Исследование осцилляций мюонных нейтрино в эксперименте T2K

Ю.Г. Куденко

ИЯИ РАН

X Марковские чтения
ИЯИ РАН, 12 мая 2012 г.

ν oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

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

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**

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

$\theta_{12}\sim 34^0$ $\theta_{23}\sim 45^0$

?? θ_{13} , mass hierarchy , δ ??

Issues in neutrino physics

- Absolute mass scale
- Neutrino mixing θ_{13}
- Mass hierarchy $m^2_{23} > 0$ or $m^2_{23} < 0$
- CP violation δ_{CP}
- Dirac or Majorana
- Sterile neutrinos

Long-Baseline Neutrino Oscillation Experiment

- 12 countries
- 59 institutes
- $\simeq$ 500 collaborators

Canada, France, Germany, Italy, Japan, Korea, Poland, Russia, Spain, Switzerland, UK, USA.

Oscillation experiments:

Appearance and Disappearance

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \Phi_{ij} \mp 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin 2\Phi_{ij}$$

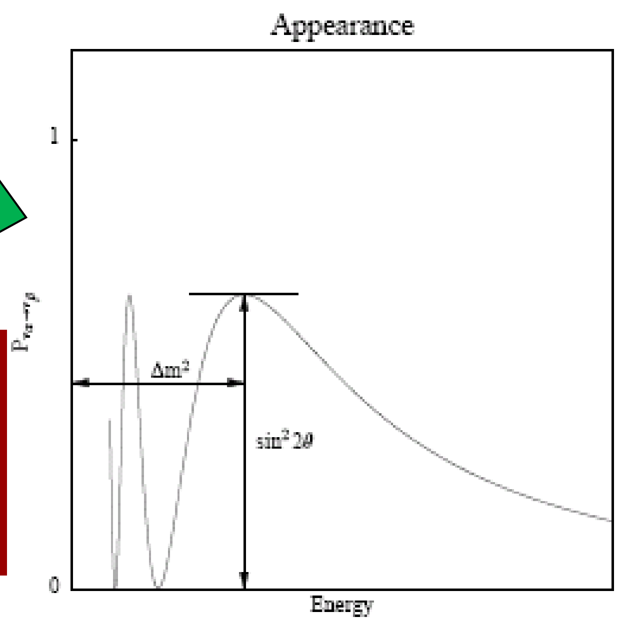
$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right),$$

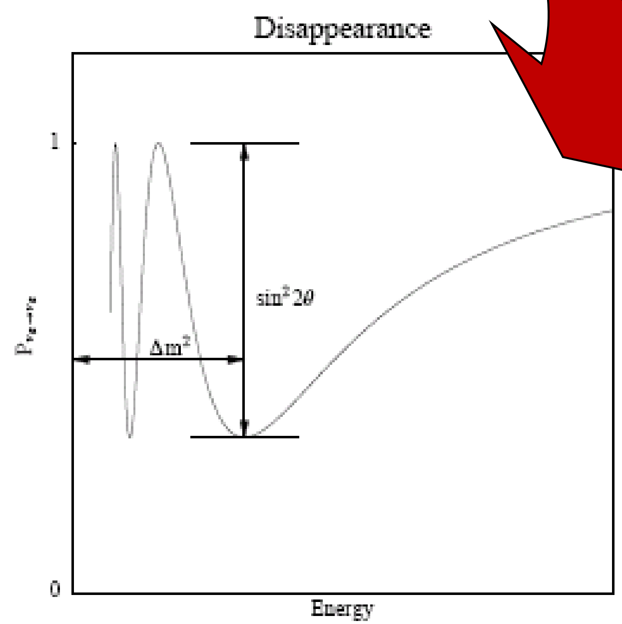
$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$\Phi_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

L – distance from ν source to detector

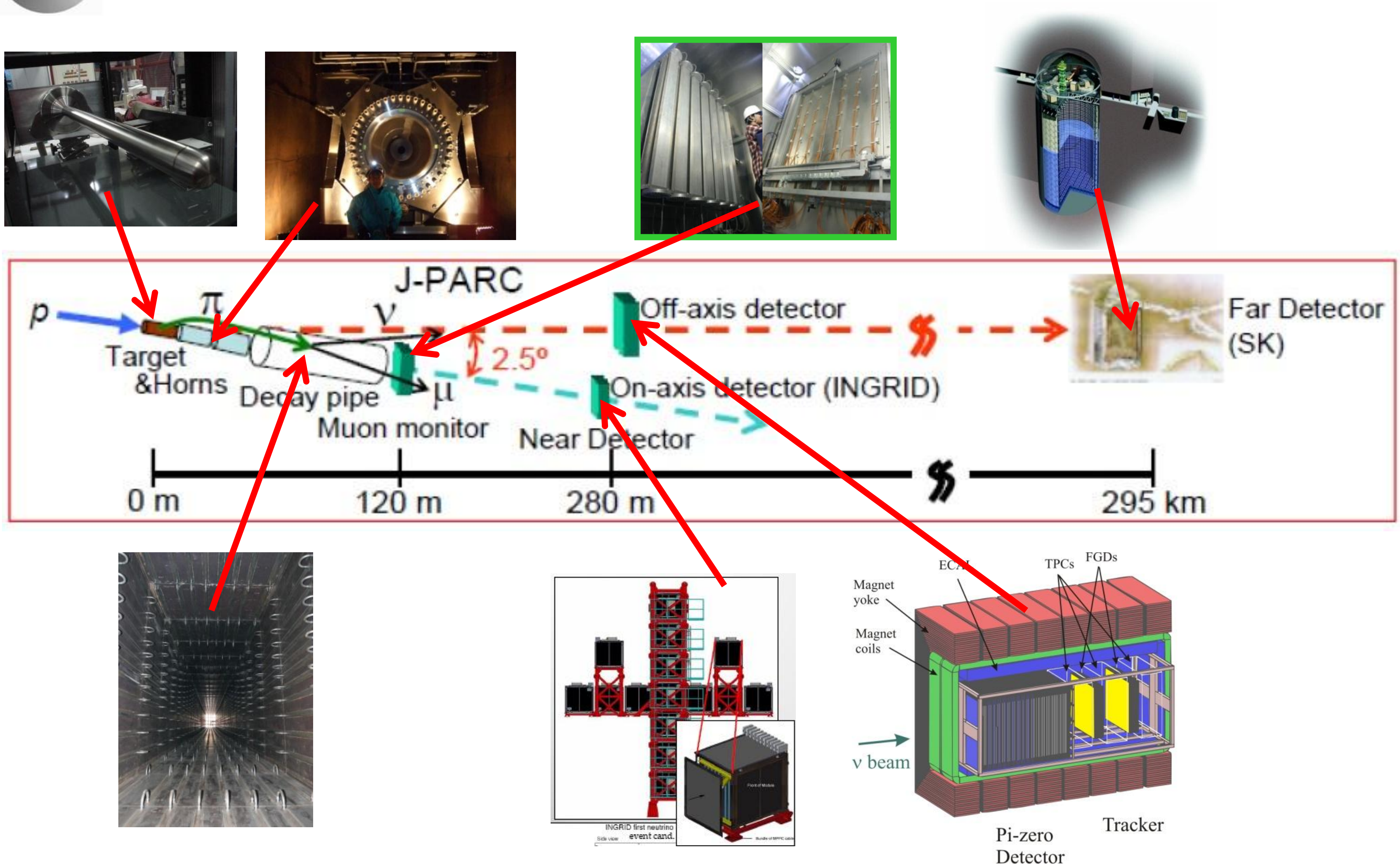
E – neutrino energy



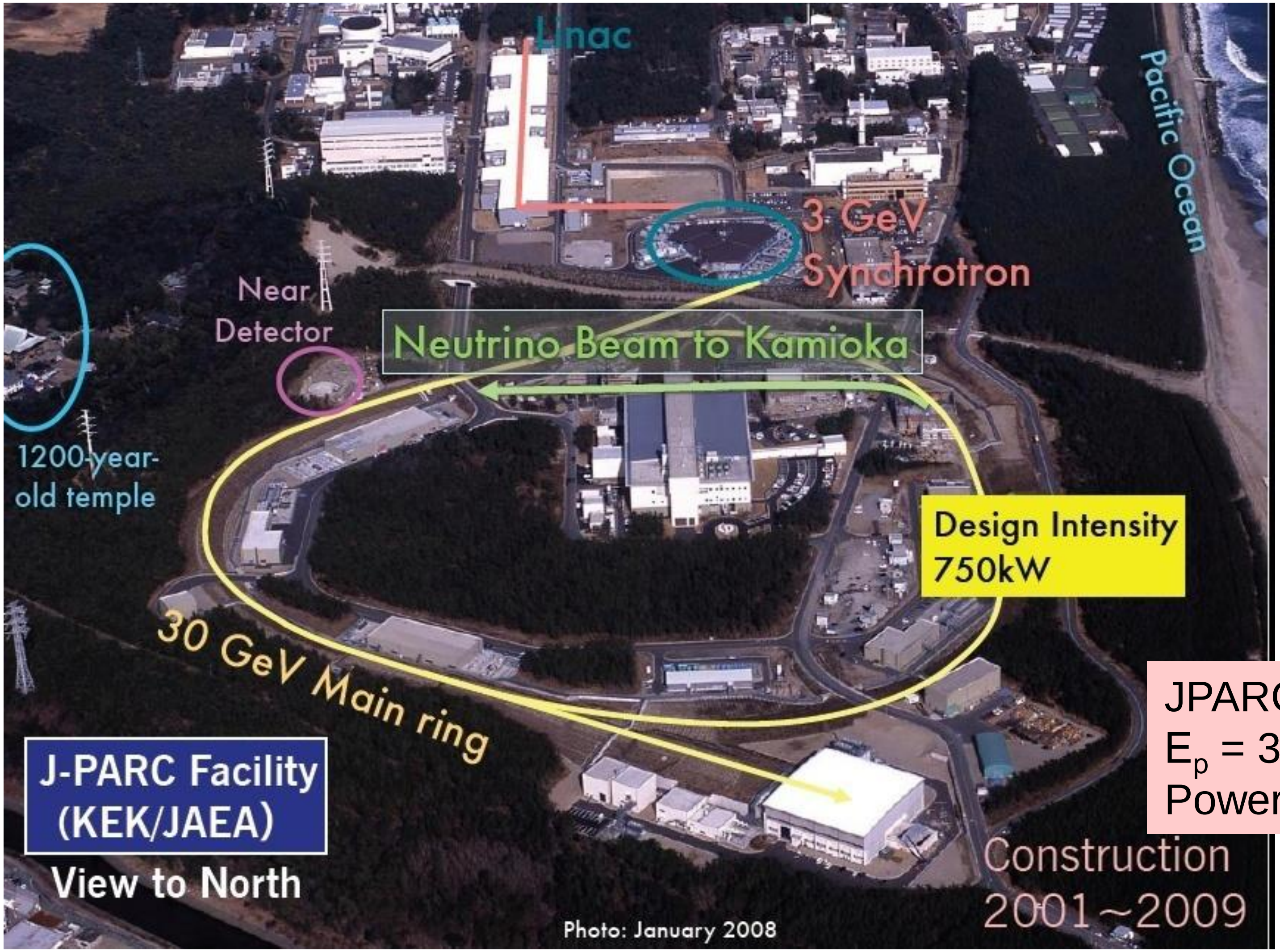


T2K measures both:
- **Appearance** ($\nu_\mu \to \nu_e$)
- **Disappearance** ($\nu_\mu \to \nu_\mu$)

