

Physics Potential of NuMI Off-Axis

3rd NuMI Off-Axis Experiment Detector Workshop

Fermilab

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Present Status

- **In the "Standard Model" of neutrino oscillations, there are 8 parameters, 5 of which we know, or will know, reasonably well:**
  - Δm_{23}^2 **(2.5 10^{-3} eV^2)**
  - Δm_{12}^2 **(6.9 10^{-5} eV^2)**
  - **sign(Δm_{12}^2) (+)**
  - **$\sin^2(2\theta_{23})$ (1.0)**
  - **$\sin^2(2\theta_{12})$ (0.83)**



Goal

- **My goal, largely for the FLRP, is to study the ultimate ability of the NuMI off-axis beam(s) to measure the other three parameters:**
  - $\sin^2(2\theta_{13})$
  - $\text{sign}(\Delta m_{13}^2)$
  - δ

$P(\nu_\mu \rightarrow \nu_e)$ (in Vacuum)

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$
  - $P_3 = mJ \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

  where $J = \cos(\theta_{23}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})$ x

  $\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

- **In matter, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.**

$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2} G_F \rho_e} \approx 11\,\text{GeV for the earth's crust.}$$

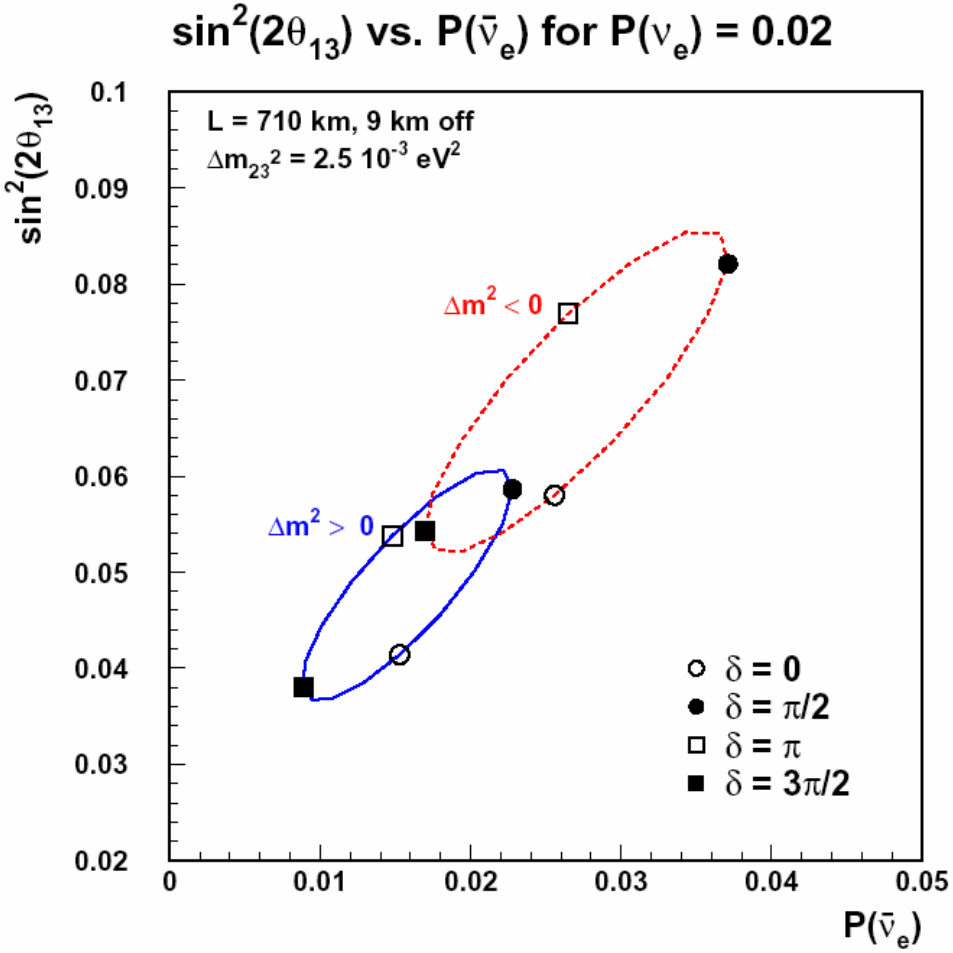
About a 30% effect on P_1 for NuMI, but only a 12% effect for JPARC.



Probability Plots

- **To understand what can be measured, I have constructed some plots similar to the bi-probability plots of Minakata and Nunokawa, but more useful.**
- **Each plot assumes a particular result for a measurement of $P(\nu_\mu \rightarrow \nu_e)$ and shows the possible values of $\sin^2(2\theta_{13})$, $\text{sign}(\Delta m_{13}^2)$, and δ versus the result of another measurement.**

