Systematic Uncertainties in the Short Baseline Neutrino Program at Fermilab

Corey Adams, Yale University

Why SBN @ FNAL?

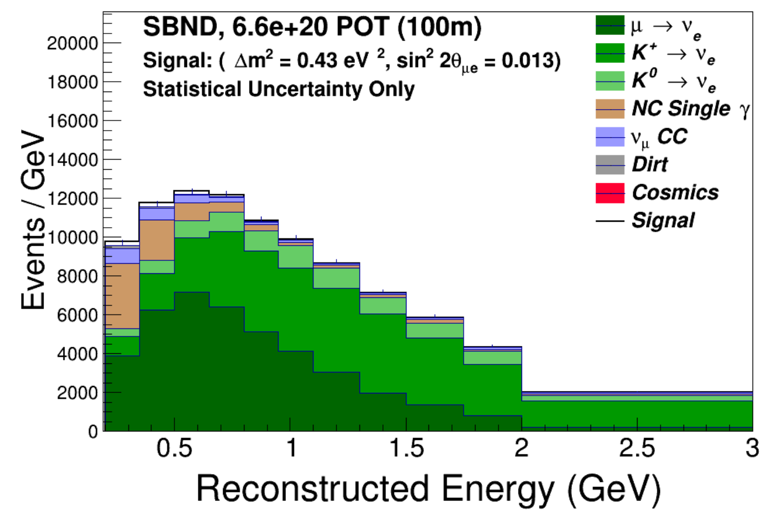
Two main advantages:

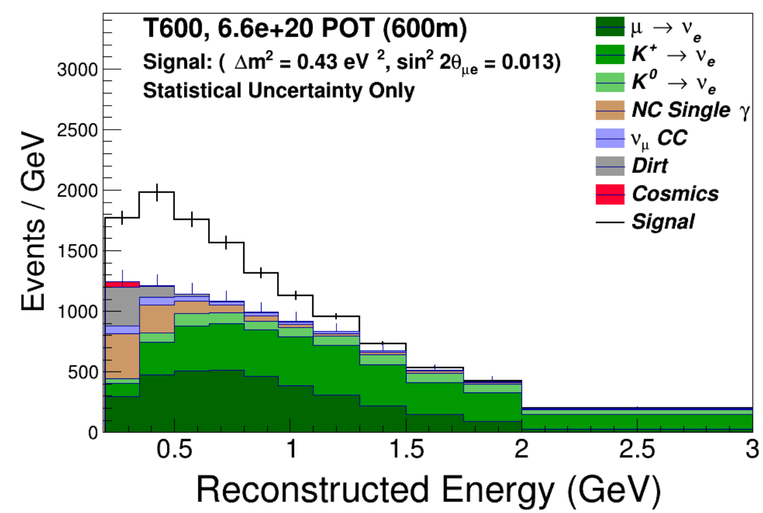
1) High precision detectors allow multiple physics searches in the same beam, with the same detectors, at the same time.
   - If you want to make a definitive statement about sterile oscillations, having multiple signals in the same experiment can really boost the credibility of “oscillations” as the culprit.

2) Strongly correlated uncertainties between detectors allow excellent sensitivity to new signals across analyses.

SBN Oscillation Sensitivity

- What would a signal look like?
- What's the significance of that signal?
  - What uncertainties in the background estimate matter, and how do you propagate them to the final calculation?
- How to accurately model and account for correlated uncertainties?





How to Compute Uncertainty

- **We need to propagate the uncertainty in our simulations to the uncertainty in our event rate predictions.**
- How do we know the error on the number of events expected that originates from, say, uncertainty on hadron production at the target?

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Figure 1: The Multiverse, an essential ingredient to error propagation.

Example: GENIE

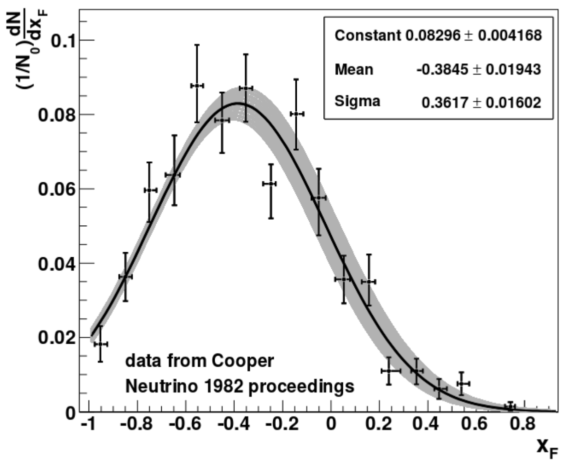

Figure 9.3: Nucleon Feynman x (x_F) pdf used in the GENIE AGKY model for generating the kinematics of 2-body $N + \pi$ primary hadronic systems.

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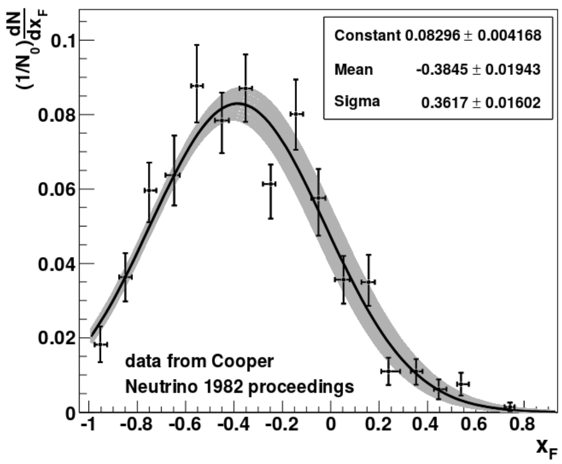

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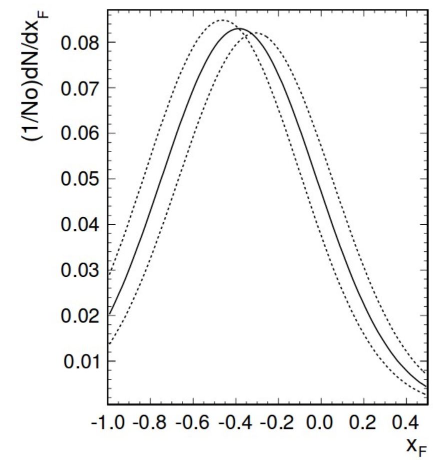

Figure 9.5: Default x_F pdf (solid line) and tweaked pdfs (dotted lines) resulting from modifying the $x^{xF1\pi}_{AGKY}$ systematic parameter by ±1.

