Extracting neutrino oscillation parameters using a simultaneous fit of the ν_e appearance and ν_μ disappearance data in the NOvA experiment

Prabhjot Singh, University of Delhi, India

On Behalf of the NOvA Collaboration

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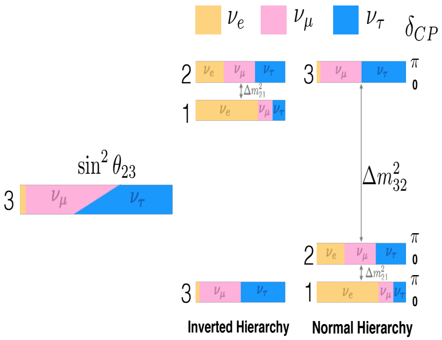
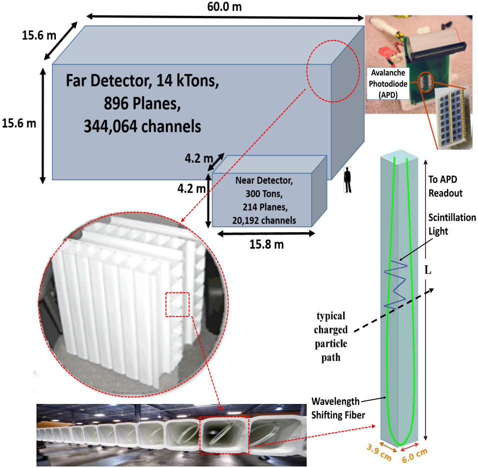
- Ordering of the neutrino masses: **Normal or Inverted hierarchies**?
- **CP violation**: do the neutrinos and anti-neutrinos oscillate differently?
- θ_{23} **angle:** is the mixing between ν_μ and ν_τ maximal or not?



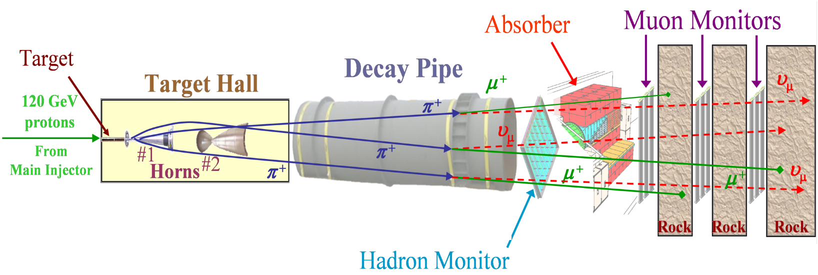
- NOvA (NuMI Off-axis ν_e Appearance) is a two detector, long baseline, neutrino oscillation experiment
  - NuMI (Neutrinos at Main Injector) beam is 97.5% ν_μ
  - NOvA is 14.6 mrad off-axis from the NuMI beam, observed energy spectrum peaks at 2 GeV peak
  - Near detector, ND, on-site at Fermilab.
  - Far detector, FD, at Ash River, MN, 810 km from the target.
- Oscillation channels
  - $\nu_\mu \to \nu_\mu$ disappearance
  - $\nu_\mu \to \nu_e$ appearance
  - Anti-neutrino modes

NOvA Detectors

- NOvA detectors are functionally identical
  - Polyvinyl chloride (PVC) and low Z scintillator detectors.
  - NOvA cells are arranged in alternating horizontal and vertical planes for 3D tracking.
- The ND is used to measure the beam before oscillations and the FD measures the oscillated spectrum.

