Neutrino –
Source of New Physics

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Outline

- **neutrino oscillations and mixing**
- **measurements of θ_{13}**
- **neutrino mass hierarchy and CP violation**
- **summary**

Standard Model

SM is a gauge theory based on local symmetry group

$SU(3)_c \times SU(2)_L \times U(1)_Y$

C – color, L – left-handed chirality, Y – weak hypercharge

Elementary particles of SM:

γ $W^{\pm}$ Z^0 8 gluons $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

I	u	d	e	ν_e
II	c	s	μ	ν_μ
III	t	b	τ	ν_τ

Fermions

$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R d_R

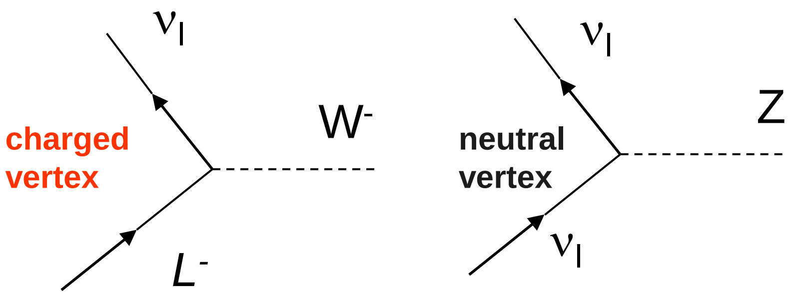
$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R ○

missing entry?
sterile ν_R ?

neutrino is purely left-handed
$m_\nu = 0$

Leptons

Neutrinos - partners of charged leptons:
$W \to e\nu_e$ $W \to \mu\nu_\mu$ $W \to \tau\nu_\tau$



Three neutrinos	ν_e	ν_μ	ν_τ
Lepton number	$L_e=+1$	$L_\mu=+1$	$L_\tau=+1$

Neutrinos are massless, L_e , L_μ , L_τ conserved

Charged leptons - Dirac particles ⇨ $l \neq \bar{l}$

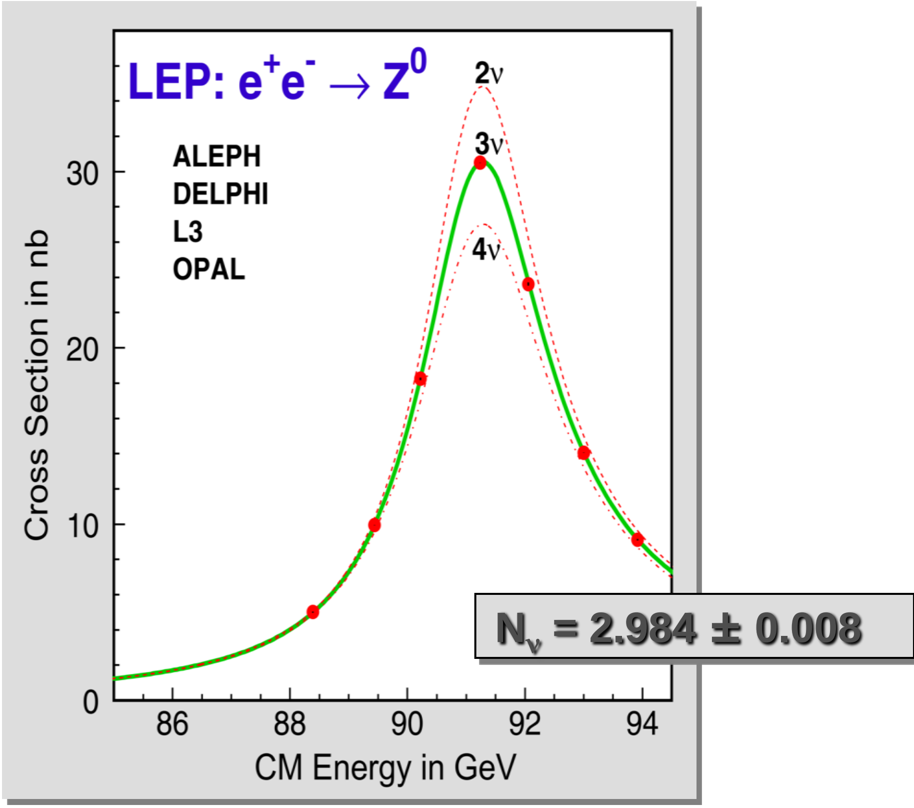
Neutrinos – Dirac or Majorana particles ⇨ $l \neq \bar{l}$ or $l = \bar{l}$

Active ν's

LEP (CERN) experiments:
from Z width

3 flavor (family) of light active neutrinos

No neutrino mixing
CP = 1



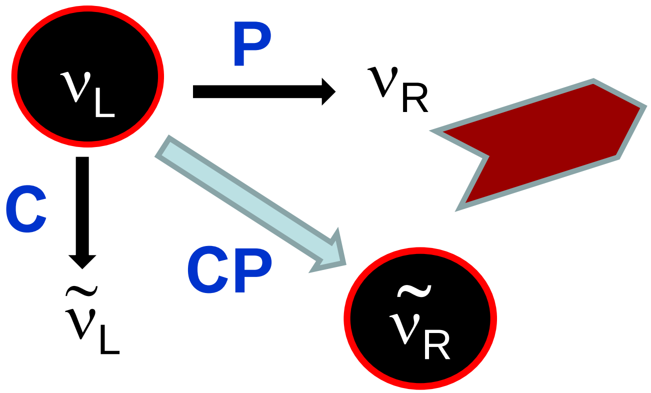
Neutrino oscillations: $\nu_i \to \nu_j$ $(i \neq j)$ $i/j = e, \mu, \tau$
$L_i \neq 1$, however $L_{total} = \Sigma L_i = 1$
at least one neutrino should have a non-zero mass for oscillations

Symmetries

Charge	**C**	particle ↔ antiparticle
Parity	**P**	x, y, z ↔ -x, -y, -z
Time	**T**	t ↔ -t

Electromagnetic and strong interactions:

C = 1, P = 1, T = 1



Weak interactions
Lepton sector, m_ν=0:
$P \neq 1$ $C \neq 1$ $T = 1$ $CP = 1$ $CPT = 1$

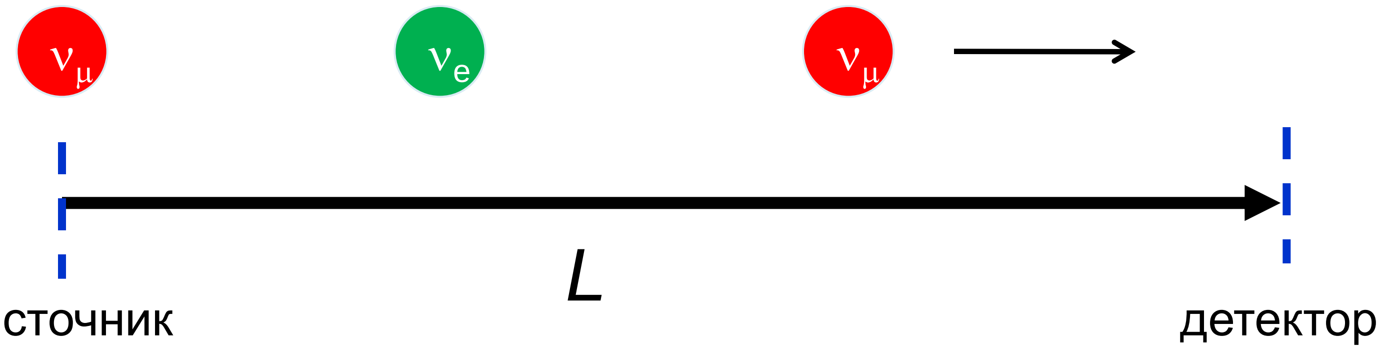
Quarks:
$CP \neq 1$
in **K** and **B** decays

Idea of neutrino oscillations

B.Pontecorvo – 1957

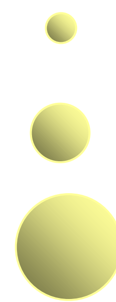
- one flavor can transform into another
- neutrino should have a non-zero mass and mix
- oscillation probability depends on

m_ν, E_ν and distance L



Weak eigenstates

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



m_1
m_2
m_3

Mass eigenstates

Weak eigenstates differ from mass eigenstates

Mixing of 2 neutrinos

Two flavors (for simplicity) ν_μ и ν_e

Mass eigenstates: ν_1 (m_1) ν_2 (m_2)

One mixing parameter - mixing angle θ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$\nu_\mu = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

2 types of oscillation experiments

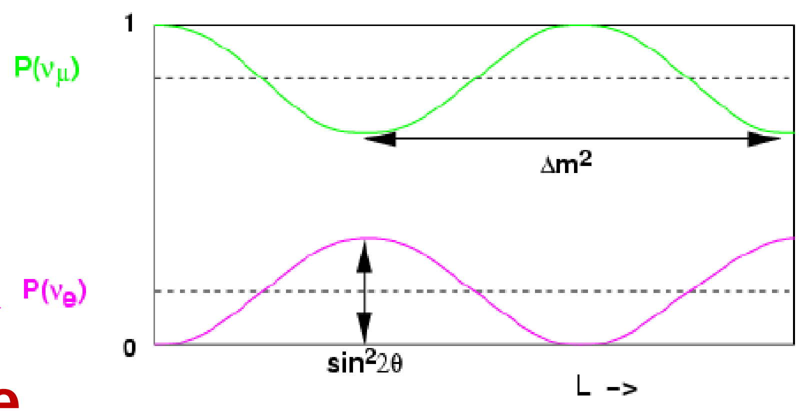
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta)\sin^2(\Delta m^2 L/E_\nu)$$
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta)\sin^2(\Delta m^2 L/E_\nu)$$

«excess» ν_e

appearance

«deficit» ν_μ

disappearance



Oscillation industry

Solar ν's

Homestake, USA

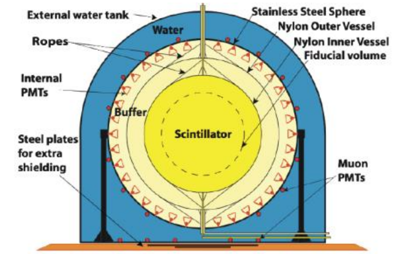
1970

Sage, Russia

1990

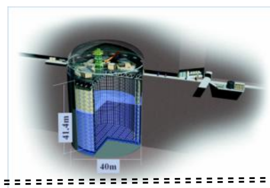
Gallex
SNO
SK

Borexino, Italy



Atpospheris ν's

SK, Japan

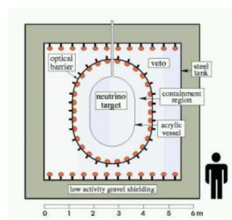


MACRO, Italy
Soudan2, USA

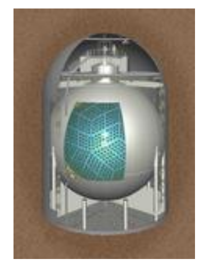
T2K
Nova
……

Reactor ν's

CHOOZ,
France



KamLand,
Japan

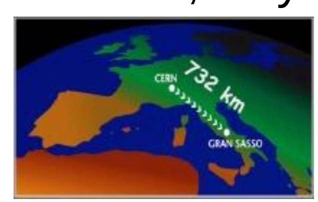


Accelerator ν's

K2K, Japan

Minos, USA

OPERA, Italy



Sterile ν's:
LSND,
MiniBooNe,
USA

ν oscillations and mixing

3 families

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \qquad U = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}$$

Pontecorvo
Maki
Nakagawa
Sakata

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

$$\Delta m_{ij}^2 = m_i^2 - m_j^2 \qquad \Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

→ **two independent Δm^2**

by Summer 2011

$$\Delta m_{12}^2 = \Delta m_{sol}^2 \approx 7.5\times10^{-5}\,\mathrm{eV}^2 \qquad |\Delta m_{23}^2| \cong |\Delta m_{31}^2| = |\Delta m_{atm}^2| \approx 2.4\times10^{-3}\,eV^2$$

$\theta_{12} = (34 \pm 1)^0$ $\theta_{23} \sim 45^0$ θ_{13} = ??

?? MH and δ ??

