

# ICARUS $\nu_{\mu}$ disappearance sensitivities with PROfit

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ICARUS Collaboration Meeting

October 15, 2024

# PROfit

- New fitting framework for SBN combining efforts of groups using CAFAna and SBNfit
- Under heavy development the last few months as we decided to use PROfit for the first ICARUS oscillation search
- Slack Channel: #profit
- Mailing List: [profit@fnal.gov](mailto:profit@fnal.gov)
- Github Repository: [github.com/markrosslonergan/Elephant\\_Vanishes](https://github.com/markrosslonergan/Elephant_Vanishes)
- Weekly meetings Friday at 1 pm CT, focus on development
- Development Team: Jacob Larkin, Mark Ross Lonergan, Nupur Oza, Ibrahim Safa, Elizabeth Worcester

# Status of PROfit

- Studies ongoing for ICARUS only,  $\nu_\mu$  disappearance search
  - Support for cosmic, NC, and  $\nu_e$  backgrounds in fits added recently
  - Support for POT scaling implemented just last week
- Implemented systematics with 1D splines, or in a covariance matrix only (assuming linear response)
- Executables for making a  $\chi^2$  surface, feldman cousins studies, mock data studies
- Multithreading implemented for  $\chi^2$  surface and feldman cousins code
- Tested and confirmed to work on both gpvms (using SL7 container, although AL9 support should be easy) and macos
- $\nu_e$  appearance and full 3+1 fits can be tested when appropriate MC samples are available

# How PROfit carries out a fit

- Configure using an XML file
  - Input ROOT files, list of systematics, POT to scale to, binning, how to oscillate each subchannel ( $\nu_\mu$  CC,  $\nu_e$  CC, NC, cosmics), plot colors, etc
  - Examples files in xml/ directory in the git repo
- Choose one of the available executables (or write your own)
  - PROsurf ( $\chi^2$  surfaces), PROfc (Felman Cousins), PROmock (mock data)
  - Located in the bin/ directory in the git repo

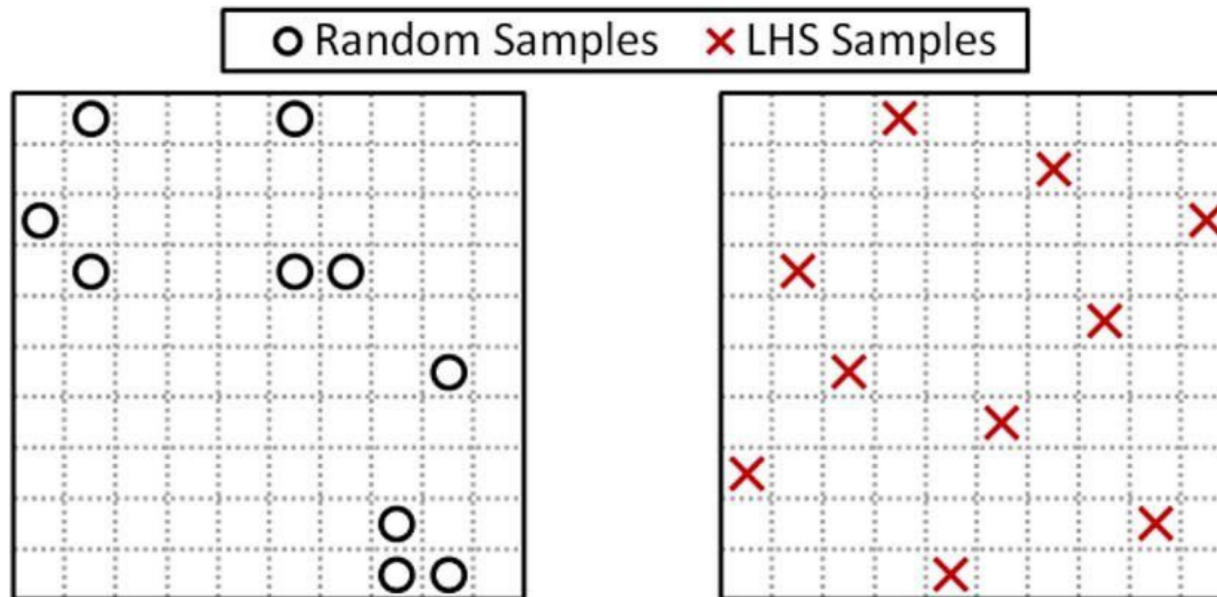
- Using L-BFGS-B for minimization, with the following  $\chi^2$

$$\chi^2 = (D - M)^T V^{-1} (D - M) + \sum_{s \in \text{Syst}} s^2$$

- Located in inc/PROchi.h and src/PROchi.h
- Hard coded right now, but we have plans to generalize this to support multiple  $\chi^2$  calculations

