Исследование нейтринных осцилляций на ускорителях

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ИЯИ РАН

IV Черенковские чтения, ФИАН, Москва
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Outline

- Neutrino oscillation parameters
- Short-baseline experiments:
  LSND; MiniBooNE - anomalies
- First generation of Long-baseline experiments:
  K2K; MINOS; OPERA – results
- New generation of Long-baseline experiments:
  T2K – first results; NOvA
- Conclusions

New Physics

- Neutrino oscillations discovered in atmospheric, solar, reactor and accelerator experiments -> new physics beyond Standard Model (SM)
- Accurate measurements of the oscillation parameters are necessary to formulate/select Extensions of SM

Neutrino Mixing

Flavor states ≠ Mass states

ν mixing: 3×3 unitary matrix U_{PMNS} (PMNS= Pontecorvo-Maki-Nakagawa-Sakata)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"atmospheric" "solar"

Parameters: 3 mixing angles (θ_{23}, θ_{13}, θ_{12})

+ 1 CP phase (δ)

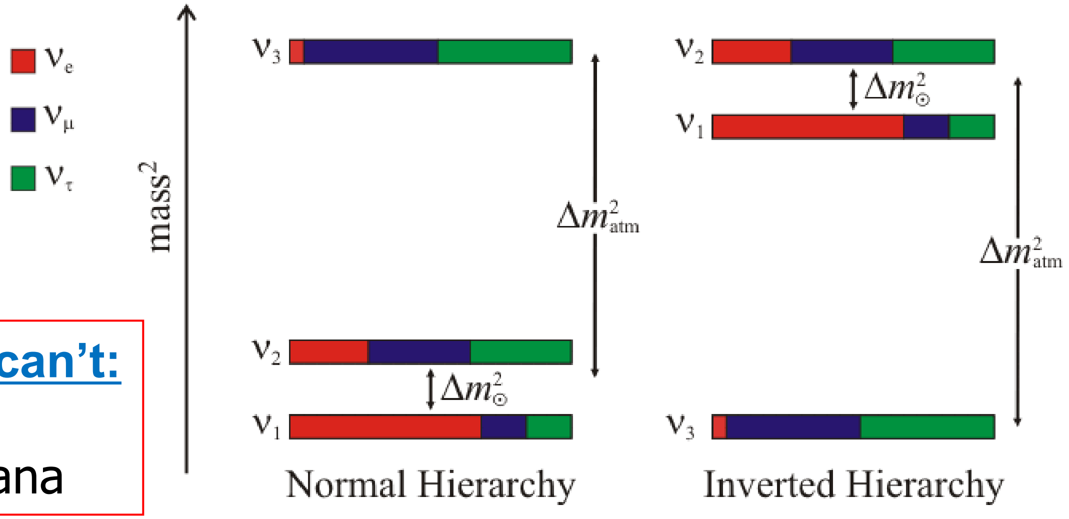
+ 2 mass² differences Δm^2_{12} , Δm^2_{23}

($\Delta m_{ij}{}^2 \equiv m_j{}^2 - m_i{}^2$; $\Delta m^2_{12} + \Delta m^2_{13} + \Delta m^2_{23} = 0$)

Known and unknown parameters

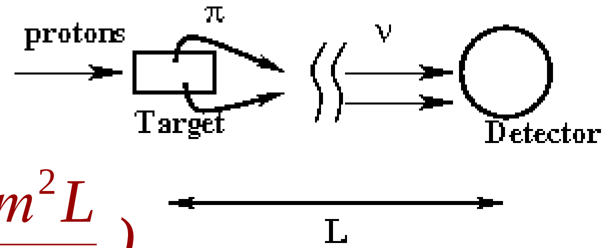
- **(1,2)**: $\theta_{12} \approx 34°$, $\Delta m_{12}^2 \approx 7.6 \times 10^{-5}$ eV^2 (solar + reactor)
- **(2,3)**: $\theta_{23} \approx 45°$, $\Delta m_{23}^2 \approx 2.3 \times 10^{-3}$ eV^2 (atm. + accelerator)
- **(1,3)**: $\theta_{13} < 11°$ only upper limit (reactor(CHOOZ) + accelerator)
- CP-phase δ *and* **sign of Δm^2**

(***Normal "+"*** or ***Inverted Hierarchy "–"***?)



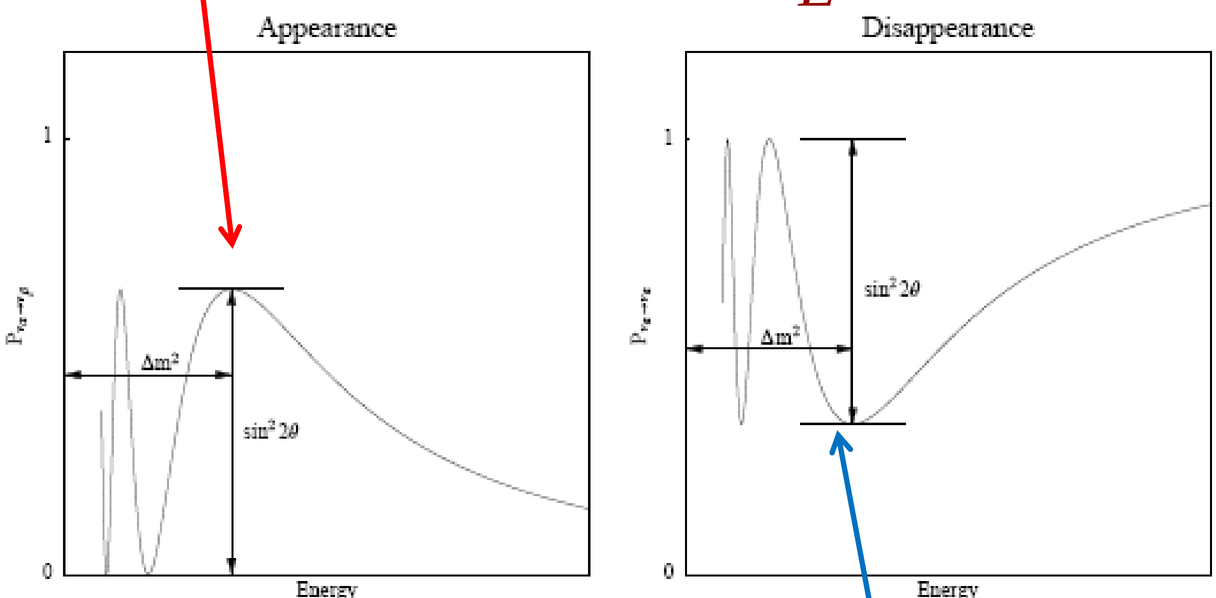
Accelerator ν-experiments can't:
- measure absolute masses
- distinguish btw Dirac/Majorana

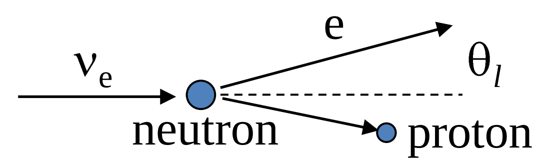
Oscillation Probability at a distance *L*

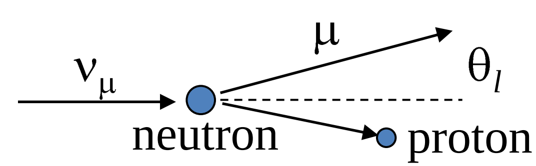


Appearance:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 (1.27\frac{\Delta m^2 L}{E})$$







Disappearance:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\vartheta \sin^2 \left(\frac{1.27 \Delta m^2 (eV^2) L(km)}{E(GeV)} \right)$$

How to measure the oscillation parameters

Experiment:

- observed events N_{obs};
- reconstructed energy spectrum E_{ν}.

Prediction (theory + MC):

- expected events N_{exp};
- expected energy spectrum E^{exp}.

Deficit or **Excess**?

YES

Best fit of N_{obs} and/or E_{ν}, using $\mathbf{P(\nu\rightarrow\nu)}=f(\Delta m^2, \theta)$

$(\Delta m^2, \theta)$

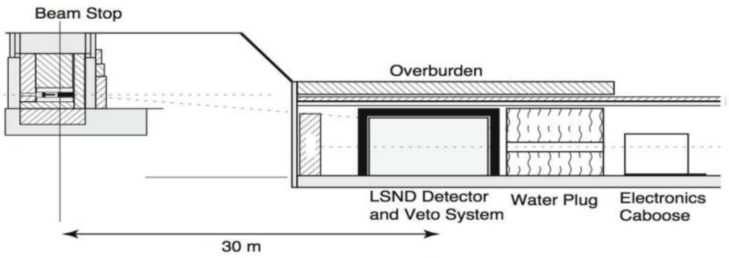
The main accelerator ν-experiments

Experiment	Run	Proton Energy	Proton Target	$\langle E_\nu \rangle$	L (Baseline)	Det. Tech.	Near/Far Det. Mass	Goal	
K2K*	1999-2004	**12** GeV	**Al** 2 horns	**1.3** GeV	**250** km	**Water Ch**	**1kt / 50 kt**	$\nu_\mu \to \nu_\mu$	LBL
MINOS	2005-	**120** GeV	**C** 2 horns	**3** GeV 9 GeV	**735** km	**Fe+Sci.**	**≈1kt / 5.4 kt**	$\nu_\mu \to \nu_\mu$ +anti-ν_μ	LBL
OPERA	2008-	**400** GeV	**C** 1 horn	**17** GeV	**732** km	**Pb+Emul +Track.**	**1.25 kt**	$\nu_\mu \to \nu_\tau$	LBL
T2K*	2010-	**30** GeV	**C** 3 horns	**0.6** GeV	**295** km **OA=2.5°**	**Sci./Water Ch**	**2kt / 50 kt**	$\nu_\mu \to \nu_e$	LBL
NOνA	2013?	**120** GeV	**C** 2 horns	**2** GeV	**810** km **OA=0.8°**	**Liq.Sci.+ WLS**	**0.22kt / 14 kt**	$\nu_\mu \to \nu_e$	LBL
LSND*	1993-1998	**798** MeV	Water/ Metals	**20-53** MeV	**30** m	(CH_2) **Ch**+Sci.	**167 t**	$\bar{\nu}_\mu \to \bar{\nu}_e$	SBL
MiniBooNE*	2002-	**8** GeV	**Be** 1 horn	**600** MeV	**541** m	(CH_2) **Ch+Sci.**	**800 t**	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_e$	SBL

* - Cherenkov Light used (**Ch**)

LBL=Long Baseline; **SBL**= Short Baseline
OA= Off-Axis

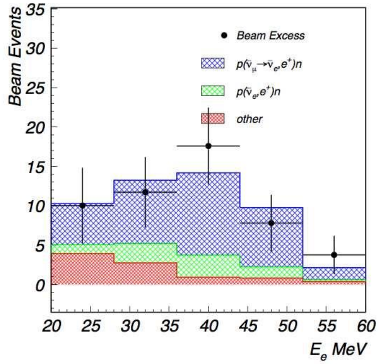
Short-Baseline experiment: LSND
(Liquid Scintillator Neutrino Detector)

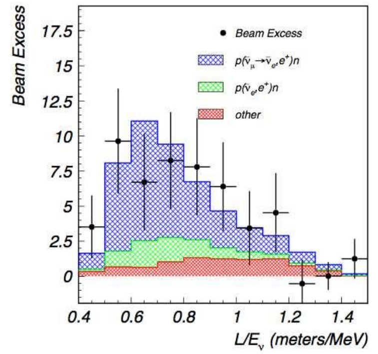


- Los Alamos, USA. 1993-1998.
- **anti-ν_μ** (from μ^+-decays at rest)
- Detector: 167 t of mineral oil (CH_2)
- **L=30 m / E=20-53 MeV**
- Excess of **anti-ν_e** events: 87.9±22.4 ± 6.0 (3.8σ)
- Best fit: **Δm^2=** 0.2-10 eV^2 (very large!)

  $\sin^2(2\theta)$ ~ 0.001-0.04 (includes constraints)

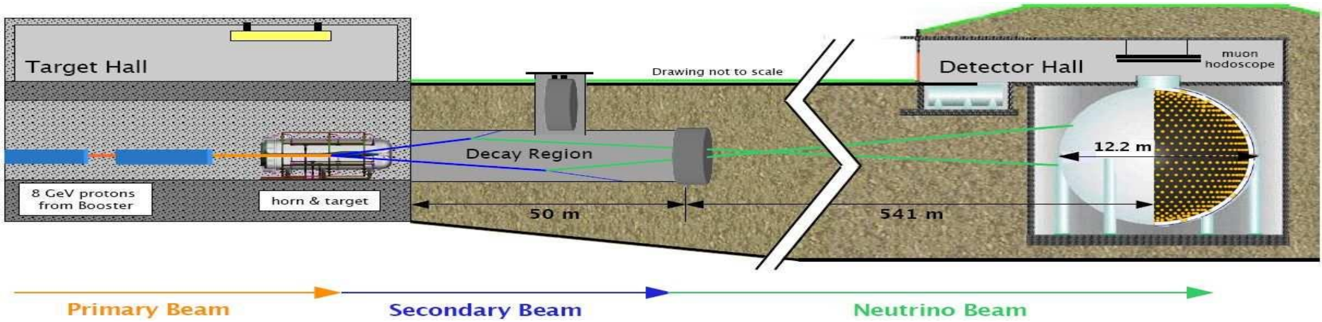
  Phys.Rev. D64, 11207, 2001
- KARMEN (UK): no confirmation
- To confirm/refute: MiniBooNE (see next slide)





Short-Baseline experiment: MiniBooNE (Mini-Booster Neutrino Experiment)

- FermiLab, IL, USA.
- 2002-…
- ν_μ and anti-ν_μ
- Detector: 800 t of mineral oil (CH_2)
- **L=541 m / E=200-1450 MeV**
- Goal: confirm/refute LSND results



"The data are consistent with anti-$\nu_\mu \rightarrow$ anti-ν_e oscillations in the **0.1 to 1.0 eV² Δm²** range and with the evidence for antineutrino oscillations from the Liquid Scintillator Neutrino Detector at Los Alamos National Laboratory."