$\nu_\mu \rightarrow \nu_e$ in matter

Physics reach oscillation mode for accelerator LBL experiments is $\nu_\mu \rightarrow \nu_e$

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

→ θ_{13}

→ **CP-even**

→ **CP-odd**

→ **Solar**

→ **Matter**

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

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

change sign for NH → IH

Neutrino landscape considerably changed since Summer 2011

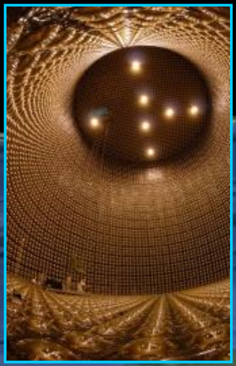
Accelerator experiments

T2K, MINOS

Reactor experiments

Double Chooz, Daya Bay, RENO

Long-Baseline Neutrino Oscillation Experiment

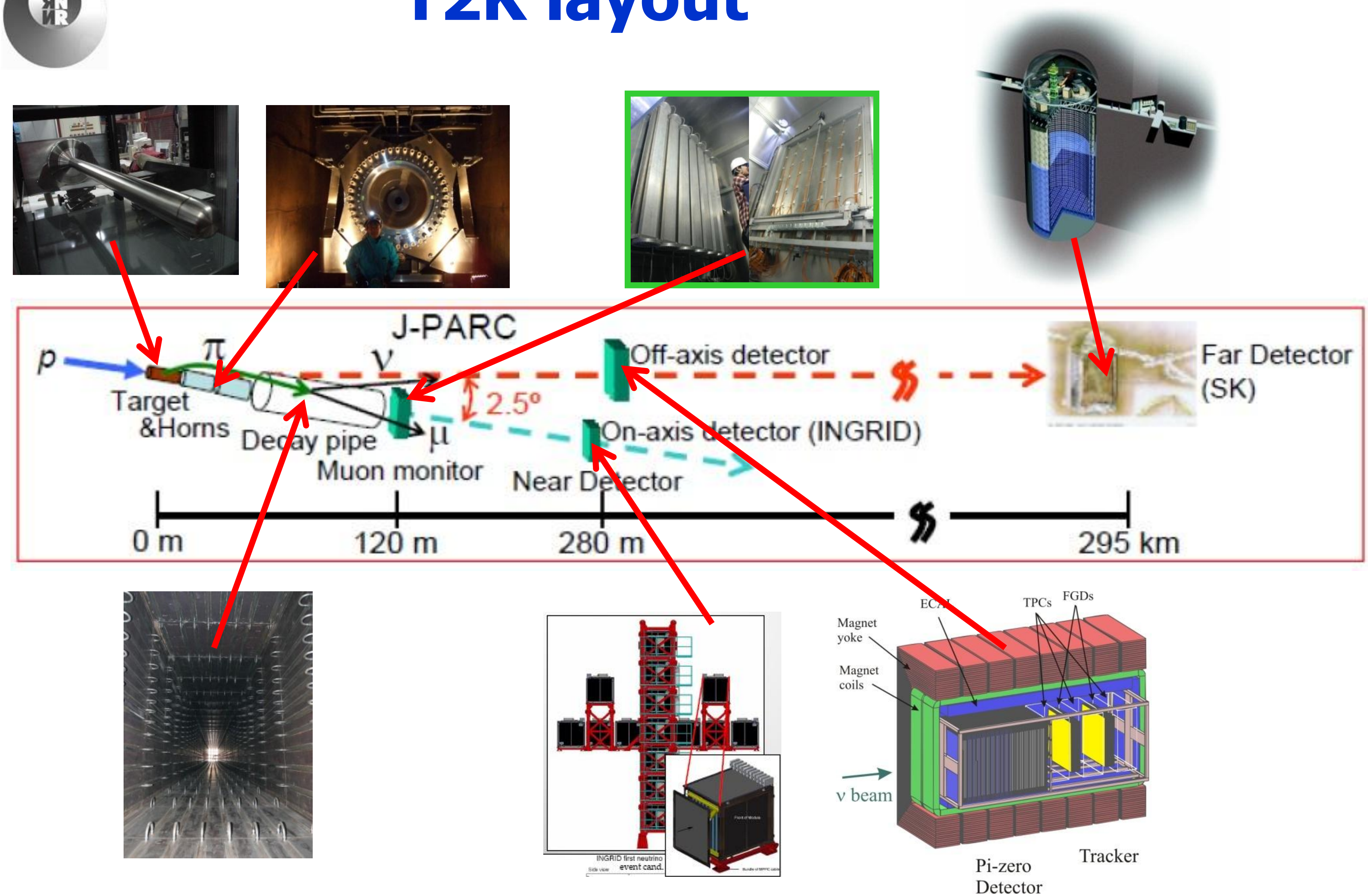


SuperKamiokande

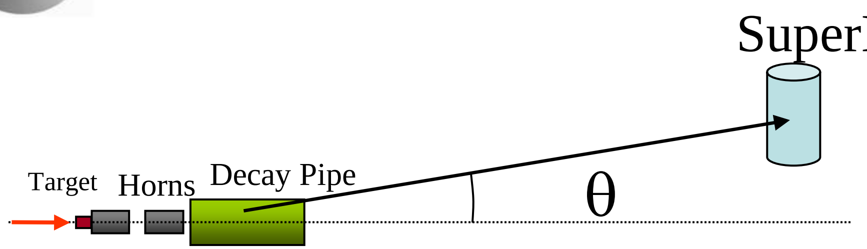
Toyama
Kamioka Mine
JPARC
Tokai
Токио
JAPAN
Tokyo/Narita Airport

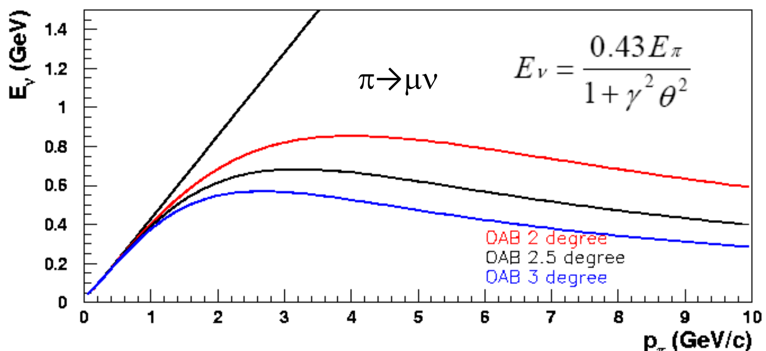
~ 500 members
59 institutions
11 countries

T2K layout

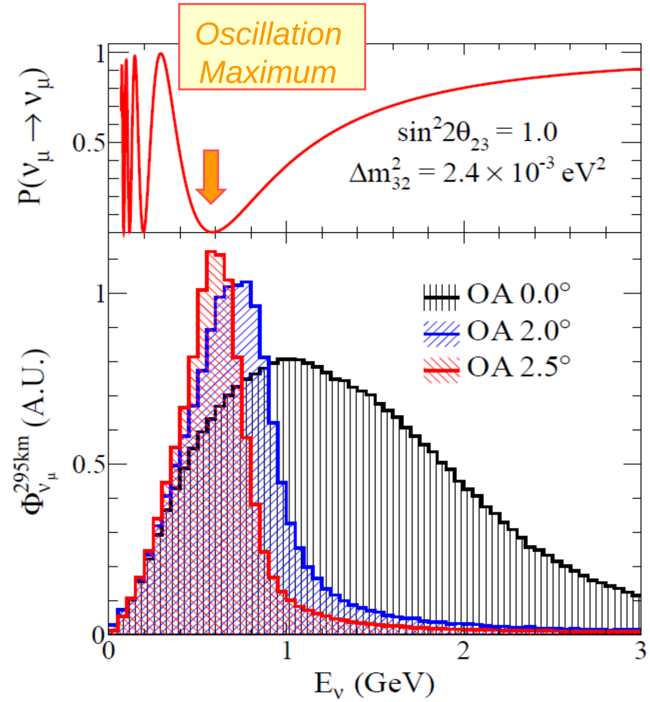

J-PARC
p
π
ν
Target
&Horns
Decay pipe
μ
Muon monitor
2.5°
Off-axis detector
On-axis detector (INGRID)
Near Detector
Far Detector
(SK)
0 m
120 m
280 m
295 km
Magnet
yoke
Magnet
coils
ECAL
TPCs
FGDs
ν beam
Pi-zero
Detector
Tracker

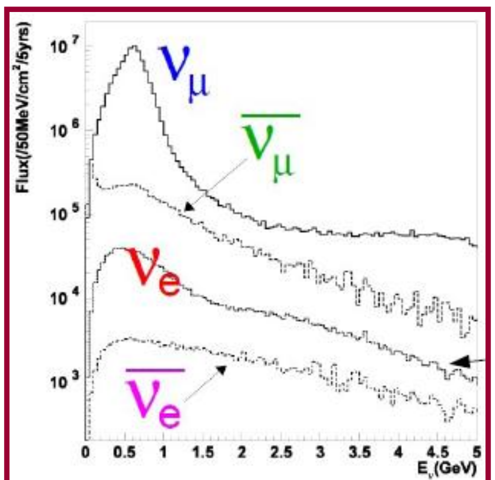
T2K off-axis ν beam





Off-Axis beam



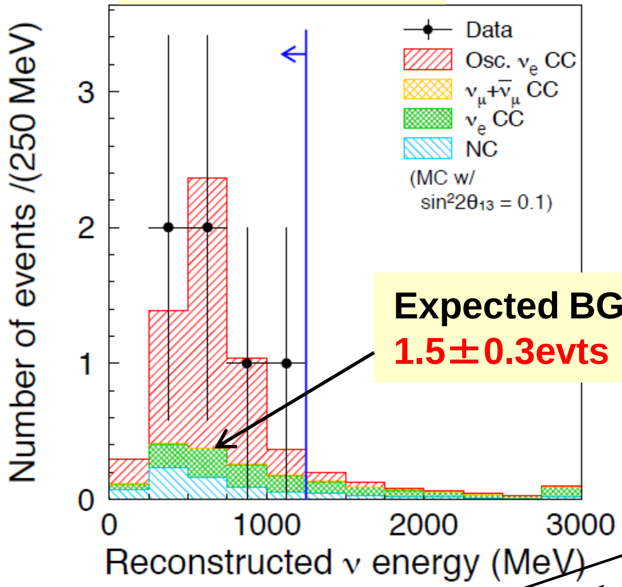


- 750 (now 235) kW 30 GeV proton beam at JPARC
- Quasi-monochromatic ν_μ (95%) beam
- Peak energy ~700 MeV tuned to oscillation maximum
- ~0.5% ν_e at peak energy
- Reduced high energy tail → reduces background

First T2K result

published in June 2011

6 ν_e events



1.43×10^{20} POT
January 2010 –
March 2011

About two years 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.

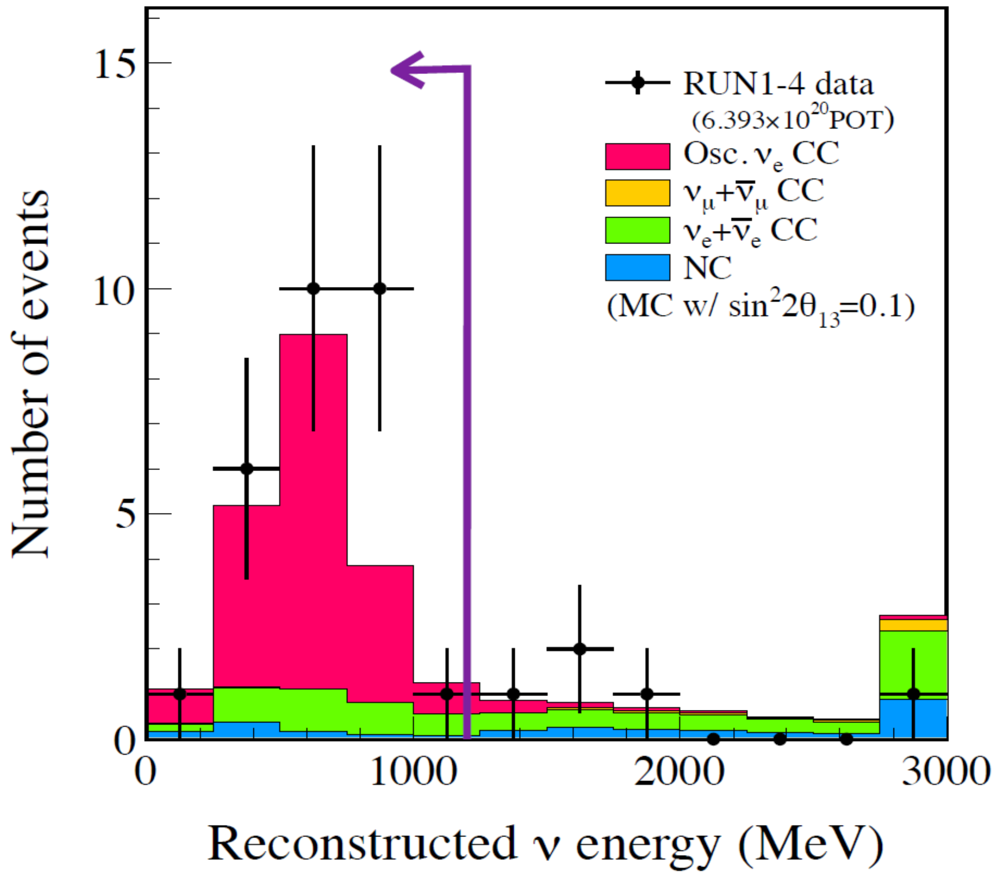
DOI: 10.1103/PhysRevLett.107.041801 PACS numbers: 14.60.Pq, 13.15.+g, 25.30.Pt, 95.55.Vj

Then,
1 - Confirmation from MINOS
2 - Precise measurements by
Double Chooz
Daya Bay
RENO

