Observation of muon neutrino to electron neutrino transformation in the T2K experiment

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INR RAS

INR seminar, 22 July 2013 г.

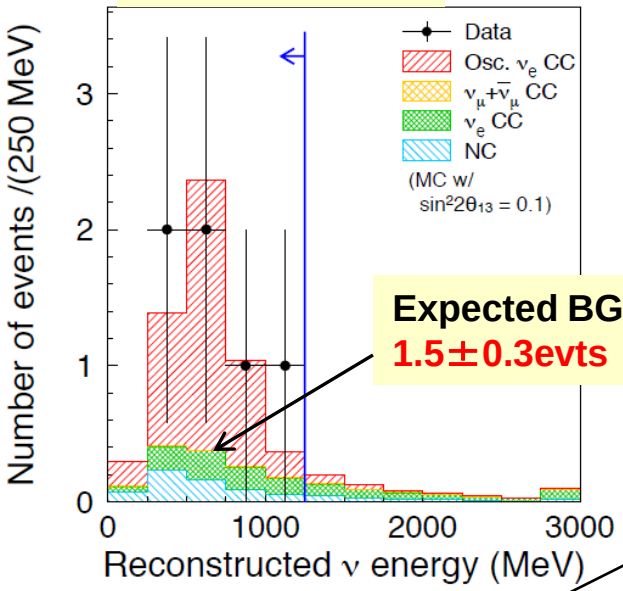
Outline

- neutrino mixing
- T2K experiment
- ν_e appearance
- perspectives
- summary

First T2K result

published in June 2011

6 ν_e events



Expected BG
1.5±0.3evts

1.43x10^{20} POT
January 2010 –
March 2011

About two years ago, T2K published FIRST clear indication of electron neutrino appearance ($\theta_{13} \neq 0$)

PRL 107, 041801 (2011) | Selected for a Viewpoint in *Physics* | PHYSICAL REVIEW LETTERS | week ending 22 JULY 2011

Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam

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The T2K experiment observes indications of $\nu_\mu \rightarrow \nu_e$ appearance in data accumulated with 1.43×10^{20} protons on target. Six events pass all selection criteria at the far detector. In a three-flavor neutrino oscillation scenario with $|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$ and $\sin^2 2\theta_{13} = 0$, the expected number of such events is 1.5 ± 0.3(syst). Under this hypothesis, the probability to observe six or more candidate events is 7×10^{-3}, equivalent to 2.5σ significance. At 90% C.L., the data are consistent with $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ for $\delta_{CP} = 0$ and a normal (inverted) hierarchy.

DOI: 10.1103/PhysRevLett.107.041801 PACS numbers: 14.60.Pq, 13.15.+g, 25.30.Pt, 95.55.Vj

Then,

1 - Confirmation from MINOS

2 - Precise measurements by

Double Chooz

Daya Bay

RENO

ν oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

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

by Summer 2013

atmospheric

solar

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix} \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

link between atmospheric and solar

***U* parameterization:** three mixing angles θ_{12} θ_{23} θ_{13} and CP violating phase δ

$$\Delta m^2_{ij} = m^2_i - m^2_j \qquad \Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$$

two independent Δm^2

$$\Delta m^2_{12} = \Delta m^2_{sol} \approx 7.5\times 10^{-5}\,\mathrm{eV}^2 \qquad \Delta m^2_{23} \cong \Delta m^2_{31} = \Delta m^2_{atm} \approx 2.4\times 10^{-3}\,eV^2$$

$\theta_{12}= (34+-1)^0$ $\theta_{23}\sim 45^0$ $\theta_{13} = (9+-0.6)^0$

?? MH and δ ??

$\nu_\mu \to \nu_e$ in matter

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E_\nu} \times \left[1 + \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right] \\
&+ 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu} \\
&- 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu} \\
&+ 4s_{12}^2 c_{13}^2(c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\frac{\Delta m_{12}^2 L}{4E_\nu} \\
&- 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E_\nu}\frac{aL}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}(1 - 2s_{13}^2), \qquad (30)
\end{aligned}
$$

→ θ_{13}

→ CP-even

→ CP-odd

→ Solar

→ Matter

$$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij} \qquad a\left[eV^2\right] = 2\sqrt{2}G_F n_e E_\nu = 7.6\times10^{-5}\rho\left[g/cm^3\right]E_\nu\left[GeV\right]$$

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ ⇒ $a \to -a \qquad \delta \to -\delta$

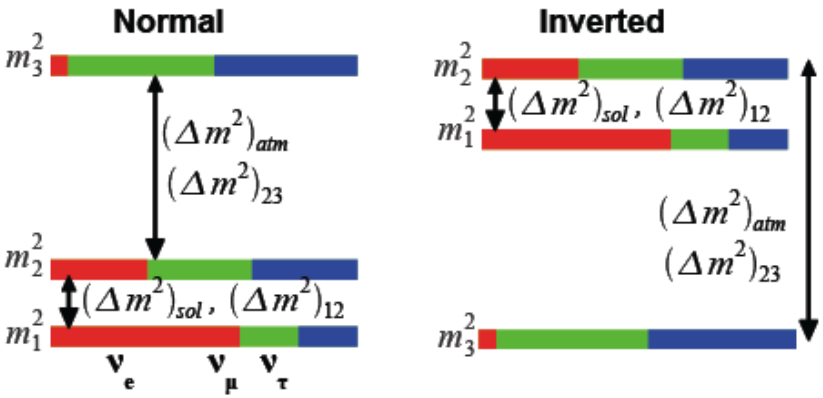
change sign for NH → IH

Physics motivation

Discovery of $\nu_\mu \rightarrow \nu_e$:

- direct detection of neutrino flavor mixing in "appearance" mode
- fundamental role of $\nu_\mu \rightarrow \nu_e$ in measurement of mass hierarchy and CP violation in lepton sector

Mass Hierarchy



CP violation

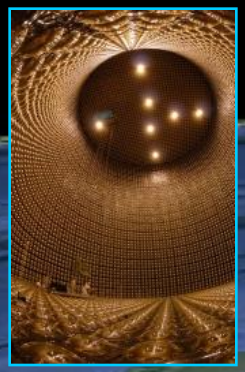
$$J_{CP} = Im(U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}) = Im(U_{e2}U_{\mu 3}U^*_{e3}U^*_{\mu 2})$$
$$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta$$

all mixing angles $\neq 0 \rightarrow$ $J_{CP} \neq 0$ if $\delta \neq 0$

Quark sector $J_{CP} \approx 3\times10^{-5}$

Lepton sector $J_{CP} \sim 0.02\times\sin\delta$

Long-Baseline Neutrino Oscillation Experiment



SuperKamiokande

Toyama

Kamioka Mine

JPARC

Tokai

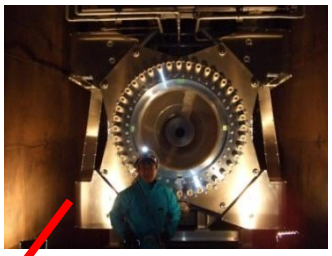
Токио

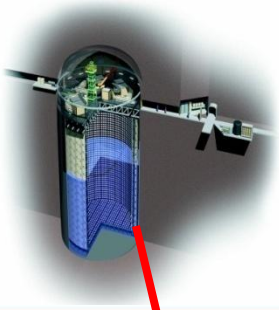
Tokyo/Narita Airport

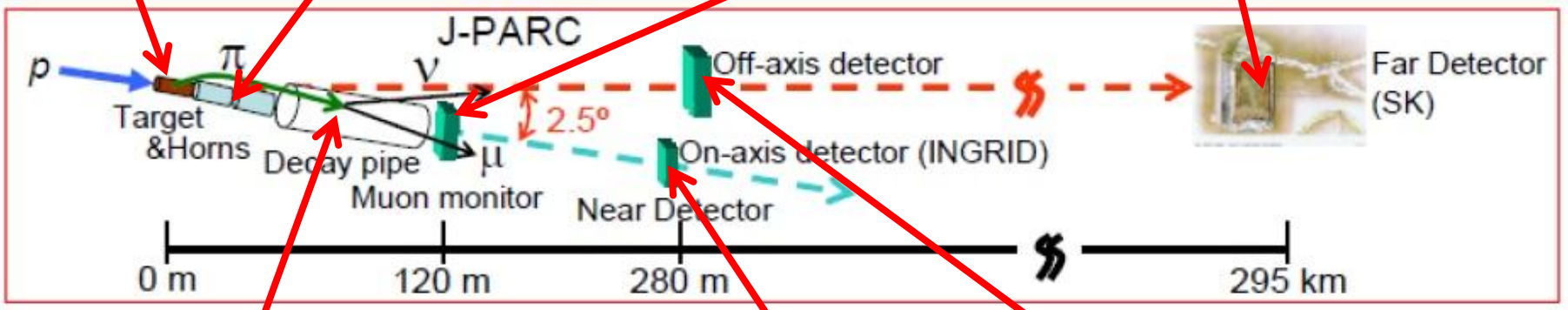
JAPAN

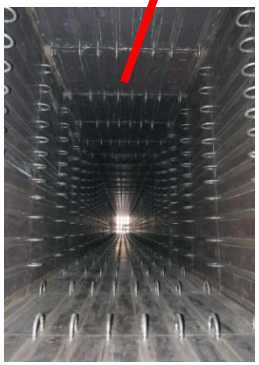
~ 500 members
59 institutions
11 countries

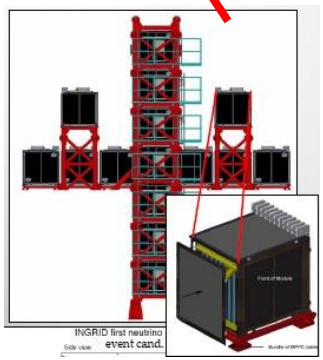
T2K layout

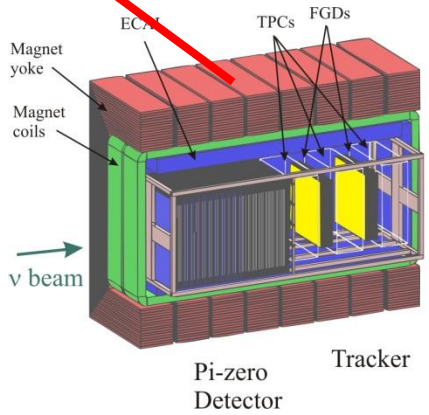




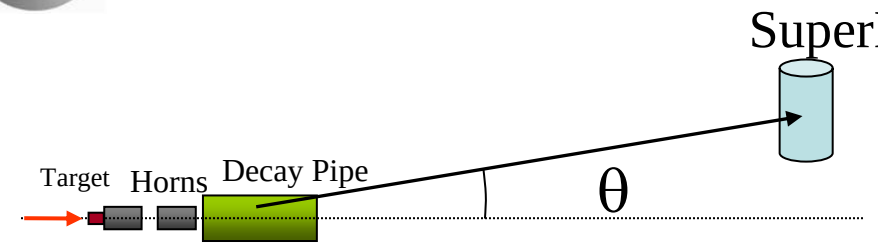

J-PARC
p
π
ν
Target
&Horns
Decay pipe
μ
Muon monitor
2.5°
Off-axis detector
On-axis detector (INGRID)
Near Detector
Far Detector
(SK)
0 m
120 m
280 m
295 km