PRL, 105, 181801 (2010)

Mode	POT	Excess in E=475-1250 MeV
$\nu_\mu \rightarrow \nu_e$	**6.46×10^{20}**	22.1 ± 35.7
anti-$\nu_\mu \rightarrow$ anti-ν_e	**5.66×10^{20}**	**20.9 ± 14.0** (1.5 σ)

Possible interpretations of LSND/MiniBooNE anomalies

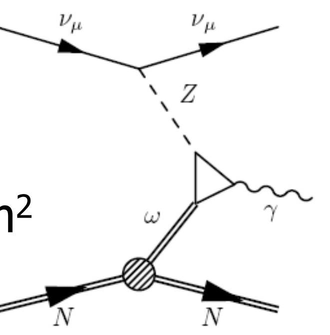
• Unexplained excess in ν-mode for E=(200-475) MeV :
128.8 ± 20.4 ± 38.3 (2.9 σ). PRL, 102, 101802 (2009)

- Non-oscillation

Coupling between γ, Z and ω

$\nu + N \rightarrow \nu + N + \gamma$

$\sigma \sim 2.6\times10^{-41}(E_\nu/\text{GeV})^6(g_\omega/10)^4\ \text{cm}^2$



С.С.Герштейн, Ю.Я.Комаченко, М.Ю.Хлопов, ЯФ 33 (1981) 1597
J.Harvey, C.Hill, R.Hill, arXiv:0708.1281
R.Hill, arXiv:0905.0291; Jenkins,Goldman, arXiv:0906.0984

- Oscillation

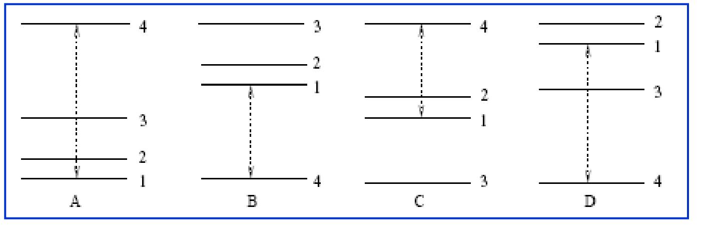
3 +1 model

M.Maltoni, T.Schwetz, arXiv:0051.0107

3 + 2 or 3 + 3 models

M.Maltoni, T.Schwetz, arXiv:0051.0107
A.Nelson, J.Walsh, arXiv:0711.1363

3+1 D.Meloni etal., arXiv:1007.2419



Extra dimensions

H.Pas, S.Pakvasa, T.Weiler, hep-ph/0504096 (predicted low-energy excess)

Lorentz violation

T.Katori, A.Kostelecky, R.Tayloe, hep-ph/0606154

Heavy Sterile Neutrino Decay

S.Gninenko, arXiv:0902.3802

VSBL Electron Neutrino Disappearance

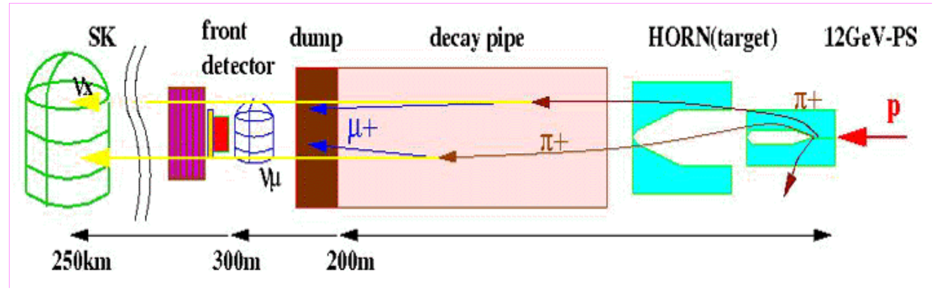
C.Giunti, M.Laveder, arXiv: 0902:1992

First Long-Baseline experiment:
K2K (KEK to Kamioka)

- KEK: Tsukuba, Ibaraki pref.
  Kamioka: Gifu pref., Japan.
- 1999-2001; 2003-2004
- $\nu_\mu \rightarrow \nu_\mu$
- Near Detector: 1 kt water Cherenkov
- Far Detector: 50 kt water Cherenkov

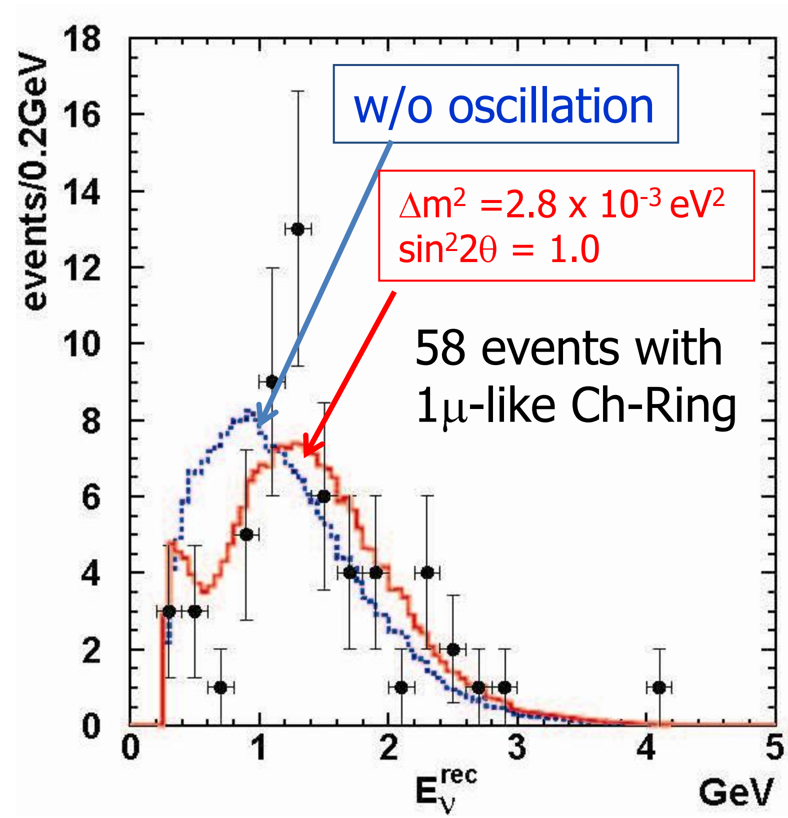
L=250 km / <E>=1.3 GeV

- Data collected: 0.9xE20 POT



Phys.Rev., D74, 072003, 2006

Confirmation of SK result:
oscillations with
atmospheric neutrino parameters



Null-oscillation is excluded at 4.3σ:

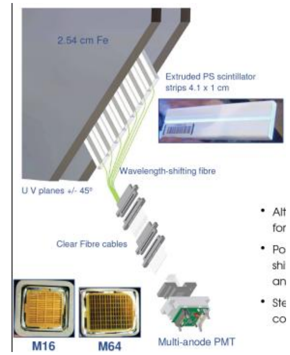
112 observed

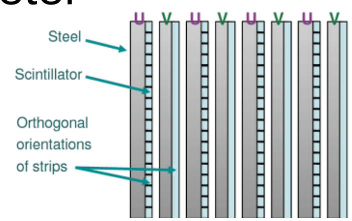
$158.1^{+9.2}_{-8.6}$ expected (null oscillation)

MINOS

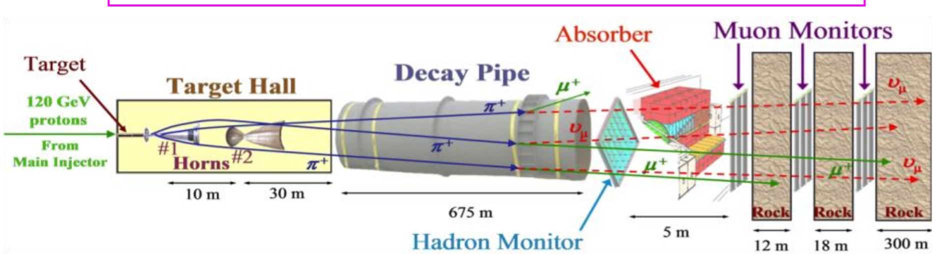
(Main Injector Neutrino Oscillation Search)

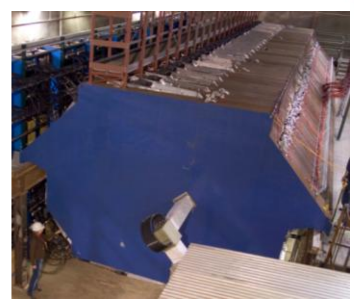
- FermiLab, IL ->Soudan mine, MN, USA
- 2005-…
- ν_μ **and anti-ν_μ**
- Near Detector: 980 t, same as Far Det.
  L (near)=1km
- Far Detector: 5.4 kt,
  magnetized Fe/Sci Tracker/Calorimeter
  L=735 km / E=3 GeV

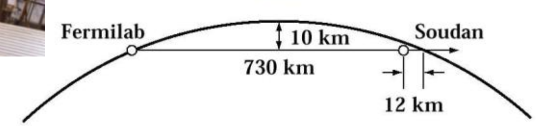




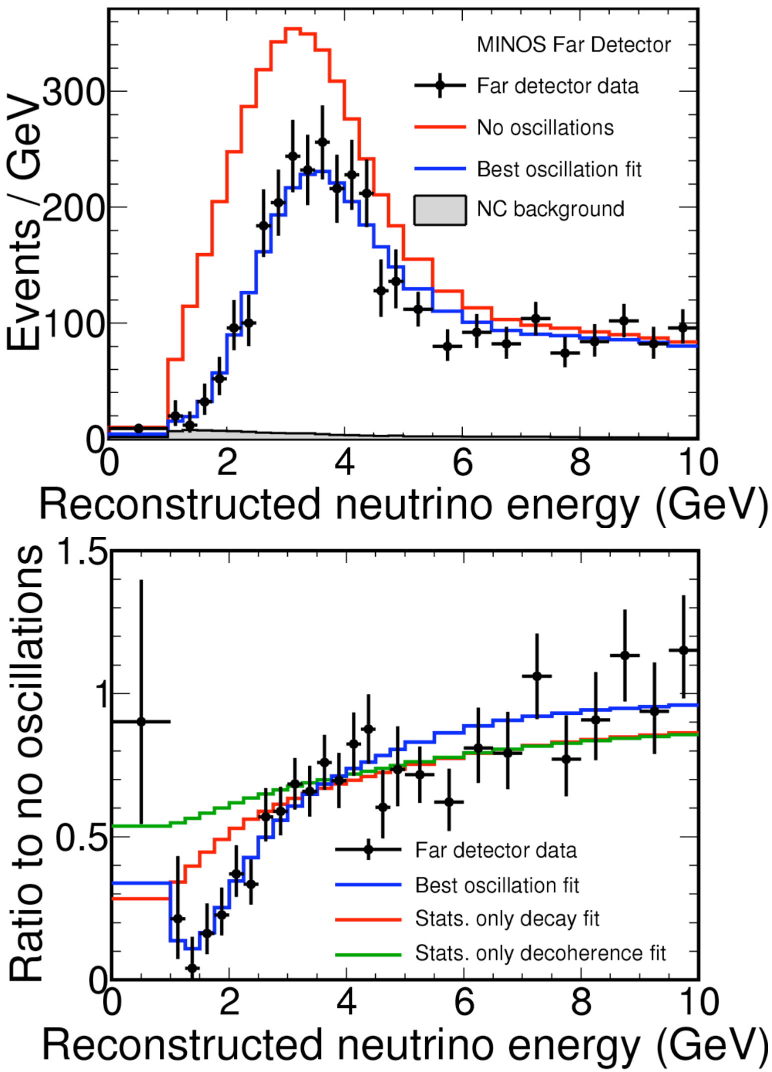
Goal: Precise study of "atmospheric" neutrino oscillations, using the NuMI beam and two detectors

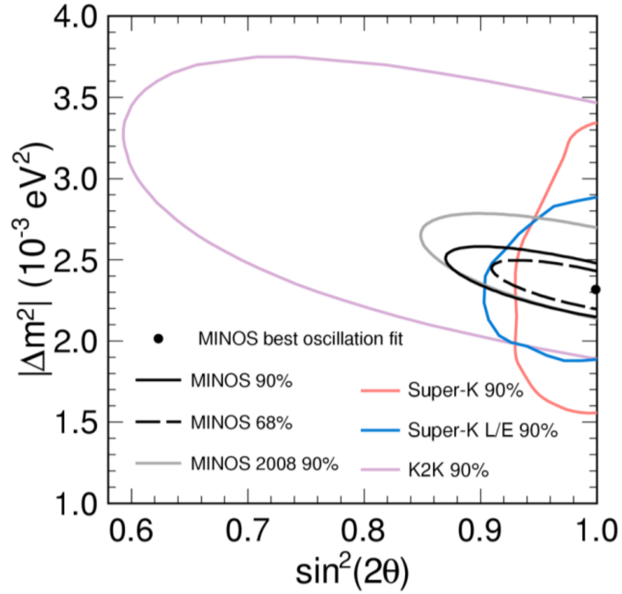






MINOS: $\nu_\mu \rightarrow \nu_\mu$ (disappearance)





7.25×10^{20} POT analyzed

# expected	(no osc.)	2451
# observed		1986

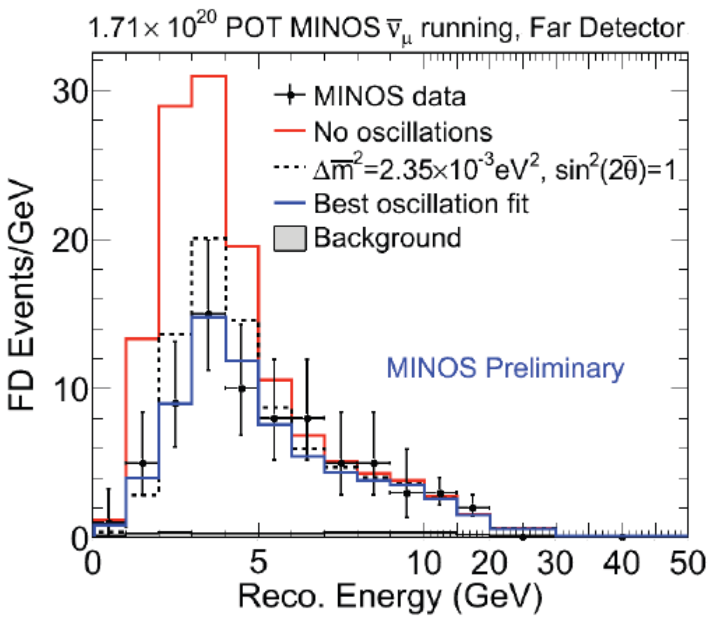
$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} eV^2$

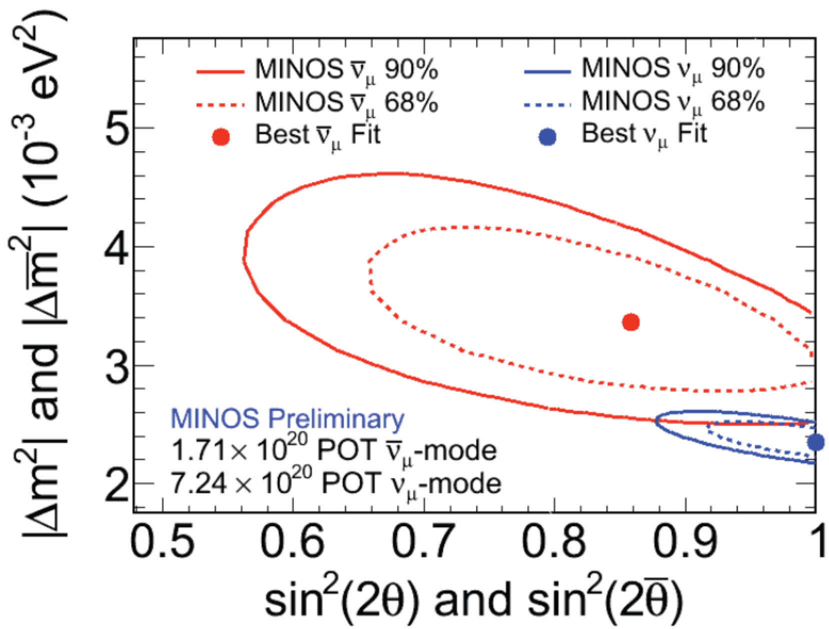
$\sin^2(2\theta) > 0.90$ (90% C.L.)

