Neutrino oscillation results from T2K

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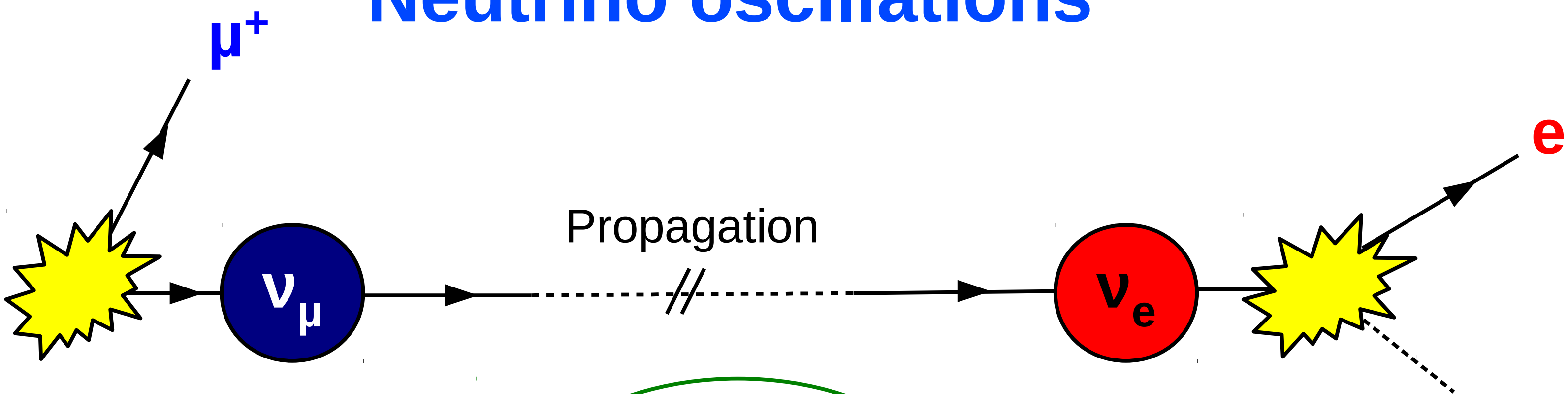
Fermilab Joint Experimental-Theoretical Physics Seminar
2016-11-02

Outline

- Neutrino oscillations and long-baseline experiments
- The Tokai to Kamioka experience
- Description of analysis chain
- Systematic uncertainties
- Dataset
- Oscillation analysis results
- Perspective for the future

Neutrino oscillations and long-baseline experiments

Neutrino oscillations



<u>Flavor eigenstates</u>
(interaction)

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

<u>Mass eigenstates</u>
(propagation)

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

$P(\nu_\alpha \rightarrow \nu_\beta)$ oscillates as a function of distance L traveled by the neutrino

- Amplitude of oscillations depends on the mixing matrix U
- Phase of the oscillation depends on energy and difference of mass squared: $\mathbf{\Delta m^2_{ij} L/E}$

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

Neutrino oscillations Parameters

In practice, for neutrino oscillations:

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{“Atmospheric”}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{“Reactor”}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{“Solar”}}$$

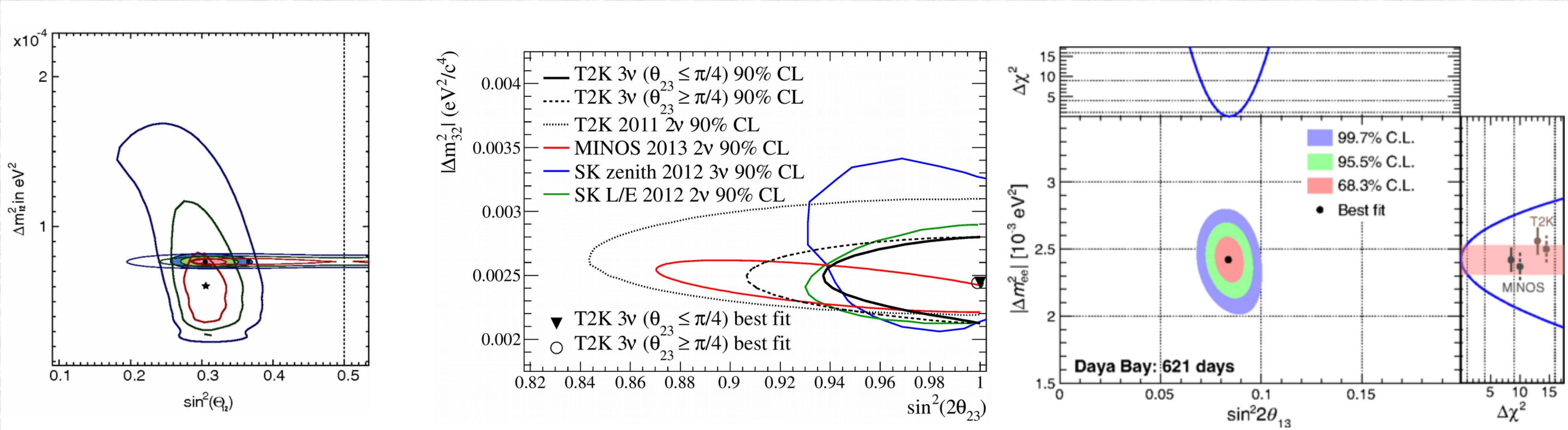
($c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$)

$P(\nu_\alpha \rightarrow \nu_\beta)$ depends on **6 parameters**:
- 3 mixing angles $\boldsymbol{\theta_{12}, \theta_{23}, \theta_{13}}$
- 2 independent mass splittings $\boldsymbol{\Delta m^2_{ij}}$
- 1 complex phase, the CP phase $\boldsymbol{\delta}$

Neutrino oscillations measurements Status

All mass splittings and mixing angles have been measured to be non-zero

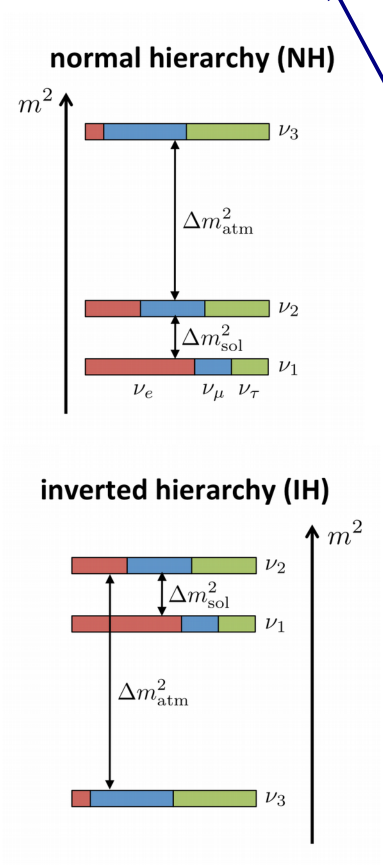
- Δm^2_{21} and θ_{21} from solar neutrinos and KamLAND
- $\Delta m^2_{32/31}$ and θ_{23} from atmospheric neutrinos and later beam neutrinos
- θ_{13} from reactor $\bar{\nu}_e$ disappearance and beam ν_e appearance



Observed **both the disappearance of neutrinos** (atmospheric, solar and reactor neutrinos) of a certain flavor, and **appearance of a different flavor** of neutrino (T2K, OPERA, NOνA)

Neutrino oscillations measurements
What are we still looking for?

Mass hierarchy:
$m_3 > m_2, m_1$?



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))

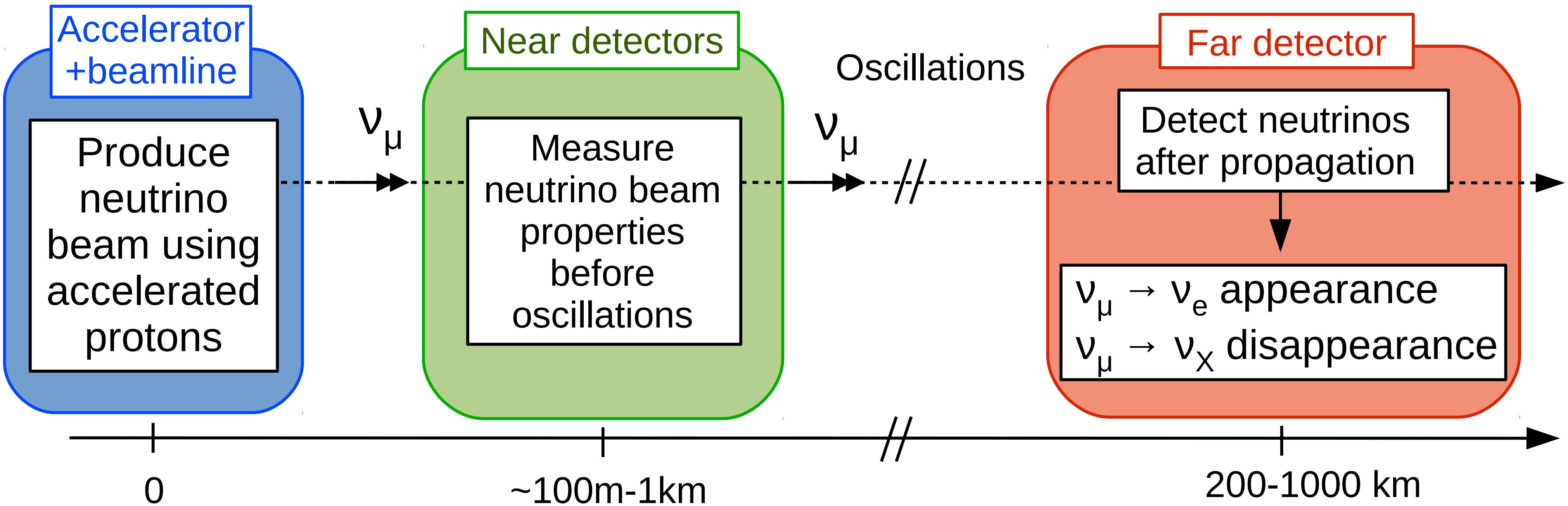
Octant of θ_{23}:
$\theta_{23}>\pi/4$?
$\theta_{23}<\pi/4$?

Violation of CP symmetry in neutrino oscillations?

+ more precise tests of the PMNS model via different channels

Long baseline experiments
Concept

Man-made neutrino beam produced by an accelerator



<u>Several advantages:</u>

- Better knowledge and control of neutrino flux
- Can select neutrino energy range
- Can use near detectors to reduce uncertainties
- Know direction of neutrinos reaching far detector
- Can produce either neutrino or anti-neutrino beam (compare oscillations of neutrinos and anti-neutrinos)

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

$\nu_\mu \rightarrow \nu_X$ disappearance

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

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

Far detector ν_e events

$\nu_\mu \rightarrow \nu_e$ appearance

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

- 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:

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

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

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

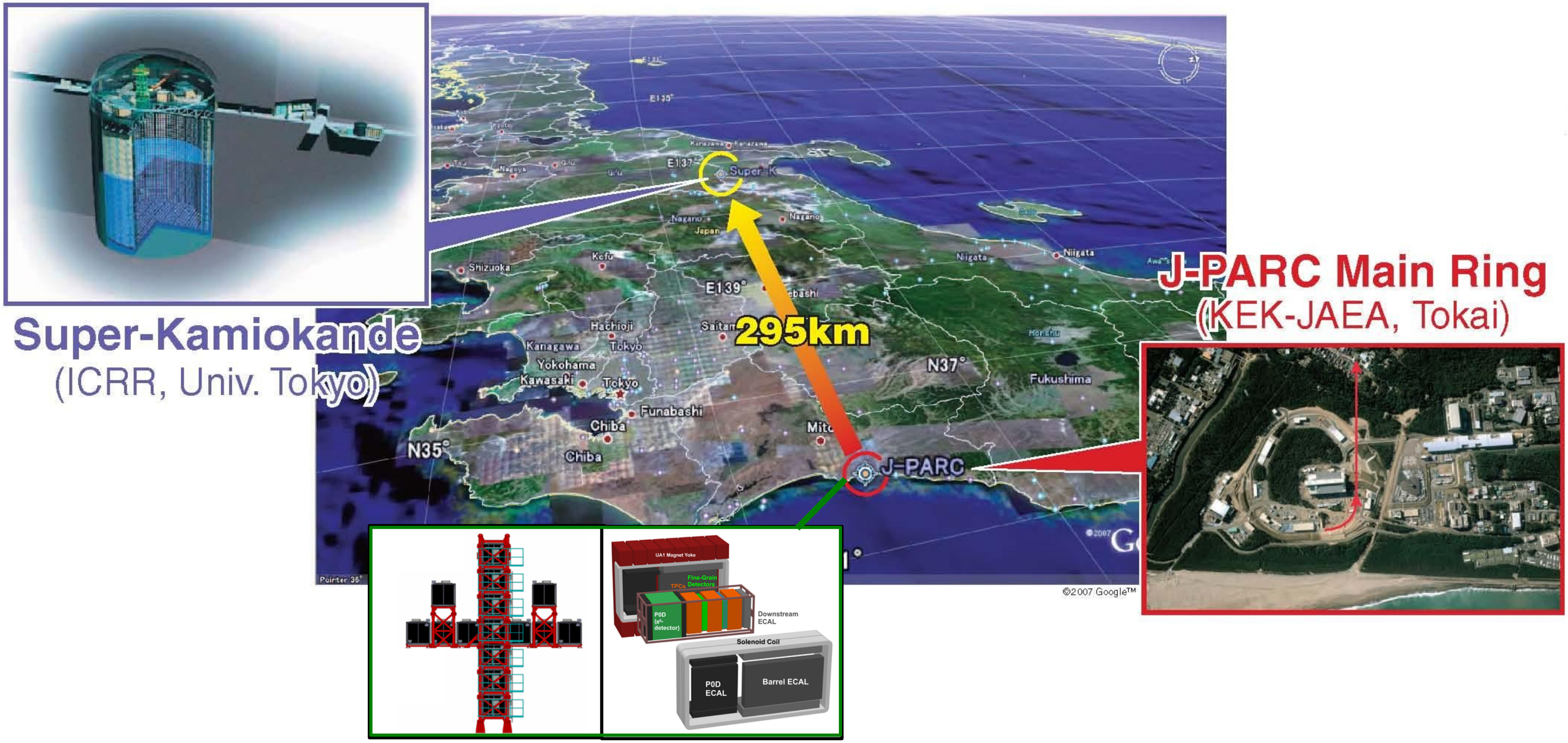
$$(a \equiv 2\sqrt{2} G_F n_e E)$$

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

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

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

The Tokai to Kamioka experiment



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

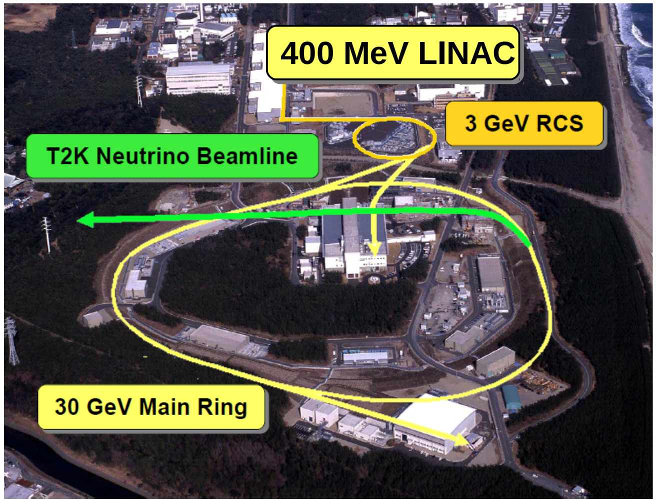
Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

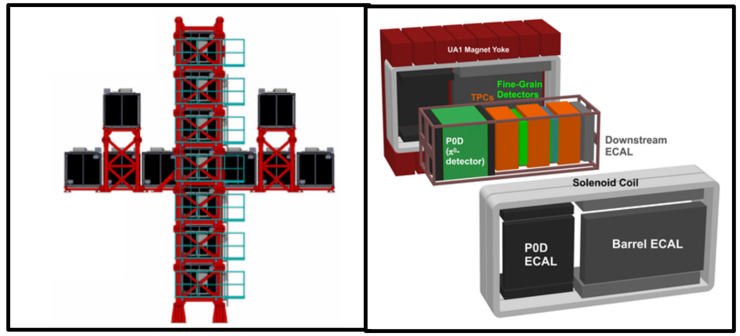
Russia
INR

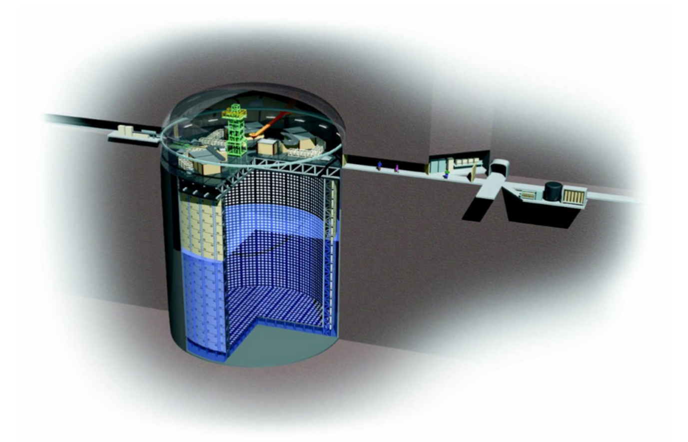
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

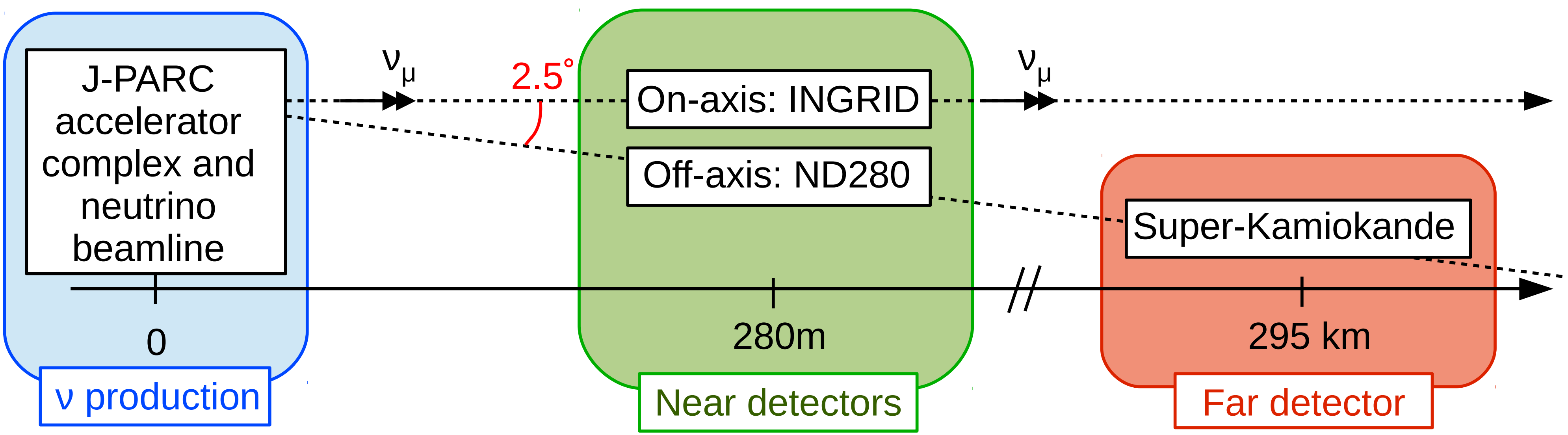
USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

The T2K experiment Overview





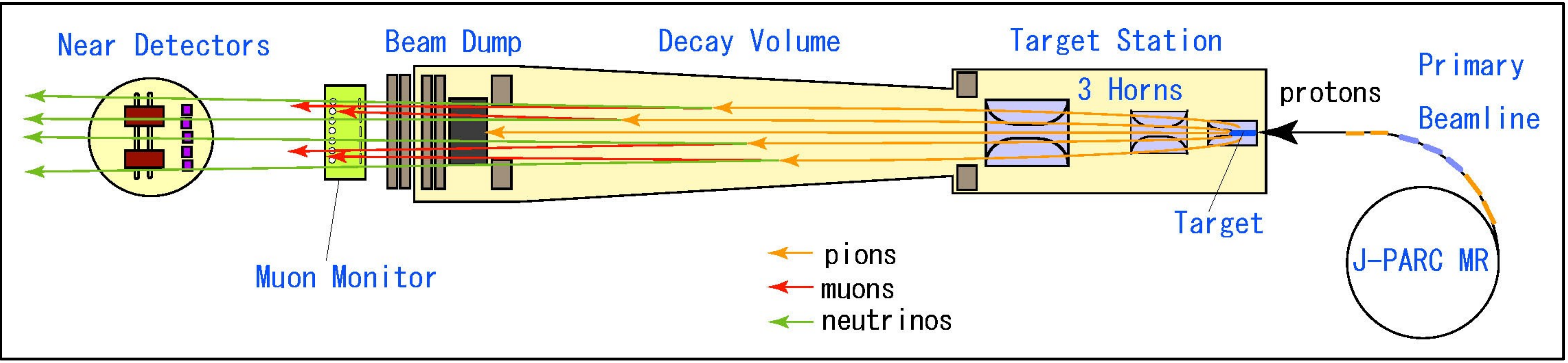




- Baseline: 295 km
- Off-axis beam

The T2K experiment
Neutrino production

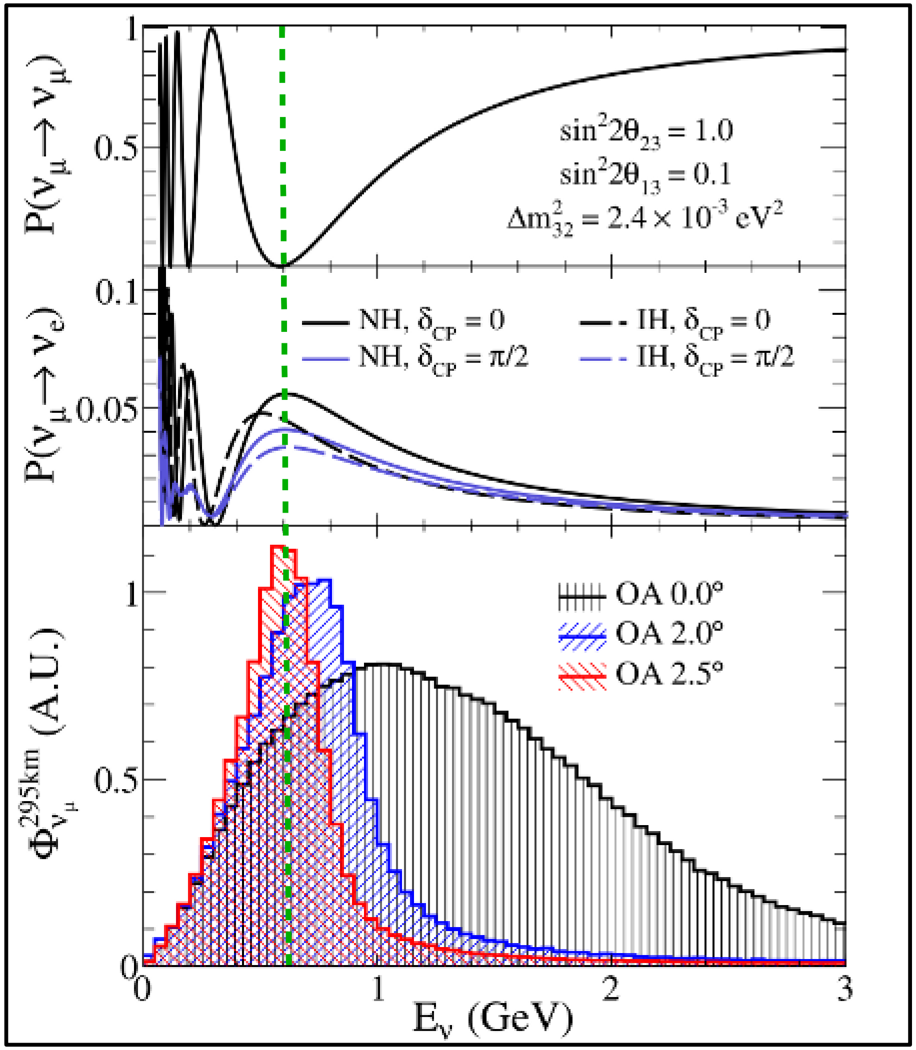
Conventional neutrino beam produced from 30 GeV protons