Experiment T2K

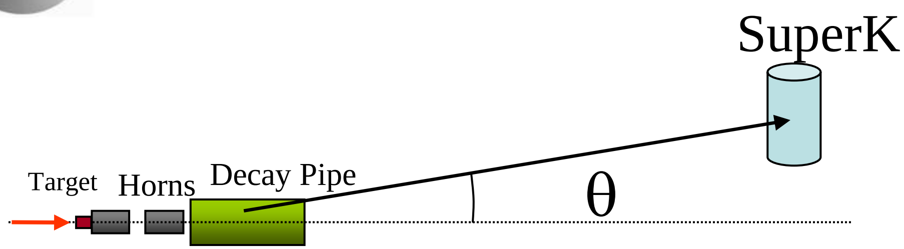


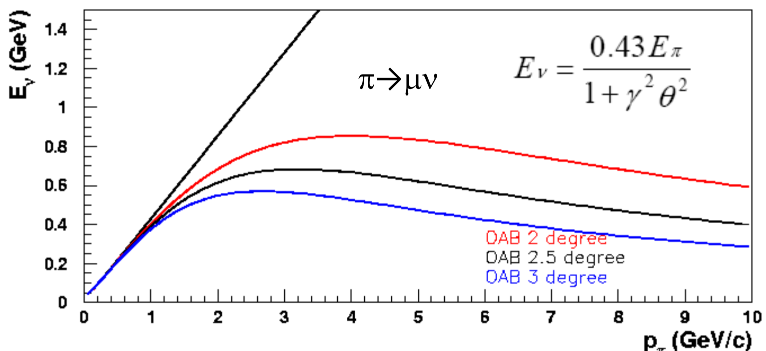
JPARC



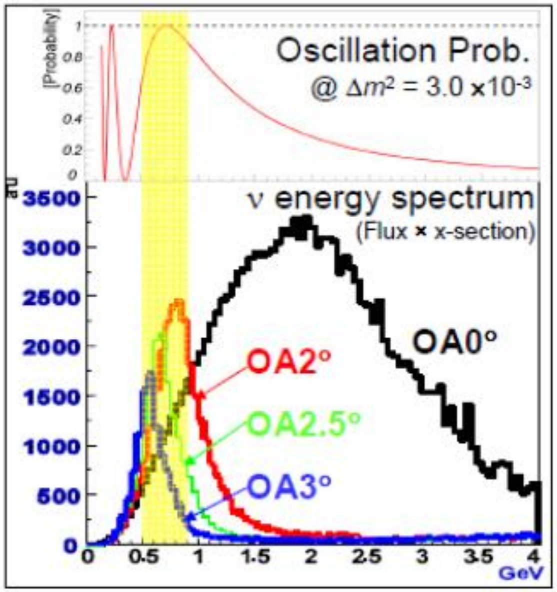
JPARC:
E_p = 30 GeV
Power = 750 kW

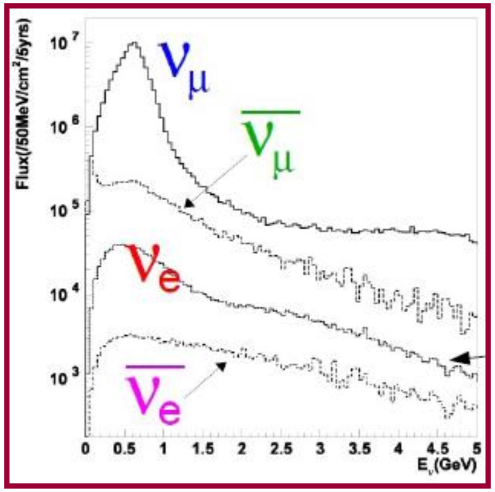
T2K off-axis beam





Off-Axis beam

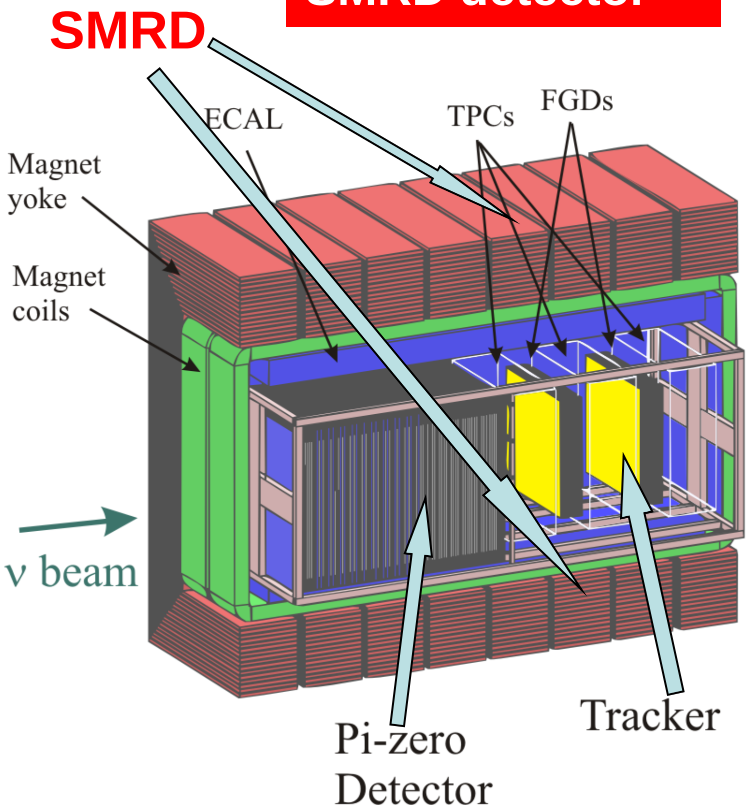




- 750 kW 30 GeV proton beam at JPARC
- Quasi-monochromatic ν_μ (95%) beam
- Peak energy ~700 MeV tuned to oscillation maximum
- ~0.4% ν_e at peak energy
- Reduced high energy tail → reduces background

ND280 off-axis detector

INR contribution: SMRD detector



280m downstream from pion production target

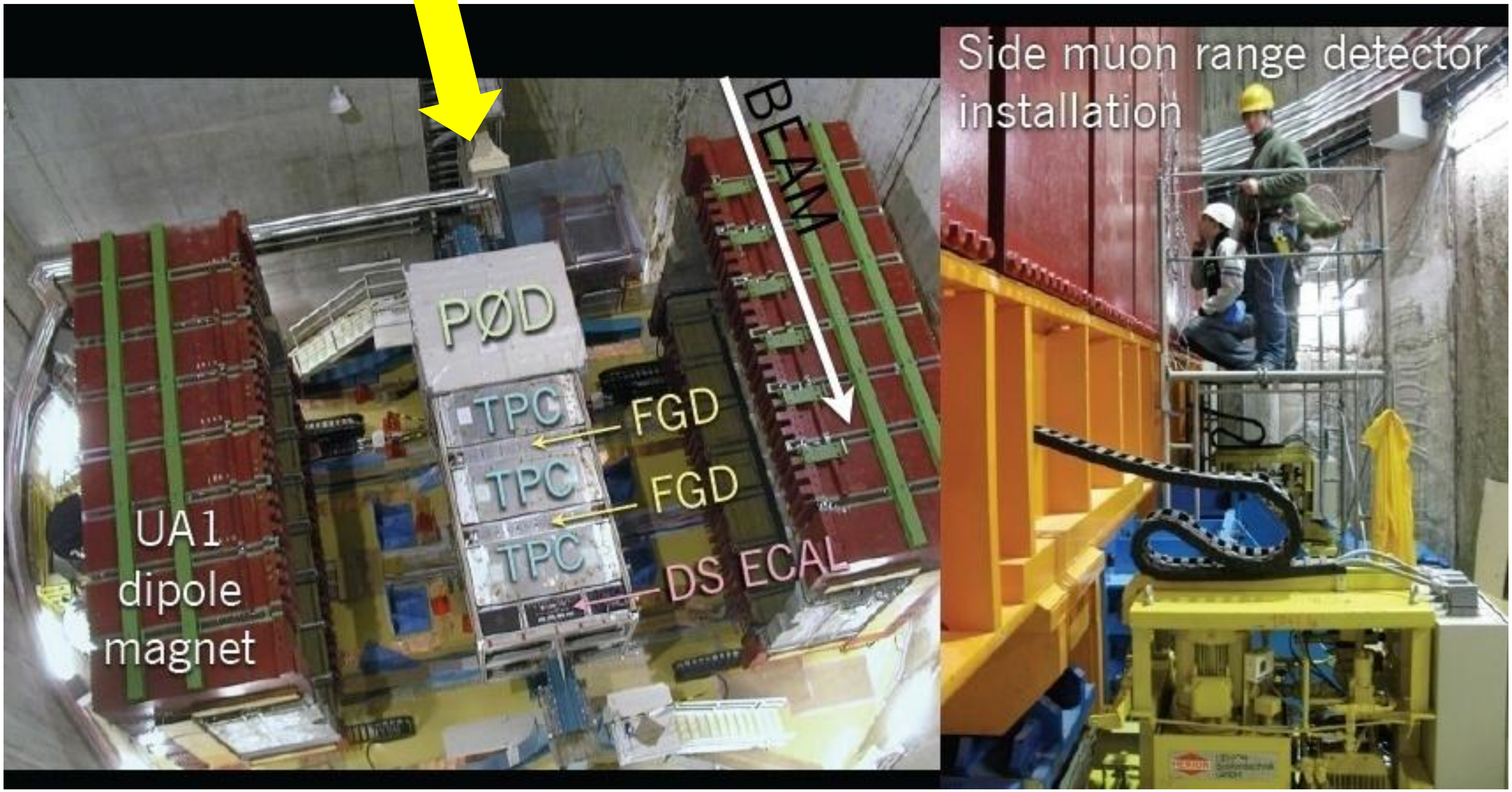
UA1/NOMAD CERN magnet
operated at 0.2 T magnetic field

- Fine Grained Detector (FGD)
  – measure ν beam flux, E_ν spectrum, flavor composition through CC ν-interactions,
  – backgrounds CC-1π
  – water and scintillator target
- Time Projection Chamber (TPC)
  – measure charged particle momenta, particle ID via dE/dx
  – measure backgrounds/pion cross section
- Pi-Zero Detector (P0D)
  – optimized for NC π^0 measurement
  – measure ν_e contamination
- Electromagnetic Calorimeter (ECAL)
  – measure ν_e contamination
  – photon detection (from π^0) in P0D and tracker
  – charge particle ID and reconstruction
- **Side Muon Range Detector (SMRD)**
  – measure momentum for lateral muons
  – cosmic rays trigger
  – background suppression

ND280 off-axis

ν beam

Completed in 2009



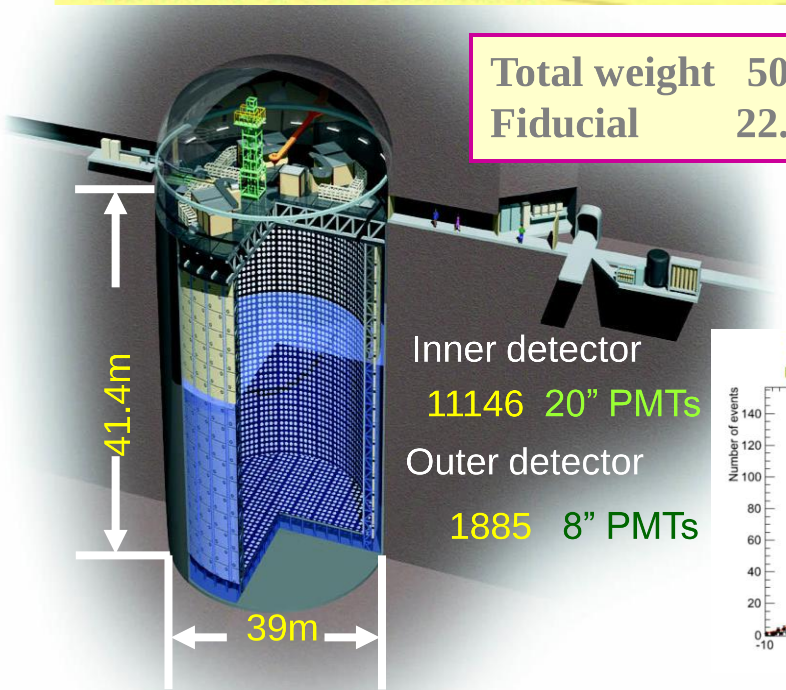
Far detector

Super-Kamiokande IV

- 4π acceptance, very efficient π^0/e separation.
- High Particle ID (μ/e) power (~99% at 600MeV/c)
- Good energy reconstruction.
- Methods are established.

~11000 PMTs
with FRP+Acrylic cover
40% photo-coverage

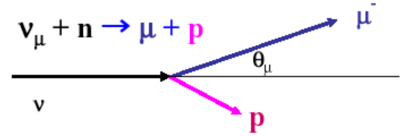
Total weight	50 kt
Fiducial	22.5 kt



Inner detector
11146 20" PMTs
Outer detector
1885 8" PMTs

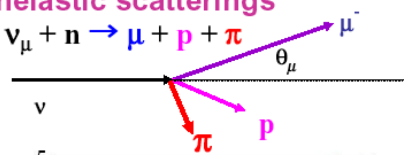
CC quasi elastic scatterings

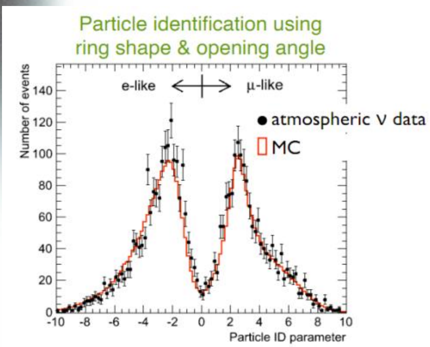
$\nu_\mu + n \rightarrow \mu + p$



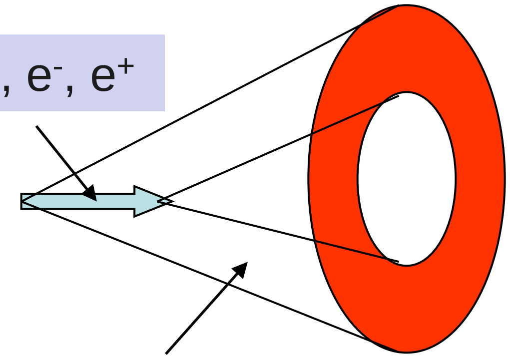
Inelastic scatterings

$\nu_\mu + n \rightarrow \mu + p + \pi$





μ^-, e^-, e^+



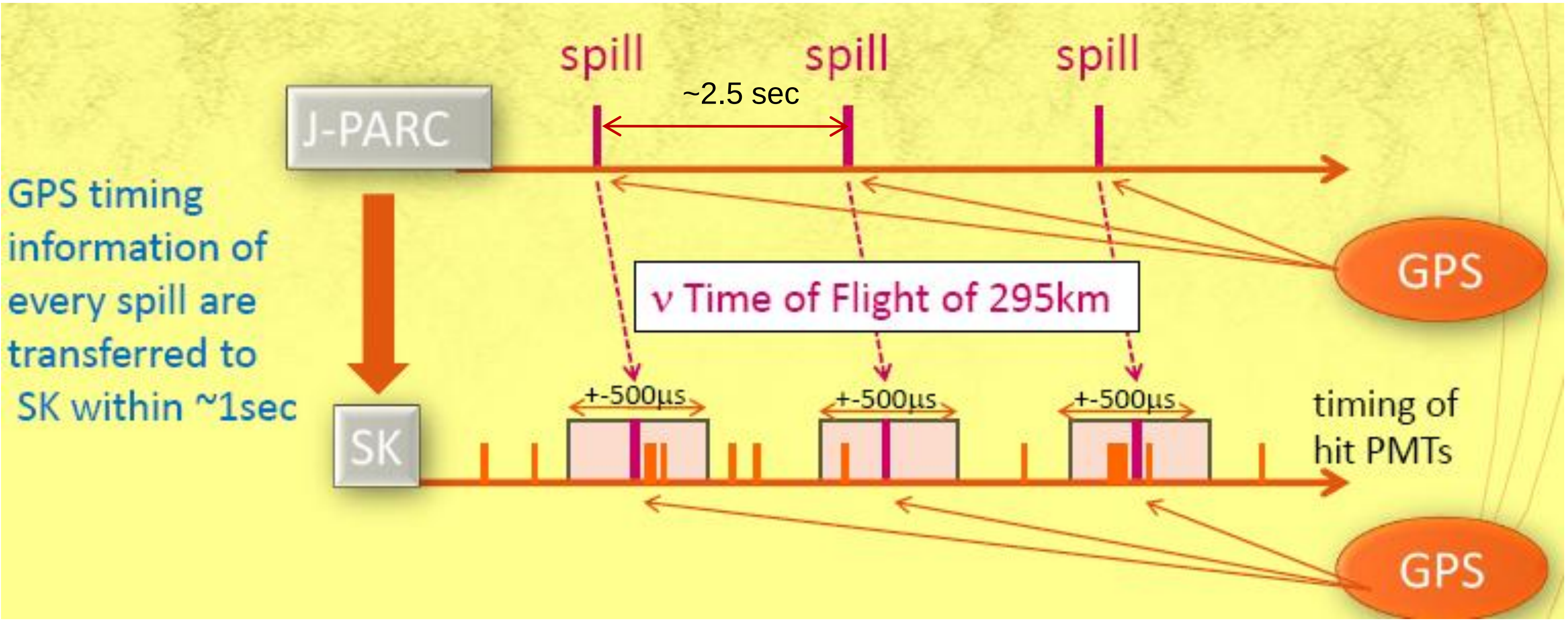
Cherenkov cone

Main backgrounds:
π^0 from neutral currents – suppression factor ~100
ν_e contamination in ν_μ beam - ~0.4% at peak energy

