Recent results from T2K

Yoshinari Hayato

for the T2K collaboration

Introduction

Neutrino oscillation ~ discovered in 1998 & extensively studied.

Flavor mixing & non-zero neutrino mass

~ Beyond the standard model ~

Parameters

- 3 oscillation angles(θ_{12}, θ_{23}, θ_{13})
- 2 mass differences(Δm^2_{12}, Δm^2_{32})
- 1 CP phase (δ)

PMNS Matrix ($U_{\alpha i}$)

$$|\nu_\alpha> = \Sigma U_{\alpha i}|\nu_i>$$

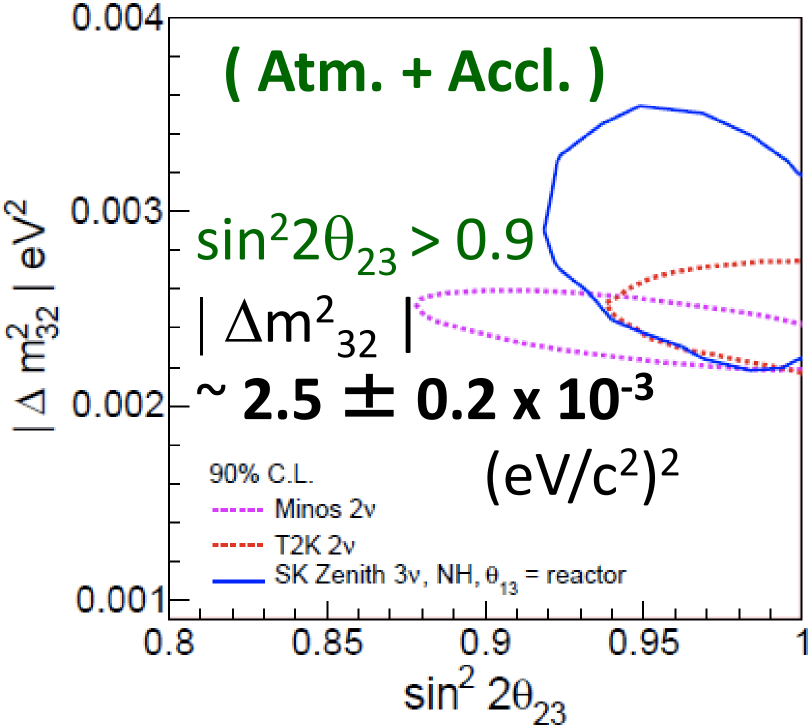
Weak ***Mass eigenstates***

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

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

Atmospheric & Accelerator **Reactor & Accelerator** **Solar & Reactor**

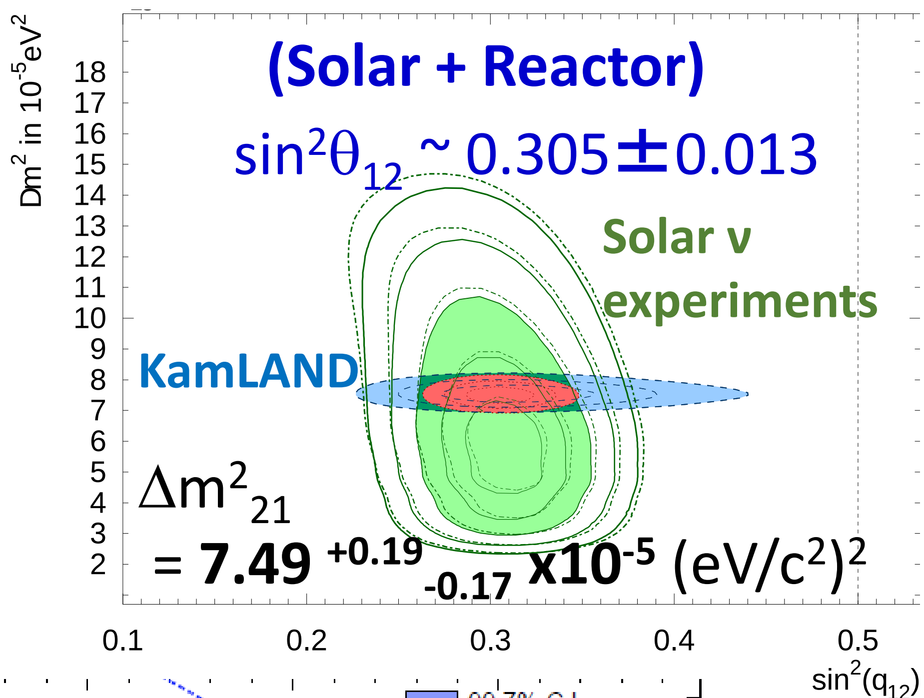
Neutrino oscillation parameter measurements



(Atm. + Accl.)

$\sin^2 2\theta_{23} > 0.9$

$| \Delta m^2_{32} |$ **~ 2.5 ± 0.2 x 10^{-3}** $(\mathrm{eV}/c^2)^2$



(Solar + Reactor)

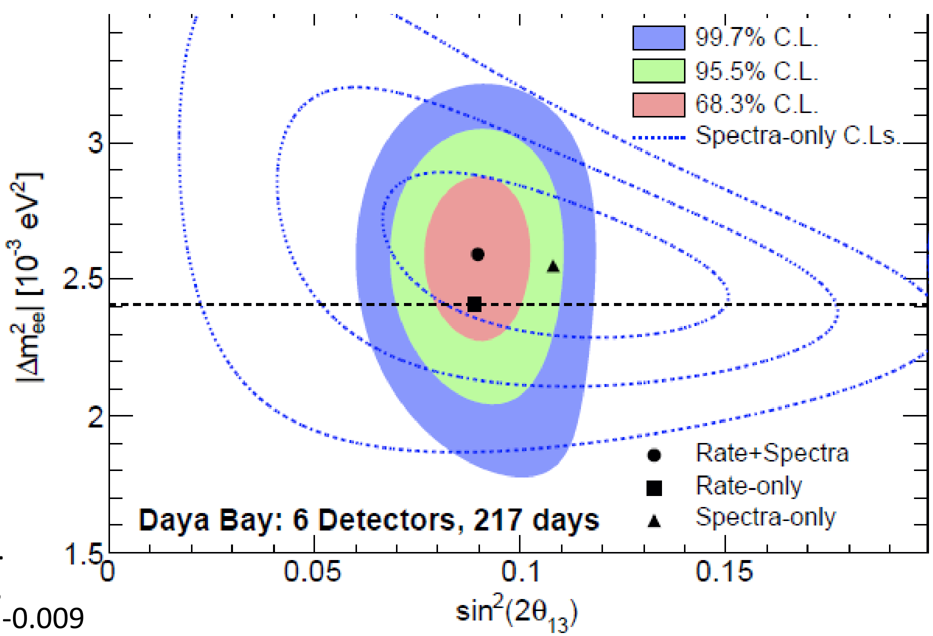
$\sin^2\theta_{12}$ ~ 0.305 ± 0.013

Solar ν experiments

Δm^2_{21} **= 7.49 $^{+0.19}_{-0.17}$ x10^{-5}** $(\mathrm{eV}/c^2)^2$

(Reactor + Accl.)

$\sin^2 2\theta_{13}$ = 0.098 ± 0.013



Daya-Bay collaboration
PRL 112 (2014) 061801
$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$

Neutrino mixing parameter measurements

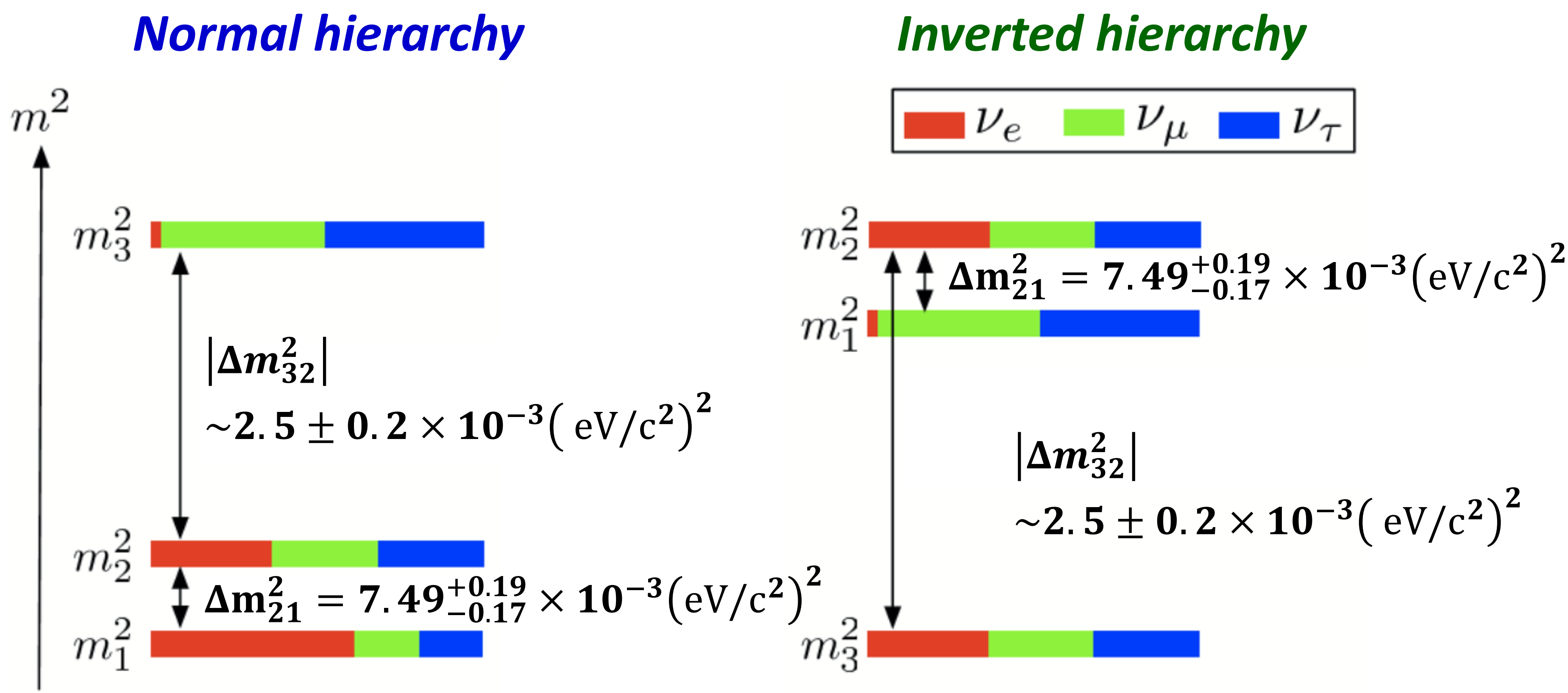
Remaining issues

1) θ_{23} is really 45° or < 45° or >45° ?

   Current uncertainty of $\sin^2\theta_{23}$ is still large

2) CP is violated or not ($\delta = 0$ or not) ?

3) Mass hierarchy ~ which is heavier ? ($\Delta m^2_{32} > 0$ or < 0 ?)



Tokai to Kamioka long baseline neutrino oscillation experiment (T2K)

Canada
TRIUMF
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U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

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IPN Lyon
LLR E. Poly.
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Germany
Aachen U.

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

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
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Osaka City U.
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Poland
IFJ PAN, Cracow
NCBJ, Warsaw
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Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

~500 members,
59 Institutes,
11 countries

Tokai to Kamioka long baseline neutrino oscillation experiment (T2K)

· *Search for the ν_e appearance*

$\rightarrow$ measure θ_{13}

· *Precision measurements of oscillation parameters with ν_μ disappearance*

$\rightarrow \delta(\Delta m^2_{23}) \sim 1\text{x}10^{-4}\ \text{eV}^2$, $\delta(\sin^2 2\theta_{23}) \sim 0.01$

· *Study CP violation in the lepton sector (& mass hierarchy)*

Neutrino mixing parameter measurements in T2K

ν_μ disappearance channel

~ precise measurement of θ_{23} & Δm^2_{32} / Δm^2_{13}

Expected sensitivity

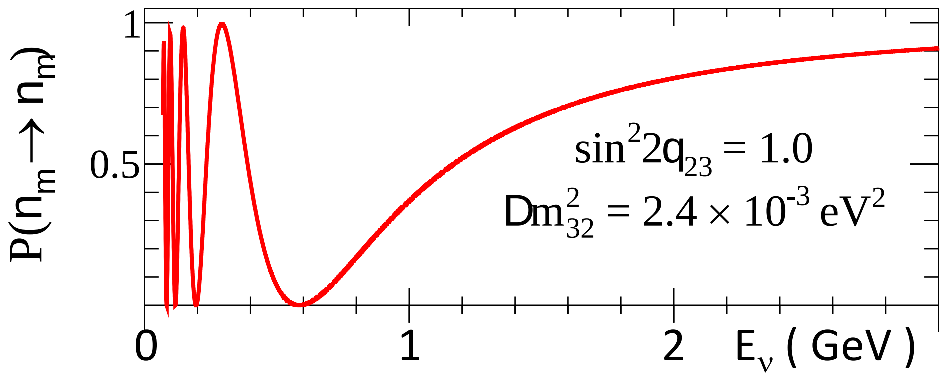
$\delta(\Delta m^2_{23})$ ~ 1 x 10^{-4} eV^2 , $\delta(\sin^2 2\theta_{23})$ ~ 0.01

To achieve this precision,

high statistics & small systematic errors are required.

ν_μ Survival probability

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2\theta_{23}) \sin^2\Delta$$



$\Delta = \Delta m^2_{32} L/4E$ (Normal hierarchy)

$\Delta m^2_{13} L/4E$ (Inverted hierarchy)

Oscillation maximum ~ 600 MeV @ 295km

Neutrino mixing parameter measurements in T2K

ν_e appearance channel

~ precise measurement of θ_{13}

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta_{31}$$ (leading term)

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

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$ CP violating term

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta) \cdot \sin^2\Delta_{21}$$

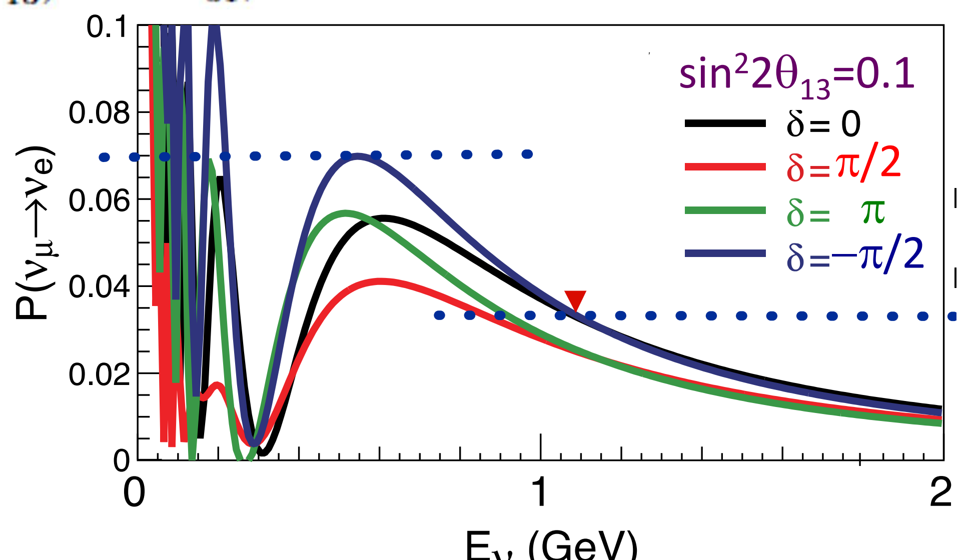
$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2\Delta_{31},$$

$$a = 2\sqrt{2} G_F n_e E_\nu$$

For anti neutrinos,

a* → -*a*, *δ* → -*δ



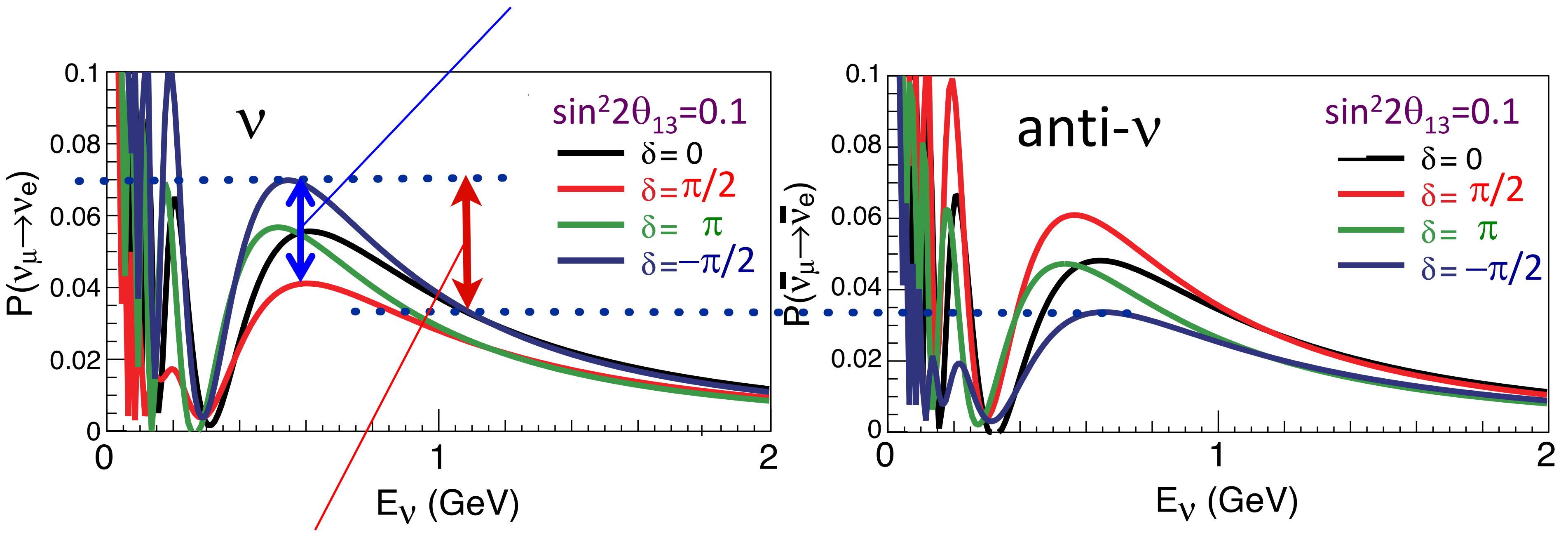
Neutrino mixing parameter measurements in T2K

ν_e appearance channel

~ Study of CP violation in lepton sector

Two methods

Use θ_{13} constraints from reactor $\bar{\nu}_e$ disappearance



Compare difference between ν and $\bar{\nu}$ oscillations

T2K is planning to run with anti-neutrino configuration (flip horn current).

Anti neutrino "test run" is planned in 2014.

T2K neutrino beam ~ Off axis beam ~

Maximize sensitivity in oscillation studies

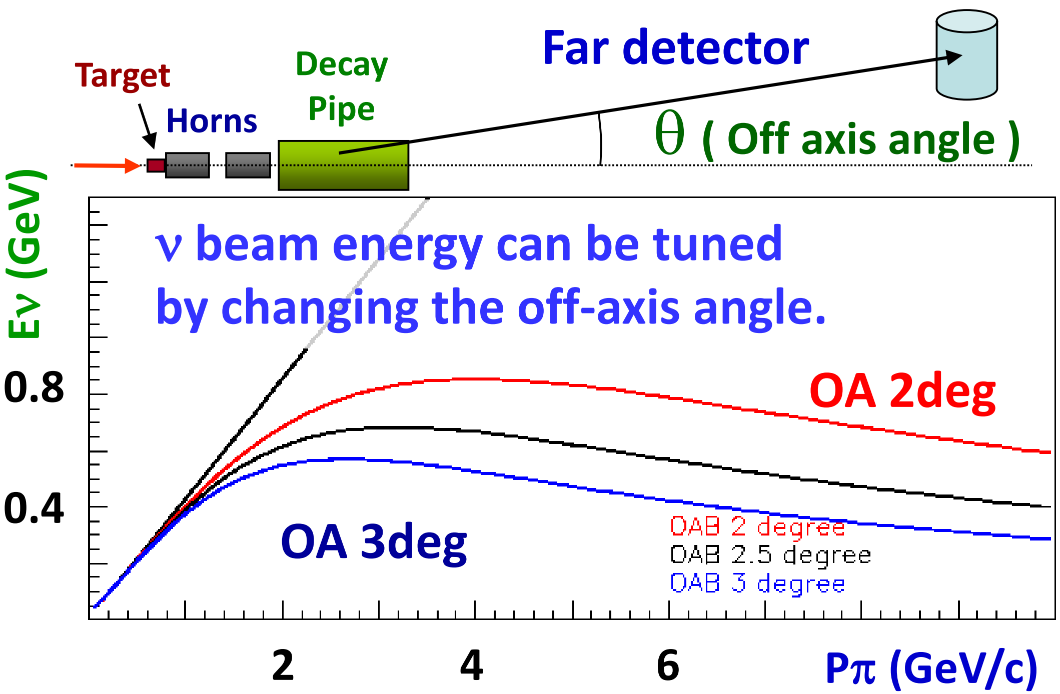
→ Use narrow band beam with peak energy at the oscillation maximum

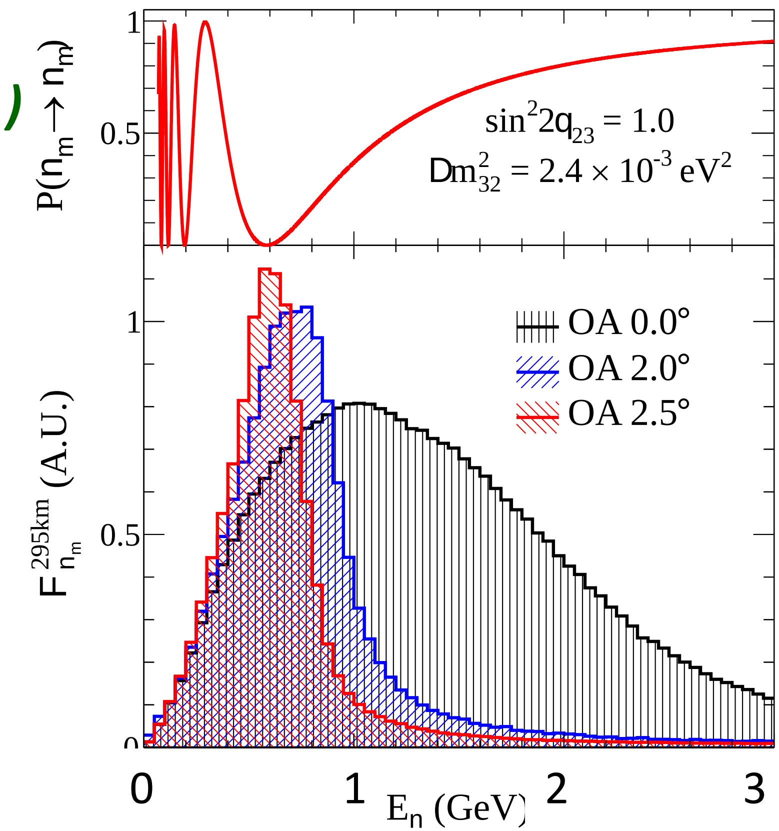
→ ***Off axis beam*** (ref.: BNL-E889 Proposal)

- Quasi-monochromatic beam ~ suppressed high energy ν
- Energy is tunable (Change off axis angle)

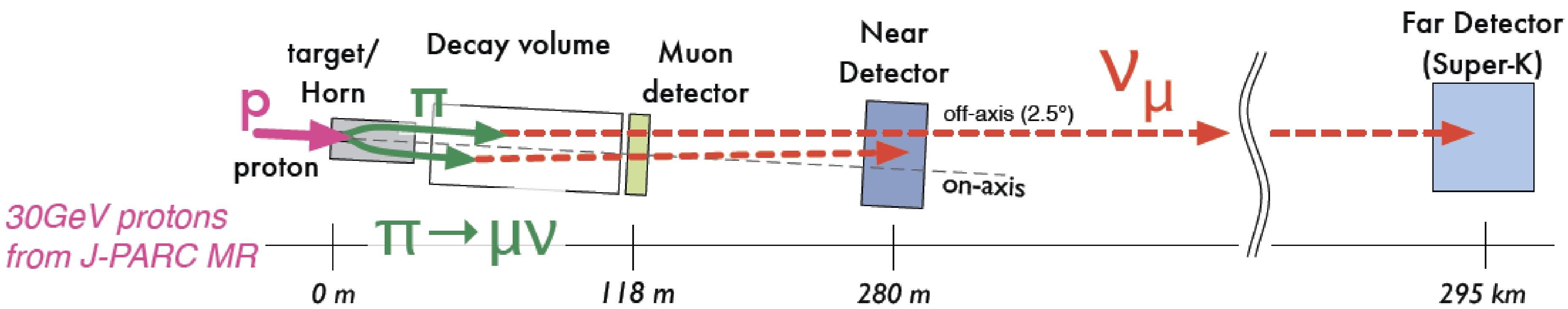
Important to monitor beam direction!

