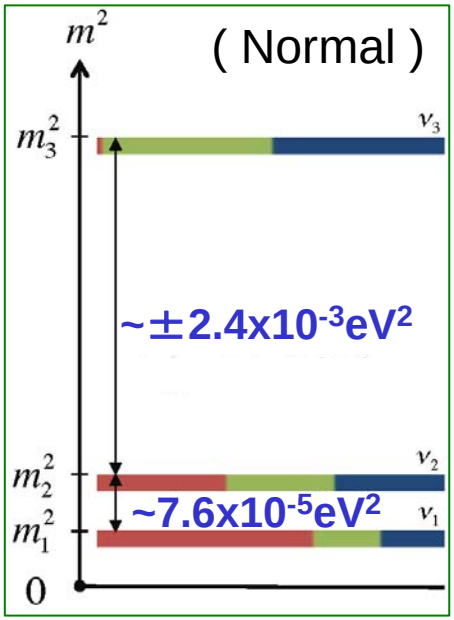
Prospects of current and near term neutrino experiments in light of T2K result and MINOS

Yoshinari Hayato
(Kamioka, ICRR, Univ. of Tokyo)

1. Neutrino oscillation

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



$$|\nu_\alpha\rangle = \Sigma U_{li}|\nu_i\rangle$$

Weak Mass eigenstates

Maki-**N**akagawa-**S**akata **Matrix ($U_{\alpha i}$)**

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

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

(Atm. + Accl.)

$\sin^2 2\theta_{23}$~1(>0.9)

$|\Delta m^2_{32}|$~2.5x10^{-5}eV^2

(Reactor)

$\sin^2 2\theta_{13} < 0.2$

Still Unknown!
zero or non zero

(Solar + Reactor)

$\sin^2\theta_{12}$~0.3

Δm^2_{21}~7.6x10^{-5}eV^2

2. Neutrino oscillation parameter θ_{13}

Use ν_μ to ν_e oscillation to measure θ_{13}

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

Leading term

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

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

CPV

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

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

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

matter

$$a = 2\sqrt{2} G_F n_e E_\nu$$ (matter parameter)

For anti neutrinos,

$a \to -a$, $\delta \to -\delta$

→ ***Finite θ_{13} allows us to study CP violation in lepton sector in the future experiments.***

3. Neutrino properties ~ Remaining issues beyond θ_{13}

- Is CP in lepton sector violated or not? ($\delta = 0$ or $\neq 0$?)

  Related to the matter – anti-matter asymmetry?

- Mass Hierarchy problem(relation of m_3 and m_2)

  Only absolute value

  ($|\Delta m^2_{32}|$)

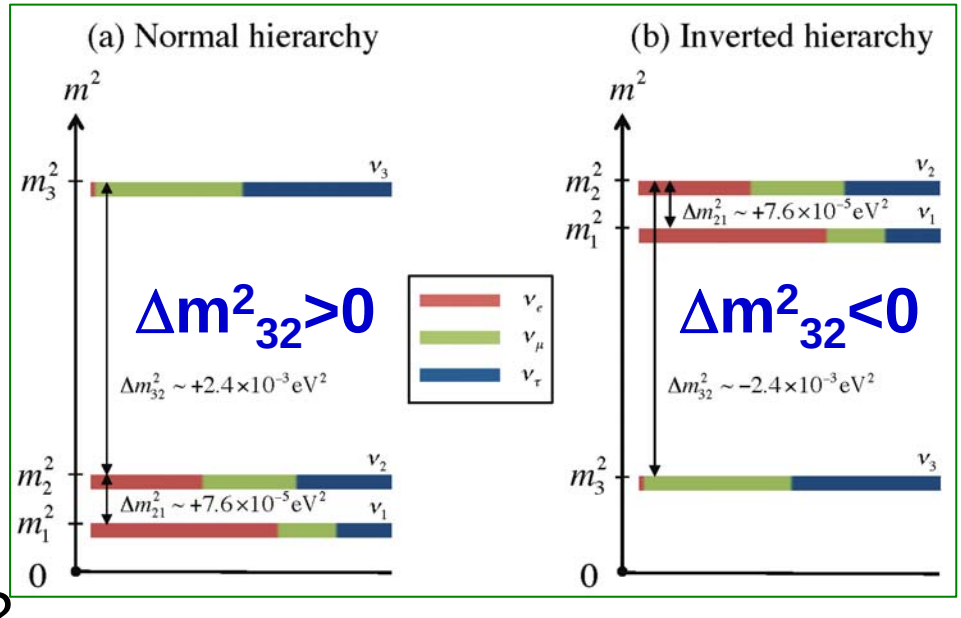
  has been measured.

  Relate to the lifetime of

  ν less double beta decay

  Related to

  the origin of ν mass ?



- $\theta_{23} = \pi/4$ (full mixing) or not ?

  If not, $\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$

- Absolute mass of ν

- Majorana particle?

4. Tokai to Kamioka long baseline neutrino oscillation experiment (T2K)

Search for the ν_e appearance

→ ***Aim to measure θ_{13}***

(~10 times better sensitivity than previous)

Precision measurements of oscillation parameters with ν_μ disappearance

→ **$\delta(\Delta m^2_{23}) \sim 1\times10^{-4}\ eV^2$, $\delta(\sin^2 2\theta_{23}) \sim 0.01$**

5. T2K neutrino beam ~ Off axis beam ~

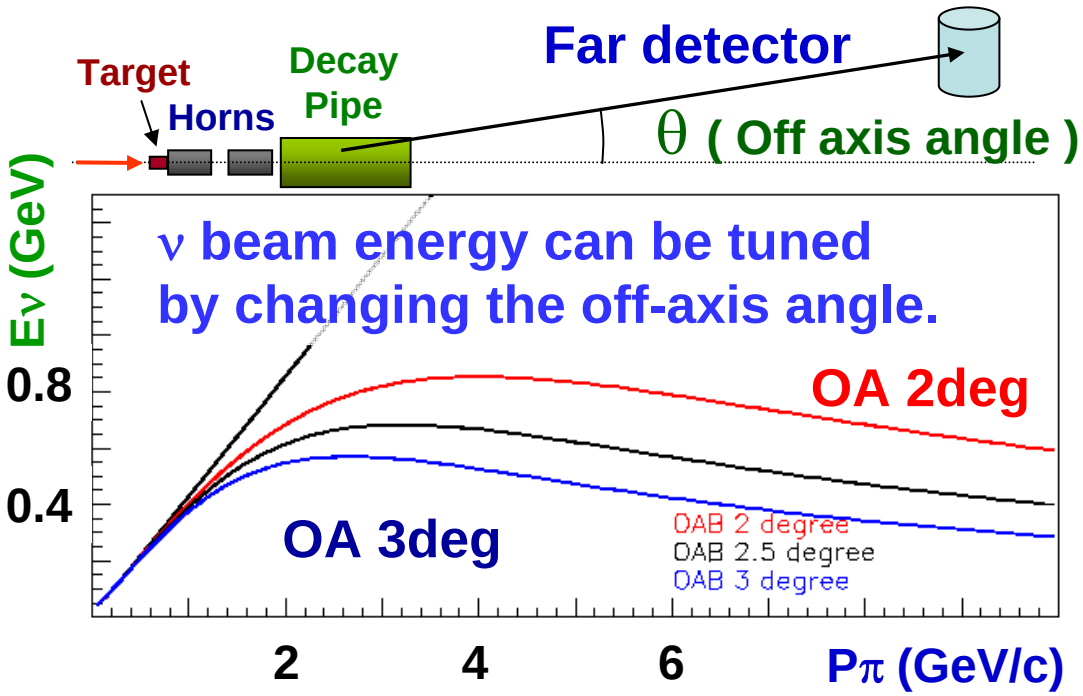
Maximize sensitivity in oscillation studies

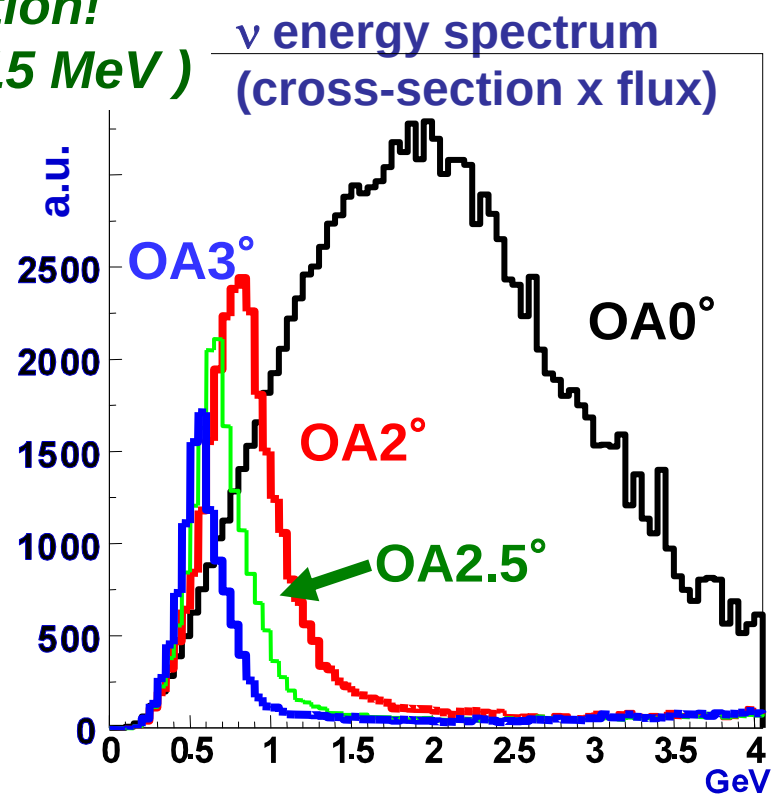
➡ Use narrow band beam with peak energy at the oscillation maximum

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

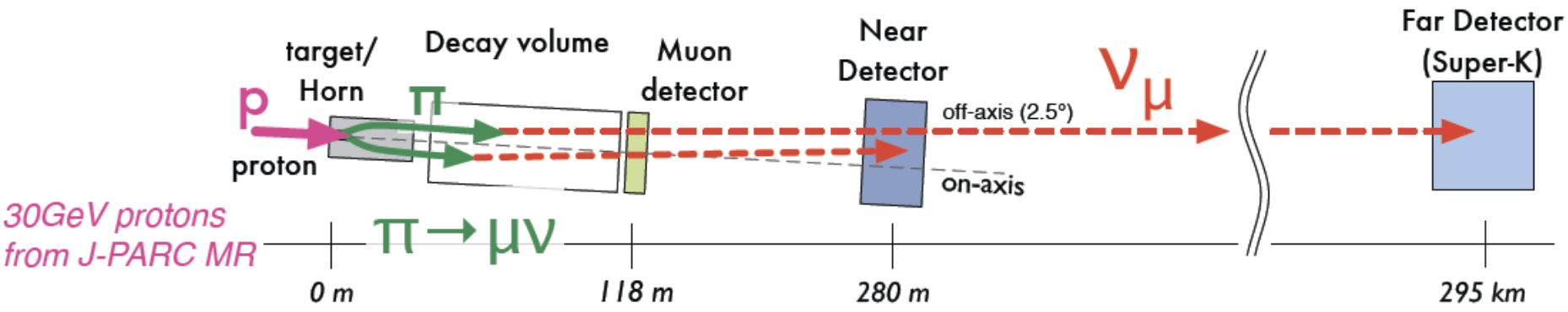
- Quasi-monochromatic beam ~ suppressed high energy ν
- Energy is tunable (Change off axis angle)

Important to monitor beam direction!
(1mrad ~ peak E_ν shifts by ~15 MeV)





6. T2K ~ Schematic diagram of the experiment



- Proton beam extracted every ~ 3 sec.
- Beam spill width ~ 5 μs

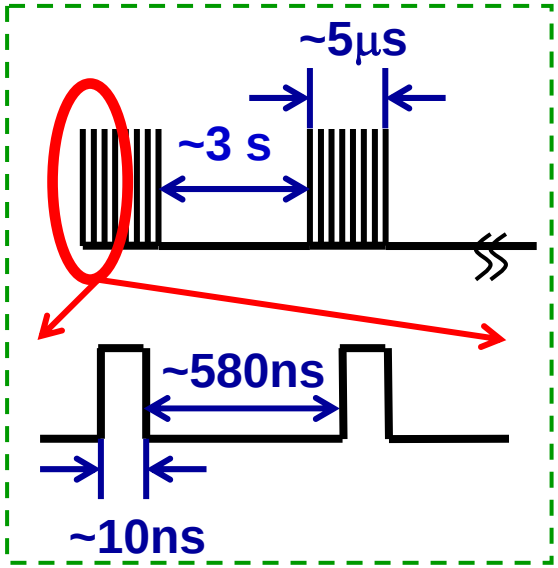
  6 bunches before Summer 2010

  8 bunches after Summer 2010
- Neutrino production target

  graphite target

  (diameter = 26mm, L=90cm)