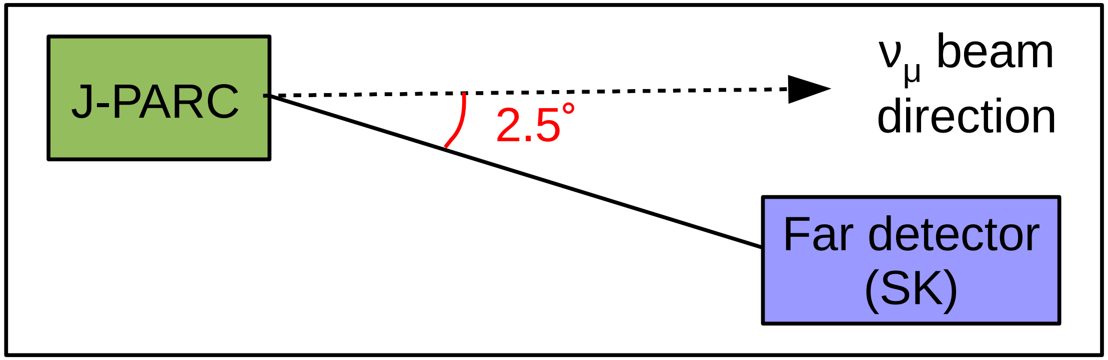


Almost pure $\nu_\mu/\bar{\nu}_\mu$ beam, with an intrinsic $\nu_e/\bar{\nu}_e$ component (<1% at peak)

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

The T2K experiment
Off-axis beam



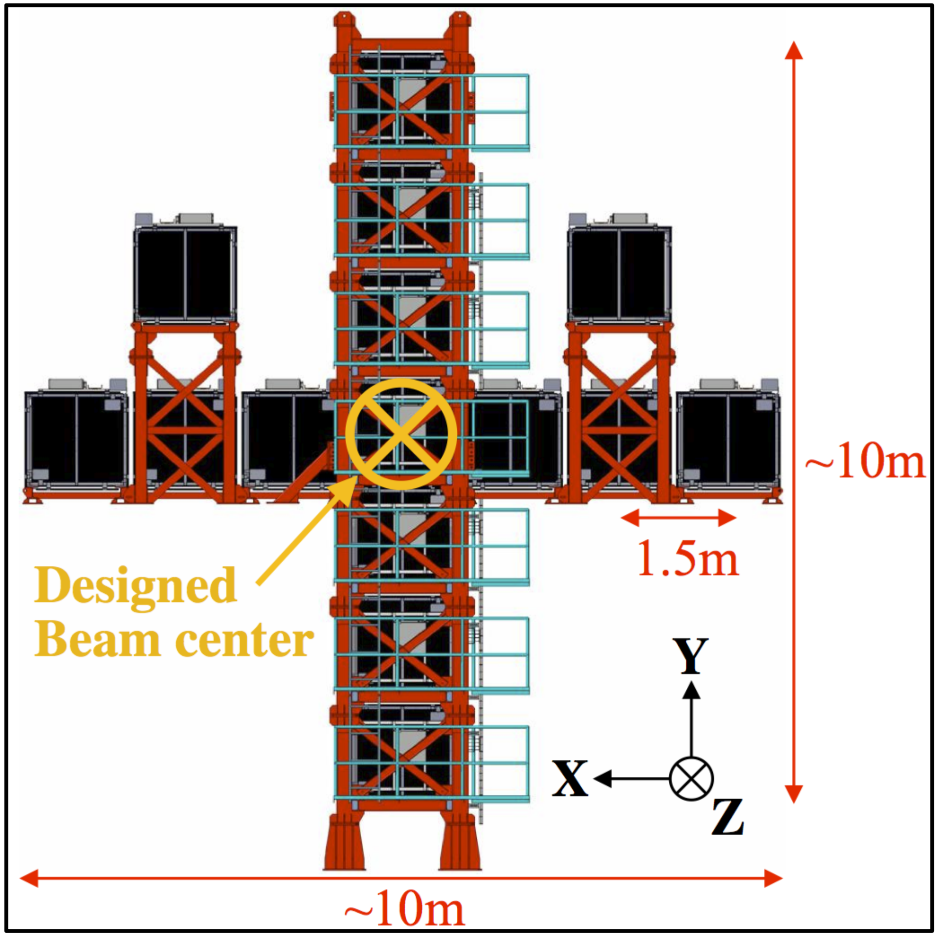


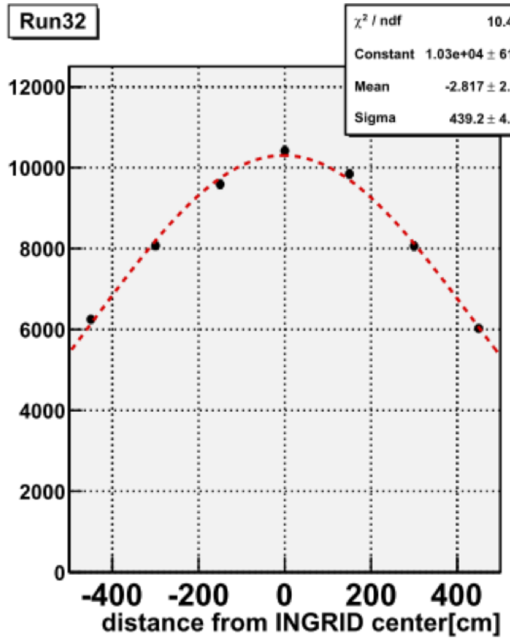
- Narrow band neutrino beam, peaked at oscillation maximum (0.6 GeV)
- Reduces high energy tail
- Reduces intrinsic ν_e contamination of the beam at peak energy
- Interactions dominated by CCQE mode

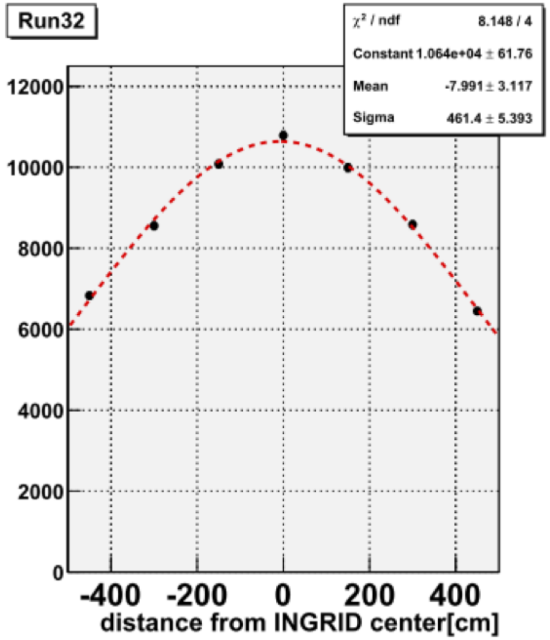
The T2K experiment
Near detectors

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

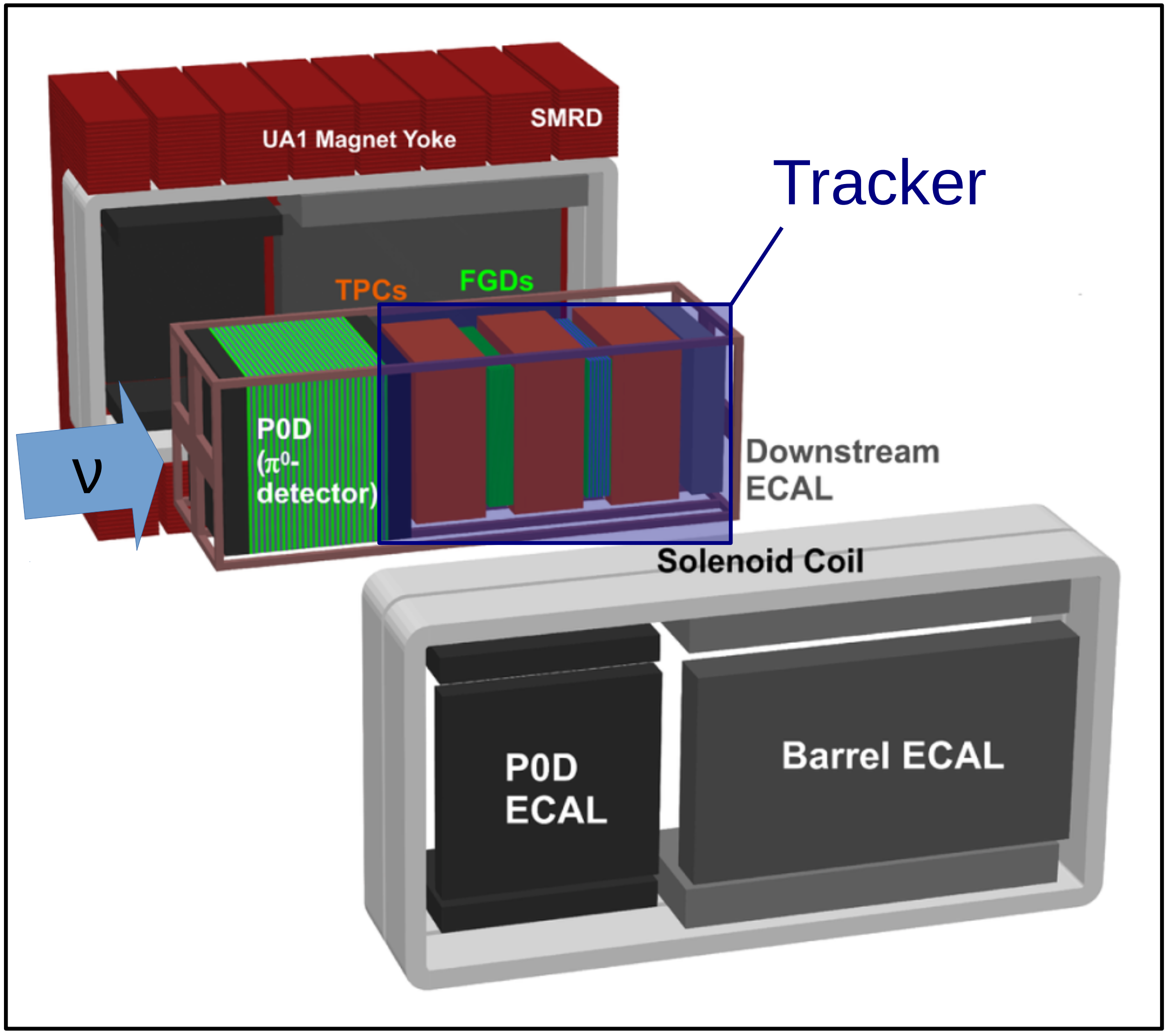




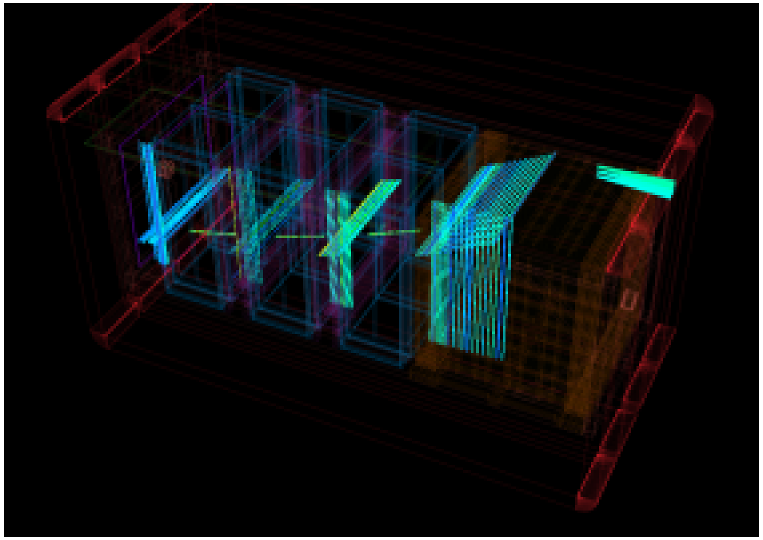


The T2K experiment
Off-axis near detectors

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



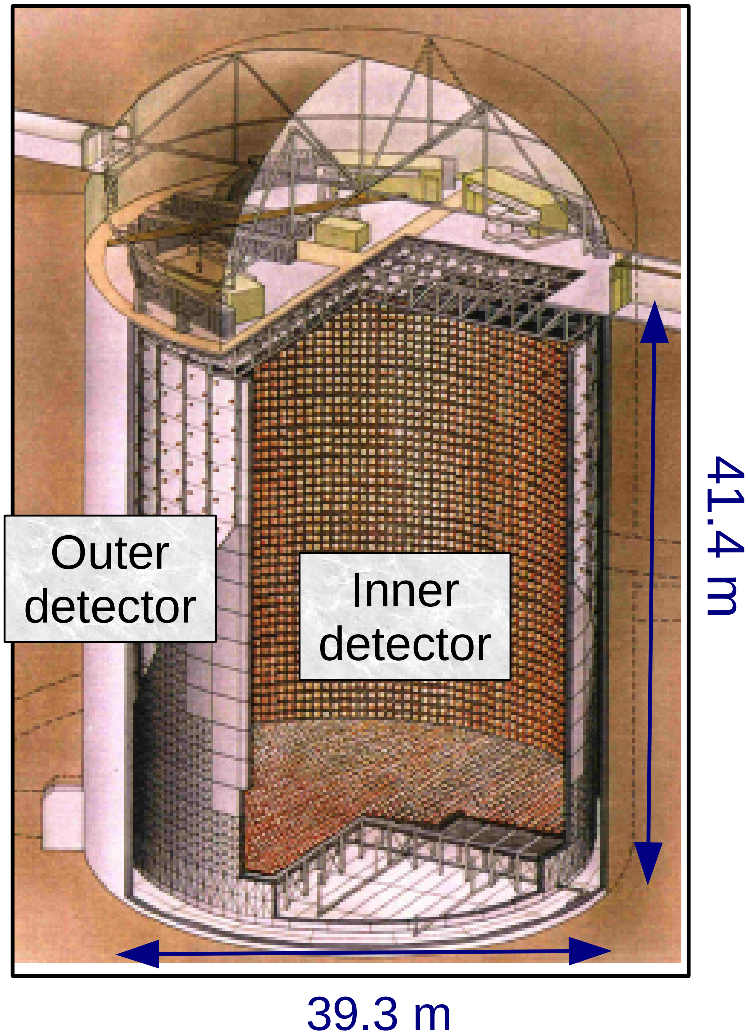
- Several detectors inside a 0.2 T magnetic field
- Good tracking capabilities
- 'Tracker' used to constrain flux and interaction uncertainties for oscillation analysis
- Rich cross-section measurement program



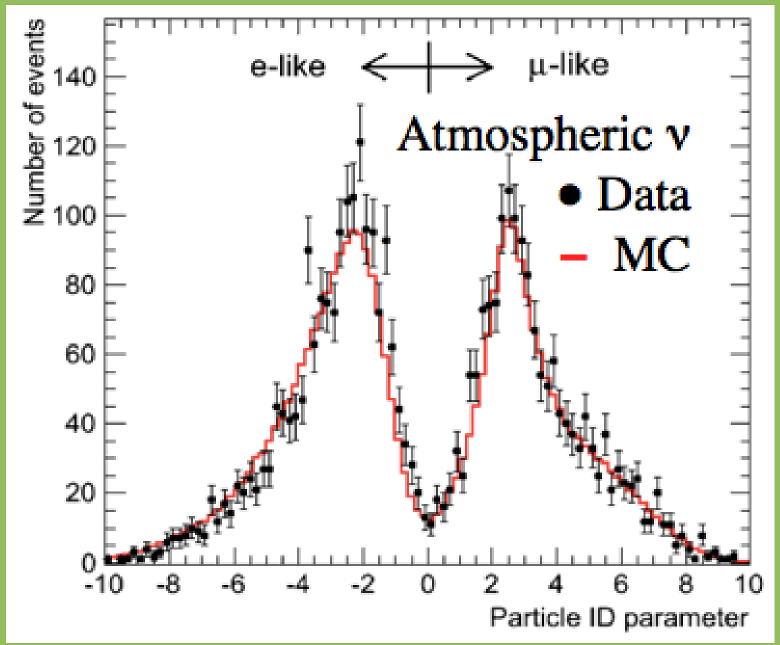
The T2K experiment
Far detector: Super-Kamiokande

Located 295 km from the target
Synchronized with beamline via GPS

- 50 kt (22.5 kt fiducial) water Cherenkov detector
- Operational since 1996



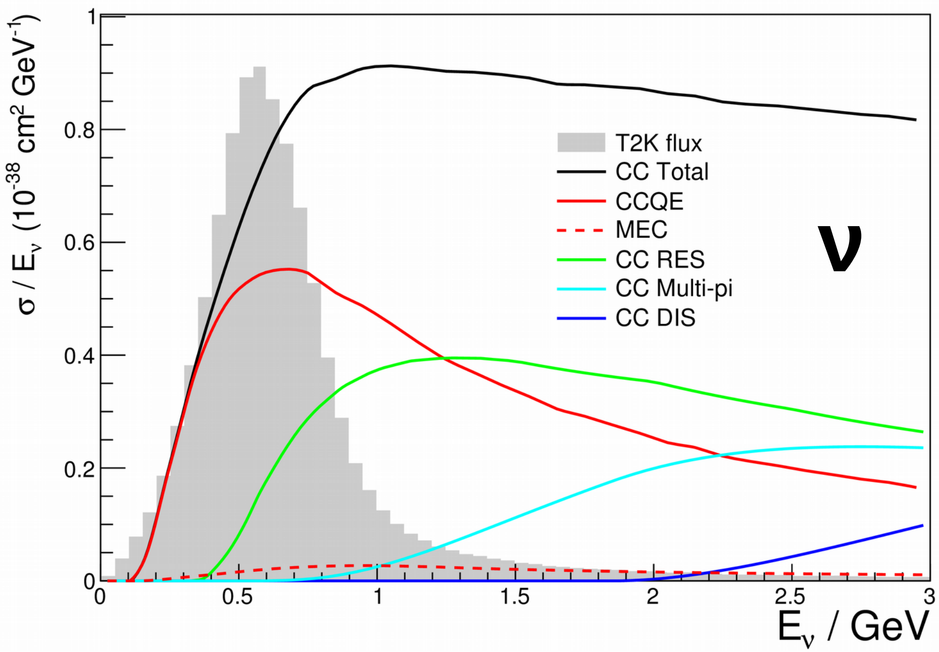
Good separation between $\mu^{\pm}$ and $e^{\pm}$ (separate ν_{μ} and ν_{e} CC interactions)

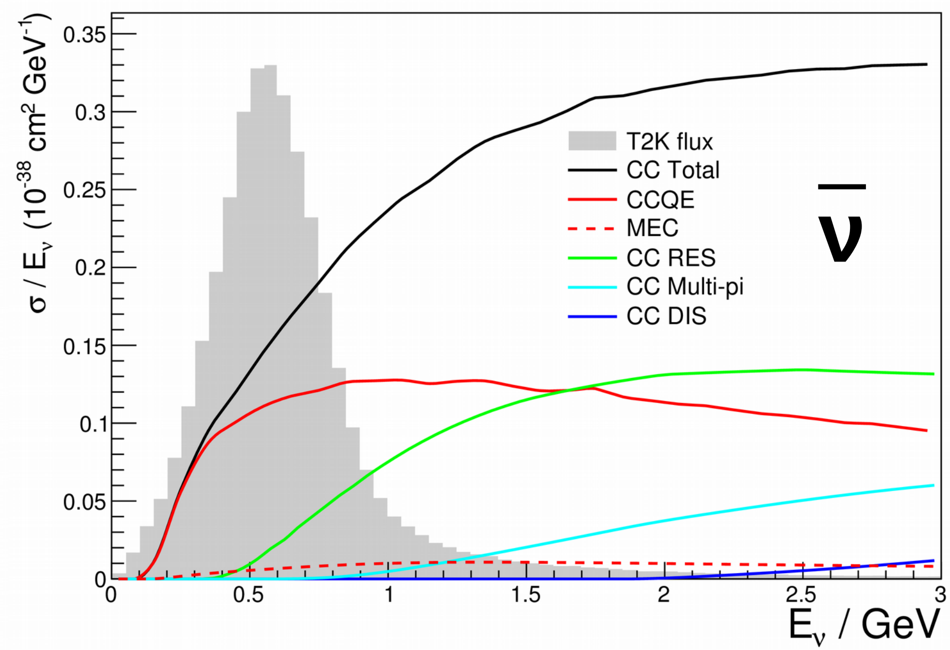


No magnetic field: cannot **separate ν and $\bar{\nu}$ on an event by event basis**

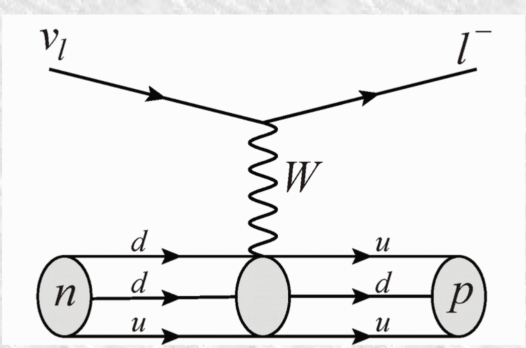
The T2K experiment
Neutrino interactions