(1mrad ~ peak E_ν shifts by ~16 MeV)





T2K ~ Schematic diagram of the experiment



- Proton beam extracted every ~ 2.5 sec.
- Beam spill width ~ 5 μs

  8 bunches (6 bunches before Summer 2010)
- Neutrino production target

  graphite target

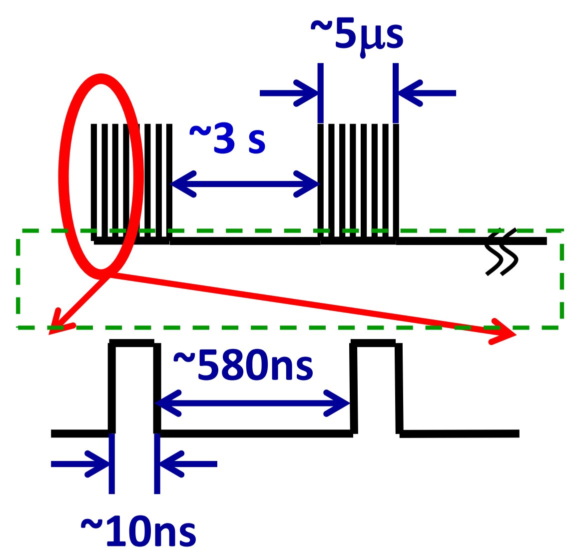
  (diameter = 26mm, L=90cm)

  He air cooled

  - π focusing ~ Triple horn system

  operated @ 250kA

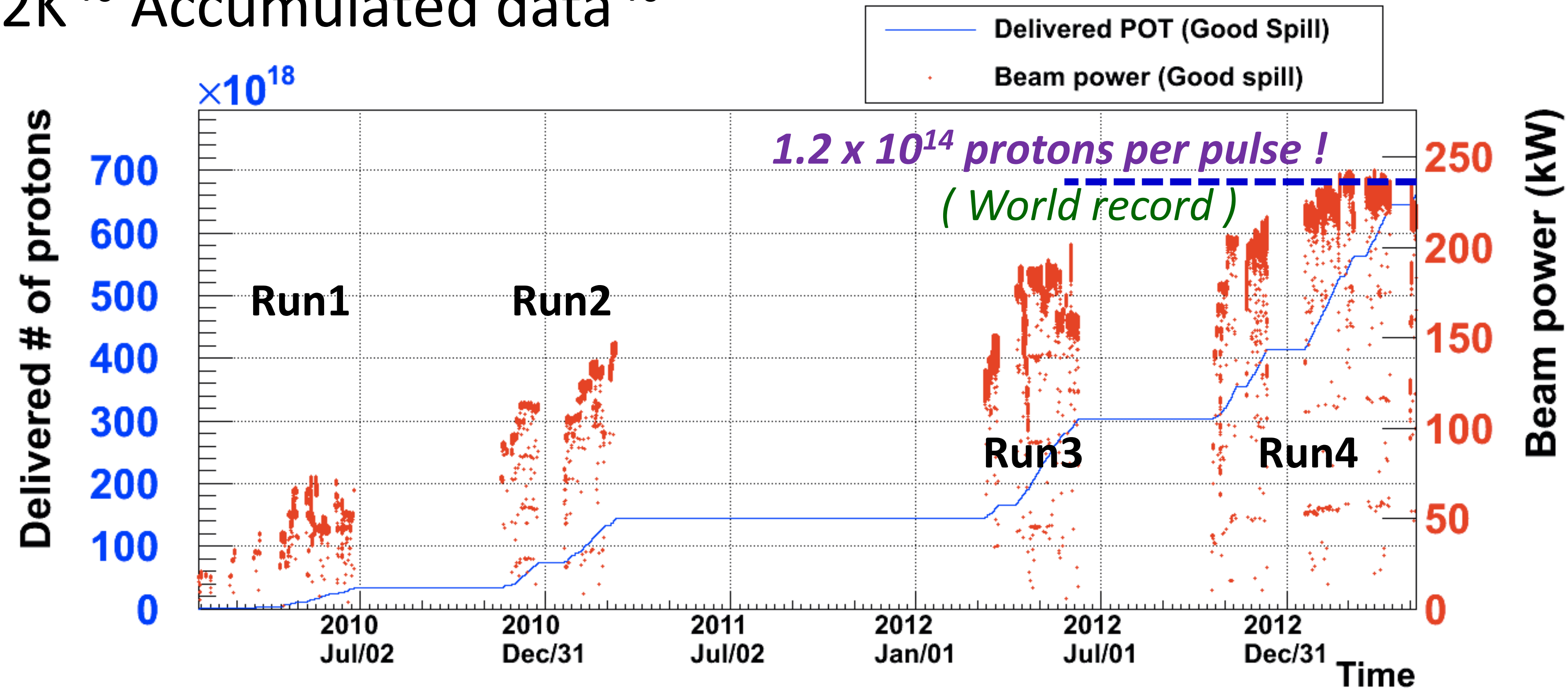
  except for short period in Run 3 (205kA , 0.21 x 10^{20} pot)



Increased beam power

~ achieved by increasing the # of protons per pulse & repetition rate

T2K ~ Accumulated data ~



Beam power has been continuously increased by

1) # of protons per spill was increased and
2) beam repetition rate has been shortened.

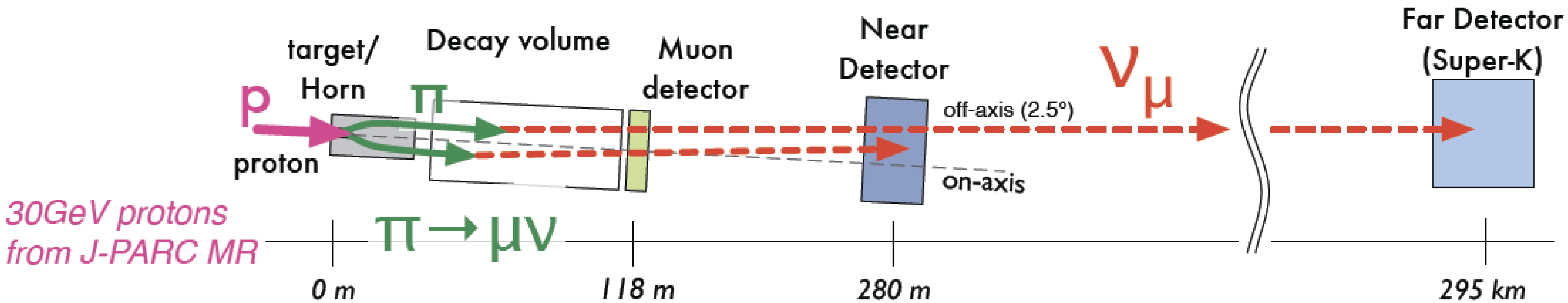
Run1(3.52s), Run2(3.2~3.04s), Run3(2.56s), Run4(2.48s)

Delivered # of protons 6.63 x 10^{20} protons on target

Analyzed # of protons 6.57 x 10^{20} protons on target

~ 8% of T2K goal

T2K ~ Schematic diagram of the experiment



Stability of the beam is very crucial

1mrad change of the neutrino beam direction

results in 2~3 % shift of the mean neutrino energy (~ 16 MeV)

- Muon monitor after the beam dump

  Spill by spill monitor

  of the neutrino direction

  and intensity of muon

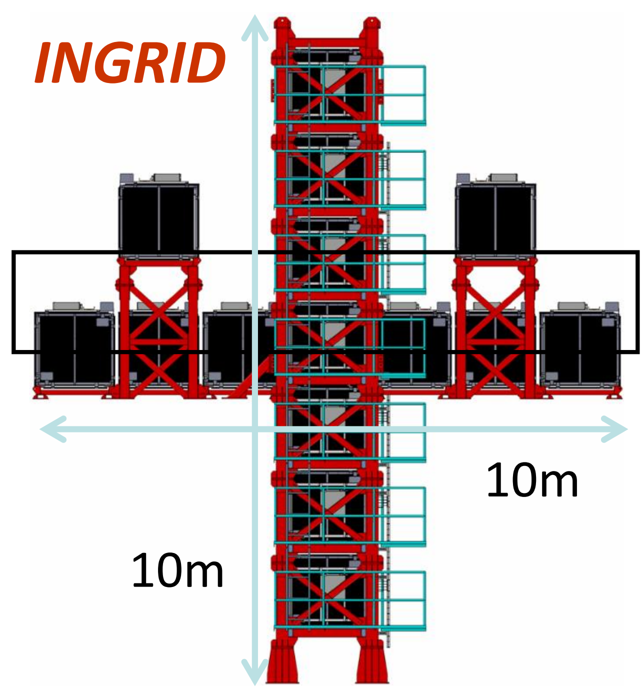
- On axis near neutrino detector

  INGRID (Fe + Scintillator)

  Day by day monitor

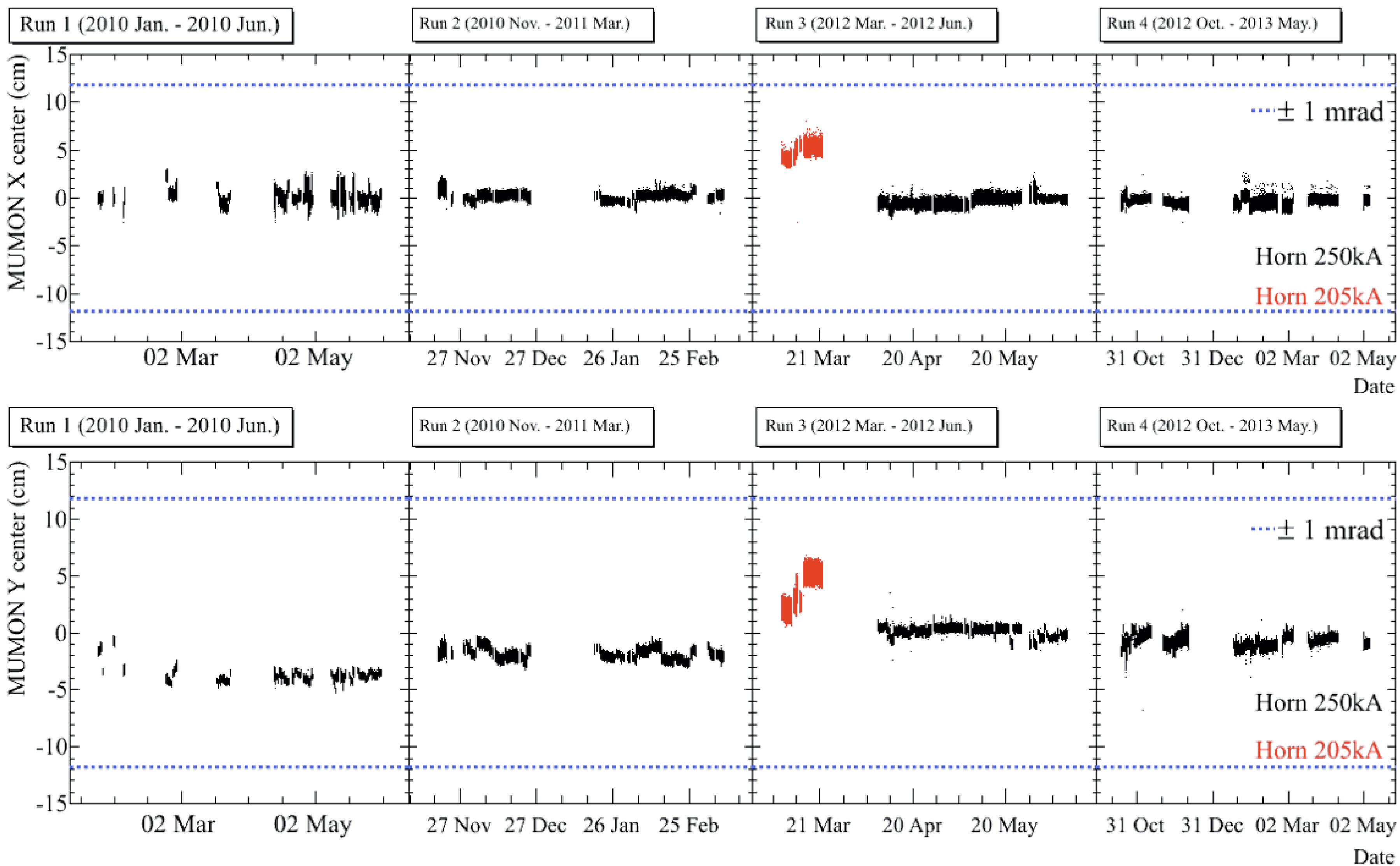
  of the neutrino interaction rate

  Neutrino beam direction monitor



T2K ~ Beam stability ~ monitored by muon monitor

Stability of beam direction is less than 1mrad throughout whole run period

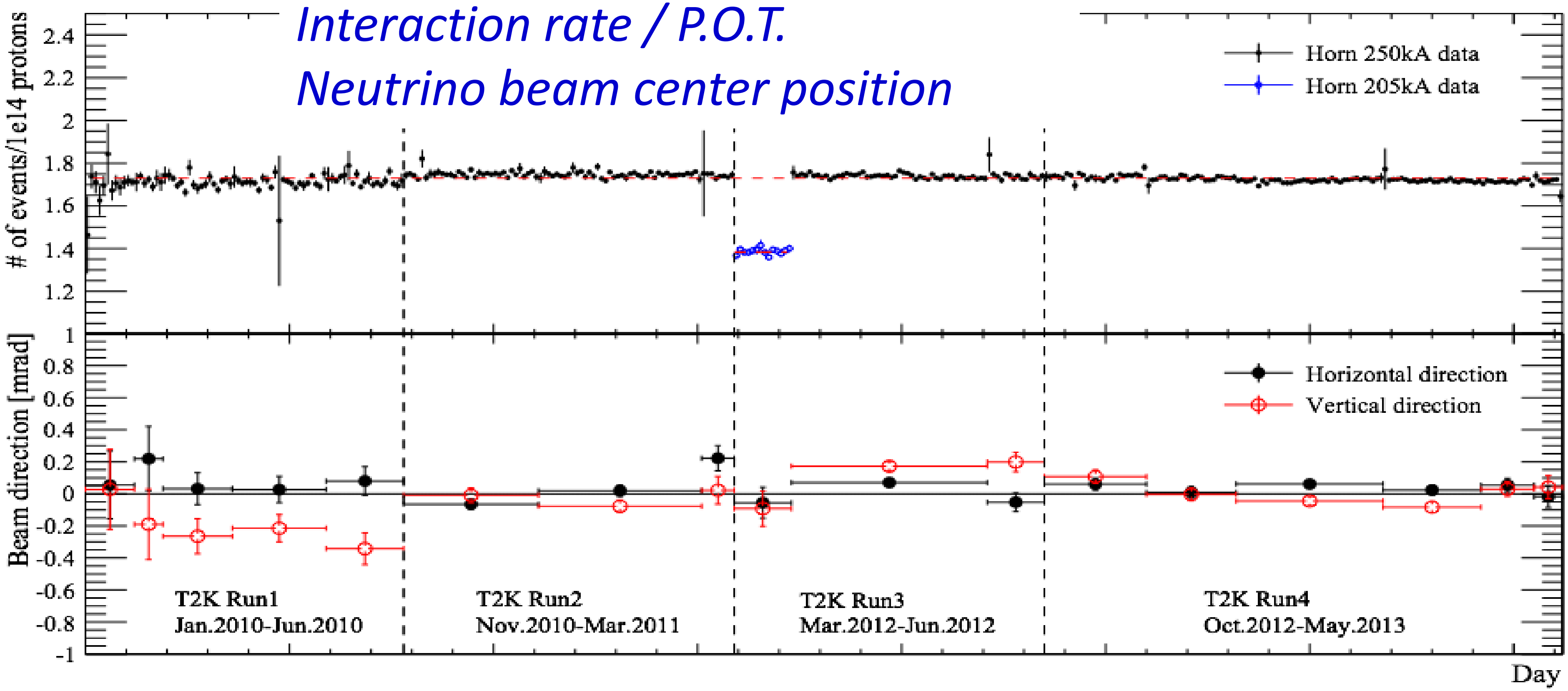


T2K ~ Beam stability ~ monitored by INGRID

Monitor the number of interactions in the detector

Interaction rate / P.O.T.

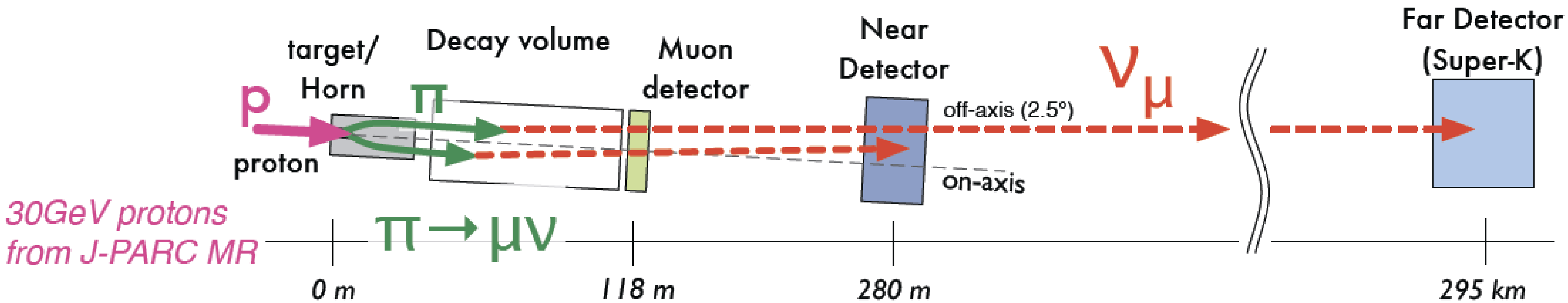
Neutrino beam center position



- Observed neutrino interaction rate per P.O.T. has been stable within 0.7%
- Neutrino beam direction is stable within 1mrad

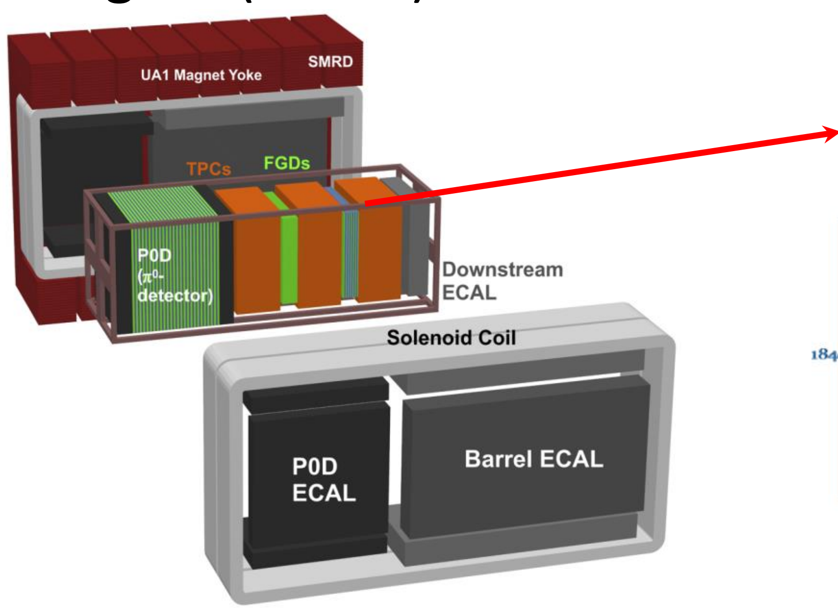
Neutrino beam has been confirmed to be stable.

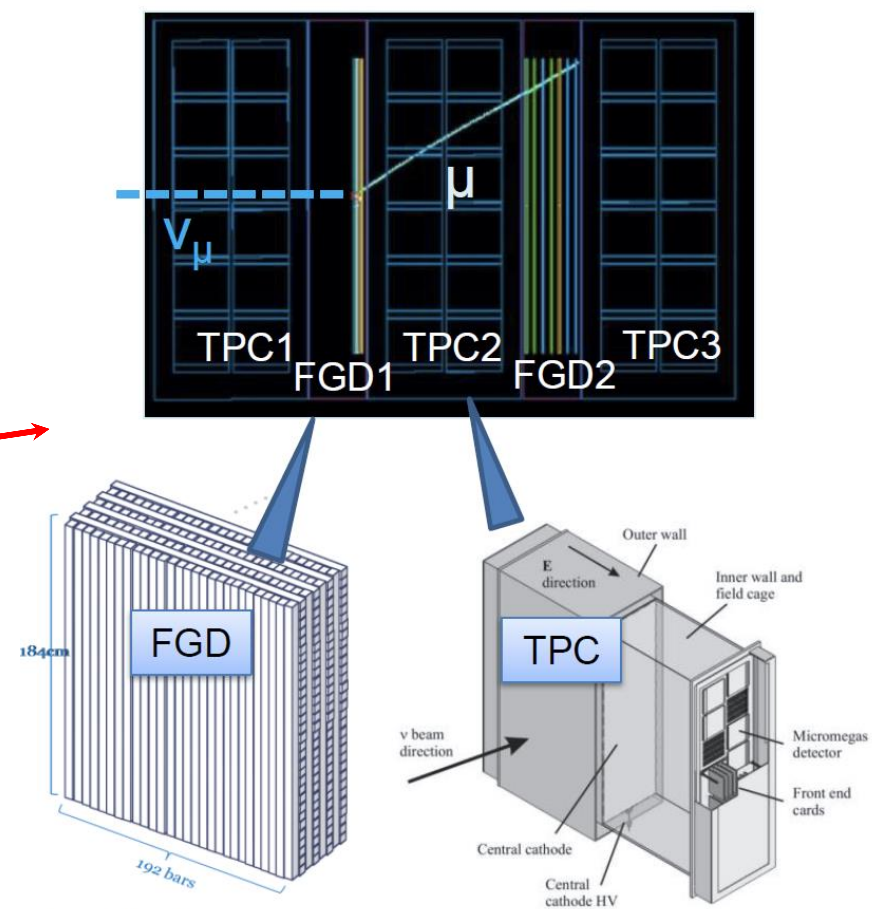
T2K ~ Schematic diagram of the experiment



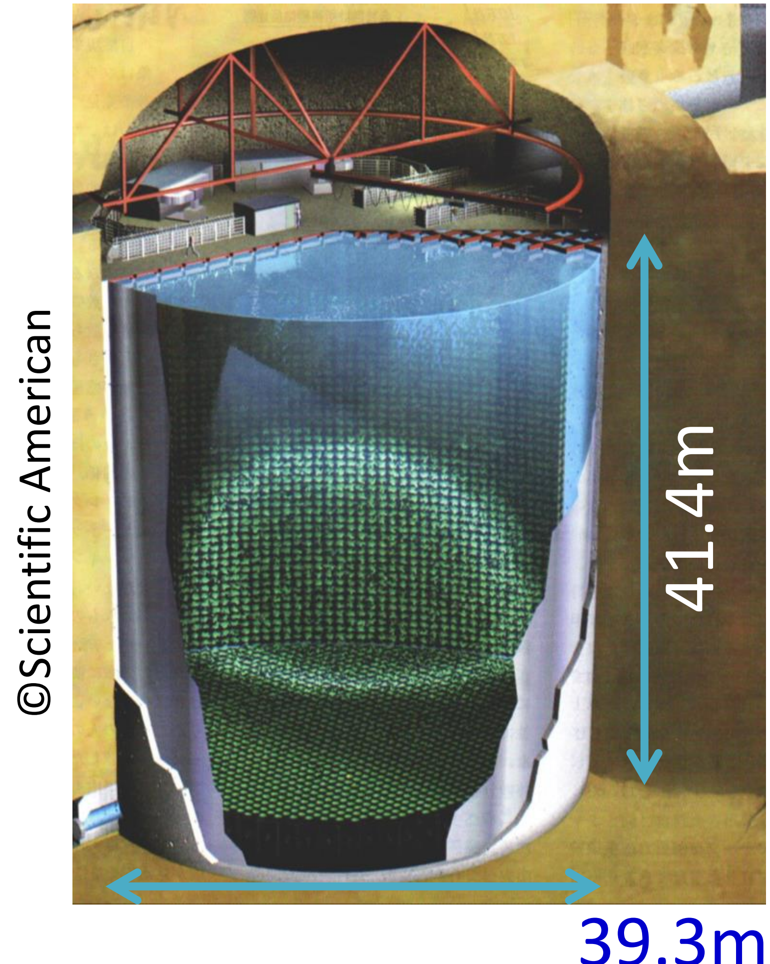
- Off axis detectors
  neutrino flux measurements
  neutrino interaction studies

  UA1 magnet (0.2 T)





T2K far detector ~ Super-Kamiokande



- Water Cherenkov detector with fiducial volume 22.5kton

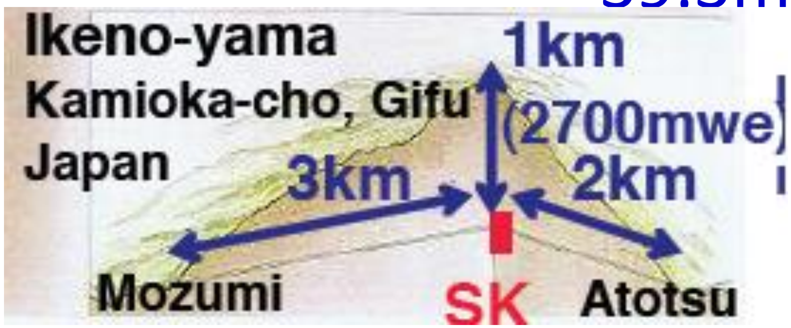
  Inner detector (ID)

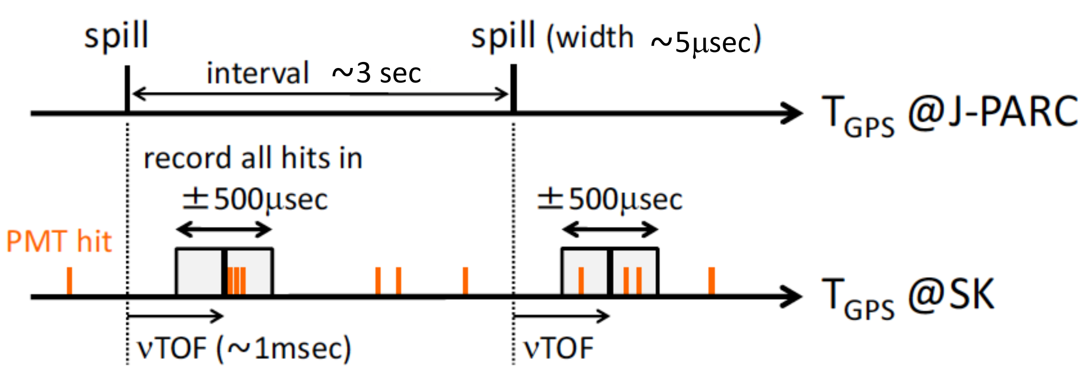
  11,129 20inch PMT

  Outer detector (OD)

  1,885 8inch PMT

- New DAQ system from 2008
- Realtime recording of all PMT hits within ±500μsec of each ν beam arrival time at SK by with GPS.