  He air cooled
- π focusing ~ Triple horn system (operated @ 250kA)



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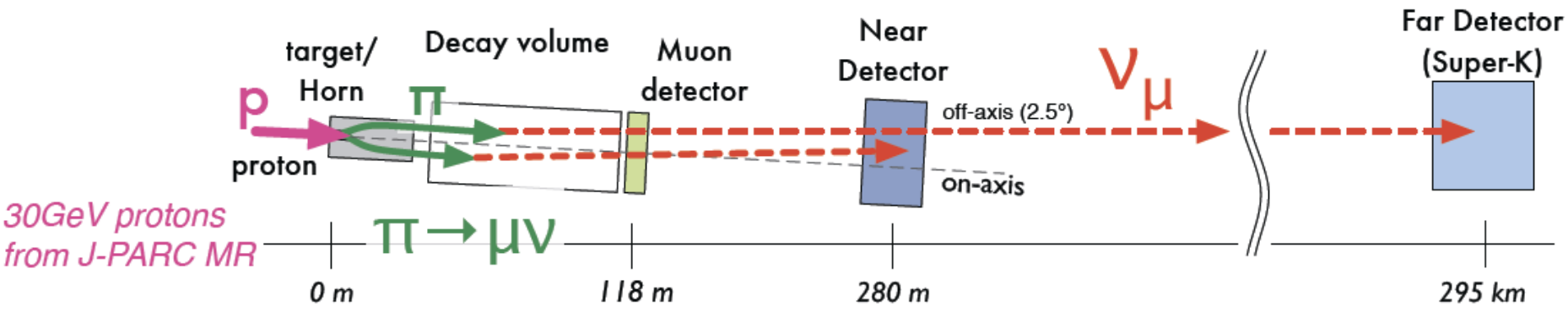
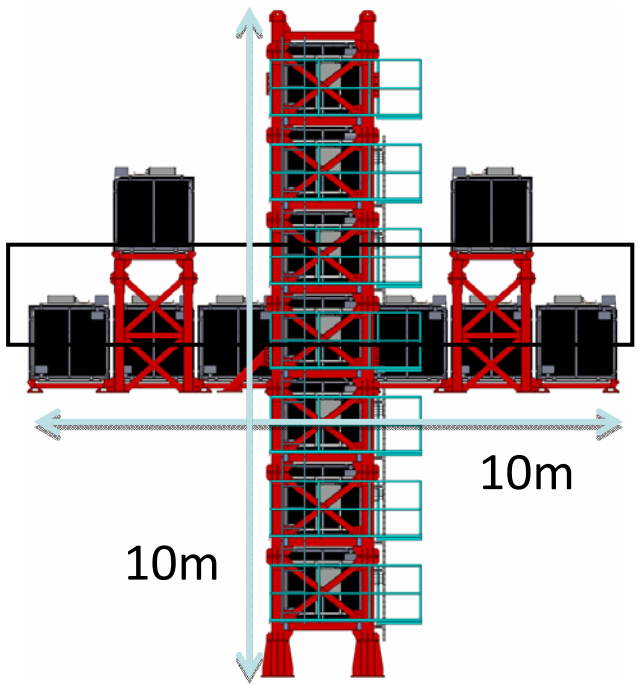


- Muon monitor after the beam dump
  - Spill by spill monitor
    - of the neutrino direction
      - and intensity of muon
- On axis near neutrino detector
  - ***INGRID*** (Fe + Scintillator)
  - Day by day monitor
    - of the neutrino interaction rate
  - Neutrino beam direction monitor

INGRID



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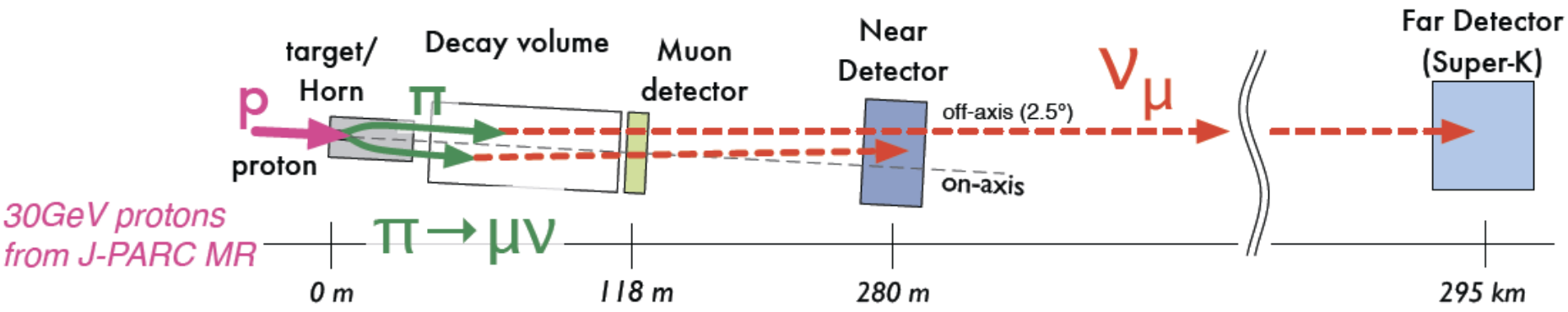
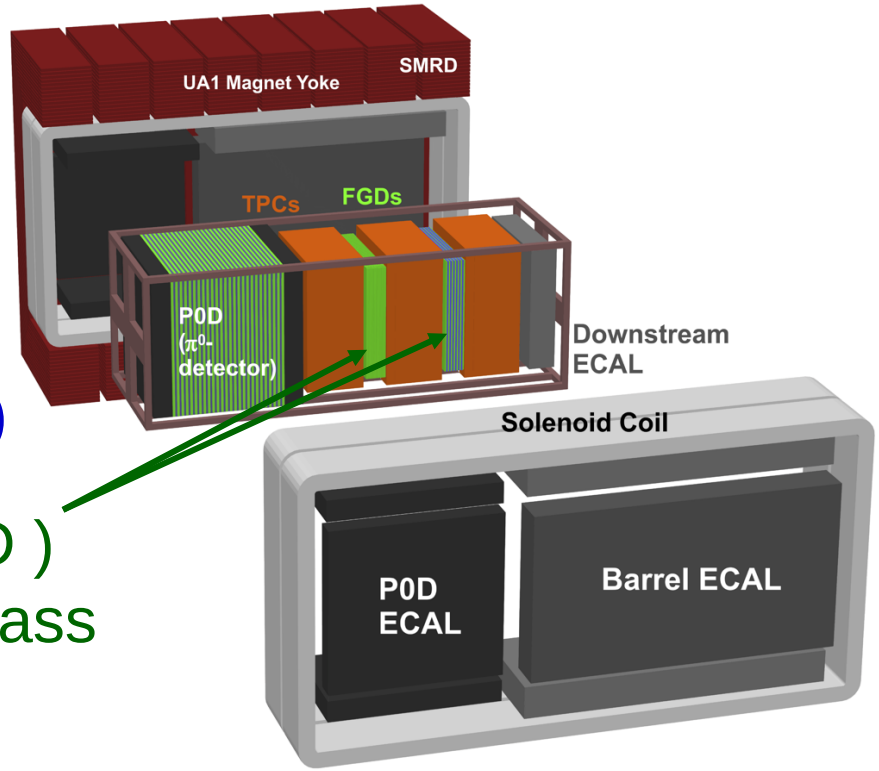


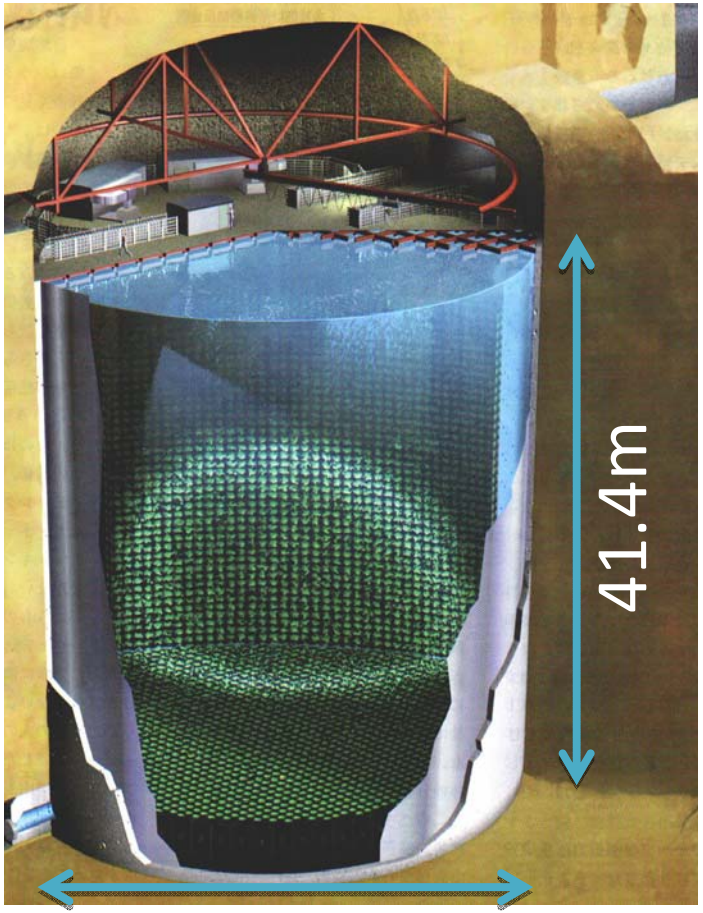
- Off axis detectors
  - neutrino flux measurements
  - neutrino interaction studies

TPC and
various scintillator detectors
in the UA1 magnet (0.2 T)

Fine grained detector (FGD)
1.6 tons of fiducial mass



7. T2K far detector ~ Super-Kamiokande



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- Water Cherenkov detector with fiducial volume 22.5kton

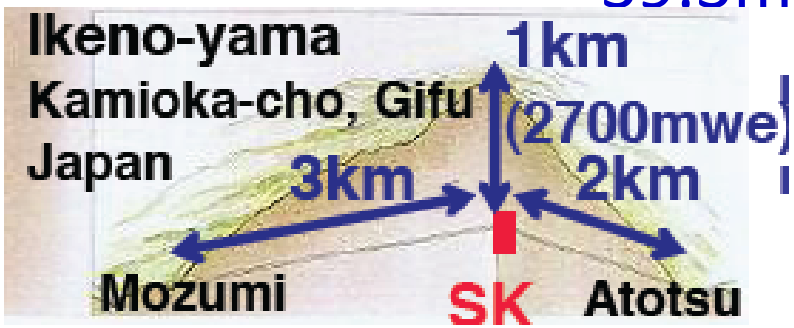
  Inner detector (ID)

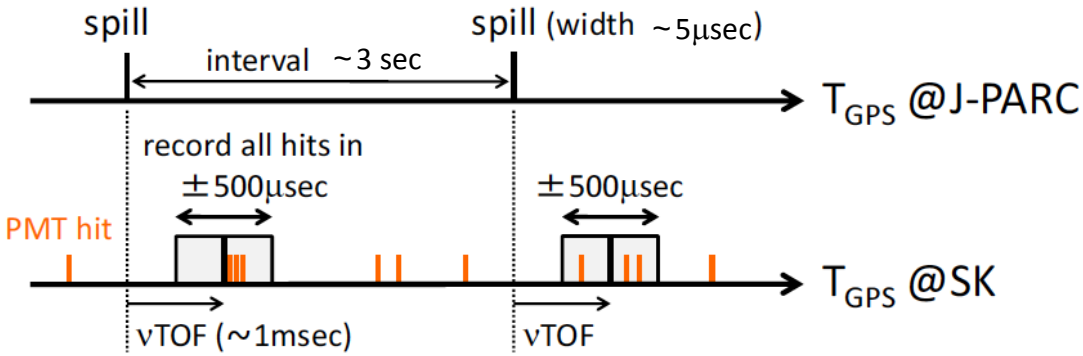
  11,129 20inch PMT

  Outer detector (OD)