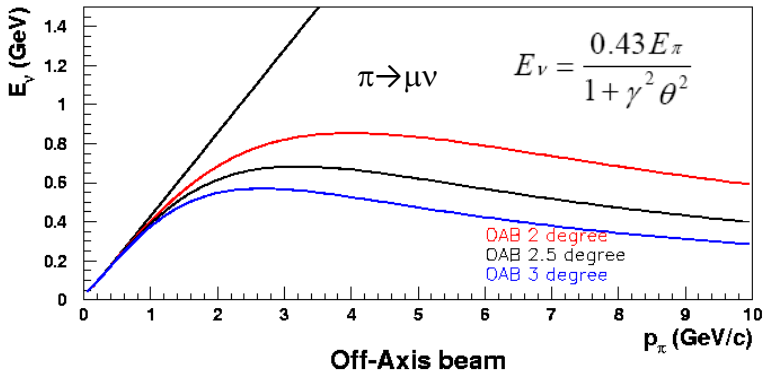




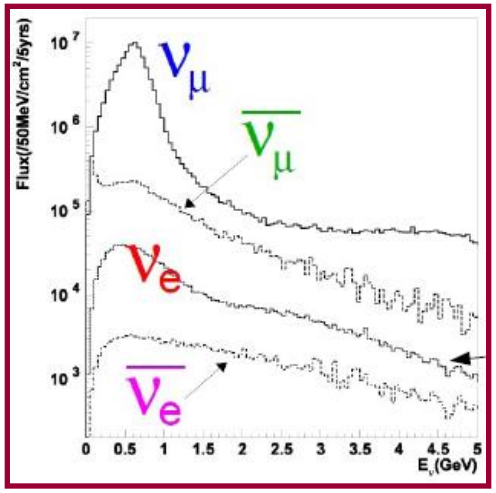

ECAL
TPCs
FGDs
Magnet
yoke
Magnet
coils
ν beam
Pi-zero
Detector
Tracker

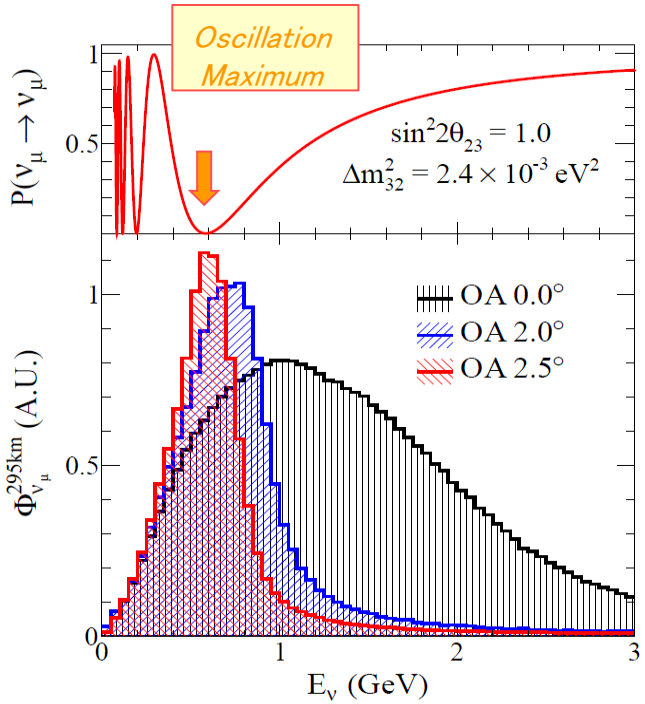
T2K off-axis ν beam





Off-Axis beam



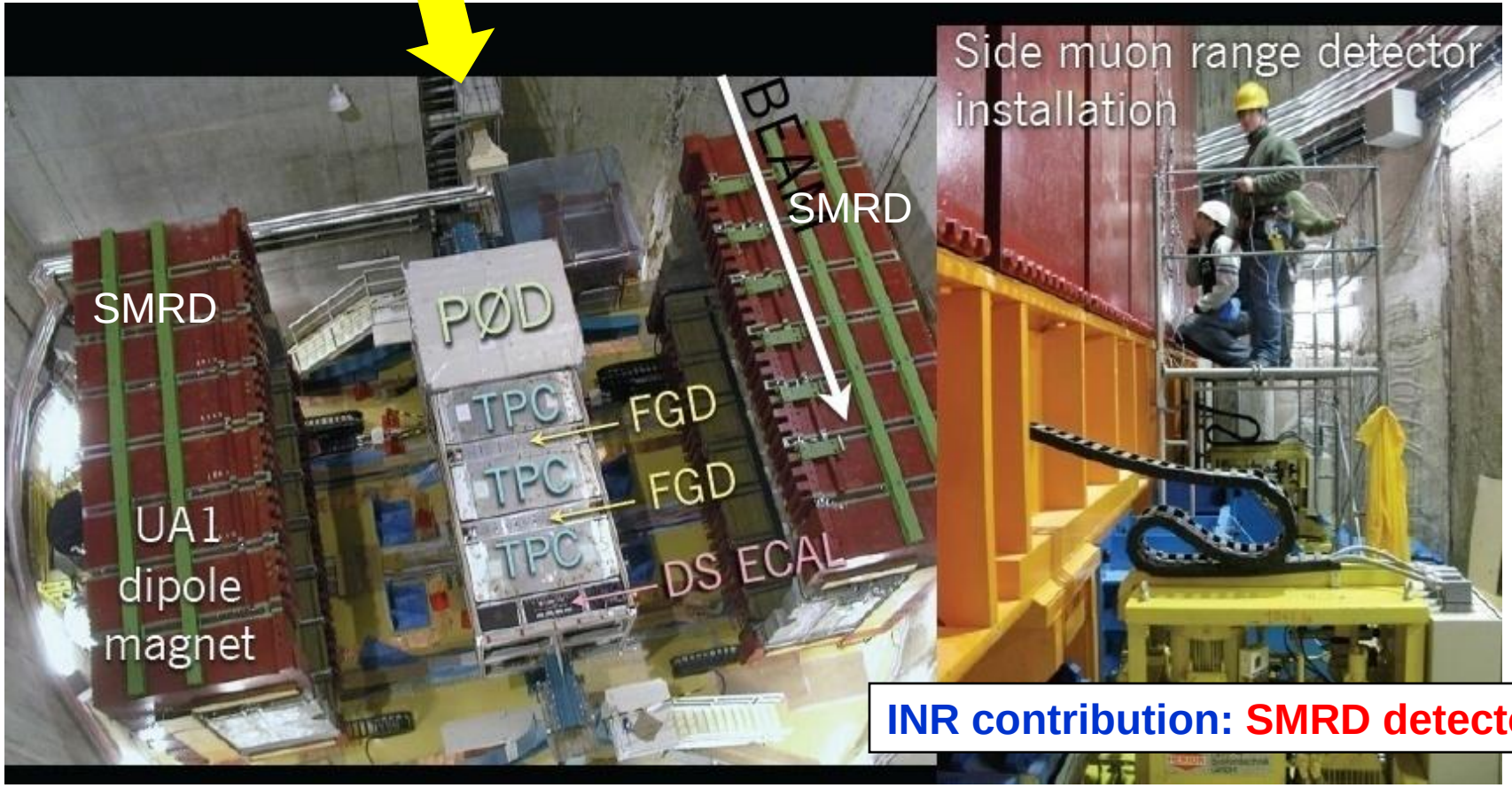


- 750 (now 235) kW 30 GeV proton beam at JPARC
- Quasi-monochromatic ν_μ (95%) beam
- Peak energy ~700 MeV tuned to oscillation maximum
- ~0.5% ν_e at peak energy
- Reduced high energy tail → reduces background

Off-axis near detector (ND280)

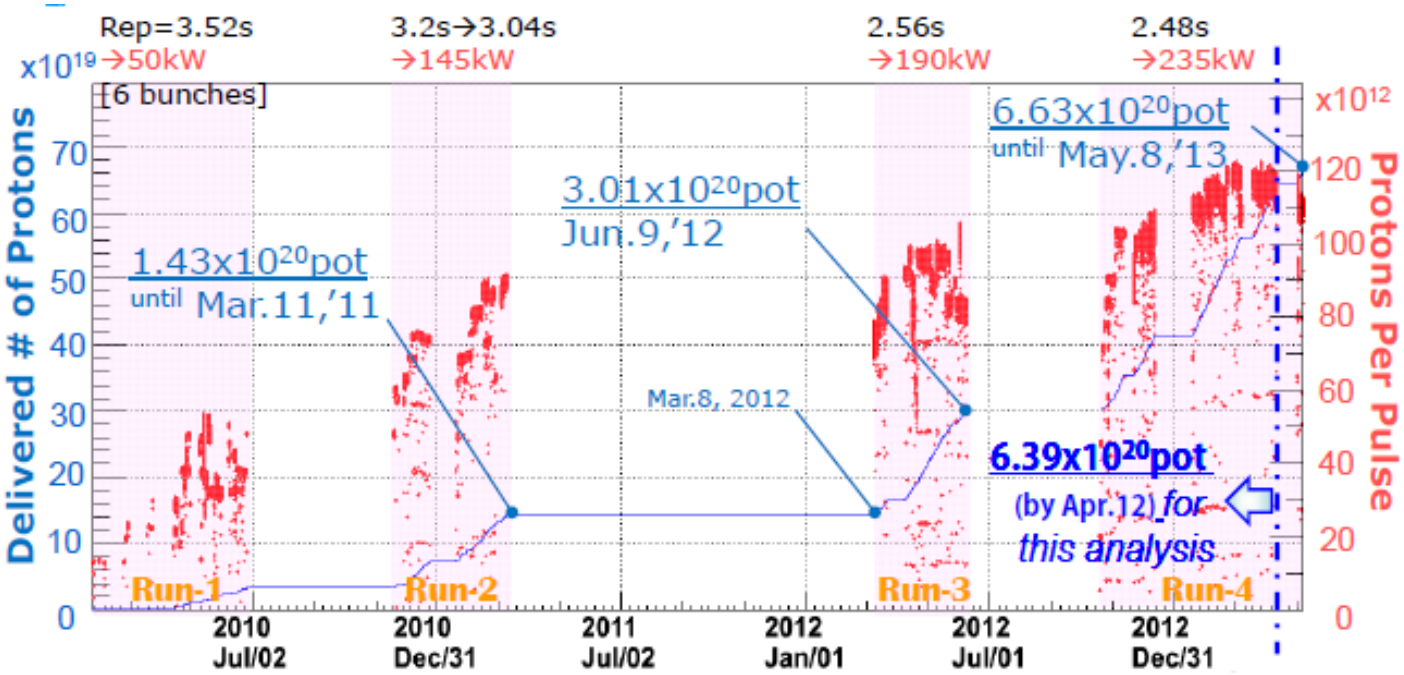
Measurement of unoscillated ν beam
Composition
Normalization
Cross section measurements

ν beam



INR contribution: SMRD detector

Delivered protons on T2K target (pot)



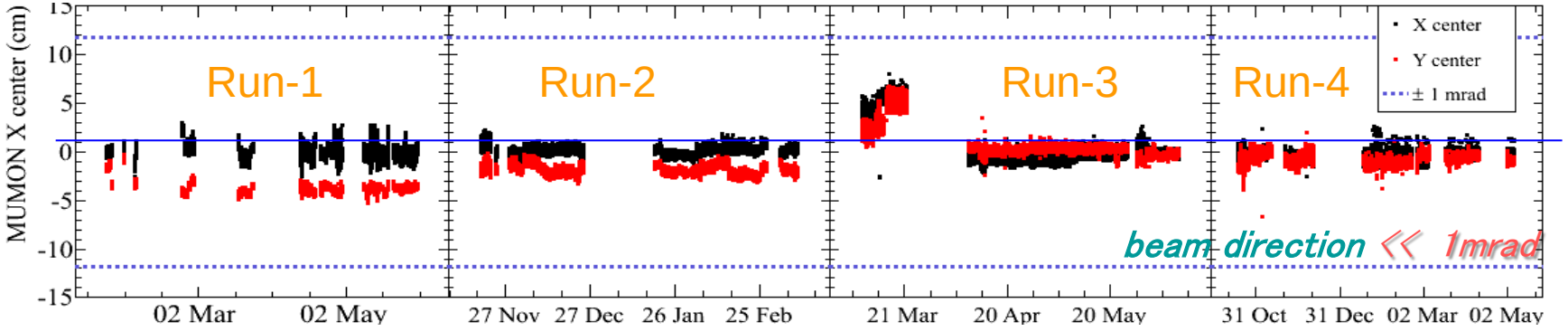
- proton beam power : 235 kW reached (stable operation 220 kW)
- # of protons per pulse > 1.2×10^{14}

6.39×10^{20} pot used for this analysis (~ 8% of all pot expected for T2K)

Neutrino beam

Muon monitors

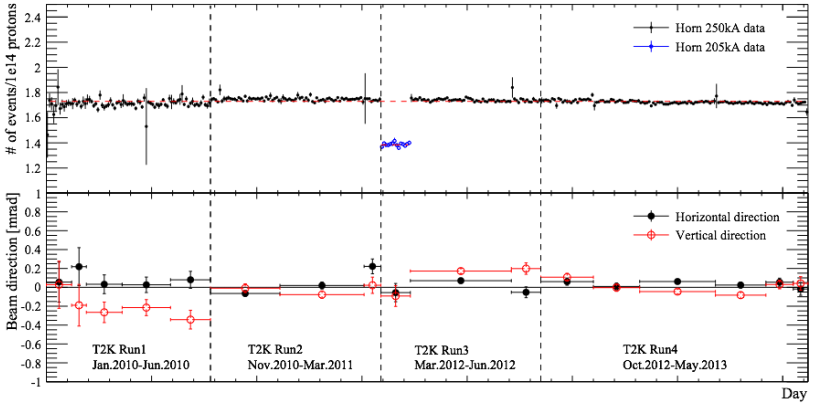
- Pulse-by-pulse monitoring of the beam center by muon monitors
- 1 mrad shift of direction → ~2% shift of neutrino peak energy



INGRID

beam direction << 1mrad

stable interaction rate within 0.7%



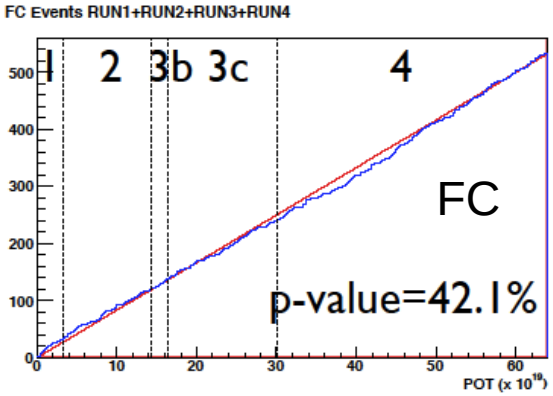
T2K events at SK

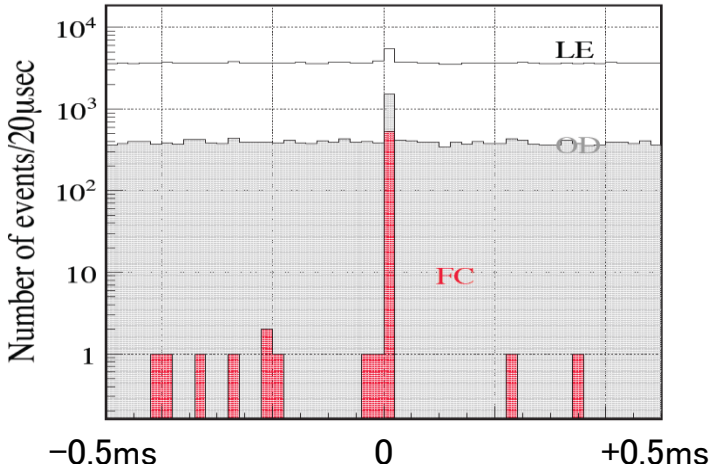
6.39x10^{20} pot (Run 1-4):

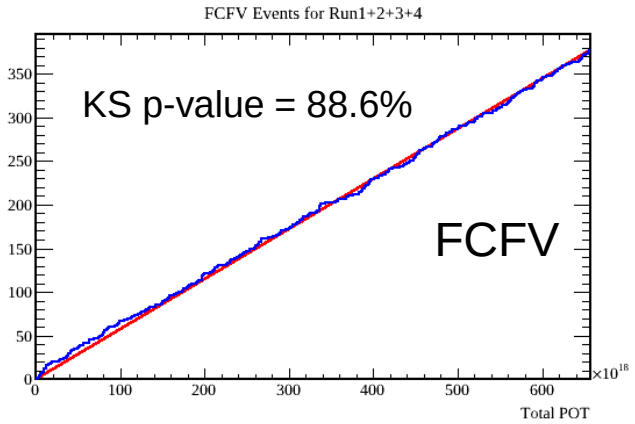
532 Fully Contained (FC) events

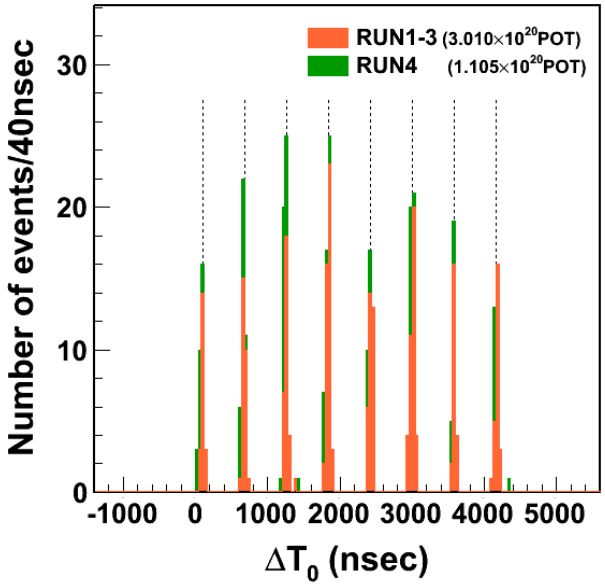
363 in Fiducial Volume (FCFV)

Expected Bkg: 0.07 (FV 0.008)





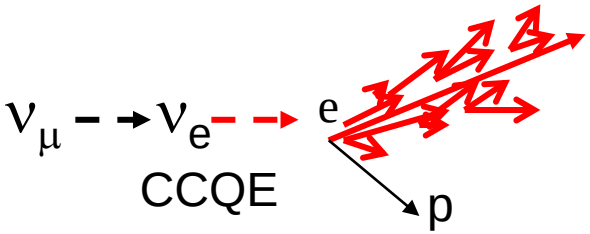


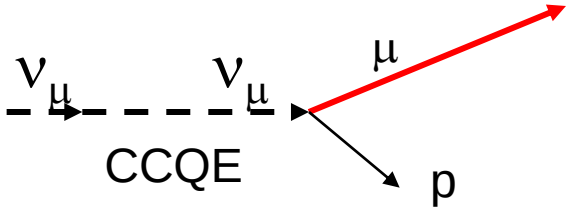


ν_μ/ν_e events

Signals and Backgrounds

SIGNALS





electrons

EM shower
Multiple Scattering
→ Ring has "fuzzy" edge
electron is relativistic
→ Opening angle is maximal

muons

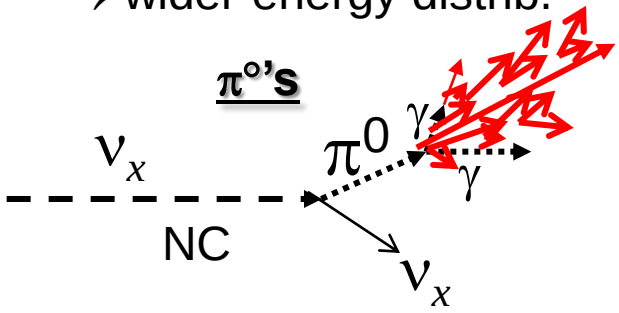
Low Scattering
→ Ring has sharp edge

BKG

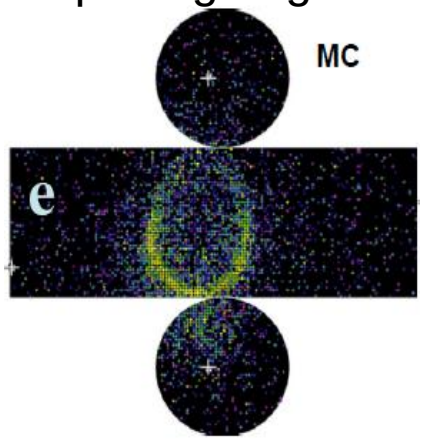
electrons

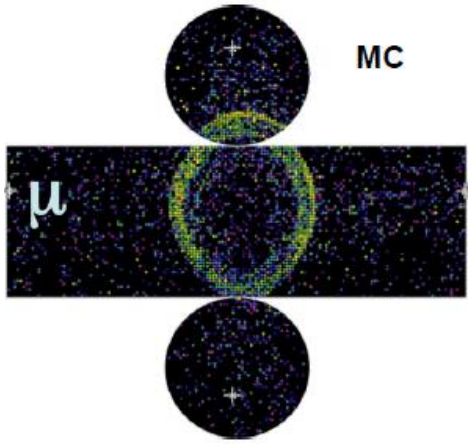
Beam intrinsic ν_e (<1%)
→ wider energy distrib.