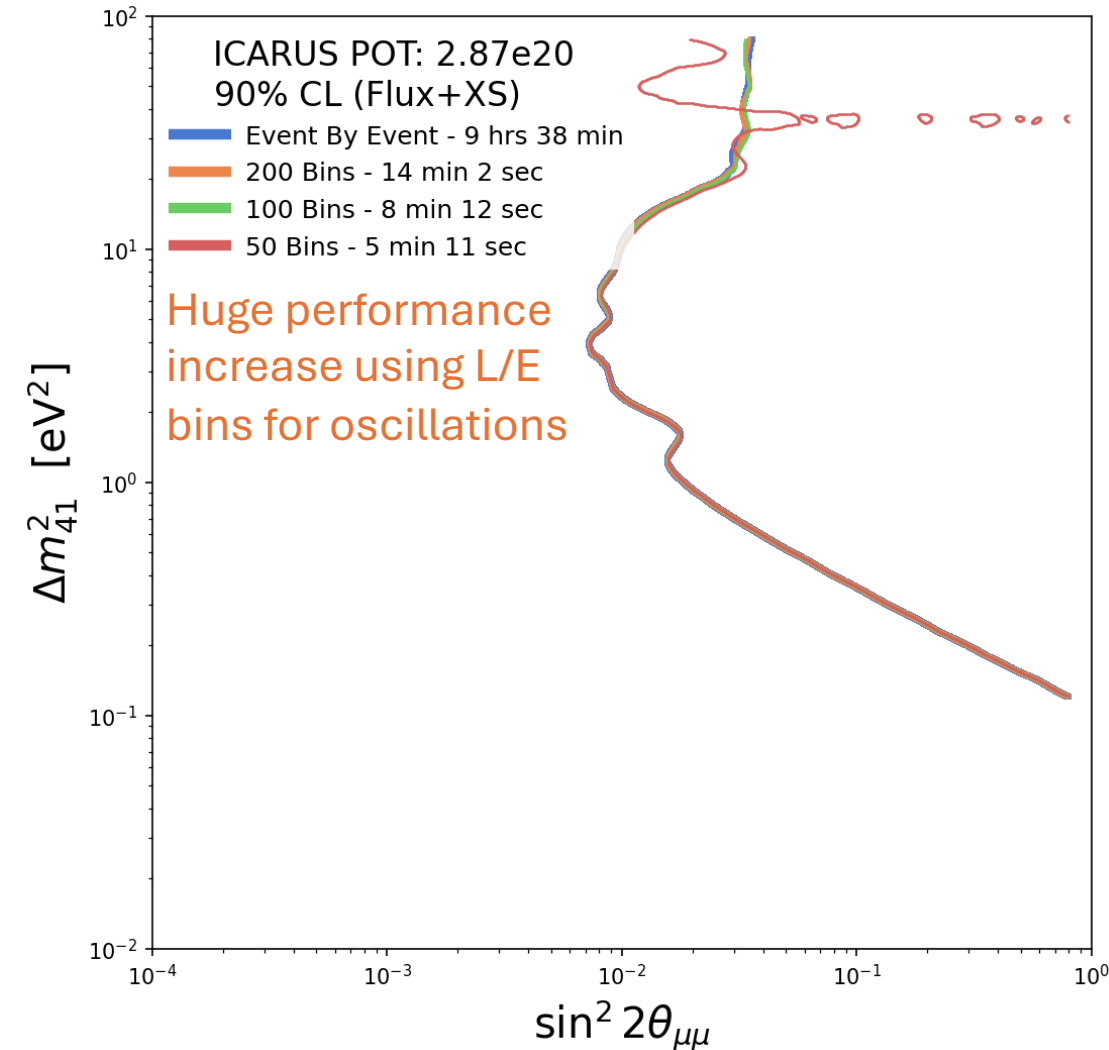
# How PROfit carries out a fit (cont.)

- Can be configured to use true L/E binning when calculating oscillations, or use event-by-event oscillations
- For each point being fit, we use a latin hypercube to sample parameter space
- Choose best N points from sampling to seed the fit
- Have another idea? Talk to us on #profit. Contributions from users are welcome. The framework is flexible enough to support multiple fit styles.



