Towards a neutrino analysis in the ICARUS detector

Imaging Cosmic And Rare Underground Signals

Fermilab 2024 Summer Students School

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24th July 2024

1222·2022 800 ANNI
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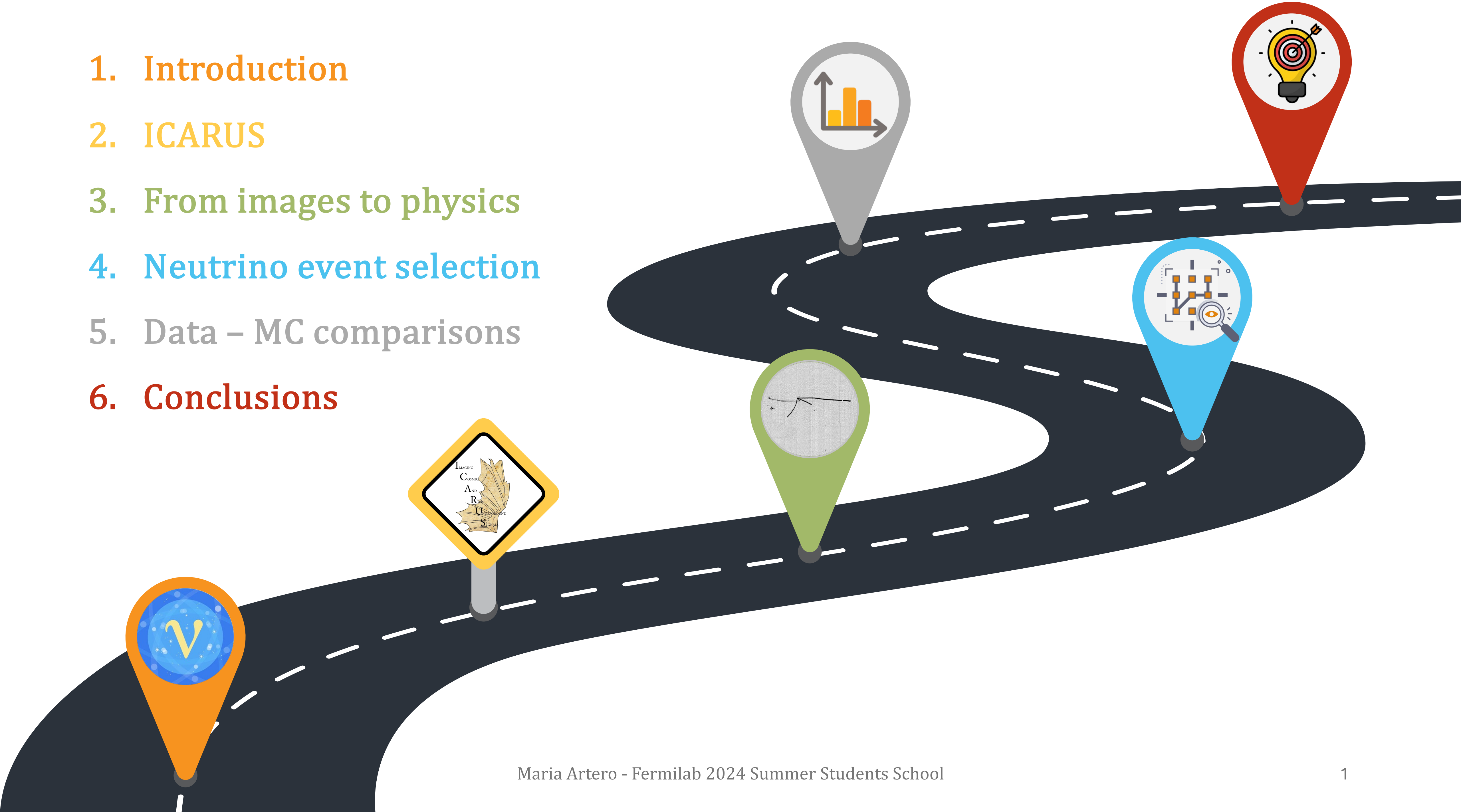
European Commission
Intense RISE
H2020-MSCA-RISE-2018
G.A. 822185

1. Introduction
2. ICARUS
3. From images to physics
4. Neutrino event selection
5. Data – MC comparisons
6. Conclusions



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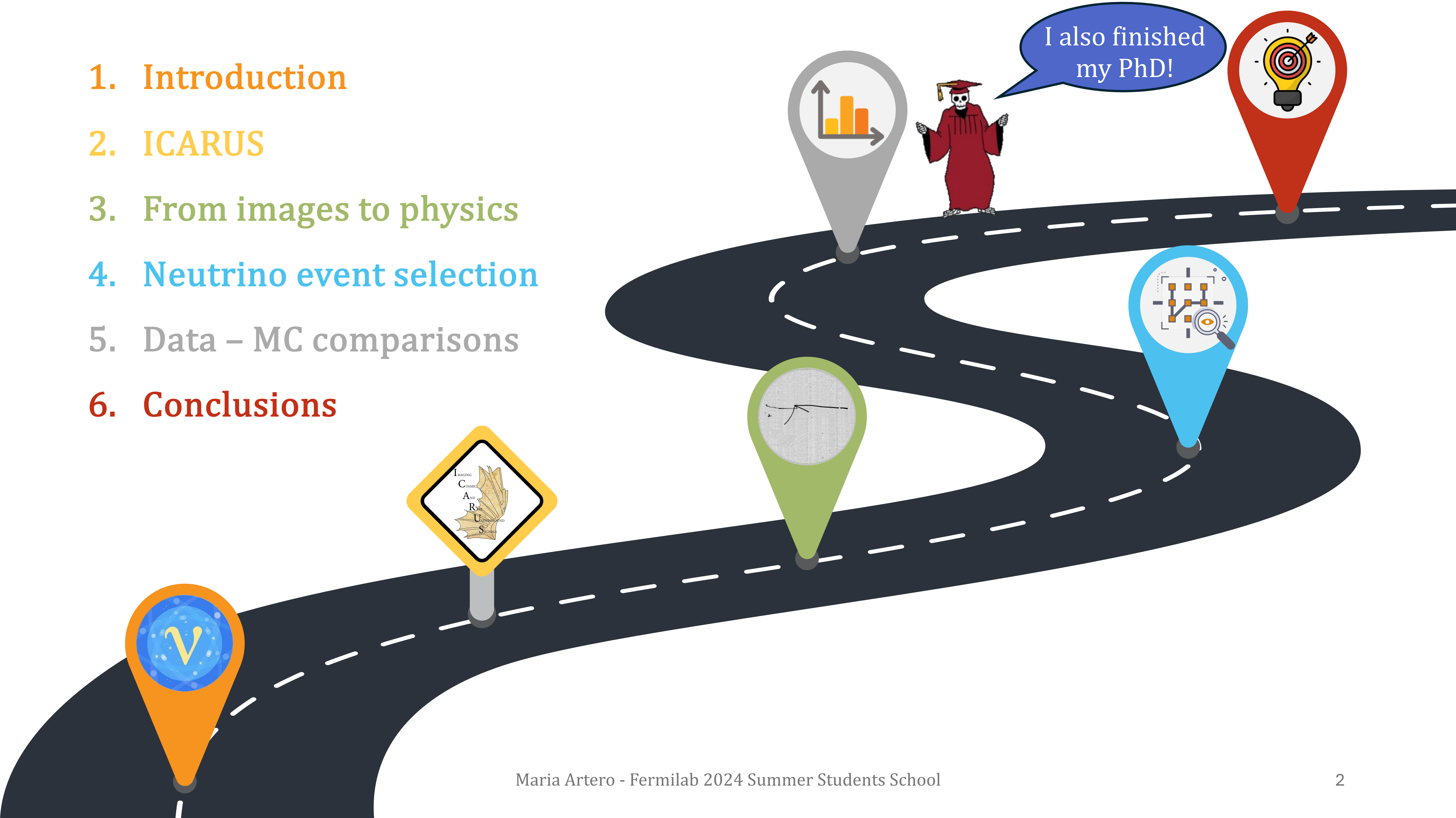
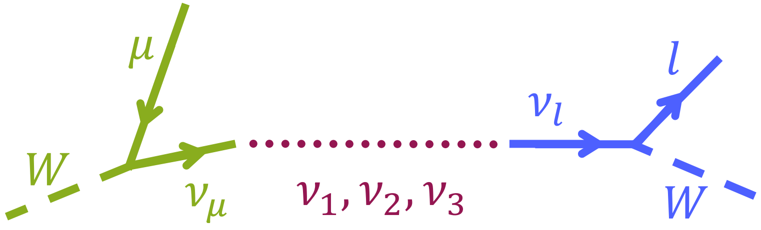
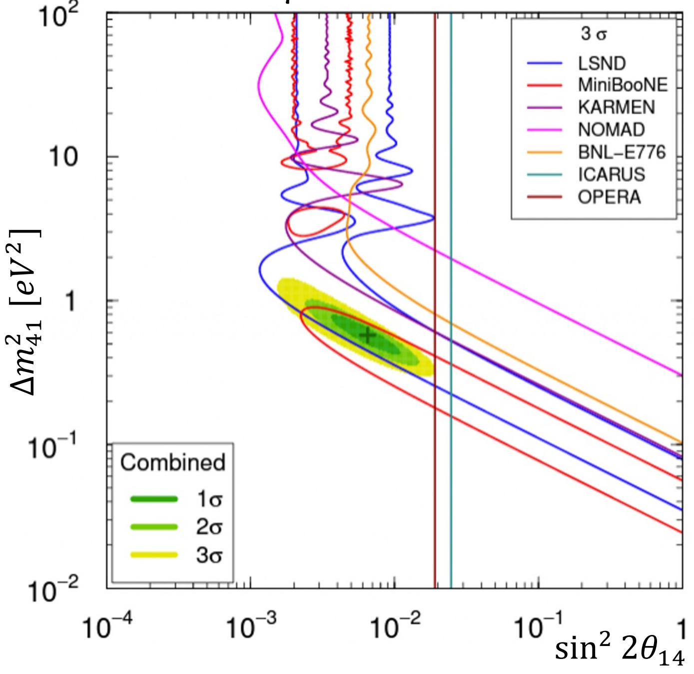


