Determining the Neutrino Mass Hierarchy with MINOS

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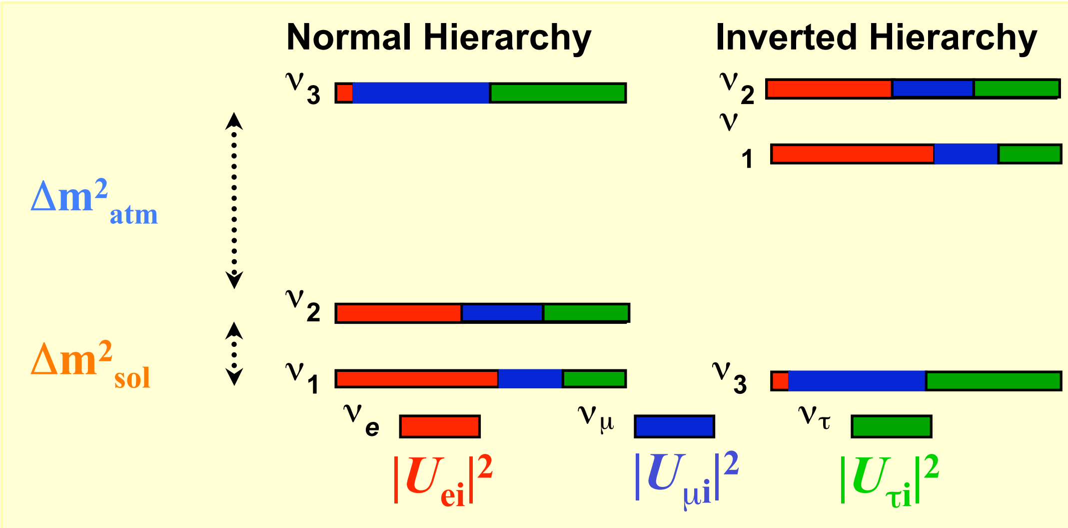
Outline

- Neutrino oscillations in matter
- Matter induced neutrino-antineutrino asymmetry as a tool to determine the neutrino mass hierarchy
- Measuring the mass hierarchy at MINOS:
  - MC study
  - Results
- Summary

Neutrino Mass Spectrum

(3 mass eigenstates - assume no $\nu_{sterile}$)



Two mass splittings:

Large (Δm^2_{atm}):

Atmospheric (up-down asymmetry)

Long baseline

Small (Δm^2_{sol}):

Solar + reactor

- Solar data suggests $|U_{e2}|^2 \sim 1/3$, and thus $|U_{e1}|^2 \sim 2/3$ (unitarity and small $|U_{e3}|^2$).
- Also, data suggests $\nu_\mu \rightarrow \nu_\tau$ dominant at Δm^2_{atm} and maximal mixing angle,

$|U_{\mu i}|^2 \sim |U_{\tau i}|^2$

➡ $|U_{e3}|^2$ is not known (bounded by reactor expts) and neither is the sign of Δm^2_{atm} which determines whether the ν mass hierarchy is normal or inverted.

Matter Effects

- ν propagating in matter interact through W (ν_e only) or Z (all flavors) exchange, giving rise to an interaction potential:

$$V_W = +\sqrt{2}\, G_F\, N_e \quad (W \text{ exchange})$$

- The sign of V is opposite for $\bar{\nu}$

➡ Oscillation probabilities in matter are modified

$$\mathrm{P}_M(\nu_e \to \nu_\mu) = \sin^2 2\theta_M \sin^2(\Delta m_M^2 \frac{L}{4E})$$

$$x \equiv \frac{V_W/2}{\Delta m^2/4E} = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

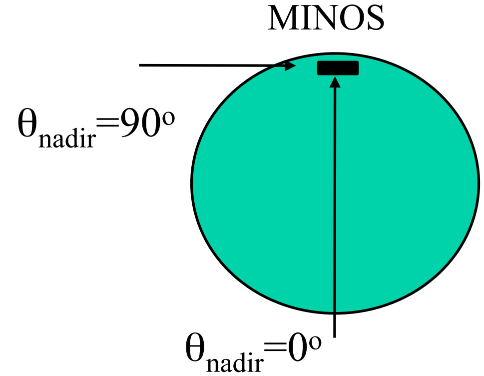
$$\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \qquad \Delta m_M^2 \equiv \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

➡ Matter alters ν, $\bar{\nu}$ oscillations differently

➡ Depending on mass hierarchy, ν or $\bar{\nu}$ oscillations are enhanced (or suppressed) $\Longrightarrow$ matter induced asymmetry

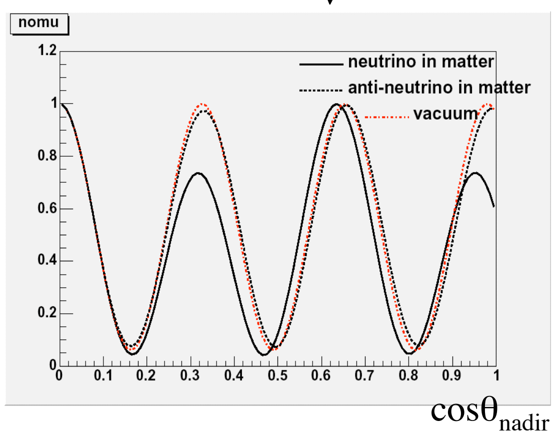
➡ Resonant effects occur

Oscillation Probabilities in Matter (mantle only)