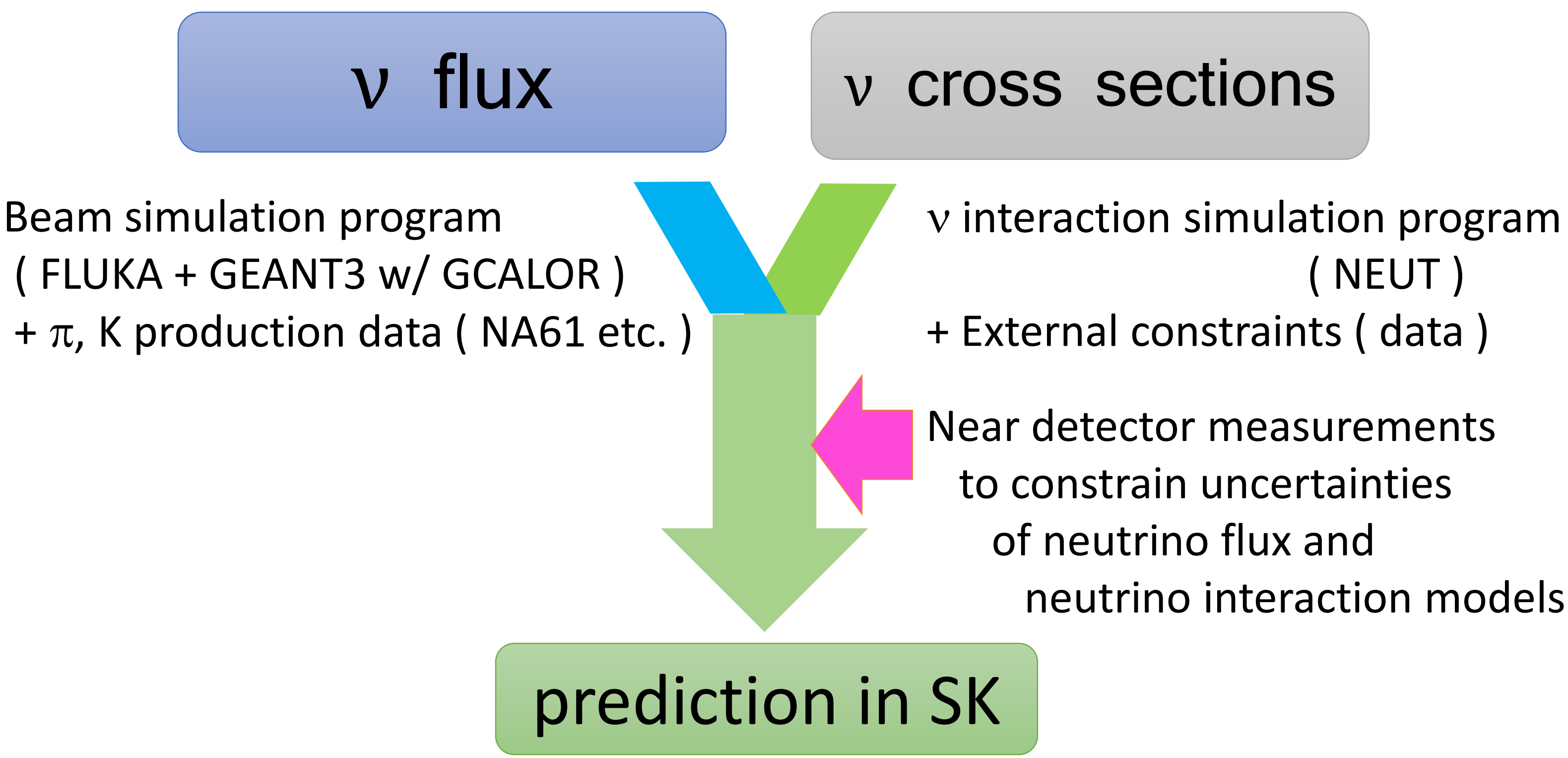
T2K experiment ~ Analysis strategy

Extracting the “oscillation parameters” from observables

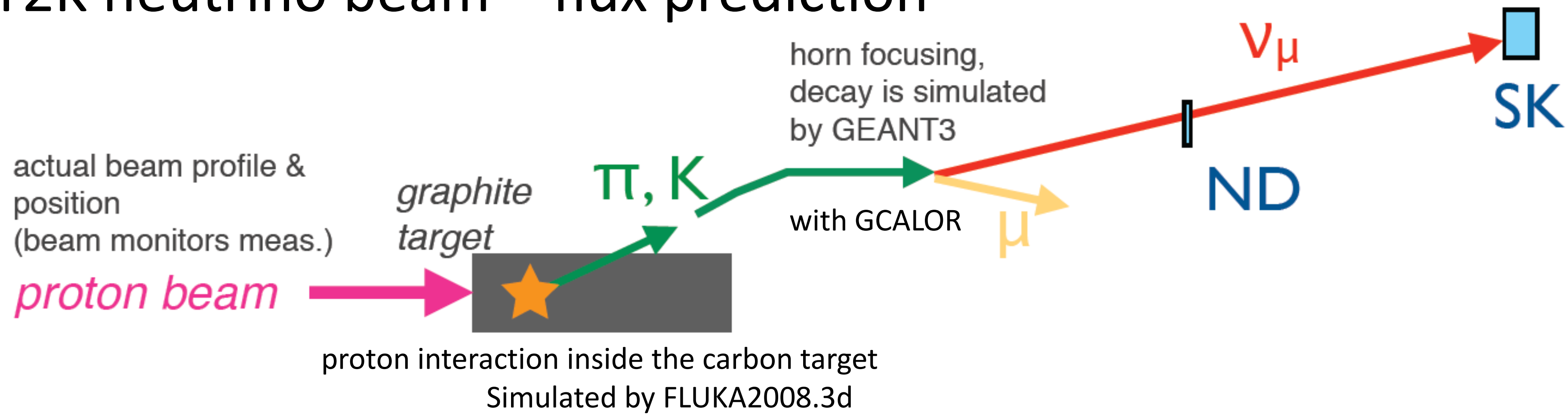
~ compare the data and the prediction with oscillations.

Prediction

Based on Monte-Carlo simulation with various constraints from the measurements



T2K neutrino beam ~ flux prediction



- Simulated with FLUKA 2008.3d + GEANT3 w/GCALOR
- Apply weights to the flux

  ~ Constraint from the external hadron production data sets

  CERN NA61/SHINE (Primarily used)

  > 90 % coverage of ν parent pions,

  ~ 60 % coverage of ν paraent kaons

  Other data sets are used for outside of the NA61 coverage

  + systematic error evaluations

  T. Eichten et al. (Nucl. Phys. B44 1972)

  J.V. Allaby et al. (Tech. Rep. 70-12 CERN, 1970) etc..

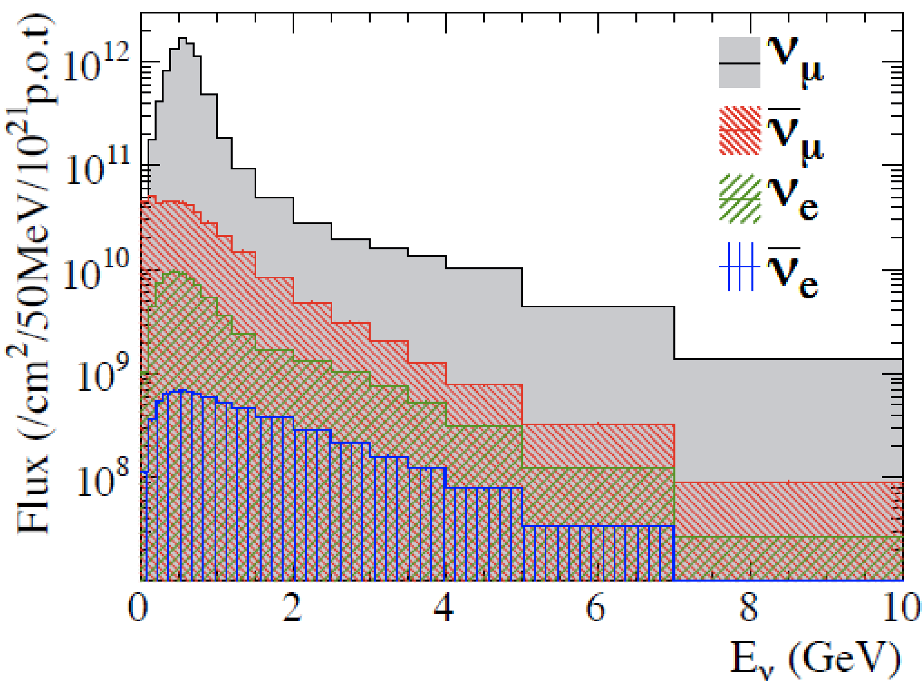
T2K neutrino beam ~ flux prediction

Beam flux predicted based on

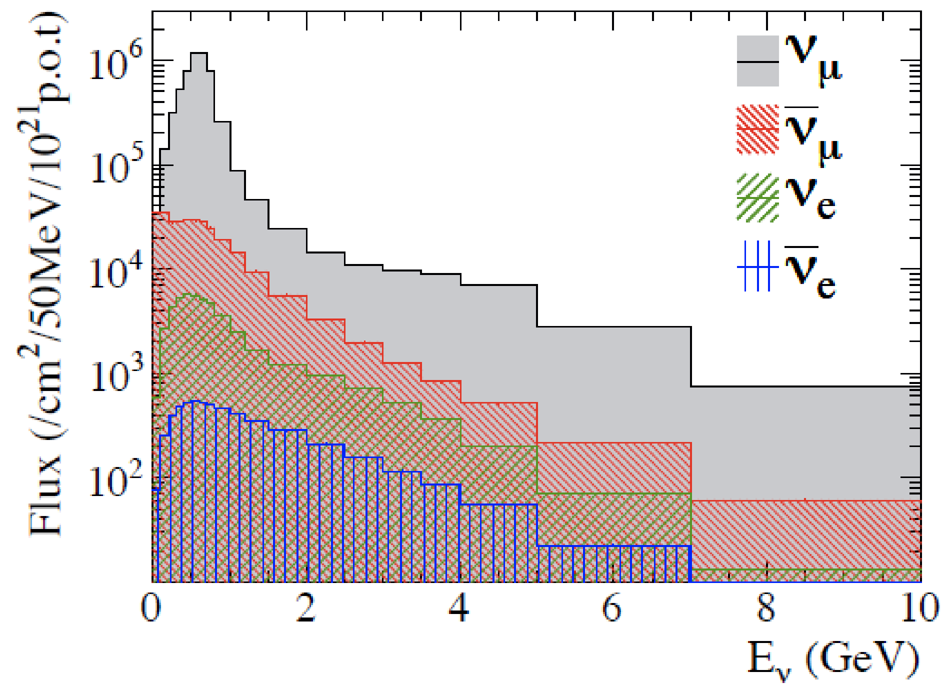
NA61/SHINE π and K production measurements and

T2K proton beam measurements

T2K run 1-4 flux at ND280



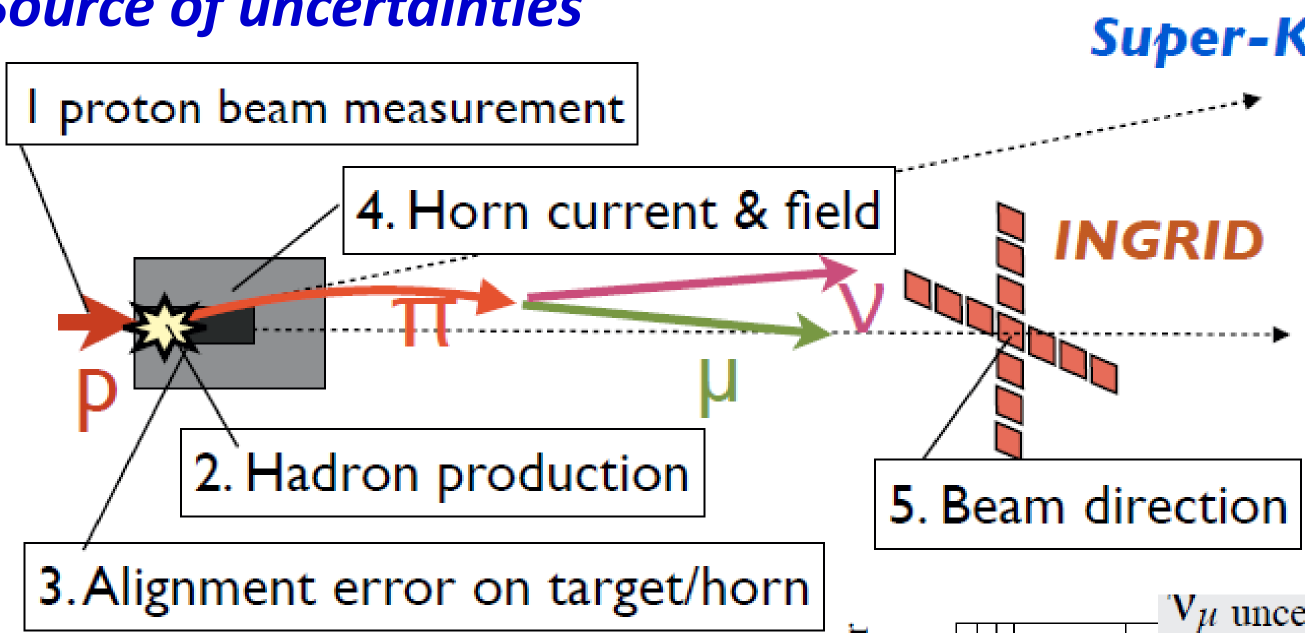
T2K run 1-4 flux at SK



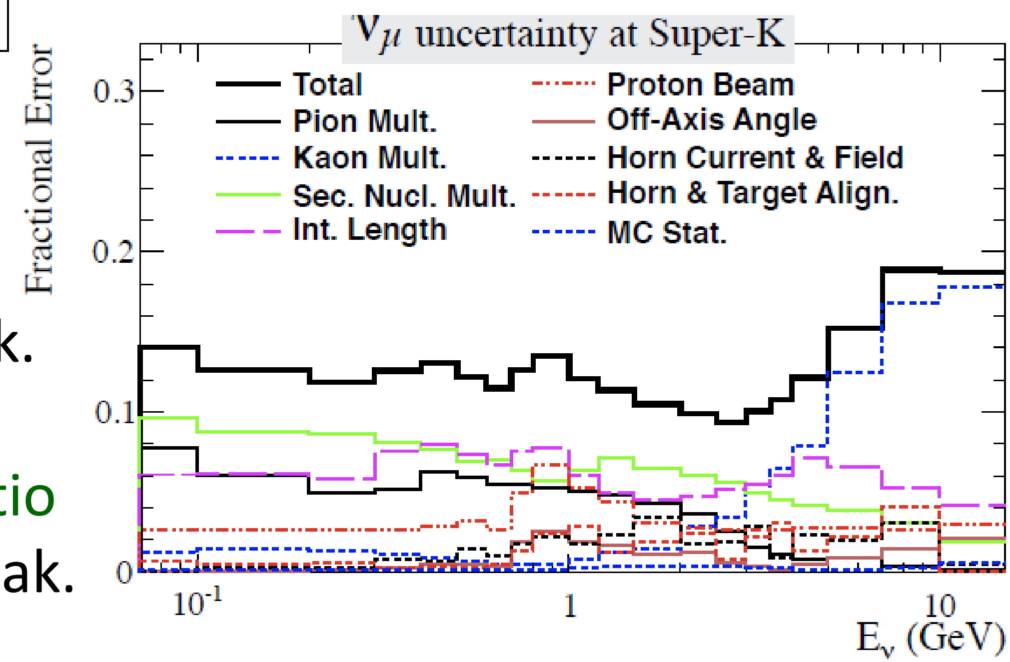
~ 95 % of ν_μ at ND280 and SK are produced from π^+

T2K neutrino beam ~ Uncertainty of the flux prediction

Source of uncertainties



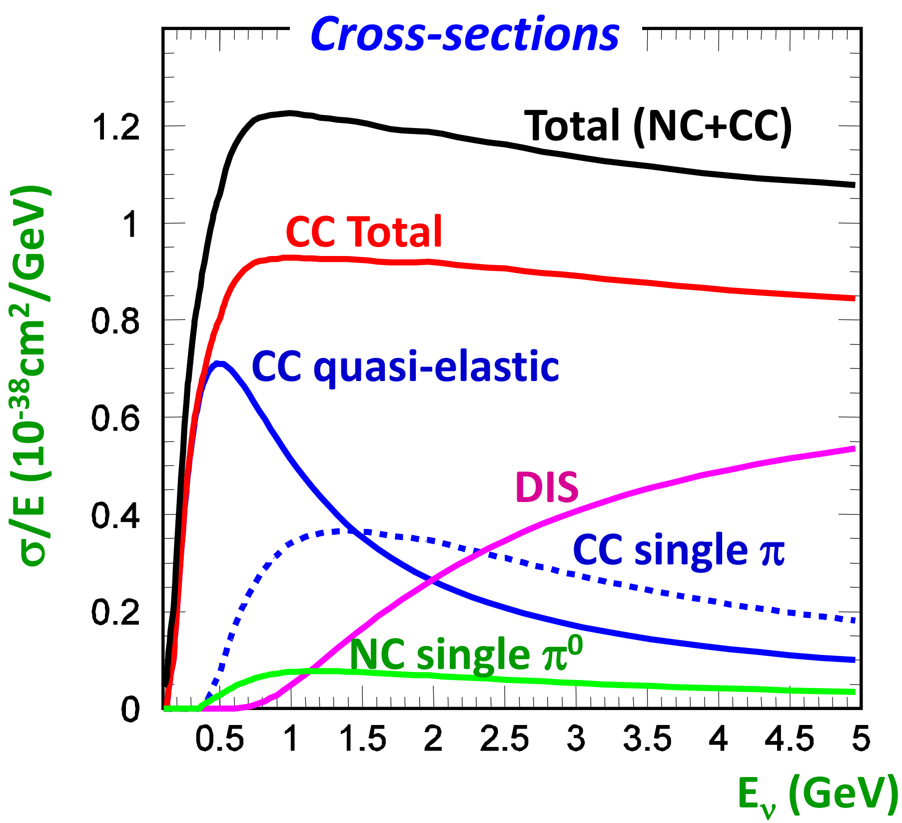
- Uncertainties on the flux prediction ***below 15%*** near the flux peak.
- Uncertainties on the ratio of the near/far ratio ***less than 2%*** near the flux peak.