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

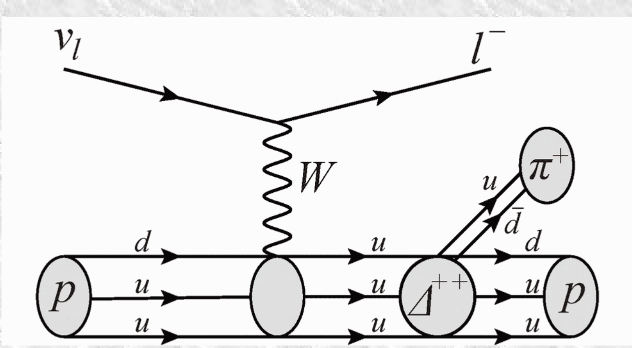




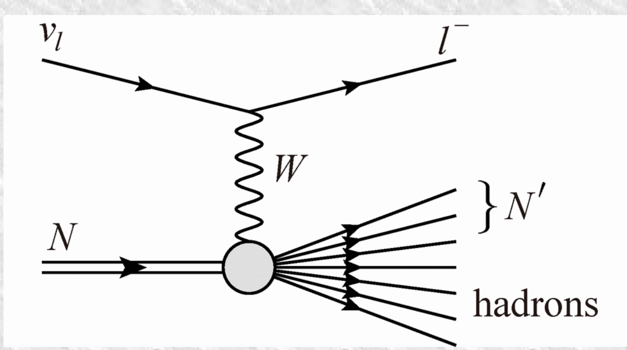
CCQE



CC RES



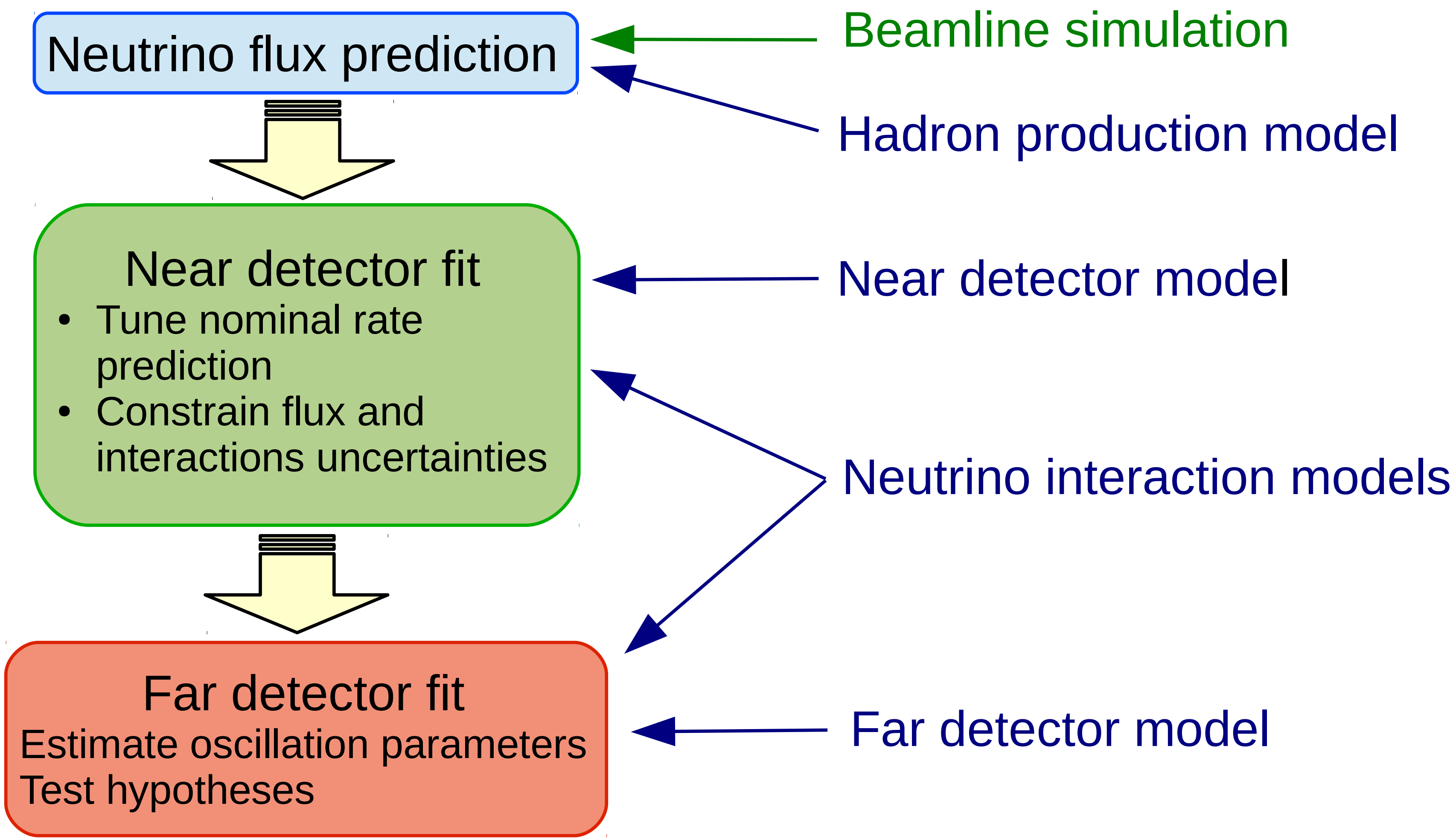
CC DIS/Multi-pi



Oscillation analysis
Analysis description

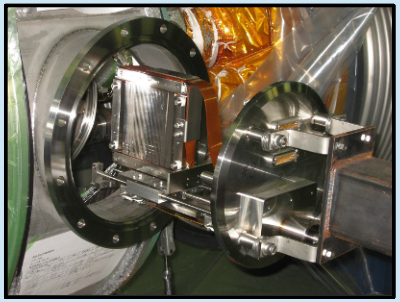
Analysis description overview

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

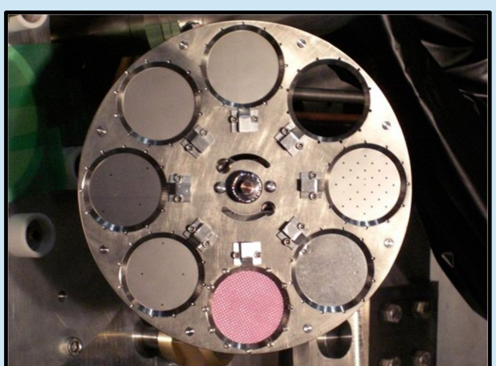


Analysis description
Neutrino flux prediction

Proton beam properties



Measured by beam monitors



Hadron production in target

$\pi^{\pm}$

$K^{\pm}$

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

Propagation and decay of hadrons in secondary beamline

$\mu^{\pm}$

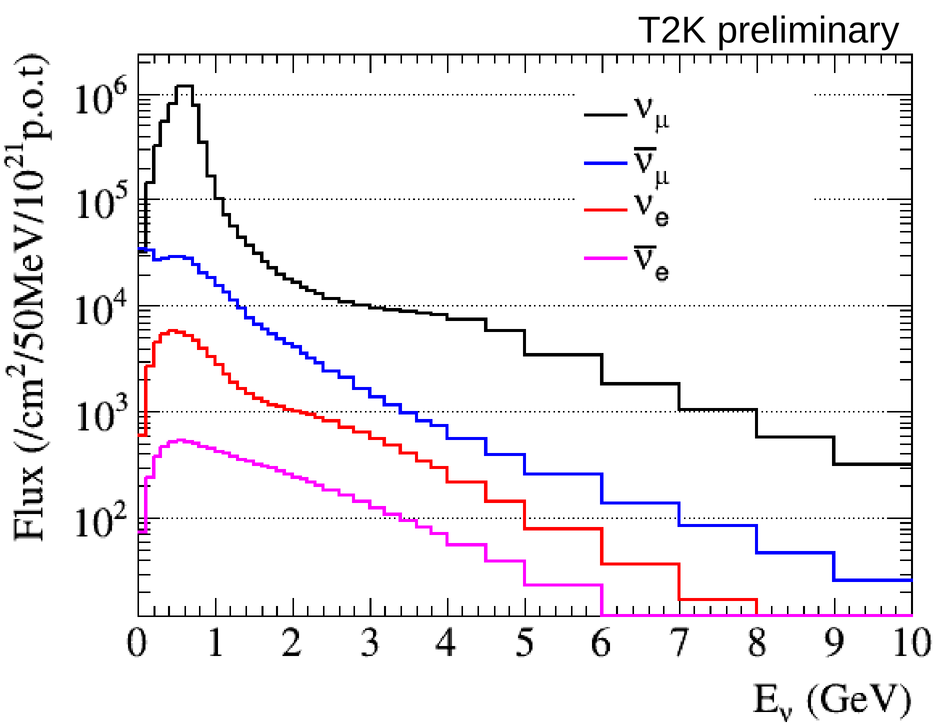
$\nu_{\mu}/\bar{\nu}_{\mu}$

GEANT3 simulation
GCALOR package

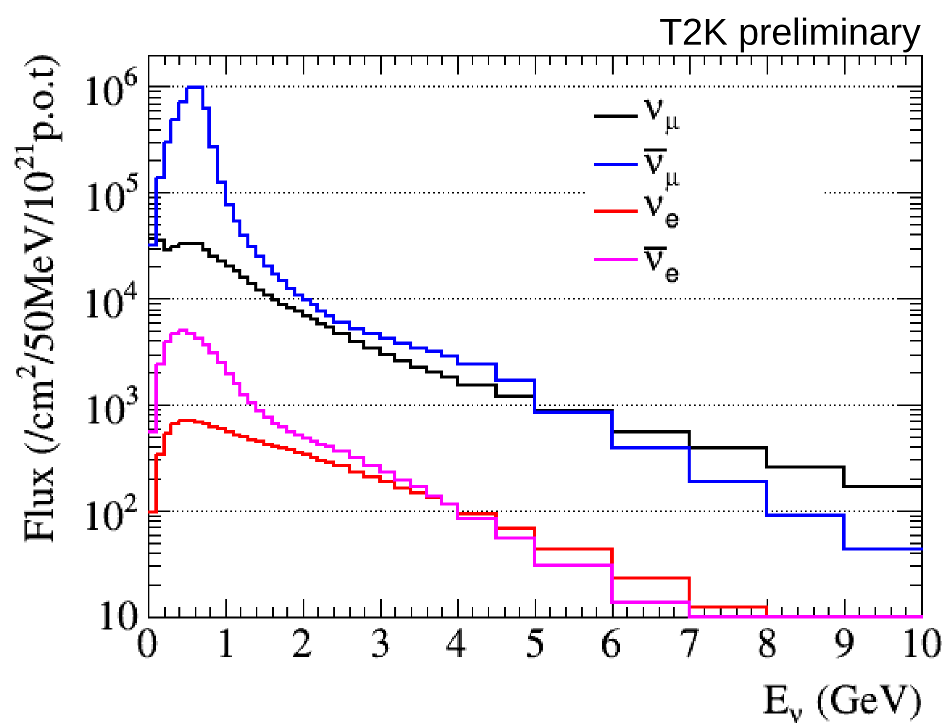
Neutrino flux predicted using a series of simulations

Analysis description
Neutrino flux prediction

“Neutrino mode”



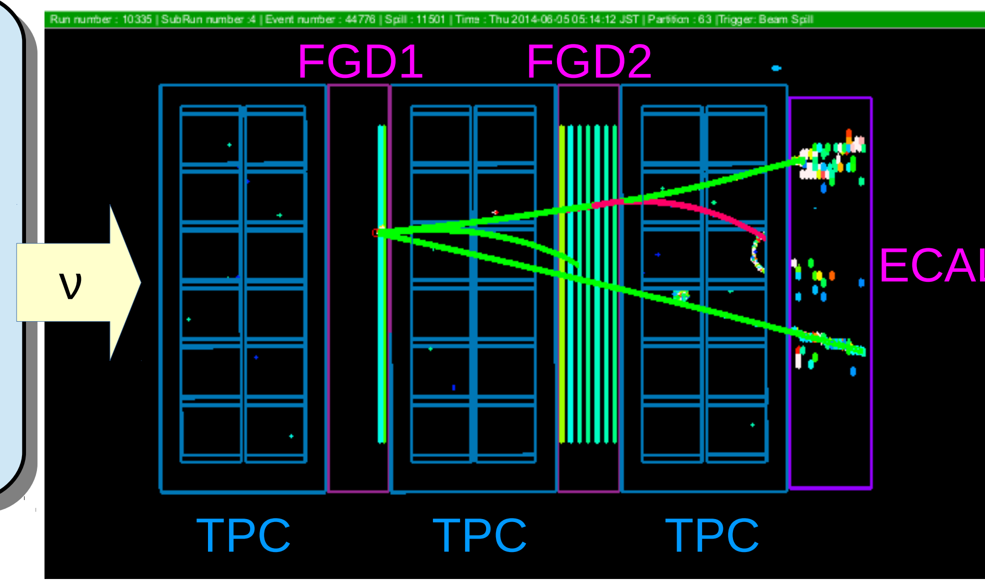
“Anti-neutrino mode”



- Intrinsic $\nu_e/\bar{\nu}_e$ component
- “Wrong sign” component
- Neutrino and anti-neutrino mode fluxes not equivalent (20% less $\bar{\nu}_\mu$ in $\bar{\nu}$-mode than ν_μ in ν-mode)

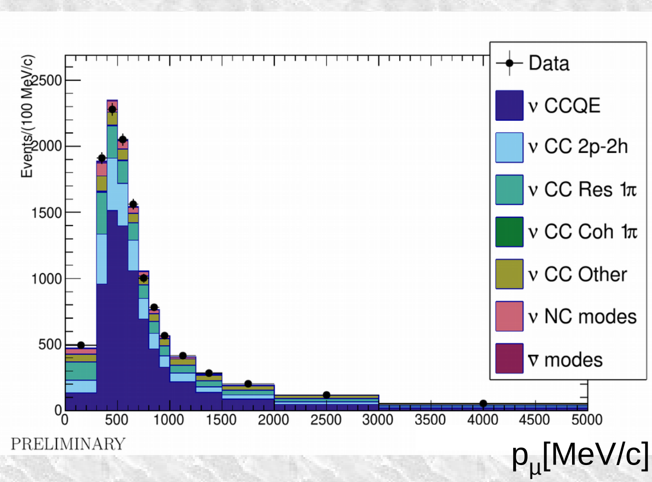
Near detector analysis
Event selection – neutrino mode

Select CC ν_μ interactions with vertex in a one of the Fine-Grained Detectors (FGD)
Samples separated by FGD:
- FGD1: CH target
- FGD2: 42% water by mass
- Separated by number of tagged pions in each case



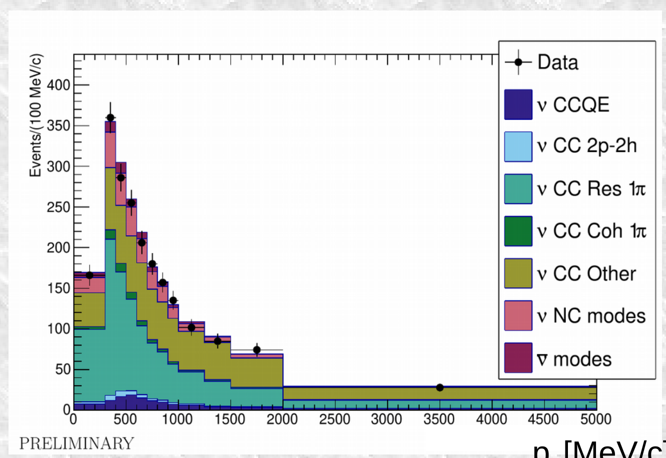
FGD1 samples
(MC tuned with ND fit)

CC0π



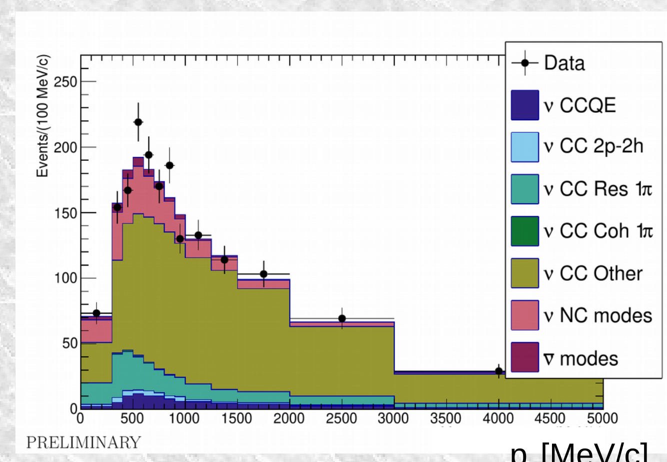
CCQE enriched

CC1π$^+$



CC resonant pion production enriched

CC other



Mainly deep inelastic

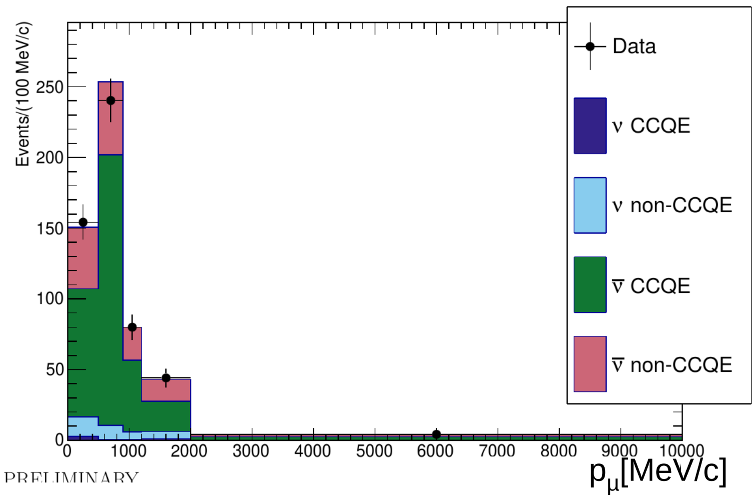
Near detector analysis
Event selection – anti-neutrino mode

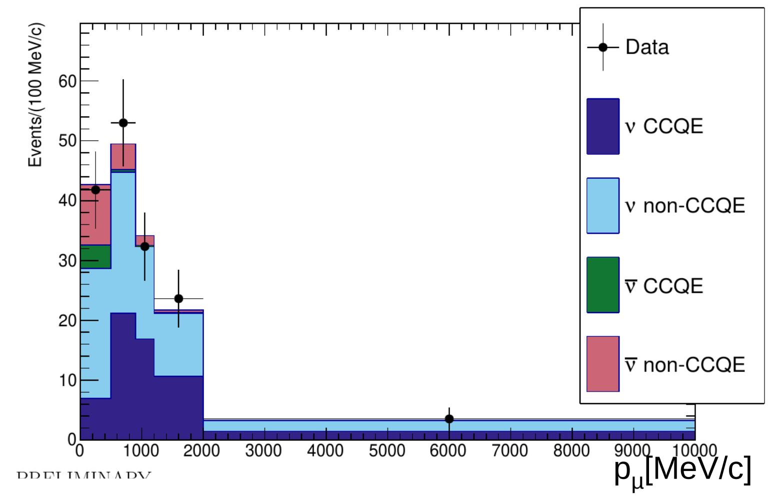
Large neutrino background in anti-neutrino mode: make wrong sign samples to constrain it

CC $\bar{\nu}_\mu$ samples (FGD1)

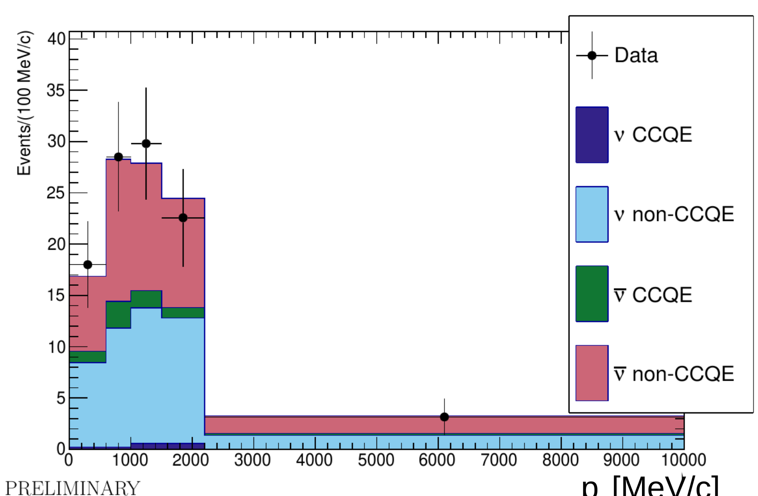
CC ν_μ samples (FGD1)

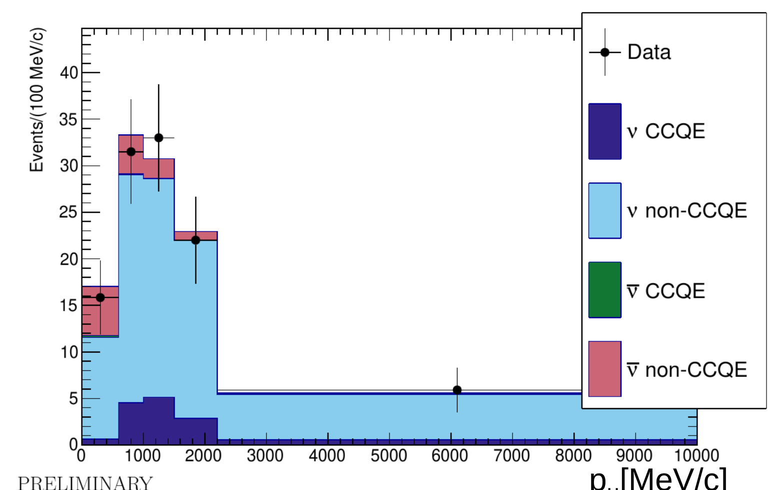
CC-1track
(CCQE enriched)





CC-Ntrack
(CC non-QE enriched)





Far detector
Energy reconstruction

Oscillations depend on E_ν

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

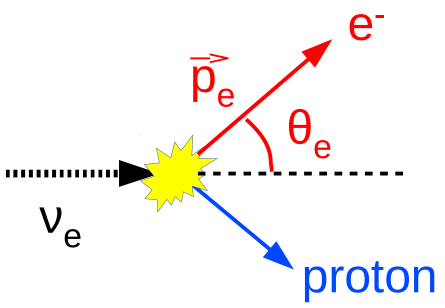
Water Cherenkov detector:

- Only sees charged particles and photons
- 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

Far detector
Event selections

Electron-like samples

Main backgrounds

Non $\nu_\mu \rightarrow \nu_e$ 1Re event
- Intrinsic beam ν_e
- $NC\pi^0 \rightarrow 2\gamma$ with missed γ

Cut	Description
Fully Contained FV	Event on timing in fiducial volume
1 ring only	Only one charged particle for CCQE events
PID	Charged particle should be a e^-/e^+
E_{vis} >100 MeV	Rejects low energy background (NC and invisible muons)
No decay e^-	Rejects events with pion/muon below threshold
E_{rec}<1.25 GeV	Reject intrinsic beam ν_e
"fiTQun" π^0 cut	Rejects $NC\pi^0$ events

Muon-like samples

Non CCQE 1Rμ events
- MEC/2p2h
- CCRes/DIS with invisible pions (FSI, below threshold)

Cut	Description
Fully Contained Fiducial Volume	Event on timing in fiducial volume
1 ring only	Only one charged particle for CCQE events
PID	Charged particle should be a μ^-/μ^+
p_μ > 200 MeV/c	
# decay e- ≤ 1	Rejects events with pions below threshold

Oscillation fits

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

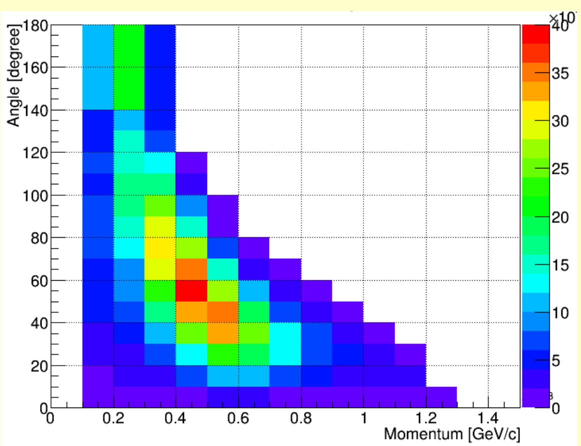
3 different analyses giving consistent results

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

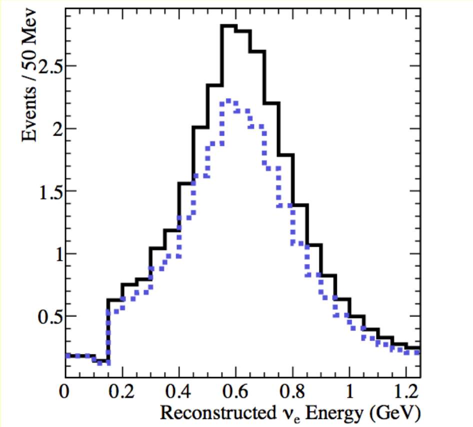
Different fitting methods:
- 2 “grid searches”
- 1 uses MCMC

Different ‘shape’ information for e-like samples

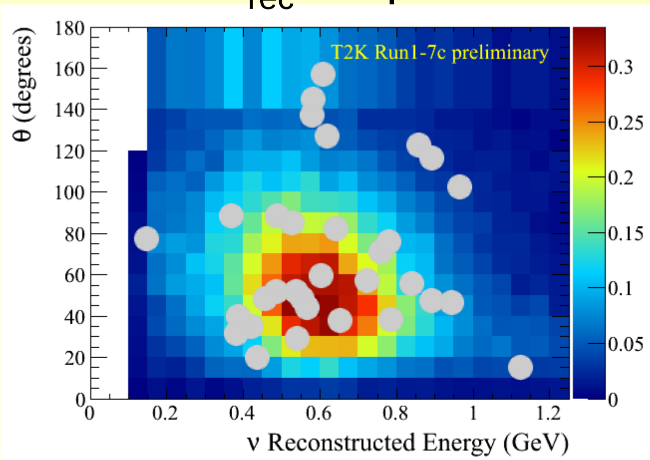
Lepton (p,θ)



Neutrino E_{rec}



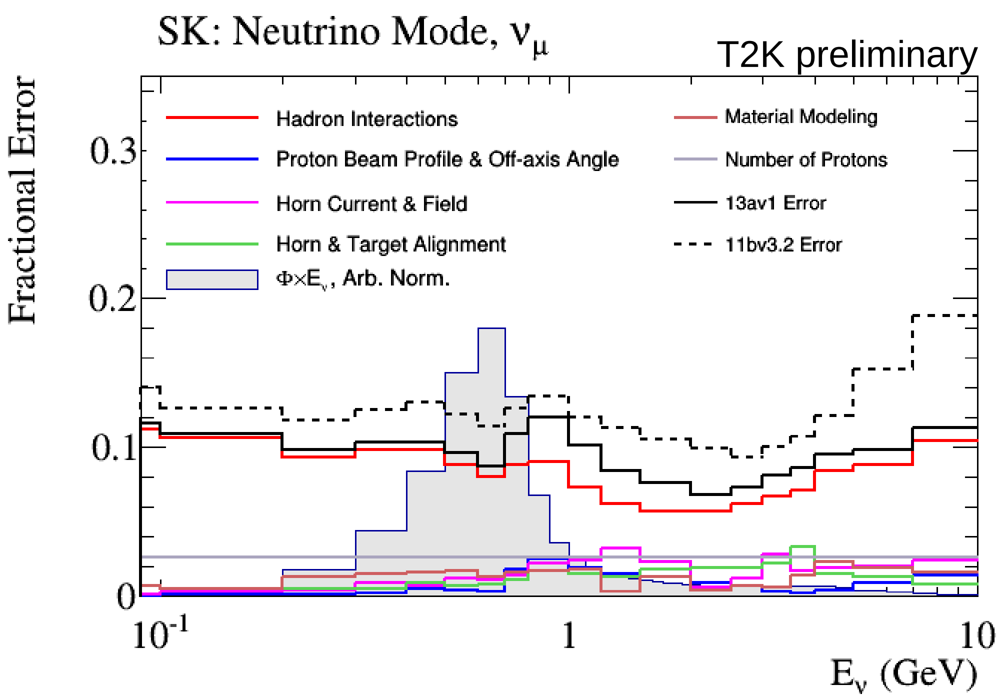
ν E_{rec} + lepton θ

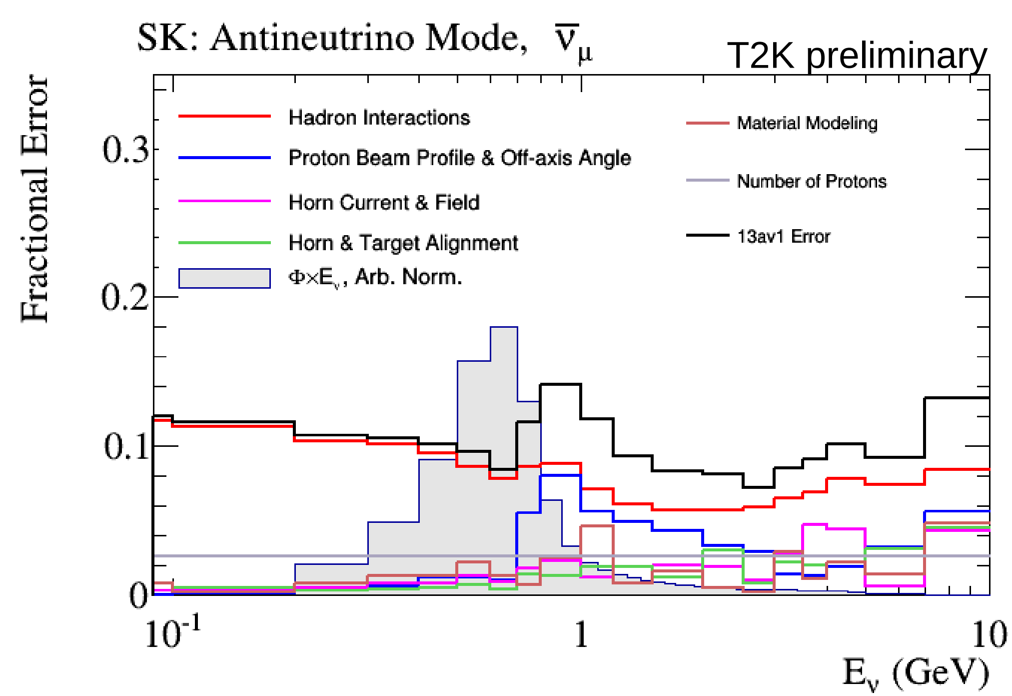


Systematic uncertainties

Systematic uncertainties
Neutrino flux

- Several sources of systematic uncertainties considered : beamline alignment, hadron production, horn current, proton beam parameters...
- Energy-dependent uncertainty for each neutrino flavor
- ~10% uncertainty at peak energy
- Dominant contribution: uncertainty on hadron interactions in target

