Review of accelerator based neutrino oscillation results and implication in astro-nuclear physics

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Neutrino and Dark Matter in nuclear physics 2012 (NDM12)

Contents

- Review latest results reported in Neutrino 2012 conference last week
- $\nu_\mu \rightarrow \nu_e$ appearance measurement: θ_{13}
- CP violation, mass hierarchy
- Implication in astro-nuclear
- Future prospects

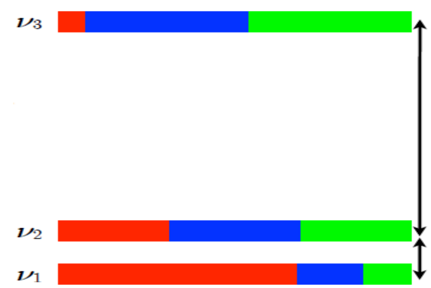
Neutrino oscillation

Neutrino mixing expressed by 3x3 PMNS matrix : $\left(\nu_e, \nu_\mu, \nu_\tau\right)^T = U_{PMNS}\left(\nu_1, \nu_2, \nu_3\right)^T$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Oscillation parameters :

- Two mass splitting $\Delta m_{21}^2, \Delta m_{32}^2$
- Three mixing angle $\theta_{12}, \theta_{23}, \theta_{13}$
- One CP violation phase δ_{CP}



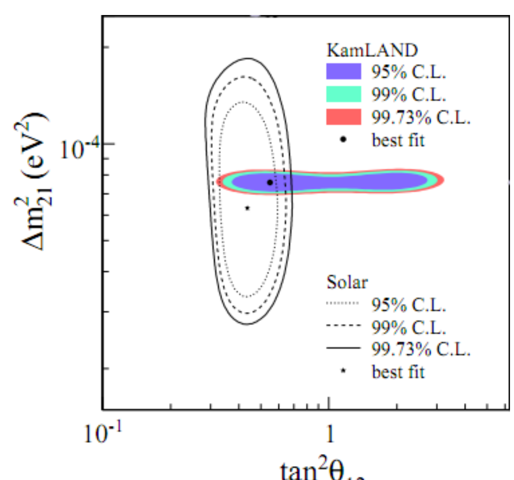
hierarchy

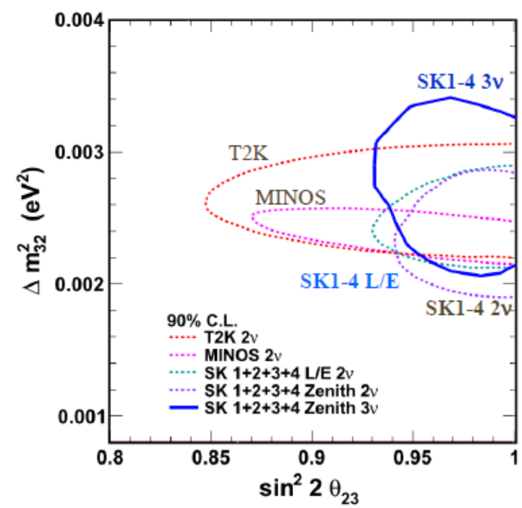
Δm_{32}^2 >0 ? or <0 ?

Δm_{21}^2

Δm_{21}^2 and 12 mixing angle measured by solar nu and KAMLAND

Δm_{32}^2 and 23 mixing angle by atmospheric and accelerator experiments

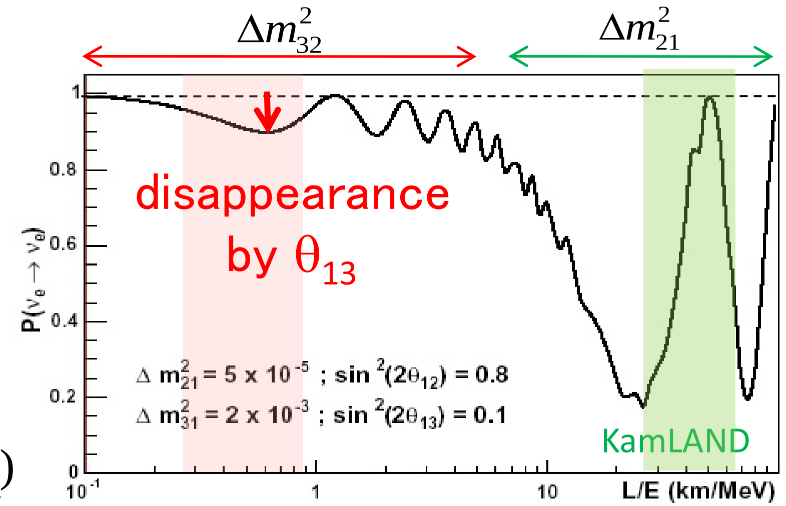




13-mixing angle (θ_{13}) measurements

- Using reactor neutrino:
  - Observe small disappearance of anti electron nu. from reactor
  - $\langle E_\nu \rangle$ ~ 4 MeV, Δm_{32}^2 oscillation at L ~ O(1km)

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \underline{\sin^2(2\theta_{13})} \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right) + \underbrace{O(10^{-3})}_{\Delta m^2_{21}\text{ term}}$$

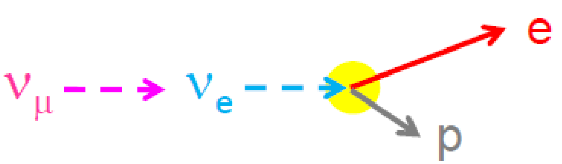


- Using accelerator neutrino:
  - Observe electron appearance via $\nu_\mu \rightarrow \nu_e$ oscillation
  - Leading term θ_{13}, sub-leading term by CP, matter effect, solar term

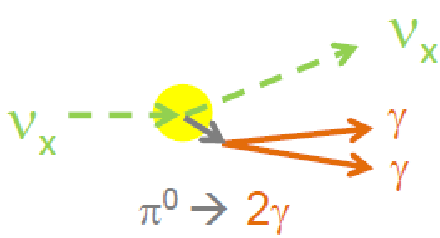
$$P(\nu_\mu \to \nu_e) = \underline{\sin^2(2\theta_{13})} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m_{32}^2 L}{4E_\nu}\right) + \text{"sub-leading term"}$$

ν_e appearance in accelerator exp.

- High purity and high power ν_μ beam from pion decay
  - Contamination of intrinsic electron neutrino : < ~1 %
- Two detectors scheme (Near / Far)
  - Measure neutrino flux, cross section, BG before oscillation
- L and E_ν optimized to be osc. maximum: $\sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) \sim 1$
- Signal events
  - Charged-current (CC) ν_e events
  - Identified by EM shower

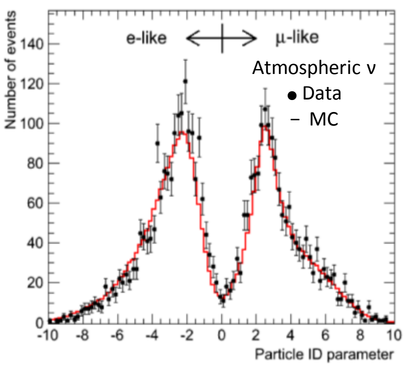


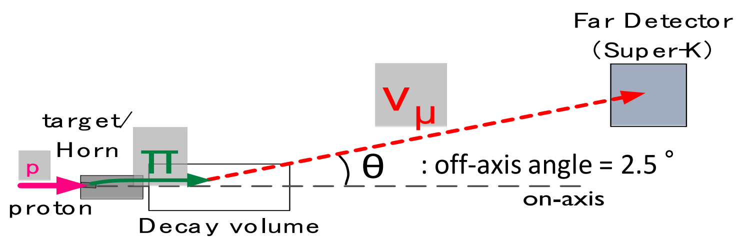
- Background events
  - CC ν_μ events --- rejected by PID
  - NC hadronic events (π^0)
  - Intrinsic beam ν_e