T2K Timing

L = 295 км
TOF = 985 μs
GPS stability ~50 ns

Each spill has 8 microbunches
56 ns width
580 ns separation



Analysis principles

Flux prediction:
- proton beam measurements
- hadron production data (NA61 CERN)

ND280 measurements:
- inclusive CC ν_μ → $R\mu^{ND,Data}/R\mu^{ND,MC}$
- ν_e rate measurement as a cross-check

Neutrino interactions:
- ν interactions models
- external cross-section data

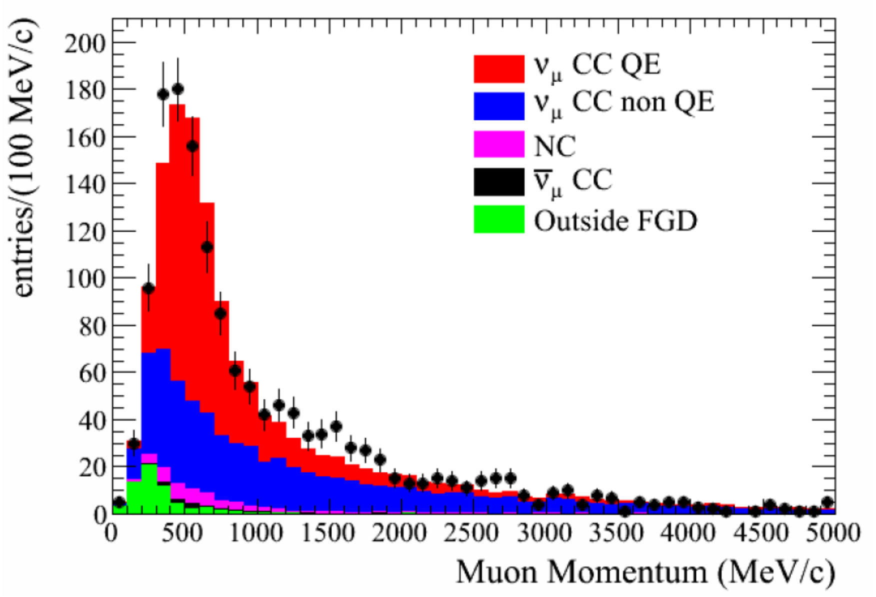
Super-K measurements:
- select CCQE ν_μ and ν_e candidates
- compute NSK^{MC} w/o oscillations
- normalize NSK^{MC} using ND280 measurements →

$NSK^{exp}=(R\mu^{ND,Data}/R\mu^{ND,MC})\times NSK^{MC}$

- evaluate oscillations parameters by comparing with NSK^{obs}
  - ν_e: number of events
  - ν_μ: number of events and E spectra shape combined

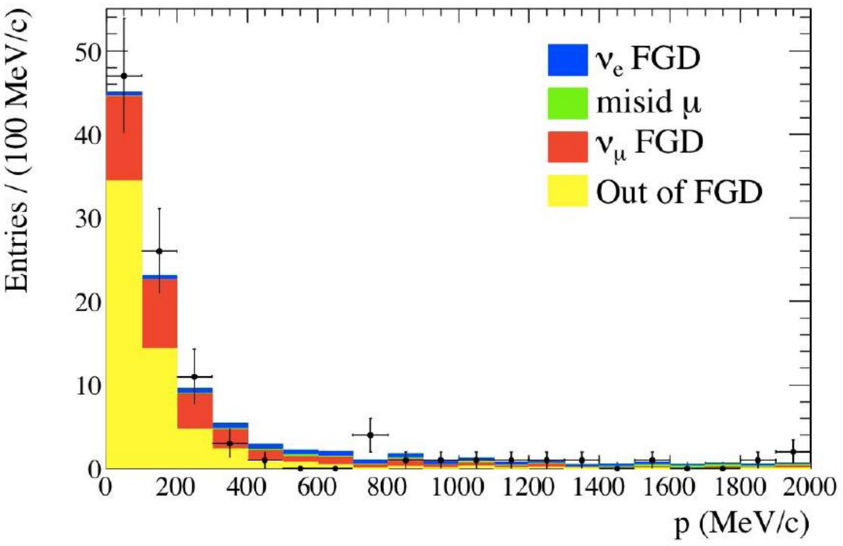
ND280 input

Inclusive ν_μ CC quasielastic



$$\frac{N_{ND}^{obs}}{N_{ND}^{MC}} = 1.036 \pm 0.028(\text{stat})^{+0.044}_{-0.037}(\text{det. syst}) \pm 0.038(\text{phys. model})$$

Intrinsic beam ν_e component



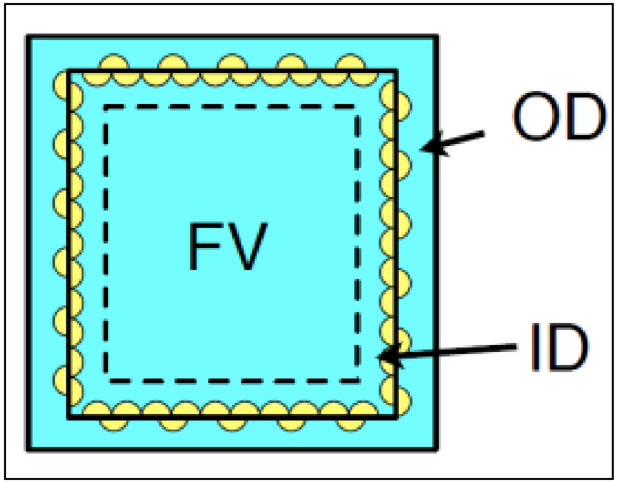
$$R(\nu_e/\nu_\mu) = (1.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}))\%$$

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

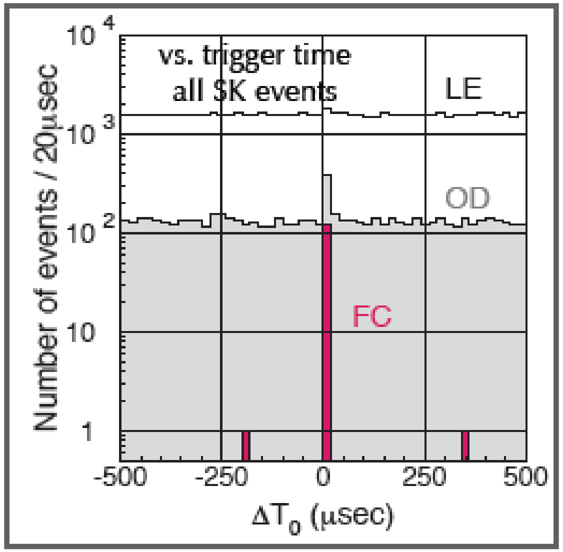
Event selection in SK (I)

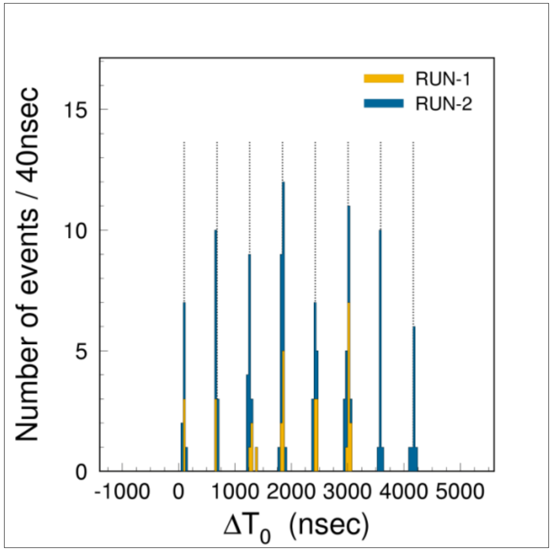
Event selection for both ν_μ and ν_e:

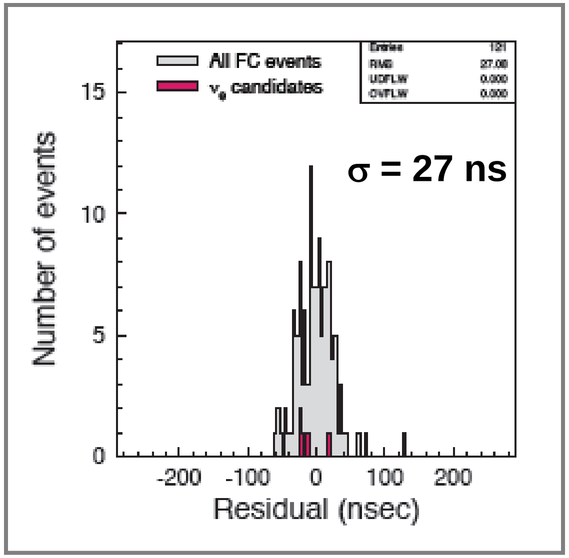
- SK synchronized to beam timing using GPS
- Fully contained (FC) events in the Inner Detector, minimal activity in the Outer Detector
- Vertex in Fiducial Volume (FCFV)
- Number of rings = 1
- PID algorithm to distinguish e-like and μ-like events



121 FC events



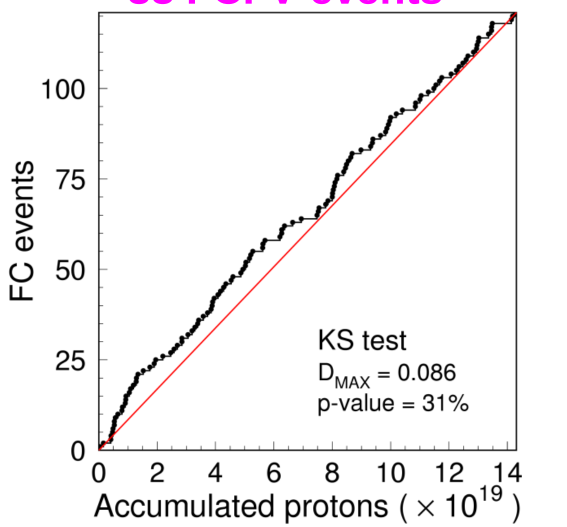




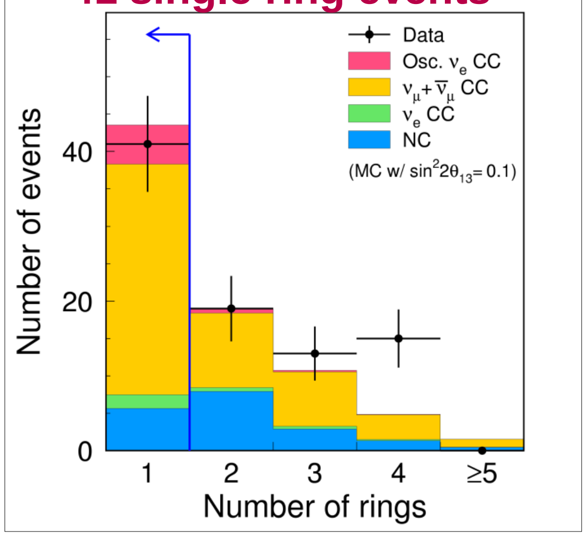
Event selection in SK (II)

Fiducial Volume Full Contained events (FCFV) → **Number of rings = 1** → **PID: e-like and μ-like events**