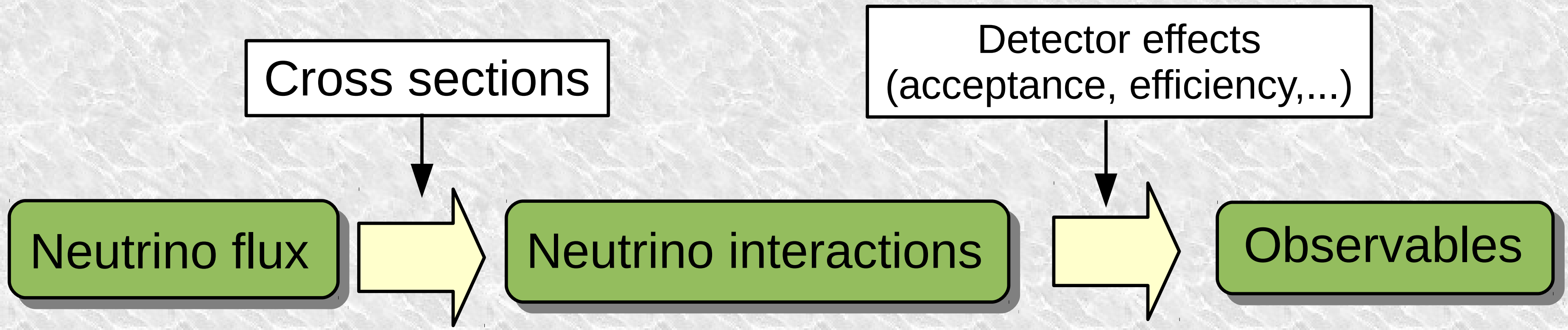




Systematic uncertainties
Near to far extrapolation

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



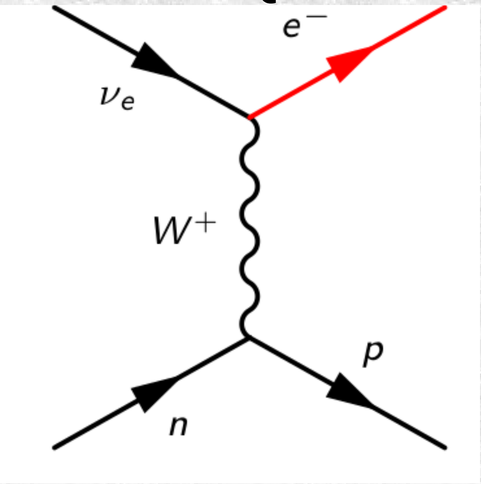
Differences between ND and FD:
- different fluxes (oscillations)
- different target material
- different acceptance
- different detector technologies

⇒ Use models for extrapolation

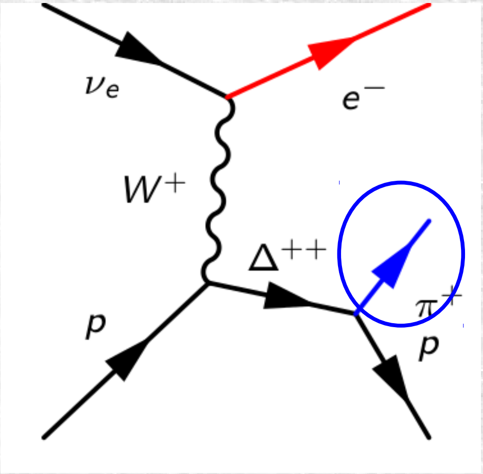
Systematic uncertainties
Neutrino interactions – why it matters

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

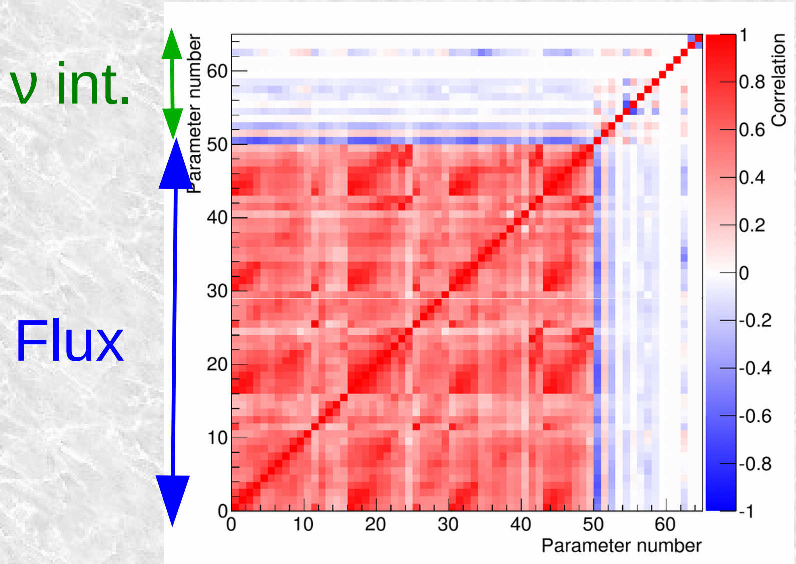
Same observables, but different near to far extrapolation

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

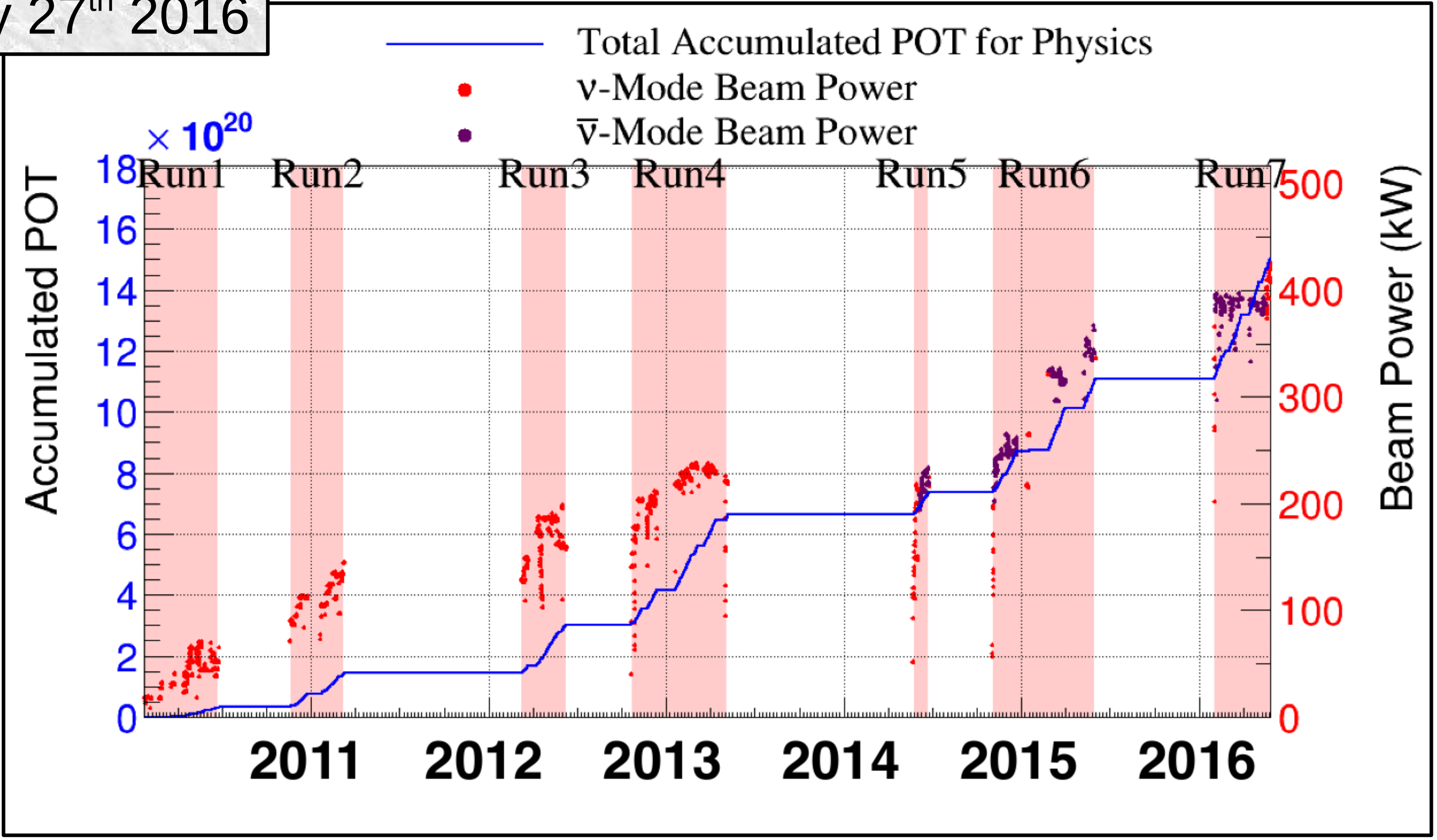


Result applied to FD prediction

Dataset

Dataset
Run 1-7 data

Using data taken until May 27th 2016



Near detector analysis

ν-mode: 5.82 x 10^{20} POT

ν̄-mode: 2.84 x 10^{20} POT

Far detector analysis

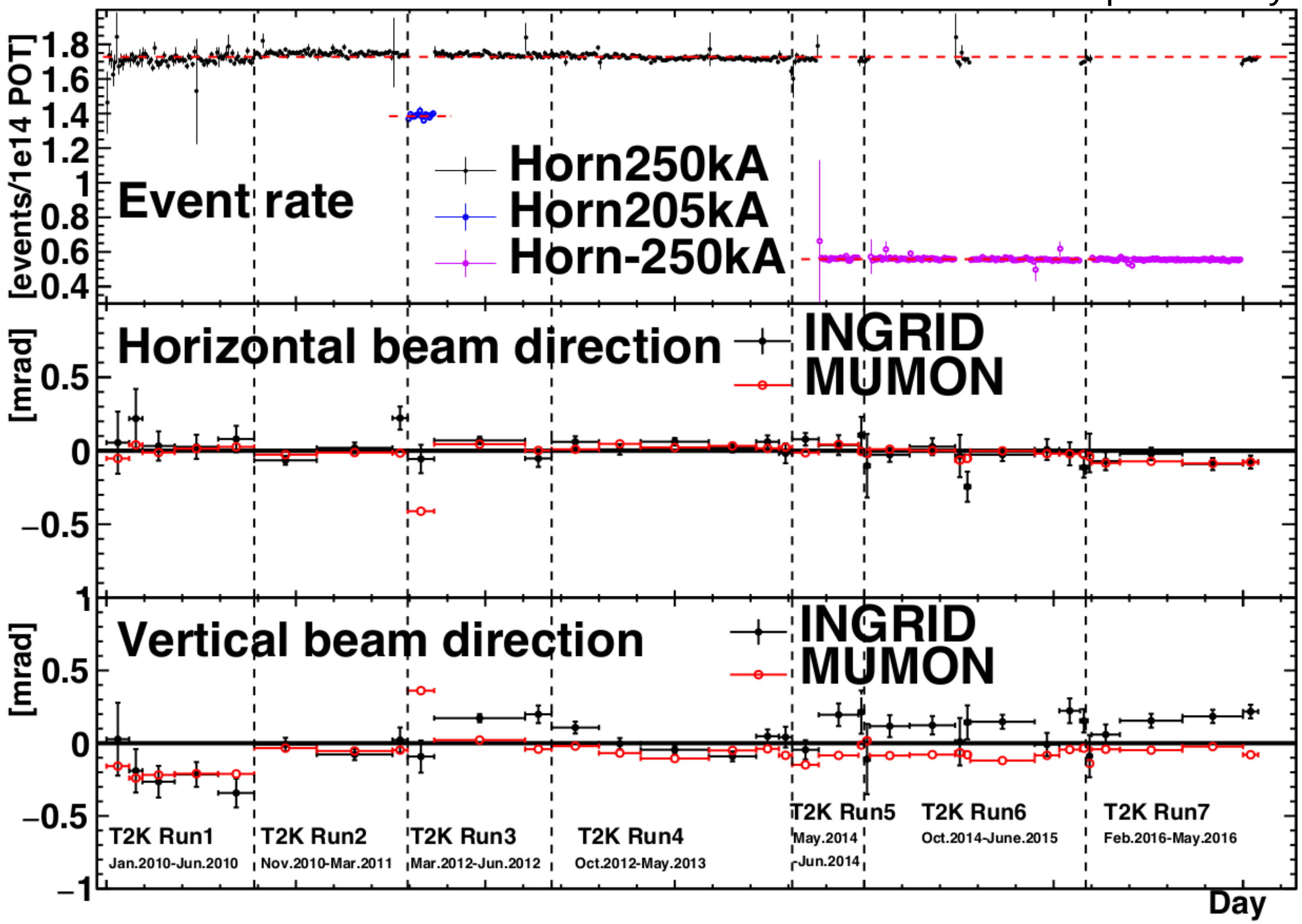
ν-mode: 7.482 x 10^{20} POT

ν̄-mode: 7.471 x 10^{20} POT

Beam stability

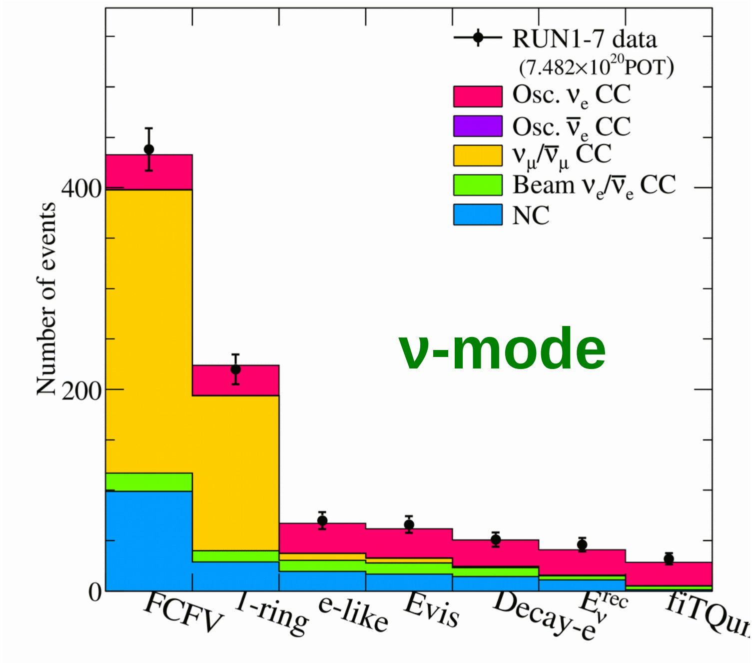
Stable event rate and beam direction from muon monitor and on-axis near detector measurements

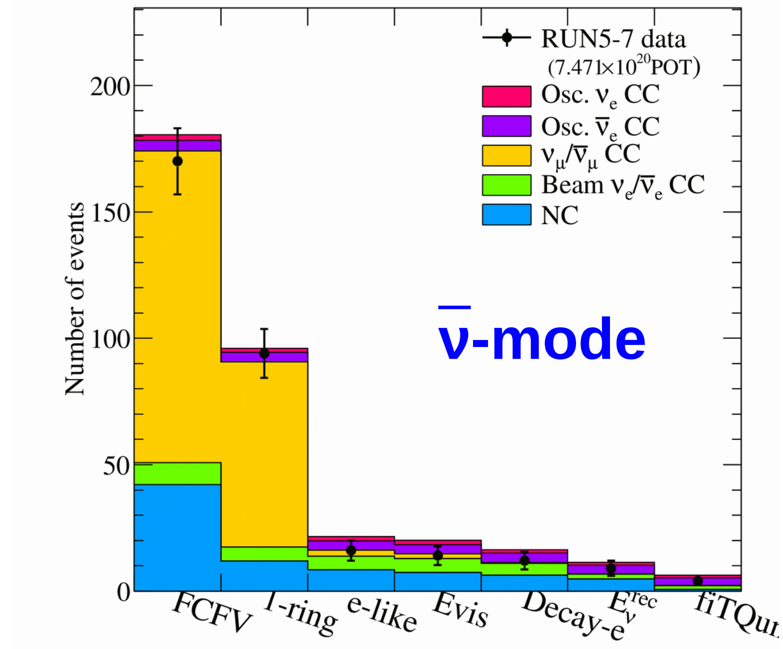
T2K preliminary



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

Far detector data
Electron-like samples

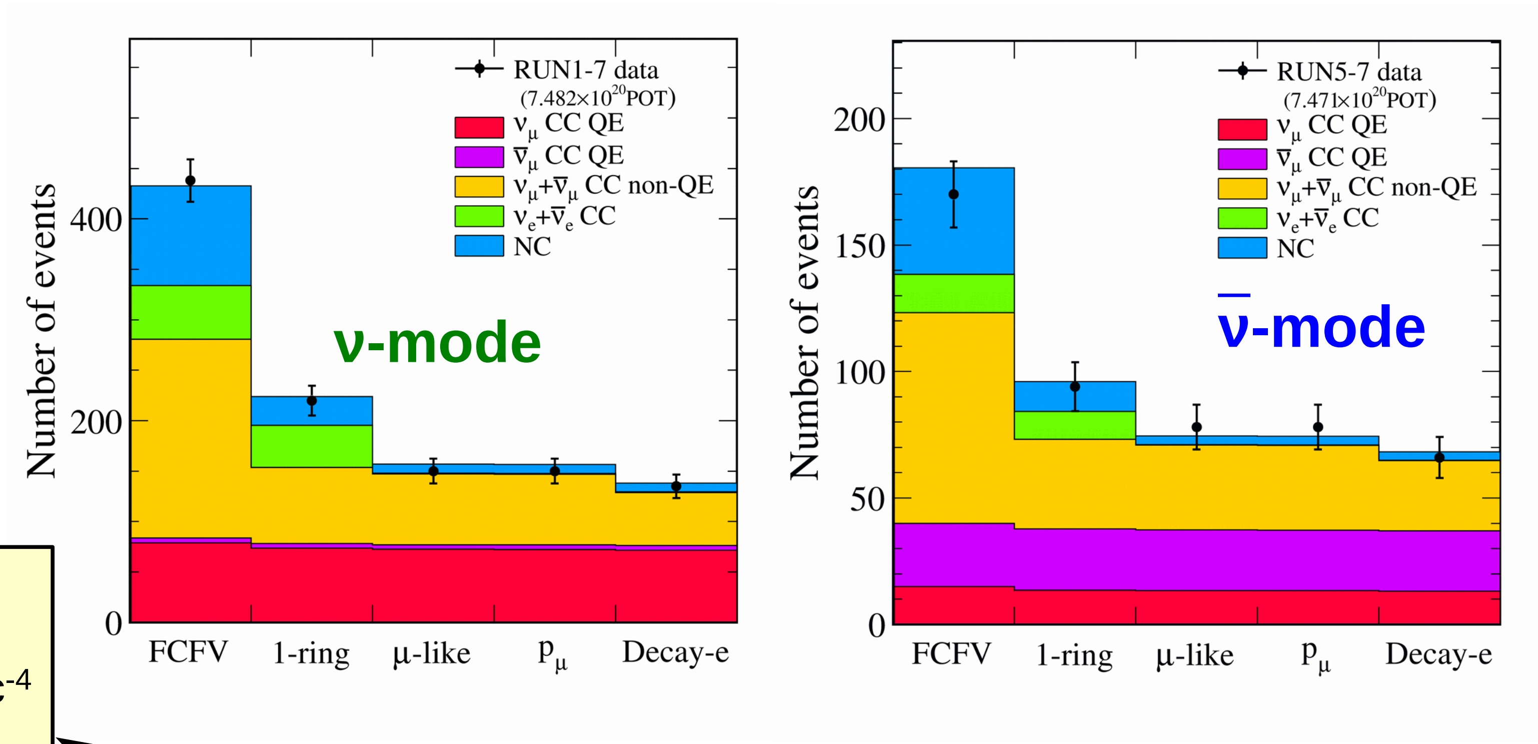




$\sin^2(\theta_{23})=0.528$
$\Delta m^2_{32}=2.509*10^{-3}\ \mathrm{eV}^2c^{-4}$
$\sin^2(\theta_{13})=0.0217$

Sample	Mass hierarchy	δ=0 MC	δ=π MC	δ=-π/2 MC	δ=π/2 MC	Observed
Neutrino mode	Normal	24.2	24.1	28.7	19.6	**32**
	Inverted	21.3	21.3	25.4	17.1	
Antineutrino mode	Normal	6.9	6.8	6.0	7.7	**4**
	Inverted	7.4	7.4	6.5	8.4	

Far detector data
Muon-like samples



δ=-1.601
$\sin^2(\theta_{23})$=0.528
Δm^2_{32}=2.509*10^{-3} eV^2c^{-4}
$\sin^2(\theta_{13})$=0.0217

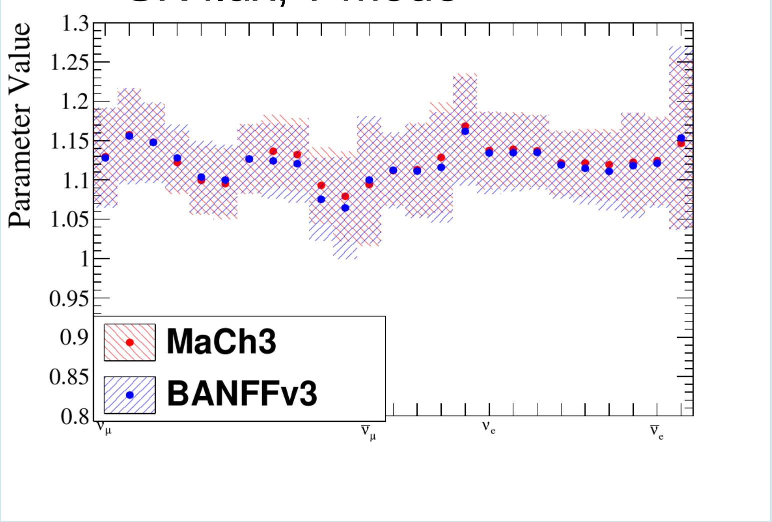
Sample	Oscillated MC	No oscillations MC	Observed
Neutrino mode	135.8	521.8	135
Anti-neutrino mode	64.2	184.8	66

Results

Near detector analysis
Fit results

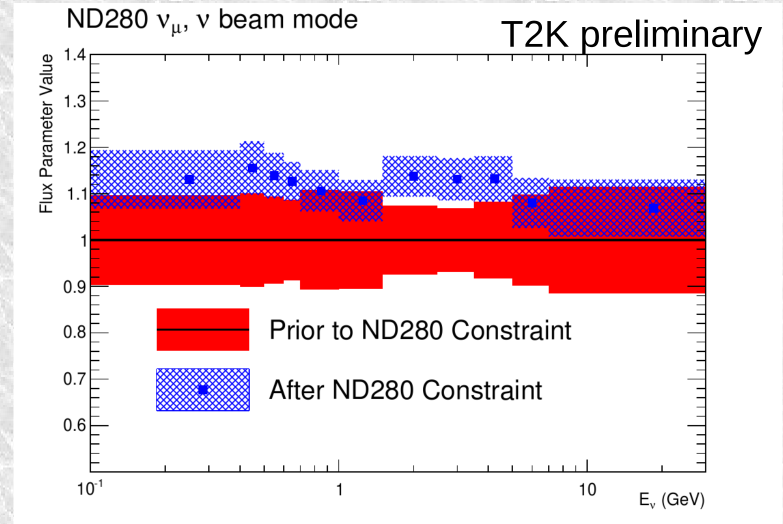
2 different fits:
- Minuit minimization “BANFF”
- MCMC “Mach3”

