Performance of Muon Neutrino Reconstruction at ICARUS using SPINE Machine Learning

NPML 2025

October 20-31, 2025 at University of Tokyo

Dante Totani - Colorado State University

Oct. 29, 2025

Overview

- A key requirement for the **neutrino oscillation measurements** is **robust event reconstruction**, including accurate and precise particle identification (PID) and kinematic reconstruction across a wide range of topologies.

- To achieve the required performance, we employ the **SPINE** framework
    - a state-of-the-art machine learning reconstruction framework.

- This talk presents the status of **muon neutrino reconstruction** using **SPINE** at **ICARUS**, including the evaluation of reconstruction performance
    - focusing on the **1μNp0π** channel (and **1μ1p0π** channel).

- **Precise muon neutrino reconstruction** is the “cornerstone” of the **muon neutrino disappearance** analysis, which will enable the full physics program at **ICARUS** and at the **SBN Program**.

The SBN Program at Fermilab

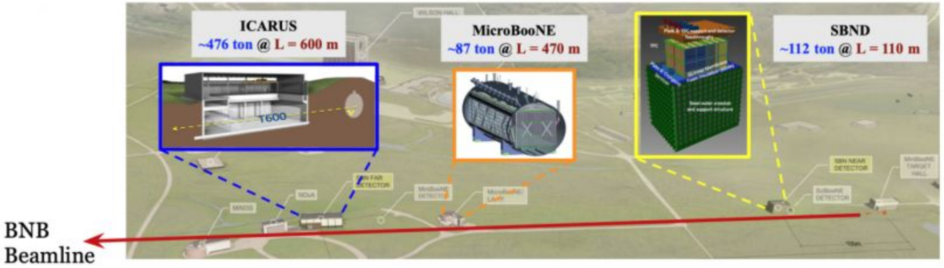
https://arxiv.org/pdf/1909.11670

The Short-Baseline Neutrino (SBN) Program at Fermilab is a neutrino experiment, using multiple Liquid Argon Time Projection Chamber (LArTPC) detectors, namely ICARUS (far detector) and SBND (near detector).

The detectors are exposed to the same beam, Booster Neutrino Beam (BNB), on axis at different distances from the beam target.

SBND	**~110m / 270 tons**
MicroBooNE	~470m / 170 tons
ICARUS	**~600m / 760 tons**

(MicroBooNE is a 3rd LArTPC detector currently decommissioned, in the same beam line)



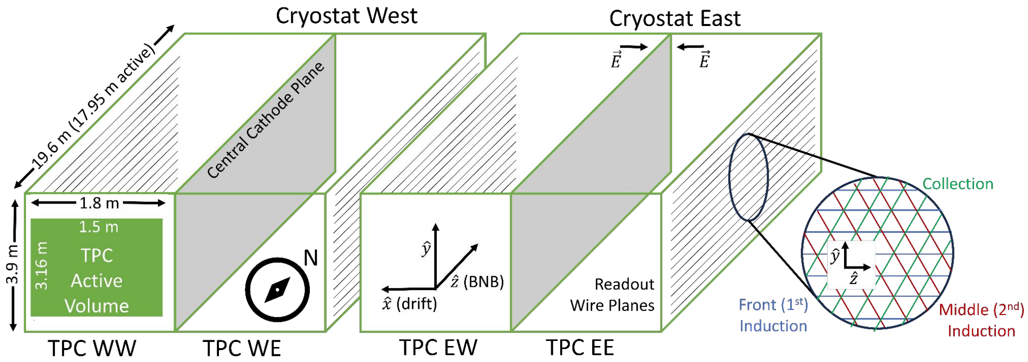
The primary objective of the SBN Program is to probe neutrino oscillation physics at short baselines to conclusively search for the existence of one or more additional "sterile" neutrino states driving oscillations at $\mathbf{\Delta m^2 \sim 1eV^2}$ and a relatively small mixing angle ($\mathbf{\sin^2 2\theta}$), which could explain anomalies observed in past experiments.

The key aspect of SBN is the capability of measuring both **muon neutrino disappearance** and **electron neutrino appearance** with multiple detectors, using the same detector technology exposed to the same neutrino beam.

The far detector: ICARUS T600

ICARUS is the **largest LArTPC** of the SBN Program:

- Surface-level detector
- Operational since 2020
- 760 tons of liquid argon / 470 tons fiducial mass
- TPC: two cryostats, four TPCs
- PDS: 360 PMTs (90 per TPC)
- CRT: 4π coverage



ICARUS is exposed to:

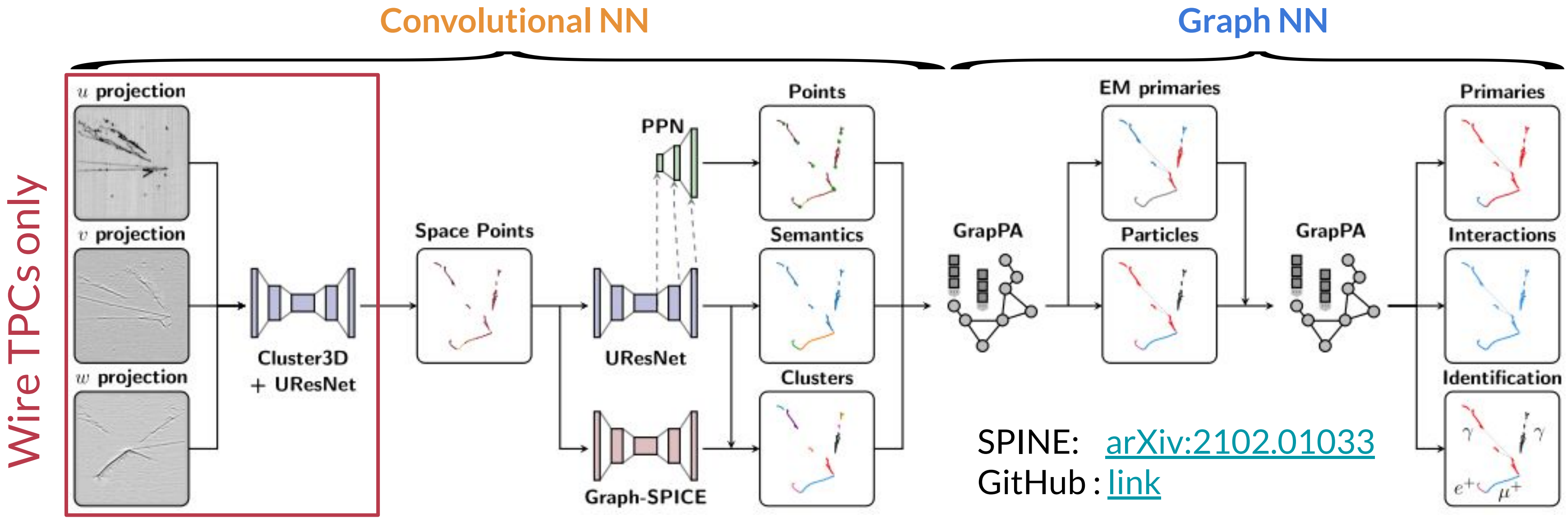
- the BNB beam, **~600m**, on-axis
- the NuMI beam, ~803m, off-axis, (0.097 rad)

https://arxiv.org/pdf/2407.12969

SPINE - Scalable Particle Imaging with Neural Embeddings

- a state-of-the-art machine learning reconstruction framework
- end-to-end reconstruction chain of particles and interactions in the TPC
- significantly improved performance compared to other approaches

More about SPINE in François' talk



SPINE: arXiv:2102.01033
GitHub : link

UResNet for pixel feature extraction, **GrapPA** for superstructure formation.

Muon Neutrino Signal Channels

$1\mu 1p0\pi$ and **$1\mu Np0\pi$** channels:

- Mature SPINE selections already exist for ICARUS
  - well-understood tracking and particle identification
  - neutrino energy reconstruction simpler due to lack of pions in selection
  - low cosmic background

ν_μCC inclusive channel:

- Analysis is ongoing
- Target selection in view of a SBN-wide analysis
  - larger statistics
  - reduced cross-play between selection efficiency and systematics (e.g. proton threshold)
  - cosmic rejection more challenging

ν_μCC incl. ($1\mu 0e$)

↓

$1\mu Np0\pi$ ($0e0\gamma$)

↓

$1\mu 1p0\pi$ ($0e0\gamma$)

The **$1\mu 1p0\pi$** channel is a subset of **$1\mu Np0\pi$** channel

Np →(N>0)p

The **$1\mu Np0\pi$** channel is a subset of **ν_μCC inclusive**

1μ, 0e, any p,π,γ

Event Selection

Visibility requirements on final state primaries:

$L_{\mu} > 50$ cm, $T_p > 50$ MeV, $T_{\pi,e,\gamma} > 25$ MeV

Topology selection on final state primaries:

- 1μ, 0e → required for all cases
- 1p/Np → at the least one proton
- 0π → $0\pi^{\pm}$ and 0γ (→ $0\pi^0$)

TPC requirement:

- ***ν***-Vertex in Fiducial Volume (FV)
- With and w/o Containment

Scintillation light match (PMTs):

- With and w/o Flashmatch

The target selection is w/o containment cut In view of SBN-wide analysis.

Due to the very different sizes of SBND and ICARUS, containment sculpts the signal kinematics differently in the two detectors.

Containment cut would help to remove background, critical for the ν_μCC inclusive selection

Optimization of scintillation light match and CRT veto ongoing to improve the cosmic rejection in view of ν_μCC inclusive selection

Event Selection

Multiple combinations of cuts are analyzed for both 1μNp0π and 1μ1p0π channels. This talk focuses on the most inclusive selection **1μNp0π**.

- **1μNp0π**
- **In Fiducial Volume** (F.V.)
- **With Flashmatch** (F.M.)
- **with and w/o Containment Cut** (C.C.)

Data are from ICARUS Run 2, on-beam* and off-beam, with BNB

*(10% Run 2 BNB unblind data)

Primary μ and p Reconstruction Performance

$1\mu Np0\pi$, w/o C.C.

Softmax Scores Index:

PID probability produced by the neural network in identifying particle type and primary vs. secondary

Top left:

- leading muon as muon

Top right:

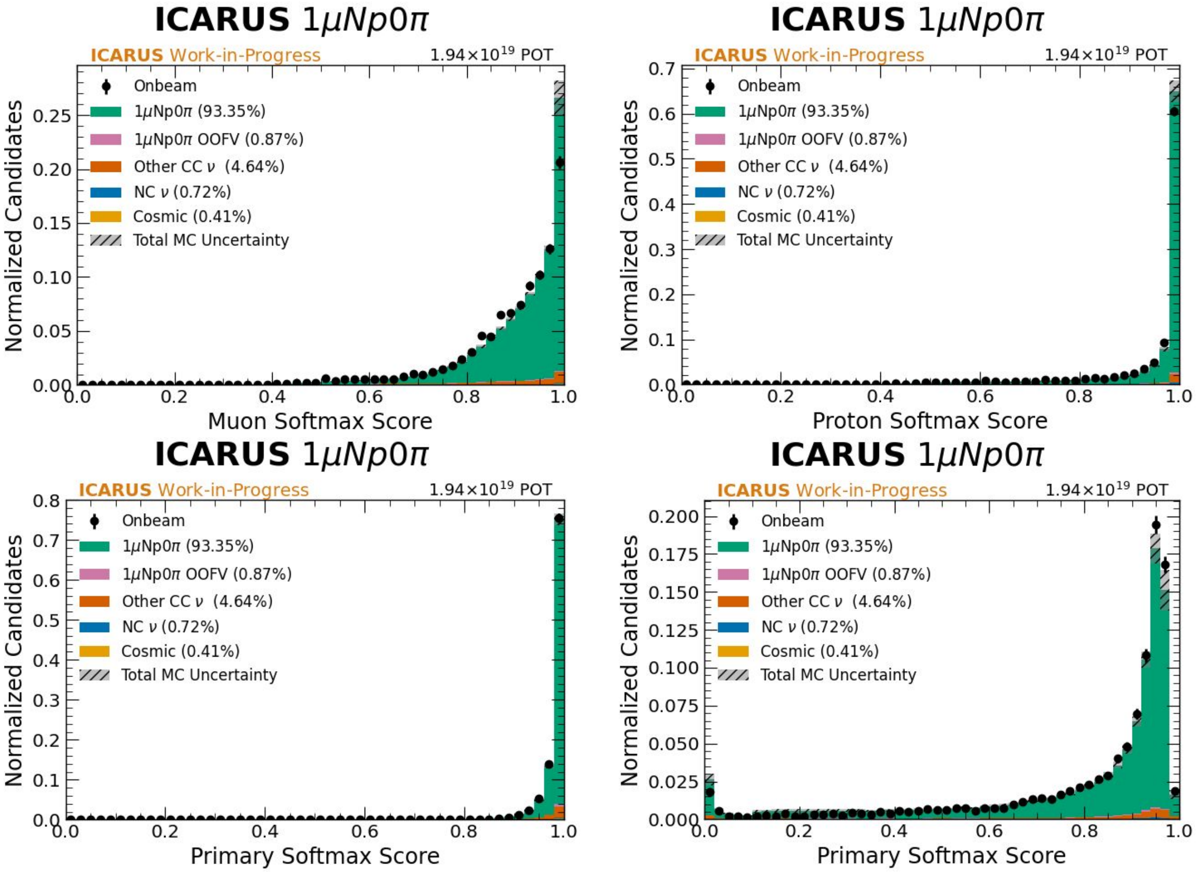
- leading proton as proton

Bottom left:

- leading muon as primary

Bottom right:

- leading proton as primary



Primary μ and p Reconstruction Performance

1μNp0π, with C.C.

