Long-baseline searches for sterile neutrinos using neutral current interactions in NOvA

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New Perspectives 2018
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Introduction

- Previous NOvA talks considered neutral currents as a background to charged current processes. This talk discusses NOvA's 2018 searches for **neutral current disappearance**, in which NCs are the signal!

- Overview:
  - Motivation and experimental overview.
  - Search for NC disappearance in **neutrino** data, and upcoming plans with new covariance method.
  - Search for NC disappearance in **antineutrino** data, using standard extrapolation technique.
  - Future plans for NOvA sterile neutrino searches.

3+1 sterile neutrino oscillations

- Search for evidence of mixing between active neutrino states (ν_e, ν_μ, ν_τ) and fourth sterile state (ν_s).
- Look for disappearance among neutral current (NC) events, which are insensitive to standard three-flavour oscillations.
- Approximate near detector (SBL) and far detector (LBL) oscillation probabilities on right.
  - Note that in analysis, use exact treatment of 3+1 oscillation probabilities.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

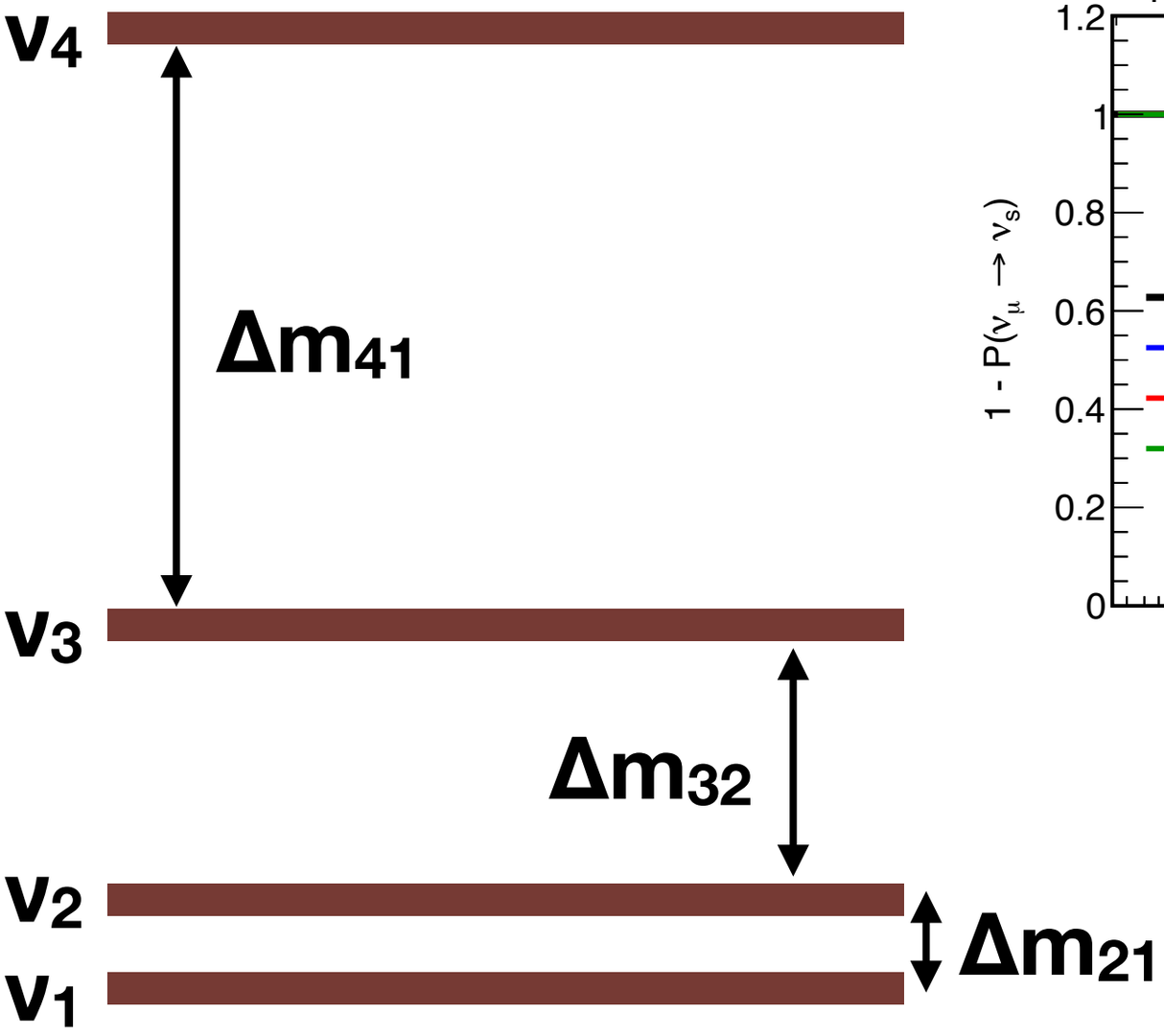
$$P^{SBL,3+1}_{\nu_\mu \to \nu_\mu} = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\sin^2\Delta_{41} = 1 - \cos^2\theta_{14}\sin^2\theta_{24}\sin^2\Delta_{41}$$

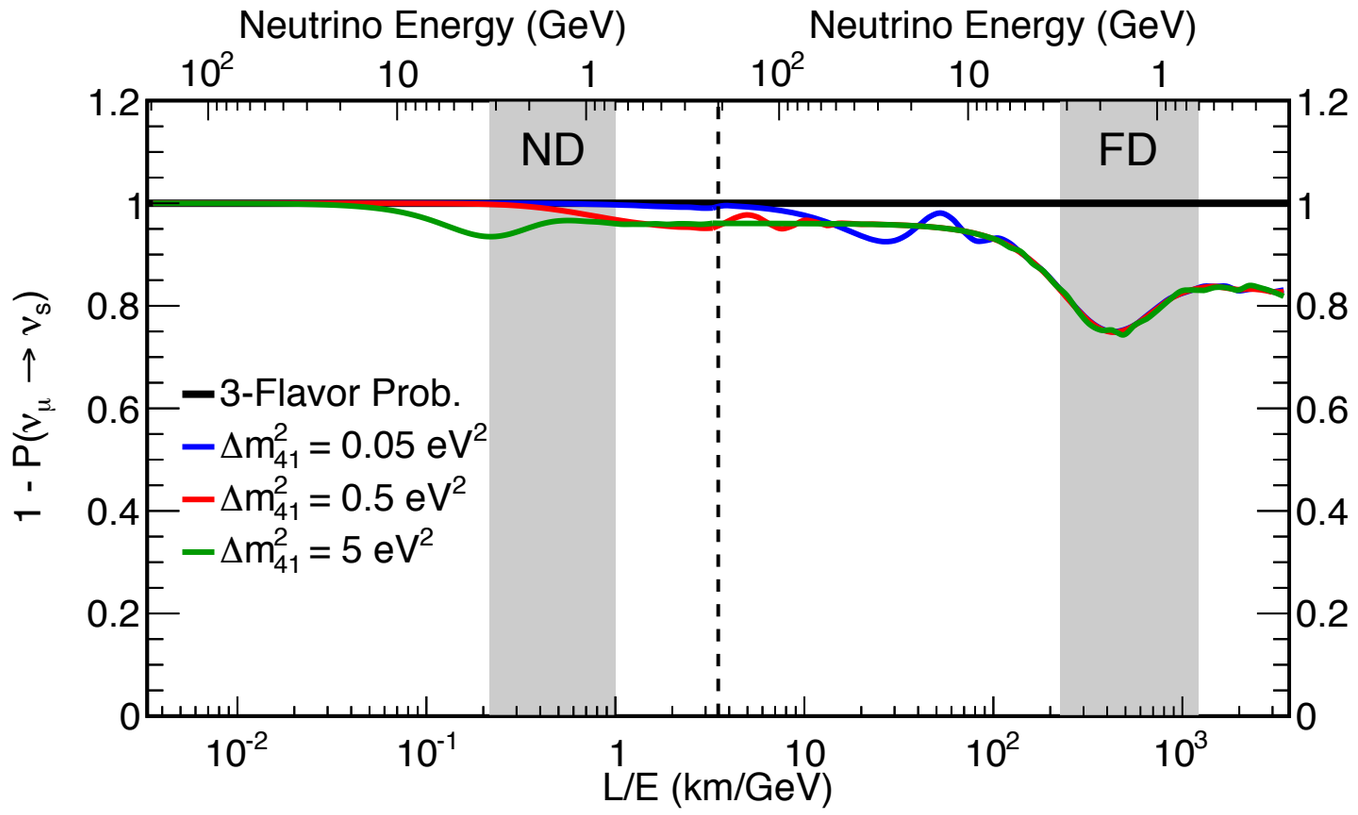
$$1 - P^{LBL,3+1}_{\nu_\mu \to \nu_s} \approx 1 - \frac{1}{2}\cos^4\theta_{14}\cos^2\theta_{34}\sin^2\theta_{24} + A\sin^2\Delta_{31} - B\sin 2\Delta_{31}$$

$$\Delta_{ab} = \frac{\Delta m^2_{ab} L}{4E} \qquad A = \sin^2\theta_{34}\sin^2 2\theta_{23}$$

$$B = \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{34}\sin 2\theta_{23}$$