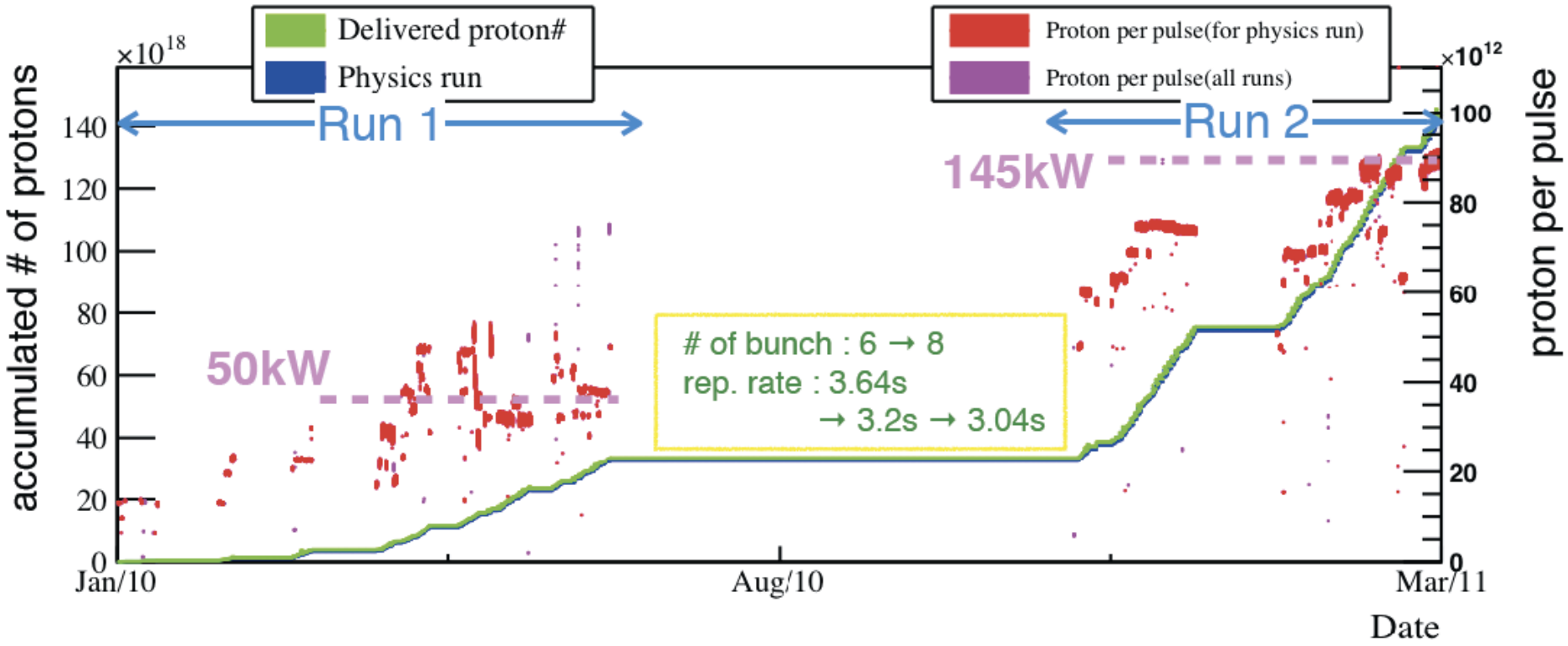
  1,885 8inch PMT

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





8. T2K Data taking



Run 1 (Jan. '10 - June '10)

- 3.23 x 10^{19} p.o.t. for analysis
- 50kW stable beam operation

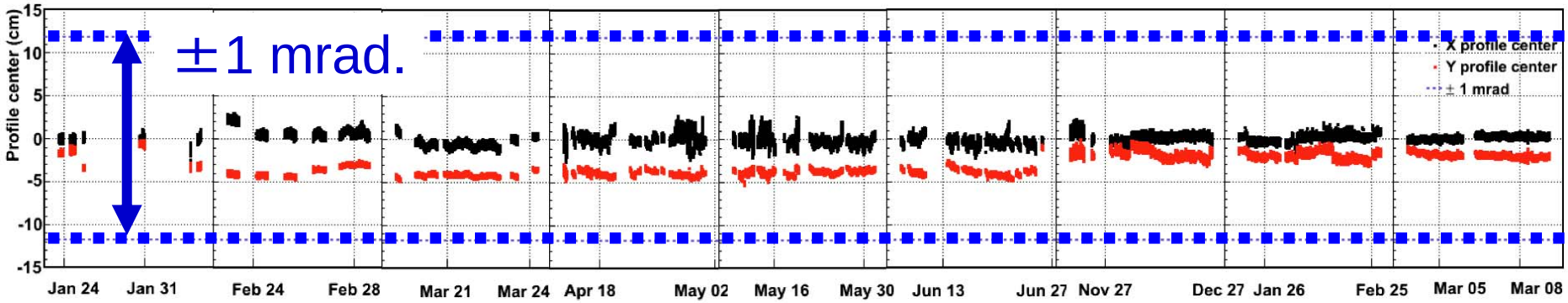
Run 2 (Nov. '10 - Mar. '11)

- 11.08 x 10^{19} p.o.t. for analysis
- ~145kW beam operation

1.43 x 10^{20} POT is used for the current analysis
(~ 2% of the final goal)

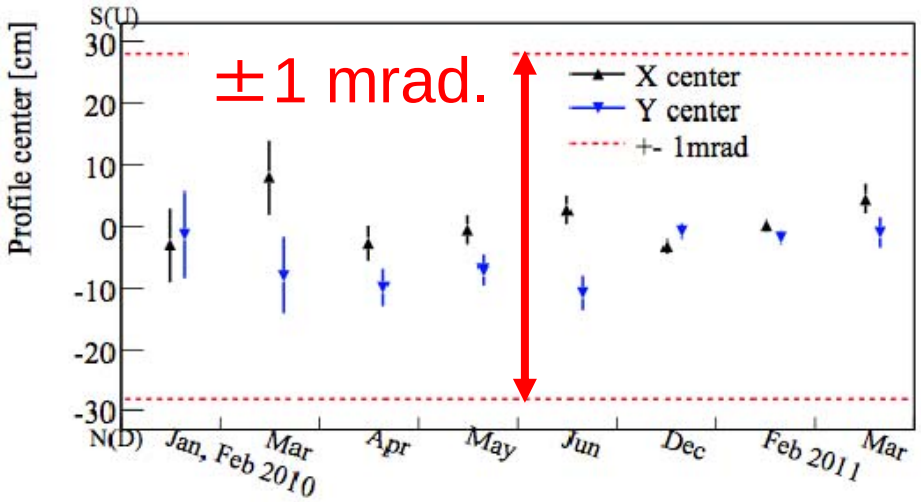
9. T2K ~ stability of the neutrino beam

Muon monitor : stability of the beam direction

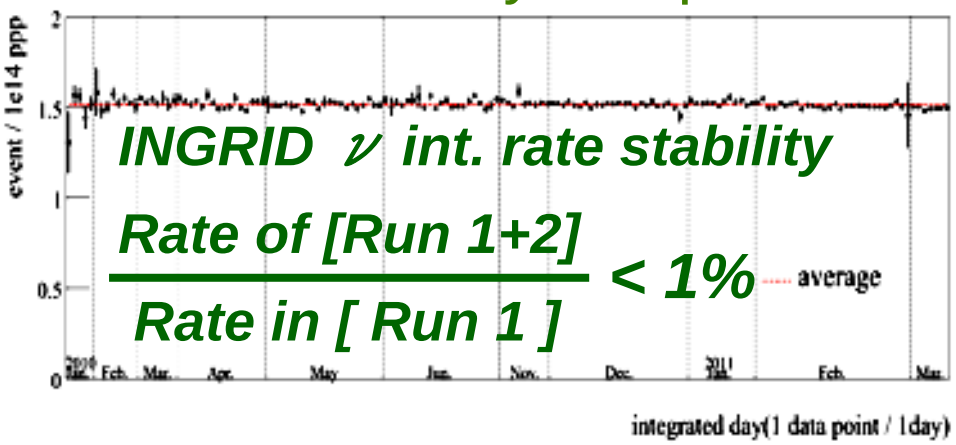


INGRID

Stability of ν beam direction



Stability of ν interaction rate normalized by # of protons



INGRID ν int. rate stability

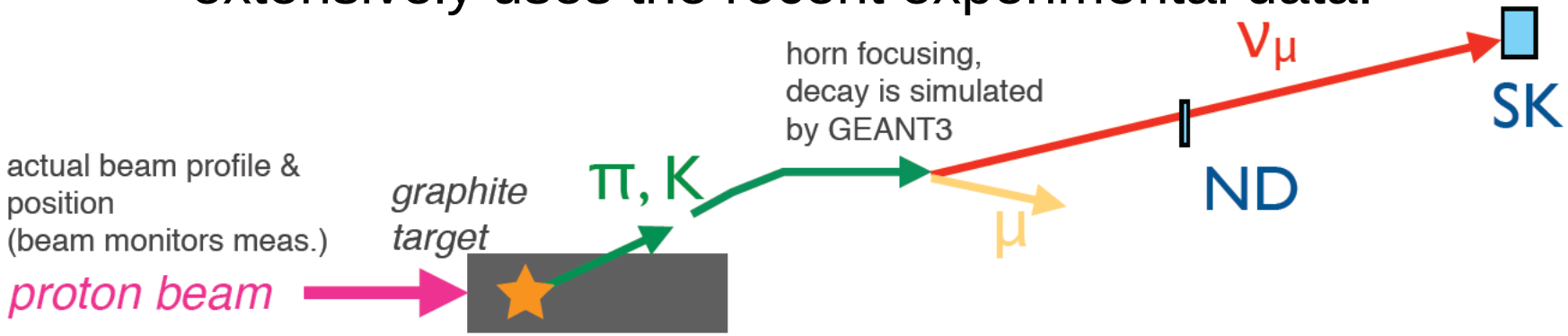
$$\frac{\textit{Rate of [Run 1+2]}}{\textit{Rate in [Run 1]}} < 1\%$$

ν beam dir. and interaction rates were stable.

10. T2K neutrino beam flux prediction

Dedicated neutrino beam simulation program
has been developed.

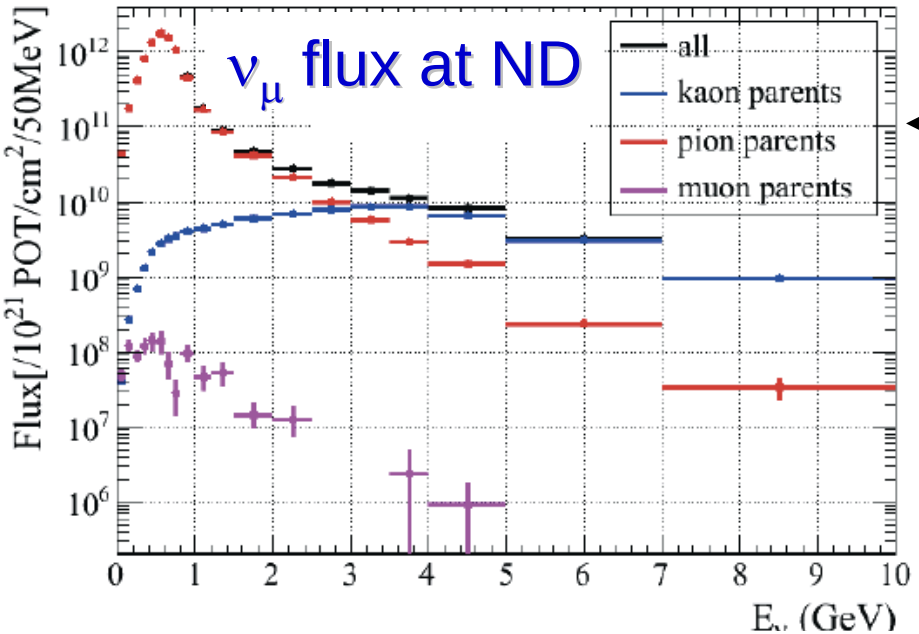
This simulation program
extensively uses the recent experimental data.