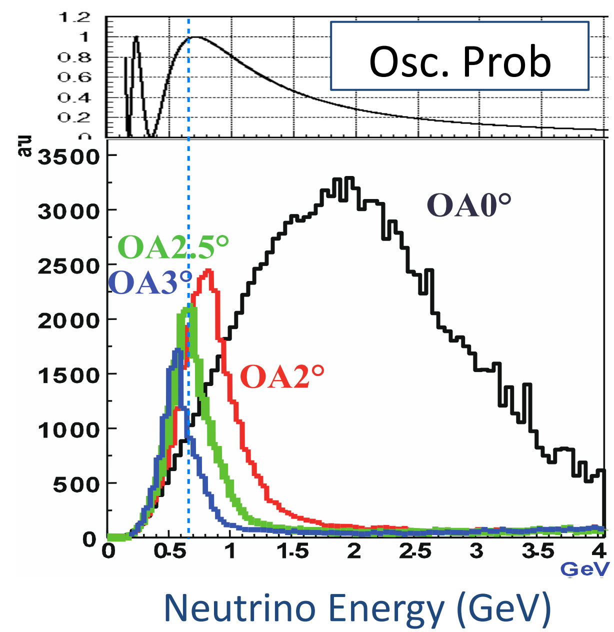


T2K experiments

T. Nakaya @ NU2012





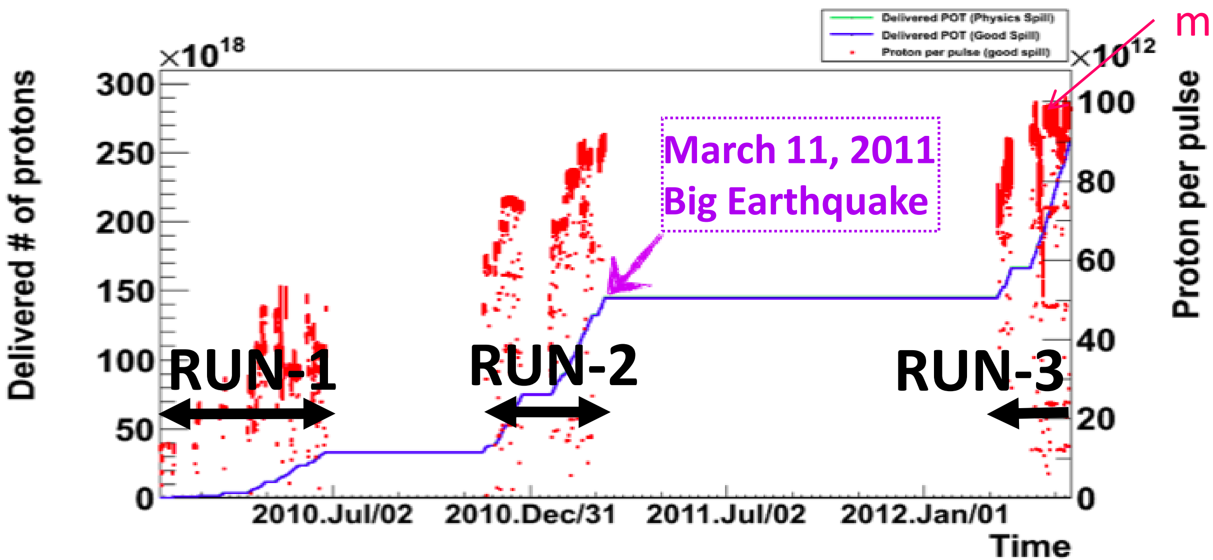


- J-PARC accelerator: high power and high quality nu. beam
- Baseline length L=295km
- Good S/N ratio designed for ν_e measurement
  - Narrow band off-axis beam (E~600 MeV)
  - Far detector: good particle ID (~99%), π^0 rejection (95%)
- J-PARC facility recovered from damage of Earthquake, and nu beam resumed in Dec. 2011

T2K data update

T. Nakaya @ NU2012

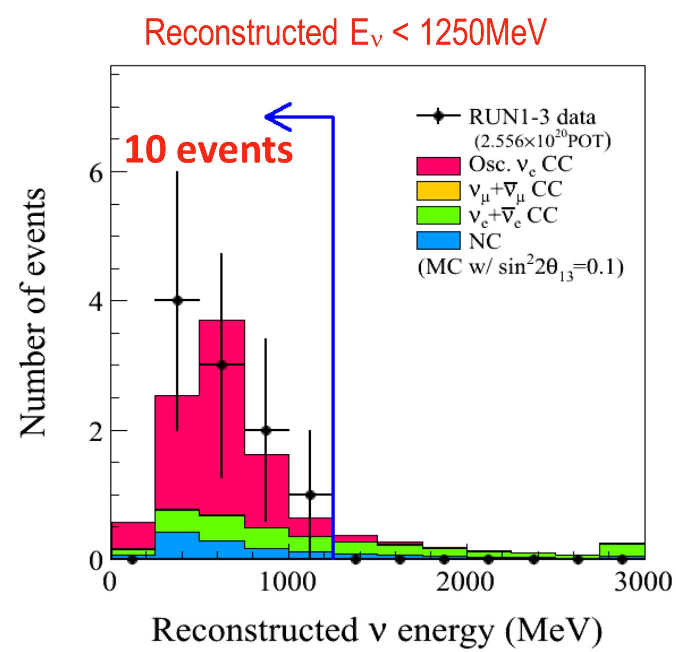
max. 200 kW



- Analysis by May 15th, 2012
- 2.56×10^{20} POT (Protons On Target)
  - RUN-1 (2010): 0.32×10^{20} POT
  - RUN-2 (2010-2011): 1.11×10^{20} POT
  - RUN-3 (2012): 1.12×10^{20} POT
    - including 0.21×10^{20} POT with 200kA horn operation (13% flux reduction at peak)

- Selection cuts : single-ring electron-like events, π^0 rejection, and energy cut
- 10 ν_e events are observed
- Exp. BG: 2.73 $\pm$0.37 (sys) evts
- Prob. 10 evts or more: 0.08% (3.2 σ)

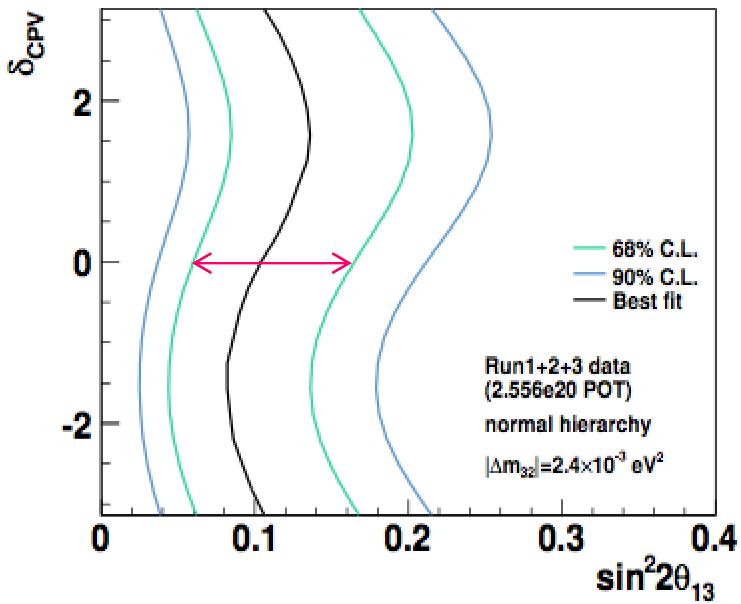
→ Evidence for electron nu. appearance



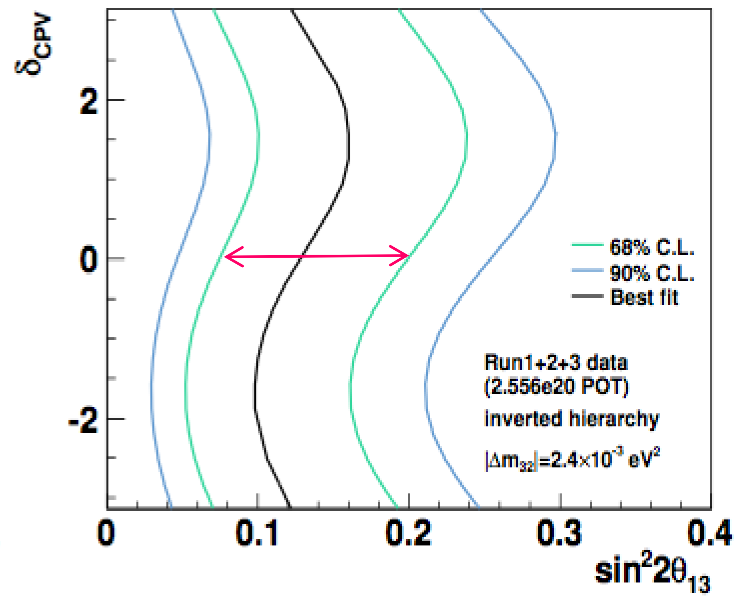
T2K ν_e result

T. Nakaya @ NU2012

normal hierarchy



inverted hierarchy



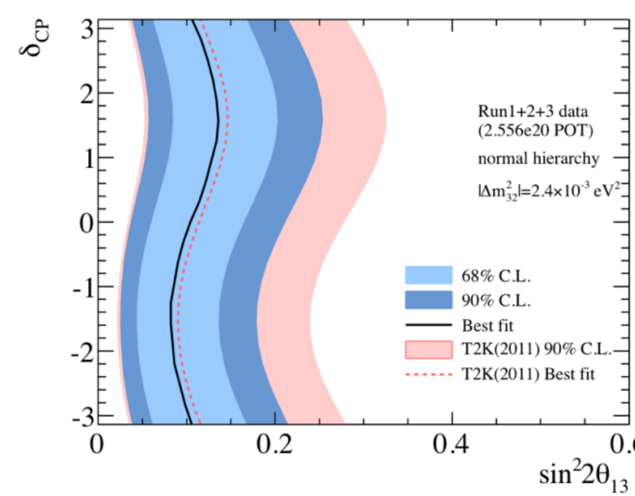
- 1σ (68%) allowed region (δ_{CP}=0):

$$\sin^2 2\theta_{13} = 0.104 \,{}^{+0.060}_{-0.045} \quad \text{(NH)}$$

$$\sin^2 2\theta_{13} = 0.128 \,{}^{+0.070}_{-0.055} \quad \text{(IH)}$$

($\theta_{23}=\pi/4$)