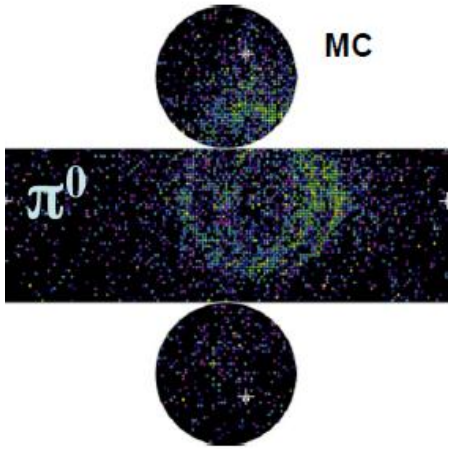
π°'s



EM showers of γ's from π° can fake an electron





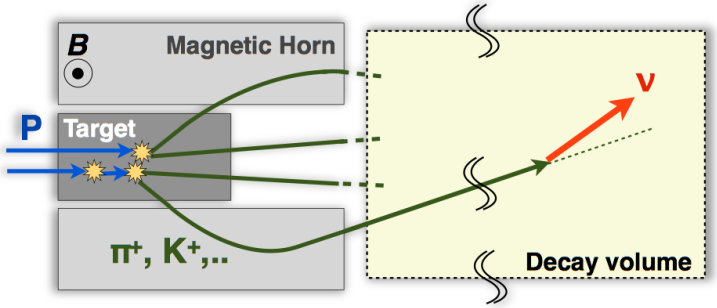


Monte-Carlo prediction

Interaction of primary beam in the target [FLUKA2008.3d]

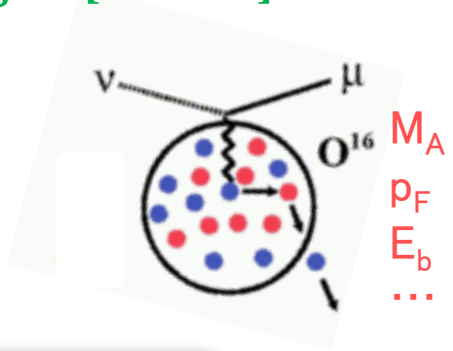
π/ K production (Mainly CERN NA61)

Neutrino-Nucleus interactions in a few GeV region [NEUT]



ν flux

ν cross section



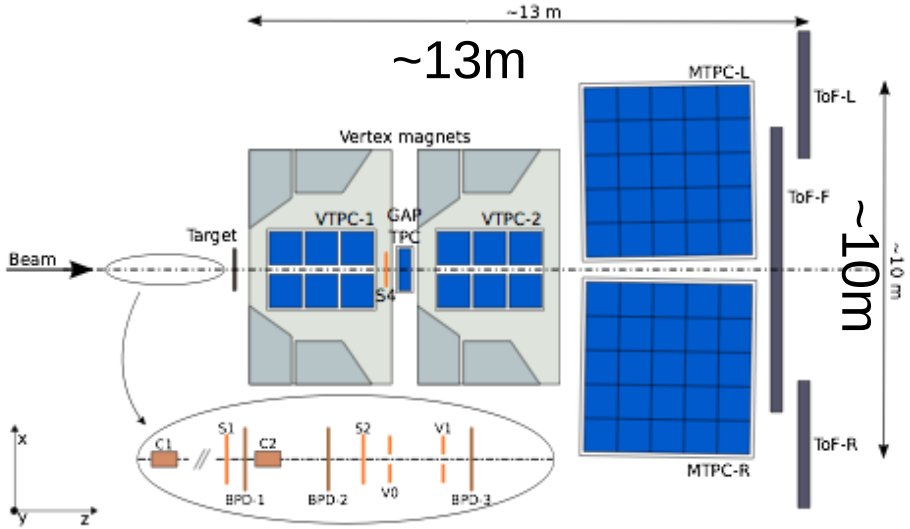
Near detector constraints

Prediction at far detector SK

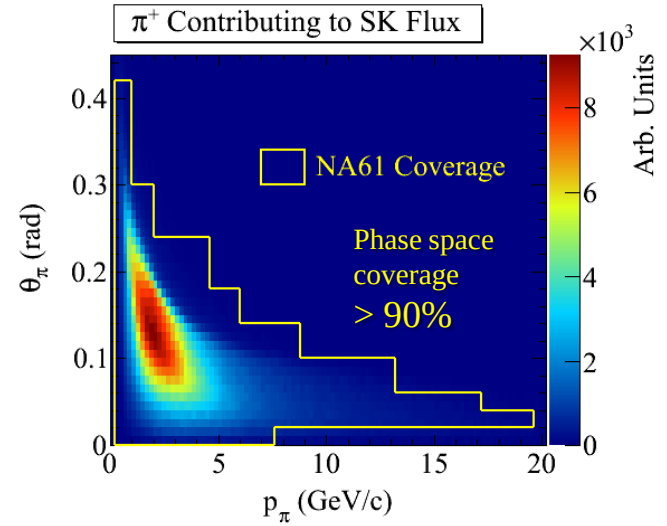
- Based on ν flux Ⓧ cross section MC models
- Weighted by using as many of external data as input
- Further constrain these predictions by the near detector measurements

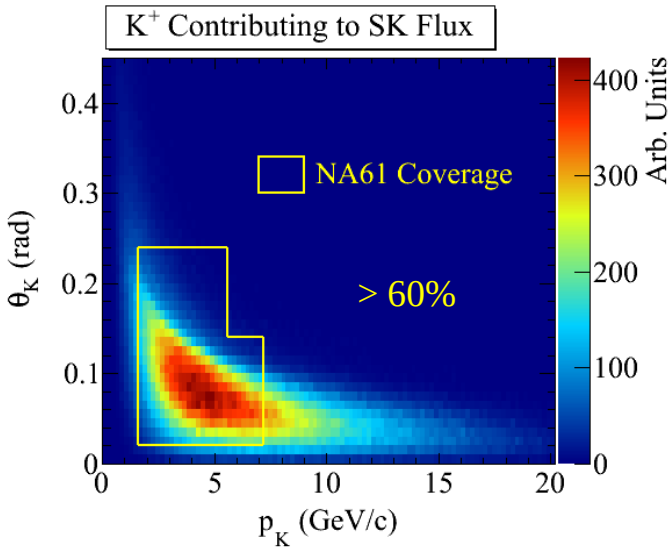
Hadron production measurements

CERN NA61/SHINE experiment

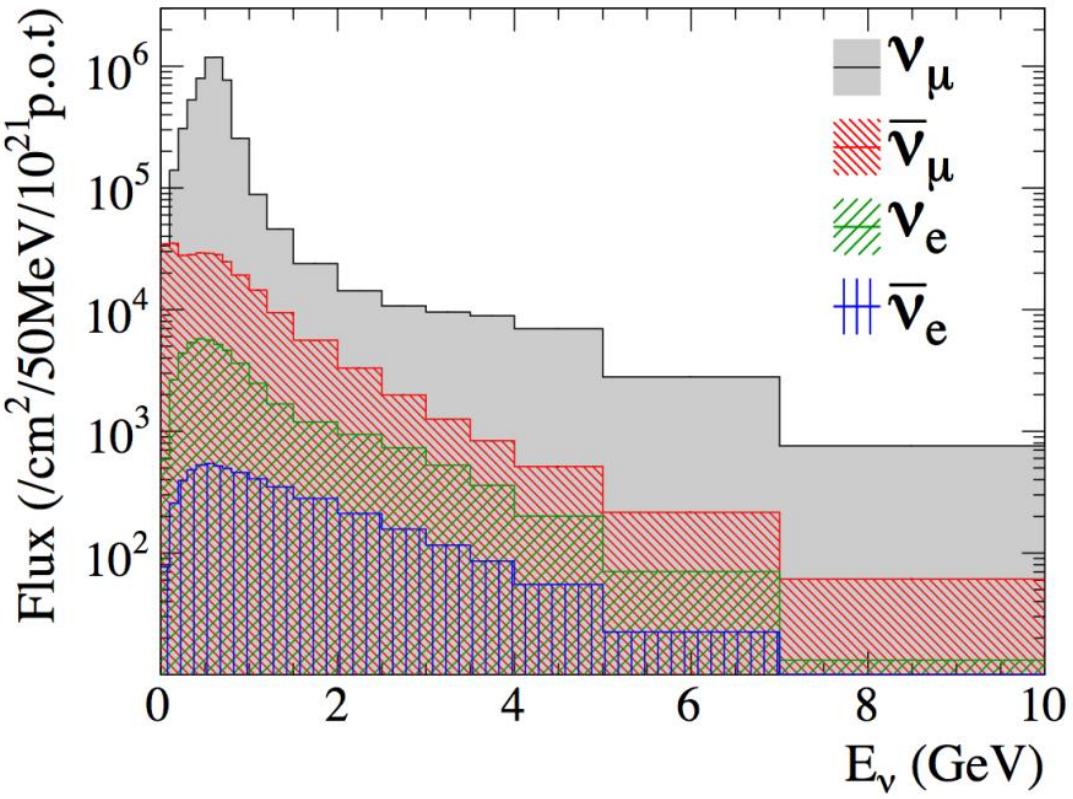


- Large acceptance spectrometer + TOF
- Measure hadron(π, K) yield distribution in 30 GeV p + C inelastic interaction





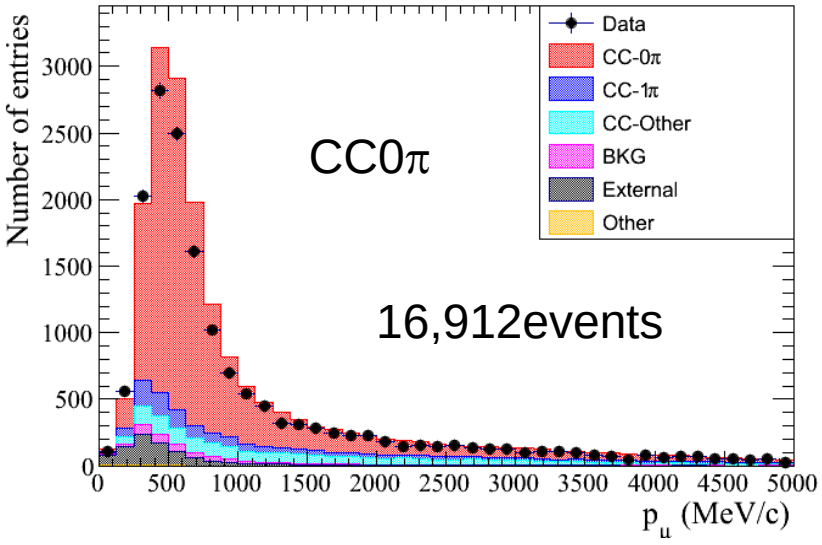
ν flux prediction

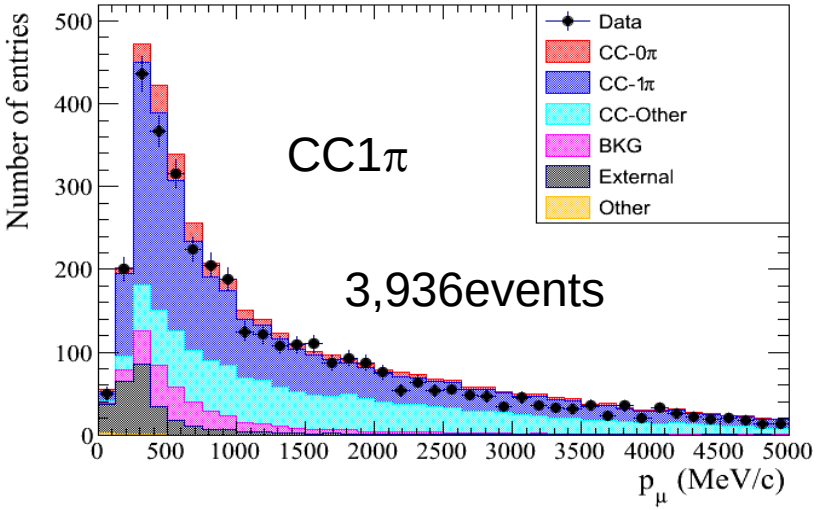


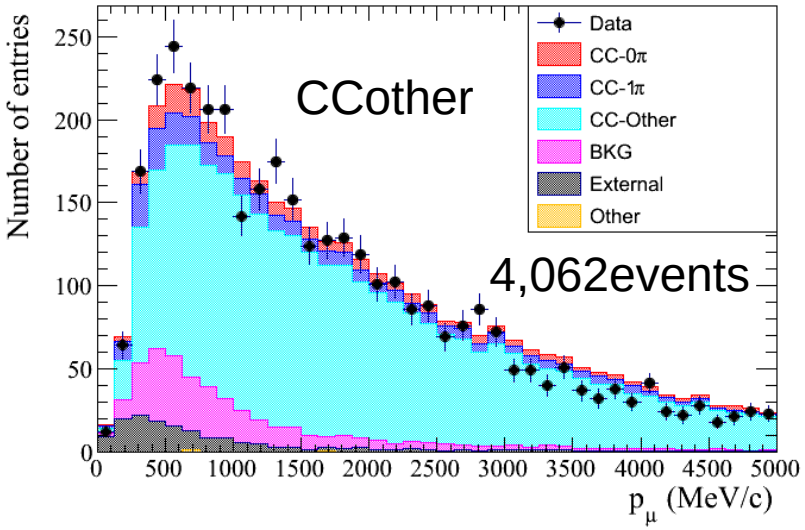
ν_μ	92.6%
anti-ν_μ	6.2%
ν_e	1.1%
anti- ν_e	0.1%

ν_e component in T2K beam: *~1.1%* (intrinsic BG for ν_e appearance) in neutrino energy interval 100-2000 MeV

ND280 constraints







ND280: in total 24,910 events (RUN1-4)

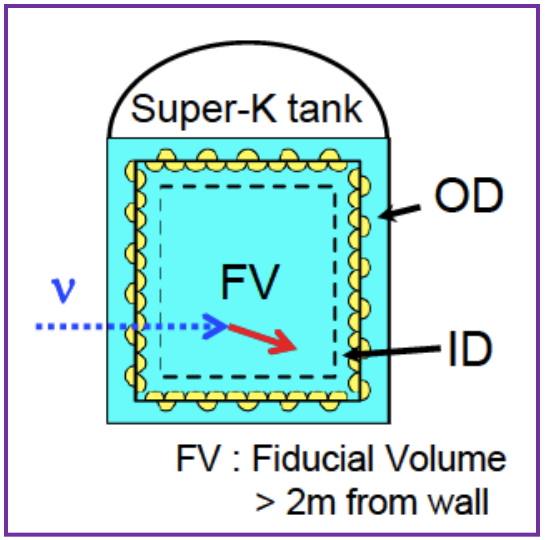
	CC0π purities	CC1π purities	CCother purities
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-nu)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