$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 710 km



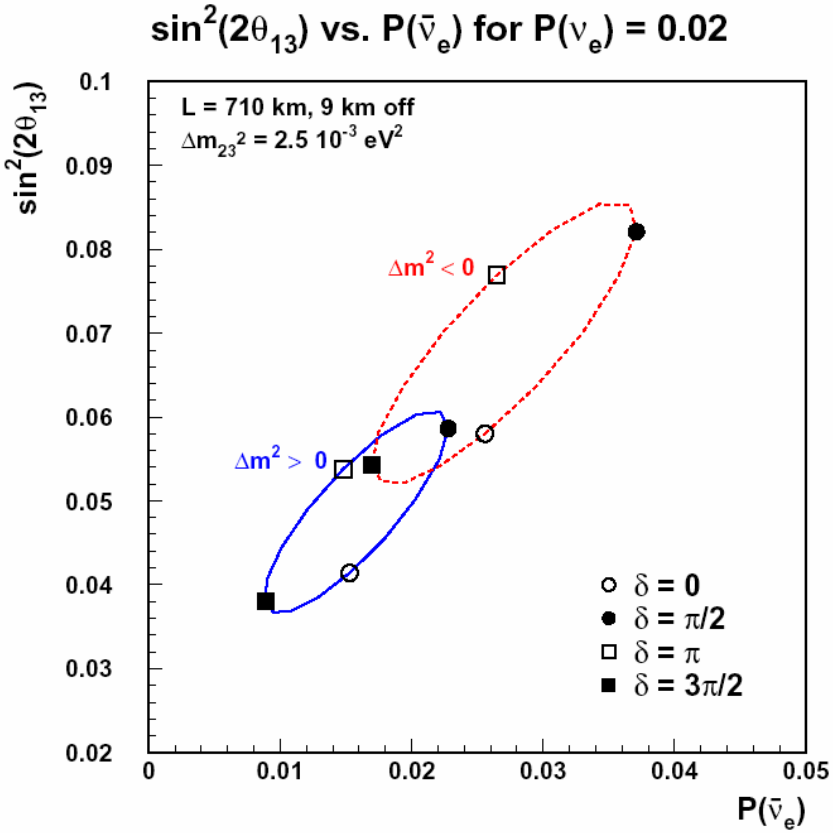
Note

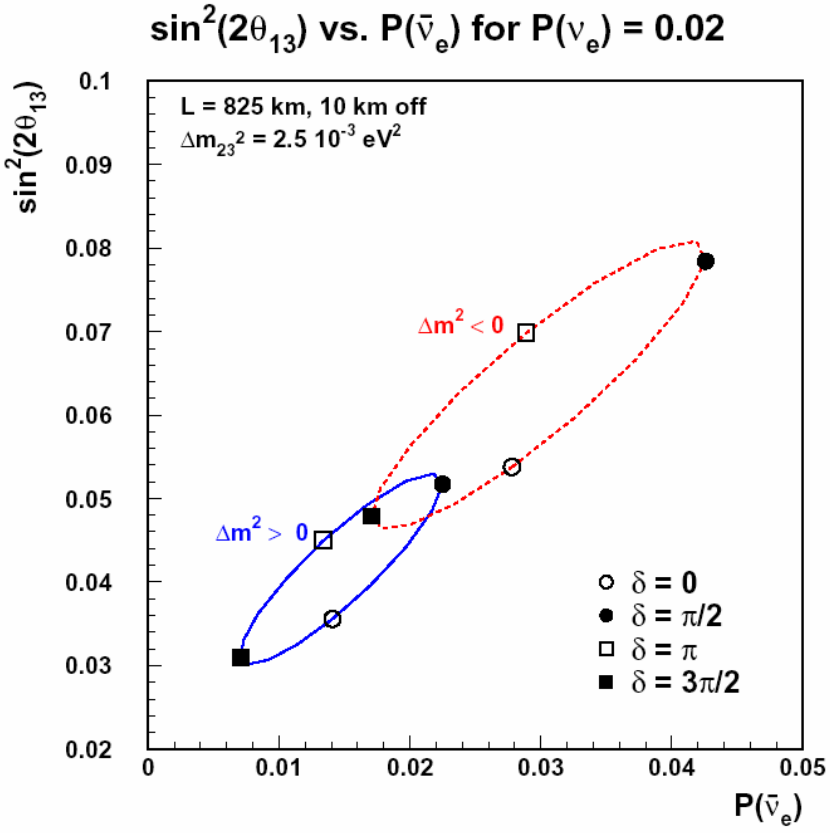
(1) Effect of cos(δ) term

(2) Ambiguities

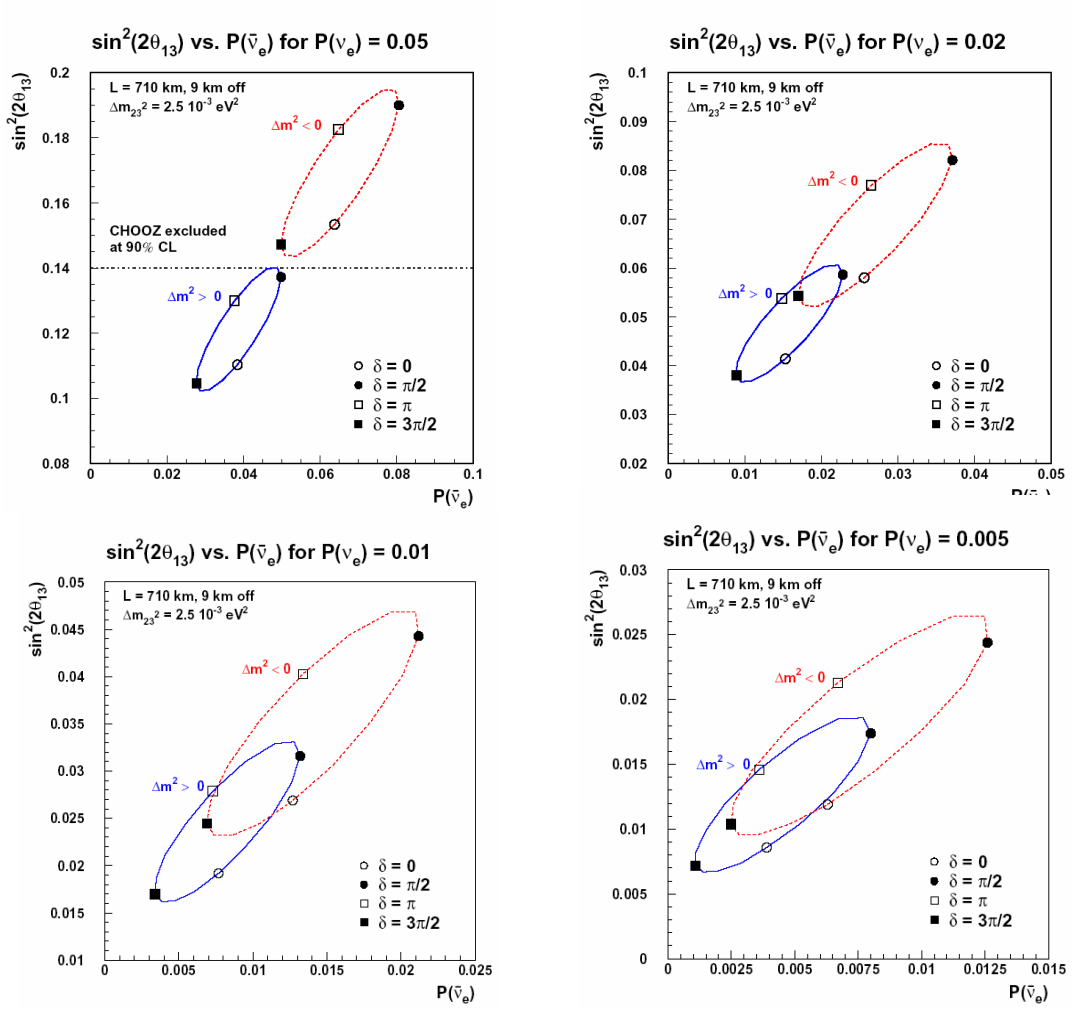
(3) Rough equivalence of reactor and antineutrino measurements