3+1 sterile neutrino oscillations

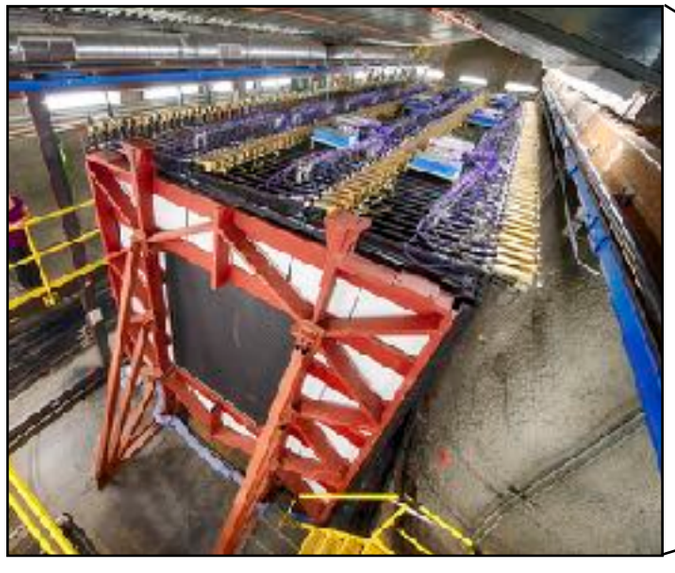


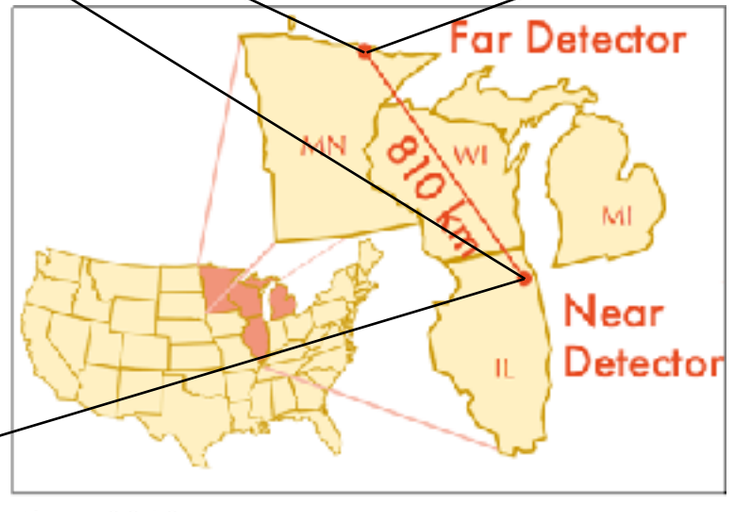


- Signal is always a deficit, never an excess — “smoking gun”.
- Sensitive to mixing parameters **θ24**, **θ34**, **Δm41²** and **δ24**.