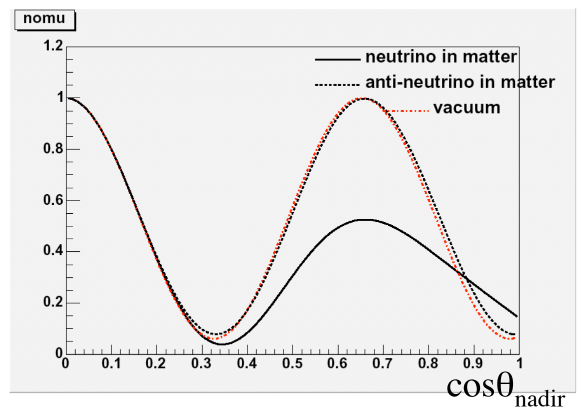


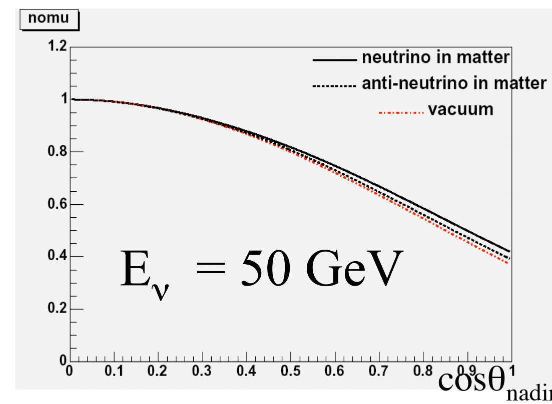
$\nu_\mu \longrightarrow \nu_\mu$

$E_\nu = 5$ GeV

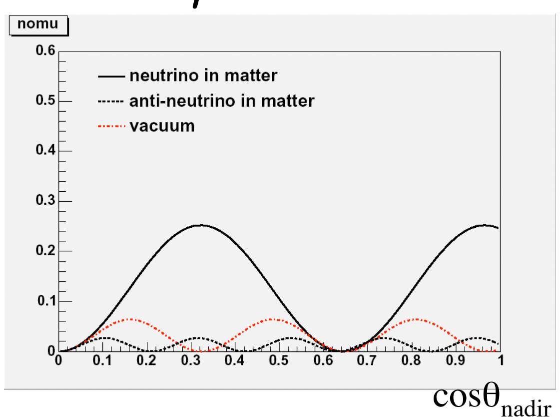


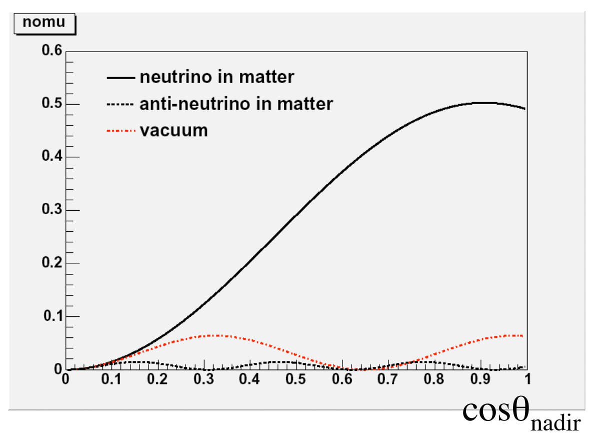
$E_\nu = 10$ GeV

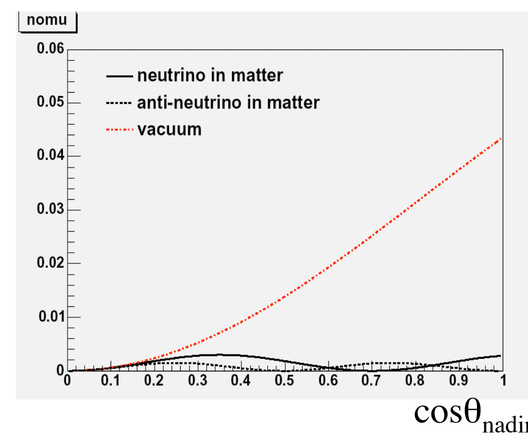




$\nu_e \longrightarrow \nu_\mu$





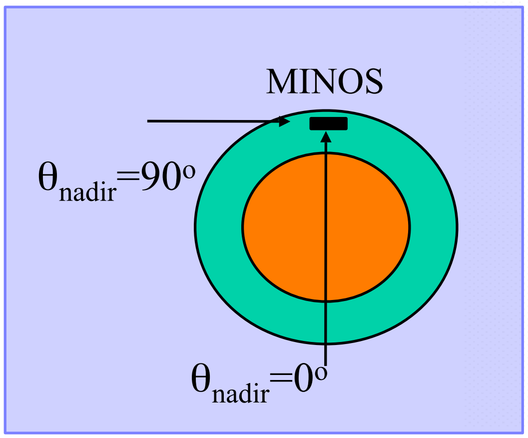


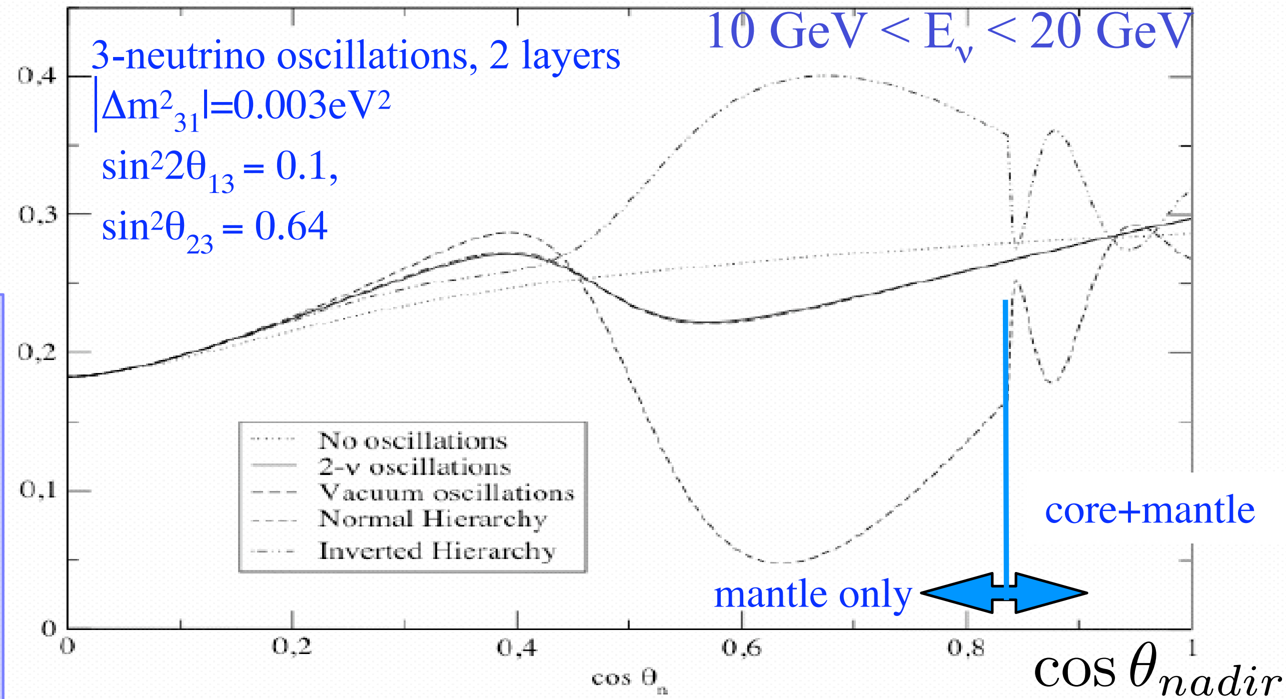
$|\Delta m^2_{31}|=0.003\text{eV}^2$, $\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.64$

Charge Asymmetry-Atmospheric ν

(Ref: J. Bernabeu, S. Palomares, and S. Petcov, hep-ph/0305152)

$$\frac{N(\mu^-) - N(\mu^+)}{N(\mu^-) + N(\mu^+)}$$





- The charge asymmetry for neutrino induced muons can be significantly modified by matter effects and it could carry the signature of the underlying mass hierarchy
- Resonant enhancement occurs for E_ν~7-11 GeV and $\cos\theta_{nadir}$ >0.4

Sensitivity Study

- The MINOS far detector is the first large underground detector with a magnetic field and thus able to discriminate the muon charge

➡ **We explored the possibility of using the atmospheric ν data collected at MINOS to discriminate between normal and inverted hierarchy.**

- We determine the sensitivity using simulated atmospheric neutrino events reconstructed at the MINOS far detector
- We consider different topologies:

Contained vertex ν events: ν interaction occurs in the detector (6,500 years exposure in the MC)
Upward-going μ: ν interaction occurs in rock (2,500 years exposure in the MC)

MC Event Selection

- Select upward going CC ν_μ interactions with muon energy > 2 GeV
- Require one track. Track must:
  - pass the fitter internal consistency checks; have fit $\chi^2/ndf < 2$
  - contain 40% of the total PH in the event

Contained vtx ν:

- Track vertex in fiducial volume (50 cm from edge and 5 planes from SM boundaries
- track crosses >10 planes and is >1 meter long
- $\sigma_{qp}/qp < 0.4$ or track length > 8 m for better charge separation