T2K new result

July 2013

6.4×10^{20} POT

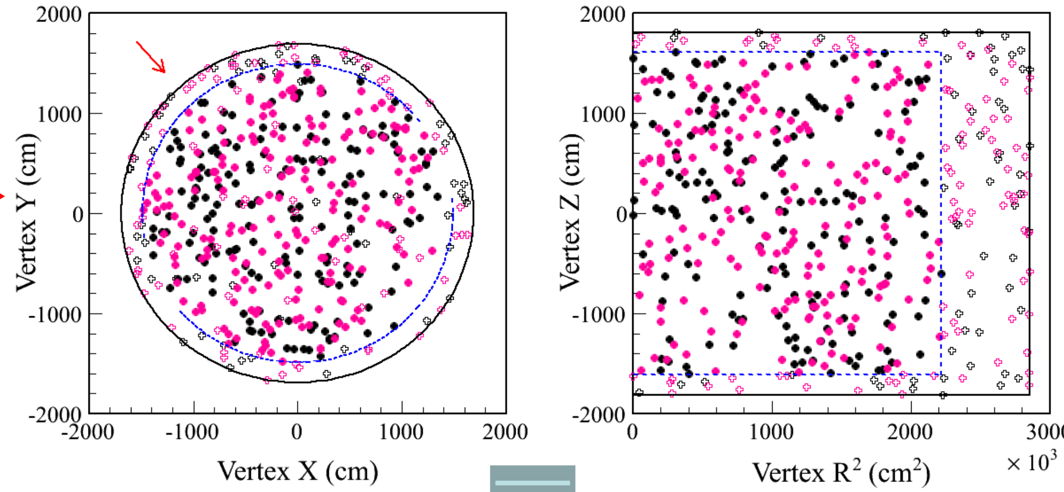


after all cuts
28 ν_e candidates

Expected background
($\sin^2 2\theta_{13} = 0.0$)
4.64 ± 0.52 events

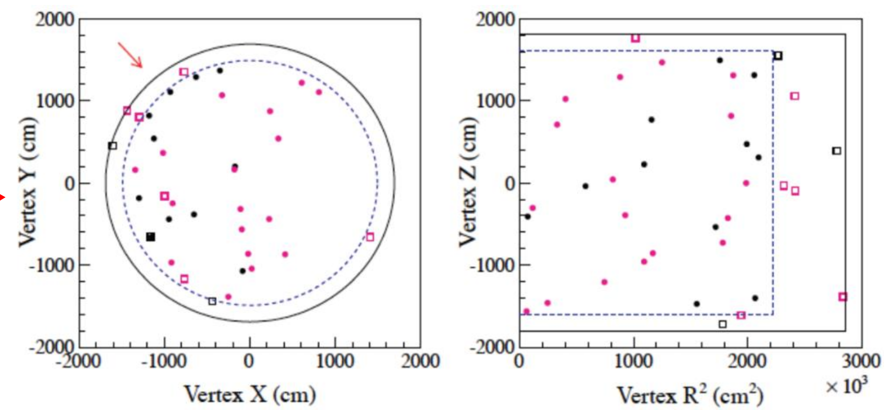
T2K events

Events fully contained in ID and vertex within fiducial volume (FCFV)



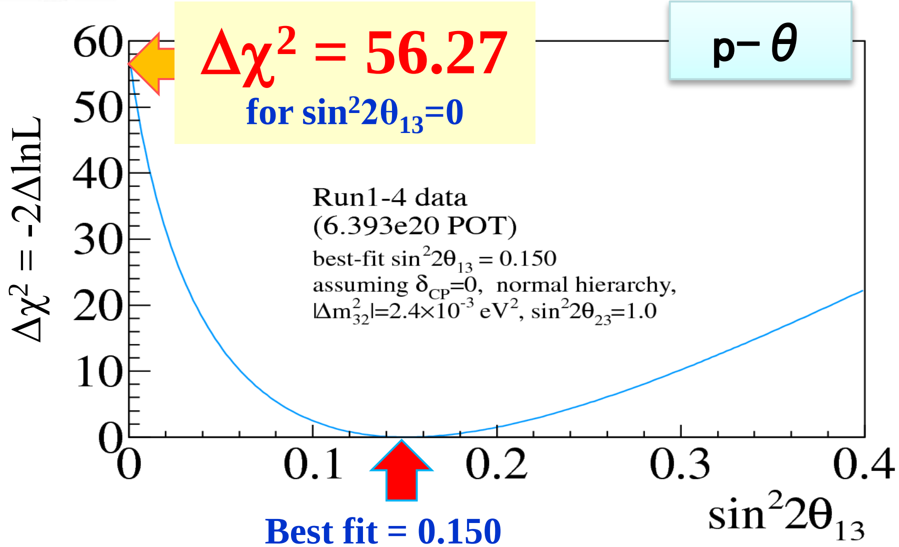
applying selection criteria

ν_e candidates

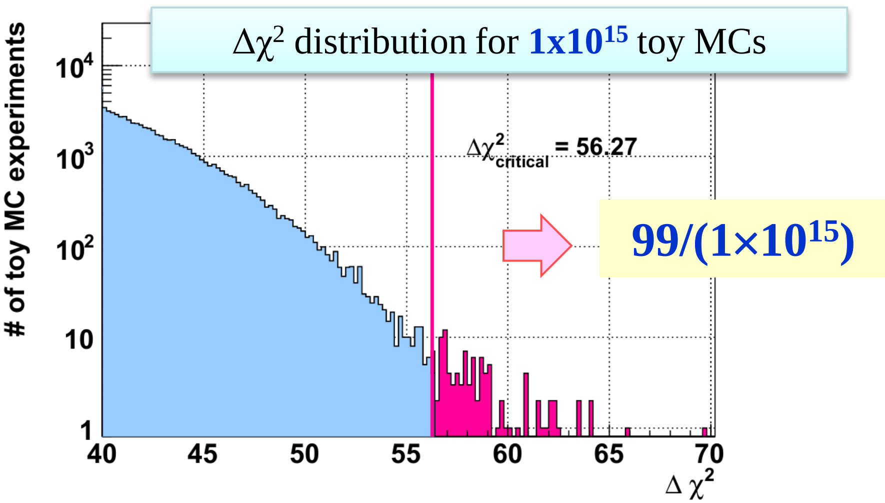


Significance

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



Best fit = 0.150



28 ν_e events detected
expected background
4.64 ± 0.52 events

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

p-value is calculated as follows:

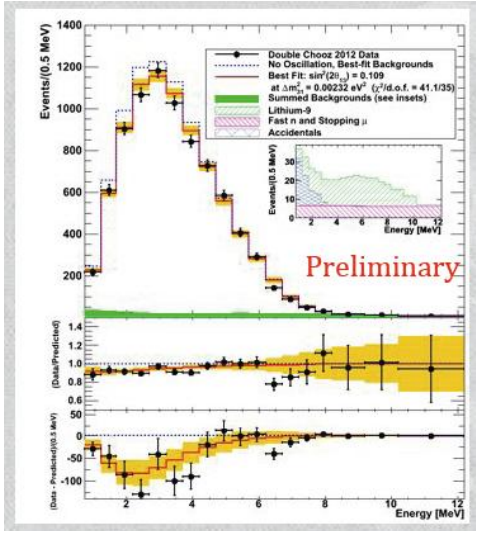
1. Generate 1e15 toy experiments with $\sin^2 2\theta_{13}=0.0$.
2. Fit each toy experiment extract $-2\Delta\ln L$ ($=\Delta\chi^2$).
3. p-value is the fraction of toy experiments above $\Delta\chi^2_{data}$

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

Discovery of ν_e appearance

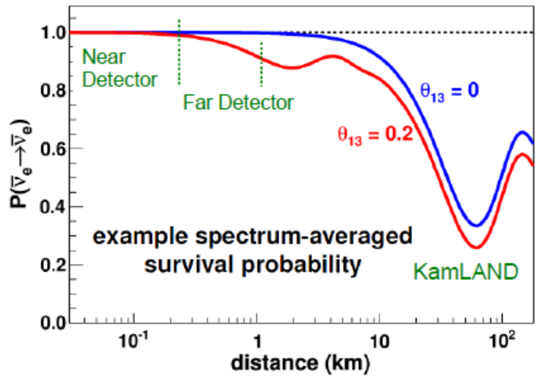
Reactor experiments

DChooz



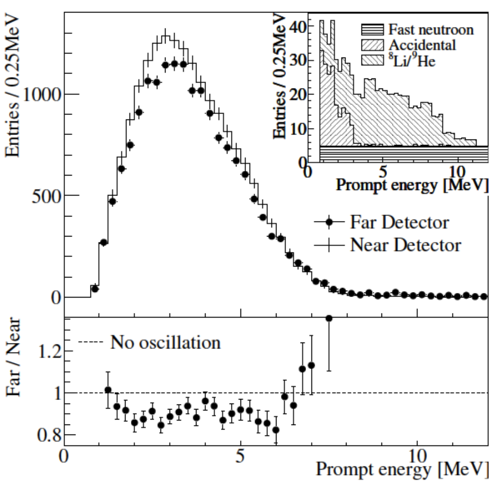
Measurements of reactor neutrino disappearance

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

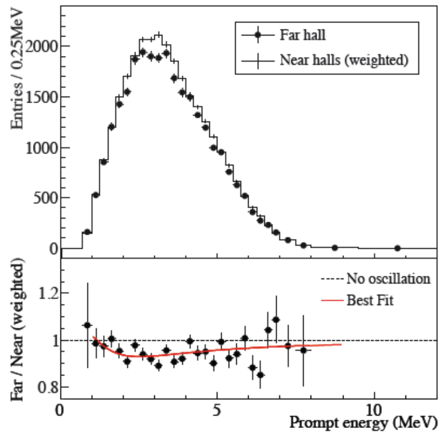


baseline ~ 1 km
best sensitivity to θ13

Reno

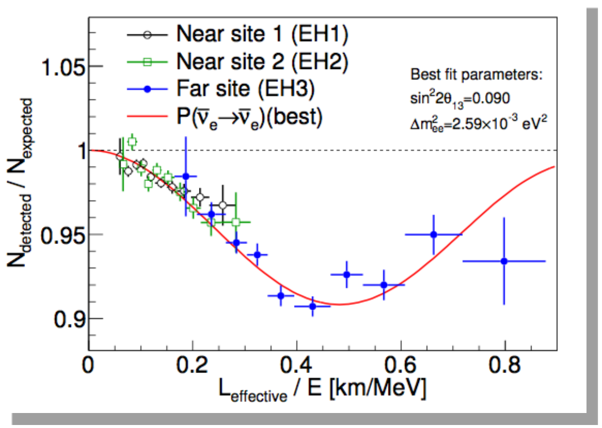


Daya Bay



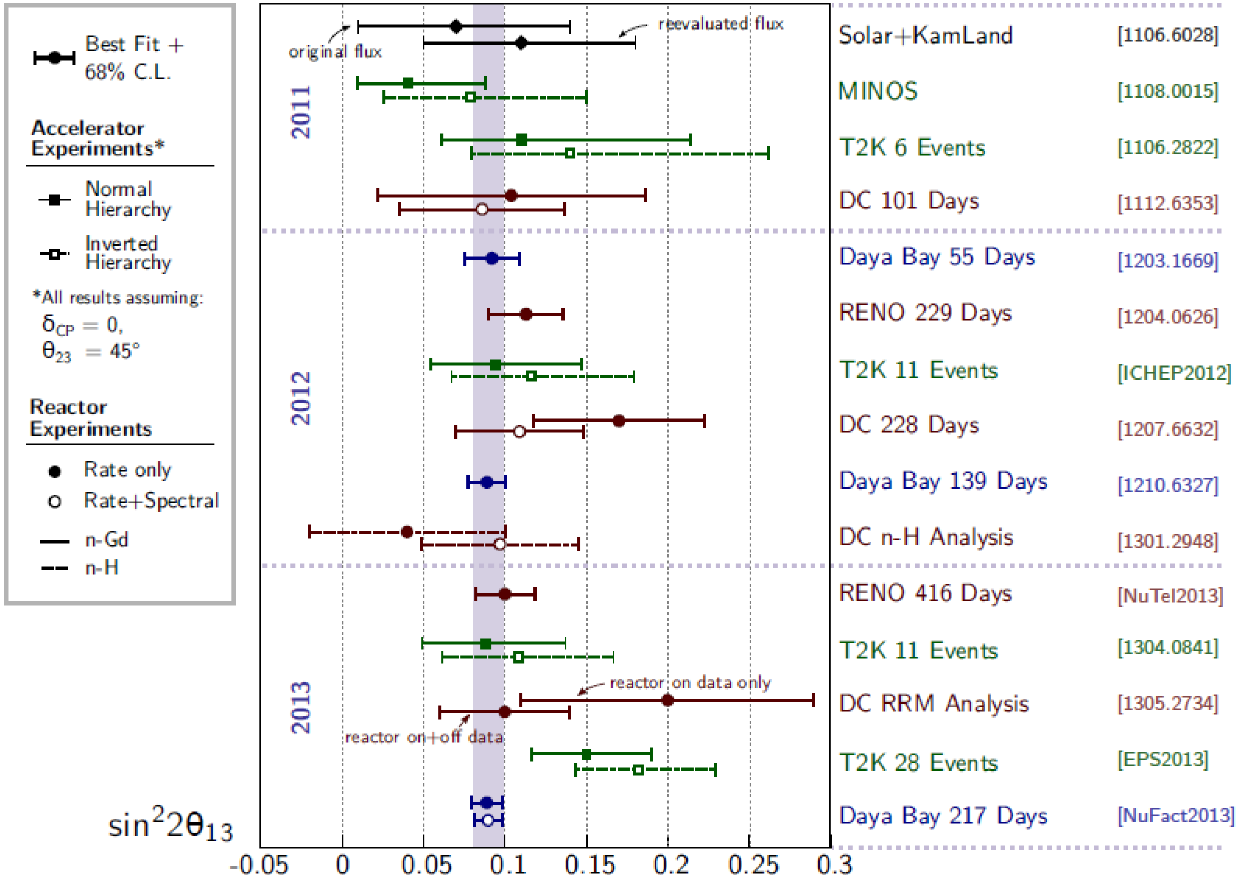
Daya Bay:

$$\sin^2 2\theta_{13} = 0.089 \pm 0.009$$



History of θ_{13} measurements

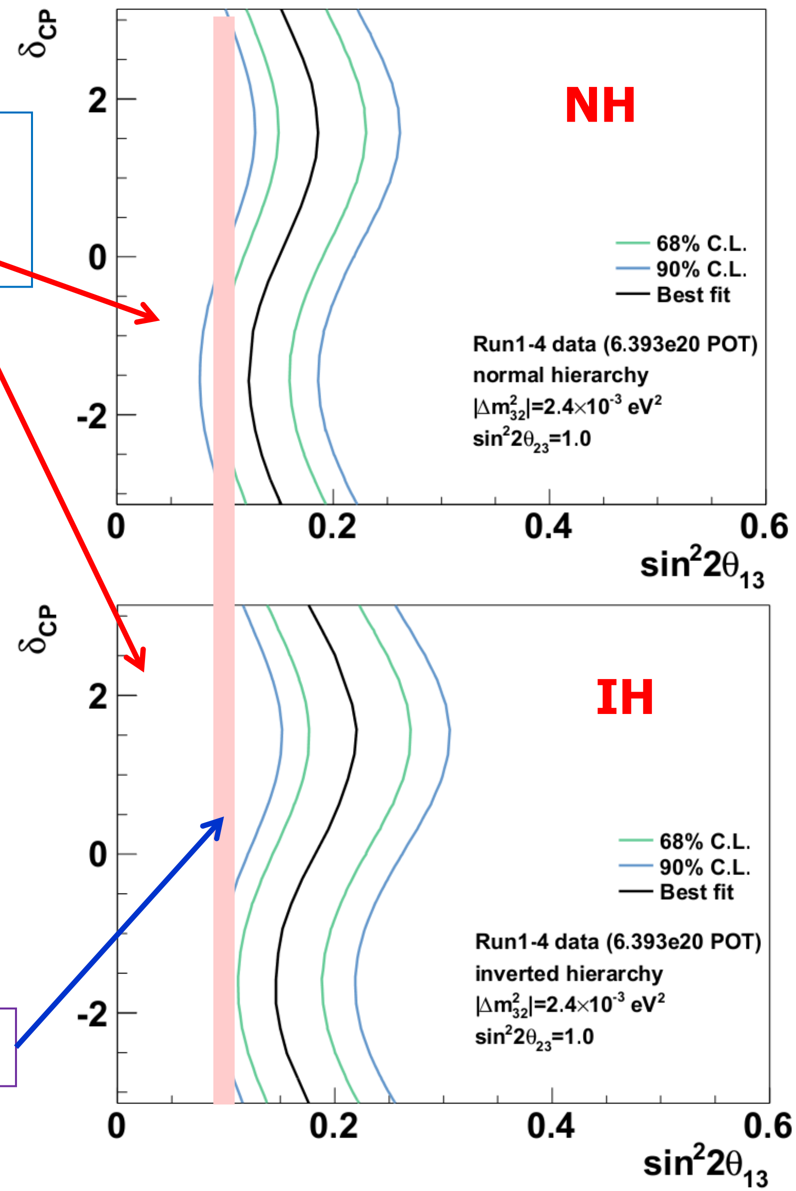
Only 2 years of measurements! **S. Jetter, Nufact2013**



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

T2K and reactor data

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



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

NH

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

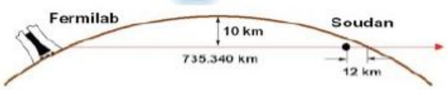
IH

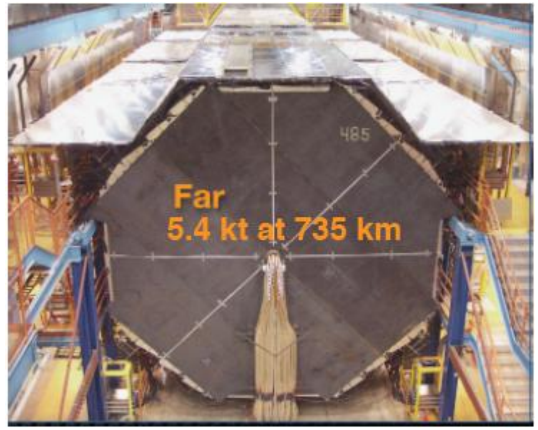
$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

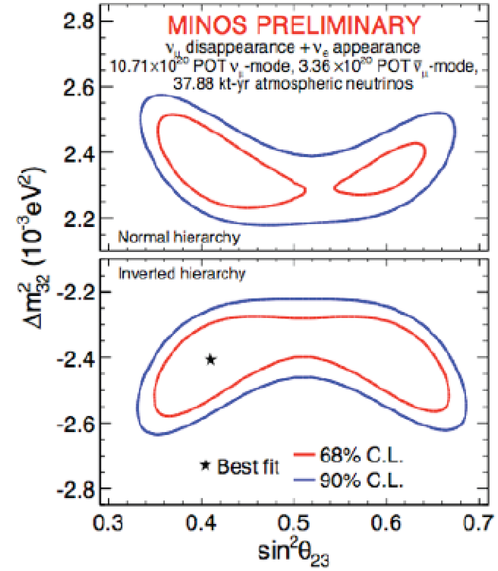
PDG(2012): $\sin^2 2\theta_{13}$: 0.098±0.013

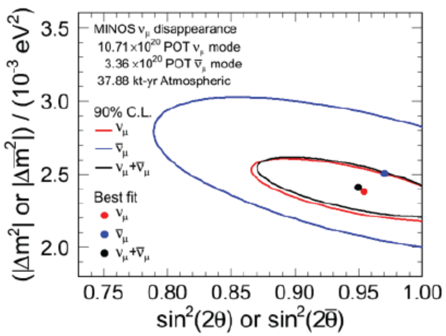
MINOS

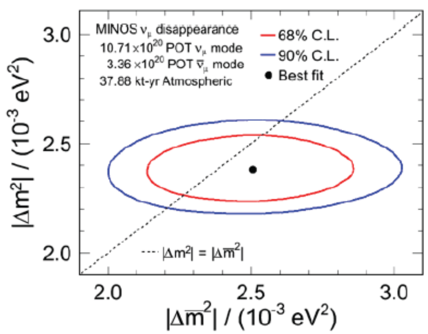
Neutrino beam from FNAL to Soudan

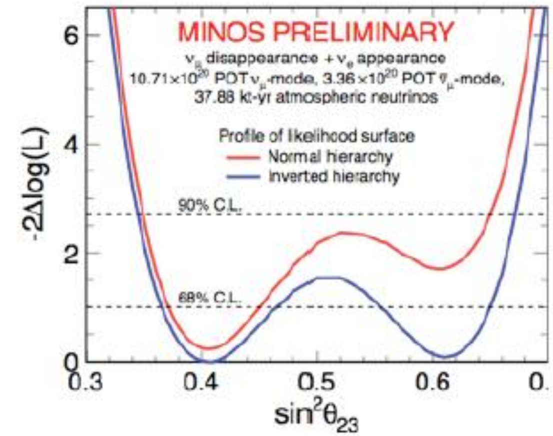












$\bar{\nu}$ oscillation parameters

$$\sin^2(2\bar{\theta}) = 0.97^{+0.03}_{-0.08}$$

$$\Delta\bar{m}^2 = 2.50^{+0.23}_{-0.25} \times 10^{-3} eV^2$$

$$\sin^2(2\bar{\theta}) > 0.83\ (90\% C.L.)$$

ν oscillation parameters

$$\sin^2(2\theta) = 0.95^{+0.035}_{-0.036}$$

$$|\Delta m^2| = 2.41^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

$$\sin^2(2\theta) > 0.89\ \ (90\% C.L.)$$

MINOS preferences:

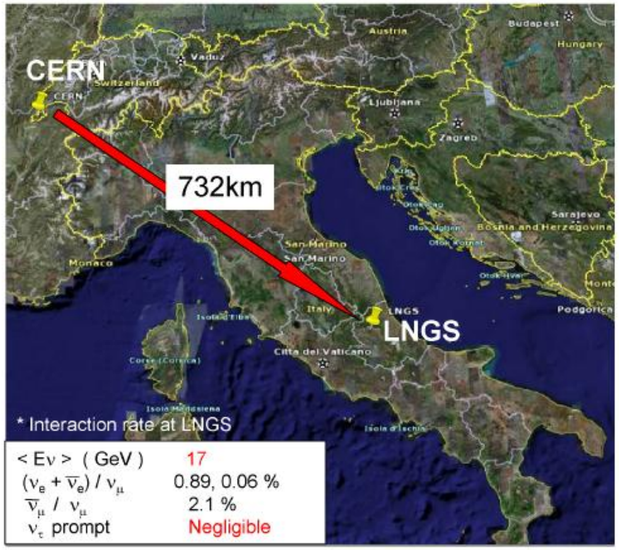
Low octant

Non-maximal mixing

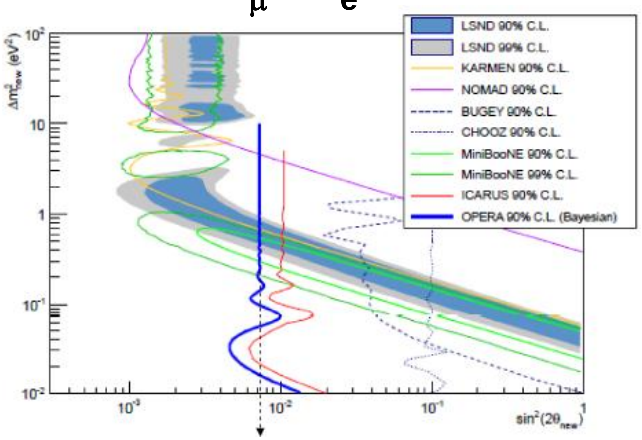
Inverted mass hierarchy

OPERA

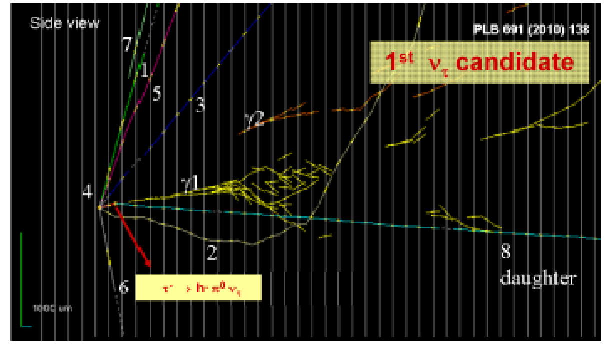
Neutrino beam from CERN to Gran Sasso

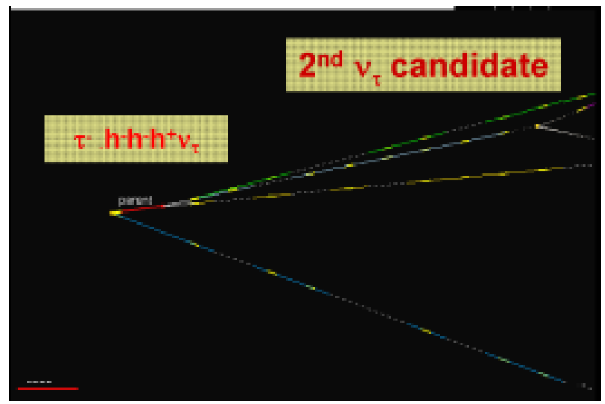


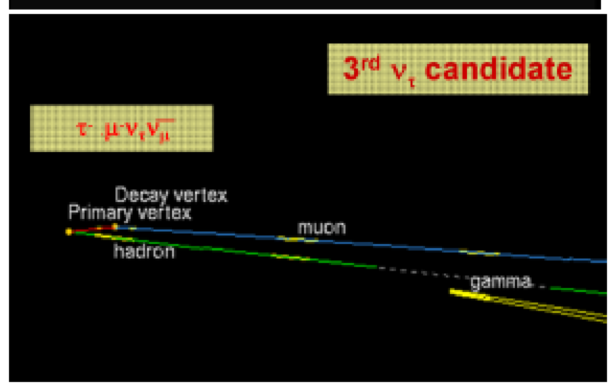
$\nu_\mu \rightarrow \nu_e$



$\nu_\mu \rightarrow \nu_\tau$







Data 2008-2009

Expected bkg 0.226 ν_τ events

3 ν_τ events: significance **3.2σ**

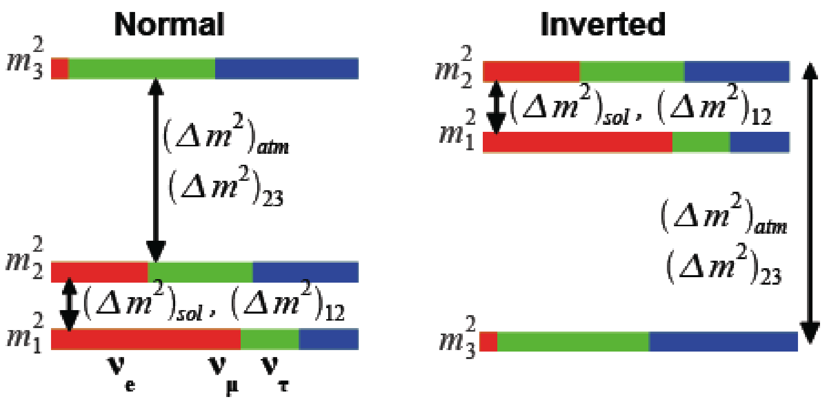
p-value of background **7.3×10⁻³**

Next targets ?