ArXiv:1103.0340 (2011)

MINOS: anti-ν_μ disappearance

Expected $\mathbf{N_{exp} = 156}$; Observed $\mathbf{N_{obs} = 97}$ (6.3σ excl. no oscillation)





"The probability that the underlying ν_μ and anti-ν_μ oscillation parameters are identical is 2.0%."

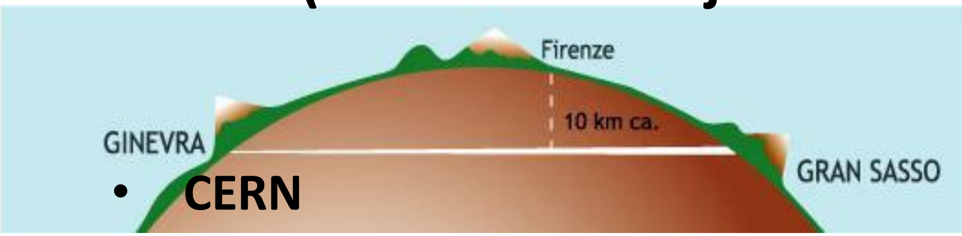
<u>ν-mode:</u> $|\Delta m^2|=2.32^{+0.12}_{-0.08}\times10^{-3}eV^2$; $\sin^2(2\theta) > 0.90$ (90% C.L.)

<u>anti-ν-mode:</u> $|\Delta m^2|=(3.36^{+0.46}_{-0.40}(stat.) \pm 0.06(syst.)) \times 10^{-3}\ eV^2$;
$\sin^2(2\theta) = 0.86^{+0.11}_{-0.12}(stat.) \pm 0.01(syst.)$

ArXiv:1104.0344 (2011)

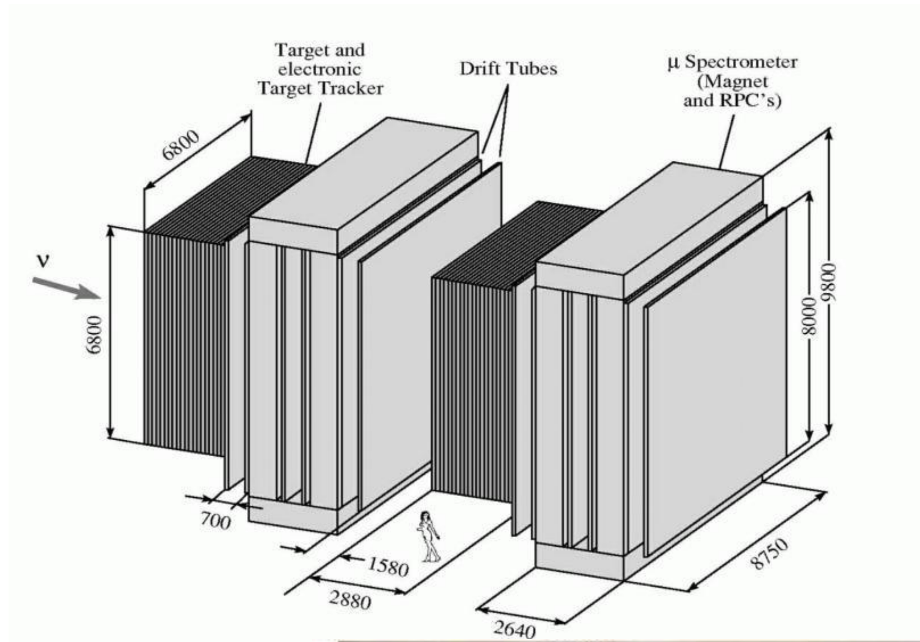
OPERA

(Oscillation Project with Emulsion-tRacking Apparatus)

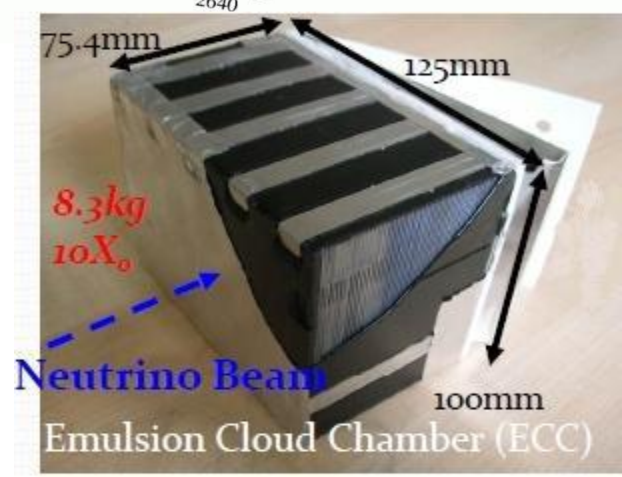


- **CERN**

  Gran-Sasso, Italy
- **2008-…**
- $\nu_\mu \to \nu_\tau$ **(ν_τ-direct search)**
- Detector: Lead/Emulsion Hybrid + Sci.+…
- **L = 732 km / <E> = 17 GeV**



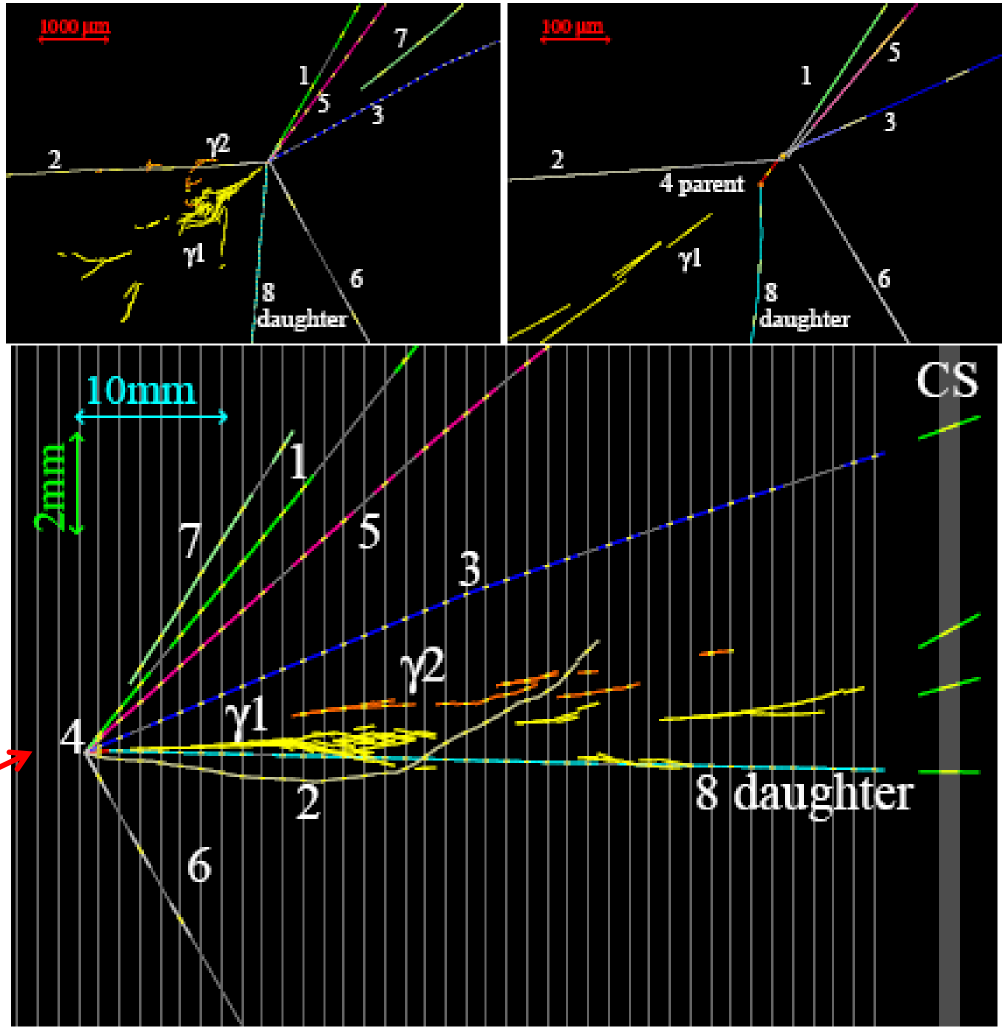
Hybrid Detector:
- Two supermodules – Target Mass ~1.25 ktons
- 2 Magnetic spectrometers with RPC & Drift tubes
- 2 x [31 Target Tracker planes and Target Walls]
- "ECC bricks" (56 Pb/57 Emulsion layers): 150000
- 12 M Emulsion plates (thin double-coated)



OPERA: first ν_τ candidate

Phys. Lett. B 691 (2010) 138; arXiv:1006.1623 [hep-ex]

Accumulated in 2008-10 ~ **9.34 x 10^{19} POT**
Analysis of data with **1.85 x 10^{19} POT**



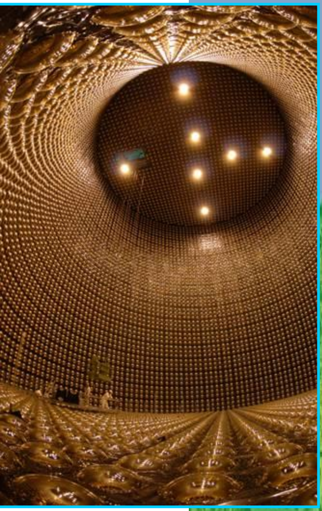
- Expected number of ν_τ events 0.54 ± 013 (syst)
- Probability that this event due to background fluctuation 4.5%
- Significance of observation 2.01σ

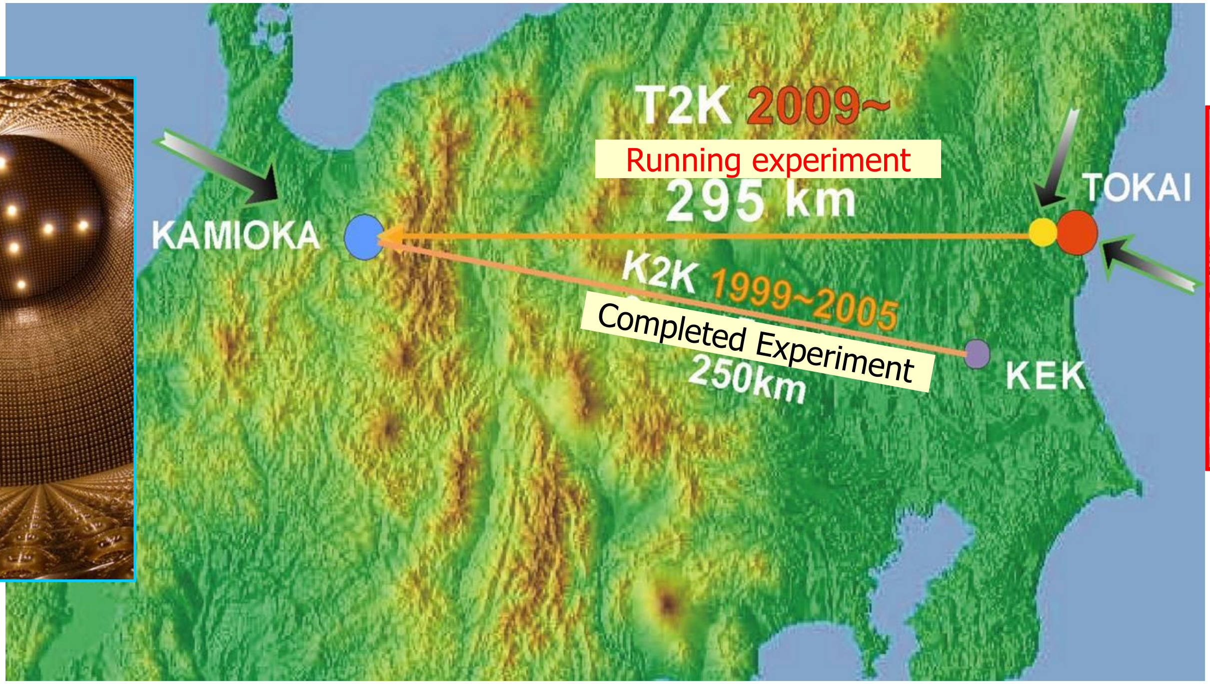
- 20 charm decays observed
- expectation from MC 16.0 ± 2.9

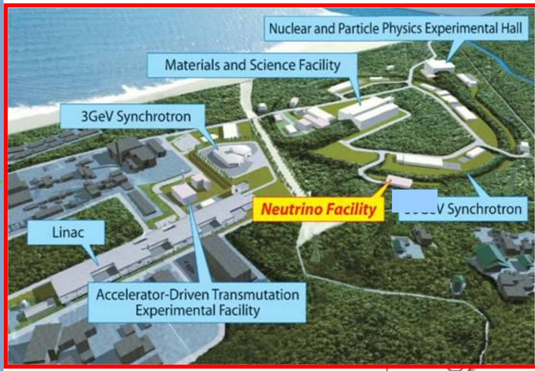
decay
$\tau^- \rightarrow h^-(n\pi^0)\nu_\tau$

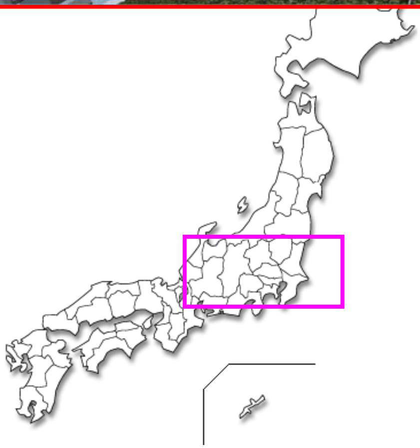
ν_τ interaction point

T2K (Tokai to Kamioka)