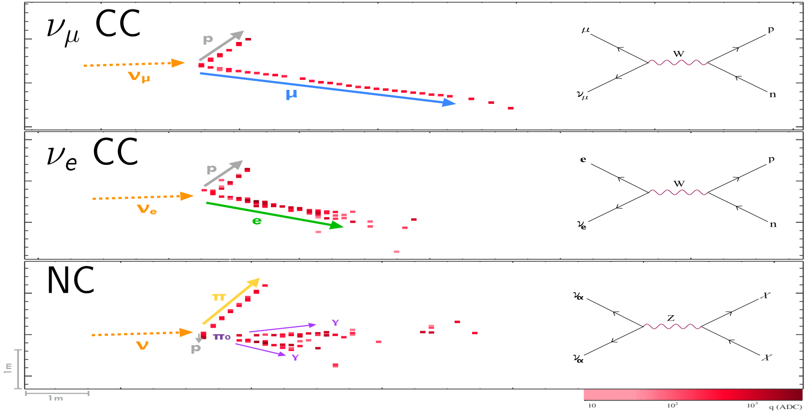


NuMI (Neutrinos at Main Injector) beam



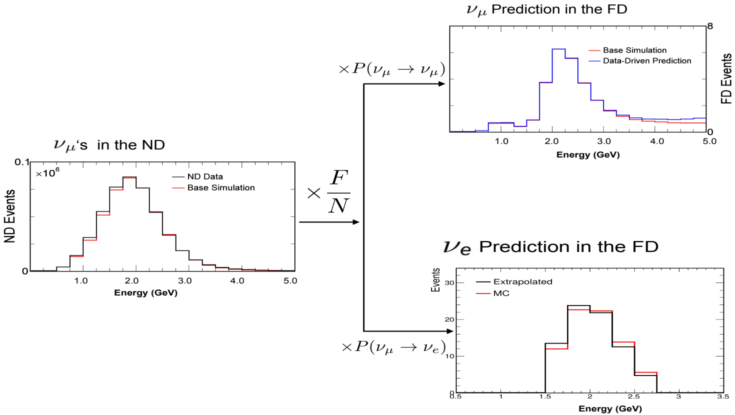
- A beam of high energy protons from the Main Injector are impinge on a fixed graphite target producing pions and kaons.
- Magnetic horns selects particles of the desired charge & momentum and focus them into a narrow beam.
- Charged pions and kaons spontaneously decay into muons and neutrinos.
- Rock after absorber filters out muons neutrinos produced in decay pipe.
- We are left with the neutrino beam.

Neutrino events in NOvA



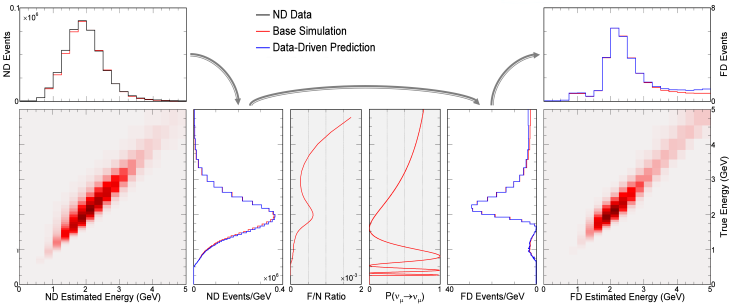
- ν_μ CC is the signal for the ν_μ ($\bar{\nu}_\mu$) disappearance anaysis.
- ν_e CC is the signal for the ν_e ($\bar{\nu}_e$) appearance anaysis.
- NC is a background in above analyses.

- ND spectra are used to predict the signal and backgrounds in the FD.
- Both $\nu_\mu \rightarrow \nu_\mu$ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance analyses use ν_μ's in the ND.
- The P($\nu_\alpha \rightarrow \nu_\beta$) and the simulated spectra from ND and FD are used in the form of Far over Near, F/N, ratios to make the FD predictions.



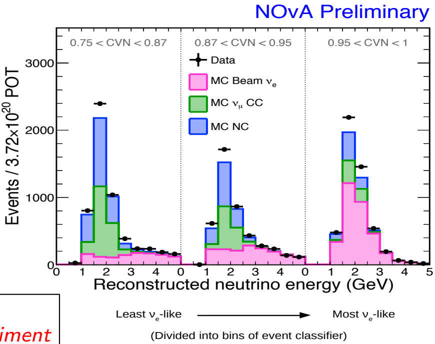
Extrapolation: Far detector signal prediction

- The reconstructed ND ν_μ CC energy spectrum is used to correct the FD simulated prediction.
- True energy distribution is corrected so that the reconstructed data & MC agree at the ND.
- The FD and ND MC spectra along with the oscillation probability for the $\nu_\mu \to \nu_\mu$ disappearance and $\nu_\mu \to \nu_e$ appearance are used to extrapolate corrected ND true spectra to the FD.
- The extrapolated true energy distrbution is converted to the reconstructed energy distrbution by using $E_{true} \to E_{reco}$ distribution.