The ν_μ spectrum at the near detector is fit to extract flux and cross section constraints at the far detector

Selection criteria

Analysis of the T2K data accumulated for 6.39×10^{20} POT (Run 1-4)

- Event time compatible with expected arrival time
- Fully contained in the fiducial volume (>2m from the wall)



ν_e events

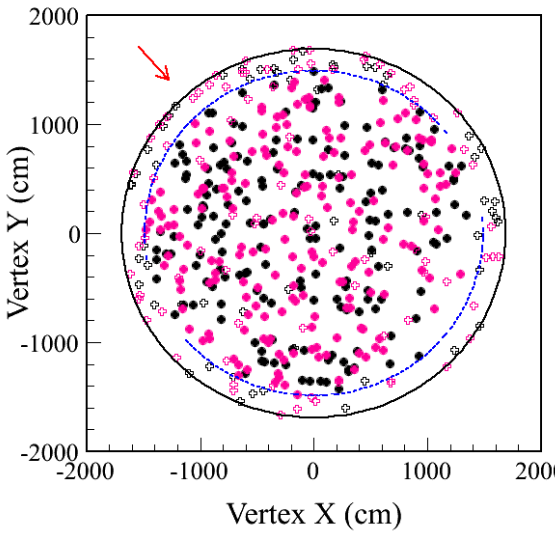
Fully-contained events with:

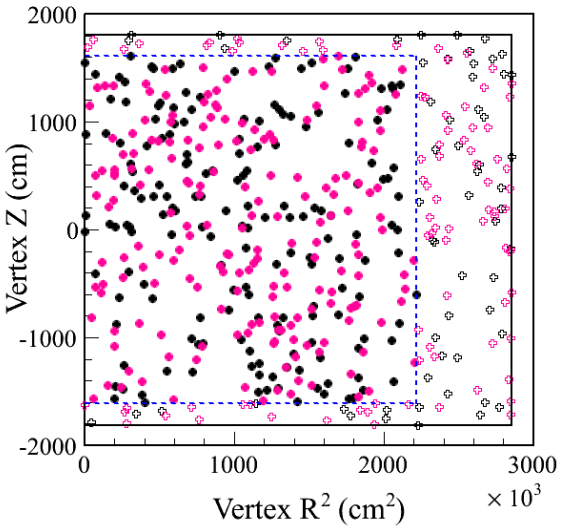
- **1 electron-like ring**
- **Visible energy > 100 MeV**
- **No decay electron**
- **Invariant mass not consistent with π^0**
- **100 MeV < Energy < 1250 MeV**

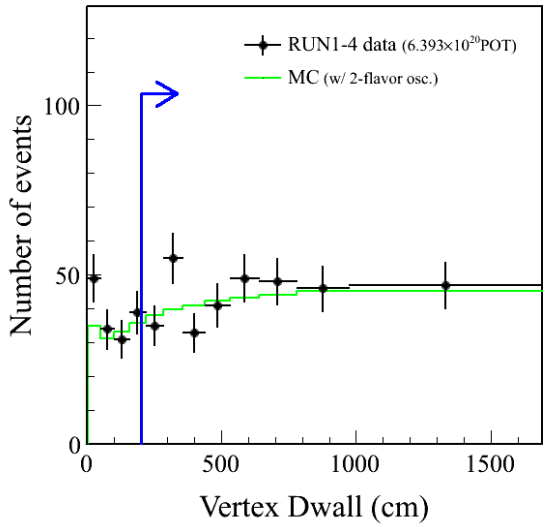
ν_e selection (1)(1)

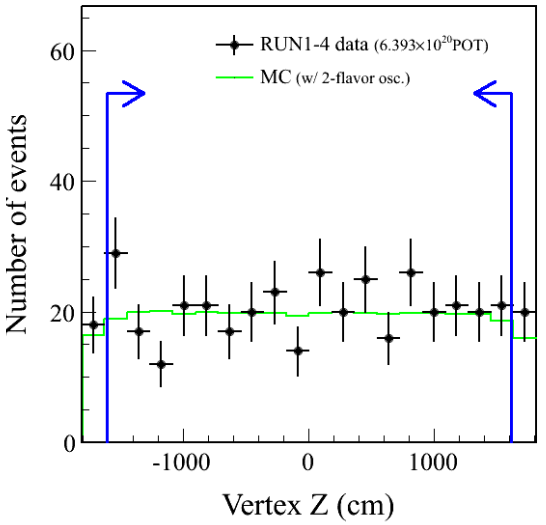
ν_e SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. Event's invariant mass not consistent with π^0 mass
7. Reconstructed ν energy E_ν^{rec} <1,250MeV









Parameters for MC

These parameters are used in MC simulations of neutrino events at SK

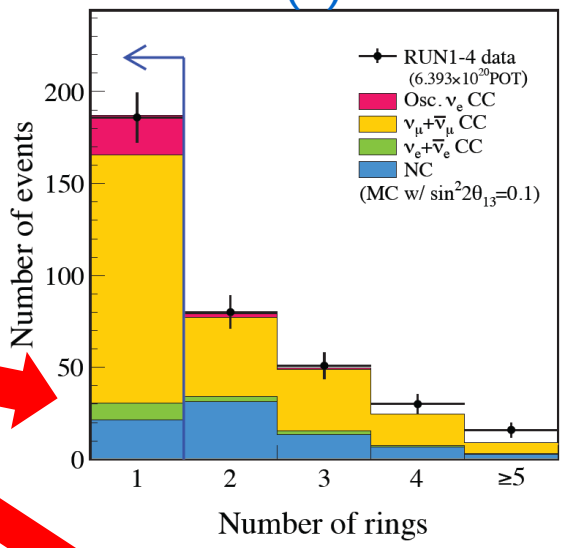
Parameter	Value
Δm^2_{21}	$7.6 \times 10^{-5}\mathrm{eV}^2$
Δm^2_{32}	$2.4 \times 10^{-3}\mathrm{eV}^2$
$\sin^2 2\theta_{12}$	0.8495
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{13}$	0.1 (or 0)
δ_{CP}	0
Mass hierarchy	Normal
ν travel length	295 km
Earth density	$2.6\mathrm{g/cm}^3$

ν_e selection (2)

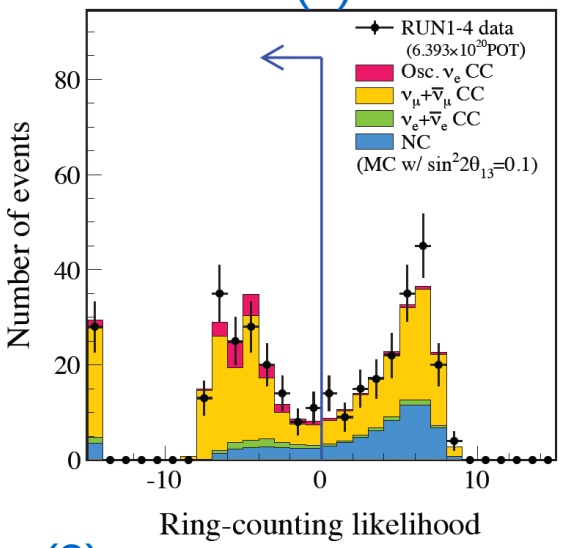
ν_e SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. Event's invariant mass not consistent with π^0 mass
7. Reconstructed ν energy E_ν^{rec} <1,250MeV

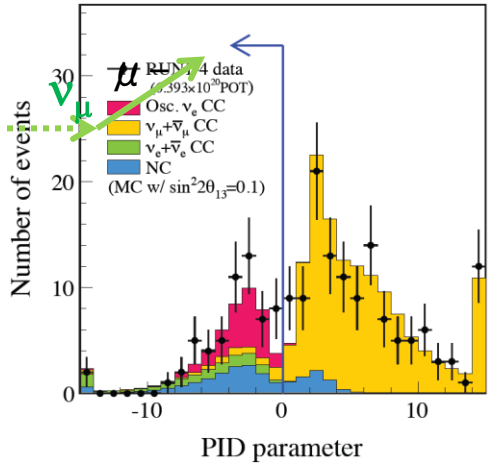
(2)



(2)



(3)

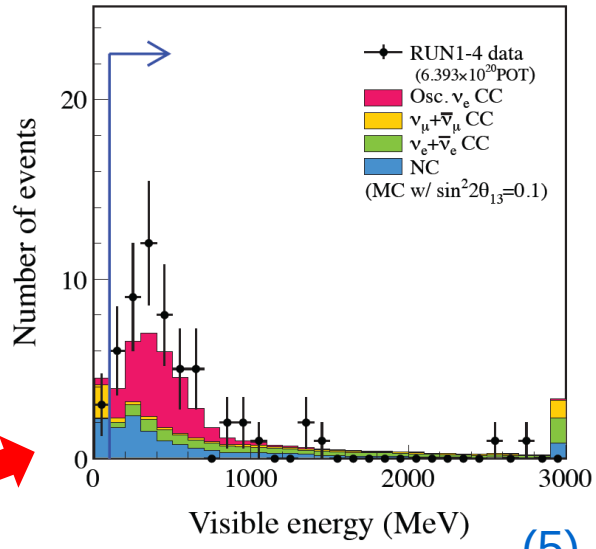


ν_e selection (3)

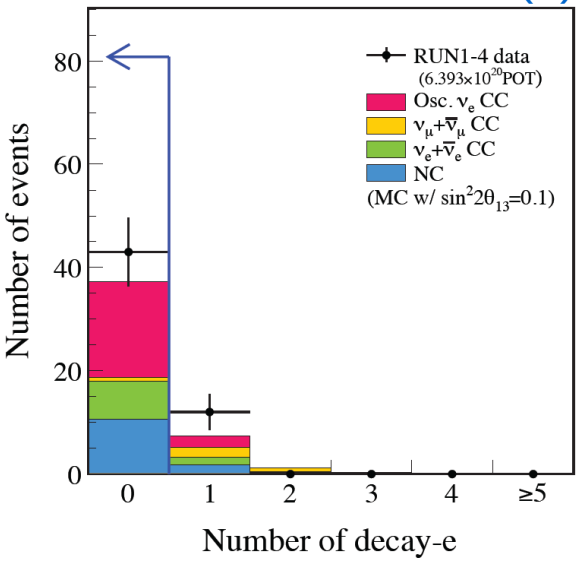
(4)

ν_e SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. Event's invariant mass not consistent with π^0 mass
7. Reconstructed ν energy E_ν^{rec} <1,250MeV



(5)



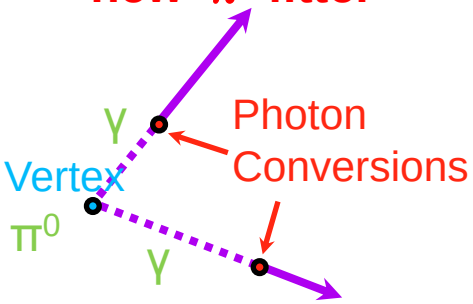
ν_e selection (4)

π^0 background reduction (1)

ν_e SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. Event's invariant mass not consistent with π^0 mass → new 2D cut
7. Reconstructed ν energy E_ν^{rec} <1,250MeV

new π^0 fitter



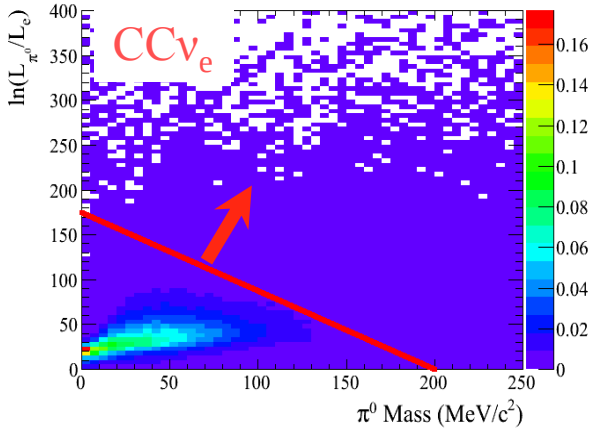
Assumption two electron rings produced at a common vertex
[12 parameters]

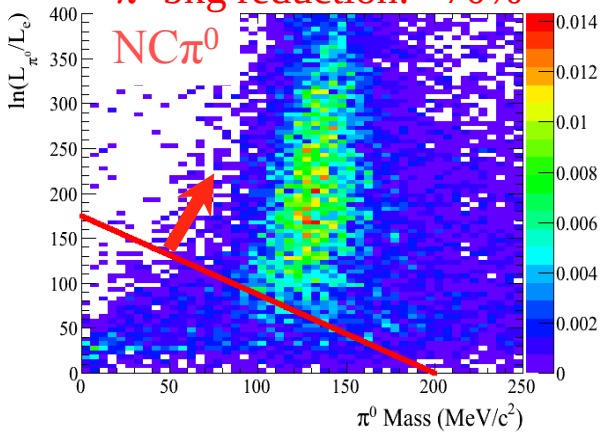
- Vertex(X,Y,Z,T)
- Directions(θ_1, φ_1, θ_2, φ_2)
- Momenta (p_1, p_2)
- Conversion lengths (c_1, c_2)

2D cut : π^0 mass and the likelihood ratio $\ln(L_{\pi 0}/L_e)$

Efficiency: decreased only by 2%

π^0 bkg reduction: ~70%



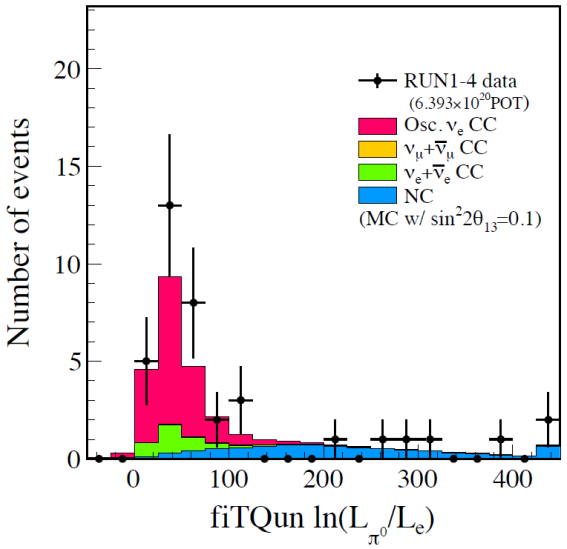


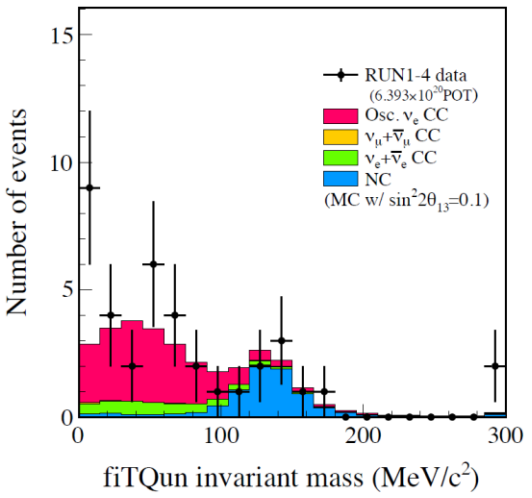
ν_e selection (5)

π^0 background reduction (2)

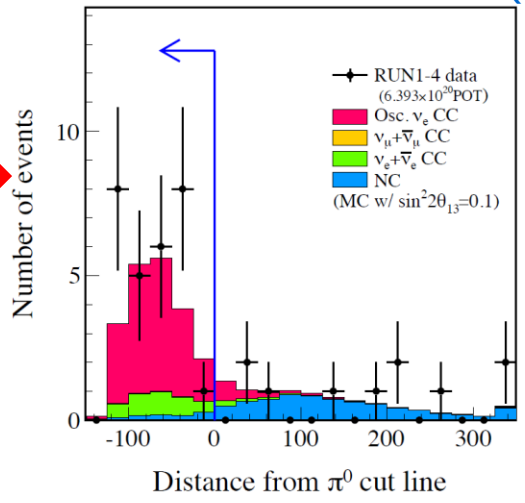
ν_e SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. 2D cut : π^0 mass and the likelihood ratio $\ln(L_{\pi 0}/L_e)$
7. Reconstructed ν energy E_ν^{rec} <1,250MeV





