Optimization of long baseline accelerator neutrino experiment sensitivity for measuring neutrino mass hierarchy

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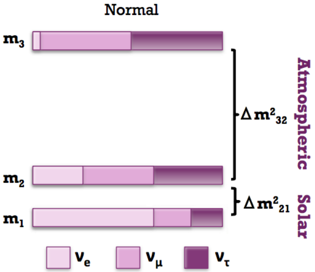
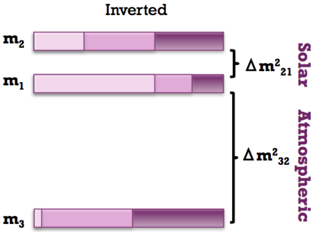
Mass Hierarchy Problem





Oscillation Parameters:

$$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\ \text{eV}^2,$$
$$\text{NH}: \Delta m^2_{32} = 2.44^{+0.021}_{-0.021} \times 10^{-3}\ \text{eV}^2,$$
$$\text{IH}: \Delta m^2_{32} = -\ 2.52^{+0.07}_{-0.07} \times 10^{-3}\ \text{eV}^2,$$
$$\delta_{\text{CP}} \in [0; 2\pi],$$

$$\sin^2 2\theta_{12} = 0.846^{+0.021}_{-0.021},$$
$$\text{NH}: \sin^2 2\theta_{23} = 0.999^{+0.001}_{-0.018},$$
$$\text{IH}: \sin^2 2\theta_{23} = 1.000^{+0.000}_{-0.017},$$
$$\sin^2 2\theta_{13} = 0.093^{+0.008}_{-0.008}.$$

General Long Baseline Experiment Simulator

$$N \sim Probability \times Flux \times Cross\ Section \times Detector\ Efficiency$$

$$\chi^2 = 2 \sum_{exp} \sum_{rules} \sum_{bins} \left(N^{th} - N^{obs} + N^{obs} \log \frac{N^{obs}}{N^{th}} \right) + \chi^2_{pull} + \chi^2_{prior}$$

$$\chi^2_{pull} = \frac{a^2}{\sigma_a^2} + \frac{b^2}{\sigma_b^2} + \frac{c^2}{\sigma_c^2} + \frac{d^2}{\sigma_d^2}$$

pull-method:

$$N_i^{obs} = s_i(a, b) + b_i(c, d)$$

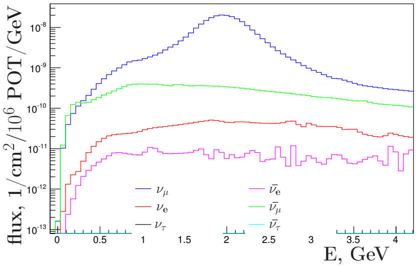
$$s_i(a) = (1 + a) \cdot s_i$$

$$s_i(a, b) = s_i(a) + b \cdot s_i \cdot \frac{E_i - E_{mean}}{E_{max} - E_{min}}$$

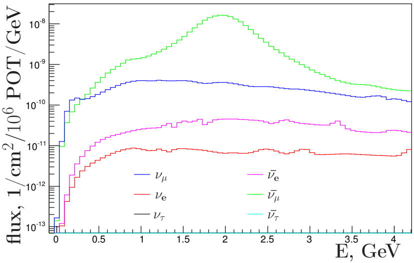
NOνA Configuration for Simulation. Fluxes ...

ν_e appearance and ν_μ disappearance experiment
base 810 km
proton beam with intensive 0.7 MW with 6×10^{20} POT/year
density 2.75 g/cm^3
Medium Energy horn:

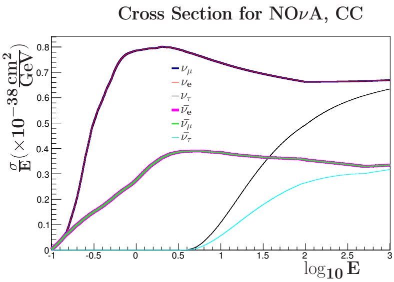
Flux for NOνA, ν mode

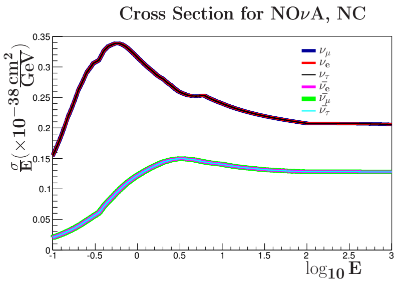


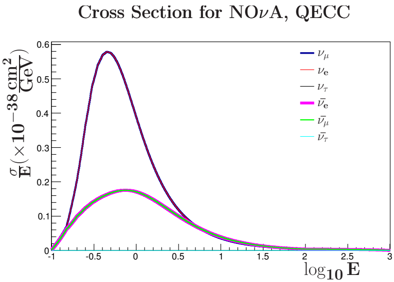
Flux for NOνA, $\bar{\nu}$ mode



… Cross Sections. Efficiencies. Background.