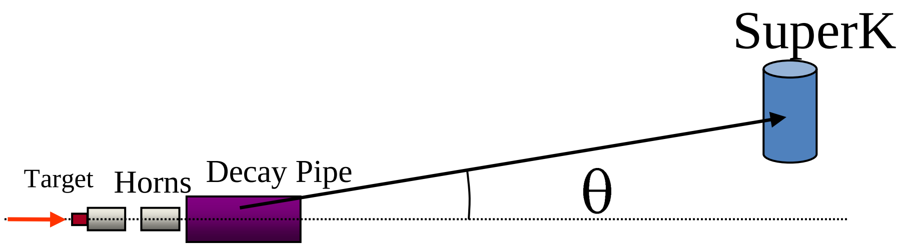


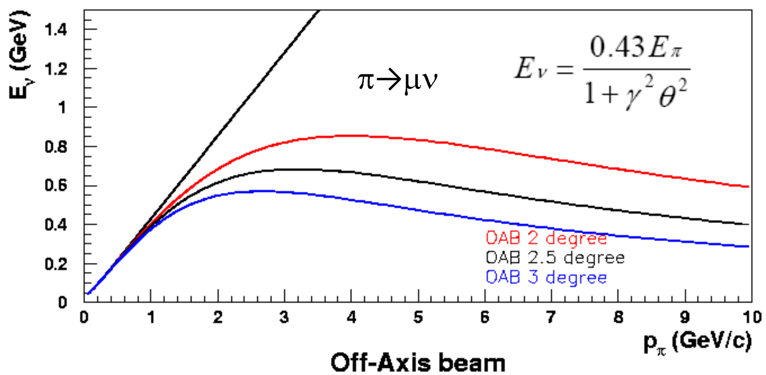


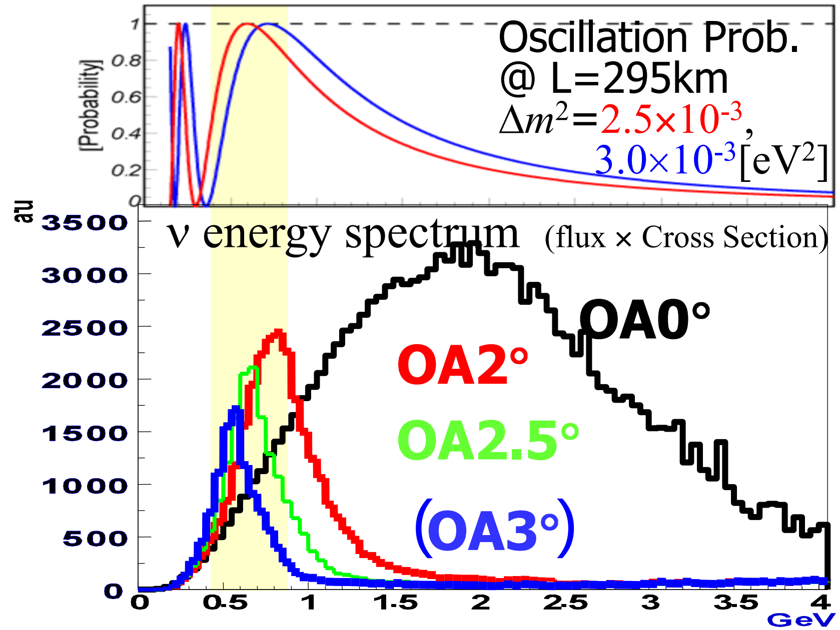
- **J-PARC**, Tokai-mura, Ibaraki pref. -> **Kamioka**, Gifu pref., Japan (J-PARC= Japan Proton Accelerator Research Complex)
- Near det-s (280 m) **off-axis**: FGD, TPC, P0D, ECAL, SMRD + **on-axis**: INGRID
- Far detector: Super-Kamiokande. **L = 295 km**; **<E> = 0.6 GeV**
- Goals: Searches for $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance, θ_{13} =x10 better than CHOOZ)

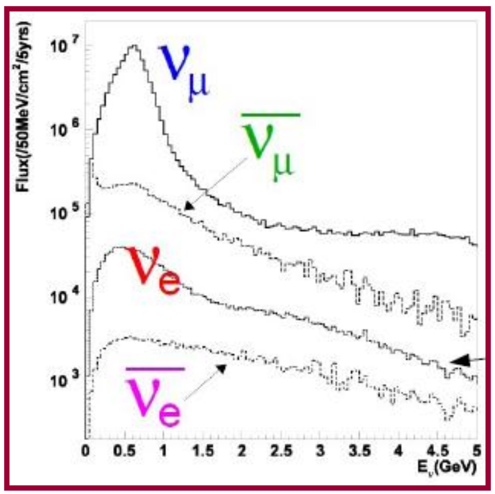
  Precise measurement of $\nu_\mu \rightarrow \nu_\mu$ (ν_μ disappearance)
- 2010-…

T2K off-axis beam



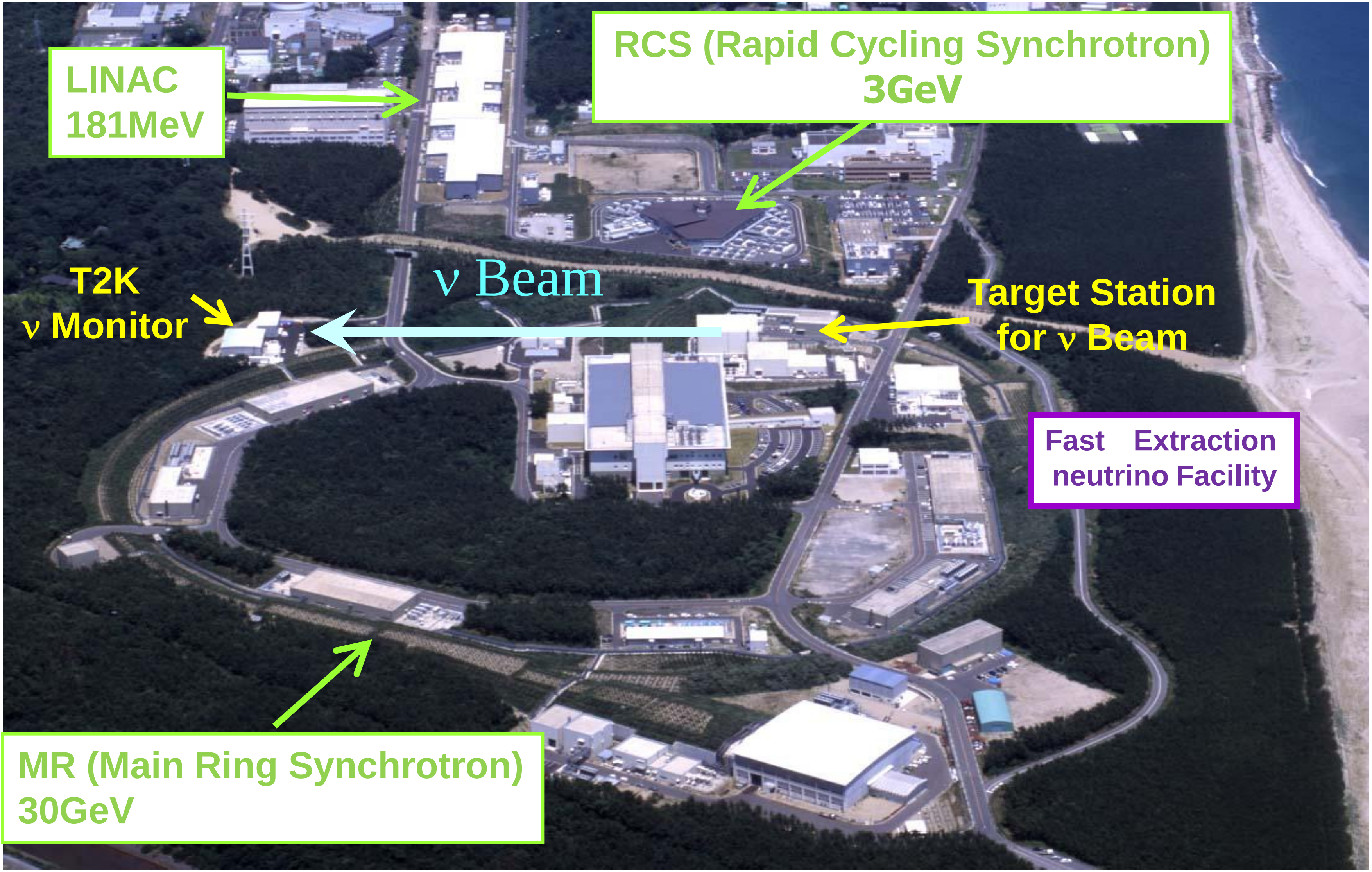




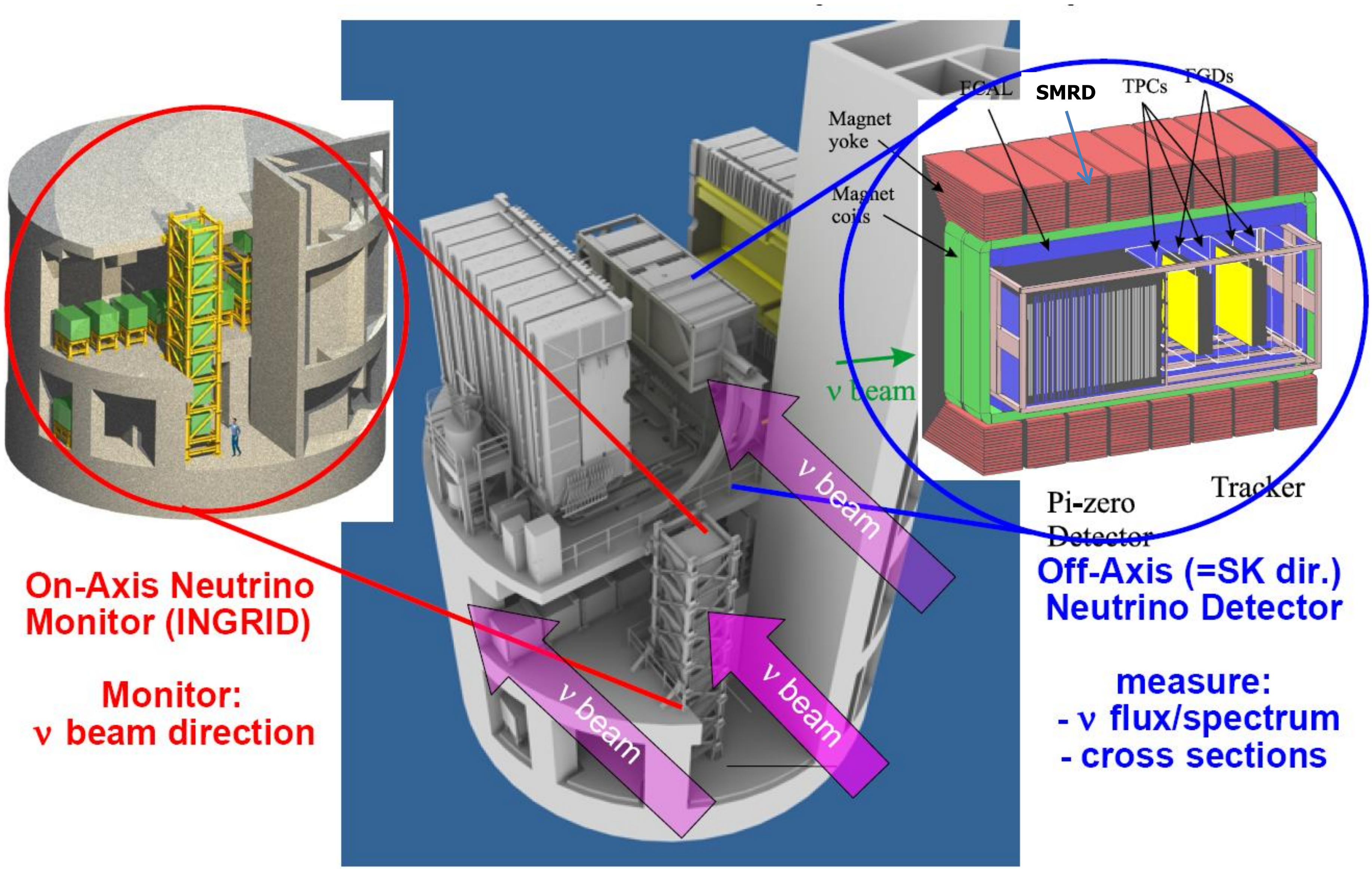


T2K:
145 kW (plan:750 kW) 30 GeV proton beam
Quasi-monochromatic ν_μ (95%) beam
~0.4% ν_e at peak energy ~600 MeV

J-PARC : Accelerator



Near Detectors



On-Axis Neutrino Monitor (INGRID)

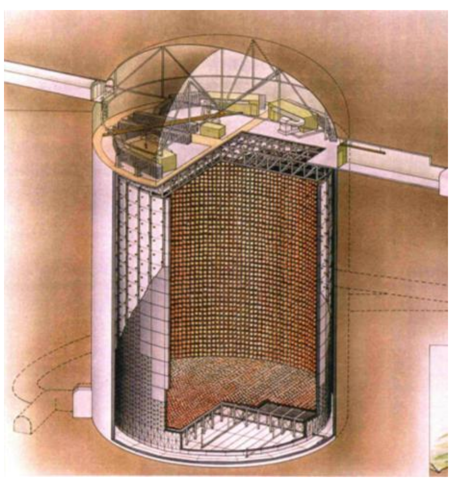
Monitor: ν beam direction

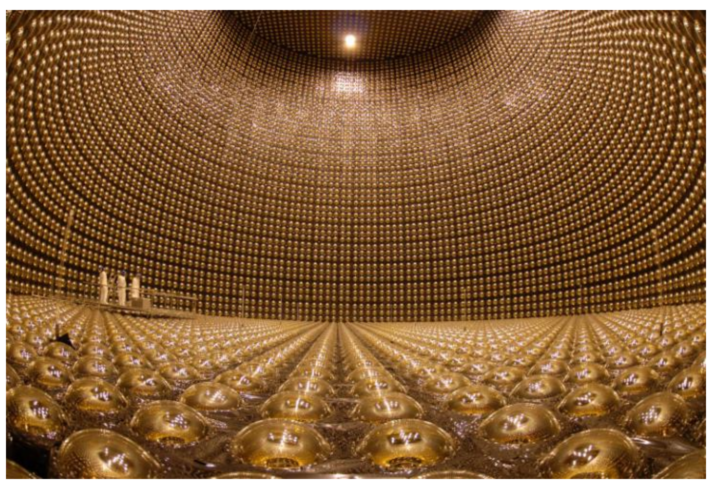
Off-Axis (=SK dir.) Neutrino Detector

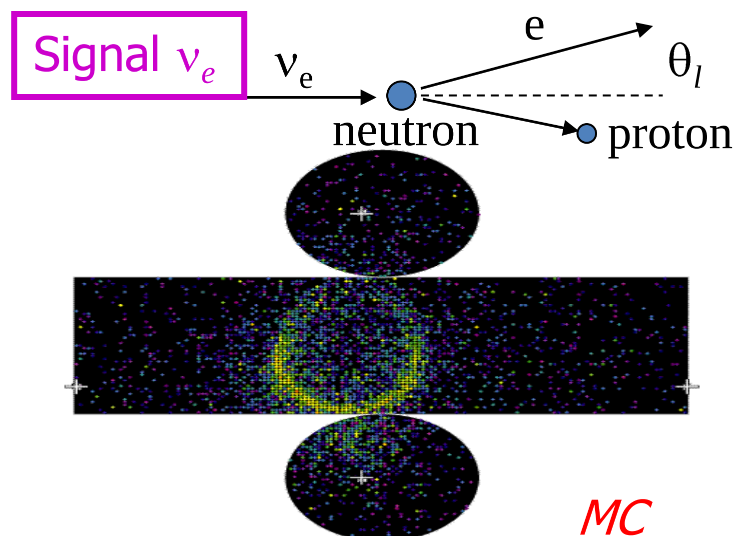
measure:
- ν flux/spectrum
- cross sections