Softmax Scores Index:

all distributions are peaked at one, indication of robust PID capability

Top left:

- leading muon as muon

Top right:

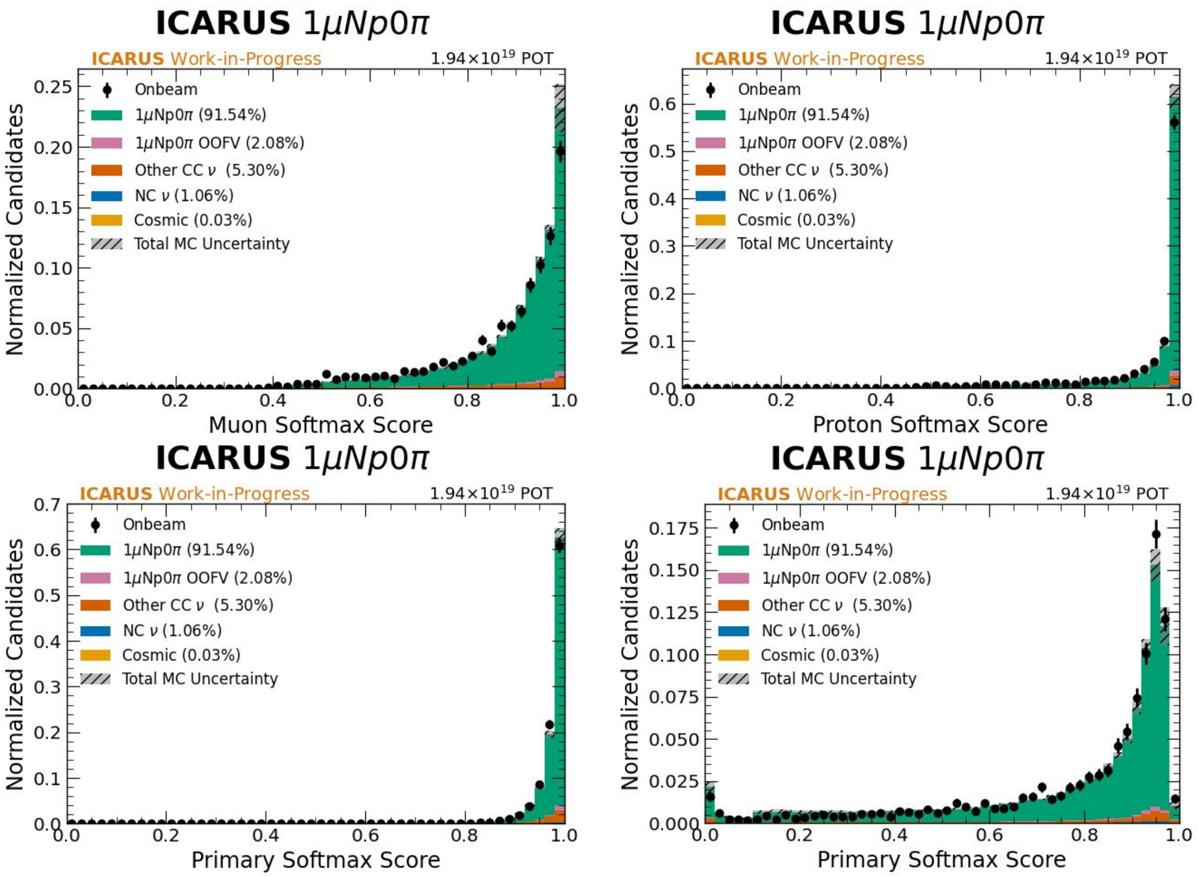
- leading proton as proton

Bottom left:

- leading muon as primary

Bottom right:

- leading proton as primary



Primary μ and p Reconstruction Performance

$1\mu Np0\pi$, w/o C.C.

Kinetic Energy Resolution:

performance is also characterized comparing reco vs. true values using MC events

Top left:

- leading muon $(T_{reco} - T_{true}) / T_{true}$

Top right:

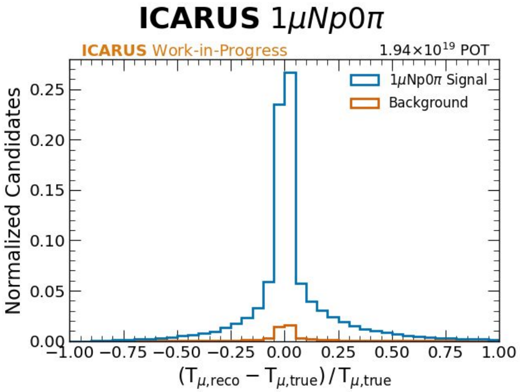
- leading proton $(T_{reco} - T_{true}) / T_{true}$

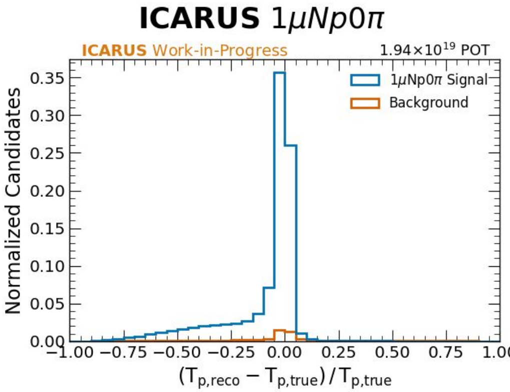
Bottom left:

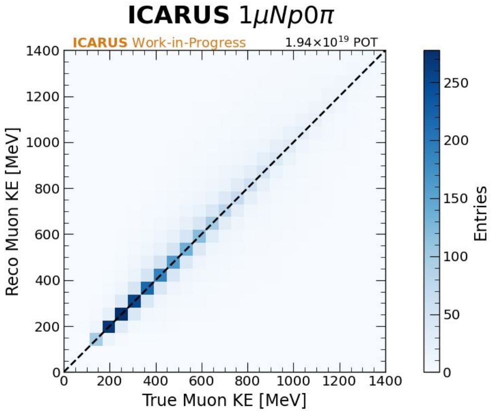
- leading muon (T_{reco} vs. T_{true})

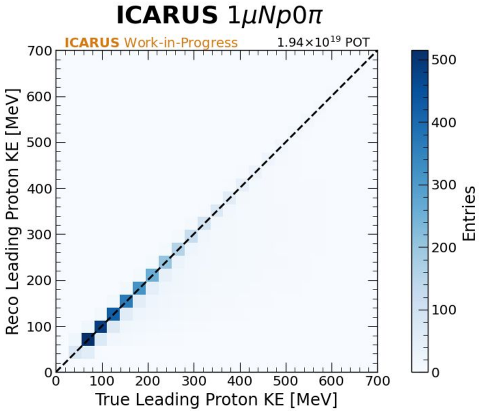
Bottom right:

- leading proton (T_{reco} vs. T_{true})







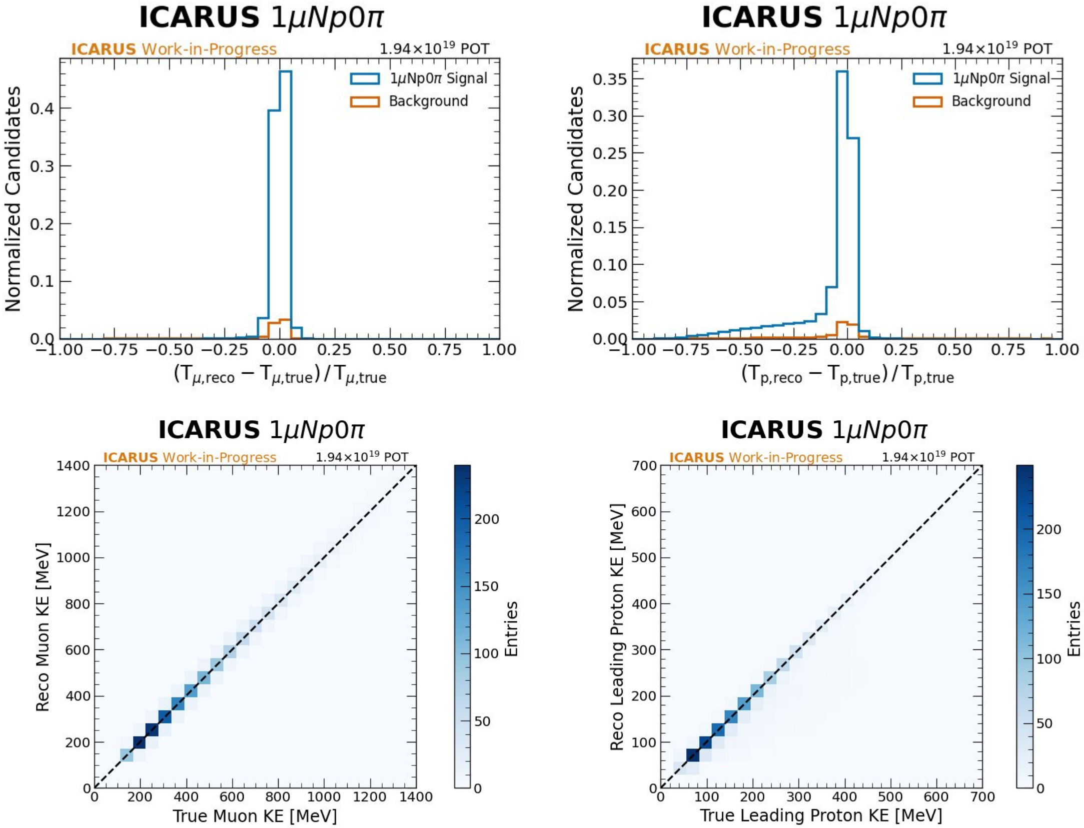


Primary μ and p Reconstruction Performance

1μNp0π, with C.C.

Kinetic Energy Resolution:

sharp peak at zero, excellent reco-true correlation highlight the reconstruction accuracy



Top left:

- leading muon $(T_{reco} - T_{true}) / T_{true}$

Top right:

- leading proton $(T_{reco} - T_{true}) / T_{true}$

Bottom left:

- leading muon (T_{reco} vs. T_{true})

Bottom right:

- leading proton (T_{reco} vs. T_{true})

Efficiency and Purity

SPINE shows excellent performance, significantly improved compared to other approaches:

1μNp0π, w/o C.C.

- **Purity = 93.3%**
- **Efficiency = 81.1%**

1μNp0π, with C.C.