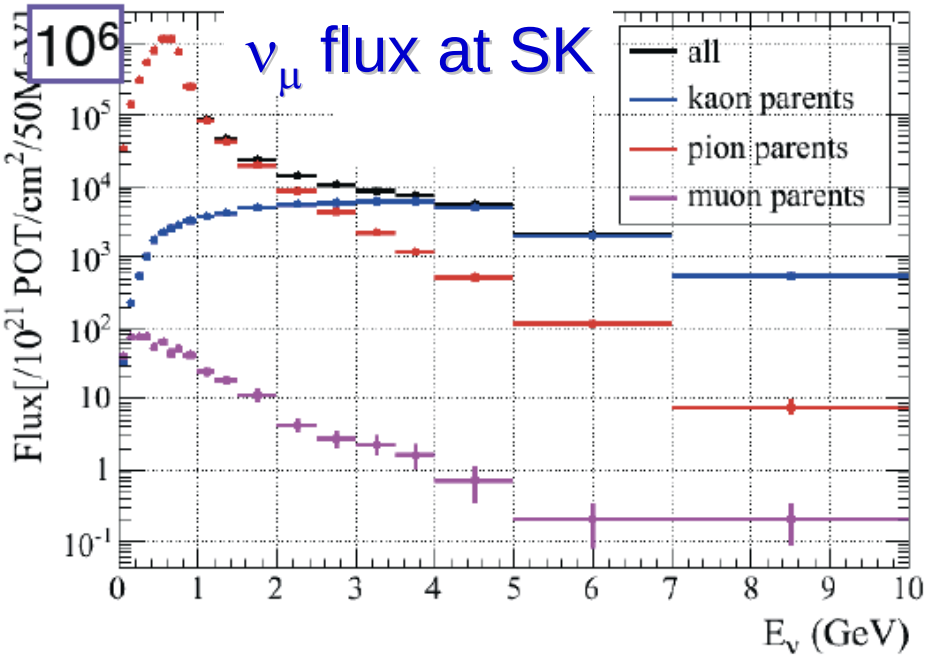
Primary beam (30 GeV) + Target (Carbon) interactions

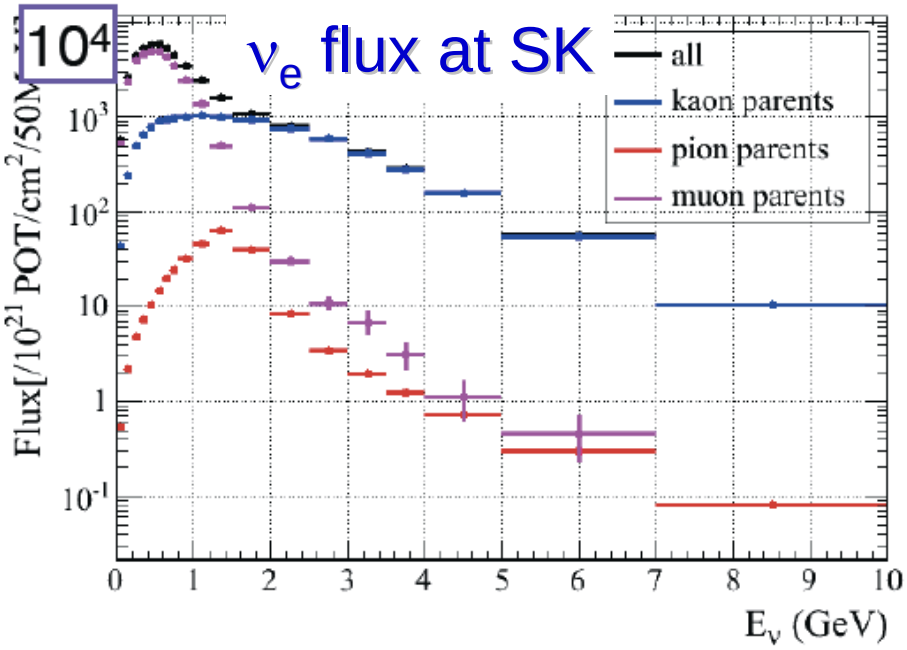
- CERN NA61/SHINE π production data is used.
  (> 95% coverage of ν parent pions)
- K, π outside of NA61 acceptance,
  and other interactions in the target
  were simulated using FLUKA
- Secondary interaction cross-sections outside the target
  were based on the experimental data.

10. T2K neutrino beam flux prediction



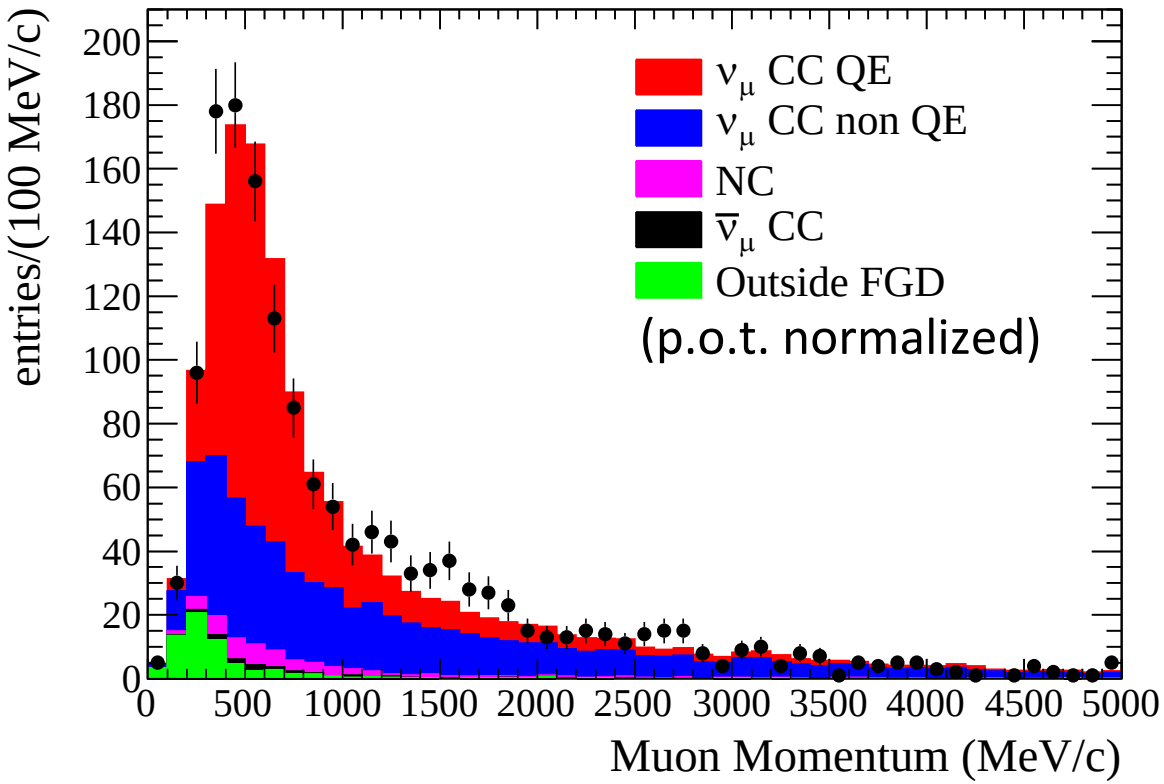
Measure ν fluxes
at near detectors
to validate the results.

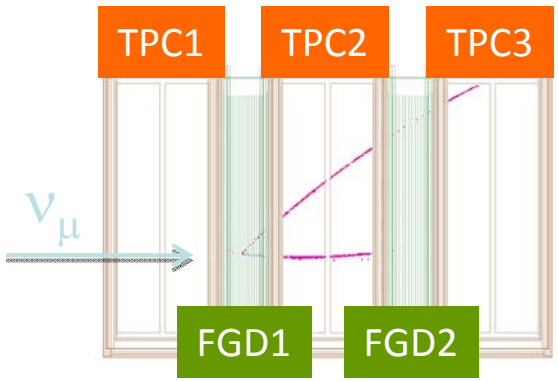




11. T2K neutrino flux measurement at ND

Inclusive ν_μCC measurement





Select events starting in the FGD FV with most energetic negative track compatible with a muon

(90% purity, 38% efficiency)

Data is consistent with MC based on the NA61 data and ν interaction simulation

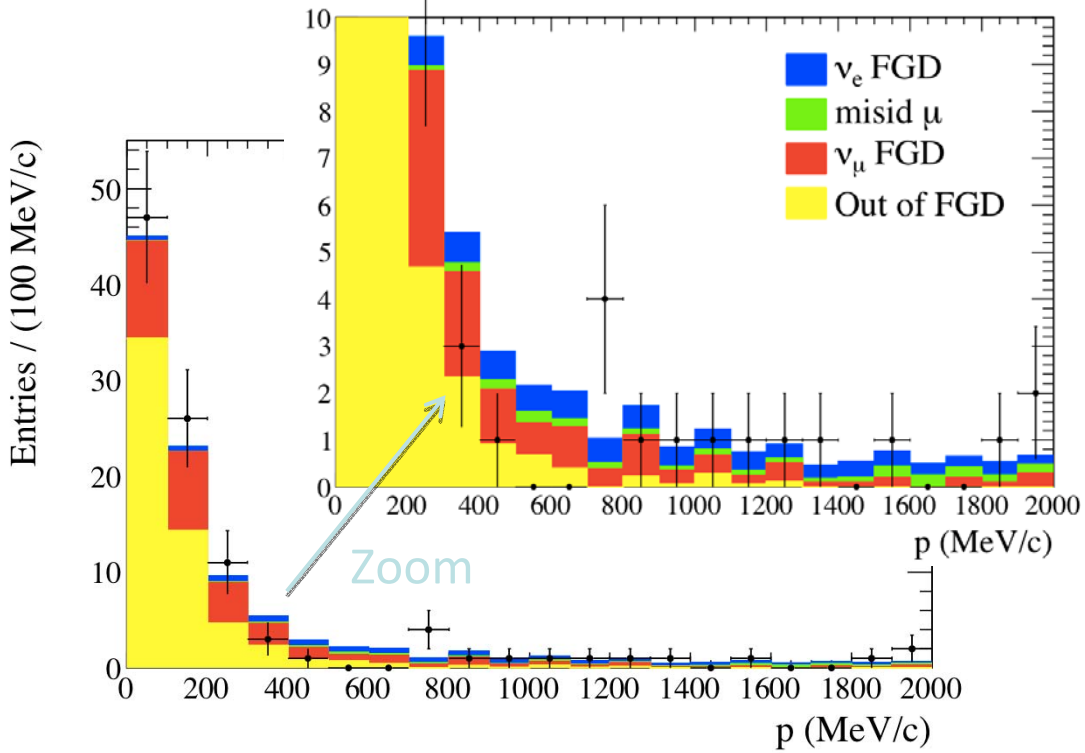
$$R_{ND}^{\mu,\,Data} = 1529 \text{ events} / 2.9 \times 10^{19} \text{ p.o.t.}$$

$$\frac{R_{ND}^{\mu,\,Data}}{R_{ND}^{\mu,\,MC}} = 1.036 \pm 0.028(\text{stat.})^{+0.044}_{-0.037}(\text{det. syst.}) \pm 0.038(\text{phys. syst.})$$

11. T2K neutrino flux measurement at the ND

Beam ν_e measurement

- Selecting electrons ~ Use dE/dx in the TPC
- BG from mis-ID μ estimated using sand muon data
- BG from γ conversion constrained by control sample (data)
- Likelihood fit on the electron momentum to measure N (ν_e)



$R(\nu_e/\nu_\mu)$
$= (1.0 \pm 0.7(\text{stat.}) \pm 0.3(\text{syst.}))\ \%$
$< 2.0\ \%$ @ 90%C.L.

$$\frac{N(\nu_e)^{Data}/N(\nu_\mu)^{Data}}{N(\nu_e)^{MC}/N(\nu_\mu)^{MC}}$$
$= 0.6 \pm 0.4(\text{stat.}) \pm 0.2\ (\text{syst.})$