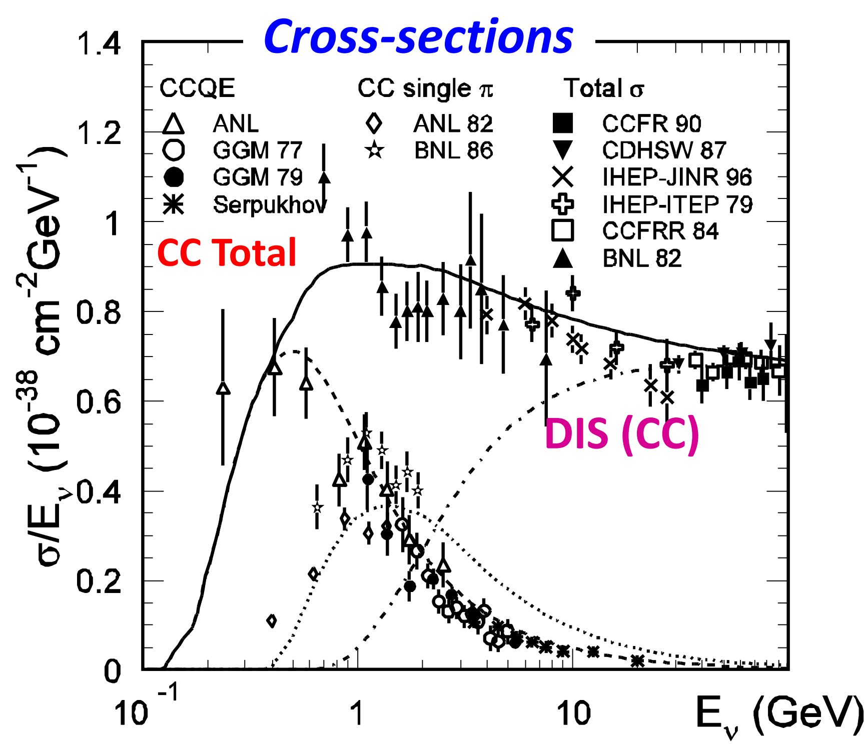


Neutrino interactions

Charged current quasi-elastic scattering	$\nu + n \rightarrow l^- + p$
Neutral current elastic scattering	$\nu + N \rightarrow \nu + N$
Single π,η,K resonance productions	$\nu + N \rightarrow l + N' + \pi\ (\eta, K)$
Coherent pion productions	$\nu + X \rightarrow l + X' + \pi$
Deep inelastic scattering	$\nu + N \rightarrow l + N' + m\pi(\eta, K)$

(l : lepton, N,N' : nucleon, m : integer)

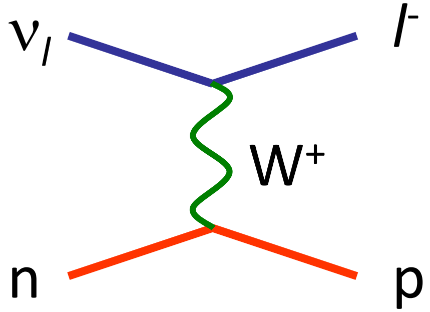


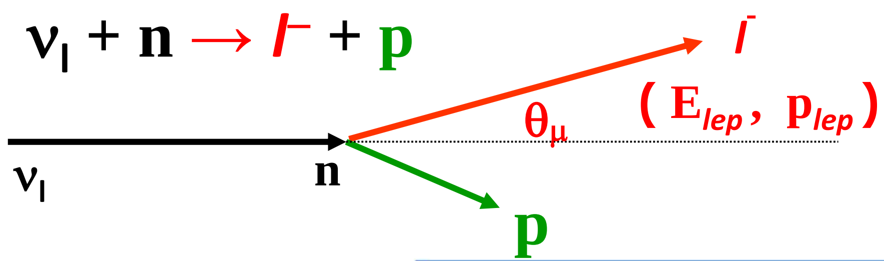


Neutrino interactions in the detectors

Use charged lepton

from charged current quasi-elastic scattering (CCQE)

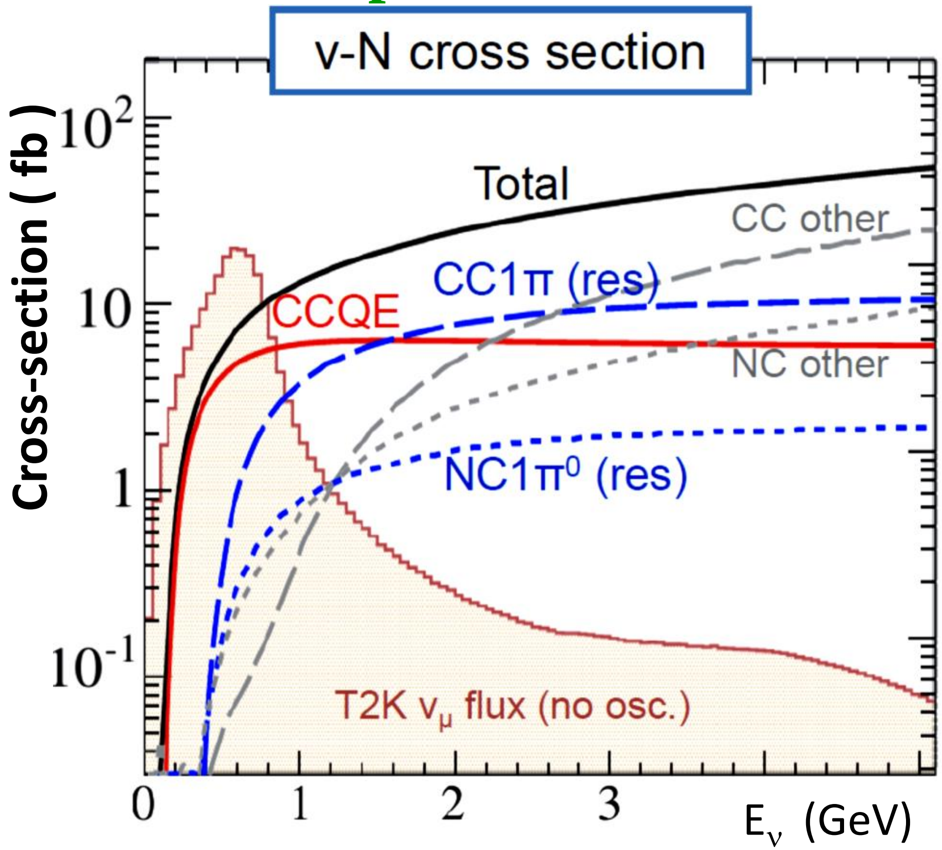




Dominant interaction

around the oscillation peak

~ flux peak



can be reconstructed

from measured E_{lep} & θ_{lep}

$$E_{\rm reco} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

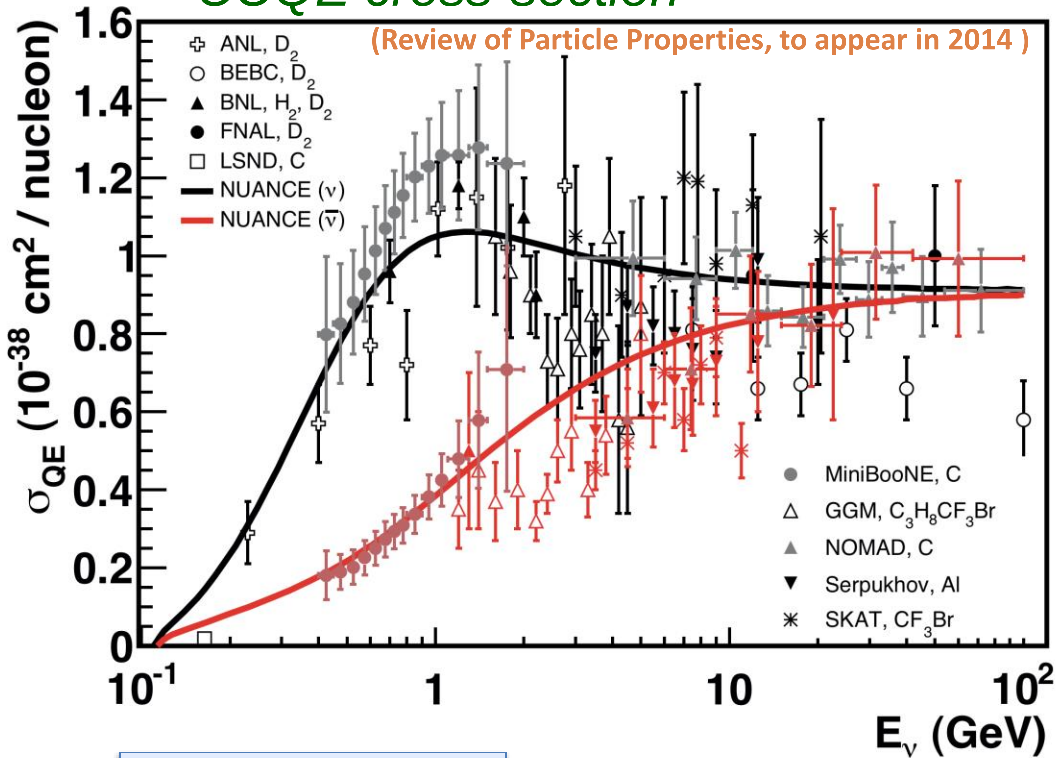
(E_b : Binding energy)

Neutrino interactions in the detectors

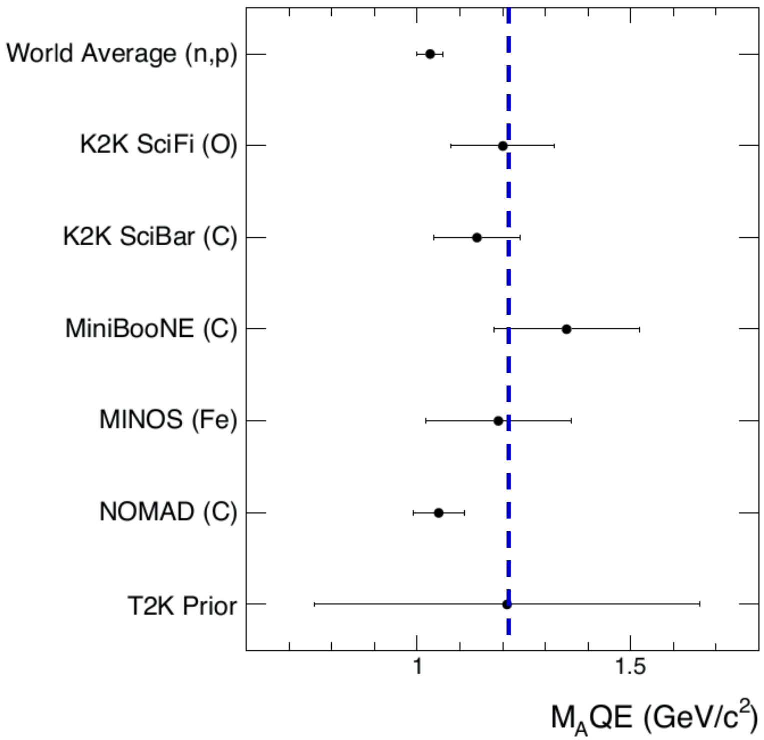
Charged current quasi-elastic scattering (CCQE)

Fitting external data to determine the nominal and the error of the input parameters before fitting the T2K ND280 data

CCQE cross-section



$$F_A(q^2) = \frac{F_A(0)}{\left(1 + \frac{q^2}{M_A^2}\right)^2}$$



Parameters (CCQE)	
M_A^{QE}	1.21 ± 0.45 GeV/c^2
CCQE norm	1 ± 0.11

Neutrino interactions in the detectors

Possible background

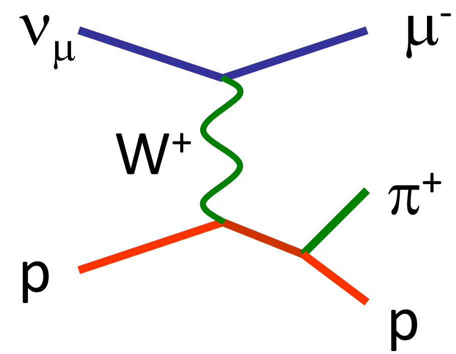
- ν_μ disappearance
  - Around oscillation peak

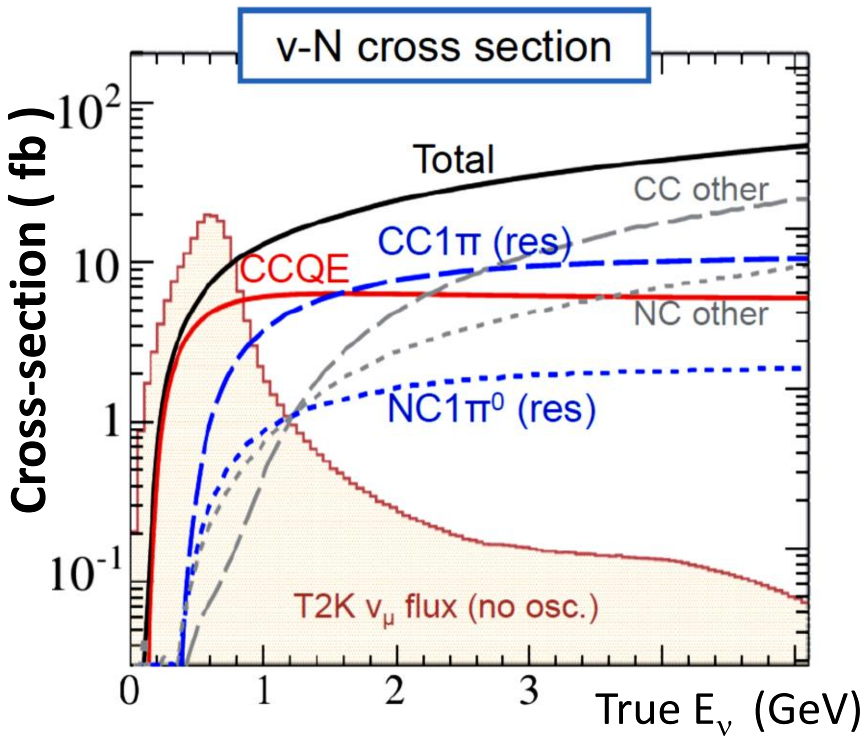
$$\nu + N \rightarrow \mu^- + N' + \pi^\pm$$

- proton and charged π from NC interactions

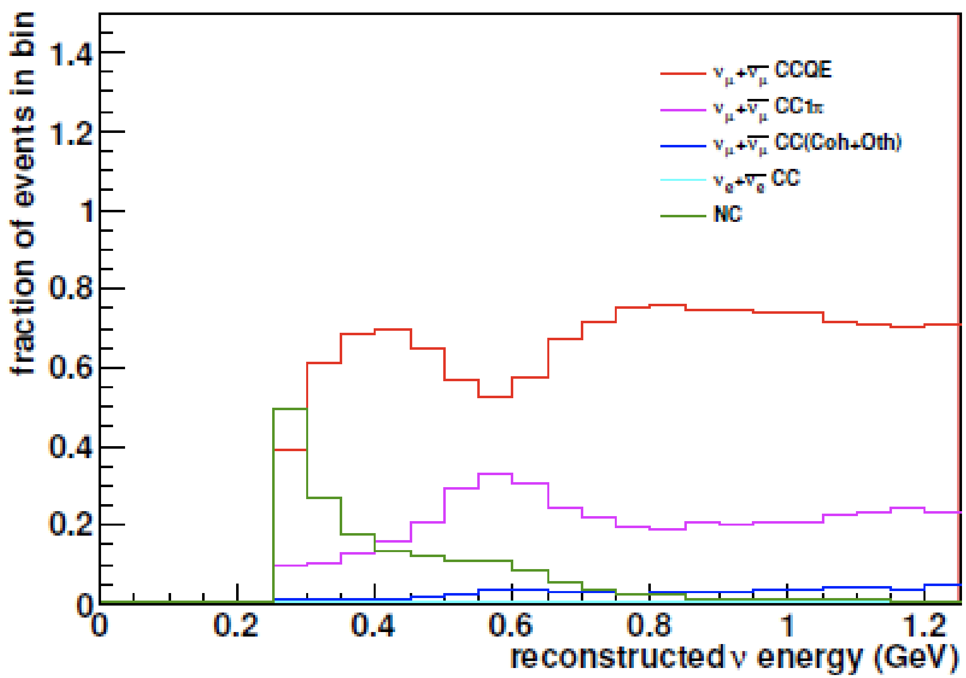
$$\nu + N \rightarrow \nu + p$$

$$\nu + N \rightarrow \nu + N' + \pi^\pm$$





Fraction of each interaction



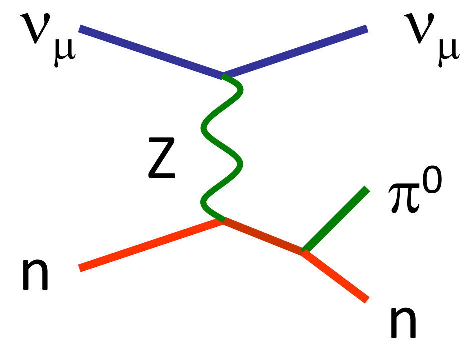
Neutrino interactions in the detectors

Possible background

ν_e appearance

NC 1 π^0 production

$$\nu + N \rightarrow \nu + N' + \pi^0$$

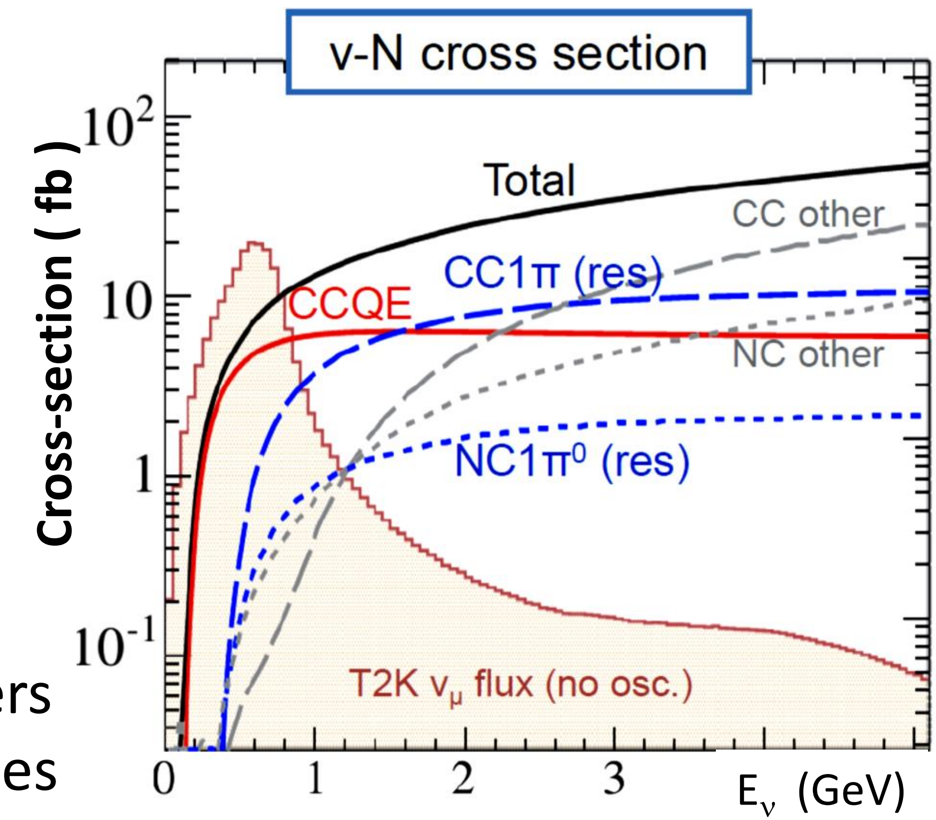


If one of the γ from decay of π^0 can not be identified, identified as a candidate.

\# of π^0
~ Interaction cross-section

Decay kinematics
~ Momentum distribution of π^0

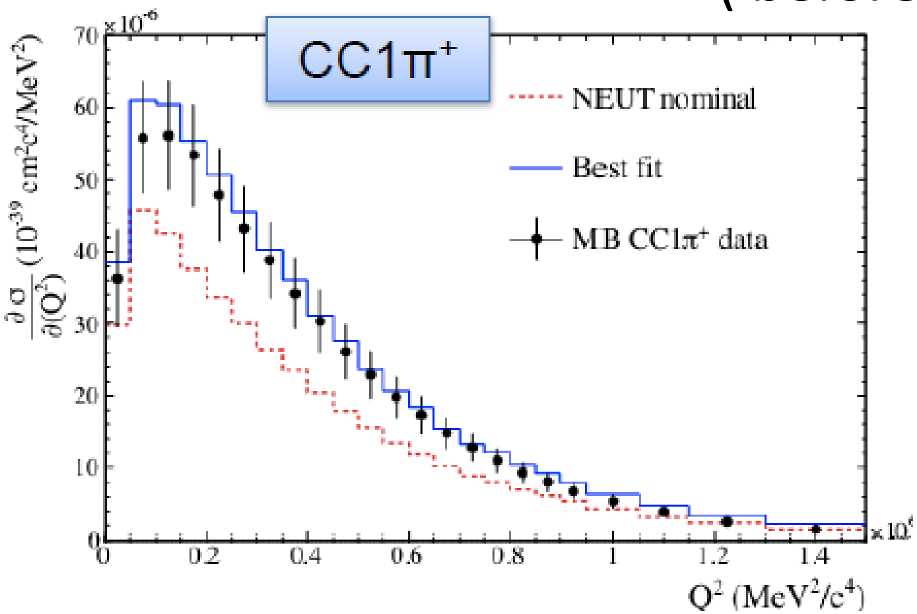
Source of errors in measuring oscillation parameters
~ Need careful studies

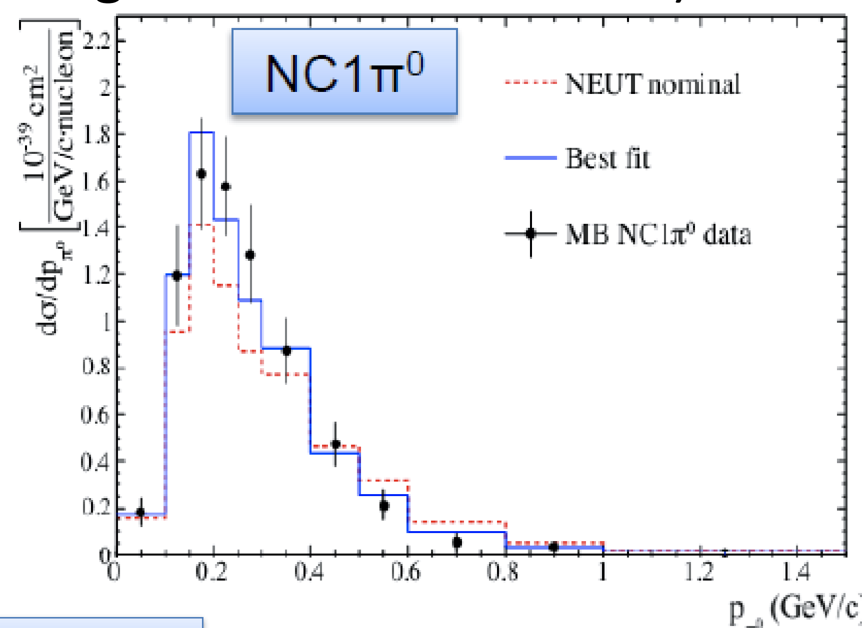


Neutrino interactions in the detectors

Charged current quasi-elastic scattering (single pion productions)

Fitting external data (mainly from MiniBooNE) to determine the nominal and the error of the input parameters (before fitting the T2K ND280 data)





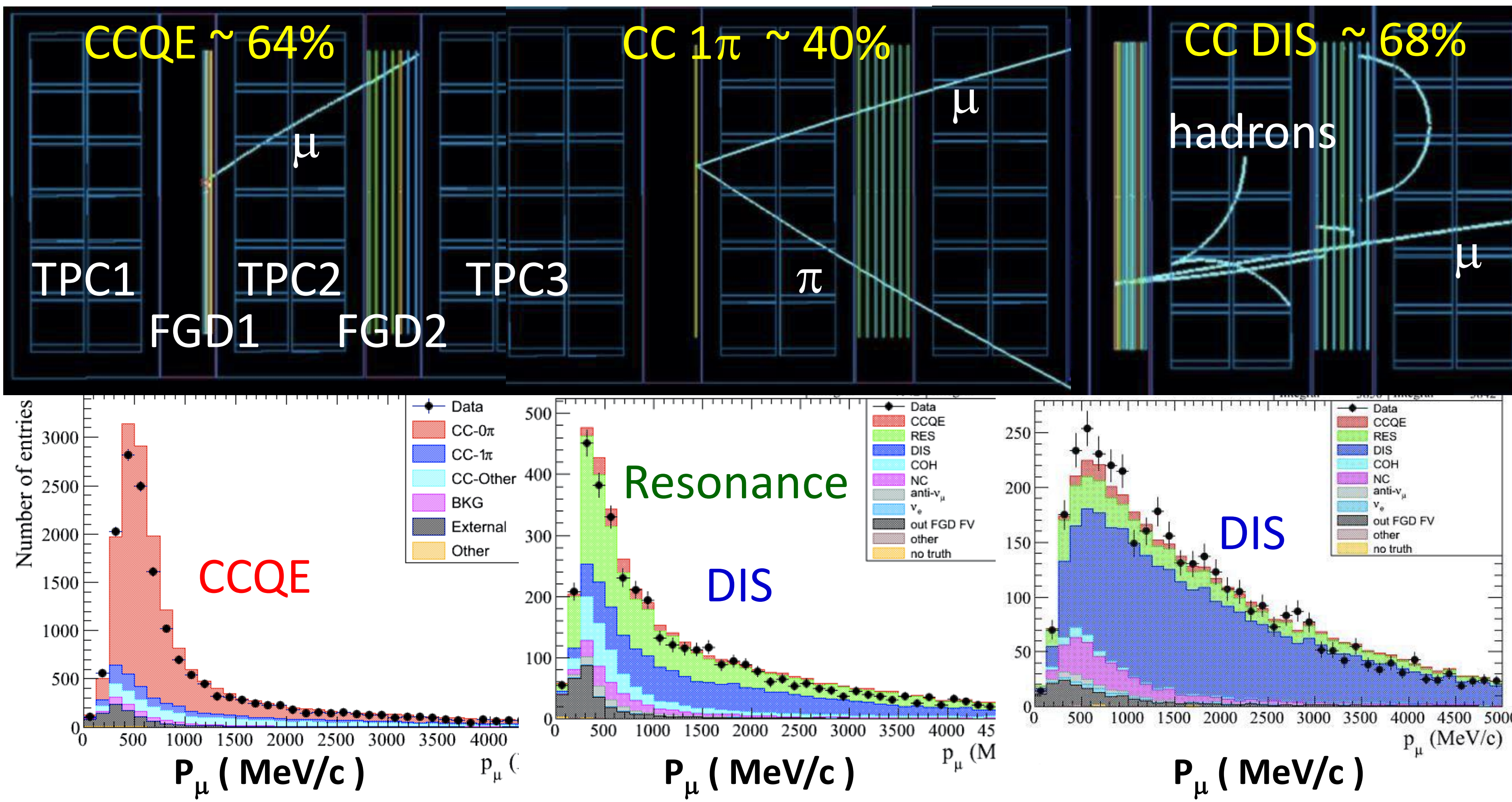
Parameters (resonant π)	
M_A^{RES}	1.41 ± 0.22 GeV/c²
CC1π norm	1.15 ± 0.32
$NC1\pi^0$ norm	0.96 ± 0.33