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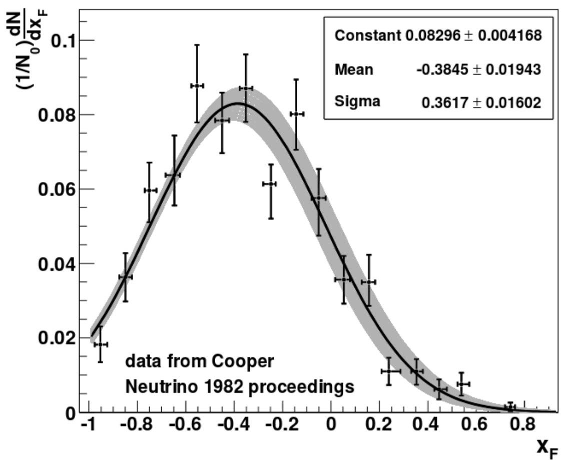

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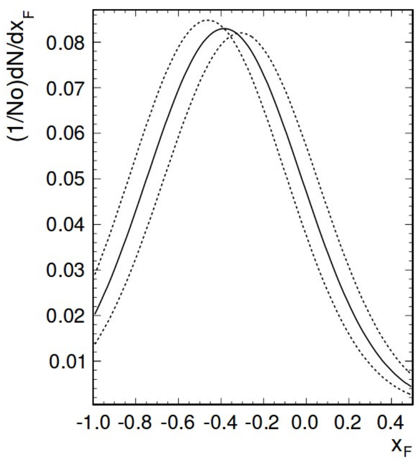

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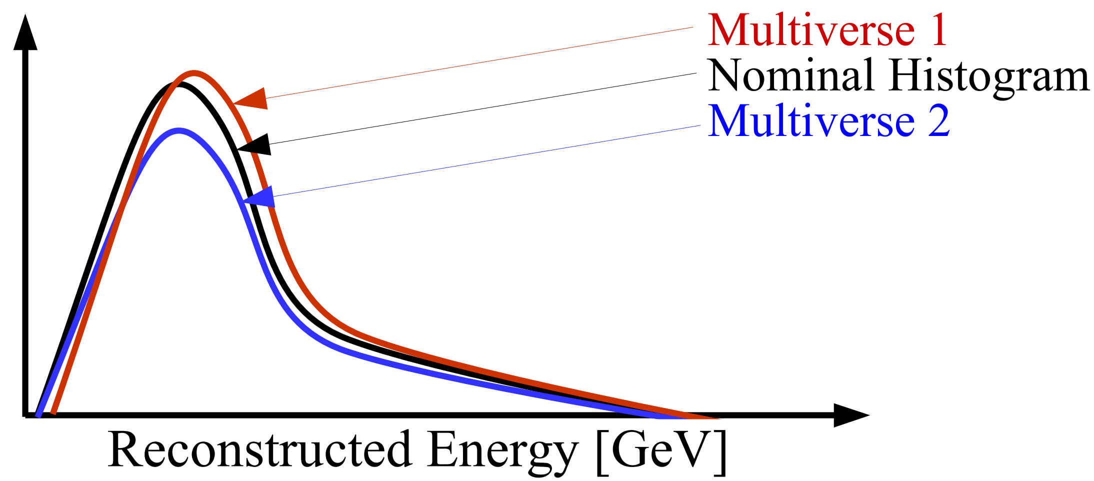
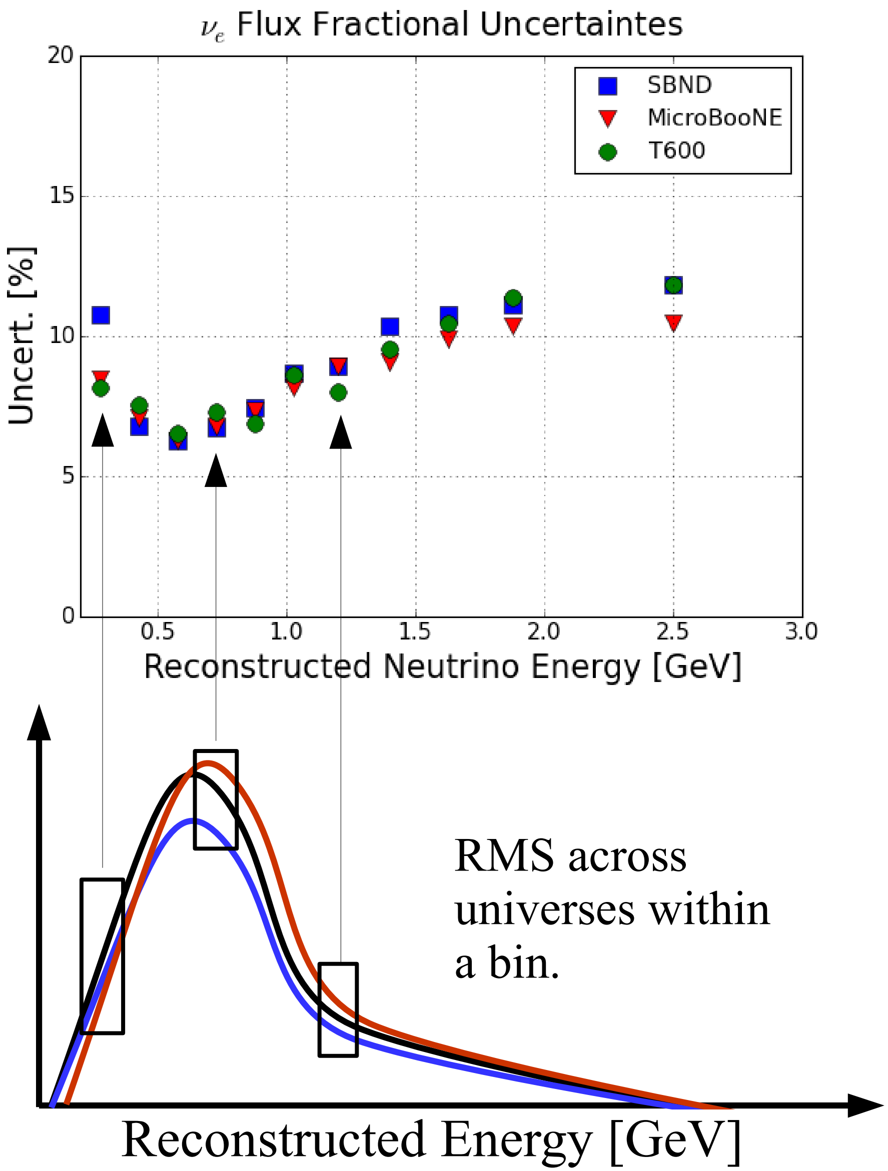


Propagated Uncertainties



RMS across universes within a bin.