- Purity = 91.5%
- Efficiency = 77.4%

Systematics

Meaningful comparisons between data and Monte Carlo simulations require a proper characterization of uncertainties:

Monte Carlo includes:

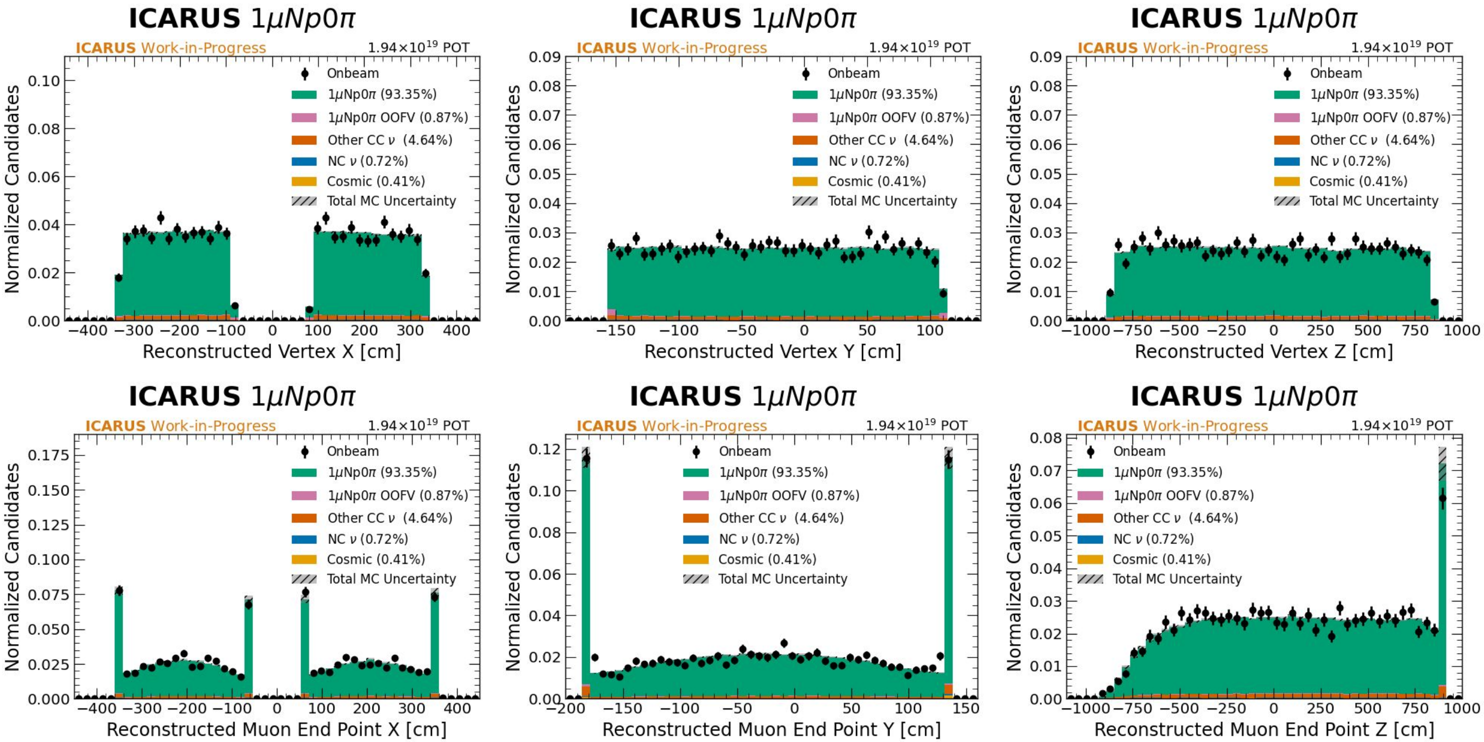
Statistical Uncertainty:	**[0.16 - 0.25]%**
Detector Systematics:	**[3.0-3.3]%**
Flux Systematics:	**[4.6 - 5.2]%**
Interaction Systematics:	**[14.9 - 15.9]%**
Total MC Uncertainty (%)	**[16.6 -17.3]%**

1μNp0π normalization uncertainties spanning selections with and w/o C.C.

Reconstructed *ν* Interaction Vertex and μ Endpoint

Selection w/o containment reduces biases in the neutrino phase space
→ uniform *ν* vertex distribution across all spatial coordinates (x, y, z).

1*μ*Np0π, w/o C.C.



- ***μ*** **endpoint edge peaks are expected for non-contained selection**
- **MC reproduces the data accurately**

Top row:

- *ν* vertex

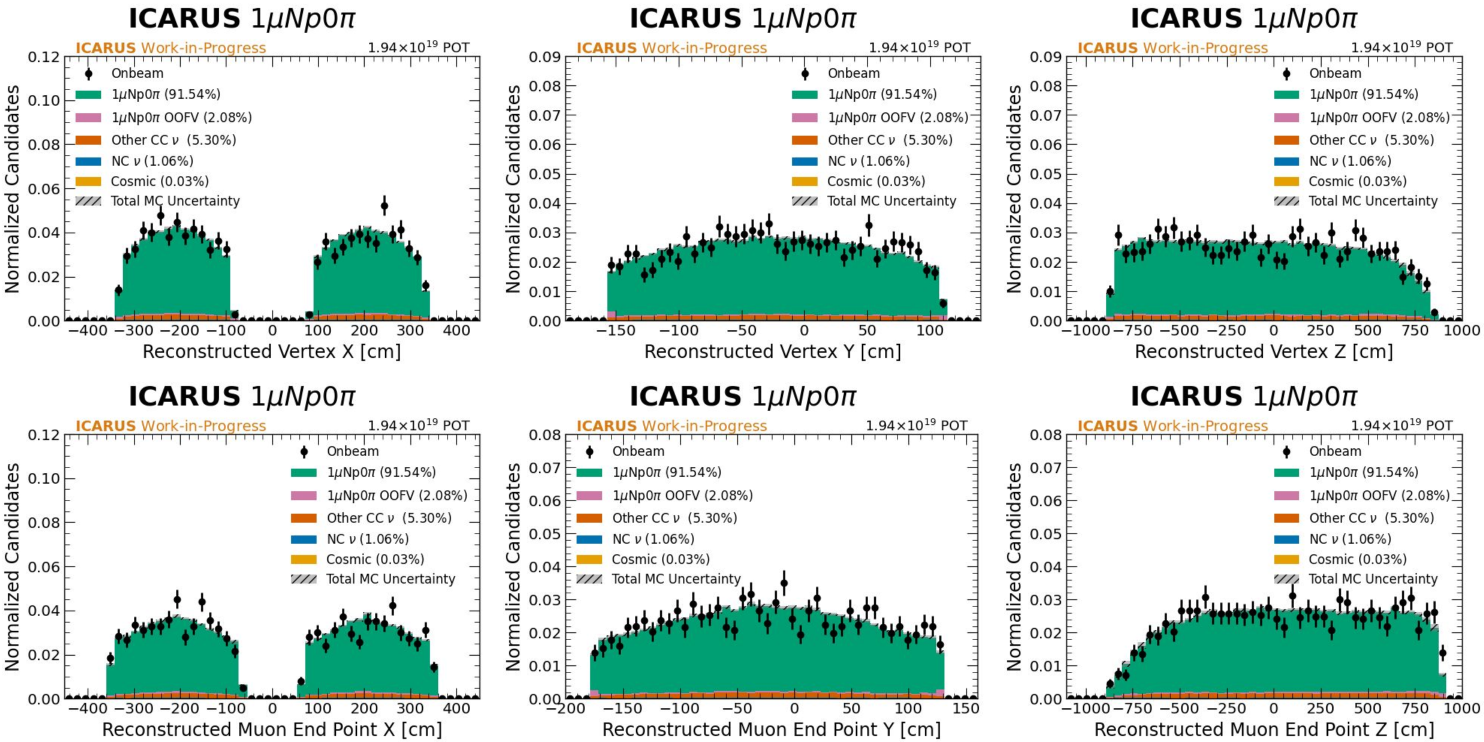
Bottom row:

- *μ* end point

Reconstructed ***ν*** Interaction Vertex and μ Endpoint

Selection with containment cut introduce some biases in the neutrino phase space → edge effects on *ν* vertex distribution

1*μ*Np0π, with C.C.



- contained selection helps to reject cosmic background

- MC reproduces the data accurately

Top row:

- *ν* vertex

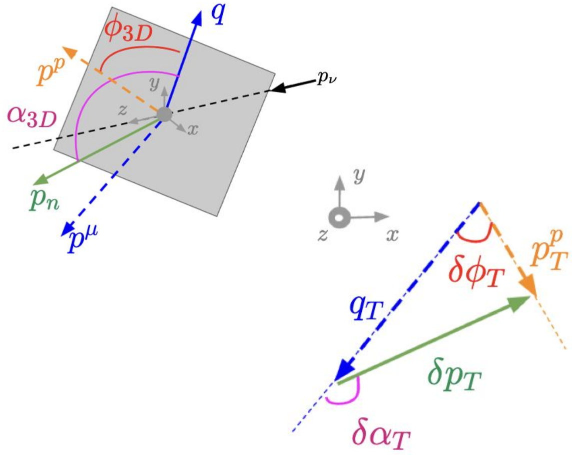
Bottom row:

- *μ* end point

Reconstructed Kinematic Variables

Along with the **reconstructed neutrino energy E_ν** (not shown in this talk), several **kinematic variables** are being studied:

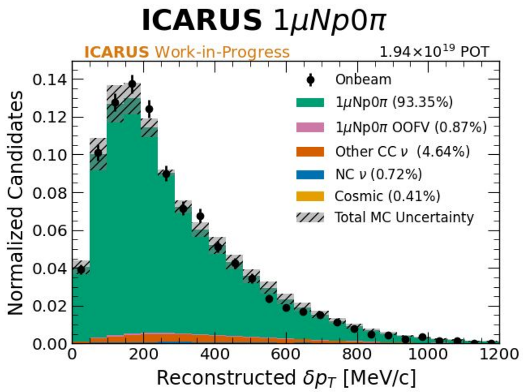
- **TKI - Transverse momentum: δp_T**
  - sensitive to nuclear effects and final-state interactions.
- **GKI - Total missing momentum: p_n**
  - provides information on initial-state nucleon motion and multi-nucleon processes.
- **Leading proton kinetic energy**
  - correlated with the energy transfer in the interaction and useful to study for systematics evaluation.

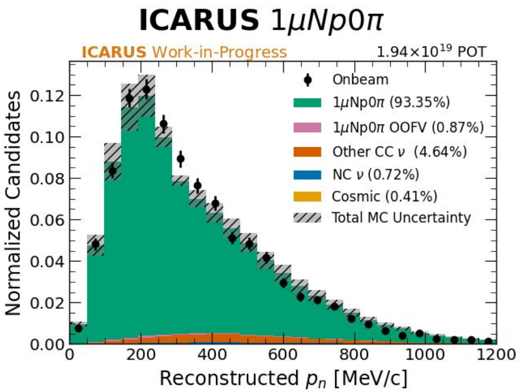


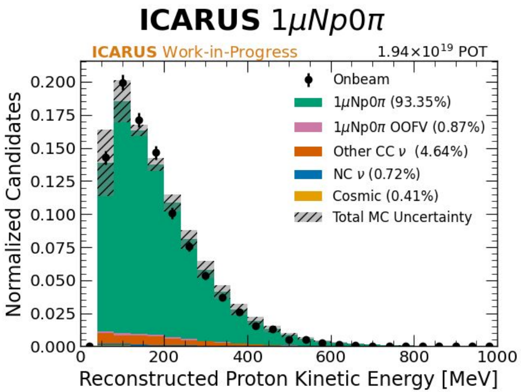
A **2D fit**, combining one of these observables (e.g., δp_T or p_n) with E_ν, enables a more precise separation of **signal and background components** and provides improved constraints on **nuclear effects** and **interaction modeling** (https://arxiv.org/pdf/2310.06082).

Reconstructed Kinematic Variables

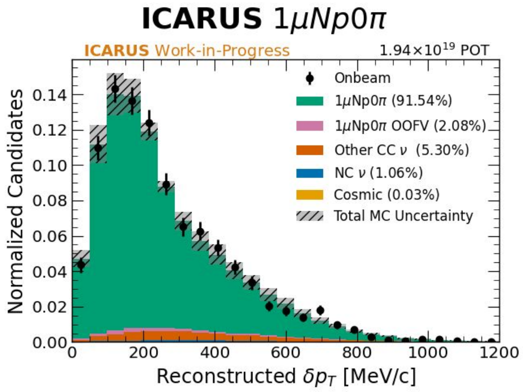
Transverse momentum: δp_T | Total missing momentum: p_n | (Leading) Proton KE

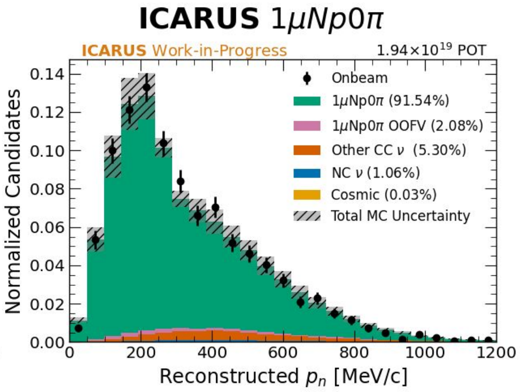


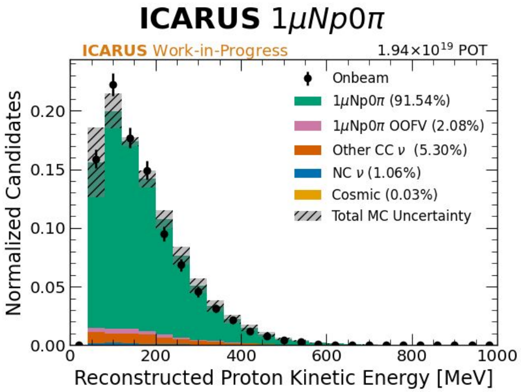




1μNp0π, w/o C.C.







1μNp0π, with C.C.