2011-2013 Great milestones

- $\theta_{13} = (9 \pm 0.6)^0$
- ν_e appearance observed at 7.5σ

Mass Hierarchy



+

precision measurement of oscillation parameters

$\theta_{23} \geq 45^o$ or $\leq 45^o$

CP violation

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

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

CKM **PMNS**

$$\begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix} \quad \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

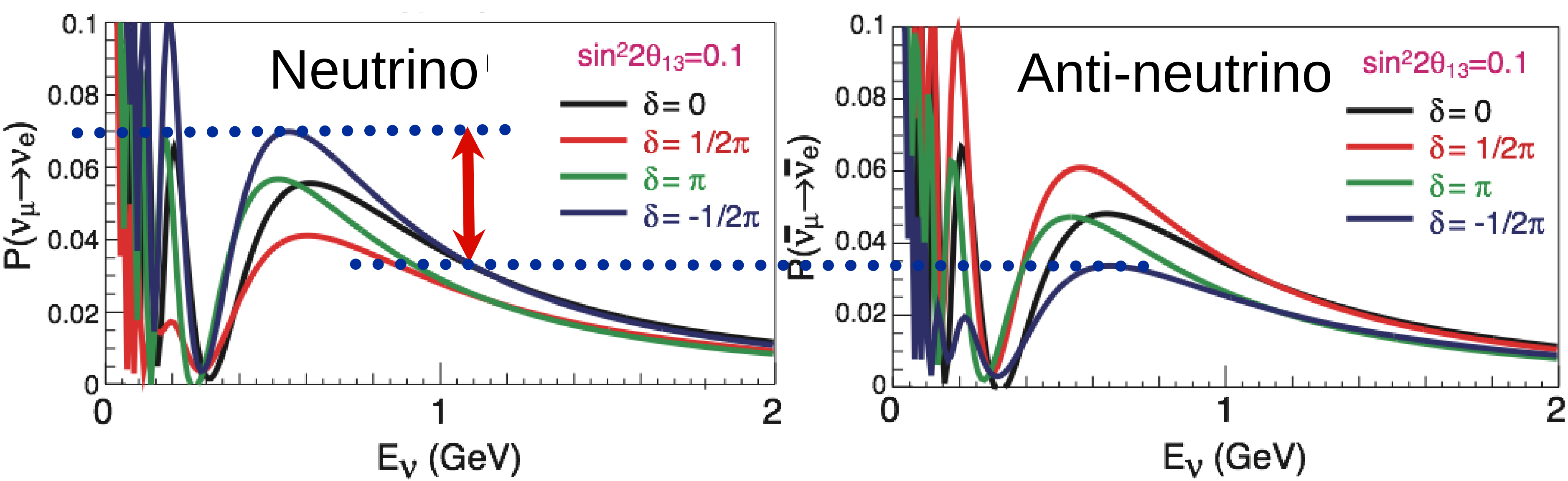
Quark sector $J_{CP} \approx 3\times 10^{-5}$

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

Measurement of CP asymmetry

$P(\nu_\mu \to \nu_e)$: ν_e appearance probability

for 295km baseline,
normal hierarchy



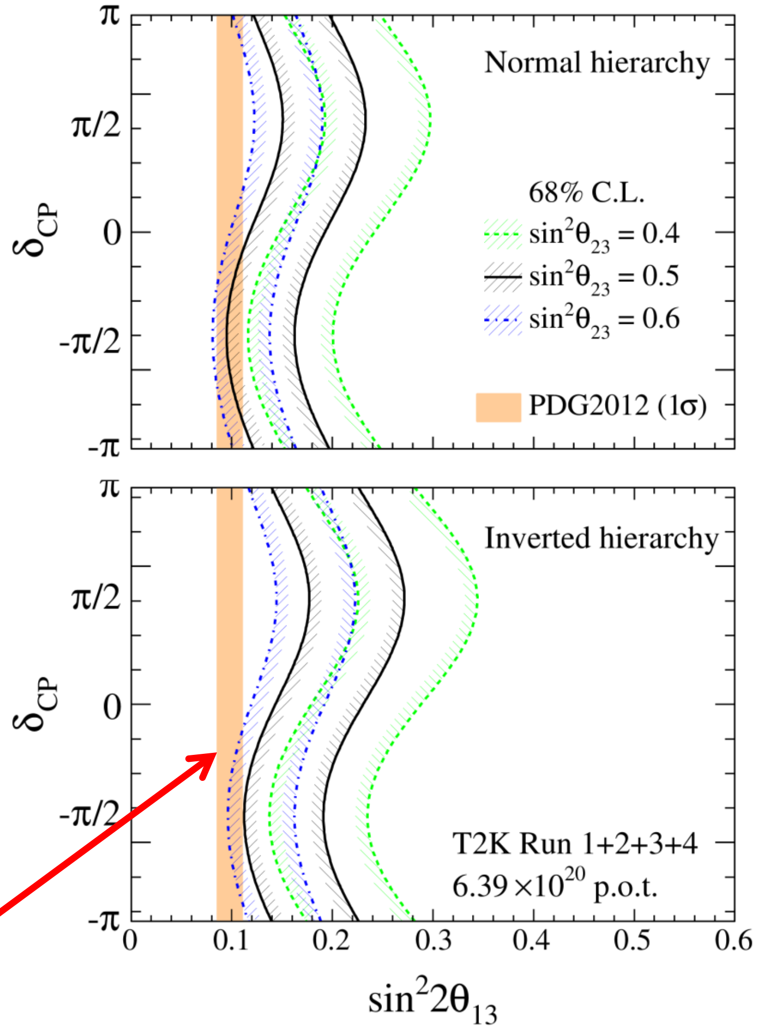
- Comparison of $P(\nu_\mu \to \nu_e)$ and $P(\nu_\mu \to \nu_e)$
  Max. ~±25% (L=295 km) change from δ=0 case
- Measure 1st and 2nd oscillation maxima in **$P(\nu_\mu \to \nu_e)$**
- Comparison of accelerator **$P(\nu_\mu \to \nu_e)$** and reactor **P(anti-ν_e → anti-ν_e)**

Matter effect → fake CP violation, BUT sensitive instrument to determine mass hierarchy

θ_{23} issue

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

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



PDG(2012)

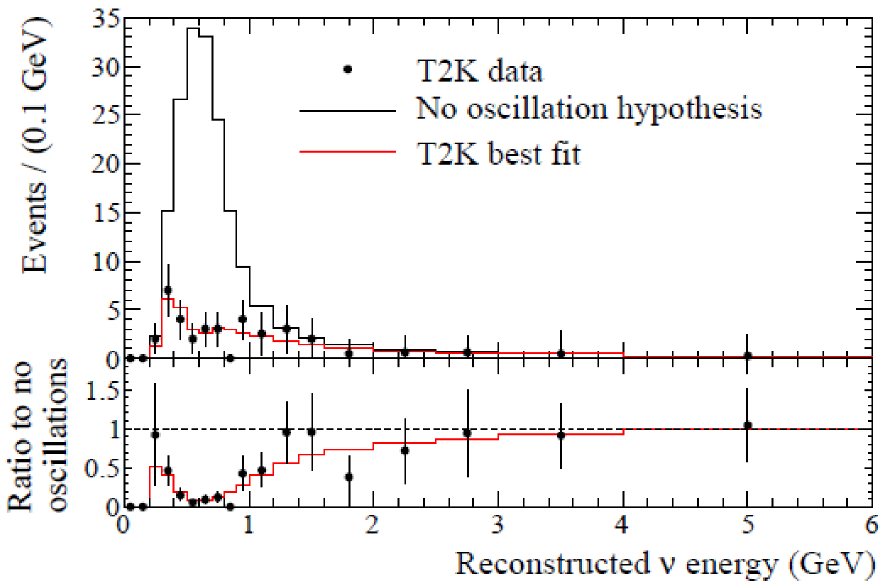
- **Oscillation probability is dependent on $\sin^2\theta_{23}$ (octant)**
  - **PDG2012: $\sin^2(2\theta_{23}) > 0.95$**
    - **$\sin^2\theta_{23} = 0.50 \pm 0.11$**
    - **$\theta_{23} = 45 \pm 6.5°$**
  - **Reduction of $\sin^2\theta_{23}$ error is critical for further improvements**

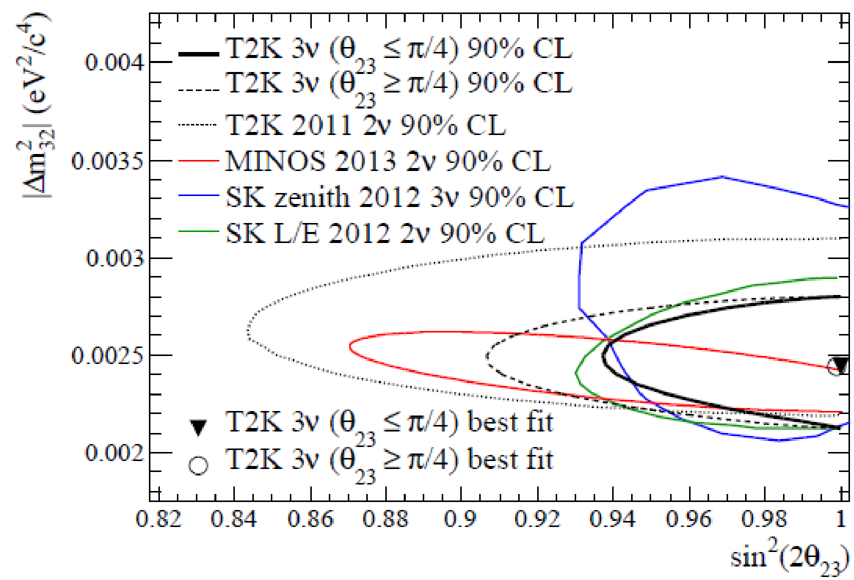
Near Future
(5-10 years)

θ_{23} measurement

ν_μ disappearance

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



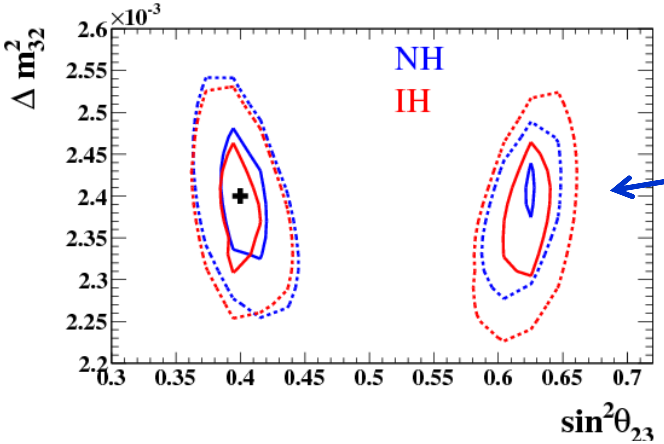


$\sin^2\theta_{23} = 1 \to$ maximal mixing

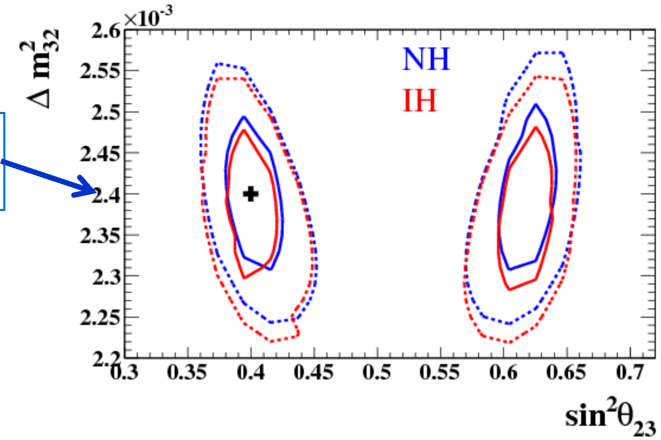
Perspectives: θ_{23}

T2K

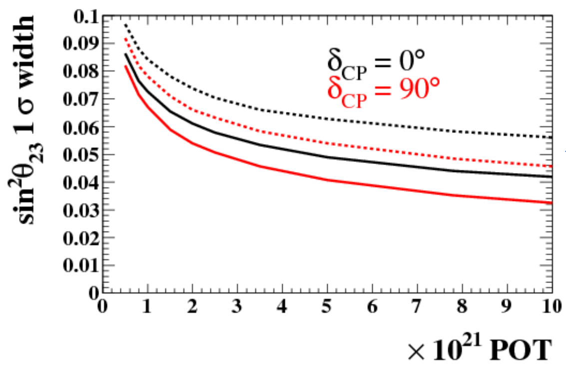
7.8×10^{21} pot
100% ν running 90% CL
$\sin^2 2\theta_{13}$ = 0.1 + reactor data
solid: stat only; dashed: stat +current sys