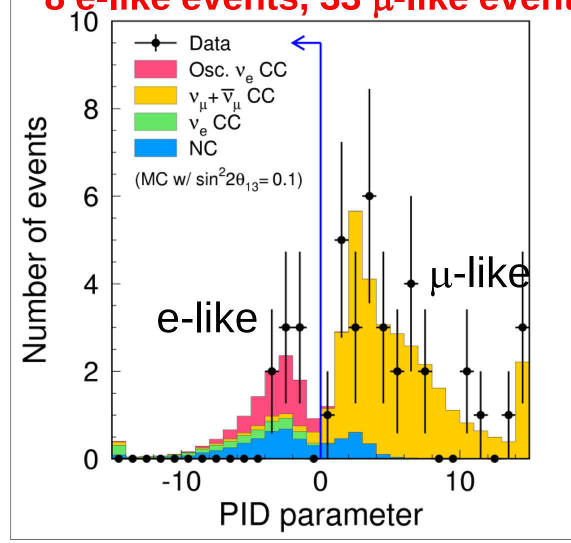
88 FCFV events



41 single ring events



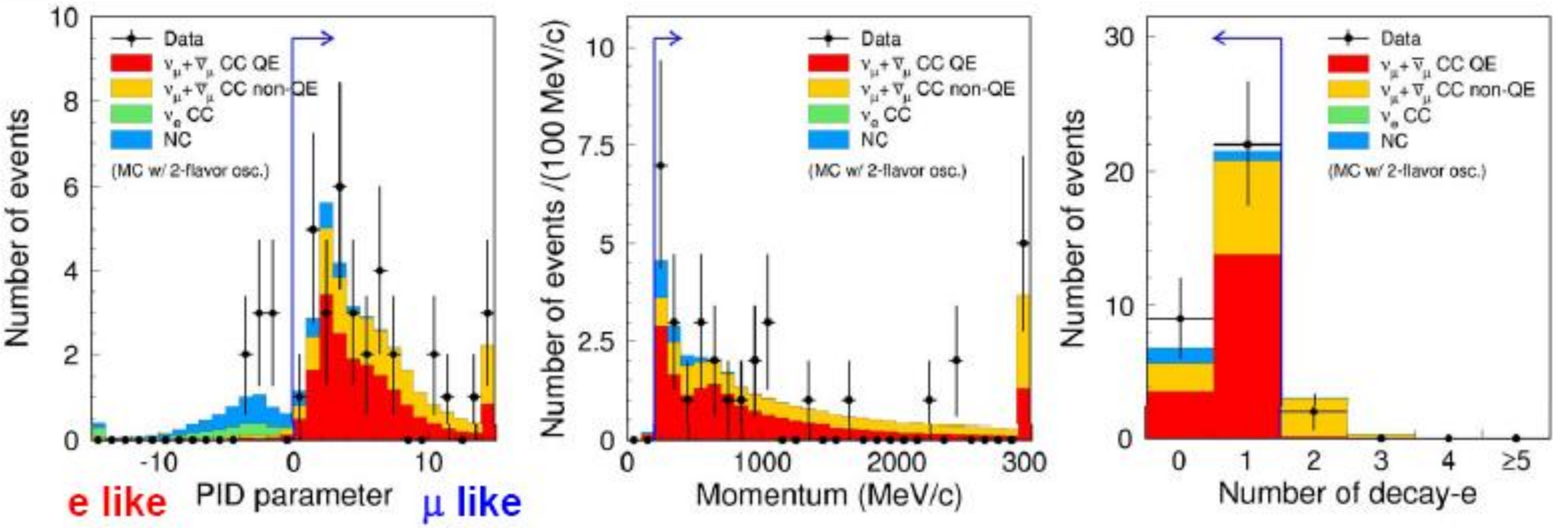
8 e-like events, 33 μ-like events



8 e-like events and 33 μ-like events

ν_μ disappearance

ν_μ events

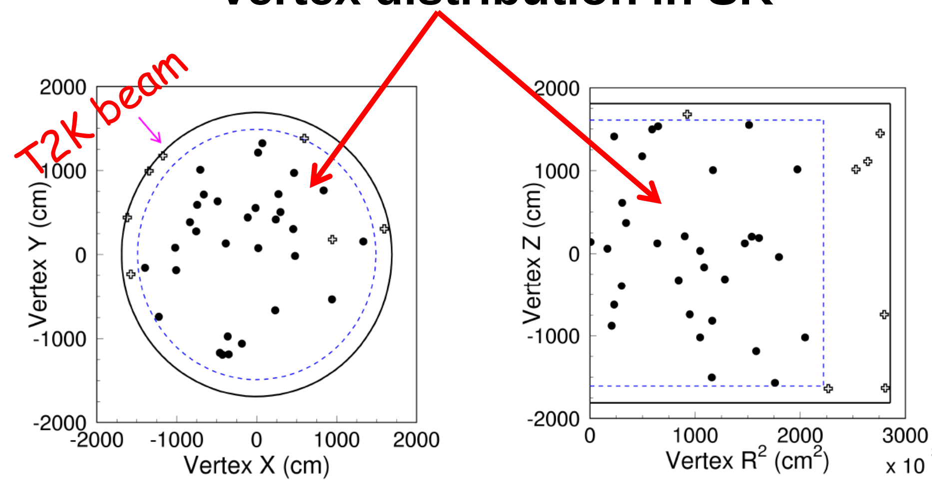


Cut Sequence for ν_μ CCQE

Criteria	# of events
single ring μ-like	33
muon momentum p_μ > 200 MeV/c	33
# of decay electron < 2	31

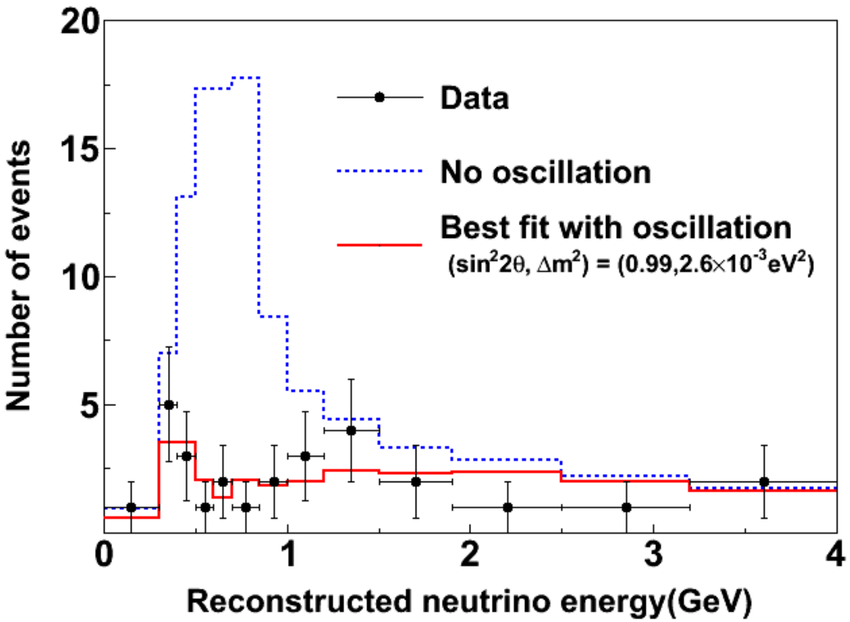
103.6 ν_μ **events in case of no oscillation**

Vertex distribution in SK

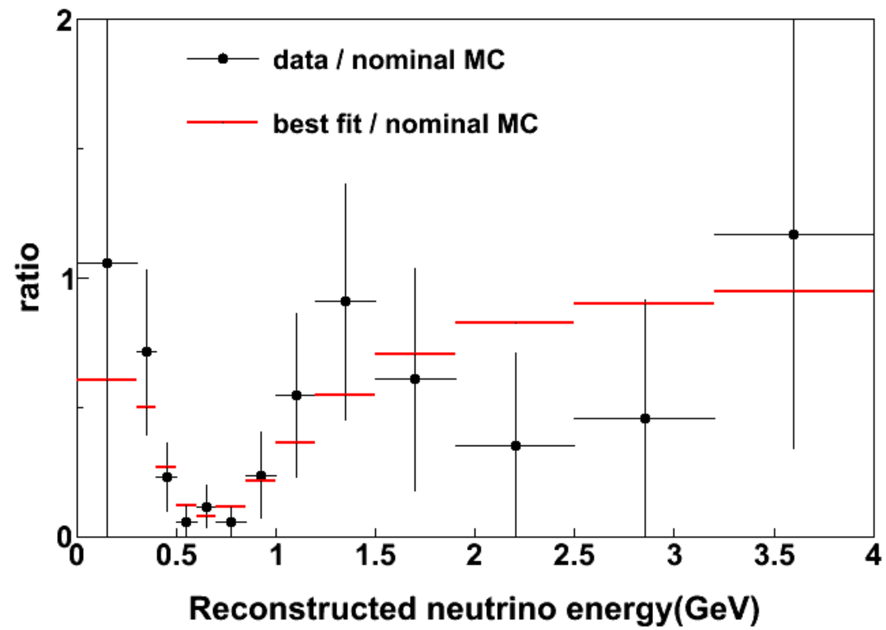


ν_μ disappearance

Reconstructed E_ν



Reconstructed E_ν
ratio: data/ MC (w/o oscillation)



No oscillation hypothesis excluded at 4.5σ

Systematic uncertainties

Systematics on SK expected events

$N^{SK}_{exp.}$ error table

Error source	$\sin^2 2\theta = 1.0, \Delta m^2 = 2.4$	Null Oscillation
SK Efficiency	+10.3% 10.3%	+5.1% -5.1%
Cross section and FSI	+8.3% -8.1%	+7.8% -7.3%
Beam Flux	+4.8% -4.8%	+6.9% -5.9%
ND Efficiency and Overall Norm.	+6.2% -5.9%	+6.2% -5.9%
Total	+15.4% -15.1%	+13.2% -12.7%

Oscillation result

Two independent oscillation fits
Both use Feldman-Cousins unified method
Maximum likelihood (method A) and likelihood ratio (Method B)

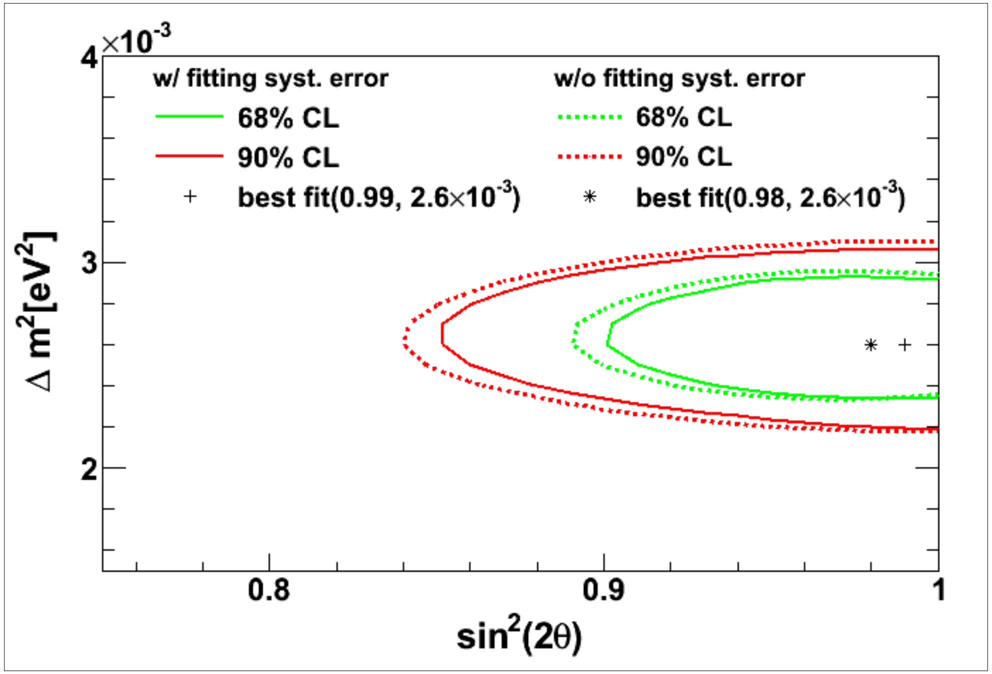
Method A:
Best fit:
$\sin^2(2\theta_{23})=0.99$, $|\Delta m^2_{23}|=2.6\text{x}10^{-3}$ eV^2

$\sin^2(2\theta_{23})>0.85$
$2.1\text{x}10^{-3}<|\Delta m^2_{23}|(\text{eV}^2)<3.1\text{x}10^{-3}$

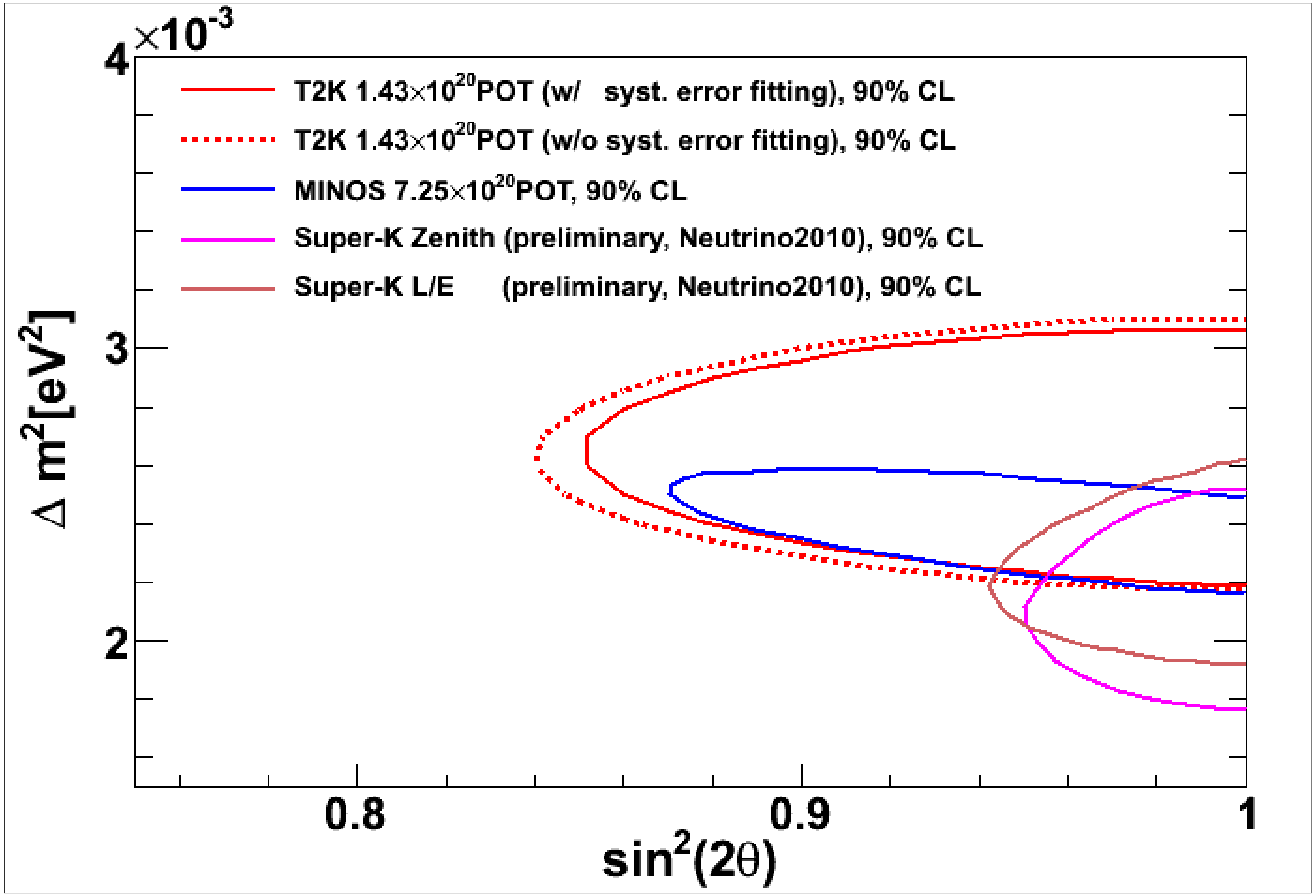
Method B:
Best fit:
$\sin^2(2\theta_{23})=0.98$, $|\Delta m^2_{23}|=2.6\text{x}10^{-3}$ eV^2

$\sin2(2\theta_{23})>0.84$
$2.1\text{x}10^{-3}<|\Delta m^2_{23}|(\text{eV}^2)<3.1\text{x}10^{-3}$