Summary

COLORADO STATE UNIVERSITY

- **SPINE Framework** demonstrates a robust event reconstruction and an excellent PID performance.
- **1μNp0π** channel (and 1μ1p0π channel) is a well-understood selection at **ICARUS** with reliable reconstruction and strong cosmic rejection.
- **SPINE 1μNp0π** selection at **ICARUS**:

SPINE

93% Purity, **81% Efficiency.**

Imaging Cosmic And Rare Underground Signals

Next Steps and Future Goals

Next Steps:

- Advancing **ν_μCC** inclusive selection at **ICARUS** (and **SBND**) using **SPINE**.
- Extending the analysis to **ν_e** selections at **ICARUS** (and **SBND**) using **SPINE**.

The **ν_μCC** selection is the first step to laying the groundwork toward a **SBN-wide oscillation analysis,** aiming for two-detector **ν_μ disappearance** and **ν_e appearance** measurements using **SPINE**.

Part of a large effort in Prof. Mike Mooney's group at CSU for using SPINE for the SBN physics program, with plans to further develop SPINE for the DUNE far detector.

Acknowledgement

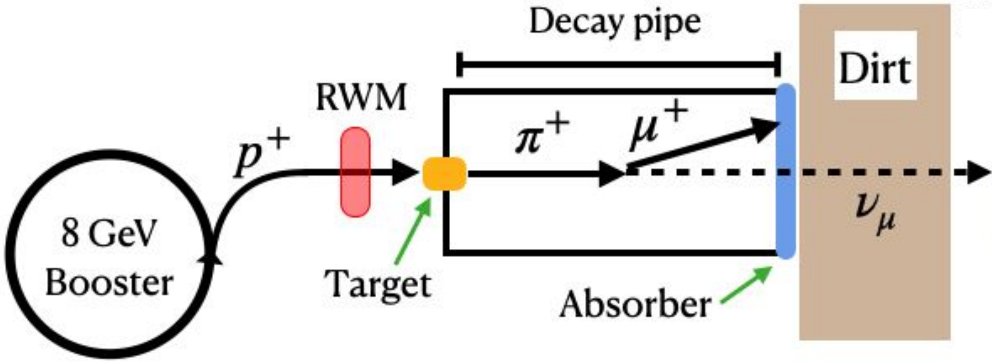
COLORADO STATE UNIVERSITY

This work is supported by the Department of Energy under grant numbers DE-SC0017740.

Backup Slides

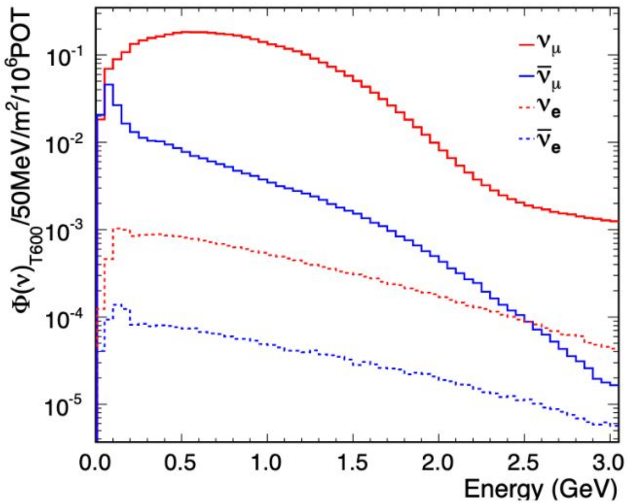
Booster Neutrino Beamline (BNB)

- 8 GeV protons from Booster
  - Up to 5.3 Hz repetition rate
  - 5 x 10^{12} protons per pulse, 1.6 μs spil
  - **⟨E_ν⟩ ~ 700 MeV**



BNB ν flux at ICARUS

https://arxiv.org/pdf/1503.01520



- Interaction rates:
  - * 0.03 Hz ν
  - * 0.07 Hz cosmic

*https://indico.global/event/13925/contributions/125635/attachments/59096/113781/sbnprogram_neatworkshop_may27_2025.pdf

ICARUS role in the SBN Program

With a baseline of L_ν ~600 m and the BNB ν energy E_ν~700 MeV

$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\,\mathrm{m}}{700\,\mathrm{MeV}} \sim \mathcal{O}\left(1 \frac{\mathrm{km}}{\mathrm{GeV}}\right)$$

Boost in the sensitivity for oscillations at Δm^2 ~1eV^2 for BNB ν.

The same Δm^2 region highlighted by experimental anomalies for possible sterile neutrino states.

The key aspect of SBN that is ONLY enabled with multiple detectors is that ν_e appearance cannot occur in without ν_μ disappearance

SBND (Near Detector, ~110 m)

- Primary role: **flux + cross-section precise measurement, systematics control.**
  - Measures un-oscillated BNB flux (ν_μ, ν_e).

ICARUS (Far Detector, ~600 m)

- Primary role: **oscillation sensitivity**
  - Observes oscillated spectrum (ν_μ disappearance, ν_e appearance).

Physic Goals of the SBN Program

In a 3 + 1 sterile neutrino model with: $\Delta m^2_{41} >> |\Delta m^2_{32}|, \Delta m^2_{21}$ and $m_4 >> m_{1,2,3}$ oscillations at short-baseline experiments can be well described by a two-flavor vacuum oscillation formula,

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 |U_{\alpha\beta}|^2 \left(\delta_{\alpha\beta} - |U_{\alpha\beta}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Each oscillation channels $\nu_\alpha \to \nu_\beta$ is driven by a effective mixing angle: $\theta_{\alpha\beta}$

$\nu_\mu \to \nu_e$ ⟶ $\sin^2(2\theta_{\mu e}) = 4|U_{\mu 4}|^2 |U_{e4}|^2$ ⟶ (LSND, MiniBooNE)

$\nu_e \to \nu_e$ ⟶ $\sin^2(2\theta_{ee}) = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$ ⟶ (reactor, gallium)

$\nu_\mu \to \nu_\mu$ ⟶ $\sin^2(2\theta_{\mu\mu}) = 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right)$ ⟶ (no anomalies observed)

Physic Goals of the SBN Program

The key aspect of SBN that is ONLY enabled with multiple detectors is that ***ν*** $_e$ appearance cannot occur in without ***ν*** $_\mu$ disappearance

$$P^{3+1}_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2(2\theta_{\mu\mu})\ \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

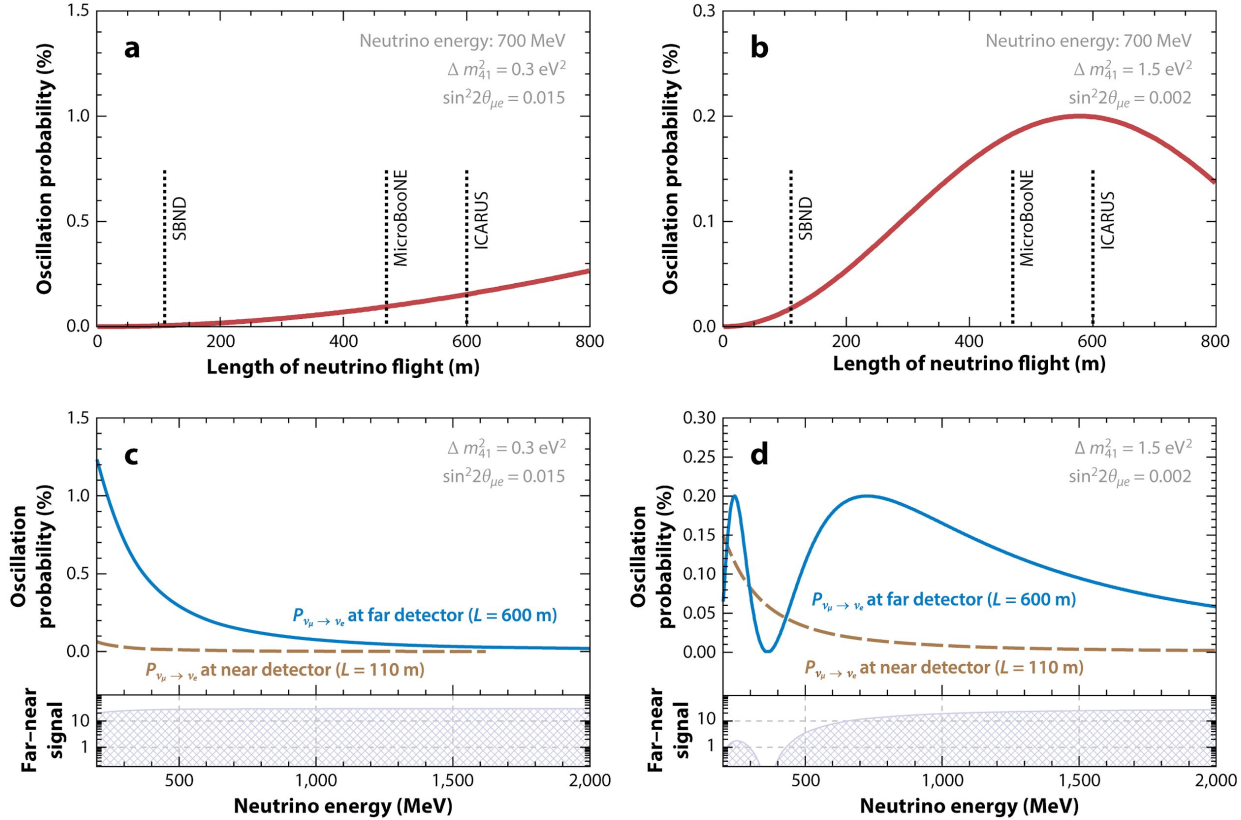
$$P^{3+1}_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta_{\mu e})\ \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$P^{3+1}_{\nu_e \rightarrow \nu_e} = 1 - \sin^2(2\theta_{ee})\ \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

The parameters dependence can be used to overconstrain the parameter space by observing ***ν*** $_e$ appearance together with ***ν*** $_\mu$ disappearance (and ***ν*** $_e$ disappearance).

NOTE: BNB is not a pure ***ν*** $_\mu$, a disappearance of the BNB ***ν*** $_e$ component need to be take into account.

SBN Near and Far Detectors



Machado PAN, et al. 2019.
Annu. Rev. Nucl. Part. Sci. 69:363–87

The locations of the near and far detectors are optimized for maximal sensitivity in the most relevant ranges of oscillation parameters.

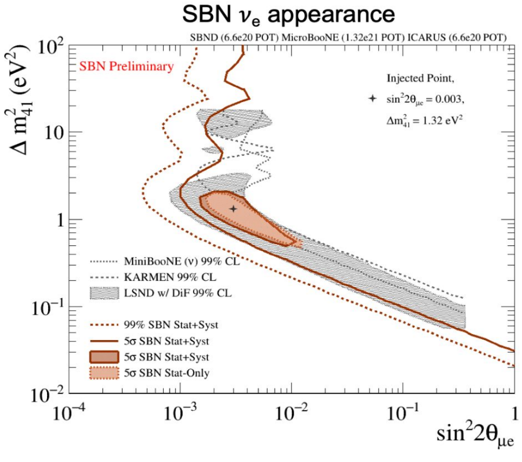
(a,b) $\boldsymbol{\nu}_\mu \rightarrow \boldsymbol{\nu}_e$ oscillation probability for a 700 MeV neutrino as a function of the baseline for two different benchmark points in a 3+1 sterile neutrino scenario.

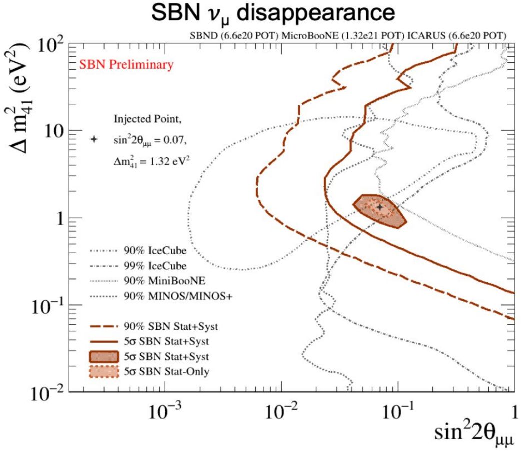
(c,d) $\boldsymbol{\nu}_\mu \rightarrow \boldsymbol{\nu}_e$ oscillation probabilities, at 110 m and 600 m, as a function of the neutrino energy for the same benchmark points.