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

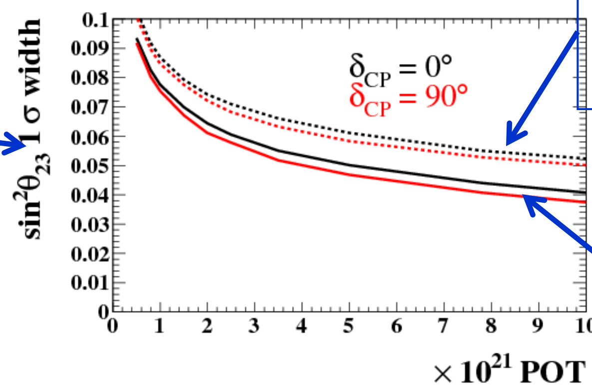


Octant



θ_{23}

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

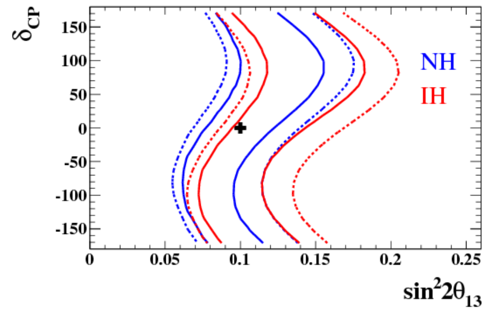


stat + current syst

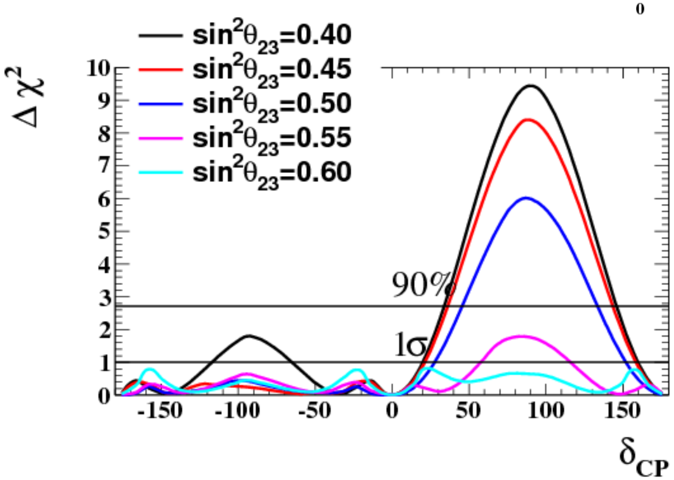
stat only

Perspectives: CPV

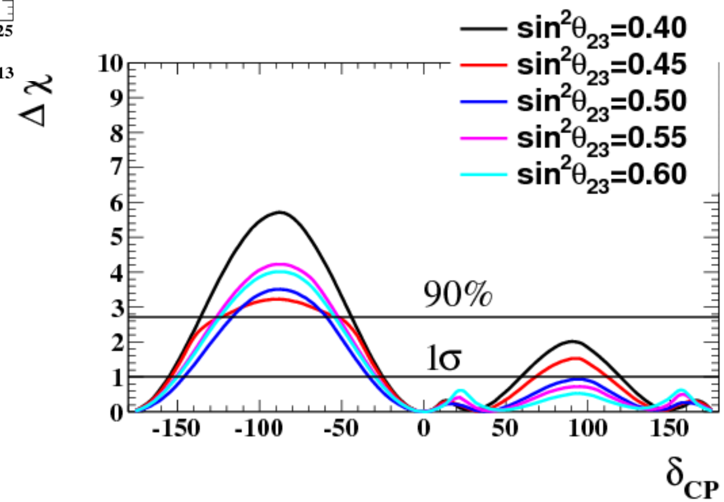
IH 7.8×10^{21} pot
100% ν running
$\sin^2 2\theta_{13} = 0.1$
+ reactor data



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

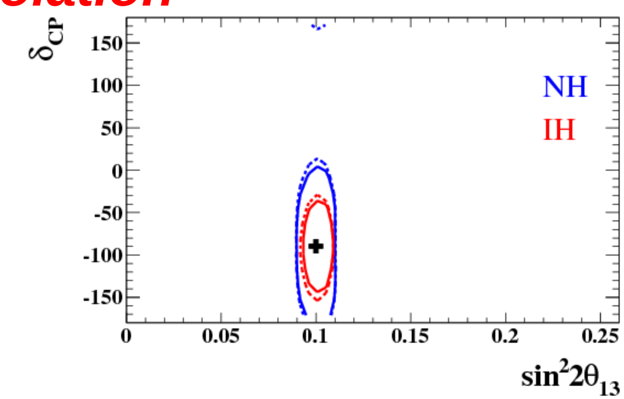


T2K



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

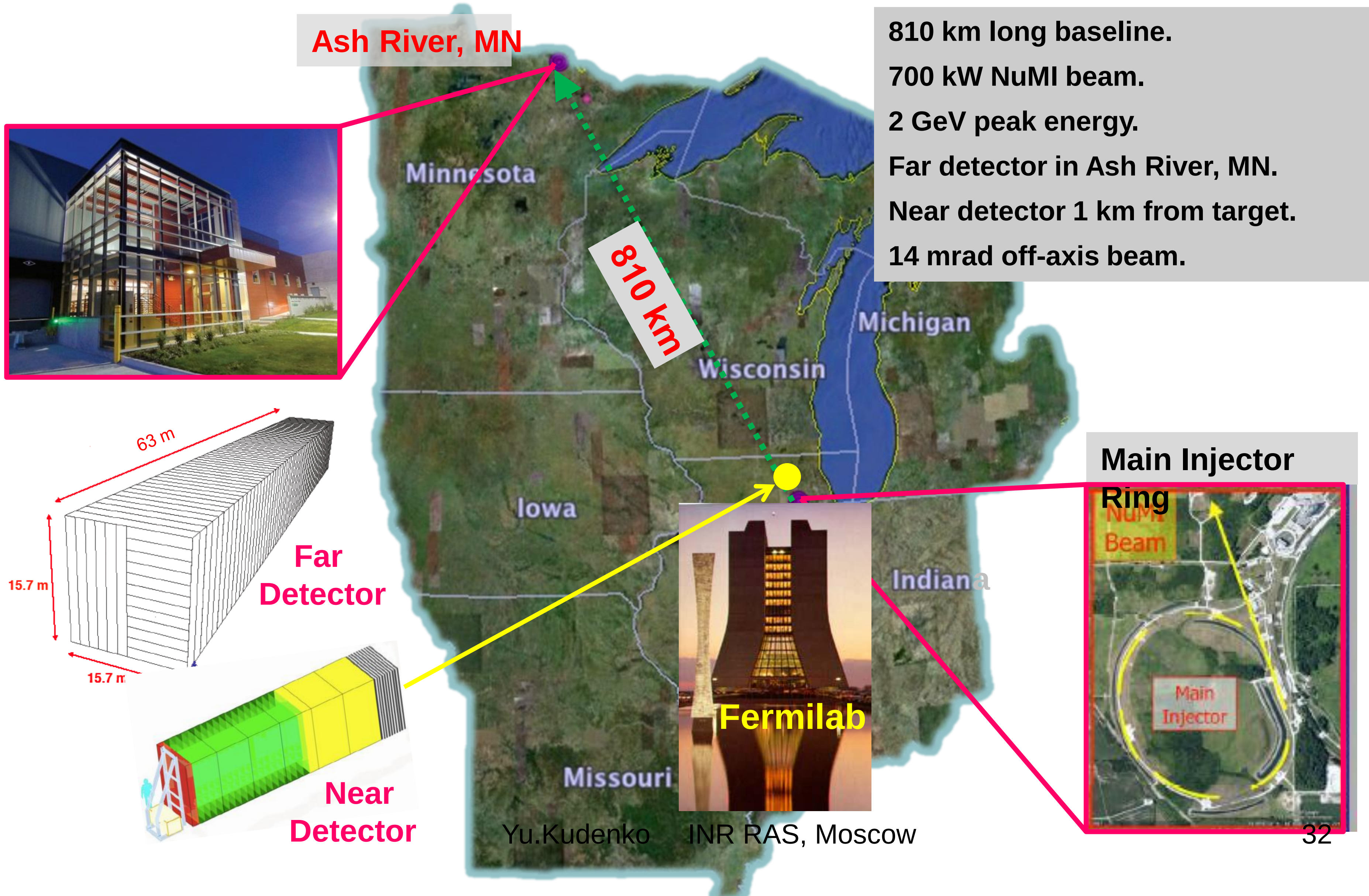
7.8×10^{21} pot
50% ν - 50% anti-nu running
$\sin^2 2\theta_{13} = 0.1$ + reactor data
$\sin^2 2\theta_{23} = 0.5$
δ= -90 deg



Nova

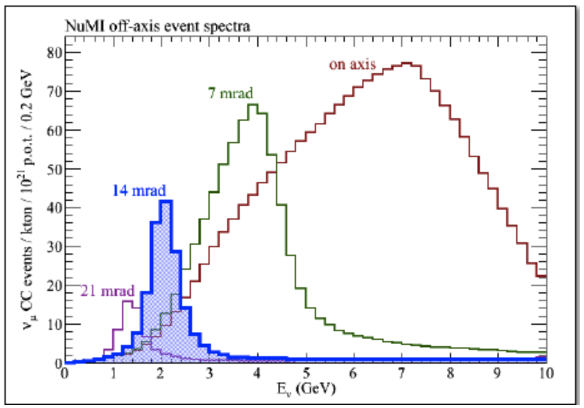
Neutrino off-axis narrow-band beam from FNAL

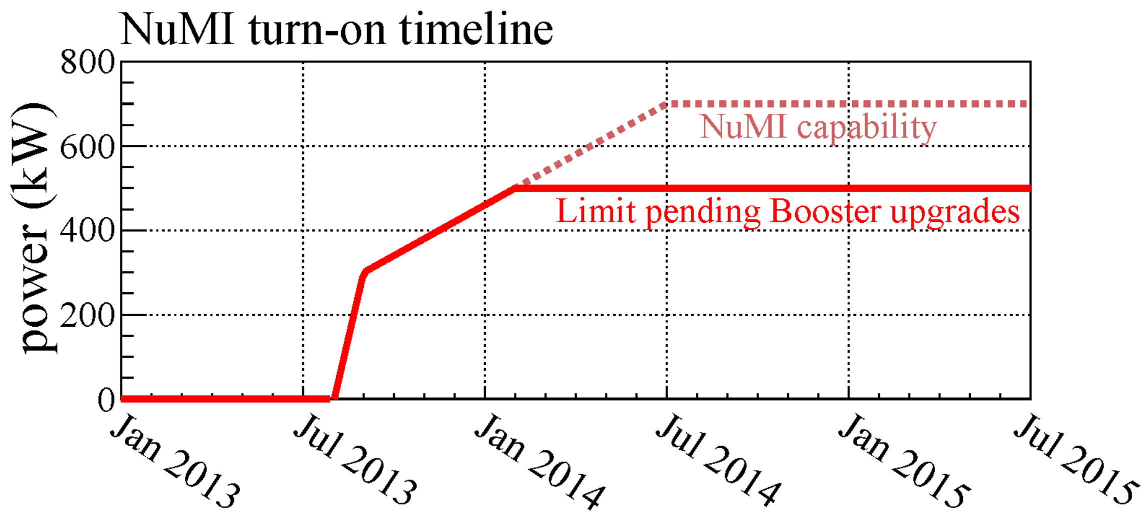
- 810 km long baseline.
- 700 kW NuMI beam.
- 2 GeV peak energy.
- Far detector in Ash River, MN.
- Near detector 1 km from target.
- 14 mrad off-axis beam.



Beam schedule

NOvA started data taking in September 2013



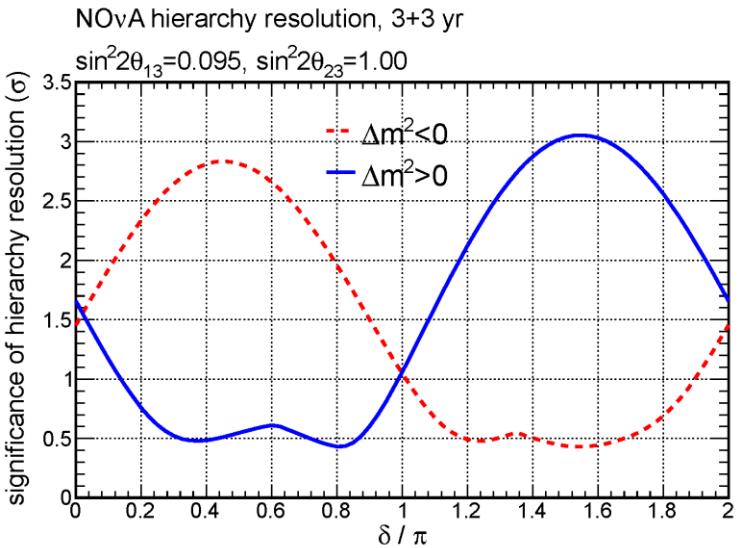


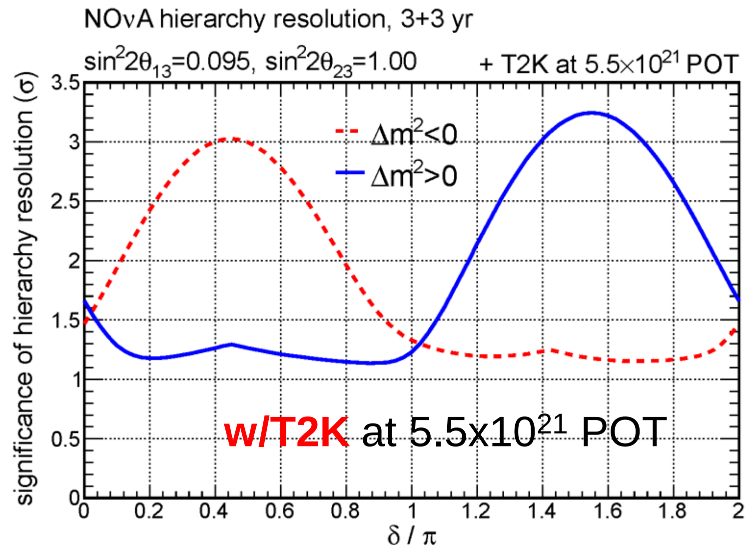
Beam intensity will be increased up to 500 kW next year and to 700 kW in 2 years.