Up μ:

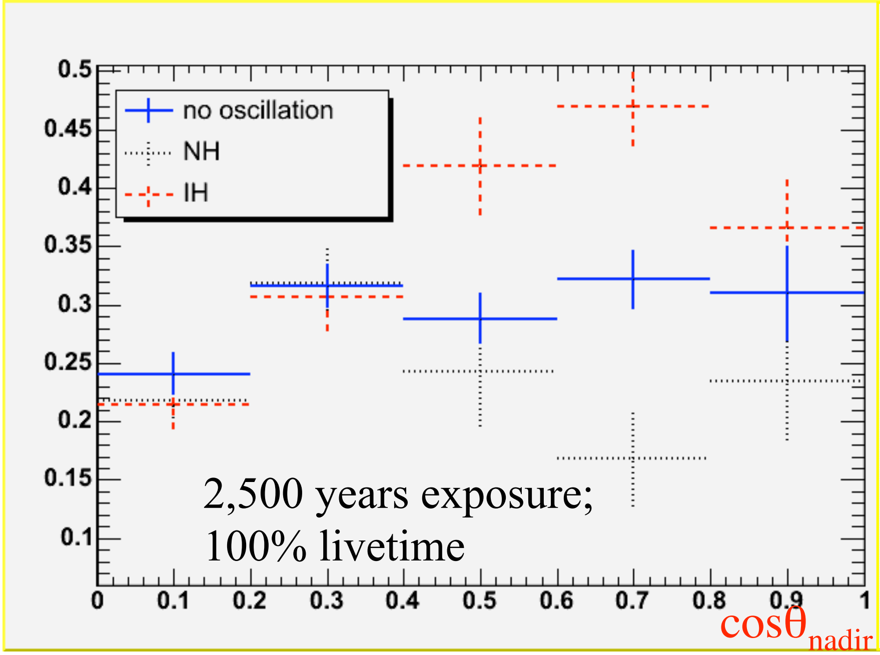
- Track vertex out of fiducial volume (30 cm from edge and 15 cm from SM boundaries)
- Track crosses >20 planes and is >2 meter long
- Track contains 40% of the total number of planes in the event
- χ^2_{line}/ndf (measures deviation of track from straight line)> 10 for better charge separation

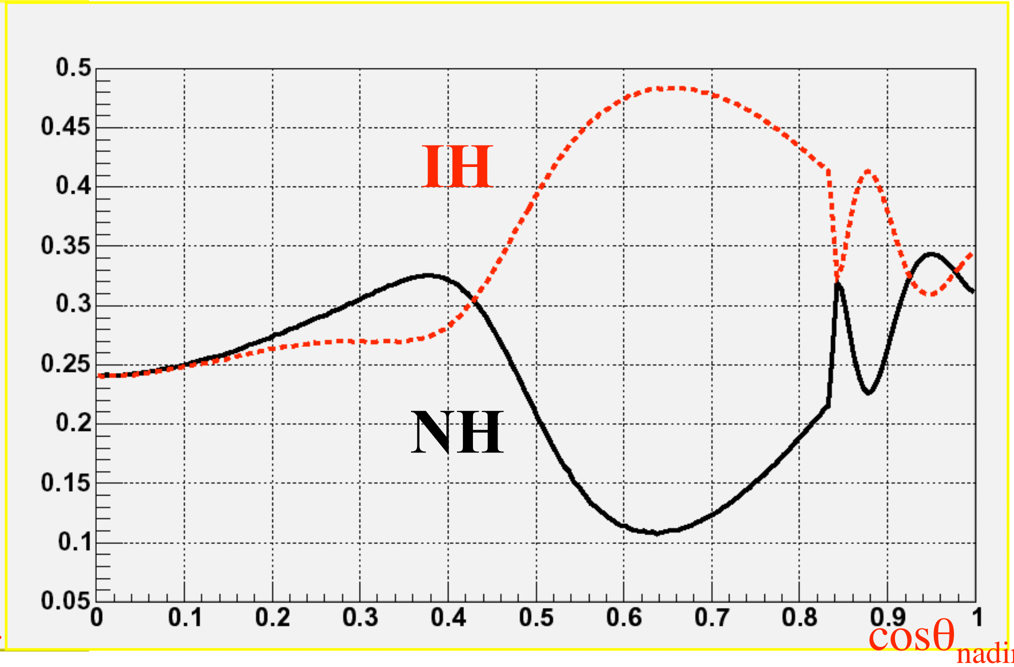
→ No significant improvement in mass hierarchy discrimination with tighter cuts but 15~30% reduction in statistics

Charge Asymmetry - MC

Contained vtx ν with 10 GeV < E_ν < 20 GeV

$|\Delta m^2_{31}|=0.003 eV^2$, $\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.64$

