Neutrino oscillation results from the T2K experiment

Yu. G. Kudenko

Institute for Nuclear Research, Moscow

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OVERVIEW

- **Neutrino oscillations**
- **T2K features**
  - ***- Off-axis neutrino beam***
  - ***- Near and Far neutrino detectors***
  - ***- Analysis principles***
- **Experimental data**
- **Oscillation results**
  - **-** ν_μ ***Disappearance***
  - **-** ν_e ***Appearance***
- **Future prospects**

Стандартная Модель

Три типа (аромата) нейтрино: ν_e ν_μ ν_τ

Нейтрино – партнеры заряженного лептона

$$W \to e\nu_e \quad W \to \mu\nu_\mu \quad W \to \tau\nu_\tau$$

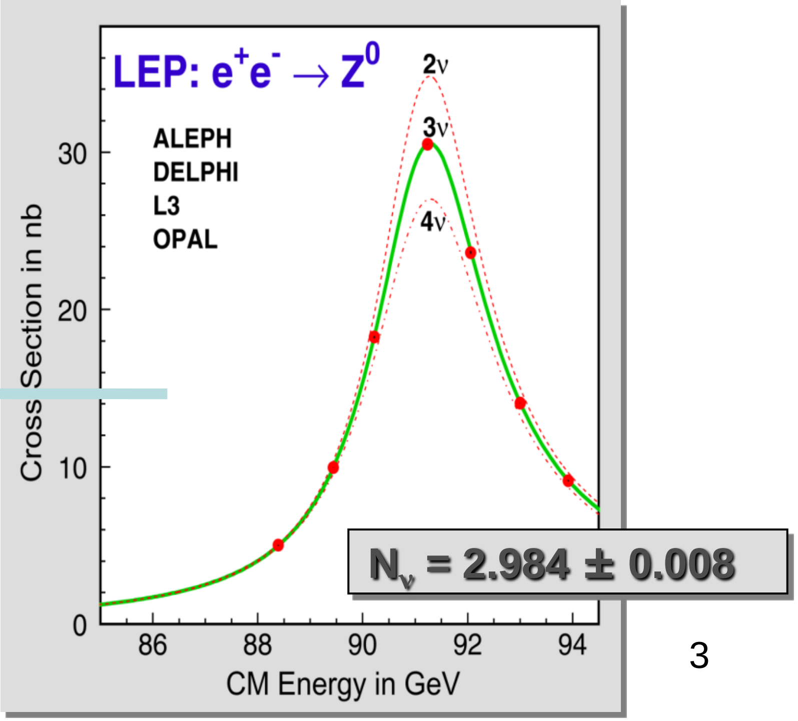
Нейтрино - безмассовые частицы

Сохраняются лептонные числа L_e L_μ L_τ

Невозможны переходы (осцилляции) одного типа нейтрино в другой

CP в лептонном секторе сохраняется

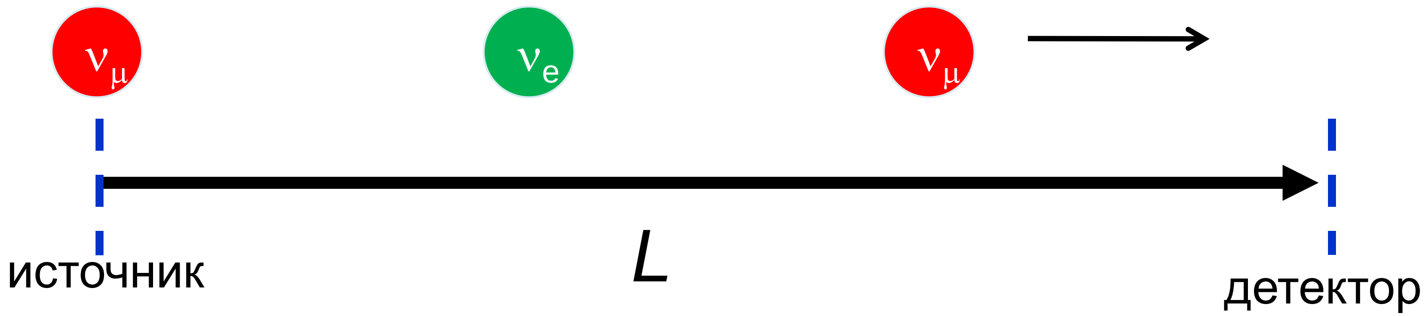
Эксперименты на LEP (ЦЕРН): из ширины распада Z бозона следует, что существуют только **три типа** легких активных нейтрино



Гипотеза нейтринных осцилляций

Б.М. Понтекорво: идея массивных нейтрино и осцилляций – 1957 г.

- один тип нейтрино переходит в другой
- необходима ненулевая масса и смешивание
- вероятность осцилляции зависит от массы нейтрино, энергии нейтрино E_ν и расстояния L



Собственные состояния слабого взаимодействия

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad \begin{matrix} m_1 \\ m_2 \\ m_3 \end{matrix}$$

массовые состояния

Собственные (активные) состояния не совпадают с массовыми состояниями

Oscillation industry

Solar ν's

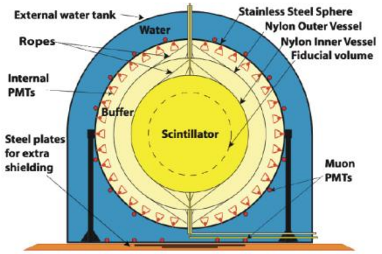
Homestake, USA

1970 → ....

Sage, Russia

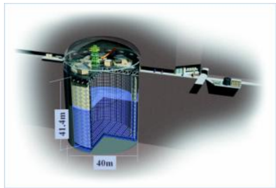
Gallex
SNO
SK

Borexino, Italy



Atmospheric ν's

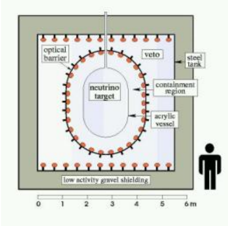
SK, Japan



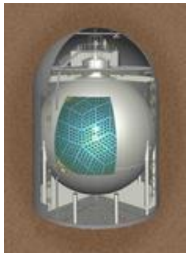
MACRO, Italy
Soudan2, USA

Reactor ν's

CHOOZ, France



KamLand, Japan

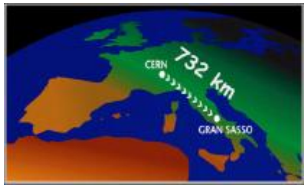


Accelerator ν's

K2K, Japan

Minos, USA

OPERA, Italy



.... → 2011

LSND,
MiniBooNe,
США

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

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

$\Delta m^2_{23} \cong \Delta m^2_{31} = \Delta m^2_{atm} \approx 2.4 \times 10^{-3} eV^2$

***U* parameterization:**

three mixing angles θ_{12} θ_{23} θ_{13}

CP violating phase δ

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

$$\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$$

→ **two independent Δm^2**

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

$\Delta m^2_{12} = \Delta m^2_{sol} \approx 7.5 \times 10^{-5} \text{eV}^2$

$\sin^2 2\theta_{13} < 15^0$ at 90% CL

?? θ_{13} , mass hierarchy , δ ??

Issues in neutrino physics (by Summer 2011)

- 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

(Neutrino mixing, mass hierarchy, CP violation: T2K)

Oscillation experiments:

Appearance and Disappearance

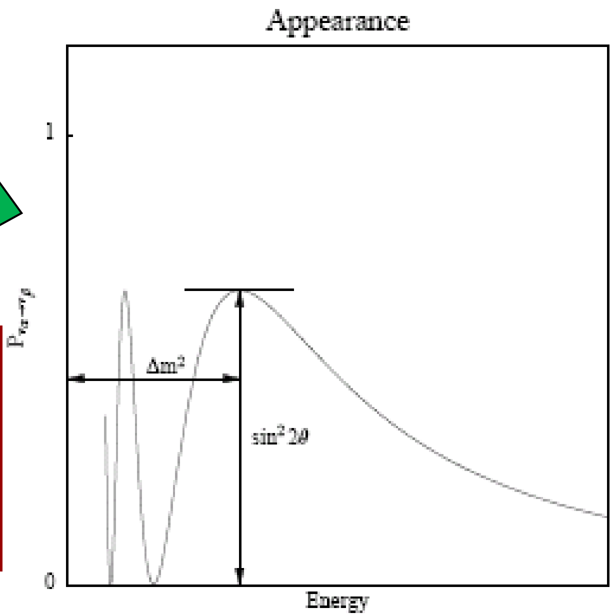
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \Phi_{ij} \mp 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin 2\Phi_{ij}$$

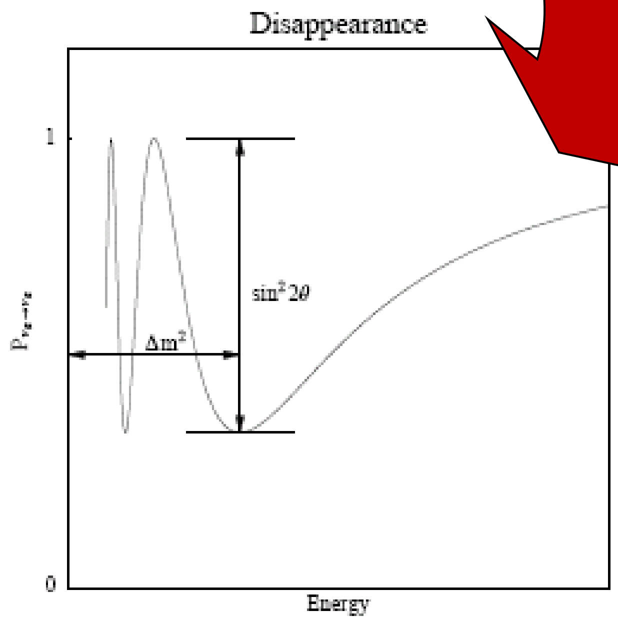
$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E}\right),$$

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

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

L – distance from ν source to detector
E – neutrino energy





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

Long-Baseline Neutrino Oscillation Experiment

- 12 countries
- 59 institutes
- ≃ 500 collaborators

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

T2K milestones

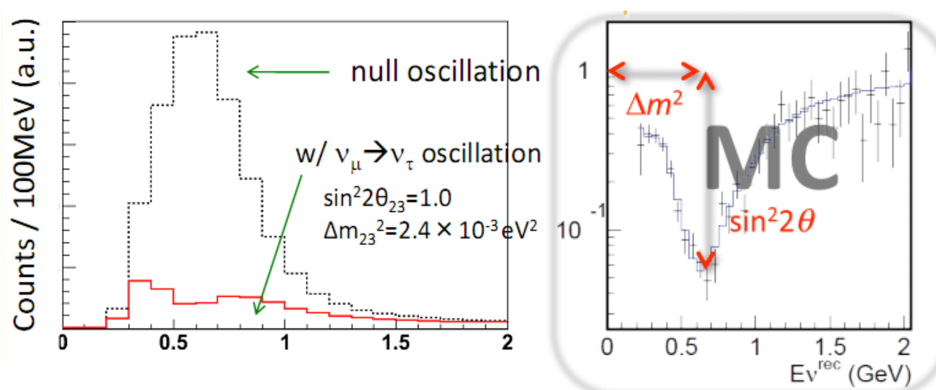
Proposal approval	2003
Construction	2004-2009
Start data taking	2010
Earthquake	11 March 2011
First physics result	June 2011
JPARC recovery	December 2011
Restart data taking	January 2012
Physics Run	March 2012 – June 2012

Principles of measurement

- Intensive neutrino source
- Near detector → measurement of unoscillated neutrino spectrum
- Far Detector → measurement of oscillated neutrino spectrum
- Extrapolate flux from Near Detector to Far Detector (Far/Near ratio)
- Estimate ν_μ rate (without oscillation) at Far Detector
- Compare to measured ν_e (ν_μ) rate (spectrum) to observe oscillation and extract oscillation parameters
- Reduction systematic errors using data from K2K, NA61, SciBooNe, MiniBooNe

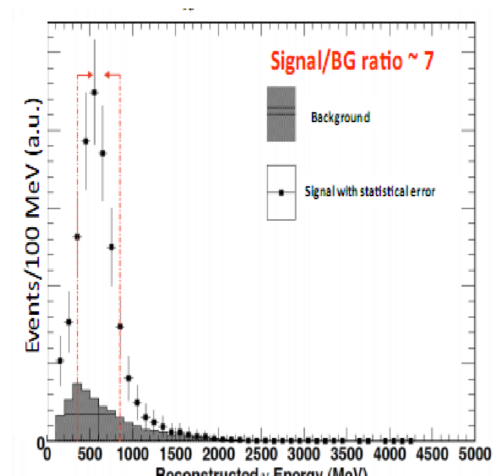
Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{23} L/4E_\nu)$$

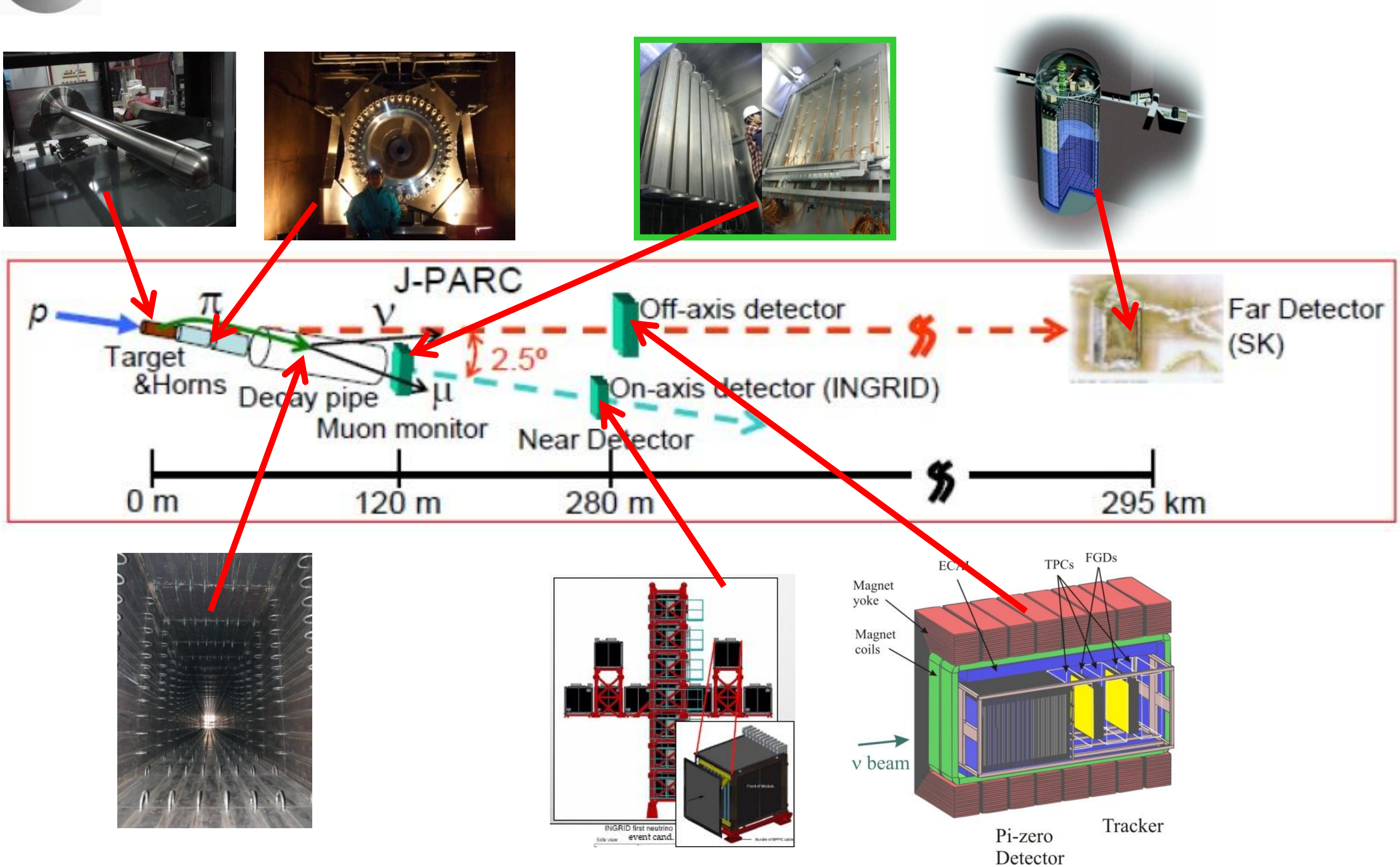


Appearance

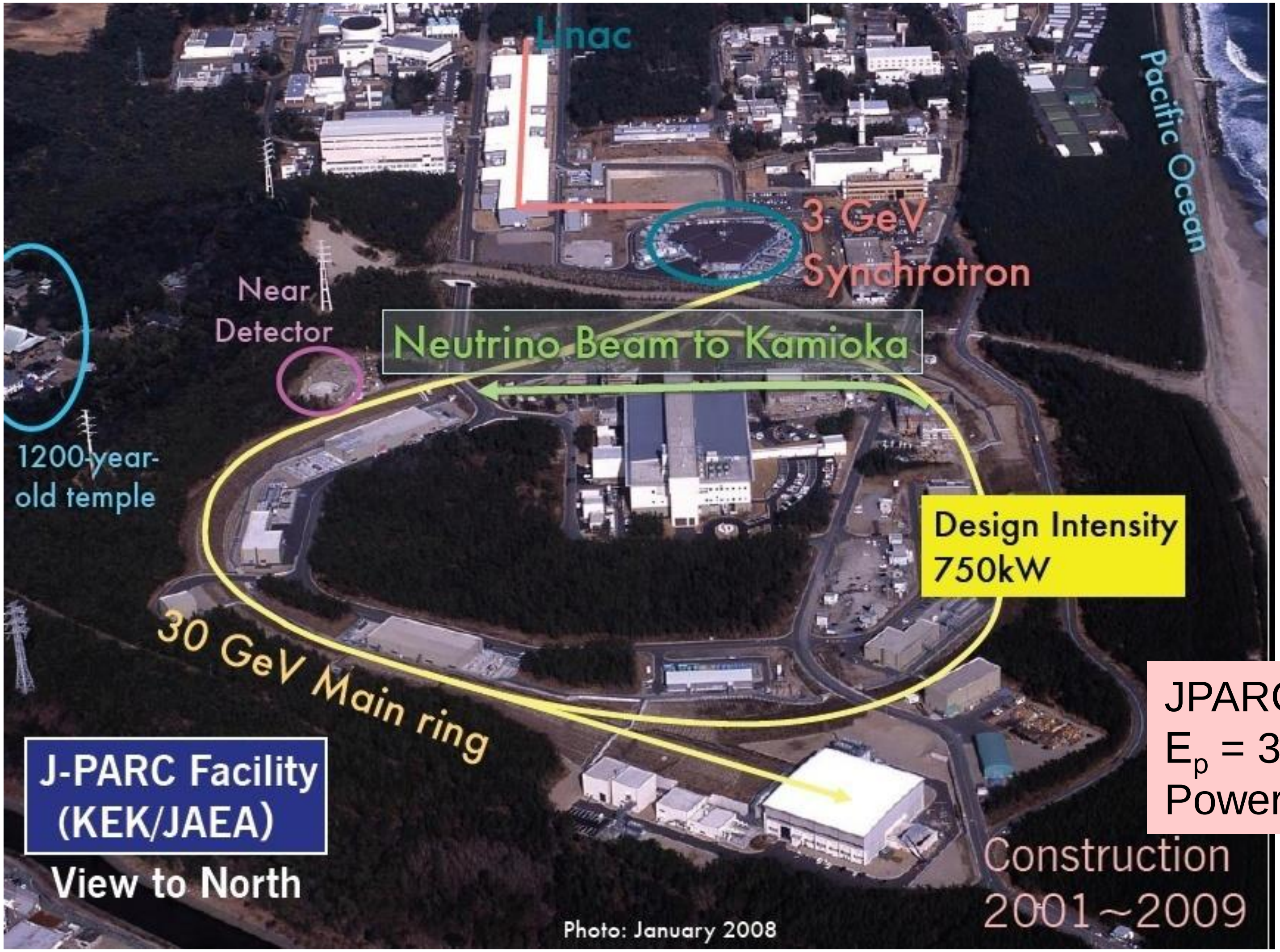
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{13} L/4E_\nu)$$