45% for ν_e and $\bar{\nu_e}$ CC

100% for ν_μ and $\bar{\nu_\mu}$ QE

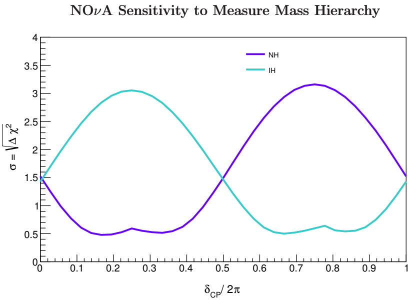
bg: 1) misidentified μ: 0.83% ν and 0.22% $\bar{\nu}$ CC 2) ν_μ, identified as ν_e: 1.35% ν, 1.6% $\bar{\nu}$ NC 3) admixture ν_e ($\bar{\nu_e}$) in initial ν_μ ($\bar{\nu_\mu}$) beam: 26% ν, 18% $\bar{\nu}$

Sensitivity

$$\sigma = \sqrt{\Delta\chi^2} = \sqrt{\chi^2_{hyp} - \chi^2_{hyp2}}$$

Mass Hierarchy (MH):
- Normal Hierarchy (NH) or
- Inverted Hierarchy (IH)

$$\Delta\chi^2 = |\chi^2_{MH^{test}} - \chi^2_{MH^{true}}|$$

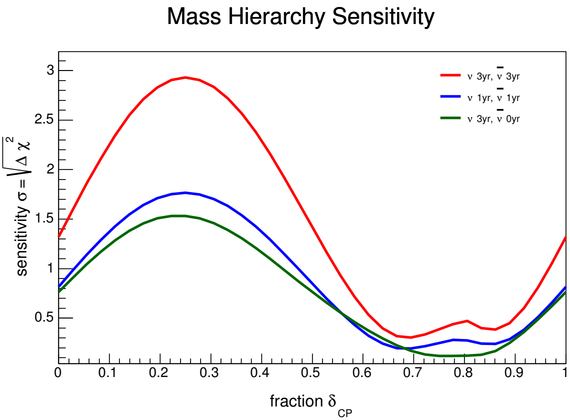


Two possibilities:

1) true hierarchy is normal, fit hierarchy — inverted

2) true hierarchy is inverted, the fit hierarchy — normal

Sensitivity and time



3yr ν $\sim 1.5\sigma$

2yr $1\nu + 1\bar{\nu}$ $\sim 1.8\sigma$

Approximate Formulas and their Accuracy

evolution equation in matter:

$$i\dot{S}(t) = (UH_0U^\dagger + W(t))S(t) = H(t)S(t)$$

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

$$H = U \begin{pmatrix} 0 & & \\ & \frac{\Delta m^2_{21}}{2E} & \\ & & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} \pm\sqrt{2}G_f N_e & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

$$S = Q \begin{pmatrix} e^{-iL\lambda_1} & & \\ & e^{-iL\lambda_2} & \\ & & e^{-iL\lambda_3} \end{pmatrix} Q^\dagger$$

$$P(\nu_\alpha \to \nu_\beta) = |S_{\beta\alpha}|^2$$

$[1\alpha]$

[Jianming Bian, The *NOνA* Experiment: Overview and Status, DPF2013, arXiv:1309.7898]

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} +$$

$$+2\alpha \sin\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta -$$

$$-2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad A \equiv \pm \frac{G_f n_e L}{\sqrt{2}\Delta}, \quad A\Delta = \frac{L}{3500km}$$

$[2\alpha]$

[Combined Analysis of ν_μ disappearance and $\nu_\mu \to \nu_e$ Appearance in MINOS using Accelerator and Atmospheric Neutrinos, The MINOS Collaboration, Phys. Rev. Lett. 112, 191801 (2014).]