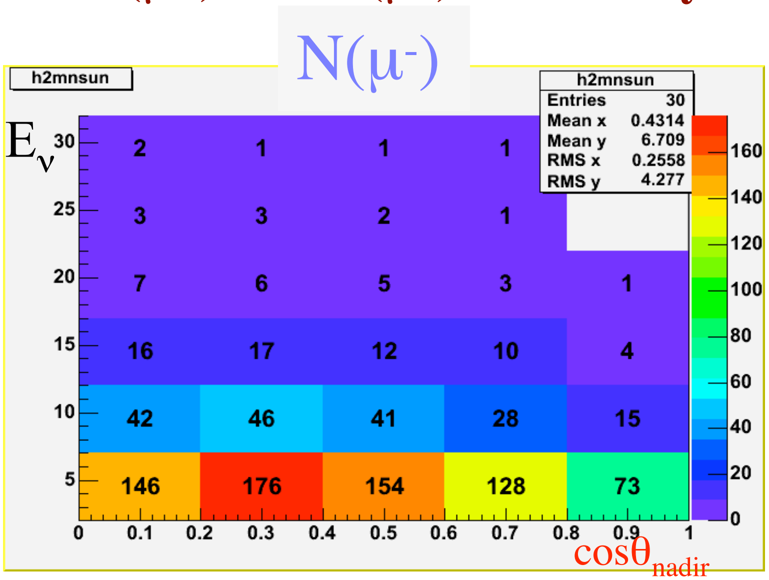


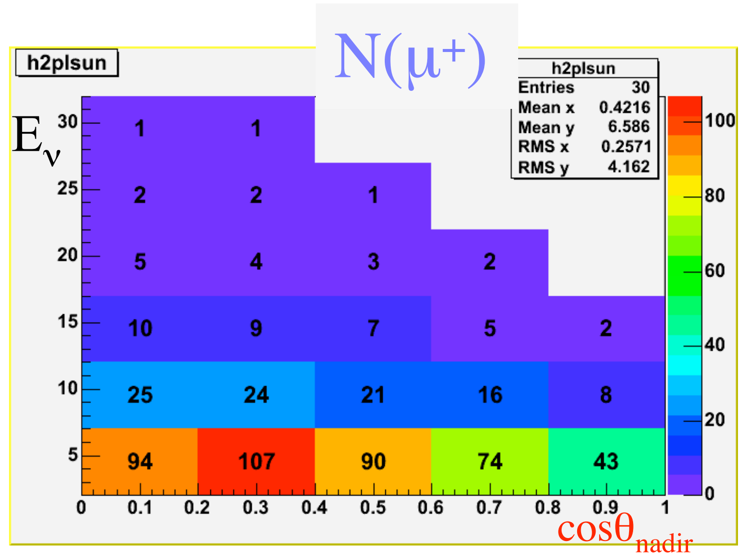


Good agreement between MC charge asymmetry and theory prediction

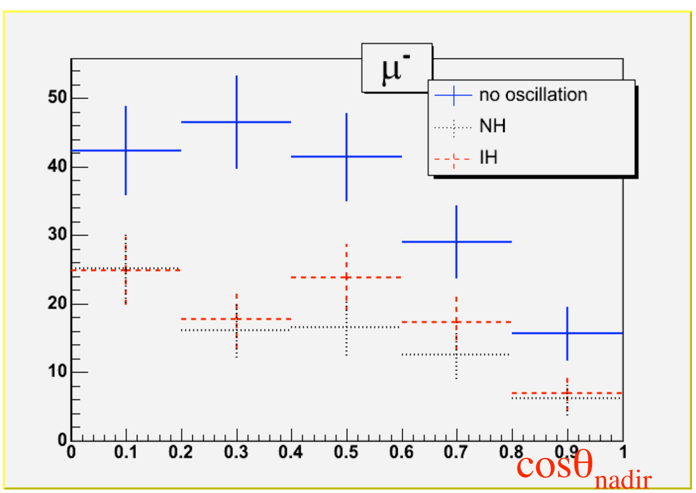
Event Rates - 100 yrs

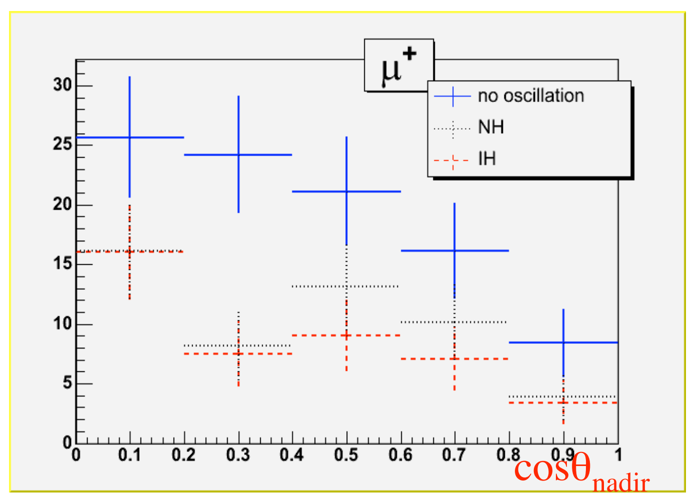
N(μ -) and N(μ+) after **100 years, contained vertex ν, no oscillation:**





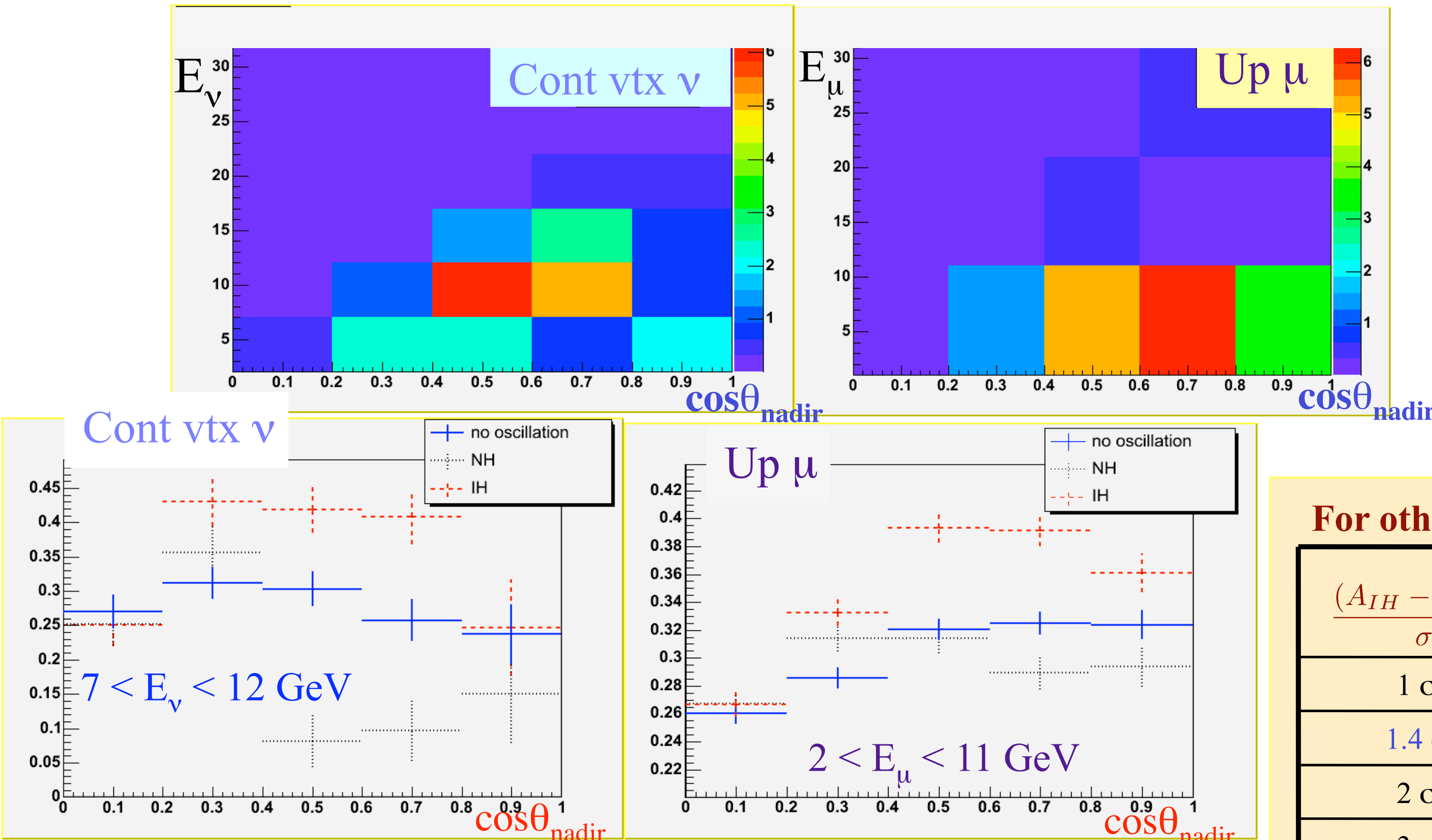
N(μ -) and N(μ+) vs $\cos\theta_{nadir}$ **for 7 GeV < E_ν < 12 GeV:**





Statistical Significance

➡ Statistical significance $|A_{IH} - A_{NH}|/\sigma$ after **2,500 years**:



For other exposures:

$\frac{(A_{IH} - A_{NH})}{\sigma}$	# of years
1 σ	52
1.4 σ	100
2 σ	203
3 σ	456
5 σ	1266

➡ Comparable discrimination can be achieved for the two topologies

Likelihood Study

- Build likelihood function L to discriminate between normal and inverted hierarchy.
- For a given set of data, the ratio R = L_{NH}/L_{IH} measures whether the data is more consistent with the NH or IH hypothesis.
- Generate large number of pseudoexperiments for a given exposure assuming NH (IH) and evaluate R_{NH} (R_{IH}).
- In practice, calculate L=-2ln(L) and determine **ΔL** = $L_{NH} - L_{IH}$ (the test statistics)
- The larger the separation between the two distributions ($\mathbf{\Delta L_{NH}}$ and $\mathbf{\Delta L_{IH}}$), the better the two mass hierarchies can be discriminated.
- Determine the 95% C.L. sensitivity for rejecting IH(NH) by calculating the fraction of pseudoexperiments generated assuming NH (IH) with less than 5% IH(NH) contamination.
- Repeat for different exposures and values of $\sin^2 2\theta_{13}$ and $\sin^2 \theta_{23}$

Likelihood Function

- Unbinned likelihood for contained vtx ν and upward going μ:

Poisson constraints on total numbers of events

$$L = \frac{(\lambda^-)^{N^-} e^{\lambda^-}}{N^-!} \times \prod_{i=1}^{N^-} f^-(E_i, \cos\theta_{nadir,i}) \times \frac{(\lambda^+)^{N^+} e^{\lambda^+}}{N^+!} \times \prod_{i=1}^{N^+} f^+(E_i, \cos\theta_{nadir,i})$$

Shape constraints

$N^{\pm}$: observed number of $\mu^{\pm}$.