Experiment T2K

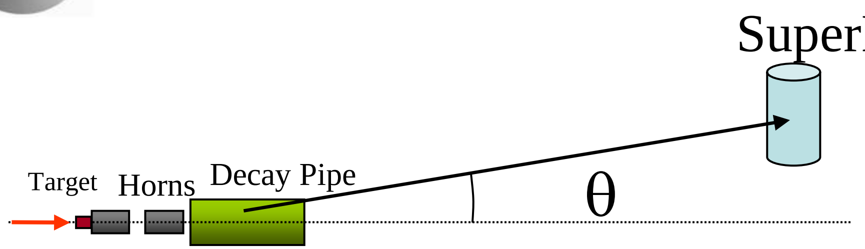


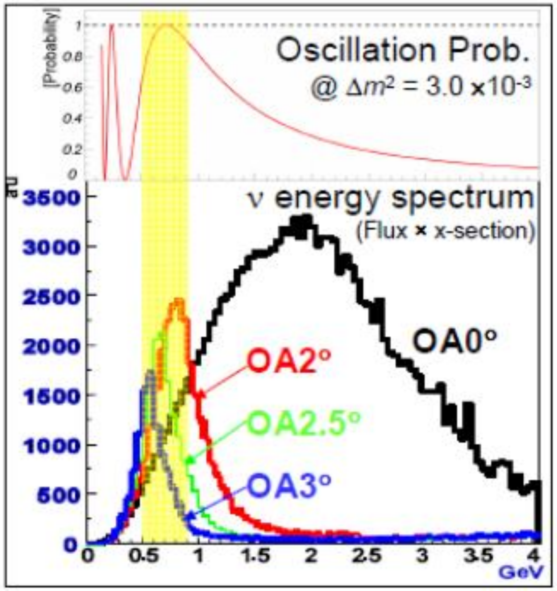
JPARC

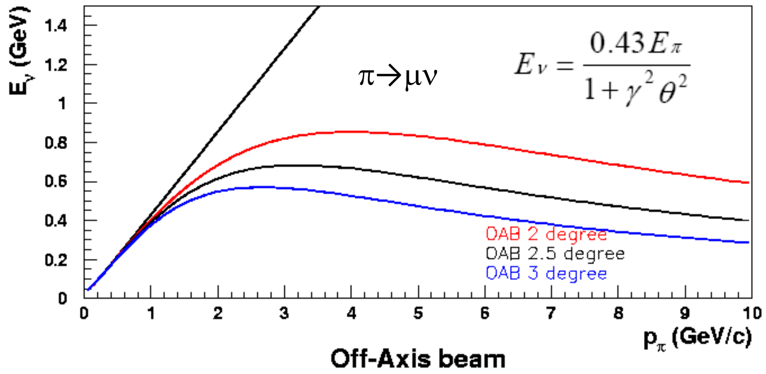


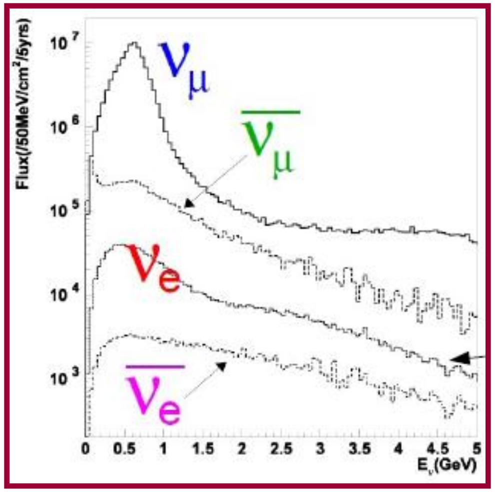
JPARC:
E_p = 30 GeV
Power = 750 kW

T2K off-axis beam



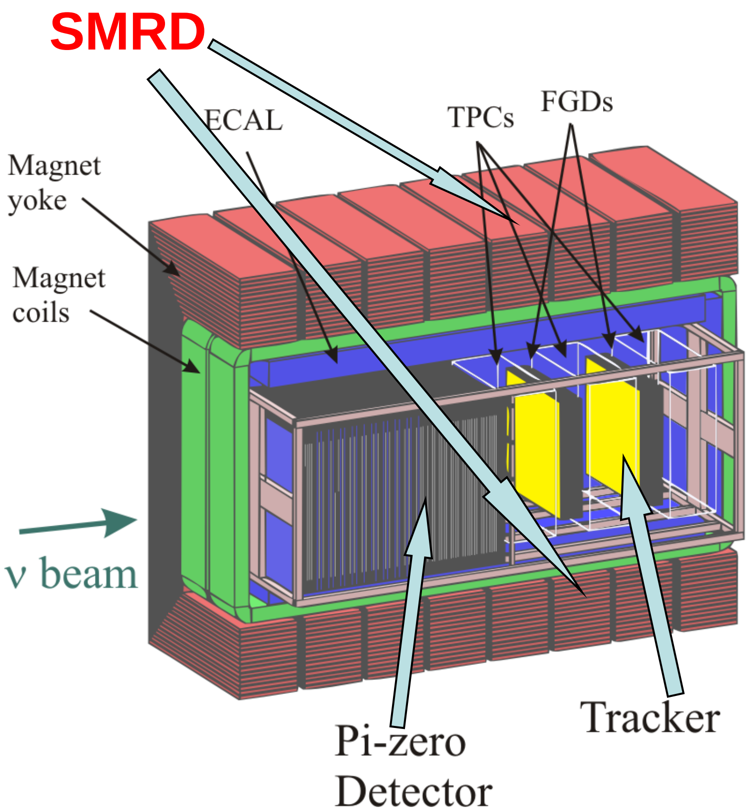






- 30 GeV proton beam at JPARC
- Quasi-monochromatic ν_μ (95%) beam
- Peak energy ~700 MeV tuned to oscillation maximum
- ~0.4% ν_e at peak energy
- Reduced high energy tail → reduces background

ND280 off-axis detector



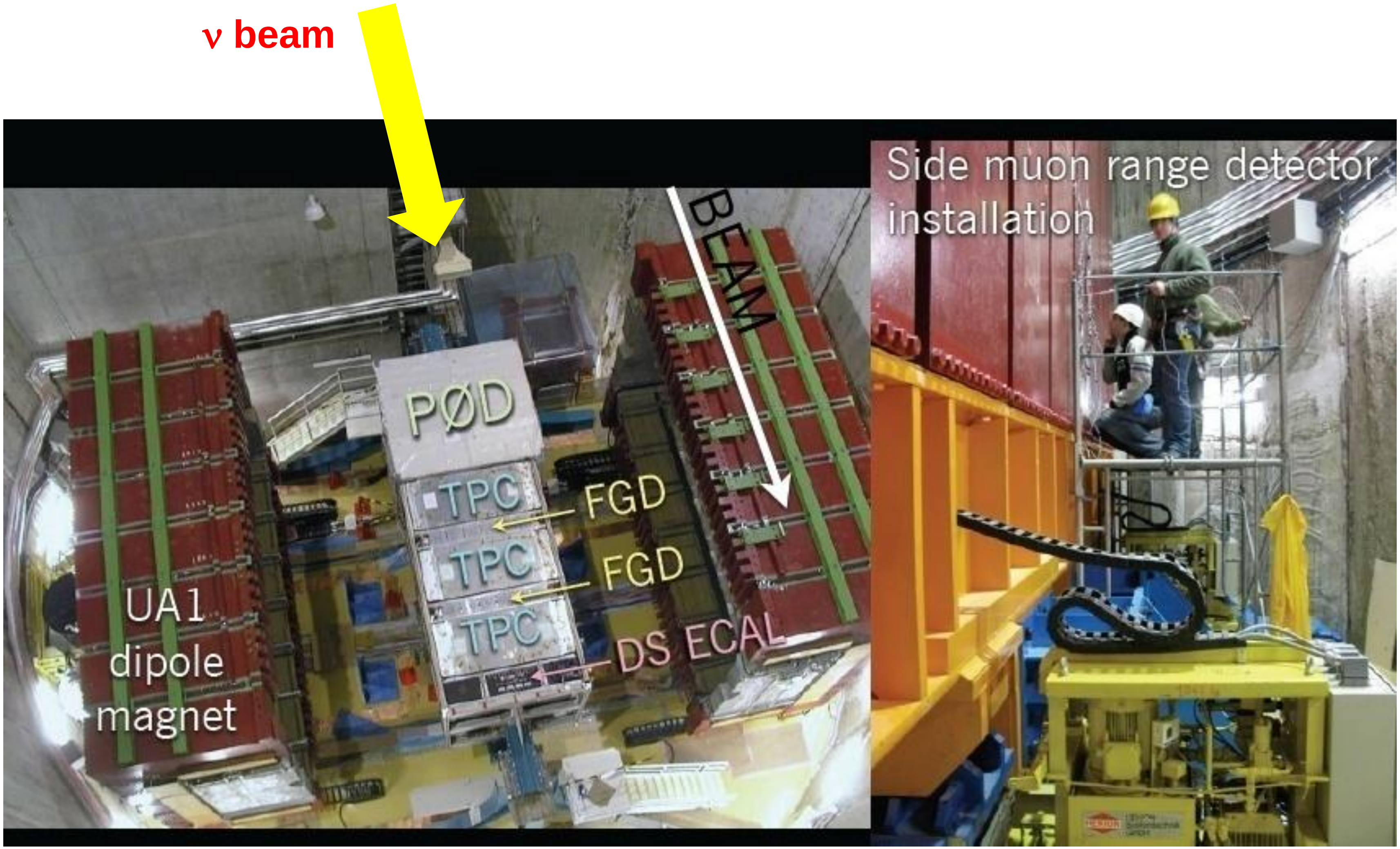
280m downstream from pion production target

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



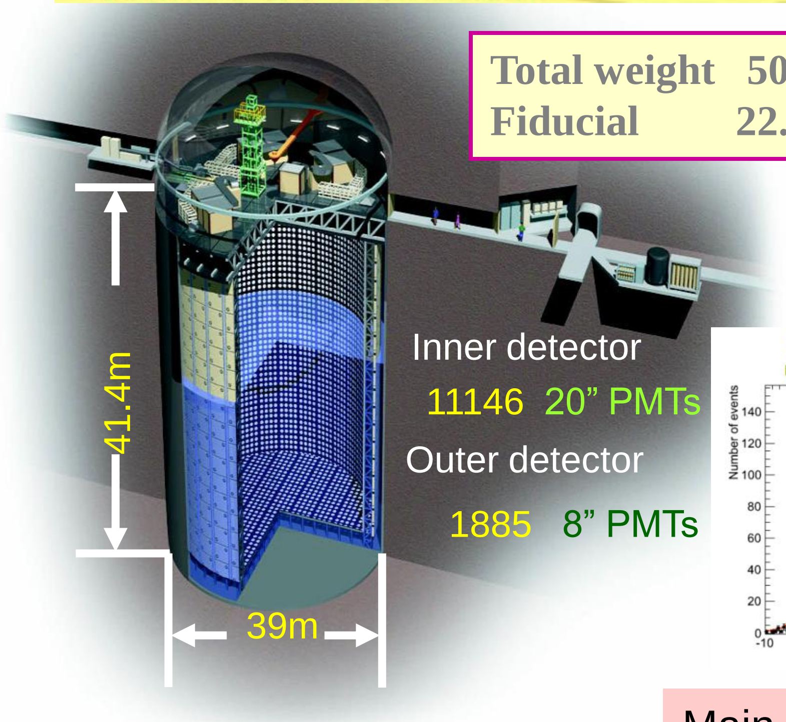
Far detector

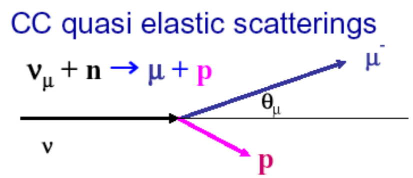
Super-Kamiokande IV

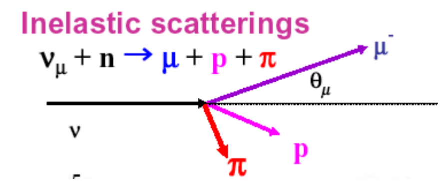
- 4π acceptance, very efficient π^0/e separation.
- High Particle ID (μ/e) power (~99% at 600MeV/c)
- Good energy reconstruction.
- Methods are established.

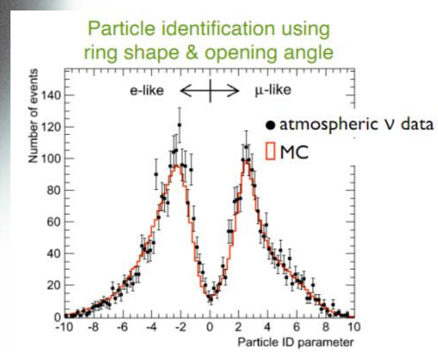
~11000 PMTs
with FRP+Acrylic cover
40% photo-coverage

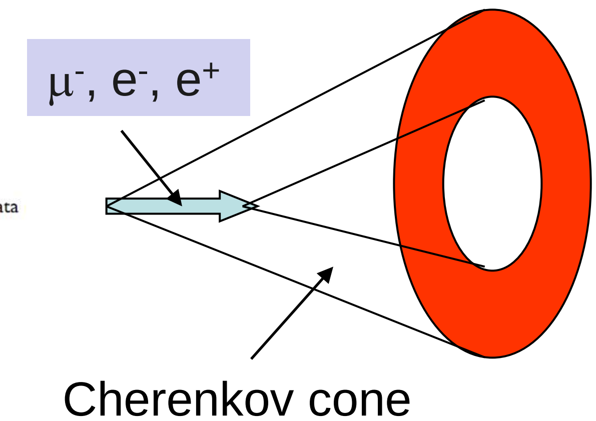
Total weight	50 kt
Fiducial	22.5 kt









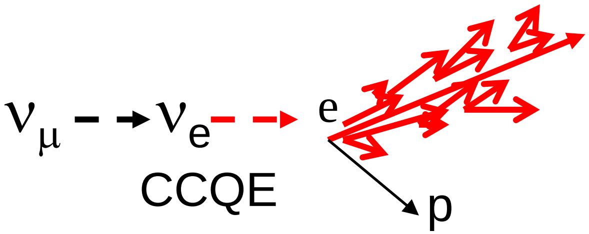


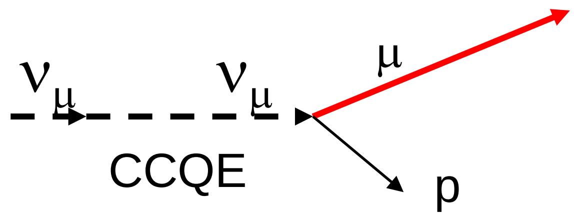
Main backgrounds in appearance measurements:
π^0 from neutral currents – suppression factor ~100
ν_e contamination in ν_μ beam - ~0.4% at peak energy