Neutrino interaction measurements in the near detectors

Measure muon momentum & angular distributions in ND280

Use 3 samples ~ enrich different interaction modes

CC 0π sample — CC $1\pi^+$ sample — CC other sample

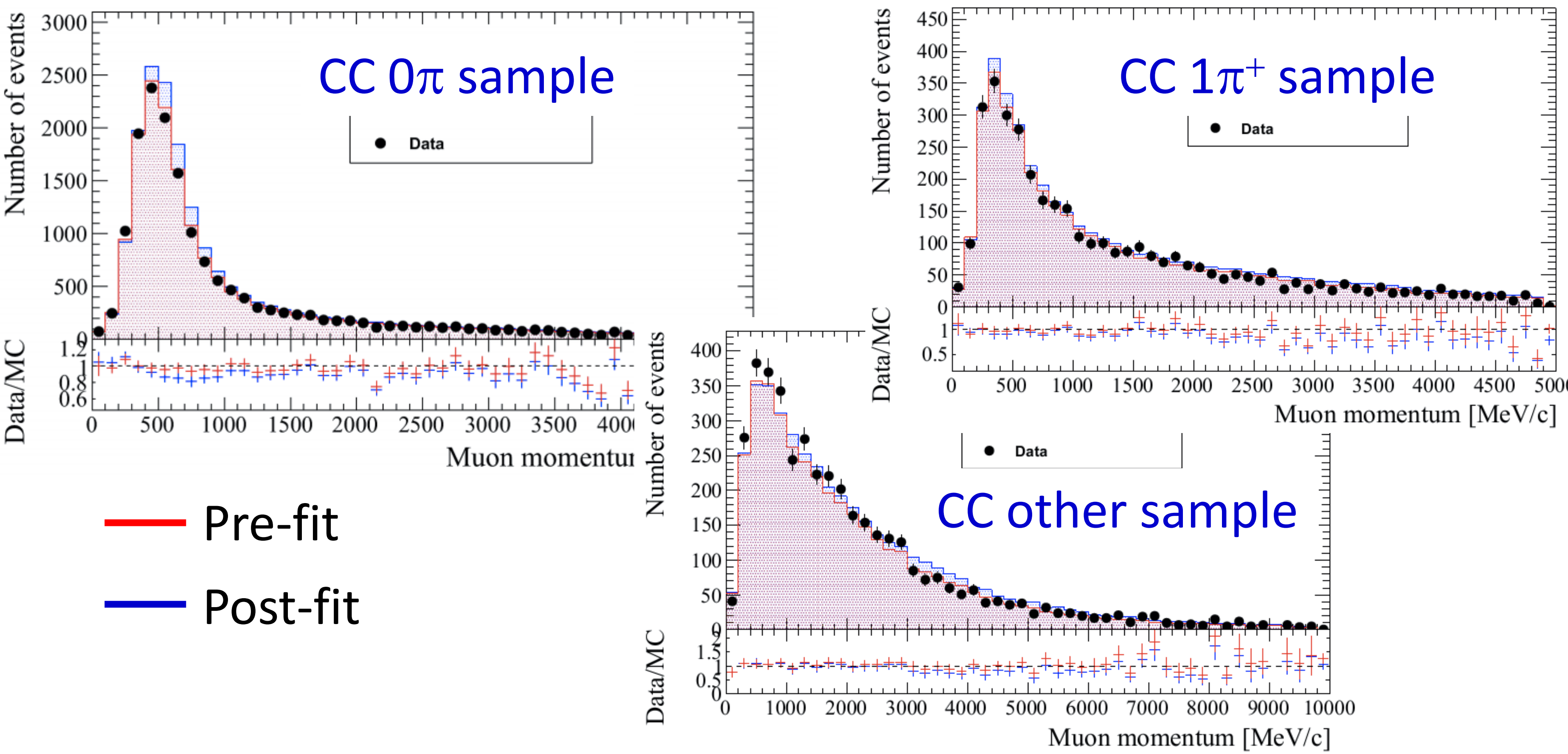


Neutrino interaction measurements in the near detectors

Fit neutrino flux and neutrino interaction model parameters using $p_\mu - \cos\,\theta_\mu$ distributions of 3 samples from ND280

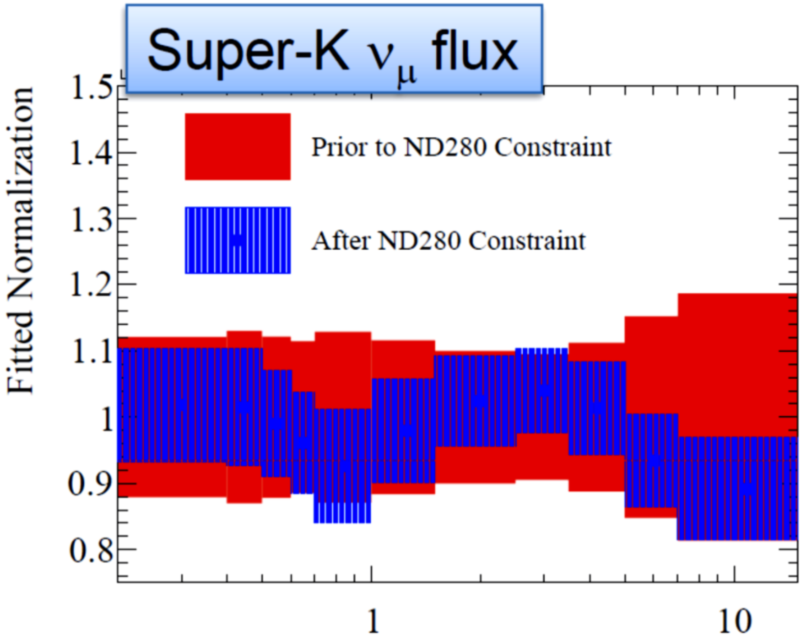
Constrain uncertainties on

1) Neutrino flux at SK
2) Correlated neutrino interaction related parameters



Neutrino interaction measurements in the near detectors

Results from the ND280 neutrino interaction measurements



Neutrino interaction parameters

Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.223 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.963 ± 0.063
CCQE Norm.*	1.00 ± 0.11	0.961 ± 0.076
CC1π Norm.**	1.15 ± 0.32	1.22 ± 0.16
NC1π^0 Norm.	0.96 ± 0.33	1.10 ± 0.25

*For E_ν<1.5 GeV **For E_ν<2.5 GeV

Both uncertainties on neutrino flux and neutrino interaction parameters are well constrained.

Neutrino interaction measurements in the near detectors

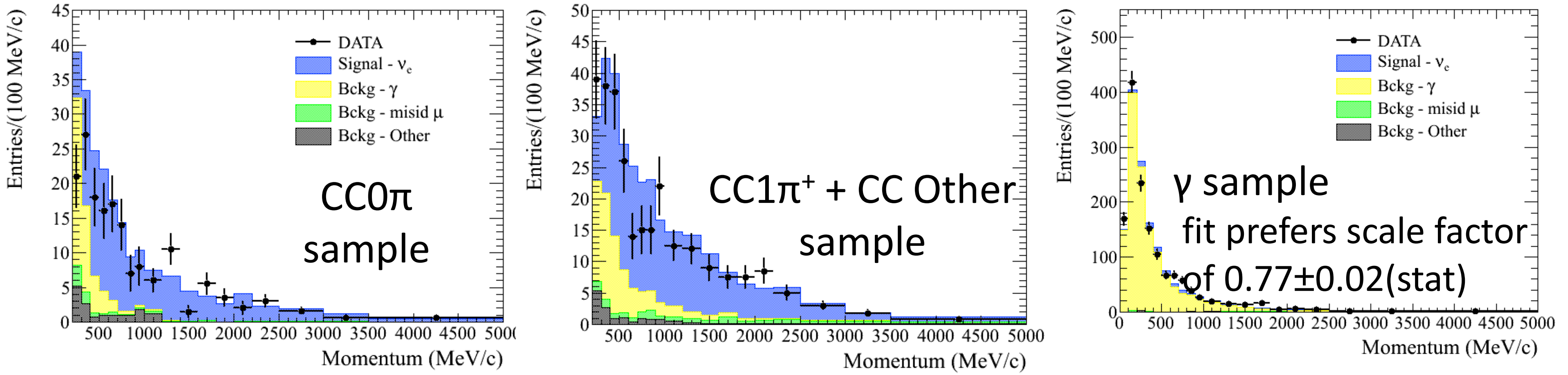
Measure electron momentum & angular distributions in ND280

Use 3 samples ~ enrich different interaction modes

Interactions in FGD and particle ID in TPC

Major background: photons from π^0 decays

Fit CC0π, CC1π^+ + CC Other and γ sideband sample



$$\frac{\text{measured } \nu_e \text{ flux}}{\text{predicted } \nu_e \text{ flux}} = 1.06 \pm 0.06(\text{stat}) \pm 0.08(\text{syst})$$

Validation MC prediction of the intrinsic beam ν_e background using the data from ND280.

T2K ν_μ disappearance analysis

arXiv:1403.1532[hep-ex]

T2K ν_μ disappearance analysis

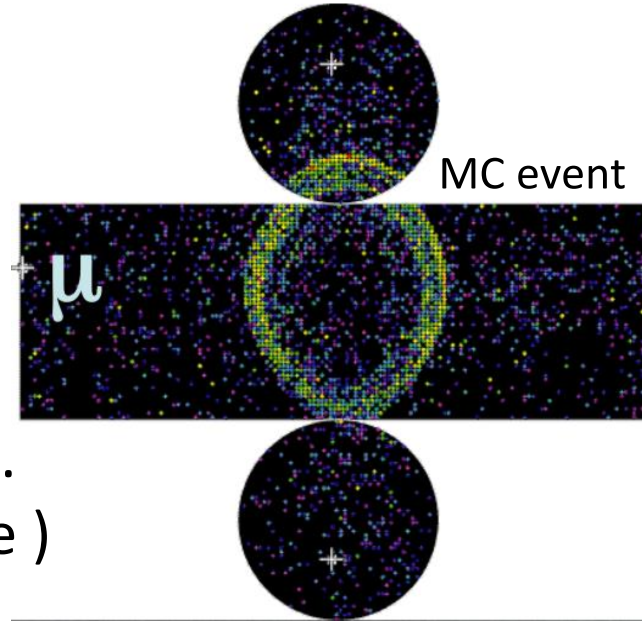
ν_μ Signal events in SK

Charged current quasi-elastic scattering

$\nu_\mu + n \rightarrow \mu^- + p$

Observed as single ring μ-like event in SK.

(μ-like events has sharp ring edge)

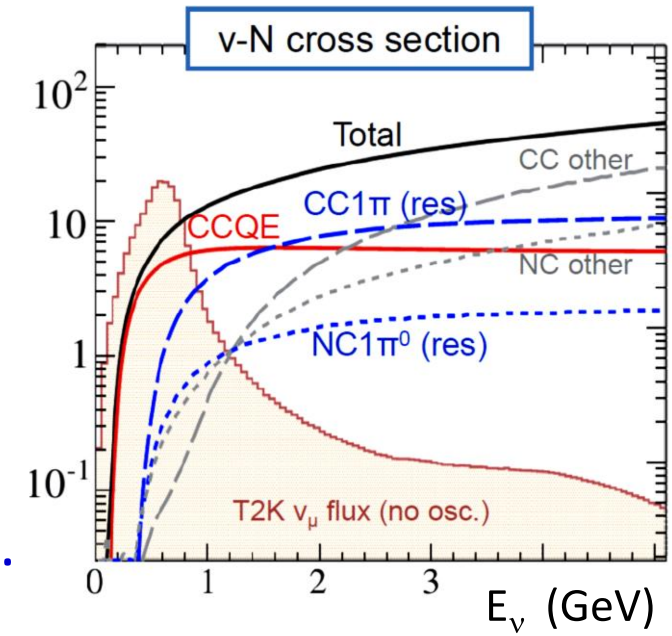


Background sources

Other charged current interactions

Only μ was detected.

Some of those background events could be eliminated by using decay electrons for example $\pi \rightarrow \mu \rightarrow e$.



protons and/or charged π from neutral current interactions

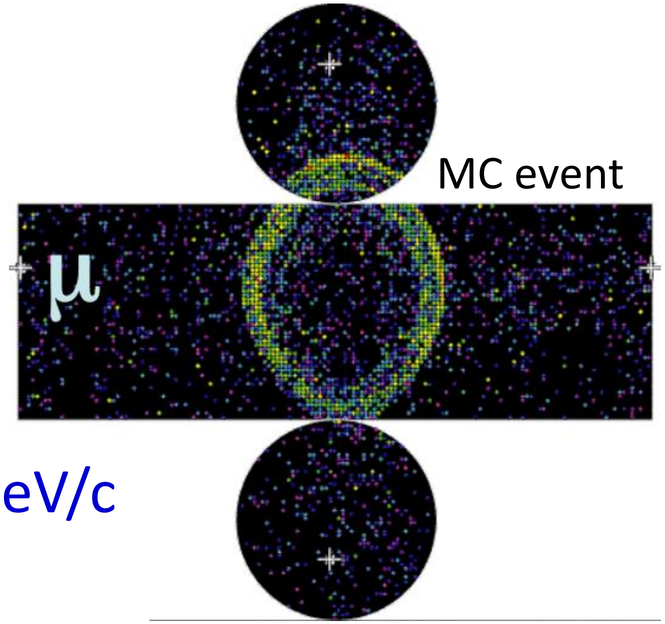
T2K ν_μ disappearance analysis

ν_μ Signal events in SK

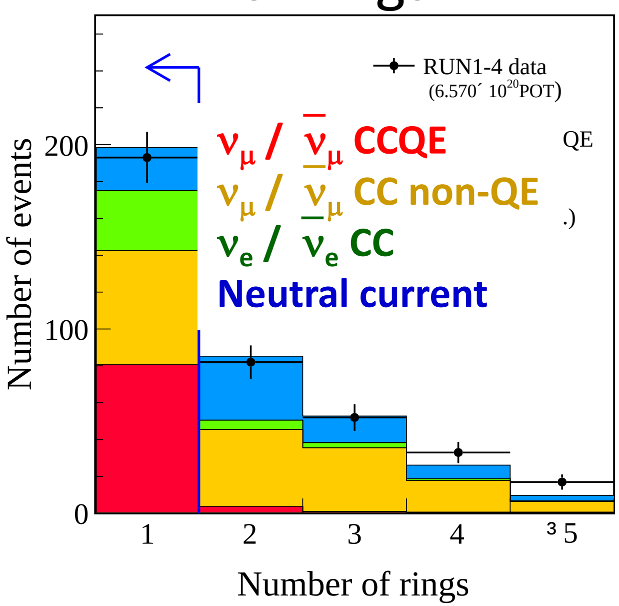
Event selection criteria

- Fully contained in fiducial volume
- 1 ring and identified as μ-like
- Reconstructed momentum of μ > 200 MeV/c
- 0 or 1 decay electrons

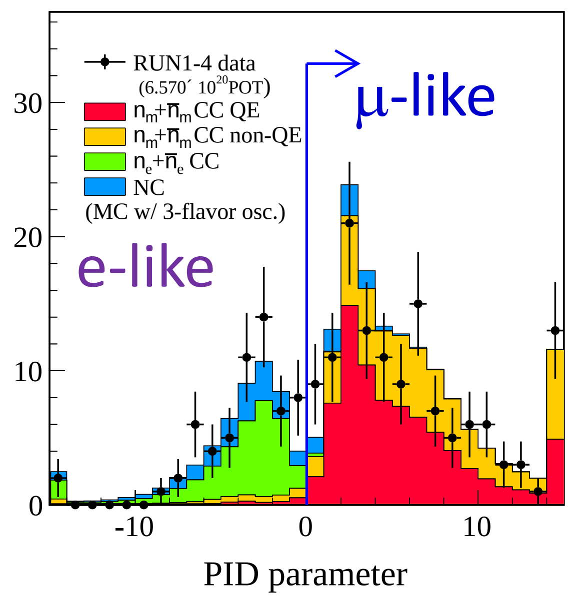
120 events are selected (6.57 x 10^{20} pot)



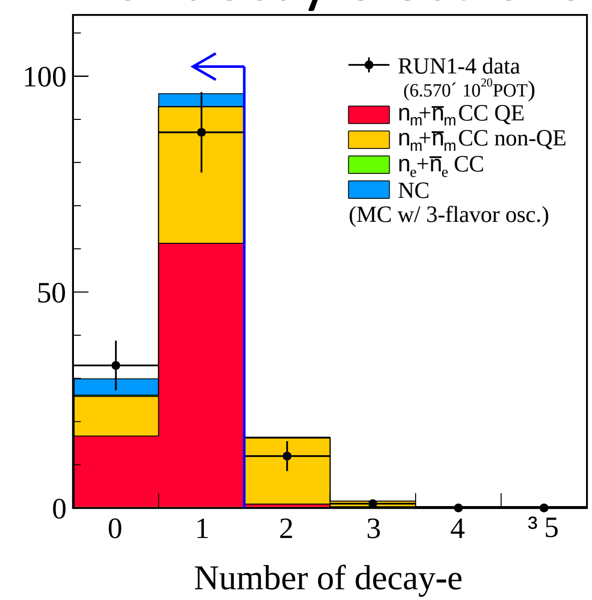
# of rings



Particle ID



# of decay electrons



T2K ν_μ disappearance analysis

Run 1 ~ 4 (6.57 x 10^{20} P.O.T.)

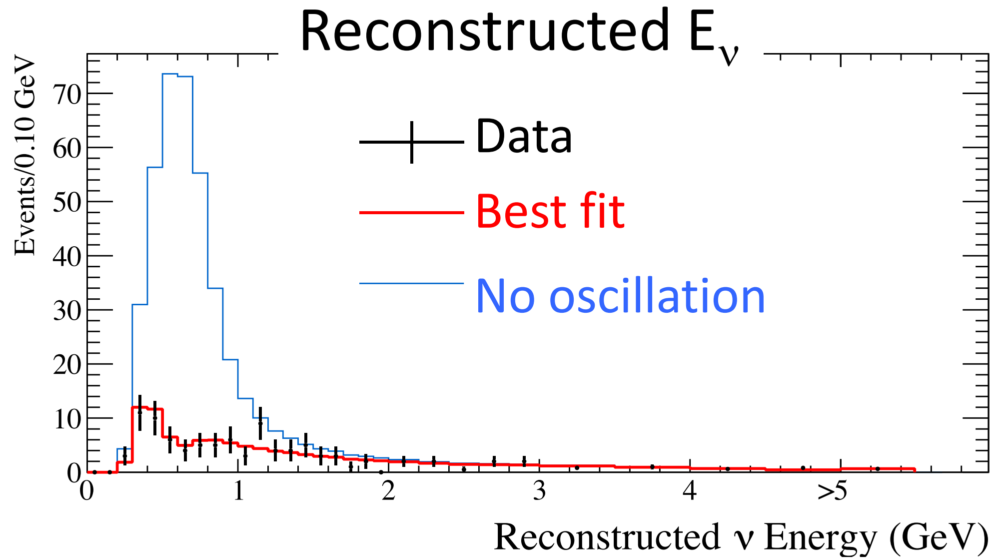
Expected # of events
without oscillation
$= 446.0 \pm 22.5\ (syst.)$

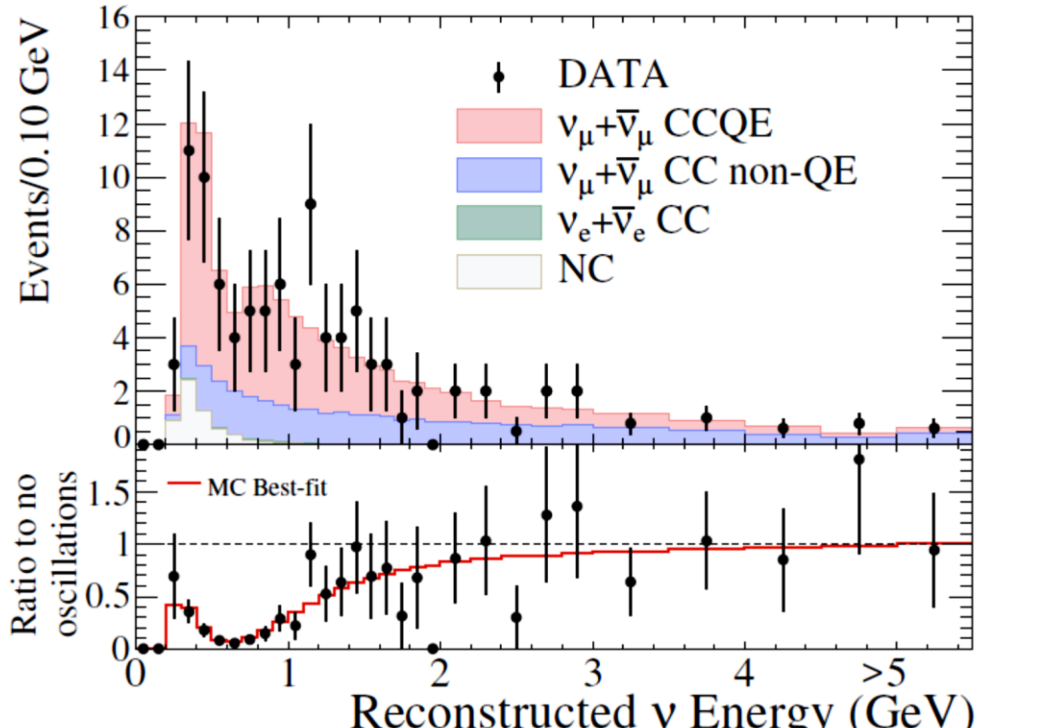
Observed # of events
$= 120$

Expected # of events
with oscillation

$(\sin^2\theta_{23}, \Delta m^2_{32}) = (0.5, 2.4 \times 10^{-3}\ eV^2/c^4)$

Event category	# of events
ν_μ CCQE	77.93
ν_μ CC non-QE	40.78
ν_e CC	0.35
NC All	6.78
Total	125.85





T2K ν_μ disappearance analysis

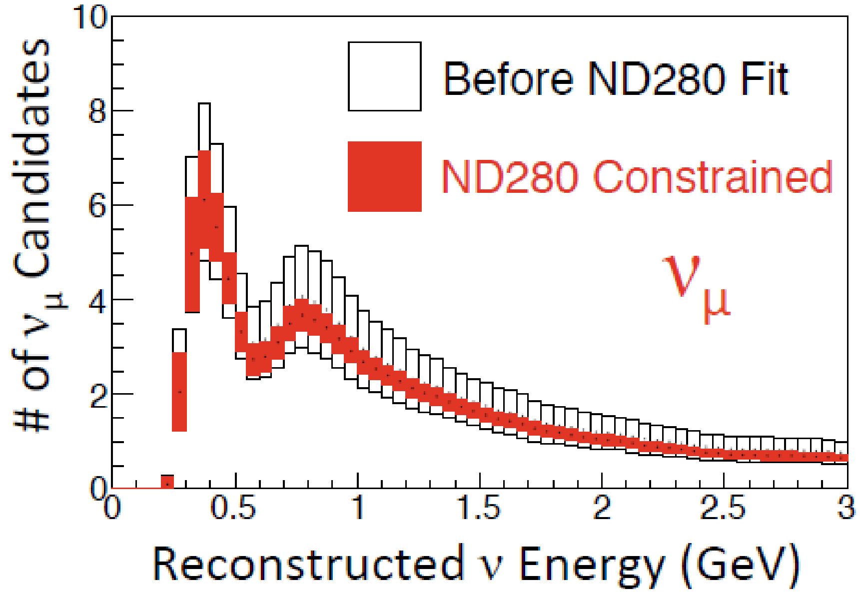
Systematic uncertainties for # of events*

$(\sin^2\theta_{23},\ \Delta m^2_{32}, \delta CP) = (0.5, 2.4 \times 10^{-3}\ eV^2/c^4, 0)$

Systematics	Uncertainties
Flux/XSEC (ND280 constraint)	2.7%
Other XSEC	4.9%
Super-K +FSI	5.6%
Total	8.1%

* Binding energy and SK energy scale are some of the dominant uncertainties affecting T2K Δm^2_{32} precision, but they don't appear in the left table of # of events since they don't affect the overall normalization.