$\lambda^{\pm}$: expected number of $\mu^{\pm}$. Depend on oscillation parameters.

$f^{\pm}$: normalized shapes of $\mu^{\pm}$ rates as a function of $\cos\theta_{nadir}$ vs E distributions. Depend on oscillation parameters.

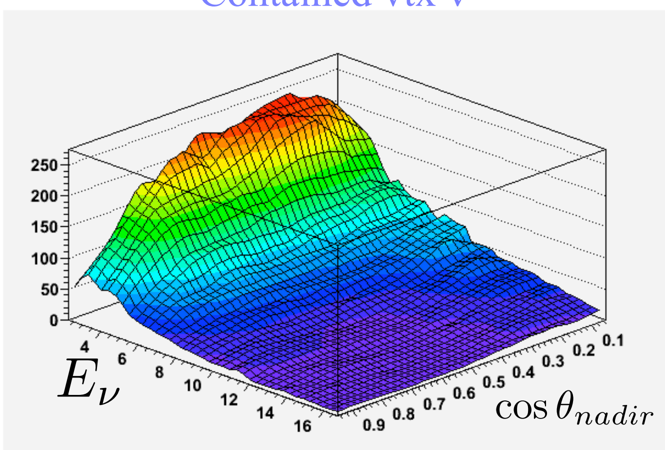
- Fix all oscillation parameters, except for the sign of Δm^2_{31} and consider the following values of:

$$\sin^2 2\theta_{13} = 0.05, 0.1, 0.15 \qquad \sin^2\theta_{23} = 0.5, 0.64$$

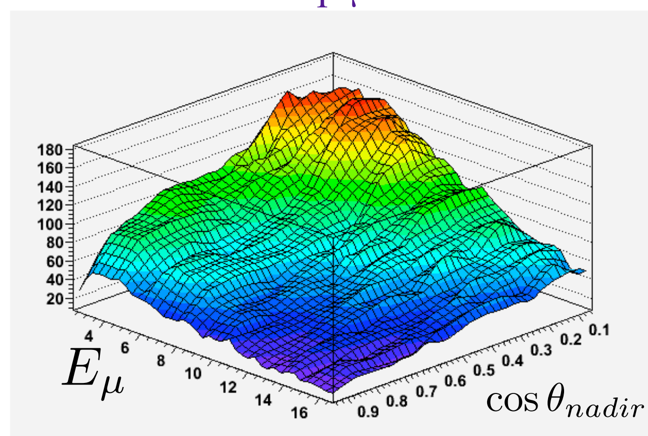
Pseudoexperiments

- Generate number of events (μ^+,μ^-, for cont vtx ν and up μ) according to Poisson statistics for a given exposure.
- Interpolate $\cos\theta_{nadir}$ vs energy MC distributions and randomly generate $\cos\theta_{nadir}$, E for each event according to these shapes and both hierarchies.

Contained vtx ν



Up μ



$\sin^2 2\theta_{13} = 0.1, \sin^2\theta_{13} = 0.64, \mu^-, NH$

- Determine $\Delta\mathbf{L}_{\mathbf{NH}}$ and $\Delta\mathbf{L}_{\mathbf{IH}}$ for each pseudoexperiment
- Repeat for several exposures and values of the mixing angles

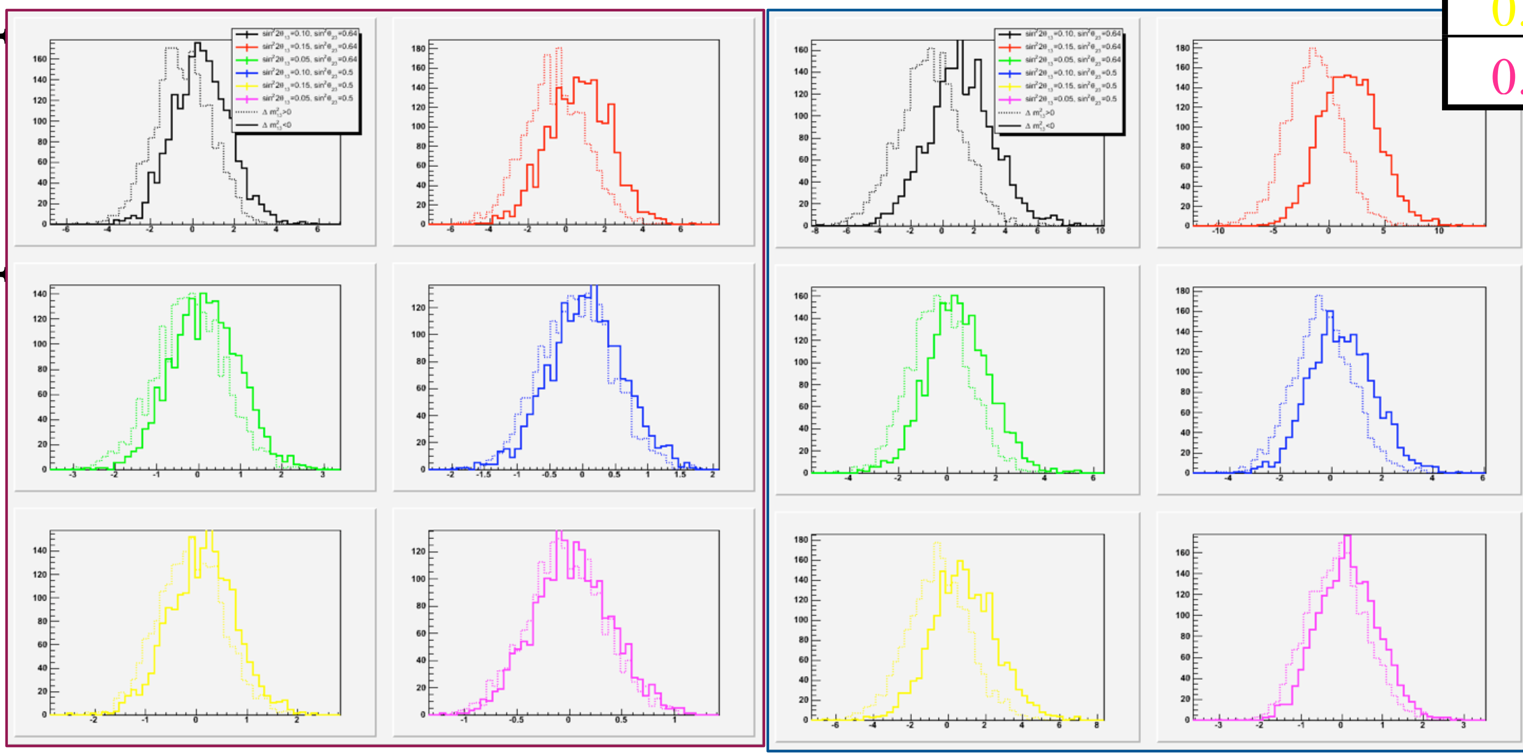
ΔL for Cont vtx ν-10 yrs

✱Compare ΔL for NH (dashed) and IH (solid) hypotheses

$\sin^2 2\theta_{13}$	$\sin^2 \theta_{23}$
0.10	0.64
0.15	0.64
0.05	0.64
0.10	0.50
0.15	0.50
0.05	0.50