Source of Uncertainty	ν_μ	ν_e
π^+ production	14.7%	9.3%
π^- production	0.0%	0.0%
K^+ production	0.9%	11.5%
K^0 production	0.0%	2.1%
Horn field	2.2%	0.6%
Nucleon cross sections	2.8%	3.3%
Pion cross sections	1.2%	0.8%

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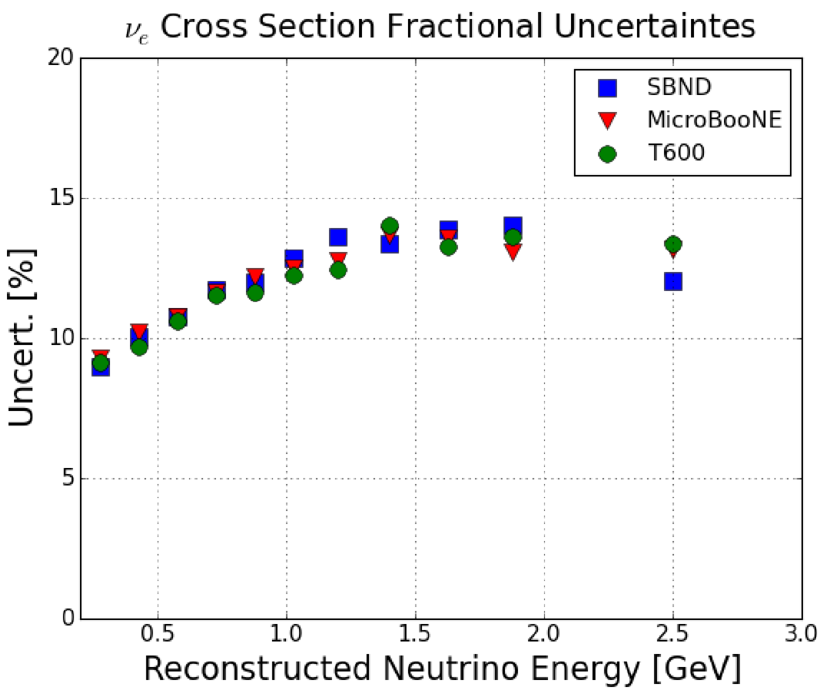

Parameter	1σ Uncertainty (%)
M_A^{CCQE}	-15%+25%
M_A^{CCRES}	$\pm$20%
M_A^{NCRES}	$\pm$20%
$R_{bkg}^{\nu p,CC1\pi}$	$\pm$50%
$R_{bkg}^{\nu p,CC2\pi}$	$\pm$50%
$R_{bkg}^{\nu n,CC1\pi}$	$\pm$50%
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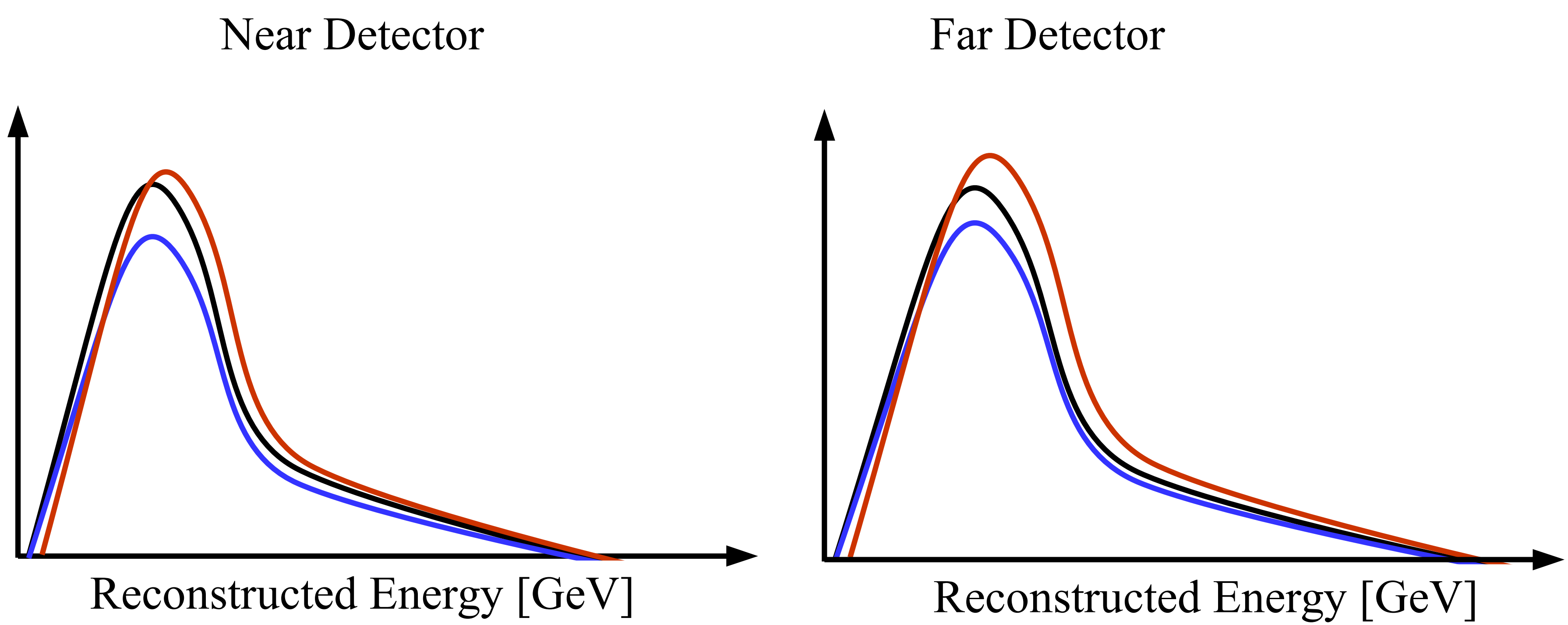
$R_{bkg}^{\nu n,NC1\pi}$	$\pm$50%
$R_{bkg}^{\nu n,NC2\pi}$	$\pm$50%
NC	$\pm$25%
DIS-NuclMod	Model switch

