Measuring cross sections of neutrino-nucleus interactions with associated charged pions in the NOvA near detector

Cathal Sweeney (University College London)

for the NOvA Collaboration

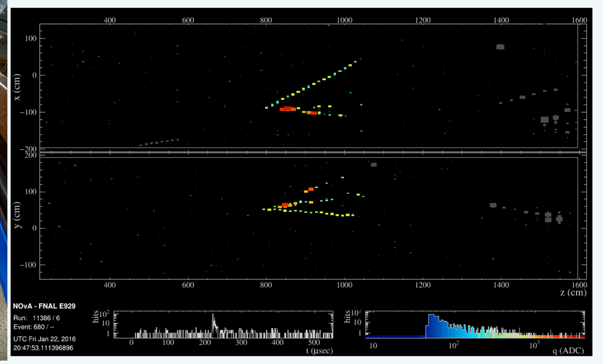
NOvA Near Detector

- NOvA is a long-baseline oscillation experiment
- 293 ton Near detector is used to measure neutrino-nucleus interactions
- Liquid-scintillator-based tracking calorimeter

Element	H	C	O	Cl	Ti
Percentage	10.76	66.71	2.98	16.06	3.22

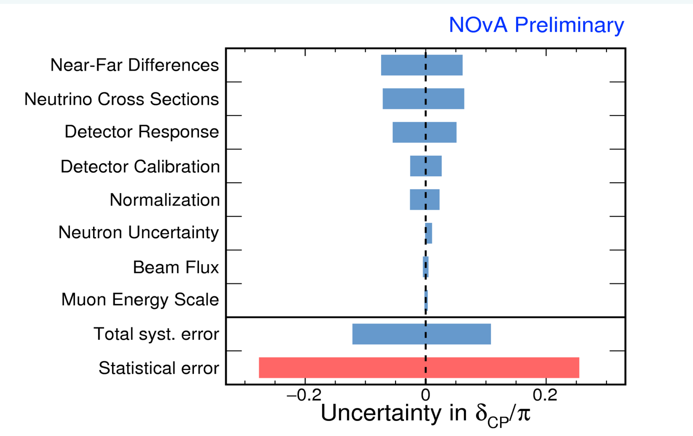
Composition of NOvA Near Detector fiducial volume (i.e.excluding components at edges of detector e.g. electronics). Percentages of each element are by mass. Elements which make up less than 1% of composition are omitted.

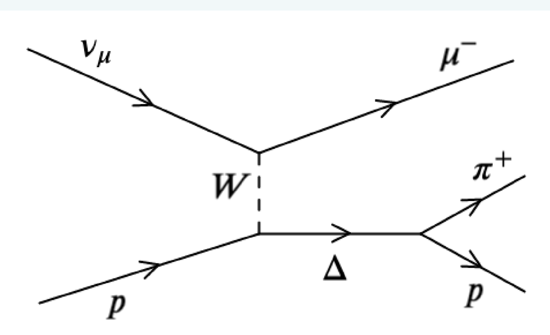
- 4m x 4m x 16m (final 3m is muon catcher, containing plates of steel to range out muons for energy estimation)
- Alternating planes of horizontal and vertical cells



Left: *Image of Near Detector.* Right: *Event display of charged current neutrino interaction generated using Monte Carlo simulation*

Motivation

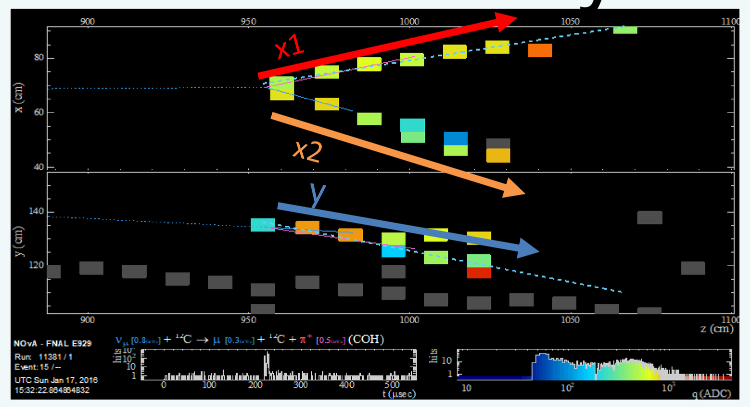




Left: *Contribution of different systematics to uncertainty on measurement of δ_{CP} in NOvA 2019 oscillation analysis.* Right: *Feynman diagram showing resonant pion production*