$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 710 and 825 km

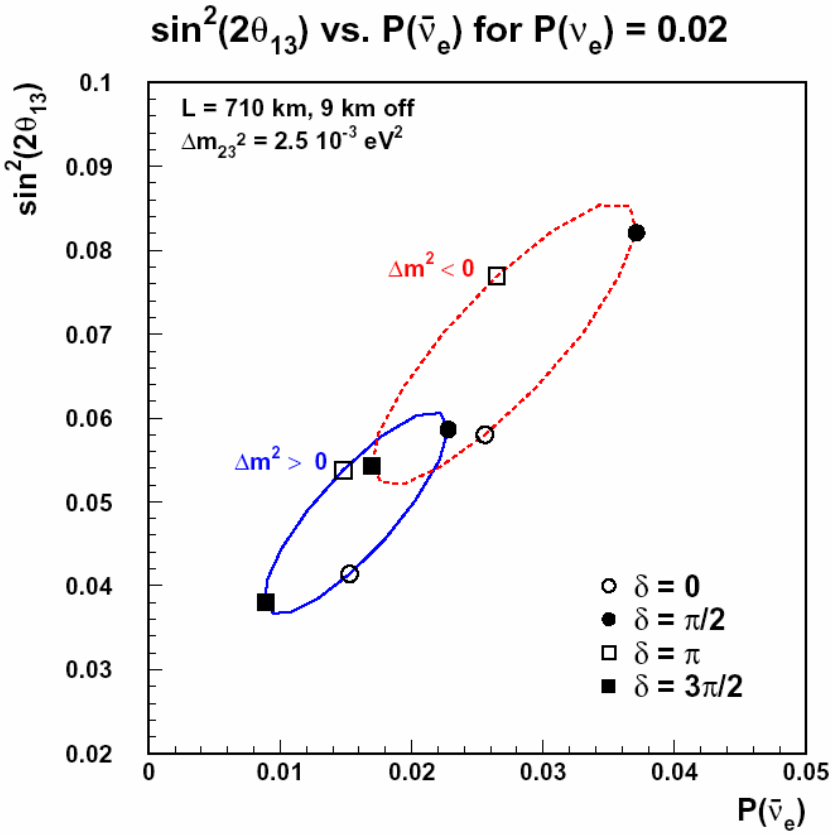


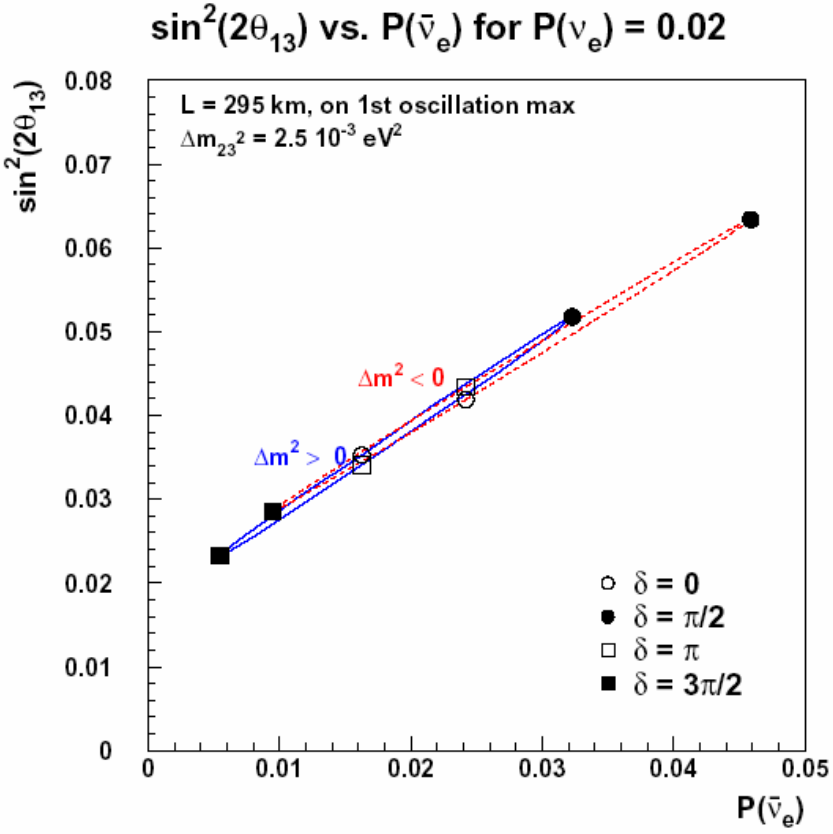


$P(\nu_\mu \rightarrow \nu_e)$ = 0.05, 0.02, 0.01, and 0.005 at 710 km

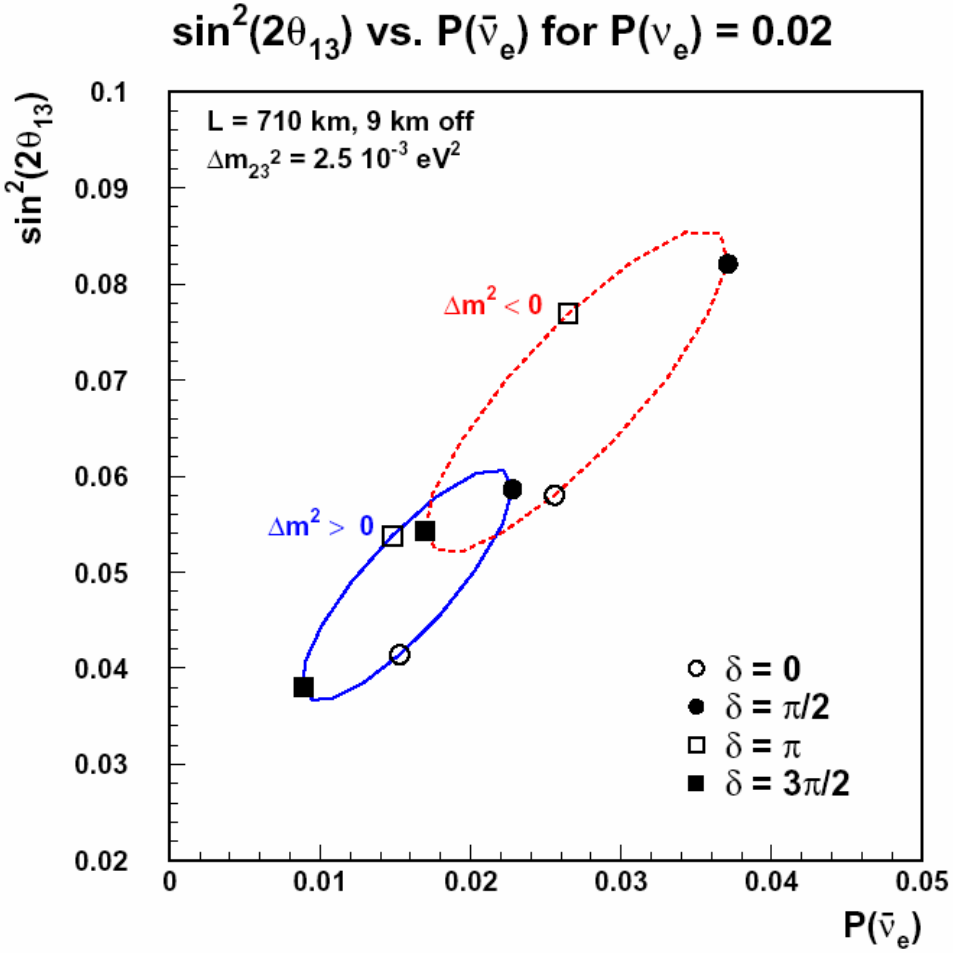


$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 710 and 295 km





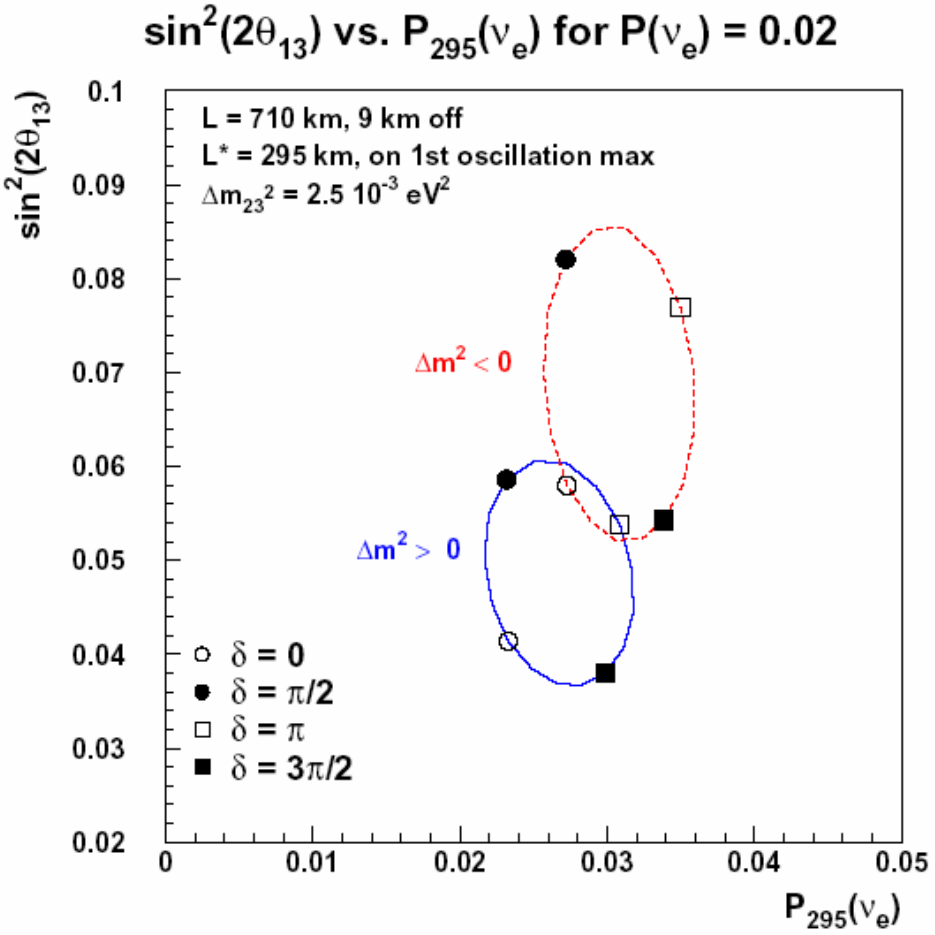
$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 710 km



Note ambiguities between no CP violation for normal hierarchy and maximal CP violation for inverted hierarchy and vice-versa.