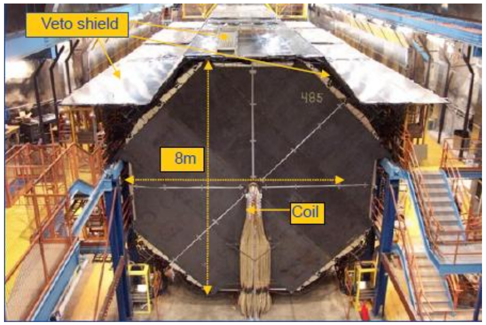
- Consistent with previous result in 2011

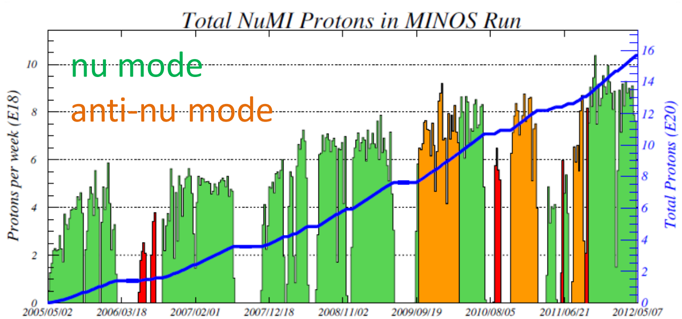


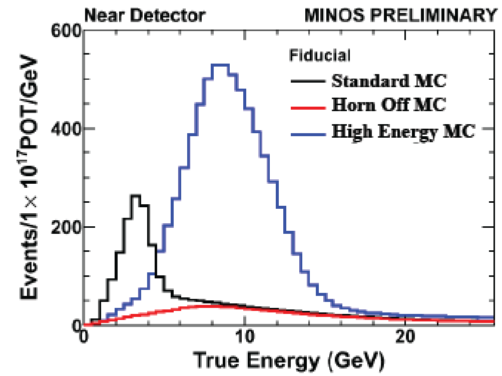
MINOS

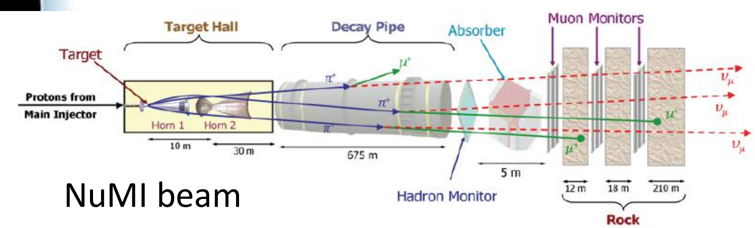
R. Nichol @ NU2012

Far Detector









NuMI beam

- Baseline length = 735 km
- NuMI beam at FermiLab
- 120 GeV proton injection,
  350 kW typical beam power
- Peak energy ~ 4 GeV at LE mode
- nu and anti-nu beam mode

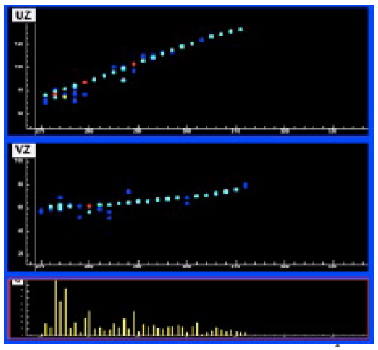
- Far detector: 5.4 kton magnetized
- tracking detector consists of iron and scintillator planes

MINOS ν_e selection

R. Nichol @ NU2012

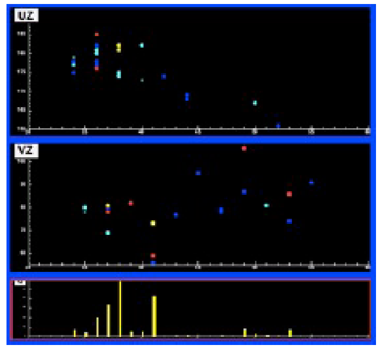
Monte Carlo

ν_μ CC Event



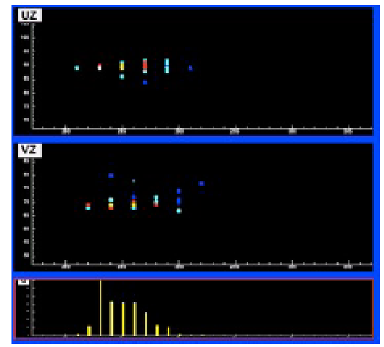
long μ track & hadronic activity at vertex

NC Event



short event, often diffuse

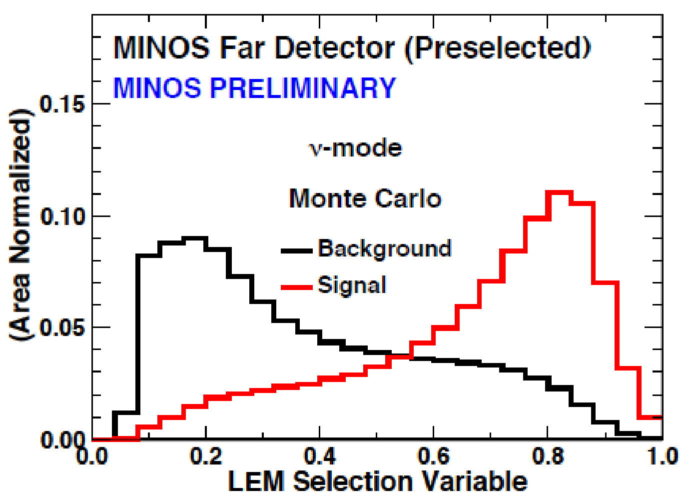
ν_e CC Event

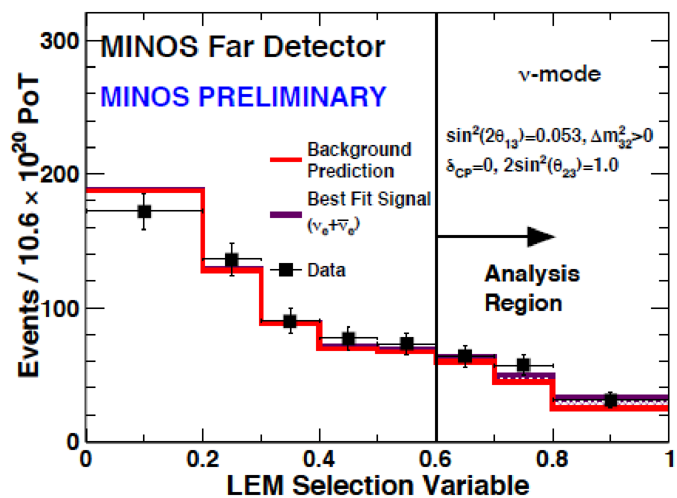


short, with typical EM shower profile

ν_e events discriminated by event matching technique

Events selected for signal-like region, and see excess in data





ν mode:
152 events
(BG exp. 128.6 ev)