Decomposition and Extrapolation of Backgrounds in ν_e appearance

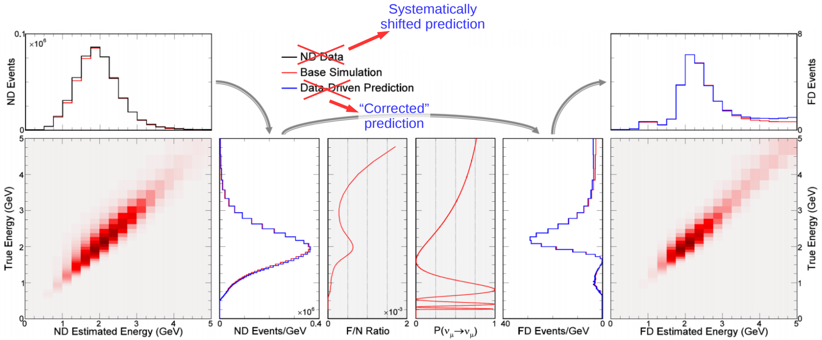
- We use deep learning to seperate the signal and backgrounds into 3 bins of ID confidence from least ν_e like to the most ν_e like.
- The ν_e selected beam ν_e CC, ν_μ CC and NC interactions in the ND are backgrounds in the FD.
- The ND spectrum is decomposed into NC, beam ν_e CC and ν_μ CC.
- Each component is extrapolated from the ND to the FD for background predictions in the FD.



See talk:
Deep Learning Applications in the NOvA Experiment
- Fernanda Psihas

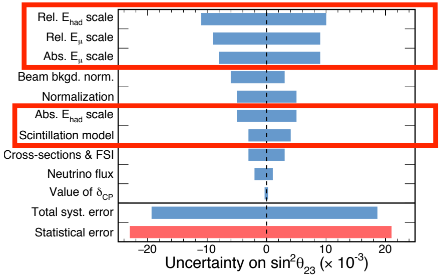
Extrapolation: Systematic uncertainties

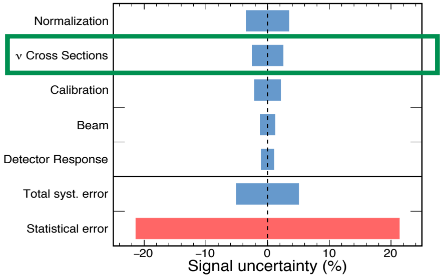
- Systematic uncertainties in the analysis are extrapolated from the ND to the FD using the same extrapolation technique.
- The ND Data is replaced by the ND prediction under a systematic shift.
- The corrected ND true energy spectra is extrapolated to the FD.



Systematic uncertainties in the ν_μ disappearance and ν_e appearance analyses

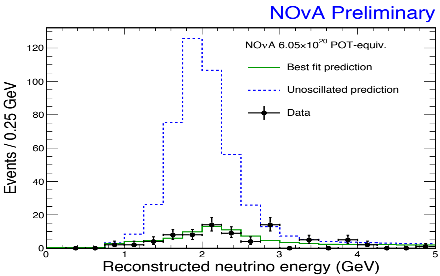
- Systematic uncertainties are included as nuisance parameters in the fit for all analyses.
- The functionally identical near and far detectors allow most uncertainties to cancel when predicting the FD spectrum.

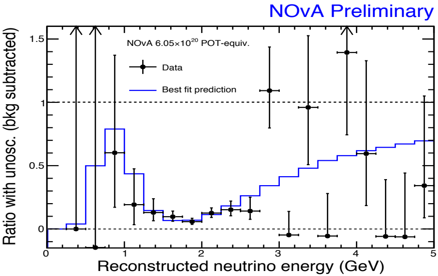


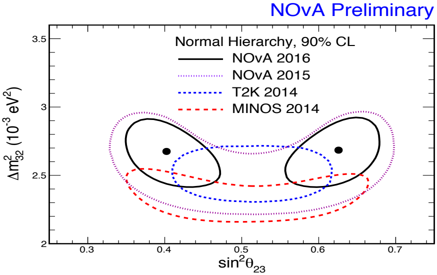


- In the disappearance analysis, uncertainties due to **detector response** are dominant but smaller than the statistical uncertainties.
- In the appearance analysis, **cross section** uncertainties are important for signal, but small compared to statistical uncertainties.