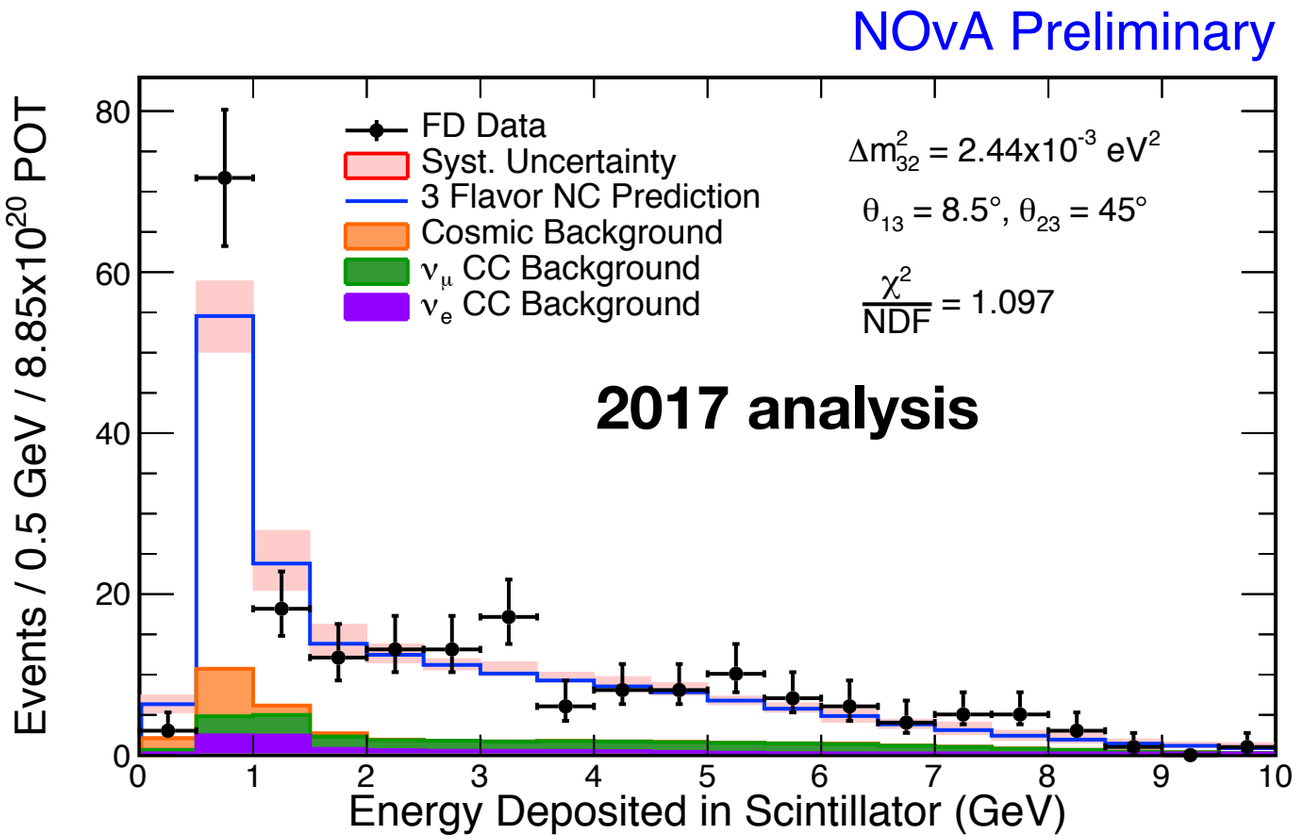
The NOvA experiment

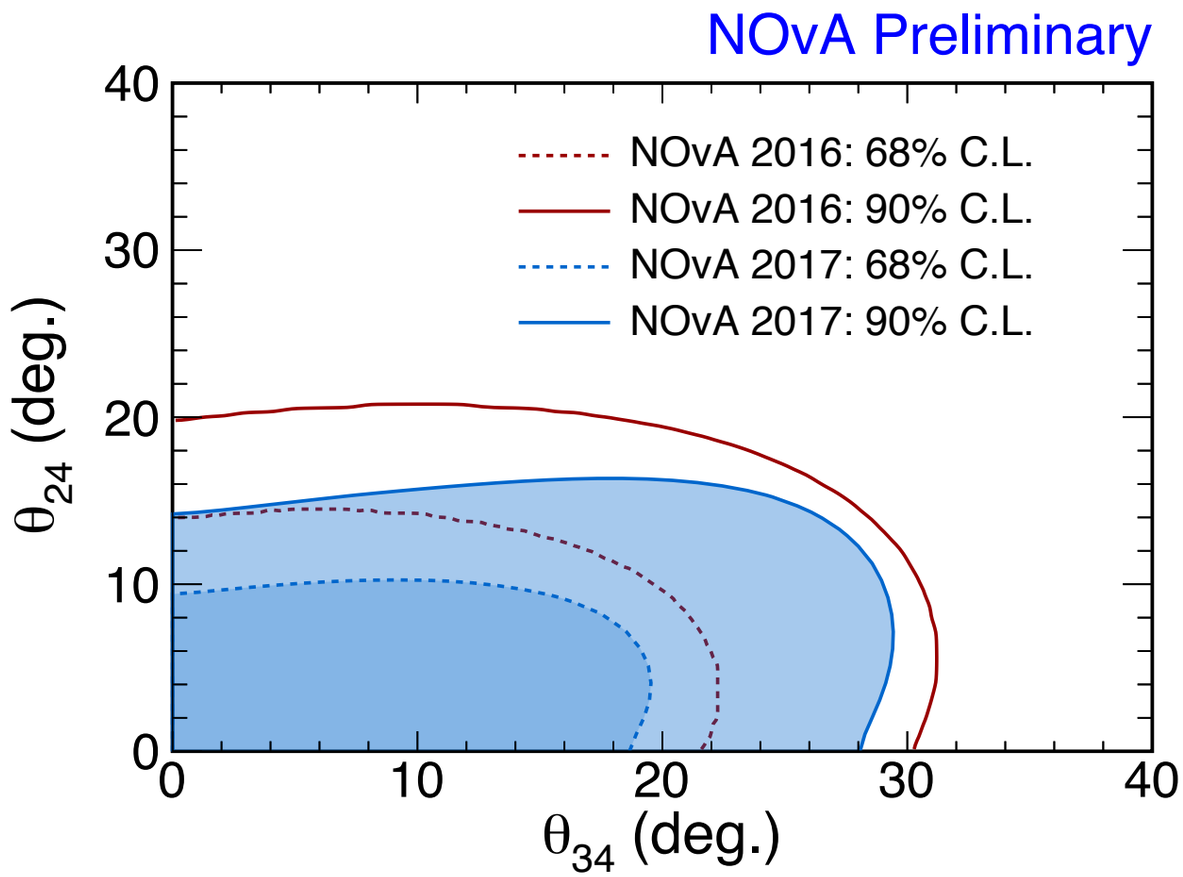
- **NOvA** (NuMI Off-axis ν_e Appearance) is a long-baseline accelerator experiment based at Fermilab.
- Measures neutrinos from Fermilab's **NuMI beam**.
- Functionally identical **plastic scintillator** near and far detectors.
  - ND: 1km baseline, FNAL, 300 tons.
  - FD: 810km baseline, Ash River, 14 kt, 14 mrad off-axis.





Previous NOvA NC analyses



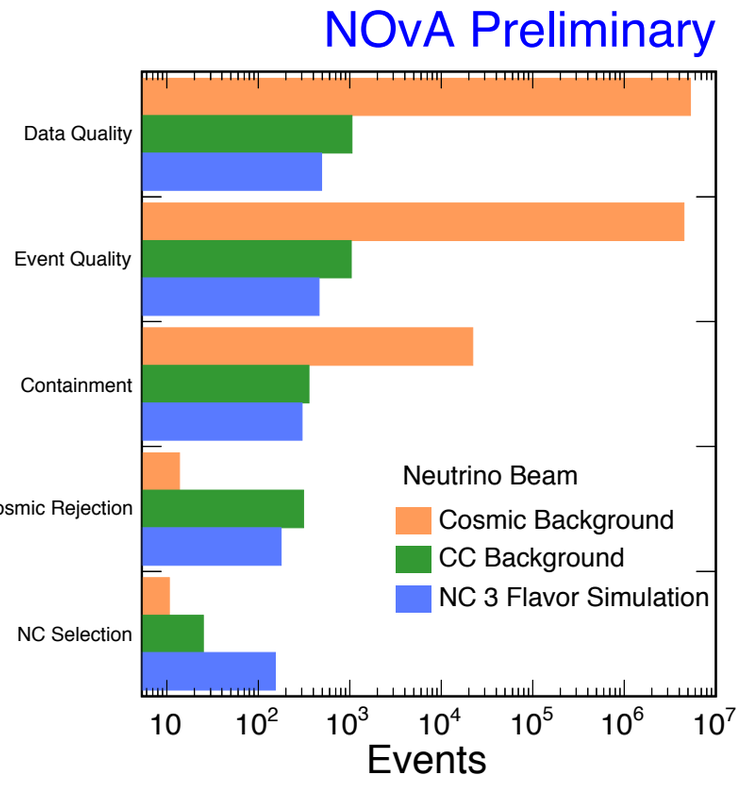


- Previous NOvA analyses searched for NC disappearance in neutrino data using standard extrapolation technique.
- Allowed regions in θ_{24} vs θ_{34} parameter space produced at fixed values of Δm_{41}^2.
- Extrapolation technique limited to parameter space where no sterile oscillations occur in near detector, $\Delta m_{41}^2 < 5$ eV^2.

New NOvA NC analyses

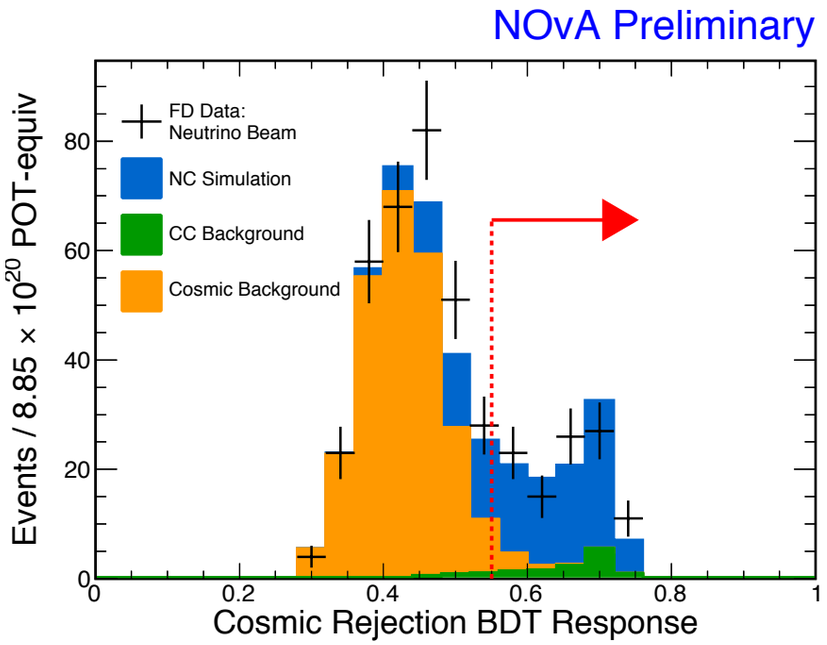
- **Two new analyses** for 2018:
  - Re-analyse **neutrino beam** dataset with new event selection and joint two-detector method.
  - Analyse new **antineutrino beam** dataset with previously used extrapolation technique.
- Both analyses utilise NOvA's machine learning-based **CVN** (see previous talk by M. Groh) for event selection — arXiv:1604.01444
- Cosmic rejection and event selection retrained since previous analysis.
  - Sample purity improved without sacrificing signal selection efficiency.