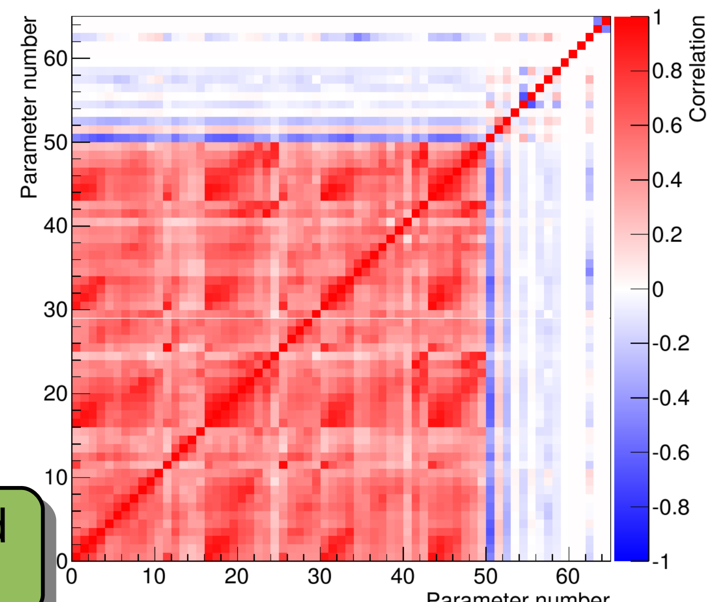
SK flux, ν mode



Consistent results

Increases predicted flux





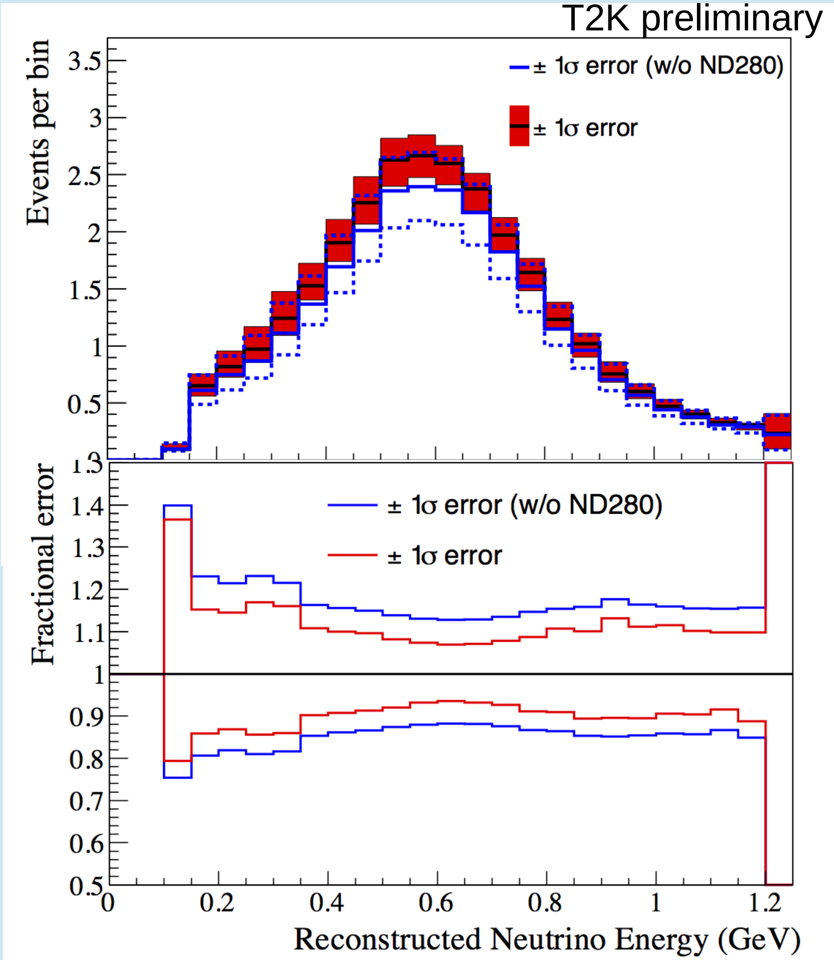
Goodness of fit: **p-value=0.086**

Creates anti-correlations between flux and interaction systematics

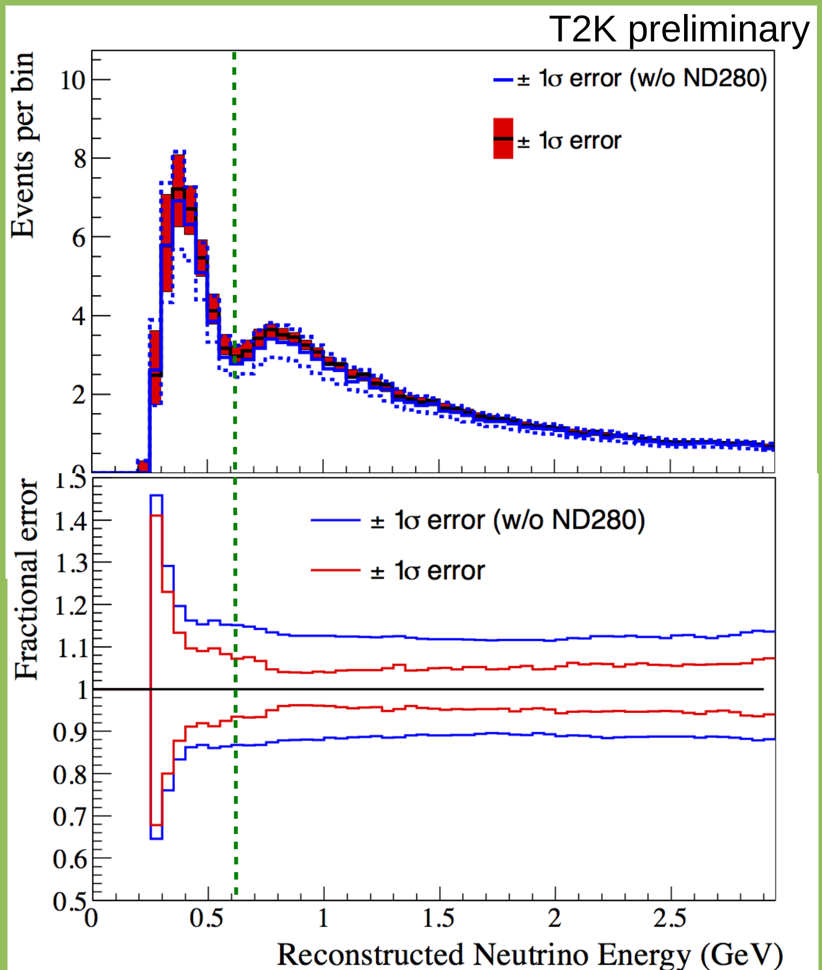
Near detector analysis
Systematic uncertainty reduction

Both changes the nominal rate predictions and reduces the uncertainties

Neutrino mode electron-like



Neutrino mode muon-like



(δ=-1.601, $\sin^2(\theta_{23})$=0.528 Δm^2_{32}=2.509*10^{-3} eV^{2}c^{-4}, $\sin^2(\theta_{13})$=0.0217)

Near detector analysis
Systematic uncertainty reduction

Significantly reduces uncertainty on expected number of events at SK

	ν_e sample	ν_μ sample	$\bar{\nu}_e$ sample	$\bar{\nu}_\mu$ sample
Flux + Xsec (w/o ND fit)	11.4 %	10.9 %	12.8 %	11.6 %
Flux +Xsec (with ND fit)	4.1 %	2.8 %	4.6 %	3.2 %
Far detector (after ND fit)	3.6 %	4.1 %	3.7 %	3.9 %
Total (w/o ND fit)	12.1 %	12.0 %	13.4 %	12.5 %
Total (with ND fit)	**5.1 %**	**5.0 %**	**6.0 %**	**5.0 %**

(δ=-1.601, $\sin^2(\theta_{23})$=0.528 Δm^2_{32}=2.509*10^{-3} eV^2c^{-4}, $\sin^2(\theta_{13})$=0.0217)

Combined ν-$\bar{\nu}$ analysis

Initially:

- ν_e appearance → θ_{13}, δ
- ν_μ disappearance → θ_{23}, $|\Delta m^2|$

But observables depend on all 4 parameters:

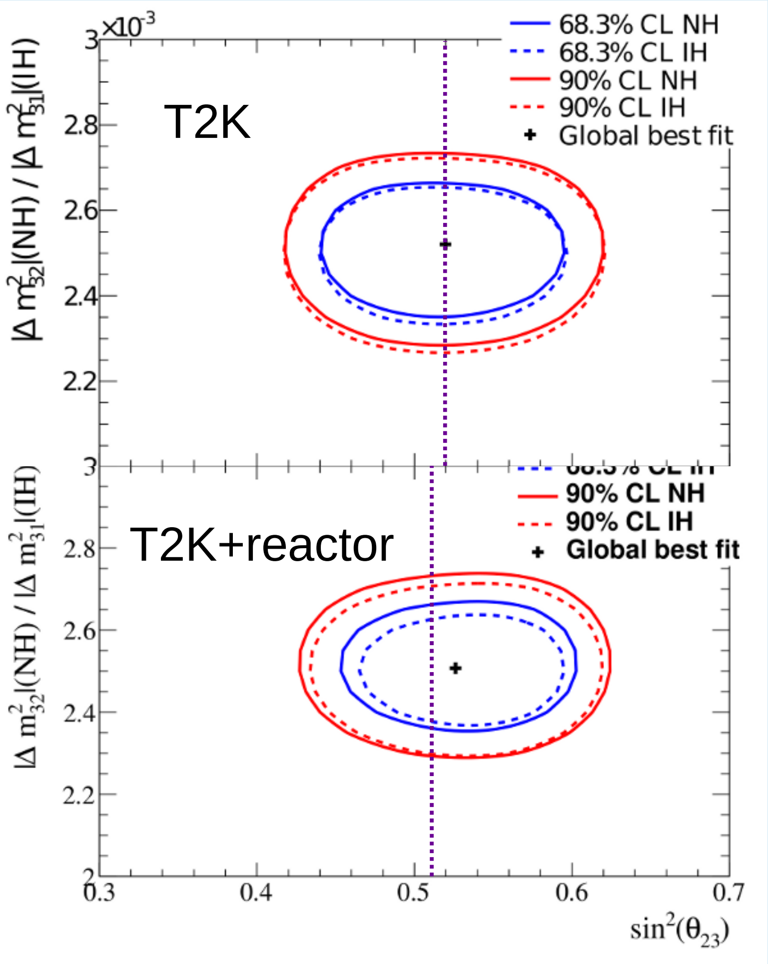
$$P(\nu_\mu \to \nu_e) \sim 2\sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(\Delta m^2_{31} L/4E)$$

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \cos^4(\theta_{13})\sin^2(2\theta_{23})\sin^2(\Delta m^2_{31} L/4E) - \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(\Delta m^2_{31} L/4E)$$

Use all samples for most precise measurement of PMNS parameters:

- Electron-like neutrino mode
- Muon-like neutrino mode
- Electron-like anti-neutrino mode
- Muon-like anti-neutrino mode

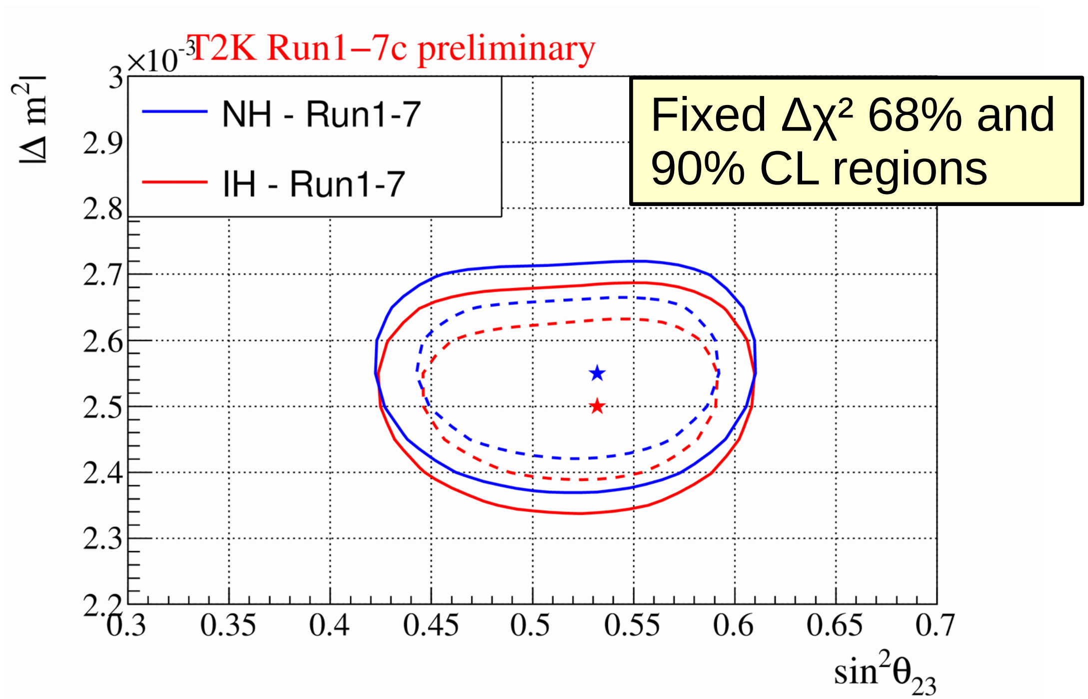
2014 joint 1Re/1Rμ analysis



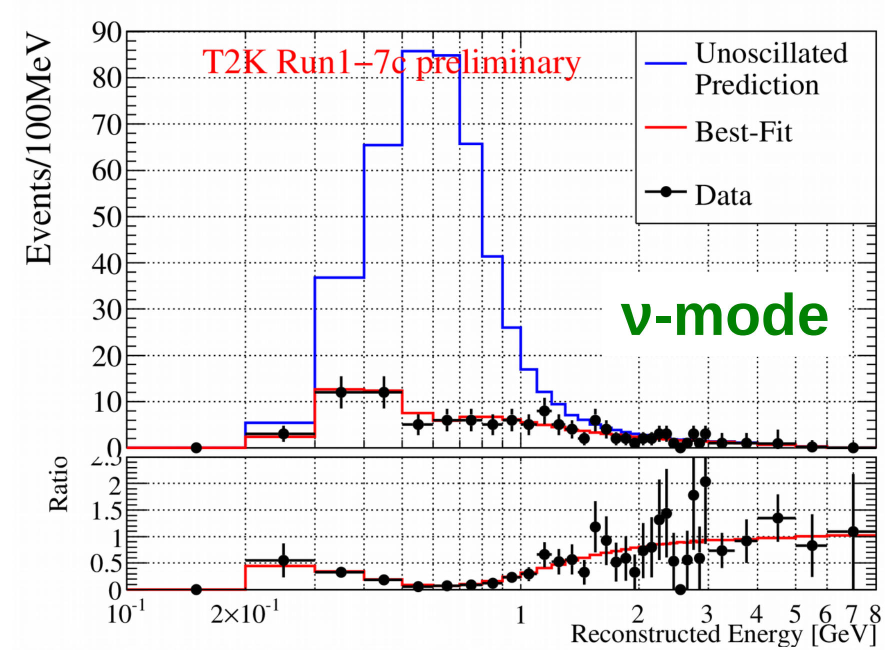
1Re sample also influences measurement of θ_{23} and Δm^2_{32}

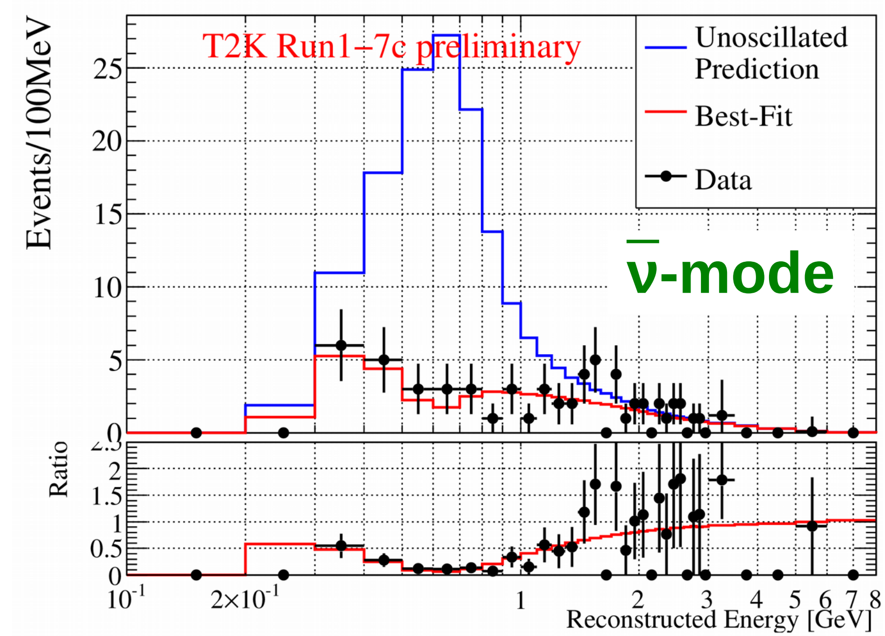
Combined ν-$\bar{\nu}$ analysis
Atmospheric parameters

Reactor constraint (PDG2015)
$\sin^2(2\theta_{13})=0.085 \pm 0.005$



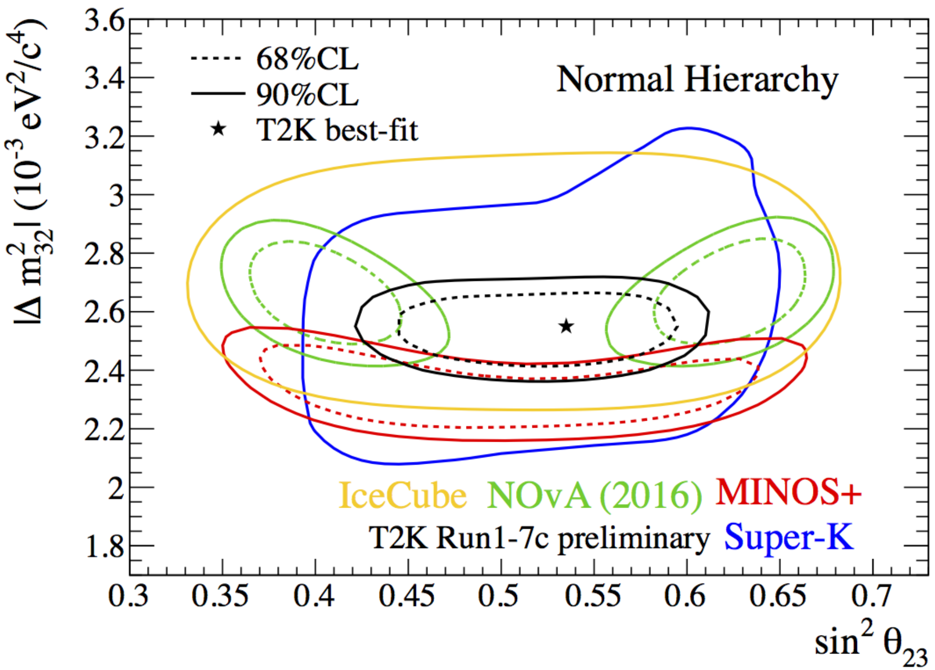
Parameter	Normal hierarchy	Inverted hierarchy
$\sin^2(\theta_{23})$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\lvert\Delta m^2_{32}\rvert$ (10^{-3}eV²/c⁴)	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

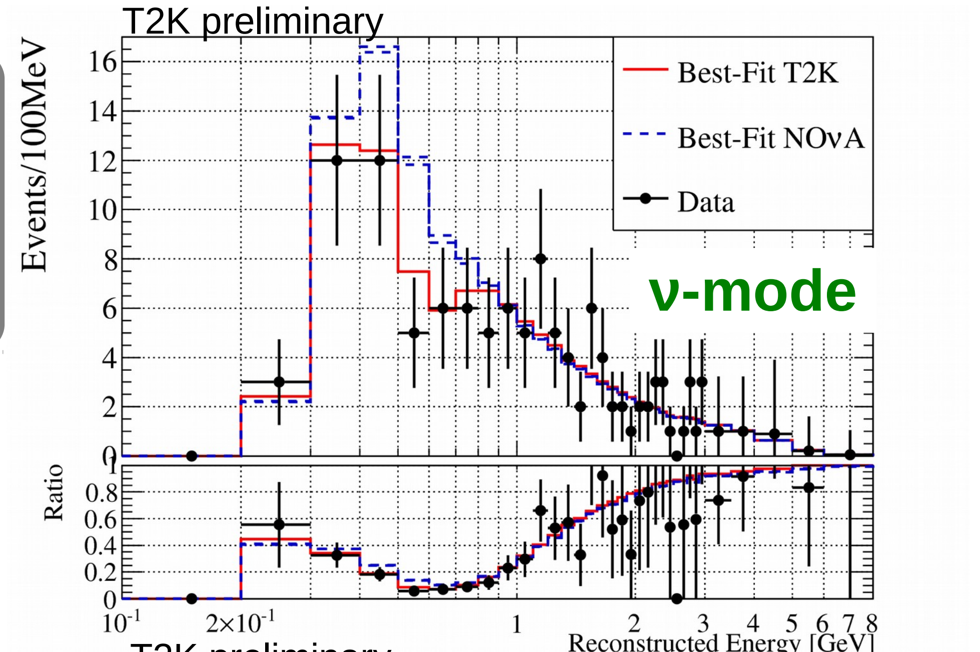


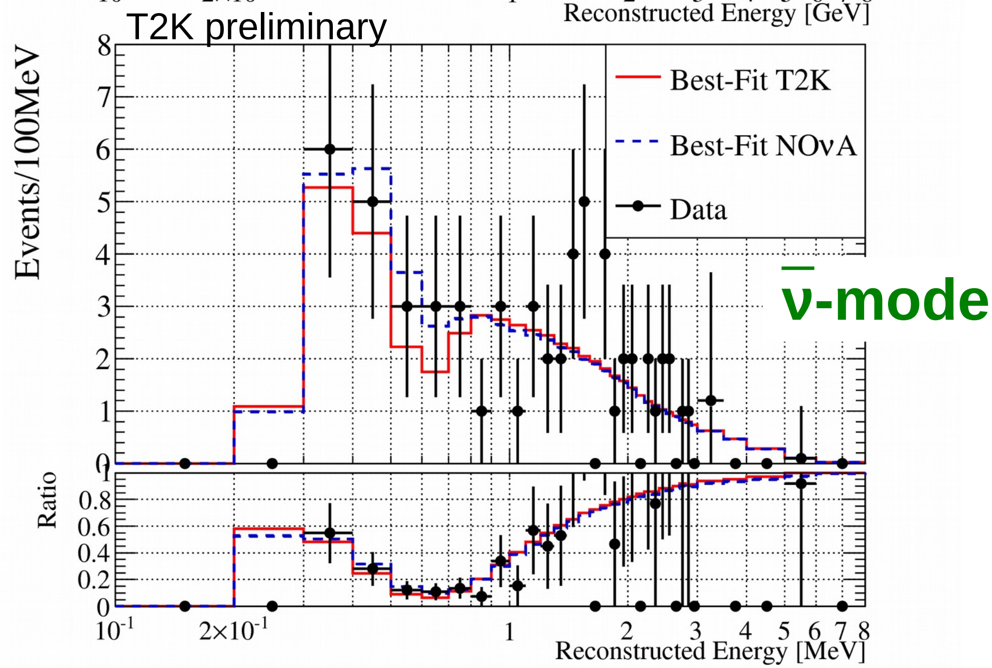


Combined ν-ν̄ analysis
Atmospheric parameters

- Measurements compatible with other experiments results
- T2K and NOνA slightly favour different values of the parameters





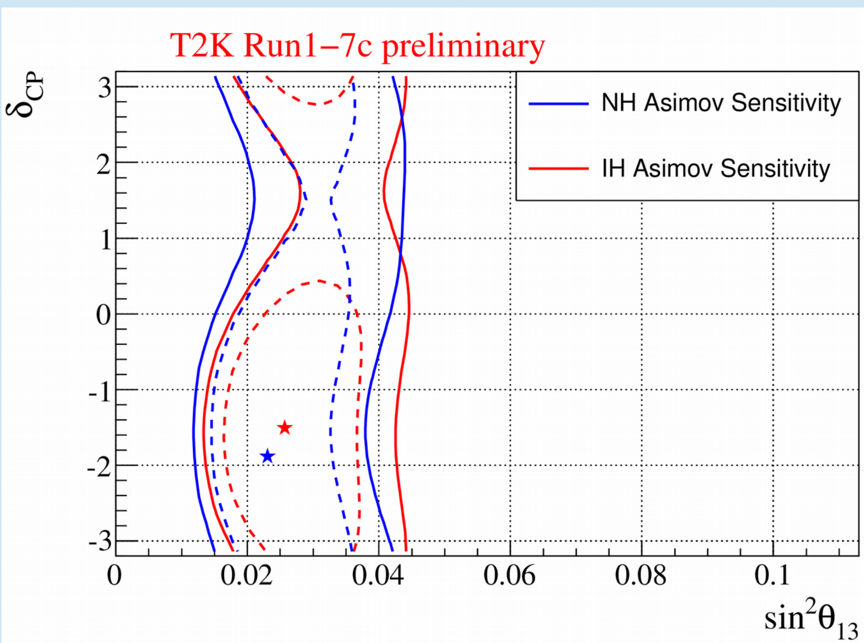


Combined ν-$\bar{\nu}$ analysis
θ_{13} and δ – T2K only

- Compare θ_{13} measurement from accelerator and reactor experiments
- Measure δ by comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Favor δ~-π/2 with T2K data alone
- Compatible with reactor θ_{13} measurement