Neutrino oscillations



- Neutrinos are produced and detected as well-defined flavour eigenstate, however they propagate via mass eigenstates
- Despite the well-established 3 flavour ν mixing picture, several anomalies from accelerator experiments (LSND and MiniBooNE), reactor and radioactive sources have been reported in the last 20 years, unable to fit inside the scheme
- Results suggest a new *sterile* ν flavour at $\Delta m^2 \sim eV^2$ and small mixing angle, thus driving short distance oscillations

(Anti-) $\nu_\mu \rightarrow \nu_e$ appearance



arXiv:2106.05913

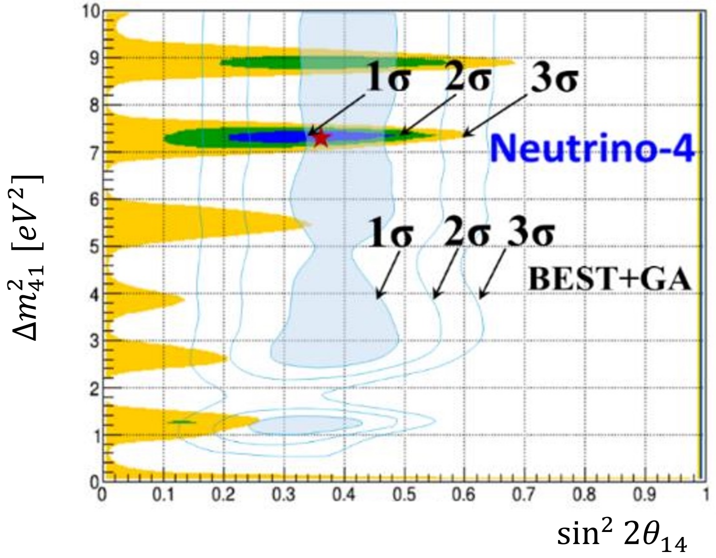
The sterile neutrino puzzle

- The Neutrino-4 collaboration reported a hint of oscillation signature at higher mass splitting [arXiv:2005.05301]
  - Reactor $\bar{\nu_e}$ disappearance with $\Delta m^2 \sim 7\ eV^2$ and $sin^2 2\theta\ \sim 0.26$
  - Combining Neutrino-4 results with data from GALLEX, SAGE, and BEST experiments the confidence in previously claimed results has increased to 5.8σ CL [arXiv:2302.09958]

- Clear tension between appearance and disappearance results is observed in global constraint plots

Measuring both channels with the same experiment will help clarify the scenario

(Anti-) ν_e Disappearance



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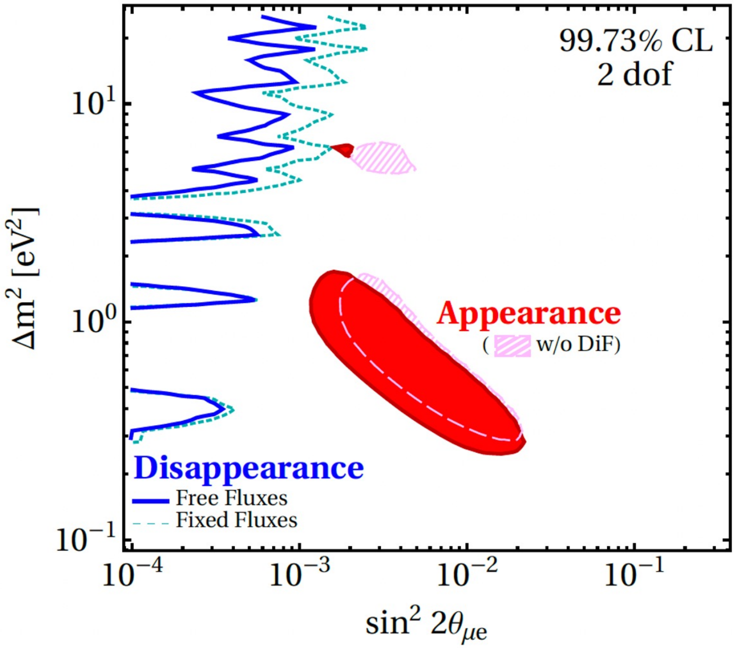
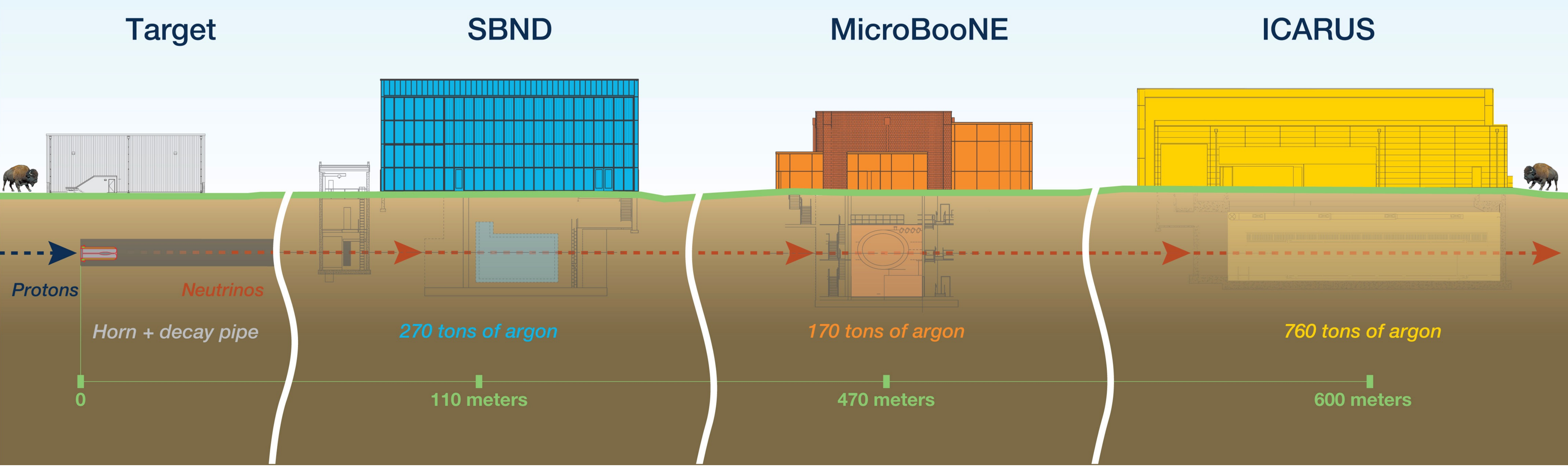
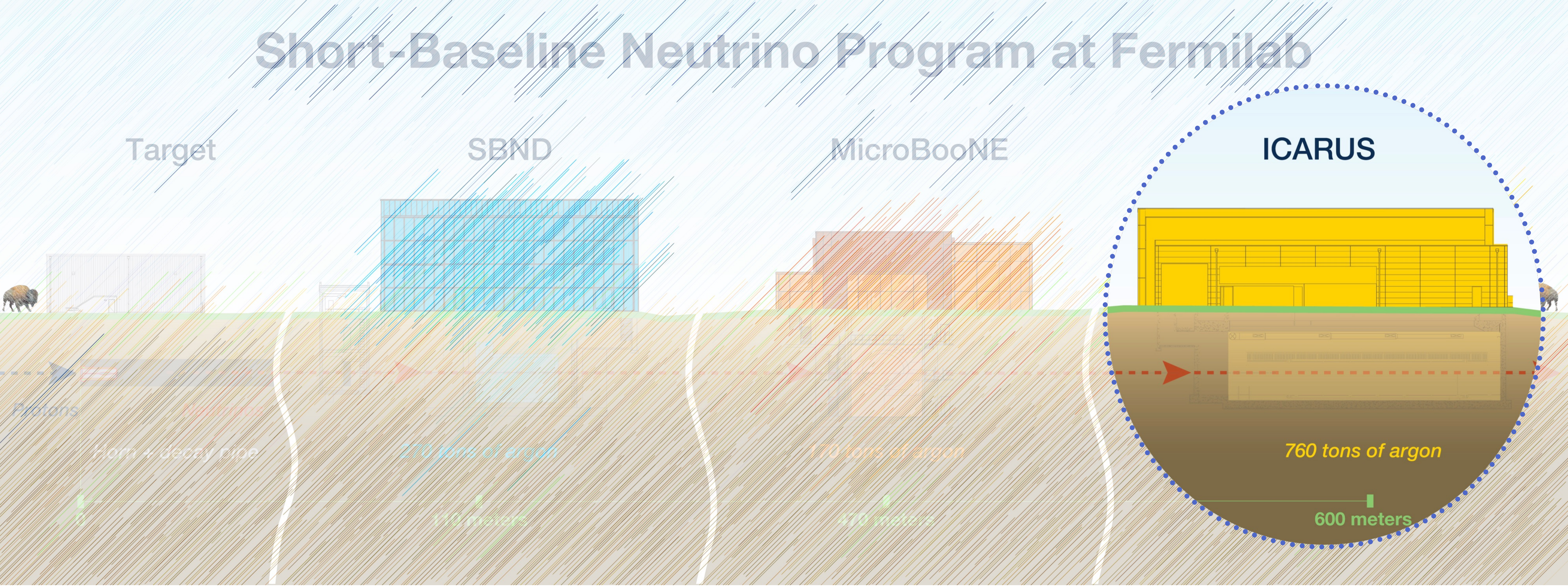