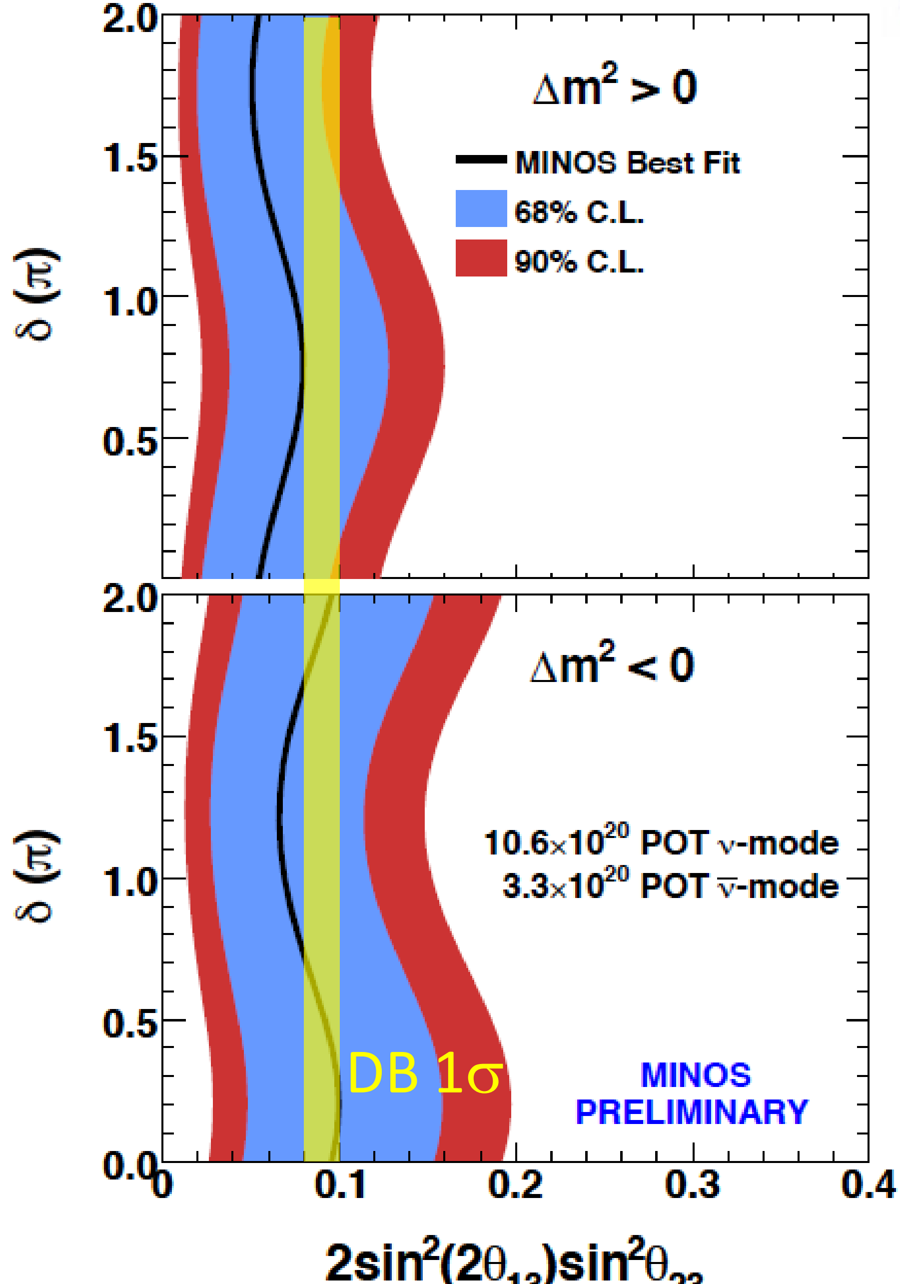
anti- ν mode:
20 events
(BG exp. 17.5 ev)

Observed marginal excess

MINOS ν_e result

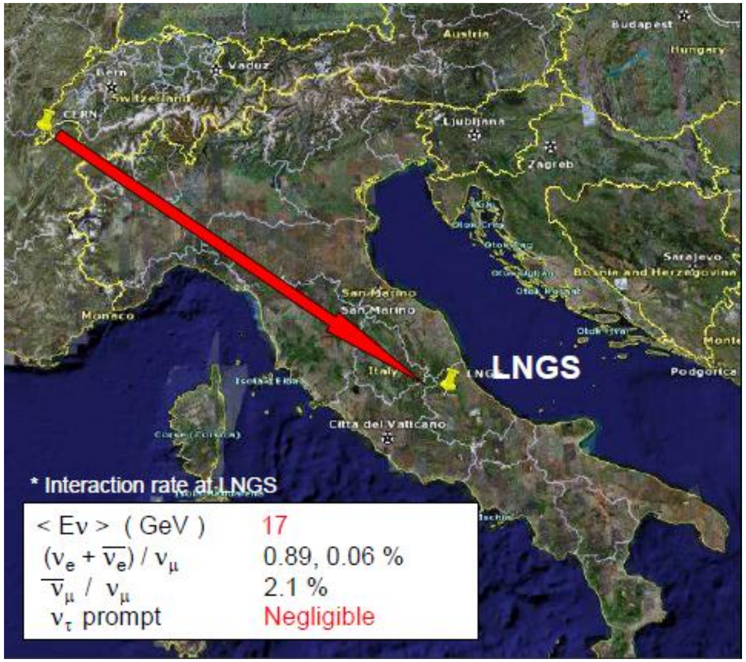
R. Nichol @ NU2012

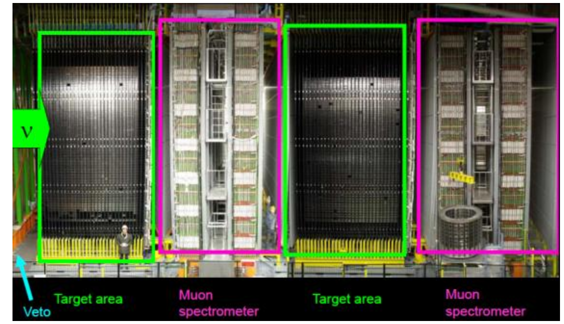
- disfavor θ_{13}=0 at 96% C.L. for normal hierarchy, δ_{cp}=0
- With reactor result, inverted hierarchy slightly preferred, but not significant (-2ΔlnL=0.20)

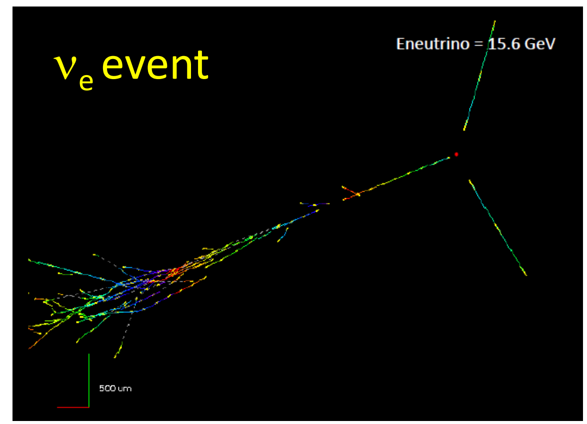


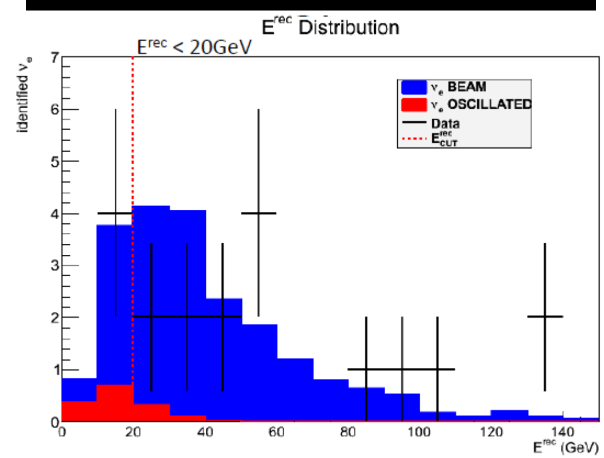
OPERA ν_e (preliminary)

M. Nakamura @ NU2012





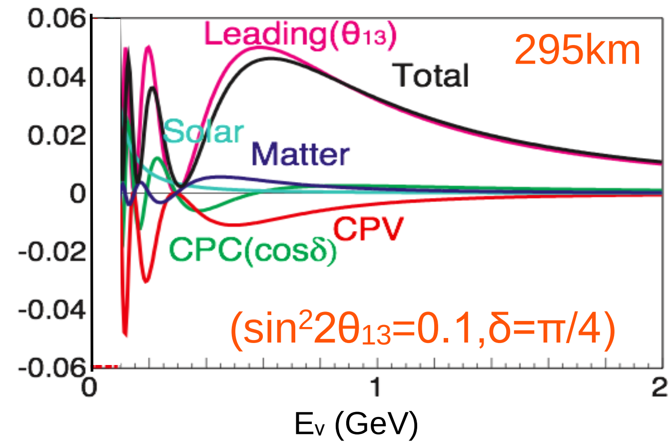




- CERN → LNGS , 17 GeV, L=735km
- Emulsion + muon spectrometer
- 19 events observed. After eliminating E>20 GeV, 4 ν_e candidates event
- 1.1 (3.7) evnts signal (BG) expected

Beyond θ_{13}: leptonic CP violation

- non-zero 13 mixing angle θ_{13} opened the window to probe CP violation phase (δ_{cp}) by accelerator nu. experiment
  - last unknown parameter in PMNS matrix
  - may give explanation to matter dominated Universe



- $\nu_\mu \rightarrow \nu_e$ osc. probability

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

leading term

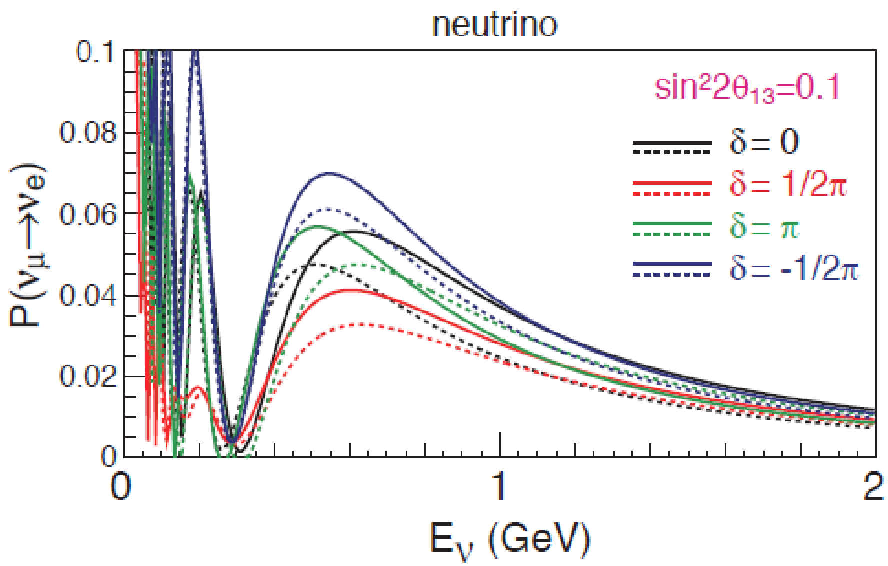
CP violating (flips sign for anti-ν)