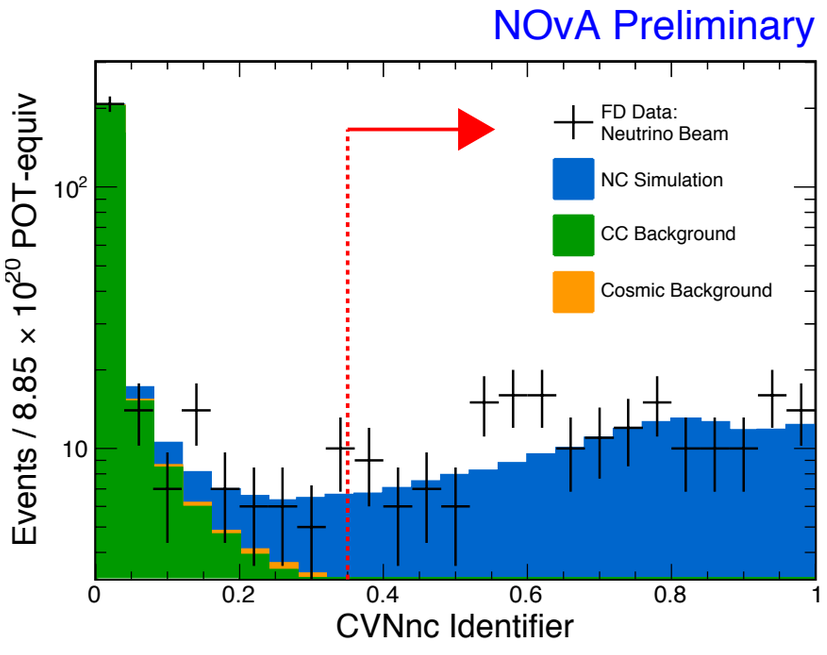
Neutrino beam data event selection



Cosmic rejection:

- EM showers travelling away from beam.
- Transverse momentum cut.
- Activity close in time to candidate event.
- NC-specific boosted decision tree (BDT) trained to reject cosmics.

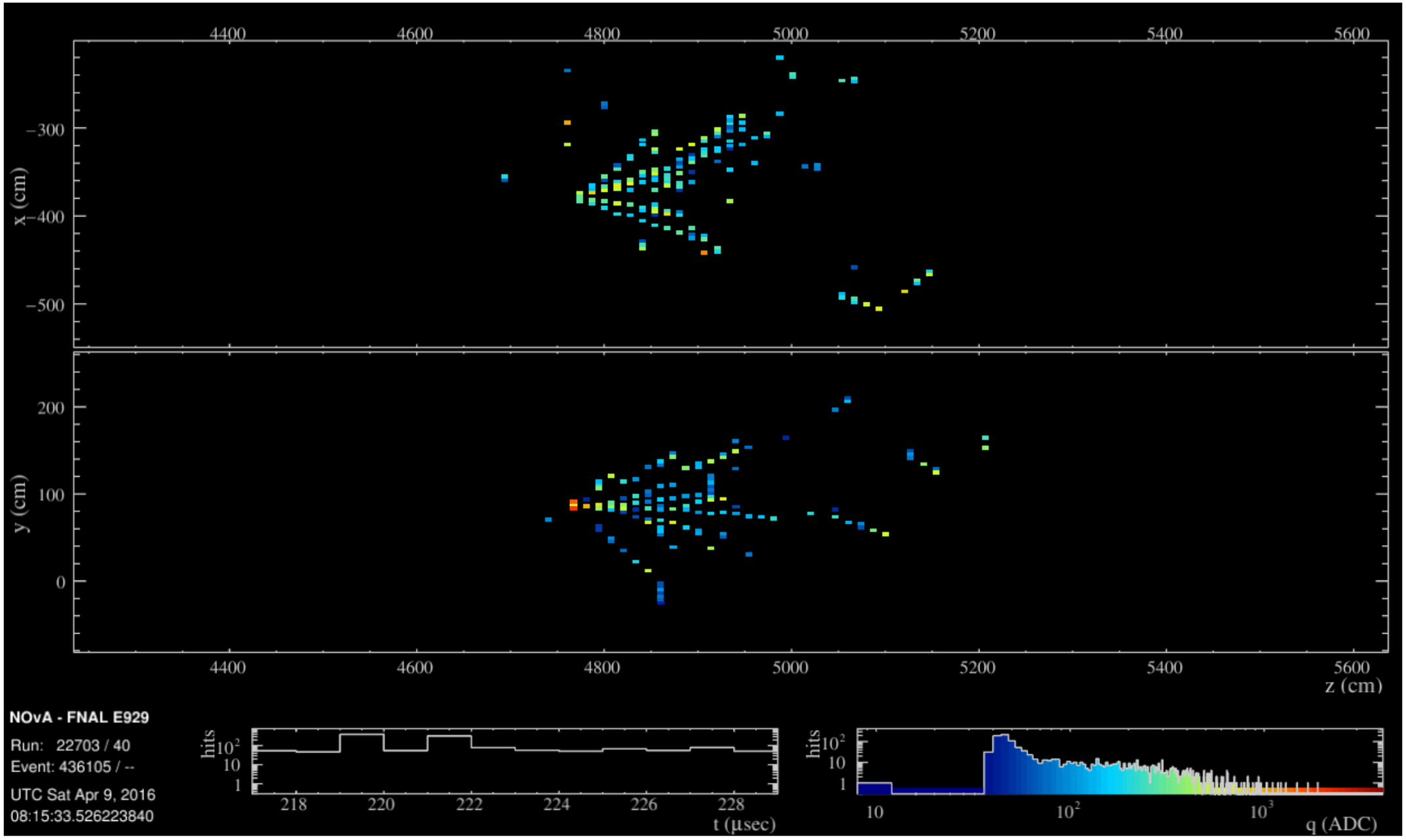




Event selection:

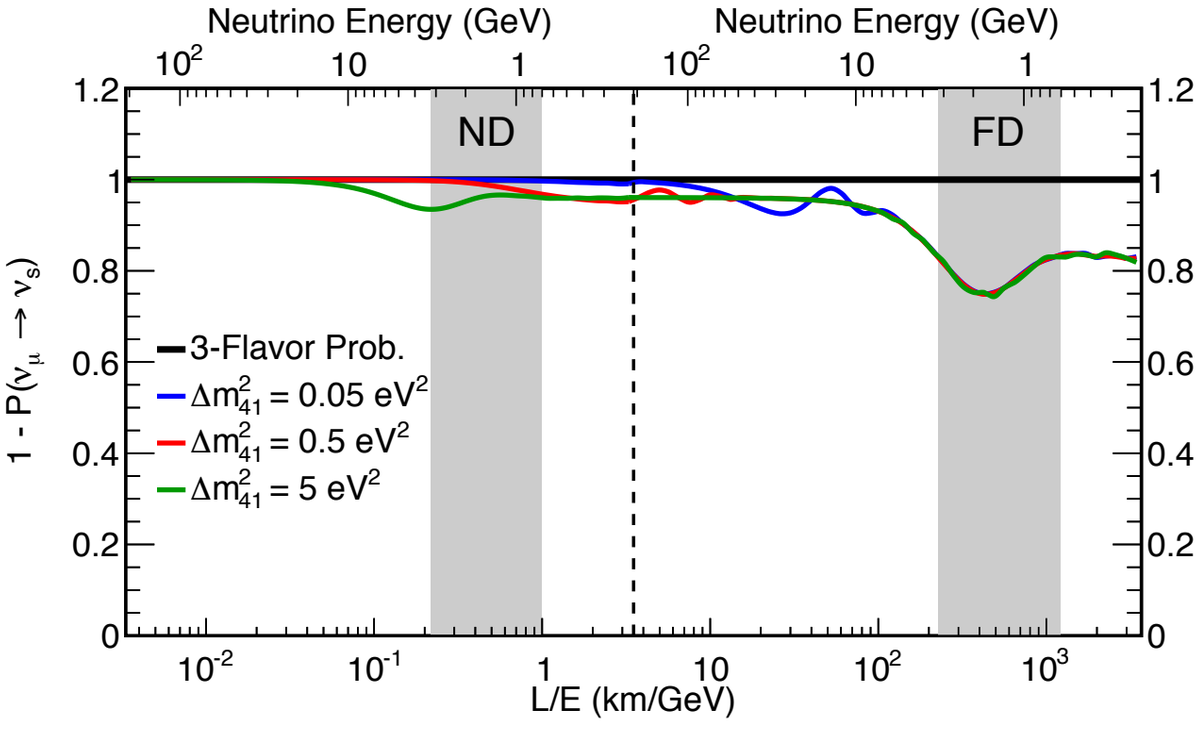
- Use Convolutional Visual Network (CVN) event selection technique to identify NC events.
- Dominant backgrounds are charged current (CC) and cosmic interactions.