ν_μ / ν_e events in T2K

Signals and Backgrounds

SIGNALS



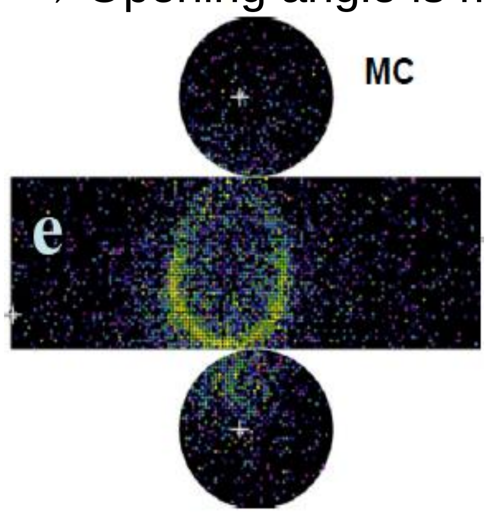


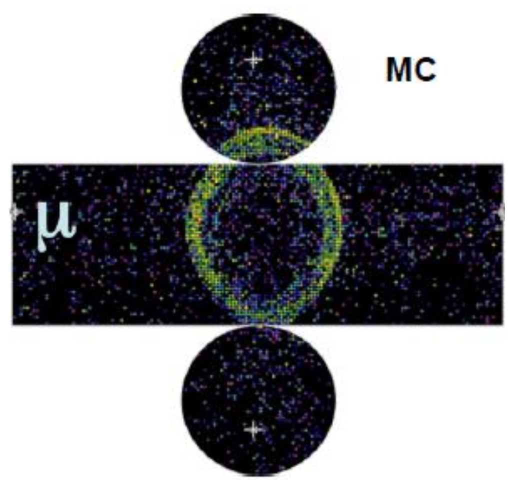
electrons

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

muons

Low Scattering
→ Ring has sharp edge



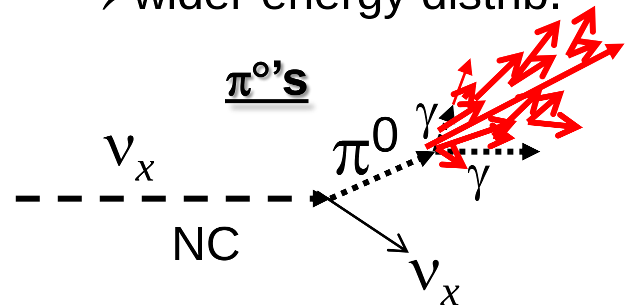


BKG

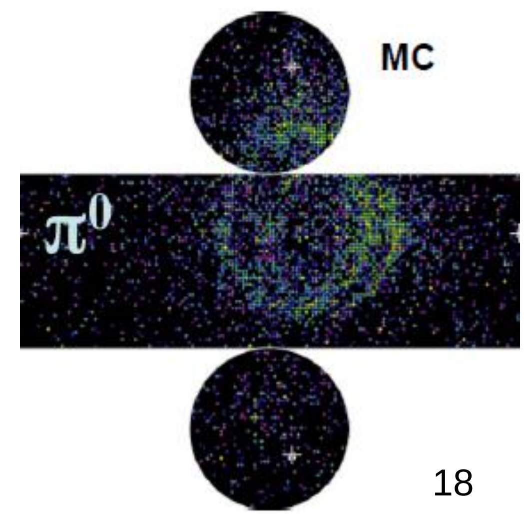
electrons

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

π^o's



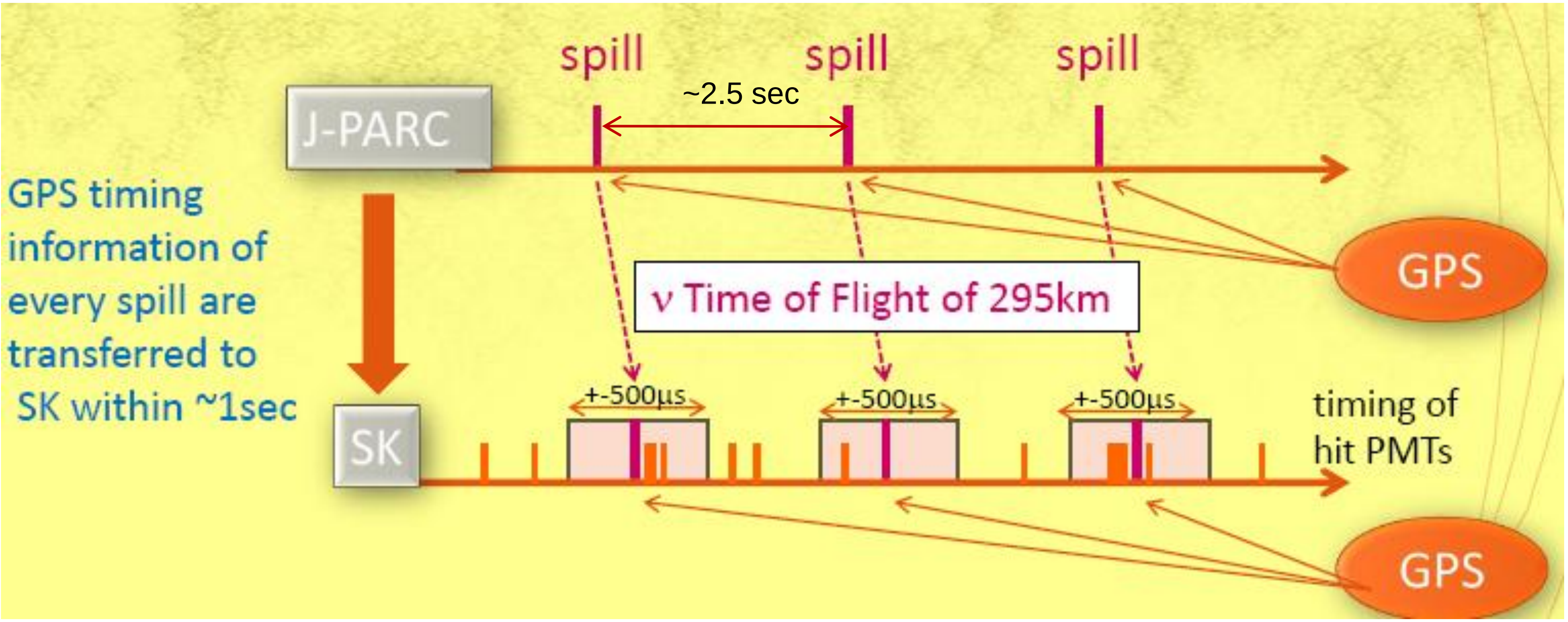
EM showers of γ's from π° can fake an electron



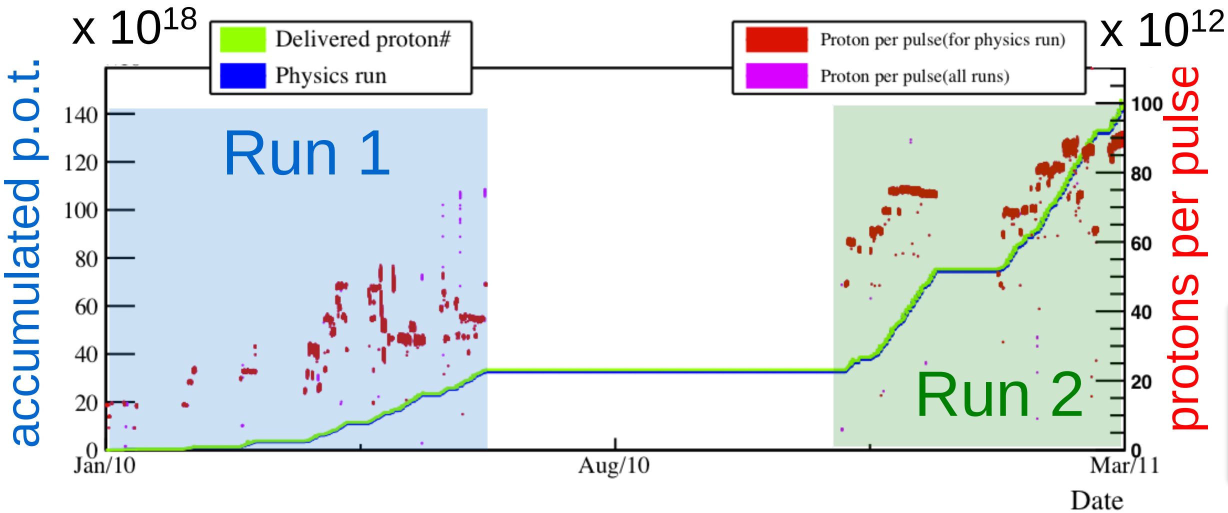
T2K Timing

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

Each spill has 8(6) microbunches
56 ns width
580 ns separation



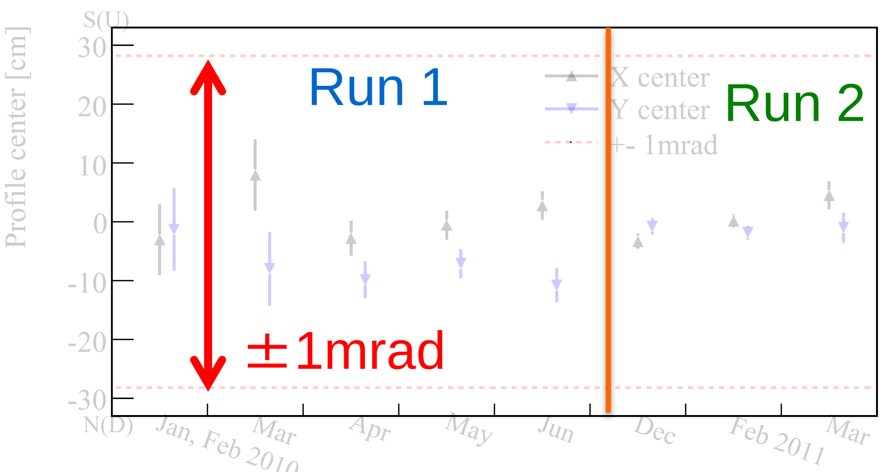
Beam data



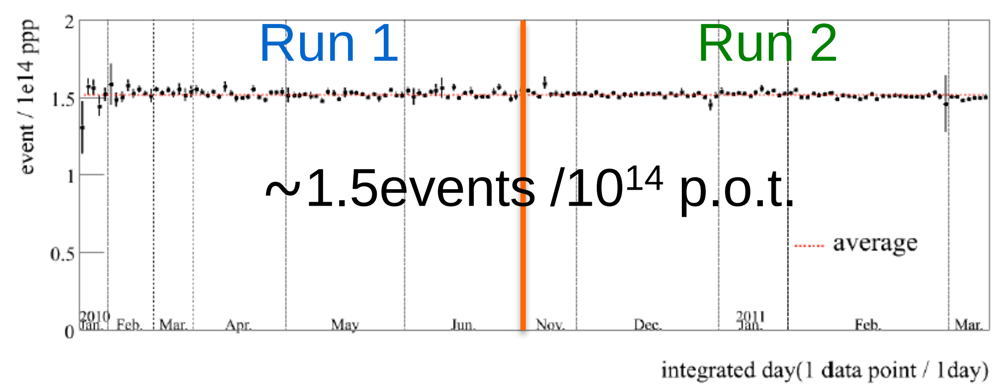
Run 1 (2010 Jan - 2010 Jun)
50kW stable operation

Run 2 (2010 Nov - 2011 Mar)
reached 145kW

Total p.o.t. : 1.43 x 10^{20}
~2% of T2K final goal



ν beam center measured by INGRID
well within ±1mrad (δE<<2%@SK)

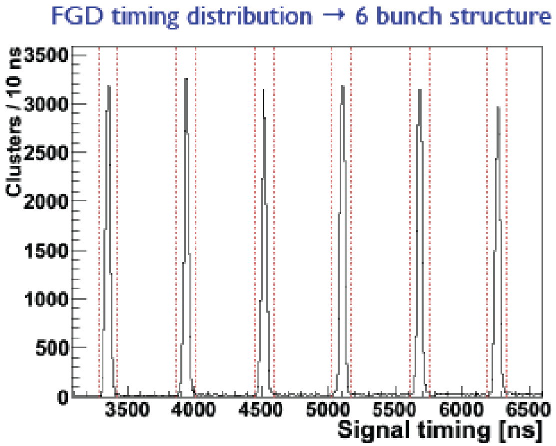


INGRID interaction rate stable for Run 1 & 2

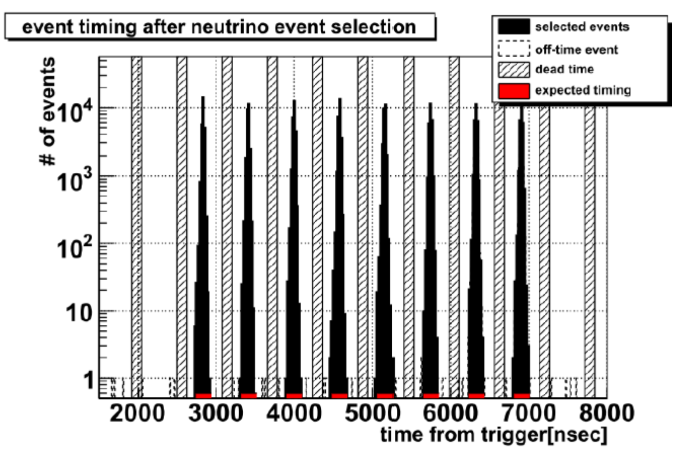
(Beam direction & intensity also monitored by Muon Monitor spill-by-spill)

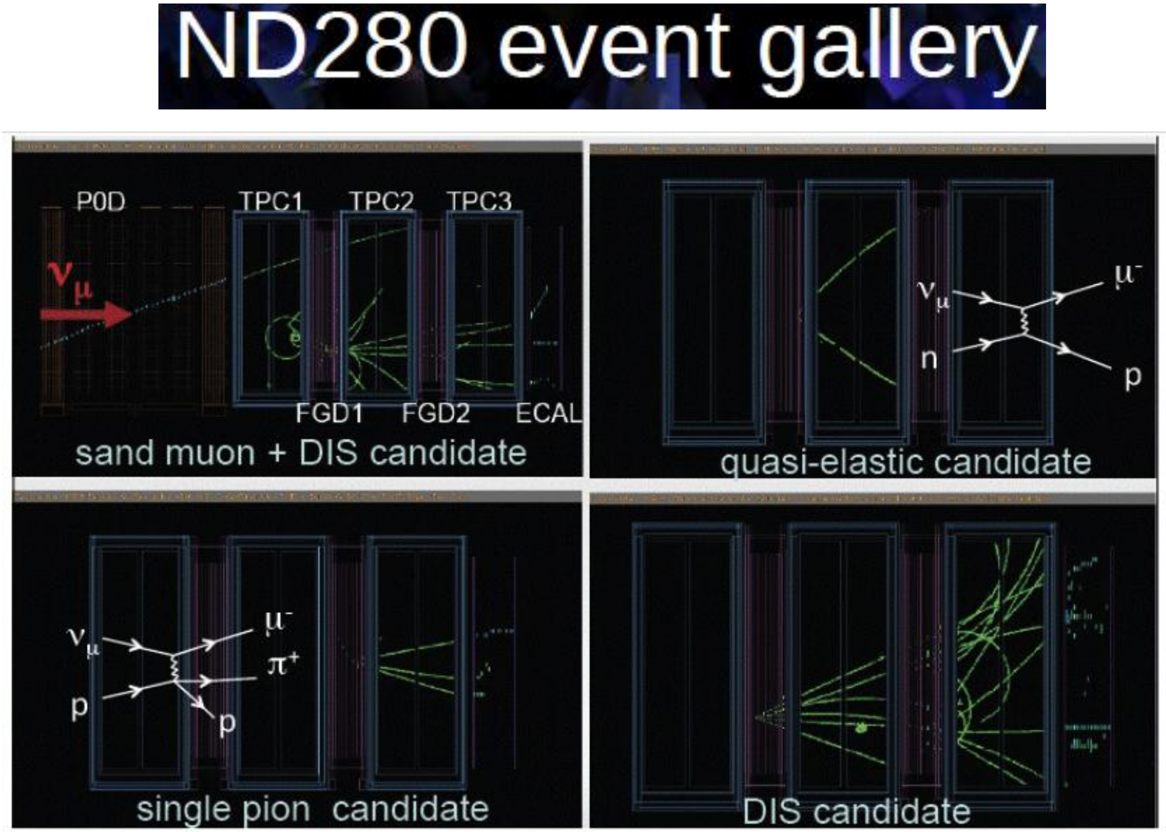
ν events in ND280

FGD, Run 1, 6 microbunches



INGRID, Run2, 8 microbunches





Clear timing structure of neutrino events in ND280 corresponds to the JPARC beam structure

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

Neutrino flux prediction

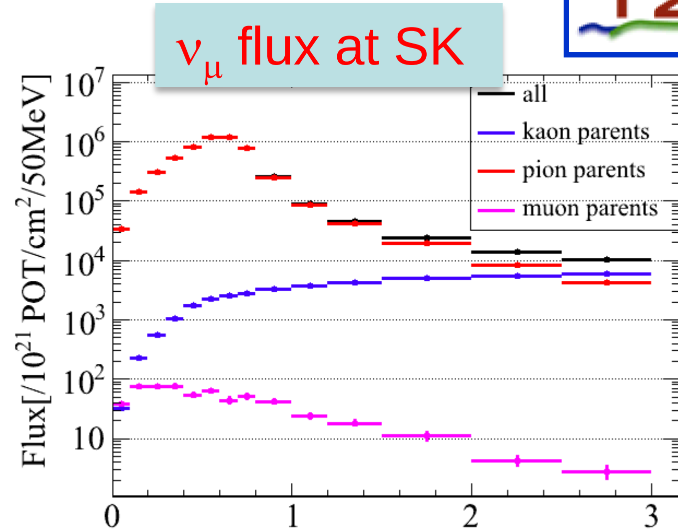
T2K beam simulation based on hadron production measurements

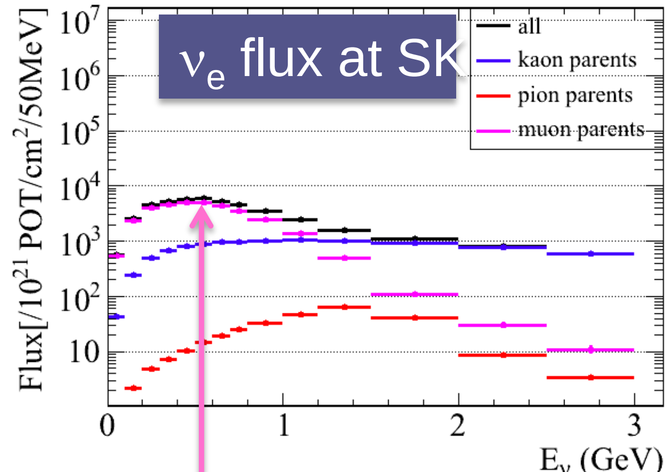
- NA61/SHINE (CERN) measured hadron production in (p, θ) using 30GeV protons and graphite target
- π outside NA61 acceptance and K production modeled with FLUKA

Total number: ν_μ in ND ν_e in SK

Error source (ν_e analysis)	$R^{\mu,\,MC}_{ND}$	N^{MC}_{SK}	$\frac{N^{MC}_{SK}}{R^{\mu,\,MC}_{ND}}$
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%

Partial error cancellation after ND correction





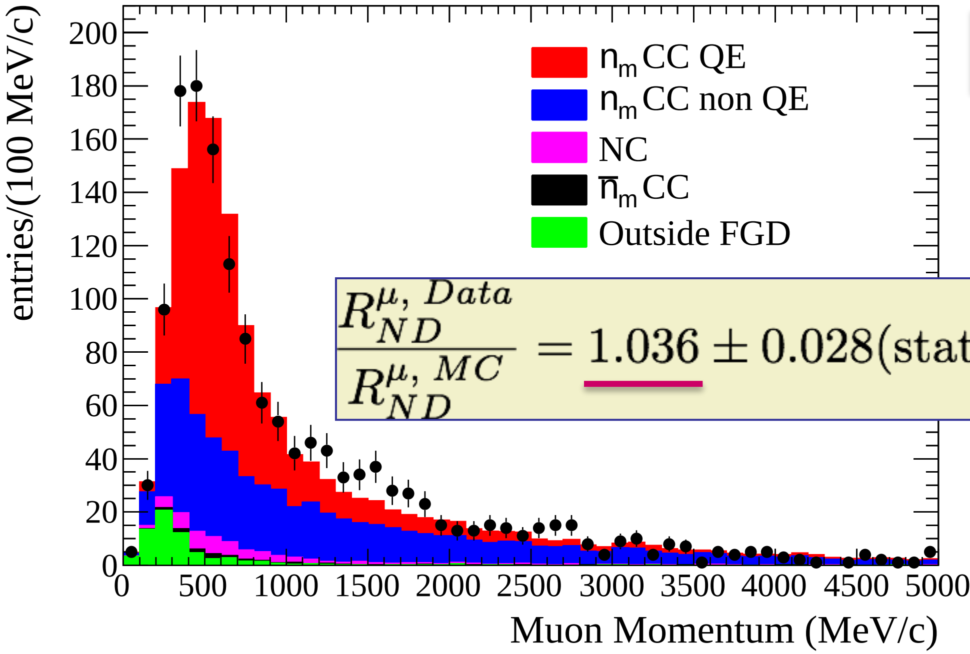
μ decay is dominated at low E_ν

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

→ can accurately be predicted by NA61 π measurement

ND280 measurements

Using Run 1 data (2.9 x 10^{19} p.o.t.)



