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Status of the NOvA cross-section analyses

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NuMI beam

- Narrow band beam centred around 2GeV
- Both neutrino and antineutrino mode
- Hadron production uncertainty constrained by external hadron production data



NuMI beam performance



- NuMI beam running at 700 kW design power since January 2017.
 (> 18 x 10¹⁸ protons per week). Highest power beam in the World!
- Recorded:
 - ~12 x 10²⁰ POT in neutrino mode
 - ~12 x 10²⁰ POT in anti-neutrino mode

NOvA ND

- ND is at **1 km** from source, **underground** at Fermilab.
- PVC cells filled with liquid scintillator, 193 ton fully active mass and 97 ton downstream muon catcher.
- Alternating planes of orthogonal views.

Low-Z, fine-grained: 1 plane ~0.15X₀ (38 cm)





Percentage of total detector mass

NOvA event topologies



Current NOvA analyses

NC Coherent π⁰

νμ-CC Semi-inclusive π⁰

 $\nu\mu$ -CC Inclusive ν e-CC Inclusive

ALMOST **RESULTS!**

RESULTS!

 $\nu\mu$ -CC Semi-inclusive π +/- $\overline{\nu}\mu$ -CC Semi-inclusive π^{0} $\nu\mu$ -CC 0π

COMING OUT SOON

NC Coherent π⁰



- Renormalised background using energy and angle 2D space.
- Measured flux-averaged cross-section using background subtraction:

 $\sigma = 14.0 \pm 0.9(stat.) \pm 2.1(syst.)x10^{-40}cm^2/nucleus$

• Total uncertainty 16.7%, systematic dominant

Paper submitted to PRD (arXiv:1902.00558)

v_{μ} CC semi-inclusive π^{0}



- Signal: v_{μ} -CC events with at least one primary π^0 in the final state.
- Measured: flux-average cross section as a function of muon and neutral pion kinematics (angle respect to the beam and momentum), Q2 and W.

Paper is in final Collaboration Review, publication very soon!

v_{μ} CC inclusive

- Double differential cross section in muon kinematics variables
- Analysis is performed completely in 3D of quasi-orthogonal variables: (cosθ_µ,T_µ, E_{avail}) and projected to 2D.

Signal	CC Inc. $\overline{\mathbf{v}}_{\mu}$	NC	CC Inc.	Non-fiducial
CC Inc. v_{μ}			$v_e + \overline{v}_e$	
86.4 %	2.57%	7.60%	0.44%	2.96%
(1.18x10 ⁶)				



- E_{avail} is a proxy for the hadronic energy and independent of the muon kinematics
- E_{avail} is the energy that can be reliably observed in the detector with less model dependence

•
$$E_{avail} \sim T_p + T_\pi + E(e, \gamma, \pi^0, K)$$

 v_{μ} CC inclusive



Analysis in final stage, results in early 2020!

v_{μ} CC inclusive: 2p2h

- Double differential cross section as a function of E_{avail} and |q|
- According to Empirical MEC model, most 2p2h for NOvA is at $E_{avail} < 0.6~GeV$ and |q| < 1.2~GeV

Efficiency

Empirical MEC distribution



Analysis in initial stage

ve CC inclusive

- Double differential cross section in electron kinematics variables (never done before!)
- Challenge: v_e component is ~1%



Event rates 1-5 GeV	,
ν_{μ} : 96.3%	
ν_{μ} : 2.7%	
$v_e + v_e : 1.1\%$	

- Convolutional Visual Network (CVN) trained on single simulated particles drown from flat kinematic distributions
- Electron ID using CVN, shower gap from vertex and prong width

ve CC inclusive

- Template fit: data driven technique to extract signal and background estimates
- Electron ID template is generated and fit to data in each analysis bin. $0.94 \le \cos \theta_e < 0.97$ $2.00 \le E_e < 2.50$



Analysis is in final stage, expect results in early 2020

Other Analyses

- $\nu\mu$ -CC Semi-inclusive $\pi^{+/-}$
 - selection based on $\nu\mu$ -CC analysis
 - template fit based on pion ID (same technique as ve-CC analysis)
- νμ-CC 0π
 - selections based on $\nu\mu$ -CC analysis
 - currently investigating
- $\nu\mu$ -CC Semi-inclusive π^0
 - based on FHC analysis
 - using CVN for selection
- v-on-e analysis in progress

Conclusions

- NOvA has an excellent opportunity to make high precision neutrino-nucleus cross section measurements for both FHC and RHC.
- CC inclusive channels have the highest priority as they will be the base for the semi-inclusive measurements
- Both CC inclusive measurements are in the very final stages and we expect results to go public in early 2020
- Stay tuned for other analyses also following soon!
- Our next oscillation analysis will use GENIE 3, work ongoing

Thank you!

Fermilab

NO YA

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NO YA

NOVA ND



Event rates at NOvA ND

Even with a narrow band beam, NOvA is still sensitive to many different nu+A channels.

High data rate at the ND (~10⁶ interactions in the whole data taking period).



Simulation



Interactions in the NOvA ND



- Hits associated in time and space are used to form a candidate interaction.
- Vertices, tracks and showers are reconstructed from these hits.

v_{μ} CC inclusive: Reco + Selection



- Vertices should be inside a fully active (fiducial) region to cut rock muons.
- Muon candidates should be contained in the active region + Muon Catcher and any other track only in the active region to avoid shower leaking.