INSS 2019 – Group 4

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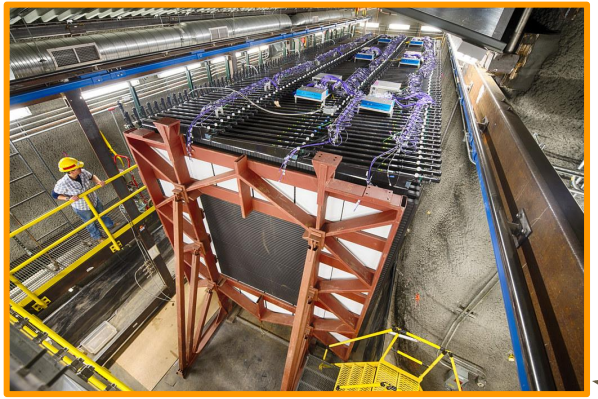
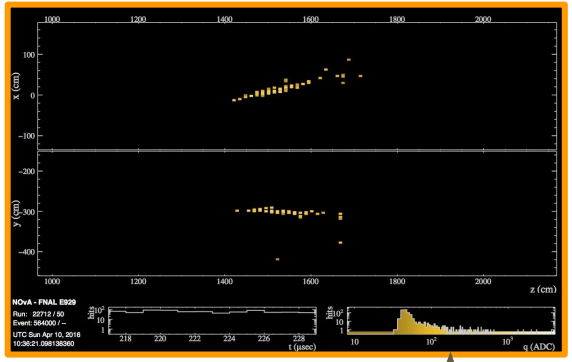
Long Baseline Oscillation Experiments - NOvA

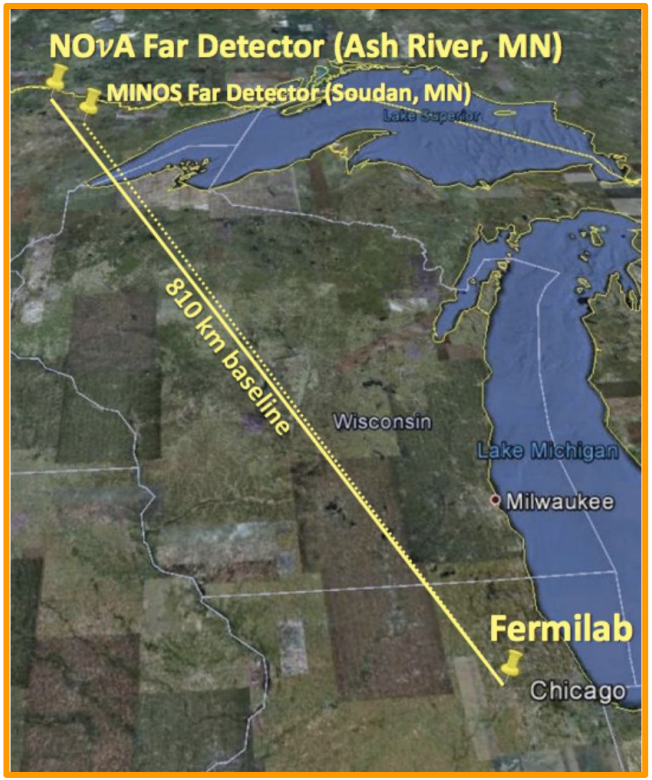
- 810 km baseline, 1.9 GeV peak neutrino energy
- 14 mrad off-axis from FNAL's NuMI beam
- Near and far detectors made of liquid scintillator cells



Near detector at FNAL



Event display



Questions

1. Given expected S and B, what is the optimal run plan (neutrino or antineutrino beam mode, or admixture?) for NOvA to determine specifically the **mass hierarchy**?
2. Invent a physics scenario of your own choosing that might cause you to make the **incorrect hierarchy selection**.