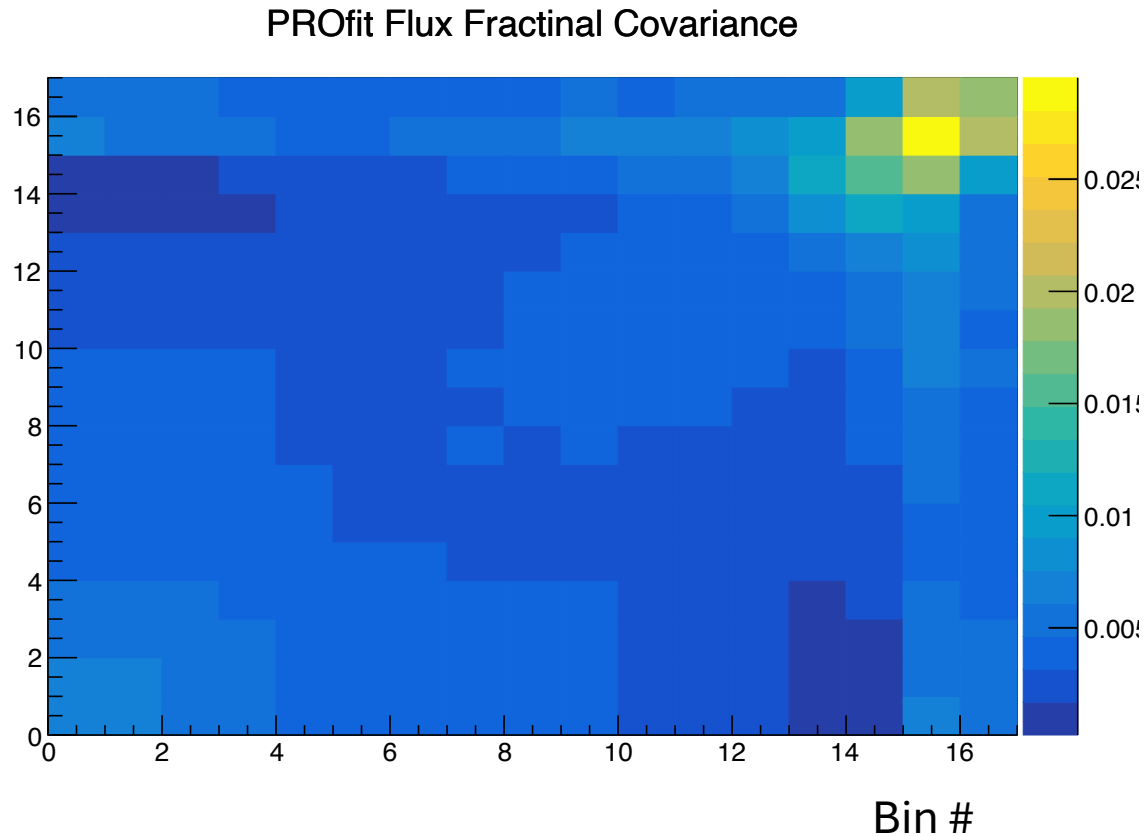
# PROfit Performance

- Multithreading implemented using `std::thread` for  $\chi^2$  surface and Feldman Cousins code
  - Roughly linear performance improvement with number of threads (up to total number of fits to be performed)
  - Discussion ongoing on using `openmp` instead of `std::thread`
- Have implemented true L/E binning for oscillation calculations
  - Analyzers can choose between binning in L/E or doing event-by-event oscillations



Using 100 - 200 true L/E bins for oscillations doesn't seem to have a visible effect on 90% ICARUS only sensitivity contours