Poisson constraint only   Poisson+Shape constraint

# of pseudoexpts



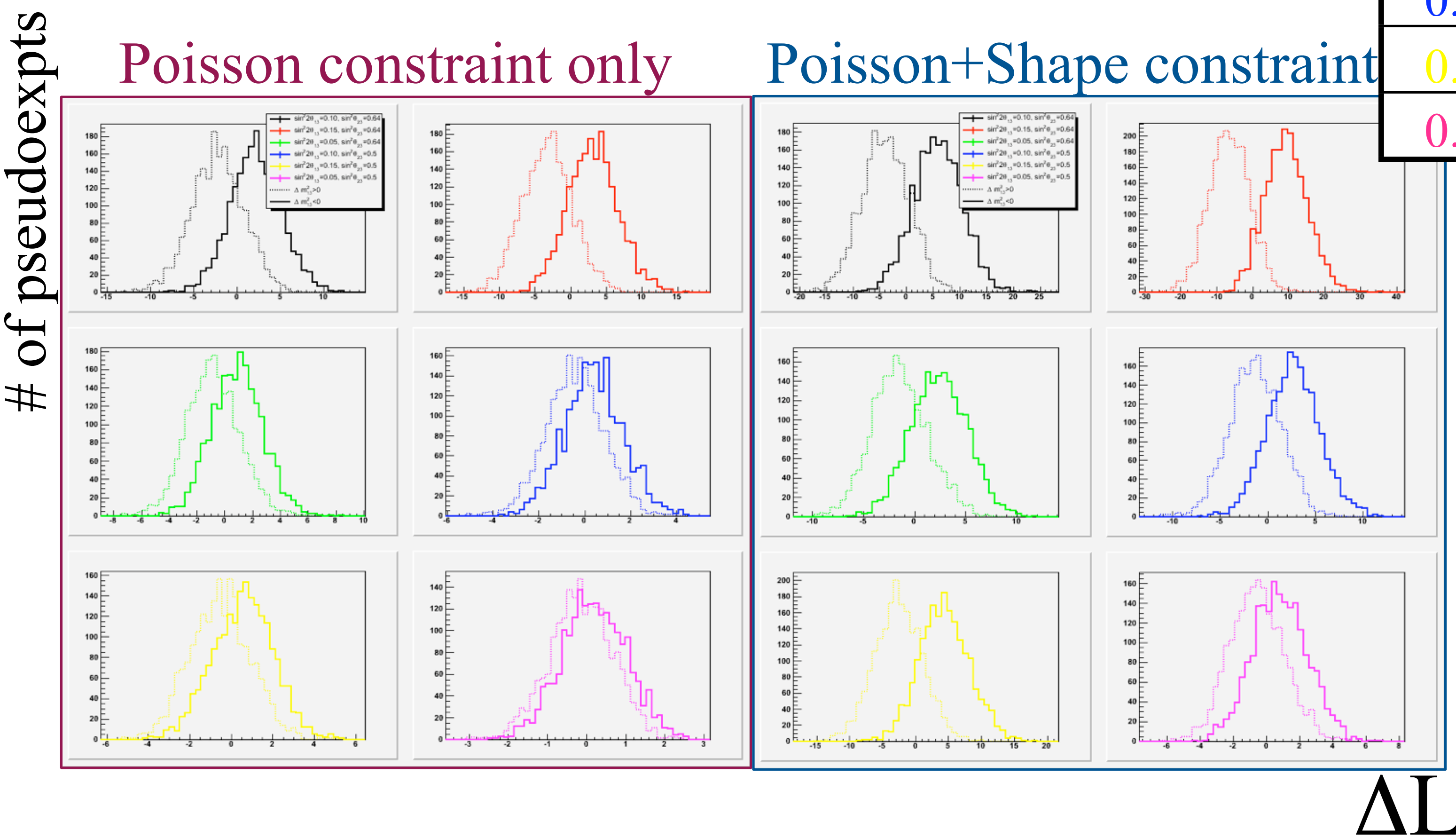
——— $\Delta m^2_{31} < 0$
······ $\Delta m^2_{31} > 0$

ΔL

➡Better discrimination achieved by making use of shape information in the likelihood

ΔL for Cont vtx ν-50 yrs

$\sin^2 2\theta_{13}$	$\sin^2 \theta_{23}$
0.10	0.64
0.15	0.64
0.05	0.64
0.10	0.50
0.15	0.50
0.05	0.50



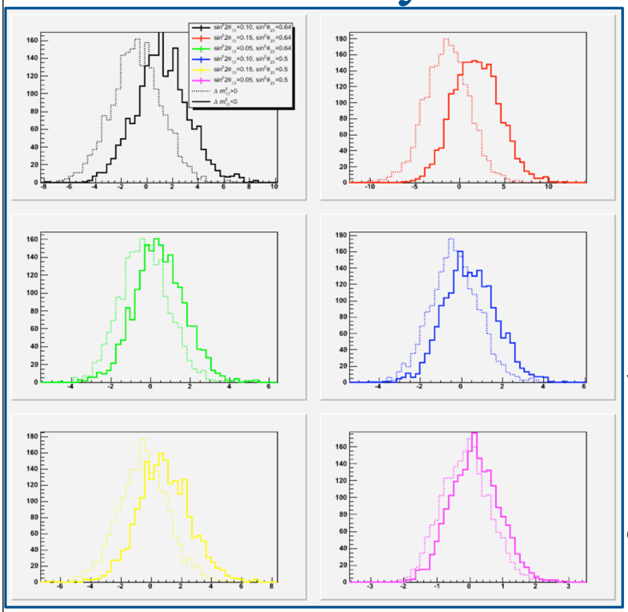
———	$\Delta m^2_{31} < 0$
······	$\Delta m^2_{31} > 0$

