IOWA STATE
UNIVERSITY

Status of the ν_μ Charged-Current (CC) Zero Mesons Cross-Section Measurement in the NOvA Near Detector

Sebastian Sanchez-Falero,
on behalf of the NOvA collaboration

New Perspectives 2021

August 19th, 2021

Why ν_μ CC Zero Mesons?

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

Why ν_μ CC Zero Mesons?

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

More *elastic* interactions are **easier to fully reconstruct**

Why ν_μ CC Zero Mesons?

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

More *elastic* interactions are **easier to fully reconstruct**

Quasielastic
Nuclear environment blurs
underlying interaction:

- Partially known initial state
- Re-scattering
- Scattering off multi-particles

Why ν_μ CC Zero Mesons?

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

More *elastic* interactions are **easier to fully reconstruct**

Quasielastic
Nuclear environment blurs
underlying interaction:

- Partially known initial state
- Re-scattering
- Scattering off multi-particles

But we can measure a **final state**

*More inelastic
Higher energy
Smaller scale*

Why ν_μ CC Zero Mesons?

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

More *elastic* interactions are **easier to fully reconstruct**

Quasielastic
Nuclear environment blurs
underlying interaction:

- Partially known initial state
- Re-scattering
- Scattering off multi-particles

But we can measure a **final state**

*More inelastic
Higher energy
Smaller scale*

Why ν_μ CC Zero Mesons?

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

More *elastic* interactions are **easier to fully reconstruct**

Quasielastic
Nuclear environment blurs
underlying interaction:

- Partially known initial state
- Re-scattering
- Scattering off multi-particles

But we can measure a **final state**

Why ν_μ CC Zero Mesons?

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

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**

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

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

Flux at the Near Detector

96% ν_μ

$\langle E \rangle \sim 2 \text{ GeV}$

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

The **Near Detector** receives a

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

Flux at the Near Detector

96% ν_μ

$\langle E \rangle \sim 2 \text{ GeV}$

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

The **Near Detector** receives a

- high **intensity**, high **purity** beam
- in a **dynamic** energy region (interaction modes)

making it an excellent lab for neutrino interactions!

Flux at the Near Detector

96% ν_μ

$\langle E \rangle \sim 2 \text{ GeV}$

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

The **Near Detector** receives a

- high **intensity**, high **purity** beam
- in a **dynamic** energy region (interaction modes)

making it an excellent lab for neutrino interactions!

Flux at the Near Detector

96% ν_μ

$\langle E \rangle \sim 2$ GeV

How do ν_μ CC Zero Mesons look at NOvA?

How do ν_μ CC Zero Mesons look at NOvA?

Zero Mesons

Zero Mesons
(also)

Meson:
Charged pion

Meson:
Neutral pion

How to select ν_μ CC Zero Mesons events?

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

How to select ν_μ 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)**

Detector picture

How to select ν_μ 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)**

Prong reconstruction

How to select ν_μ CC Zero Mesons events?

The 5-label Single Particle Prong CVN

- **Convolutional Visual Network (CVN)**
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)**

How to select ν_μ 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)**

How to select ν_μ 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)**

How to select ν_μ CC Zero Mesons events?

Detector picture

How to select ν_μ CC Zero Mesons events?

Event with CVN ID

How to select ν_μ CC Zero Mesons events?

Event with CVN ID

Find a muon

- The longest prong longer than 5 m

OR, if none

- The prong with highest MuonID

**Separate this prong
from further selection**

How to select ν_μ CC Zero Mesons events?

Event with CVN ID

Find a muon

- The longest prong longer than 5 m
- OR, if none*
- The prong with highest MuonID

Separate this prong from further selection

Reject events with Mesons

- Tag **neutral pions**

Reject event if any prong has high $EMID = ElectronID + PhotonID$

- Tag **charged pions**

Rank prongs by PionID:

(1st) Leading pion candidate

2nd Leading pion candidate

3rd Leading pion candidate

...

Use *ProtonID*, *MuonID* and *PionID* to reject background events

How to select ν_μ CC Zero Mesons events?

Event with CVN ID

Find a muon

- The longest prong longer than 5 m
- OR, if none*
- The prong with highest MuonID

Separate this prong from further selection

Backgrounds

- Wrong sign: Anti- ν_μ CC
- ν_μ CC N-Mesons (most likely pions)
- ν_e or Anti- ν_e CC events
- NC events
- Others

Reject events with Mesons

- Tag **neutral pions**

Reject event if any prong has high $EMID = ElectronID + PhotonID$

- Tag **charged pions**

Rank prongs by PionID:

(1st) Leading pion candidate

2nd Leading pion candidate

3rd Leading pion candidate

...

Use *ProtonID*, *MuonID* and *PionID* to reject background events

ν_μ CC Zero Mesons Selection: Summary

(1) Preselection

Based on parent ν_μ 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

ν_μ CC Zero Mesons Selection: Number of Prongs

- Very few **signal** events have five or more prongs
- Interactions that tend to produce less particles

ν_μ 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% $\rightarrow$ 47%
Efficiency: drops by <1%

ν_μ 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

ν_μ 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 x Purity is maximum, EMID ≤ 0.872**

Purity 47% $\rightarrow$ 49%

Efficiency drops by $<1\%$

ν_μ 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

ν_μ 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
- **Cut where Efficiency x Purity is maximum**
ProtonID > 0.072

Purity 47% → 55%

Efficiency drops by 4%

ν_μ 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

ν_μ 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% $\rightarrow$ 62%
Efficiency drops by 5%

ν_μ 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 $\sim 0.2\%$ purity gain

ν_μ 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 $\sim 0.2\%$ purity gain
- **Cut where Efficiency x Purity is maximum**
ProtonID > 0.042
Purity 61.6% $\rightarrow$ 61.8%
Efficiency drops by 0.5%

ν_μ 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 ≤ 4

(3) Highest EMID ≤ 0.872

(4) Leading Pion Candidate (1st Pi)

- ProtonID > 0.072
- PionID ≤ 0.662

(5) Second Pion Candidate (2nd Pi)

- ProtonID > 0.042

ν_μ 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

ν_μ CC Zero Mesons Selection: 1st Pion Candidate: PionID

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