Correlated Detectors

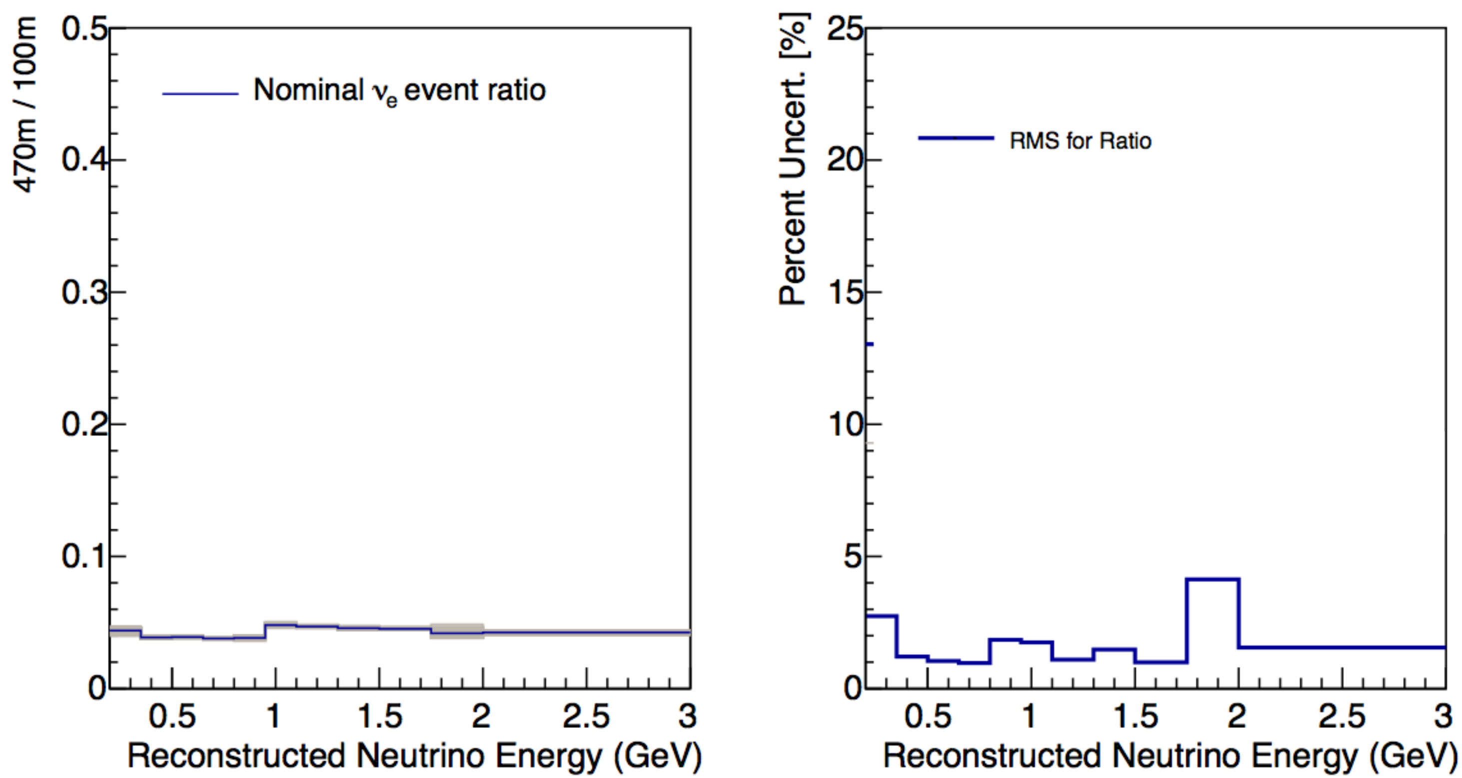
The flux and cross-section uncertainties in each detector are highly correlated.

How to take advantage of that?



Correlated Universes

- Ratio of Near to Far should be **much** less variable in across all multiverses.



Grey band is ALL ratios plotted on top of each other.