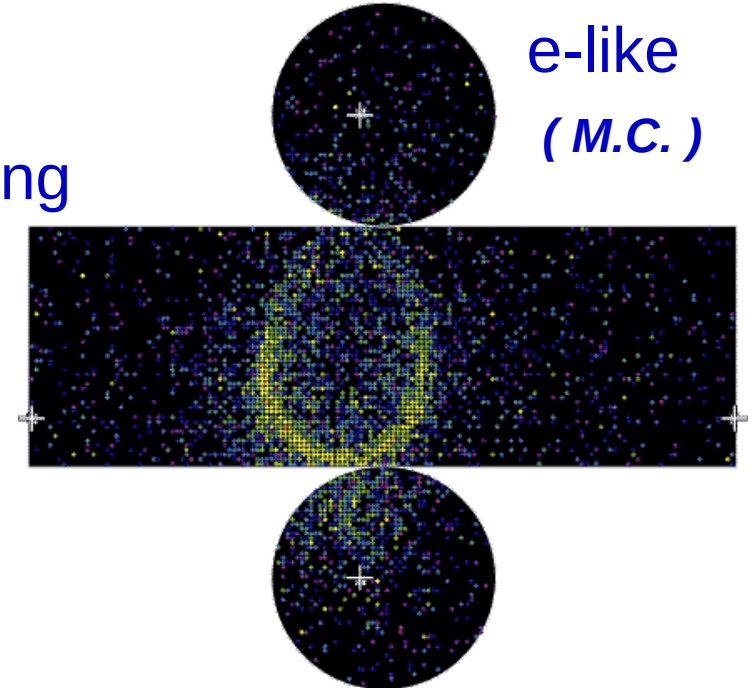
Measured ν_e/ν_μ ratio is consistent with MC expectation

11. T2K ν_e appearance search

Charged current quasi-elastic scattering

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

Observed as single ring e-like event in SK



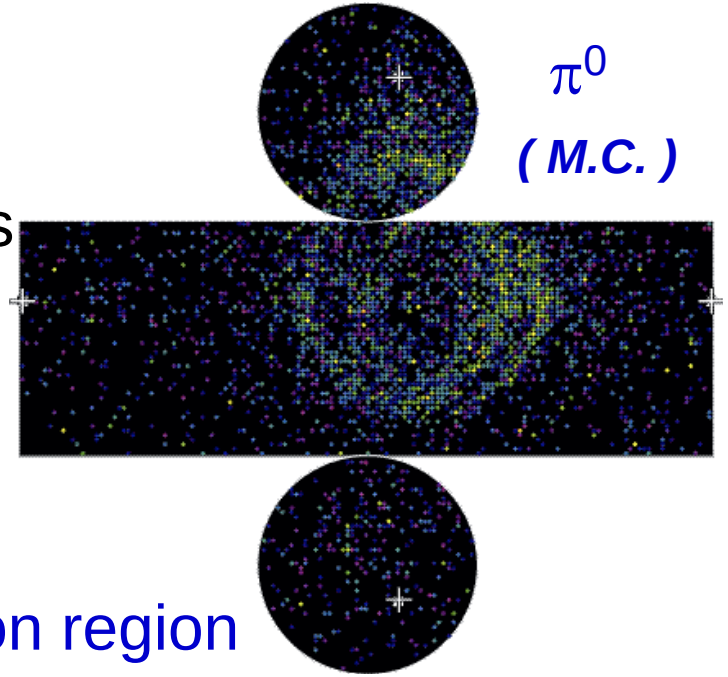
e-like

(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.)

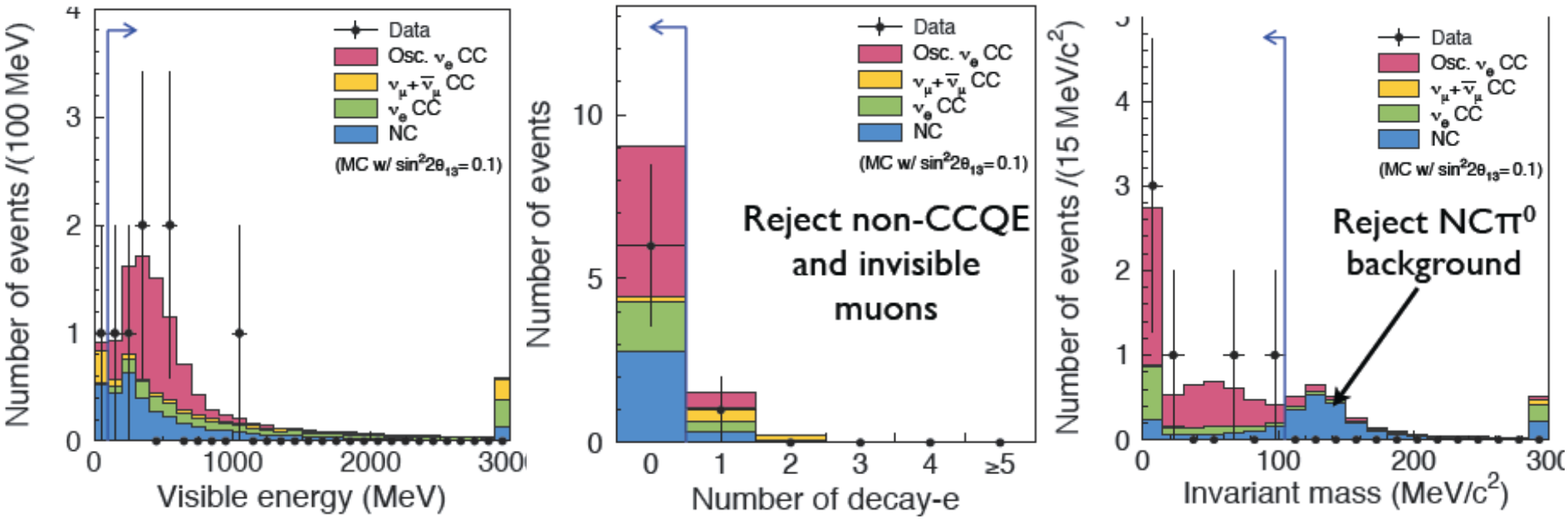
→ Search for the 1 ring e-like events
No decay electrons
not π^0 like (dedicated π^0 rejection)
Reconstructed E_ν is in the oscillation region

11. T2K ν_e appearance search ~ 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 candidate π^0 mass from special tool

< 105 MeV/c^2

Visible energy ***# of decay electrons*** ***π^0 mass***



11. T2K ν_e appearance search ~ event selection in SK

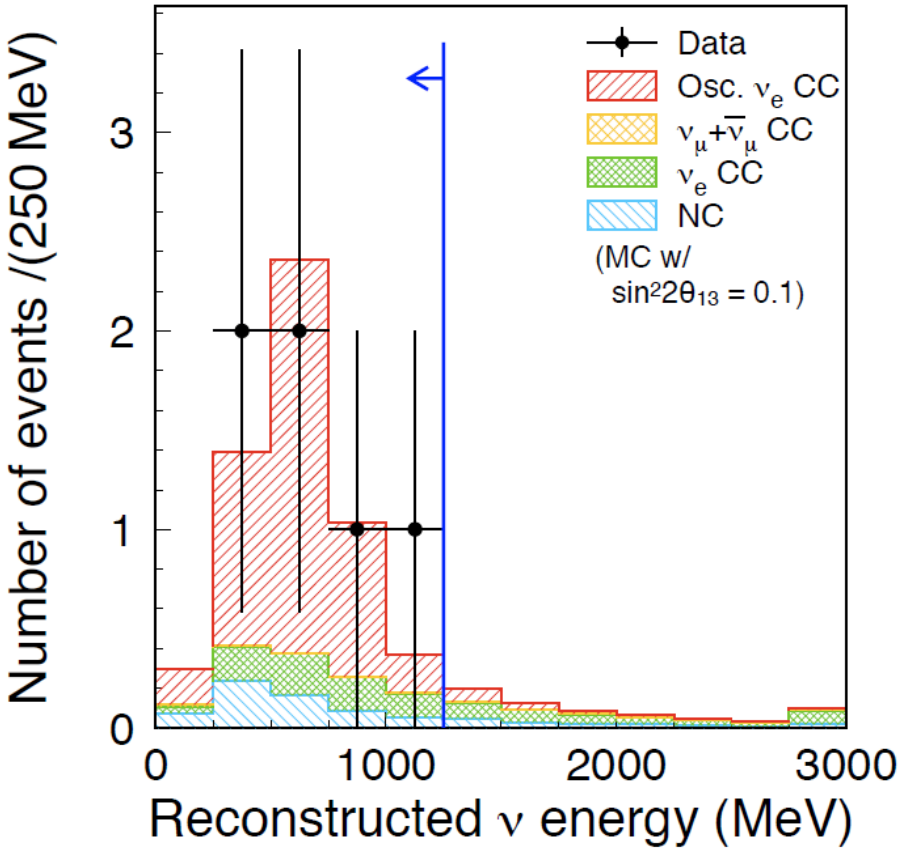
Reconstructed E_ν < 1250 MeV

ν_e appearance signal has peak at the oscillation maximum (~ 600 MeV)

Remove intrinsic beam ν_e in the high energy region

- Signal efficiency 66 %
- Background rejection
  - beam ν_e 77%
  - NC events 99 %

➡ ***6 events passed all the cuts***



11. T2K ν_e appearance search
~ Expected # of candidate events in SK

$$N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$$

$$\frac{\int \Phi^{SK}_{\nu_\mu(\nu_e)}(E_\nu) \cdot P_{osc.}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\; dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\; dE_\nu}$$

Expected # of events estimated by MC

for beam ν_μ, ν_e, $\bar{\nu}_\mu$, and
oscillation signal ($\nu_\mu \rightarrow \nu_e$)

Normalization by measured ND ν_μ event rate

Measurement of the number of inclusive ν_μ charged-current events in ND per p.o.t. using data collected in Run 1 (2.88 x 10^{19} p.o.t.)

Stability of the beam event rate is confirmed by INGRID measurement

INGRID ν int. rate stability Run 1+2 / Run 1 < 1%

11. T2K ν_e appearance search
~ systematic uncertainties

$$N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$$

$$\frac{\int \Phi^{SK}_{\nu_\mu(\nu_e)}(E_\nu) \cdot P_{osc.}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\, dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\, dE_\nu}$$

error source	syst. error
(1) ν flux	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$
(5) Near det. statistics	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$

11. T2K ν_e appearance search

~ Expected # of candidate events in SK

for $\sin^2(2\theta_{13})=0$

The expected number of events with 1.43 x 10^{20} p.o.t.

$$N_{SK}^{\exp} = 1.5 \pm 0.3(syst.) \text{ events}$$

(Δm_{23}^2 =2.4x10^{-3} eV^2, $\sin^2(2\theta_{23})$=1.0, δ_{CP}=0)

	Beam ν_μ CC background	**Beam ν_e CC background**	**NC background**	**Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)**	**Total**
Expected # of events	0.03	0.76	0.61	0.09	1.49

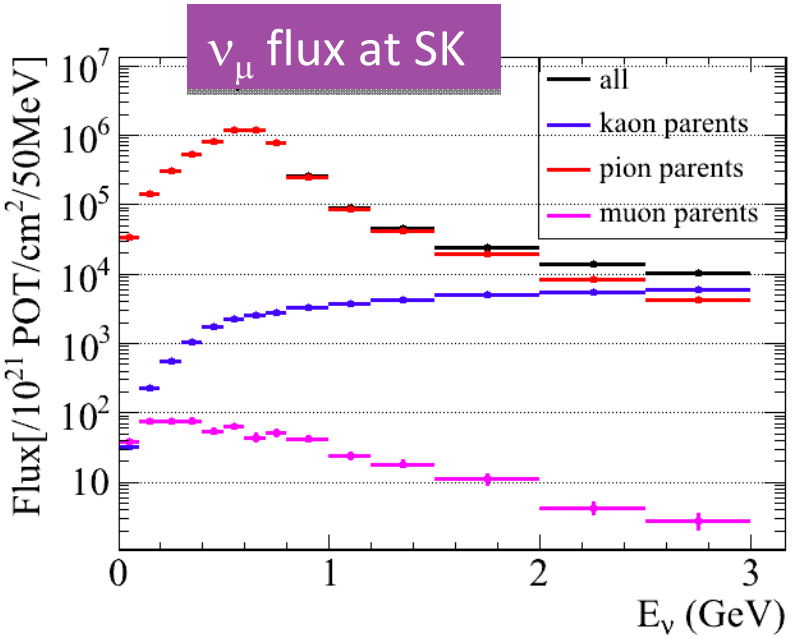
74% of NC background is due to 1π^0 events