Very good consistency between the two fits



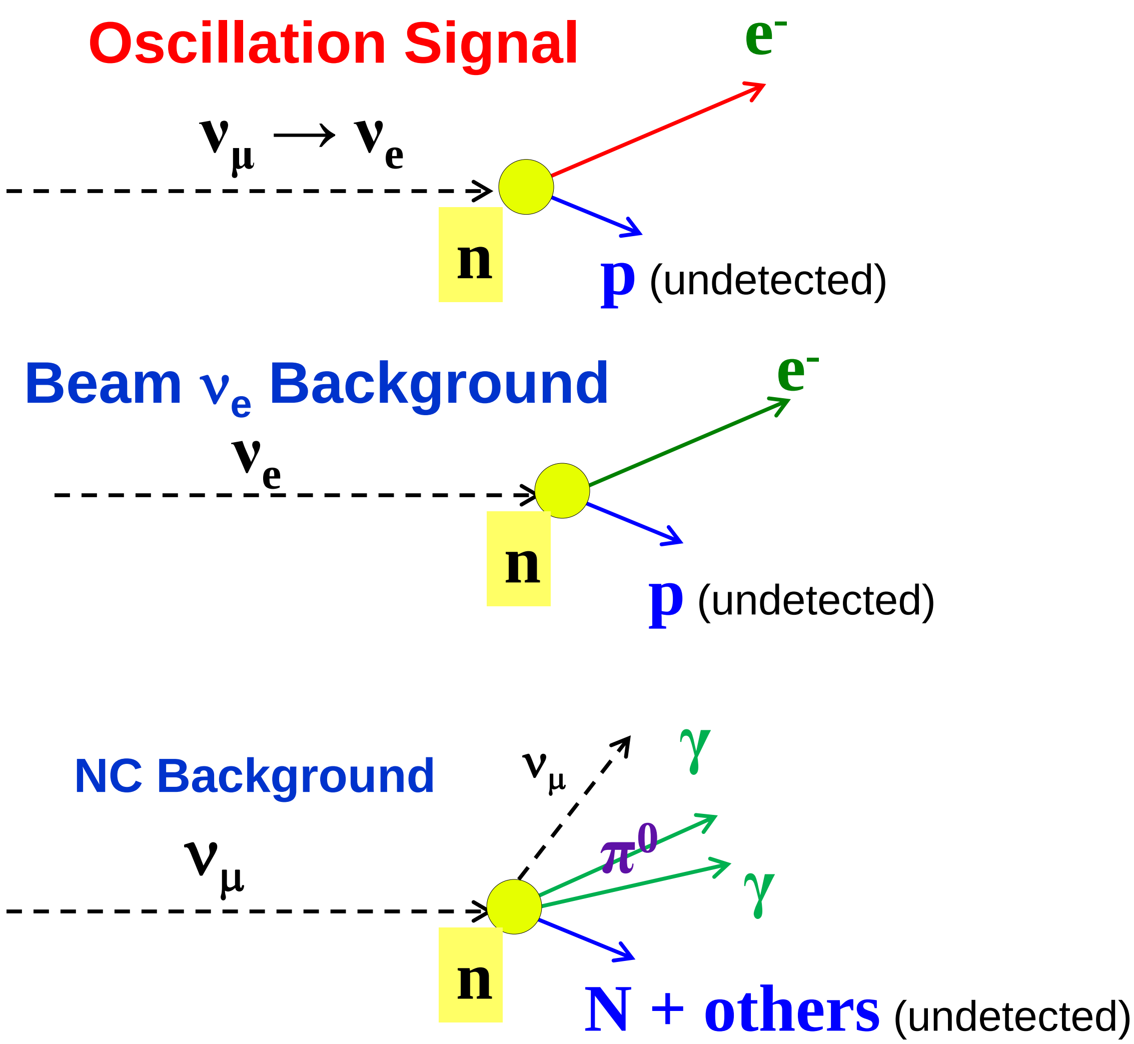
T2K, SK and MINOS

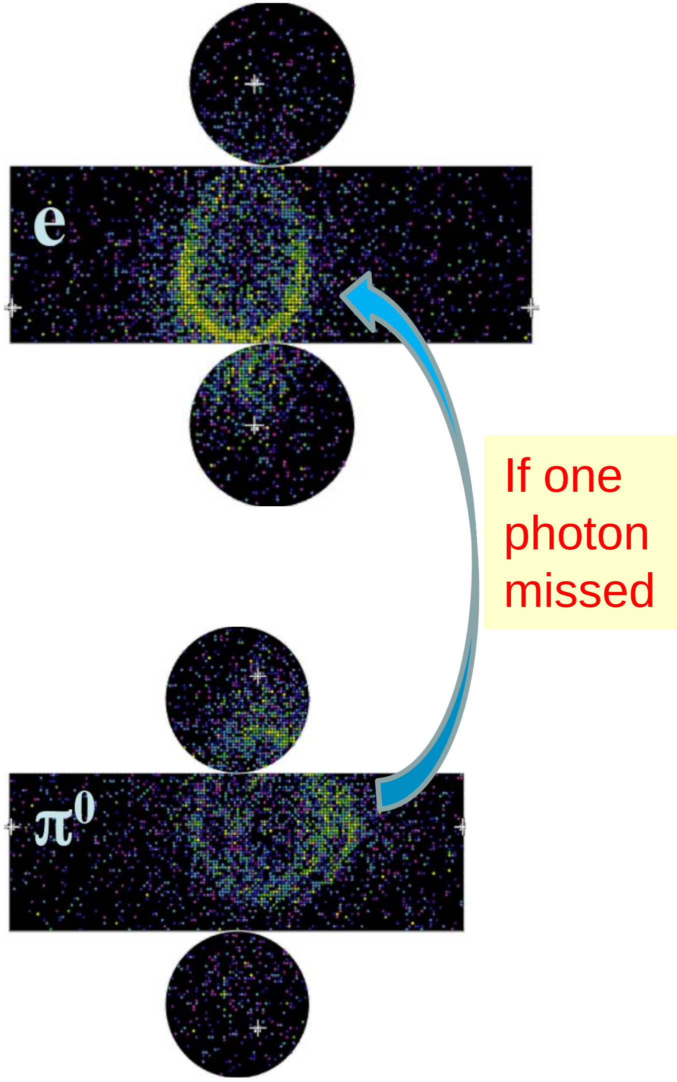


T2K result is in a good agreement with SK and MINOS

ν_e appearance

ν_e Signal & Background at SK





ν_e events

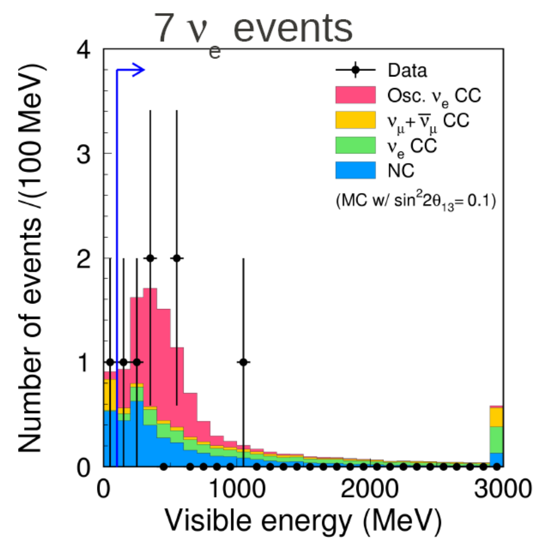
Energy deposited in ID >100 MeV→ 7 events

8 e-like single-ring FCFV events after "basic" selection criteria

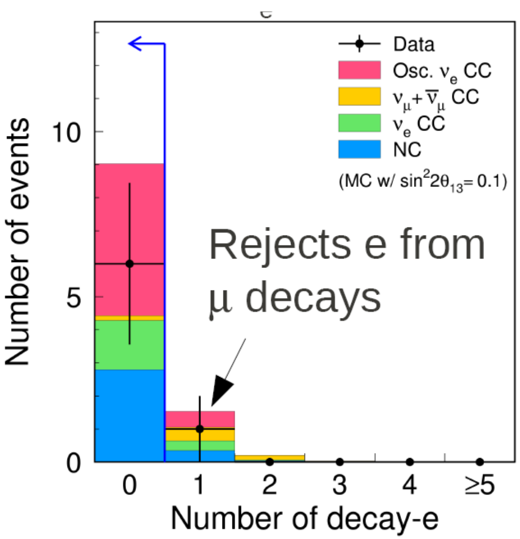
T2K ν_e selection cuts in SK optimized for intrinsic beam ν_e and NCπ^o background minimization

After all cuts:

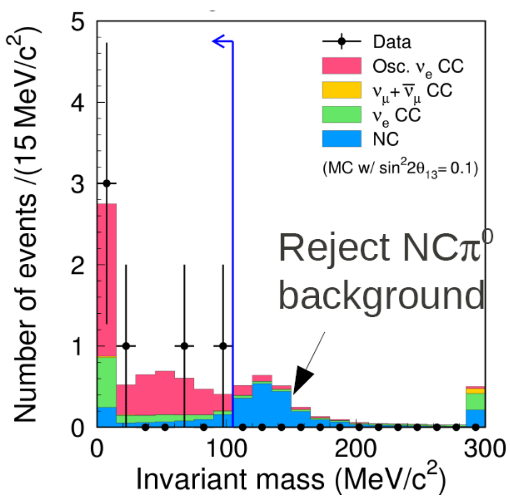
- signal efficiency 66%
- intrinsic νe rejection 77%
- NC background rejection 99%



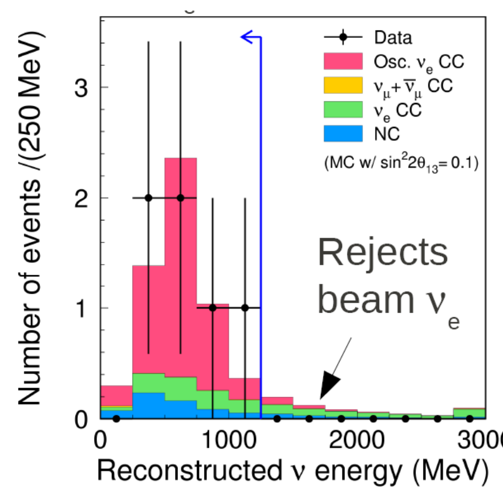
No Michel electrons → 6 events



Force reconstruction to fit two e-like rings assumption, require Minv<105 MeV → 6 events



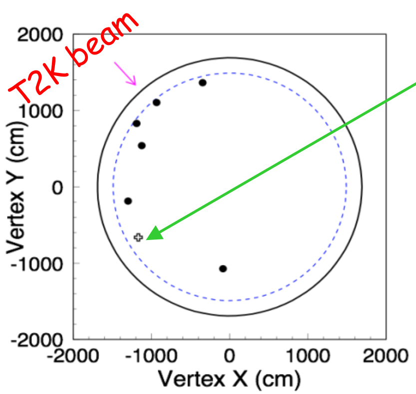
Reconstructed neutrino energy <1250 MeV → 6 events

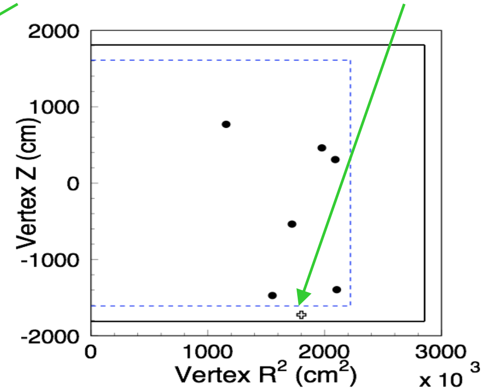


ν_e vertex distributions

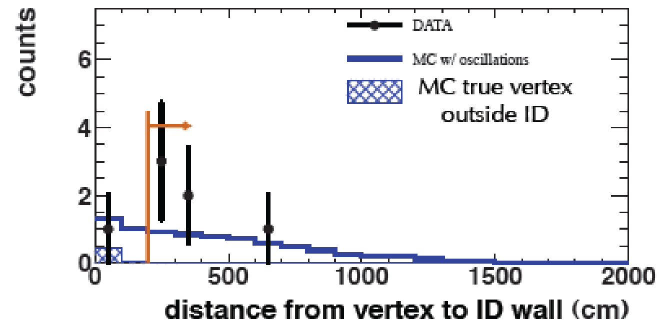
After all cuts 6 final candidate events remained!

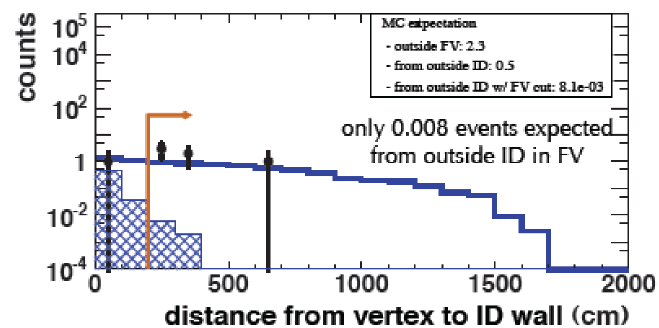
Event outside SK FV



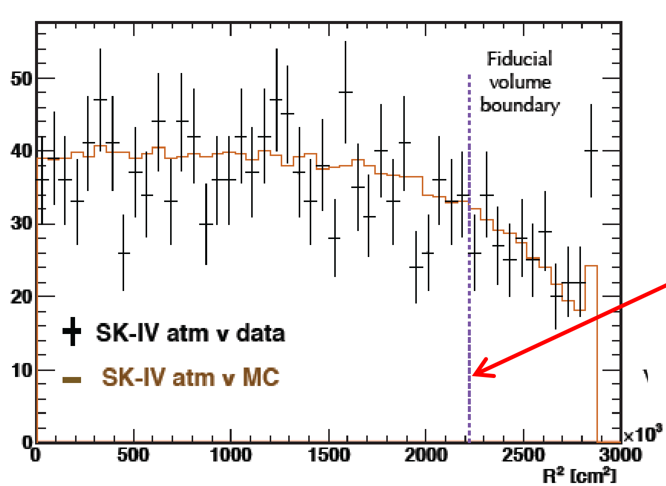


Vertex distribution
tests using MC





T2K-like event selections used



SK atm data and MC agree well near FV boundary

Selected events clustering at large R
KS: 0.03 p-value for such R^2 distribution

Expected background

1.5 ν_e candidates expected with zero θ_{13} hypothesis

	Beam ν_e background	NC background	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	Total
The expected # of events at SK	0.8	0.6	0.1	1.5

Systematic uncertainties

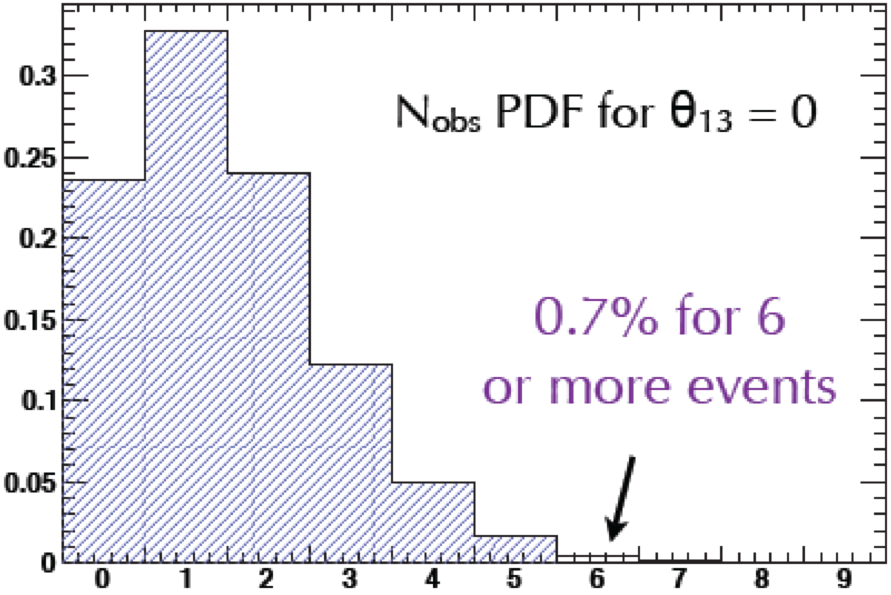
Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