Inclusive ν_μCC measurements

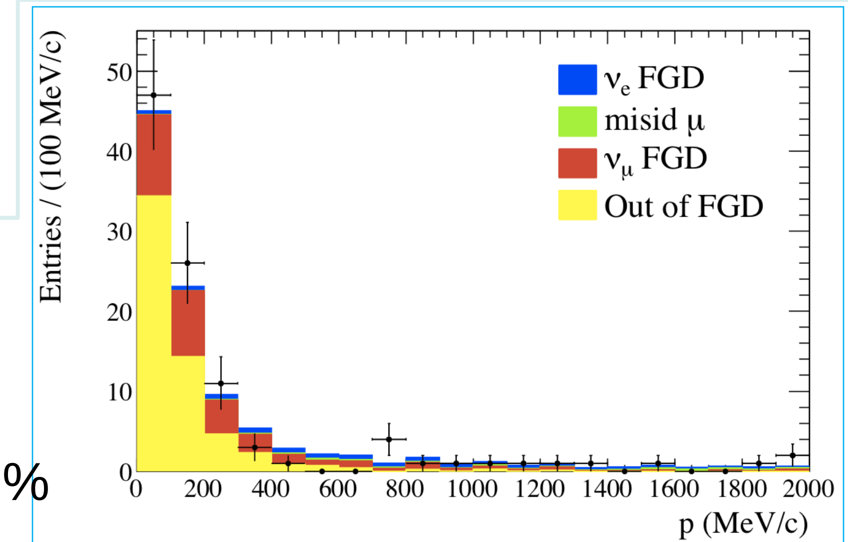
Tracks starting in FGD and identified as μ by TPC dE/dx and curvature

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

Intrinsic beam ν_e measurement

TPC dE/dx to select electron tracks

R(ν_e/ν_μ) = 1.0 ± 0.7(stat.) ± 0.3(sys.) %

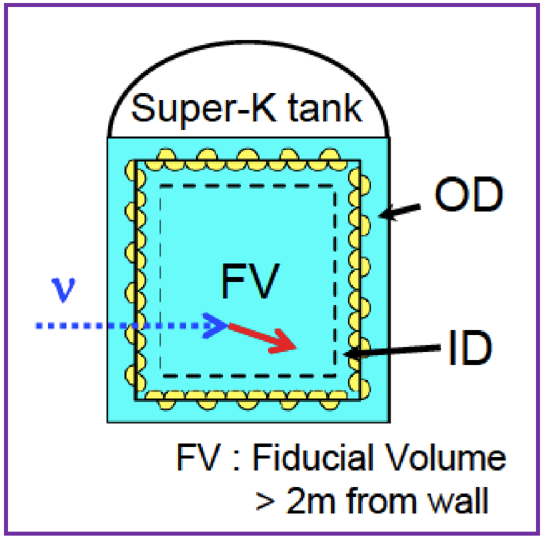


Data consistent with MC based on NA61 data and ν interaction simulations

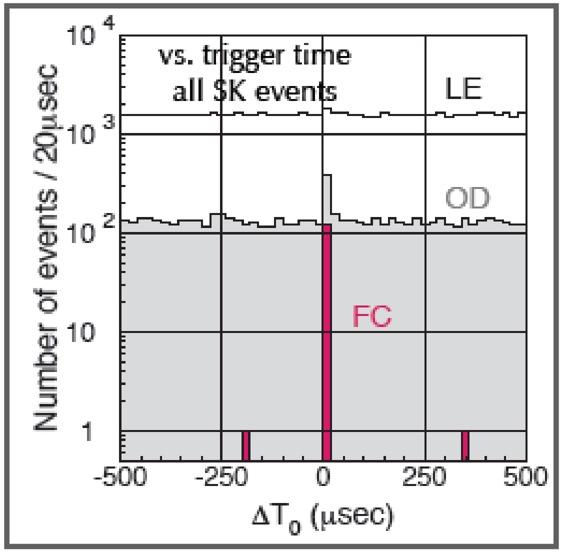
Event selection in SK (I)

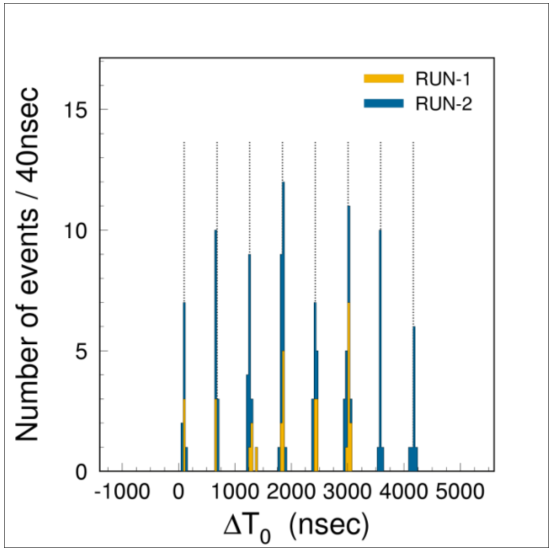
Event selection for both ν_μ and ν_e:

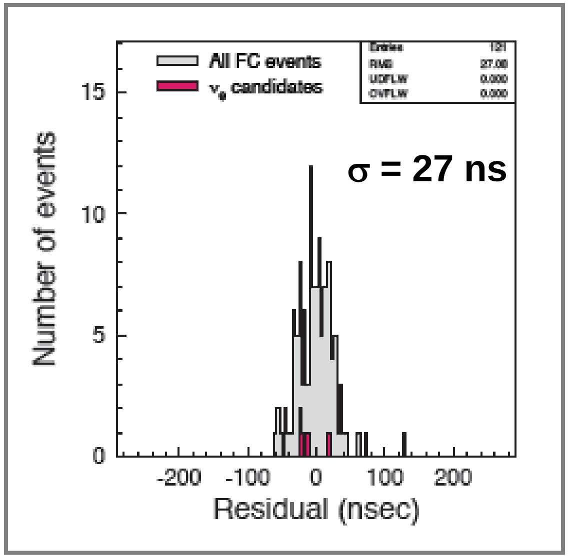
- SK synchronized to beam timing using GPS
- Fully contained (FC) events in the Inner Detector, minimal activity in the Outer Detector
- Vertex in Fiducial Volume (FCFV)
- Number of rings = 1
- PID algorithm to distinguish e-like and μ-like events



121 FC events

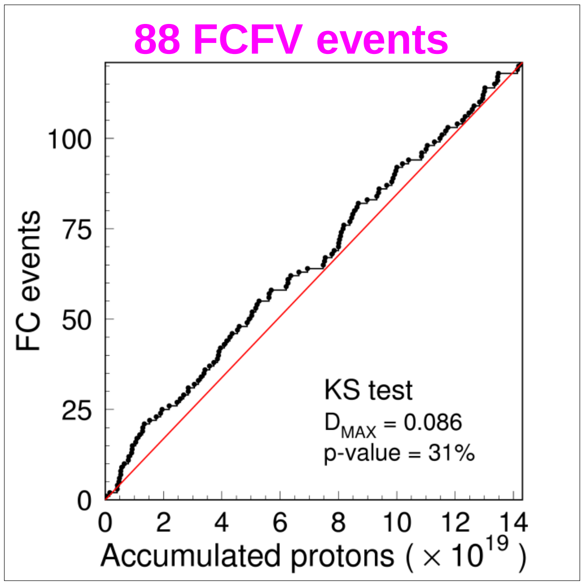


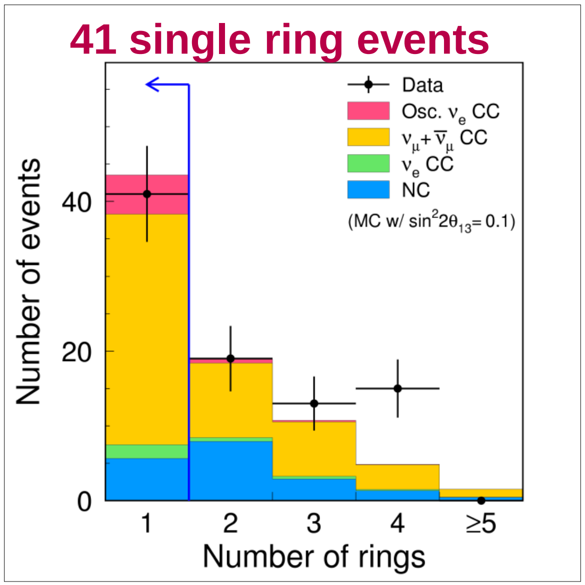


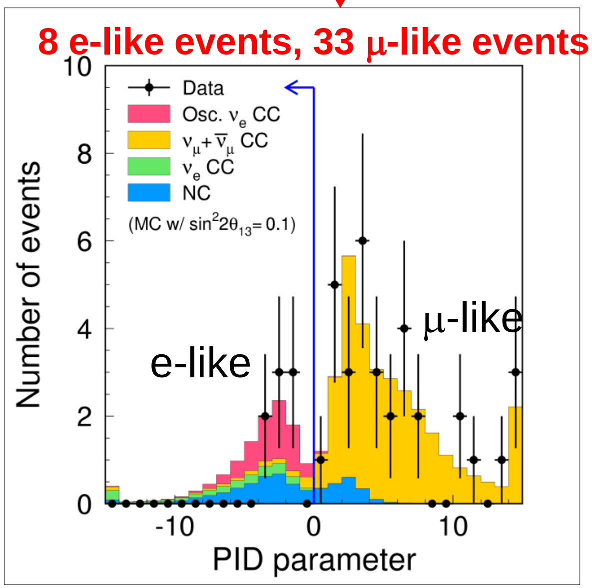


Event selection in SK (II)

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





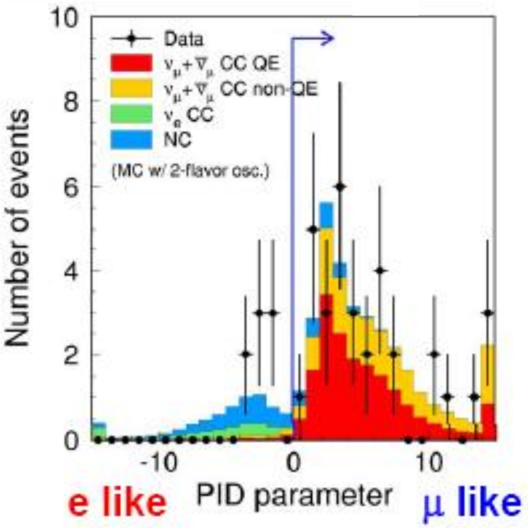


8 e-like events and 33 μ-like events

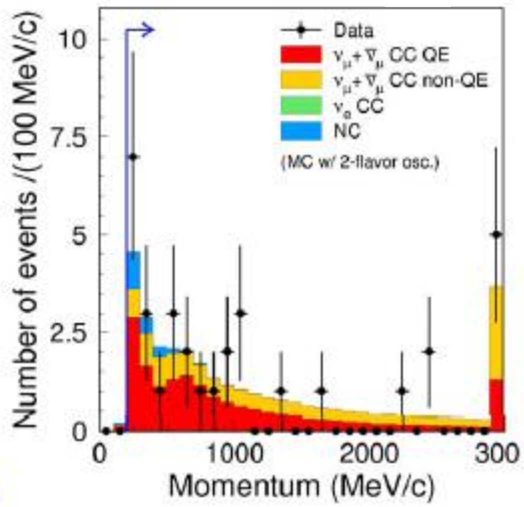
ν_μ disappearance

ν_μ events

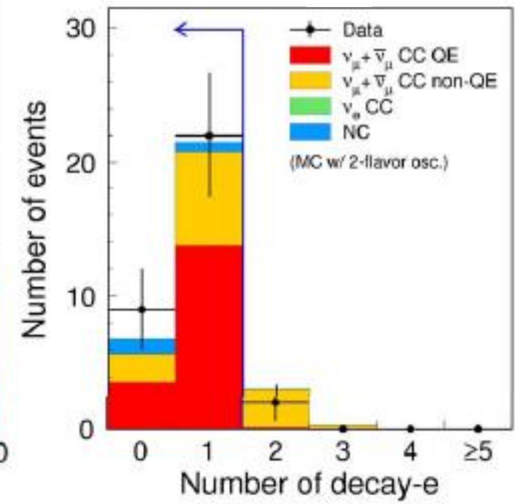
1



2



3

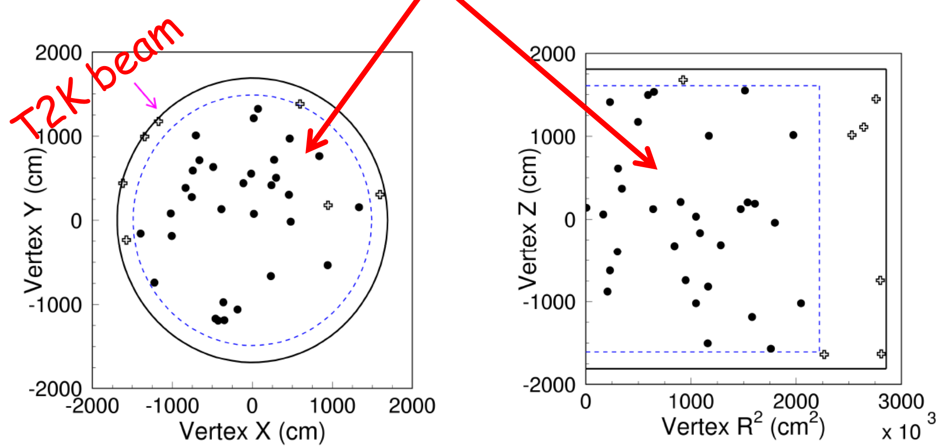


Cut Sequence for ν_μ CCQE

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

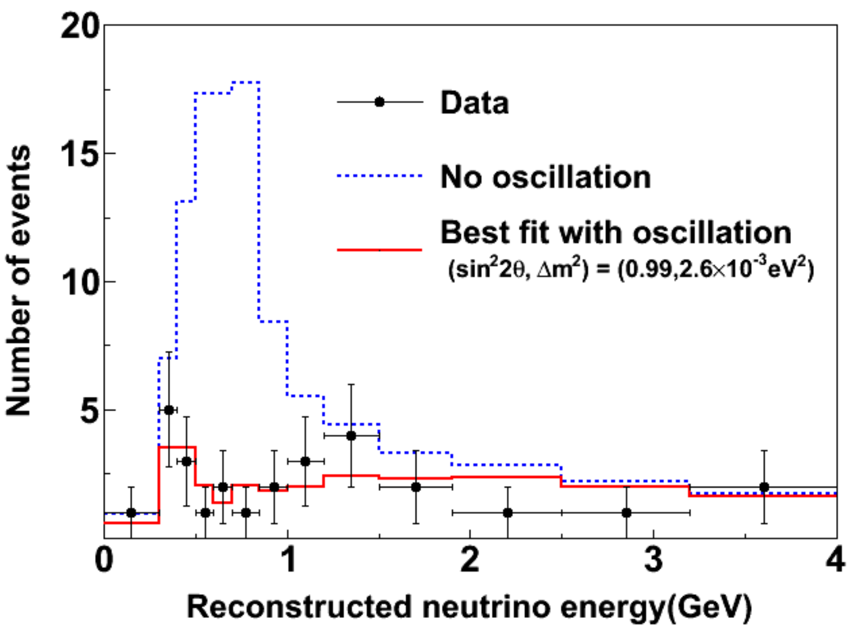
103.6 ν_μ **events in case of no oscillation**

Vertex distribution in SK

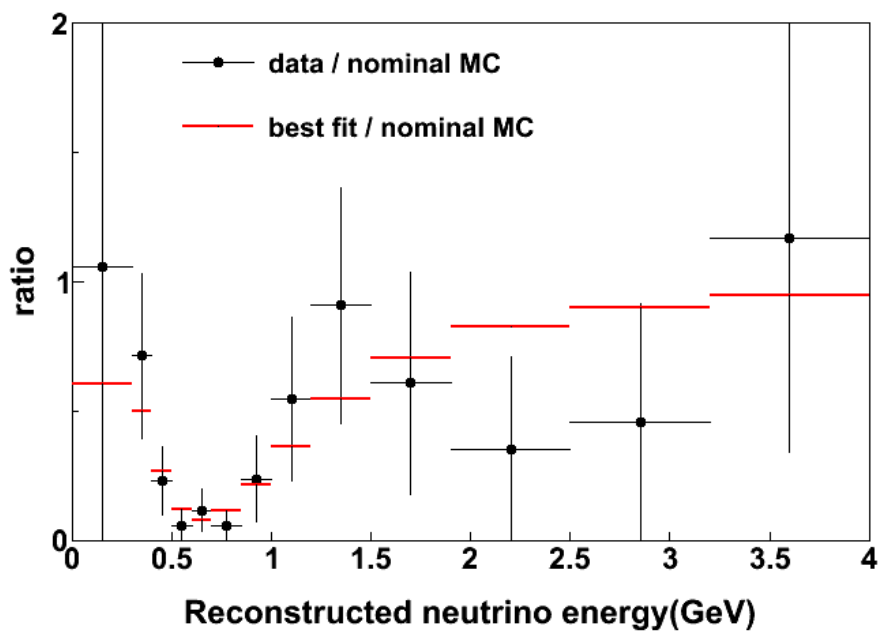


ν_μ disappearance

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)

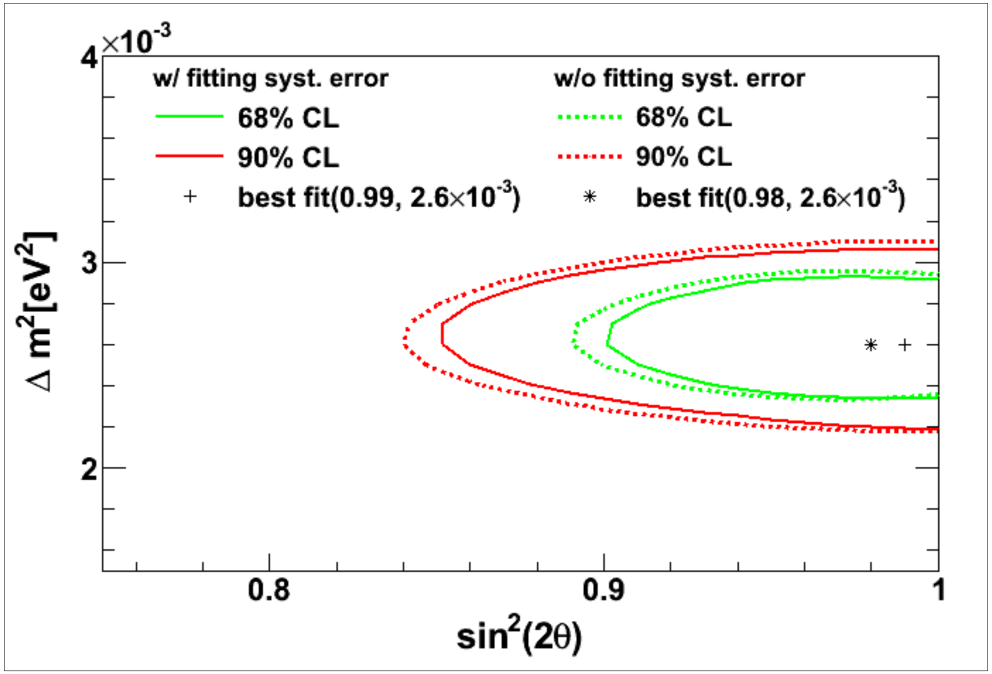
Method A:
Best fit:
$\sin^2(2\theta_{23})=0.99$, $|\Delta m^2_{23}|=2.6\times10^{-3}$ eV^2

$\sin^2(2\theta_{23})>0.85$
$2.1\times10^{-3}<|\Delta m^2_{23}|(\text{eV}^2)<3.1\times10^{-3}$