- Neutrino energy spectrum (which is necessary for extracting oscillation parameters) is affected by cross section. Cross section uncertainty is a leading systematic uncertainty in oscillation parameters as shown above
- Pion production is common at energies of NOvA and DUNE fluxes (peak ~ 2-3 GeV). This is the energy range at which the transition from quasi-elastic to DIS occurs, where resonant interactions contribute significantly
- Different interaction models can be quantitatively compared to NOvA measurements

Reconstruction & Systematics

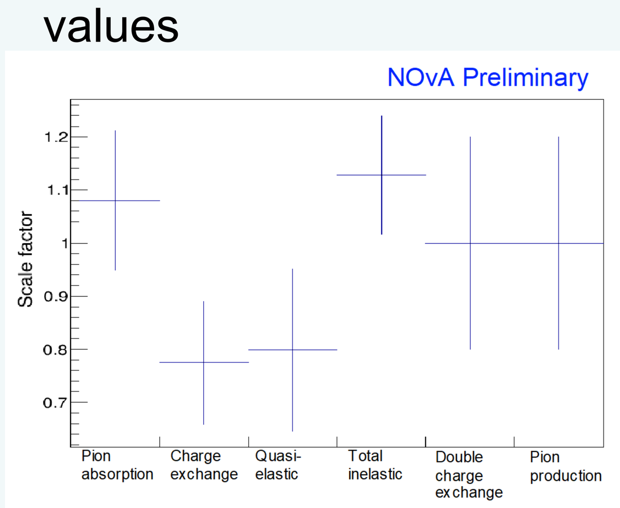


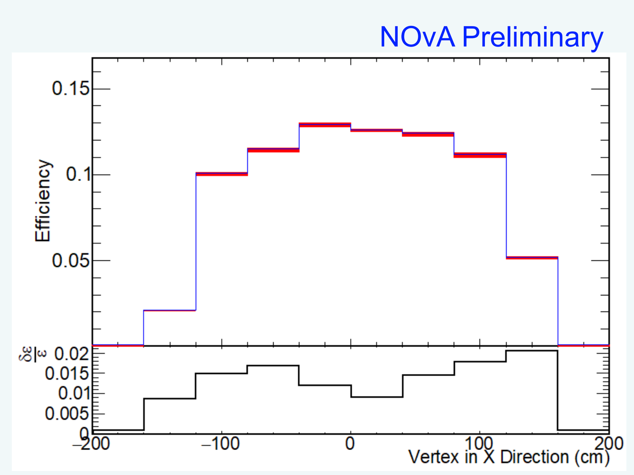
Event display showing event where particle paths overlap in y-view, so only one 3D prong is formed. Each 2D prong is marked with an arrow. Event generated using Monte Carlo simulation.

- Prongs are reconstructed objects consisting of collection of cell hits emanating in one direction from the reconstructed interaction vertex. The collection of hits roughly corresponds to a final state particle
- To make 3D prongs there is one-to-one matching of 2D prongs in x-view and y-view
- This can lead to mis-reconstruction of pions (as well as other particles) when prongs overlap in one view (shown above)
- Efforts in progress to allow two-to-one matching, along with other improvements

Geant4 Reweighting

- Existing systematic uncertainties for cross section measurements include
  - Energy calibration shape, energy calibration normalization, light level, cherenkov: $\frac{\delta\epsilon}{\epsilon} \sim 2\%$ each
  - GENIE multiverse systematic: $\frac{\delta\epsilon}{\epsilon} \sim 4\%$
- Work in progress to investigate the effect of uncertainties in pion scattering
- Uses externally developed package Geant4Reweight to calculate events weights
- Scales cross section for pion scattering modes by factor determined from fit to world pion scattering data in Carbon
- Event weight calculated from ratio of pion survival probability with nominal (σ) and best fit (σ') cross section values





