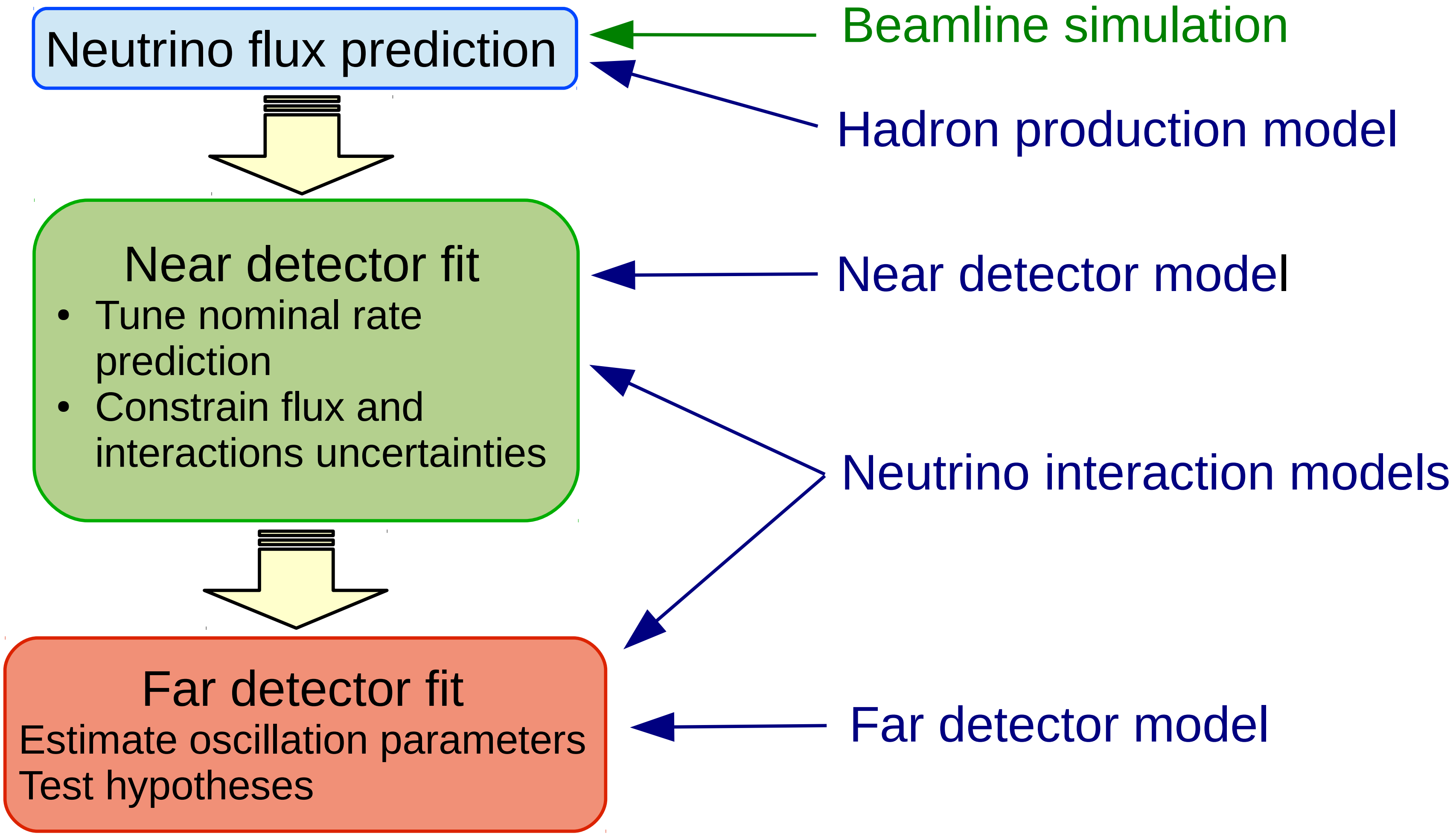
$\delta \rightarrow -\delta$

Change in expected appearance probability (at first maximum) wrt δ=0 or π (~27% effect in T2K)

Oscillation	δ > 0	δ < 0
$\nu_\mu \rightarrow \nu_e$	Suppressed	Enhanced
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Enhanced	Suppressed

Analysis description overview

Likelihood analysis: compare observed data at the far detector to predictions based on a model of the experiment to make measurements



Neutrino flux prediction

Beamline simulation

Hadron production model

Near detector fit

- Tune nominal rate prediction
- Constrain flux and interactions uncertainties

Near detector model

Neutrino interaction models

Far detector fit

Estimate oscillation parameters

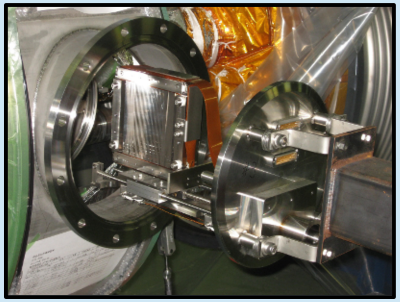
Test hypotheses

Far detector model

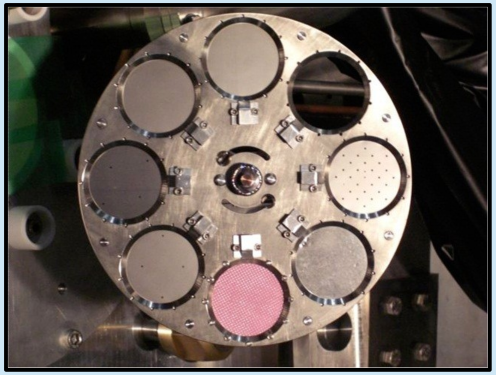
Analysis description
Neutrino flux prediction

Neutrino flux predicted using a series of simulations

Proton beam properties



Measured by beam monitors



Hadron production in target

FLUKA 2011
Tuned to external data
(NA61/Shine @ CERN)

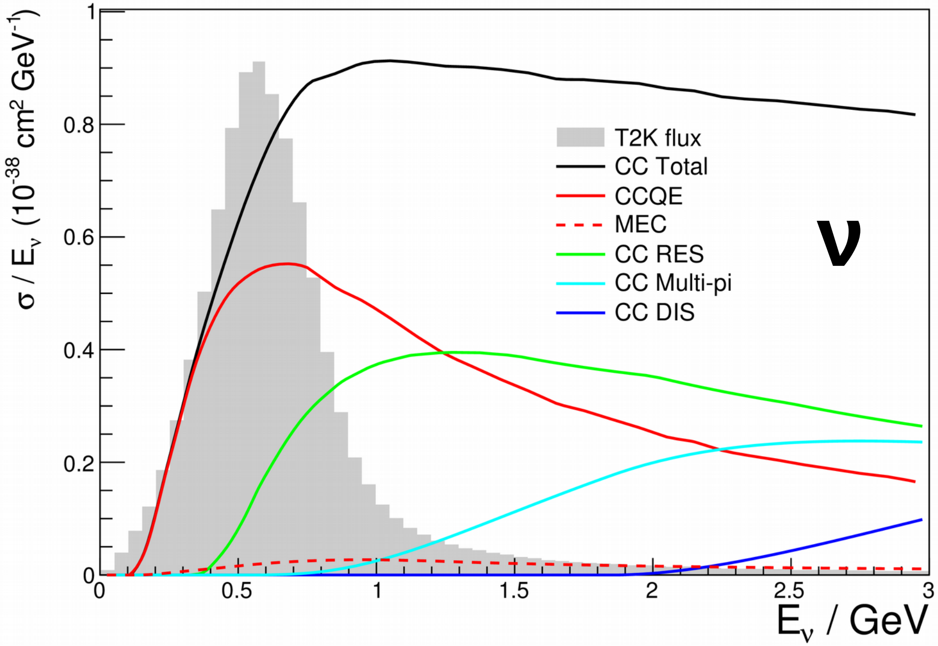
Propagation and decay of hadrons in secondary beamline

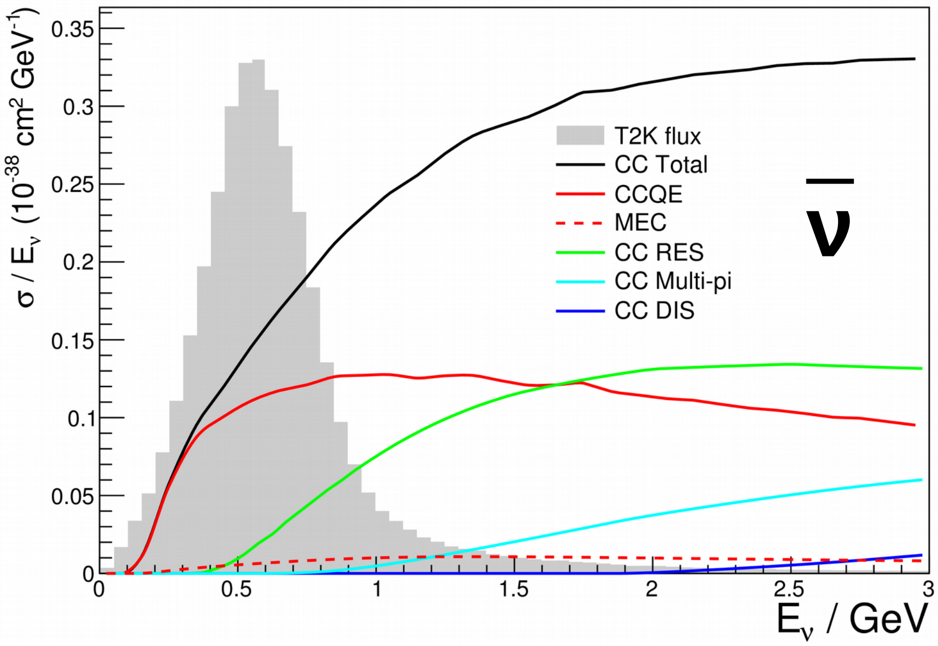
GEANT3 simulation
GCALOR package

Uncertainty on flux prediction varies between 8 and 12%, depending on neutrino flavor and energy

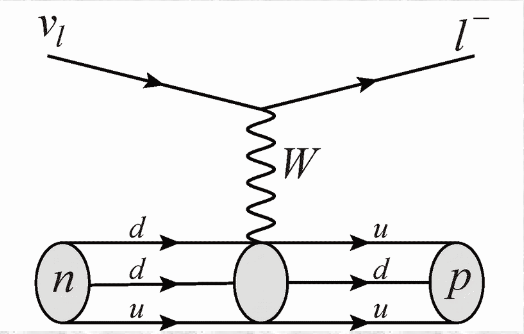
Neutrino interactions

- Need to detect neutrino flavor => charged-current interactions
- At T2K energies, dominant interaction mode is charged-current quasi-elastic

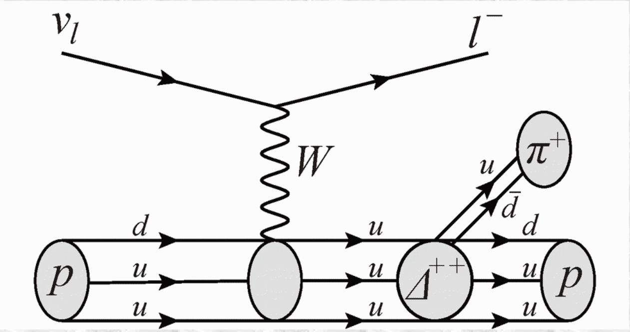




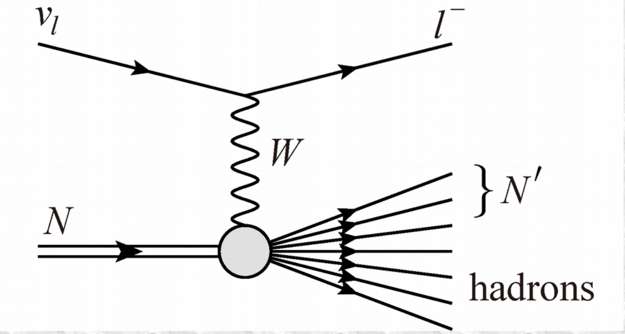
CCQE



CC RES

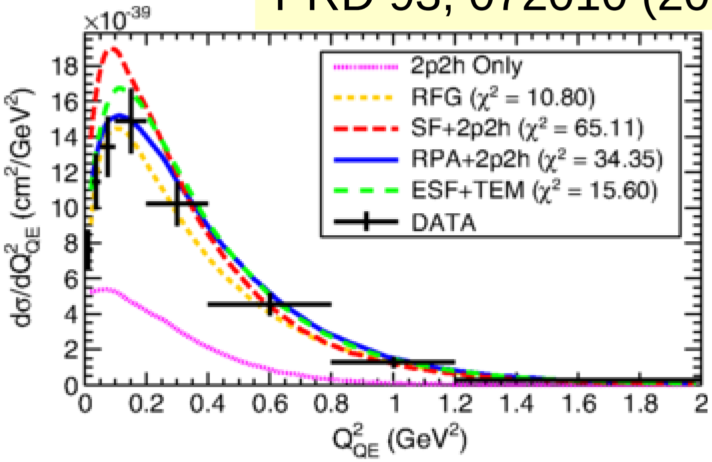


CC DIS/Multi-pi



Neutrino interaction model

- Select interaction models using external data
- Nominal predictions from NEUT
- Uncertainties on model parameters (M_A, pF,…)
- Additional normalization uncertainties for certain modes / sub-modes



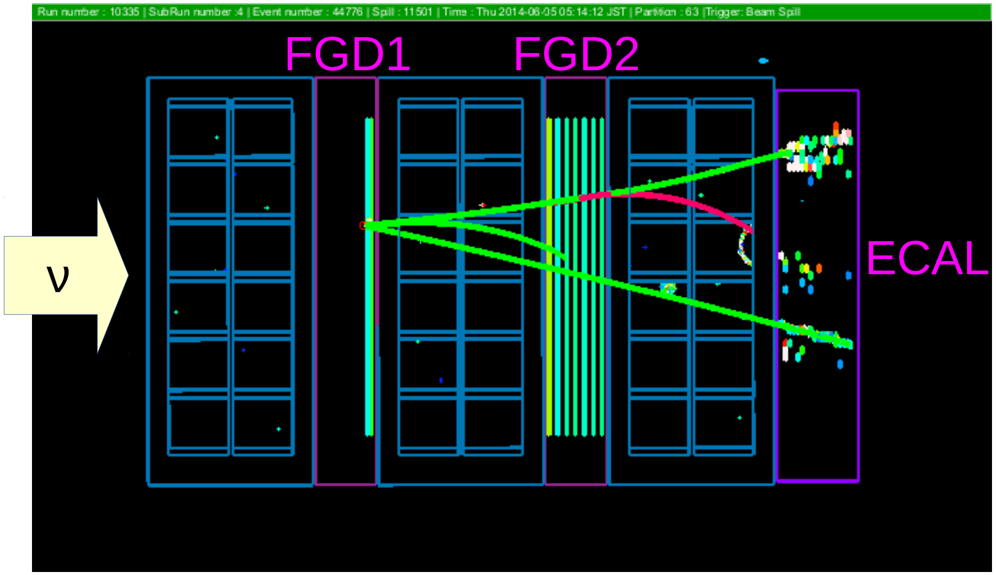
PRD 93, 072010 (2016)