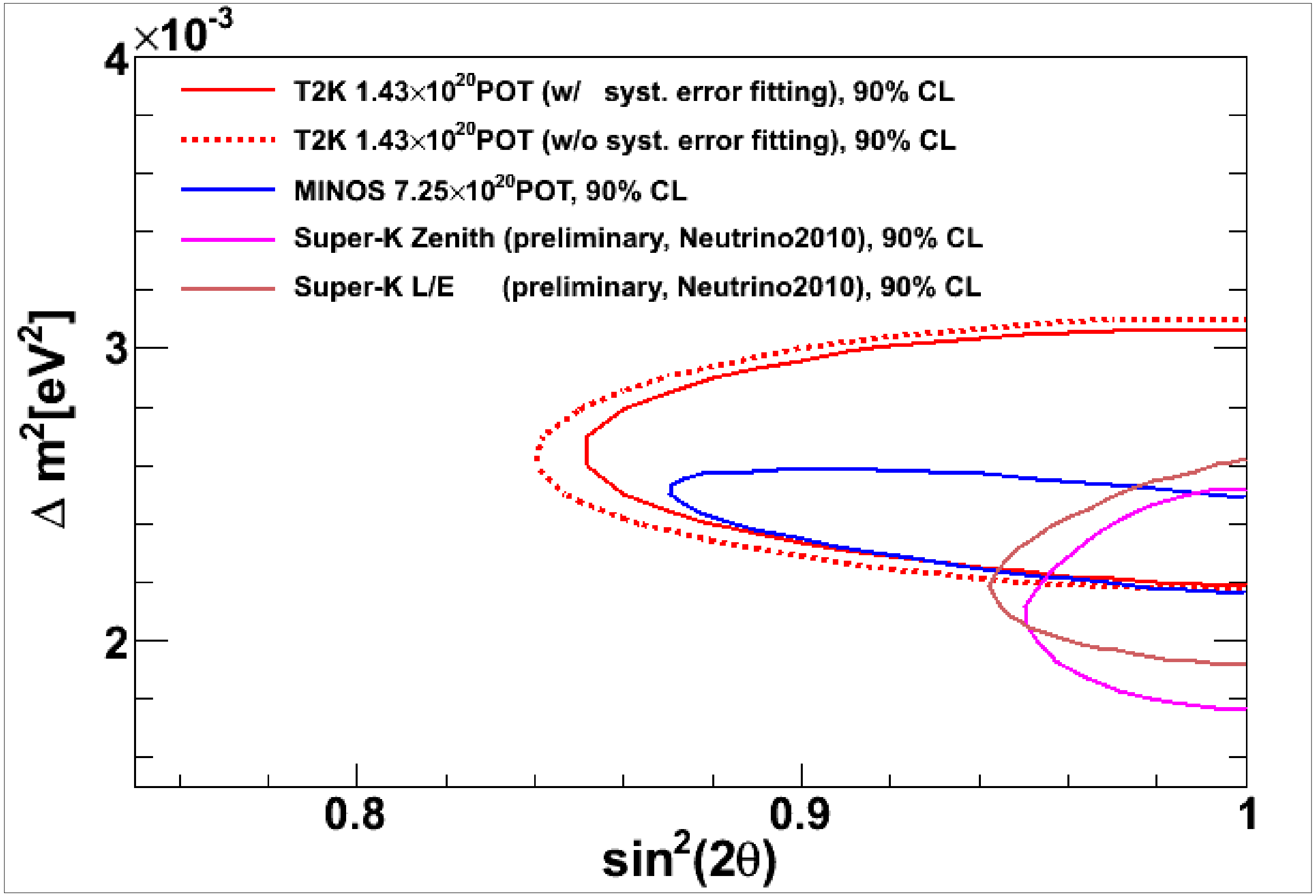
Method B:
Best fit:
$\sin^2(2\theta_{23})=0.98$, $|\Delta m^2_{23}|=2.6\times10^{-3}$ eV^2

$\sin2(2\theta_{23})>0.84$
$2.1\times10^{-3}<|\Delta m^2_{23}|(\text{eV}^2)<3.1\times10^{-3}$

Very good consistency between the two fits



T2K, SK and MINOS

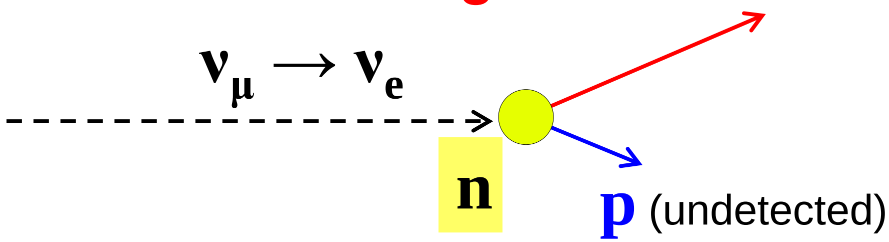


T2K result is in a good agreement with SK and MINOS

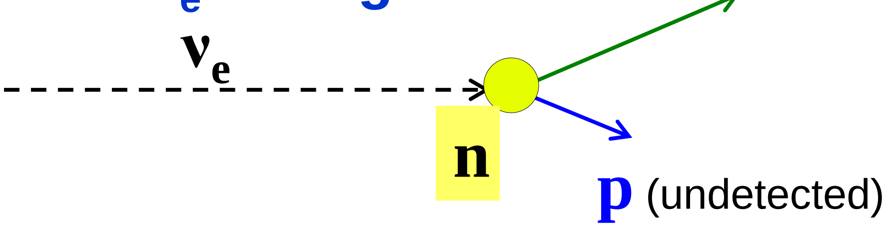
ν_e appearance

ν_e Signal & Background at SK

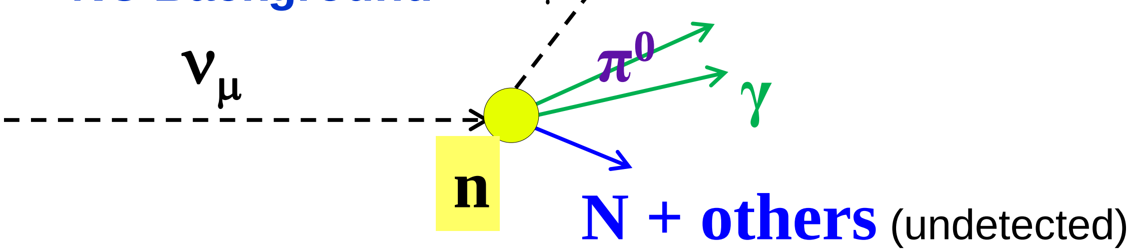
Oscillation Signal

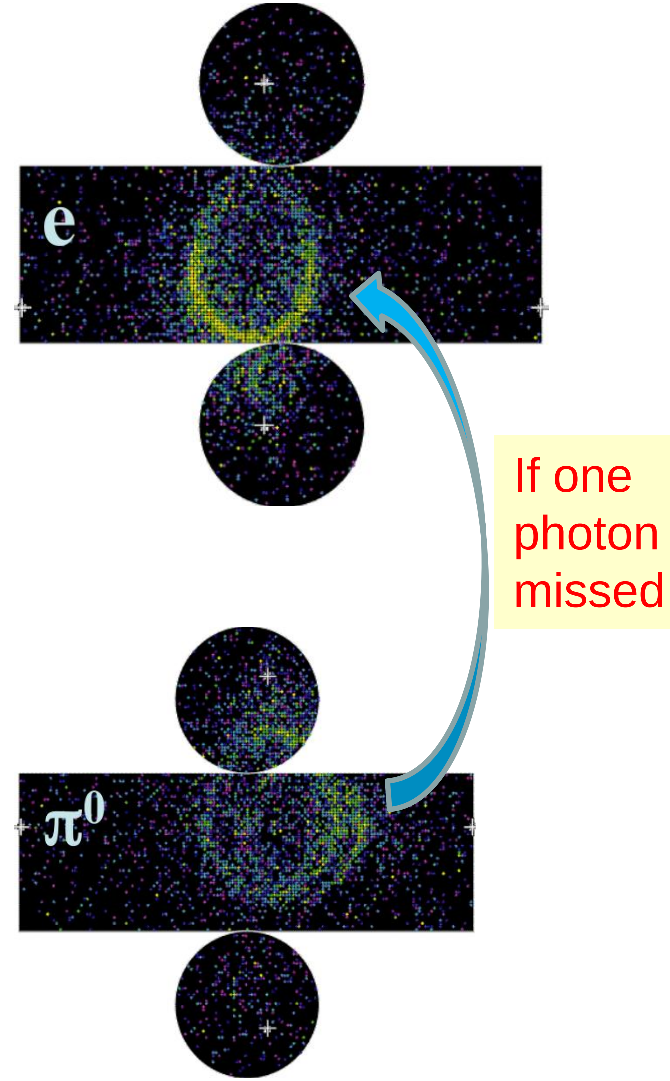


Beam ν_e Background



NC Background





ν_e events

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

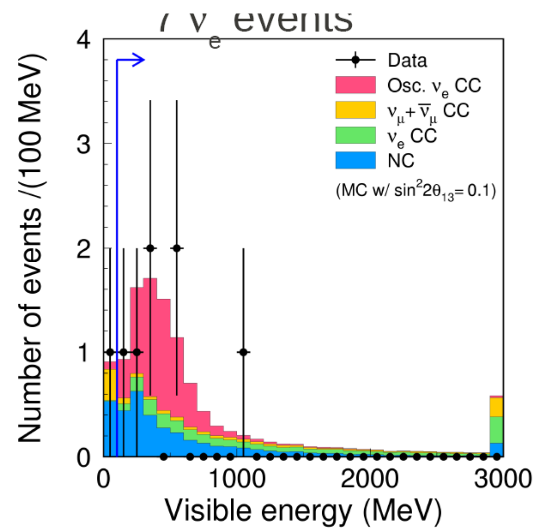
T2K ν_e selection cuts in SK optimized for intrinsic beam ν_e and NCπ^o background minimization

After all cuts:

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

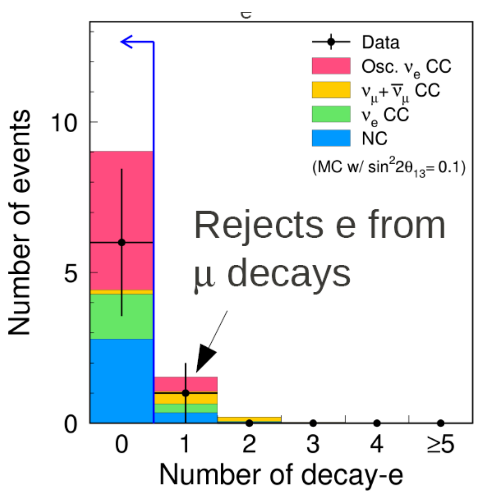
(1)

Energy deposited in ID >100 MeV→ 7 events



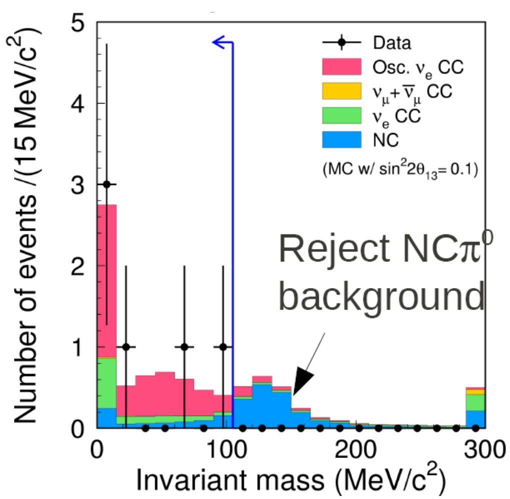
(2)

No Michel electrons → 6 events



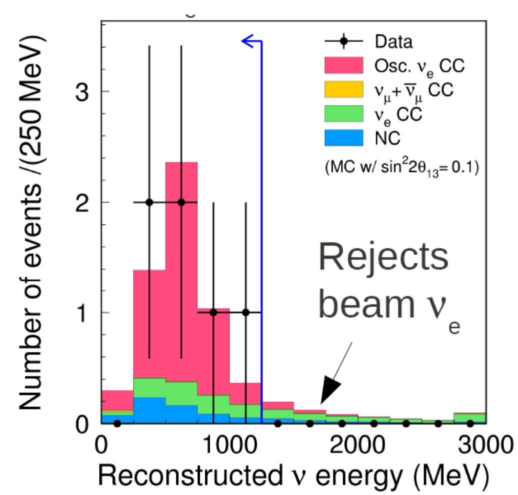
(3)

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



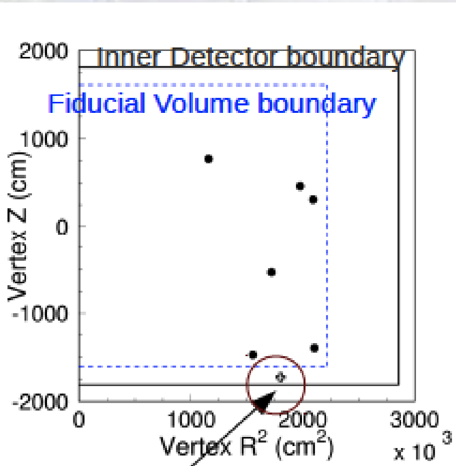
(4)

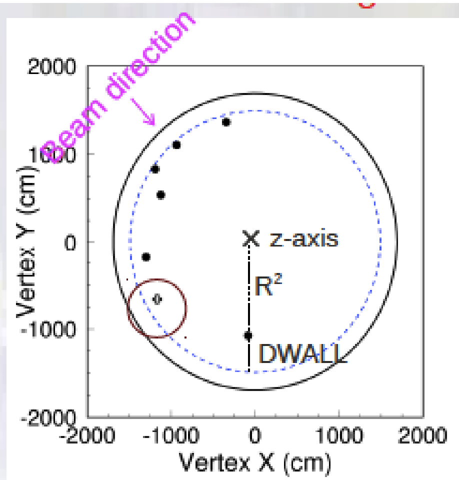
Reconstructed neutrino energy <1250 MeV → 6 events



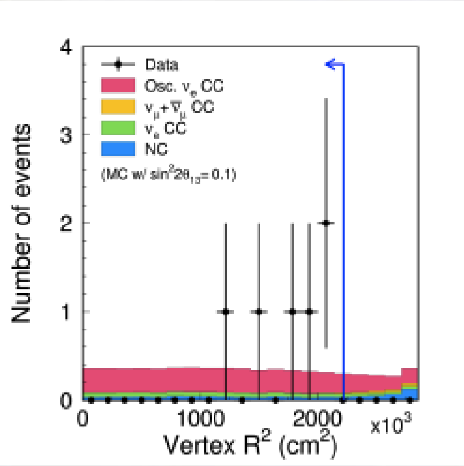
ν_e vertex distributions

After all cuts 6 final candidate events remained!





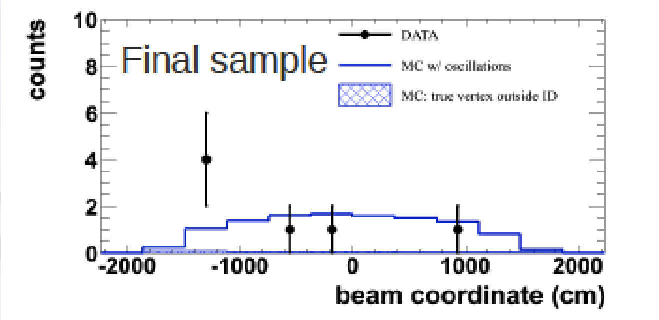
Kolmogorov-Smirnov test on the R^2 distribution → 3% p-value (other distributions have p-values 1-20%):

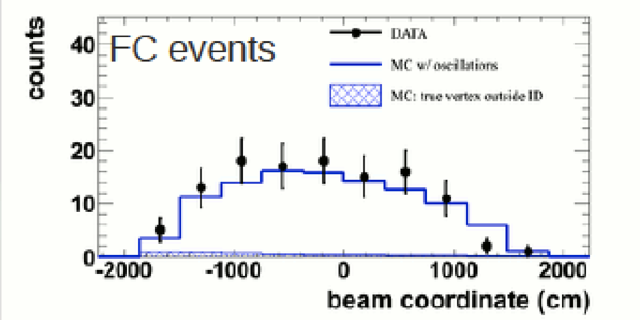


Only one event seen outside fiducial volume that passes all other cuts:

- if beam related background from outside FV, expect more events in this region.

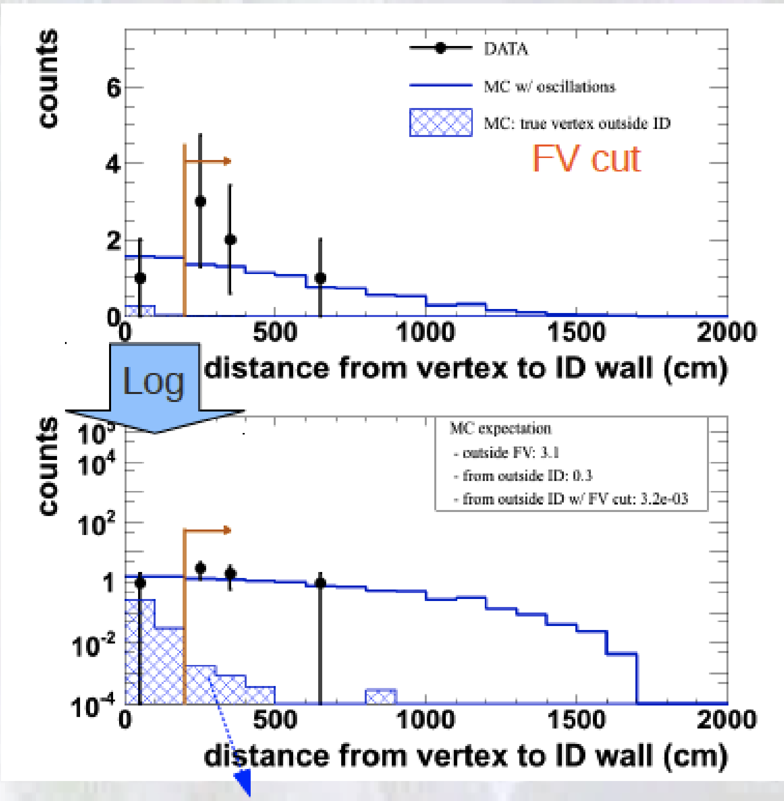
Vertex distribution along beam direction consistent with MC:



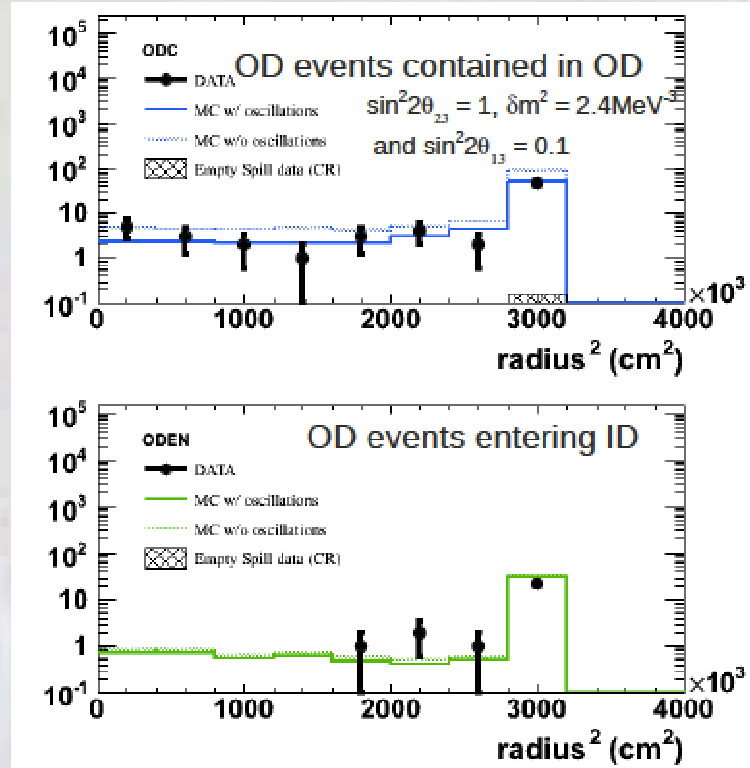


ν_e events OD distributuions

Vertices after FC cuts but w/o FV cut:



OD event vertex distributions:



From outside ID w/ FV cut: 3.2×10^{-3} expected events.