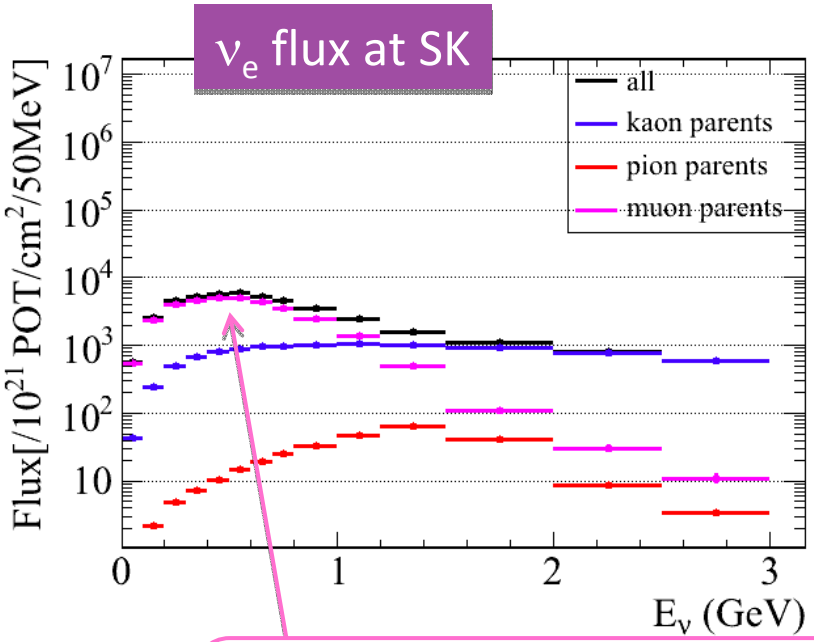
For your reference

$\sin^2 2\theta_{13}$=0.1:

#sig = 4.1 #bkg = 1.3

11. T2K ν_e appearance search
~ beam flux systematic uncertainties





Error source	$R_{ND}^{\mu,\,MC}$	N_{SK}^{MC}	$\frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$
Pion production	5.7%	6.2%	2.5%
Kaon production	10.0%	11.1%	7.6%
Nucleon production	5.9%	6.6%	1.4%
Production x-section	7.7%	6.9%	0.7%
Proton beam position/profile	2.2%	0.0%	2.2%
Beam direction measurement	2.7%	2.0%	0.7%
Target alignment	0.3%	0.0%	0.2%
Horn alignment	0.6%	0.5%	0.1%
Horn abs. current	0.5%	0.7%	0.3%
Total	15.4%	16.1%	8.5%

μ decay is dominated at low E_ν

$$\pi^+ \rightarrow \mu^+ \nu_\mu\,,\ \ \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

→can accurately be predicted by NA61 π measurement

Flux uncertainty is significantly reduced by making the ratio to the ND expectation

11. T2K ν_e appearance search
~ neutrino interactions systematic uncertainties

Main ν interaction in each event category

NC background : NC1π^0
Beam ν_e background : ν_e CCQE
Signal : ν_e CCQE
ND CC event : CCQE(50%)
CC1π(23%)

Assign systematic uncertainties based on the past experiments

Process	Cross section uncertainty relative to the CCQE total x-section
CCQE	energy dependent ($\sim \pm 7\%$ at 500 MeV)
CC 1π	30% ($E_\nu < 2$ GeV) – 20% ($E_\nu > 2$ GeV)
CC coherent π^0	100% (upper limit from [30])
CC other	30% ($E_\nu < 2$ GeV) – 25% ($E_\nu > 2$ GeV)
NC $1\pi^0$	30% ($E_\nu < 1$ GeV) – 20% ($E_\nu > 1$ GeV)
NC coherent π	30%
NC other π	30%
Final State Int.	energy dependent ($\sim \pm 10\%$ at 500 MeV)

Uncertainty of $\sigma(\nu_e)/\sigma(\nu_\mu) = \pm 6\%$

Estimated systematic error on the expected # of events in SK

Error source	syst. error on N_{SK}^{exp}
CC QE shape	3.1%
CC 1π	2.2%
CC Coherentπ	3.1%
CC Other	4.4%
NC $1\pi^0$	5.3%
NC Coherentπ	2.3%
NC Other	2.3%
$\sigma(\nu_e)$	3.4%
FSI	10.1%
Total	14.0%

11. T2K ν_e appearance search

~ systematic uncertainties in SK event selection

Error source	$\frac{\delta N^{MC}_{SK\ \nu_e\ sig.}}{N^{MC}_{SK\ \nu_e\ sig.}}$	$\frac{\delta N^{MC}_{SK\ bkg.\ tot.}}{N^{MC}_{SK\ bkg.\ tot.}}$
π^0 rejection	-	3.6%
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass cut	5.1%	8.7%
Fiducial volume cut etc.	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay electron finding	0.1%	0.3%
Muon PID	-	1.0%
Total	**7.6%**	**15%**

11. T2K ν_e appearance search
~ Oscillation analysis results

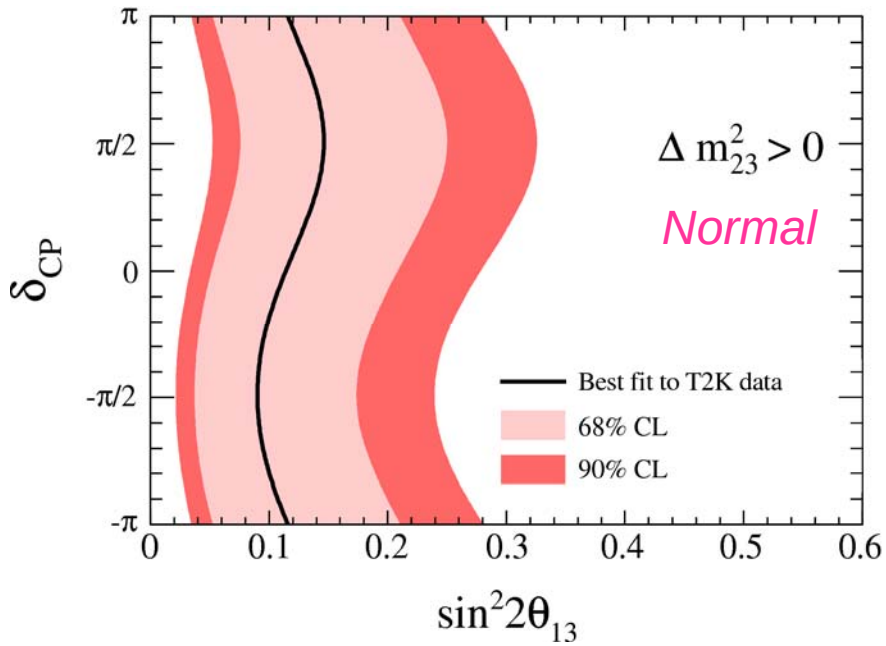
6 events obs. , exp'd 1.5 $\pm$0.3 (syst.) events for $\sin^2(2\theta_{13}) = 0$

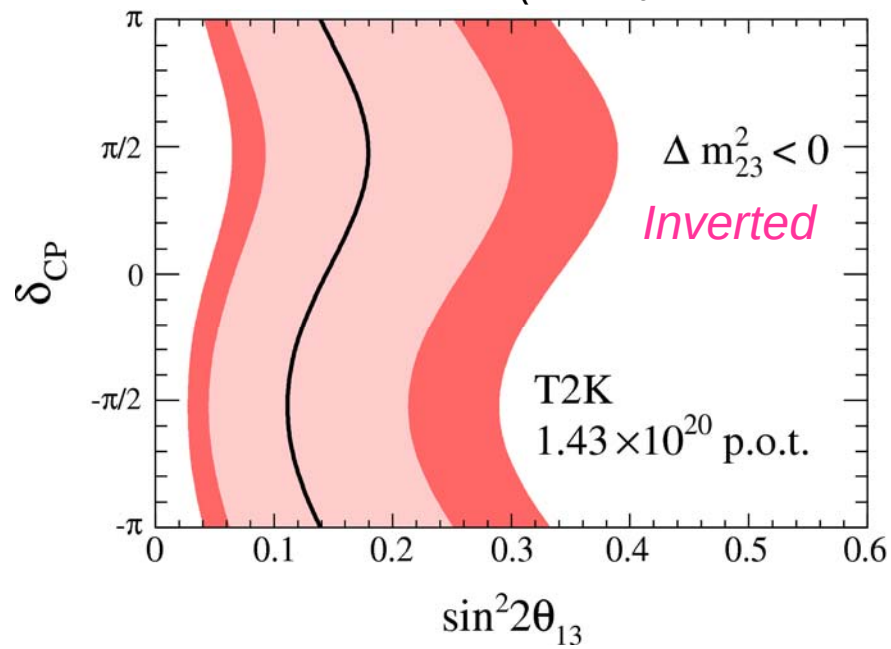
p-value = 0.7% and excluding θ_{13}=0 at 2.5σ significance

1-dimensional $\sin^2 2\theta_{13}$ limit for each δ_{CP}

Feldman-Cousins method was used for constructing confidence intervals

(Δm^2_{23}=2.4 x 10^{-3} eV^2)





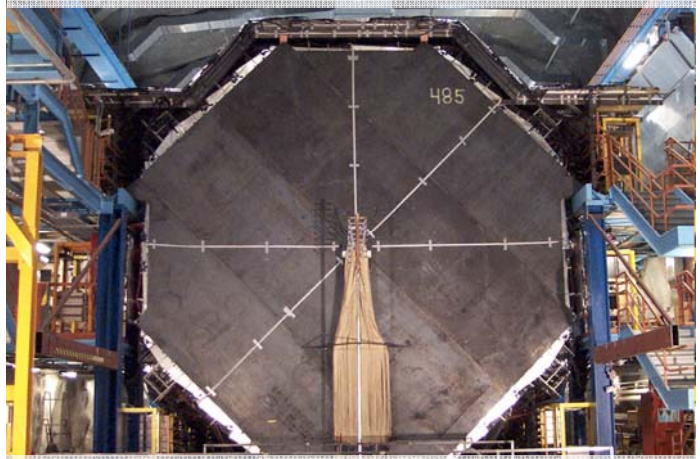
90% C.L. interval and best fit (for Δm^2_{23}=2.4 x 10^{-3} eV^2, δ_{CP}=0)

$0.03 < \sin^2 2\theta_{13} < 0.28$ $\qquad$ $0.04 < \sin^2 2\theta_{13} < 0.34$

Central value : $\sin^2 2\theta_{13}$ =0.11 $\qquad$ Central value : $\sin^2 2\theta_{13}$ =0.14

12. The MINOS experiment ~ From FNAL to Soudan

Far detector @735km

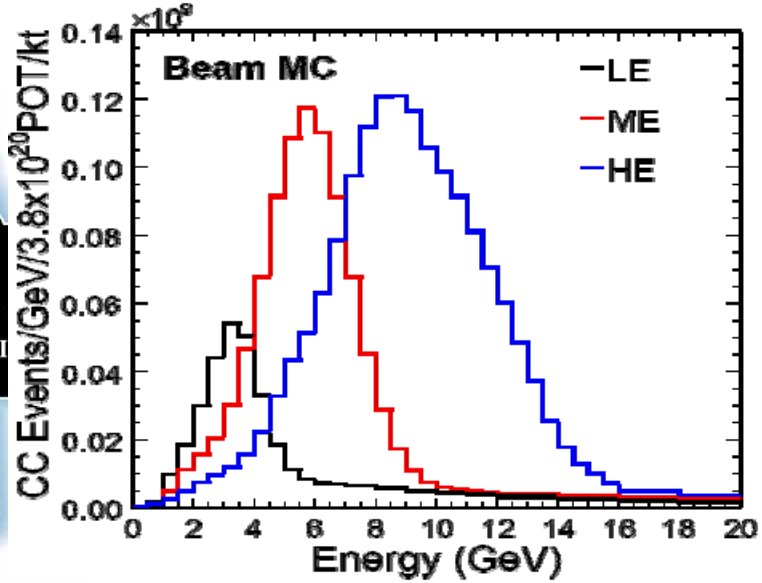


700m under the ground

5.4kt (8m tall), 486 planes

On axis neutrino beam

120GeV proton from Main Injector



Near and Far detectors

Tracking sampling calorimeters

Scintillator + Fe sandwich

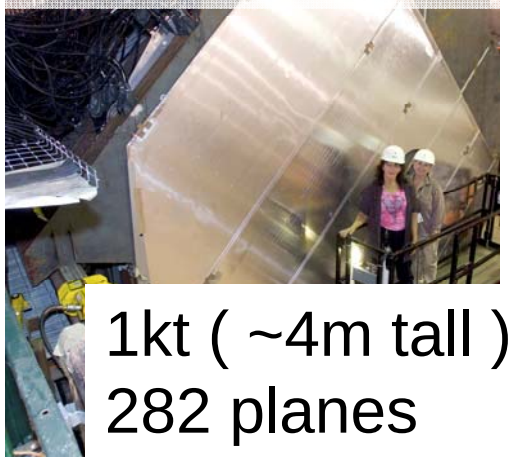
Magnetized (1.3 T)