Significant improvements for 2017 analysis:

- ✓ implementation of Valencia 2p-2h model
- ✓ more detailed parameterization of uncertainties on 2p-2h interactions
- ✓ addition of long range correlations in the nucleus (RPA) for CCQE interactions
- ✓ Effective parameterization of the uncertainties on those
- ✓ improved pion production model

Near detector analysis

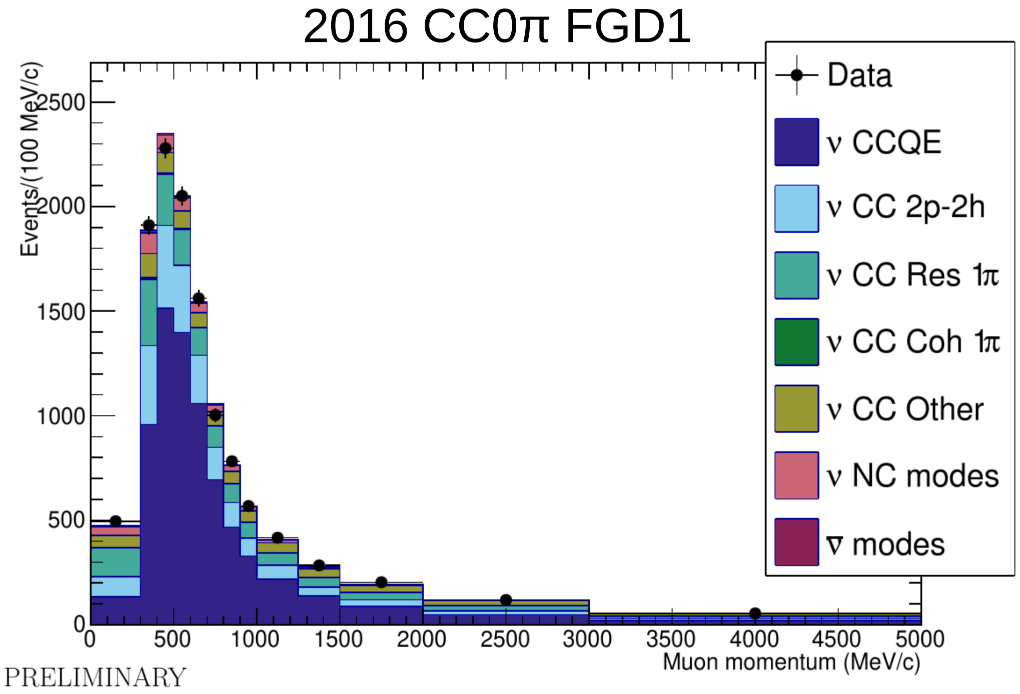
Select CC ν_μ interactions with vertex in one of the Fine-Grained Detectors (FGD)



Samples separated by FGD:
- FGD1: CH target
- FGD2: 42% water by mass

Additional separation by topology:
- Number of π^+ (ν mode)
- Number of tracks ($\bar{\nu}$ mode)

Neutrino and anti-neutrino samples in anti-neutrino mode to constrain wrong sign background



Far detector Strategy

Oscillations depend on E_ν

$$phase \propto \frac{\Delta m_{ij}^2 L}{E_\nu}$$

Water-Cherenkov detector:

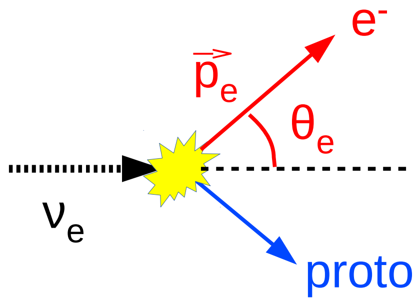
- Only sees charged particles
- Has a momentum threshold

See only leptons and pions at T2K energies

CCQE interactions

$\nu + n \rightarrow p + l^-$

$\bar{\nu} + p \rightarrow n + l^+$



Knowing ν direction, can reconstruct E_ν from lepton (p,θ)

Build CCQE enriched samples

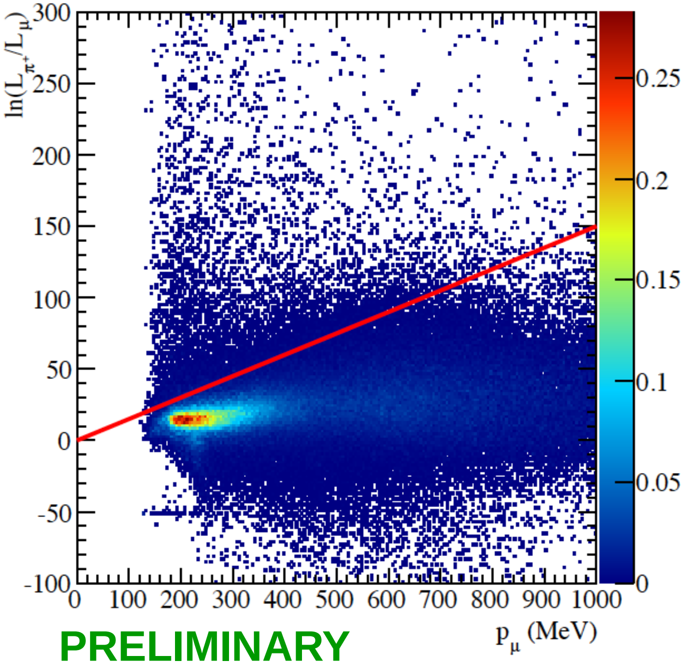
(can also use CC1π: proton ↔ π^+)

Far detector
Analysis improvements

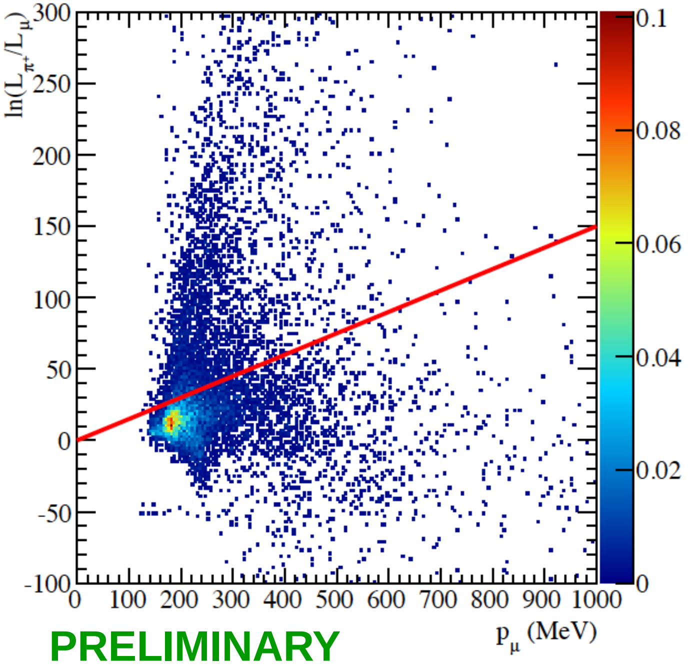
Major updates of the far detector analysis for the 2017 analysis:

- Use of fiTQun reconstruction algorithm instead of APFit: improved PID, better vertex and momentum resolution
- Introduction of a new likelihood cut to reduce the NC1π background for disappearance analysis
- Optimization of the selection cuts to increase sensitivity
- New estimation of the detector systematic uncertainties

Signal: ν_μ CCQE



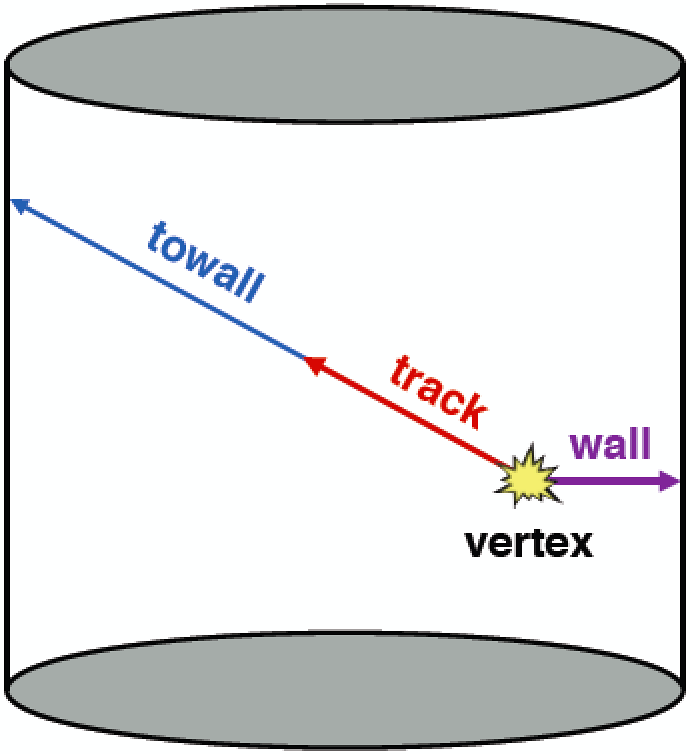
Background: ν_μ NC1$\pi^\pm$



Far detector
Fiducial volume optimization

Fiducial volume cuts optimized to improve sensitivity

- for appearance samples, optimized to improve sensitivity to CP violation
- for disappearance samples, optimized to improve precision of θ_{23} measurement



Previous analysis: wall>200 cm for all samples

Sample	ToWall cut	Wall cut
ν-mode 1Re	170 cm	80 cm
ν-mode 1Rμ	250 cm	50 cm
ν-mode CC1π	270 cm	50 cm
$\bar{\nu}$-mode 1Re	170 cm	80 cm
$\bar{\nu}$-mode 1Rμ	250 cm	50 cm

Far detector
Effects of improvements

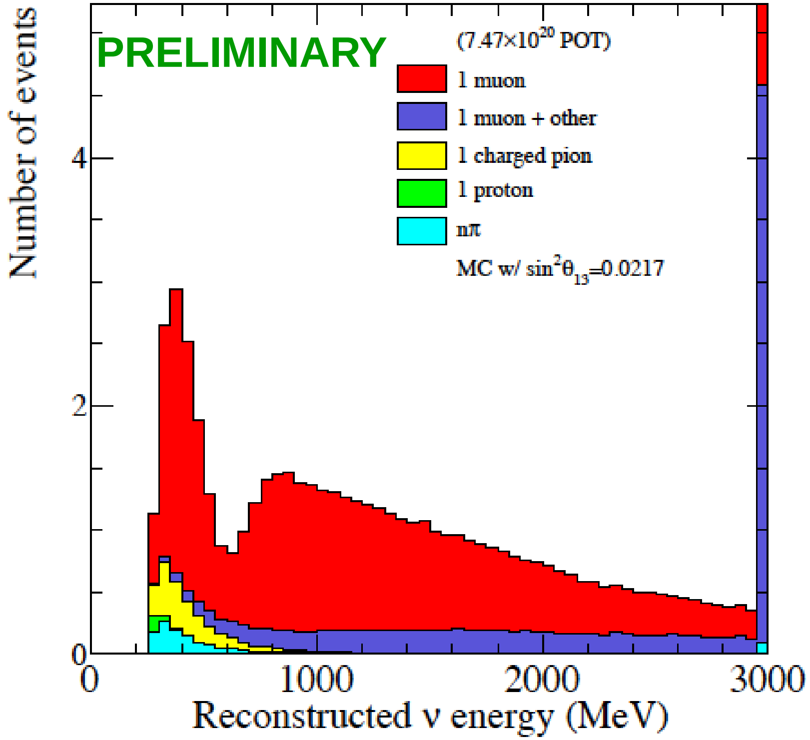
Increase of statistics for the appearance samples:
- 25% increase in 1R e-like samples
- 33% increase for ν-mode CC1π signal with 70% decrease in main background

Small decrease in statistics for disappearance samples, but better signal/background:
- 15% increase in CCQE signal interaction
- 50% decrease in NC1π background

Expected number of events (Run 1-8)

Sample	New analysis	Previous analysis
ν-mode 1Re	69.5	56.5
ν-mode 1Rμ	261.6	268.7
ν-mode CC1π	6.9	5.6
$\bar{\nu}$-mode 1Re	7.6	6.1
$\bar{\nu}$-mode 1Rμ	62.0	65.4

ν-mode 1Rμ, previous analysis



Oscillation fits

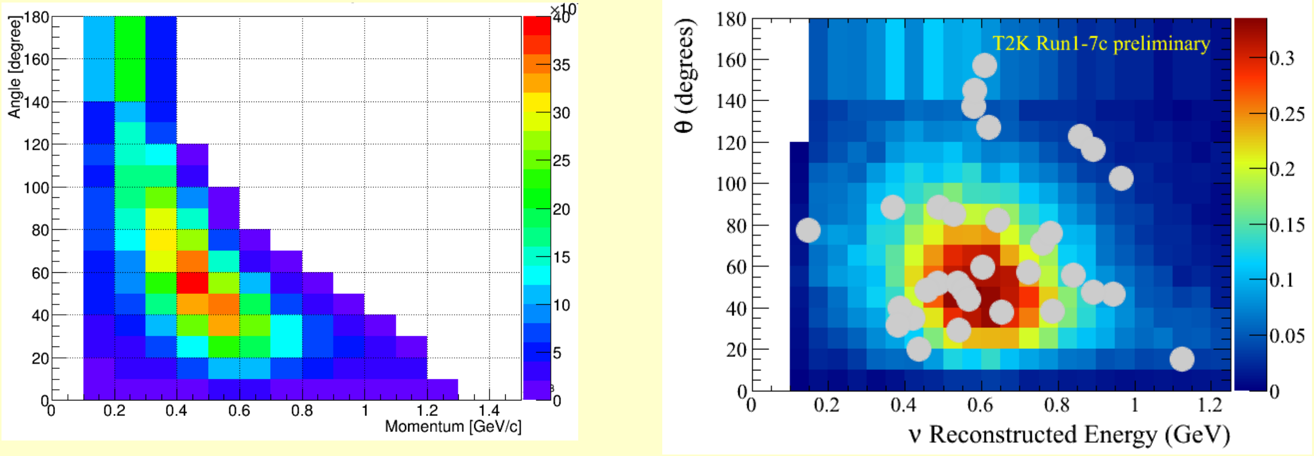
- Maximum likelihood methods to measure the PMNS parameters
- Marginalize (integrate) over the nuisance parameters
- Bayesian and frequentist results