JHEP08 (2018) 010

Short-Baseline Neutrino Program at Fermilab



- Short Baseline Neutrino (SBN) Program main goal is to search for sterile neutrino oscillations both in appearance and disappearance channels (at $\sim eV^2$ mass scale)
- 3 Liquid Argon Time Projection Chambers (LArTPC) sampling the same Booster Neutrino Beam (BNB) at different distances



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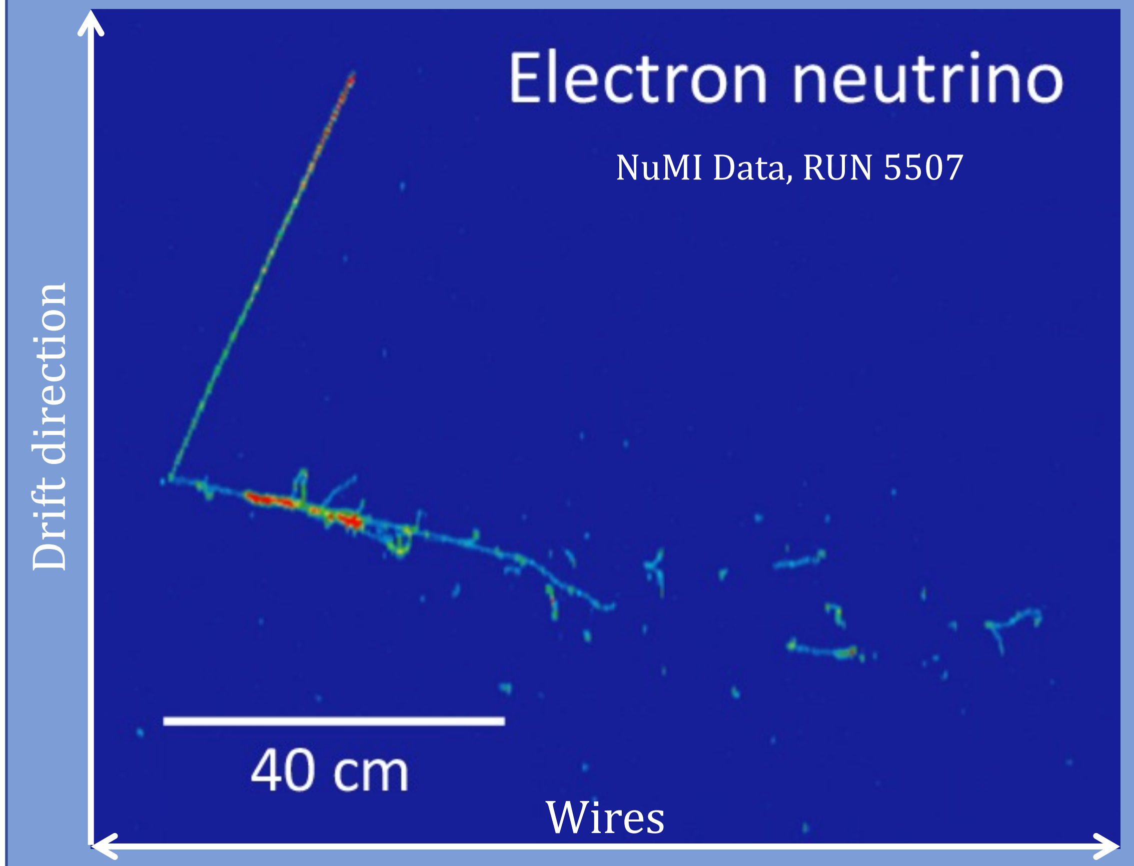
From images to physics

- LArTPC detectors produce high resolution images of particle interactions

  ➜ Need to reconstruct these interactions from raw images to perform high level analysis

- An important piece in the reconstruction process is the pattern recognition algorithm which must:
  - Identify the individual particles and their relationship to each other
  - Arrange these particles into production hierarchies
  - Determine their 3D trajectories



$$\nu_e + n \longrightarrow p + e$$

Electron neutrino interaction that produced a proton (1) and an electron. The later produced an EM shower with photons and electrons (2)

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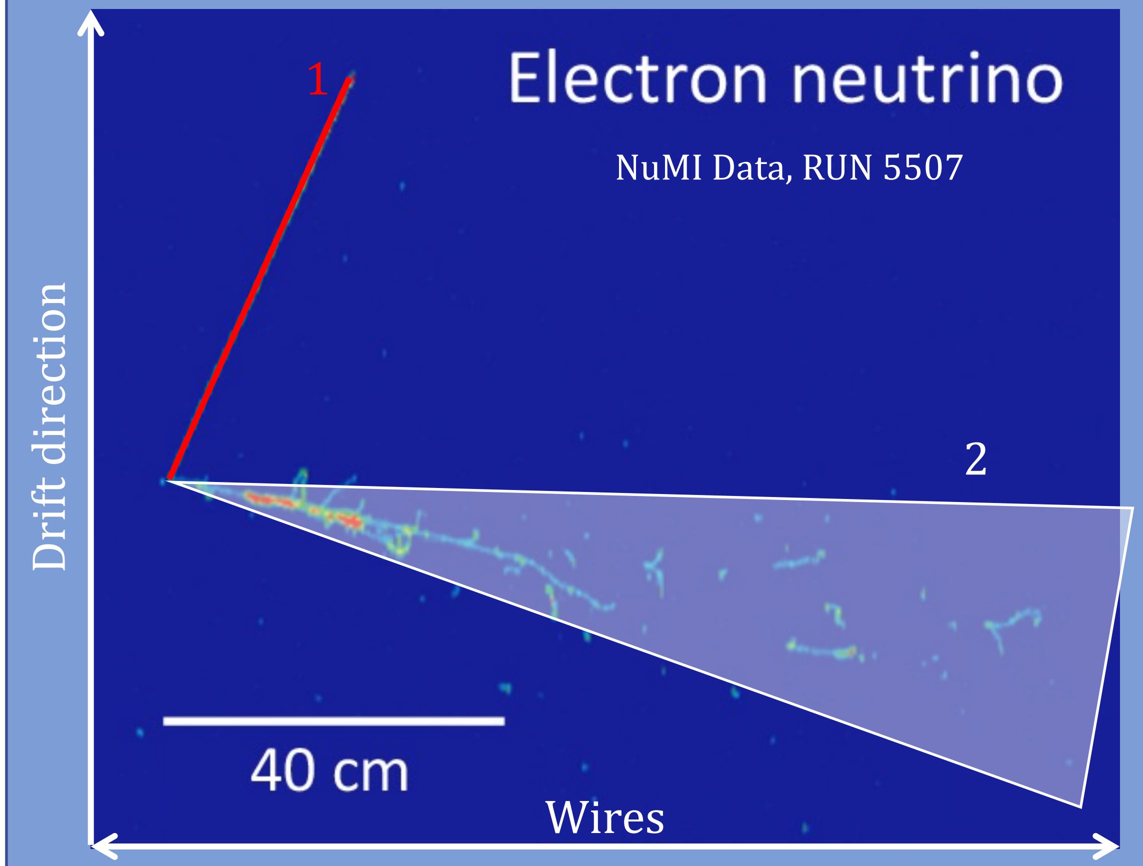

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From images to physics

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  ... s from ... alysis

Due to the large amount of data to analyse, an automated solution is mandatory

- An impor... ess is the pattern re...
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The reconstruction pipeline

Detector Data → Low-level image processing → Hit finding → Pattern recognition → Particle fits → High Level Analysis

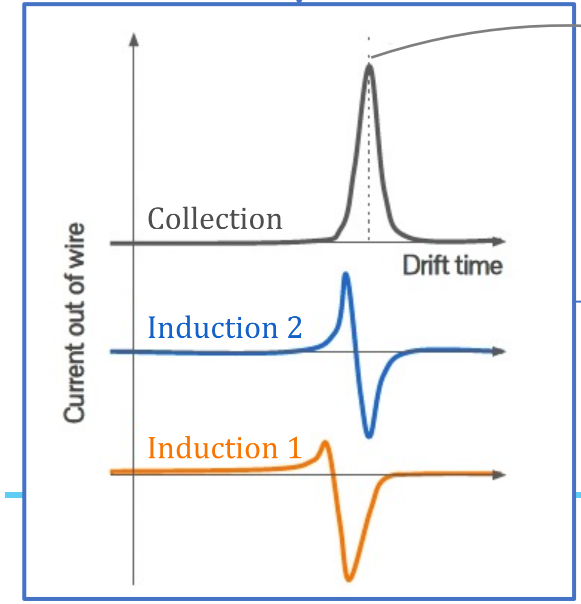
Low-level image processing:
- Decoding
- Deconvolution
- ROI Finding