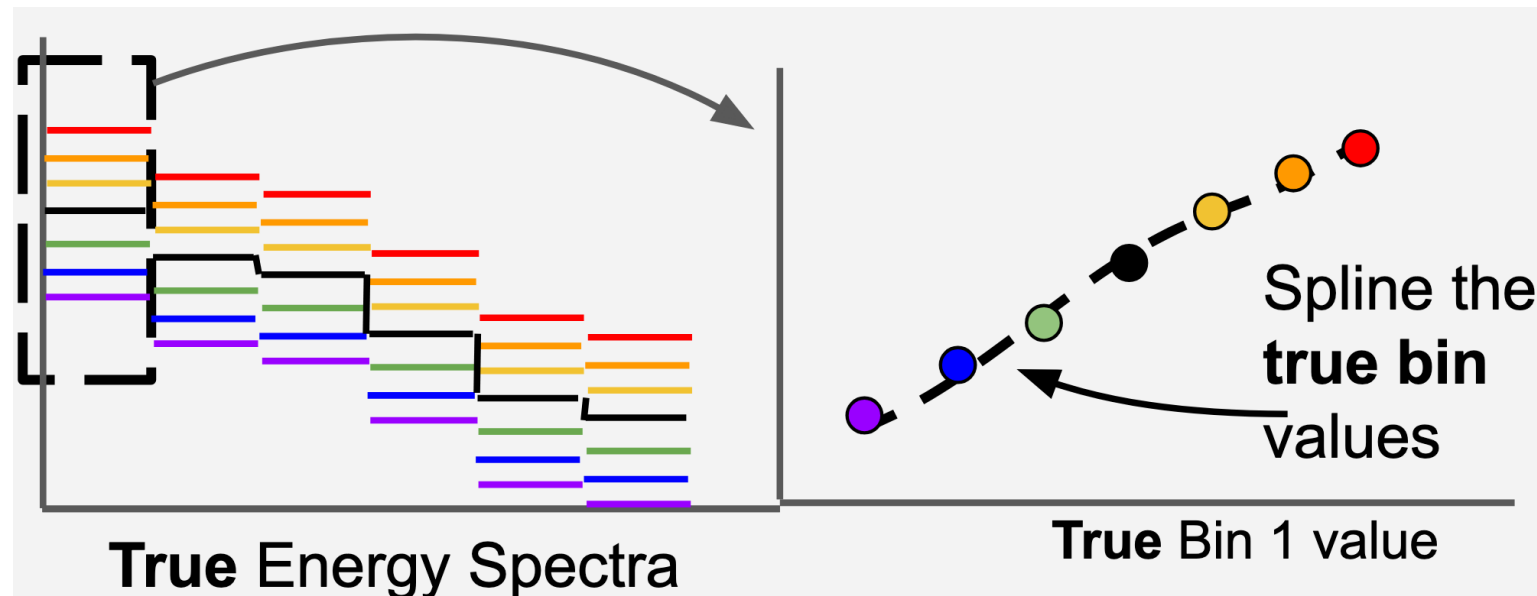
# Systematics



- Systematics can be included as nuisance parameters (by making splines) or included in the covariance matrix only (assuming a linear response)
- Right now, flux systematics are assumed to have a linear response and are included in the covariance matrix only
  - We can make splines for 8 of the 13 flux systematics, but this is not implemented right now
  - 2% uncertainty on POT not included in these fits

# Systematics (cont.)

- Detector systematics are implemented in CAFAna and we use the CAFAna implementation to save the +/- 1, 2, 3 sigma weights which PROfit uses to make splines
- Xsec systematics can be included as splines or only in the covariance matrix on a case by case basis
  - For the fits shown here, all xsec systematics are treated as nuisance parameters in the fits using splines
  - After consulting with Stephen, Jaesung, and Chris, we will likely add a few more xsec systs in the near future