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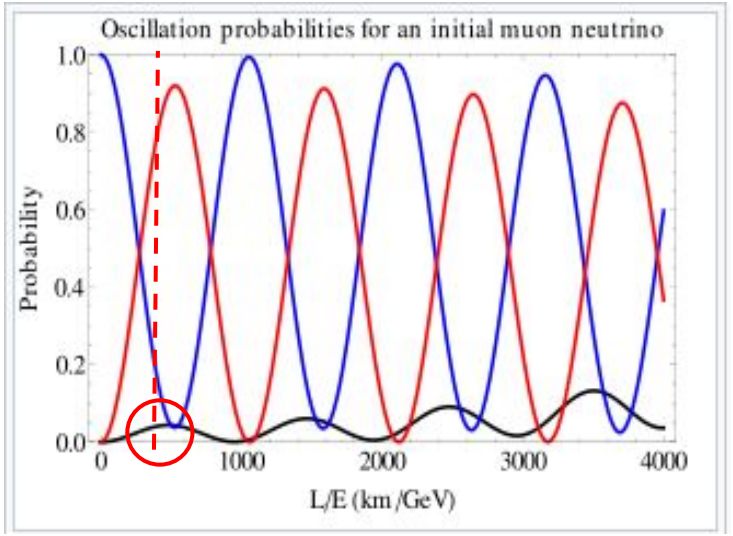
2. Invent a physics scenario of your own choosing that might cause you to **change the run plan**.

Input parameters

- $\Delta m_{12}^2 = 7.5 \times 10^{-5}\ eV^2$, $\Delta m_{23}^2 = 2.5 \times 10^{-3}\ eV^2$
- $\sin^2(2\theta_{13}) = 0.085$, $\sin^2(2\theta_{12}) = 0.87$
- L/E ~ 400 km/GeV
- Will accumulate 36×10^{20} POT
  - Expected amount after 6 years of NOvA running
- Number of S and B ν_e events are given for ν and $\bar{\nu}$ beam mode and for different values of oscillation parameters
  - Number of events given for 6×10^{20} POT

Wikipedia

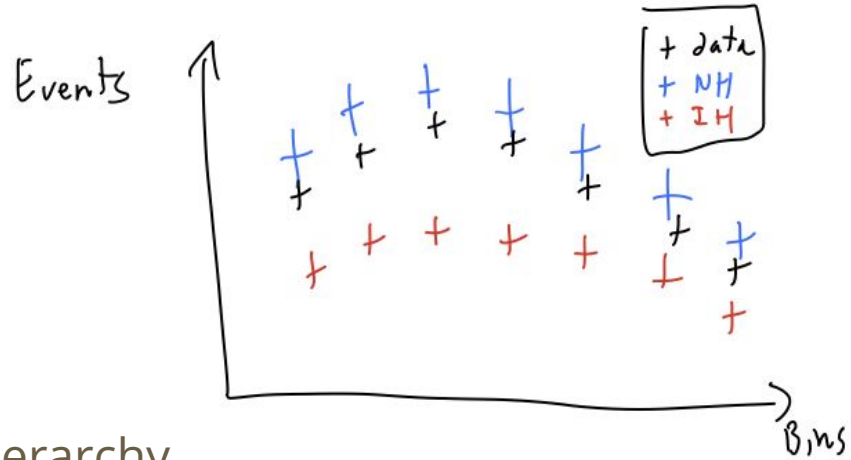


Red: ν_τ
Blue: ν_μ
Black: ν_e

Assumptions

1. Large number of events such that χ^2 represents actual sensitivity
2. Systematic uncertainties negligible compared to statistical uncertainties
3. Background events are independent of oscillation parameters
4. Neutrino and antineutrino events are independent of one another
5. Background events scale with POT