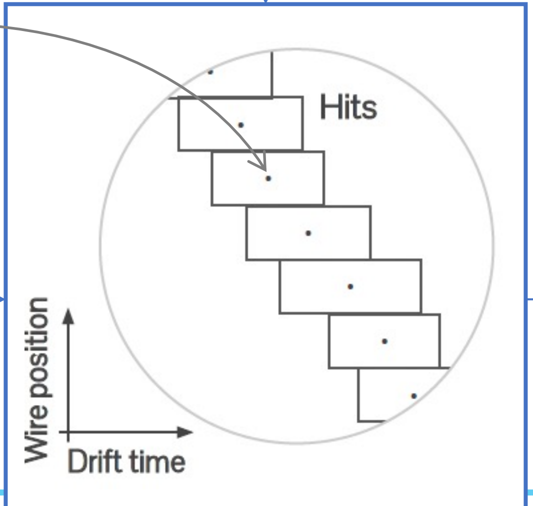
Hit finding:
- Gaussian hits
- Cluster 3D

Pattern recognition:
- Pandora Algorithm

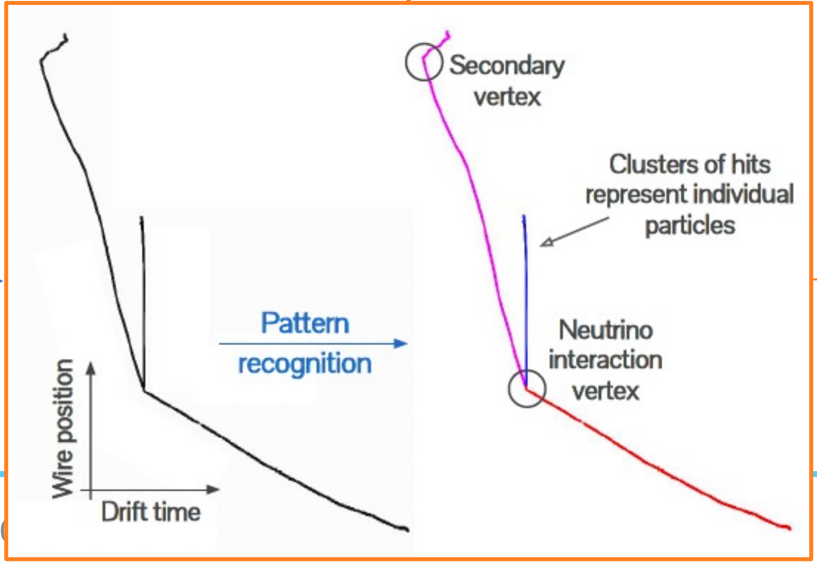
[software development toolkit]

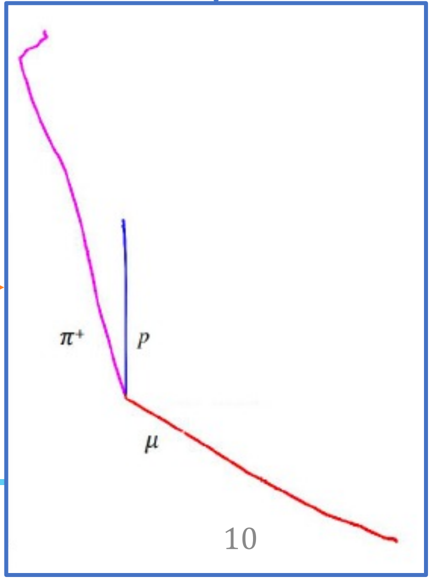
Particle fits:
- Track, shower fits
- Calorimetry
- Particle ID





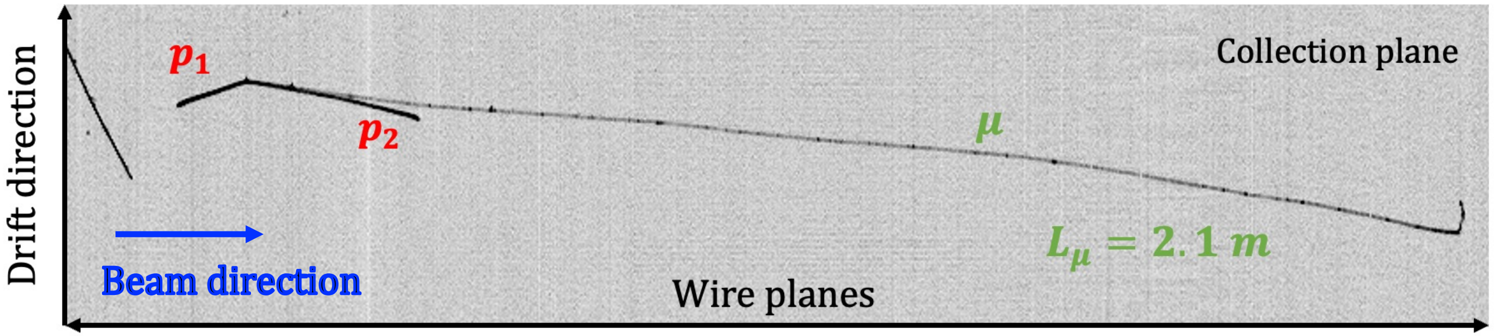
*hit: identified signal induced by a track on a wire.





Ongoing physics analysis

- While the near detector is getting ready to join the SBN program, ICARUS-standalone phase is addressed to test the Neutrino-4 oscillation hypothesis in the same L/E range (~ 1-3 m/MeV), but collecting ~ ×100 more energetic events
  - ν_e disappearance channel from NuMI: selecting contained EM showers from quasi-elastic ν_e CC interactions
  - ν_μ disappearance channel from BNB: focusing on contained quasi-elastic ν_μ CC interactions
- BNB studies are performed on ν_μCC fully contained events with a single muon and at least a proton in the final state



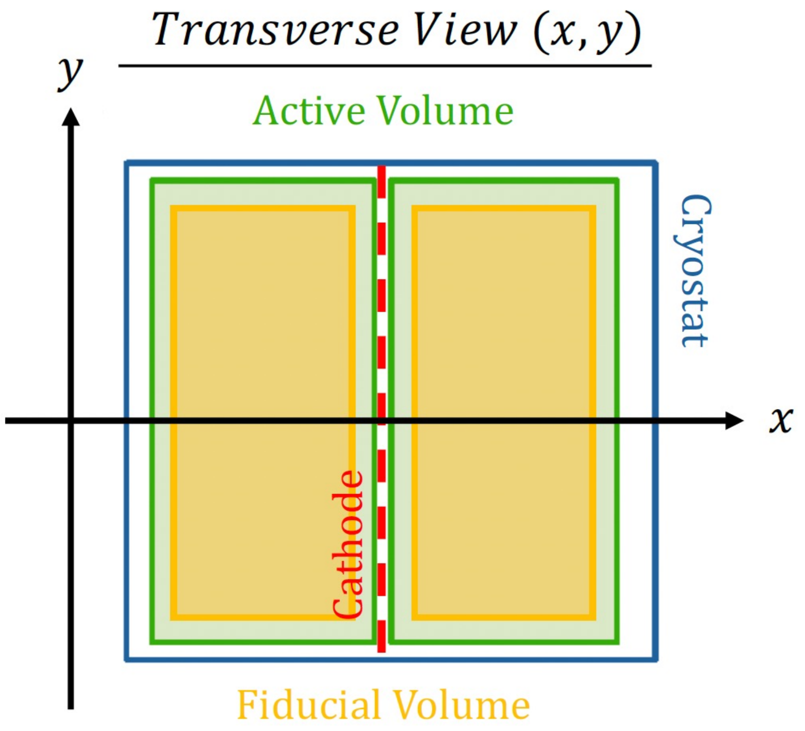
Neutrino event selection

- A first step towards this goal is to select events which:

    1. ν **vertex** should be inside the fiducial volume i.e., 25 cm apart from the lateral TPC walls and 30/50 cm from the upstream/downstream walls
    2. **Fully contained** interactions i.e., no signal in the last 5 cm of the LAr active volume
    3. Stopping muon of $L_\mu > 50$ cm

- To further simplify, consider **$1\mu1p$** candidates

    4. Only 1 proton $L_p > 1$ cm produced at the primary vertex



$1\mu1$p visually selected events

- Performance validation of the available automatic reconstruction tools
  - Sample of 520 $1\mu1$p visually selected data events
- For each event, the 3D position of the vertex, end muon and end proton were saved
  - Comparison between manually and automatically reconstructed variables
- Stringent quality requirements were defined to
  - assess Pandora's reconstruction algorithm
  - identify a set of well reconstructed $1\mu1$p events

Quality cuts	Selected events
Total events	520 - 100%
1. Well reconstructed vertex	405 - 78%
2. Primary muon track and of L_μ >50 cm	400 - 77%
3. Well reconstructed start muon	353 - 68%
4. Well reconstructed end muon	247 - 48%
5. Correct identification of muon	246 - 47%
6. Proton track candidate	183 - 35%
7. Correct identification of proton	120 - 23%

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Automatically selected and well reconstructed events

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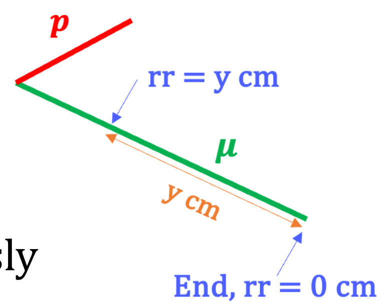
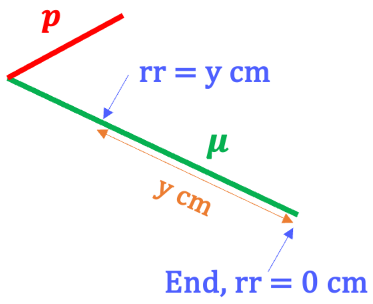
Particle identification