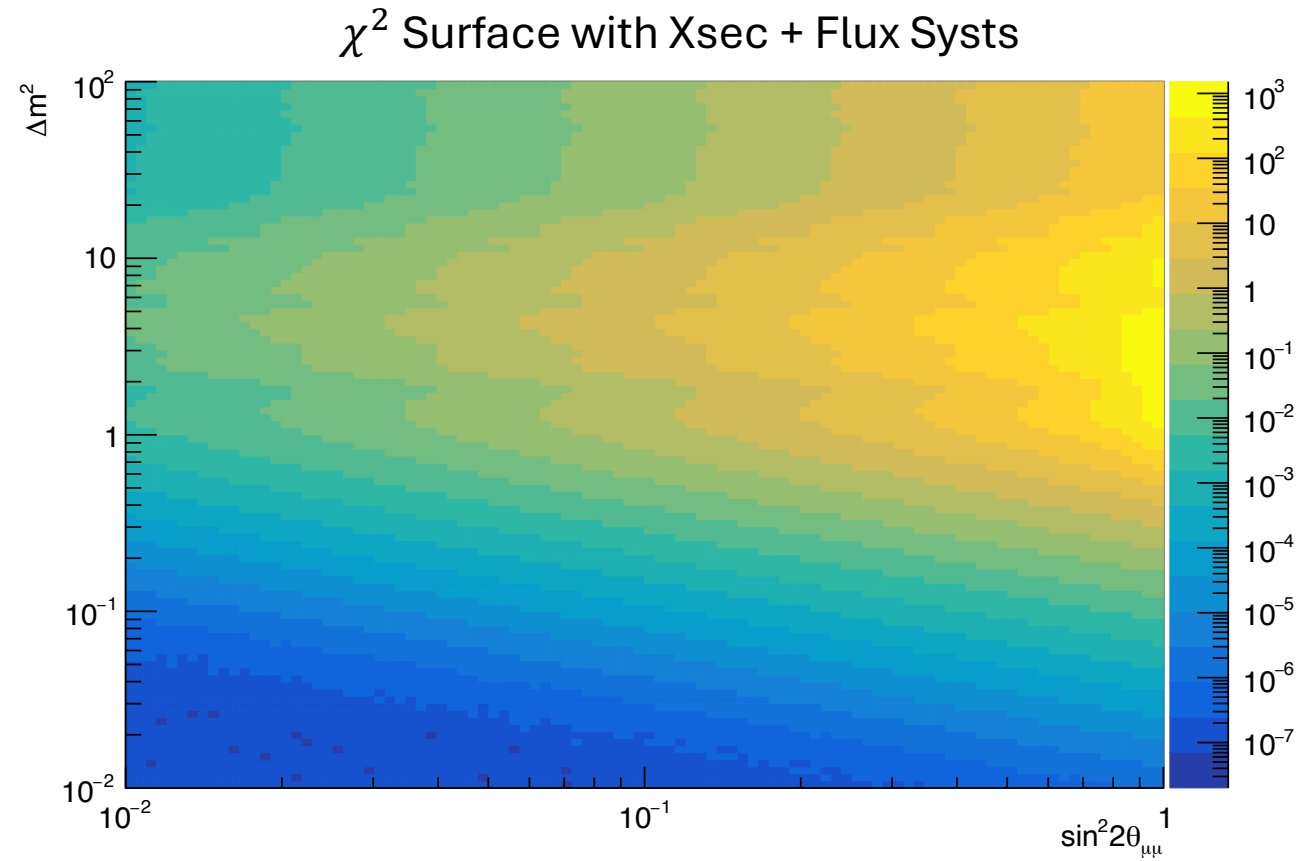
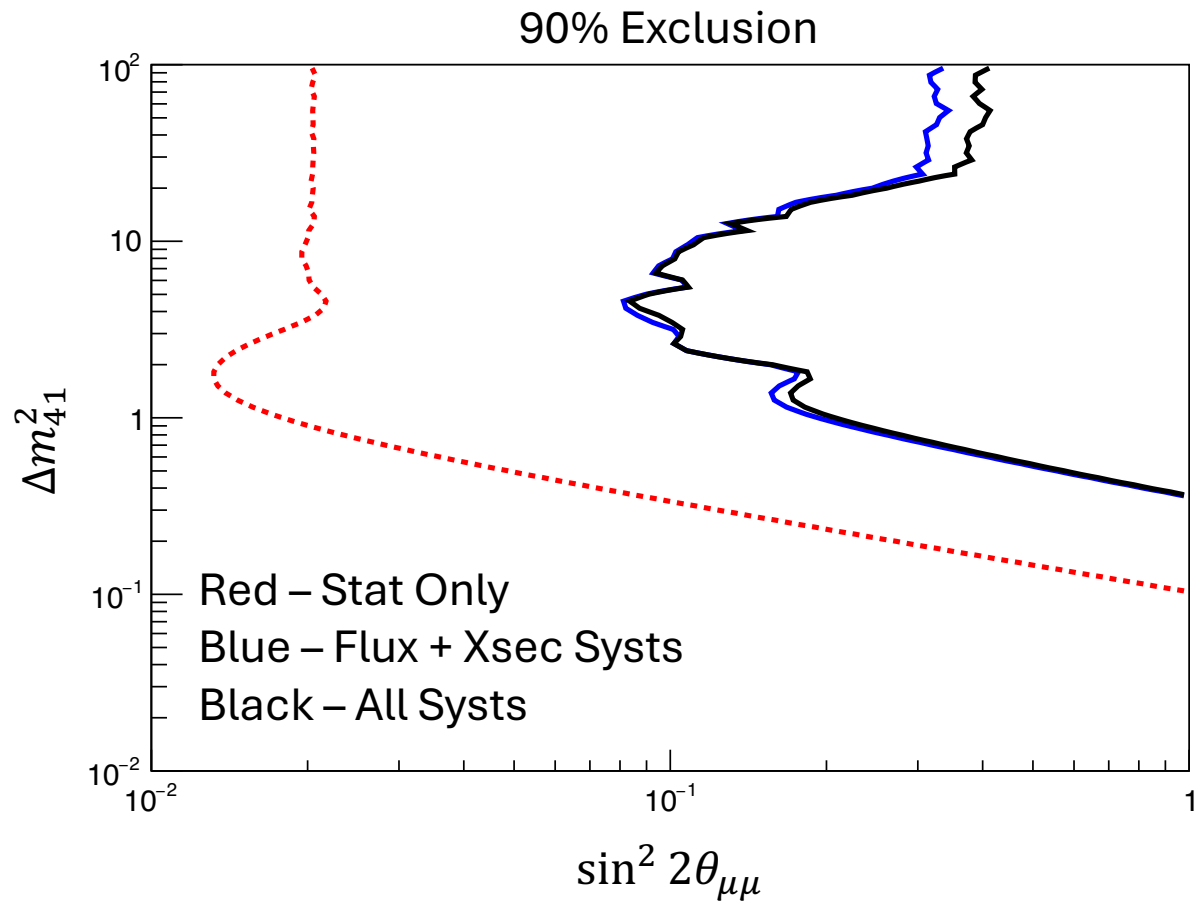