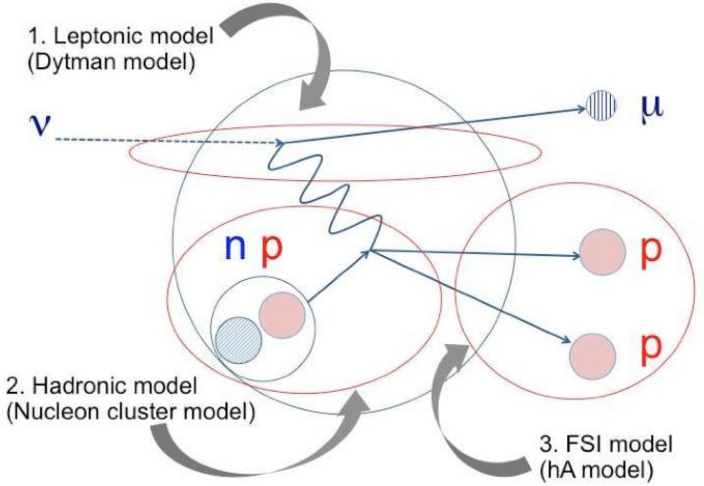
N_{SK} per reconstructed energy (bin) with error

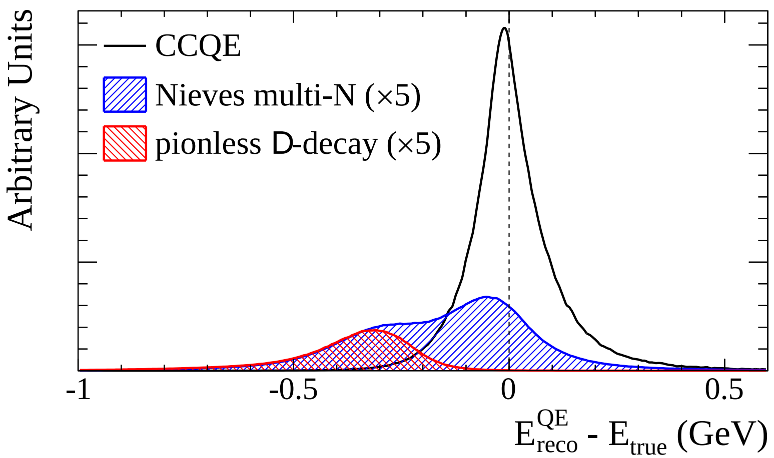


T2K ν_μ disappearance analysis

Uncertainties from the ν interactions with multi-nucleon in nucleus

- Lively discussion motivated by CCQE cross section inconsistency between MiniBooNE and the other experiment
- Not incorporated directly into this analysis
  - But we have a large systematic uncertainty (100%) on decays of Δ resonances w/ prompt π absorption ("π-less Δ-decay"). It has similar impact on neutrino energy reconstruction as a 100% uncertainty in the multi-nucleon interaction model (Nieves model)
  - **Dedicated MC study shows the impact on oscillation analysis is small relative to our current statistical**





T2K ν_μ disappearance analysis

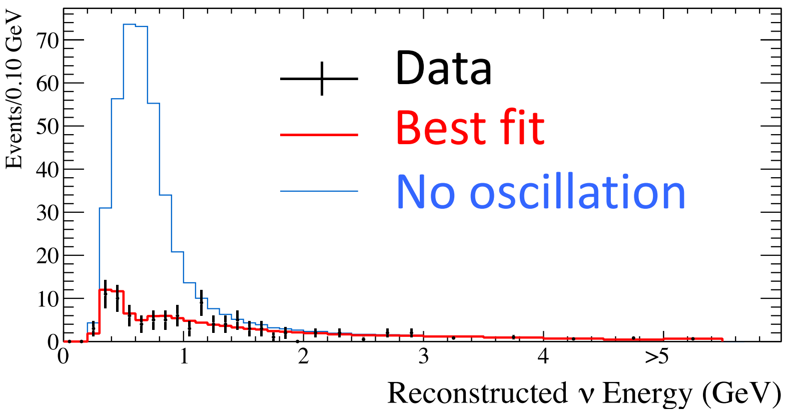
Oscillation parameter fitting

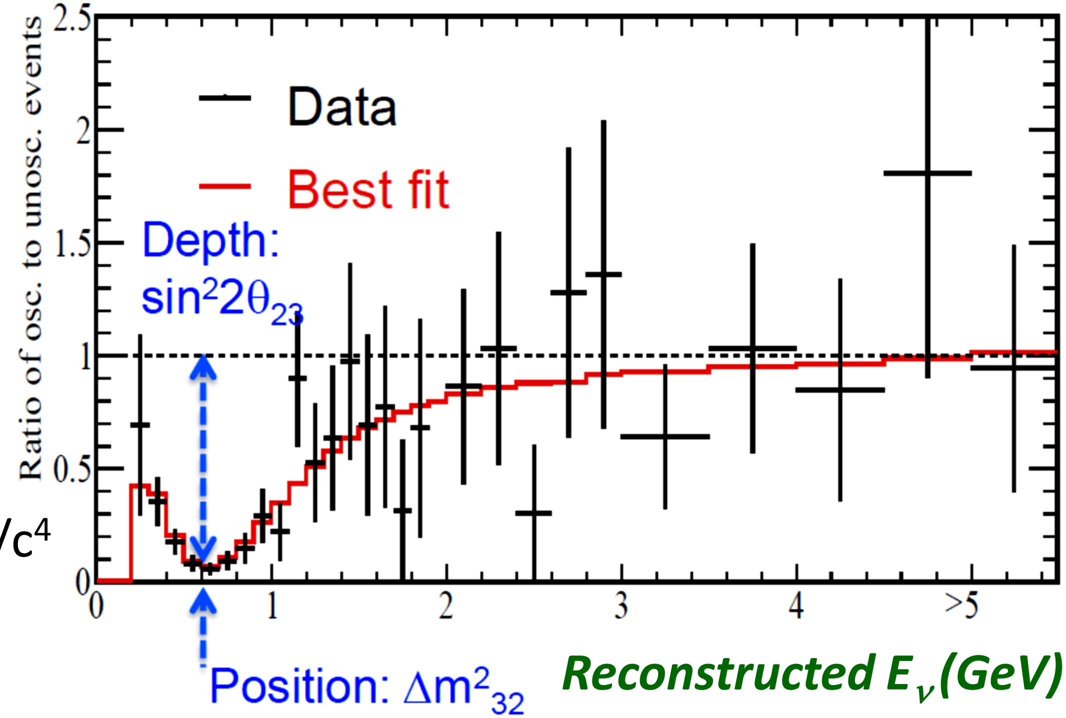
Maximum likelihood fit based on

\# of observed events in SK (N_{SK}) and

reconstructed energy of neutrino (E_ν^{rec})

$$L = L_{norm.} \times L_{shape} \times L_{syst.} \times L_{osc.}$$





Constraints from the other exp's.

$\sin^2\theta_{12} = 0.312 \pm 0.016$

$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV^2/c^4

$\sin^2\theta_{13} = 0.0251 \pm 0.0035$

(from PDG 2012)

** δ_{CP} is unconstrained.

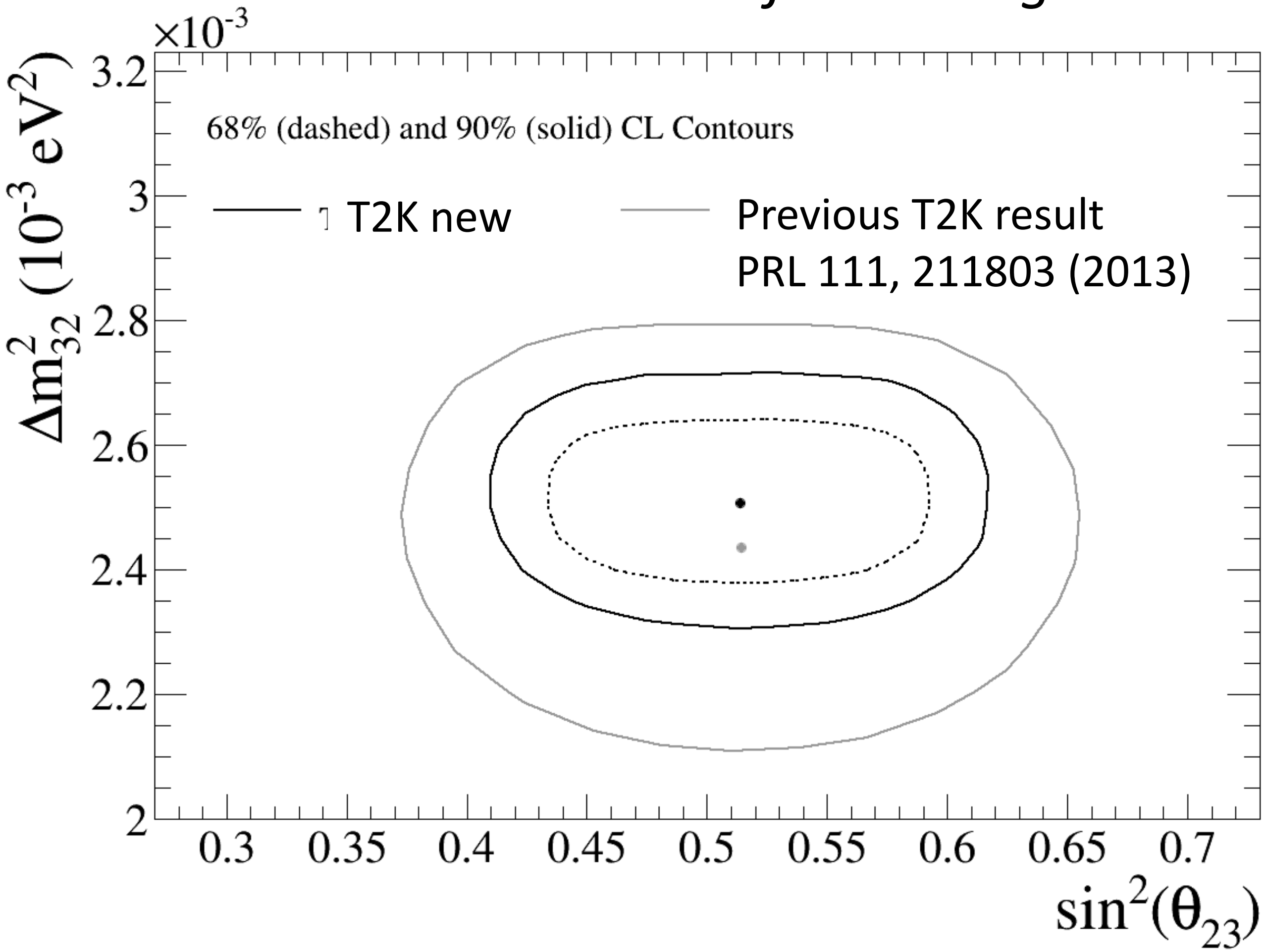
T2K ν_μ disappearance analysis

Fit results ~ allowed oscillation parameter regions

Large improvements from the previous publication.

(3.01 x 10^{20} POT $\rightarrow$ 6.57 x 10^{20} POT)

Feldman-Cousins 2D confidence regions

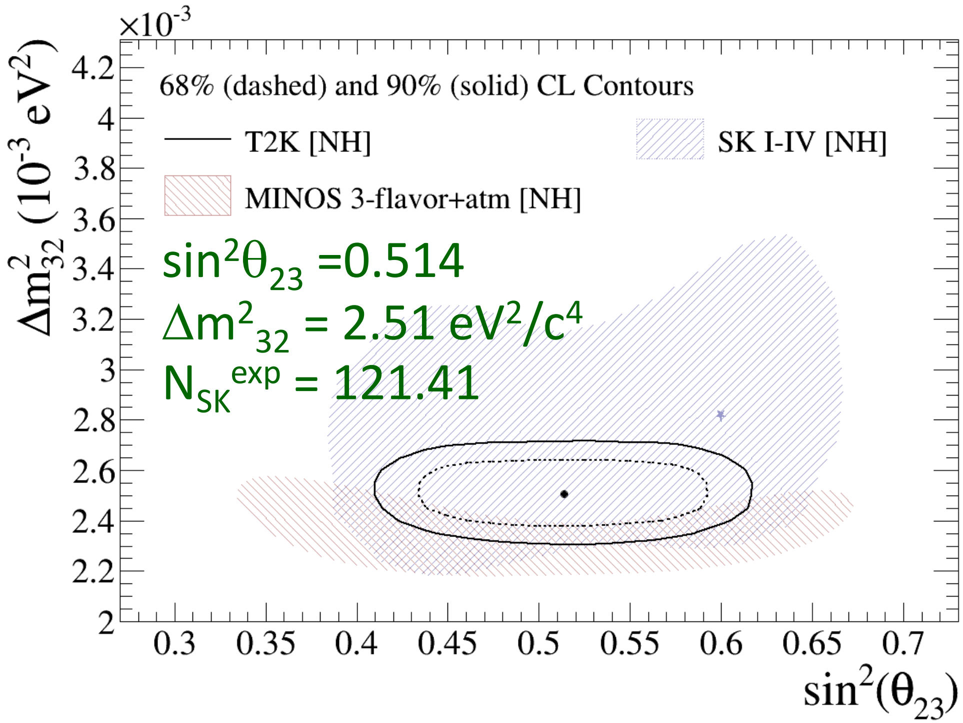


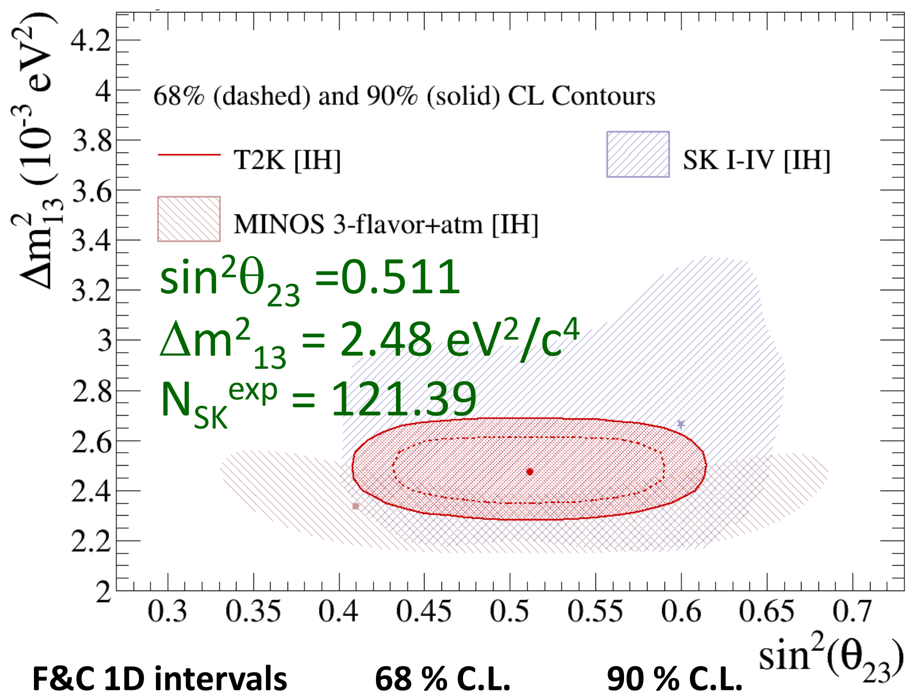
Best fit parameters

$\sin^2\theta_{23}$ [NH] ([IH])	0.514 (0.511)
Δm^2_{32} [NH] (Δm^2_{13} [IH]) eV^2/c^4	2.51 (2.48)
N_{SK}^{exp} [NH] ([IH])	121.41 (121.39)

T2K ν_μ disappearance analysis

Fit results ~ allowed oscillation parameter regions





F&C 1D intervals	68 % C.L.	90 % C.L.
$\sin^2(\theta_{23})$ [NH]	[0.458,0.568]	[0.428,0.598]
Δm^2_{32} (x10^{-3}) [NH]	[2.41,2.61]	[2.34,2.68]
$\sin^2(\theta_{23})$ [IH]	[0.456,0.566]	[0.427,0.596]
Δm^2_{13} (x10^{-3}) [IH]	[2.38,2.58]	[2.31,2.64]
θ_{23} [NH]	[42.6° , 48.9°]	[40.9° , 50.7°]
θ_{23} [IH]	[42.5° , 48.8°]	[40.8° , 50.5°]

Most precise measurement of θ_{23}

~ Favors (almost) maximal mixing

T2K ν_e appearance analysis

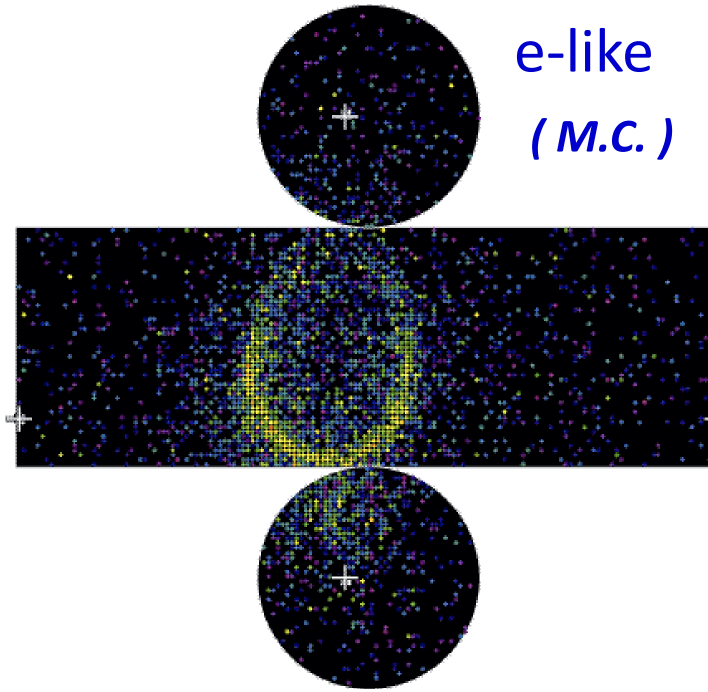
Phys. Rev. Letter 112, 061802 (2014)

T2K ν_e appearance analysis

Charged current quasi-elastic scattering

$\nu_e + n \rightarrow \underline{e^-} + p$

Observed as single ring e-like event in SK

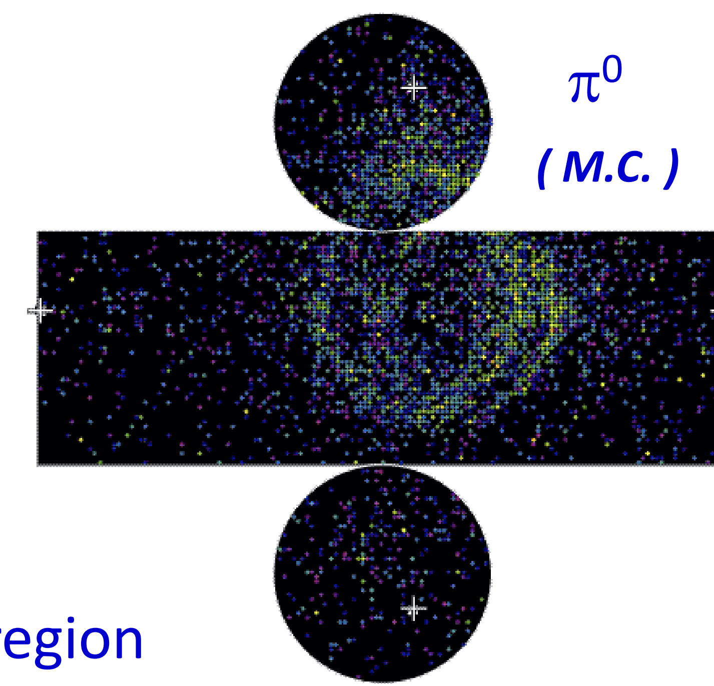


e-like
(M.C.)

Dominant background

1) ν_e in the beam
intrinsic background

2) π^0 identified as 1 ring
One γ is not identified
small opening angle of 2 rings
low momentum faint ring



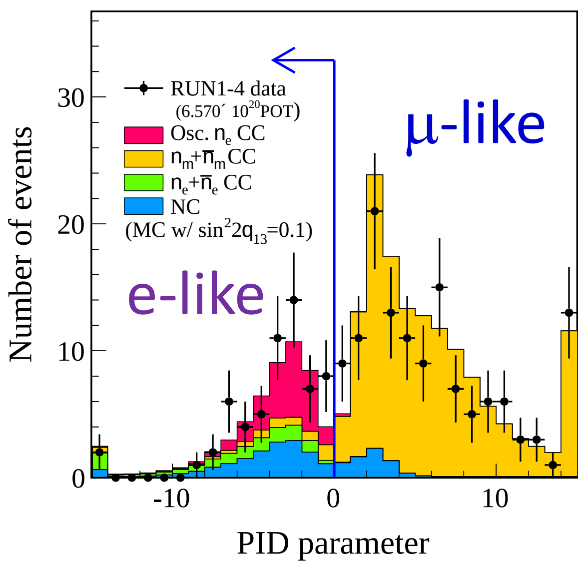
π^0
(M.C.)

➡ Search for the 1 ring e-like events
No decay electrons
not π^0 like (dedicated π^0 rejection)
Reconstructed E_ν is in the oscillation region

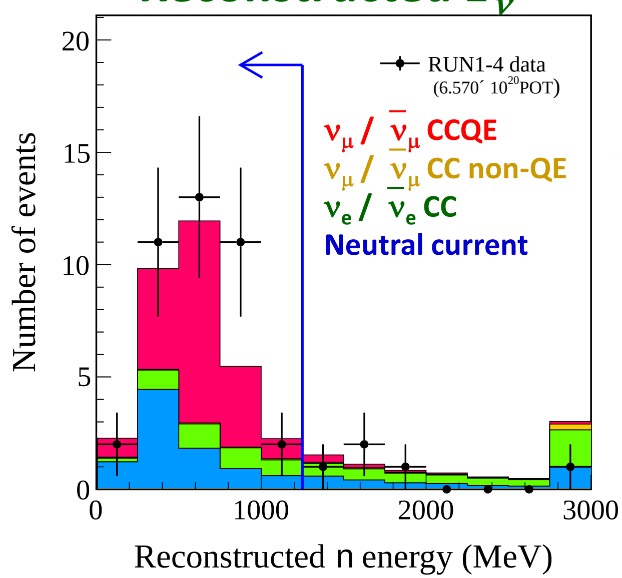
T2K ν_e appearance analysis ~ event selection in SK

- Fully contained event ~ no activity in the outer detector
- Reconstructed in the fiducial volume (> 200cm from the wall)
- 1 ring and PID is electron-like
- Visible energy (electron equiv. energy) > 100 MeV
- No decay electrons
- Reconstructed E_ν < 1.25 GeV
- special π^0 identifier (New π^0 rejection)

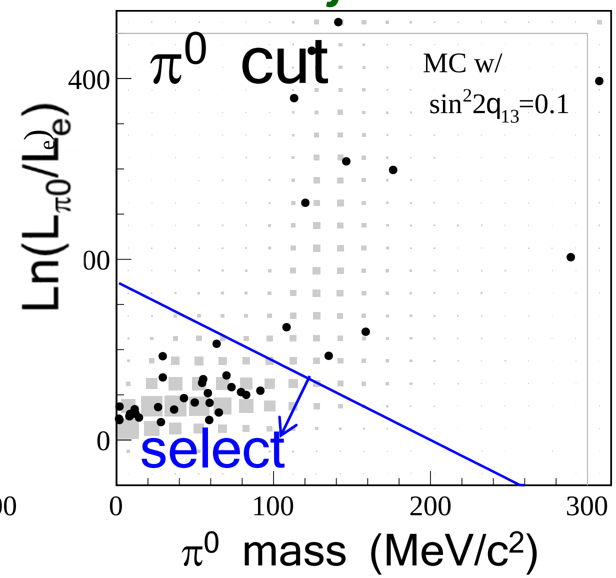
Particle ID



Reconstructed E_ν



π^0 rejection



T2K ν_e appearance analysis

Expected # of events and observed # of events in Run 1 ~ 4 (6.57×10^{20} P.O.T.)