(6)

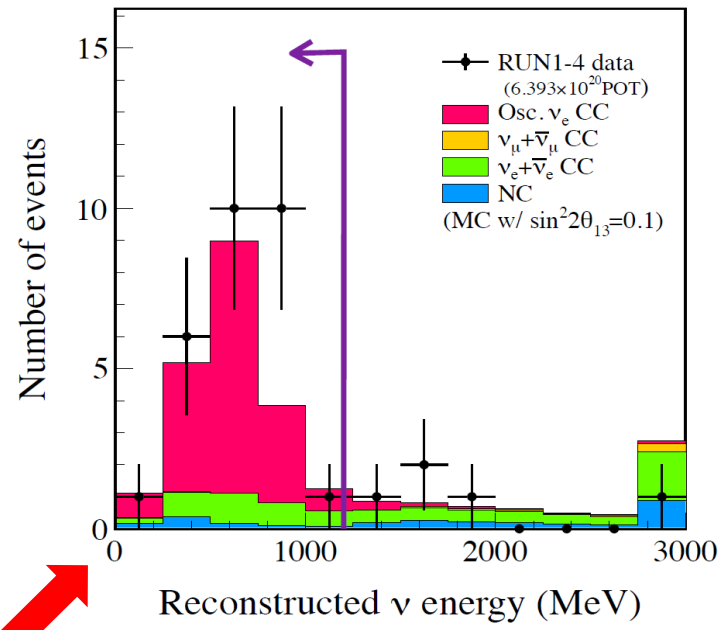


ν_e selection (6)

(7)

ν_e SELECTION CRITERIA

1. Event fully contained in the ID and vertex is within the fiducial volume (FCFV)
2. Only one reconstructed ring (1R)
3. Ring is electron-like
4. Visible energy Evis >100MeV
5. No Michel electron
6. 2D cut : π^0 mass and the likelihood ratio $\ln(L_{\pi 0}/L_e)$
7. Reconstructed ν energy E_ν^{rec} <1,250MeV



after all cuts
28
ν_e
candidates

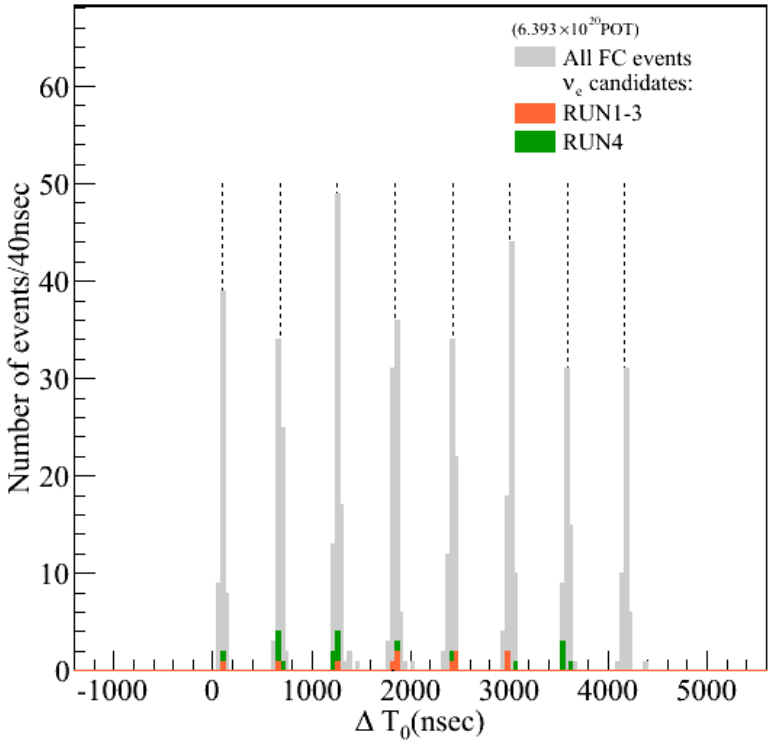
MC and data

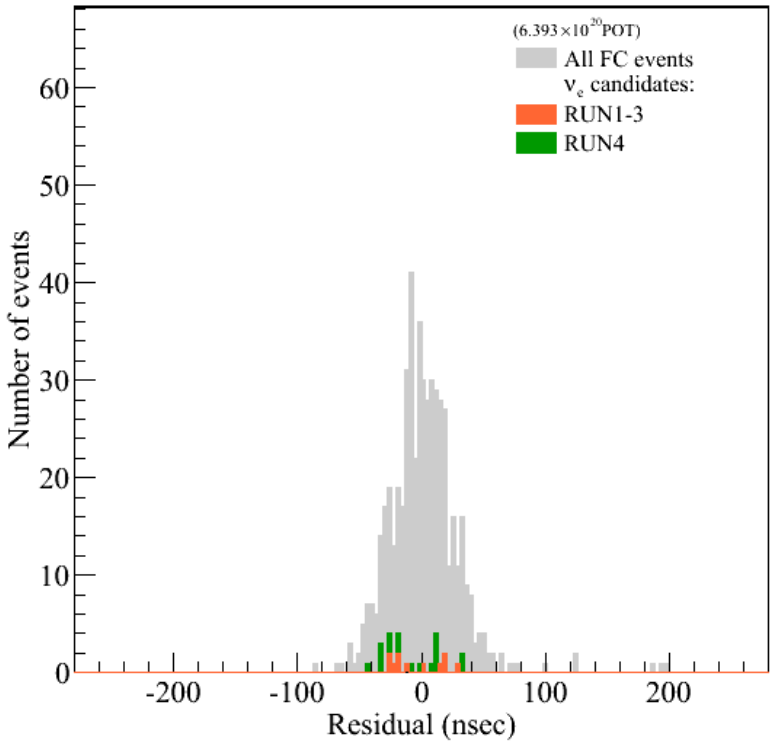
RUN1-4 6.393×10^{20}POT	MC Expectations w/ $\sin^2 2\theta_{13}=0$					Data
	$\nu_\mu+\nu_\mu$ CC	$\nu_e+\nu_e$ CC	NC	BG total	Signal	
True FV	308.01	15.48	271.56	595.05	0.53	-
FCFV	234.75	14.89	76.50	326.13	0.51	363
One-ring	134.94	9.59	21.59	166.12	0.46	186
e-like	5.32	9.52	14.86	29.70	0.46	58
E_{vis}>100MeV	3.46	9.45	12.66	25.58	0.44	55
No decay-e	0.65	7.71	10.64	19.01	0.41	43
E_ν^{rec}<1250MeV	0.20	3.78	8.04	12.02	0.40	38
fiTQun π^0	0.06	3.29	0.87	4.23	0.38	28
Efficiency [%]	0.0	21.3	0.3	0.7	72.3	-

Beam ν_e + anti ν_e

solar term $\sim\sin^2\theta_{12}$

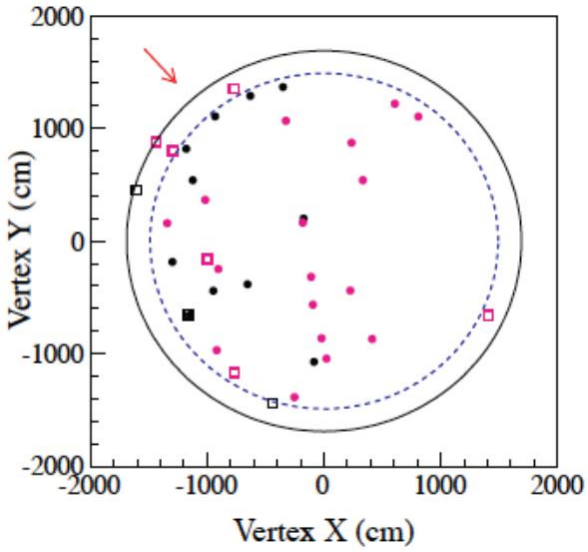
Timing

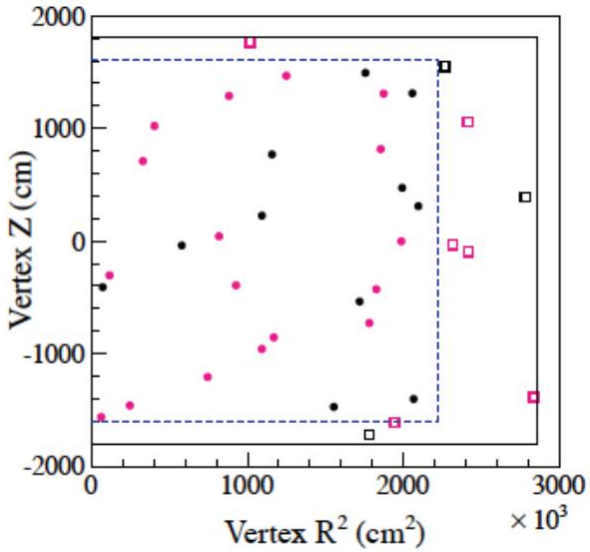




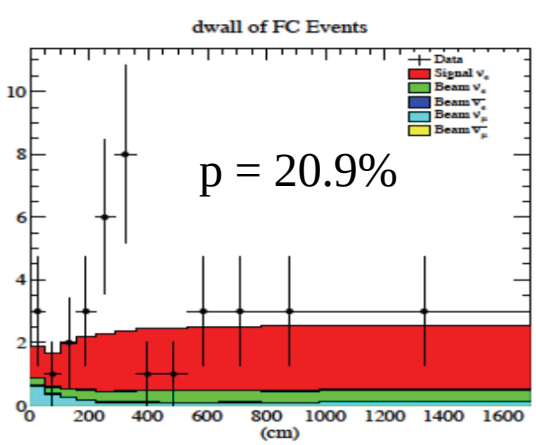
ν_e events shown in green and red

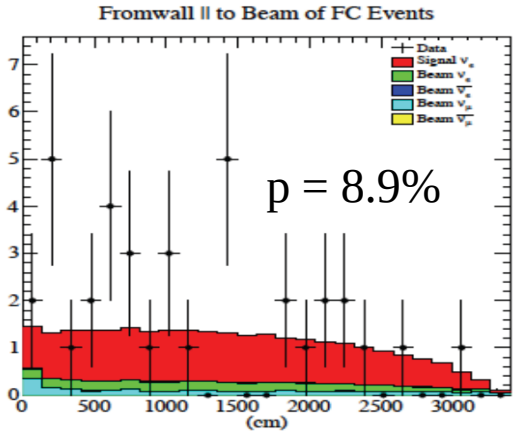
Vertex distributions





Run 1-3 black
Run 4 red

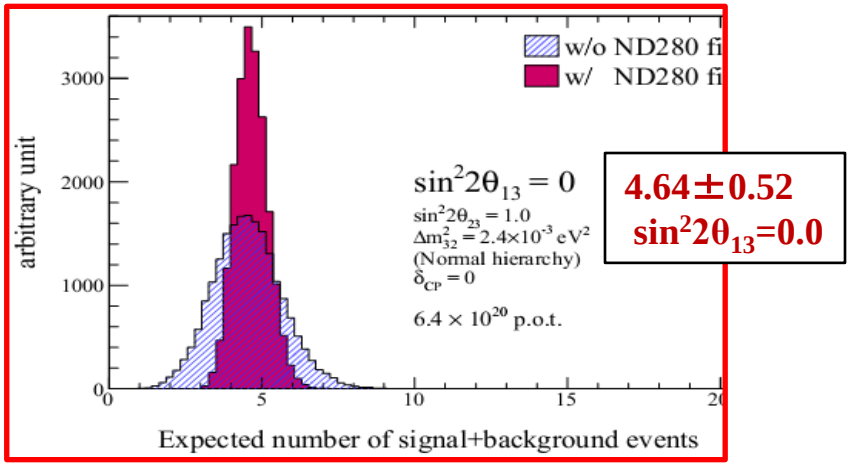




Systematic uncertainties

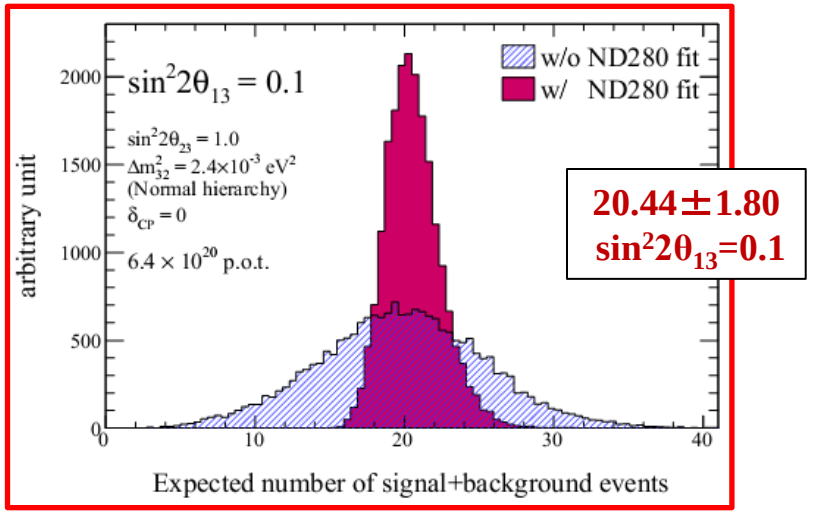
Predicted # of events w/ 6.4×10^{20} POT

Event category	$\sin^2 2\theta_{13}$=0.0	$\sin^2 2\theta_{13}$=0.1
ν_e signal	0.38	16.42
ν_e background	3.17	2.93
ν_μ background (mainly NCπ^0)	0.89	0.89
$\nu_\mu + \nu_e$ background	0.20	0.19
Total	4.64	20.44



Systematic uncertainties

Error source	$\sin^2 2\theta_{13}$=0.0	$\sin^2 2\theta_{13}$=0.1
Beam flux + ν int. in T2K fit	4.9 %	3.0 %
ν int. (from other exp.)	6.7 %	7.5 %
Far detector	7.3 %	3.5 %
Total	11.1 %	8.8 %
Total (2012)	13.4 %	10.3 %
w/o ND280	24%	27%

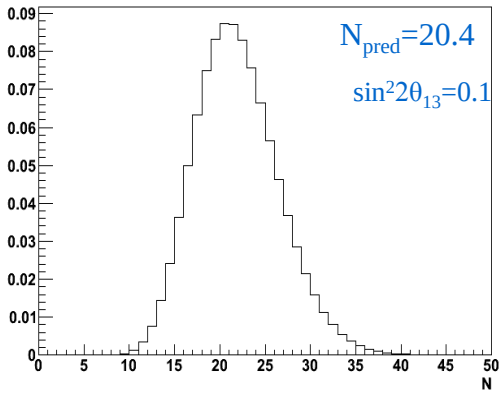


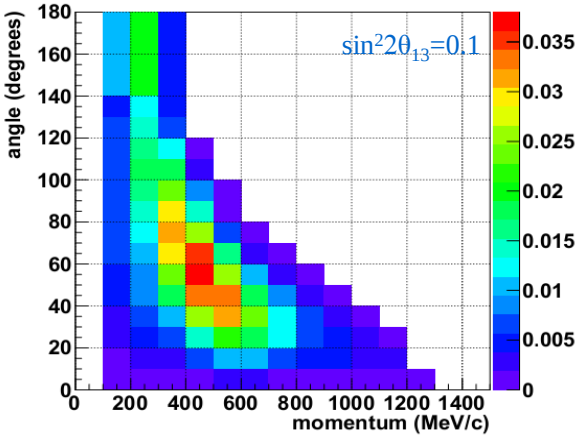
Maximum likelihood fit

$$\mathcal{L} = \mathcal{L}_{norm} \times \mathcal{L}_{shape} \times \mathcal{L}_{syst}$$