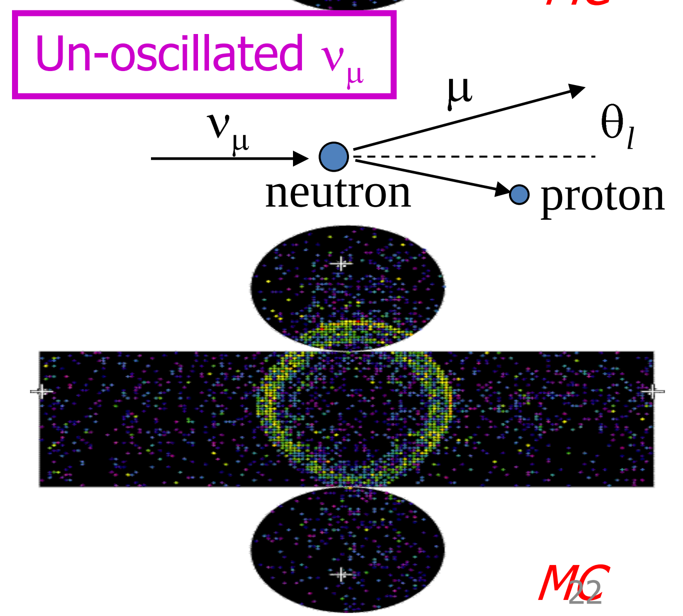
Far Detector: SK-IV

- 50kt Water Cherenkov detector (Fiducial 22.5kt)
  @ underground (2700 m water equivalent)
- 20' ID PMT×11,129: 40% Photo coverage
  + 8' OD PMT×1885 :
- Dead-time less DAQ system (2008~)
- Good performance for sub-GeV ν detection
  - 1[st] oscillation maximum : *E*ν ~0.6GeV at SK position.
  - Charged current quasi-elastic (CC QE) interaction is dominant process.
    - Good e / μ separation
    - Energy reconstruction: ΔE/E ~10% (←2-body kinematics)

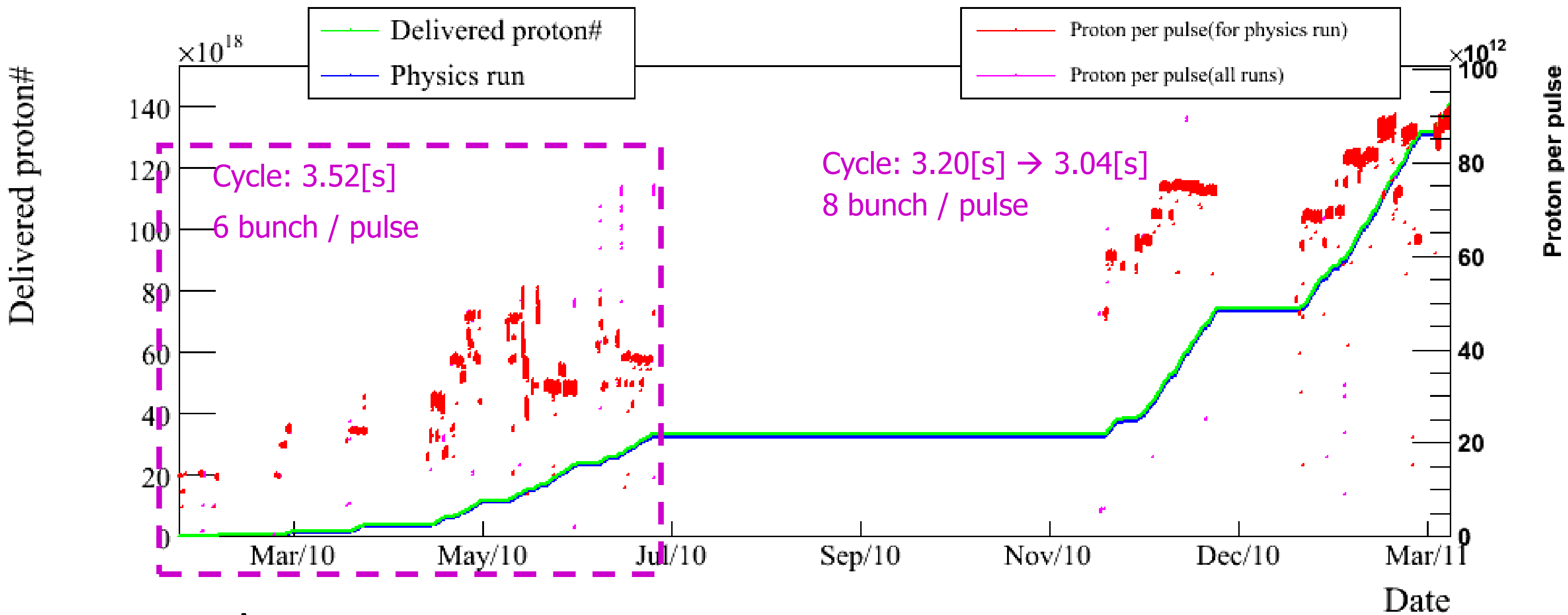








Accumulated # of protons so far



- T2K physics run: 2010, Jan~
  → Before 11/Mar/11: ~9.3×10^{13}[p/pulse], 3.04[s] cycle
  → Beam power = 145kW

  Integrated POT reaches 1.45×10^{20}.
- Physics results shown:
  - Analysis of the data taken from Jan. 2010 to Jun. 2010 (3.23×10^{19} POT)

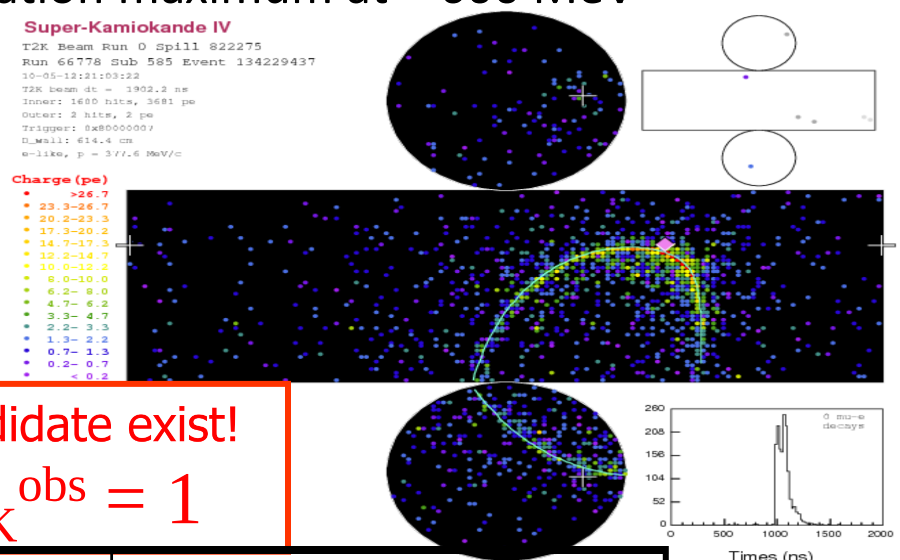
T2K event selection

"good beam spill" accepted by SK = $3.23x10^{19}$ POT

	Data	MC	
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$ $\sin^2 2\theta_{13} = 0.0$
Fully-Contained	**33**	54.5	24.6
Fiducial Volume, E_{vis} > 30MeV	**23**	36.8	16.7
Single-ring μ-like (P_μ>200MeV/c)	**8**	24.5 ±3.9	7.1 ±1.3
Single-ring e-like (P_e>100MeV/c)	**2**	1.5 ±0.7	1.3 ±0.6
Multi-ring	**13**	10.2	8.0

T2K ν_e appearance: 1 candidate

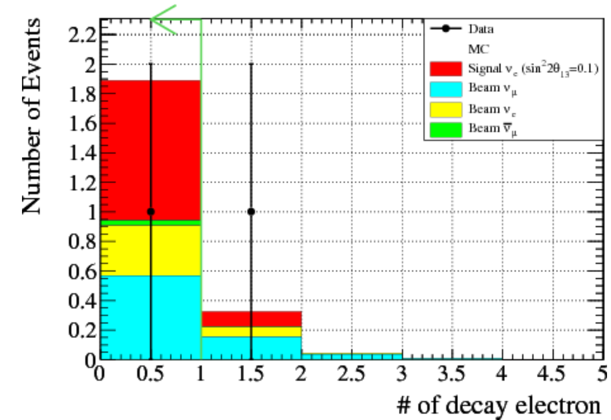
- # of decay electron ($\mu \rightarrow e + \nu_e$) =0
  - Reject ν_μ contamination : 1 event rejected.
- Reconstructed invariant mass assuming 2γ rings exist <105MeV
  - Reject π^0
- Reconstructed ν energy < 1250 MeV
  - Oscillation maximum at ~600 MeV

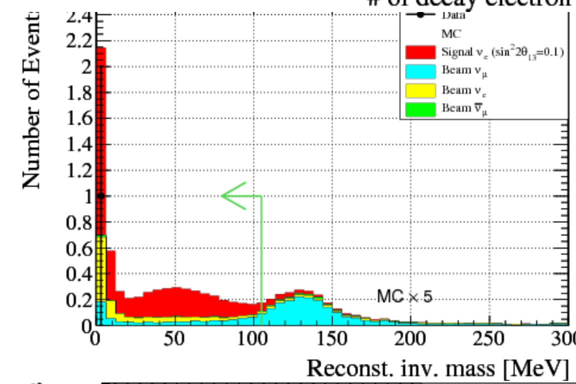


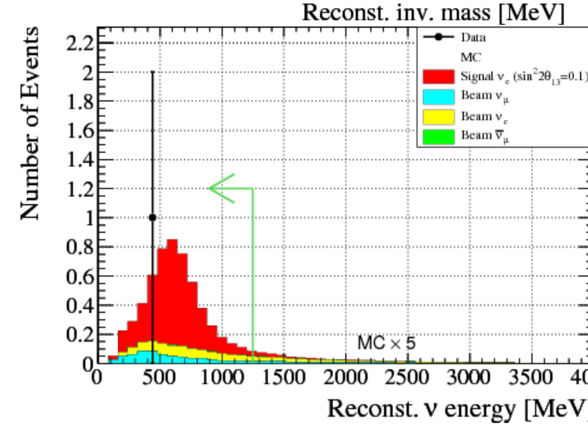
1 candidate exist!

$$N_{SK}^{obs} = 1$$

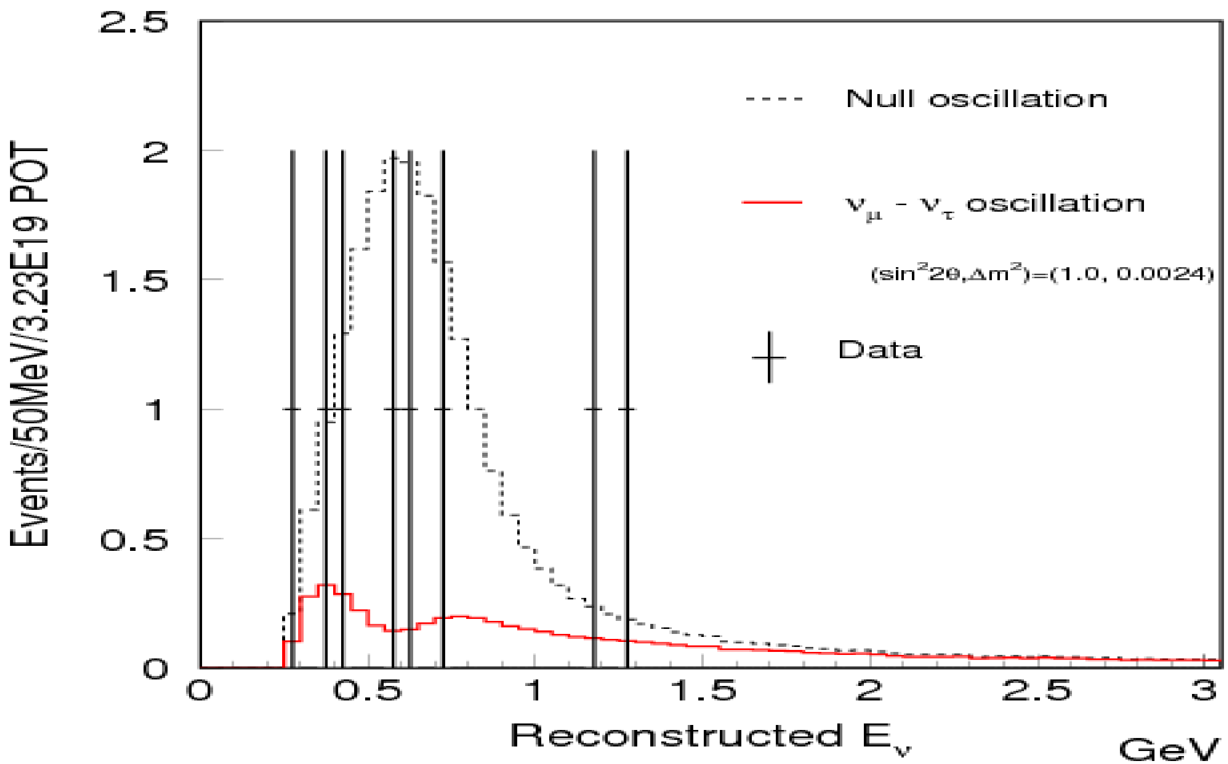
Bkg total	0.30 ± 0.07 (syst.)







T2K ν_μ disappearance analysis



- **8 ν_μ** events observed (null oscillation: 24 expected).
- # of events agree with MINOS / SK measurements.