Smaller cross-section and SK uncertainties for signal events

$$N^{exp}_{SK,total} = 1.5 \pm 0.3 \;\; (\textit{for accumulated}\; 1.43 \times 10^{20}\; p.o.t.)$$

Significance

Observed 6 Events, with 1.5±0.3 events background at $\theta_{13} = 0$

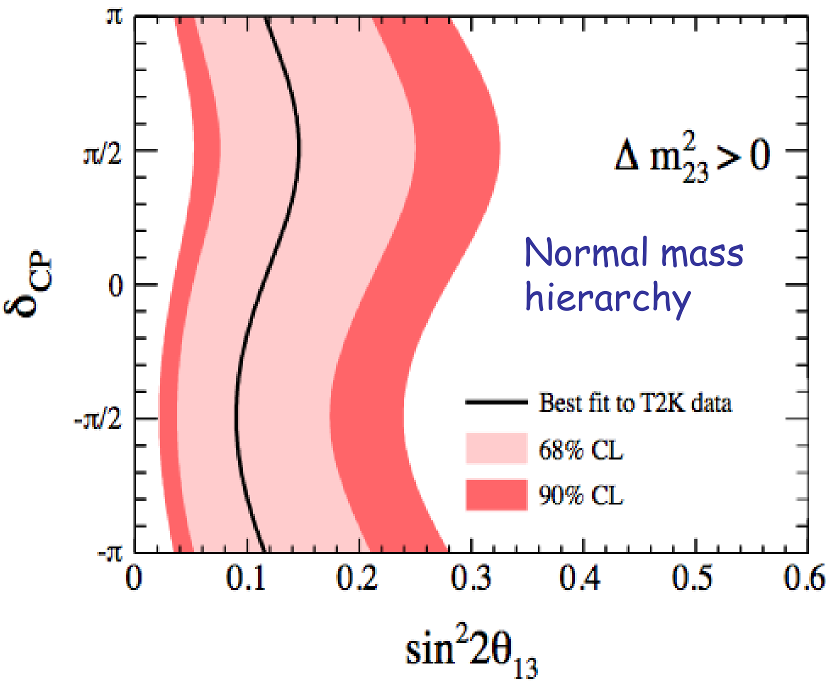


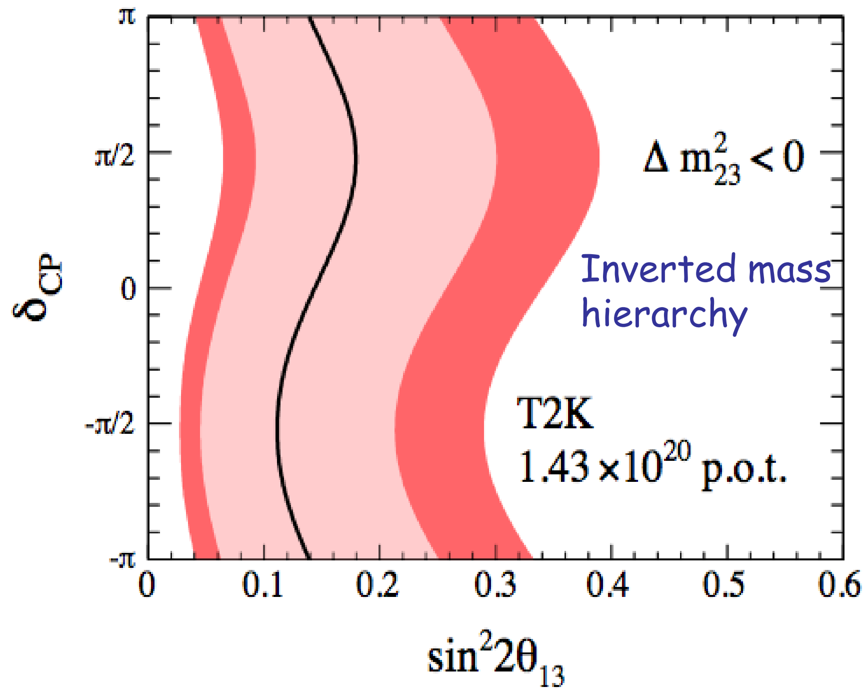
p-value of 0.7%
2.5σ significance

- Clear signal of ν_e appearance
- Indication of large θ_{13}

θ_{13}

Feldman-Cousins method to produce confidence intervals for $\sin^2 2\theta_{23}=1.0$ and $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2





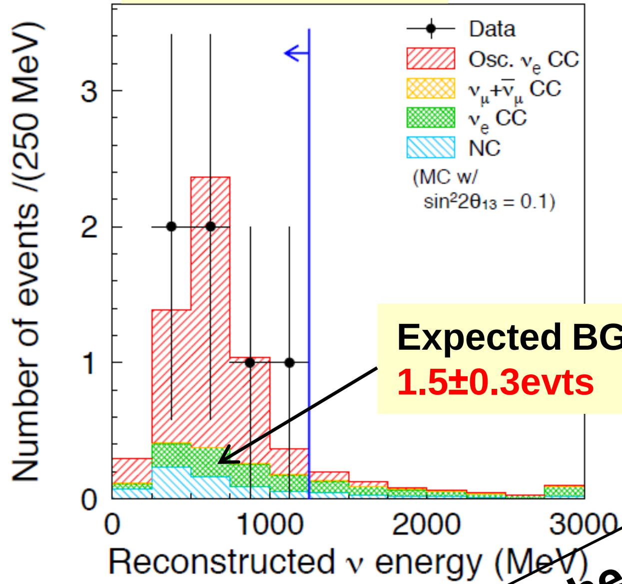
Normal mass hierarchy and $\delta_{CP}=0$:

- best fit: $\sin^2 2\theta_{23}=0.11$
- $0.03<\sin^2 2\theta_{23}<0.28$ at 90% C.L.

Inverted mass hierarchy and $\delta_{CP}=0$:

- best fit: $\sin^2 2\theta_{23}=0.14$
- $0.04<\sin^2 2\theta_{23}<0.34$ at 90% C.L.

6 ν_e events



Expected BG
1.5±0.3evts

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

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

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

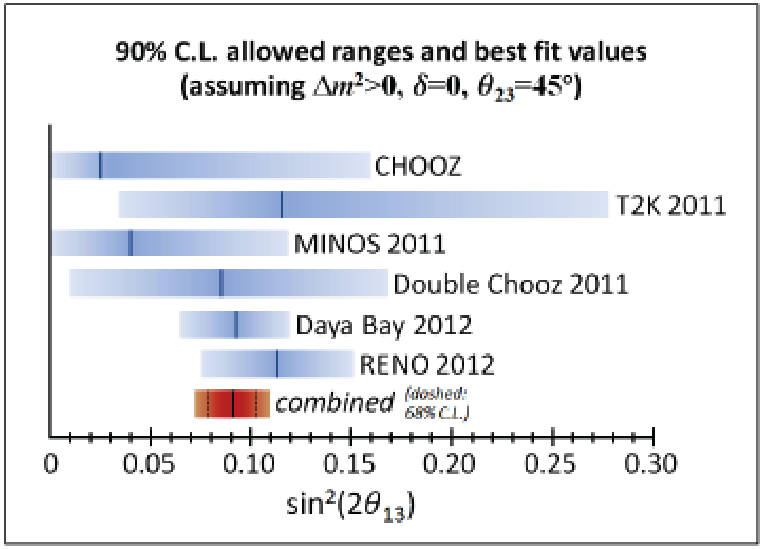
K. Abe,[49] N. Abgrall,[16] Y. Ajima,[18,†] H. Aihara,[48] J. B. Albert,[13] C. Andreopoulos,[47] B. Andrieu,[37] S. Aoki,[27] O. Araoka,[18,†] J. Argyriades,[16] A. Ariga,[3] T. Ariga,[3] S. Assylbekov,[11] D. Autiero,[32] A. Badertscher,[15] M. Barbi,[40] G. J. Barker,[56] G. Barr,[36] M. Bass,[11] F. Bay,[3] S. Bentham,[29] V. Berardi,[22] B. E. Berger,[11] I. Bertram,[29] M. Besnier,[14] J. Beucher,[8] D. Beznosko,[34] S. Bhadra,[59] F. d.M. M. Blaszczyk,[8] A. Blondel,[16] C. Bojechko,[53] J. Bouchez,[8,*] S. B. Boyd,[56] A. Bravar,[16] C. Bronner,[14] D. G. Brook-Roberge,[5] N. Buchanan,[11] H. Budd,[41] D. Calvet,[8] S. L. Cartwright,[44] A. Carver,[56] R. Castillo,[19] M. G. Catanesi,[22] A. Cazes,[32] A. Cervera,[20] C. Chavez,[30] S. Choi,[43] G. Christodoulou,[30] J. Coleman,[30]

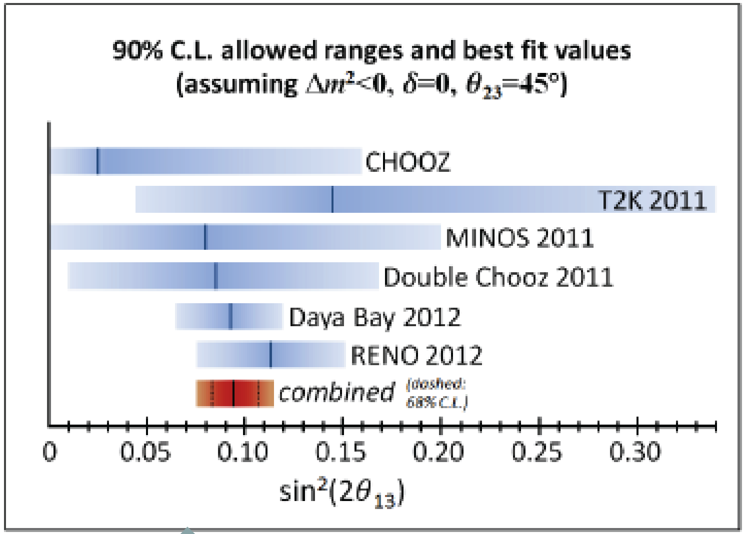
The T2K experiment observes indications of $\nu_\mu \rightarrow \nu_e$ appearance in data accumulated with 1.43×10^{20} protons on target. Six events pass all selection criteria at the far detector. In a three-flavor neutrino oscillation scenario with $|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$ 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

θ_{13} landscape

5 experiments published θ_{13} results since June 2011



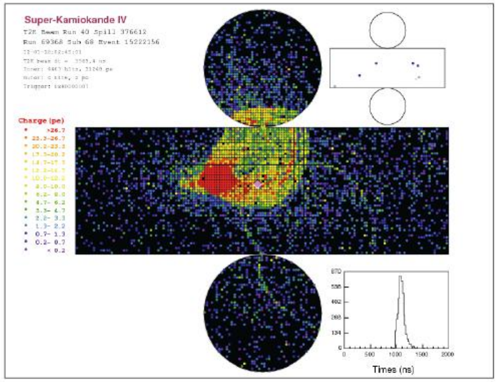


$\theta_{13} \approx 9^o$

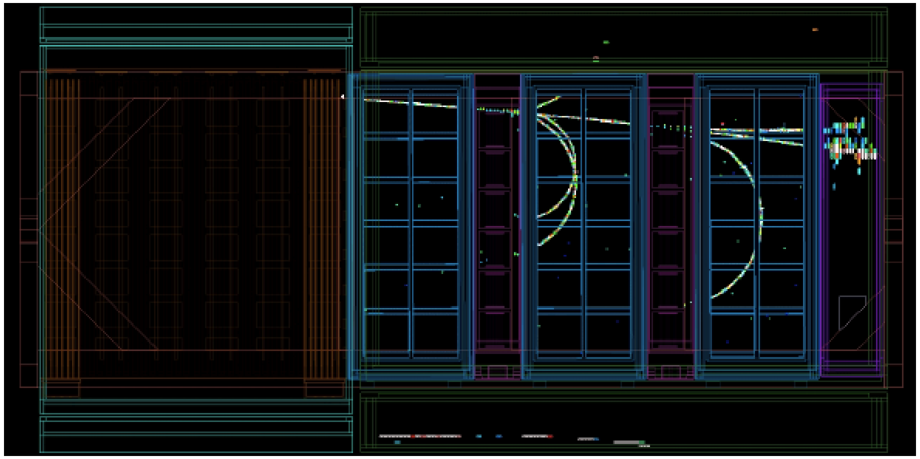
Recovering from 11 March Earthquake

- JPARC resumed operation in December 2011
- Neutrino beam is back in December 2011
- T2K short test run in January 2012
- Data taking since March 2012

First ν event at SK



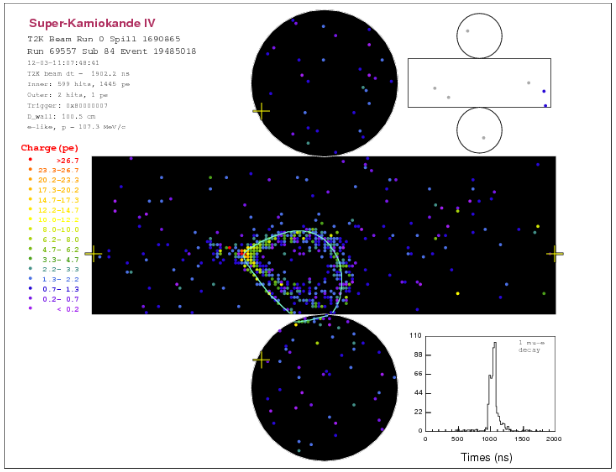
Event seen in T2K on 26th January 2012



ND280 off-axis event on 23-1-2012 (beam spill)