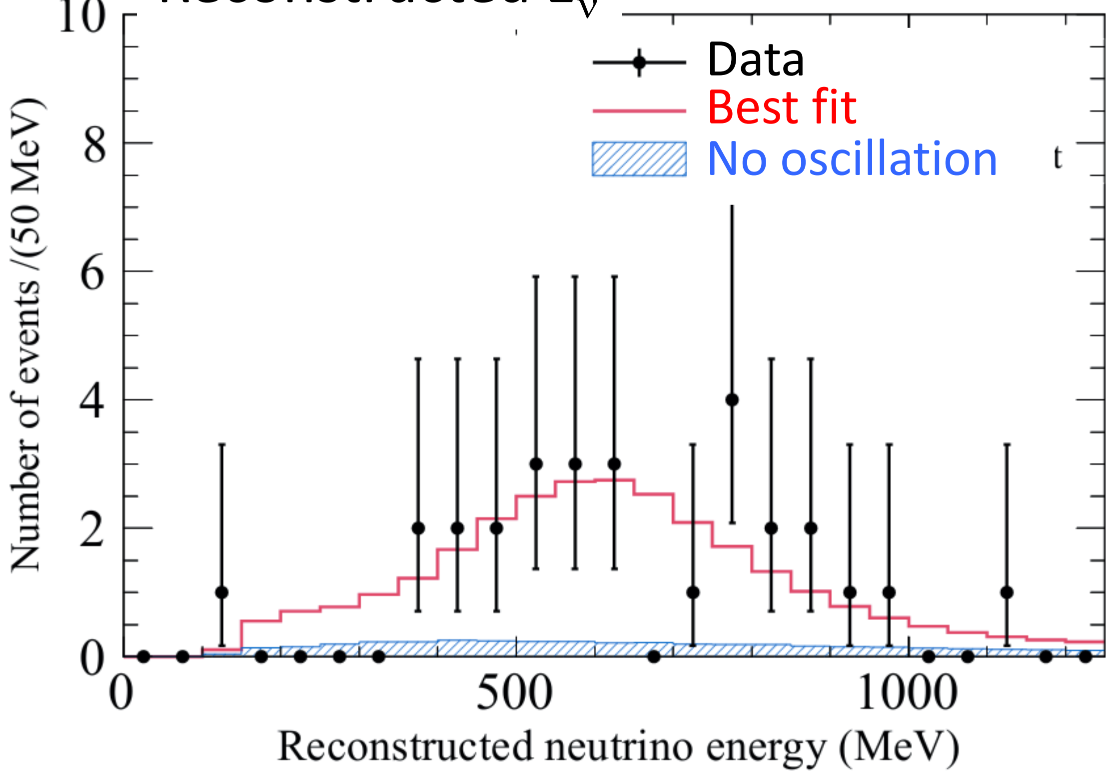
Expected # of events for θ_{13} = 0

$= 4.9 \pm 0.6\ (syst.)$

Total	4.92
ν_e signal	0.40
ν_e background	3.37
ν_μ background	0.94
$\bar{\nu}_\mu$ background	0.05
$\bar{\nu}_e$ background	0.16

Observed # of events = 28

Reconstructed E_ν



T2K ν_e appearance analysis

Oscillation parameter fitting

Maximum likelihood fit based on

# of observed events in SK (N_{SK}) and

observed momentum and direction of electron (p_e, θ_e)

$$L = L_{norm.} \times L_{shape} \times L_{syst.} \times L_{osc.}$$

Constraints from

T2K Run 1-3 results

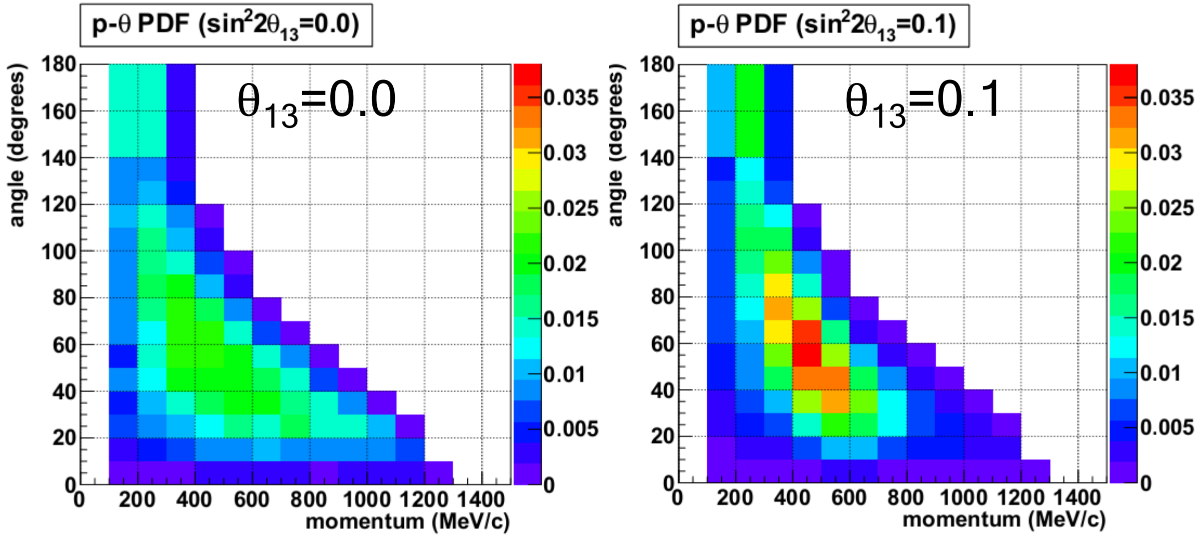
(PRL 111, 211803 (2013))

and

the other experiments.

Parameter	Value
Δm^2_{12}	7.6×10^{-5} eV^2
Δm^2_{32}	2.4×10^{-3} eV^2
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{12}$	0.8495
$\sin^2 2\theta_{13}$	0.1
δ_{CP}	0 degree
Earth matter density	2.6 g/cm^3
Mass hierarchy	normal
Base-line length	295 km

Electron momentum vs. angle distribution (MC)



T2K ν_e appearance analysis

Expected # of events & Systematic uncertainties for # of events

($\sin^2\theta_{23}$, Δm^2_{32}, δCP) = (0.5, 2.4×10^{-3} eV^2/c^4, 0)

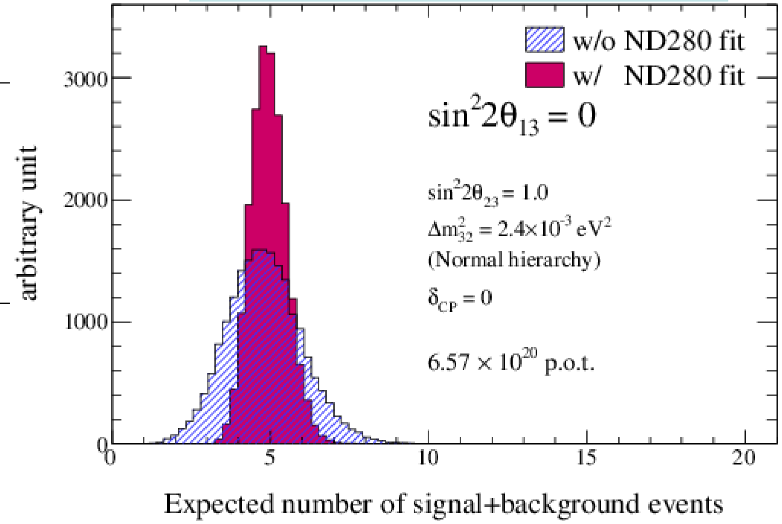
Expected # of events w/ 6.57×10^{20} POT

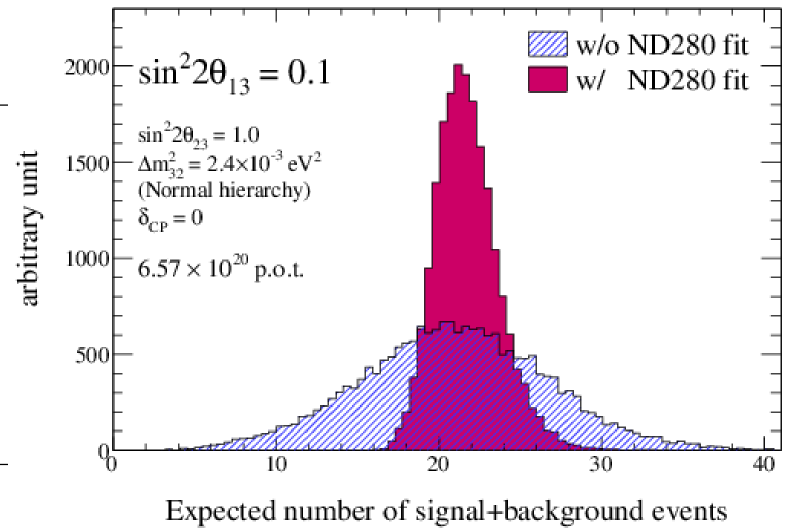
Event category	$\sin^2 2\theta_{13}$=0.0	$\sin^2 2\theta_{13}$=0.1
ν_e signal	0.40	17.30
ν_e background	3.37	3.12
ν_μ background (mainly NCπ^0)	0.94	0.94
$\nu_\mu + \nu_e$ background	0.21	0.20
Total	4.92	21.56

Systematic uncertainties for expected # of events

Error source	$\sin^2 2\theta_{13}$=0.0	$\sin^2 2\theta_{13}$=0.1
Beam flux + ν int. constrained from ND280	4.8 %	2.9 %
ν int. (from other exp.)	7.1 %	7.6 %
Far detector + Final state interactions + photo nuclear effects	7.3 %	3.5 %
Total	11.4 %	8.9 %

Expected # of events

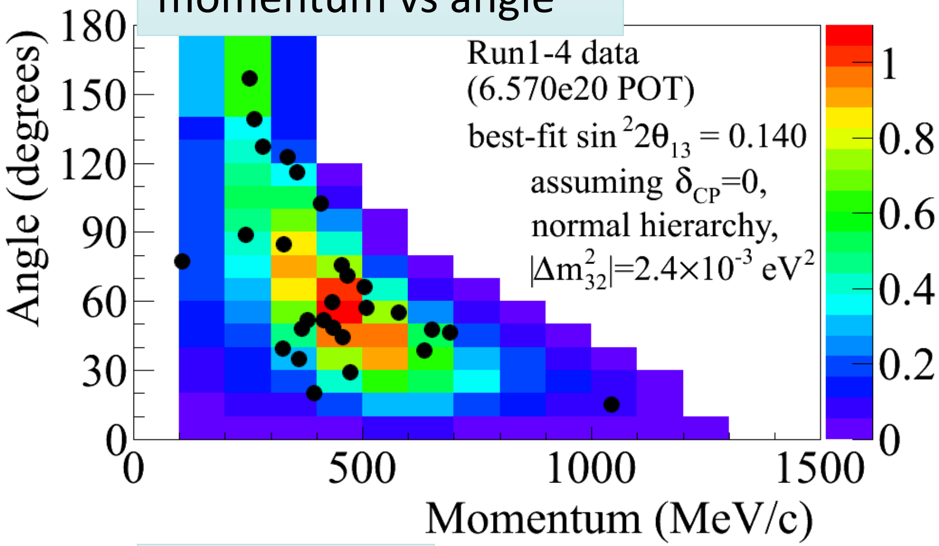




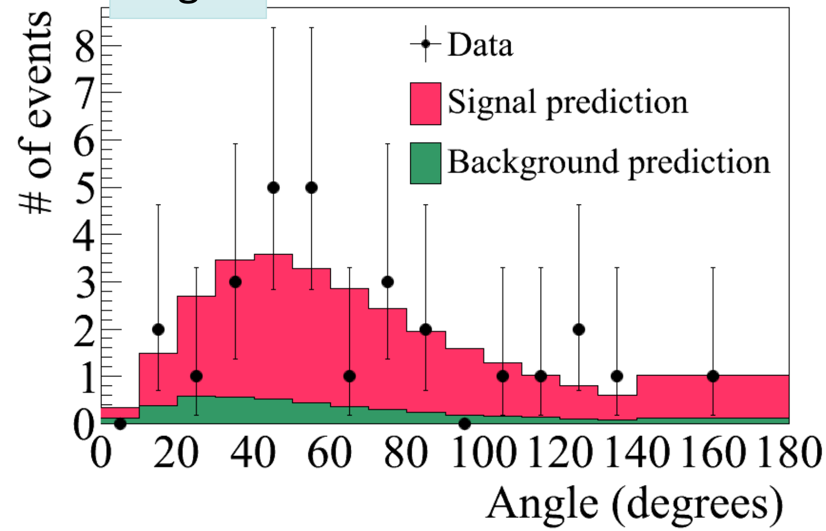
T2K ν_e appearance analysis

Fit results ~ comparison with data and MC with best fit parameter

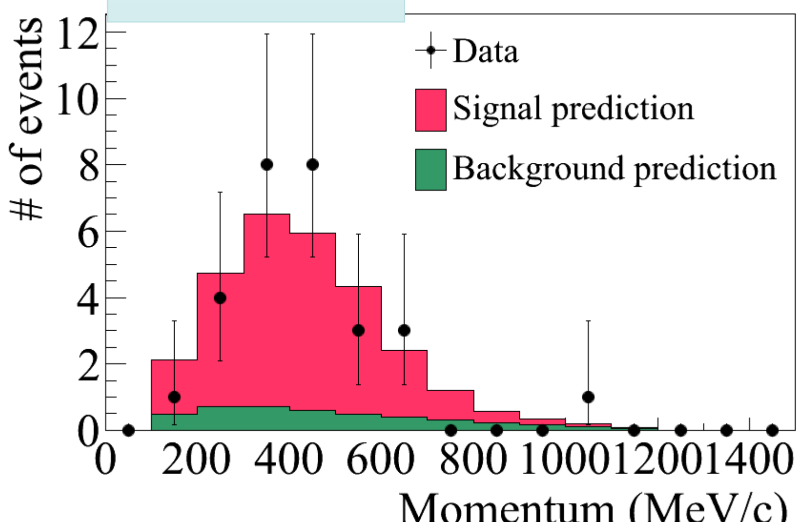
momentum vs angle



angle



momentum



Exclude θ_{13}=0 at 7.3 σ level

Best fit w/ 68% C.L. error:

$$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$$

90% allowed region:

$$0.090 < \sin^2 2\theta_{13} < 0.205$$

With following assumptions:
δ_{CP}=0, normal hierarchy,
$|\Delta m^2_{32}|$=2.4 × 10^{-3} eV^2 and $\sin^2 2\theta_{23}$=1

T2K ν_e appearance analysis

Allowed oscillation parameter regions

Best fit parameters

w/ 68% C.L. erros @ δ_{CP}=0

Normal hierarchy

$$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$$

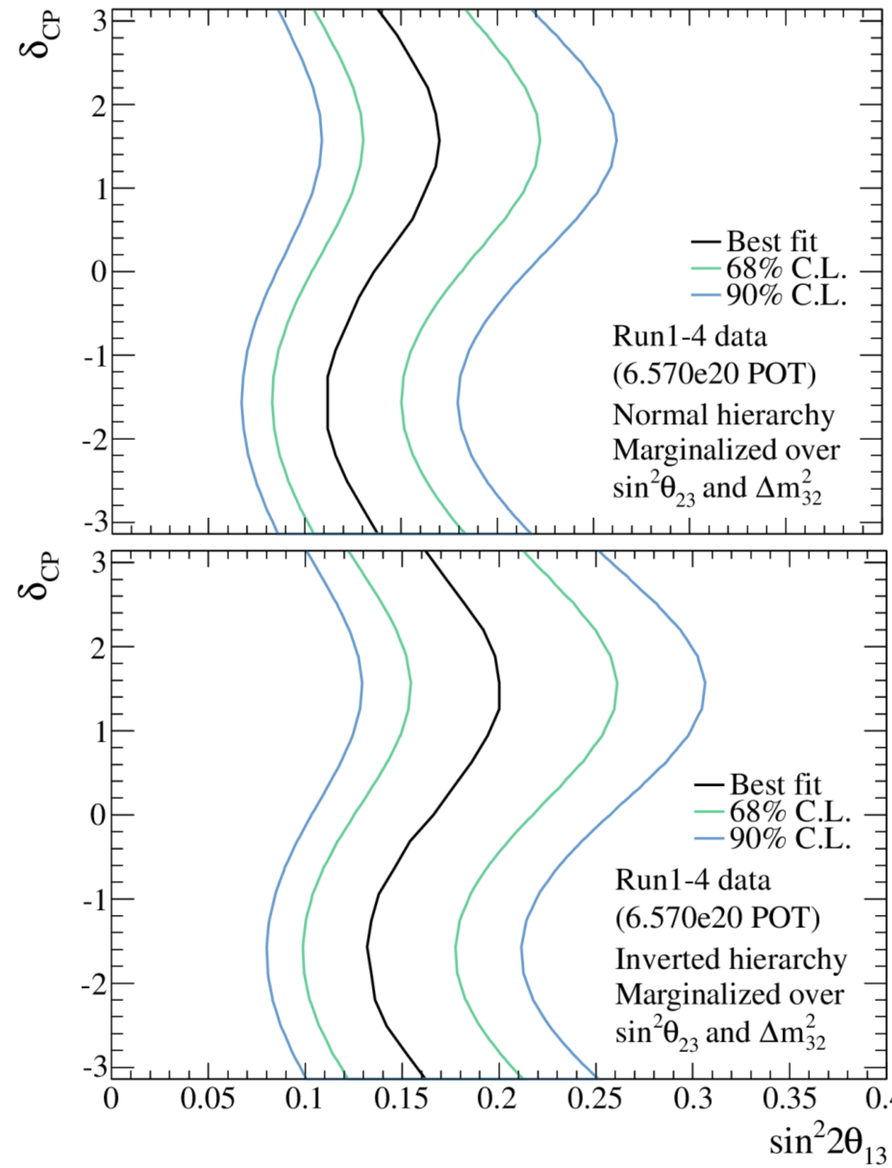
Inverted hierarchy

$$\sin^2 2\theta_{13} = 0.170^{+0.044}_{-0.037}$$

Constraints on the other parameters in the fit

Parameter	Value
Δm^2_{12}	7.6×10^{-5} eV^2
Δm^2_{32}	2.4×10^{-3} eV^2
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{12}$	0.8495
Earth matter density	2.6 g/cm^3
Mass hierarchy	normal
Base-line length	295 km

Allowed regions of θ_{13} for various δ_{CP}



T2K ν_e appearance analysis

Allowed oscillation parameter regions

Comparison with θ_{13} from reactor

From T2K

Normal hierarchy

$$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$$

Inverted hierarchy

$$\sin^2 2\theta_{13} = 0.170^{+0.044}_{-0.037}$$

From reactor experiments

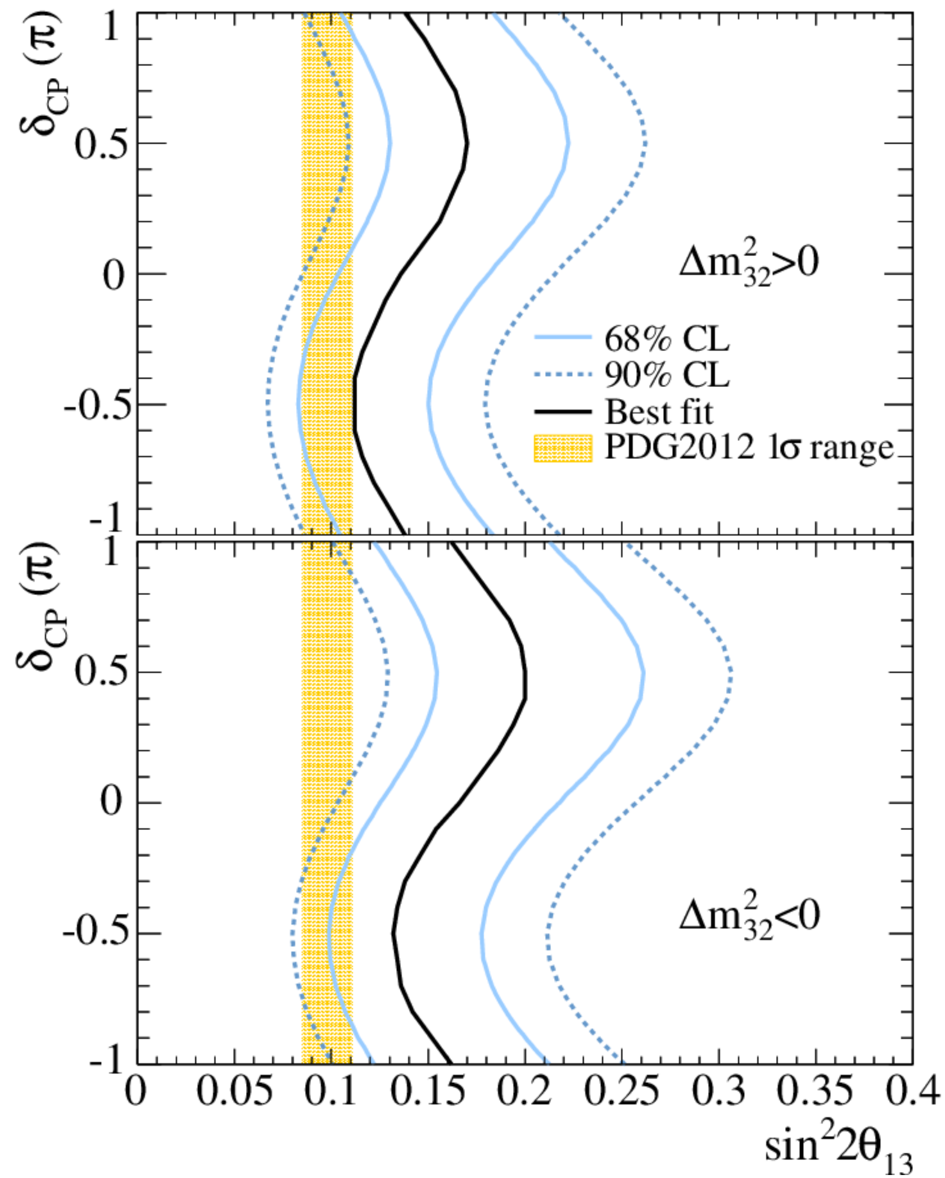
(PDG 2012)

$$\sin^2 2\theta_{13} = 0.098 \pm 0.013$$

→ Discrepancy

Signature of non-zero δ_{CP}??

Allowed regions of θ_{13} for various δ_{CP}



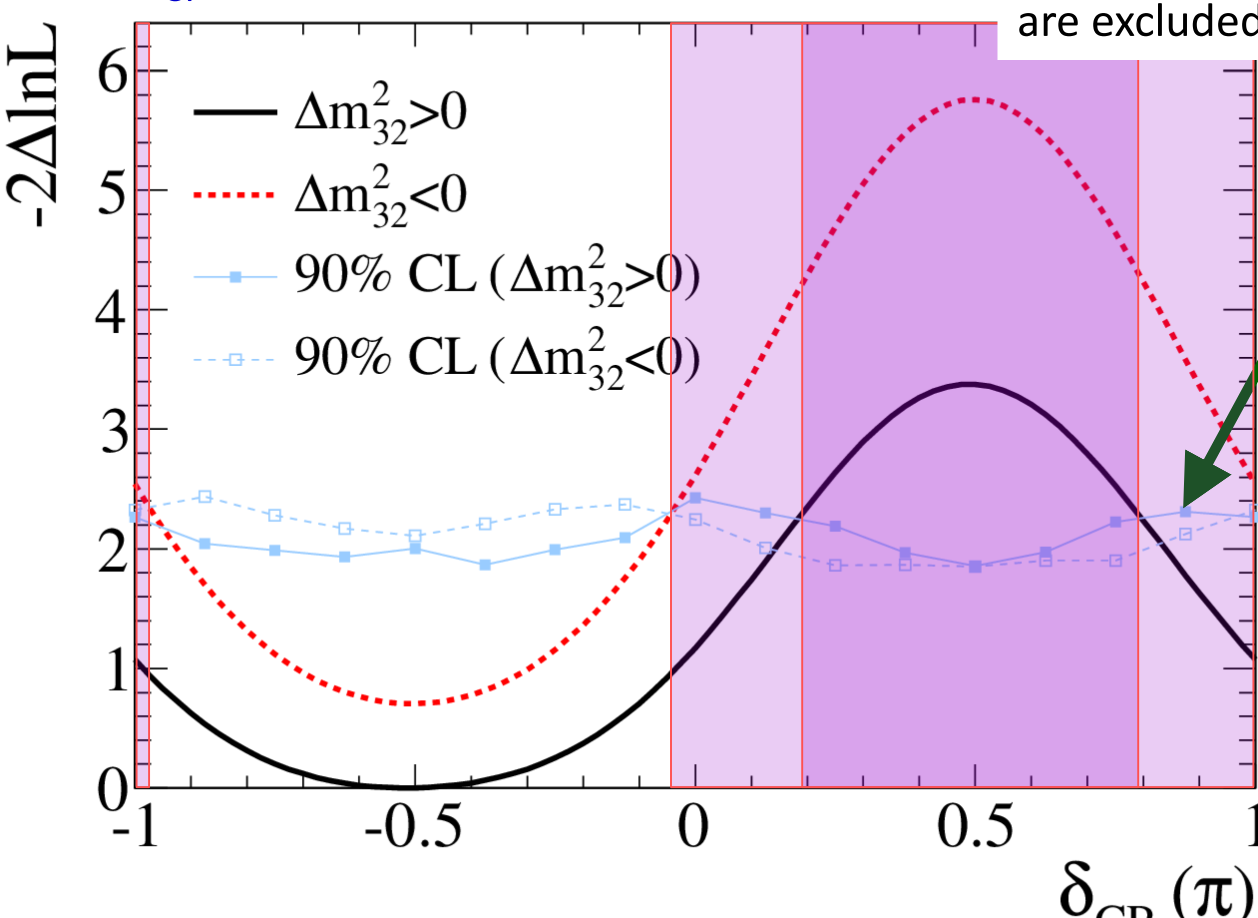
T2K ν_e appearance analysis

Combined fit with reactor constraints (from PDG 2012)

$\sin^2 2\theta_{13} = 0.098 \pm 0.013$

δ_{CP} negative log likelihood

Regions above these lines (derived by Feldman-Cousins method) are excluded with 90% C.L.