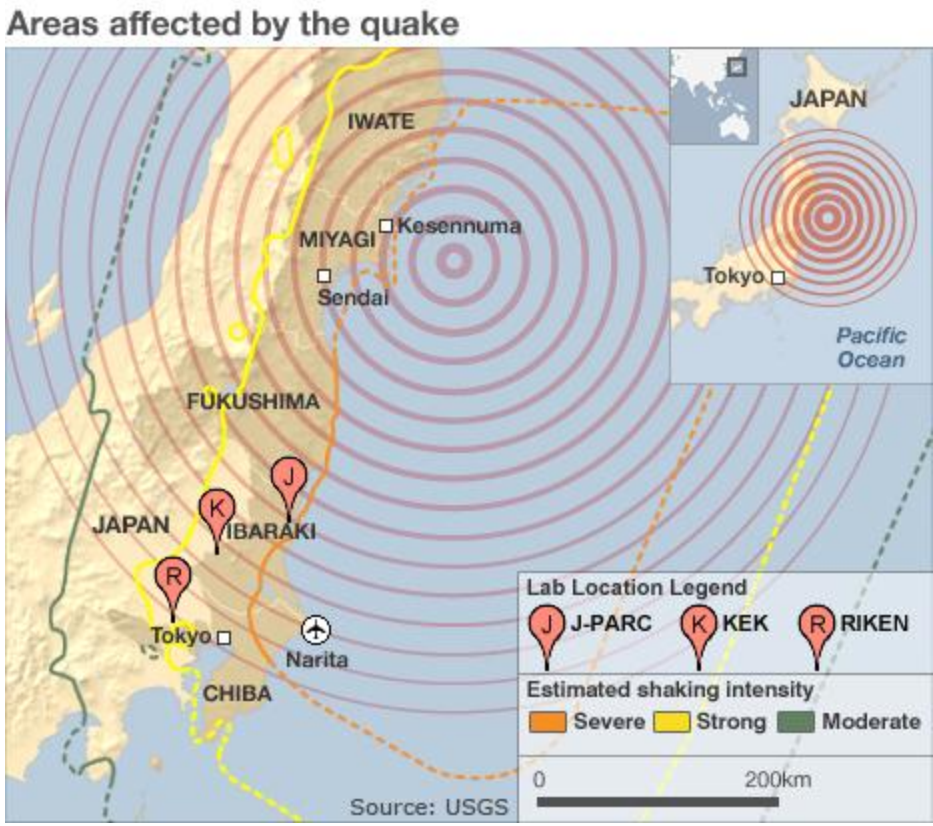
Earthquake in Japan

• 14:46 JST (08:46 MSK), March 11th, 2011, Japan experienced a severe earthquake followed by a tsunami

• No reported injuries to members of the T2K collaboration or JPARC employees
• All foreign collaborators have returned home safely

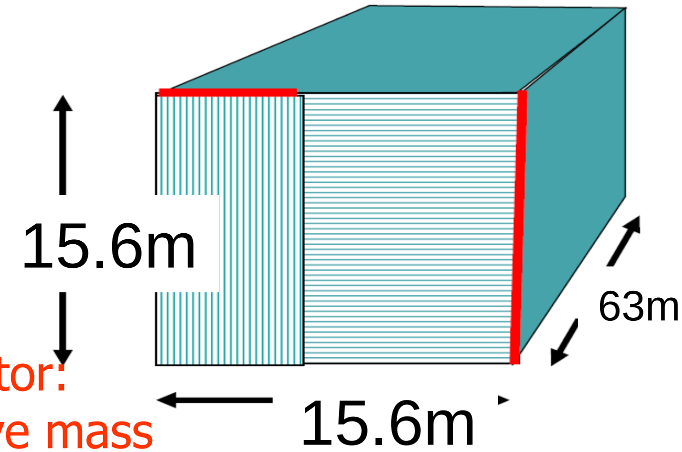
• The tsunami did not reach J-PARC
• Inspection of the lab is ongoing
• Priority is to restore water, power, and gas systems

• SK (Kamioka) is OK and running (for solar/atm/supernovae)

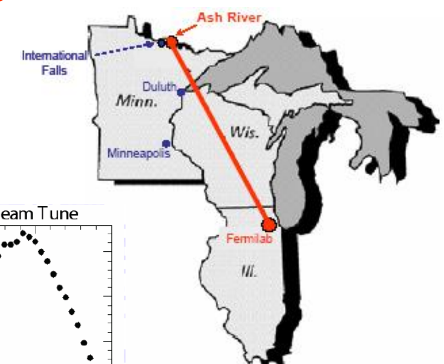


NOνA
(NuMI Off-axis ν_e Appearance)

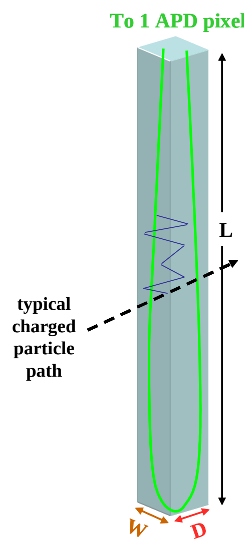
- FermiLab, IL -> Ash River, MN, USA
- 2013 - ...
- **Goal:** ν_e appearance, mass hierarchy
- Off-axis = 0.8°.
- Near detector: 0.22 kt @ 1 km
- Far detector: 14 kt. Both: PVC filled with mineral oil + WLS fiber -> APD
- **L = 810 km / <E> = 2 GeV** .

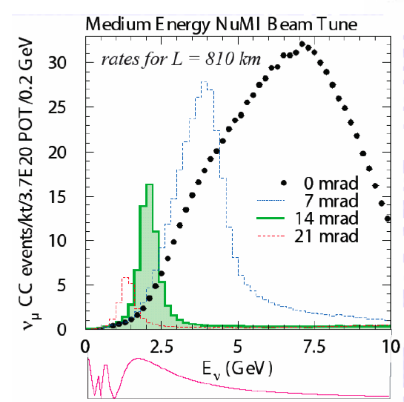


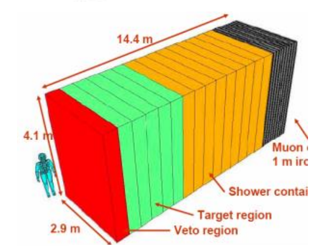
Far Detector:
65% active mass



Active element:
Liquid scintillator
U-shaped WLS fiber







Scintillator cells 3.9 x 6.0 x 1560 cm^3
Read out from one side per plane with APDs

Near detector: 4.2 x 2.9 x 14.3 m

Conclusion

- **Neutrino oscillations – physics beyond the Standard Model**

- Accelerator experiments: very productive and provide exciting results

- **MINOS, OPERA, MiniBooNE** successfully taking data

- **T2K** running for physics since January 2010

- Main goal for LBL accelerator experiments: θ_{13} – key parameters which determines the future of these experiments

- Non-zero θ_{13} will give us a chance to measure mass hierarchy and to probe **CP violation** in lepton sector

- LSND/MiniBooNE: Anomalies -> sterile neutrinos?
- MINOS: ν and anti-ν results show some tension

New results are coming soon!

Backup Slides

Accelerators as Neutrino sources

General idea (since 1960s):

$$p \rightarrow A \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\rightarrow \pi^- \rightarrow \mu^- + \text{anti-}\nu_\mu$$

Progress in Accelerator technology:

- High intensity: ~10^{13}-10^{14} p/spill

  Beam power: 100-400 kW (plan: 700-800 kW)
- Proton Beam Timing: spill length/cycle: ~few μs/~few s

  + spill micro-structure= 2-9 bunches
- High purity: ν_μ – 92÷98%; $\nu_e \leq 1\%$
- Off-axis neutrinos

Appearance Probability (detailed)

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\Delta m^2{}_{31} L/4E \right)$$

$$\mp 4 J_r \sin\delta \sin\left(\Delta m^2{}_{21} L/2E \right) \sin^2\left(\Delta m^2{}_{31} L/4E \right) + \ldots$$

$$J_r \equiv \cos\theta_{12} \sin\theta_{12} \cos\theta_{23} \sin\theta_{23} \cos^2\theta_{13} \sin\theta_{13}$$

– for ν
+ for anti-ν

CP-phase

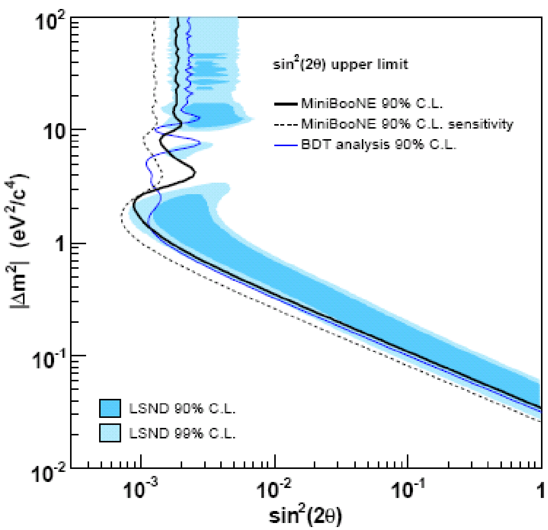
mass hierarchy

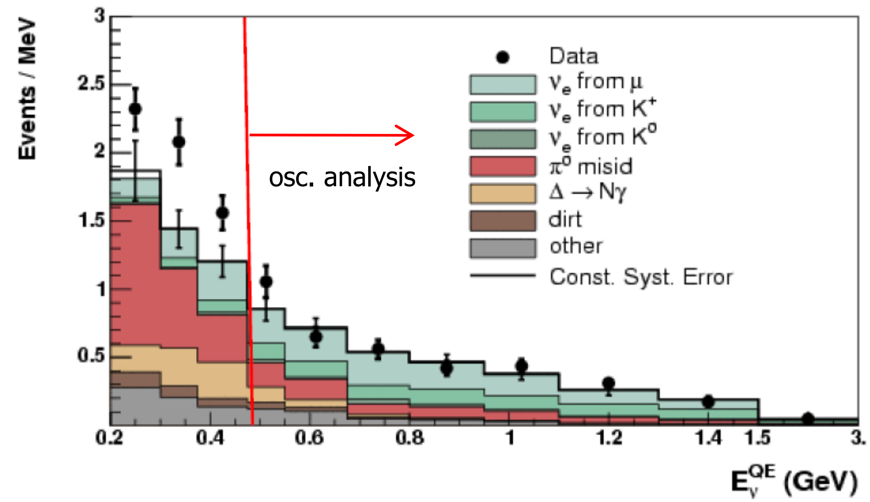
MiniBooNE $\nu_\mu \rightarrow \nu_e$

PRL 98:231801, 2007
PRL 102:101802,2009

6.46 x 10^{20} POT

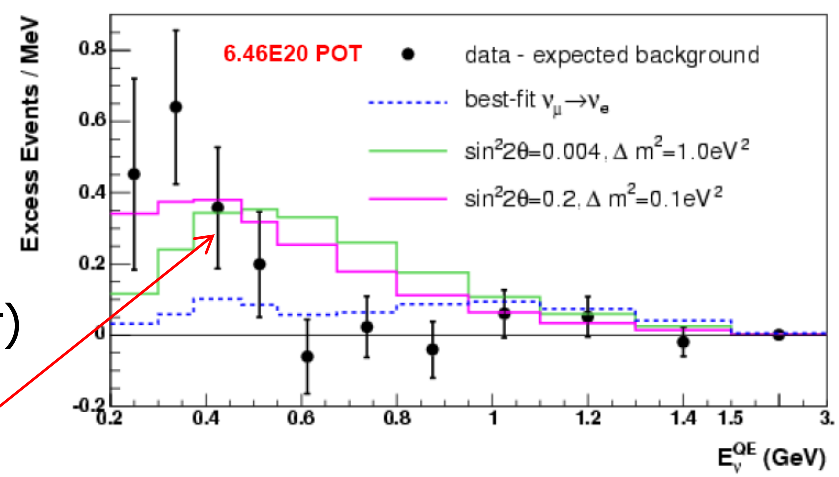
No ν_e excess in oscillation signal region E_ν> 475 MeV





however

Excess 128.8 ± 20.4 ± 38.3 events (2.9σ) above background for 200-475 MeV

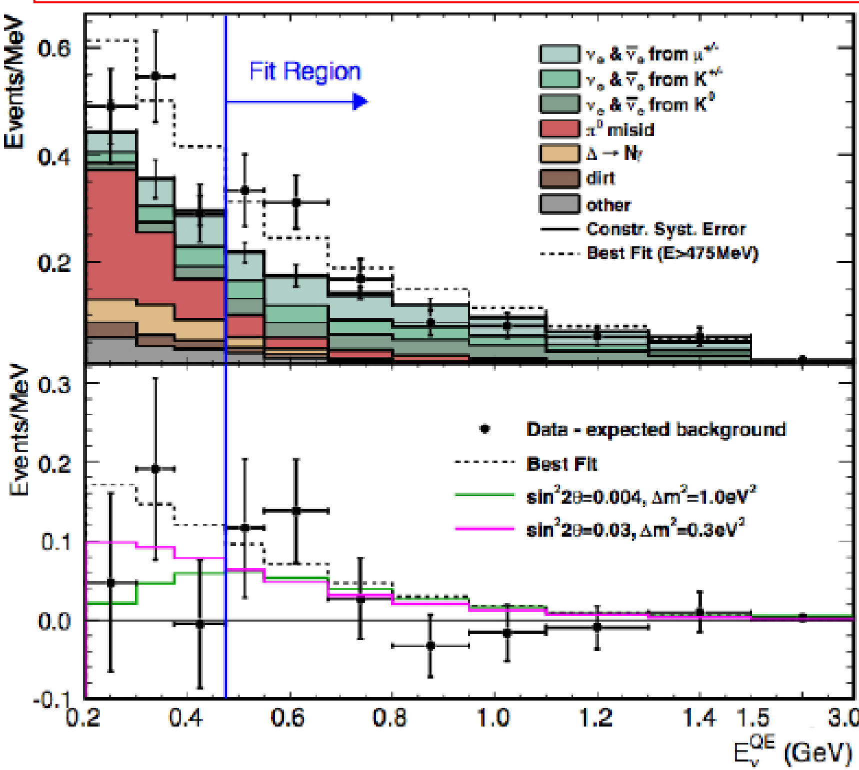


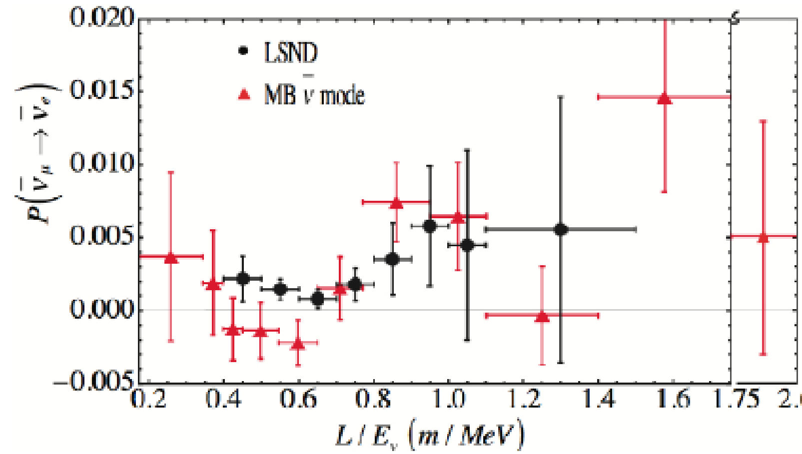
Background-subtracted

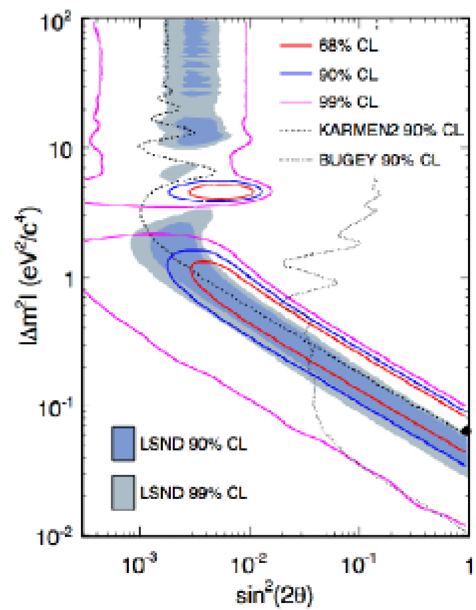
MiniBooNE anti-$\nu_\mu \rightarrow$ anti-ν_e

PRL, 105, 181801 (2010) 5.66 x 10^{20} POT

"The data are consistent with anti-$\nu_\mu \rightarrow$ anti-ν_e oscillations in the **0.1 to 1.0 eV² Δm²** range and with the evidence for antineutrino oscillations from the Liquid Scintillator Neutrino Detector at Los Alamos National Laboratory."







