Status of the $\nu_\mu$ Charged-Current (CC) Zero Mesons Cross-Section Measurement in the NOvA Near Detector

Sebastian Sanchez-Falero,
on behalf of the NOvA collaboration

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Why $\nu_\mu$ CC Zero Mesons?

Solving open questions in neutrino physics requires that we understand their interactions.

Quasielastic (QE)  

Resonance (RES)  

Deep Inelastic (DIS)  

More inelastic  
Higher energy  
Smaller scale
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More elastic interactions are easier to fully reconstruct.

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- Partially known initial state
- Re-scattering
- Scattering off multi-particles
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**enhanced fraction of close-to-elastic modes** (QE, MEC)
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More **elastic** interactions are **easier to fully reconstruct**

This channel also provides windows to:

- Probe **weak-interaction structure** of nucleons
- Constrain **nuclear and Final State Interaction** models

Stepping stone for more **exclusive analyses**

Important **signal process** for **oscillation experiments**

one muon = $\nu_\mu$ CC

enhanced fraction of close-to-elastic modes (QE, MEC )
Why at the NOvA Near Detector?

- **Long-baseline** accelerator neutrino experiment at Fermilab
- **Two detectors** (functionally identical) to measure **oscillations**
- Liquid scintillator **tracking calorimeters**
- **77% hydrocarbon**, 16% Chlorine, 6% TiO$_2$

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Why at the NOvA Near Detector?

- **NuMI beamline**
- **Decay Pipe**

Flux at the Near Detector

96% $\nu_\mu$

$\langle E \rangle \sim 2$ GeV

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- high **intensity**, high **purity** beam

![Flux at the Near Detector]

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Great potential to contribute to **joint fits**
with experiments at other **neutrino energies** and **atomic number** ranges

**NuMI beamline**

**Flux at the Near Detector**

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How do $\nu_\mu$ CC Zero Mesons look at NOvA?

Prong = a trackable energy deposit
How do $\nu_\mu$ CC Zero Mesons look at NOvA?

**Zero Mesons**

*Also*

**Meson: Charged pion**

**Meson: Neutral pion**

*Prong = a trackable energy deposit*
How to select $\nu_\mu$ CC Zero Mesons events?

Need a tool to identify individual prongs by how they look in the detector.

Prong = a trackable energy deposit
How to select $\nu_\mu$ CC Zero Mesons events?

**The 5-label Single Particle Prong CVN**

- **Convolutional Visual Network**
  Takes pictures of the detector => applies convolutions to extract features

- **Training**
  individual uniformly simulated particles of 5 classes: muon, proton, pion, electron and photon

- **Application**
  Takes a prong => provides five particle ID scores, for each class of particle

- The **CNN** in Akhsay’s talk acts at the **event-level**
  (used in NOvA oscillation analysis)

- This **CVN** acts at the **prong-level (sub-event)**

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Event with CVN ID
How to select $\nu_\mu$ CC Zero Mesons events?

Find a muon

- The longest prong longer than 5 m

OR, if none

- The prong with highest MuonID

Separate this prong from further selection
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Reject events with Mesons

- Tag neutral pions
  Reject event if any prong has high $EMID = ElectronID + PhotonID$

- Tag charged pions
  Rank prongs by PionID:
  
  (1$^{st}$) Leading pion candidate
  2$^{nd}$ Leading pion candidate
  3$^{rd}$ Leading pion candidate
  ...

  Use ProtonID, MuonID and PionID to reject background events
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Backgrounds

- Wrong sign: Anti-$\nu_\mu$ CC
- $\nu_\mu$ CC N-Mesons (most likely pions)
- $\nu_e$ or Anti-$\nu_e$ CC events
- NC events
- Others
(1) **Preselection**

Based on parent $\nu_\mu$ CC Inclusive analysis:

- Reconstruction **quality**
- **Containment** of tracks and showers
- Interaction vertex in a **fiducial** volume
- **MuonID**: Find a muon using a Boosted Decision Tree taking dE/dX and scattering likelihood of tracks as inputs
**νµ CC Zero Mesons Selection: Number of Prongs**

- Very few **signal** events have five or more prongs
- Interactions that tend to produce less particles
$\nu_\mu$ CC Zero Mesons Selection: Number of Prongs