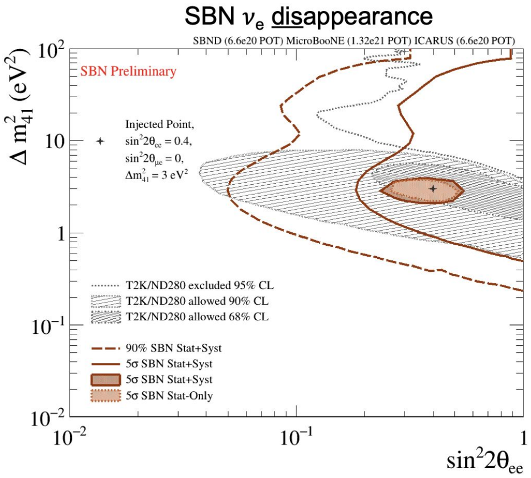
(Bottom) The far–near ratio of appearance probabilities.

https://doi.org/10.1146/annurev-nucl-101917-020949

SBND + ICARUS Sterile Oscillation Sensitivity







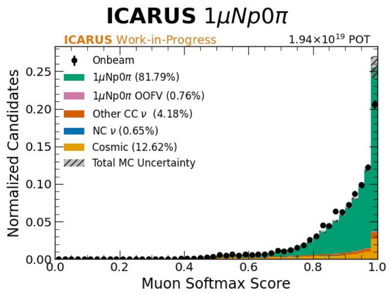
- Address conclusively the LSND and MiniBooNE anomalies.
- SBND will measure the ν_e and ν_μ components of the BNB with large statistics.
- ICARUS will search for an excess of ν_e and a deficit of ν_μ using SBND's measurement as reference.

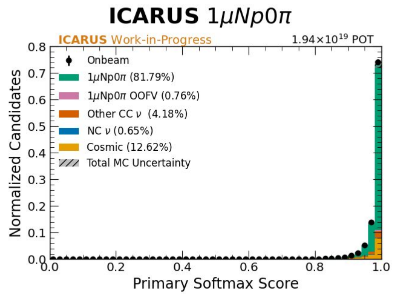
SBND+ICARUS will be able to explore the LSND-favored region with 5σ and will covers almost the full allowed LSND-MiniBooNE region with 5σ.

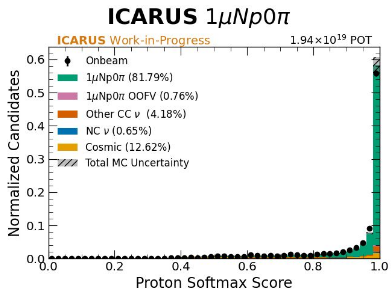
1μNp0π FV, w/o Containment Cut, Softmax Scores

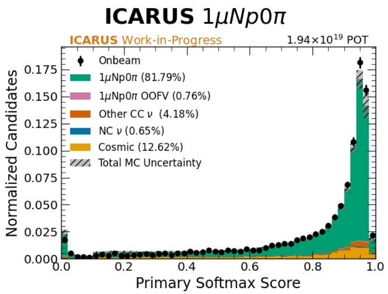
Muon | Leading Proton

No Flash cut

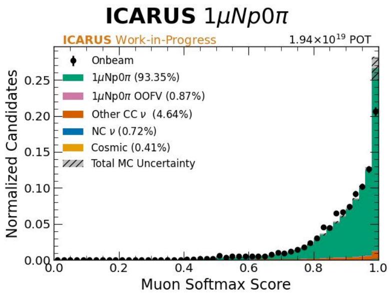


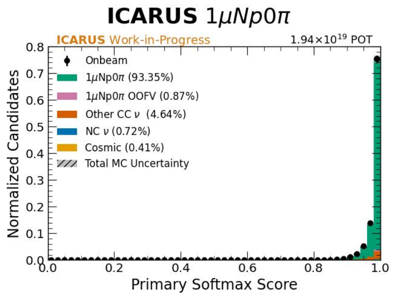


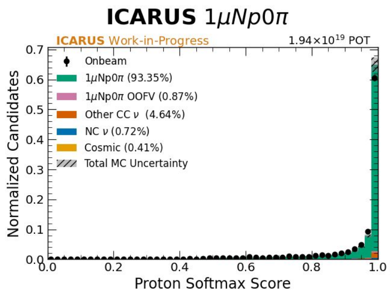


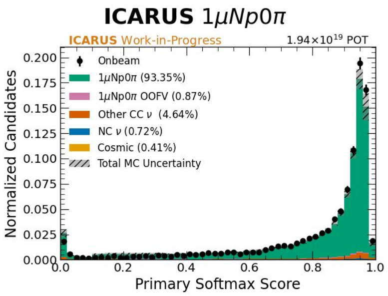


Flash cut



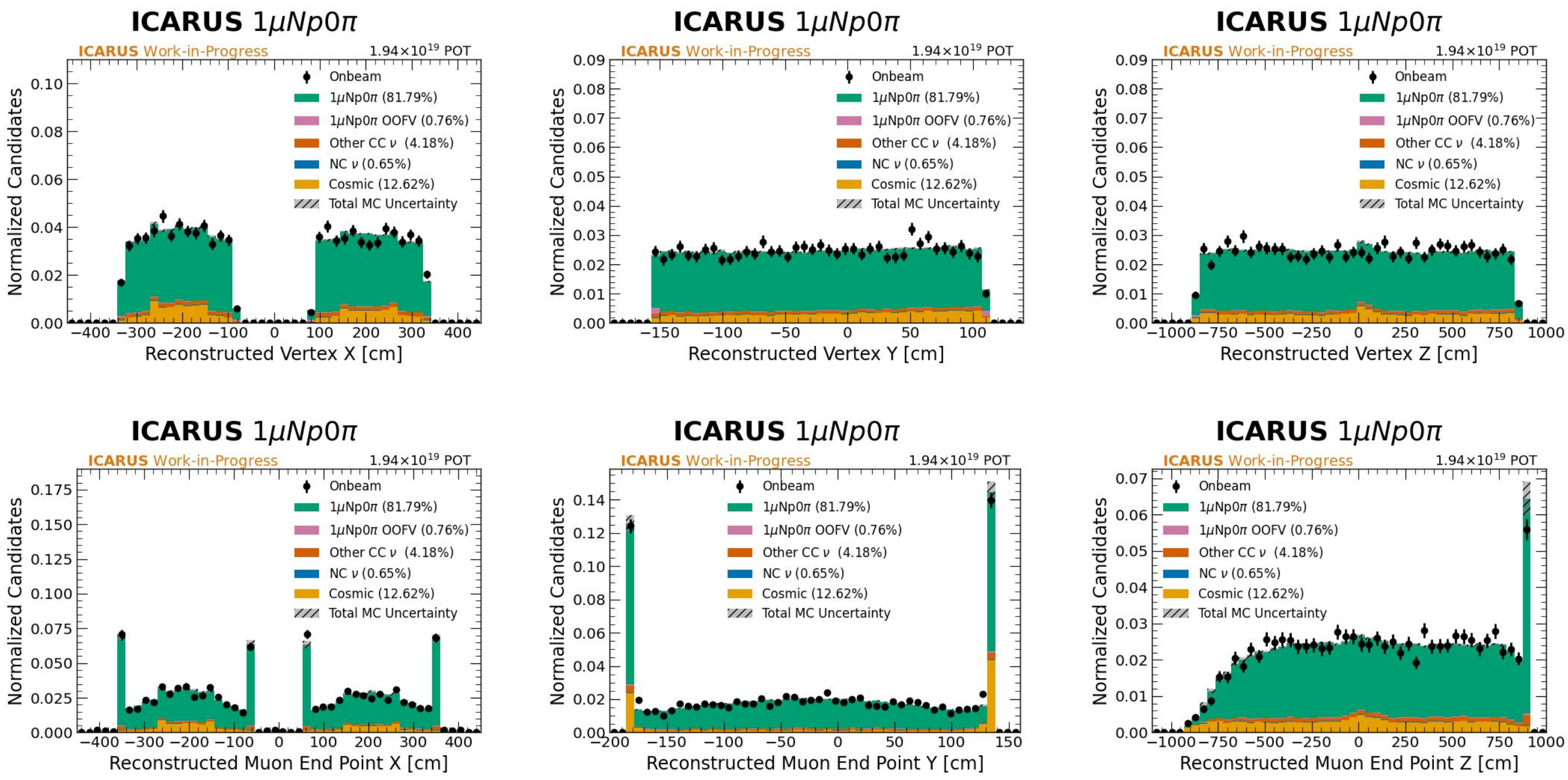






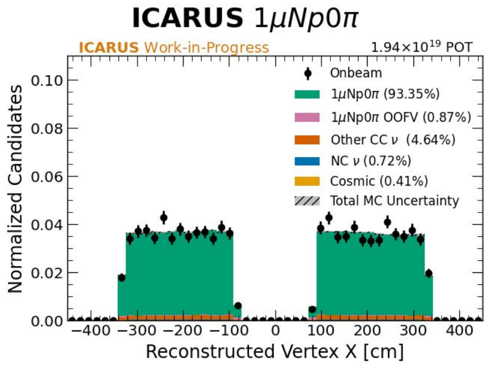
1μNp0π, in FV, w/o Containment Cut and w/o Flash Cut

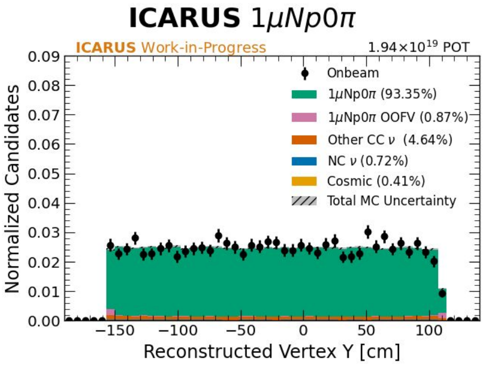
Neutrino interaction vertex coordinates and leading muon endpoint coordinates

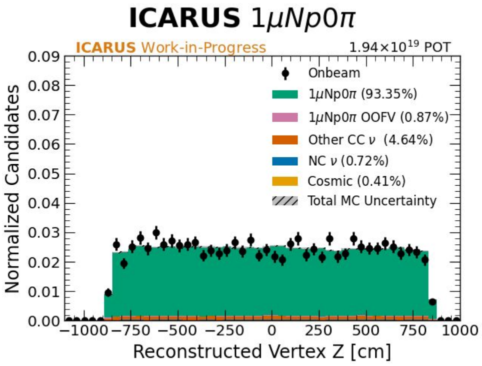


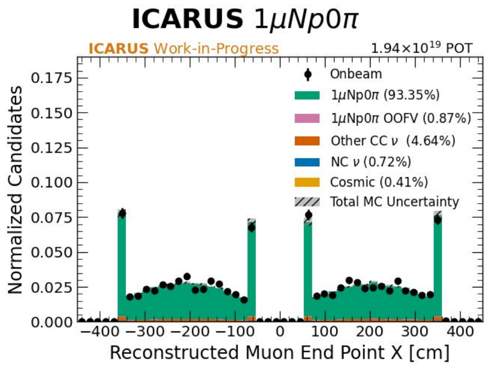
1μNp0π, in FV, w/o Containment Cut and with Flash Cut

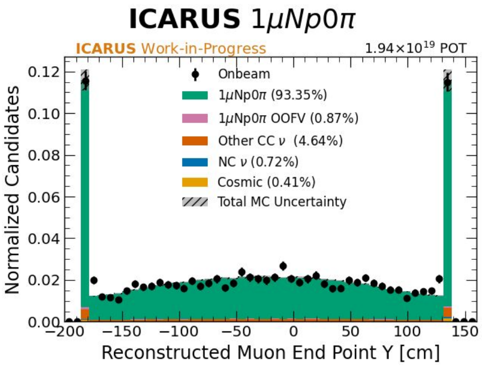
Neutrino interaction vertex coordinates and leading muon endpoint coordinates