3 different analyses giving consistent results

Different use of near detector data:
- 1 joint near/far analysis
- 2 use result of ND fit as input

Different fitting methods:
- 2 “grid searches”
- 1 uses Markov Chain MC

Different ‘shape’ information for e-like samples

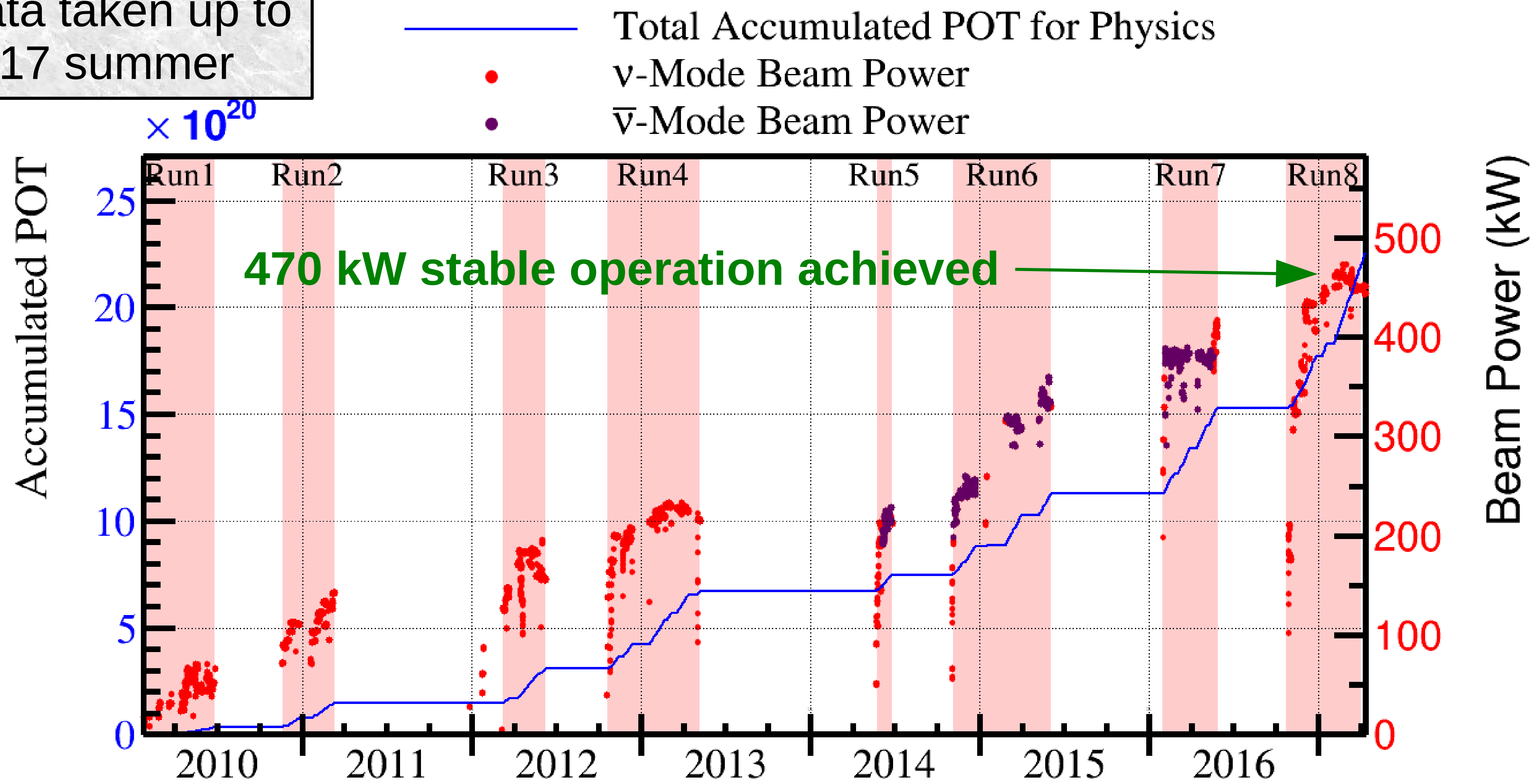

Lepton (p,θ)

ν E_{rec} + lepton θ

Dataset

Dataset
Run 1-8 data

Data taken up to 2017 summer



470 kW stable operation achieved

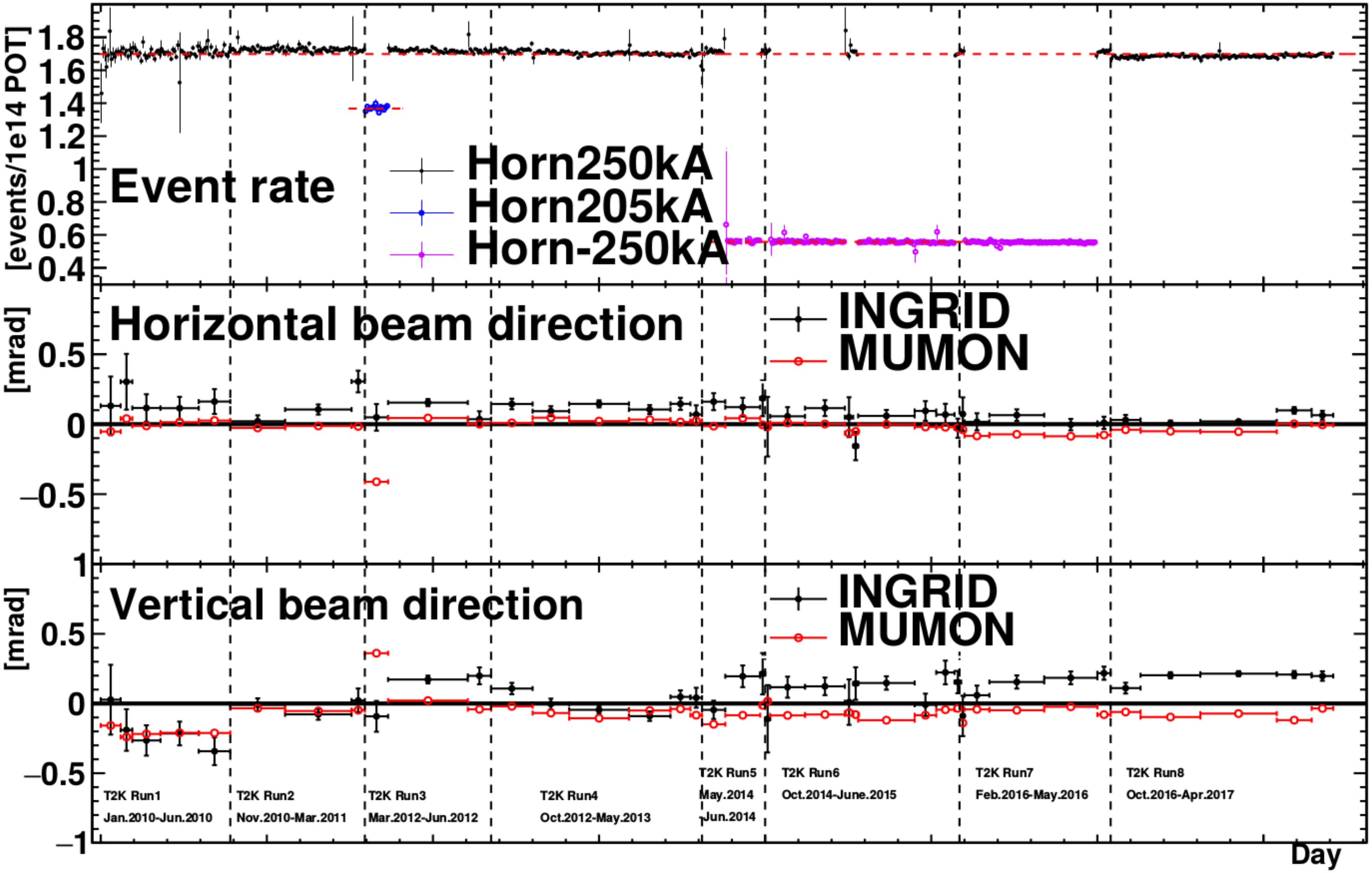
Near detector analysis
ν-mode: 5.80 x 10^{20} POT
$\bar{\nu}$-mode: 3.858 x 10^{20} POT

Far detector analysis
ν-mode: 14.7341 x 10^{20} POT
$\bar{\nu}$-mode: 7.557 x 10^{20} POT

Statistics given in terms of POT: Proton On Target

Beam stability

Stable event rate and beam direction from muon monitor and on-axis near detector measurements



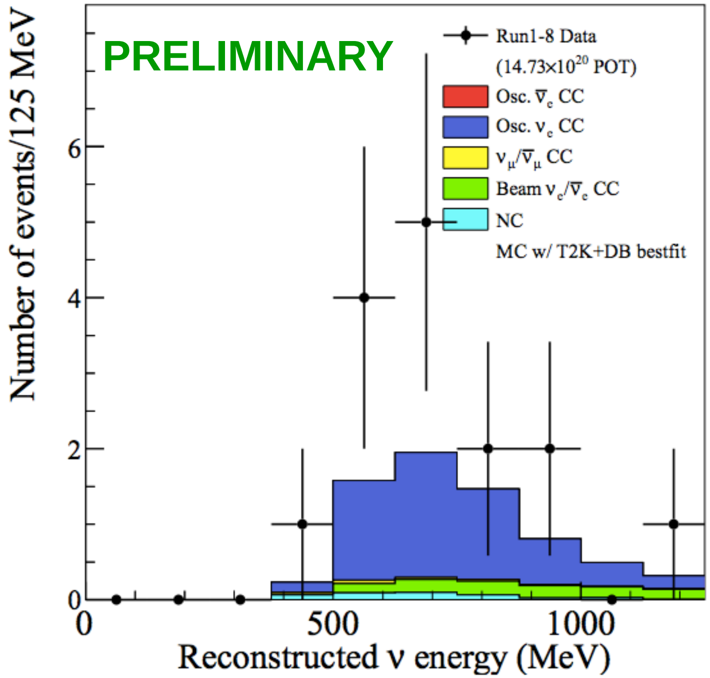
Off-axis angle controlled better than 1 mrad target uncertainty (= 2% uncertainty on peak energy at SK)

Far detector data
Appearance samples

Sample	δ=0 MC	δ=π MC	δ=-π/2 MC	δ=π/2 MC	Observed
ν-mode 1Re	61.46	61.98	73.51	49.93	**74**
$\bar{\nu}$-mode 1Re	9.035	8.93	7.921	10.04	**7**
ν-mode CC1π	6.01	5.78	6.923	4.868	**15**

MC with $\sin^2(\theta_{23})=0.528$, $\Delta m^2_{32}=2.509*10^{-3}$ eV^2c^{-4}, $\sin^2(\theta_{13})=0.0219$, Normal hierarchy

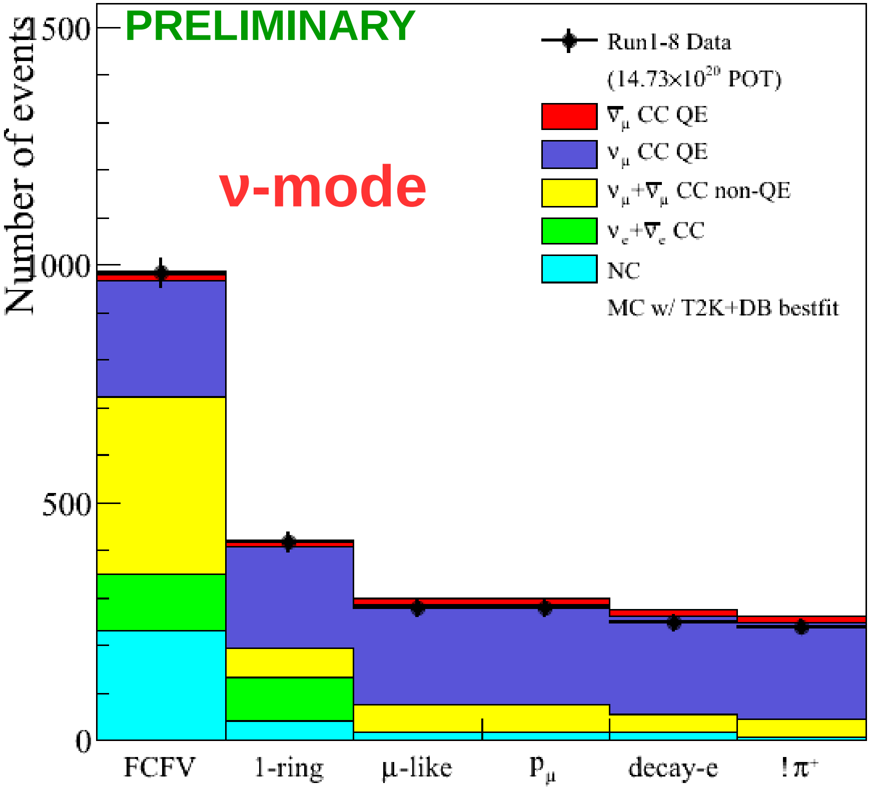
- Observation in line with expectations for δ=-π/2 for 1 ring e-like samples
- Excess of events for the CC1π sample
  - shape of reconstructed energy coherent with MC predictions
  - p-value for such a fluctuation in a sample is 2.5% (11.9% to have one of 5 samples fluctuate by that much)