➡As expected, discrimination improves for larger $\sin^2 2\theta_{13}$

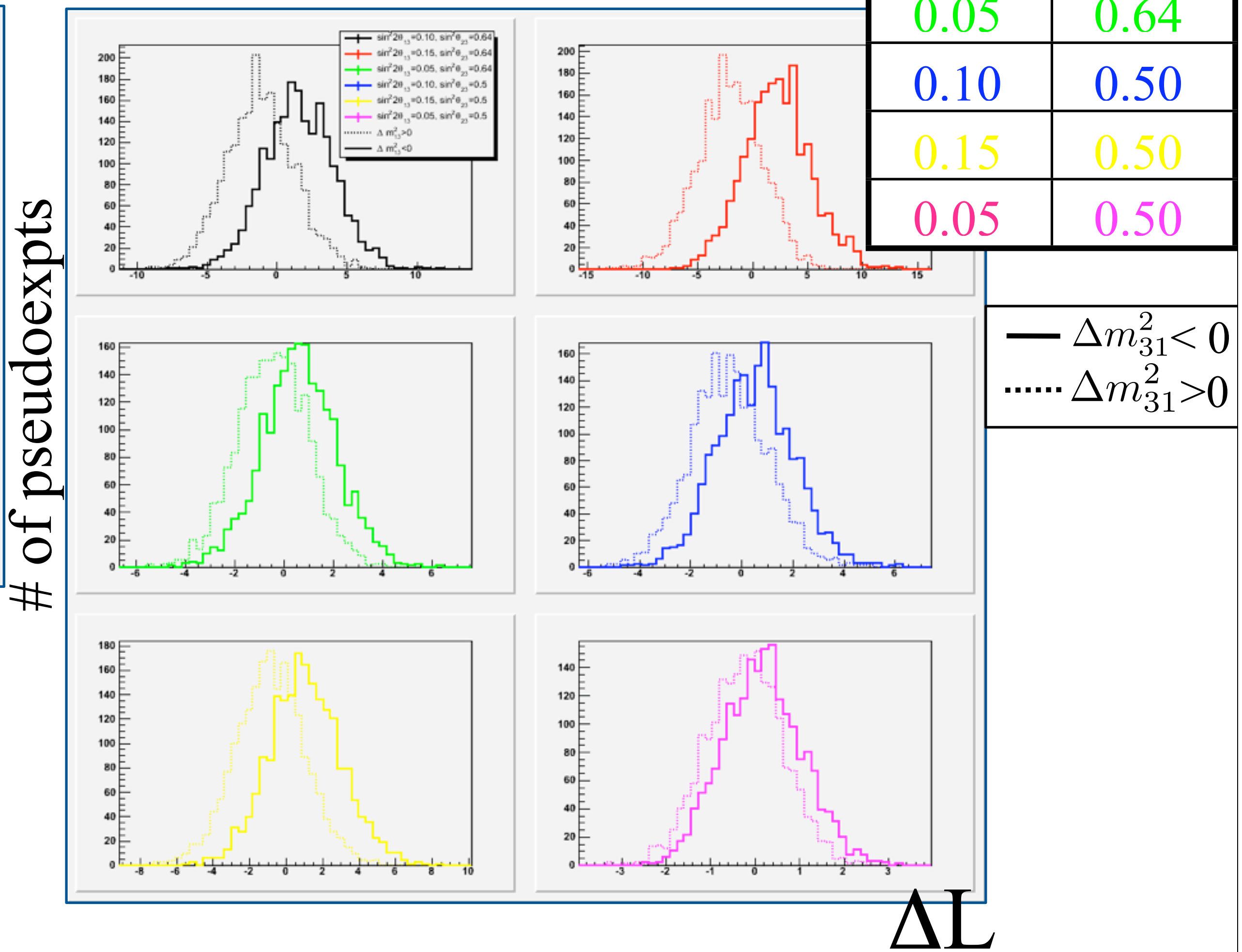
Combined ΔL -10 yrs

$\sin^2 2\theta_{13}$	$\sin^2 \theta_{23}$
0.10	0.64
0.15	0.64
0.05	0.64
0.10	0.50
0.15	0.50
0.05	0.50

Cont vtx ν only

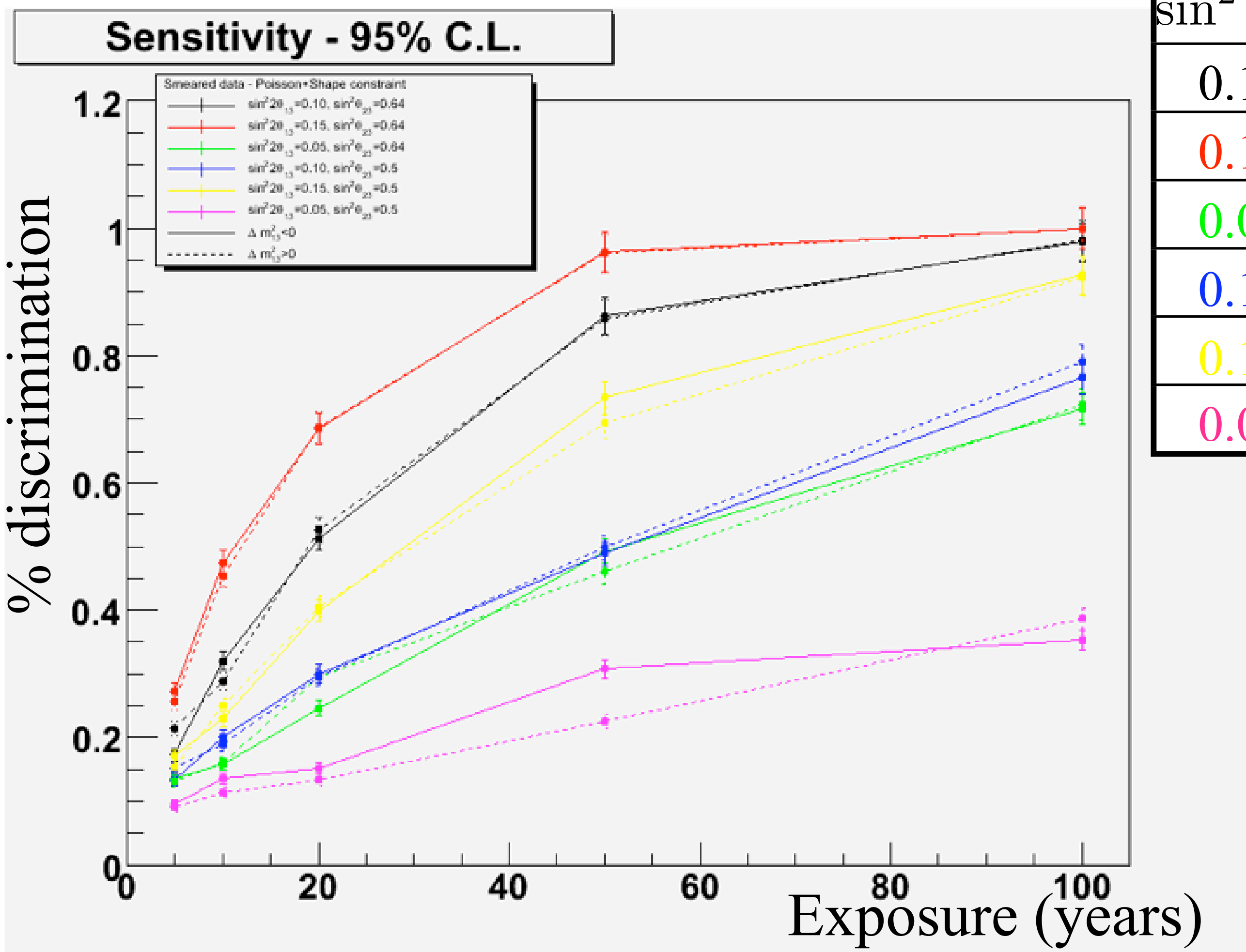


Combined



➡Further improvement is obtained by combining the contained vertex ν sample with the upgoing μ sample