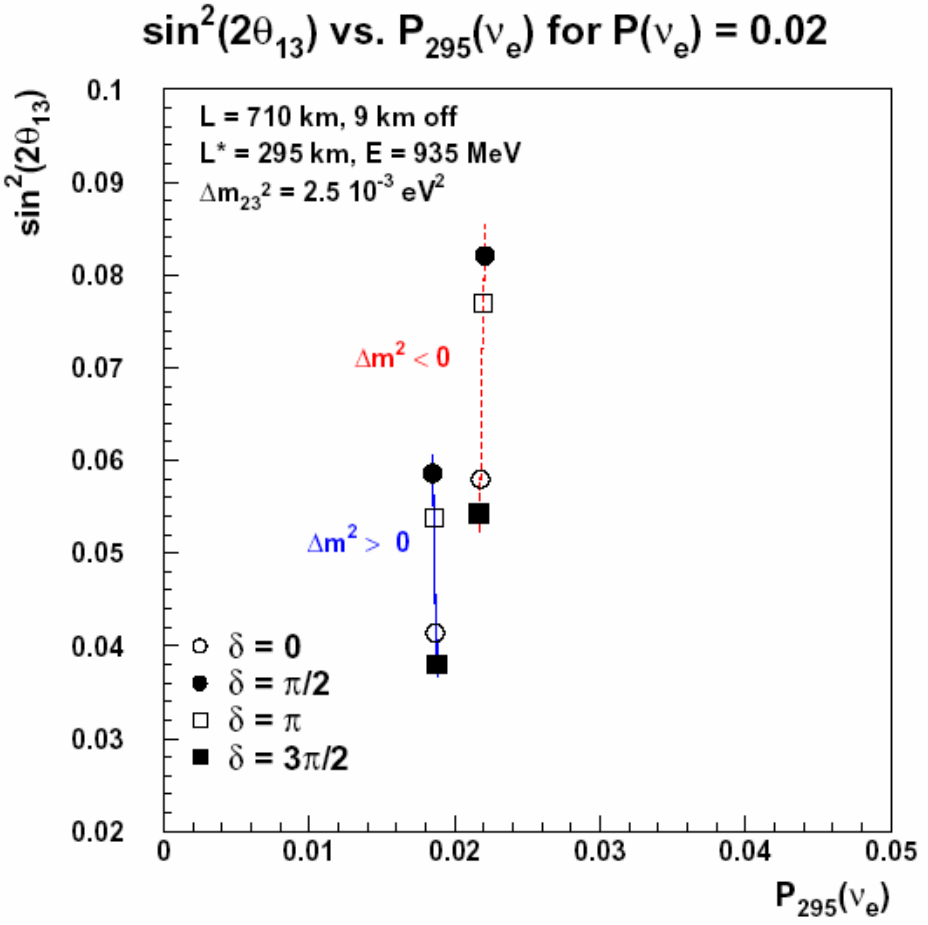
Can JPARC help?

$P(\nu_\mu \rightarrow \nu_e)$ = 0.02 at 710 km vs. $P(\nu_\mu \rightarrow \nu_e)$ at 295 km



As warned by Parke et al., hierarchy is not resolved by just neutrino running.

Same, but Smaller Off-Axis Angle at 295 km



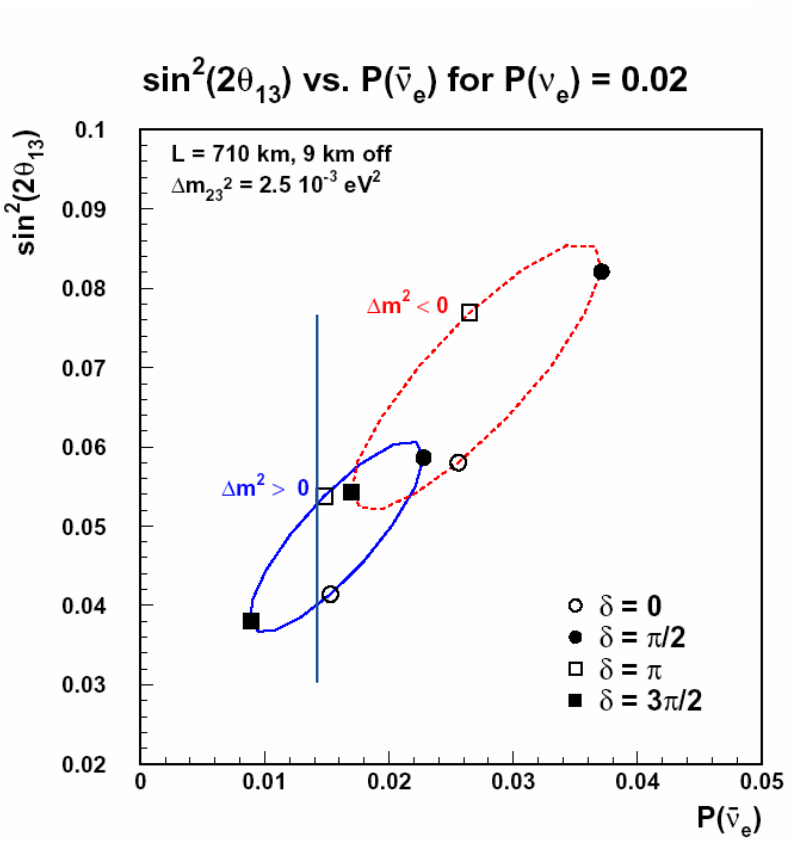
Hierarchy now resolved in principle, but difference is very small.

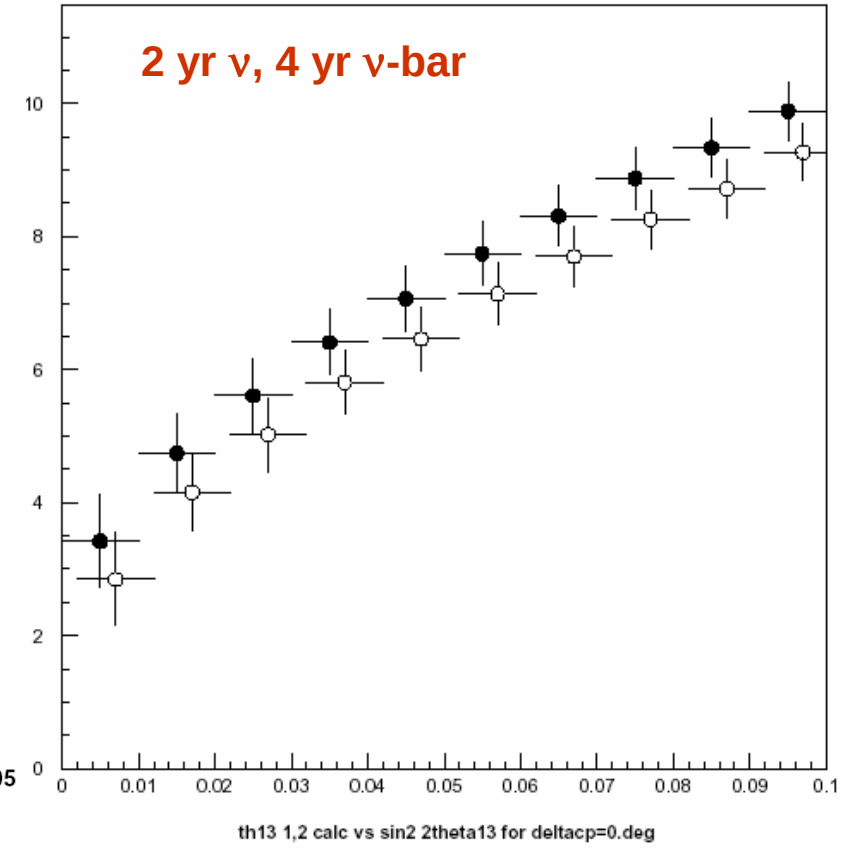
Sensitivities

- We now want to consider sensitivities.
- Two approaches:
  - Leslie and Adam have been throwing experiments and plotting the distribution of central values.
  - I consider one experiment (or one set of experiments) with the expected results and calculate 1, 2, and 3 σ contours based on $\Delta\chi^2$'s.