Test statistic



Pearson's chi-square

$$\chi^2 = \sum_{i \in \text{bins}} \frac{(O_i - E_i)^2}{E_i}$$

Assumption 1

Assumption 2

Two hypotheses: Inverted and normal hierarchy

$$\chi^2_{\text{I}} = \sum_{i \in \text{bins}} \frac{\left(O_i - (S_i^{\text{I}} + B_i^{\text{I}})\right)^2}{S_i^{\text{I}} + B_i^{\text{I}}}$$

$$\chi^2_{\text{N}} = \sum_{i \in \text{bins}} \frac{\left(O_i - (S_i^{\text{N}} + B_i^{\text{N}})\right)^2}{S_i^{\text{N}} + B_i^{\text{N}}}$$

Want to maximize χ^2 difference

$$\Delta\chi^2 = \chi^2_{\text{opposite}} - \chi^2_{\text{true}}$$

$$\text{sensitivity} = \sqrt{\Delta\chi^2}\ [\sigma]$$

Expected hierarchy sensitivity

For definiteness, assume nature has chosen normal hierarchy

$$\Delta\chi^2 = \chi^2_{\mathrm{I}} - \chi^2_{\mathrm{N}}$$

For expected sensitivity, replace observed events by expected events

$$O_i = S_i^{\mathrm{N}} + B_i^{\mathrm{N}}$$

$$\chi^2_{\mathrm{I}} = \sum_{i \in \mathrm{bins}} \frac{\left((S_i^{\mathrm{N}} + B_i^{\mathrm{N}}) - (S_i^{\mathrm{I}} + B_i^{\mathrm{I}})\right)^2}{S_i^{\mathrm{I}} + B_i^{\mathrm{I}}}$$

$$\chi^2_{\mathrm{N}} = \sum_{i \in \mathrm{bins}} \frac{\left((S_i^{\mathrm{N}} + B_i^{\mathrm{N}}) - (S_i^{\mathrm{N}} + B_i^{\mathrm{N}})\right)^2}{S_i^{\mathrm{N}} + B_i^{\mathrm{N}}}$$

$$B_i^{\mathrm{N}} = B_i^{\mathrm{I}}$$

Assumption 3

$$\sqrt{\Delta\chi^2} = \sqrt{\sum_{i \in \mathrm{bins}} \frac{\left(S_i^{\mathrm{N}} - S_i^{\mathrm{I}}\right)^2}{S_i^{\mathrm{I}} + B_i^{\mathrm{I}}}}$$

Sensitivity for exercise

Two independent bins: ν and $\bar{\nu}$ beam mode

Assumption 4

$$\sqrt{\Delta\chi^2} = \sqrt{\frac{\left(S_\nu^{\mathrm{N}} - S_\nu^{\mathrm{I}}\right)^2}{S_\nu^{\mathrm{I}} + B_\nu^{\mathrm{I}}} + \frac{\left(S_{\bar{\nu}}^{\mathrm{N}} - S_{\bar{\nu}}^{\mathrm{I}}\right)^2}{S_{\bar{\nu}}^{\mathrm{I}} + B_{\bar{\nu}}^{\mathrm{I}}}}$$

Want to optimize run plan: introduce optimization parameter

$$f_\nu = \frac{\nu\ \mathrm{POT}}{\nu\ \mathrm{POT} + \bar{\nu}\ \mathrm{POT}}$$

$$\sqrt{\Delta\chi^2} = \sqrt{6 f_\nu \frac{\left(S_\nu^{\mathrm{N}} - S_\nu^{\mathrm{I}}\right)^2}{S_\nu^{\mathrm{I}} + B_\nu^{\mathrm{I}}} + 6(1 - f_\nu) \frac{\left(S_{\bar{\nu}}^{\mathrm{N}} - S_{\bar{\nu}}^{\mathrm{I}}\right)^2}{S_{\bar{\nu}}^{\mathrm{I}} + B_{\bar{\nu}}^{\mathrm{I}}}}$$