- Very few signal events have five or more prongs.
- Interactions that tend to produce less particles.
- Select events up to **four prongs**:
  - Purity: 42% → 47%
  - Efficiency: drops by <1%
$\nu_\mu$ CC Zero Mesons Selection: Highest EMID in the event

- Events with **2+ prongs** (at least one prong other than the muon)
- Zero Mesons (**signal** and **Wrong Sign**) fall at high EMID
$\nu_\mu$ CC Zero Mesons Selection: Highest EMID in the event

- Events with **2+ prongs** (at least one prong other than the muon)
- Zero Mesons (**signal** and **Wrong Sign**) fall at high EMID
- **Cut where Efficiency** $\times$ **Purity is maximum,** EMID $\leq 0.872$
  
  Purity 47% → 49%
  Efficiency drops by <1%
CC Zero Mesons Selection: 
1st Pion Candidate: ProtonID

- Events with 2+ prongs (at least one prong other than the muon)
- Zero Mesons (signal and Wrong Sign) fall at very low ProtonID

![Graph showing NOvA Simulation with various categories]
$\nu_\mu$ CC Zero Mesons Selection: 1\textsuperscript{st} Pion Candidate: ProtonID

- Events with 2+ prongs (at least one prong other than the muon)
- Zero Mesons (signal and Wrong Sign) fall at very low ProtonID
- Cut where Efficiency x Purity is maximum

ProtonID $> 0.072$

Purity 47% $\rightarrow$ 55%

Efficiency drops by 4%
$\nu_\mu$ CC Zero Mesons Selection:

1\textsuperscript{st} Pion Candidate: PionID

- Events with 2+ prongs (at least one prong other than the muon)
- Yields important additional purity gains
CC Zero Mesons Selection:

1st Pion Candidate: PionID

- Events with 2+ prongs (at least one prong other than the muon)
- Yields important additional purity gains
- Cut where Efficiency x Purity is maximum
  PionID <= 0.662
  Purity 55% → 62%
  Efficiency drops by 5%
\( \nu \) CC Zero Mesons Selection: 2\textsuperscript{st} Pion Candidate: ProtonID

- Events with 3+ prongs (at least two prongs other than the muon)
- Zero Mesons (signal and Wrong Sign) fall at very low ProtonID
- Yields \( \sim 0.2\% \) purity gain
**νμ CC Zero Mesons Selection:**

2nd Pion Candidate: ProtonID

- Events with **3+ prongs** (at least two prongs other than the muon)
- Zero Mesons (**signal** and **Wrong Sign**) fall at very low ProtonID
- Yields ~0.2% purity gain
- **Cut where Efficiency x Purity is maximum**
  
  Purity 61.6% → 61.8%
  
  Efficiency drops by 0.5%
$\nu_\mu$ CC Zero Mesons Selection: Summary

(1) Preselection

Reconstruction quality, containment of tracks, interaction vertex in fiducial volume and cut on MuonID

(2) Number of prongs $\leq 4$

(3) Highest EMID $\leq 0.872$

(4) Leading Pion Candidate (1$^{\text{st}}$ Pi)

- ProtonID $> 0.072$
- PionID $\leq 0.662$

(5) Second Pion Candidate (2$^{\text{nd}}$ Pi)

- ProtonID $> 0.042$
**νμ CC Zero Mesons Selection:**
Preview of Selection: Muon Kinetic Energy

**Before Selection**

**After Selection**
Summary

- I have developed a **selection** for a channel defined by a close-to-elastic final state.
- This selection currently yields **88% efficiency** (w.r.t. the starting preselected sample) and **62% purity**.

- **Next steps**
  - **Fine tune the signal**: include low energy pions that are not visible in NOvA.
  - Evaluate strategies to constrain remaining backgrounds.
  - Unfold reconstructed to true variables.
  - Efficiency studies and compute cross section.
  - Study of systematic uncertainties.
Thank you!

MAY 2020
Backup
νμ CC Zero Mesons Selection:

1\textsuperscript{st} Pion Candidate: PionID

- Events with 2+ prongs (at least one prong other than the muon)
- Plain PionID distributions before applying EMID cut.