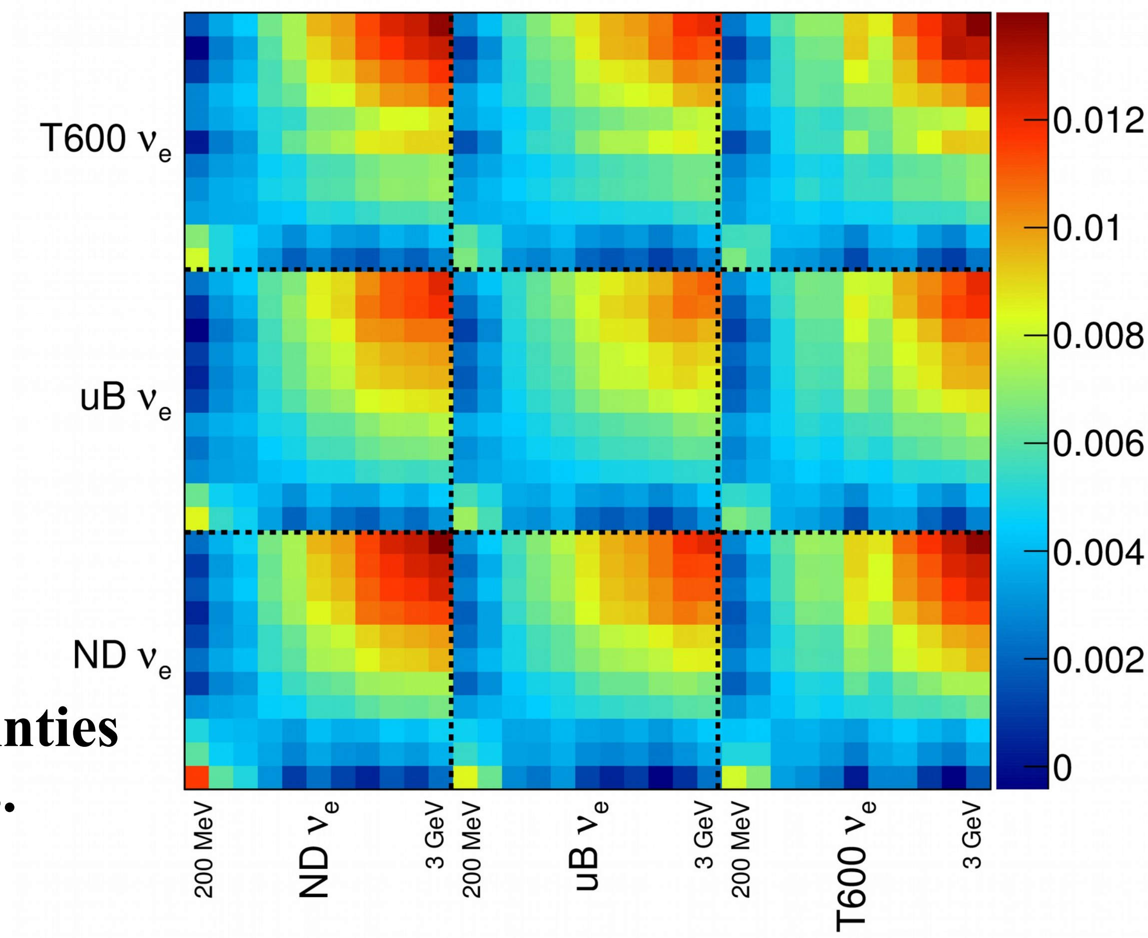
Covariance Matrix

$$E_{i,j} = \sum_{m\ Universes} [N^i_{nom.} - N^i_{\text{Univ. } m}][N^j_{nom.} - N^j_{\text{Univ. } m}]$$

This is actually the fractional covariance matrix for the flux multiverse:

$$F_{i,j} \equiv \frac{E_{i,j}}{N^i_{nom.} N^j_{nom}}$$

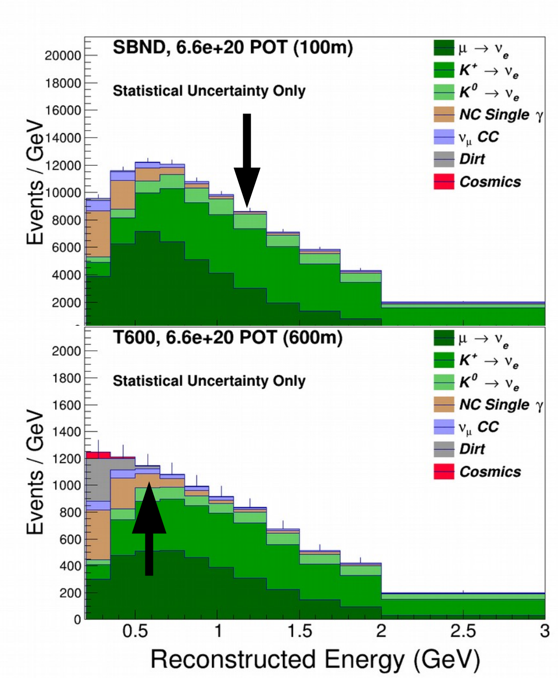
This is the statistical tool for quantifying the correlated uncertainties on our background predictions.

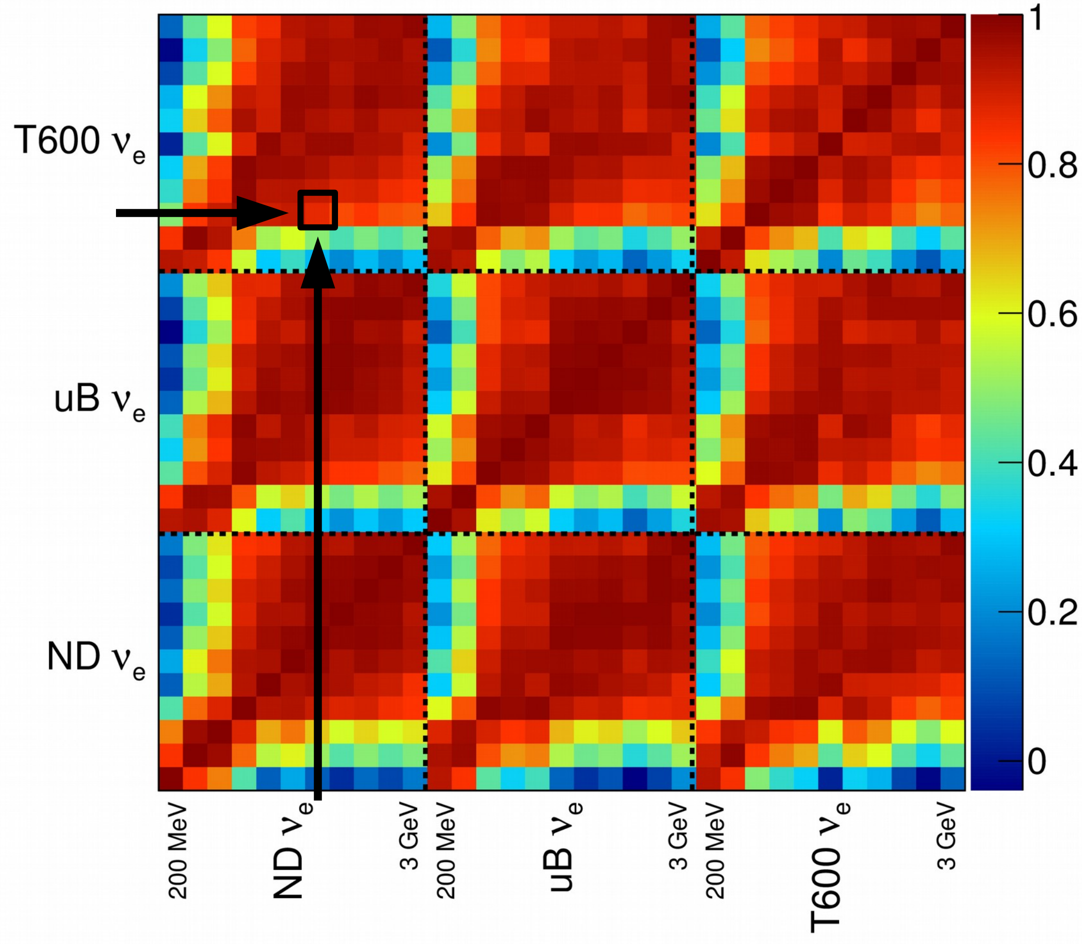


Correlation Matrix

Question: How much does the third analysis bin at the far detector vary in step with the seventh bin at the near detector?