ν_μ fit to the disappearance data



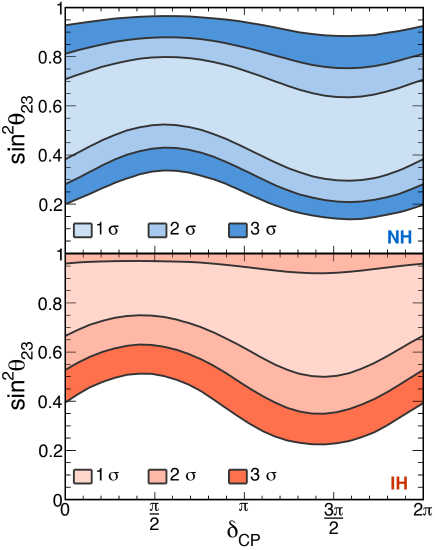


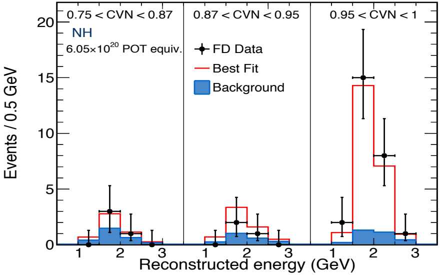


- Disappearance data is fit for the Δm^2_{32} and $\sin^2\theta_{23}$ parameters.
- Expected 473 events, observe 78 events, clear evidence of neutrino oscillations.
- Best fit in the Normal Hierarchy:
  $\Delta m^2_{32} = (2.67 \pm 0.11) \times 10^3 eV^2$

  $\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}$ or $0.624^{+0.022}_{-0.030}$
- Maximal-mixing disfavoured at 2.6 σ.

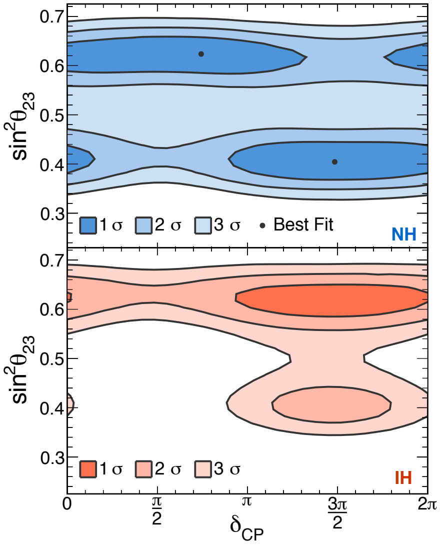
ν_e fit to the appearance data





- Appearance data is fit for the $\sin^2\theta_{23}$ and δ_{CP} parameters.
- Constrain parameters
  - $\sin^2 2\theta_{13} = 0.085 \pm 0.005$,
  - $\Delta m^2_{32} = +2.44 \pm 0.06$ (NH) $= -2.49 \pm 0.06$ (IH)
- Observe 33 events in the FD, $> 8\sigma$ significance of ν_e appearance.

Simultaneous fit of the disappearance and appearance data



- The constraints on the oscillation parameters can be improved by combining NOvA's ν_e appearance data with its ν_μ disappearance data.
- Appearance and disappearance data are simultaneous fit for the $\sin^2\theta_{23}$, δ_{CP} and Δm^2_{32} parameters.
- $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ is a constraint from the reactor experiments.
- Two statistically degenerate best fit points are in Normal Hierarchy: $\sin^2\theta_{23} = 0.404$, $\delta_{CP} = 1.48\pi$ and $\sin^2\theta_{23} = 0.623$, $\delta_{CP} = 0.74\pi$
- Inverted Hierarchy with lower θ_{23} octant for all values of δ_{CP} is rejected at $>$93% CL.

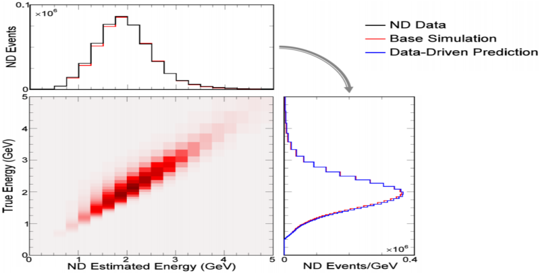
Summary

- NOvA is a two detector, long baseline, accelerator based neutrino oscillation experiment.
- The Near Detector measures NuMI beam before oscillations and helps in signal and background predictions in the Far Detector.
- Having two functionally identical detectors is advantageous for cancelling uncertainties that are common between the two detectors.
- Best fit to ν_μ disappearance data is a non-maximal value of θ_{23}, maximal mixing disfavoured at 2.6 σ.
- A simultaneous fit of the disappearance and appearance data rejects Inverted Hierarchy with lower θ_{23} octant for all values of δ_{CP} at $>$93% CL.
- Updated oscillation results soon with 50% more data.