MINOS: $\nu_\mu \rightarrow \nu_e$

7×10^{20} POT

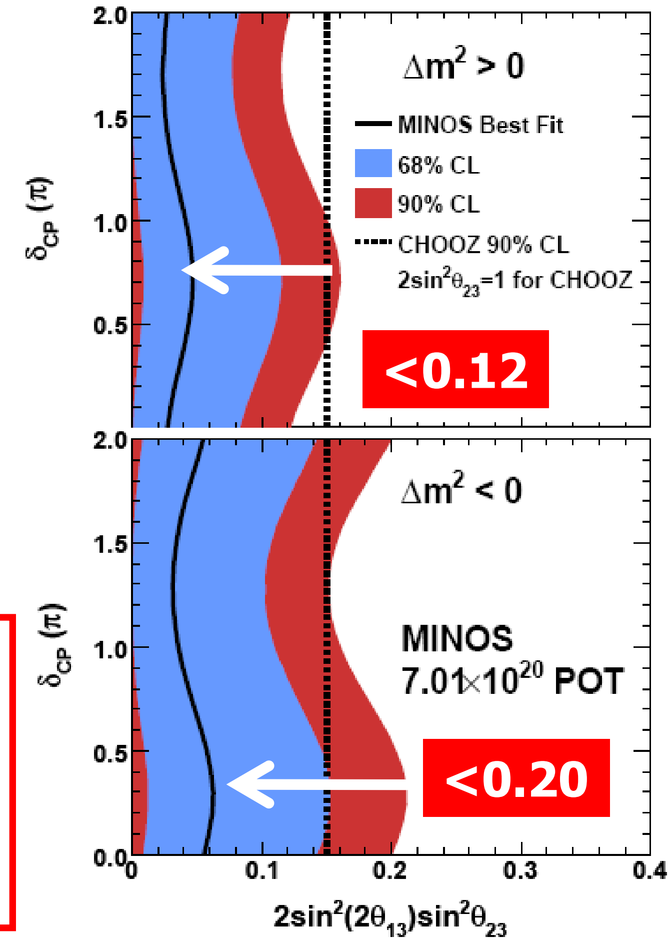
detected 54 ν_e events
expected bkg 49.1 ±7.0 (stat) ± 2.7 (syst)
(35.8 NC; 6.3 ν_μ- CC; 5.0 beam ν_e; 2.0 ν_τ)

Efficiency for selection of ν_e-CC events in Far Detector 41.6±1.0 %
Background suppression in Far Detector ~93%

for $\delta = 0$

$2\sin^2 2\theta_{13}\sin^2\theta_{23} < 0.12$ (90% c.l.) normal hierarchy

$2\sin^2 2\theta_{13}\sin^2\theta_{23} < 0.20$ (90% c.l.) inverted hierarchy



Best constraint on θ_{13} for almost all δ assuming $\Delta m^2>0$ and maximal $\sin^2\theta_{23}$

Expected Performance (Proposal)

Assumptions: Maximal mixing, 22.5×10^{19} p.o.t. (5years @ 4.5×10^{19} p.o.t./year)

τ Decay Channel	B.R. (%)	Signal	Background
$\tau \rightarrow \mu$	17.7	2.9	0.17
$\tau \rightarrow e$	17.8	3.5	0.17
$\tau \rightarrow h$	49.5	3.1	0.24
$\tau \rightarrow 3h$	15.0	0.9	0.17
Total		**10.4**	**0.75**

Expected Events:

~ 23600 ν_μ CC+NC interactions

~ 520 $\bar{\nu}_\mu$ interactions

~ 205 $\nu_e + \bar{\nu}_e$ interactions

~ 115 ν_τ CC interactions

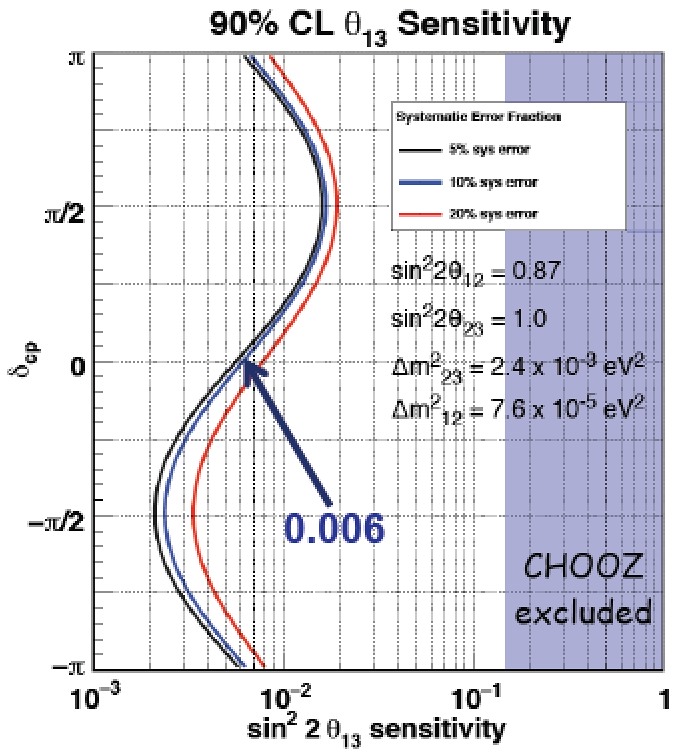
For full mixing and $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 (scales with $(\Delta m^2)^2$).

T2K physics goals

Proton energy 30 GeV, integral 8 x 10^{21} POT (~5 years)

ν_e appearance

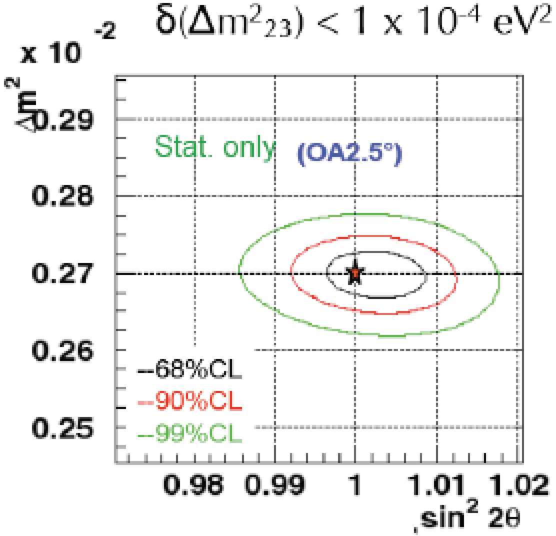
> x10 improvement from CHOOZ limit



ν_μ disappearance

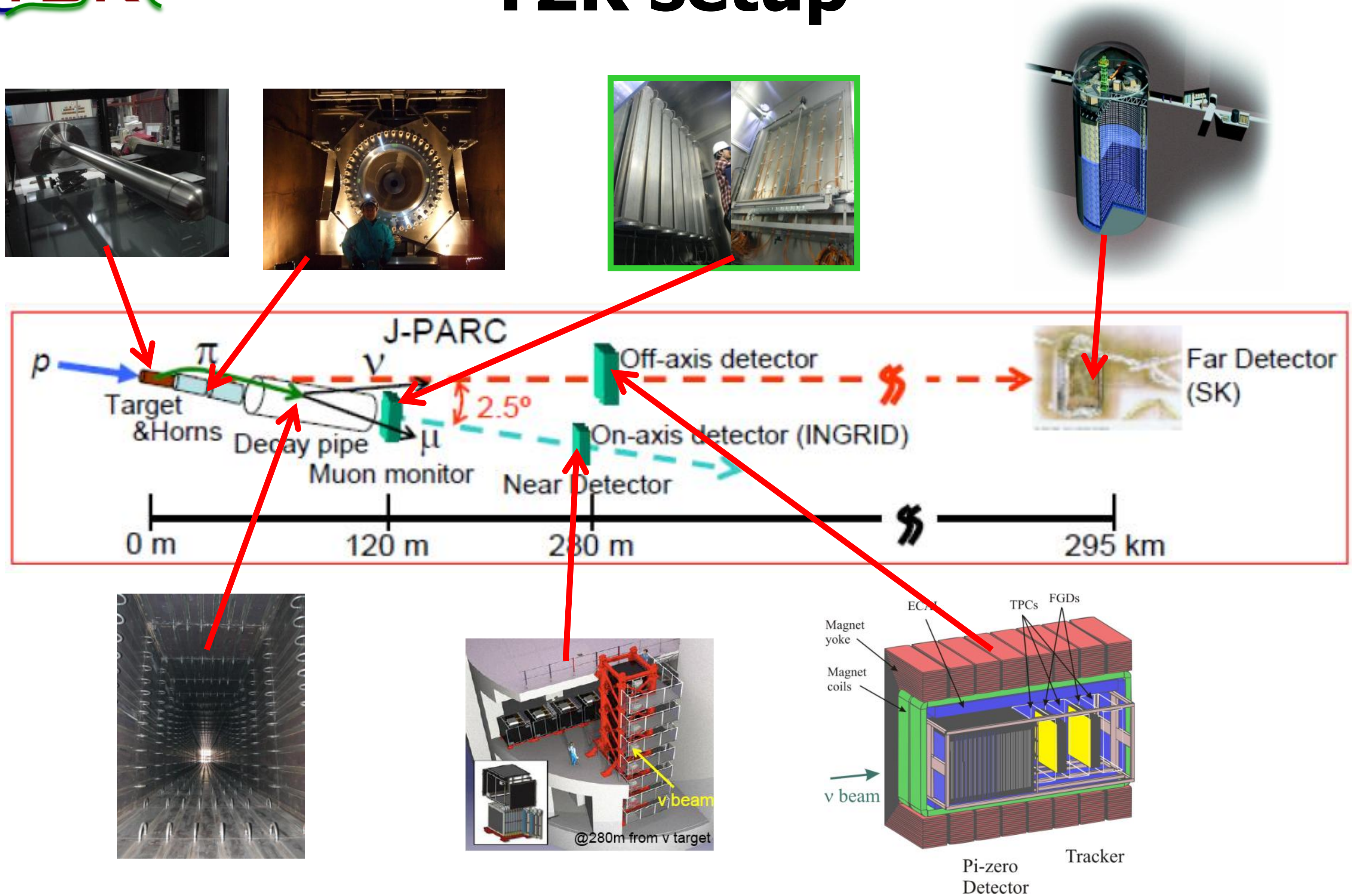
$\delta(\sin^2 2\theta_{23}) \sim 1\%$

$\delta(\Delta m^2_{23}) < 1 \times 10^{-4}\ eV^2$



@ 8 x 10^{21} protons(30GeV) on target

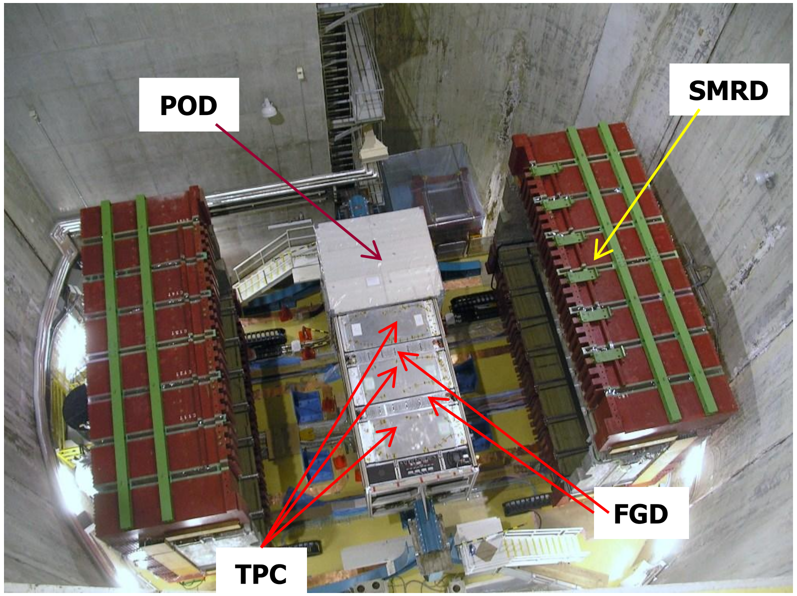
T2K setup



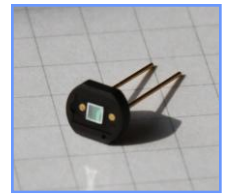
J-PARC
p
π
ν
μ
Target
&Horns
Decay pipe
Muon monitor
2.5°
Off-axis detector
On-axis detector (INGRID)
Near Detector
Far Detector
(SK)
0 m
120 m
280 m
295 km
ν beam
@280m from ν target
Magnet
yoke
Magnet
coils
ECAL
TPCs
FGDs
ν beam
Pi-zero
Detector
Tracker