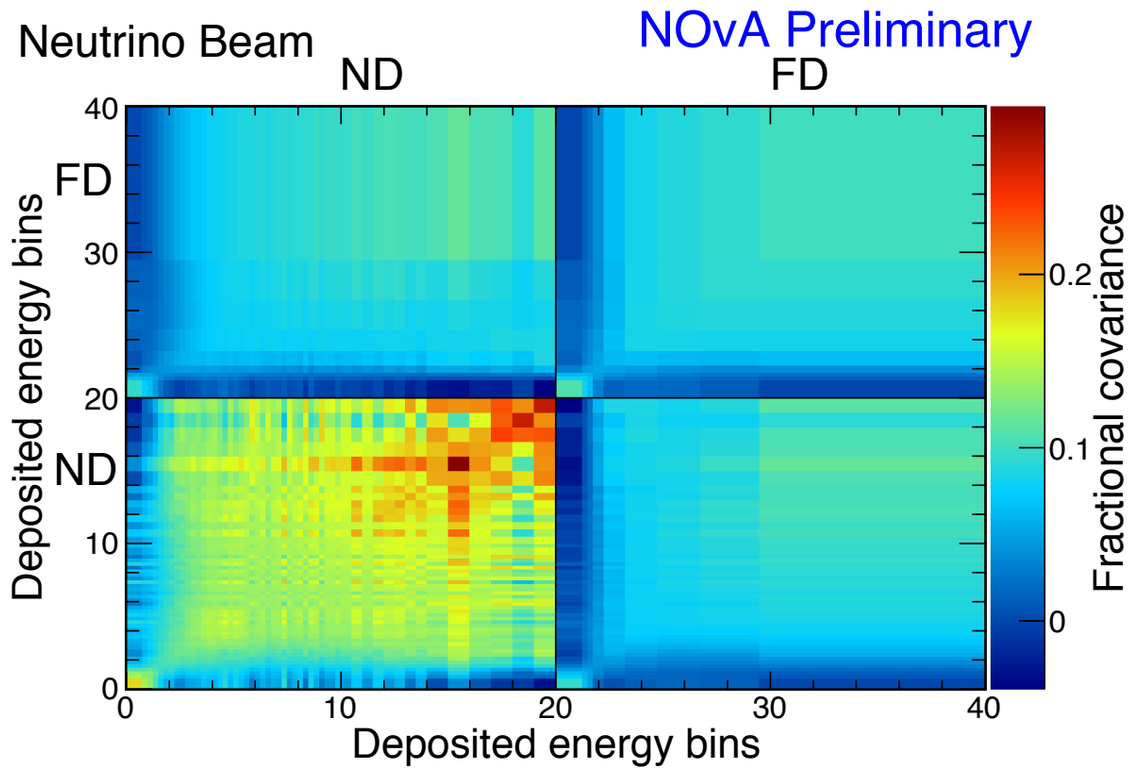
Neutral current candidate event



Covariance method

- At high sterile mass splitting Δm_{41}^2, extrapolation method breaks down due to disappearance in near detector.
- Use covariance matrix to treat both detectors on an equal footing, while still cancelling systematic uncertainties.

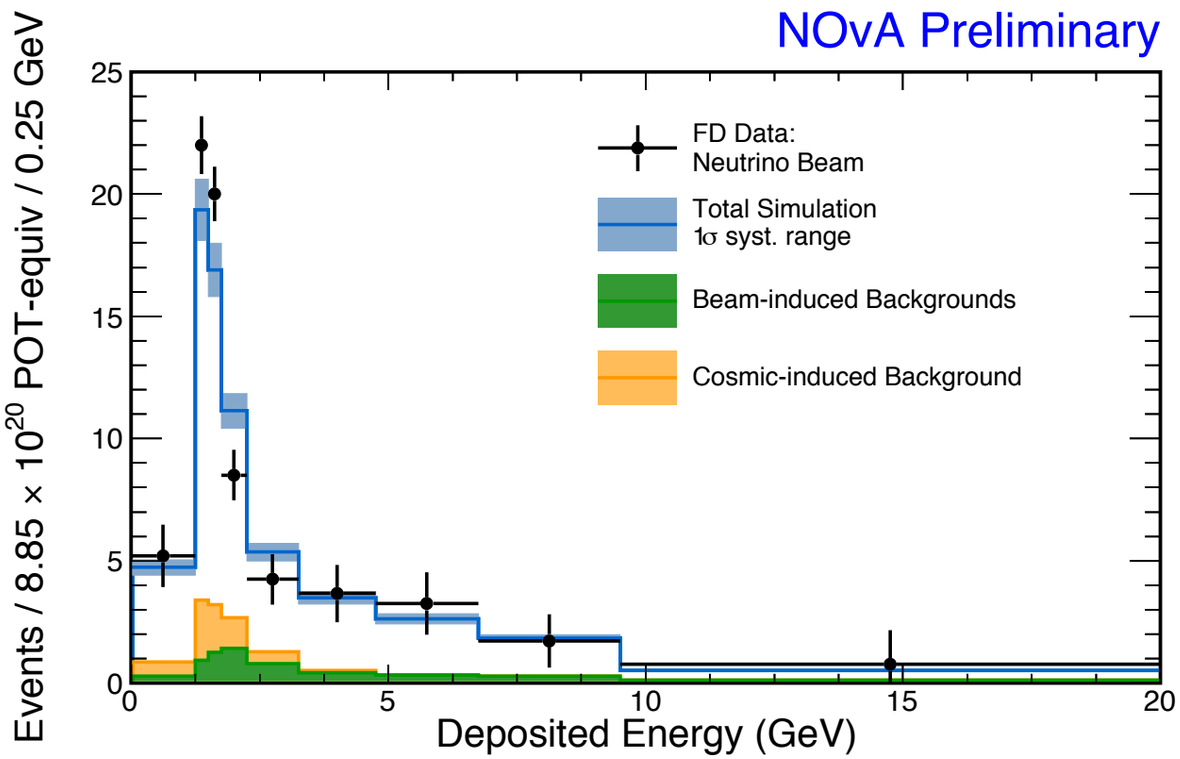




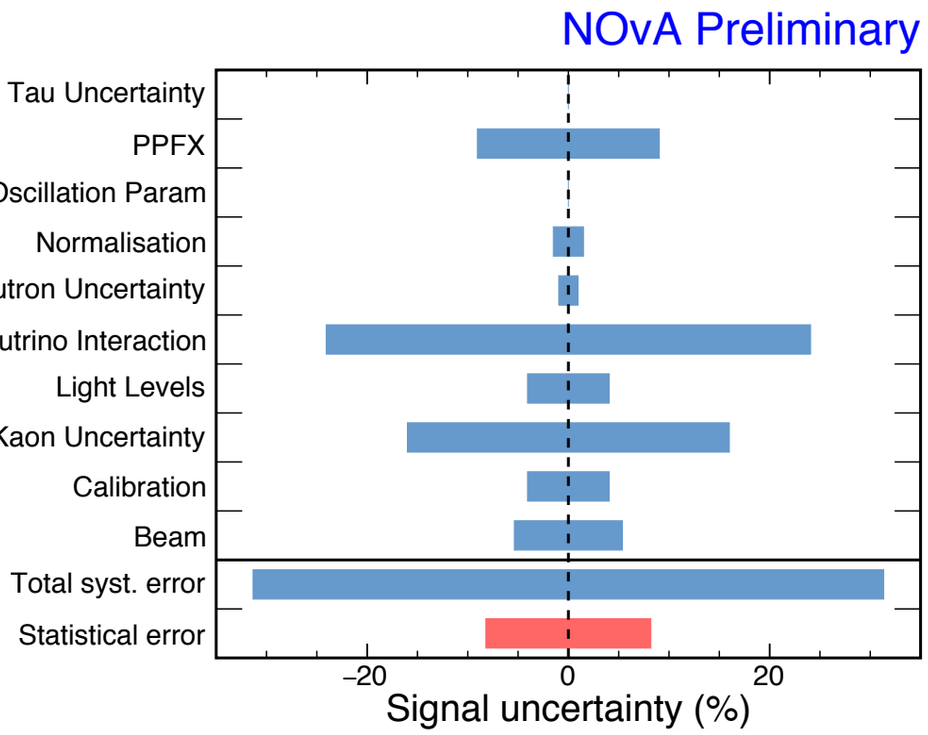
$$V_{ij,\text{syst}} = \frac{\sum_{n=1}^{U}(S_{n,i}-\mu_i)(S_{n,j}-\mu_j)}{U-1}$$