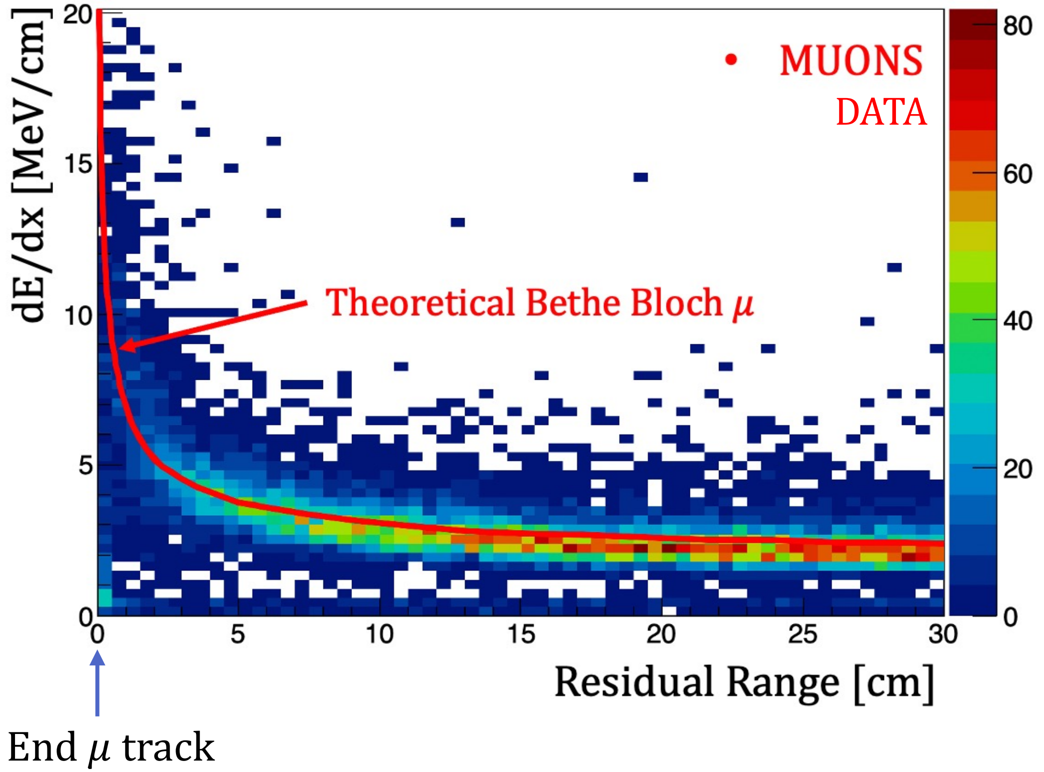
- The identification of 1μ1p ν interactions requires a Particle Identification (PID) tool to unambiguously recognize stopping muons and protons
- The current algorithm relies on the comparison between the measured dE/dx vs residual range along the track and the mean theoretical profiles from different particles (μ, p, K, π)
- The PID defines $\chi^2_k(j)$ score computed in the last **25 cm** of each track for all wire planes

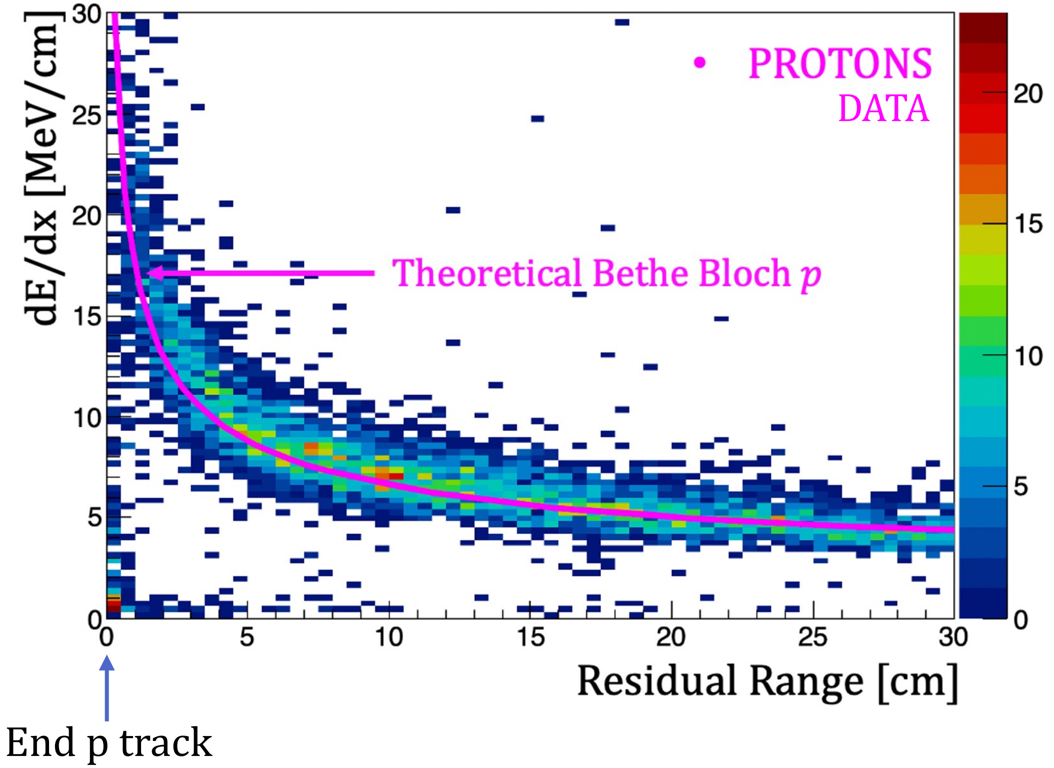
$\chi^2_k(j)$: χ^2 score for particle j under the hypothesis of being a k-particle

Particle identification



- Sample of **well reconstructed data** events together with their theoretical predictions





Neutrino transverse momentum

- **Well reconstructed** events are selected and the μ and p momenta computed from their range
- Kinematic event reconstruction is validated through the total transverse momentum
- The transverse momentum of genuine $\nu_\mu CCQE$ events ⇢ dominated by the Fermi momentum in Ar nuclei

($p_F \leq 250$ MeV/c)

Transverse kinematic variables encode information of initial nuclear state and final state interactions

Can be used as a proxy for the event interpretation and energy resolution

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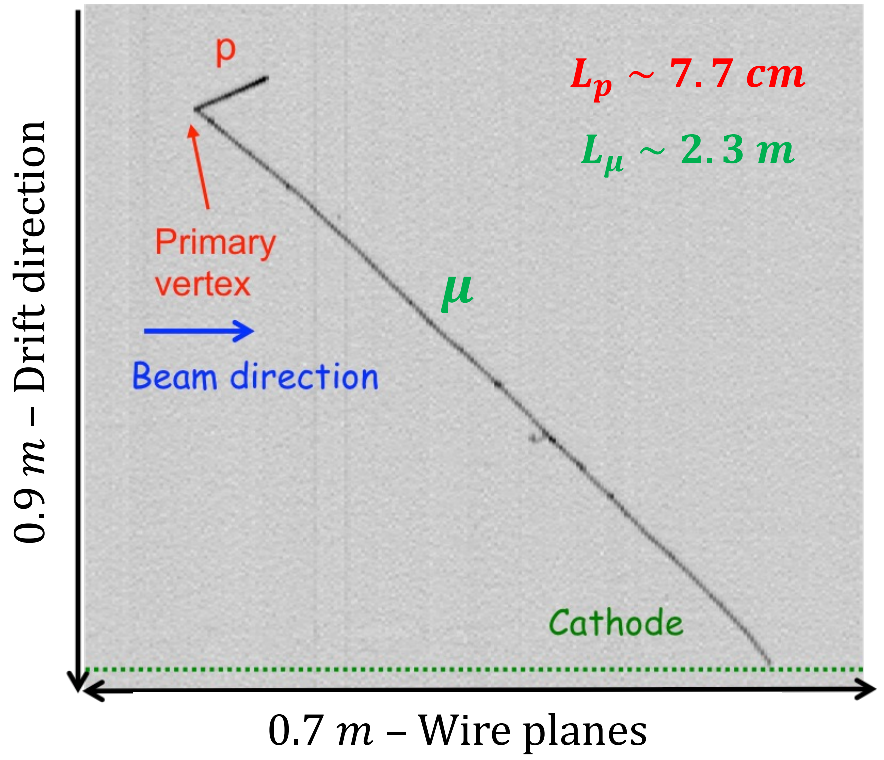