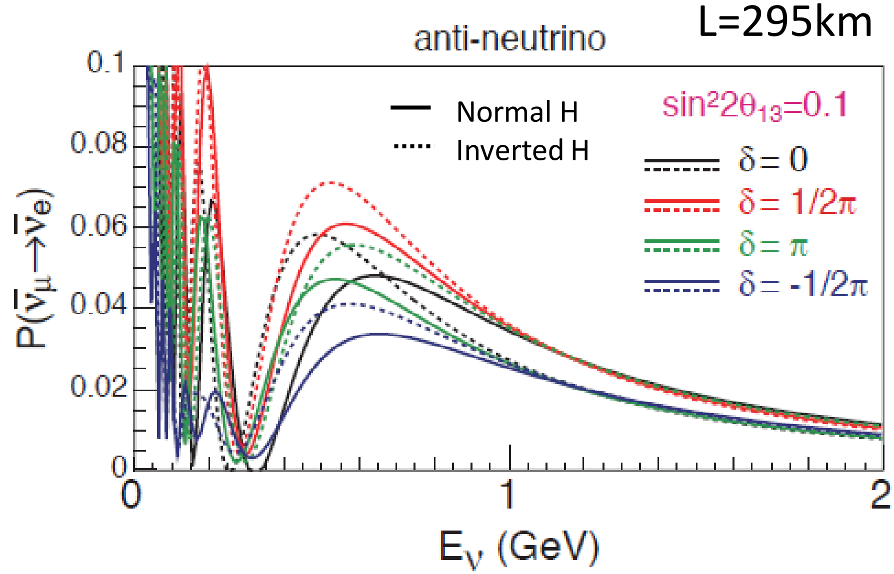
Solar

Matter

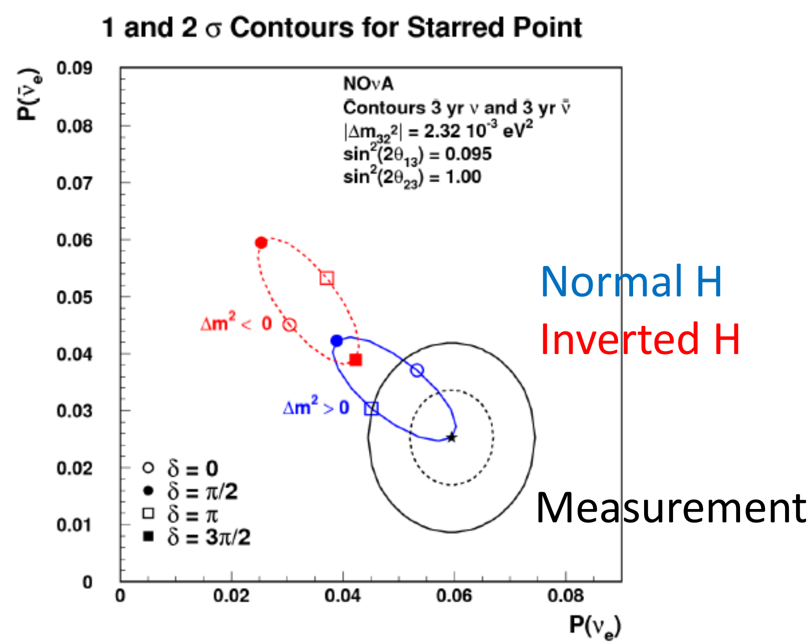
CP violation measurement

L=295km



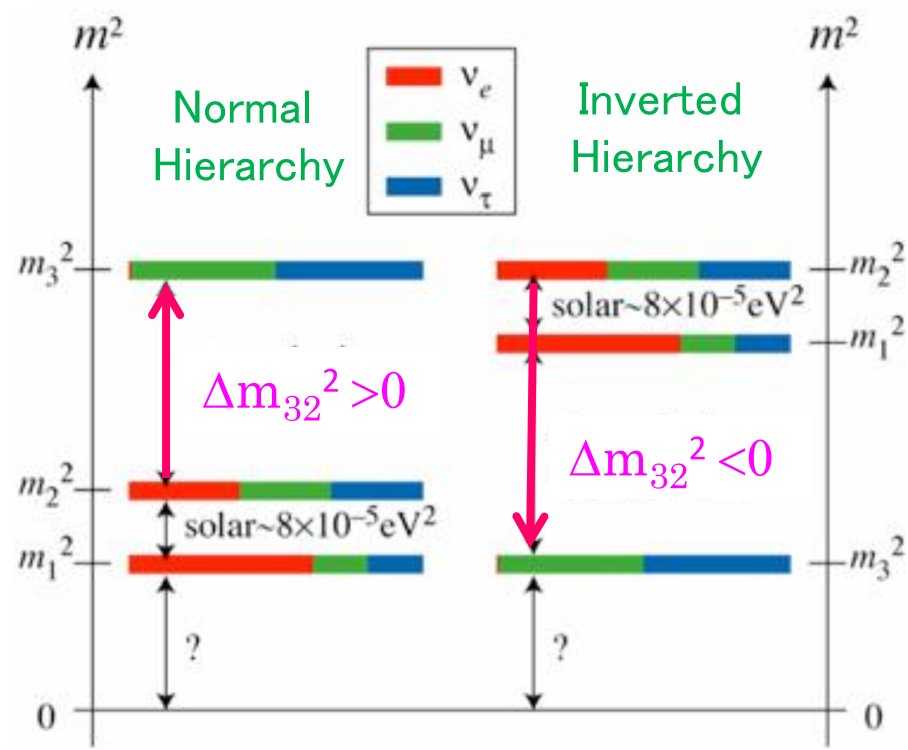


- Measure $P(\nu_\mu \rightarrow \nu_e)$ and $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ using nu and anti-nu beam runs
- Degeneracy problem of mass hierarchy if it is unknown



Mass hierarchy

- Sign of $\Delta m_{32}{}^2$ is unknown
  - only mass square difference can be measured by nu oscillation
- Two possible scenarios:
  - Normal hierarchy
  - Inverted hierarchy
- Help in understanding origin of neutrino mass beyond-SM
- Effective nu mass $m_{\beta\beta}$ > 10 meV for IH ; reachable by DBD experiment



Matter effect

- Mass hierarchy could be distinguished by matter effect which arises when neutrino travels though matter
- Effective 13 mixing angle in matter:

$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + (\cos 2\theta_{13} - a)^2} \qquad a = 2\sqrt{2} E_\nu G_F N_e / \Delta m^2$$

- Resonance occurs when a ~ $\cos(2\theta_{13})$

$$\sin^2 2\theta_{13}^m \sim 0.1 \rightarrow 1$$ if condition matches (nu. energy, electron density)

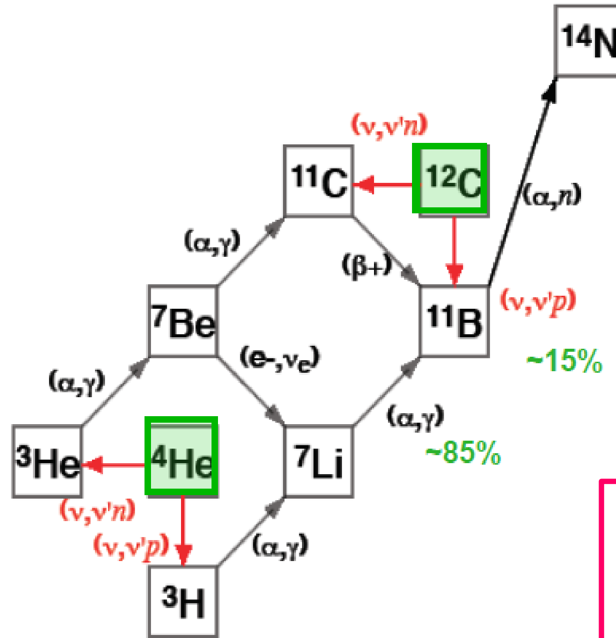
- Oscillation suppressed for anti-nu: a → -a
- Opposite situation for Inverted: $\Delta m^2 \rightarrow -\Delta m^2$

	ν	anti-ν
Normal H	Enhance	Suppress
Inverted H	Suppress	Enhance

θ13, MH in SN nucleosynthesis

PRD 85 105023 (2012)