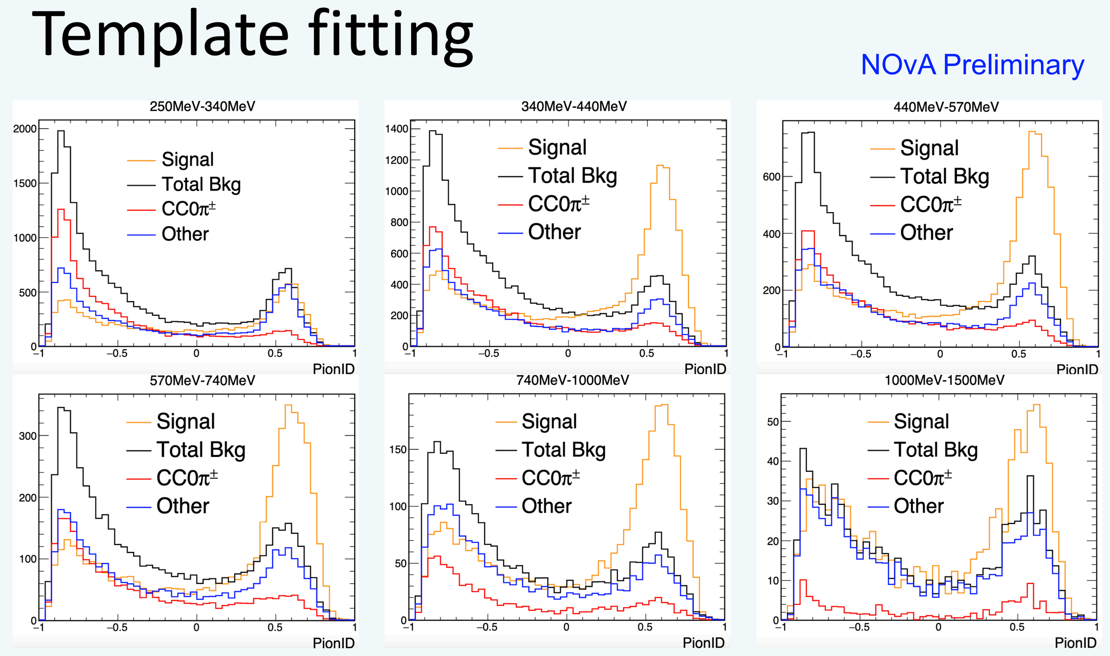
Left: *Best fit values and uncertainties on scale factors associated with pion fates. 1.0 corresponds to nominal value used in GEANT4.* Right: *Nominal pre-selection efficiency for ν_μCC $1\pi^\pm$ analysis in blue with uncertainty band due to pion scattering in red (top), and fractional uncertainty (bottom)*

ν_μCC $N\pi^\pm$

Analyzer: Paul Rojas

- Signal definition:
  - $1\mu^-$ and $\geq 1\pi^\pm$
  - E_μ > 500 MeV, E_π > 250 MeV
  - $\cos\theta_\mu$ > 0.6
- Aim is to measure differential cross section with respect to pion energy
- Pions identified using boosted decision tree (BDT) trained on dE/dx and scattering of track. BDT output is "pion ID" score.

Template fitting



Templates to be fit in bins of reconstructed pion energy. Produced using Monte Carlo simulation.