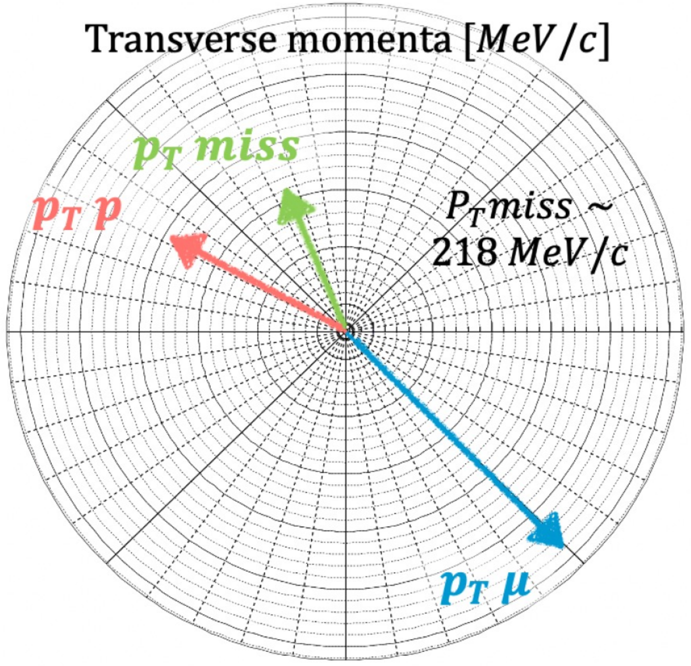

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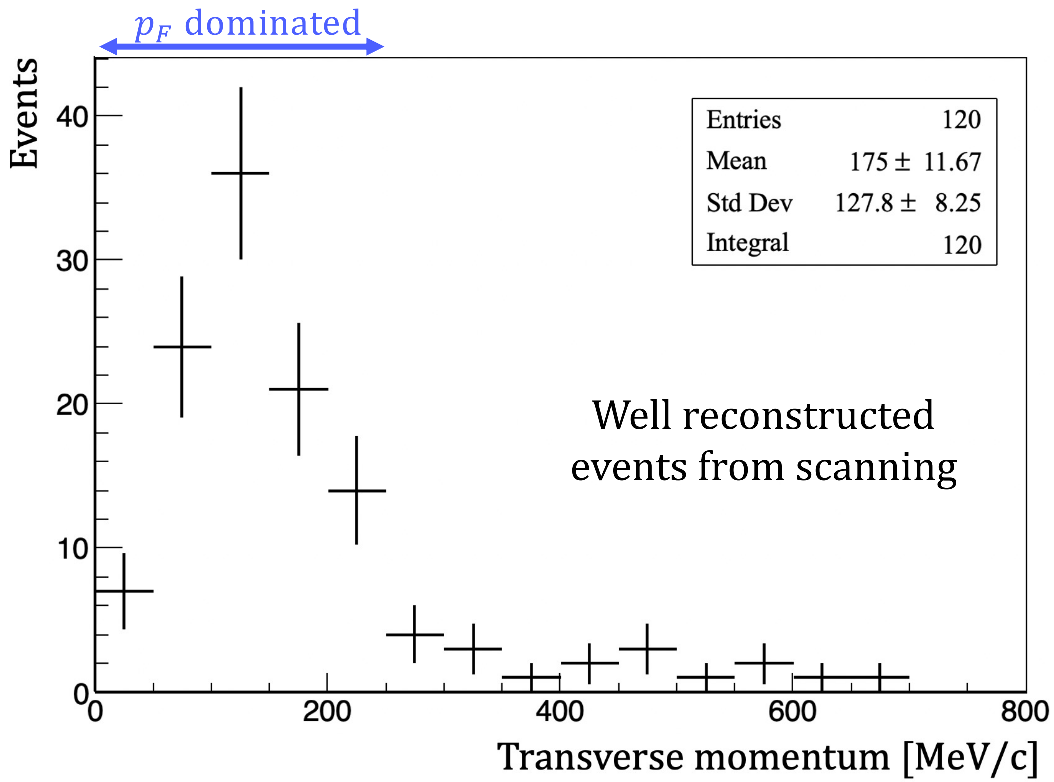

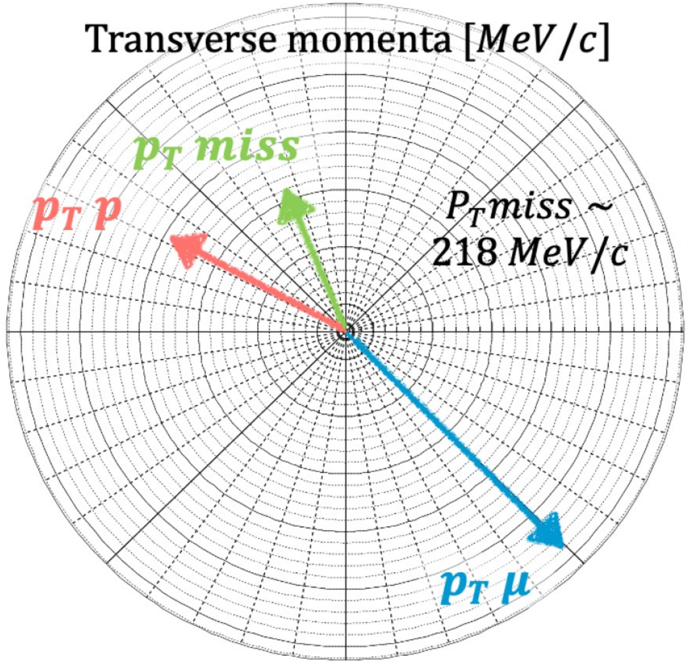

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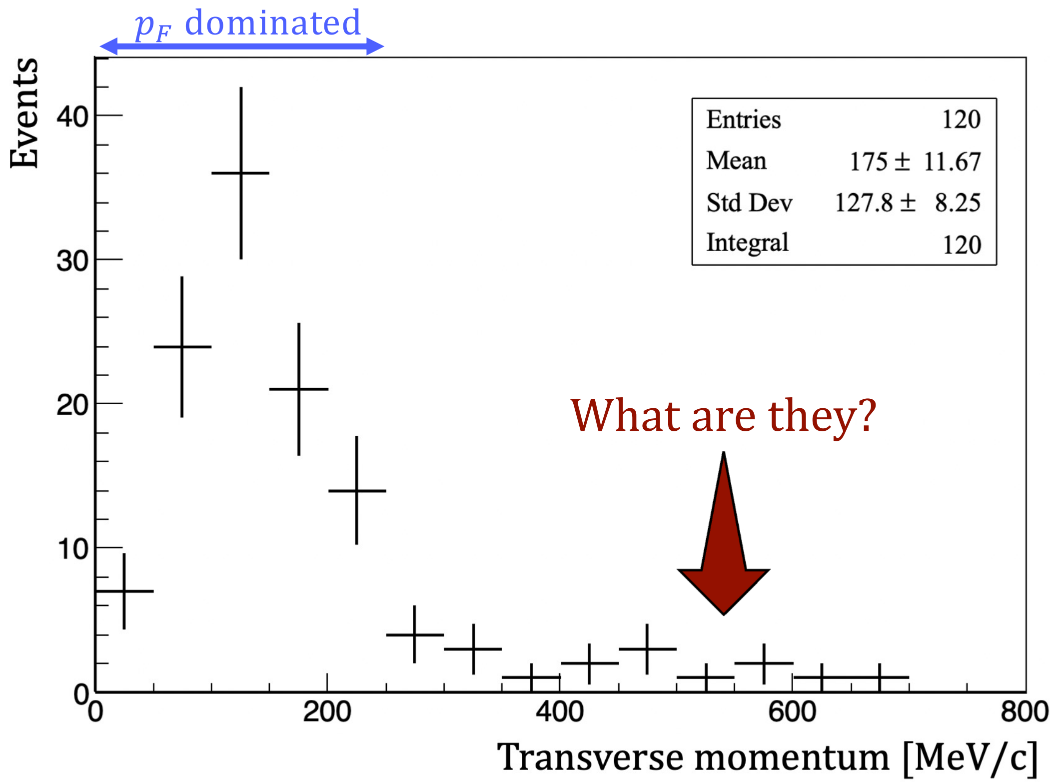
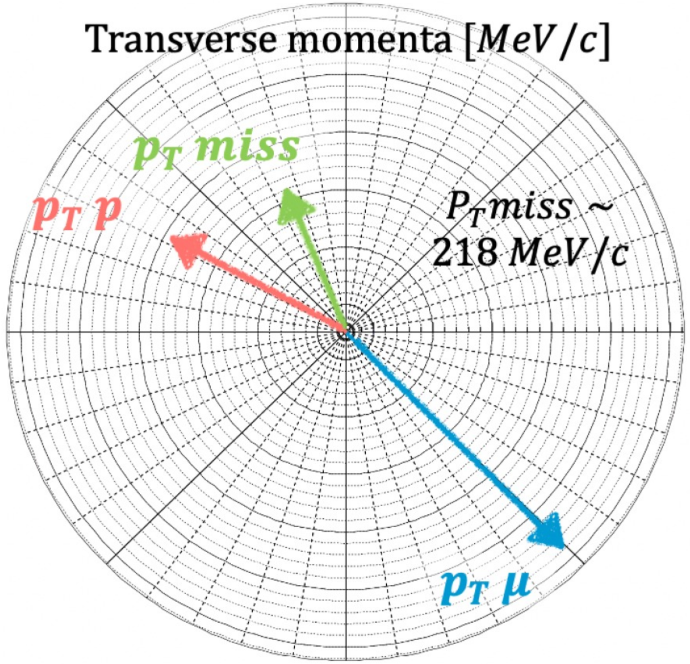
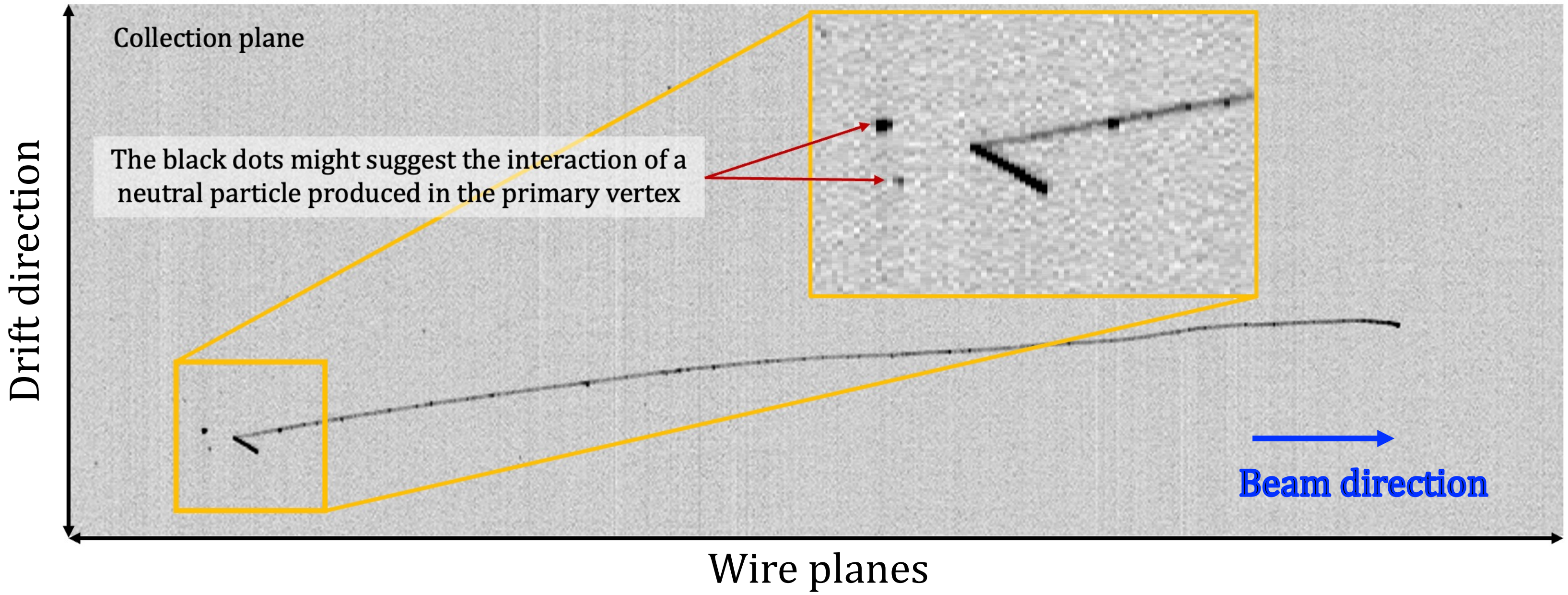