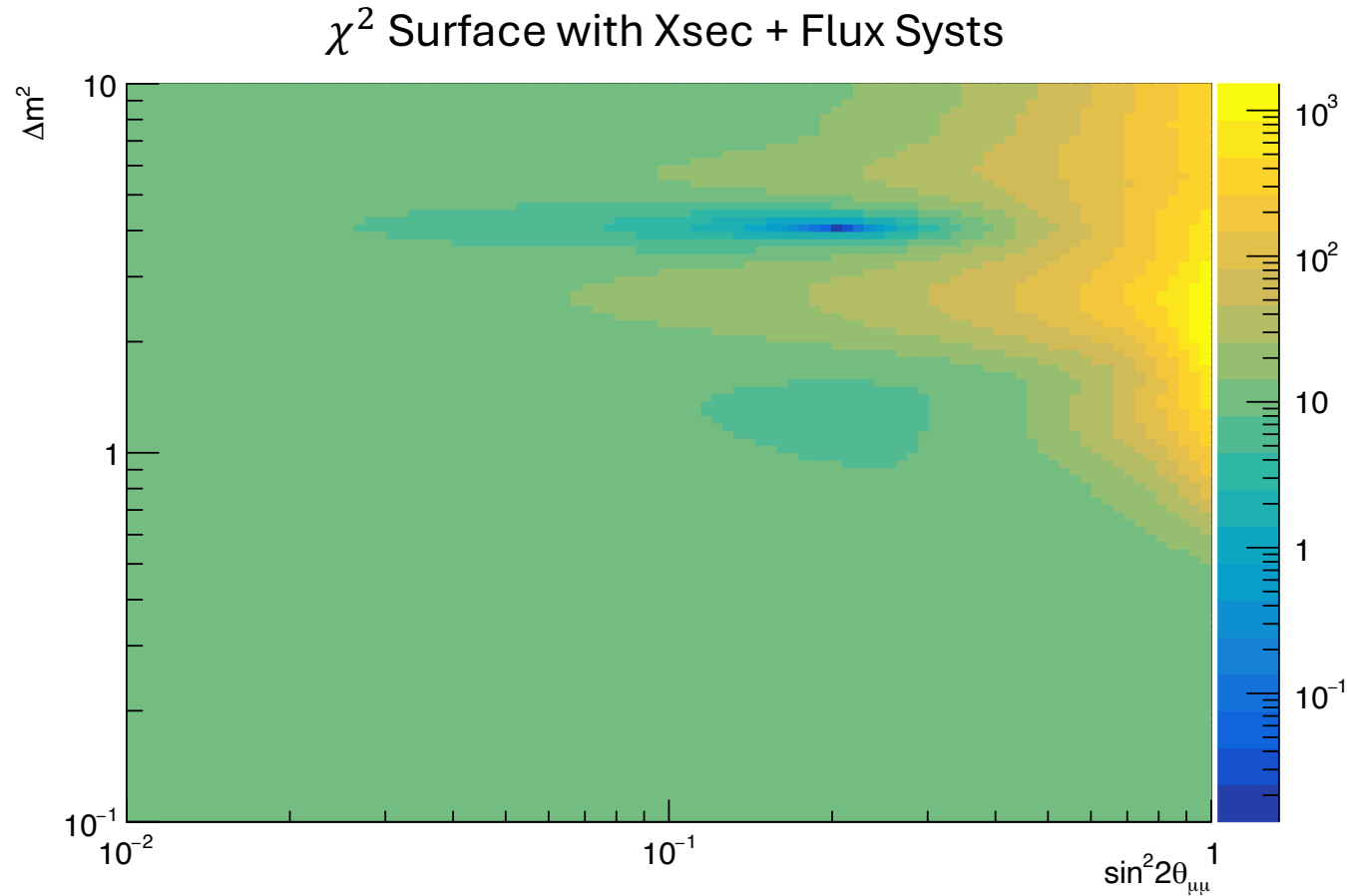