NOvA Preliminary

Energy range (MeV)	Signal	CC0π±	Other Bkg
250 - 340	6.8	18.4	15.2
340 - 440	6.0	16.4	13.1
440 - 570	5.8	24.2	15.0
570 - 740	6.6	25.5	14.2
740 - 1000	8.2	46.4	16.4
1000 - 1500	12.5	91.4	12.5

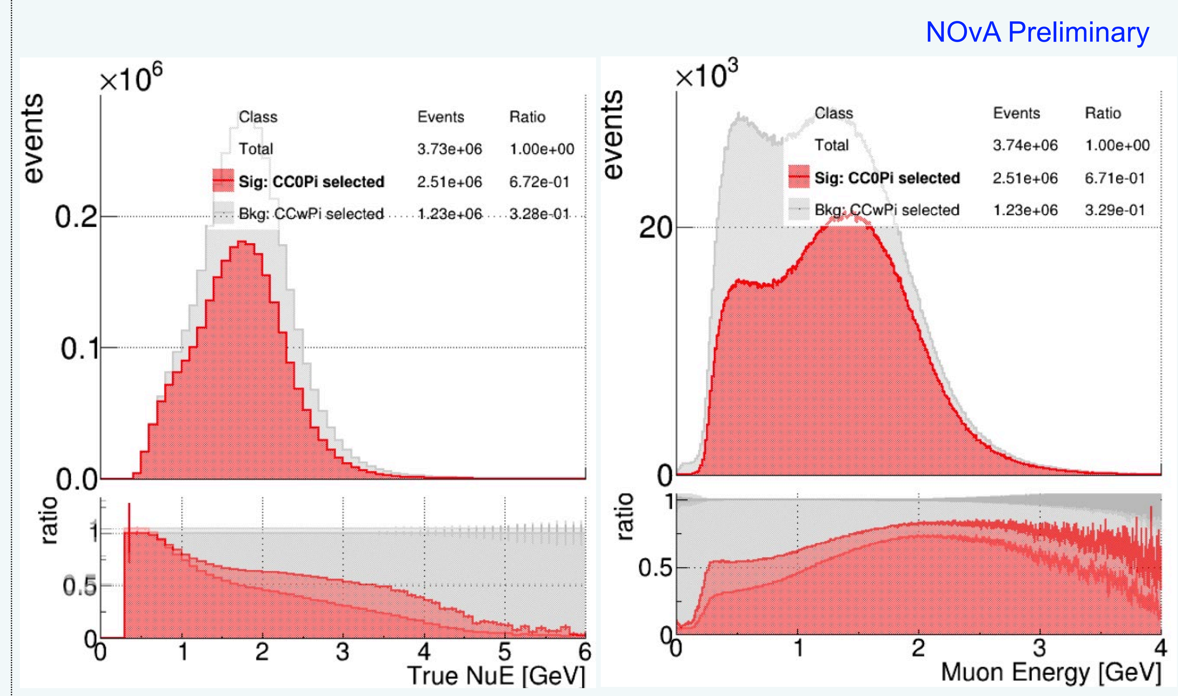
Fractional uncertainty on template normalization fit values, expressed as percentage. Fit is performed on fake data, with both statistical and systematic uncertainties accounted for

- Signal and background estimation done through template fitting method
- Here, a template is pion ID score distribution broken down by signal and background components in a given bin of pion energy, generated through simulation
- Assume simulation describes template shape reasonably well, but not normalization (shape uncertainty accounted for using covariance matrix made from systematically shifted samples)
- Fit to fake data used to find template normalizations

ν_μCC 0π

Analyzer: Sebastián Sánchez

- Signal definition:
  - 1μ and 0π
  - E_μ > 500 MeV
  - $\cos\theta_\mu$ > 0.6
- Aim is to deliver differential cross section in muon kinematics, statistics permitting



Distribution of selected signal and selected background events after pion rejection (Top) and sample purity before and after pion rejection in red and light red respectively (Bottom), versus true neutrino energy (Left) and true muon energy (Right)

- Pion rejection done using deep learning Convolutional Visual Network (CVN)
- CVN is a convolutional neural network which classifies particles using an image representation of the neutrino interaction (see event display in "NOvA Near Detector" section for example)
- "Colour" of image corresponds to calibrated hit information

Other charged pion analyses

ν_μCC $1\pi^\pm$

- Can provide probe of of Δ resonance
- May be able to measure Adler angles, which carry information about polarisation of Δ resonance

CC coherent pion production

- Rare interaction where neutrino interacts with nucleus as a whole, rather than with individual nucleon