$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(x_i-\mu_i)[V^{-1}]_{ij}(x_j-\mu_j)$$

Neutrino beam data results



Far detector spectrum



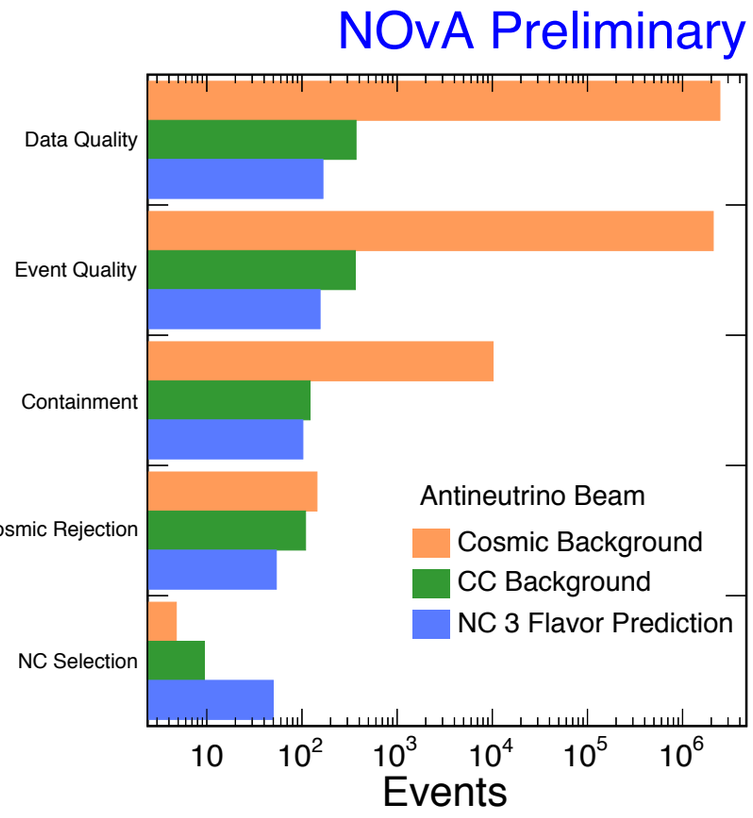
- Observed **201** events, compared to **188 ± 13** (syst.) predicted from MC simulation.
- Consistent with three-flavour oscillations.

Far detector signal systematic uncertainties dominated by cross-sections.

Large uncertainty on kaon flux in neutrino beam.

Significant contributions from flux uncertainties.

Antineutrino beam data event selection



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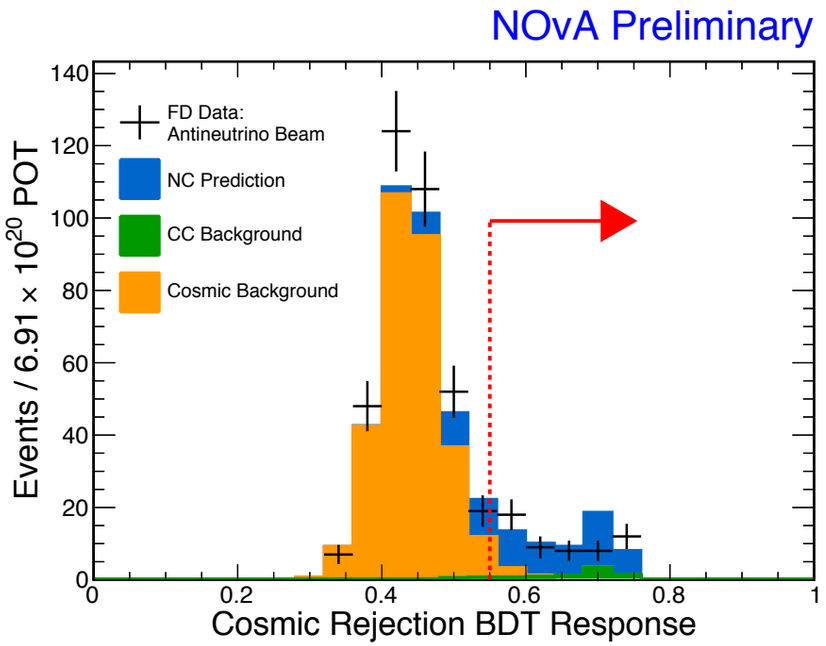
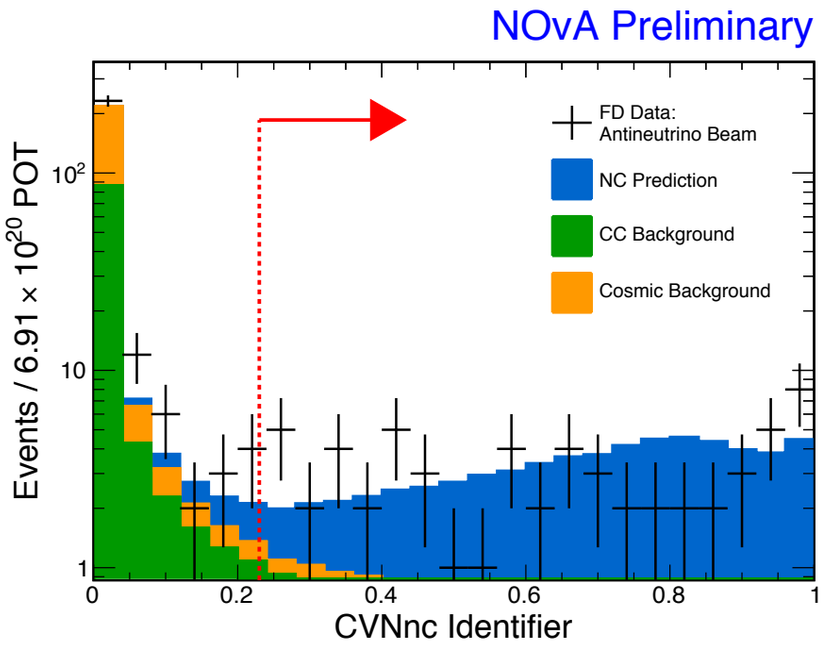




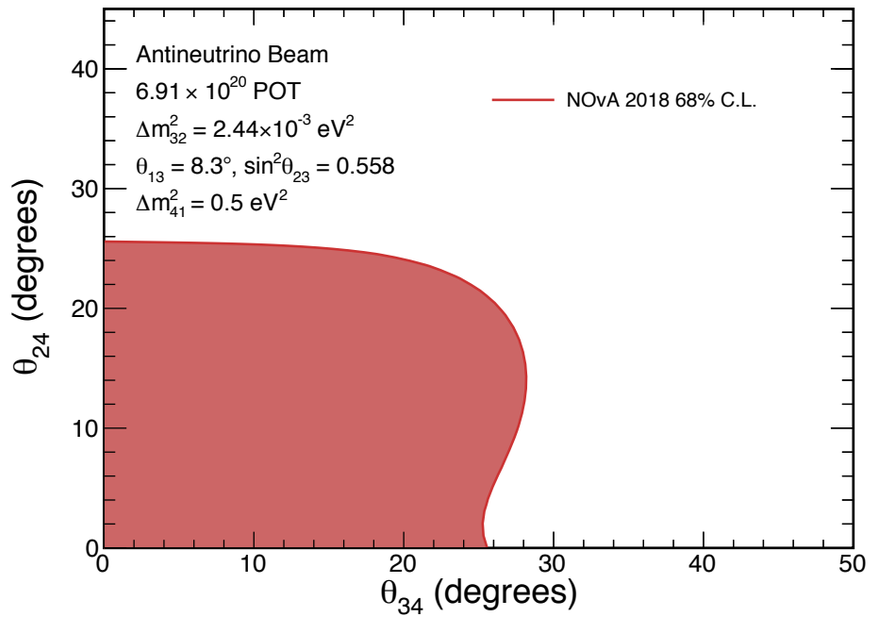
Event selection:

- Use Convolutional Visual Network (CVN) event selection technique to identify NC events.
- Dominant background are charged current (CC) and cosmic interactions.