Momentum measurements

Use curvature or range

Charge identification

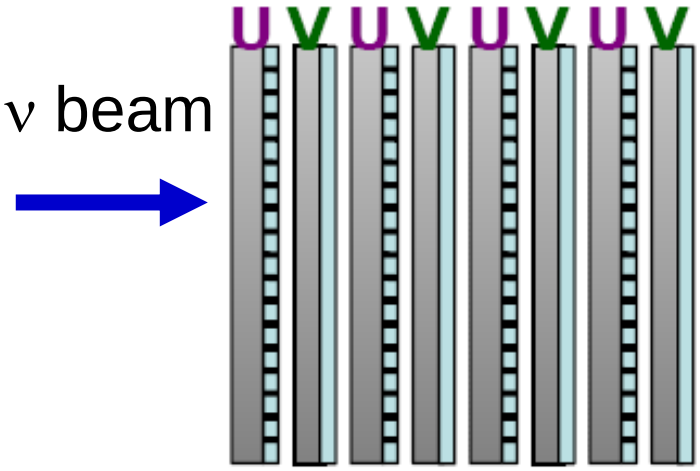
Near detector @1km

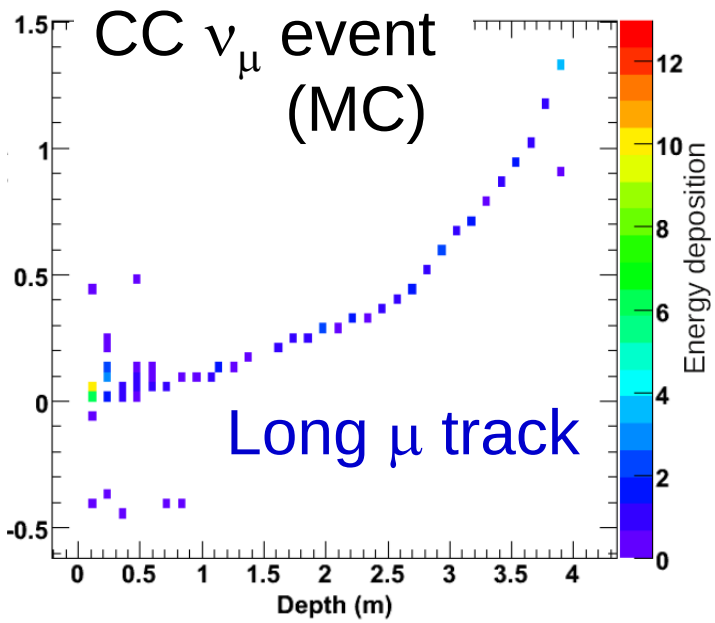


1kt (~4m tall)

282 planes

12. The MINOS experiment ~ ν_e appearance search





Signal event selection cuts

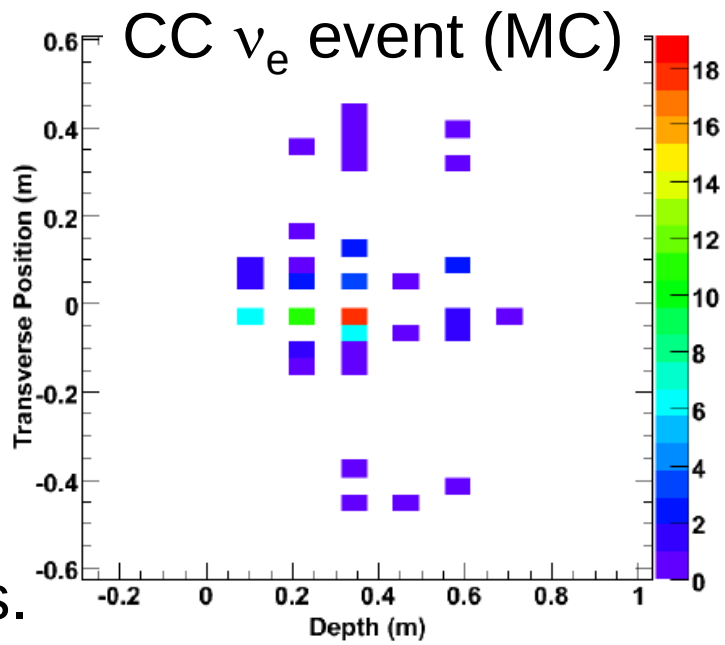
1) No long tracks
2) At least one well-formed shower
3) Visible energy 1 ~ 8 GeV

➡ NC + signal events remain

➡ ***Library event matching (LEM)***

Find best matches from a library of MC events.

Judge how signal-like an event is based on those best matches.



12. The MINOS experiment ~ ν_e appearance search

- Fraction of ν_e CC matches

  How many of the best matches are signal?

- Mean matched charge fraction

  How well do the charges overlap between the input event and the best match?

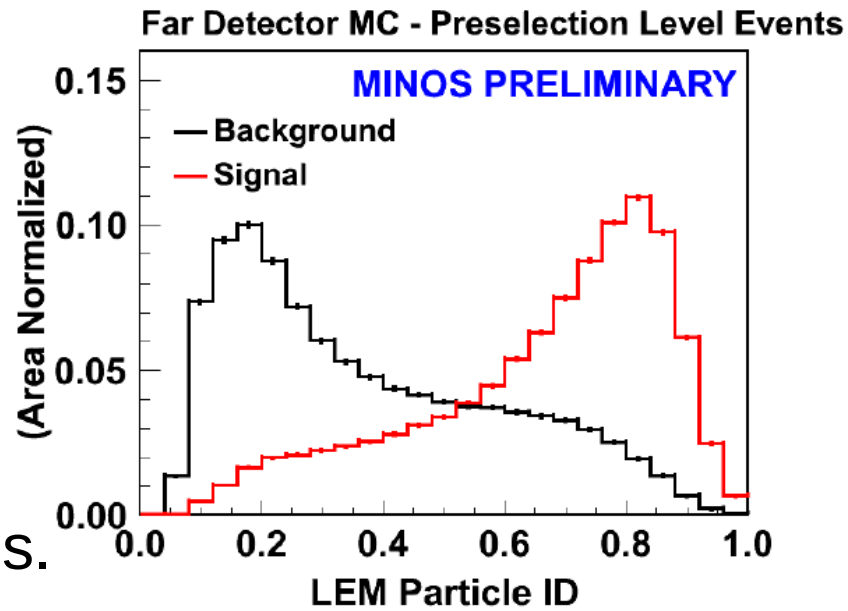
- Mean y for ν_e CC matches

  (y = fraction of n energy in the hadronic shower)

  How EM-like is the shower in the best matches?

- Reconstructed energy

→ Feed to a neural net to calculate PID parameter



Background was estimated using the near detector data with various beam configurations.

12. The MINOS experiment ~ ν_e appearance search

Expected # of events
for 8.2×10^{20} POT

Component	# Events
NC	34
ν_μ CC	7
beam ν_e CC	6
ν_τ CC	2
Total Bkgd	**49**

$\delta=0$

$\Delta m^2 = 2.32\times10^{-3}\ eV^2$

$\theta_{23} = \pi/4$

Sources
of the systematic uncertainties

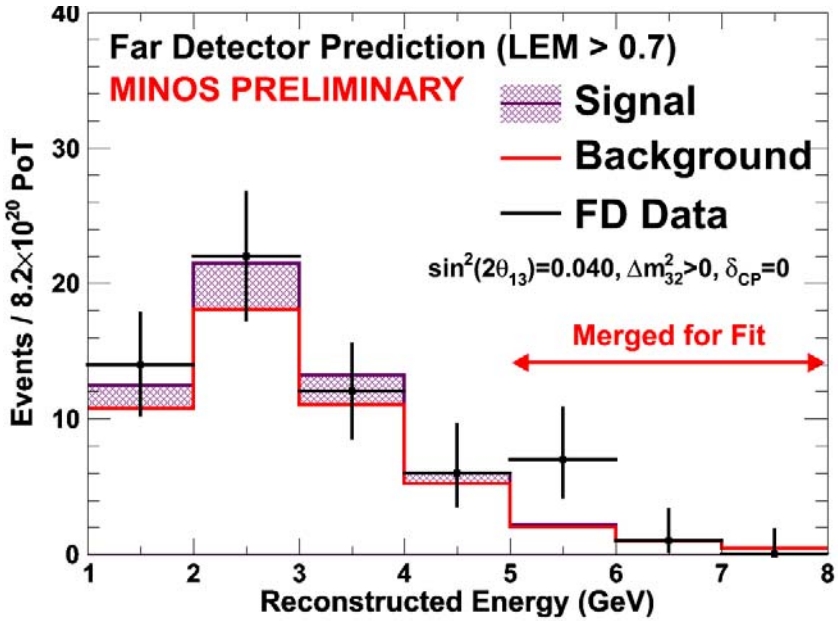
Composition of
the near detector background

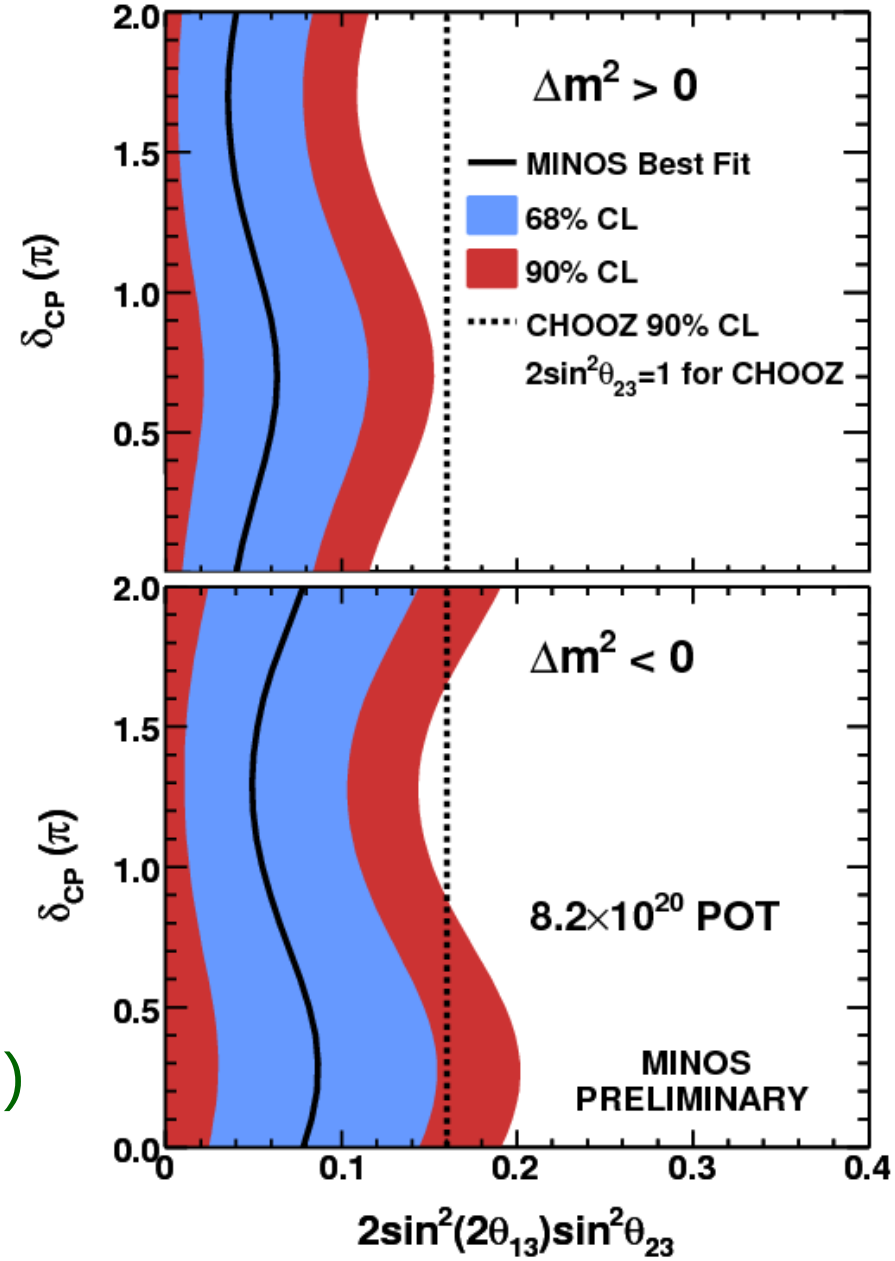
Far to Near ratio

- Calibrations
- Relative normalizations
- Hadronization model

Systematic Uncertainty 5.7%
On the background prediction in the signal-enhanced region (LEM>0.7)