Assumption 5

N ⇔ I if assuming inverted hierarchy is true

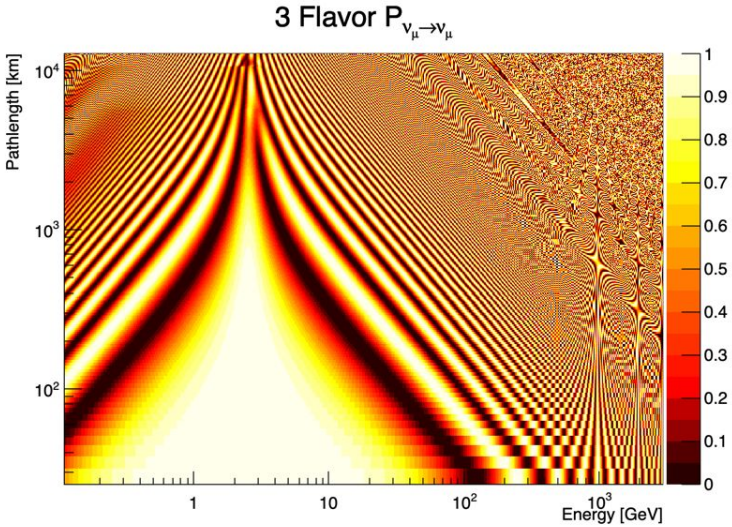
Scenarios under consideration

1. Normal mass hierarchy, $\sin^2\theta_{23} = 0.6$ and $\delta_{CP} = 3\pi/2$
2. Normal mass hierarchy, $\sin^2\theta_{23} = 0.4$ and $\delta_{CP} = 3\pi/2$
3. Inverted mass hierarchy, $\sin^2\theta_{23} = 0.6$ and $\delta_{CP} = 3\pi/2$
4. Inverted mass hierarchy, $\sin^2\theta_{23} = 0.4$ and $\delta_{CP} = \pi/2$

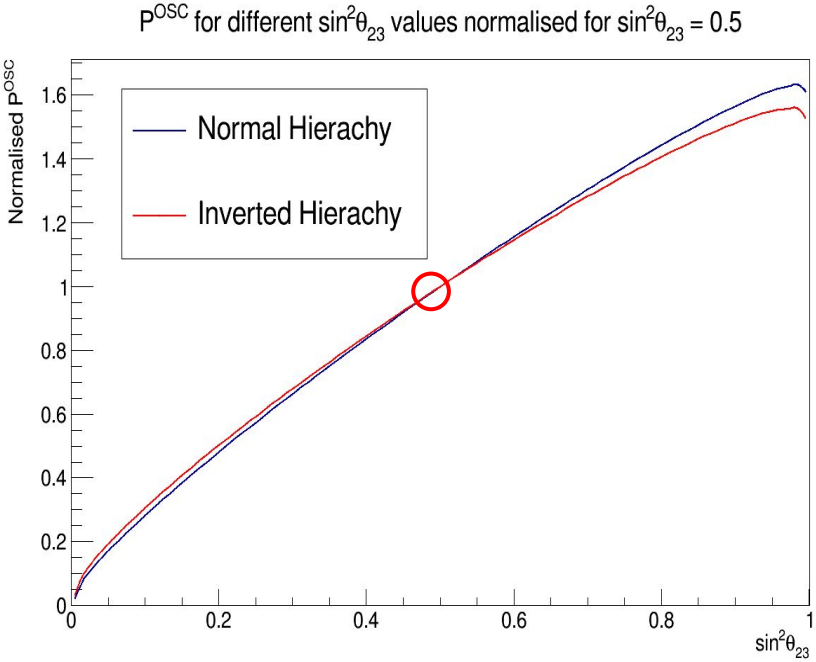
Oscillation probability

Using software: Prob3++

- C++ library for 3-flavour oscillation probabilities
- Includes matter effects
  - Using ρ=2.8 g/cm^3
- https://webhome.phy.duke.edu/~raw22/public/Prob3++/