$Poisson(N_{obs})_{\text{mean}=N_{pred}}$

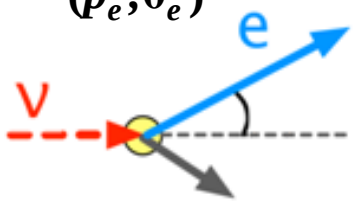
$$\prod_{i=1}^{N_{obs}} \phi(p_i, \theta_i)$$





1st method:

$N_{observed}$ (p_e, θ_e)

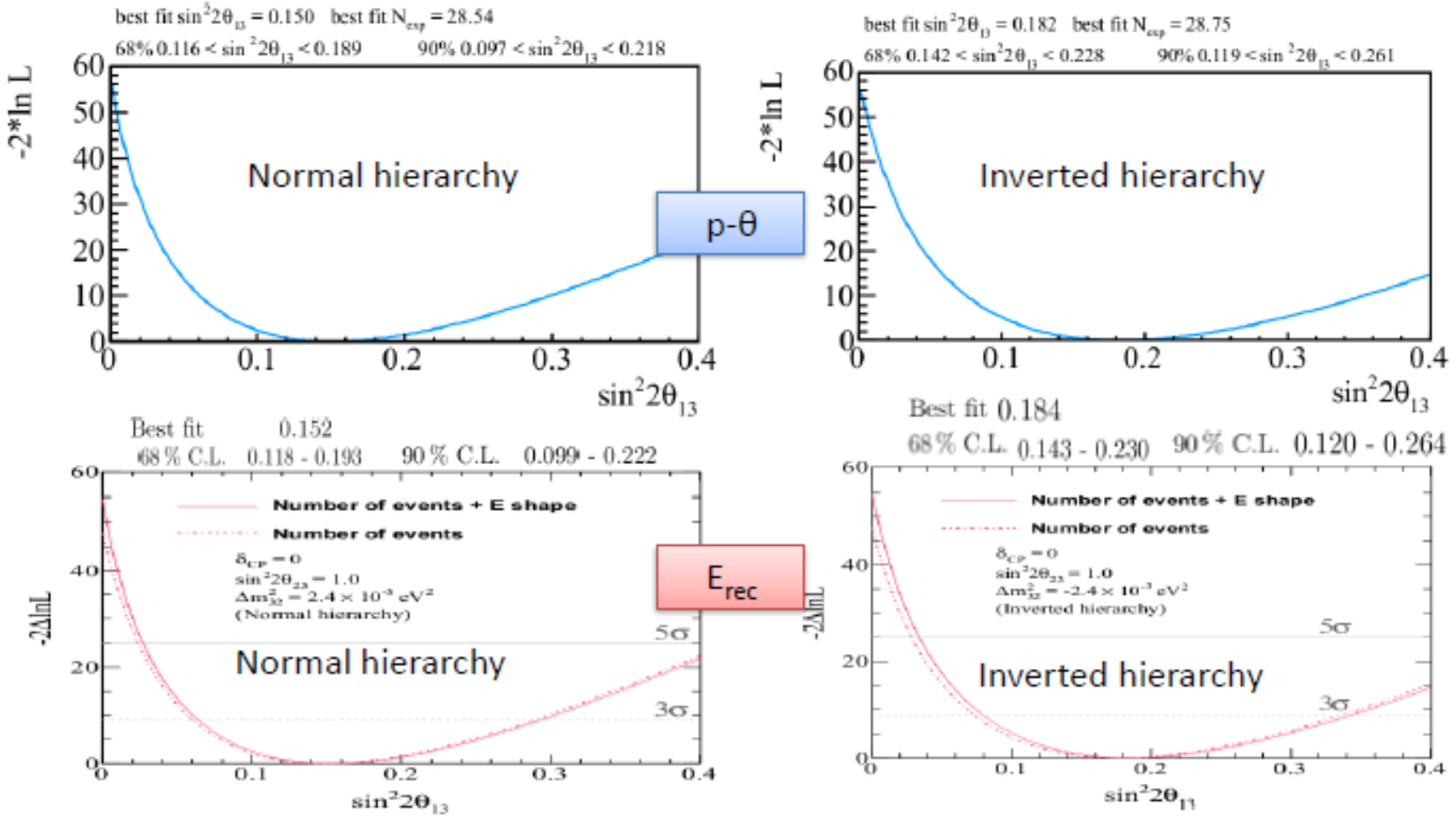


2nd method:

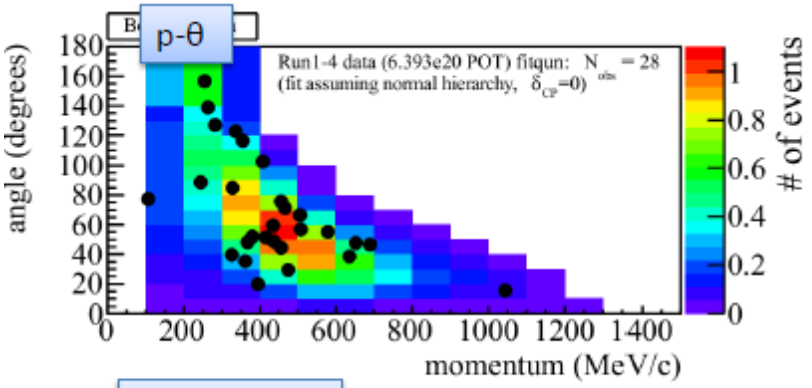
$N_{observed}$ Eν reconstructed shape (1d)

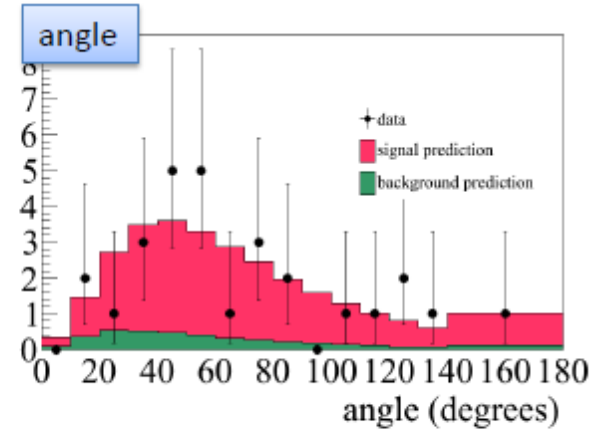
- L_{norm} : Poisson probability with mean = N_{pred} to have $N=N_{obs}$ events
- L_{shape} : Product of the probabilities that each event has a particular value of (p_e , θ_e).
  - φ: predicted Probability Density Function (PDF) .
- L_{syst} : A multivariate normal distribution of systematic parameters

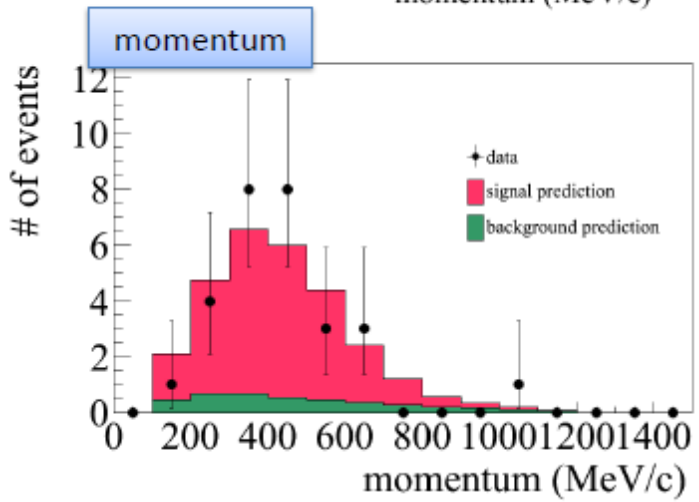
Likelihood curves



Results of the fit







Assuming $\delta_{CP}=0$, normal hierarchy,
$|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$

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

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

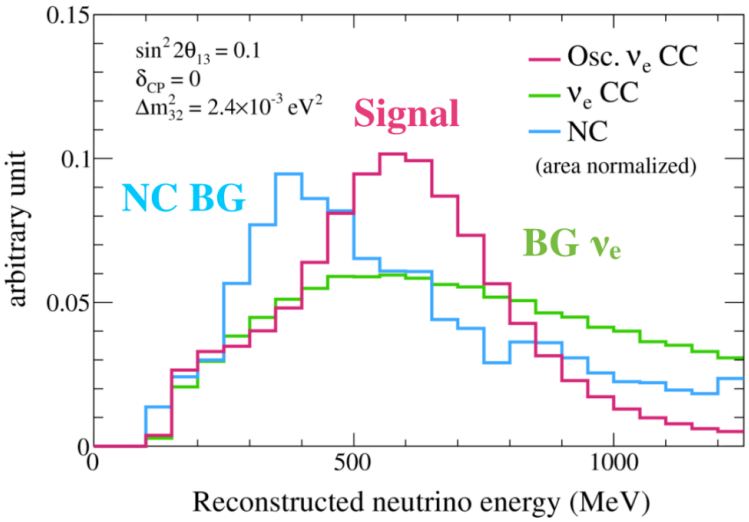
90% allowed region:

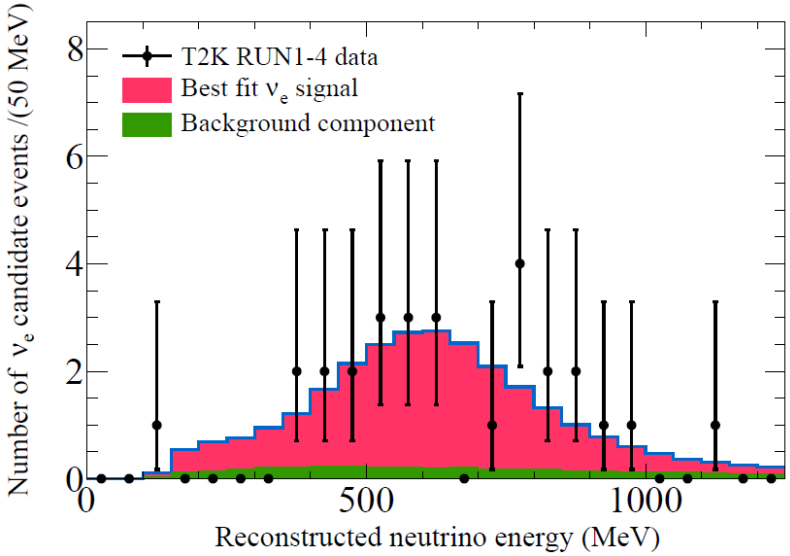
$$0.097 < \sin^2 2\theta_{13} < 0.218$$

7

2nd analysis

(rate + E_ν shape)





- **Fit data to the reconstructed energy distribution**

$$E^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

- best fit w/ 68% C.L. error:

$$\sin^2 2\theta_{13} = 0.152^{+0.041}_{-0.034}$$

assuming
$|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2
$\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$,
Normal hierarchy

- Very consistent with p-θ analysis

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

Result: θ_{13} vs δ

allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}

Best fit for $\delta_{CP}=0$

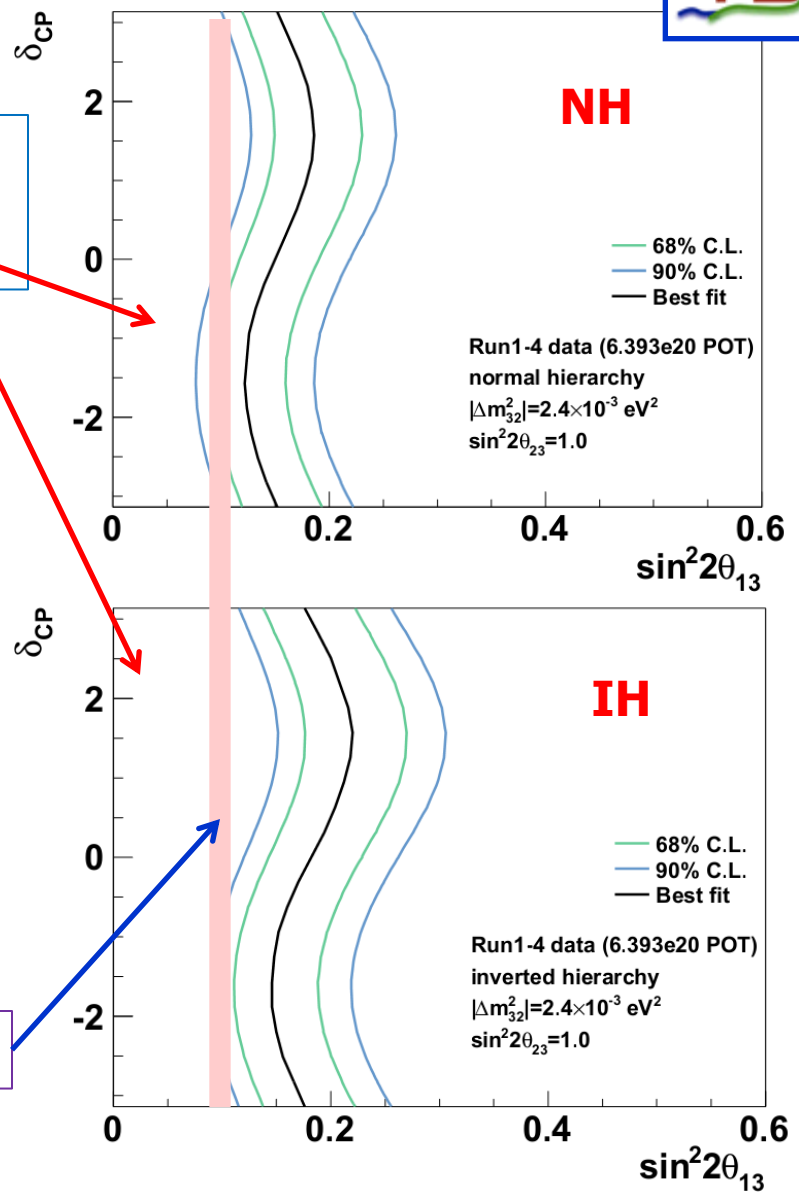
NH

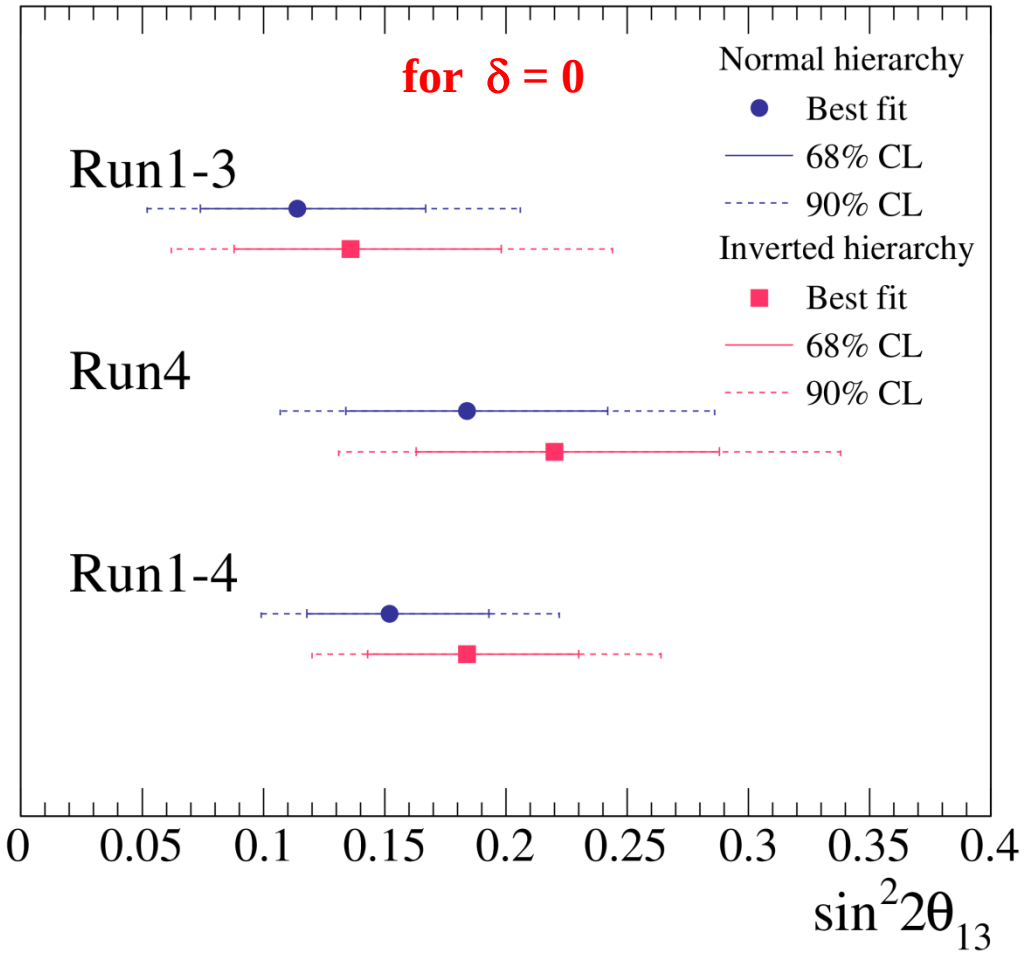
$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