Sensitivity-Combined



$\sin^2 2\theta_{13}$	$\sin^2 \theta_{23}$
0.10	0.64
0.15	0.64
0.05	0.64
0.10	0.50
0.15	0.50
0.05	0.50

—— $\Delta m^2_{31} < 0$

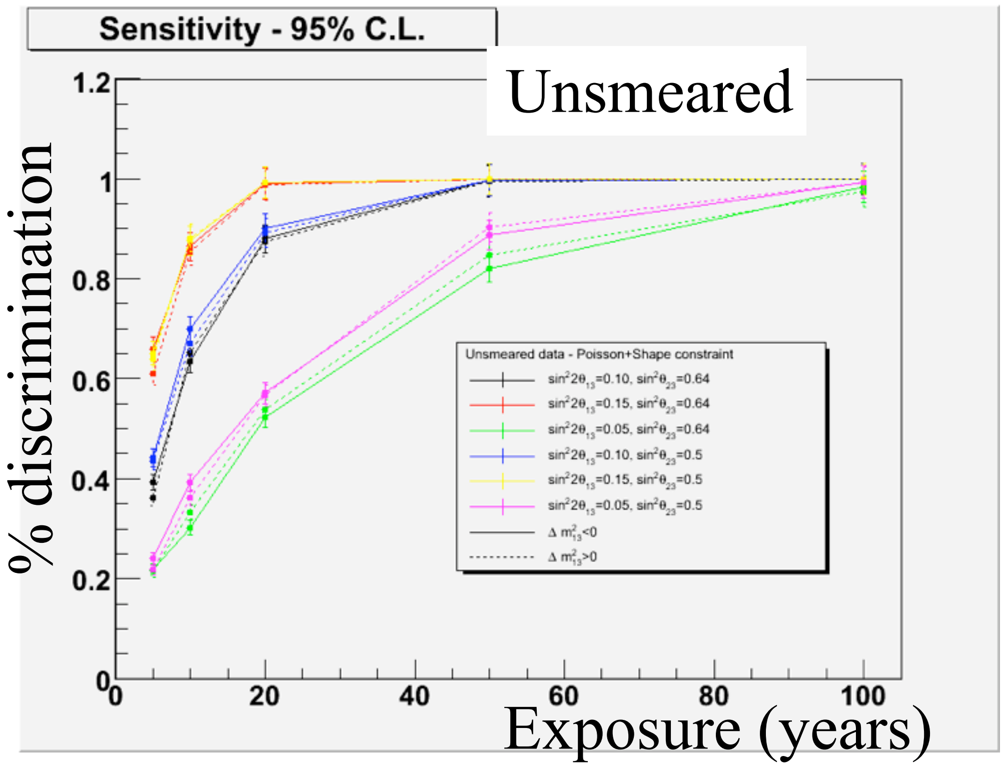
⋯⋯ $\Delta m^2_{31} > 0$

➡ Similar sensitivity achieved for NH and IH

➡ Need over 10 years of running, if oscillation parameters are favorable, for a >50% chance to determine the mass hierarchy at 95% C.L.

Sensitivity-Unsmeared

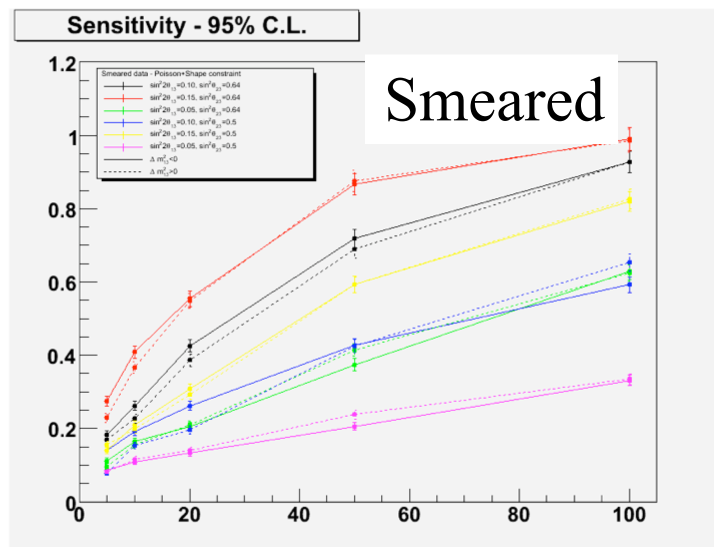
Contained vtx ν only



—— $\Delta m^2_{31} < 0$

······ $\Delta m^2_{31} > 0$

$\sin^2 2\theta_{13}$	$\sin^2 \theta_{23}$
0.10	0.64
0.15	0.64
0.05	0.64
0.10	0.50
0.15	0.50
0.05	0.50



Summary

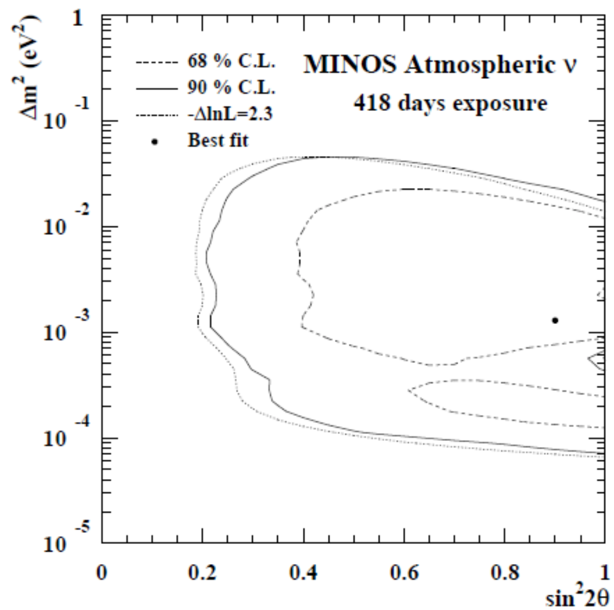
- We have studied the sensitivity of the MINOS far detector to discriminate the neutrino mass hierarchy using simulated atmospheric neutrinos (contained vertex ν events and upward going μ) reconstructed at the far detector
- We have determined the sensitivity as a function of the exposure, $\sin^2 2\theta_{13}, \sin^2 \theta_{23}$ and the sign of Δm^2_{31}
- We find that the sensitivity is comparable for NH and IH, and it improves significantly if $\sin^2 2\theta_{13}$ is large
- The analysis reveals that >10 years of exposure at the MINOS far detector would be needed to discriminate between mass hierarchies at 95% C.L.

BACKUP

Far Detector : Atmospheric Neutrino Oscillations

Phys. Rev. D73, 072002 (2006)

- The MINOS far detector is the first large magnetized underground detector. Installation completed in July 2003.
- Veto shield used to reject cosmic rays for atmospheric ν analysis
- L/E analysis excludes no oscillations at 98% CL
- First measurement of atmospheric ν_μ vs. $\bar{\nu}_\mu$ oscillations



$$\frac{R^{data}_{up/down}}{R^{MC}_{up/down}} = 0.62^{+0.19}_{-0.14}(\text{stat}) \pm 0.02(\text{syst})$$

$$\frac{R^{data}_{\bar{\nu}_\mu/\nu_\mu}}{R^{MC}_{\bar{\nu}_\mu/\nu_\mu}} = 0.96^{+0.38}_{-0.27}(\text{stat}) \pm 0.15(\text{syst})$$

MC assumes ν and $\bar{\nu}$ oscillate in the same way