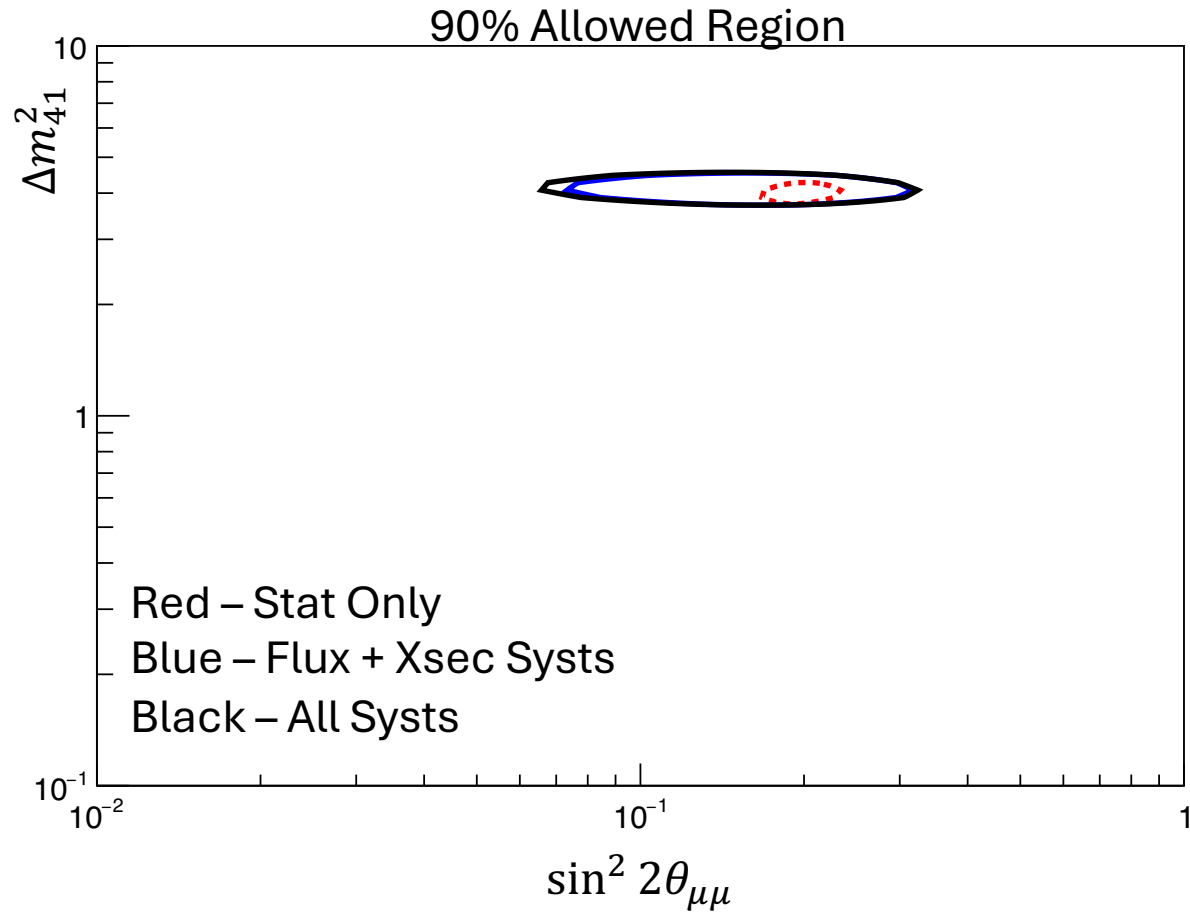
# Sensitivities