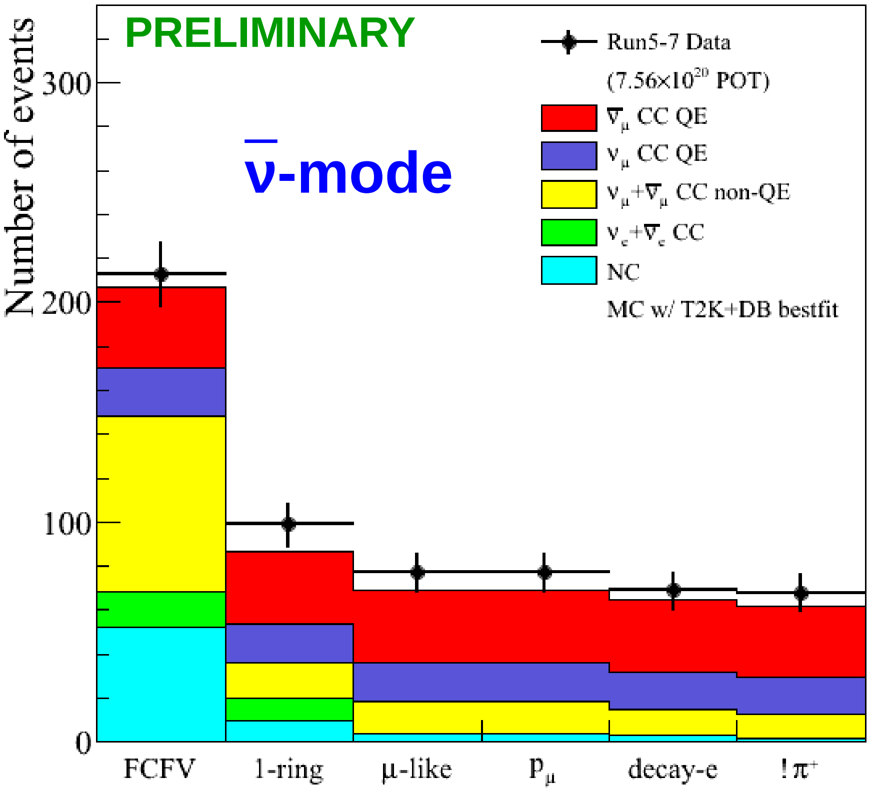


Far detector data
Disappearance samples

Sample	δ=0 MC	δ=-π/2 MC	Observed
ν-mode	267.41	267.76	**240**
$\bar{\nu}$-mode	62.91	63.05	**68**

MC with $\sin^2(\theta_{23})=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}$ eV^{2}c^{-4}, $\sin^2(\theta_{13})=0.0219$, Normal hierarchy

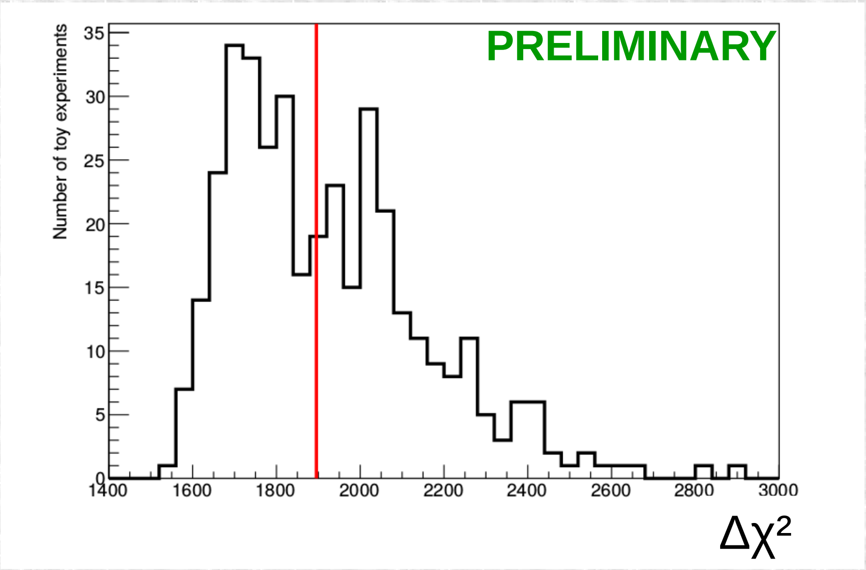




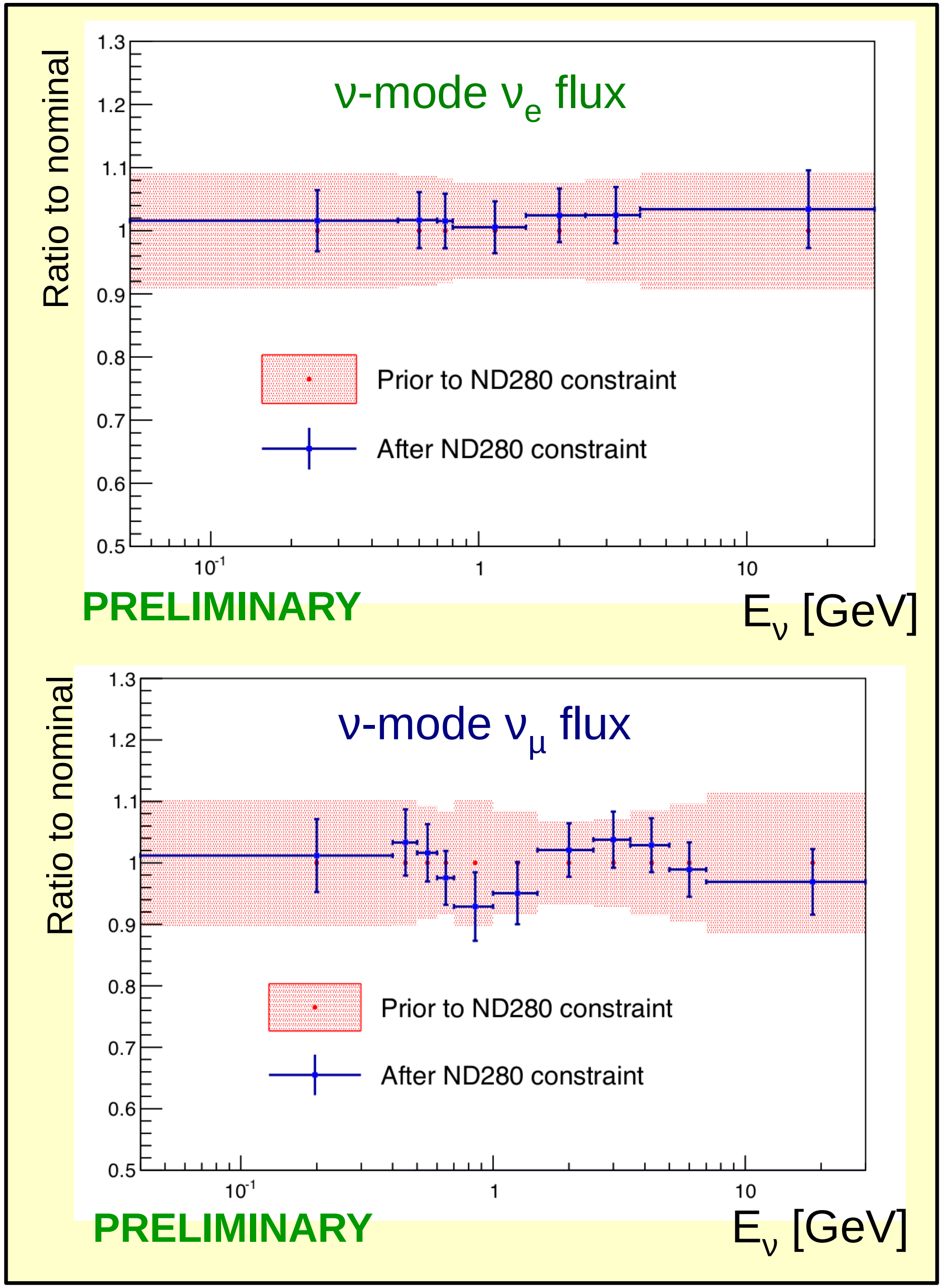
Results

Near detector fit Results

- Model able to fit data well
- Post-fit flux parameters close to nominal predictions (within 1σ error band)



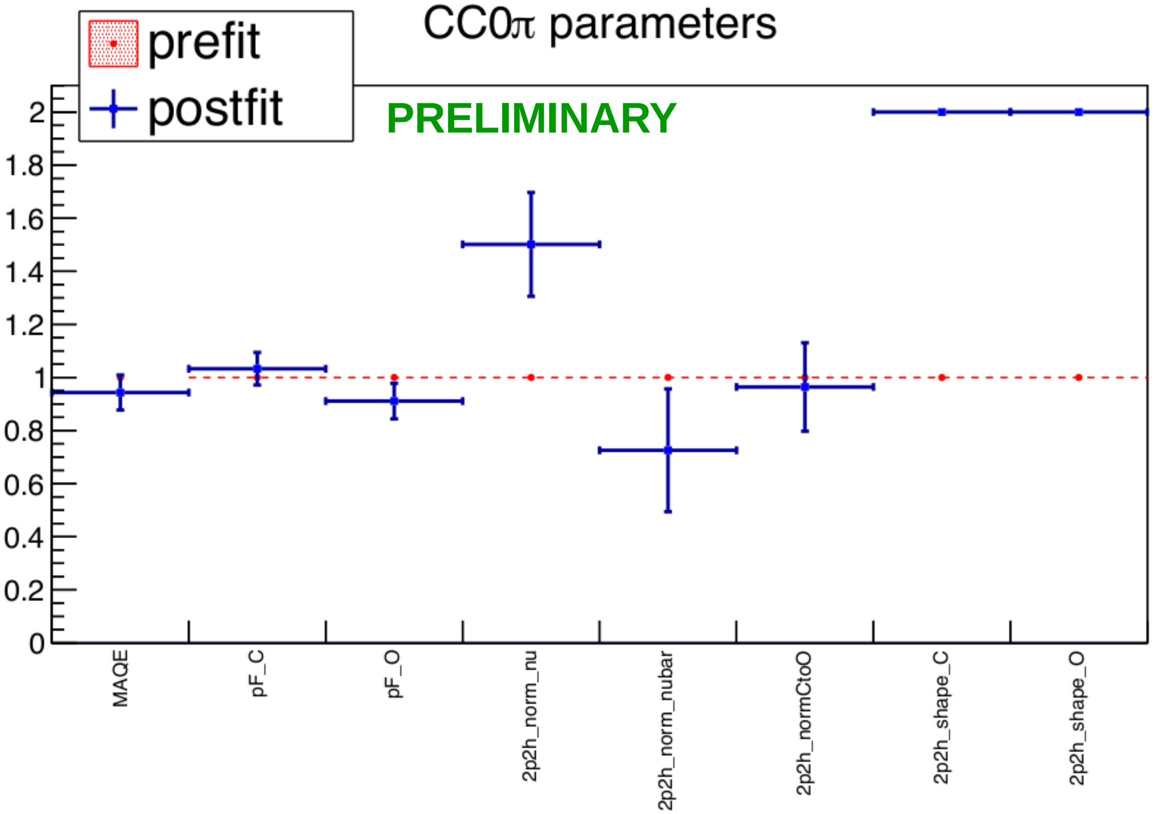
p-value: 0.47

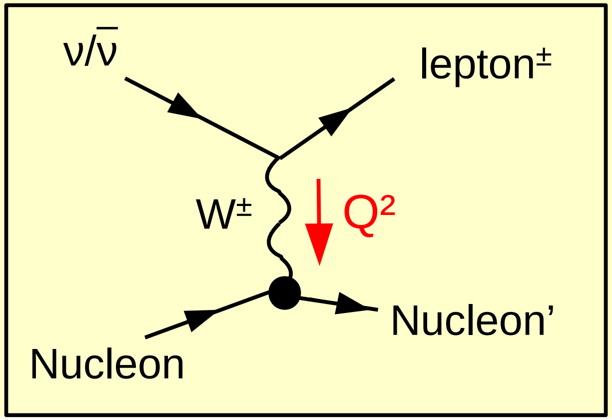


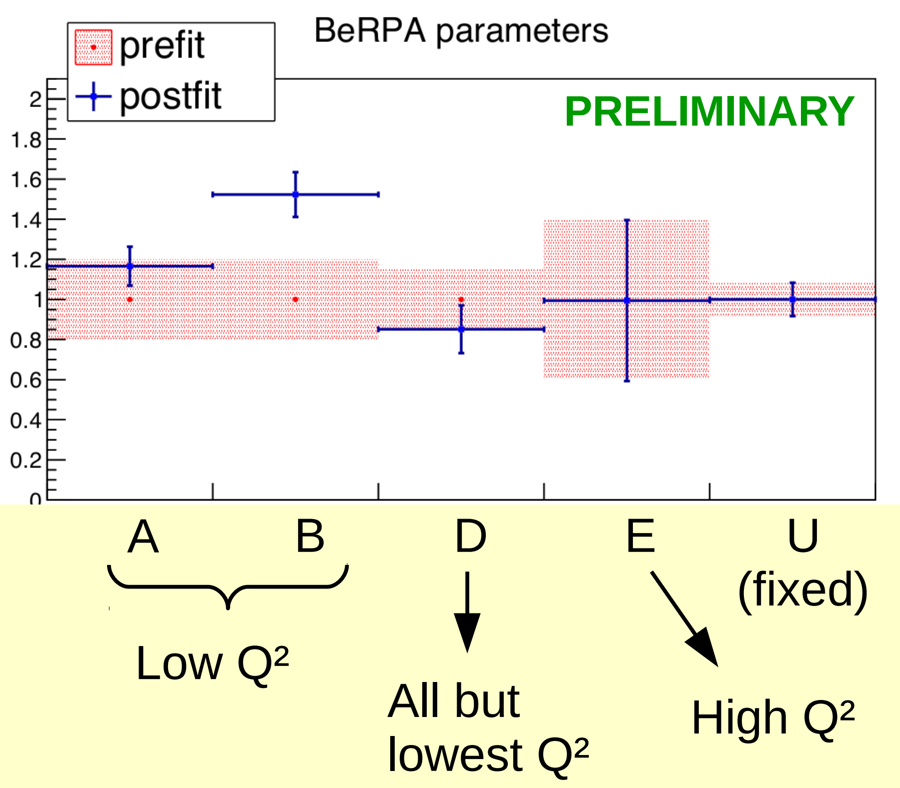
Near detector fit
Results

For the neutrino interaction model:

- Increase of the low Q^2 cross-section
- increase of the 2p2h normalization for ν
- 2p2h processes more Δ-like



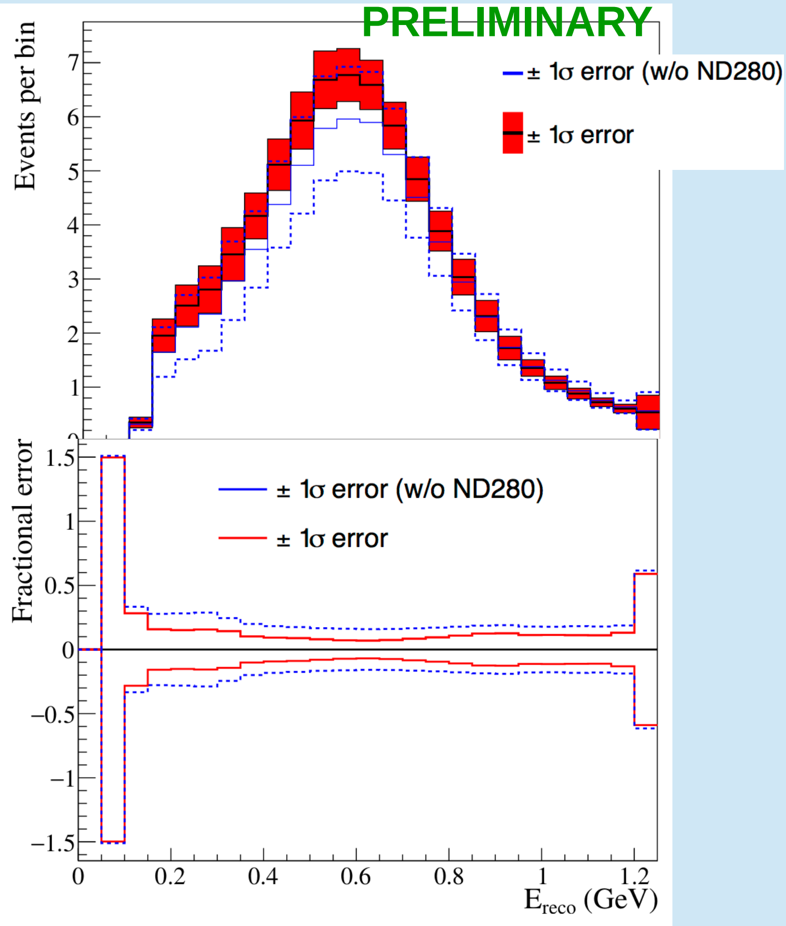




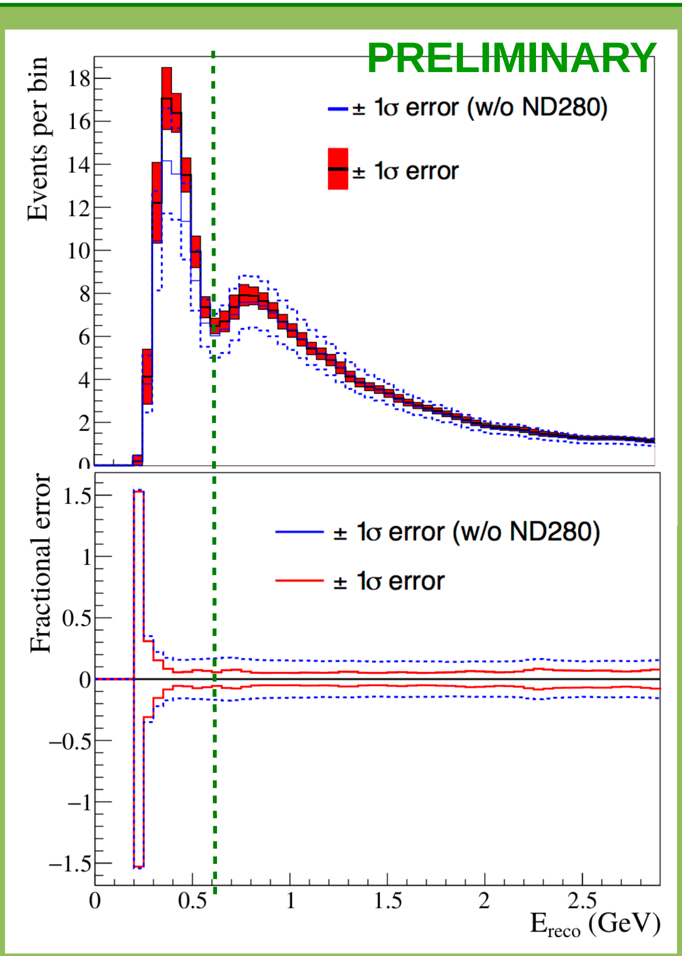
Near detector fit
Systematic uncertainty reduction

Both changes the nominal rate predictions and reduces the uncertainties

Neutrino mode electron-like



Neutrino mode muon-like



($\delta=-1.601$, $\sin^2(\theta_{23})=0.528$ $\Delta m^2_{32}=2.509*10^{-3}$ eV^2c^{-4}, $\sin^2(\theta_{13})=0.0219$)

Systematic uncertainties

Using the results of ND fit:

~4% uncertainty on the rates for disappearance sample

~6% uncertainty on the rates of 1-ring appearance sample

Larger uncertainty for the CC1π (1 ring + 1 decay e-) due to π^0 rejection and FSI-SI uncertainties

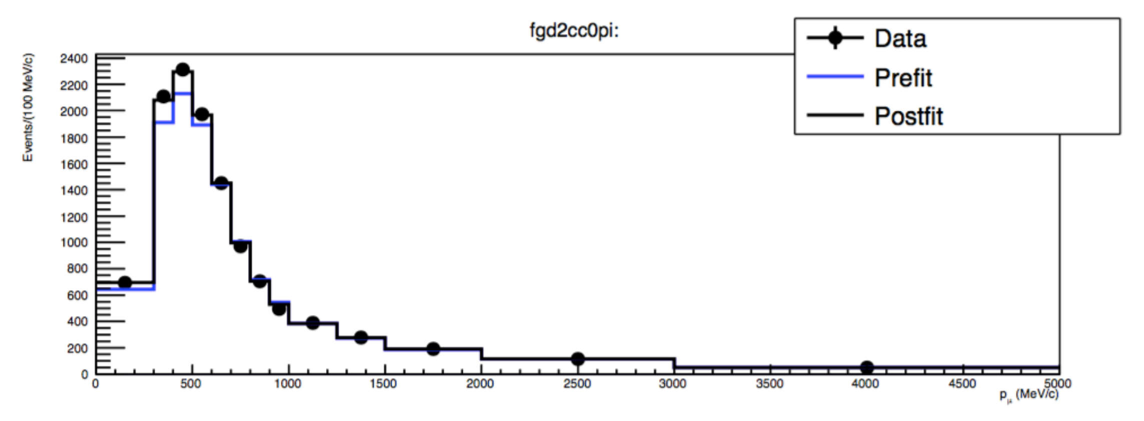
	ν_e (1 ring)	ν_e (CC1π)	ν_μ (1 ring)	$\bar{\nu}_e$ (1 ring)	$\bar{\nu}_\mu$ (1 ring)
Flux +Xsec (with ND fit)	3.2%	4.1%	3.3%	2.9%	2.7%
Far detector (after ND fit)	4.2%	19.2%	2.9%	4.8%	2.5%
Total (syst. only)	**6.3%**	**19.6%**	**4.4%**	**6.4%**	**3.8%**

($\delta=-1.601$, $\sin^2(\theta_{23})=0.528$ $\Delta m^2_{32}=2.509*10^{-3}$ eV^2c^{-4}, $\sin^2(\theta_{13})=0.0219$)

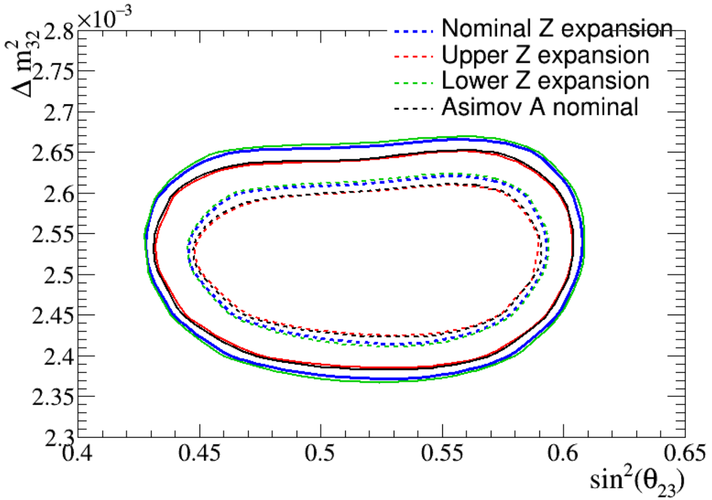
Systematic uncertainties
Remaining issues

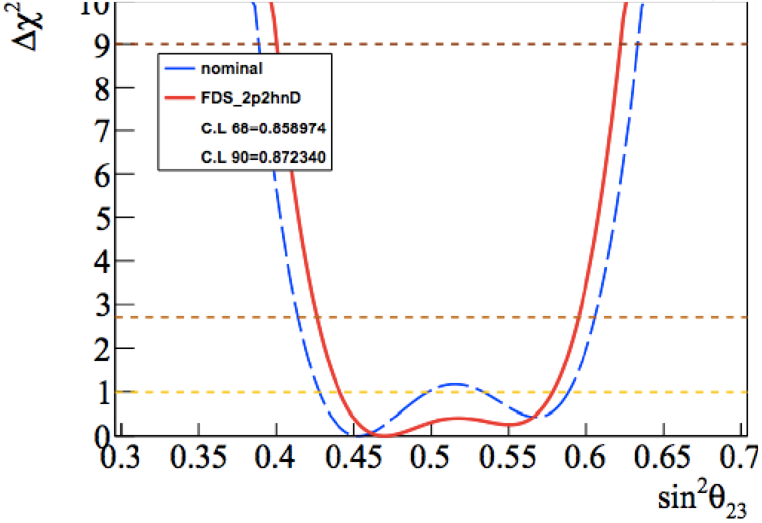
Studied effect of additional interaction uncertainties through “fake-data studies”:

- Data driven: assign difference between ND data and (prefit) model to different interaction modes



- Alternative nucleon form factors
- Uncertainty on pion spectrum

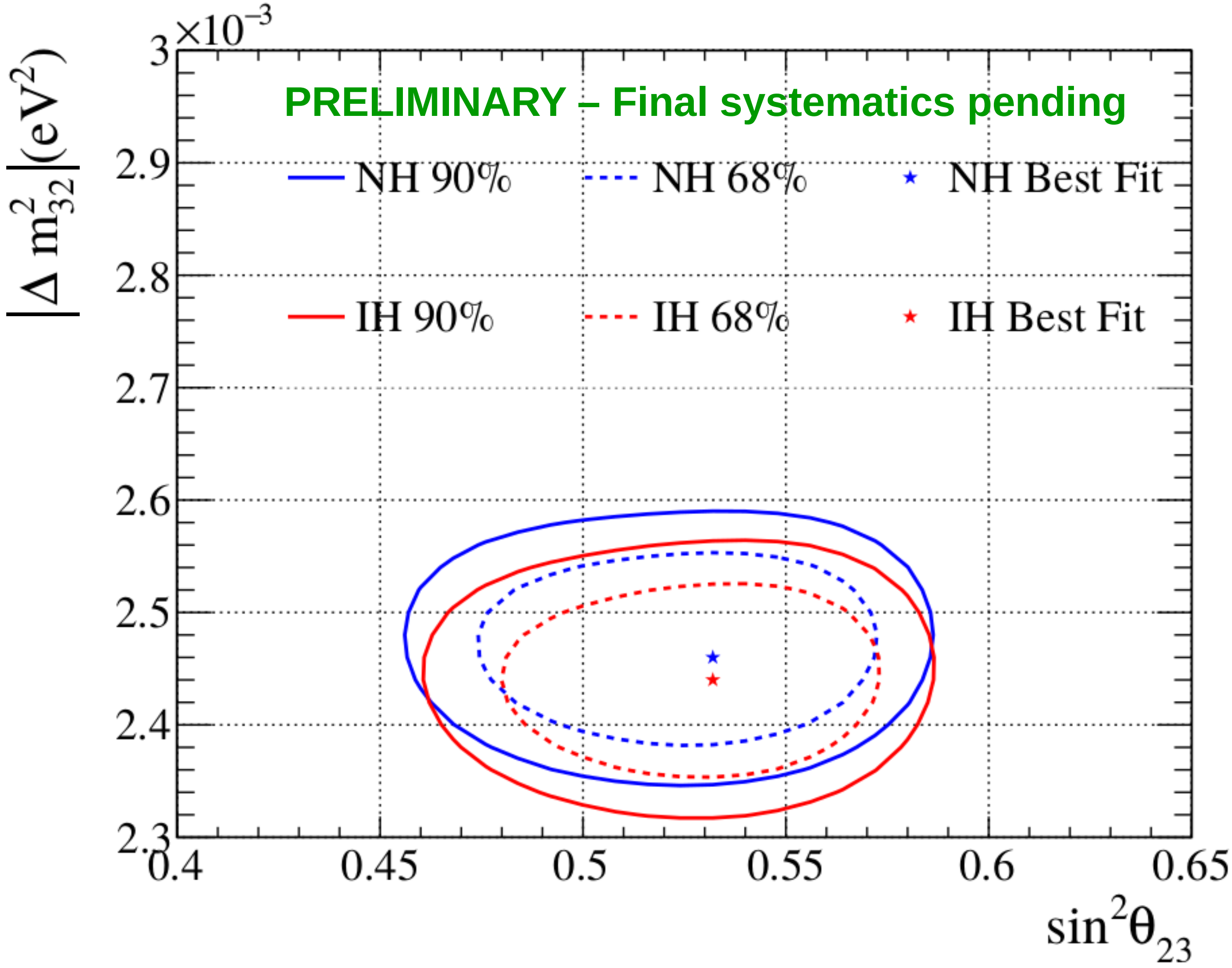




- Potential non-negligible effect on contours for atmospheric parameters
  → **Plots for θ_{23} and Δm^2_{32} should not be considered as a final result. Systematics will be updated.**
- Effect was found to be small on the δ_{CP} intervals
  → main result reported today is for appearance parameters