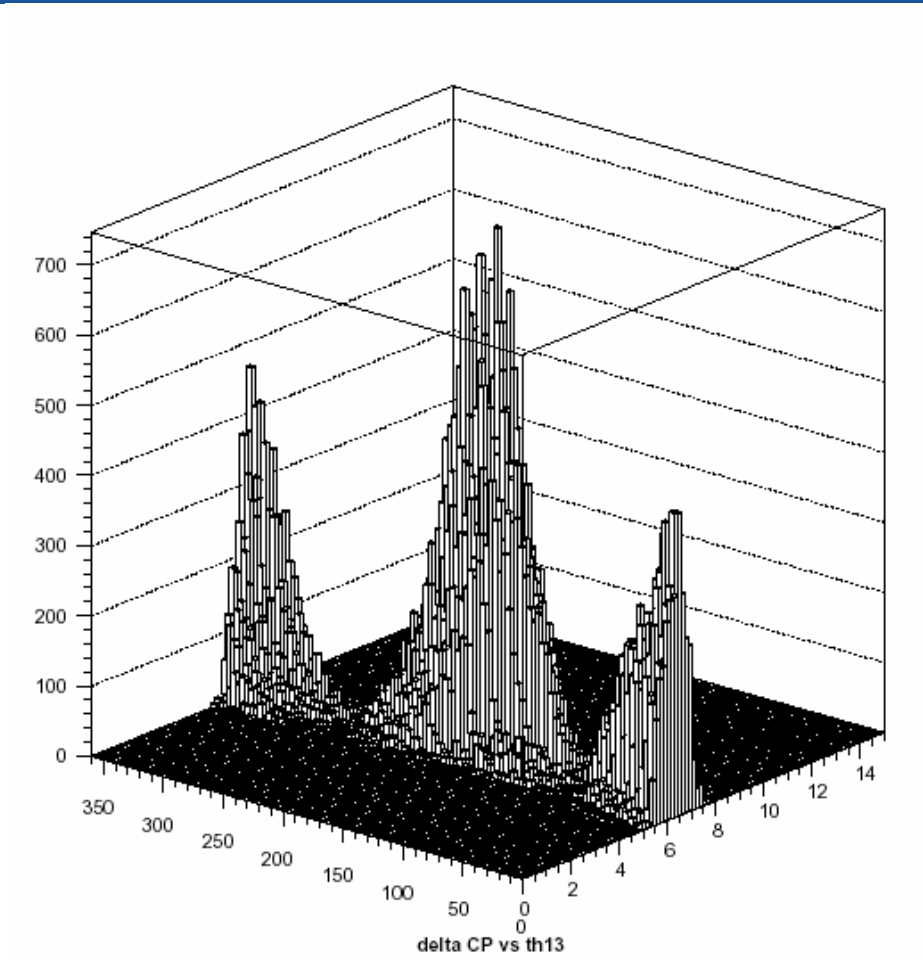
    I assume 5% systematic error on the background.
- These approaches should give comparable results.

LC: θ_{13} Reconstructed vs. $\sin^2(2\theta_{13})$ Input

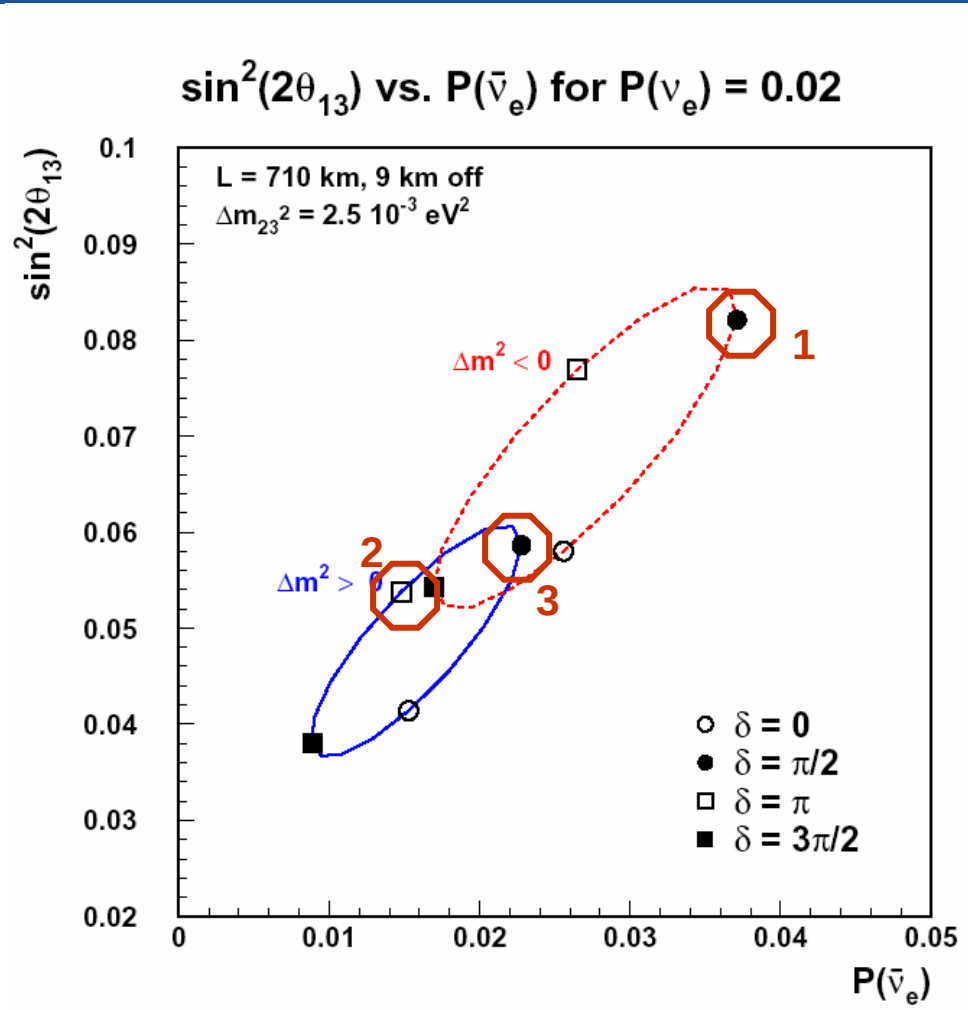




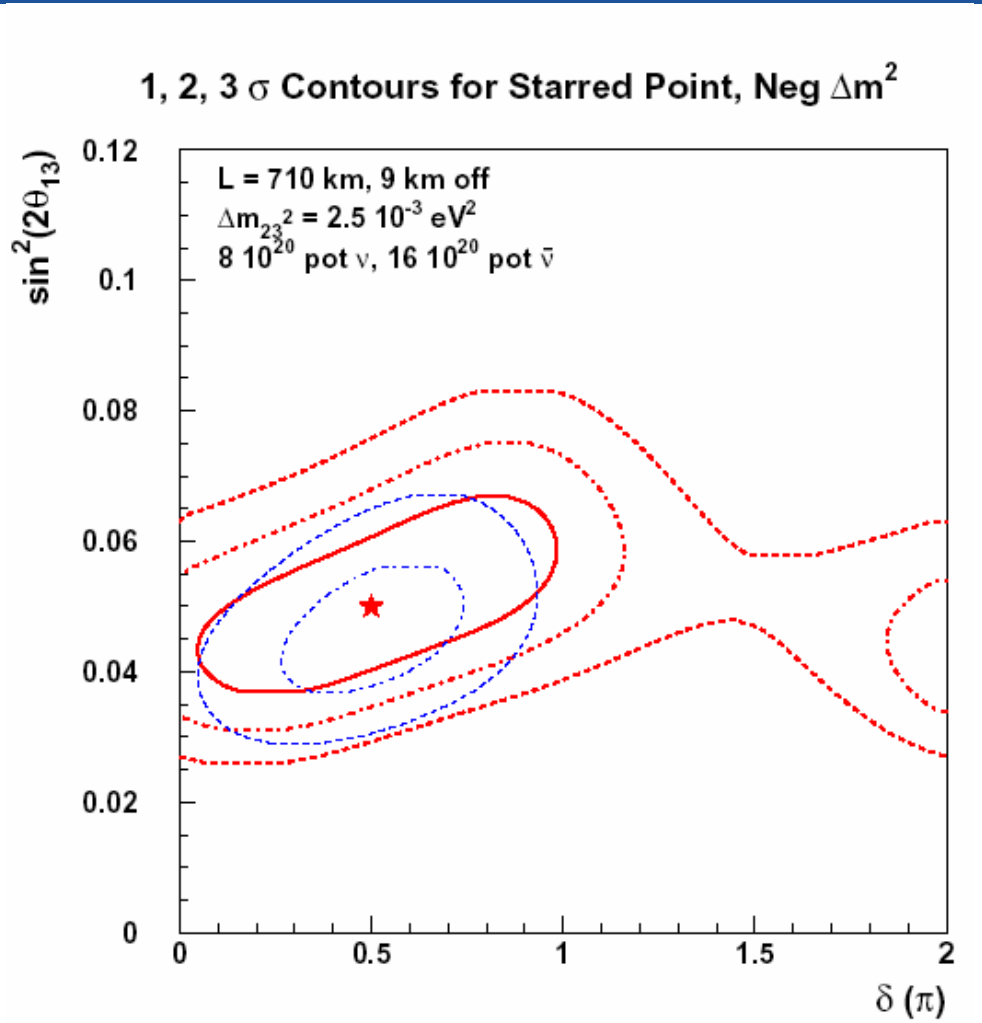
LC: θ_{13} vs. δ for $\sin^2(2\theta_{13}) = 0.05$ input