No significant excess of events in OD

OD event distributions show no indication of contribution from outside ID

Expected background

1.5 ν_e candidates expected with zero θ_{13} hypothesis

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

Systematic uncertainties

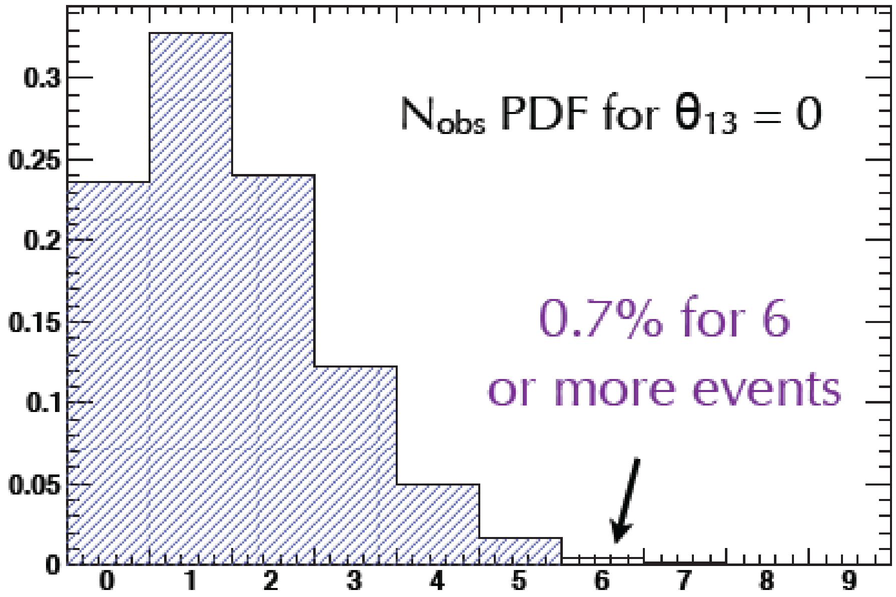
Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$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

$\nu_\mu \to \nu_e$ and θ_{13}

accelerator experiment $\nu_\mu \to \nu_e$

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

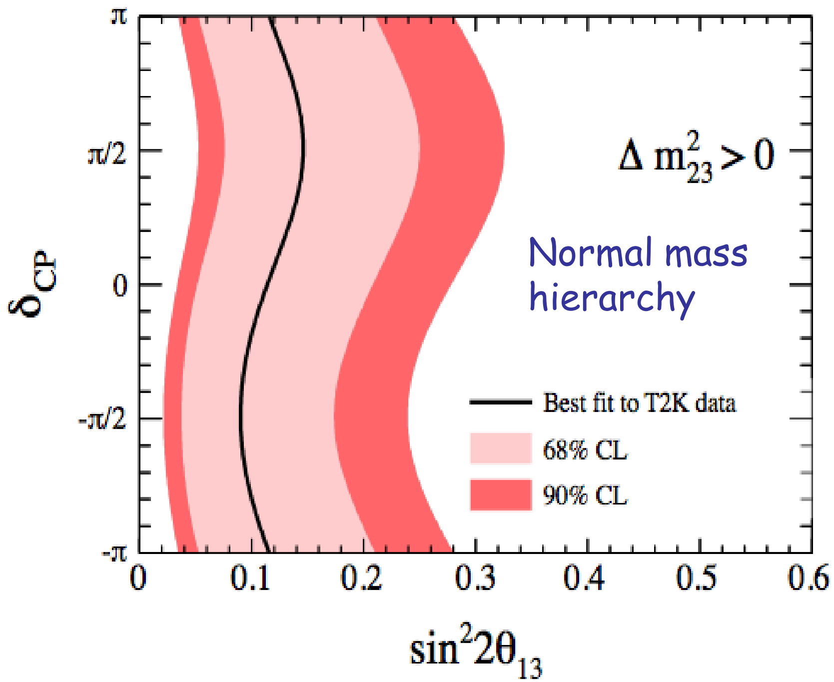
- θ_{13}
- **CP-even**
- **CP-odd**
- **Solar**
- **Matter**

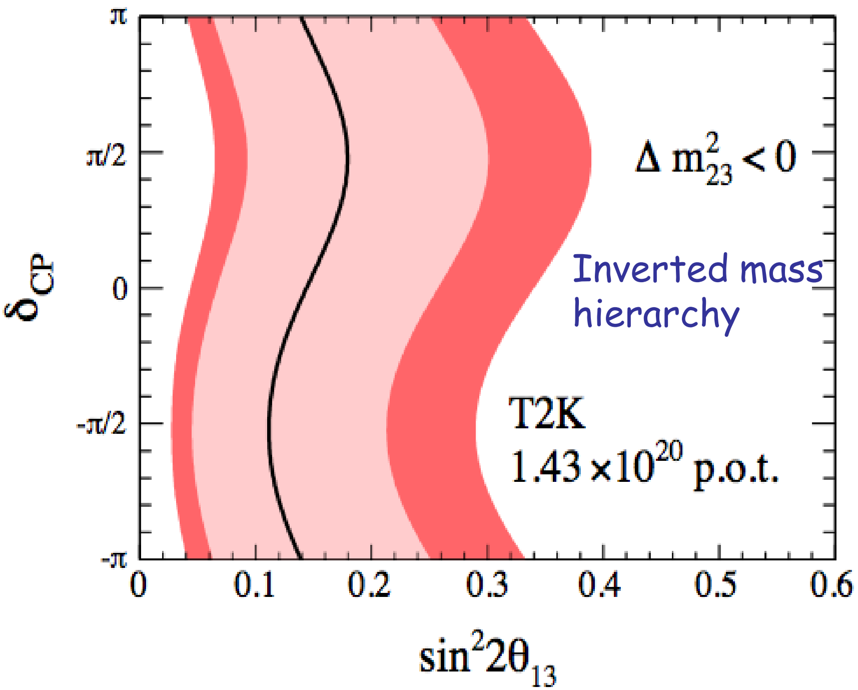
$s_{ij} = \sin\theta_{ij}$ $\quad c_{ij} = \cos\theta_{ij}$ $\quad a[eV^2] = 2\sqrt{2}G_F n_e E_\nu = 7.6\times10^{-5}\rho\left[g/cm^3\right]E_\nu[GeV]$

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

θ_{13}

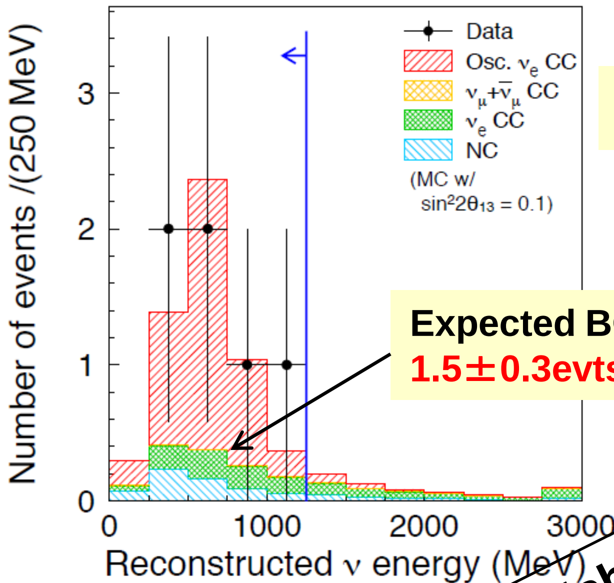
Feldman-Cousins method to produce confidence intervals for $\sin^2 2\theta_{23}=1.0$ and $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2





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]

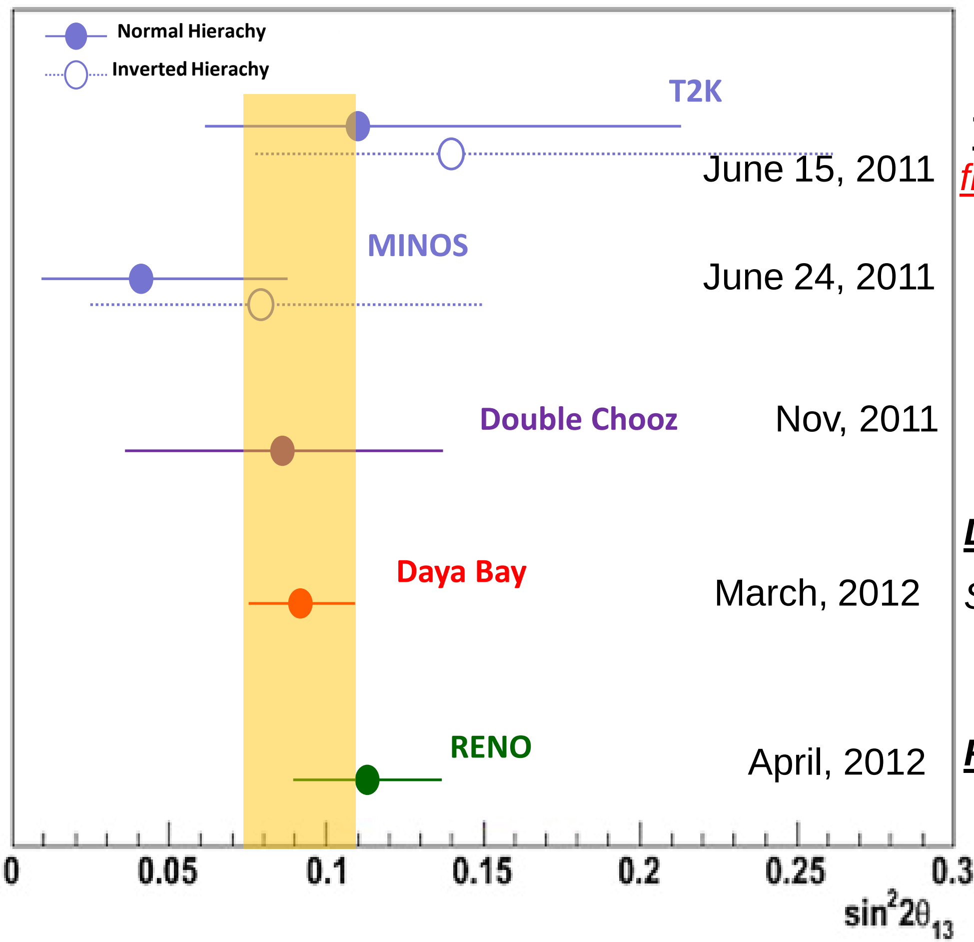
The T2K experiment observes indications of $\nu_\mu \to \nu_e$ appearance in data accumulated with 1.43×10^{20} protons on target. Six events pass all selection criteria at the far detector. In a three-flavor neutrino oscillation scenario with $|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}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

from an upper limit to precise measurement !

- θ13 has been well measured by different experiments
- Interest now focused to the *Mass Hierarchy* determination & measurement of the *CP phase*



T2K $\nu_\mu \rightarrow \nu_e$

first indication of θ13 ≠ 0 with 2.5 σ significance

MINOS $\nu_\mu \rightarrow \nu_e$

θ13 =0 *disfavored @1.7 σ*

Double Chooz $\bar{\nu}_e \rightarrow \bar{\nu}_e$

θ13 ≠ 0 *@3σ combined with T2K and MINOS*

Daya Bay $\bar{\nu}_e \rightarrow \bar{\nu}_e$

Sin²2θ13 = 0.092 ± 0.016(stat) ± 0.005(syst)
5.2σ significance

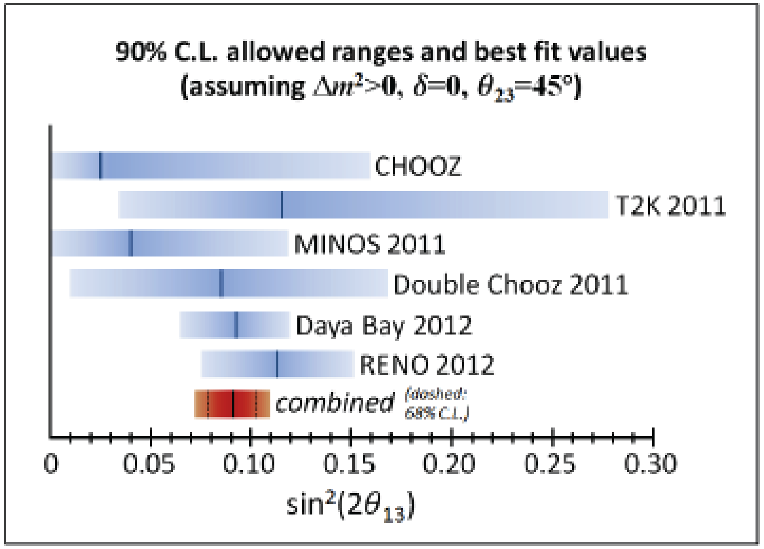
RENO $\bar{\nu}_e \rightarrow \bar{\nu}_e$

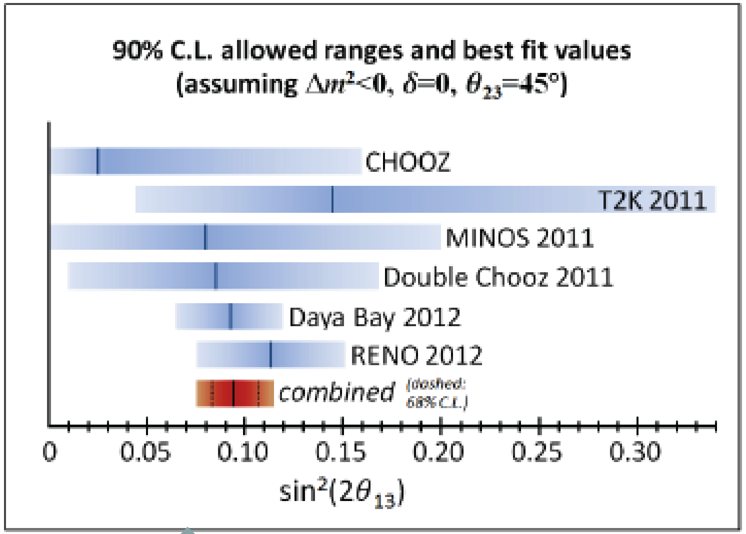
Sin²2θ13 = 0.113 ± 0.013(stat) ± 0.019(syst)
4.9σ significance

θ_{13} landscape

(May 2012)