12. The MINOS experiment ~ ν_e appearance search





Expected background events:

49.5 + 2.8 (syst) + 7.0 (stat)

Observed events in FD data : 62

⇨ $2\sin^2 2\theta_{13} \cdot \sin^2\theta_{23}$

Normal : 0 to 0.12

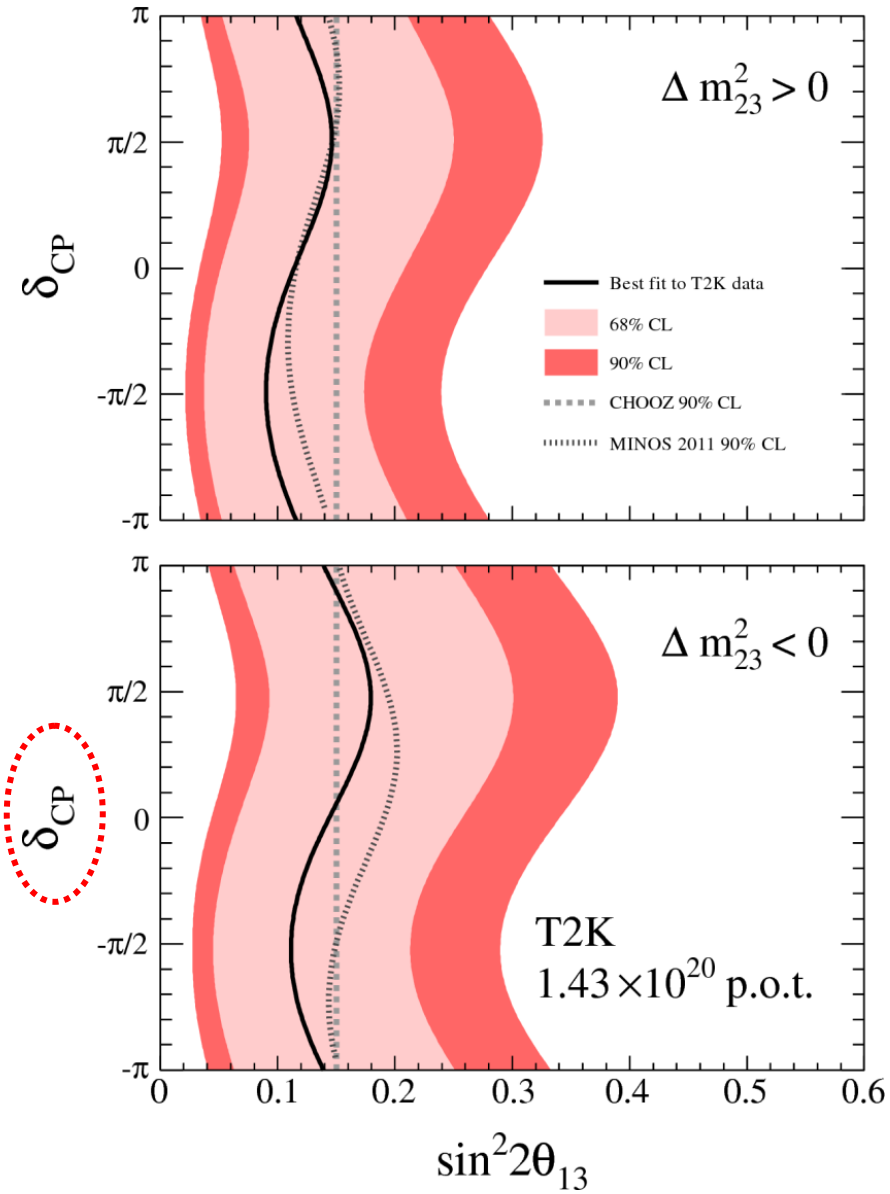
(central = 0.04),

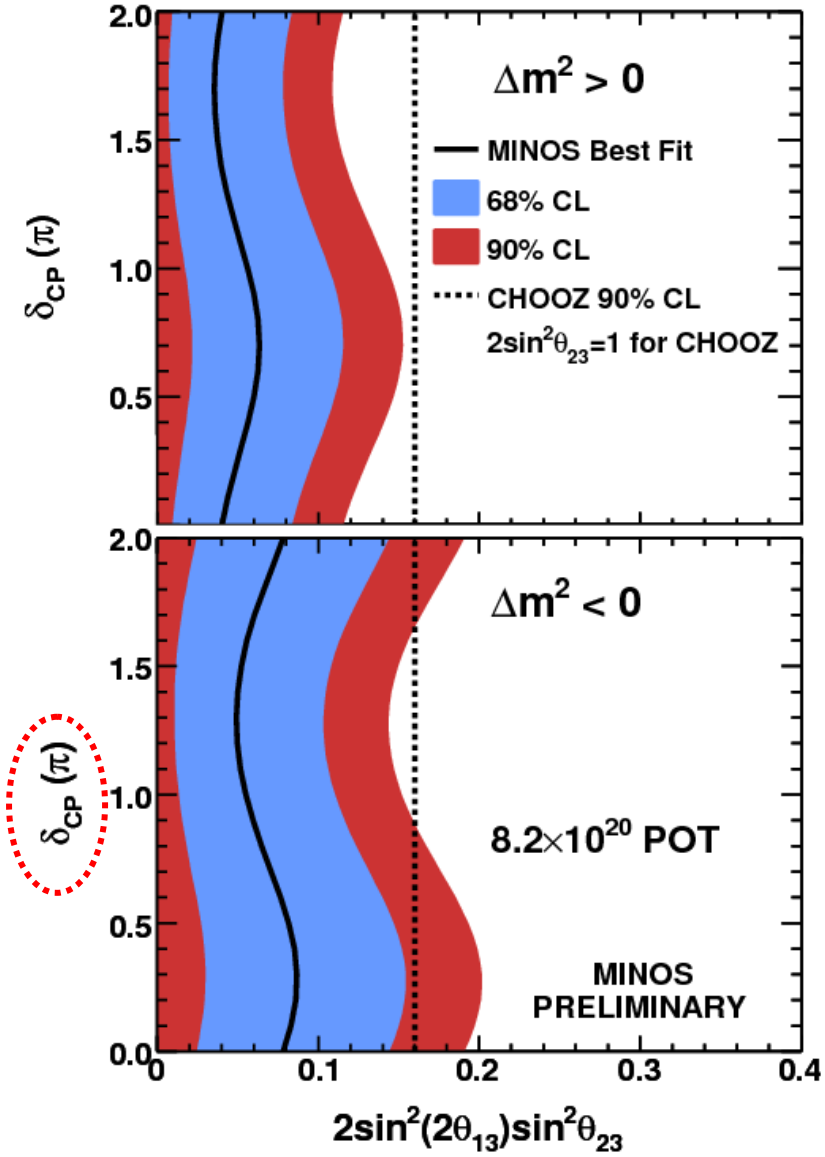
Inverted : 0 to 0.19 (inverted)

(central = 0.08)

Exclude θ_{13}= 0 at 89% CL

13. θ_{13} measurements with ν_e appearance search
~ T2K results comparison with MINOS results





14. Summary and prospects of θ_{13} measurements in T2K

1) Currently limited by statistics
   Only 2% of POT of final design goal was accumulated.

2) Event counting analysis has been performed
   Expected to be improved
   using the observed reconstructed E_ν spectrum

3) Beam systematic error reductions
   More extensive use of NA61 data (Kaon)

4) Neutrino systematic error reductions
   More extensive use of the data
   from various experiments
   including the T2K-ND280, MINERνA etc.

5) SK-detector related systematic error reductions
   Similar method of NC π^0 with the other control samples
   using the atmospheric ν data

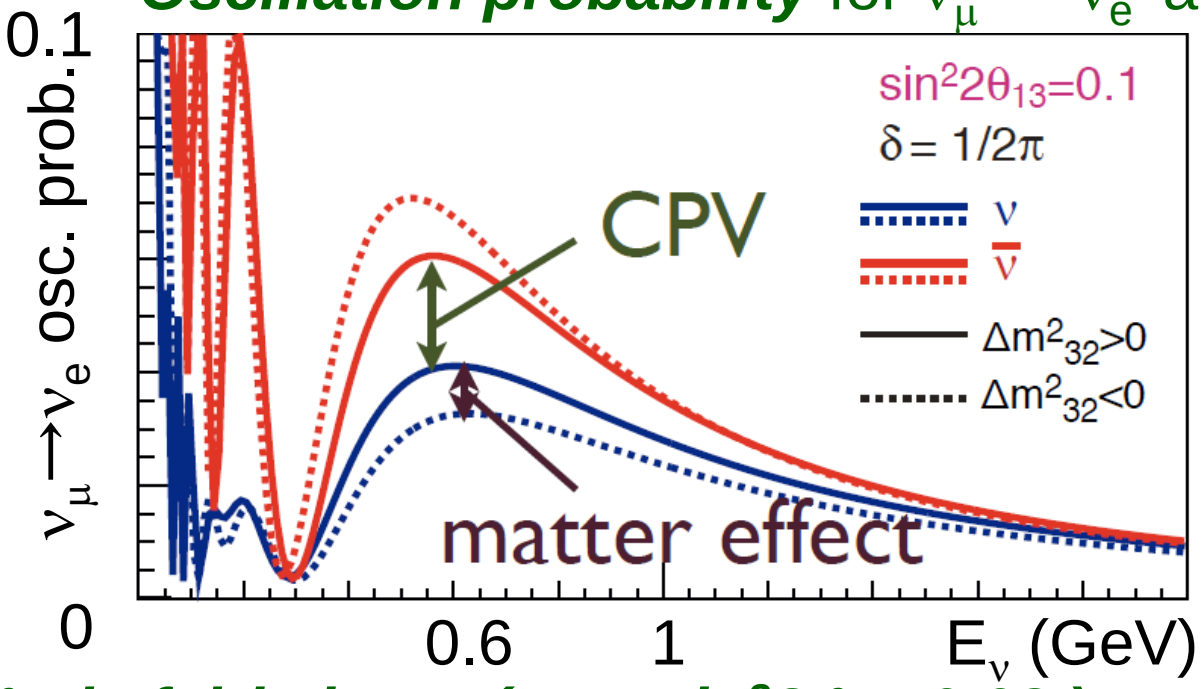
15. *CP parameter measurements*

*in the **next generation experiments***

CP violation term in the oscillation probability $\propto$ $\sin\theta_{13}\sin\delta$

(sign of δ flips for anti neutrino)

Oscillation probability for $\nu_\mu \rightarrow \nu_e$ at 295km



$\Delta m^2_{21}=7.6\times10^{-5}\mathrm{eV}^2$

$|\Delta m^2_{32}|=2.4\times10^{-3}\mathrm{eV}^2$

$\sin^2\theta_{12}=0.31$

$\sin^2\theta_{23}=0.5$

$\rho=2.6\mathrm{g/cm}^3$

If $\sin^2 2\theta_{13}$ is fairly large (e.g. $\sin^2 2\theta_{13}>0.03$).

measurement of δ will be possible

with intense beam and well-designed detectors.

Of course, we must reduce various systematic uncertainties.