Antineutrino beam data results

- Observed **61** compared to **69 ± 8** (syst.) from MC prediction.
- Use extrapolation method to create 68% CL allowed region (non-FC corrected).
- 1D 68% CL limits: **25.5°** for **θ_{24}**, **31. 5°** for **θ_{34}**.
- Anticipate limit will improve as NOvA adds more statistics.

NOvA Preliminary



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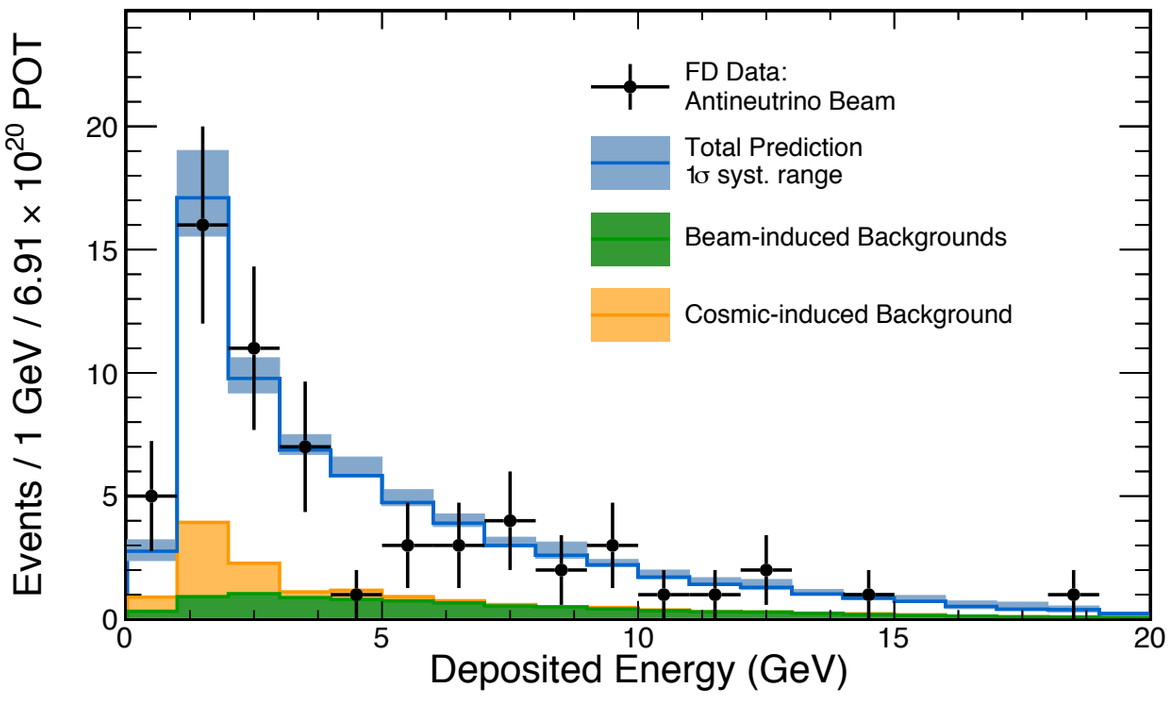
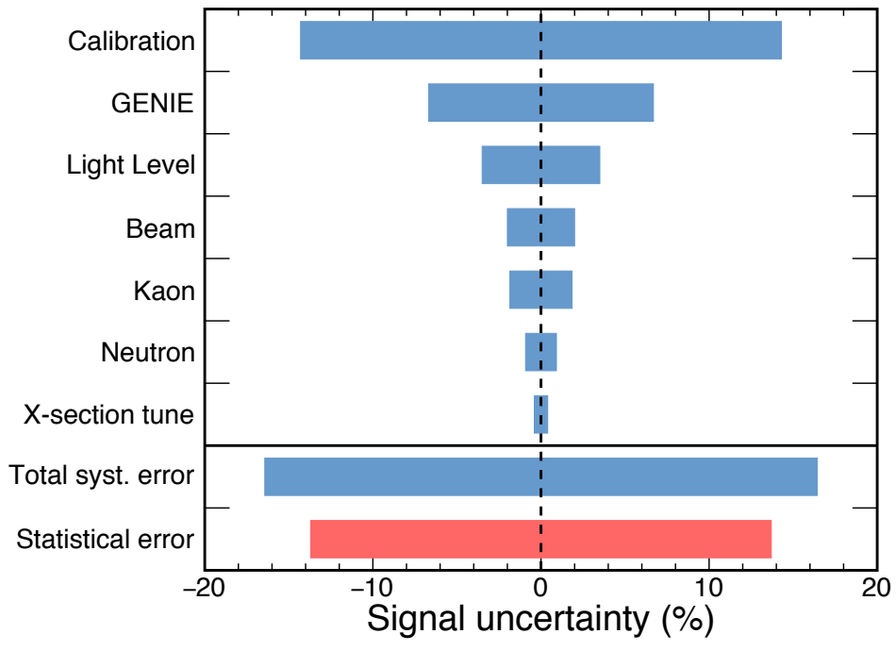
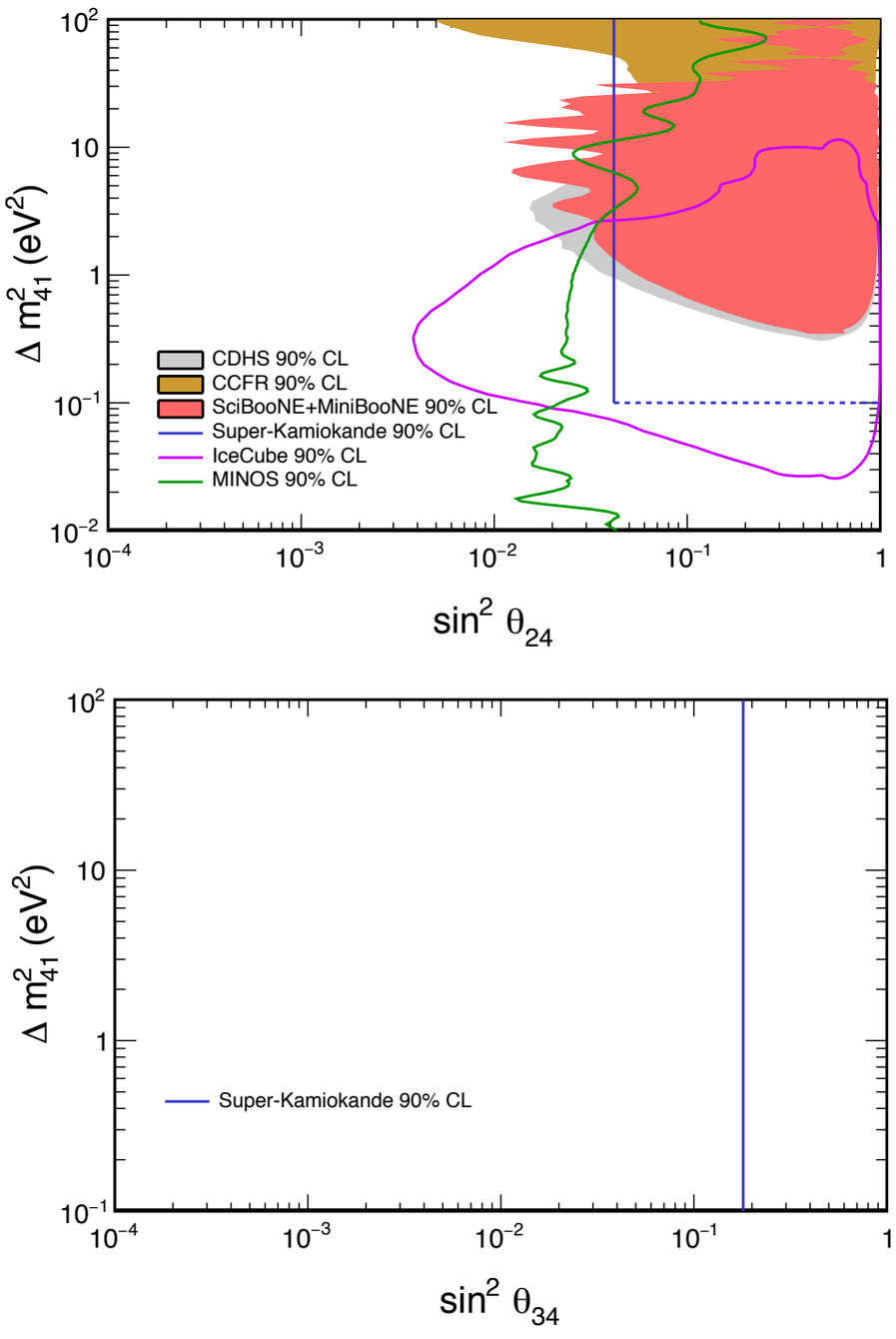