5 experiments published θ_{13} results since June 2011



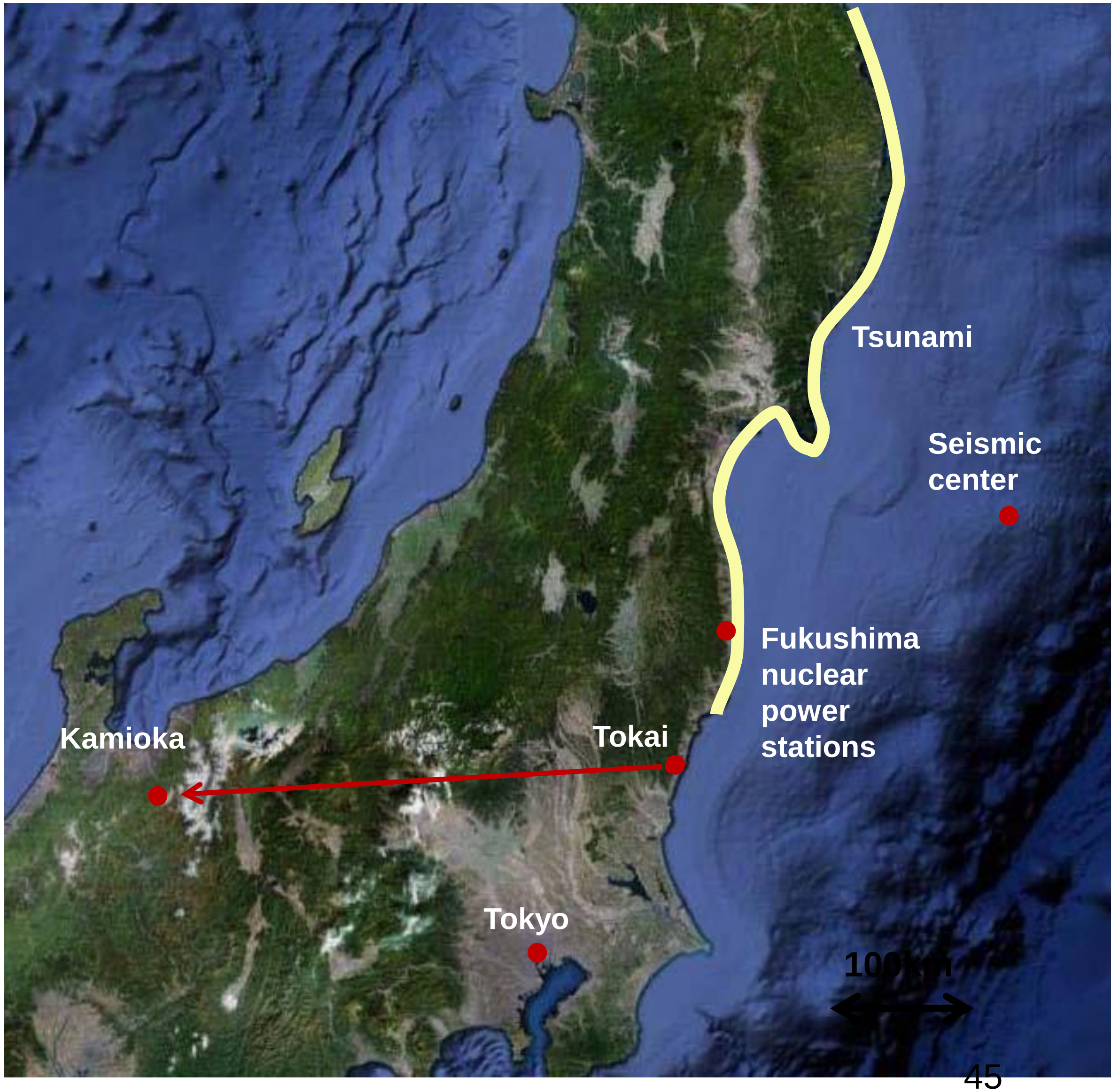


$\theta_{13} \approx 9 \pm 1$ deg

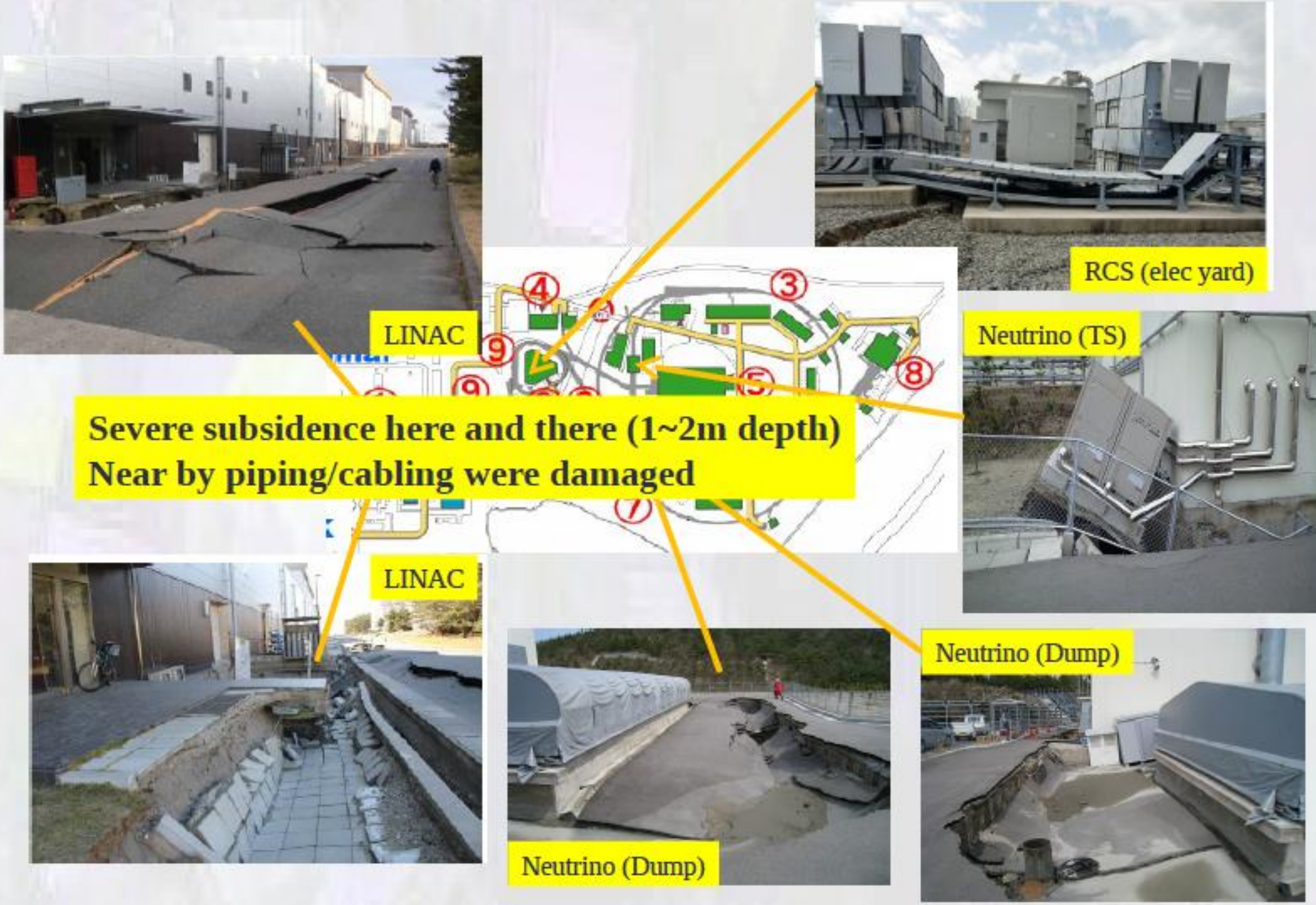
Earthquake 11 March 2011

-Землетрясение магнитудой 9.0   11 марта 2011

- около 24000 погибших и пропавших без вести из-за цунами и землетрясения



Ground Level Damage....

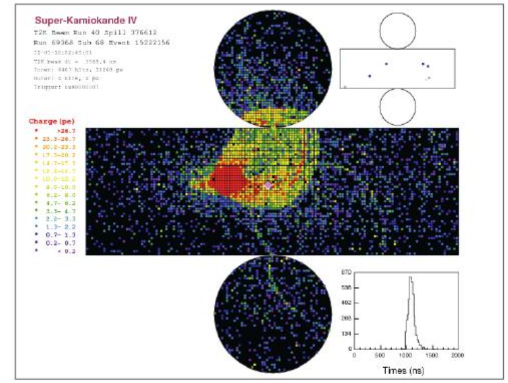


Severe subsidence here and there (1~2m depth)
Near by piping/cabling were damaged

Recovering from Earthquake

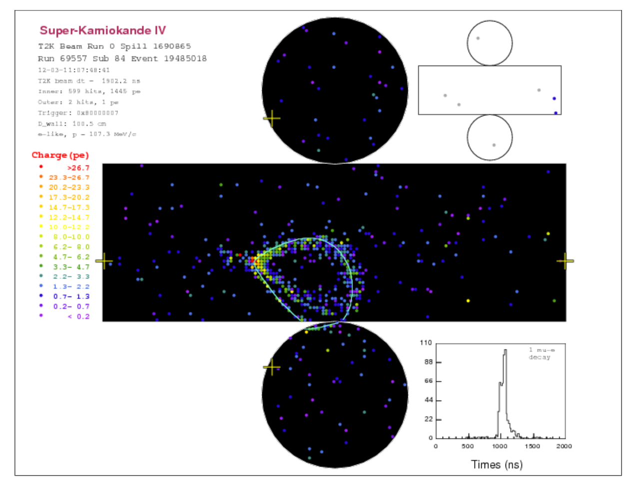
- JPARC resumed operation in December 2011
- Neutrino beam is back in December 2011
- T2K short test run in January 2012
- Data taking since March 2012

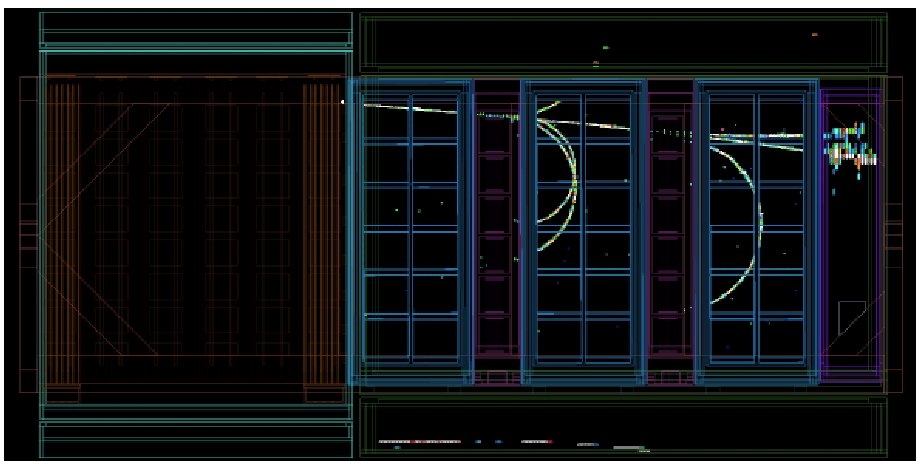
First ν event at SK



Event seen in T2K on 26th January 2012

First FC ν event at SK





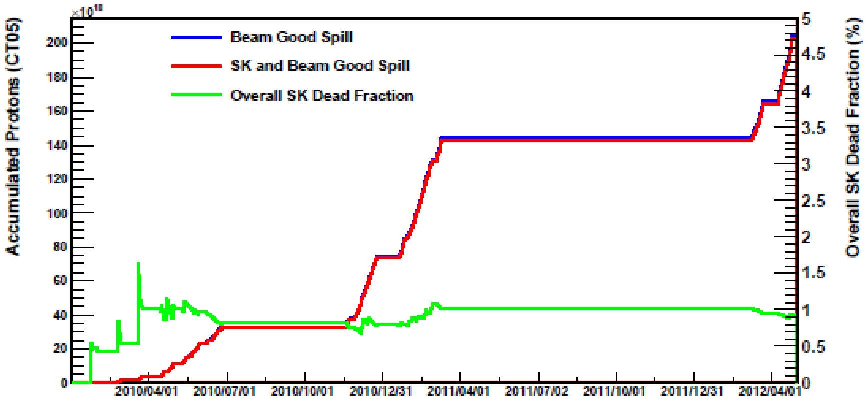
ND280 off-axis event on 23-1-2012 (beam spill)

First ν event in ND280

T2K status

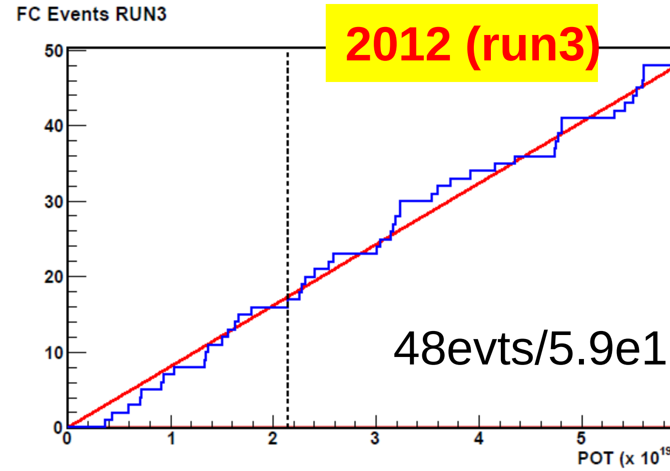
25 April 2012

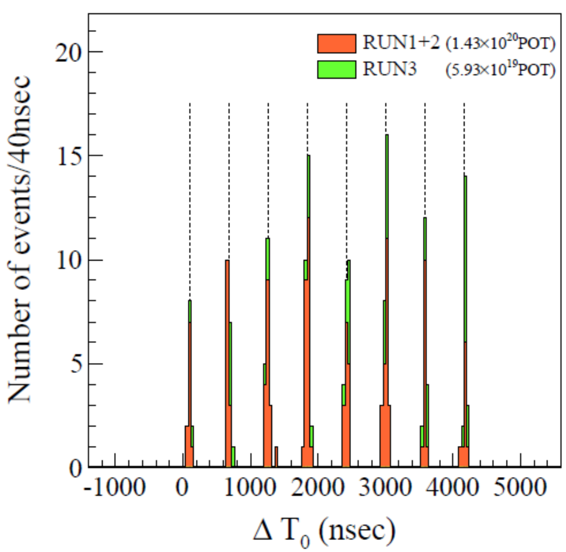
SK running efficiency > 99%



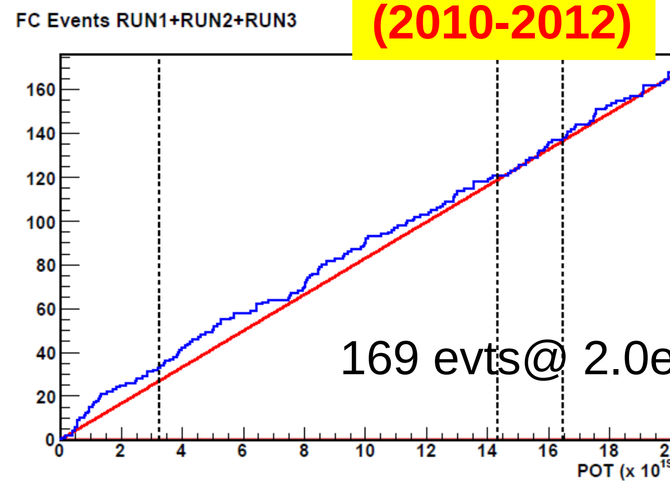
ν events at SuperKamiomande

2012 (run3)





(2010-2012)



-Taking high quality data very efficiently

- Double statistics by June 2012

θ_{13} is large → next step?