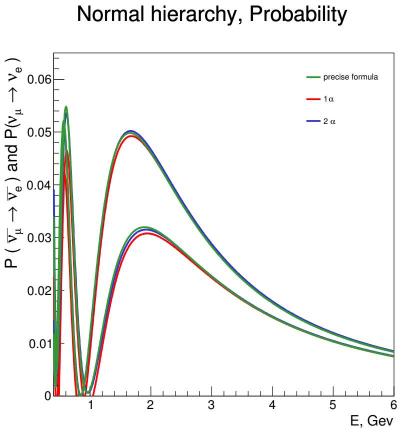
$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2 \Delta(1-A)}{(1-A)^2}$$

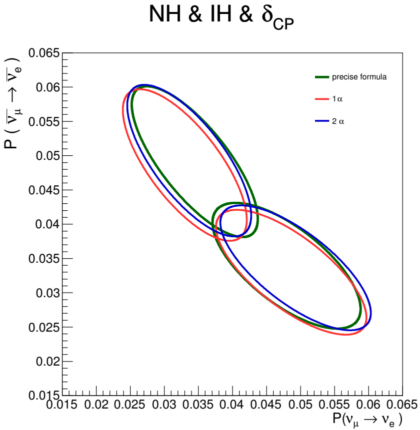
$$+\alpha \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta \pm \delta_{CP}) \frac{\sin \Delta A}{A} \frac{\sin \Delta(1-A)}{(1-A)}$$

$$+\alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 \Delta A}{A^2}$$

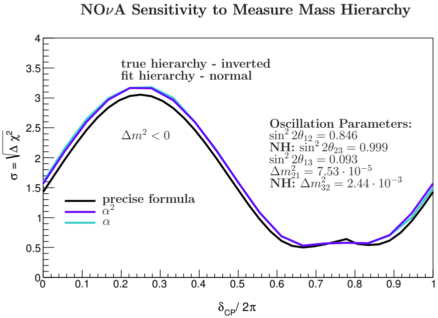
$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}}, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad A \equiv \pm \frac{G_f n_e L}{\sqrt{2}\Delta}, \quad A\Delta = \frac{L}{3500 km}$$

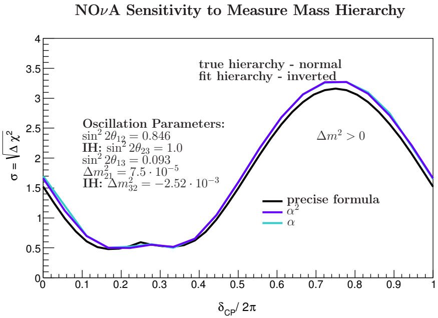
Three Formulas for Probability



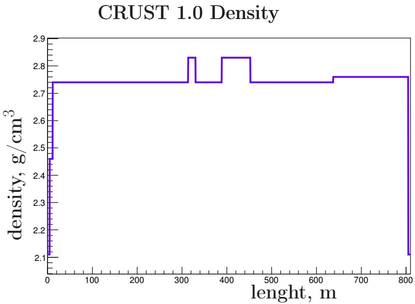


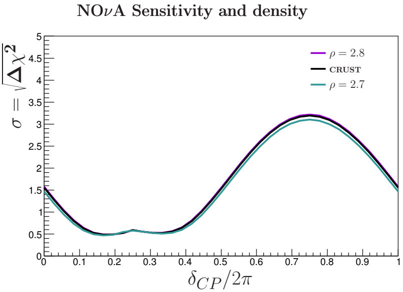
$\delta_{CP} = \frac{3\pi}{2}$ (T2K):
NH:
stat. $\sim 10\%$
syst. $\sim 6\%$





Density Uncertainty Influence





$\rho_{eff} = 2.75 \pm 0.06$ g/cm^3 (Igor Shandrov, JINR)

Results

- I've developed the algorithm that determine the influence of different factors on the mass hierarchy sensitivity.
- The scheme $3\nu + 3\bar{\nu}$ is the best variant. The result for sensitivity after 2 year work in scheme $1\nu + 1\bar{\nu}$ can be more efficient than result after 3ν run.
- The choice of approximate oscillation probability formula in fit will make contribution in systematic error (for $\delta_{cp} = 3\pi/2$ ~6% for NH)
- Possible variations in matter density in the path of the beam have little effect on systematic error - about 2% in maximum of mass hierarchy sensitivity.