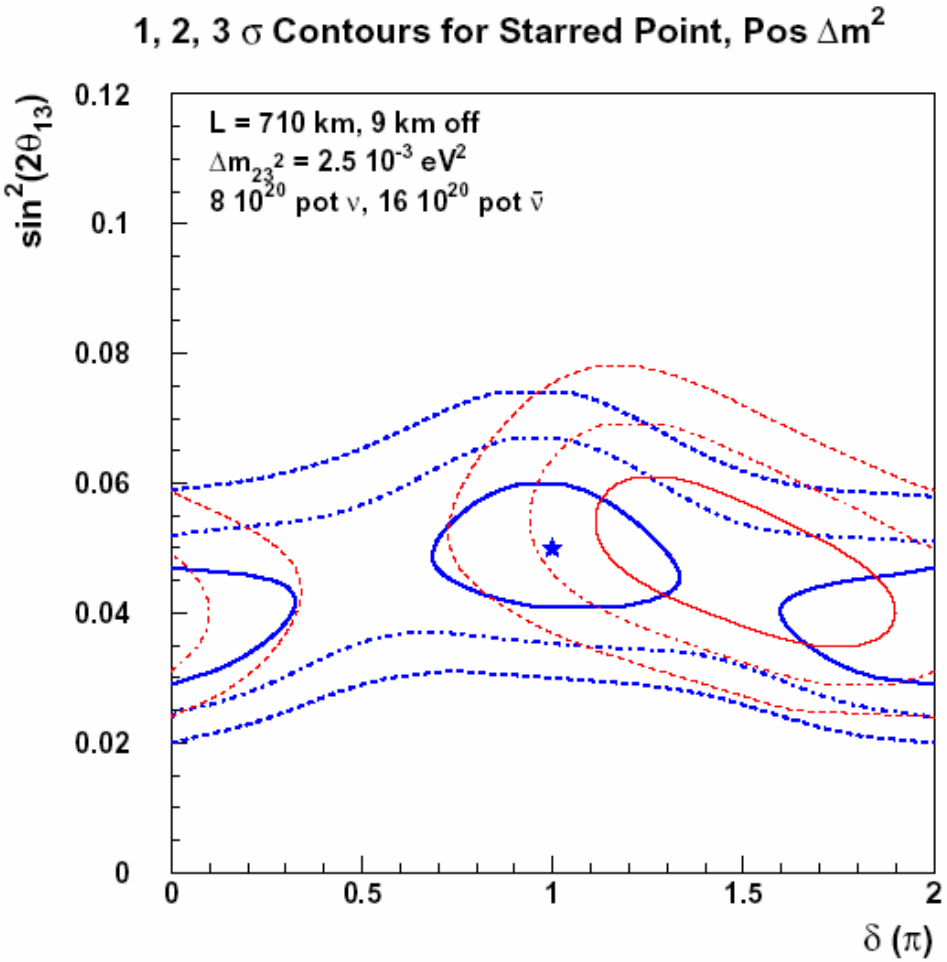
Study Points



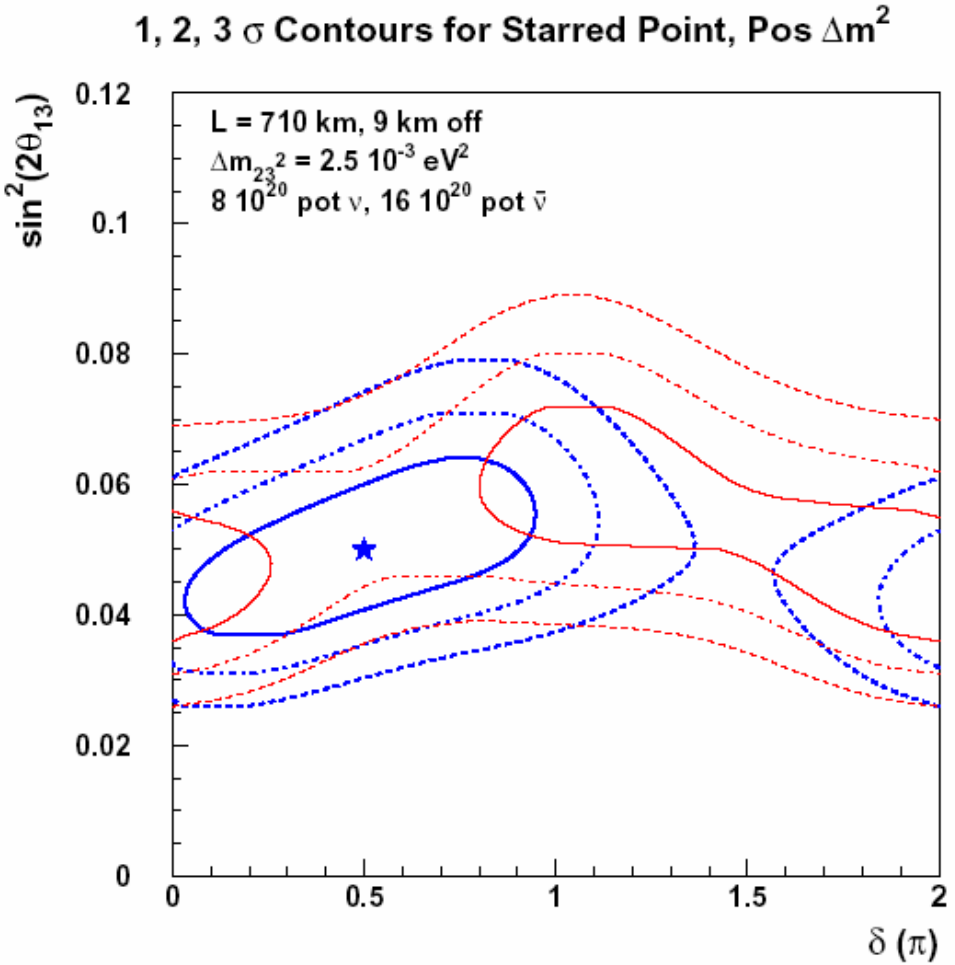
Point 1


1, 2, 3 σ Contours for Starred Point, Neg Δm²
L = 710 km, 9 km off
Δm²₂₃ = 2.5 10⁻³ eV²
8 10²⁰ pot ν, 16 10²⁰ pot ν̄
sin²(2θ₁₃)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
δ (π)