First ν event in ND280

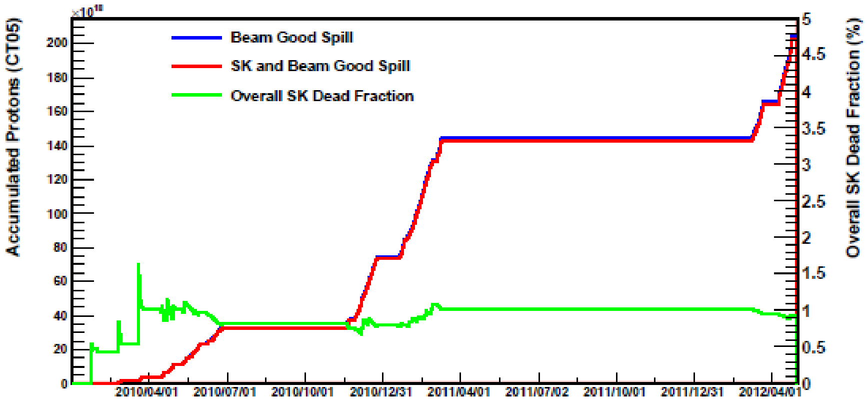
First FC ν event at SK

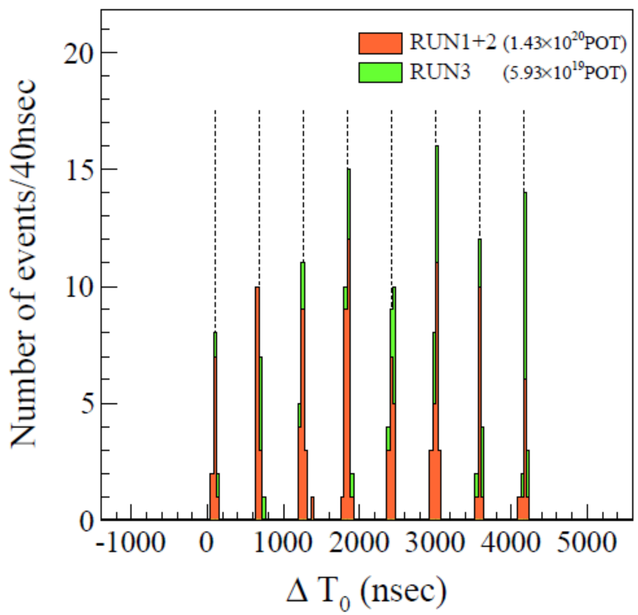


T2K status

25 April 2012

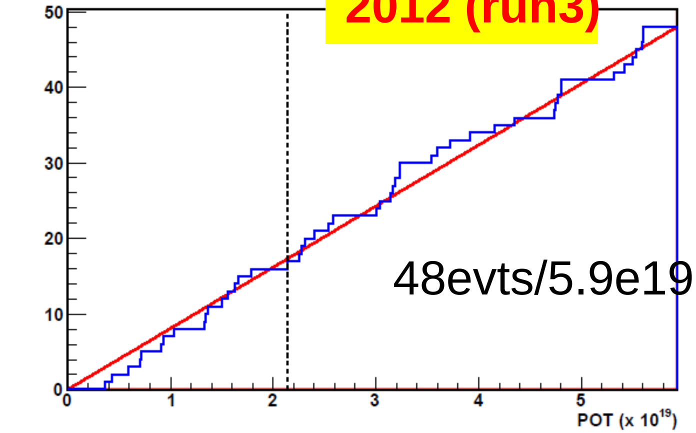
SK running efficiency > 99%



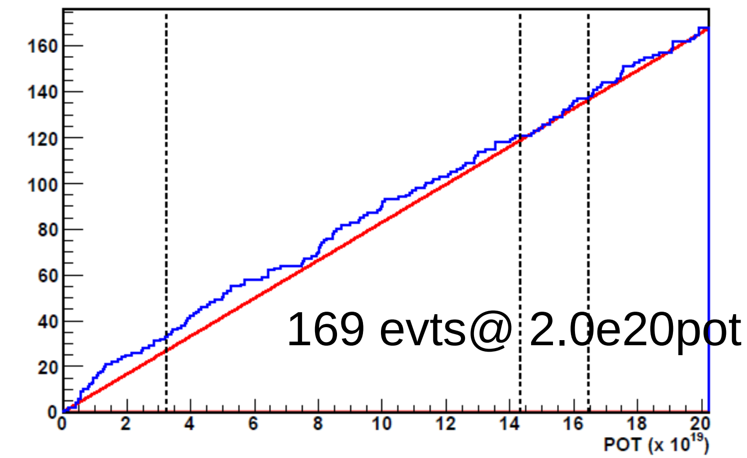


ν events at SuperKamiomande

2012 (run3)



(2010-2012)



Taking high quality data very efficiently

Near Future

- T2K will double statistics by June 2012

- Improve analysis, reduce systematics

- New appearance result will be presented at *NEUTRINO-2012* and *QUARKS-2012*

θ_{13} is large, what's next?

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \; = \; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2\Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta) \cdot \sin^2\Delta_{21} \\
& -8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2}(1 - 2S_{13}^2)\sin^2\Delta_{31}
\end{aligned}
$$

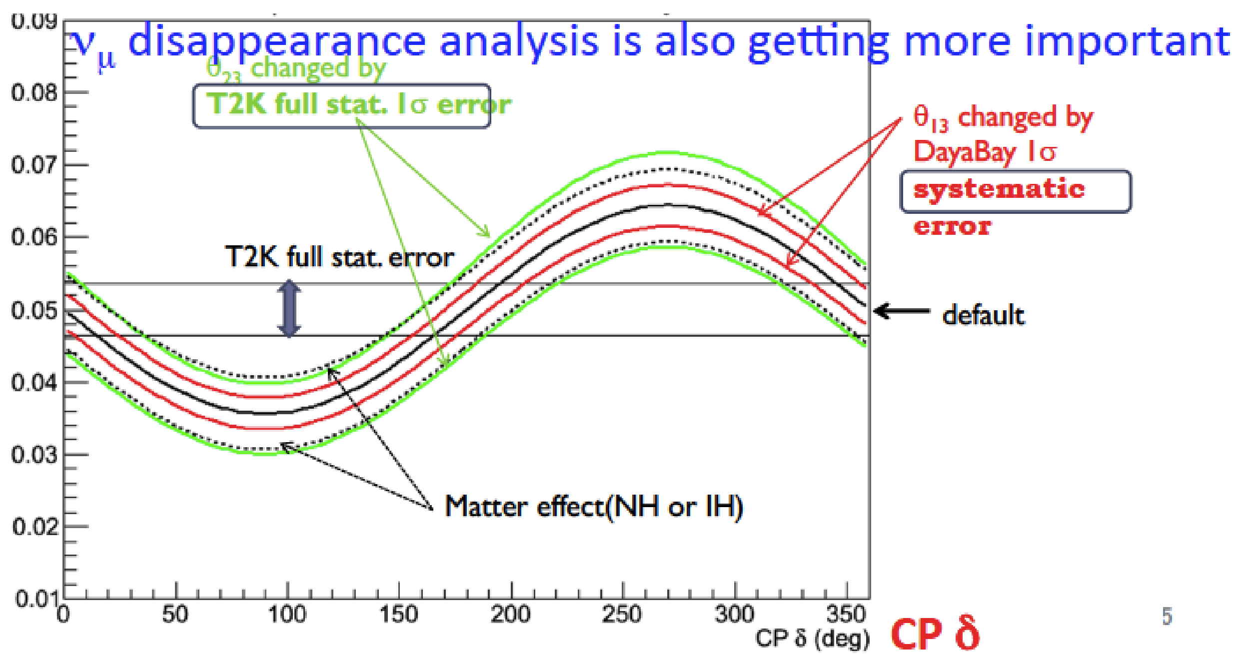
Leading

CP violating (flips sign for $\bar{\nu}$)

Solar

Matter effect

$P(\nu_\mu \rightarrow \nu_e)$

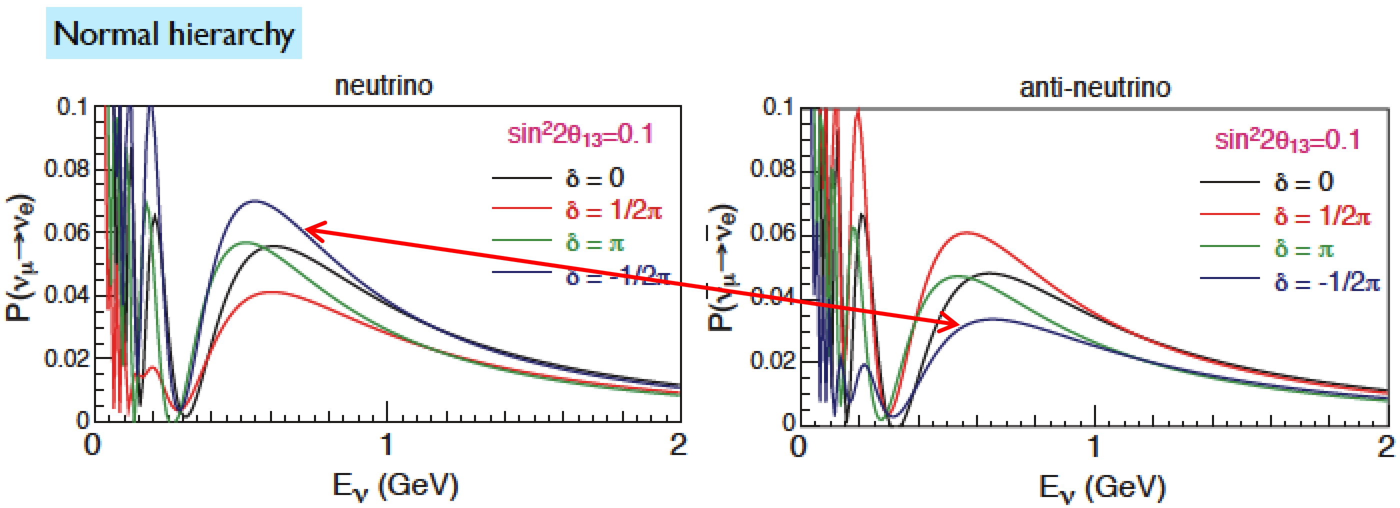


CP δ

Search for CP violation

- Leptonic CP violation, Dirac phase δ
- ν mass hierarchy, $\Delta m^2_{32}>0$ or $\Delta m^2_{32}<0$
- θ_{23} octant, $\theta_{23}<\pi/4$ or $\theta_{23}>\pi/4$

$$A_{CP}=\frac{P(\nu_\mu\to\nu_e)-P(\bar{\nu}_\mu\to\bar{\nu}_e)}{P(\nu_\mu\to\nu_e)+P(\bar{\nu}_\mu\to\bar{\nu}_e)}\cong\frac{\Delta m^2_{12}L}{4E_\nu}\cdot\frac{\sin 2\theta_{12}}{\sin\theta_{13}}\cdot\sin\delta$$



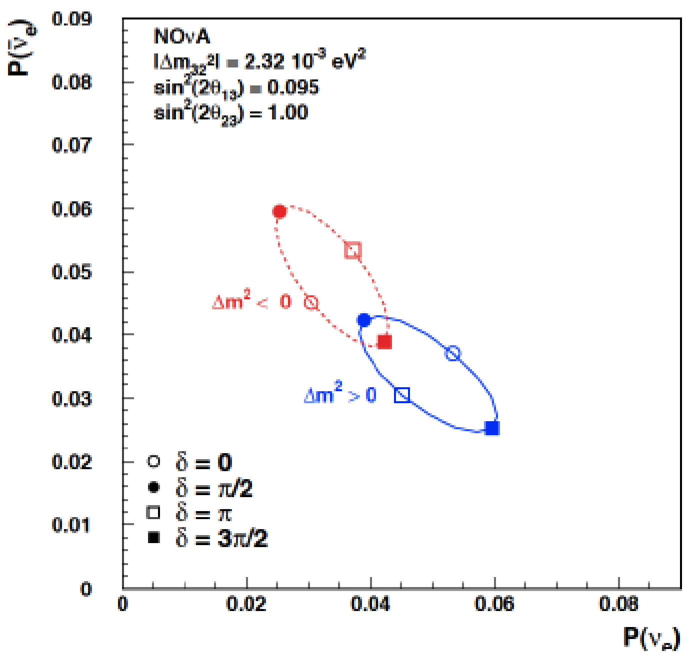
T2K and Nova

Nova, neutrinos from FNAL,
will start in late 2013

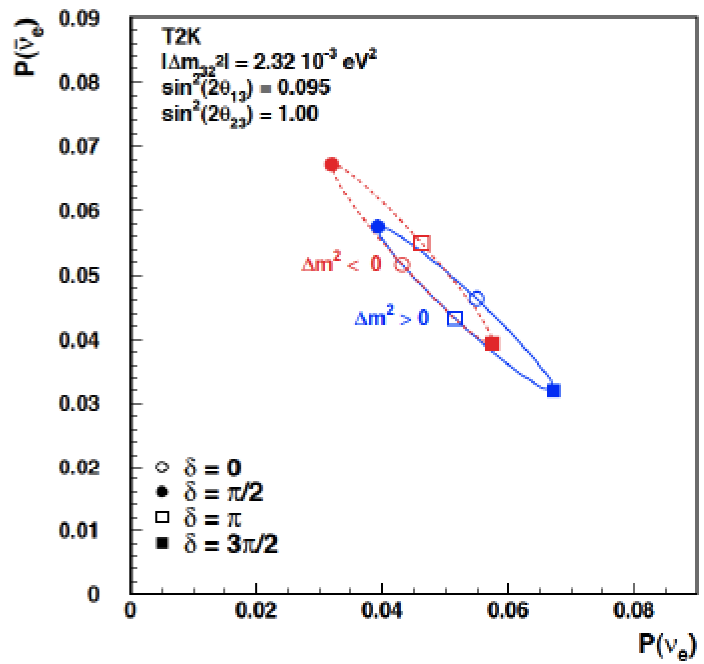
G.Feldman, LBNE Workshop, FNAL 25 April 2012