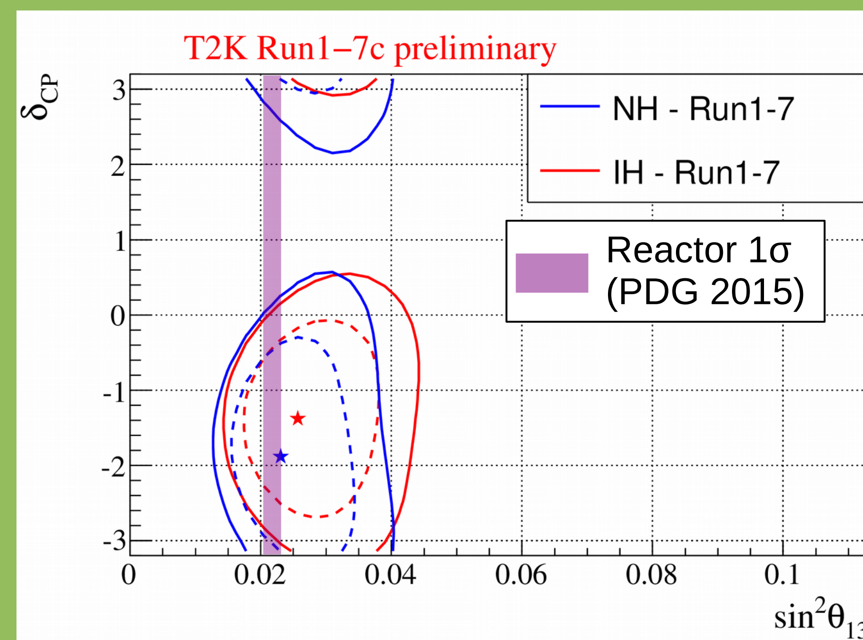
Sensitivity



δ=-1.601
$\sin^2(\theta_{23})$=0.528

Δm^2_{32}=2.509*10^{-3} eV^{2}c^{-4}
$\sin^2(\theta_{13})$=0.0217

Data fit



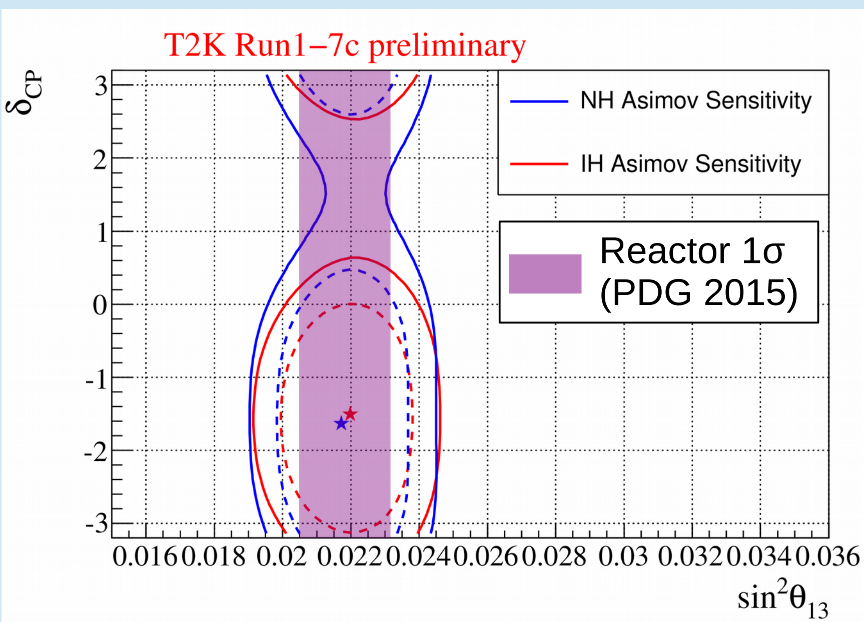
Fixed Δχ² 68% and 90% CL regions

Combined ν-$\bar{\nu}$ analysis
θ_{13} and δ – T2K + reactor

Reactor constraint (PDG2015)
$\sin^2(2\theta_{13})=0.085 \pm 0.005$

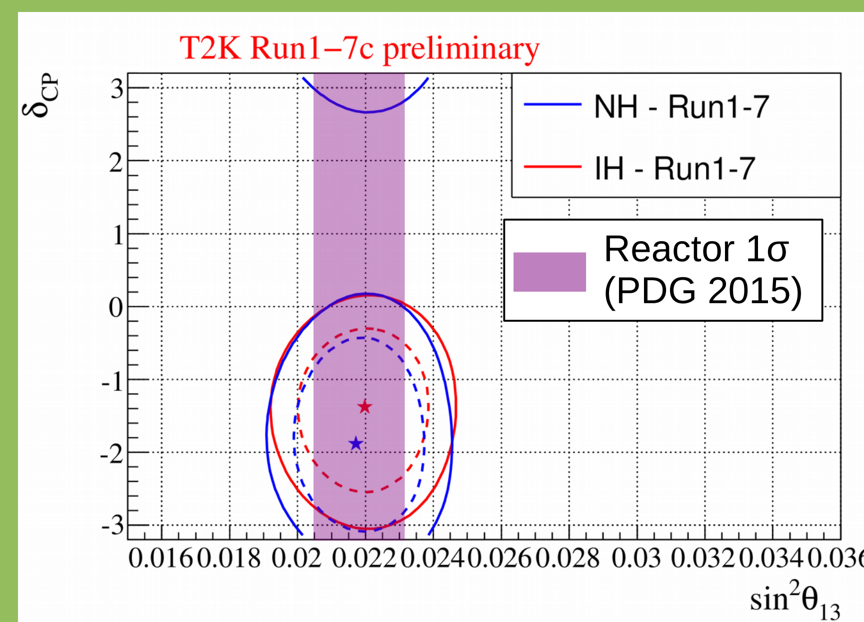
Fixed $\Delta\chi^2$ 68% and 90% CL regions

Sensitivity



$\delta=-1.601$
$\sin^2(\theta_{23})=0.528$
$\Delta m^2_{32}=2.509*10^{-3}\ eV^2c^{-4}$
$\sin^2(\theta_{13})=0.0217$

Data fit

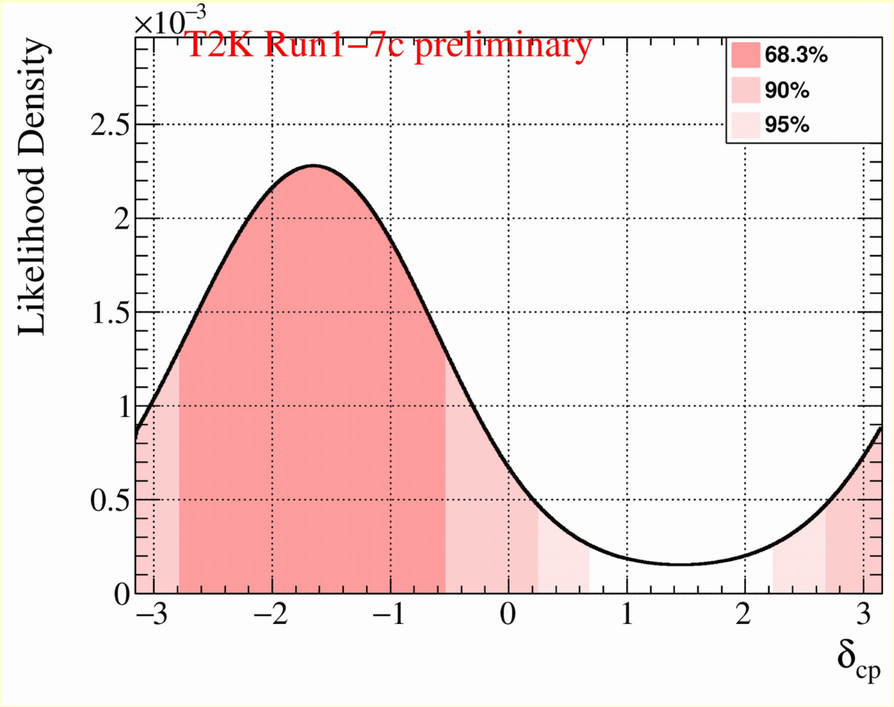


Combined ν-$\bar{\nu}$ analysis
δ – Bayesian results

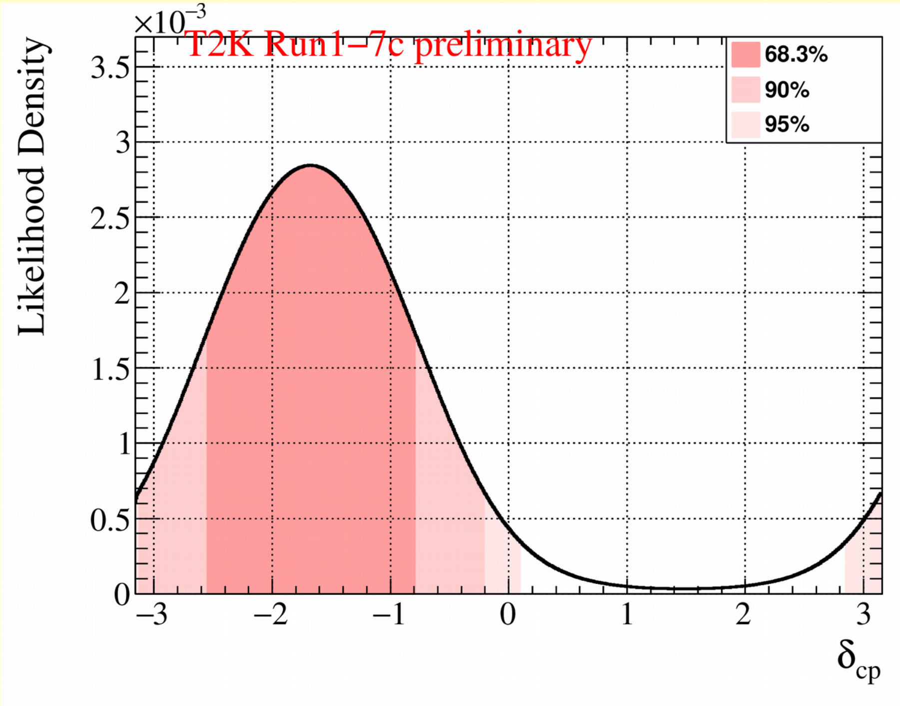
Reactor constraint (PDG2015)
$\sin^2(2\theta_{13})=0.085 \pm 0.005$

Credible intervals marginalizing over everything including mass hierarchy

T2K only



T2K + reactor



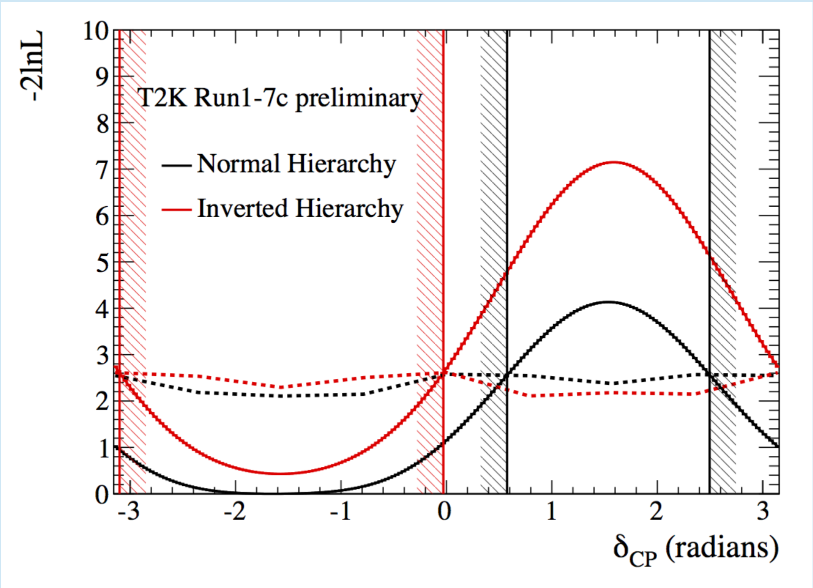
Consistent picture with and without using results of reactor experiments

Combined ν-$\bar{\nu}$ analysis
δ – Frequentist results

Reactor constraint (PDG2015)
$\sin^2(2\theta_{13})=0.085 \pm 0.005$

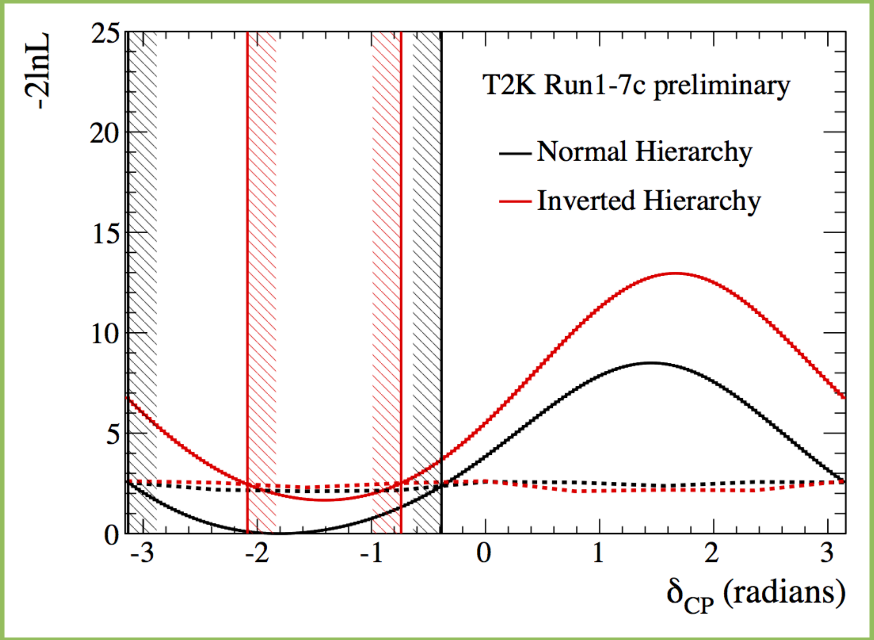
Use unified approach by Feldman and Cousins to build CL intervals

Sensitivity



δ=-1.601
$\sin^2(\theta_{23})=0.528$
$\Delta m^2_{32}=2.509*10^{-3}$ eV^{2}c^{-4}
$\sin^2(\theta_{13})=0.0217$

Data fit



CP conserving values outside of 90% CL intervals

Combined ν-$\bar{\nu}$ analysis
Model comparisons

Compare posterior probabilities of different models

T2K only

T2K Run1-7c preliminary	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Inverted hierarchy	0.19	0.22	0.40
Normal hierarchy	0.27	0.33	0.60
Column total	0.45	0.55	1

T2K + reactor

T2K Run1-7c preliminary	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Inverted hierarchy	0.10	0.14	0.25
Normal hierarchy	0.29	0.46	0.75
Column total	0.39	0.61	1

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

$\nu_\mu/\bar{\nu}_\mu$ disappearance comparison
Motivation

Can test the PMNS framework by comparing oscillations of neutrinos and anti-neutrinos in T2K data

$\nu \rightarrow \bar{\nu}$
$\delta_{CP} \rightarrow -\delta_{CP}$

$\nu_\mu/\bar{\nu}_\mu$ disappearance :
No CP odd order term, limited matter effect

$$
\begin{aligned}
P(\nu_\mu \to \nu_\mu) = 1 &- \left(c_{13}^4 \ \sin^2 2\theta_{23} + s_{23}^2 \ \sin^2 2\theta_{13}\right) \sin^2 \Delta_{atm} \\
&+ \Big\{ c_{13}^2 \left(c_{12}^2 - s_{13}^2 \ s_{23}^2\right) \sin^2 2\theta_{23} + s_{12}^2 \ s_{23}^2 \ \sin^2 2\theta_{13} - c_{13} \ \sin 2\theta_{13} \ \sin 2\theta_{23} \ \sin 2\theta_{12} \cos\delta \Big\} \\
&\times \left\{ \frac{1}{2} \sin 2\Delta_{solar} \ \sin 2\Delta_{atm} + 2 \sin^2 \Delta_{solar} \ \sin^2 \Delta_{atm} \right\} \\
&- \Big\{ \sin^2 2\theta_{12} \left(c_{23}^2 - s_{13}^2 \ s_{23}^2\right)^2 + s_{13}^2 \ \sin^2 2\theta_{23} \left(1 - c_\delta^2 \ \sin^2 2\theta_{12}\right) \\
&+ 2 s_{13} \ \sin 2\theta_{12} \ \cos 2\theta_{12} \ \sin\theta_{23} \ \cos 2\theta_{23} \ c_\delta \\
&- \frac{1}{2} c_{13} \ \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \cos\delta \ s_{23}^2 \ s_{12}^2 \\
&+ \sin^2 2\theta_{23} \ c_{13}^2 \ \left(c_{12}^2 - s_{13}^2 \ s_{12}^2\right) + s_{13}^2 \ s_{23}^2 \ \sin^2 2\theta_{13} \Big\} \times \sin^2 \Delta_{solar} \qquad (26)
\end{aligned}
$$

Expect similar disappearance pattern for ν_μ and $\bar{\nu}_\mu$

$\nu_\mu/\bar{\nu}_\mu$ disappearance comparison Analysis

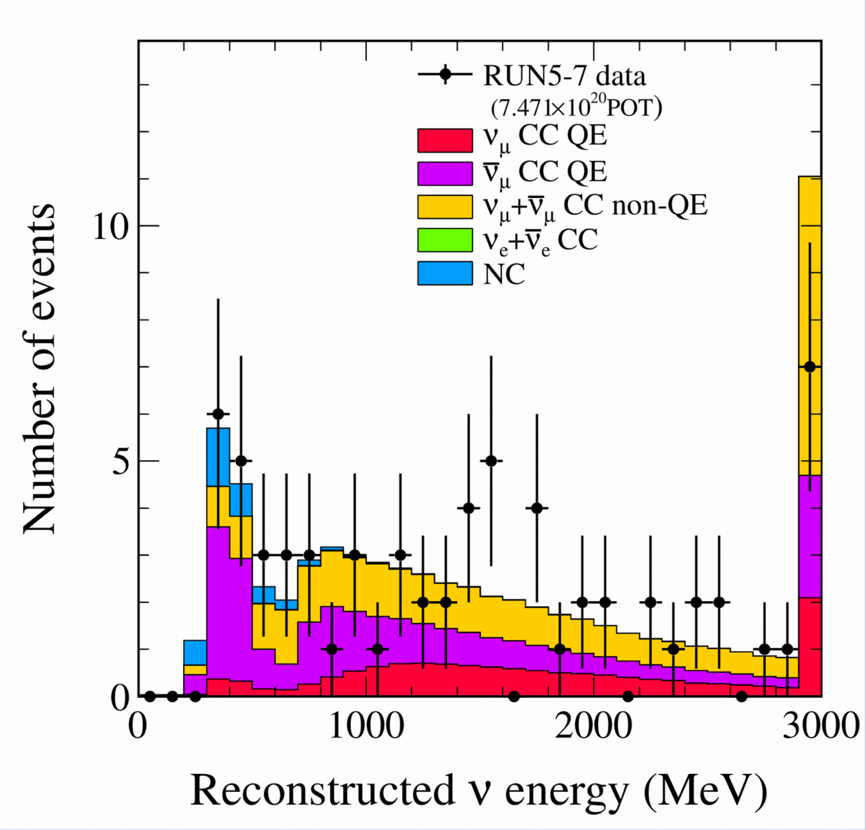
Compare values of atmospheric parameters measured with neutrinos and anti-neutrinos

$(\theta_{23}, \Delta m^2_{32})$ ν	vs	$(\bar{\theta}_{23}, \overline{\Delta m}^2_{32})$ $\bar{\nu}$

Other PMNS parameters common

- θ_{13}, θ_{12} and Δm^2_{21} constrained with PDG2015 values
- δ=0 fixed

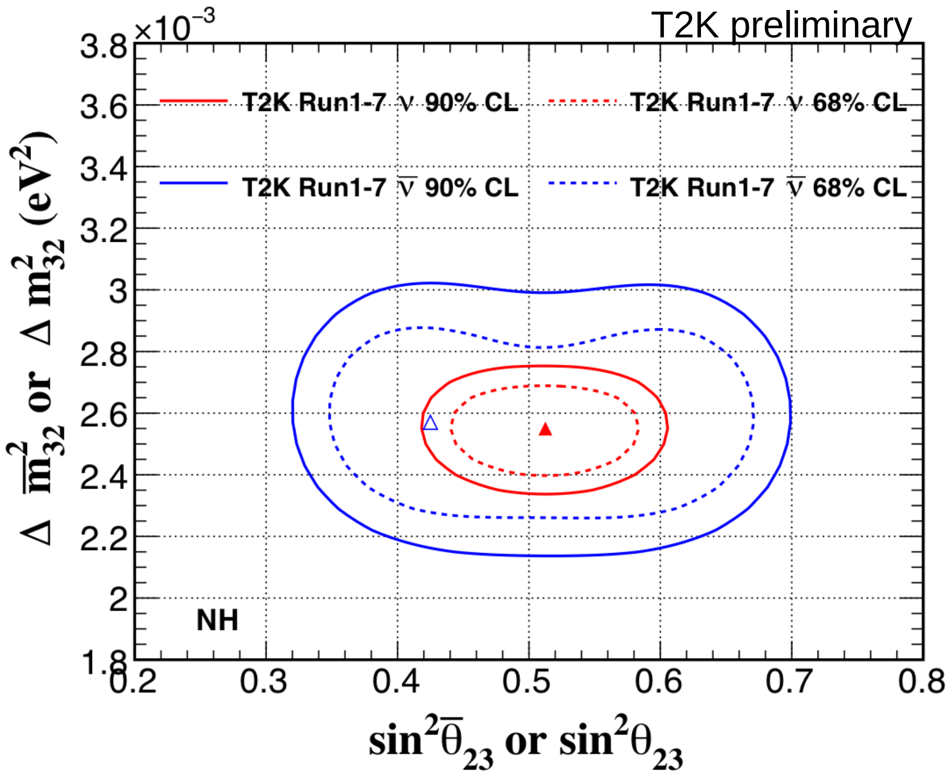
Significant ν_μ contamination in anti-neutrino mode

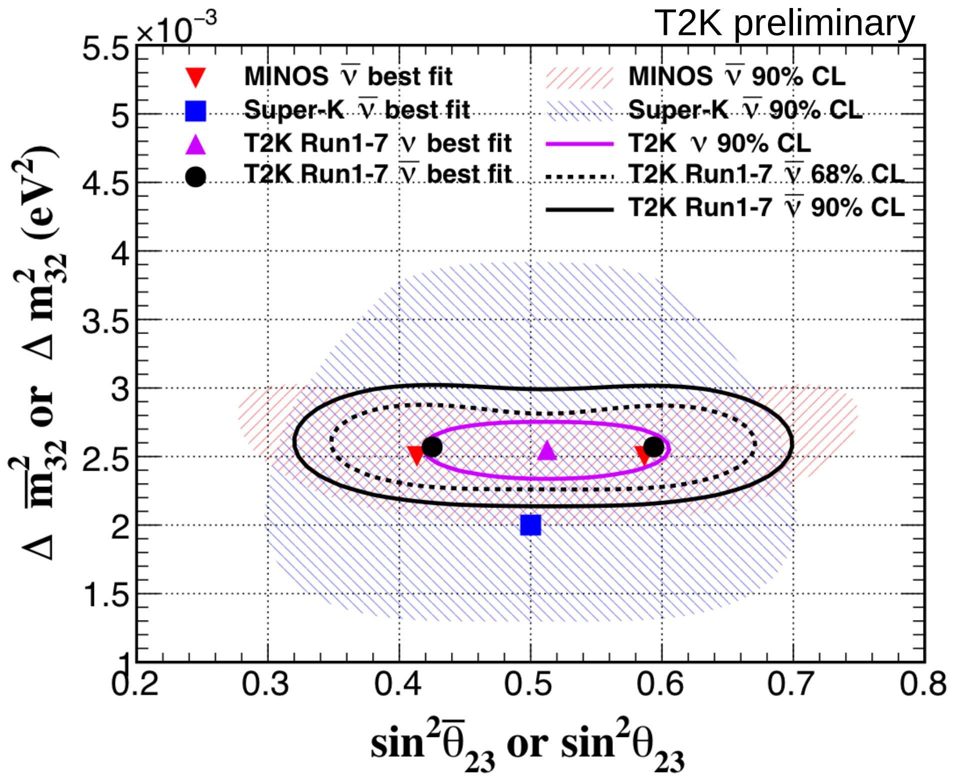


Joint fit of 1Rμ neutrino and anti-neutrino mode samples

$\nu_\mu/\bar{\nu}_\mu$ disappearance comparison
Results

- No discrepancies between values measured for neutrinos and anti-neutrinos
- Best measurement of the parameters for anti-neutrinos
- Compatible with measurements by other experiments for anti-neutrinos