Backup

Extrapolation: ND Spectra

- The $P(\nu_\alpha \rightarrow \nu_\beta)$ depends on E_{true}, but detectors measure E_{reco}.
- Detectors/reconstruction have different sensitivities to different processes, which have different $E_{true} \leftrightarrow E_{reco}$.



- The reconstructed ND ν_μ CC energy spectrum is used to correct the FD simulated prediction.
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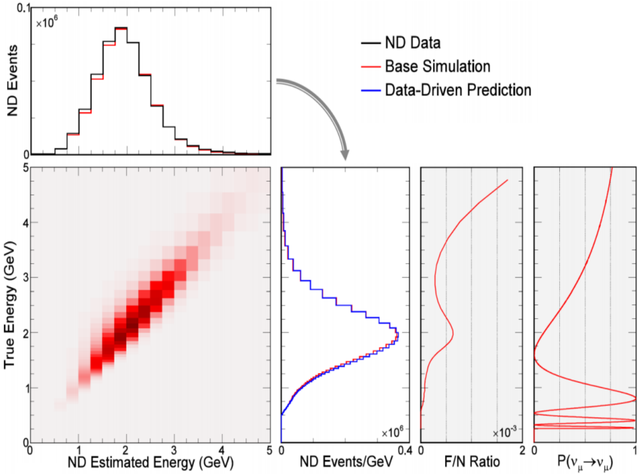
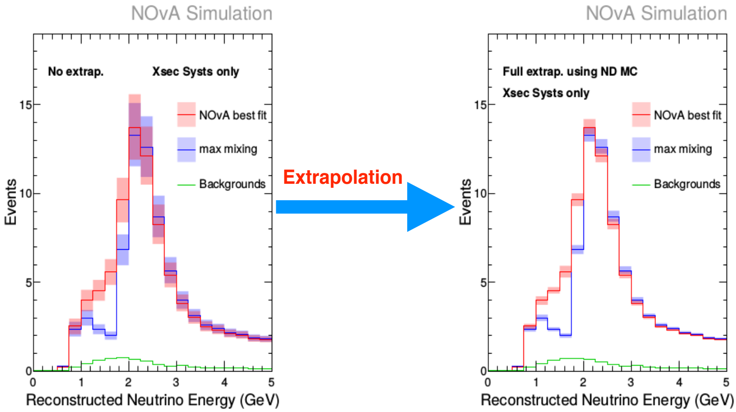
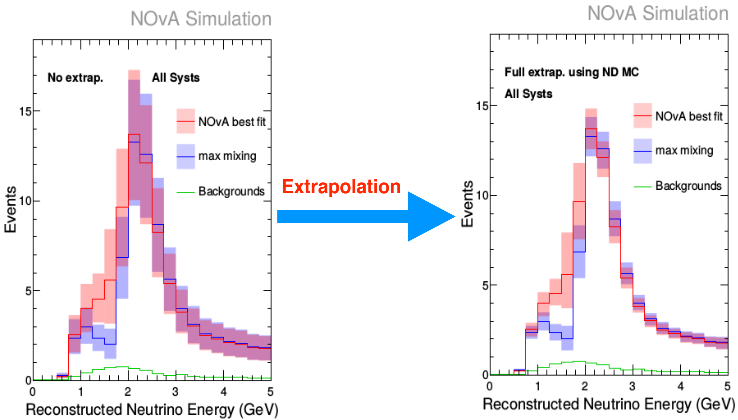


Extrapolation: all XS uncertainties



- These plots show the effect of cross-section uncertainty with and without extrapolation.
- The cross-section uncertainty is reduced when we use extrapolation method.

Extrapolation: all ν_μ uncertainties



- These plots show the effect of all ν_μ uncertainties with and without extrapolation.
- The uncertainties are reduced when we use extrapolation method.