Events with large reconstructed p_T

BNB neutrino - 1μ1p candidate
- 215 cm muon long
- 5 cm proton
- $p_T \sim 639$ MeV/c



- In the visual scanning …
  - Different hadrons might be wrongly classified as protons
  - Very short protons are not visible ⇢ mis identified as $1\mu1p$ candidates
  - Neutrons and ~ MeV photons are very difficult to recognize, unless they do some interaction

From scanning to automatic selection

- Due to the large number of collected events an automatic procedure to select 1μ1p or 1μNp candidates is mandatory
- Using the experience gained with previous analysis, a first test was performed on simulated events

→ ν + cosmics MC production with ~ 3.2×10^{20} POT

- **Truth** level definition of 1μNp events
  - $\nu_\mu CC$ events with the interaction vertex inside the fiducial volume
  - 1 muon of at least 50 cm length
  - ≥ 1 proton with deposited energy $E_{dep} > 50$ MeV
  - **All** particles contained within 5 cm from the active TPC borders
  - No other particles with $E_{dep} > 25$ MeV

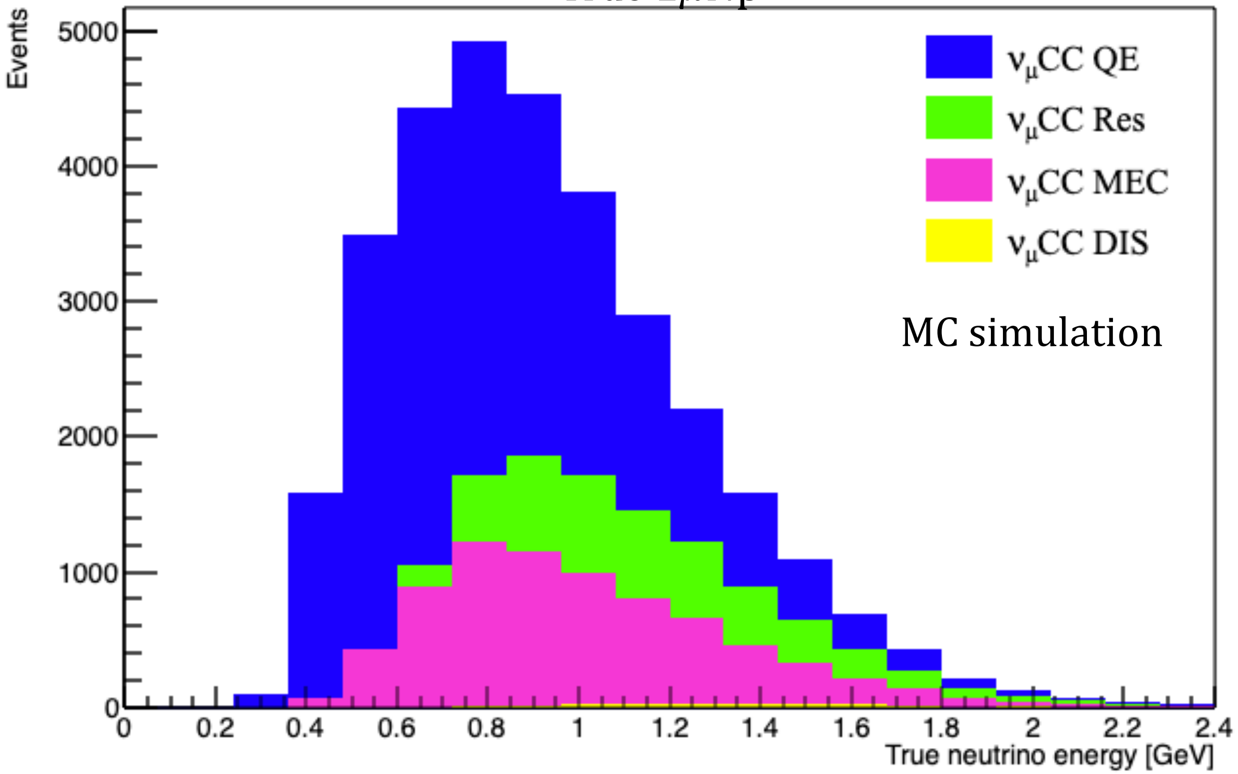
*50 MeV proton ≈ 2.3 cm length

MC Signal definition

- Using the previous definition and considering a MC exposure of $\mathbf{2.5{\times}10^{20}}$ **POT** (~ total data collected POT Run 1+2), ~32.3k 1μNp signal events are expected with the following true energy spectrum

Contribution	2.5×10^{20} POT
ν_μ CC QE	62.4%
ν_μ CC MEC	22.7%
ν_μ CC Res	14.3%
ν_μ CC DIS	0.6%
Total events	~ 32.3k

True 1μNp

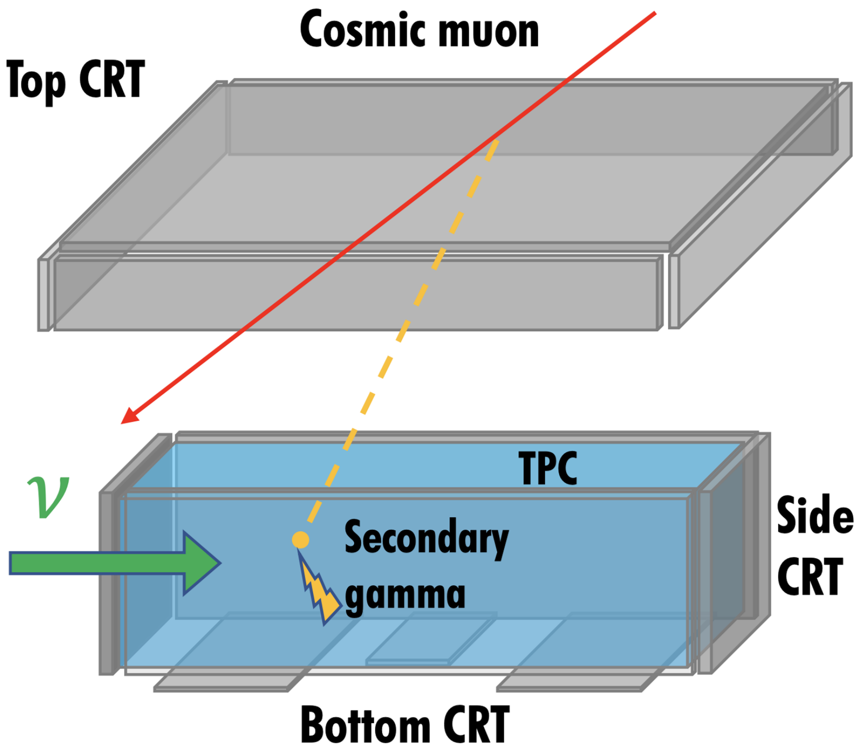


Automatic selection of $1\mu Np$ contained events

- To select this 1μNp signal the following automatic procedure was implemented

1. CRT Veto: no CRT-PMT in-time matching inside the 1.6 μs beam spill

To strongly reduce events whose trigger is produced by in-spill cosmics or not contained ν interactions