Probability scaling



Data given is for $\sin^2\theta_{23} = 0.5$

⇒ Need to multiply signal by probability ratio (~1.2 or ~0.8)

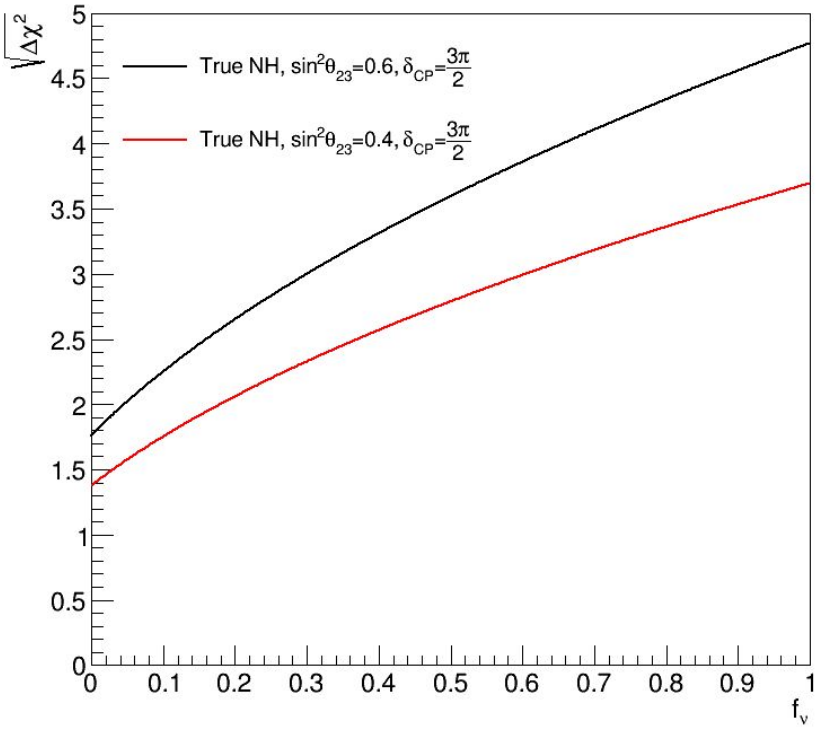
$$S \rightarrow \frac{P^{\text{osc}}(\sin^2\theta_{23})}{P^{\text{osc}}(\sin^2\theta_{23} = 0.5)} S$$