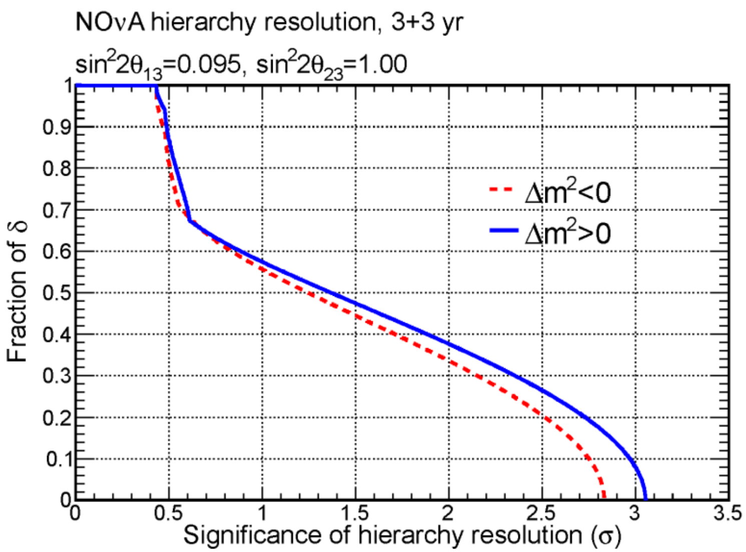
Far Detector mass will be added at a rate of about 1 kton/3 weeks.
Full installation of NOvA detectors will be completed in one year.

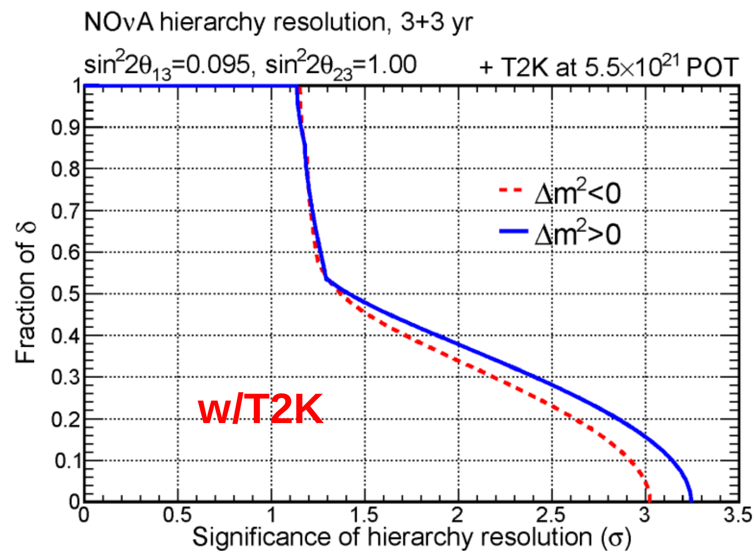
Mass Hierarchy

Significance of the MH determination



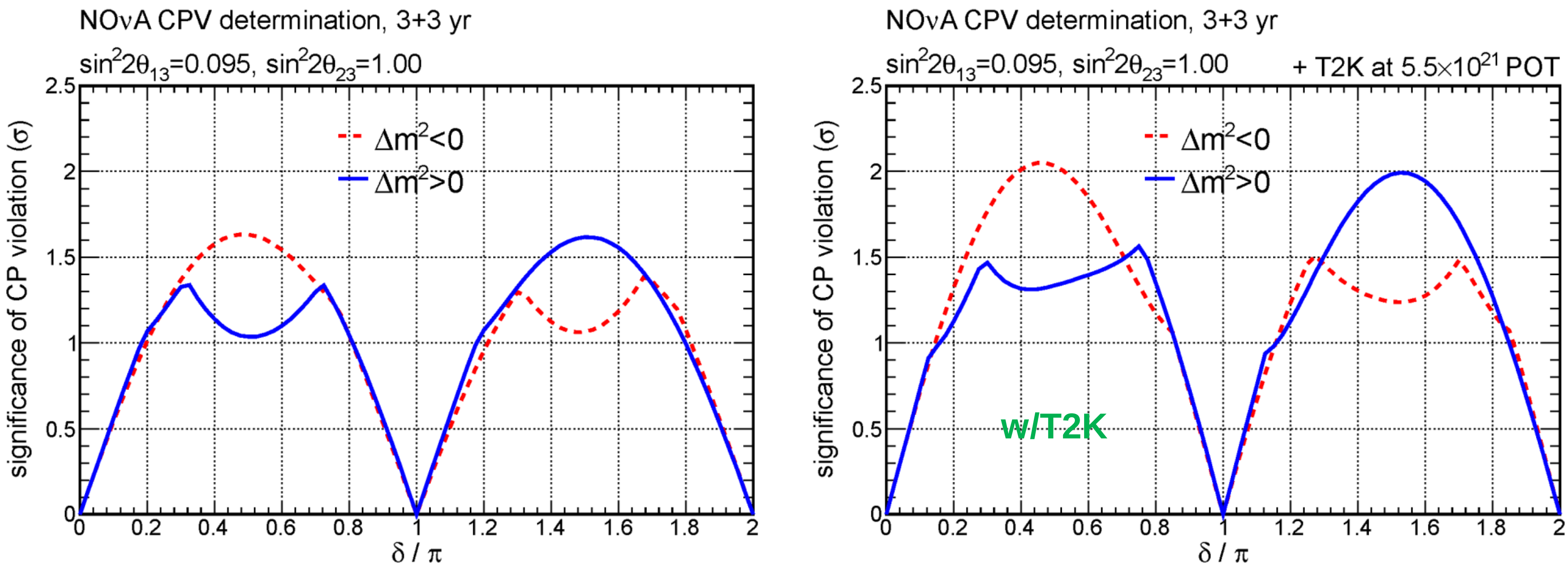






CP violation

Significance with which NOvA (+T2K) can establish CP violation.



The significance goes to zero at $\delta = 0$ and $\delta = \pi$ since there is no CP violation at those points. The dips in the peaks occur because the mass ordering has not been resolved.

Best case: CP violation at 1.6σ (Nova only) and 2.0σ (Nova + T2K)

Far Future
(> 2023)

LBNE

$\nu_\mu \rightarrow \nu_e$

The US based LBL project

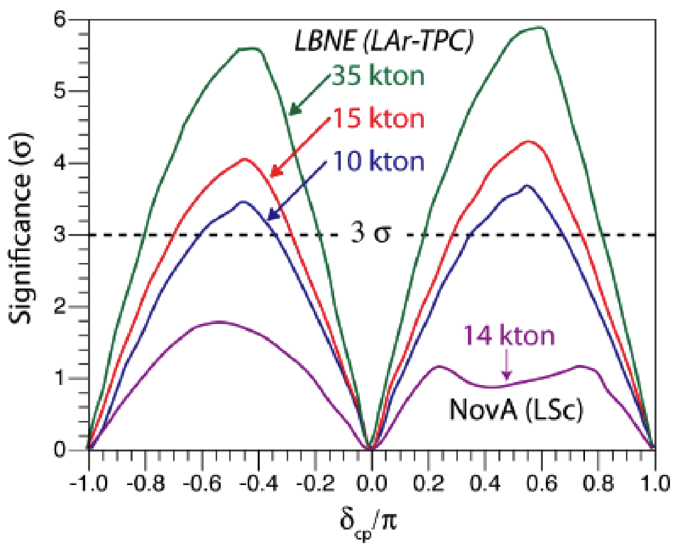
Neutrino beam from FNAL to Homestake
L = 1300 km, Ep=120 GeV, 700 kW NuMI beam,
E_ν = 0.5 – 5 GeV

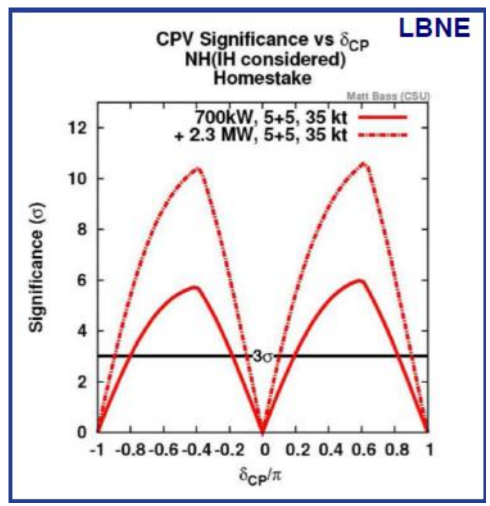
- Far detector 35 kt, LAr, underground
- No near detector

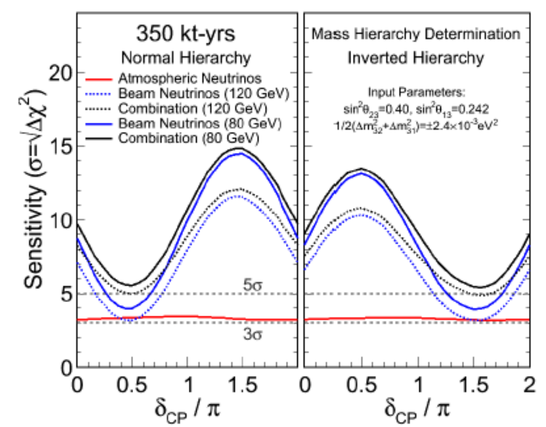
arXiv:1110.6249

Sensitivity to CP phase and MH

5 years ν + 5 years anti-ν



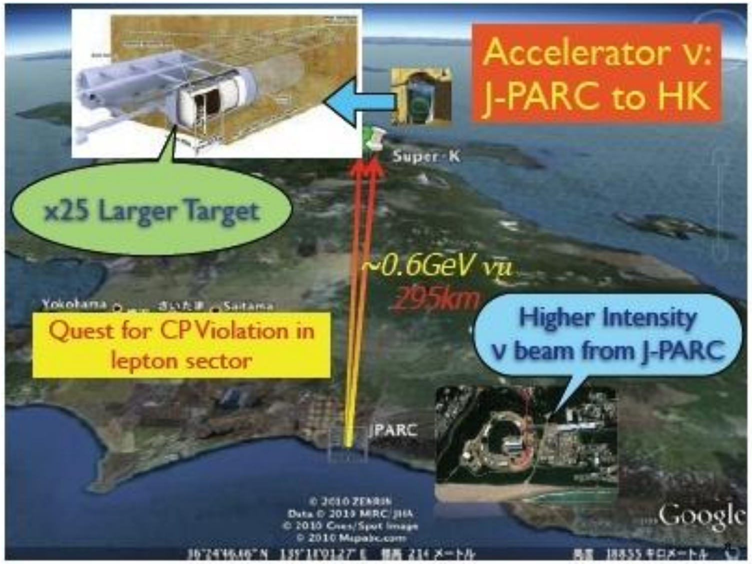




T2HK

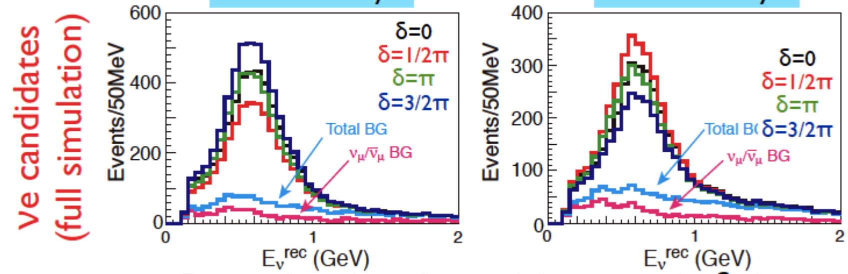
$\nu_\mu \rightarrow \nu_e$

The LBL project in Japan



Example: case of Hyper-K

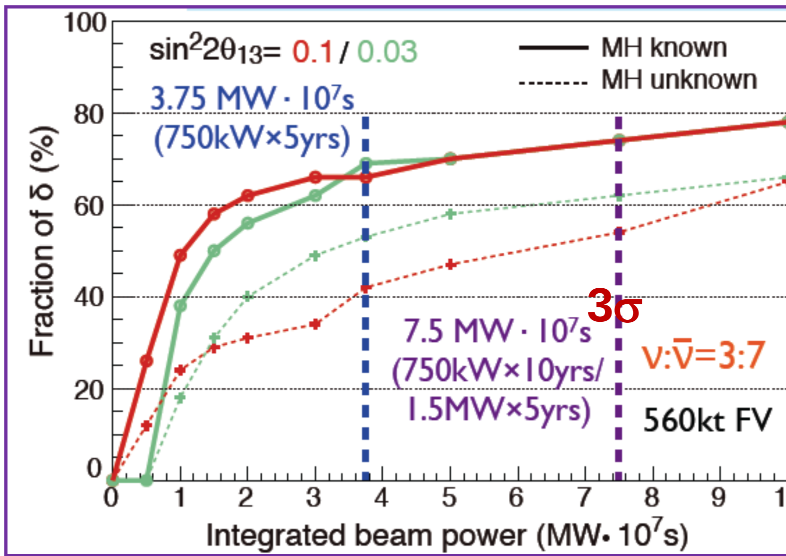
$\sin^2 2\theta_{13}=0.1$



Expected number of ν_e candidate events for $\delta=0$

$\nu_\mu \rightarrow \nu_e$ CC	3606
$\nu_\mu+\bar{\nu}_\mu$ CC	35
$\nu_e+\bar{\nu}_e$ CC	880
NC	649

$\nu_\mu \rightarrow \nu_e$ CC	2339
$\nu_\mu+\bar{\nu}_\mu$ CC	23
$\nu_e+\bar{\nu}_e$ CC	878
NC	678