$$C_{i,j} = \frac{E_{i,j}}{\sqrt{E_{i,i}}\sqrt{E_{j,j}}}$$





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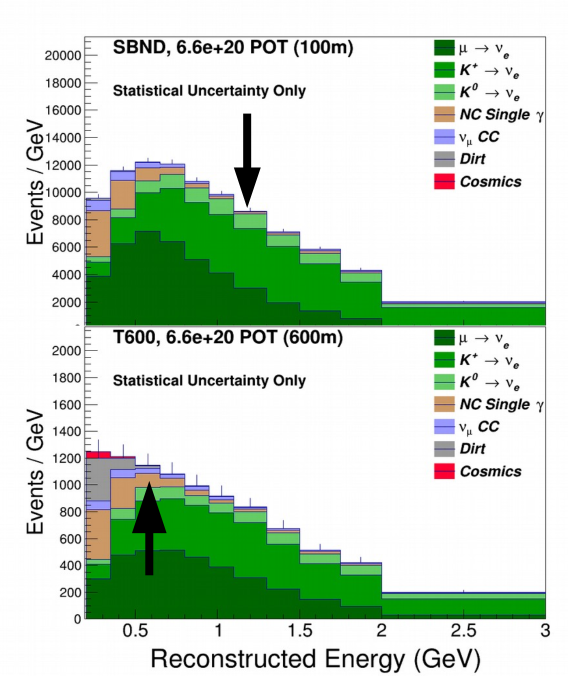

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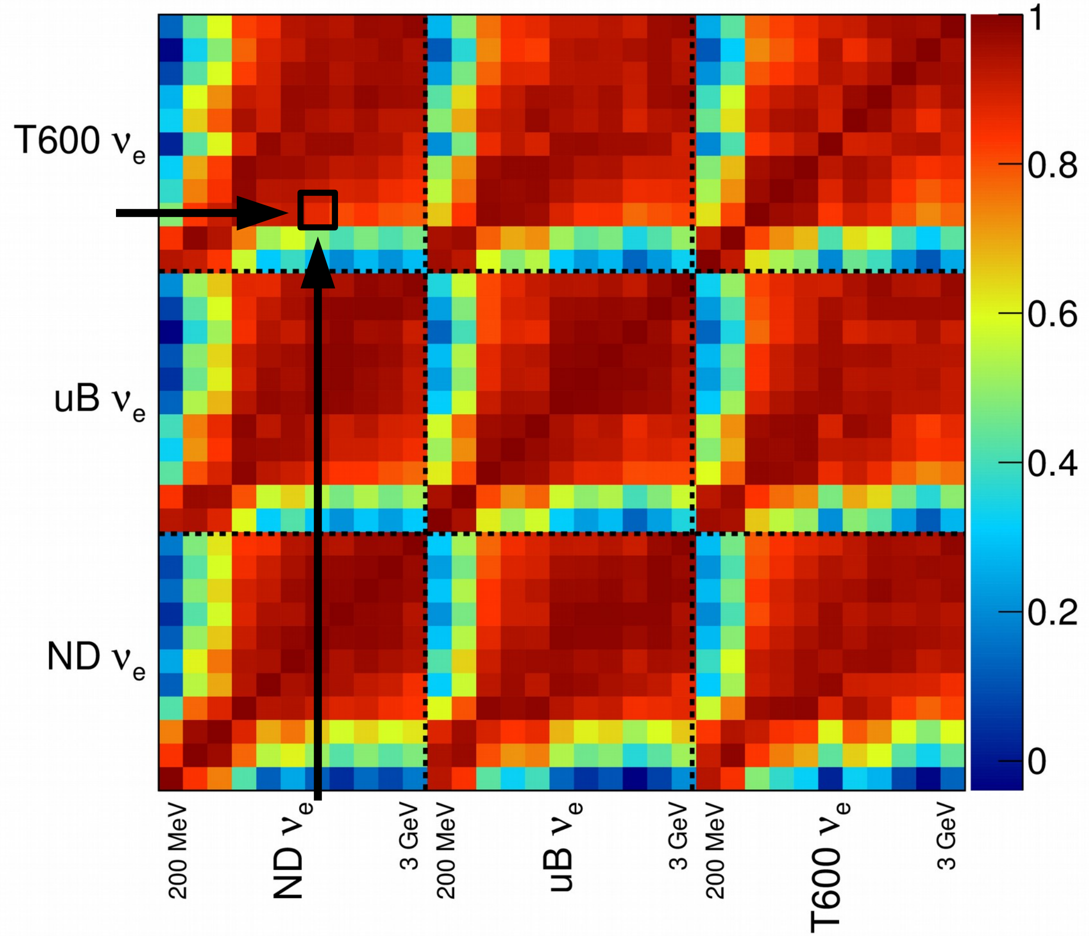

Answer: A lot! ~70% (by eye).