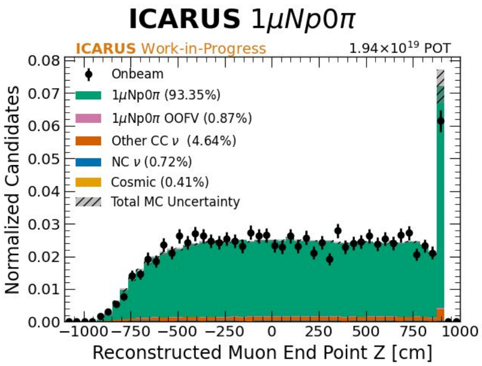






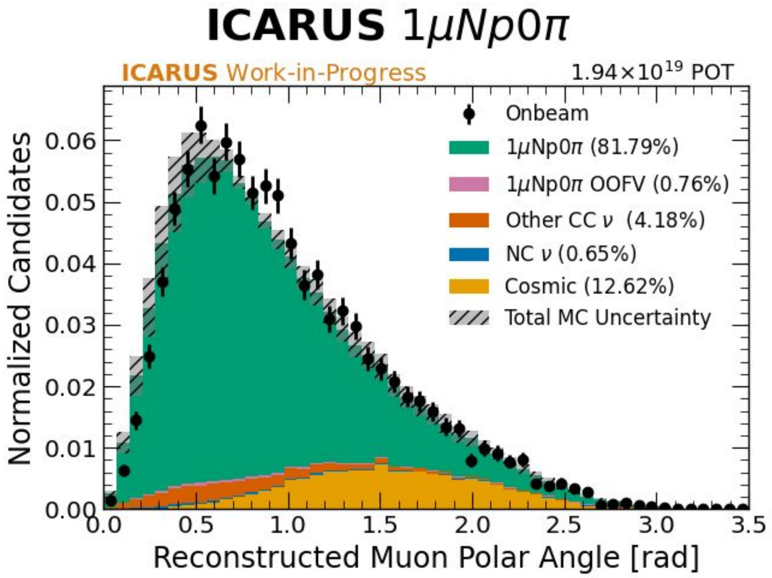


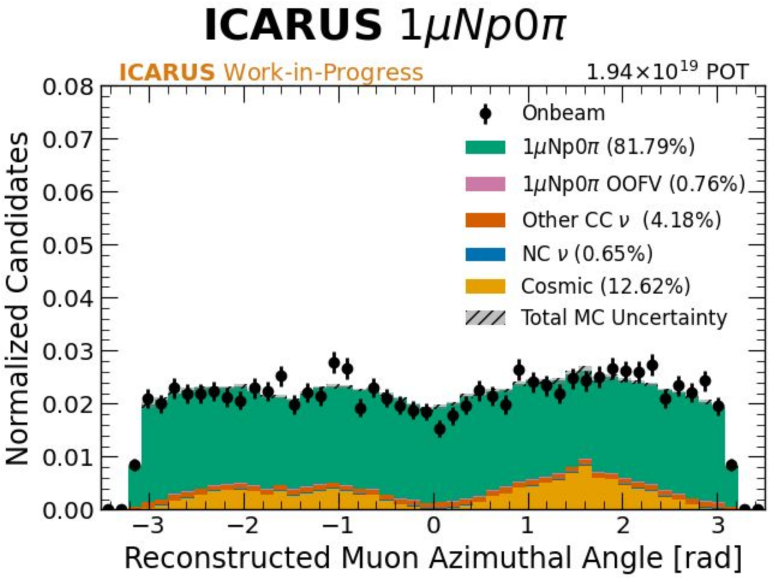




1μNp0π, in FV, w/o Containment Cut and w/o Flash Cut

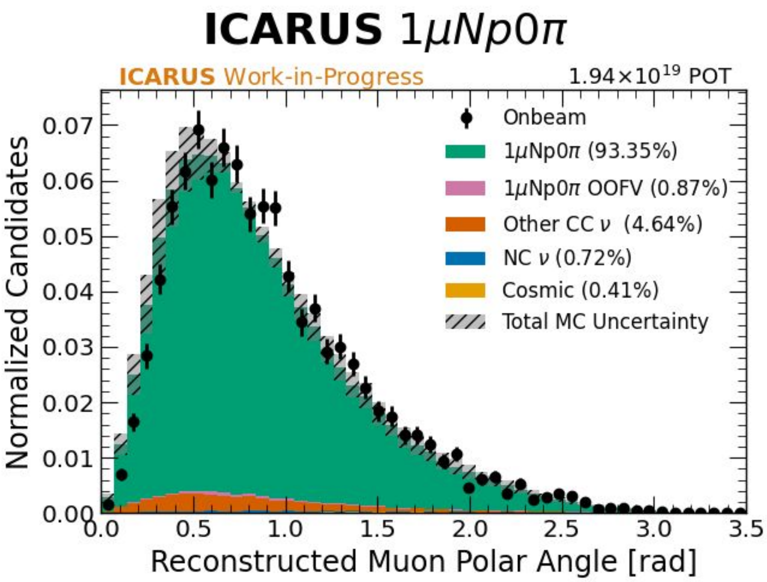
Leading muon polar angle and leading muon azimuthal angle

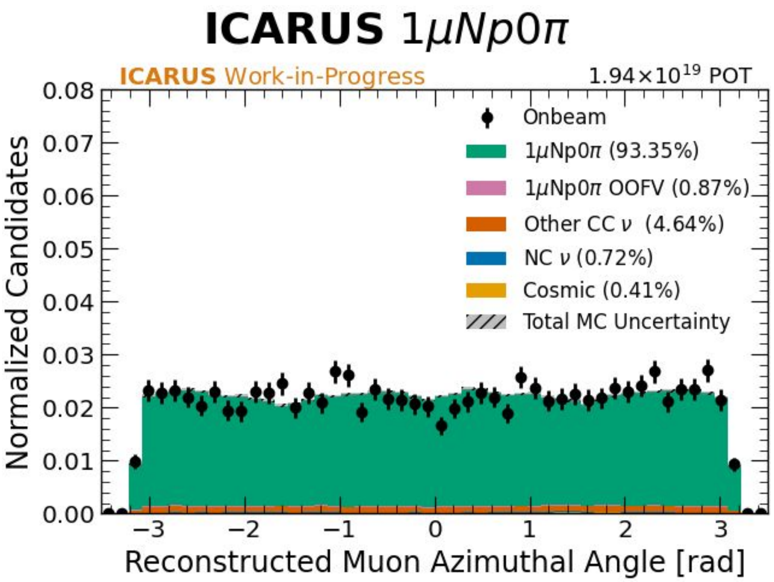




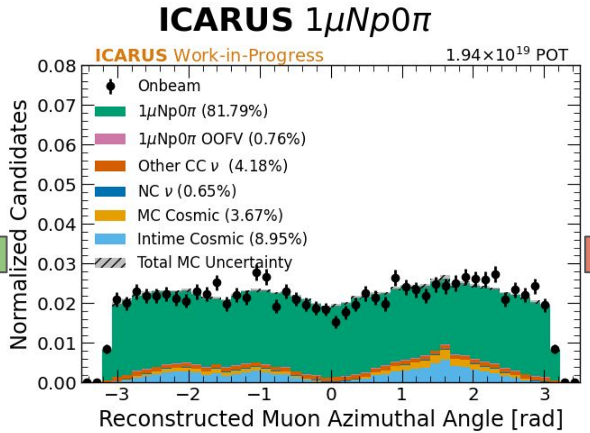
1μNp0π, in FV, w/o Containment Cut and with Flash Cut

Leading muon polar angle and leading muon azimuthal angle



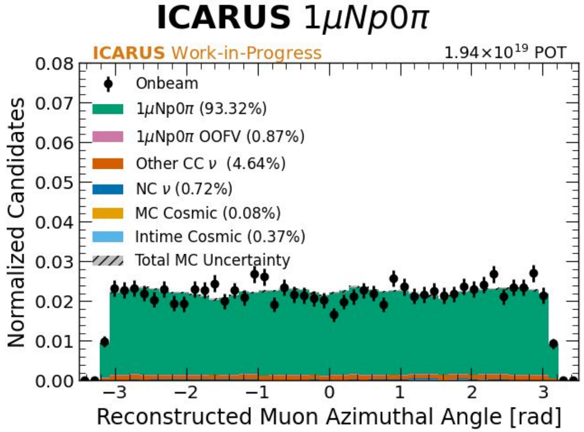


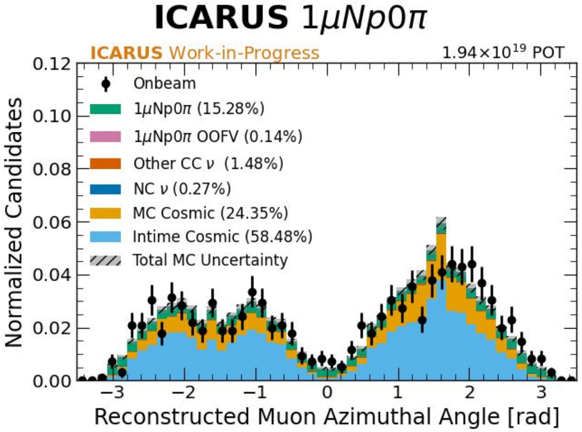
1μNp0π, in FV, w/o Containment Cut: Muon Azimuthal Angle



Selected by Flash Cut

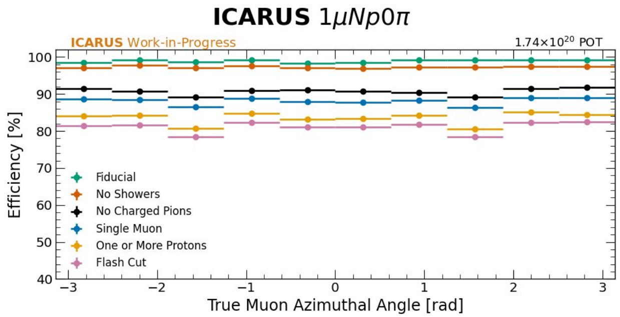
Discarded by Flash Cut



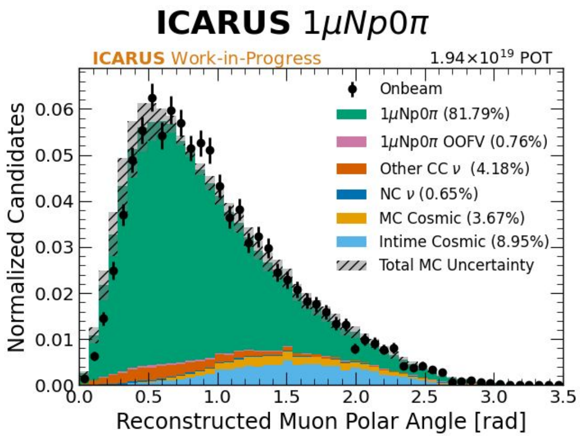


Muon Azimuthal angle is one of the most relevant variable to highlight the performance of cosmic rejection cuts.

Cosmics from MC and in-time (offbeam) samples have been split to emphasize their contribution.

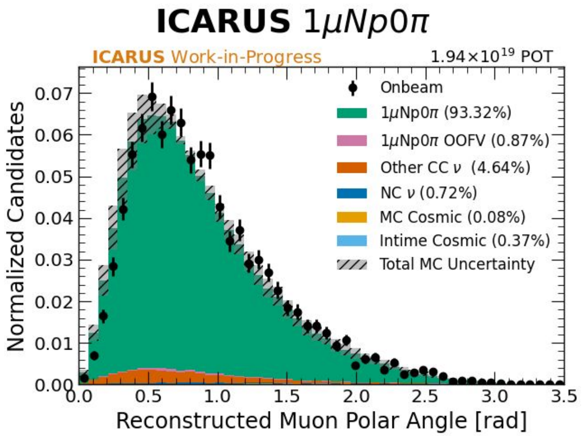


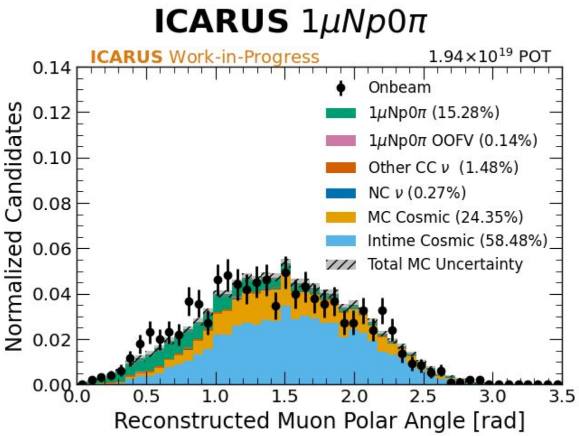
1μNp0π in FV, w/o Containment Cut: Muon Polar Angle



Selected by Flash Cut

Discarded by Flash Cut





1μNp0π Efficiency

Focusing on the most inclusive channel: 1μNp, the efficiency is studied for each subsequent cut/selection, comparing the effects of the Containment Cut and the Flash Cut

ICARUS 1μNp0π

ICARUS Work-in-Progress $1.74{\times}10^{20}$ POT

Cut	Differential Efficiency [%]	Cumulative Efficiency [%]
Fiducial	$99.34^{+0.06}_{-0.05}$	$99.34^{+0.06}_{-0.05}$
Containment	$99.41^{+0.06}_{-0.05}$	$98.79^{+0.08}_{-0.07}$
No Showers	$98.09^{+0.10}_{-0.09}$	$96.98^{+0.12}_{-0.11}$
No Charged Pions	$90.81^{+0.20}_{-0.19}$	$88.47^{+0.22}_{-0.21}$
Single Muon	$90.59^{+0.20}_{-0.19}$	$84.27^{+0.25}_{-0.24}$
One or More Protons	$91.36^{+0.19}_{-0.19}$	$79.19^{+0.28}_{-0.27}$
Flash Cut	$96.99^{+0.12}_{-0.11}$	$77.38^{+0.28}_{-0.28}$