90% excluded regions

Normal hierarchy

0.19π ~ 0.80π

Inverted hierarchy

-1.00π ~ -0.97π

-0.04π ~ 1.00π

Future Prospects

- ν_e appearance and ν_μ disappearance combined fit
- Realistic (shape-dependent) systematic errors
  - Errors are assumed to be fully correlated between ν/anti-ν

Mid-term plan of MR

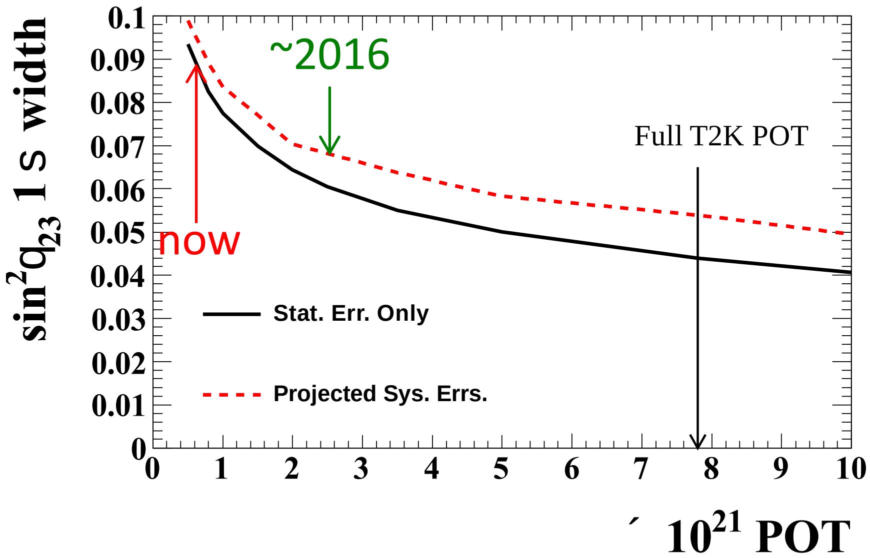
FX：We adopt the high repetition rate scheme to achieve the design beam intensity, 750 kW."
Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's and RF cavities.

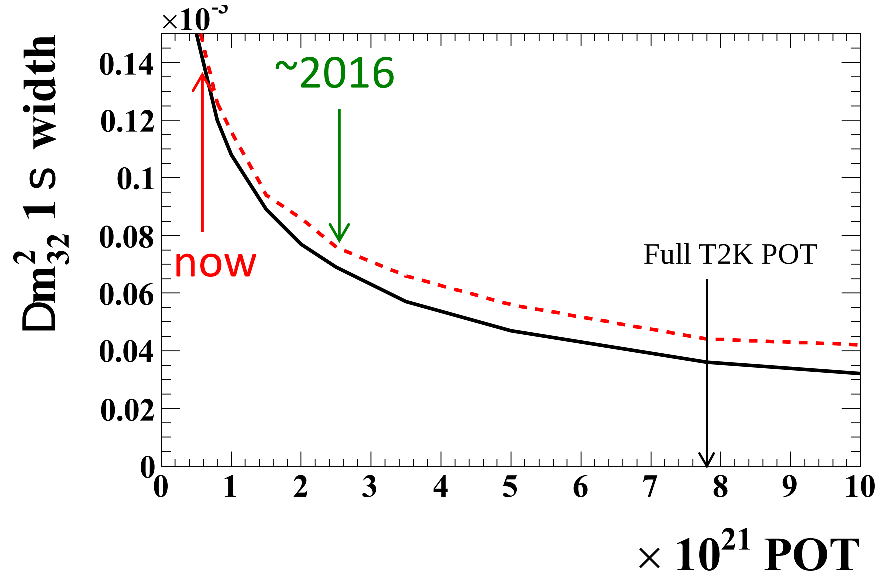
JFY	2011	2012	2013	2014	201 5	2016	2017
			Li. upgrade				
FX power [kW] SX power：User op.（study）[kW]!	150! 3 (10)	200 ! 10 (20)	240 ~ (300)! 25 (30)	~ 400! 50 (100)	→		750! 100
Cycle time of main magnet PS! **New magnet PS for high rep.**	3.04 s	2.56 s R&D	2.4 s		Manufacture installation/test		1.3 s
Present RF system ! **New high gradient rf system!**	Install. #7,8	Install. #9 R&D			Manufacture installation/test		
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW)				
Injection system! **FX system**	New injection kicker	Kicker PS improvement、Septum 2 manufacture /test LF septum, PS for HF septa manufacture /test					

Expected POT is estimated based on the information.

$\sin^2\theta_{23}/\Delta m^2_{32}$ 1σ Precision vs. POT

POT fractions: 50% ν + 50% anti-ν case





Solid Lines: no sys. err.

Red Dashed: with conservative systematic errors (~7% ν, ~14% anti-ν)

Precisions are expected to be improved drastically over the next few years.

Statistical limit of 1σ precision at full POT

- $\sin^2\theta_{23}$ (θ_{23}) ~ 0.045 (~2.6°)
- Δm^2_{32} ~ 4×10^{-5} eV^2

Assuming true: $\sin^2 2\theta_{13}$=0.1, δ_{CP}=0°, $\sin^2\theta_{23}$=0.5, Δm^2_{32}=2.4×10^{-3} eV^2, Normal hierarchy, θ_{13} constrained by $\delta(\sin^2 2\theta_{13})$ = 0.005

Appearance 90% C.L. Sensitivity

7.8×10^{21} POT (POT fractions : 50% ν + 50% anti-ν)

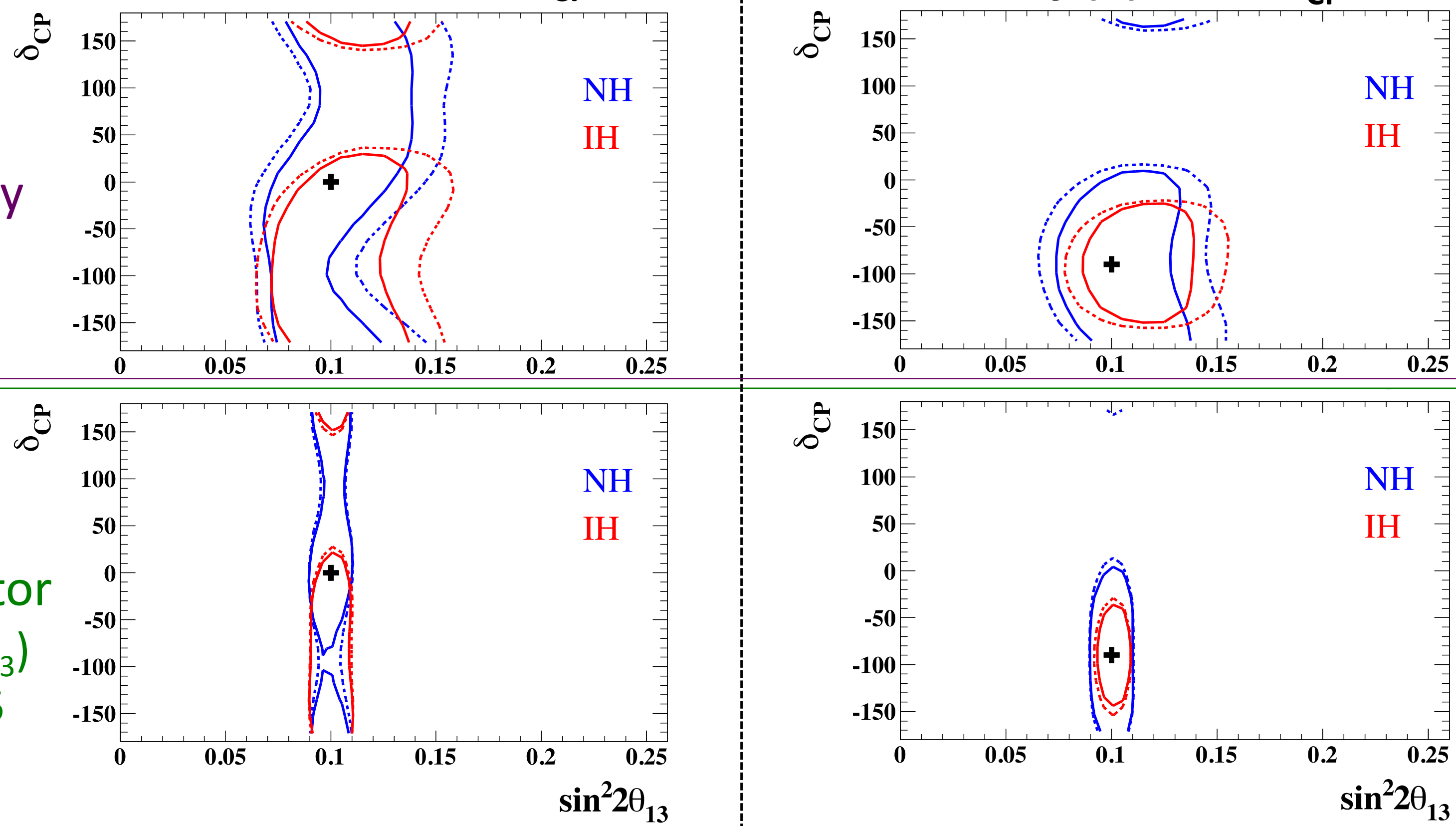
Solid Lines: no sys. err., Dashed: with 2012 sys. err. (~10% ν_e, ~13% ν_μ)

Case study (1): True $\delta_{CP} = 0^\circ$

Case study (2): True $\delta_{CP} = -90^\circ$

T2K only

T2K w/ Reactor $\delta(\sin^2 2\theta_{13}) = 0.005$



[NH] Normal hierarchy, [IH] Inverted hierarchy

Assuming true: $\sin^2 2\theta_{13}=0.1$, $\sin^2\theta_{23}=0.5$, $\Delta m^2_{32}=2.4 \times 10^{-3}$ eV^2, [NH]

Sensitivity for Resolving $\sin\delta_{CP}\neq0$

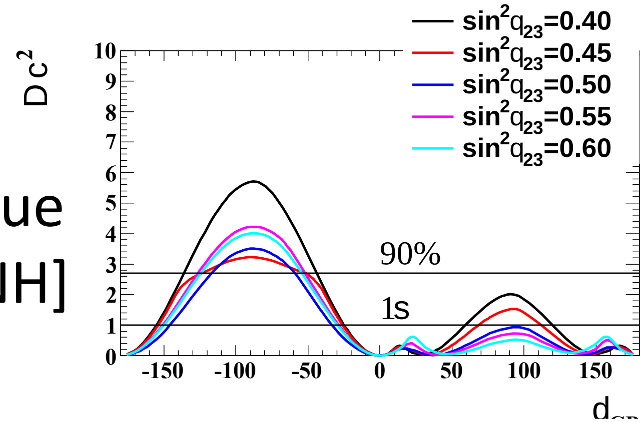
7.8×10^{21} POT (POT fractions : 50% ν + 50% anti-ν)

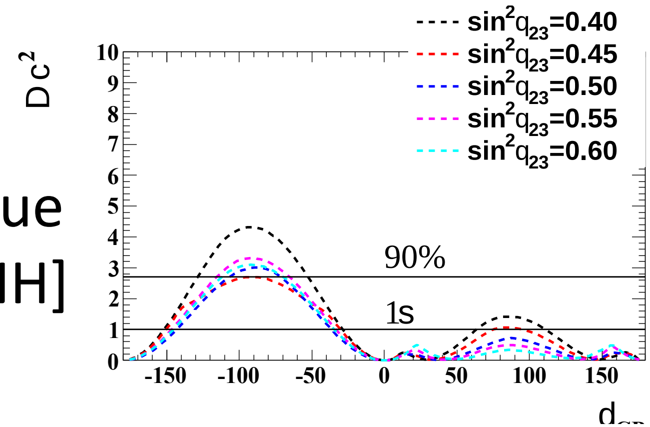
[NH] Normal hierarchy, [IH] Inverted hierarchy

No sys. err.

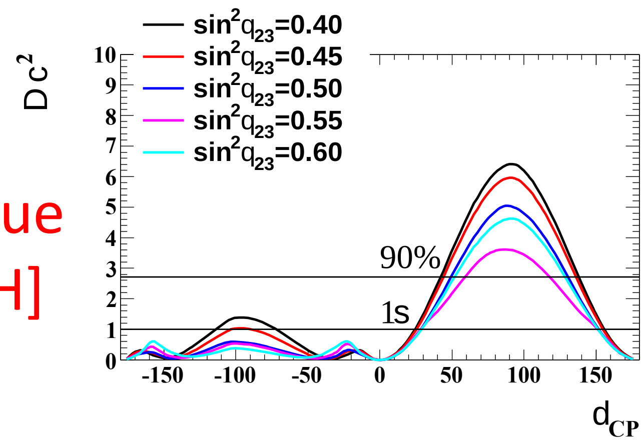
w/ 2012 sys. err. (~10% ν_e, ~13% ν_μ)

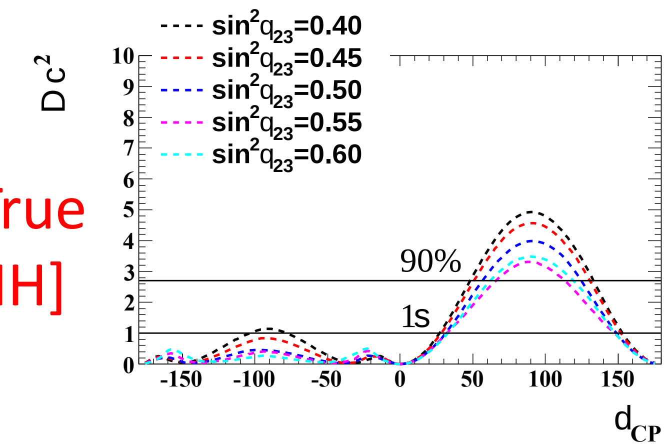
True [NH]





True [IH]





Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2

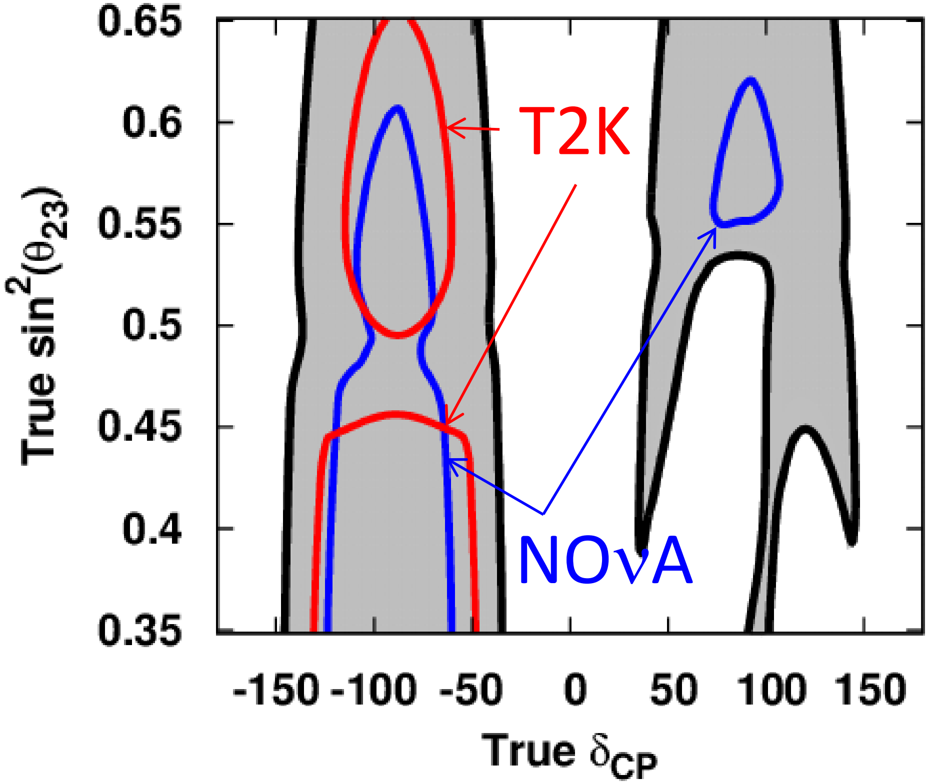
θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

T2K + NOνA Sensitivity for Resolving $\sin\delta_{CP}\neq 0$

Both T2K / NOνA : full POT (POT fraction : 50% ν + 50% anti-ν)

Plots are for normal hierarchy

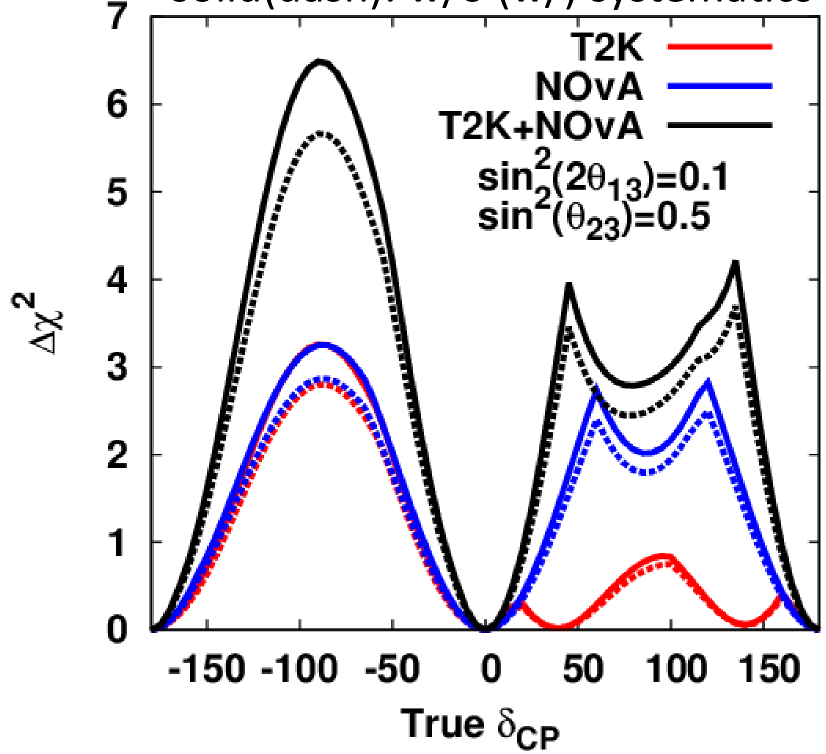
Red: T2K alone, Blue: NOνA alone, Black: T2K + NOνA



Region where $\sin\delta=0$

can be excluded by 90% C.L.

solid(dash): w/o (w/) systematics



Sensitivity to resolve $\sin\delta=0$

Assuming 5% (10%) normalization uncertainty on signal (background)

Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2, θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

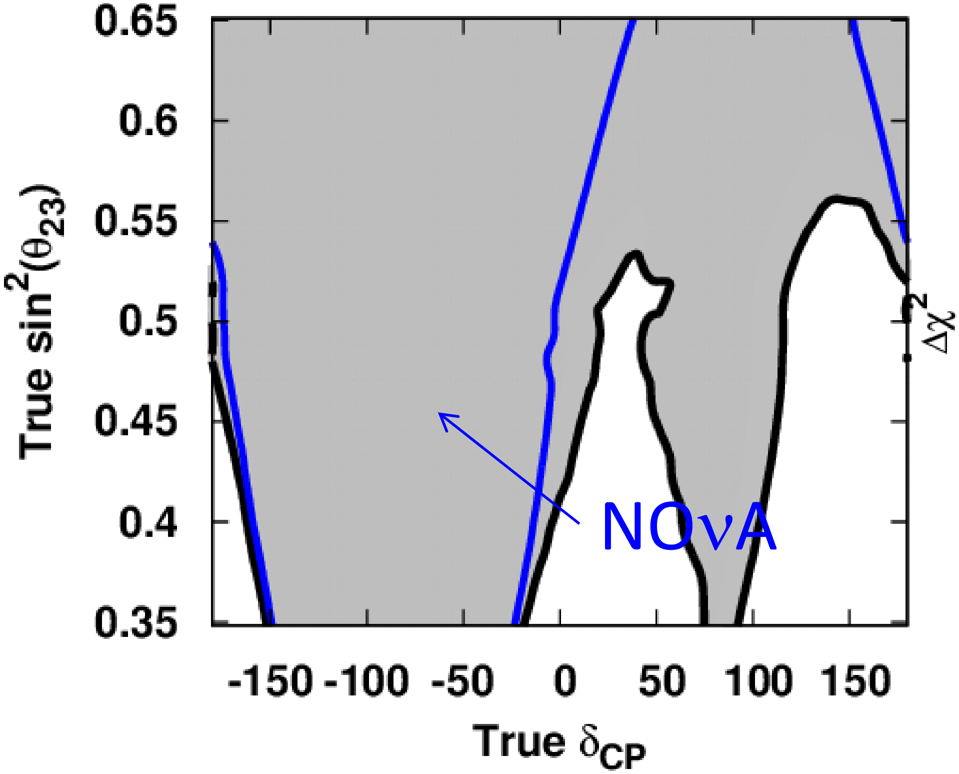
T2K + NOνA Sensitivity to Mass Hierarchy

Both T2K / NOνA : full POT (POT fraction : 50% ν + 50% anti-ν)

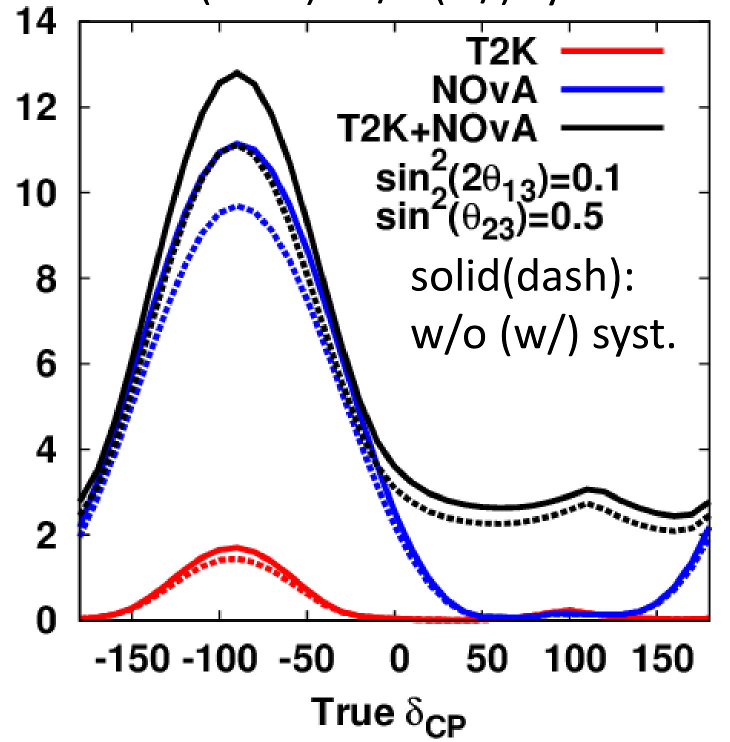
Plots are for normal hierarchy

Red: T2K alone, Blue: NOνA alone, Black: T2K + NOνA

solid(dash): w/o (w/) systematics



Region where MH can be distinguished by 90% C.L.



Sensitivity to resolve MH

Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2, θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

Summary

ν_μ disappearance results

- We have measured θ_{23} with the world-leading precision
- New result favors maximal mixing

ν_e appearance results

- We have constrain the CP violating phase δ_{CP} by combining our ν_e appearance results with the reactor measurements
- Best fit is found at very interesting point, δ_{CP} ~ $-\pi/2$.
  If it is true, severe competition with NOνA.
  Important to increase statistics ASAP.

Future sensitivity study

- May be possible to constrain δ_{CP}
- Combined analysis with NOνA enhances the sensitivities to δ_{CP} and the mass hierarchy
- Higher power at design value (750 kW) beam operation is anticipated.