$$B \rightarrow B$$

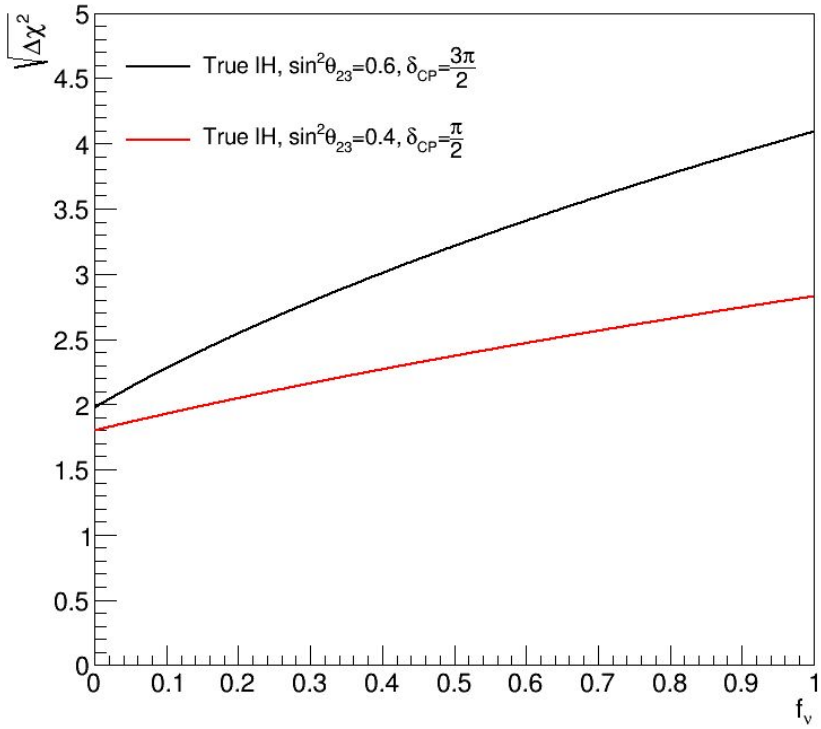
Assumption 3

Results

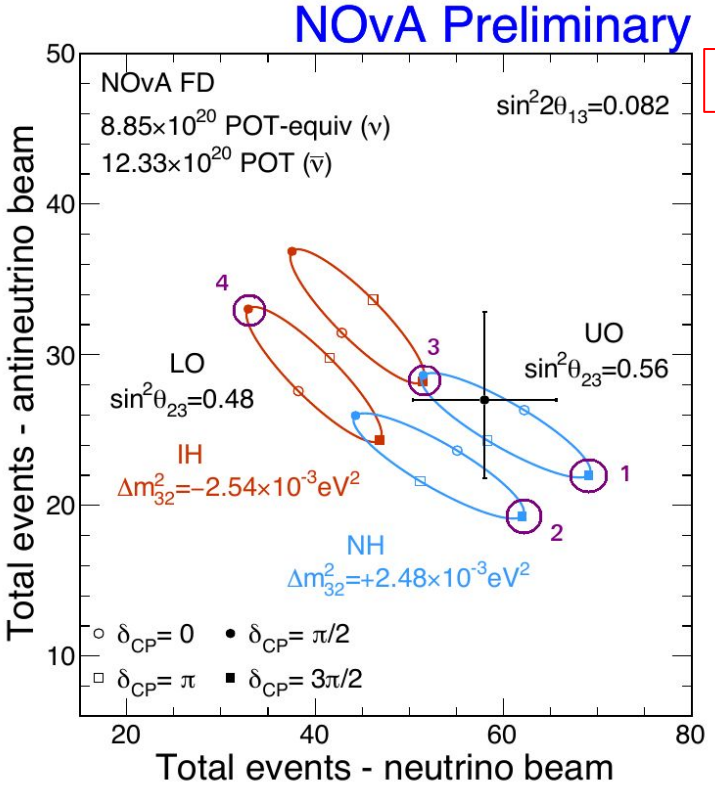
Normal Hierachy sensitivity



Inverted Hierachy sensitivity

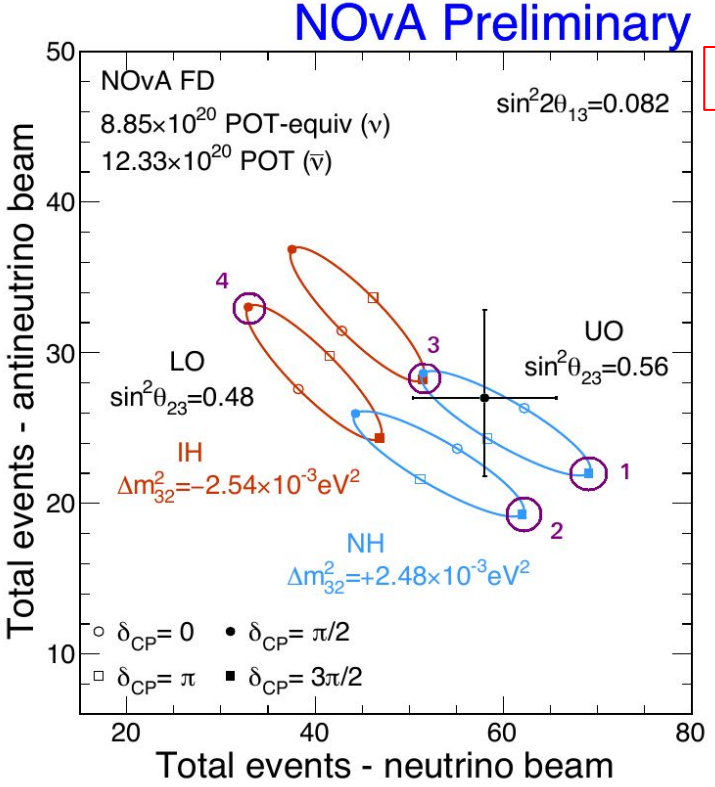


Biprobability



Patricia's lecture

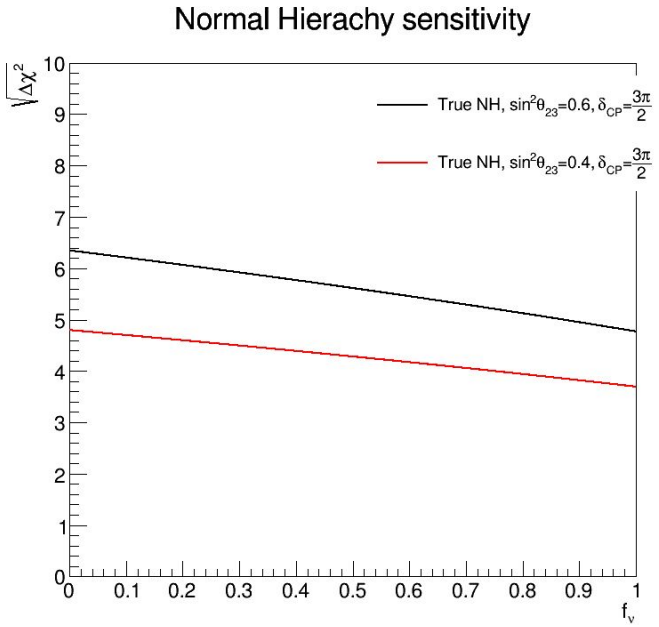
Biprobability interpretation

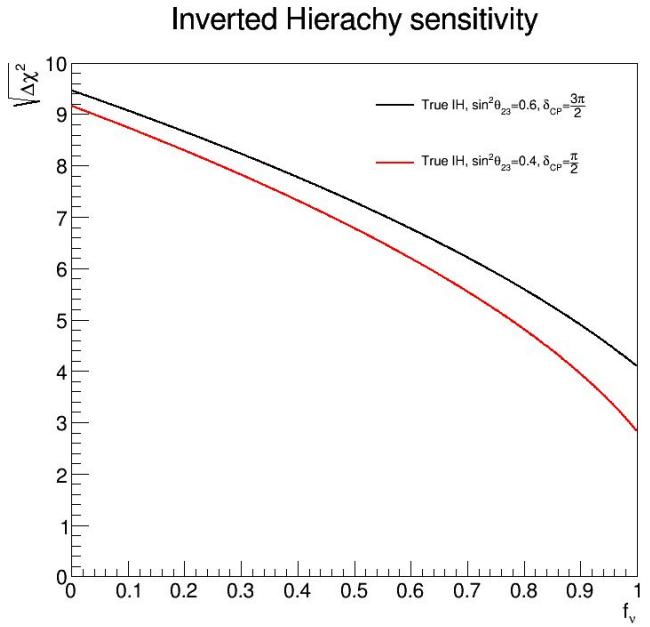


Patricia's lecture

What if...?

Assuming signal events for antineutrino mode, under inverted hierarchy, are 2x as large (sterile neutrinos?)





Conclusion

- All available POT should be dedicated to neutrino mode
  - Independent of unknown oscillation parameters
- Not enough sensitivity in any configuration for 5σ sensitivity
  - DUNE and HyperK useful!
- We learned a lot 🤓