IH

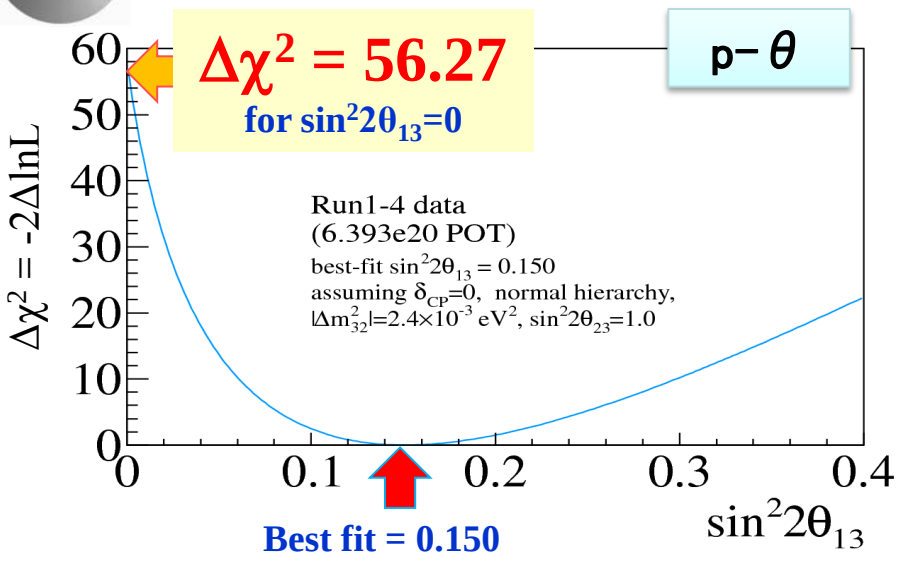
$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

PDG(2012): $\sin^2 2\theta_{13}$: 0.098 ± 0.013



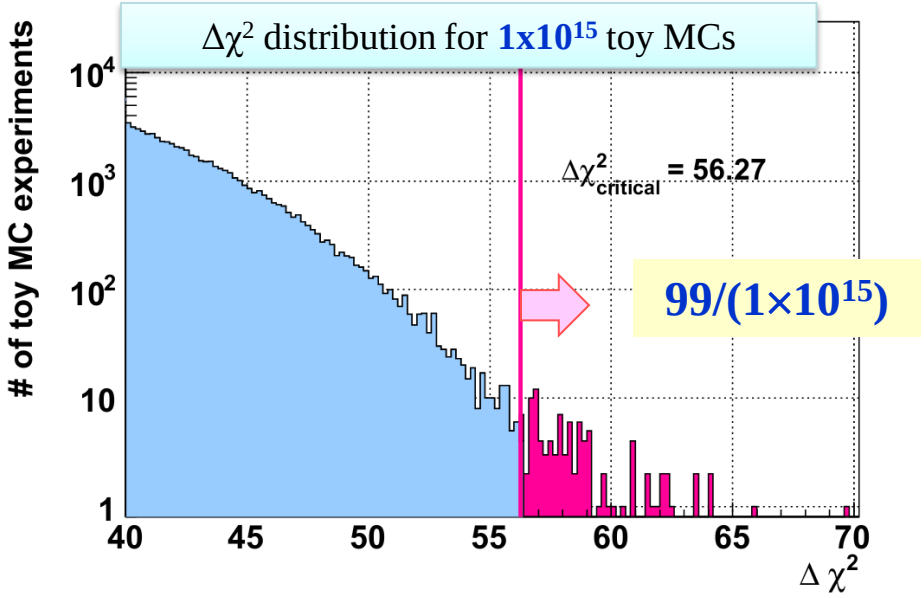

for δ = 0
Normal hierarchy
Best fit
68% CL
90% CL
Inverted hierarchy
Best fit
68% CL
90% CL
Run1-3
Run4
Run1-4
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
sin²2θ13

Significance



significance is calculated as $\sqrt{\Delta\chi^2}$

$$\sqrt{-2\Delta\ln L} = \sqrt{56.27} = 7.5\sigma$$



p-value is calculated as follows:

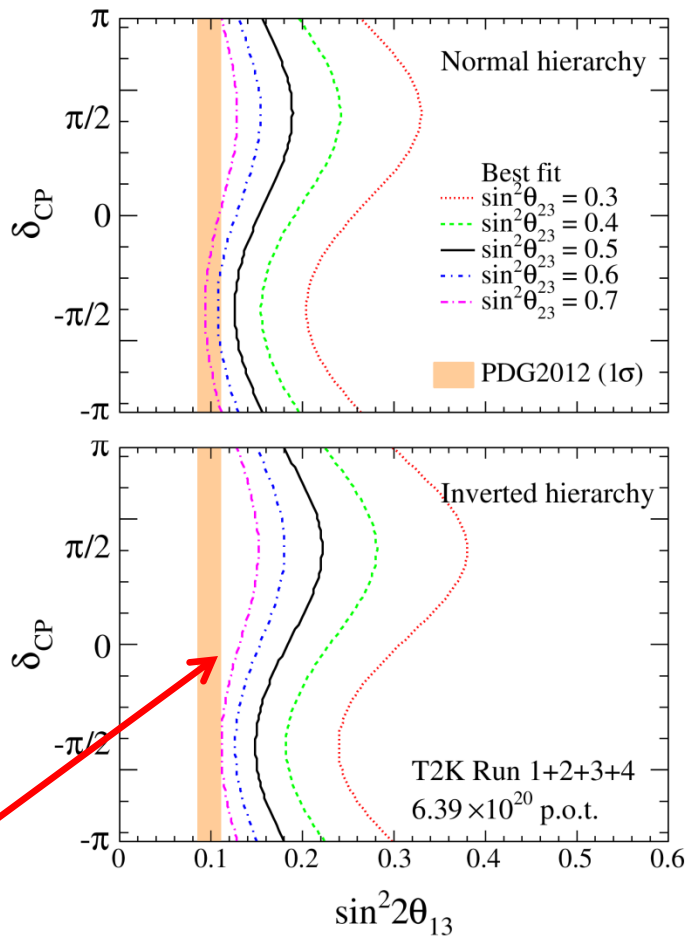
1. Generate 1e15 toy experiments with $\sin^2 2\theta_{13}=0.0$.
2. Fit each toy experiment extract $-2\Delta\ln L$ ($=\Delta\chi^2$).
3. p-value is the fraction of toy experiments above $\Delta\chi^2_{data}$

$$\text{p-value} = 9.9\times10^{-14}$$

θ_{23} issue

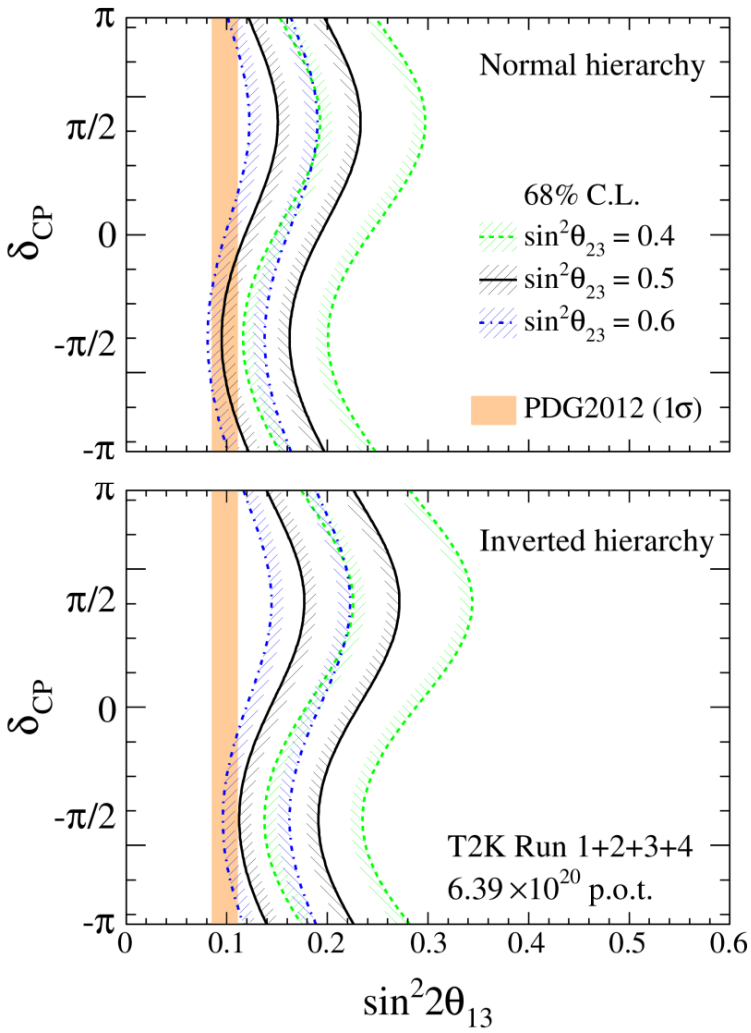
$$P_{\nu_\mu \to \nu_e} \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E_\nu}$$

- **Oscillation probability is dependent on $\sin^2\theta_{23}$ (octant)**
  - **PDG2012: $\sin^2(2\theta_{23}) > 0.95$**
    - **$\sin^2\theta_{23} = 0.50 \pm 0.11$**
    - **$\theta_{23} = 45 \pm 6.5^\circ$**
  - **Reduction of $\sin^2\theta_{23}$ error is critical for further improvements**



PDG(2012)

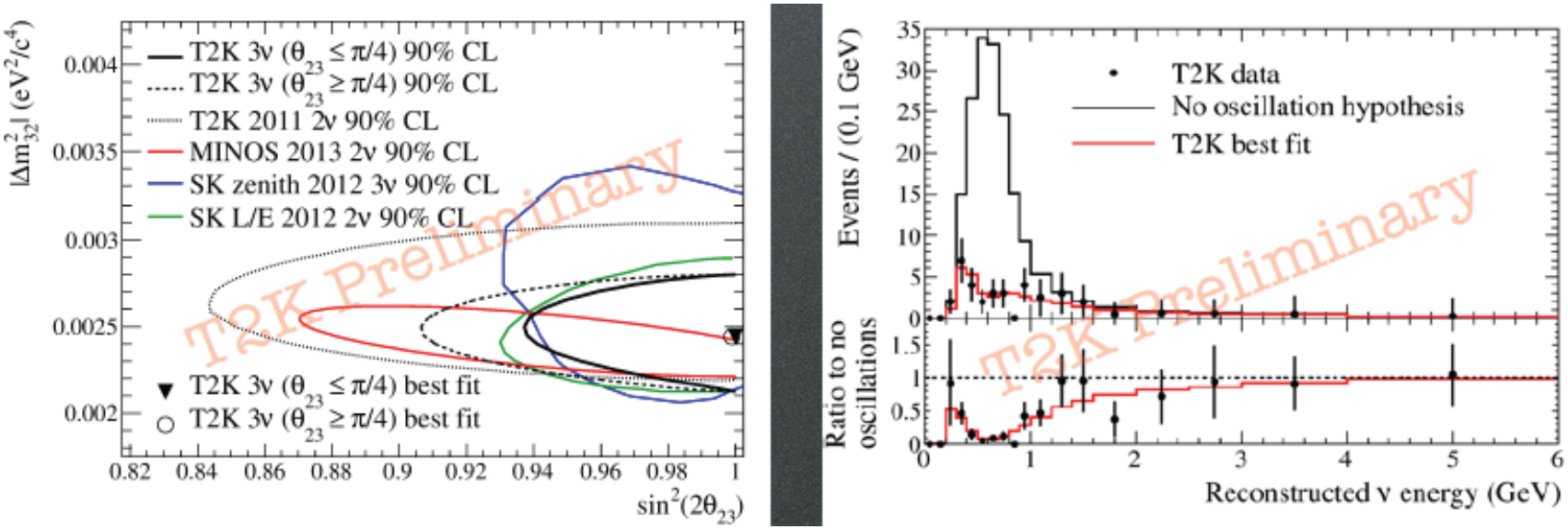
θ_{23} uncertainties dominate in δ - $\sin^2 2\theta_{13}$ plot



θ_{23} measurement

ν_μ disappearance

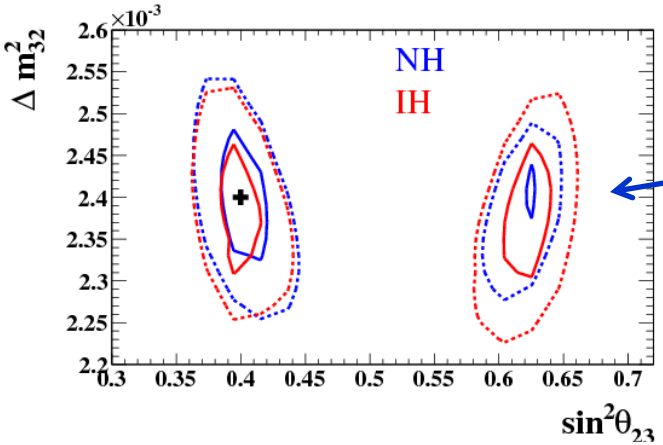
$$P\left(\nu_\mu \to \nu_\mu\right) \sim 1 - \left(\underbrace{\cos^4\theta_{13}\cdot\sin^2 2\theta_{23}}_{\text{Leading}} + \underbrace{\sin^2 2\theta_{13}\cdot\sin^2\theta_{23}}_{\text{Next-to-leading}}\right)\cdot\sin^2\frac{\Delta m^2_{31}\cdot L}{4E}$$