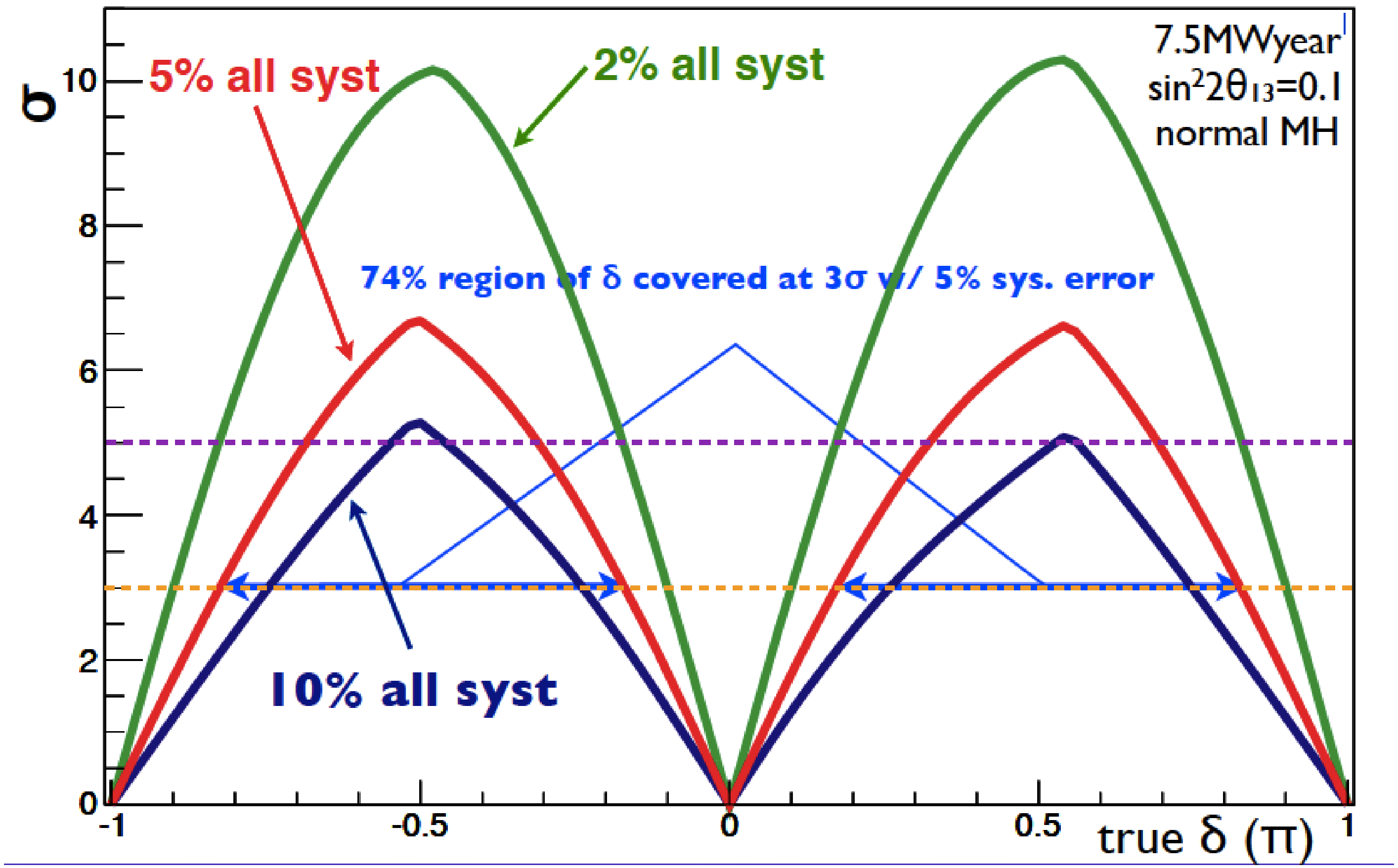


For $\sin^2 2\theta_{13}=0.1$

Integ. power ($MW\times 10^7 s$)	Mass hierarchy	
	known	unknown
3.75	69%	42%
7.5	74%	54%

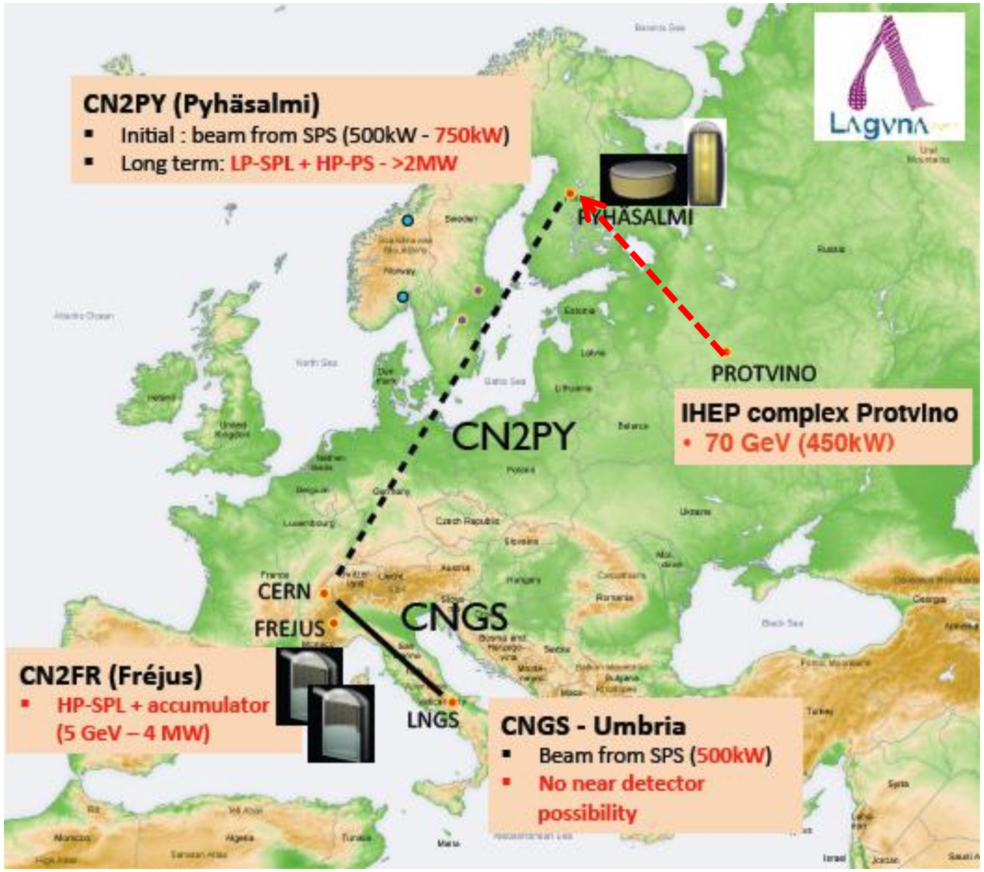
T2HK: CPV discovery potential

MH is known !

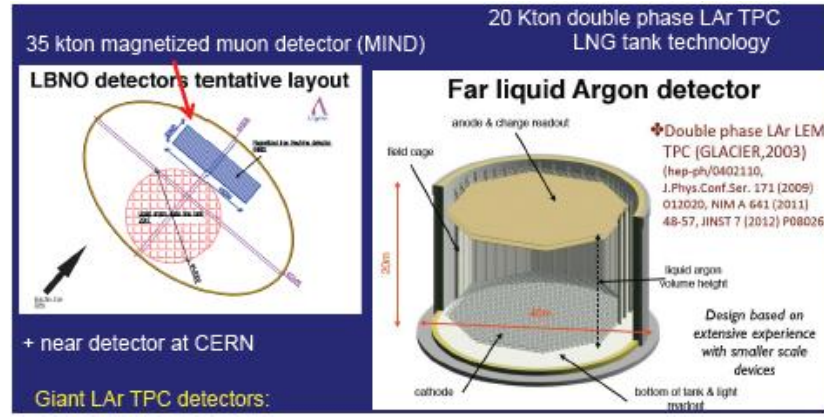


High sensitivity to CP phase for systematics < 5%

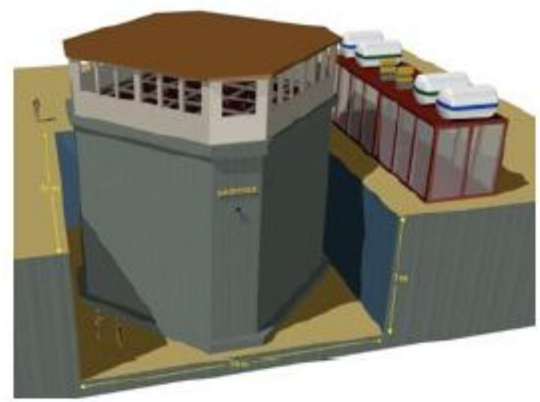
LAGUNA/LBNO



Far detector



R&D: LAr demonstrator at CERN



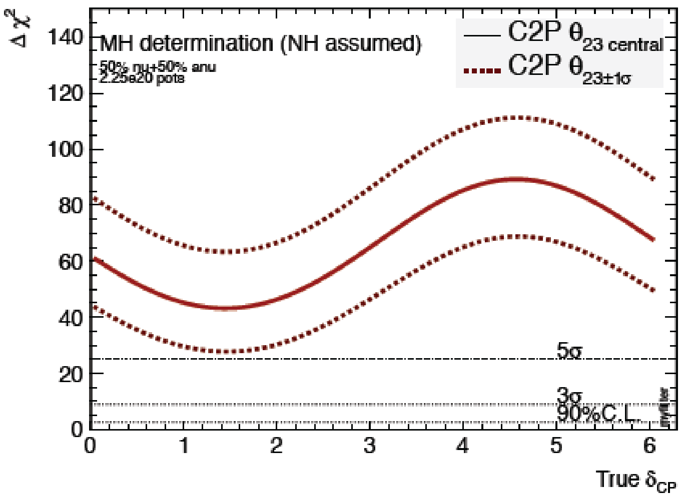
CERN – Pyhasalmi 2300 km
Protvino – Pyhasalmi 1160 km

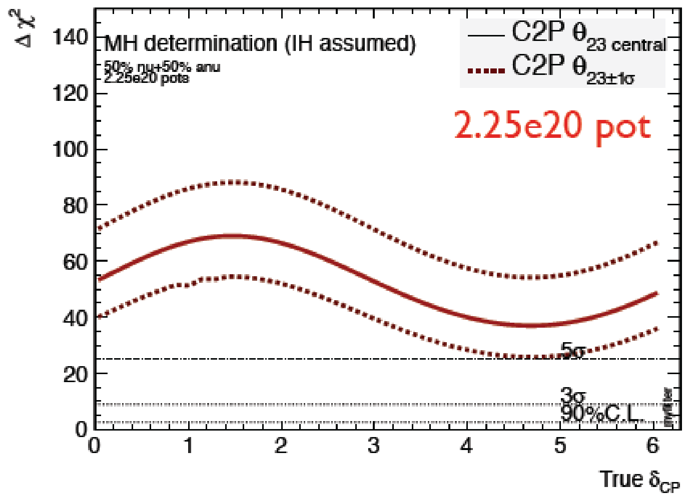
→ 1[st] and 2[nd] oscillation maximum

LAGUNA/LBNO sensitivity

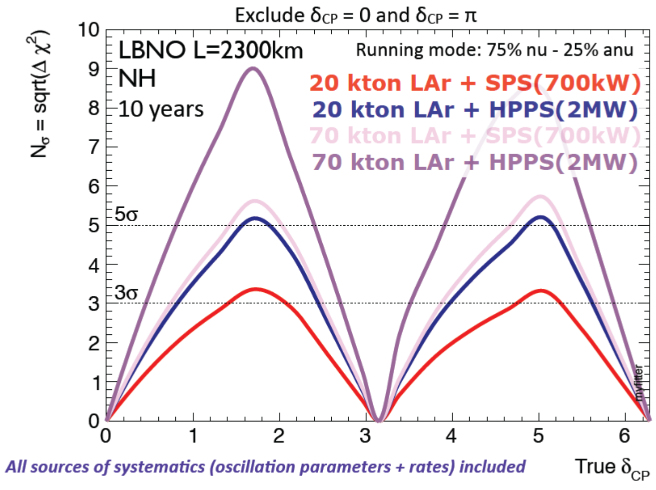
More than 5σ determination of MH for all δ values

A.Rubbia, talk at Lomonosov Conference 2013

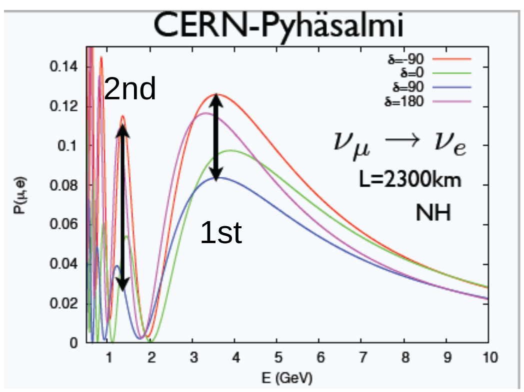


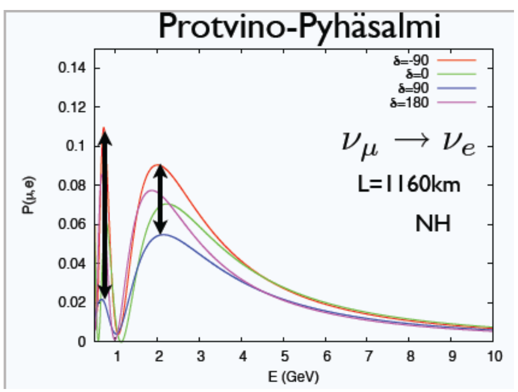


Sensitivity to δ



Measurement in 1st and 2nd oscillation maxima





Conclusion

- **2011-2013**
  - **θ_{13} is measured and large**

    Open very exiting perspectives in neutrino oscillations

  - **Observation of $\nu_\mu \rightarrow \nu_e$ appearance at 7.5 σ significance**

    A new type of transformation among neutrinos has firmly established

- **Near future:**
  - **precision measurements of neutrino mixing parameters**
  - **an initial search for CP violation in lepton sector**
  - **(sterile neutrino)**

- **Far future:**
  - **determination of neutrino mass hierarchy**
  - **measurement of CP violation in lepton sector**