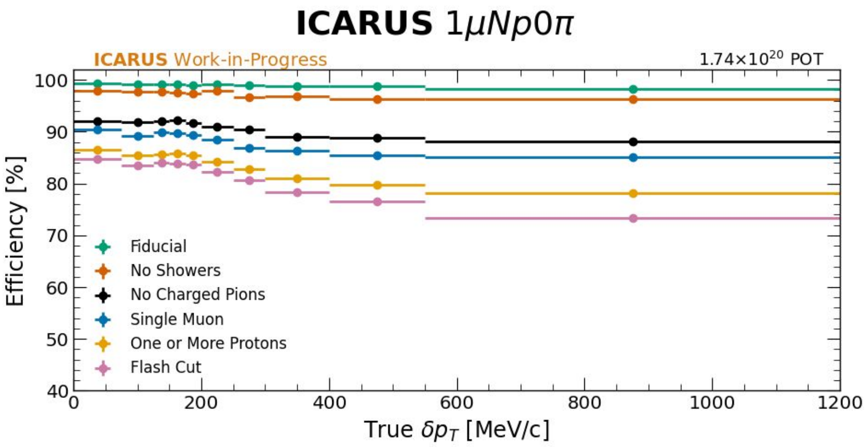
ICARUS 1μNp0π

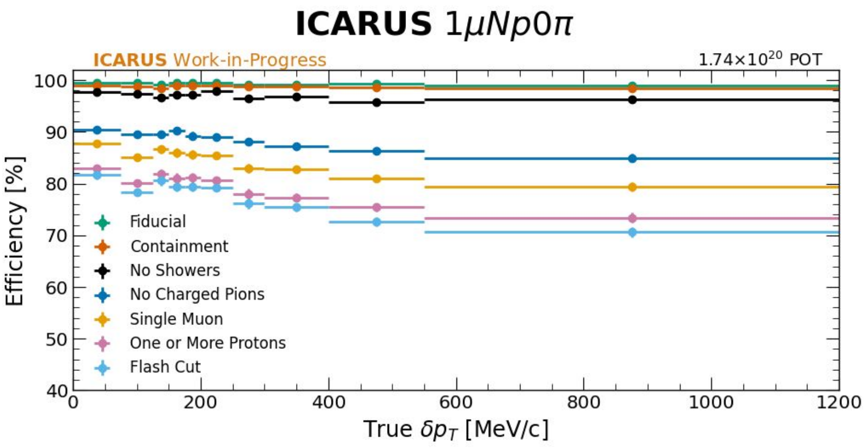
ICARUS Work-in-Progress $1.74{\times}10^{20}$ POT

Cut	Differential Efficiency [%]	Cumulative Efficiency [%]
Fiducial	$98.94^{+0.05}_{-0.04}$	$98.94^{+0.05}_{-0.04}$
No Showers	$98.30^{+0.06}_{-0.06}$	$97.28^{+0.07}_{-0.07}$
No Charged Pions	$92.97^{+0.12}_{-0.11}$	$90.69^{+0.13}_{-0.13}$
Single Muon	$94.64^{+0.10}_{-0.10}$	$88.07^{+0.15}_{-0.14}$
One or More Protons	$91.77^{+0.12}_{-0.12}$	$83.48^{+0.17}_{-0.16}$
Flash Cut	$96.56^{+0.08}_{-0.08}$	$81.10^{+0.18}_{-0.17}$

1μNp0π Efficiency

Efficiency can be evaluated as a function of different true variables.
Scanning across these variables helps identify potential non-uniformities indicative of reconstruction inefficiencies.
In the plots below, the efficiency shows a smooth trend as a function of transverse momentum (δp_T).
The same study is performed using additional variables shown in the next slides.



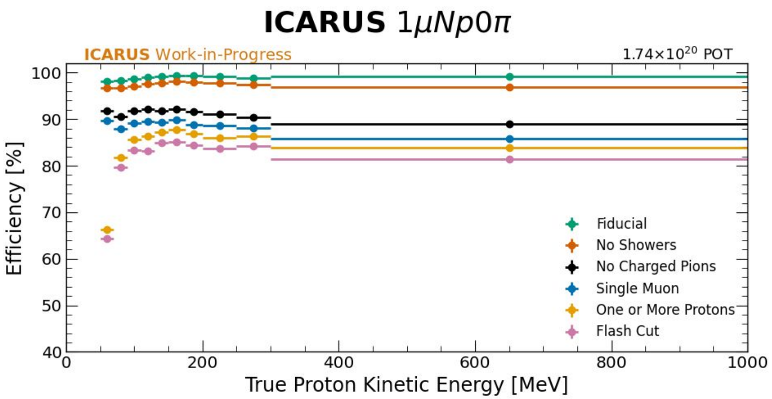


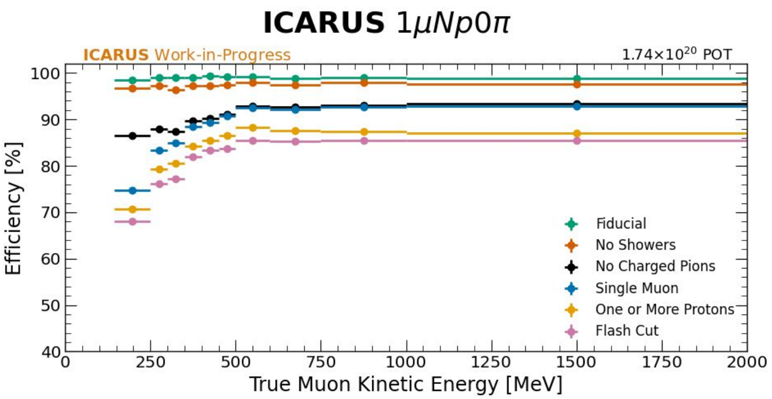
1μNp0π Efficiency

Focusing on the most inclusive channel (1μNp), without containment cut.

Scanning the efficiency across the true muon kinetic energy and the true leading proton kinetic energy, a small degradation in the selection efficiency became visible for lower values.

This is expected getting closer to the particle kinetic energy threshold.





Efficiency and Purity Summary Table

SPINE shows excellent performance in both 1μ1p and 1μNp selections.

Focusing on the most inclusive channel 1μNp,

1μNp w/o containment cut and with Flash cut:

- **Purity = 93.3%**
- **Efficiency = 81.1%**
- **Cosmic contamination = 0.4%**

The "backup" selection:

1μNp with containment cut and w/o Flash cut:

- Purity = 90.1%
- Efficiency = 79.2%
- Cosmic contamination = 1.4%

1μ1p0π			1μNp0π		
Purity	W/o C.C.	With C.C.	Purity	W/o C.C.	With C.C.
W/o F.M.	77.9%	86.6%	W/o F.M.	81.8%	90.1%
With F.M.	90.9%	88.5%	With F.M.	**93.3%**	91.5%
Efficiency	W/o C.C.	With C.C.	Efficiency	W/o C.C.	With C.C.
W/o F.M.	81.1%	77.5%	W/o F.M.	83.5%	79.2%
With F.M.	78.4%	75.5%	With F.M.	**81.1%**	77.4%
Cosmics	W/o C.C.	With C.C.	Cosmics	W/o C.C.	With C.C.
W/o F.M.	14.5%	1.7%	W/o F.M.	12.6%	1.4%
With F.M.	0.4%	<0.1%	With F.M.	**0.4%**	<0.1%

1μ1p0π Monte Carlo Simulation Uncertainty

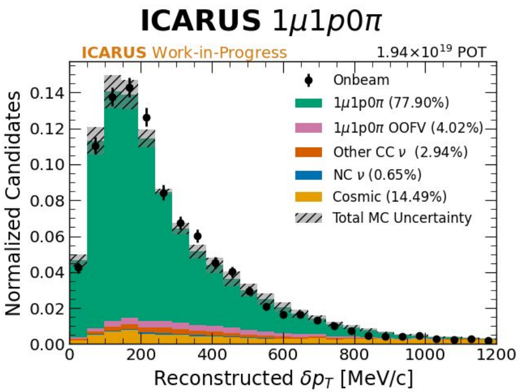
Containment cut:	w/o	w/o	with	with
Flash Match cut:	w/o	with	w/o	with
Statistical Uncertainty (%)	0.19	0.19	0.29	0.29
Detector Systematics (%)	3.22	3.33	3.33	3.29
Flux Systematics (%)	4.98	4.97	4.63	4.63
Interaction Systematics (%)	13.01	12.93	13.28	13.54
Total MC Uncertainty (%)	14.88	14.83	15.28	15.27

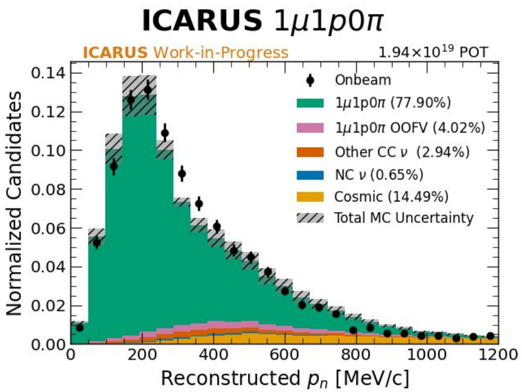
1μNp0π Monte Carlo Simulation Uncertainty

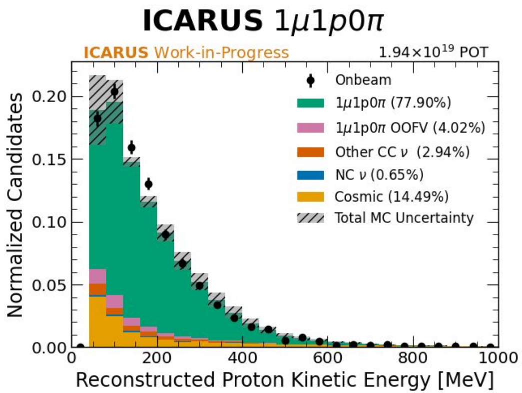
Containment cut:	w/o	w/o	with	with
Flash Match cut:	w/o	with	w/o	with
Statistical Uncertainty (%)	0.16	0.16	0.24	0.25
Detector Systematics (%)	3.24	3.24	3.24	3.06
Flux Systematics (%)	5.16	5.16	4.65	4.65
Interaction Systematics (%)	14.92	14.92	15.81	15.82
Total MC Uncertainty (%)	**16.65**	**16.65**	**17.30**	**17.27**

1μ1p0π/1μNp0π, in FV, w/o Containment Cut and w/o Flash Cut

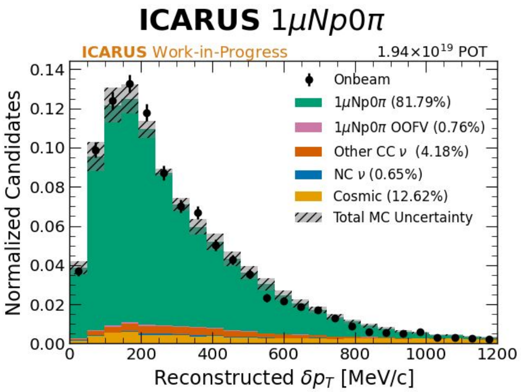
Transverse momentum: δp_T	Total missing momentum: p_n	(Leading) Proton Kinetic Energy