- Shown here are an exclusion sensitivity (i.e., assuming null hypothesis) and a sensitivity to an injected point ( $\Delta m_{41}^2 = 4 \text{ eV}^2$ ,  $\sin^2 2\theta_{\mu\mu} = 0.2$ )
  - using full Run 2 POT (2e20)
  - Injected point is a point we are sensitive to without SBND, i.e., large oscillations
- I show sensitivities with statistical uncertainties only, stat+flux+xsec, and stat+all systs (including current detector systs)
- Finally, I did 10k Feldman Cousins throws for the no oscillations case and each of the 2 syst sets (flux+xsec only and all systs)
- Comparisons between exclusion contours assuming Wilk's theorem and using the  $\Delta\chi^2$  from the FC studies are shown at the end

# Sensitivity (Exclusion)



# Sensitivity (Allowed Region)



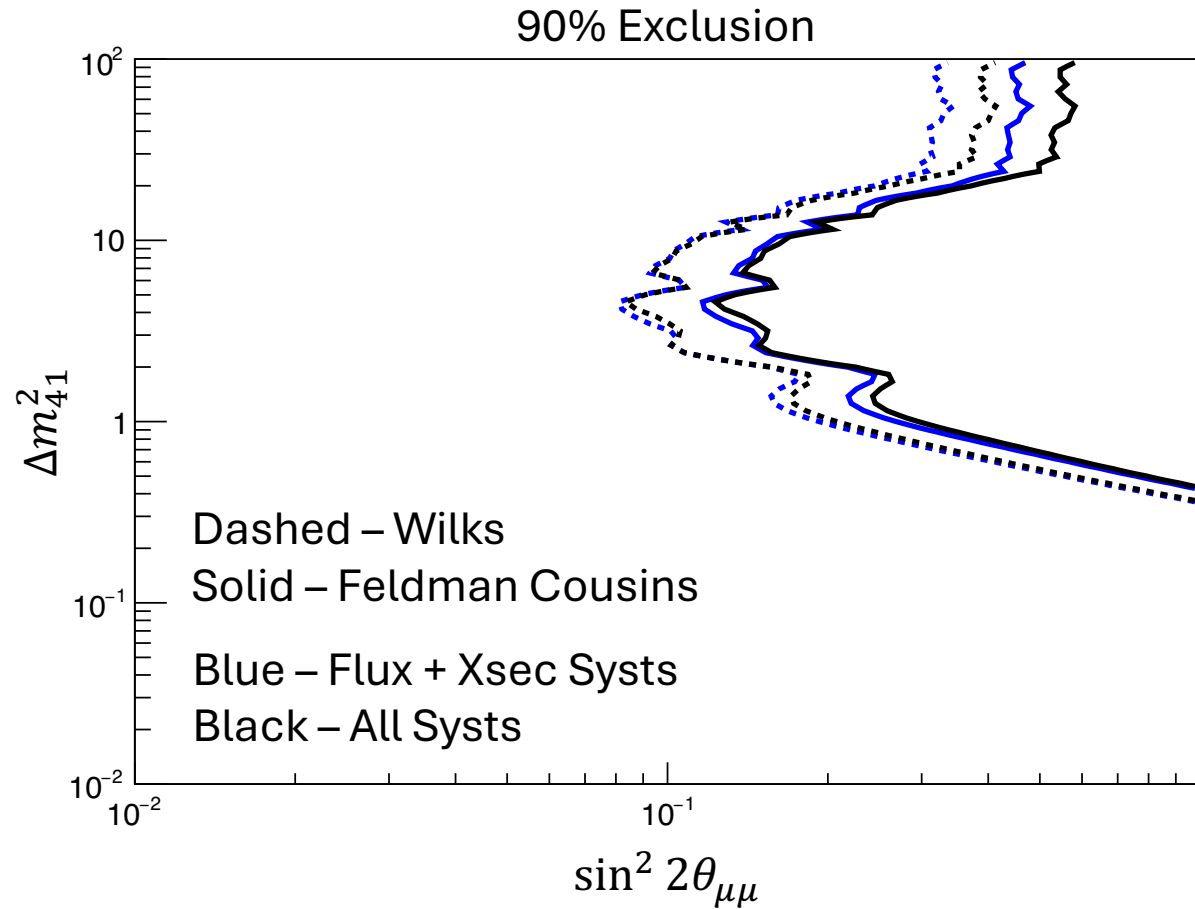
Injected Signal at  $\Delta m_{41}^2 = 4 \text{ eV}^2$ ,  $\sin^2 2\theta_{\mu\mu} = 0.2$

# Feldman Cousins

1. Assume oscillation parameters are true point
  - No osc for exclusion, injected signal for allowed region
2. Gaussian throw of systematics (nuisance parameters)  
Cholesky Decomposition of covariance matrix
3. Poisson variation of spectrum
4. Fit with nuisance parameters only
5. Fit with nuisance + osc parameters
6. Take difference
7. Repeat 1-6 many times and find 90<sup>th</sup> percentile (10k throws for this study)

	Exclusion Wilks	Exclusion (xsec+flux)	Exclusion (all syst)	Allowed Wilks	Allowed (xsec+flux)	Allowed (all syst)
90% $\Delta\chi^2$	1.64	3.5	3.7	4.61	12.8	12.8

# Sensitivity w/ Feldman Cousins (Exclusion)



# Short to Medium Term Plans for PROfit

- Tutorial/Documentation (High Priority)
- Maximal configurability from xml/command line parameters
  - Minimize need for users to mess with C++ code and recompile
- More convenient plotting and plot more things
  - Make plots of splines, covariance matrices, shifted/oscillated spectra
- Start looking at fits with SBND,  $\nu_e$  (dis)appearance, and full 3+1 oscillations
- Add more options for chi2 calculation
- Further profiling and performance improvements
  - Plenty of “low hanging fruit” still exists
- Your help with these things is welcome!!
- Find us at #profit and profit@fnal.gov

# Summary

- PROfit is ready to be used for ICARUS oscillation analysis
- Improving ease of use is a goal for the short term
- User feedback is needed and help with development is welcome
  
- Sensitivity studies with PROfit show impact of current suite of systematics
- Preliminary Feldman Cousins studies have been done using PROfit, and we can make an exclusion contour using the  $\Delta\chi^2$  from these studies