Simulating a Signal

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{\mu e} \times \sin\left(1.267 \frac{\mathrm{GeV}}{\mathrm{eV}^2\mathrm{km}} \frac{L}{E} \Delta m^2_{41}\right)$$

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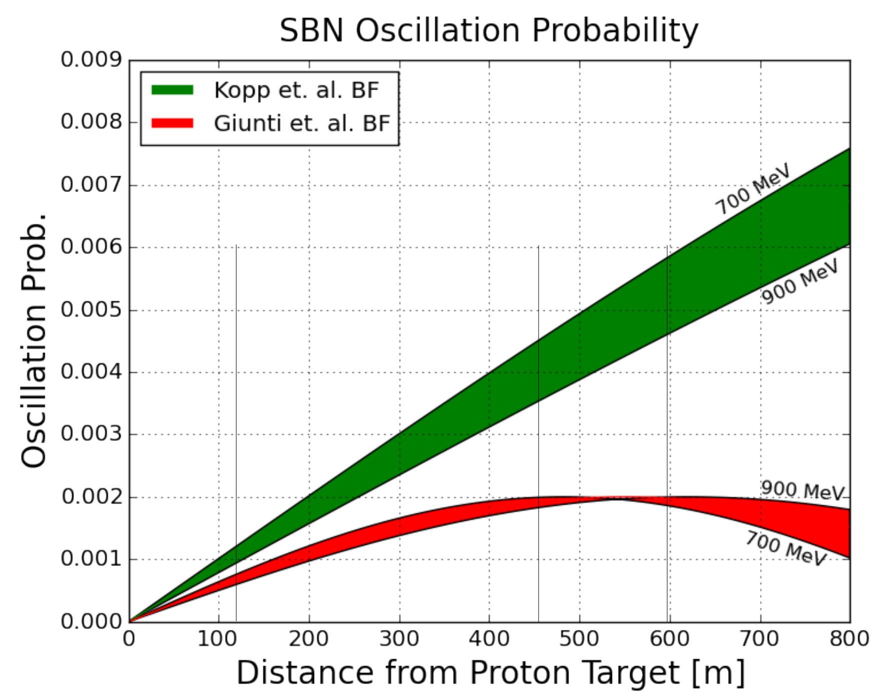

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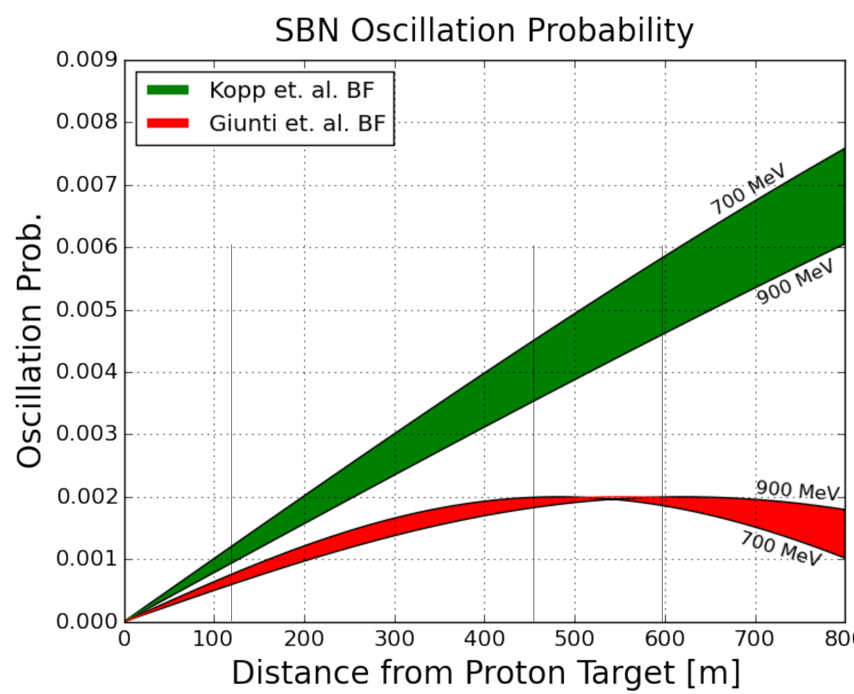
The muon neutrino spectrum is scaled neutrino-by-neutrino to form a signal simulation for each mixing angle and mass splitting combination.



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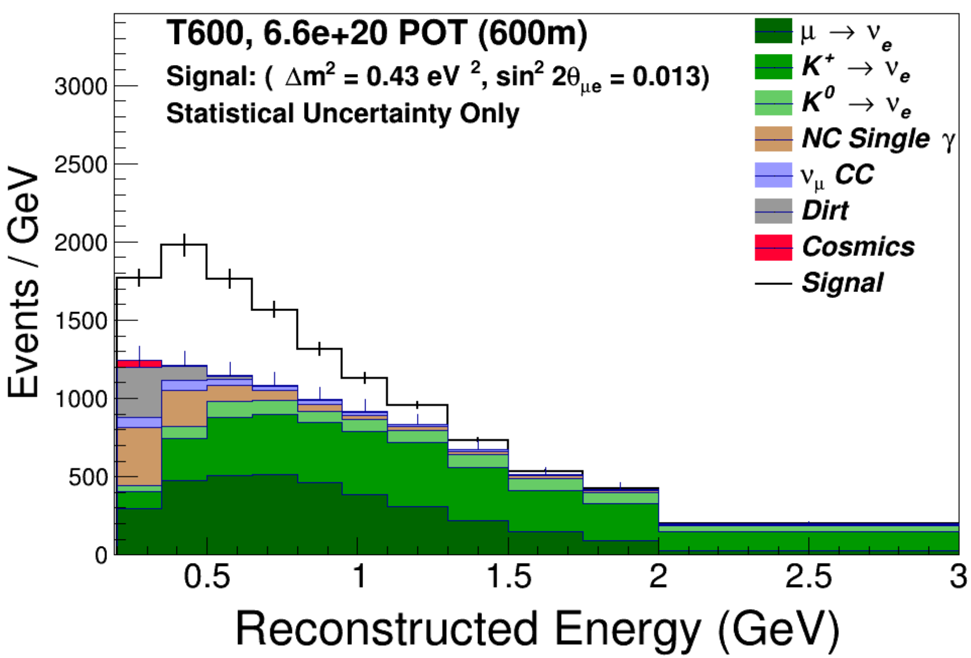