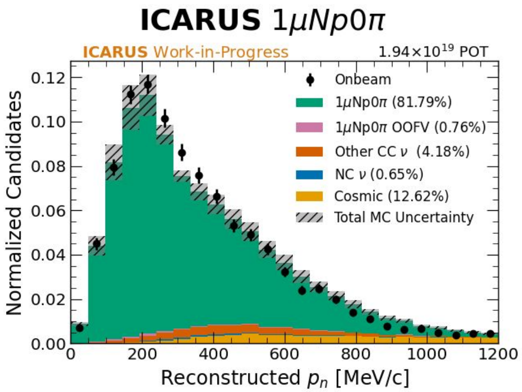


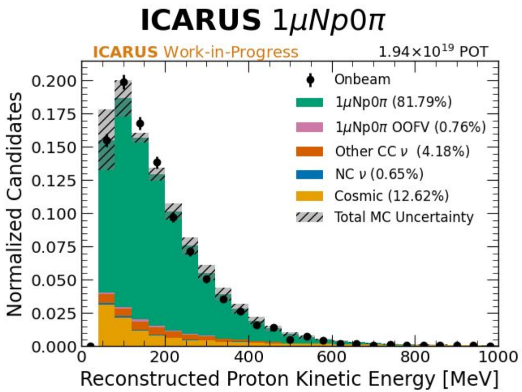




1μ1p0π



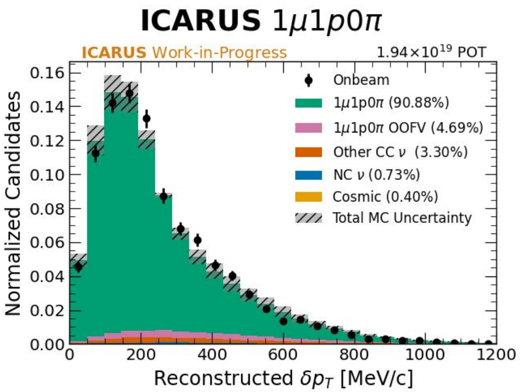


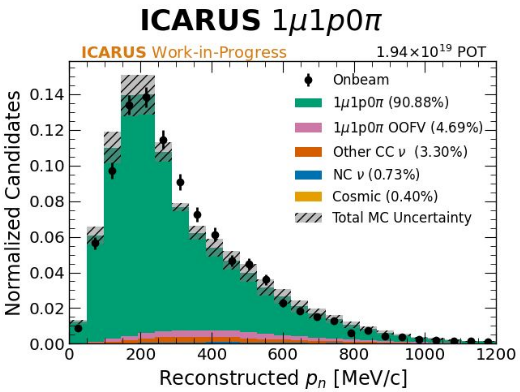


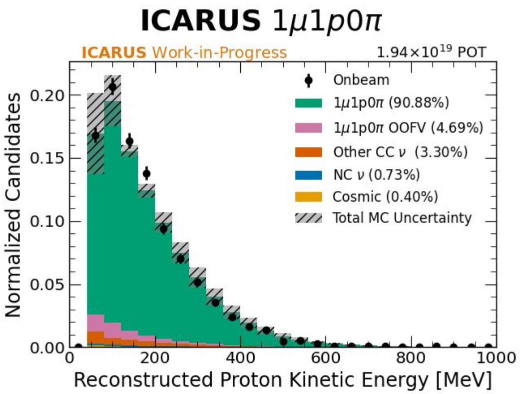
1μNp0π

1μ1p0π/1μNp0π, in FV, w/o Containment Cut and with Flash Cut

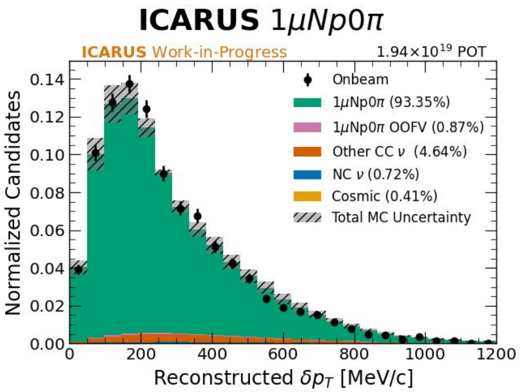
Transverse momentum: δp_T | Total missing momentum: p_n | (Leading) Proton Kinetic Energy

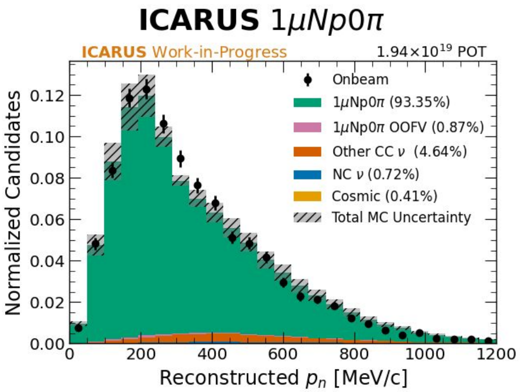


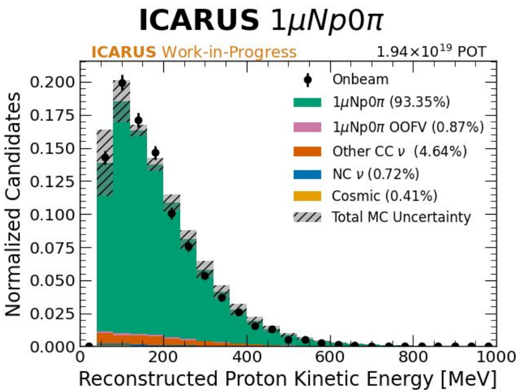




1μ1p0π







1μNp0π

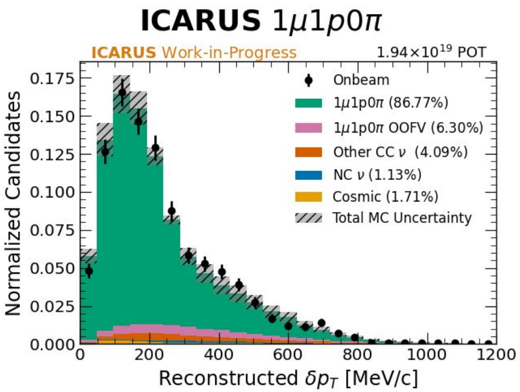
1μ1p0π/1μNp0π, in FV, with Containment Cut and w/o Flash Cut

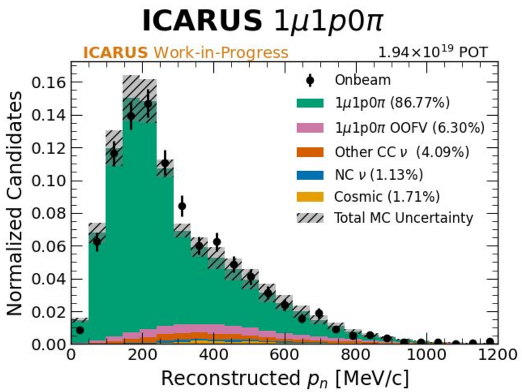
Transverse momentum: δp_T

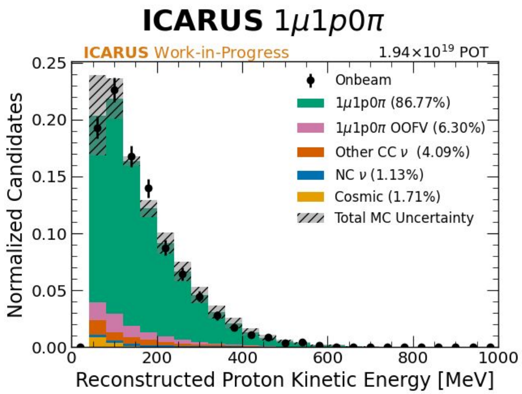
Total missing momentum: p_n

(Leading) Proton Kinetic Energy

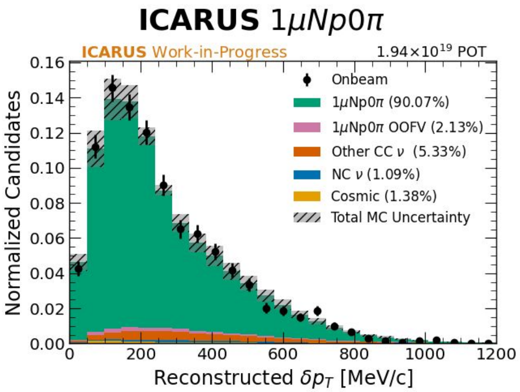
1μ1p0π

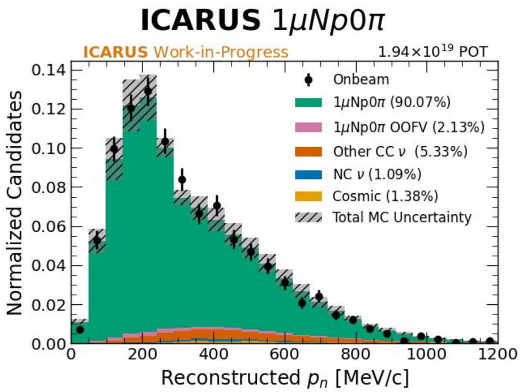


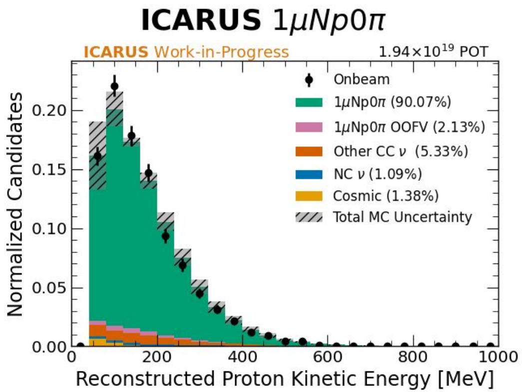




1μNp0π

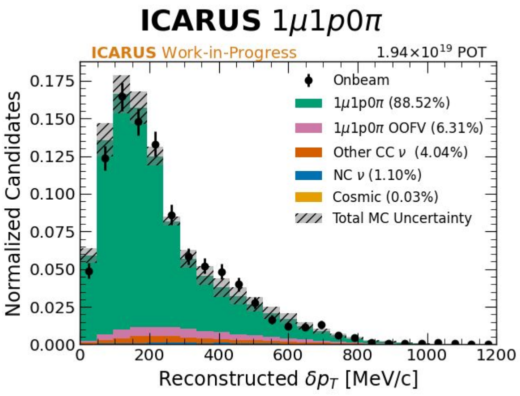


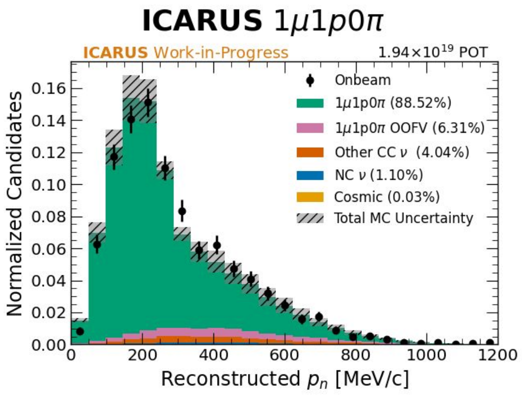


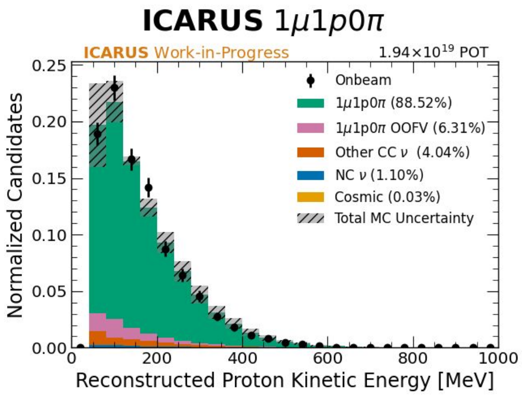


1𝝁1p0π/1𝝁Np0π, in FV, with Containment Cut and with Flash Cut

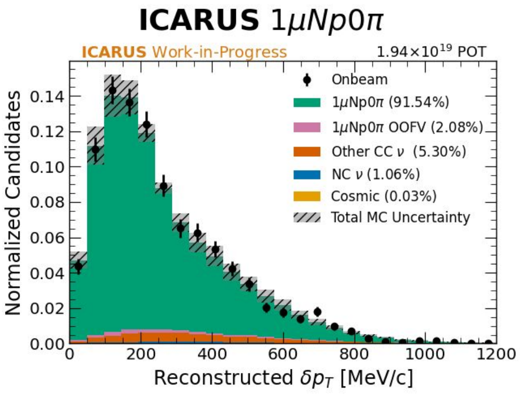
Transverse momentum: δp_T	Total missing momentum: p_n	(Leading) Proton Kinetic Energy

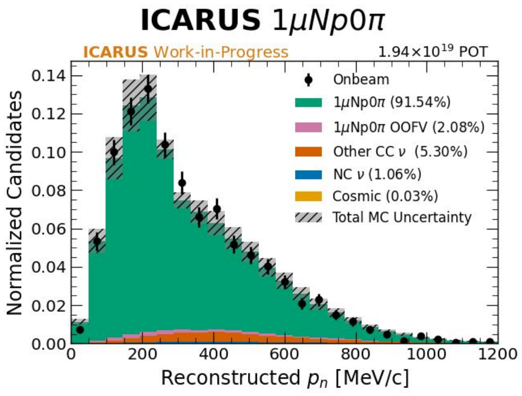


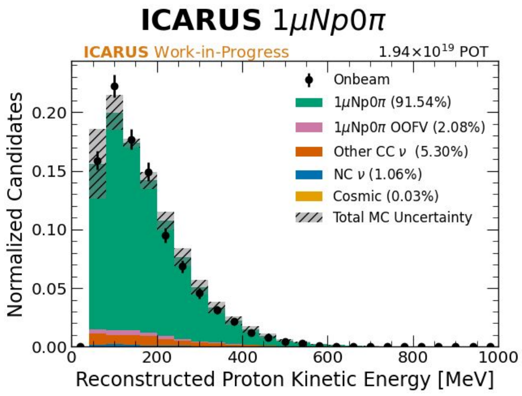




1μ1p0π







1μNp0π