Atmospheric parameters

- **Not final results** due to remaining uncertainties on interactions
- Compatible with maximal disappearance as previous results were

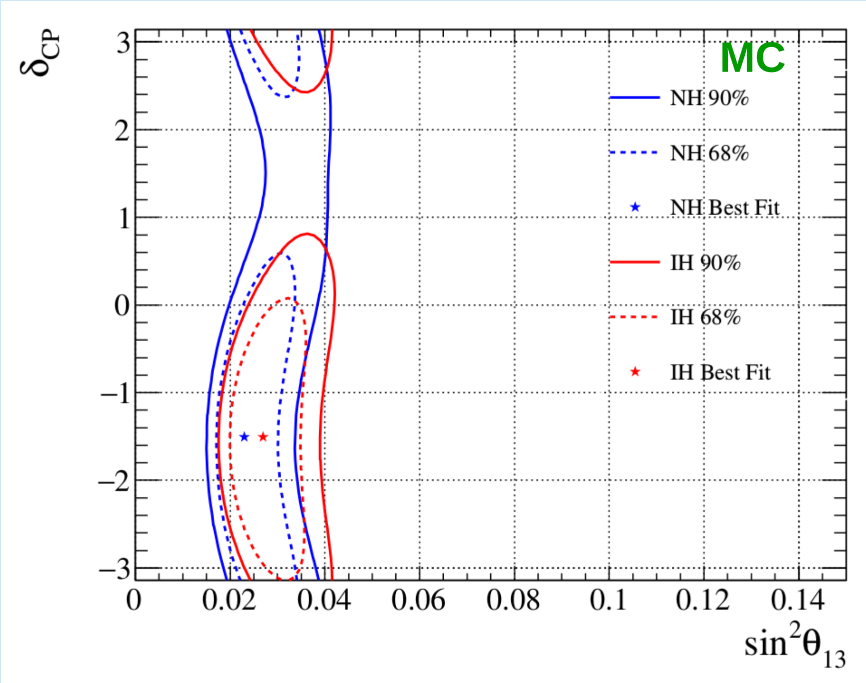


Using results of reactor experiments: $\sin^2(\theta_{13})=0.0219\pm0.0012$ (PDG 2016)

Results
θ_{13} and δ – T2K only

- Smaller contours than expected from sensitivity
- θ_{13} results compatible with measurements from reactor experiments
- Favors values of δ~-π/2 with T2K data alone

MC Sensitivity



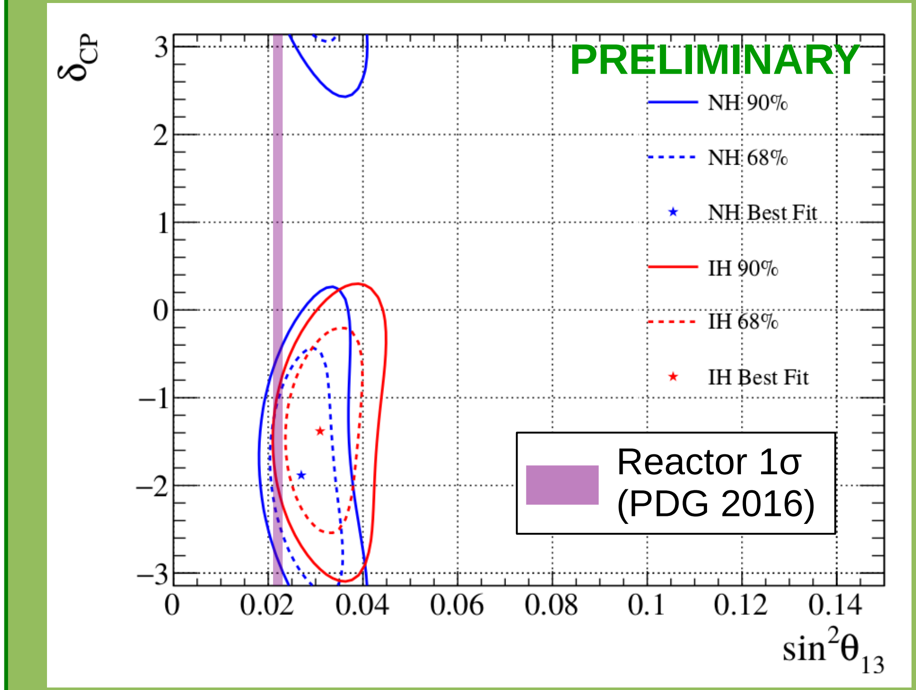
δ=-1.601

$\sin^2(\theta_{23})=0.528$

$\Delta m^2_{32}=2.509\times10^{-3}\ \mathrm{eV}^2c^{-4}$

$\sin^2(\theta_{13})=0.0219$

Data fit

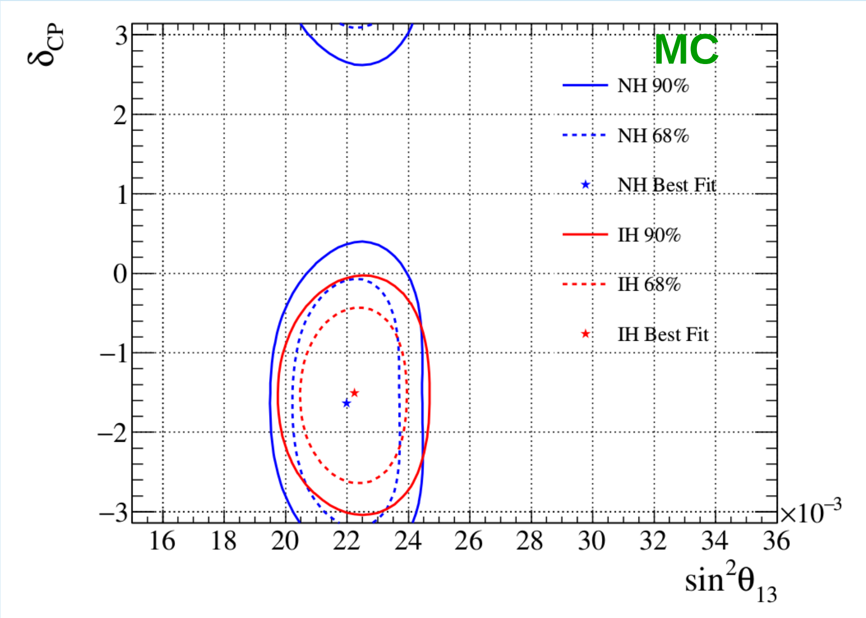


Fixed $\Delta\chi^2$ 68% and 90% CL regions

Results
θ_{13} and δ – T2K + reactor

Fixed $\Delta\chi^2$ 68% and 90% CL regions

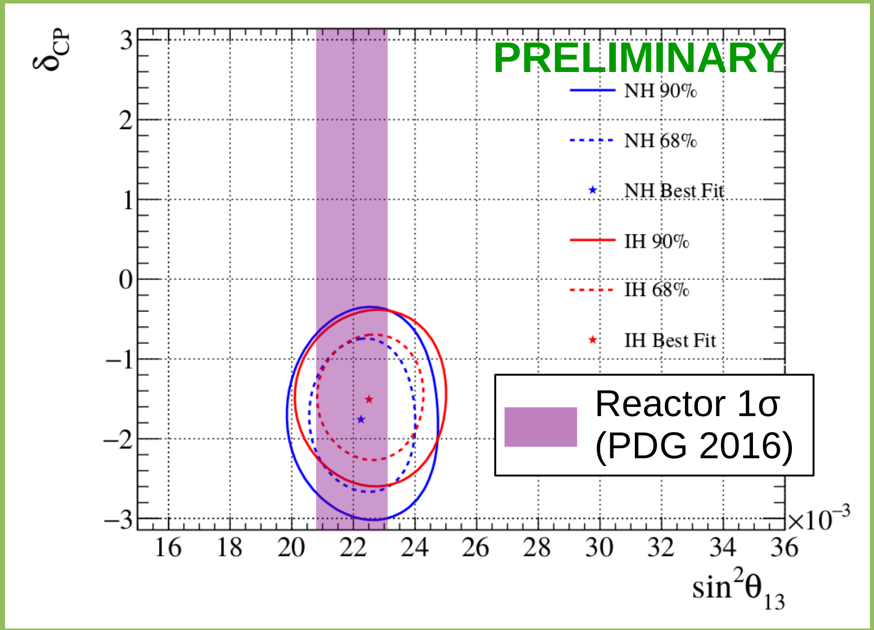
MC Sensitivity



δ=-1.601
$\sin^2(\theta_{23})$=0.528

$\Delta m^2_{32}=2.509*10^{-3}$ eV^2c^{-4}
$\sin^2(\theta_{13})$=0.0219

Data fit

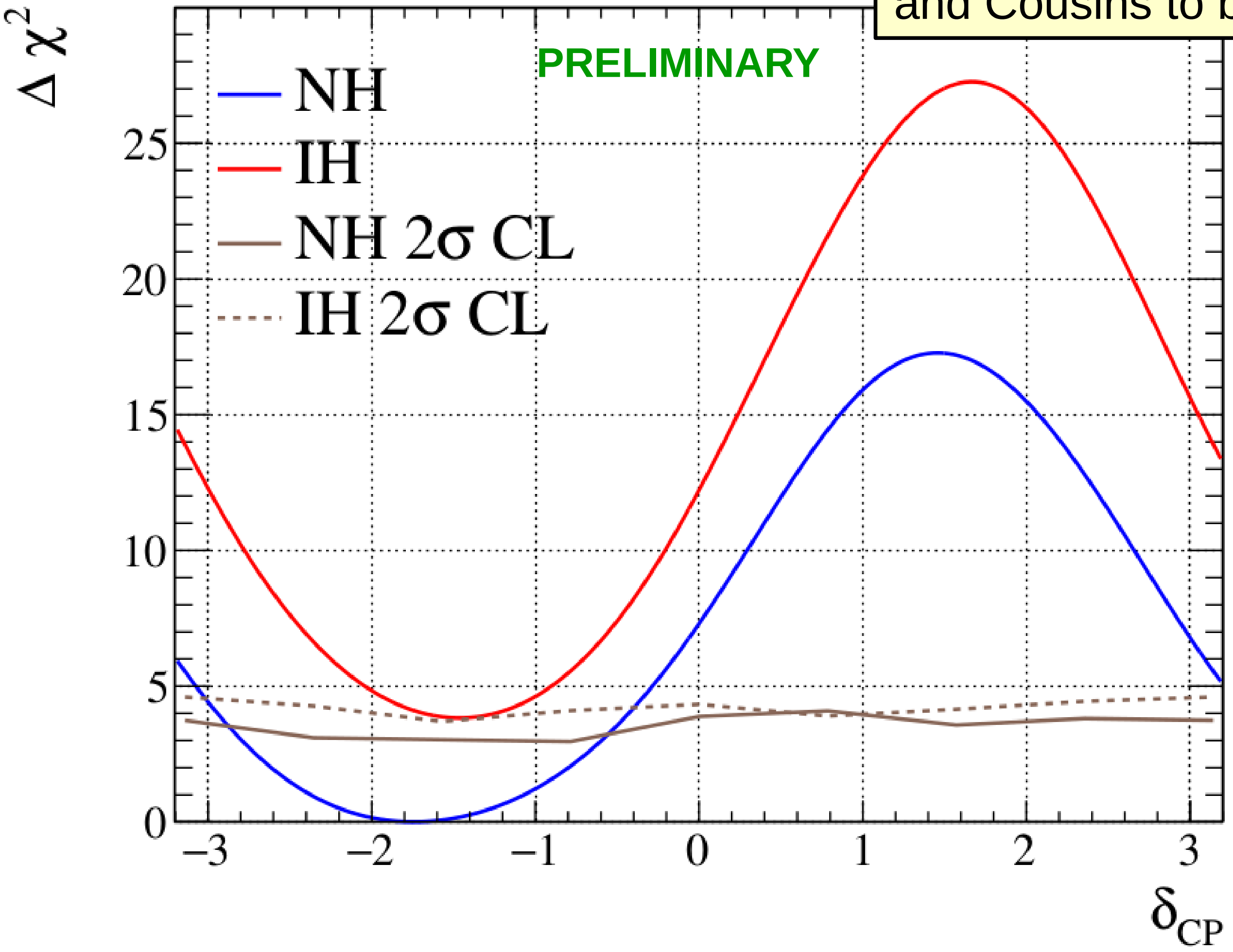


Using results of reactor experiments: $\sin^2(\theta_{13})=0.0219\pm0.0012$ (PDG 2016)

Results
δ – T2K + reactor

Using results of reactor experiments: $\sin^2(\theta_{13})=0.0219\pm0.0012$ (PDG 2016)