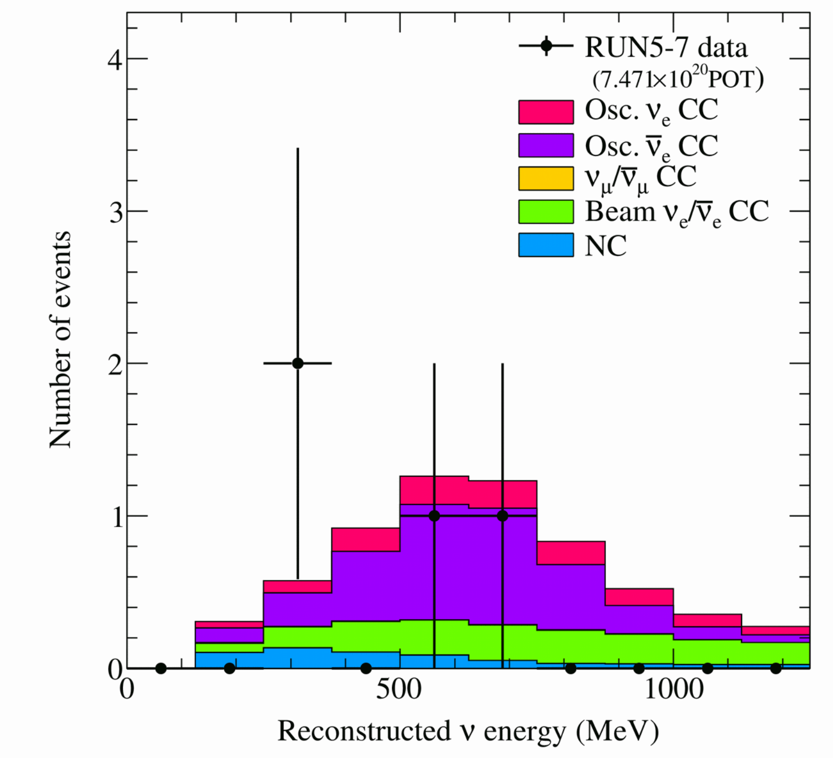


$\bar{\nu}_e$ appearance Analysis

Look for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation using all data samples

Hypothesis test:
- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e, \text{PMNS})$
- Compare compatibility of data with $\beta=1$ and $\beta=0$

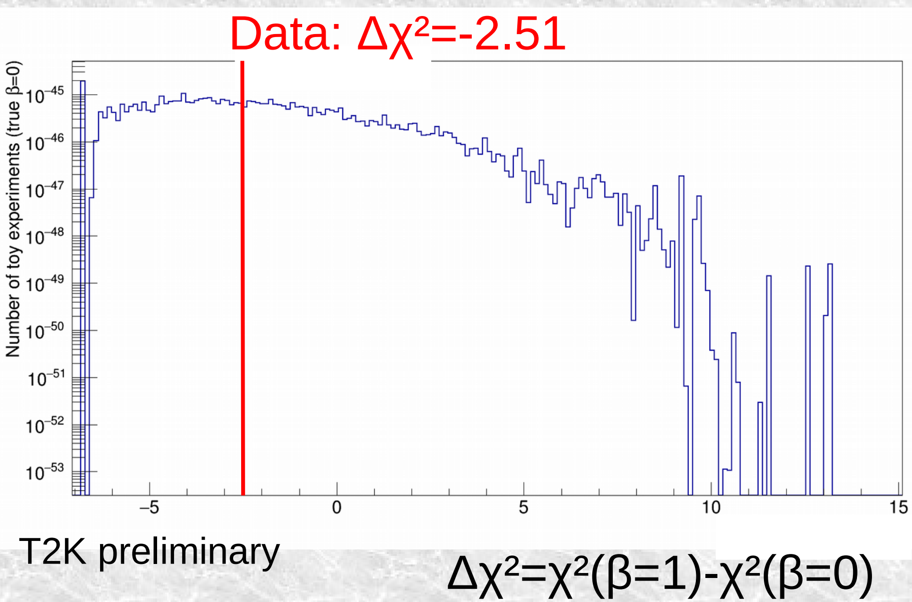
Significant ν_e contamination in anti-neutrino mode



Cannot use simple measurement of θ_{13} in 1Re anti-neutrino mode sample

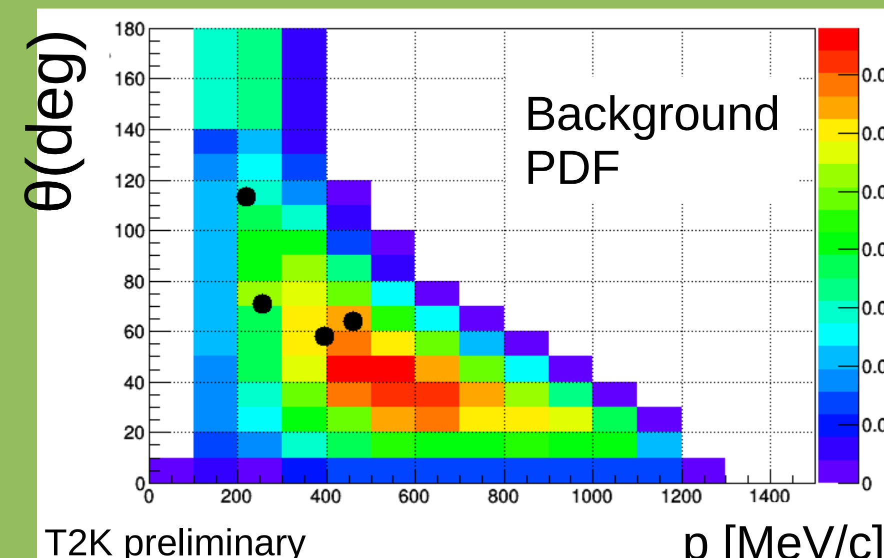
$\bar{\nu}_e$ appearance
Results – rate+shape analysis

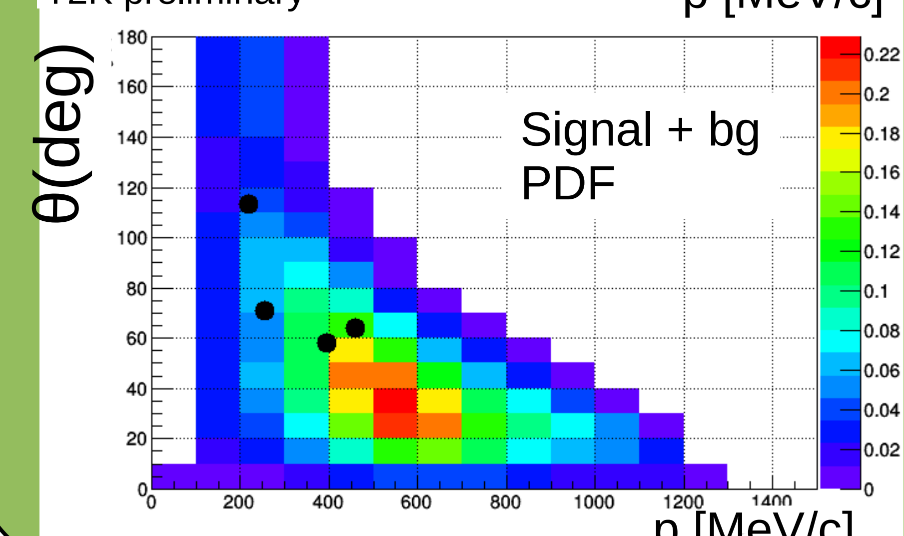
Test statistics distribution



P-value for no $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation:
Rate only: 0.41
Rate+shape (Erec-θ): 0.3742
Rate+shape (p-θ): 0.4618

Events look more background like in lepton (p,θ)

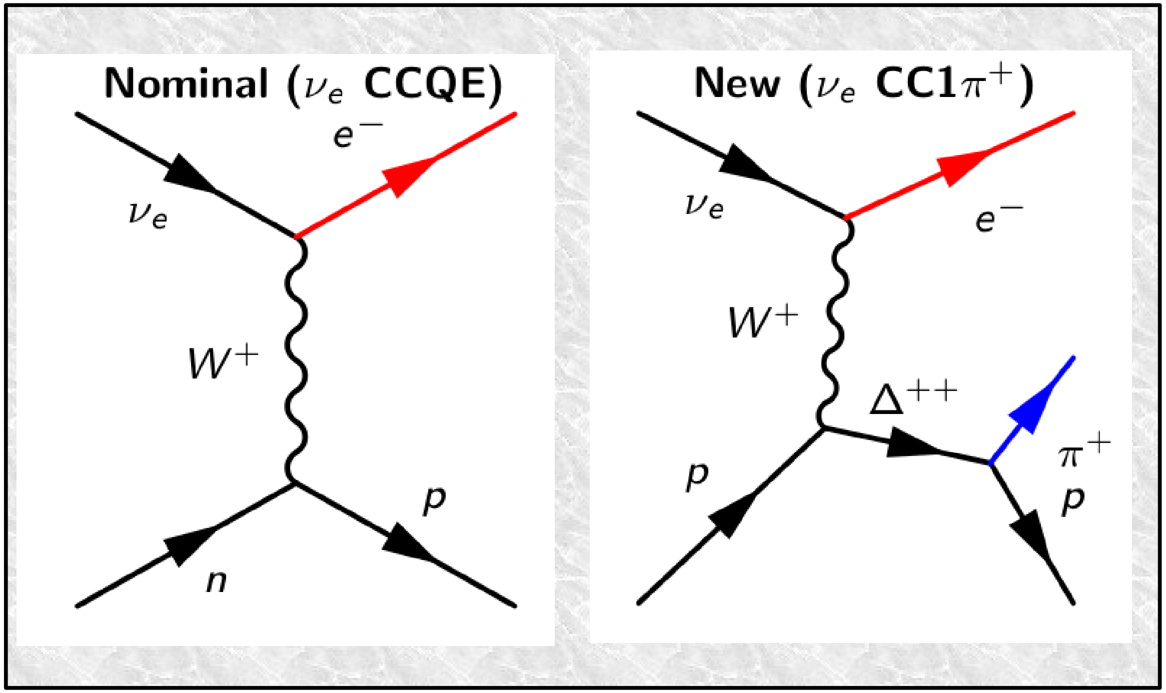


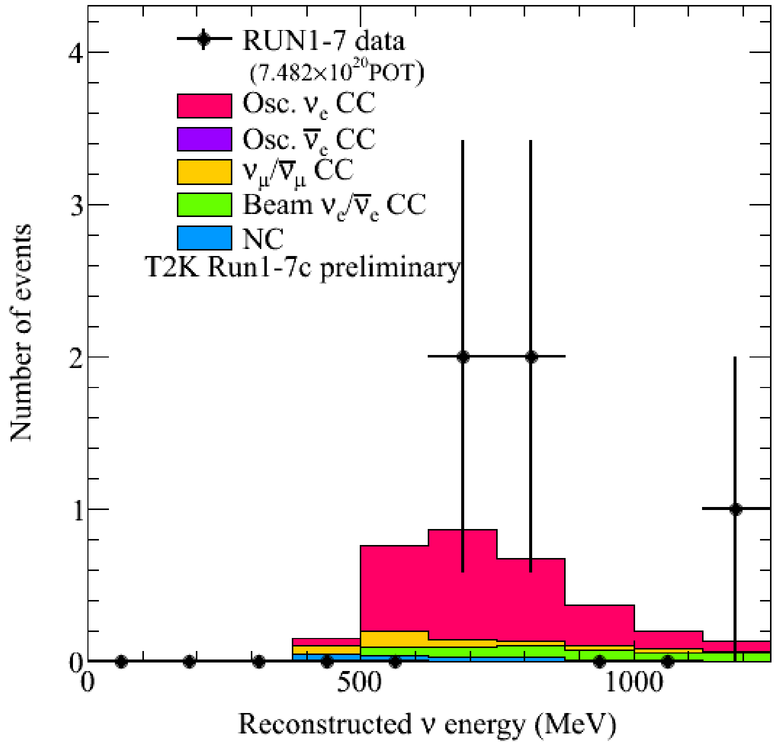


Perspective for the future

Near future
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 $\nu_\mu \rightarrow \nu_e$)

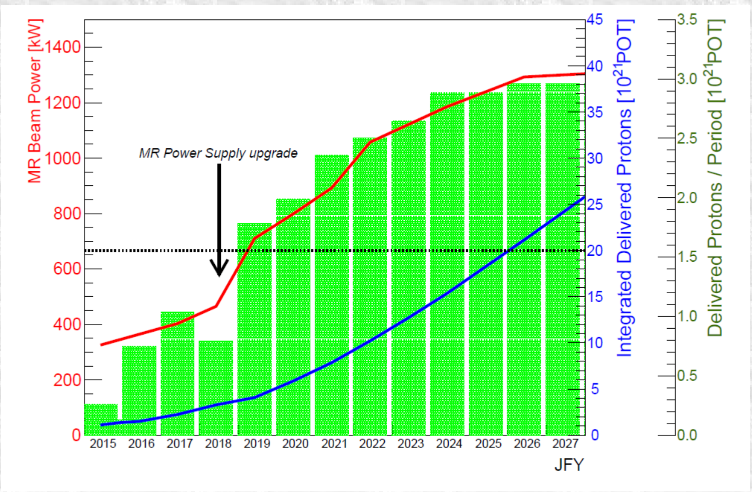




MC expectations (NH)	δ=0	δ=π	δ=-π/2	δ=π/2	Observed
	2.8	2.7	3.1	2.3	5

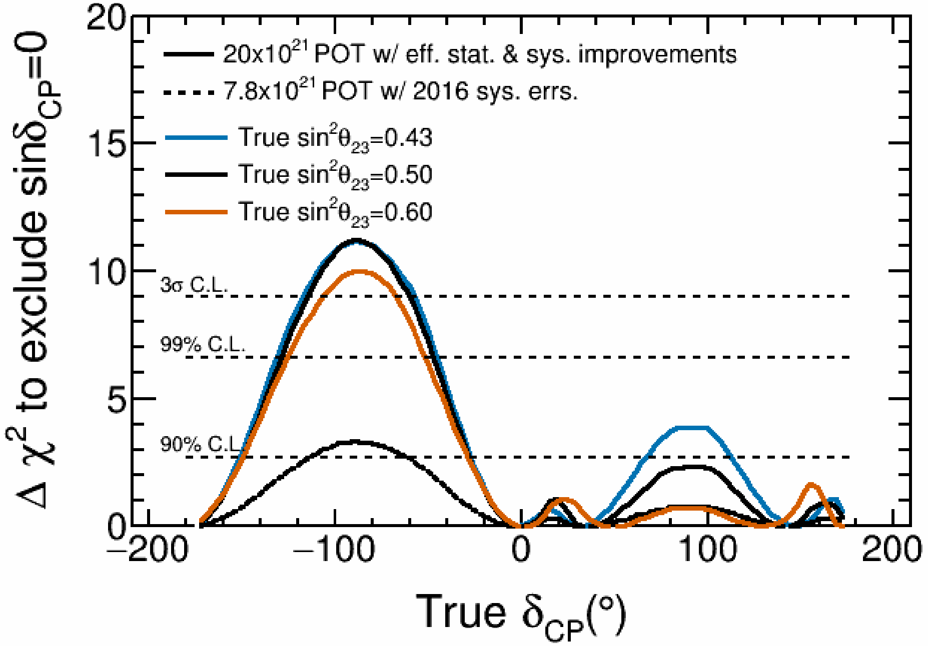
Medium term
Proposal for extended run

- 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

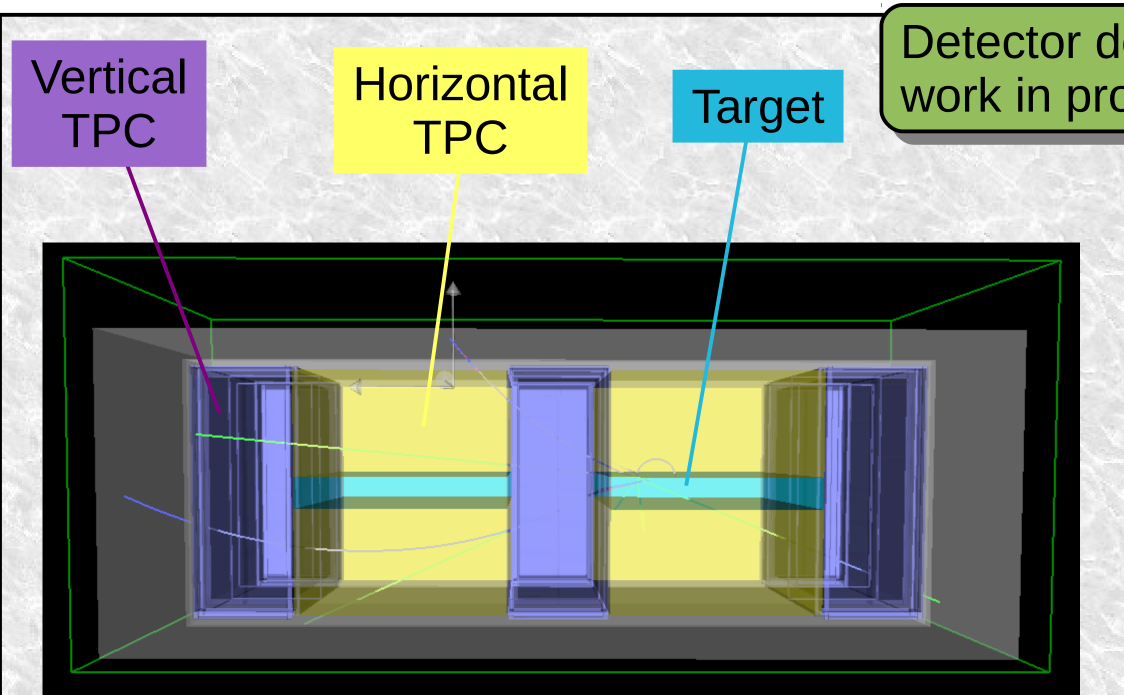
T2K phase 2 received stage 1 status at summer J-PARC PAC



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

Medium term (2021-2025)
Near detector upgrade

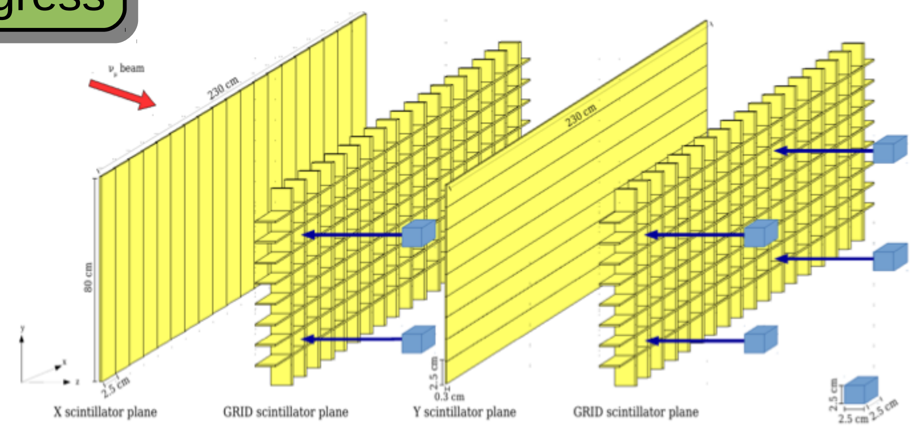
- Extended run will require lower systematic uncertainties
- Design a new off-axis detector to avoid limitations of current ND280
- Main requirements:
  - ✔ Water target
  - ✔ Large angular acceptance
  - ✔ Better efficiency for low momentum p and π



First target: CH, Second target: $CH+H_2O$

Detector design: work in progress

Possible target concept

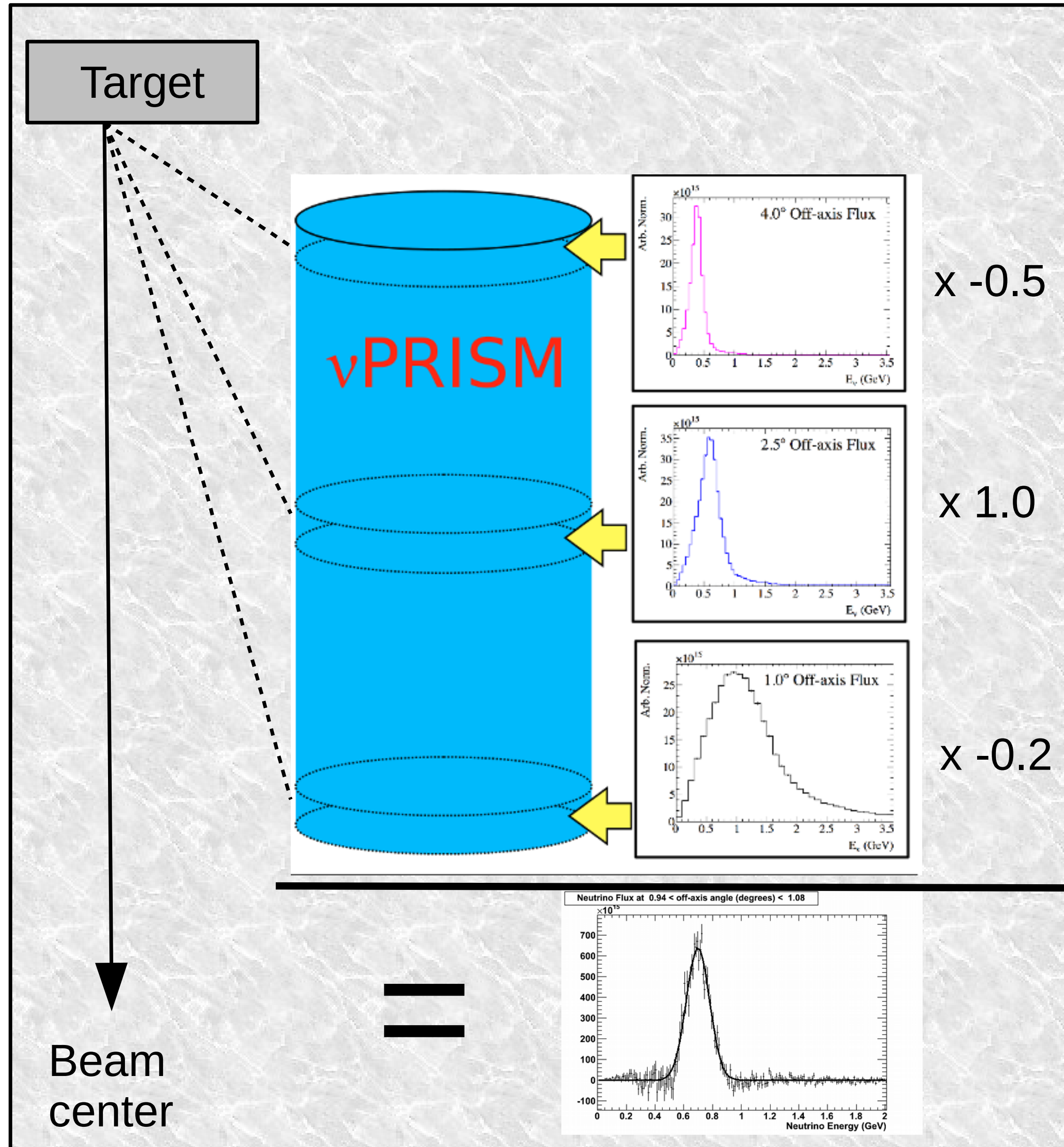


70% water in mass when filled

Workshop@CERN:
“Neutrino ND based on gas TPCs”
https://indico.cern.ch/event/568177/

Medium term
Intermediate water Cherenkov detector

- Tall (~50m) water Cherenkov detector, ~1km from target
- Spans 1-4° off-axis angles
- Same target material (H_20), angular acceptance and detection technique than far detector
- Ability to look at rates and neutrino interactions as a function of true neutrino energy
- Recreate oscillated flux at SK with little need for interaction models