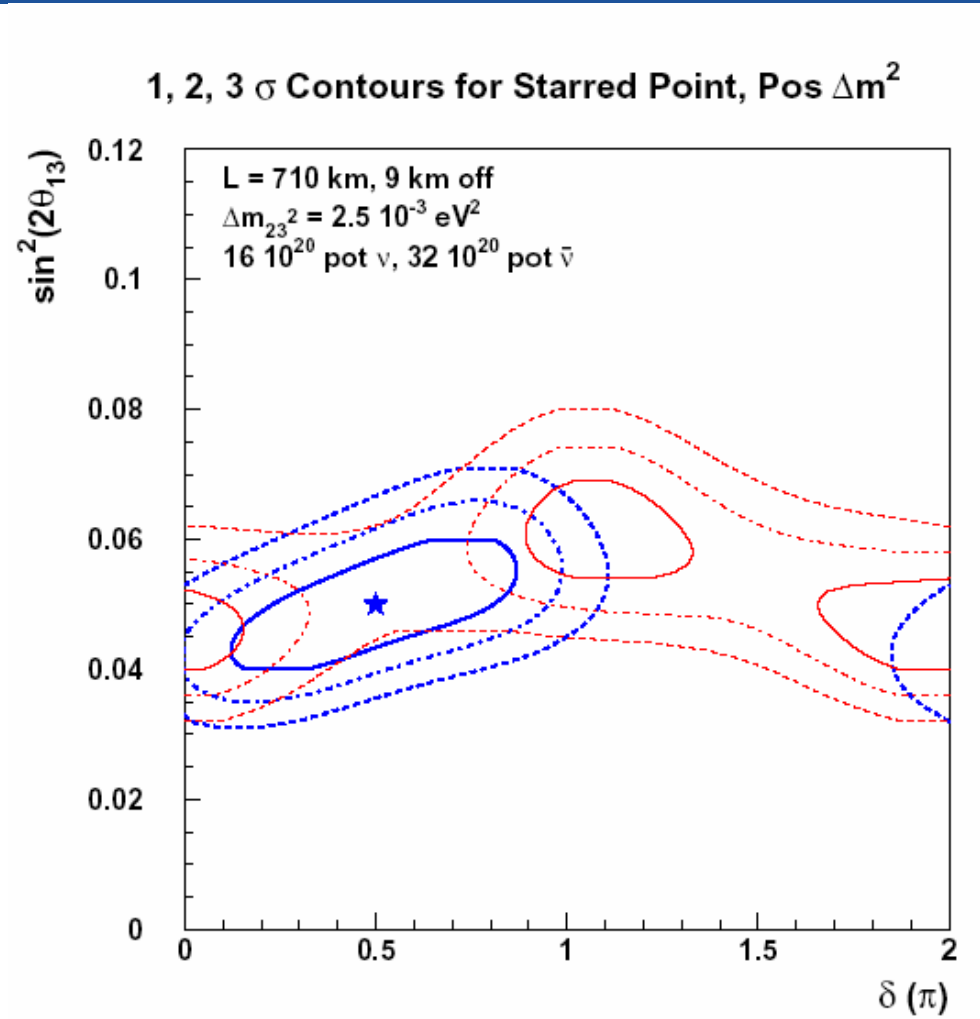
Point 2


1, 2, 3 σ Contours for Starred Point, Pos Δm²
L = 710 km, 9 km off
Δm²₂₃ = 2.5 10⁻³ eV²
8 10²⁰ pot ν, 16 10²⁰ pot ν̄
sin²(2θ₁₃)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
δ (π)

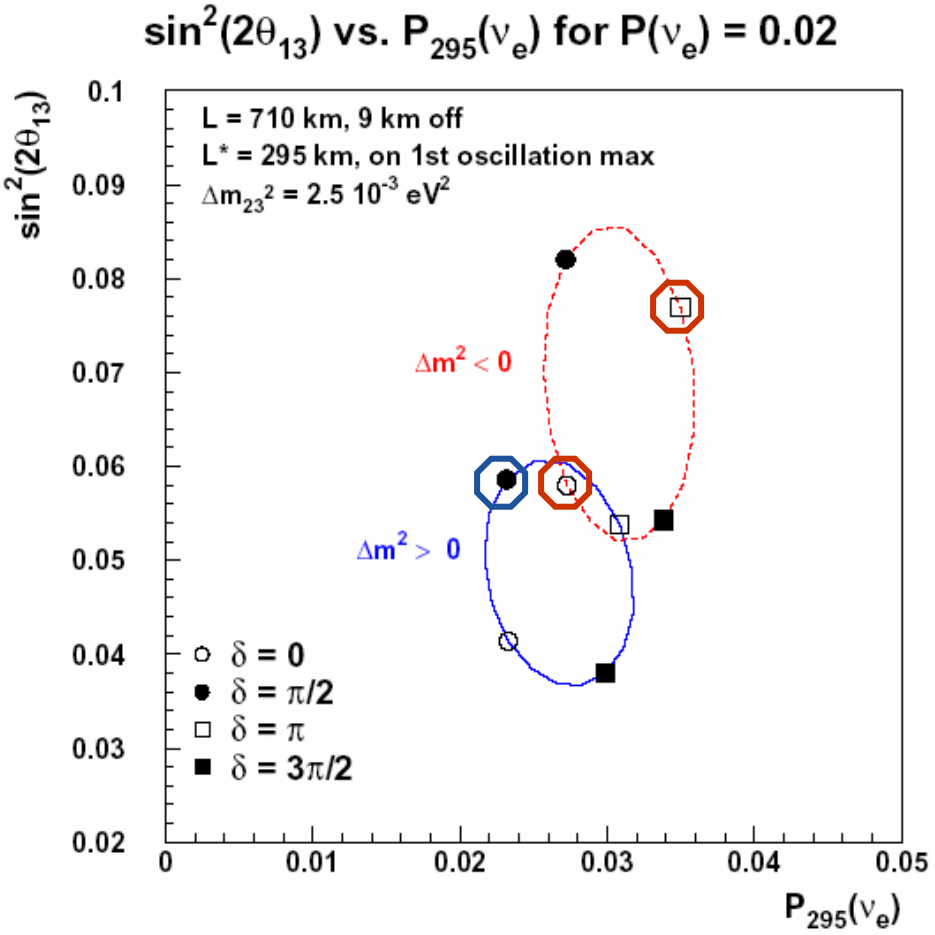
Point 3


1, 2, 3 σ Contours for Starred Point, Pos Δm²
L = 710 km, 9 km off
Δm²₂₃ = 2.5 10⁻³ eV²
8 10²⁰ pot ν, 16 10²⁰ pot ν̄
sin²(2θ₁₃)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
δ (π)