Use unified approach by Feldman and Cousins to build CL intervals

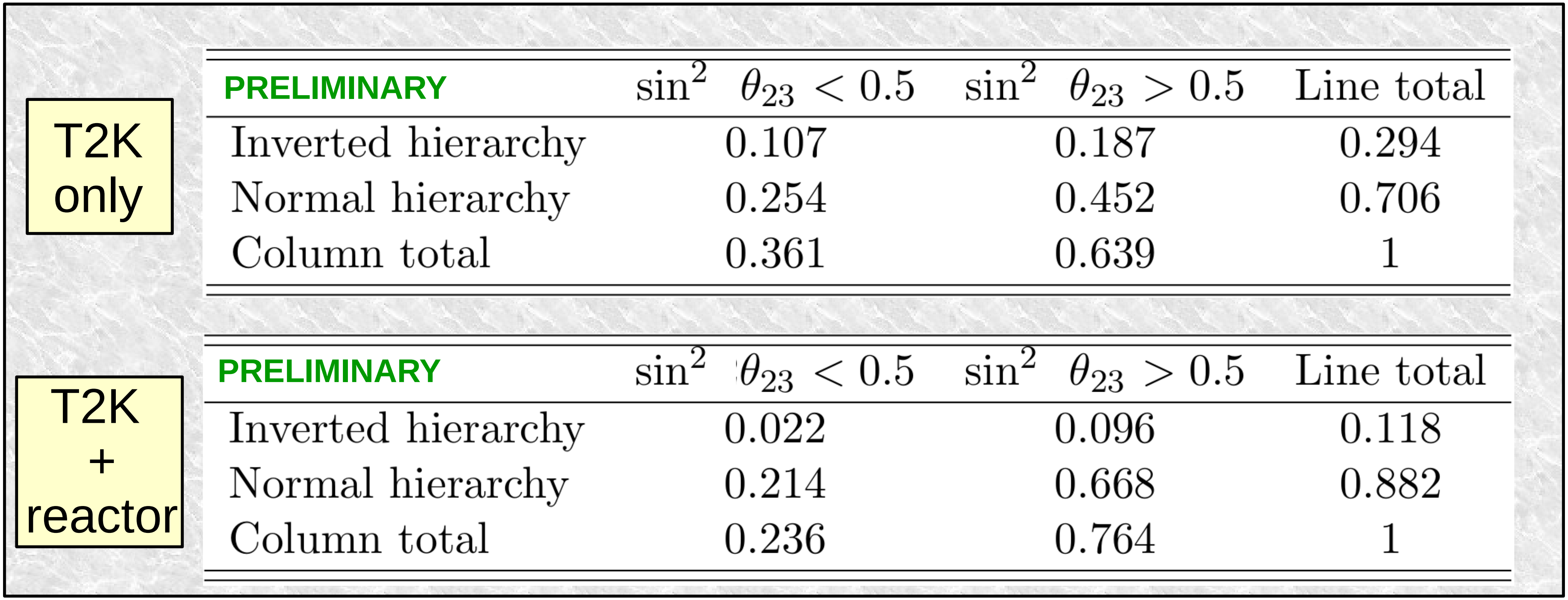


2σ intervals:
[-2.894,-0.561] (NH)
[-1.504,-1.265] (IH)

CP-conserving values outside of 2σ intervals
→ **Conservation of CP symmetry in neutrino oscillations excluded at 2σ**

Results
Model comparisons

Compare posterior probabilities of different models



T2K only

PRELIMINARY	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Inverted hierarchy	0.107	0.187	0.294
Normal hierarchy	0.254	0.452	0.706
Column total	0.361	0.639	1

T2K + reactor

PRELIMINARY	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Inverted hierarchy	0.022	0.096	0.118
Normal hierarchy	0.214	0.668	0.882
Column total	0.236	0.764	1

Mild preference for normal hierarchy and octant $\sin^2\theta_{23}>0.5$

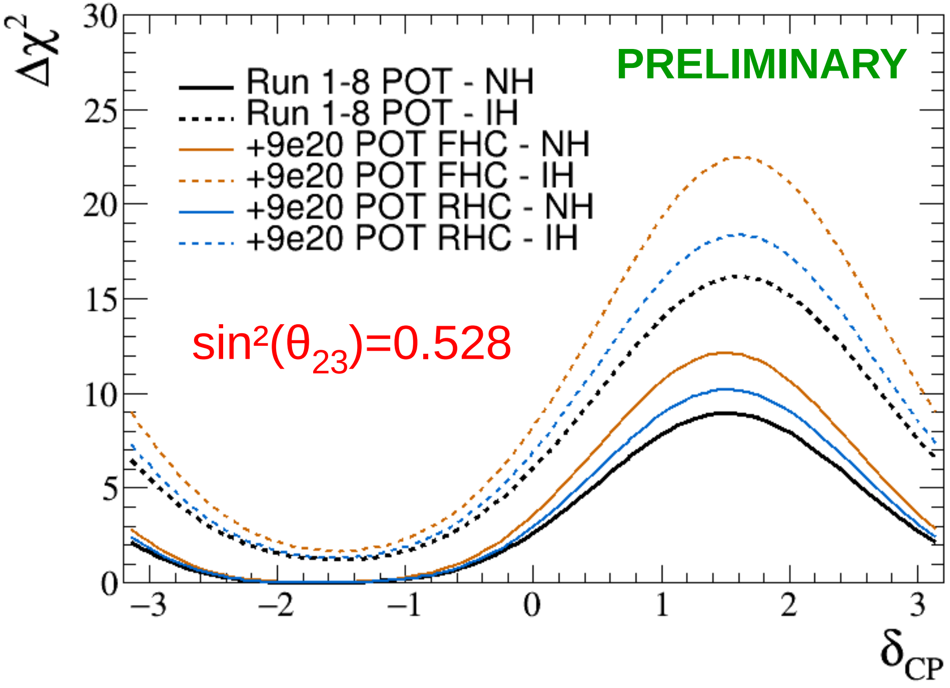
Perspective for the future

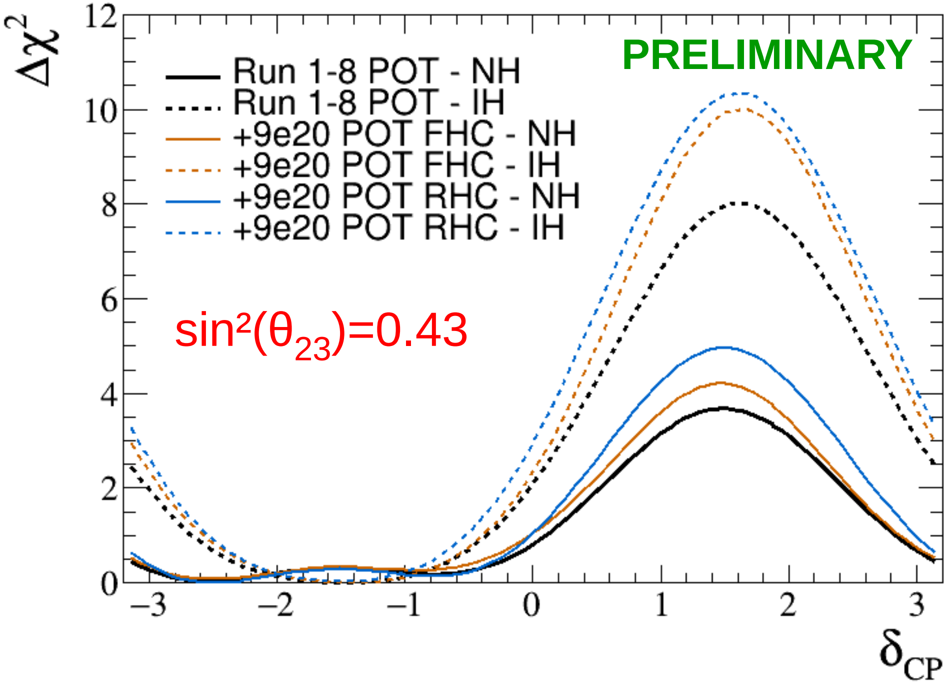
Short term
Sensitivity with one additional year of data

- Visible increase in the sensitivity to δ with an additional 9e20 POT
- Most interesting running mode depends on true value of θ_{23}
- Running in anti-neutrino mode allows us to look for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\bar{\nu}_e$ appearance sensitivity

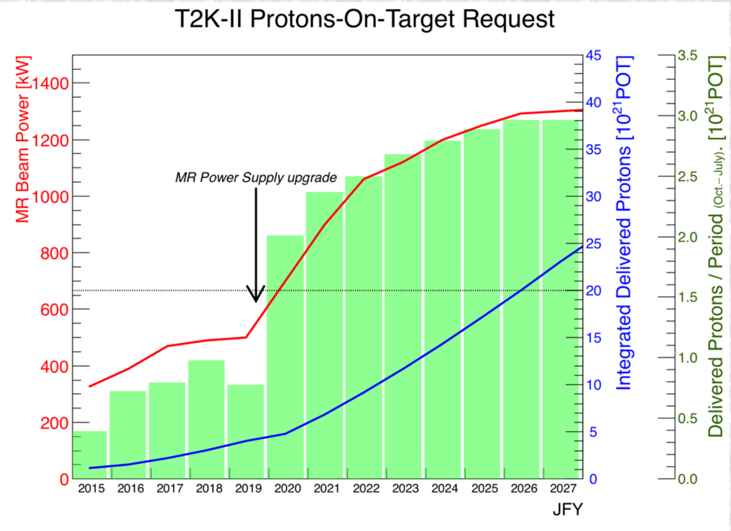
	p-value	σ
Previous result (run 1-7)	0.0477553	1.98
Current analysis (run 1-8)	0.0372762	2.08
Add 9e20 POT RHC	0.00647045	2.72



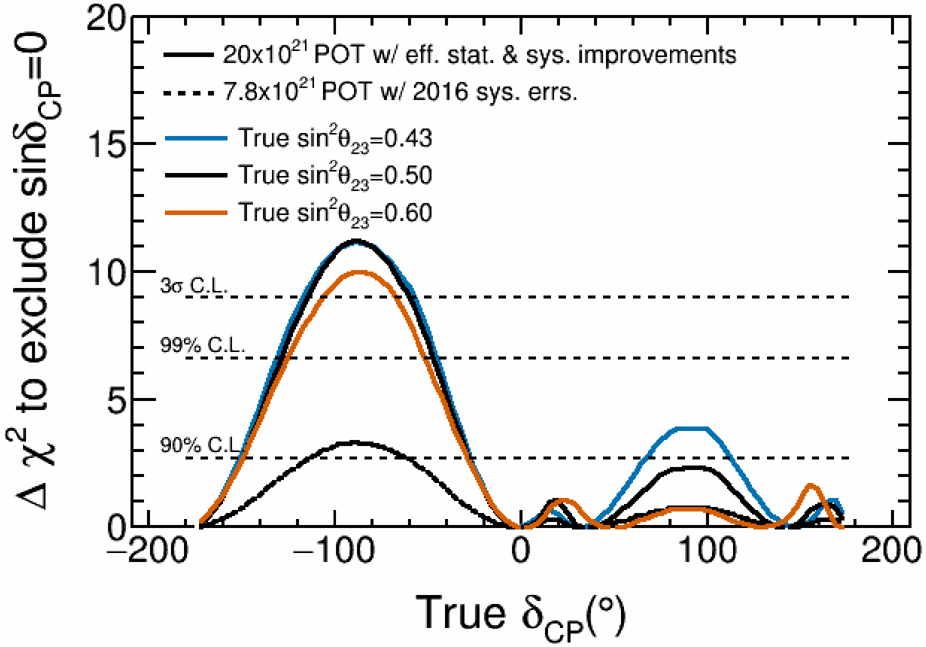


Medium term
Proposal for extended run: T2K-II

- Proposed an extended run until ~2025
- Increased statistics: 7.8×10^{21} POT → 20×10^{21} POT + analysis improvements
- Can exclude CP conservation at 3σ in favorable case



Beam intensity improvement
~400kW → 1.3MW



Assumes:
- unknown mass hierarchy
- 50% effective stat improvements
- 1/3 reduction of systematics

T2K phase 2 received stage 1 status at summer 2016 J-PARC PAC

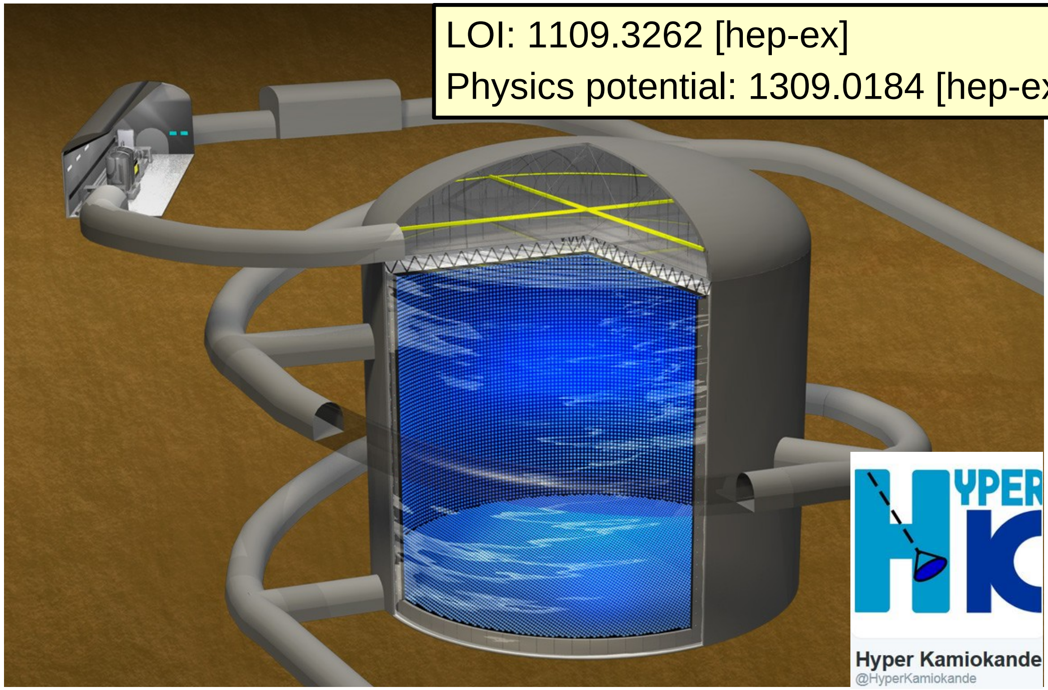
Longer term
Hyper-Kamiokande

- 60m height x 74m diameter tank
- 190 kton fiducial volume (SK:22.5 kton)
- Improved photo-sensors
- Large statistics to study neutrino oscillations

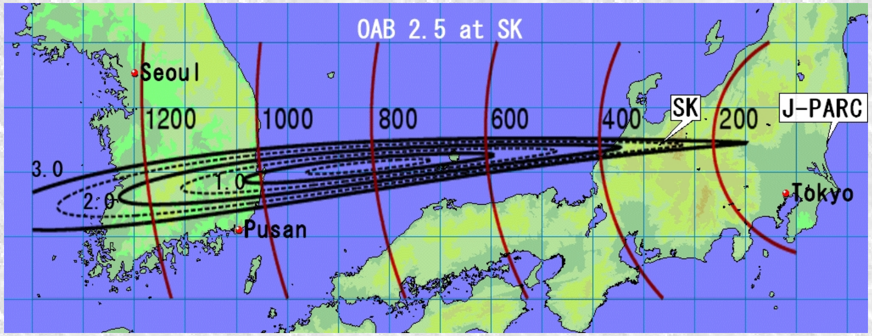
Rich physics program:

- Long-baseline neutrinos
- Atmospheric neutrinos
- Proton decay
- Solar / astrophysical / supernova neutrinos

LOI: 1109.3262 [hep-ex]
Physics potential: 1309.0184 [hep-ex]



Also proposal to have 2nd tank in Korea



Hyper-Kamiokande was selected as one of seven highest priority large scale project in MEXT 2017 roadmap

Summary

- T2K almost doubled amount of neutrino running mode data since 2016
- Implemented improved model for neutrino interactions and their uncertainties
- New reconstruction algorithm, additional background rejection cut and optimized fiducial volume cut for the far detector: increased statistics for appearance samples, and better signal over background ratio for disappearance samples
- CP-conserving values of δ excluded at 2σ
  2σ intervals (in rad): [-2.894,-0.561] (NH), [-1.504,-1.265] (IH)
- Finalizing results for the parameters $\sin^2(\theta_{23})$ and Δm^2_{32}, potential effects of additional interaction uncertainties have to be understood
- Proposals for an extended T2K run and next generation experiment Hyper-Kamiokande

Additional slides

The T2K experiment
The collaboration

~ 500 members, 62 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

Switzerland

ETH Zurich
U. Bern
U. Geneva

Italy

INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan

ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Metropolitan U.
U. Tokyo
Yokohama National U.