T2K

ND280



Hamamatsu MPPC

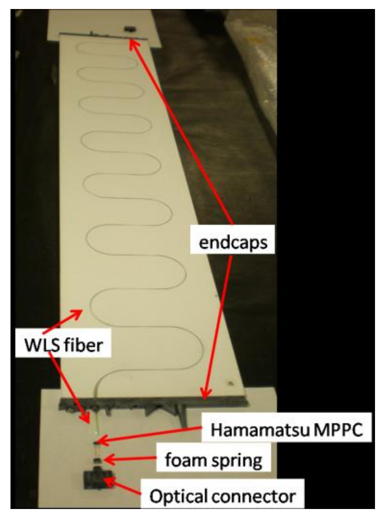


About 60k photosensors

INGRID horizontal

INGRID vertical

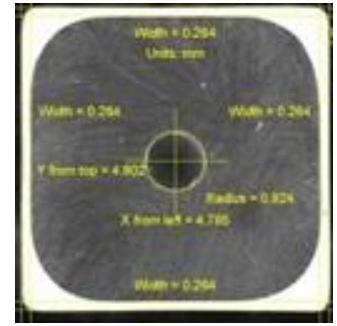
SMRD counter



UA1/NOMAD magnet

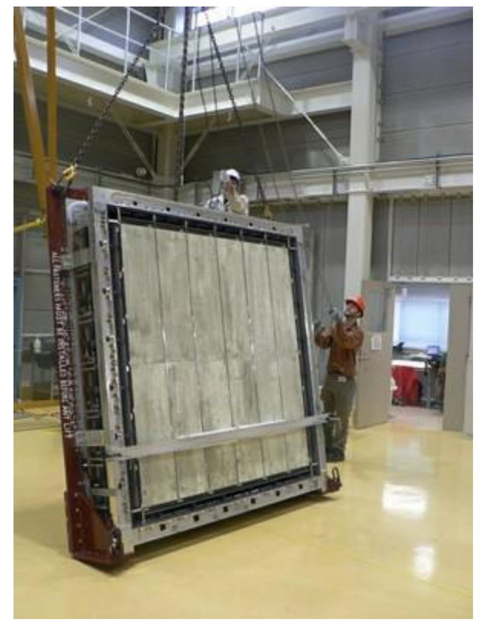
ND280

FGD scintillator bar

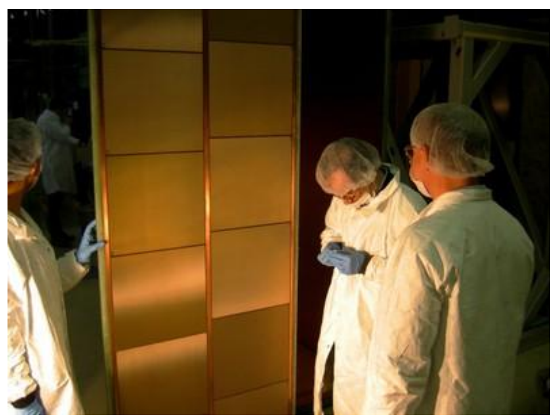


POD

FGD



TPC module

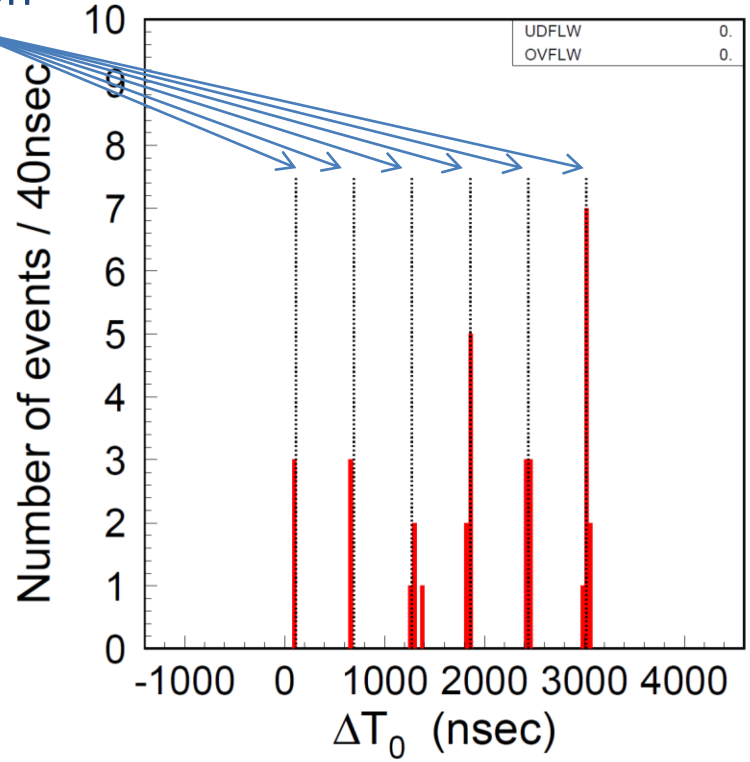


Micromegas readout plane

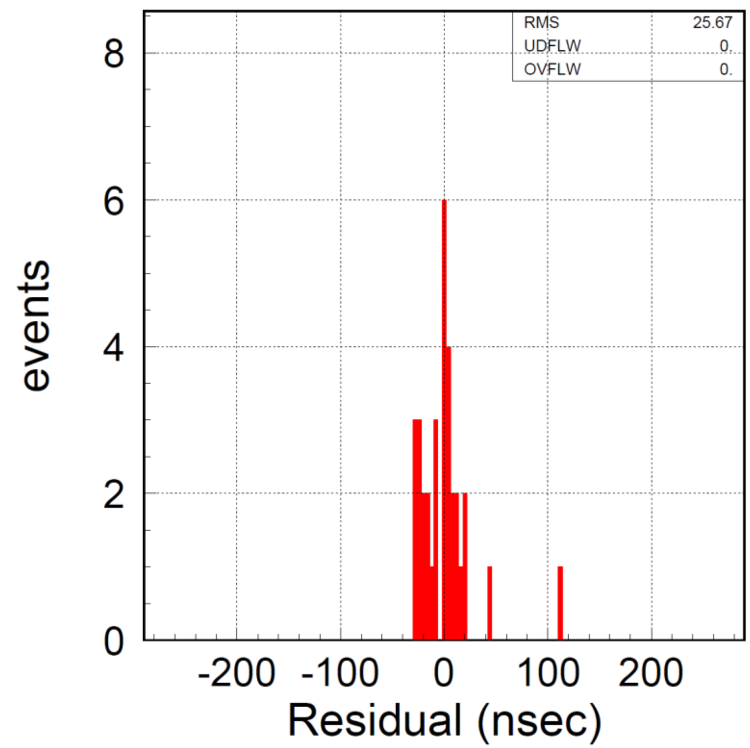
ΔT_0 distribution (SK FC events)

Fitted 581nsec-interval bunch position

ΔT_0



Residual from bunch position



No off-bunch FC events.

RMS : 26nsec

→ GPS system is working correctly.

Estimation of oscillation parameter

Upper bound of θ_{13} are evaluated by 2 independent method.

A: Feldman-Cousins

B: Classical one-sided limit

Systematic uncertainties are took into account for both analysis.

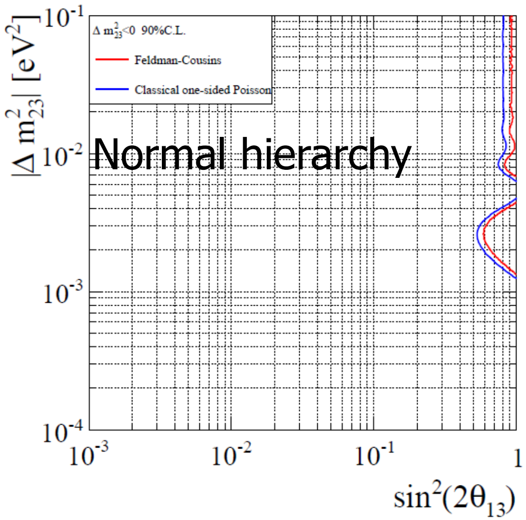
90% CL upper limit at $\Delta m^2_{23}=2.4\times10^{-3}eV^2$, $\delta_{CP} = 0$

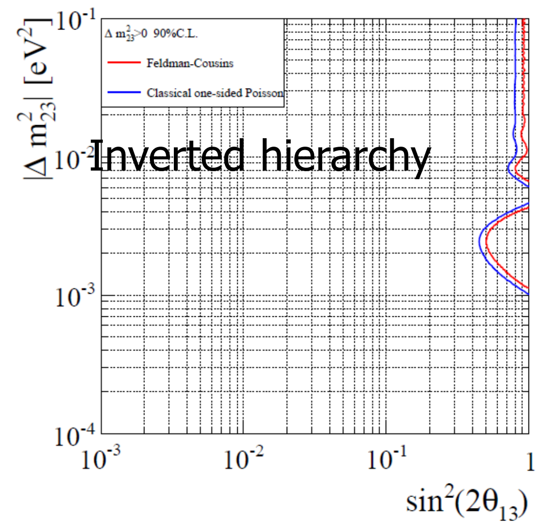
A

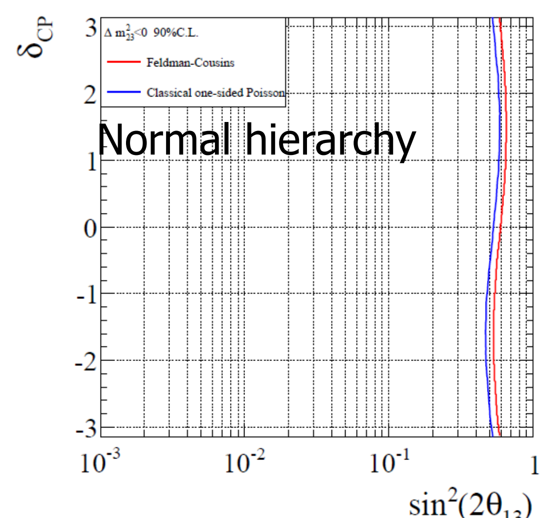
Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.50	0.35
Inverted ($\Delta m^2_{23} < 0$)	0.59	0.42

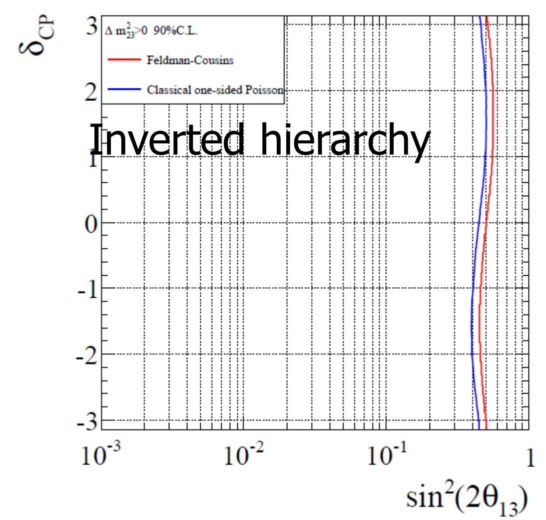
B

Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.44	0.32
Inverted ($\Delta m^2_{23} < 0$)	0.53	0.39



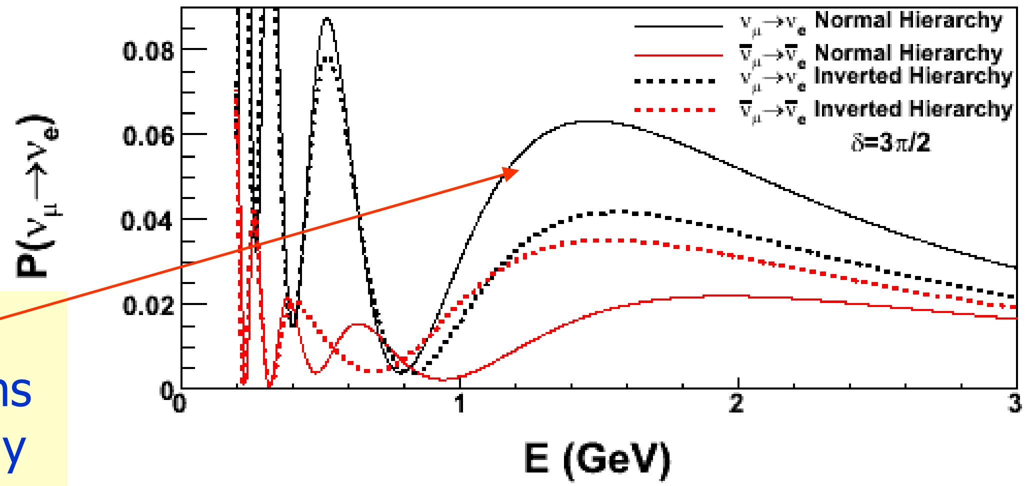






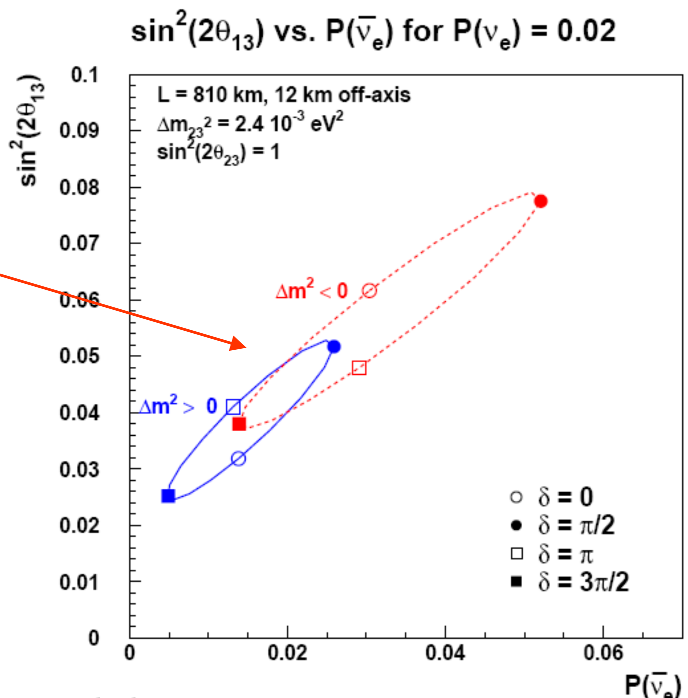
NOνA

$P(\nu_\mu \to \nu_e)$ depends on
$\sin^2 2\theta_{13}$ sign Δm^2_{23} δ_{CP}



matter effects
increase (decrease) oscillations
for normal (inverted) hierarchy
for ν

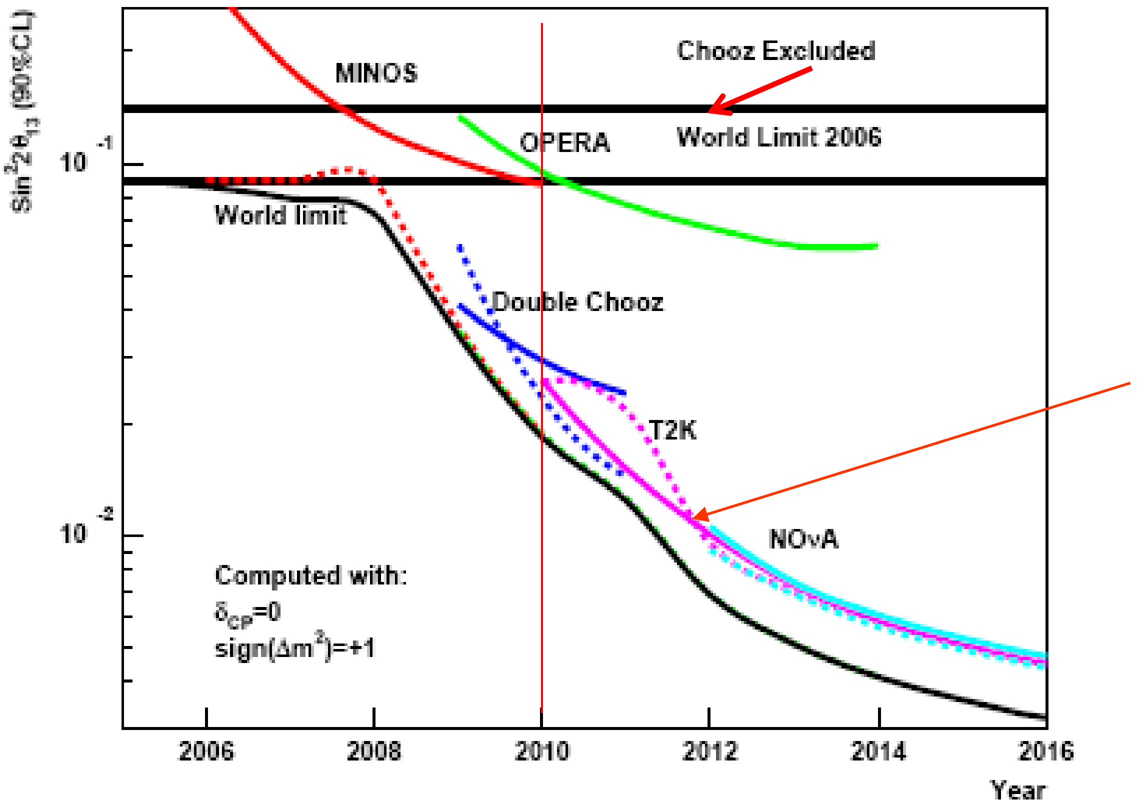
Mass hierarchy can be resolved
if θ_{13} near to present limit
using both ν and anti-ν beams and
$\sin^2 2\theta_{13}$ from T2K + reactor
experiments



Full construction started 2009
Far detector construction 2011-13

θ_{13} sensitivities vs time

as expected in 2006



A.Blondel et al., hep-ph/0606111

Short baseline reactor experiments
Double-Chooz, RENO and Daya Bay ⟶ θ_{13} **(insensitive to δ_{CP})**