Point 3 with Double Intensity

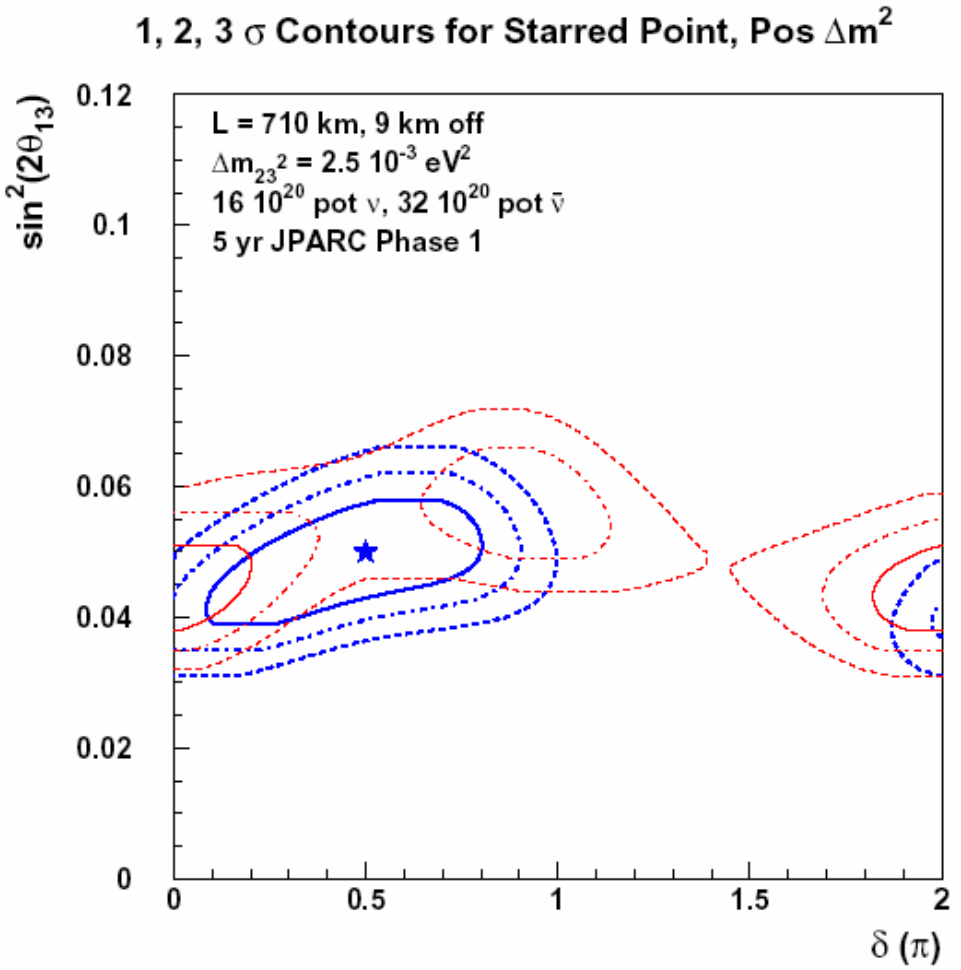


Combine with JPARC?

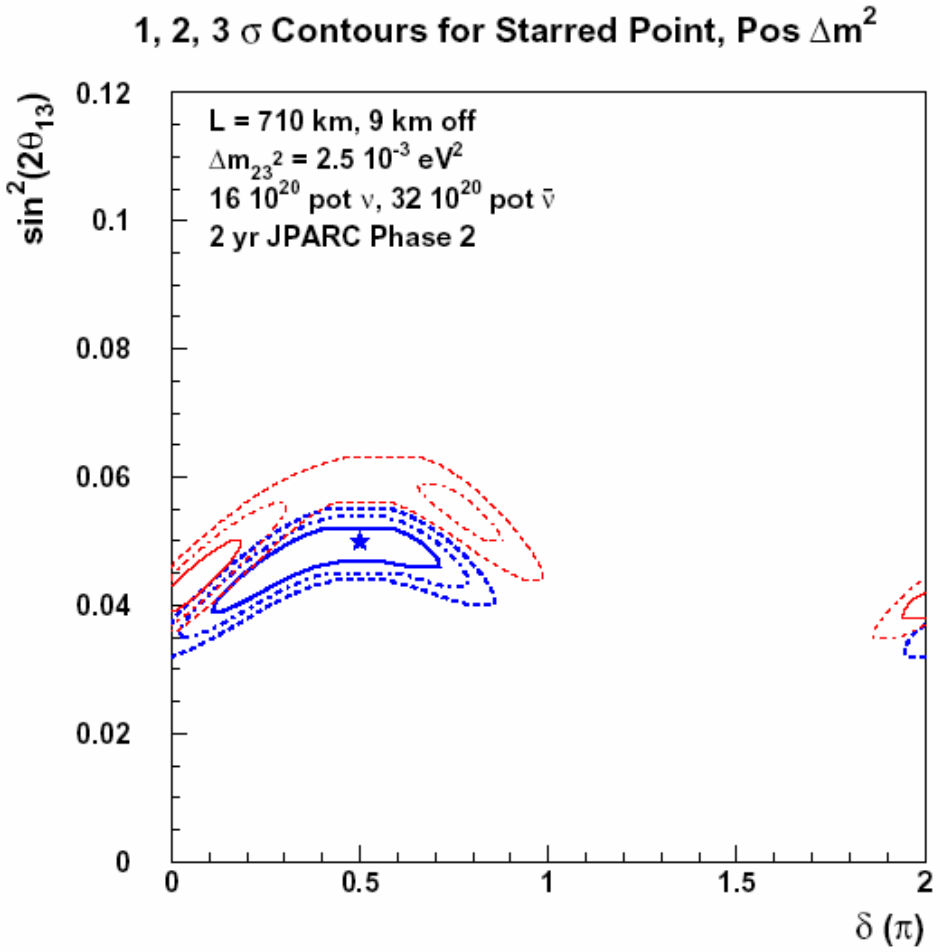


In principle, this can resolve the hierarchy.

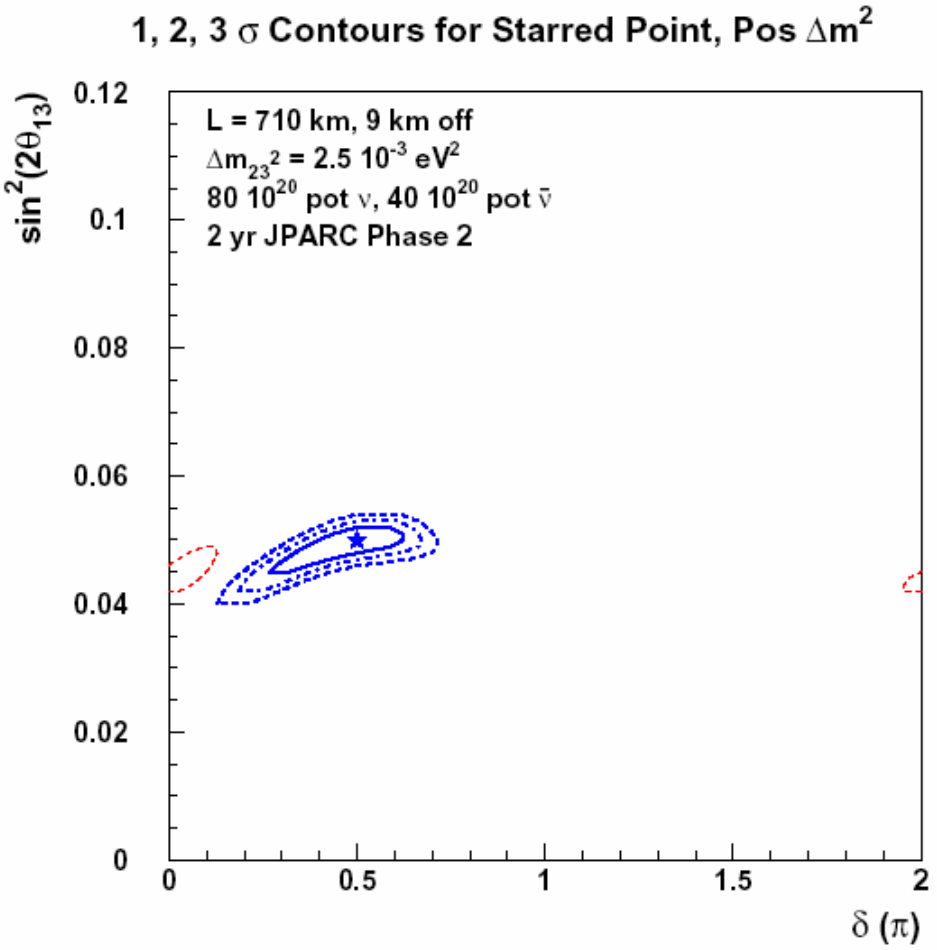
Point 3, Double Intensity and JPARC, Phase 1



Point 3, Double Intensity and JPARC, Phase 2



Point 3, Proton Driver and JPARC, Phase 2



Hierarchy finally resolvable at > 95% CL with 6 yrs of proton driver.

Is 2nd Maximum Better?