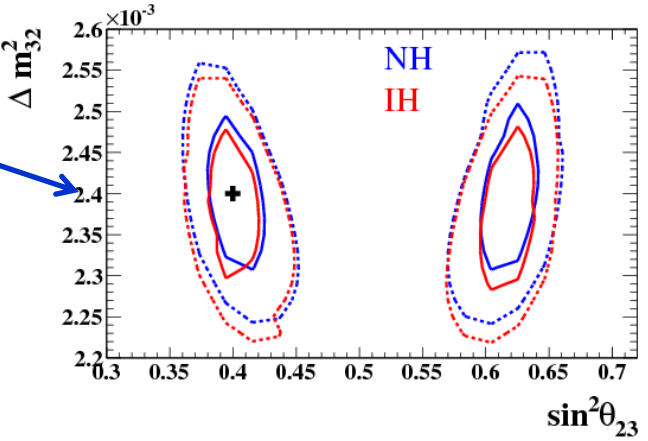
Perspectives: θ_{23}

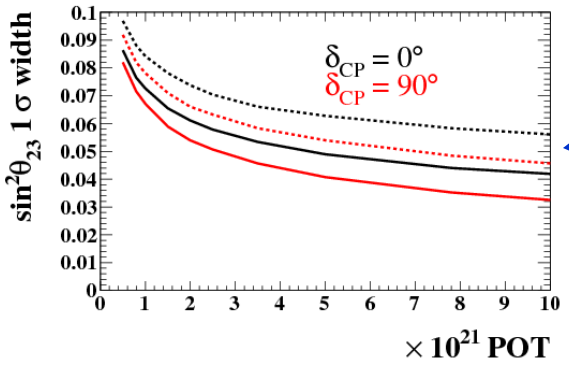
7.8×10^{21} pot
100% ν running 90% CL
$\sin^2 2\theta_{13} = 0.1$ + reactor data
solid: stat only; dashed: stat +current sys

7.8×10^{21} pot
50% ν - 50% anti-ν running 90% CL
$\sin^2 2\theta_{13} = 0.1$ + reactor data
solid: stat only; dashed: stat +current sys

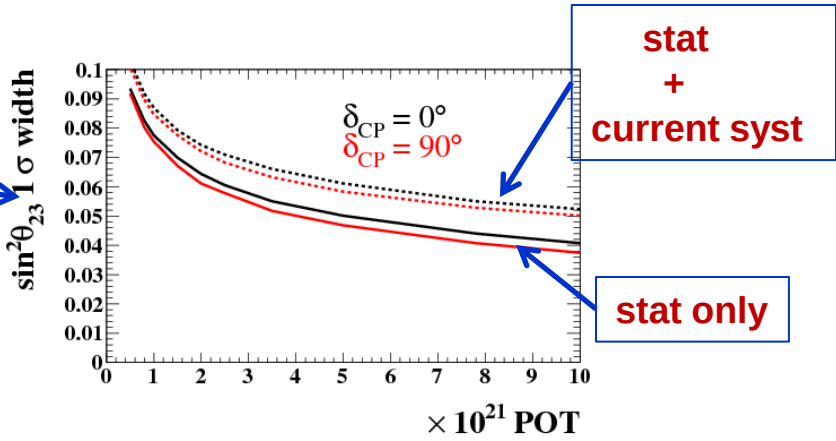


Octant





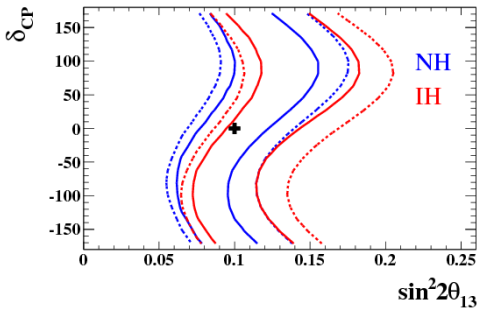
θ_{23}

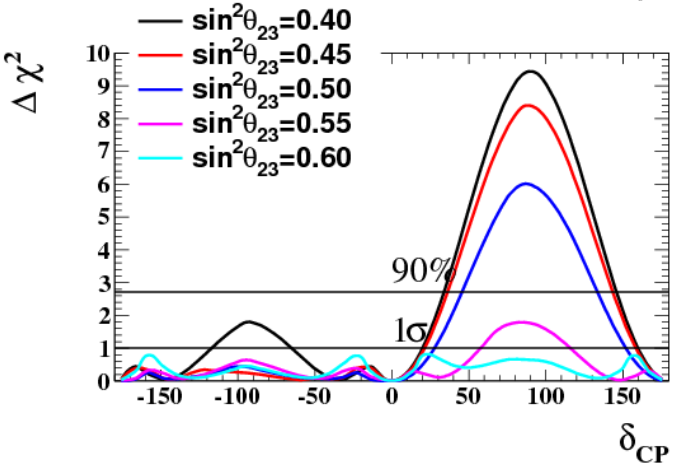


estimation
$\sigma(\theta_{23}) \sim 2$ deg

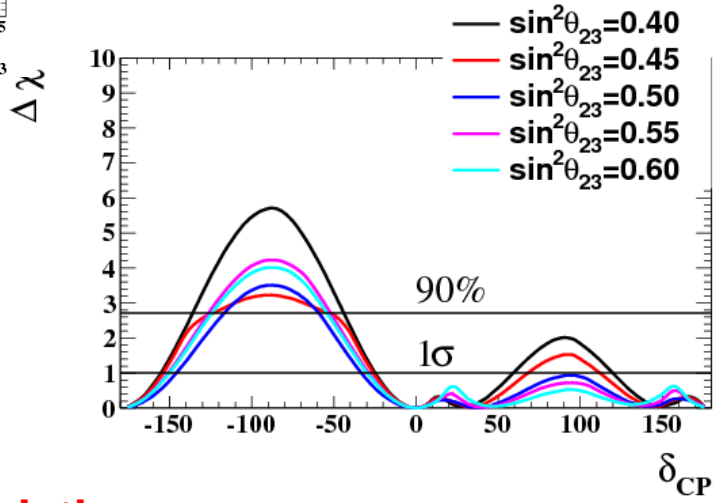
Perspectives: CPV

IH 7.8×10^{21} pot
100% ν running
$\sin^2 2\theta_{13} = 0.1$
+ reactor data



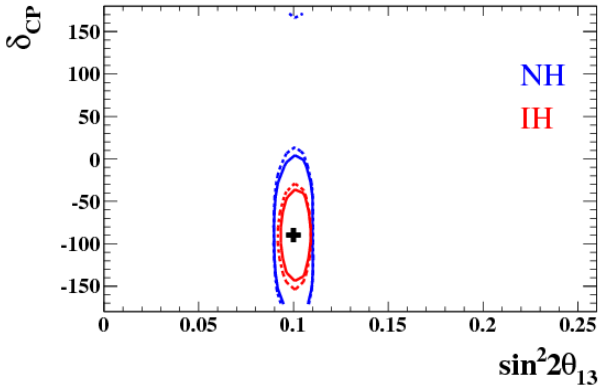


NH 7.8×10^{21} pot
50% ν - 50% anti-ν running
$\sin^2 2\theta_{13} = 0.1$ + reactor data



Chance to find an indication for CP violation if δ is about π/2 or -π/2

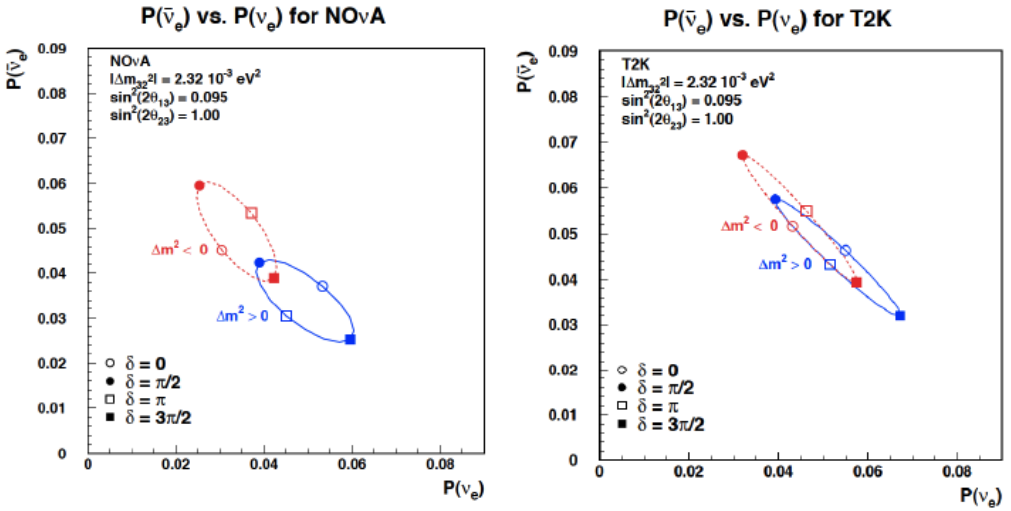
7.8×10^{21} pot
50% ν - 50% anti-nu running
$\sin^2 2\theta_{13} = 0.1$ + reactor data
$\sin^2 2\theta_{23} = 0.5$
δ= -90 deg

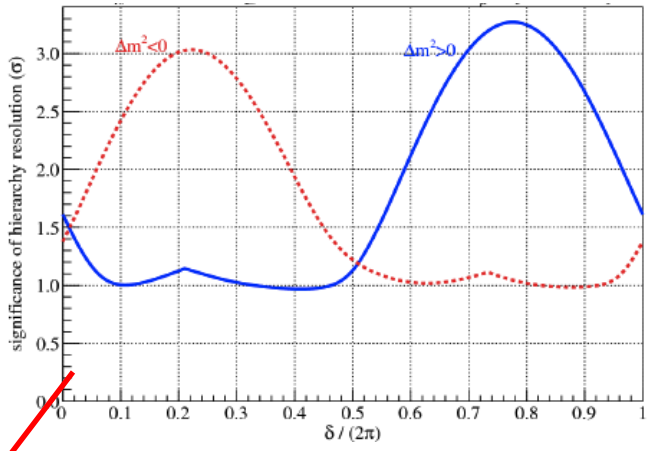


T2K and Nova

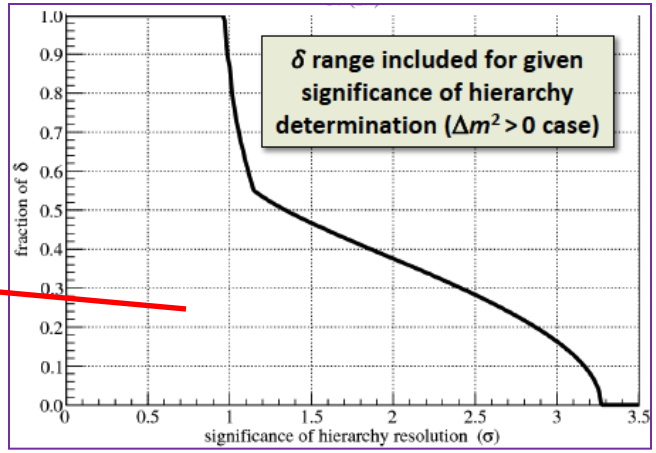
Mass Hierarchy and CP violation

MH





δ



For $\sin^2 2\theta_{13}$=0.1, approximately (at 90%C.L.):

- MH: ≈50% coverage
- CPV: ≈30-40% coverage

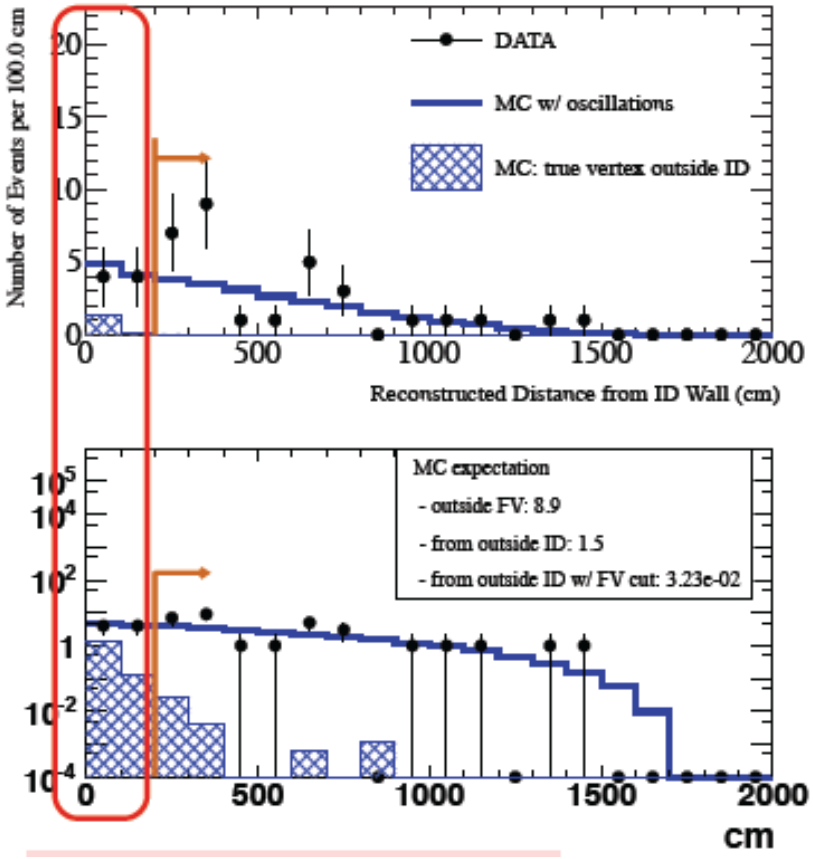
Conclusion

- **Observation of $\nu_\mu \rightarrow \nu_e$ appearance at 7.5 σ significance**
  A new type of transformation among neutrinos has firmly established"
- **Near future: precision measurements of neutrino mixing parameters**
- **Good prospects for first search for CP violation in lepton sector**

спасибо за внимание!

Backup slides

OD events



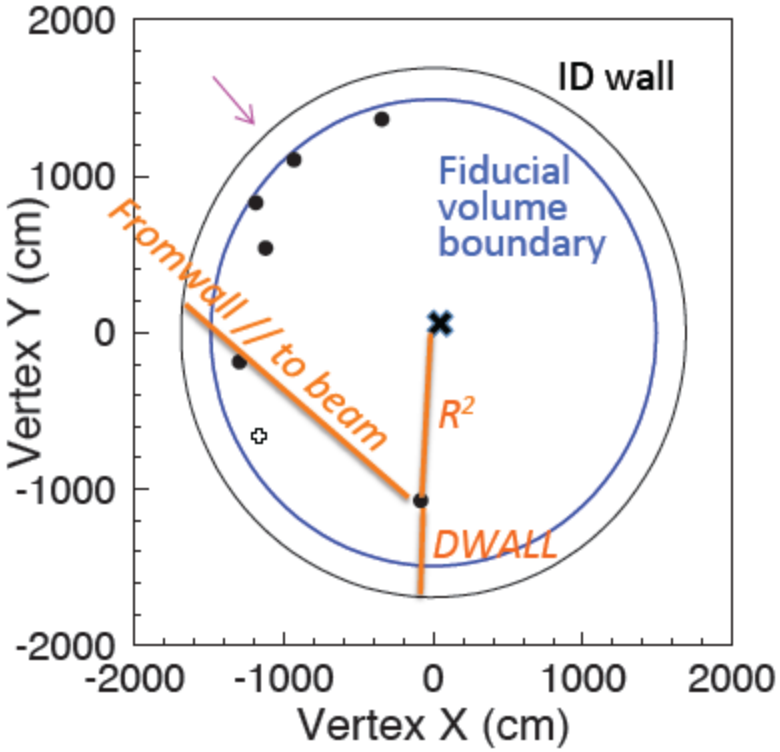
No indication of events from OD interactions

BG events from OD interactions:

0.03±0.009 events: **(0.1%) of FCFV ν_e candidates**

MC ν_e events

Data	28	
MC	$\sin^2 2\theta_{13}=0$	$\sin^2 2\theta_{13}=0.1$
oscillation $\nu_\mu \rightarrow \nu_e$	0.38	16.42
ν_e BG (beam)	3.17	2.93
ν_μ BG(NC π0)	0.89	0.89
$\nu_e + \nu_\mu$ BG	0.20	0.19
MC Total	4.64	20.44
Sys . err (%)	(11.1%)	(8.8%)
Sys. err(number)	±0.52	±1.80
Sys. err(%)-2012	(13.0%)	(9.9%)


ID wall
Fiducial volume boundary
Fromwall // to beam
R^2
DWALL
Vertex Y (cm)
Vertex X (cm)
2000
1000
0
-1000
-2000
-2000
-1000
0
1000
2000