- Synthesis of ^{11}B and ^{7}Li via ν-process in Supernovae is sensitive to neutrino mass hierarchy
- θ_{13} resonance should occur in C/O layer (E_ν~O(10MeV), ρ~10^3 g/cm^3)
- In case of inverted, production of ^{7}Li and ^{11}B are increased by anti- ν_e charged current reaction
- ^{7}Li / ^{11}B ratio is expected to be affected
- See next talk by Prof. Kajino



$^{4}\mathrm{He}(\nu,\nu' p)^{3}\mathrm{H}$

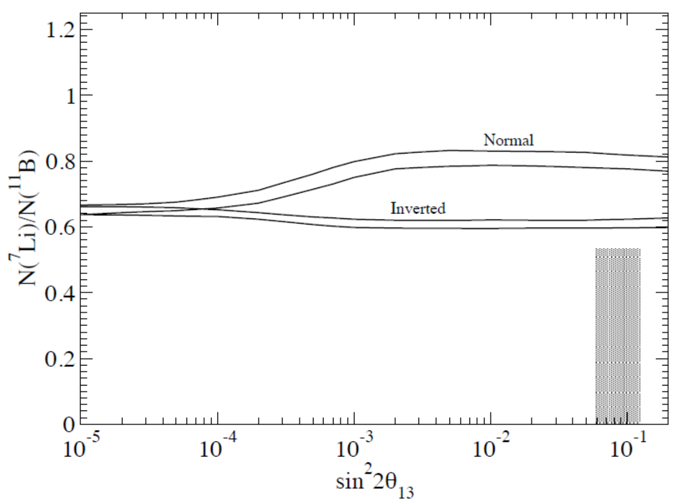
$^{4}\mathrm{He}(\nu,\nu' n)^{3}\mathrm{He}$

$^{12}\mathrm{C}(\nu,\nu' p)^{11}\mathrm{B}$

$^{4}\mathrm{He}(\nu_e,\mathrm{e}^{-} p)^{3}\mathrm{He}$

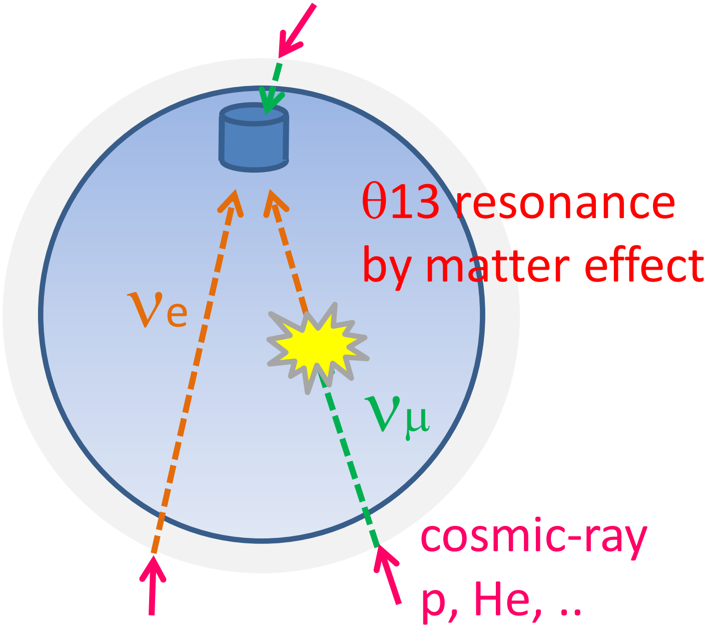
$^{12}\mathrm{C}(\nu_e,\mathrm{e}^{-} p)^{11}\mathrm{C}$

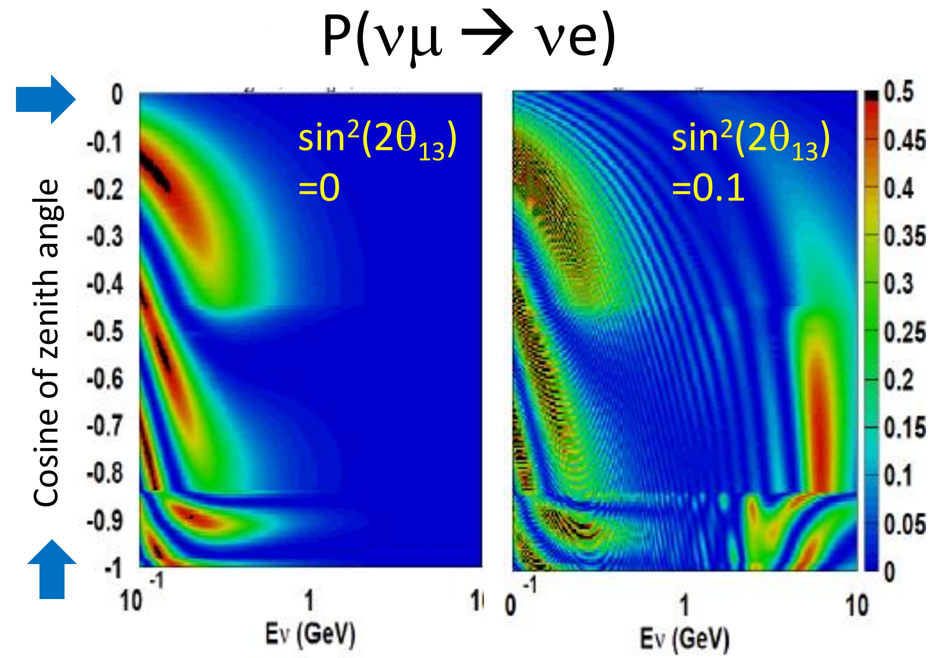
$$\boxed{\begin{array}{l} ^{4}\mathrm{He}(\bar{\nu}_e,\mathrm{e}^{+} n)^{3}\mathrm{H} \\ ^{12}\mathrm{C}(\bar{\nu}_e,\mathrm{e}^{+} n)^{11}\mathrm{B} \end{array}}$$



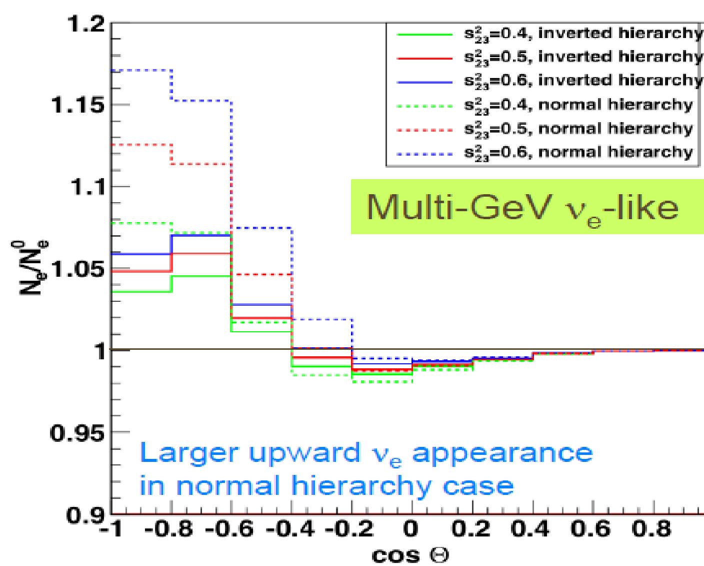
Matter effect in atmospheric ν

Y. Itow @ NU2012





- $\nu_\mu + \overline{\nu}_\mu : \nu_e + \overline{\nu}_e \sim 2 : 1$
- multi GeV neutrinos should be affected by θ_{13} resonance inside Earth ($\rho \sim O(10)$ g/cm^3)
- ν_e enhancement expected in upward direction, depending on MH
  - ~ 10 (5) % effect for NH (IH)