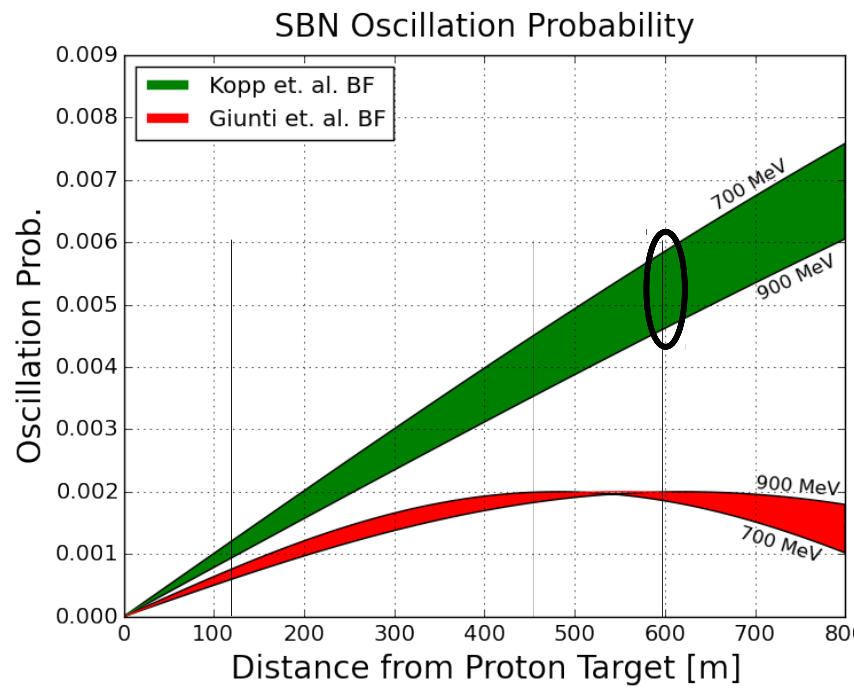

Covariance Matrix

- Correlation Matrix is great for understanding the near to far behavior of uncertainties, but the related **full covariance matrix** is used for sensitivity calculations:

$$\chi^2 \equiv \sum_{i.j} [N^i_{sig}(\Delta m^2, \sin^2 2\theta)](E^{total}_{i,j})^{-1}[N^j_{sig}(\Delta m^2, \sin^2 2\theta)]$$

$$E^{total} = E^{flux} + E^{xsec} + E^{cosmic} + E^{B.I.T.E} + E^{det} + E^{stat}$$

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Computed from Monte Carlo

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Measured in Data

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Will be measured with Monte Carlo

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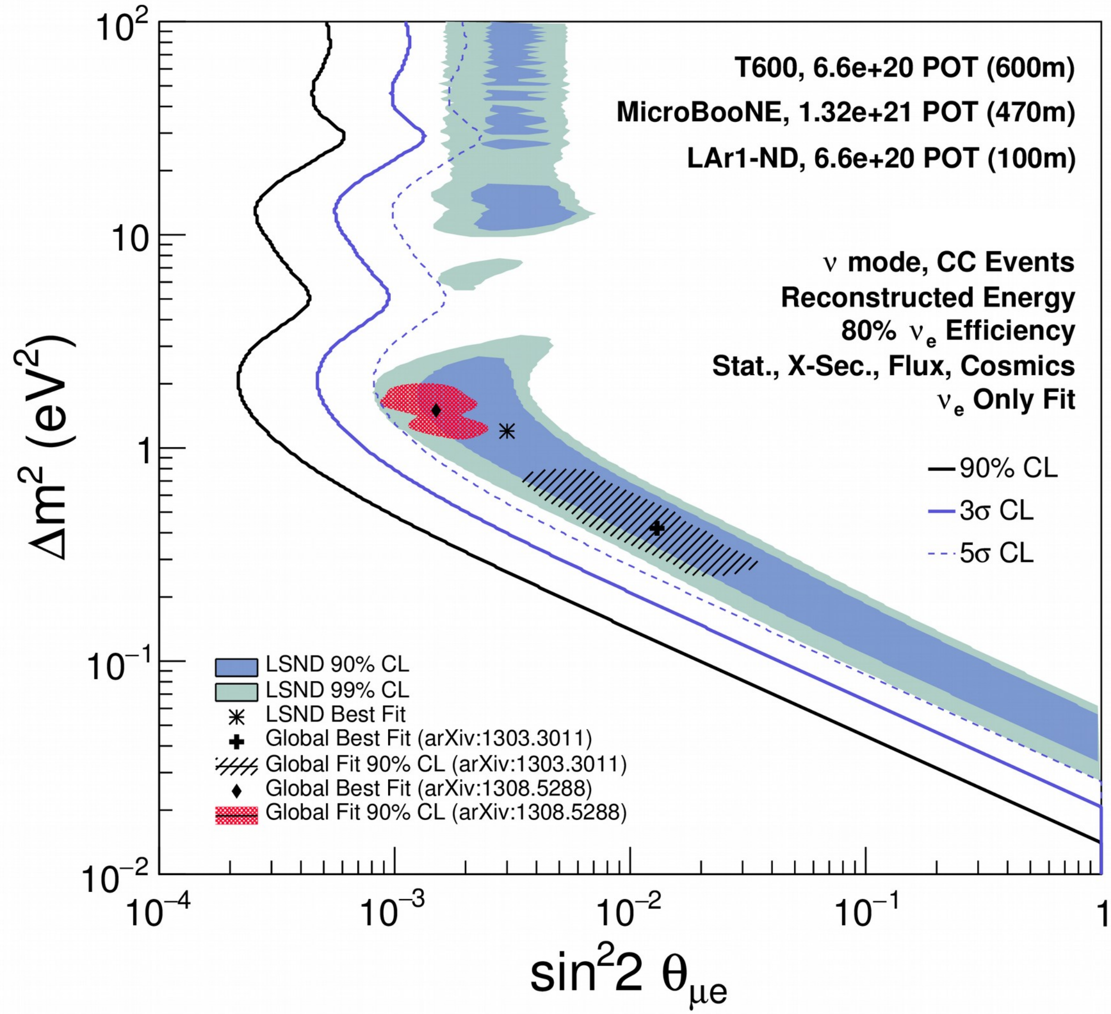
Compute chi-squared at a range of points in the $\sin^2 2\theta$, Δm^2 space, and find the contours where the chi2 crosses statistical sensitivity levels.

Oscillation Sensitivity

This plot tells us the ability to observe a signal is present on top of the background for the SBN Program, but **doesn't** say: “What's the resolution of the parameters of that signal?”



Path Forward

- Plenty of work to do to get ready for data ...
  - We are exploring ways to quantify our resolution of mixing parameters based on observed signals.
  - What can we do with joint analyses?
    - Access to muon neutrino disappearance, muon to electron neutrino oscillation, and neutral current disappearance in the same detectors, in the same beam, at the same time.
- Expect the unexpected?
  - With sensitive detectors, a tightly constrained beam, and well quantified uncertainties we should be able to make definitive statements about what's going on in Short Baseline physics … whatever that may be.