Spain

IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Poland

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

Russia

INR

United Kingdom

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

USA

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

Neutrino oscillations
Looking for second order effects

Oscillation probabilities for a muon neutrino beam

$$P(\nu_\mu \to \nu_e) = \boxed{4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}}$$

Leading term

$\boxed{\theta_{13}}$

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

CPC

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

CPV

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

Solar

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \Big(\underbrace{\cos^4\theta_{13} \times \sin^2 2\theta_{23}}_{\text{Leading-term}} + \underbrace{\sin^2 2\theta_{13} \times \sin^2\theta_{23}}_{\text{Next-to-leading}}\Big) \times \sin^2\frac{\Delta m_{31}^2 \times L}{4E}$$

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

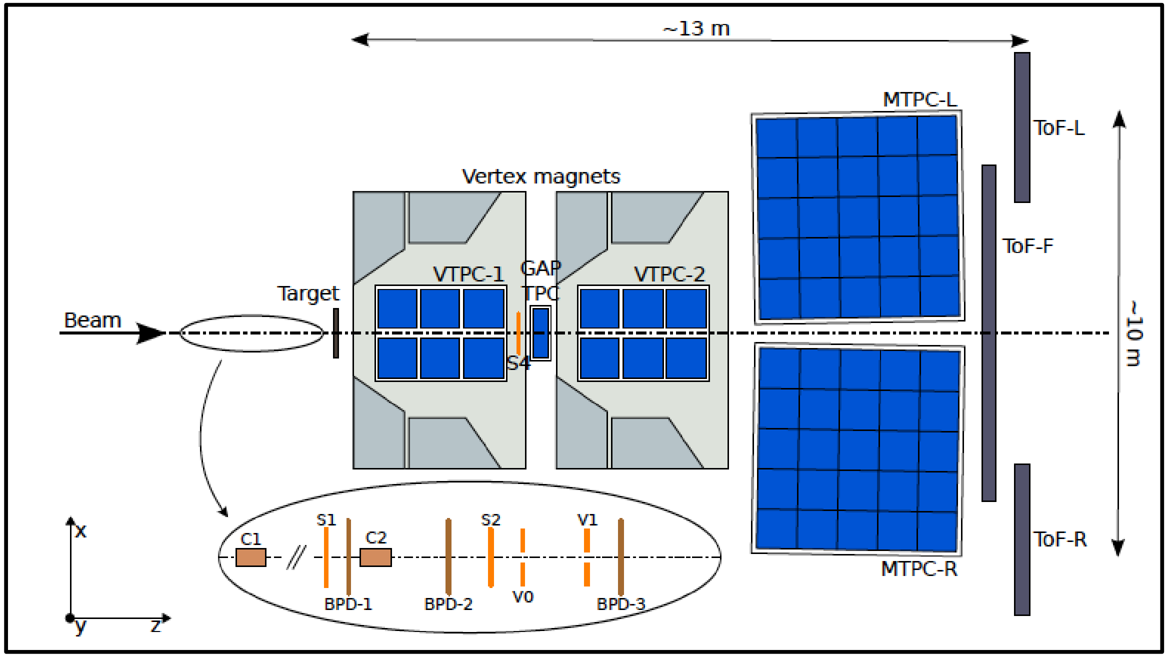
$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

(courtesy of A. Ichikawa/T2K reference slides)

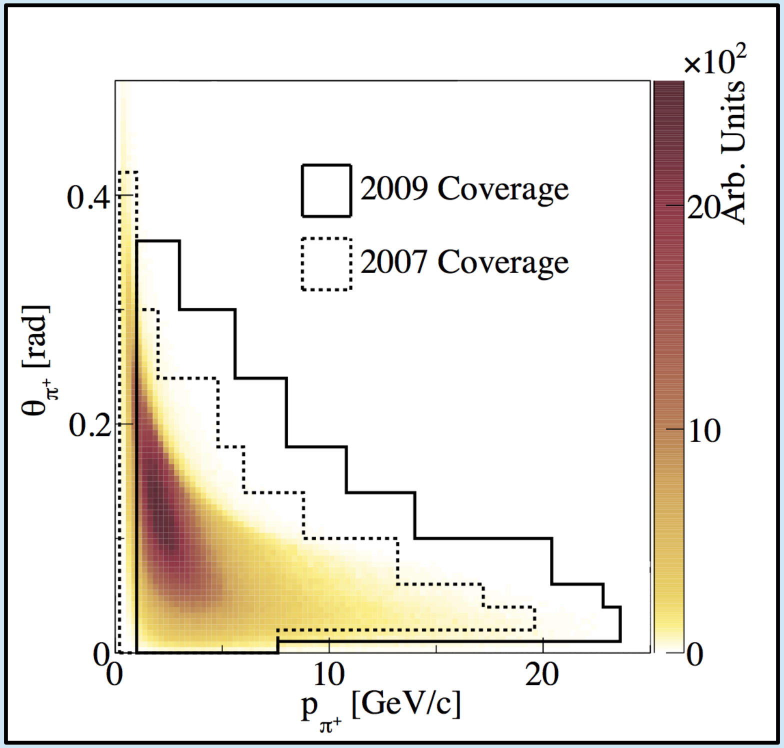
Analysis description
Hadron production measurements

The NA61/Shine experiment measures hadron production from 30 GeV protons on carbon

2 targets:
- ‘thin’ ~0.04λ
- Replica T2K target



Covers most of the phase space for T2K neutrino production



Long-baseline experiments
First measurements

In first approximation LBL experiments can measure some of the PMNS parameters through exclusive channels:

Far detector ν_μ events

ν_μ → ν_X disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \boxed{\sin^2(2\theta_{23})}\sin^2\left(1.27\frac{\boxed{\Delta m^2}\times L}{E}\right)$$

Precise measurement of θ_{23} and $|\Delta m^2|$

Far detector ν_e events

ν_μ → ν_e appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23})\boxed{\sin^2(2\theta_{13})}\sin^2\left(1.27\frac{\Delta m^2\times L}{E}\right)$$

- Observation of ν_e appearance
- Measurement of θ_{13}

And similar measurements for anti-neutrinos

Long baseline experiments
Main current physics goals

Look for more subtle effects by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

- CP violation: is $\sin(\delta) \neq 0$?
- Mass hierarchy: sign of Δm^2_{32} ?

Full probability in vacuum:

$$P(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}$$
$$+ 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$- 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\boxed{\sin\delta}\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$+ 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$

$$\sin^2\Delta_{ij} = \sin^2(1.27\,\Delta m_{ij}^2 \times L/E)$$

In matter leading term

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2 \times L}{E}\right)$$

Multiplied by $1+\frac{2a}{\Delta m_{31}^2}\left(1-2\sin^2(\theta_{13})\right)$

$(a \equiv 2\sqrt{2}\,G_F n_e E)$

$\nu \rightarrow \bar{\nu}$
$\delta \rightarrow -\delta$
$a \rightarrow -a$

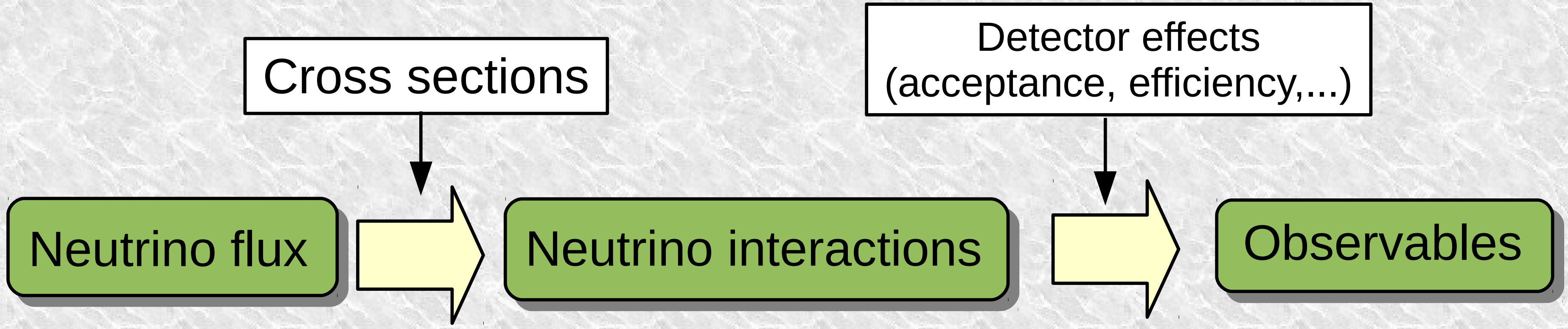
Not too long baseline (~300km):
Mainly effect of δ: **T2K** (~<27% vs ~10%)

Very long baseline: effect of δ and matter effect: **NOνA**

Systematic uncertainties
Near to far extrapolation

Detectors measure rate as a function of a reconstructed quantity from observables
e.g: reconstructed neutrino energy from lepton (p,θ)

Want to compare flux between far and near detectors, but have only access to those observables/reconstructed quantities



Cross sections

Detector effects
(acceptance, efficiency,...)

Neutrino flux → Neutrino interactions → Observables

<u>Differences between ND and FD</u>:

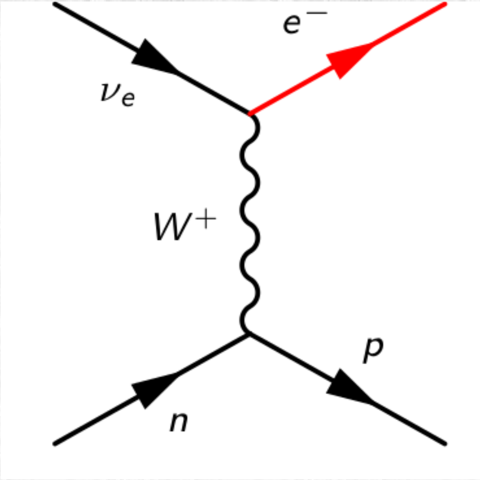
- different fluxes (oscillations)
- different target material
- different acceptance
- different detector technologies

→ Use models for extrapolation

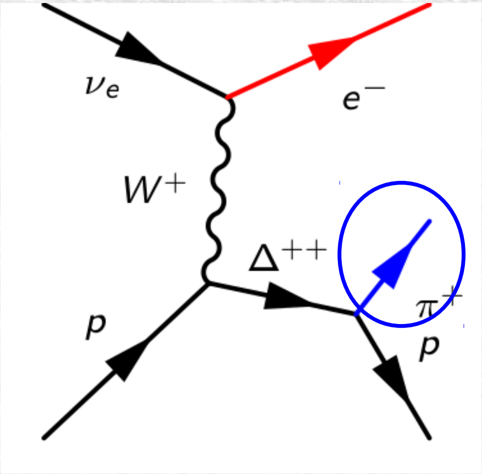
Systematic uncertainties
Neutrino interactions – why it matters

Different relations between neutrino energy and observables in detector for the different types of interactions

CCQE



CC Res $1\pi^+$



can be absorbed in nucleus

Different true energies → Different effect of oscillations at far detector

Same observables, but different near to far extrapolation

Systematic uncertainties
Neutrino interactions

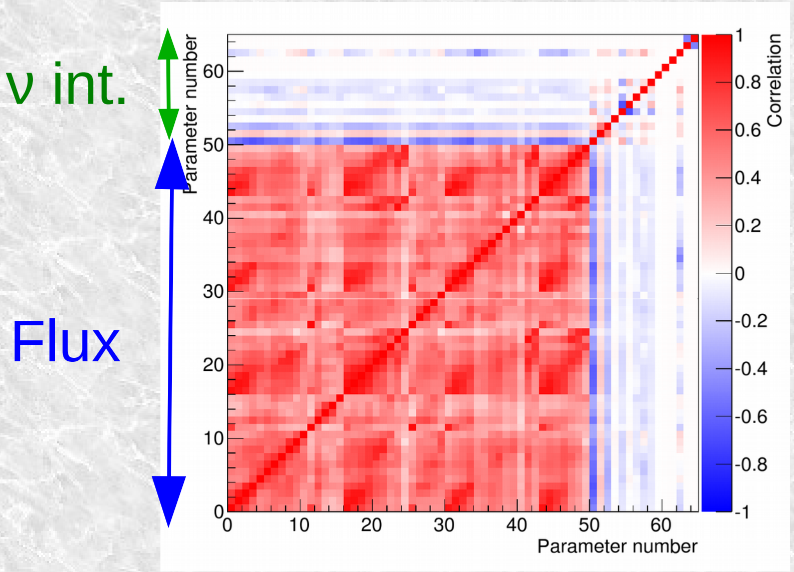
Different fluxes at near and far detectors (oscillations)

Different fraction of each interaction at ND and FD

Need uncertainties on rate and properties of each interaction type

- Select interaction models using external data
- Nominal predictions from NEUT
- Uncertainties on model parameters (M_A, pF,…)
- Additional normalization uncertainties for certain modes

Interaction uncertainties fitted in ND with flux uncertainties



Result applied to FD prediction

Additional sample – ν_e CC1π

- Selected by normal e-like selection + Michel e^-
- Increase ν-mode e-like statistics by ~11%
- 73% purity (defined as CC $\nu_\mu \rightarrow \nu_e$)