Future plans



- Development of covariance method allows for limits to be set over a broader range of parameter space.
- First, analysis of neutrino beam data using covariance method allows limits to be set in Δm_{41}^2.
- Once this method is used for neutrino beam data, it can be extended to antineutrino beam data also.
- More long-term goal: set limit using neutrino and antineutrino data simultaneously.

Summary

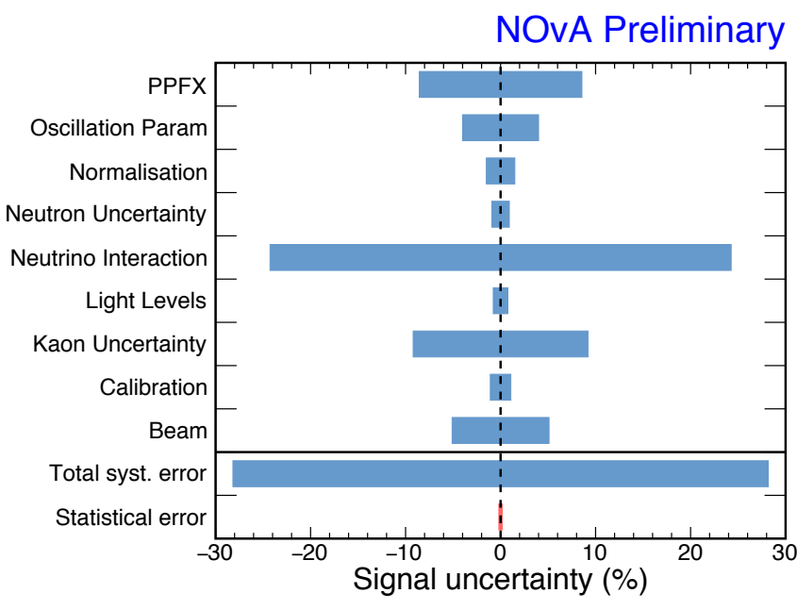
- **Search for active neutrino disappearance into a sterile flavour state in NOvA.**
- **Both neutrino and antineutrino data are consistent with three-flavor oscillations.**
- **Produced 68% CL allowed region in θ_{24} vs θ_{34} for antineutrino data using extrapolation method.**
- **Will use covariance method to perform a joint ND-FD fit to produce contours in θ_{24}, θ_{34} and Δm_{41}^2 for neutrino data.**
- **In the longer term, intend to perform similar analyses for antineutrino data, and ultimately fit neutrino and antineutrino data (and CC and NC data) simultaneously.**

http://novaexperiment.fnal.gov

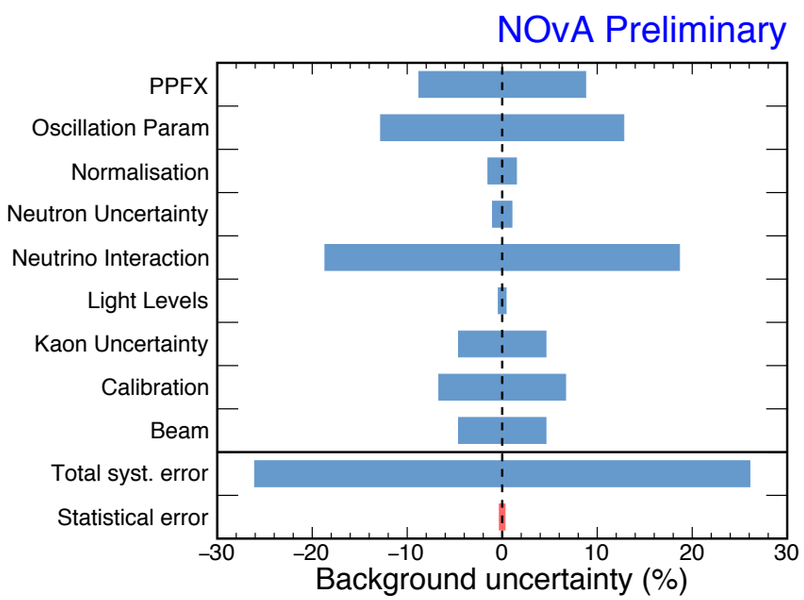
Backup slides

Neutrino beam data systematic uncertainties

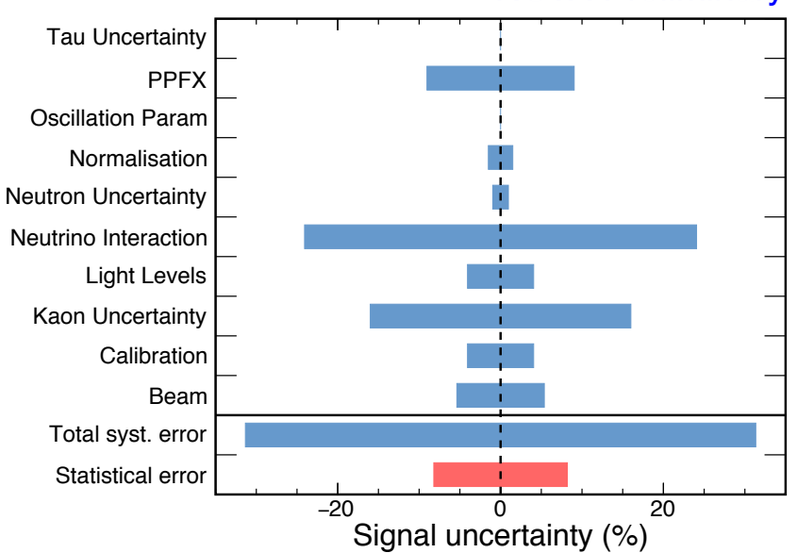
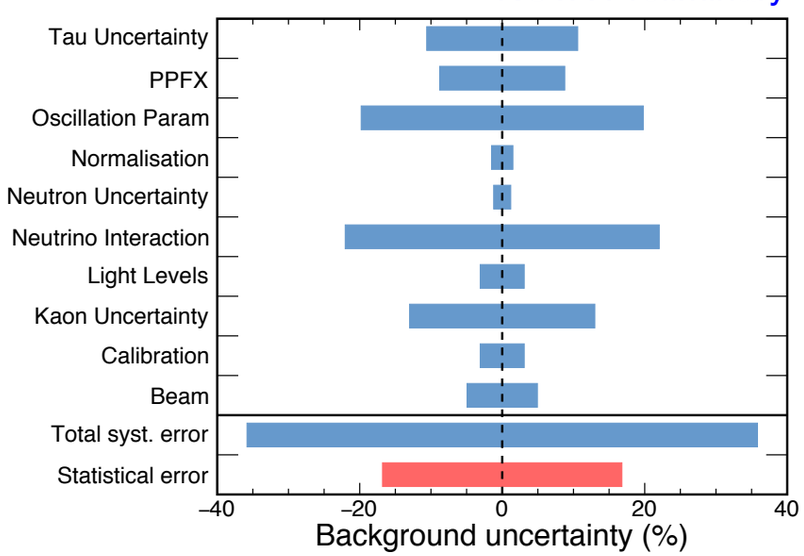
Near detector signal



Near detector background



Far detector signal



Far detector background