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

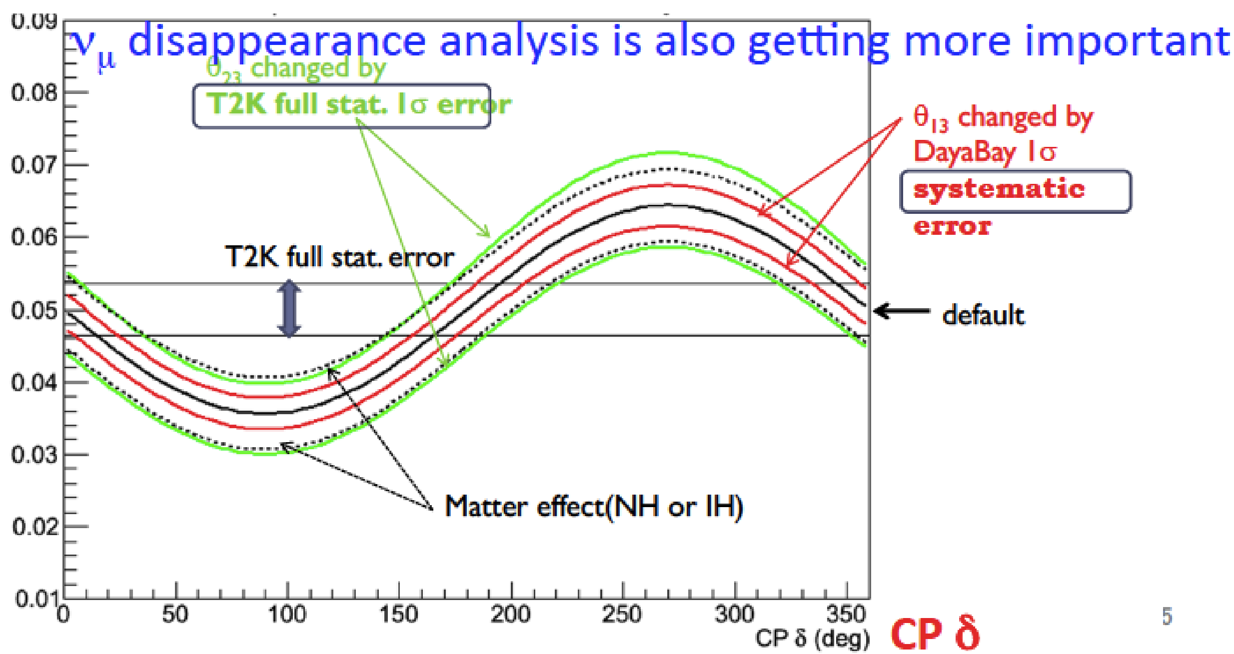
Leading

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

Solar

Matter effect

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



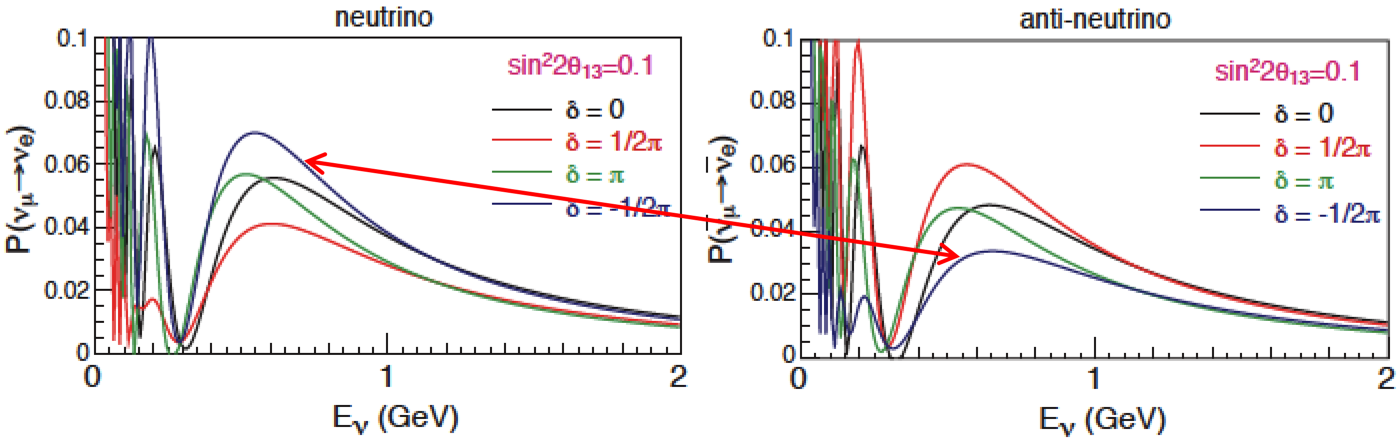
CP δ

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

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

Normal hierarchy

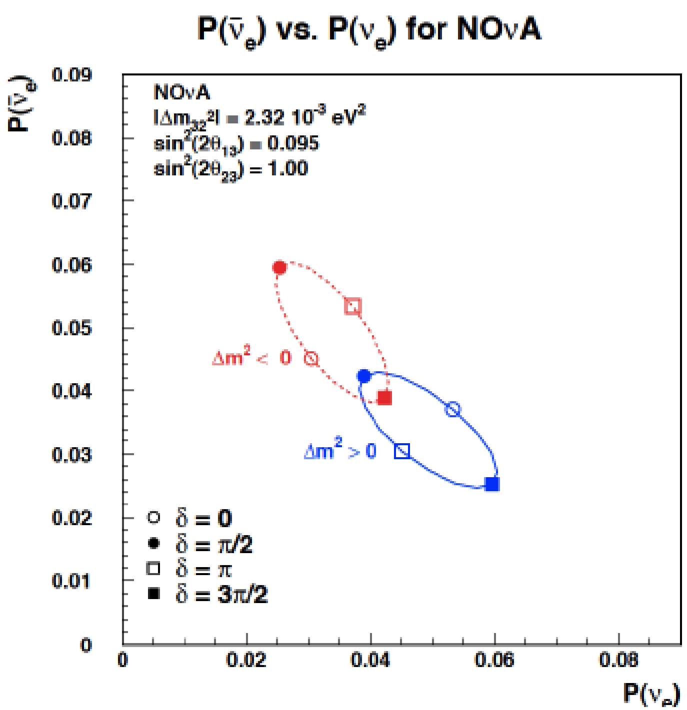


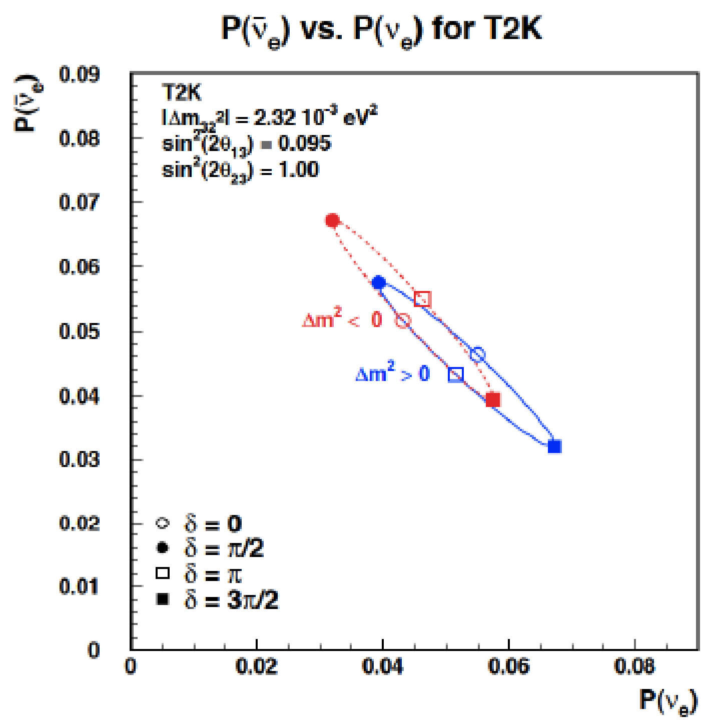
T2K and Nova

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





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

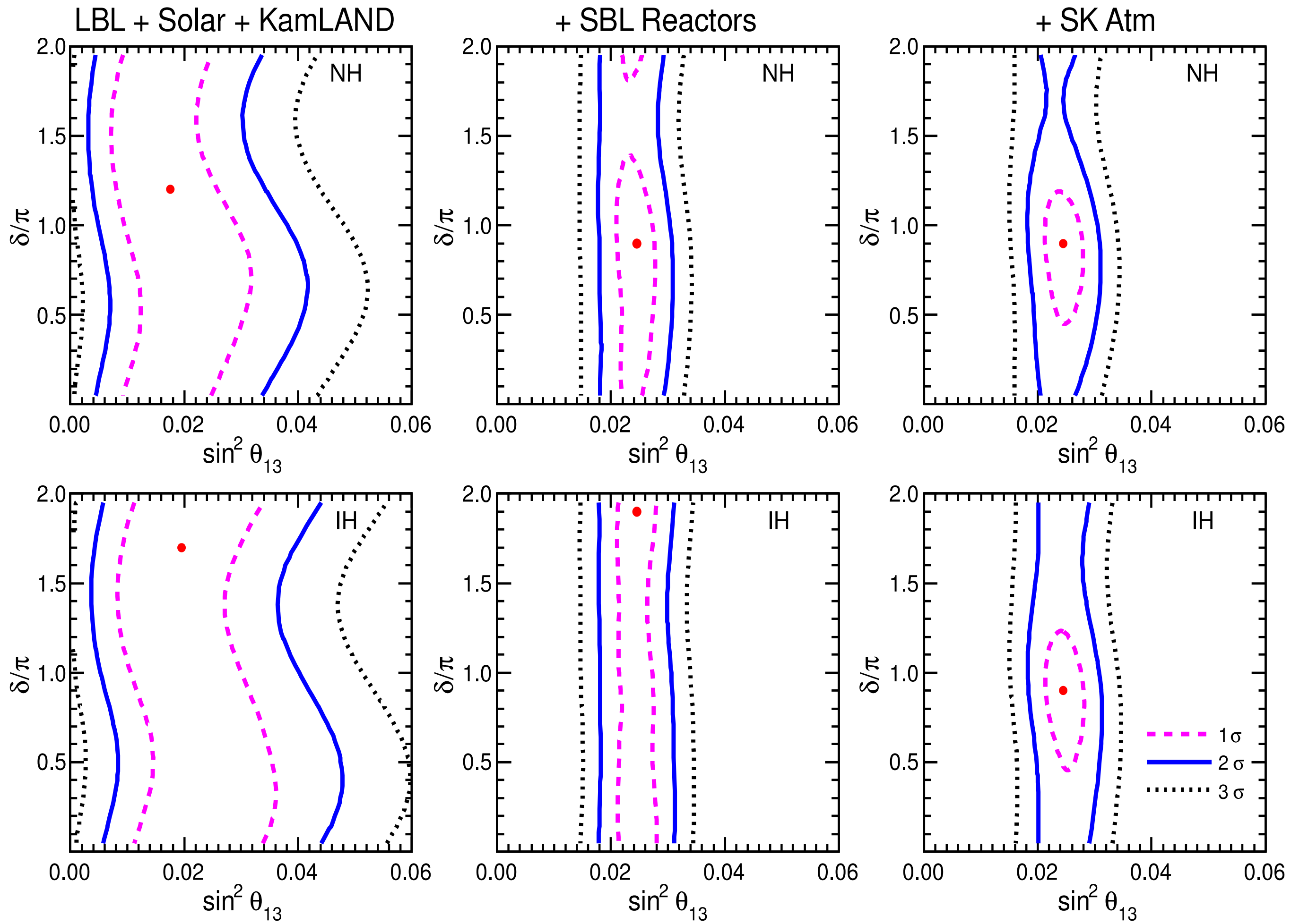
- MH: ≈50% coverage
- CPV: ≈30-40% coverage

Combined analysis all oscillation data

Gianluigi Fogli et al., arXiv:1205.5254

normal hierarchy

inverted hierarchy



~ 1σ preference for $\delta \sim \pi$

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 & δ_{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) < 3.1×10^{-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**

Large θ_{13} $\rightarrow$ Rich physics program

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

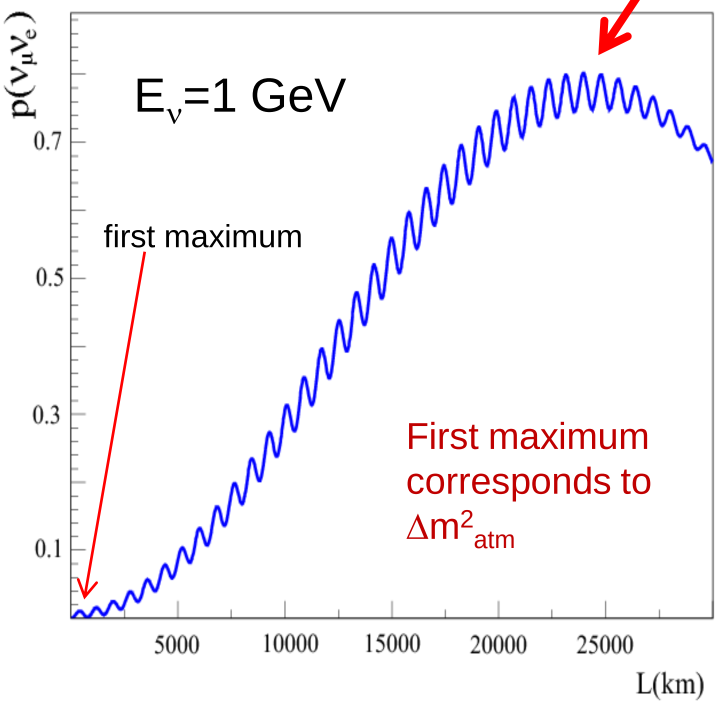
спасибо за внимание!

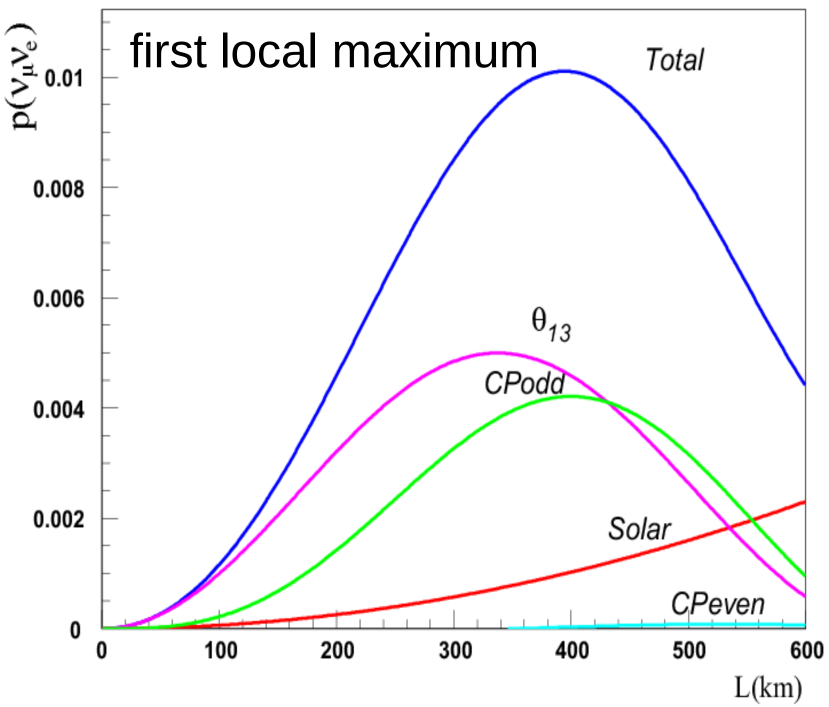
Backup slides

Accelerators: $\nu_\mu \to \nu_e$

- subdominant oscillation
- physics background:
  - ν_e contamination
  - NC π^0 background

Solar maximum





θ_{13} measurement at reactors

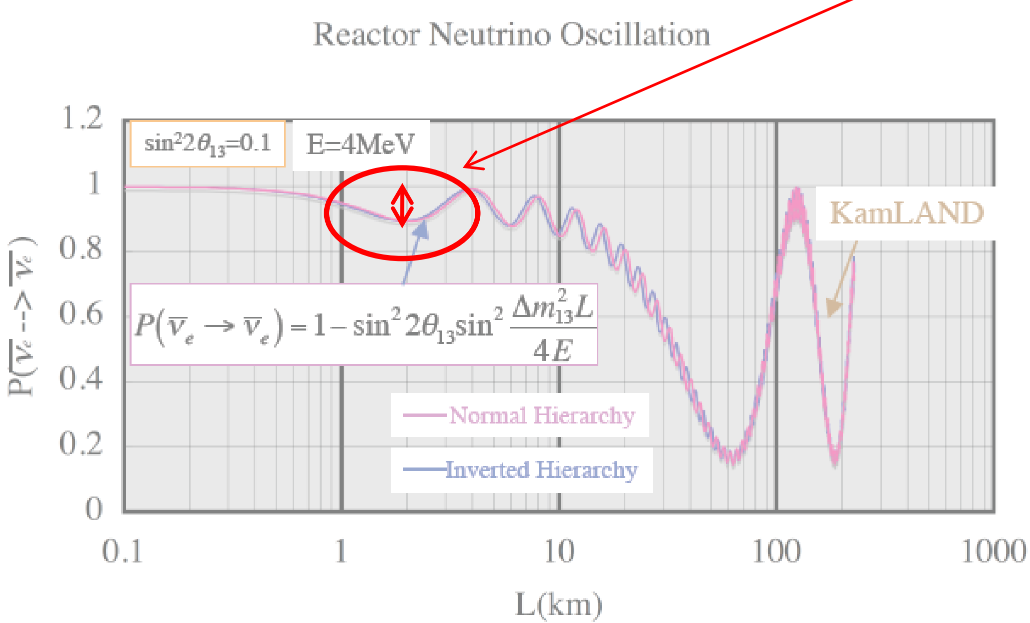
reactor experiment anti-$\nu_e \rightarrow$ anti-ν_e

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

non-sensitive to δ

insensitive to mass hierarchy

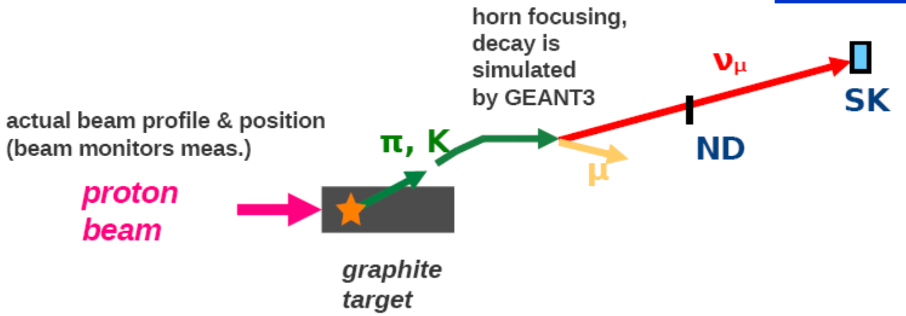
Measurement deficit of anti-nu flux at 1-2 km from reactor



sensitivity is dominated by systematics which should be $\leq$ 1% in probability

Neutrino flux prediction

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

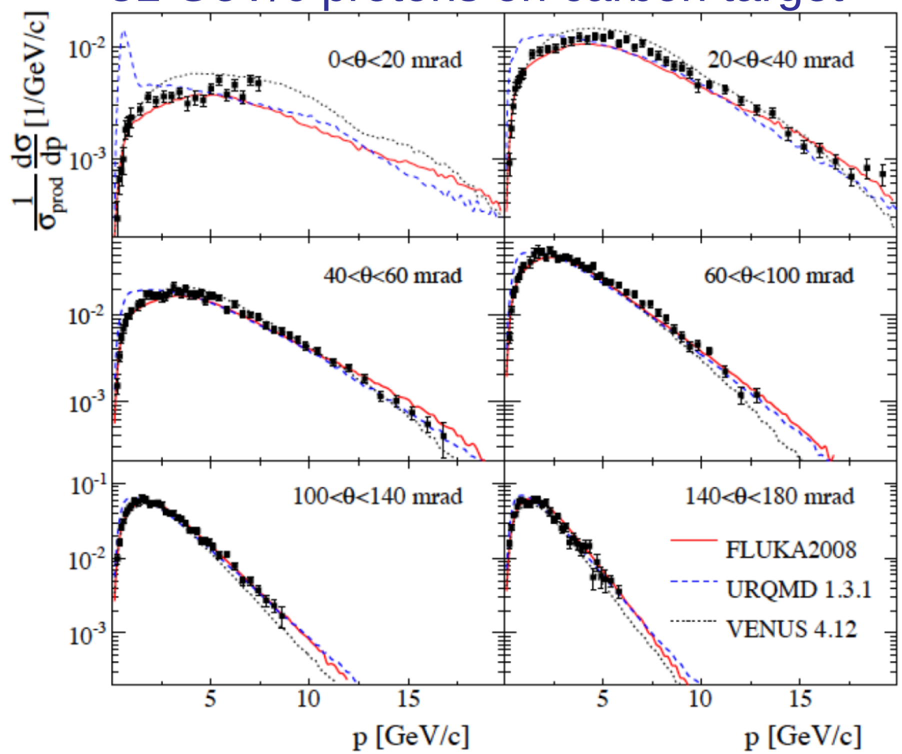


Hadron production in T2K target
- NA61 experiment at CERN
  - pions in p+C interactions
  - same proton energy and target material

- kaon production, pion outside NA61 acceptance, other target interactions modeled with FLUKA

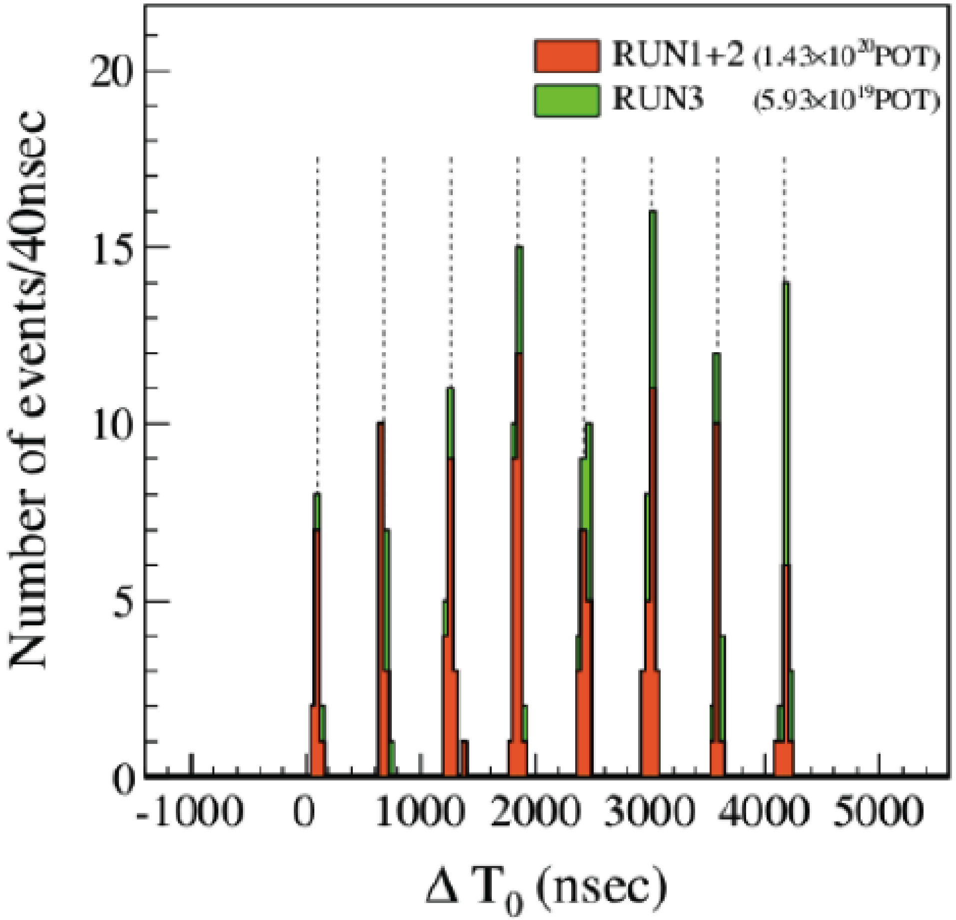
Out of target interactions, horn focusing, secondary interactions, particle decays
- GEANT3 simulation
- interaction cross-sections tuned to existing data

31 GeV/c protons on carbon target



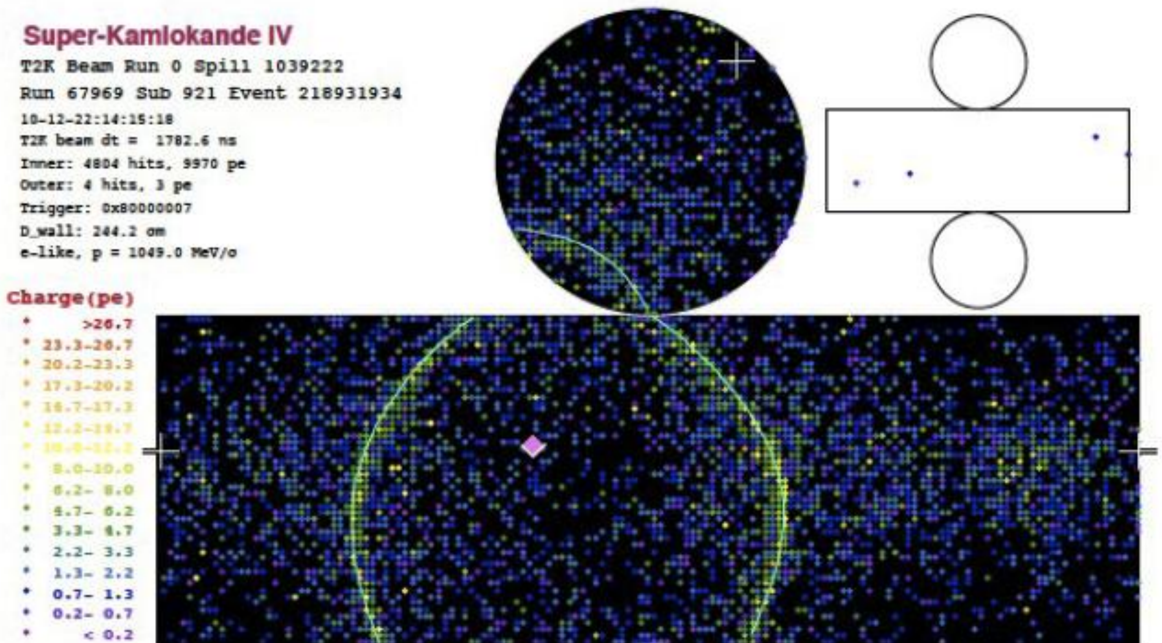
N.Abgrall et al., Phys.Rev.C (2011); arXiv:1102.0983 [hep-ex]

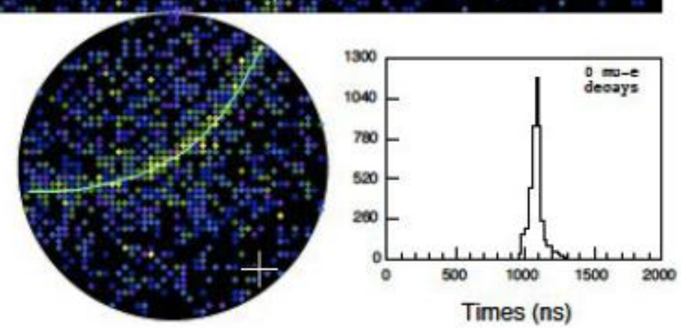
Neutrino events at SK



green - events detected after the Earthquake

ν_e event in SK





visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c^2
recon. energy : 1120.9 MeV