Possible measurement of mass hierarchy and CP violation

$P(\bar{\nu}_e)$ vs. $P(\nu_e)$ for NOνA



$P(\bar{\nu}_e)$ vs. $P(\nu_e)$ for T2K



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

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

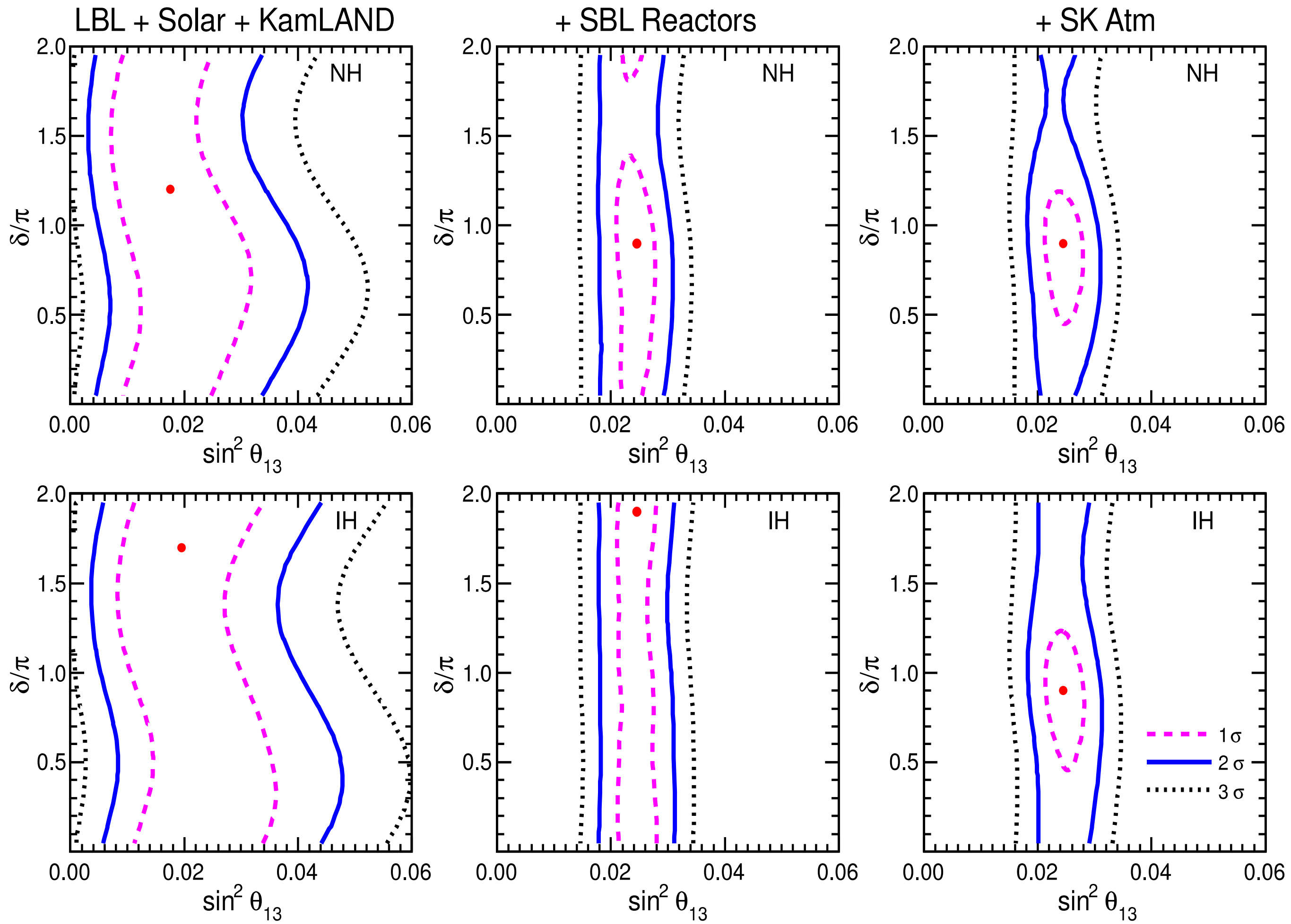
Combined analysis

all oscillation data

Gianluigi Fogli, talk at NuTurn2012, Gran Sasso, 8-10 May 2012

normal hierarchy

inverted hierarchy



~ 1σ preference for δ ~ π

Conclusion

First T2K results

6 ν_e events are observed (1.5±0.3 expected if θ_{13}=0)
$0.03(0.04)<\sin^2(2\theta_{13})<0.28(0.34)$
for normal (inverted) hierarchy & $\delta_{CP}=0$

ν_μ disappearance
No oscillation hypothesis excluded at 4.5σ
$\sin^2(2\theta_{23})>0.85$ and $2.1\times10^{-3} < \Delta m^2_{23}$ (eV^2) $< 3.1\times10^{-3}$ @ 90% CL

T2K completely recovered from the 11th March earthquake

- **JPARC restarted in December 2011**
- **T2K begun new physics run in January 2012, taking data now**
- **New results will be presented in June 2009**

Rich physics program

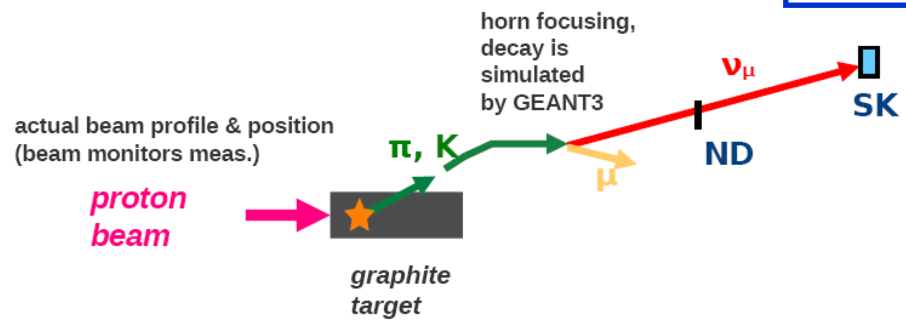
- **CP violation**
- **mass hierarchy**
- **precision measurements of oscillation parameters**

спасибо за внимание!

Backup slides

Neutrino flux prediction

Proton monitors measurements used as inputs for actual beam profile and position



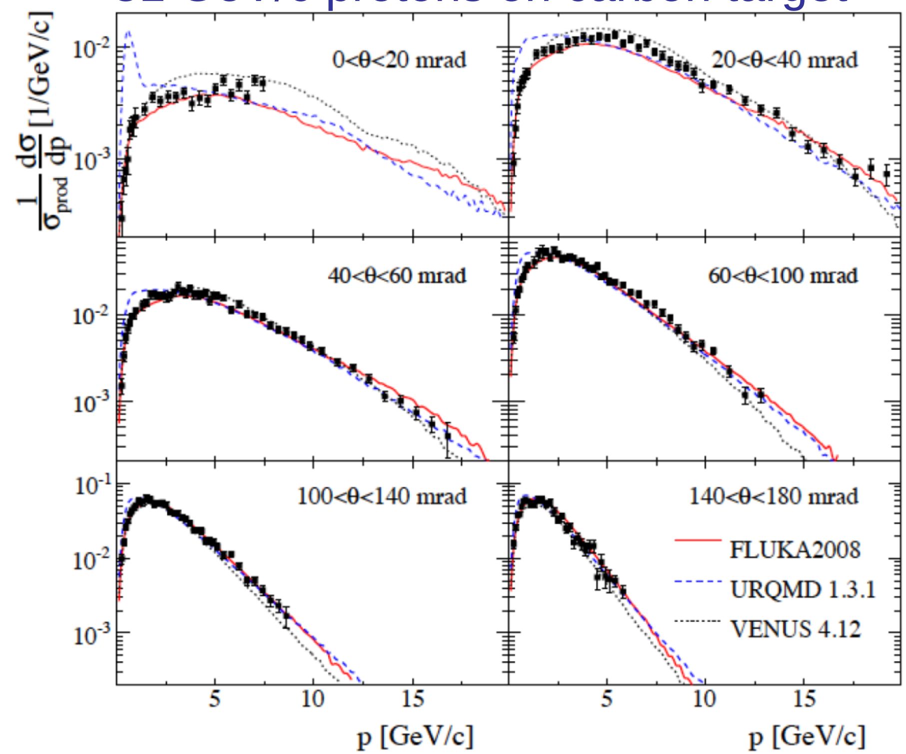
Hadron production in T2K target

- NA61 experiment at CERN
  - pions in p+C interactions
  - same proton energy and target material
- kaon production, pion outside NA61 acceptance, other target interactions modeled with FLUKA

Out of target interactions, horn focusing, secondary interactions, particle decays

- GEANT3 simulation
- interaction cross-sections tuned to existing data

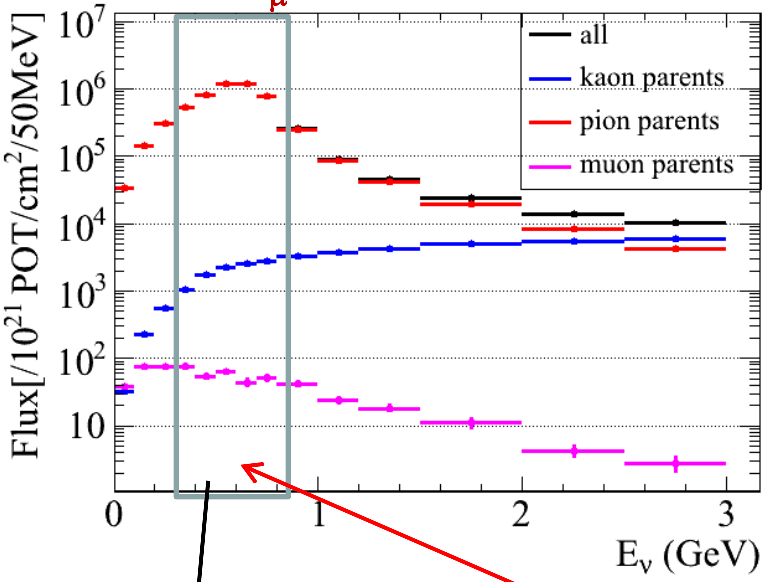
31 GeV/c protons on carbon target



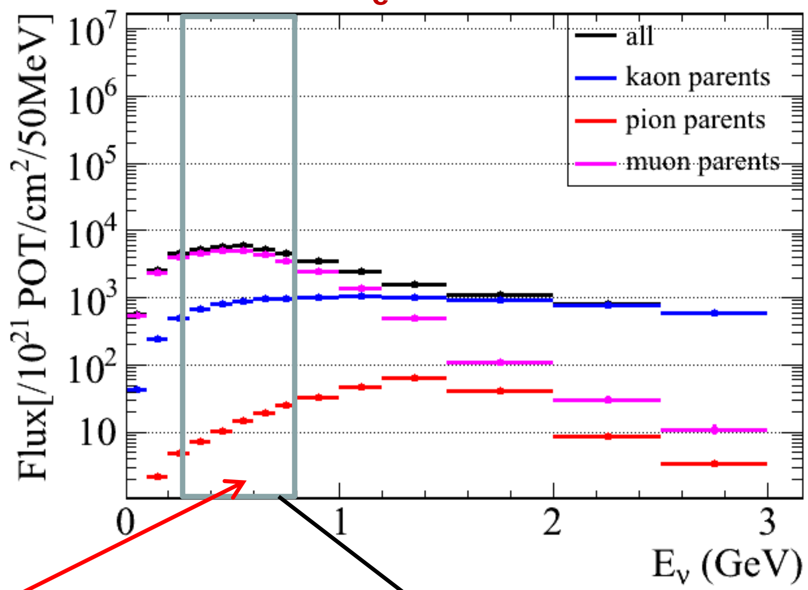
N.Abgrall et al., Phys.Rev.C (2011); arXiv:1102.0983 [hep-ex]

ν flux at SK

ν_μ at SK



ν_e at SK



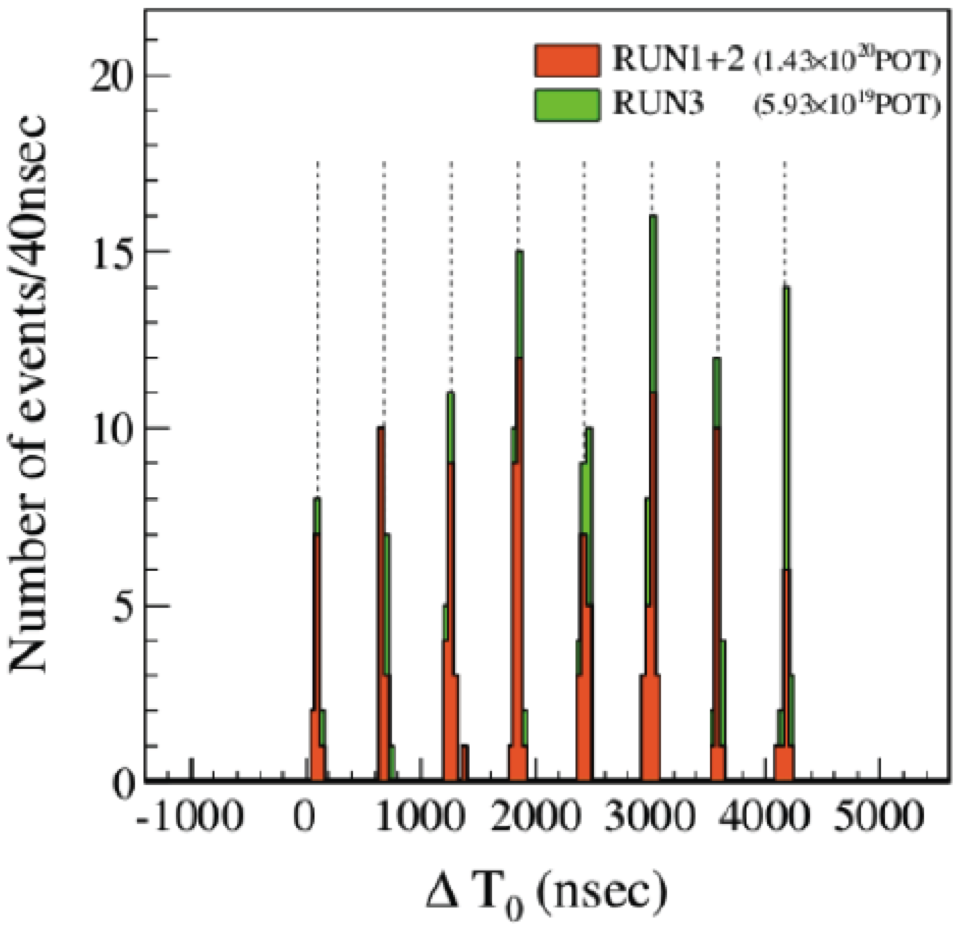
Region of oscillation maximum

intrinsic ν_e flux (~1% of total):

- mainly from μ decays:
  $\pi^+ \rightarrow \mu^+(\rightarrow e^+ \nu_\mu \bar{\nu}_e)\nu_\mu$
- NA61 pion measurement predicts the beam ν_e from the pion origin.

ν_μ flux mainly from π decays

Neutrino events at SK



green - events detected after the Earthquake