Atm. ν: Super-K result

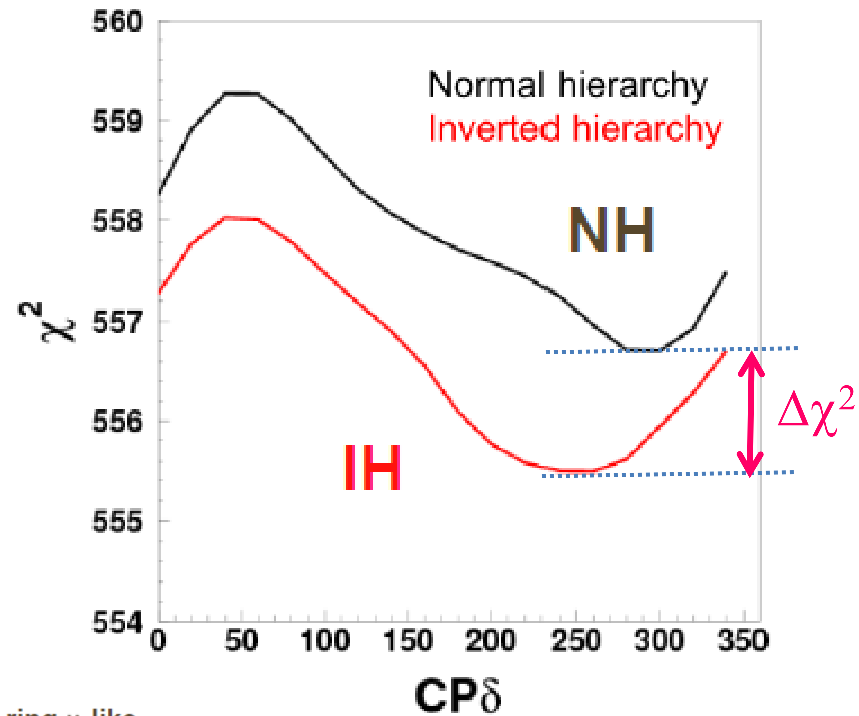
Y. Itow @ NU2012

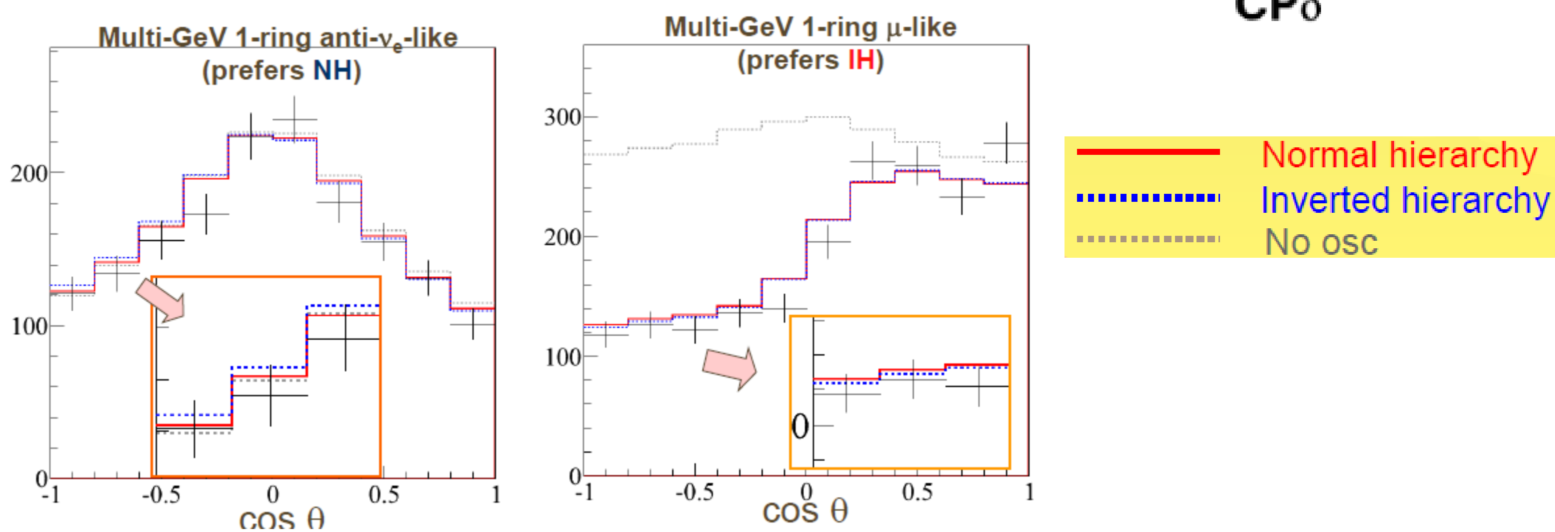
- Fit SK data with full 3-flavor scheme with reactor θ_{13} constraint
- Result is not conclusive; no strong preference

$$\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = 1.2$$

(sensitivity =0.4)

- Need more data and analysis improvement





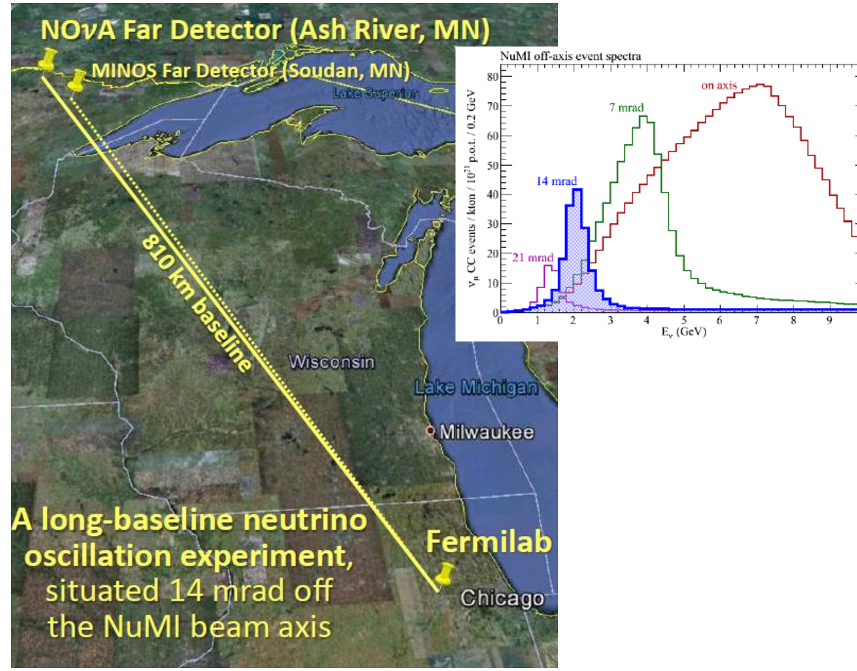
Future prospects

Nova

R. Patterson @ NU2012

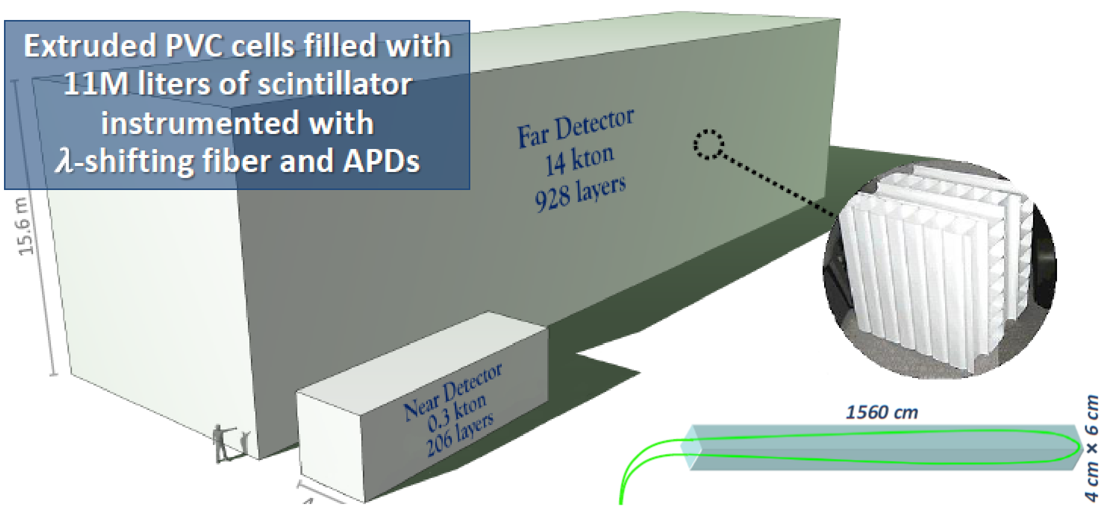
Near future experiment coming soon :

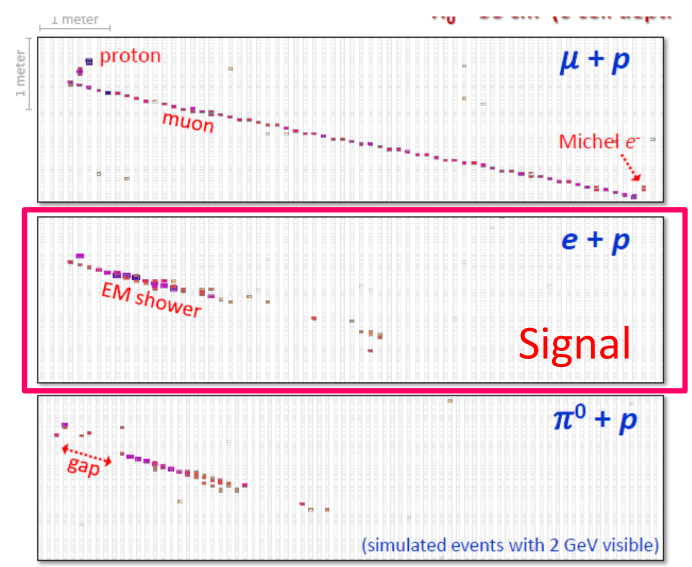
- Upgrade NuMI beam (350~700 kW)
- Baseline ~810 km, off-axis (14mrad)
- Sharp energy peak at ~ 2 GeV



Far detector:

- Full active, fine grained
- 14 kton, 11 M liters of scintillator

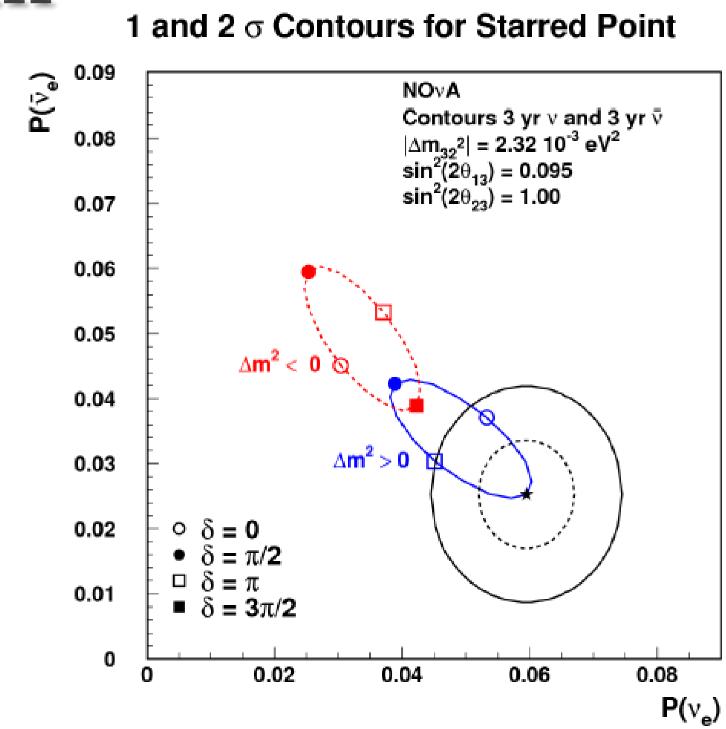




Nova: sensitivity and plan

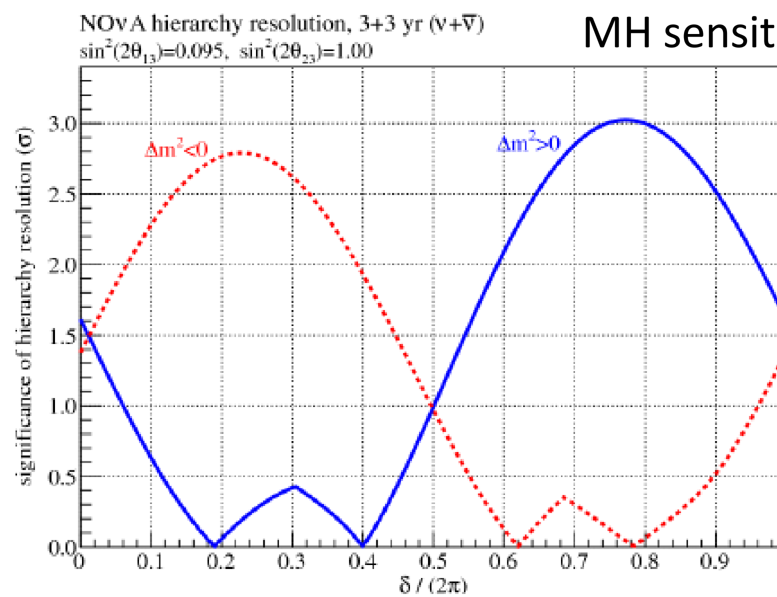
R. Patterson @ NU2012

- 5 σ detection of $\nu_\mu \rightarrow \nu_e$ by 1 year
- Measure $P(\nu_\mu \rightarrow \nu_e)$ and $P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$ with nu and anti-nu beam
- Max. ~3 σ MH sensitivity assuming 3 yr ν + 3 yr anti-ν with 6e20 p.o.t./yr
- Sensitivity depend on δ_{cp} and MH



- Experiment start from next year with partial detector
- Far detector construction will be completed in May 2014

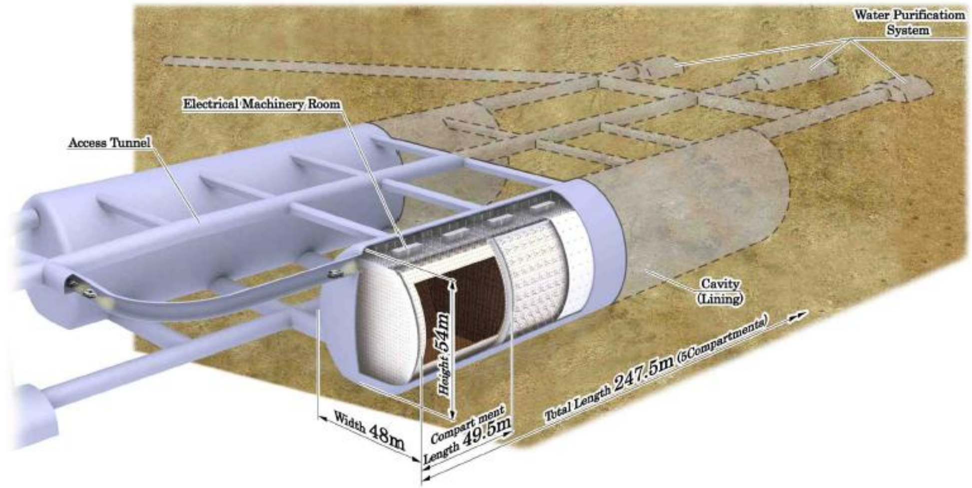
MH sensitivity



Hyper-Kamiokande

M. Yokoyama @ NU2012

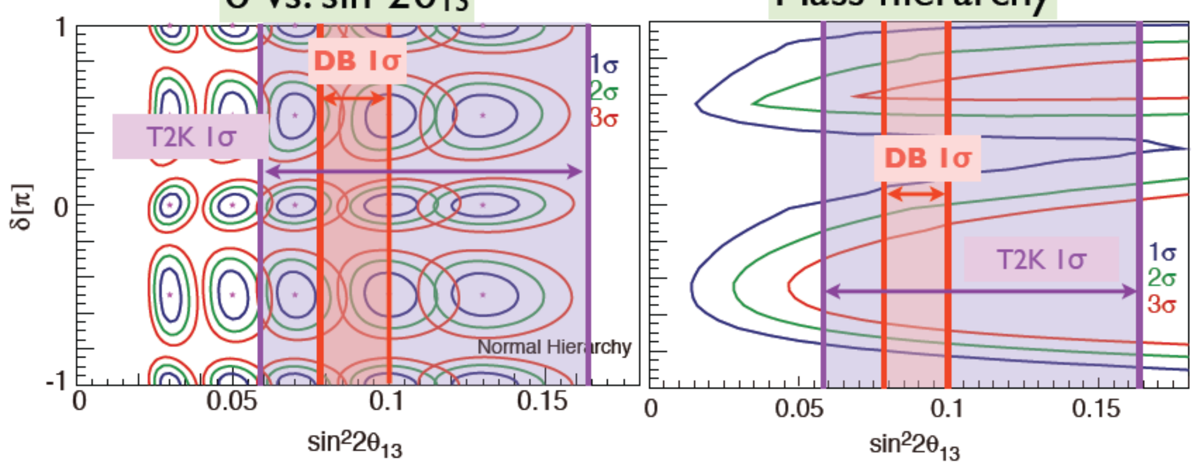
- Upgrade T2K experiment
- Fiducial volume: x25 of Super-K
- J-PARC beam → 750 kW
- LBL measurement:
  good resolution for CP and MH
- > 3σ MH discrimination
  by atmospheric nu



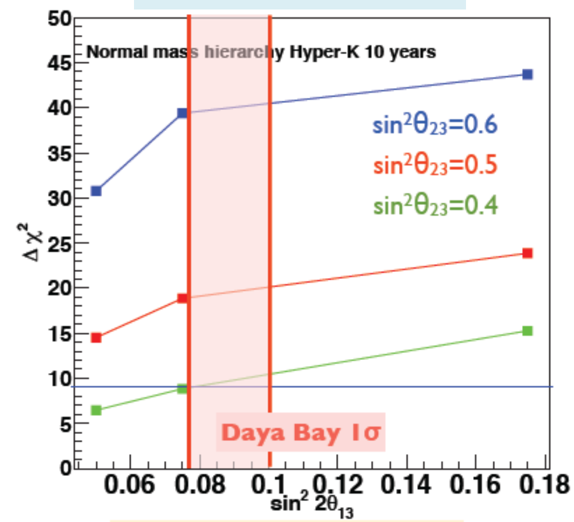
CP and MH measurement by accelerator

0.75MW×10yrs (3yrs ν, 7yrs $\bar{\nu}$)

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



MH by atm. nu



>3σ with 5-10 years

Summary

- $\nu_\mu \rightarrow \nu_e$ oscillation measurement by accelerator experiment
  - T2K achieved evidence of electron appearance
  - MINOS: consistent with $\sin^2(2\theta_{13}) \sim 0.1$
- Non-zero θ_{13} opened the window to measure CPV and MH by accelerator experiment
- θ_{13} and MH give significant impact on astro-physics
  - θ_{13} resonance in SN nucleosynthesis and atmospheric neutrinos
- Future experiments are going to be undertaken
  - Nova : CP and MH could be measurable depending on parameter
  - Hyper-K : good sensitivity for CP and MH by LBL and atm. ν