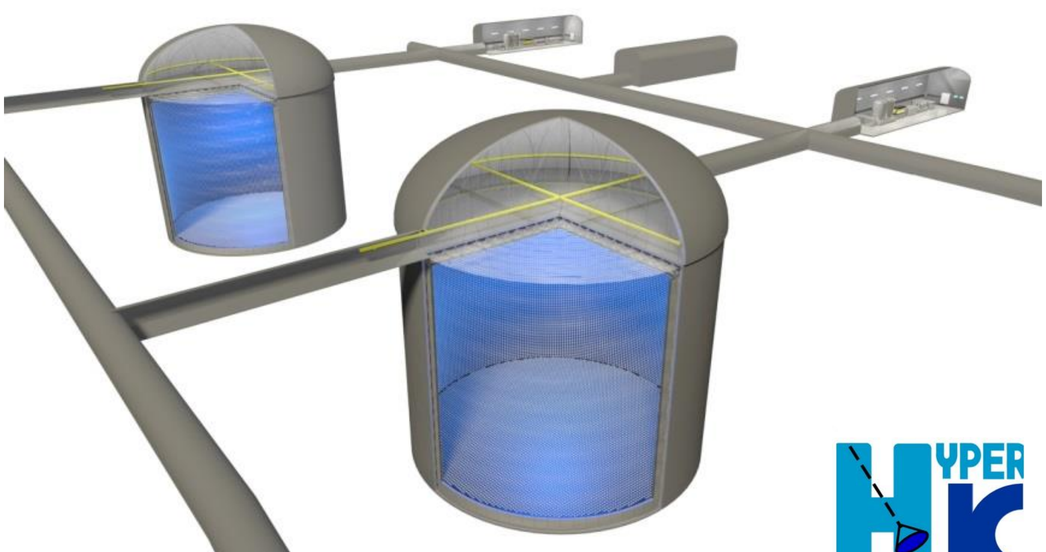


- Separate collaboration from T2K
- Received stage 1 status at July J-PARC PAC

Longer term
Hyper-Kamiokande

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

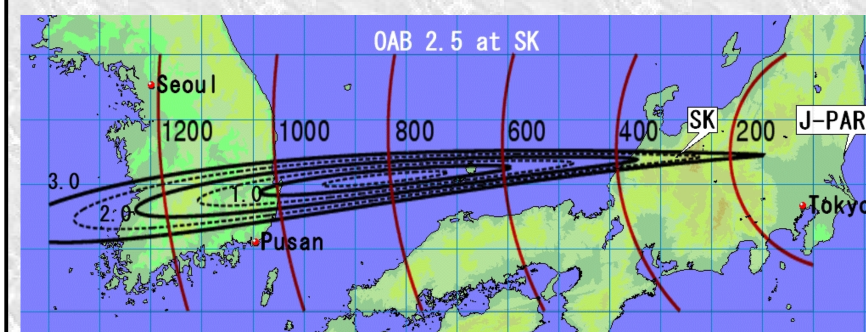
Rich physics program:
- Long baseline neutrinos
- Atmospheric neutrinos
- Proton decay
- Solar / astrophysical / supernova neutrinos



Hyper Kamiokande
@HyperKamiokande

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

Also proposal to have
2nd tank in Korea



Summary

- Presented neutrino oscillation results from combined analysis of T2K $\nu_\mu/\bar{\nu}_\mu/\nu_e/\bar{\nu}_e$ samples:
  - ✓ Results compatible with maximal ν_μ disappearance
  - ✓ θ_{13} measurement from T2K alone compatible with measurement by reactor experiments
  - ✓ Favor $\delta\sim-\pi/2$ with and without combining with reactor experiments CP conserving values outside of 90%CL interval when combining
  - ✓ Mild preference for normal hierarchy and octant $\sin^2\theta_{23}>0.5$

- Accumulated $1.5\mathrm{x}10^{21}$ POT out of $7.8\mathrm{x}10^{21}$ approved: a lot more results to come

- Proposal to extend run to $20\mathrm{x}10^{21}$ POT with upgraded near detector and additional intermediate detector

Additional slides

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 — $\boxed{\theta_{13}}$

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

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

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

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

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

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

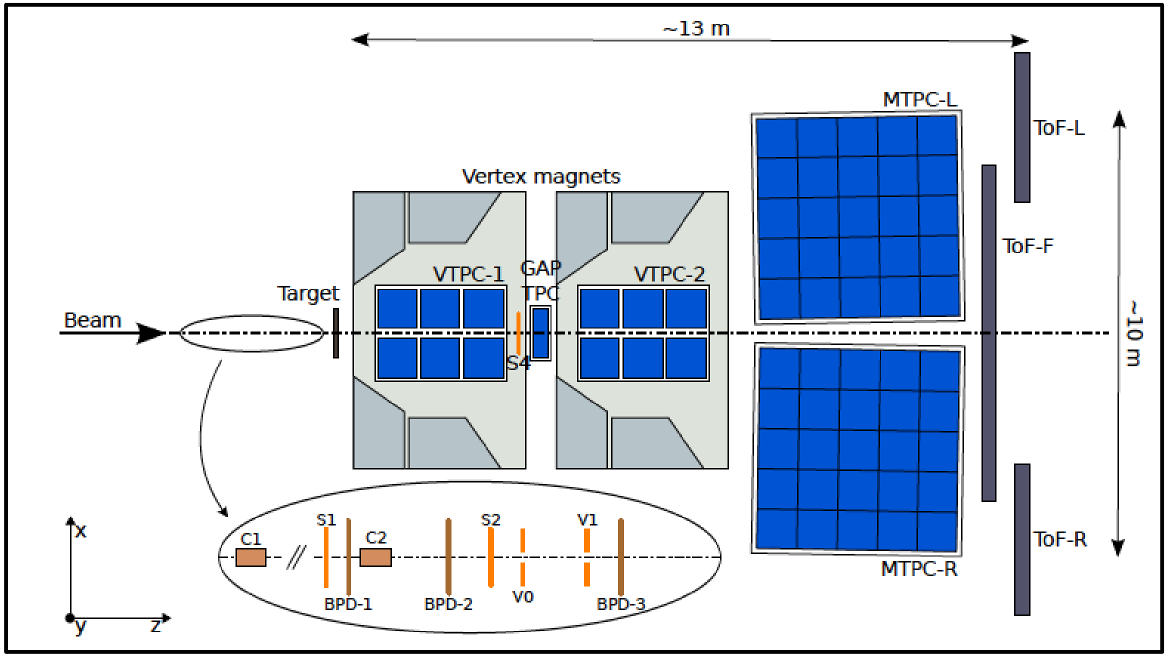
(courtesy of A. Ichikawa/T2K reference slides)

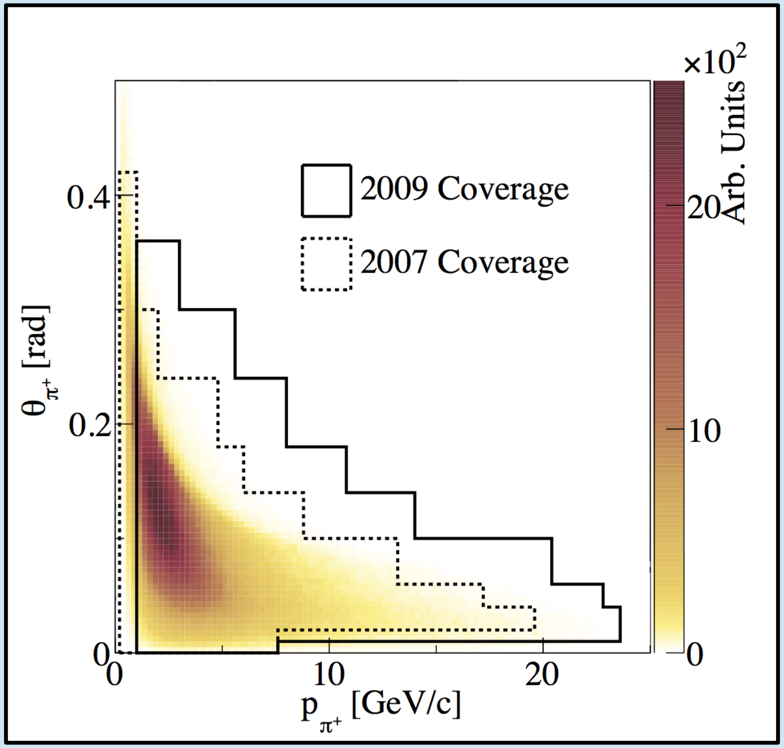
Analysis description
Hadron production measurements

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

2 targets:
- 'thin' ~0.04λ
- Replica T2K target

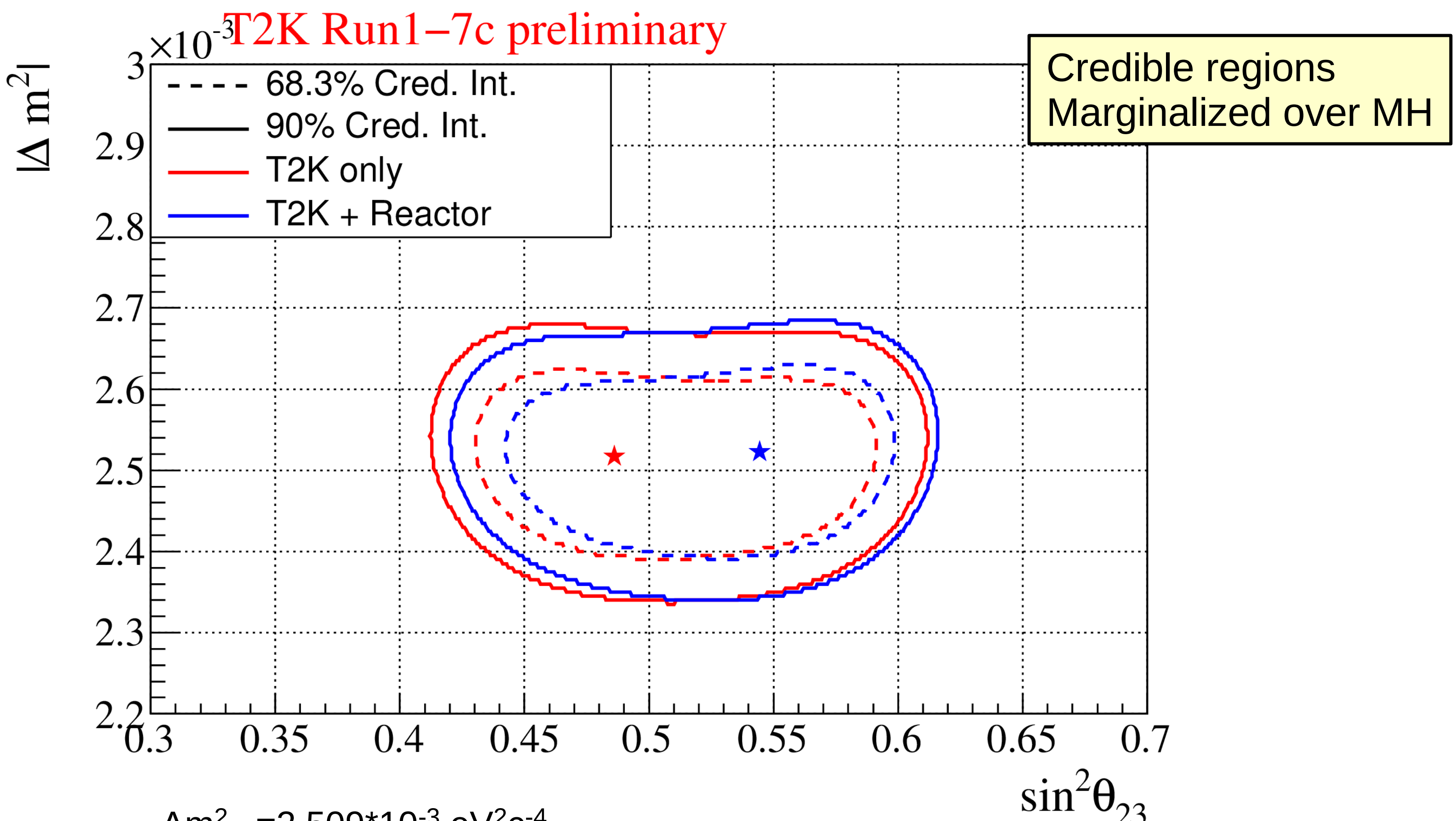
Covers most of the phase space for T2K neutrino production





Combined ν-$\bar{\nu}$ analysis
Effect of reactor constraint for atmospheric

Sensitivity for the atmospheric parameters changes depending on whether the reactor constraint is used or not



δ=-1.601
$\sin^2(\theta_{23})$=0.528

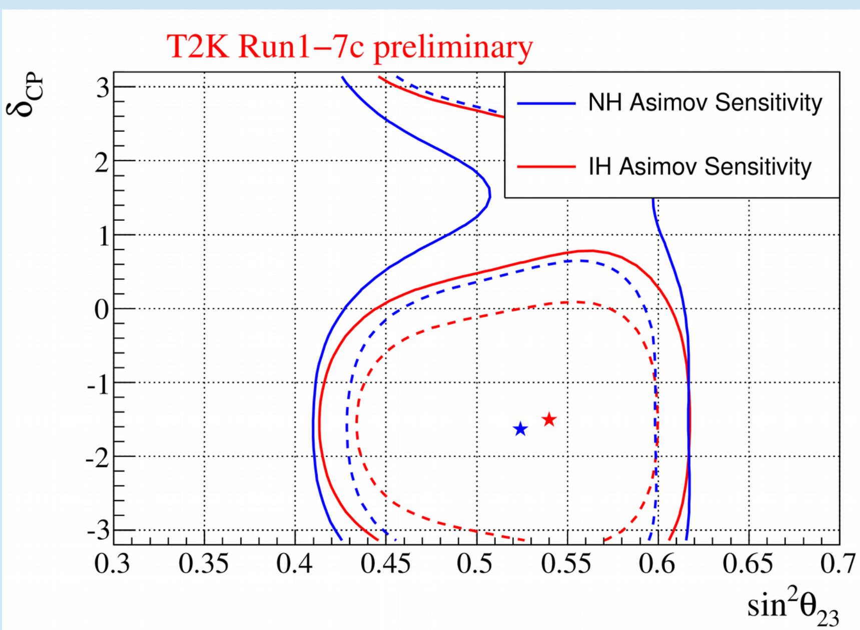
Δm^2_{32}=2.509*10^{-3} eV^2c^{-4}
$\sin^2(\theta_{13})$=0.0217

Combined ν-$\bar{\nu}$ analysis
θ_{23} and δ – T2K + reactor

Reactor constraint (PDG2015)
$\sin^2(2\theta_{13})=0.085 \pm 0.005$

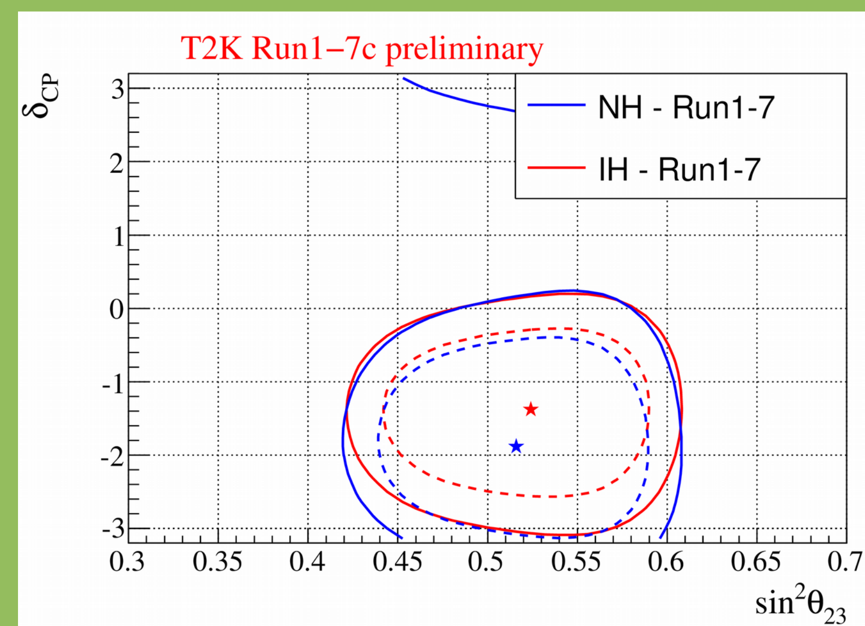
Fixed $\Delta\chi^2$ 68% and 90% CL regions

Sensitivity

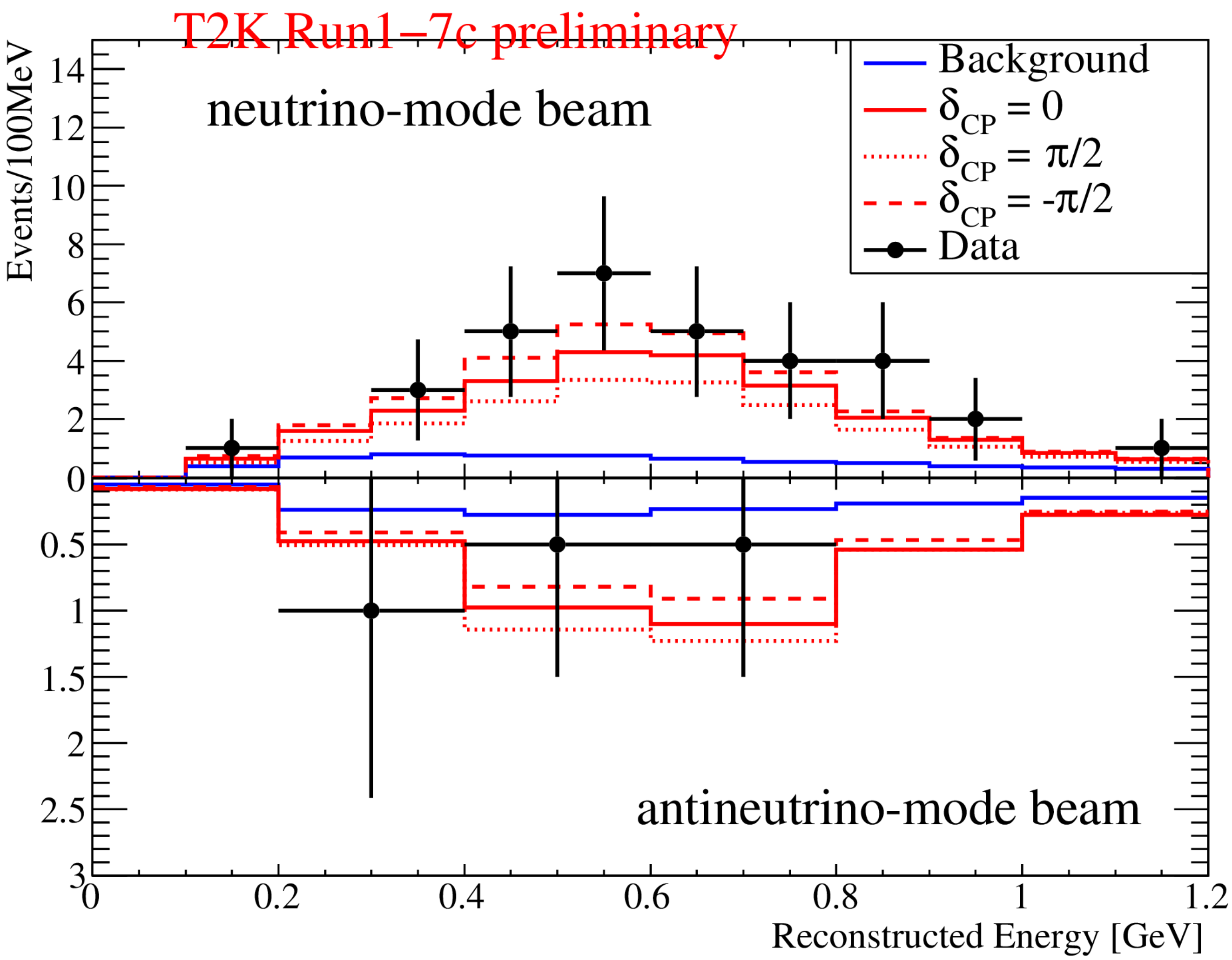


$\delta=-1.601$
$\sin^2(\theta_{23})=0.528$
$\Delta m^2_{32}=2.509*10^{-3}\ eV^2c^{-4}$
$\sin^2(\theta_{13})=0.0217$

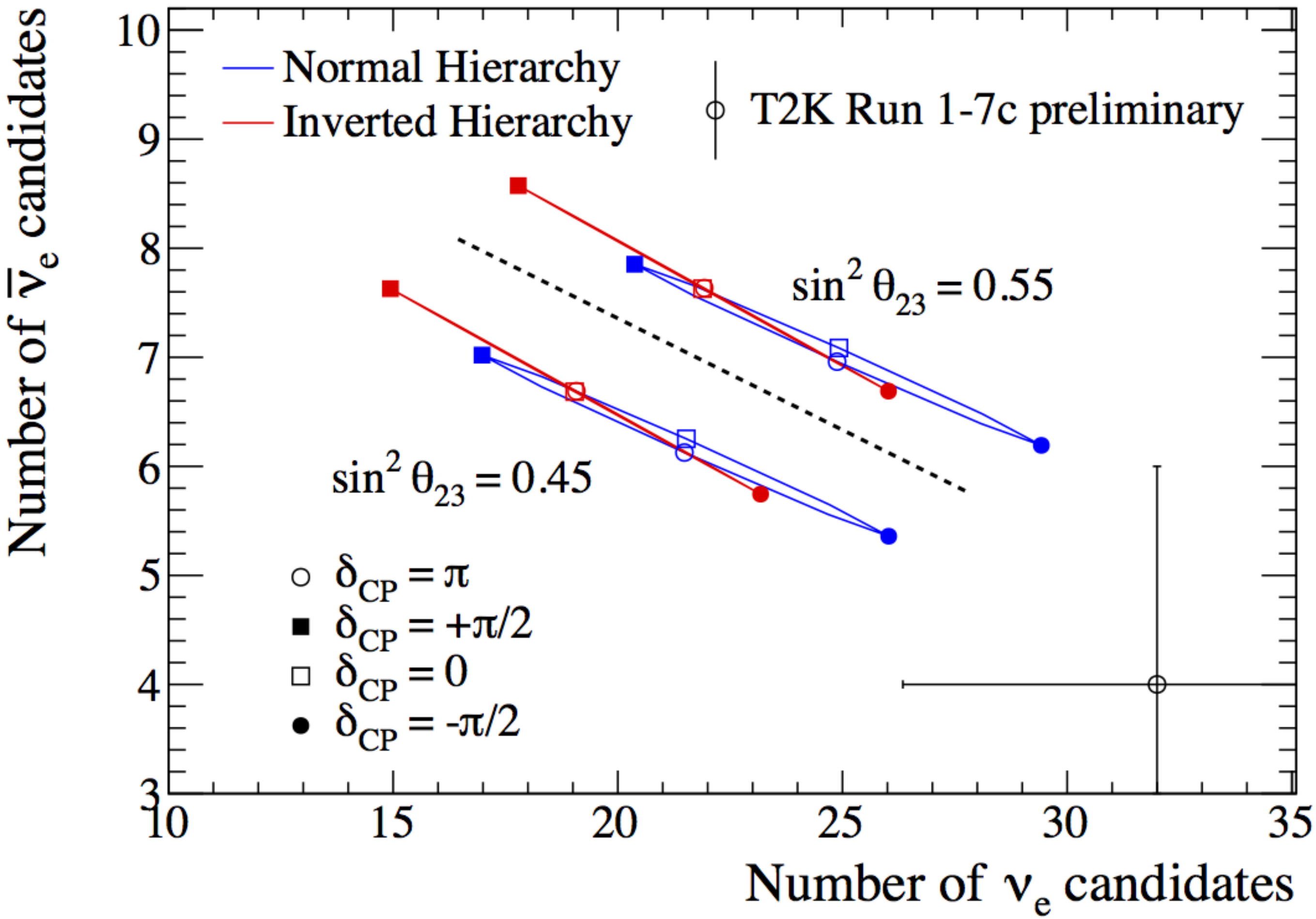
Data fit



Combined ν-$\bar{\nu}$ analysis
Electron-like spectra



Combined ν-ν̄ analysis
Electron-like number of events



Systematic uncertainties

T2K systematics uncertainties (joint oscillation analysis)

Fractional error on the number of expected events at SK with and without ND280

	ν_μ sample $1R_\mu$ FHC	ν_e sample $1R_e$ FHC	$\bar{\nu}_\mu$ sample $1R_\mu$ RHC	$\bar{\nu}_e$ sample $1R_e$ RHC
ν flux w/o ND280	7,6%	8,9%	7,1%	8,0%
ν flux with ND280	3,6%	3,6%	3,8%	3,8%
ν cross-section w/o ND280	7,7%	7,2%	9,3%	10,1%
ν cross-section with ND280	4,1%	5,1%	4,2%	5,5%
ν flux+cross-section	2,9%	4,2%	3,4%	4,6%
Final or secondary hadron int.	1,5%	2,5%	2,1%	2,5%
Super-K detector	3,9%	2,4%	3,3%	3,1%
Total w/o ND280	12,0%	11,9%	12,5%	13,7%
Total with ND280	**5,0%**	**5,4%**	**5,2%**	**6,2%**

Systematic uncertainties

T2K systematics uncertainties (joint oscillation analysis)

Fractional error on the number of expected events at SK

	ν_μ sample $1R_\mu$ FHC	ν_e sample $1R_e$ FHC	$\bar{\nu}_\mu$ sample $1R_\mu$ RHC	$\bar{\nu}_e$ sample $1R_e$ RHC	$1R_e$ FHC/RHC
ν flux+cross-section constrained by ND280	2,8%	2,9%	3,3%	3,2%	2,2%
ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$ cross-sections	0,0%	2,7%	0,0%	1,5%	3,1%
NC γ	0,0%	1,4%	0,0%	3,0%	1,5%
NC other	0,8%	0,2%	0,8%	0,3%	0,2%
Final or secondary hadron int.	1,5%	2,5%	2,1%	2,5%	3,6%
Super-K detector	3,9%	2,4%	3,3%	3,1%	1,6%
Total	**5,0%**	**5,4%**	**5,2%**	**6,2%**	**5,8%**