- No signal before the trigger: to reject external particles (cosmics)
- No signal after the trigger: to reject exiting particles

Automatic selection of $1\mu Np$ contained events

- To select this 1μNp signal the following automatic procedure was implemented

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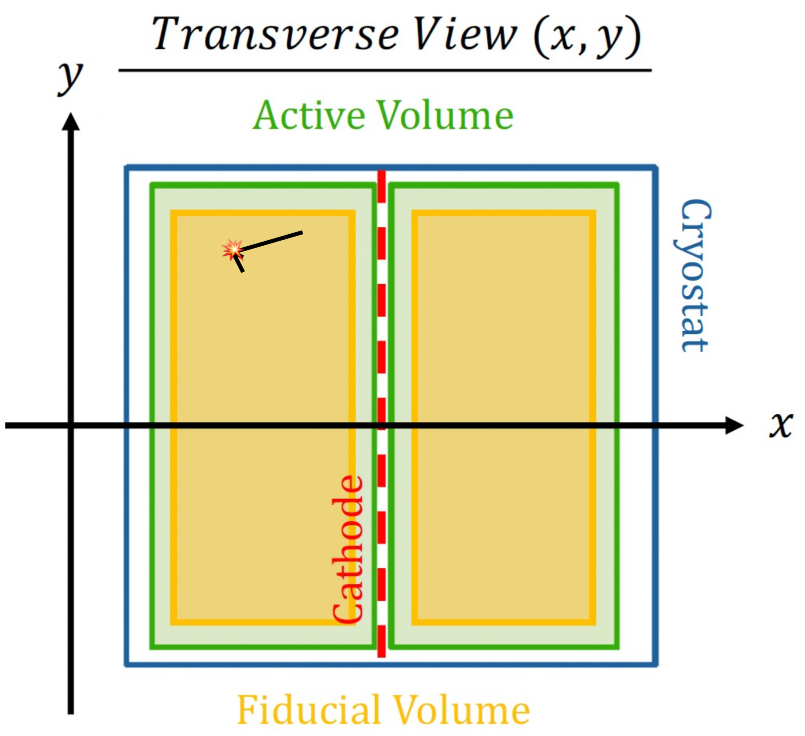
2. Events with reconstructed vertex inside fiducial volume

   To have a better control of the event reconstruction



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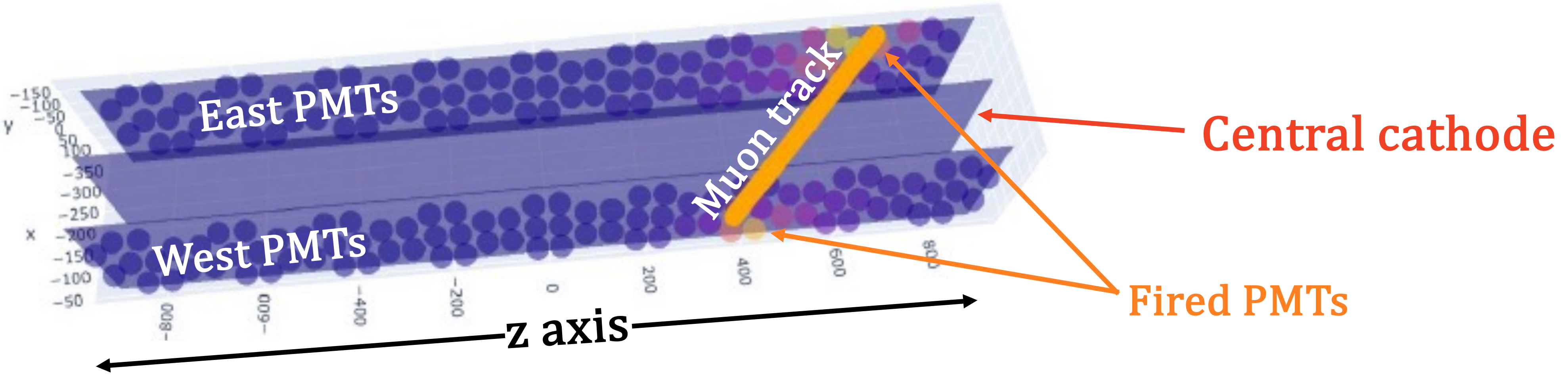
To define the region of interest where the event is located, effectively rejecting out of spill cosmic events



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4. **All reconstructed** objects inside the slice need to be contained within 5 cm from the active TPC borders

   To select contained events and avoid space charge effect distortions

*Slice = Reconstructed object that encapsulates each interaction

Automatic selection of $1\mu Np$ contained events

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4. **All reconstructed** objects inside the slice need to be contained within 5 cm from the active TPC borders
5. Muon identification corresponding to the longest track in the slice satisfying
    - Start point within 10 cm from the reconstructed vertex
    - Length of at least 50 cm
    - Tagged as a muon by the Particle identification tool

Selection of ν_μCC contained events

Automatic selection of $1\mu Np$ contained events

6. 0 reconstructed showers and pions (no other reconstructed primary tracks compatible with a muon)

   Considering only reconstructed objects with $E_k \geq 25$ MeV

*25 MeV pion ≈ 2.5 cm length

Automatic selection of $1\mu Np$ contained events

6. 0 reconstructed showers and pions (no other reconstructed primary tracks compatible with a muon)

7. Proton identification: the remaining reconstructed tracks needs to be tagged as a proton candidates
   - Start point within 10 cm from the reconstructed vertex
   - At least 50 MeV of kinetic energy, range-based measurement
   - Tagged as a proton by the Particle identification tool

Selection of 1μNp contained events ready!

*50 MeV proton ≈ 2.3 cm length

Automatic selection of $1\mu Np$ contained events

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Selection of 1μNp contained events ready!

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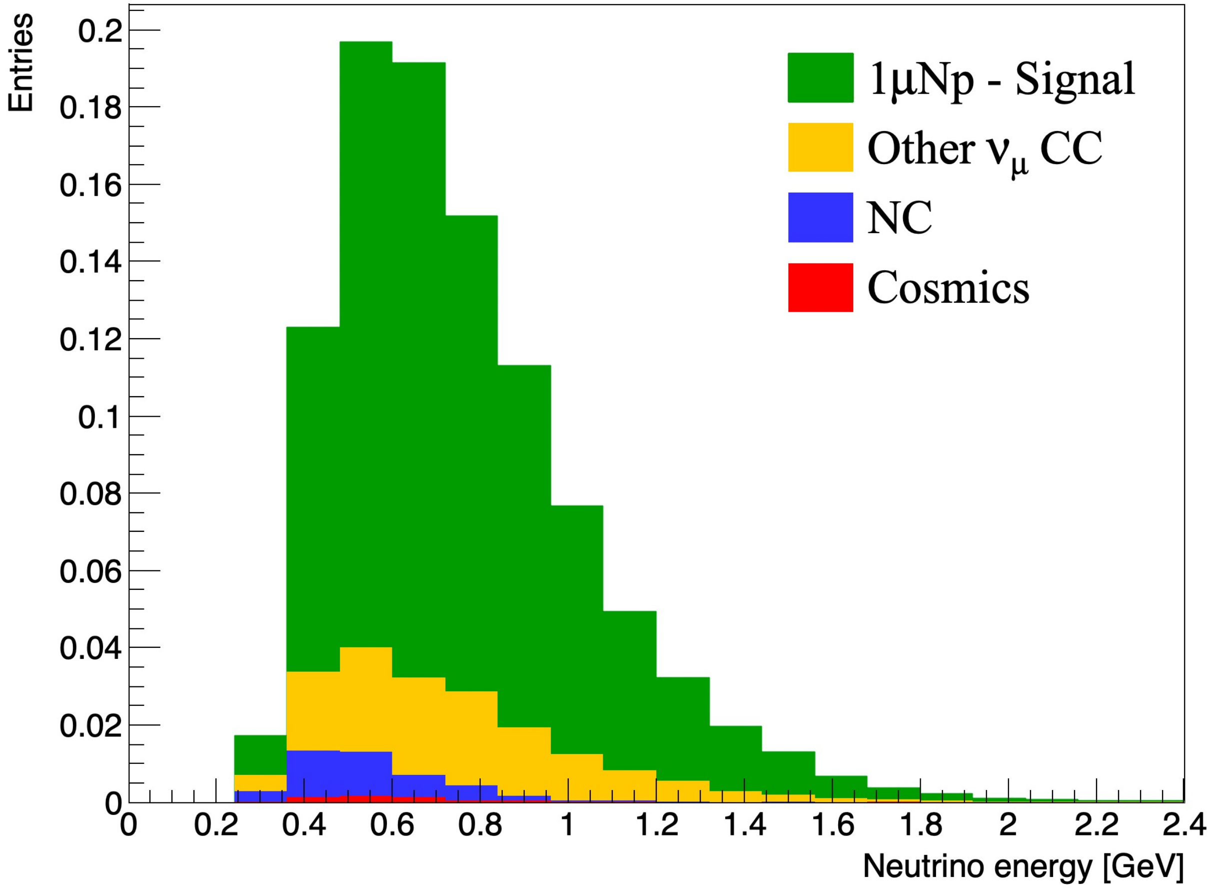
Automatic selection of $1\mu Np$ contained events

MC simulation



MC expectations

$$\text{Efficiency} = \frac{Selected\ signal}{True\ signal} \approx 48\%$$

$$\text{Purity} = \frac{Selected\ signal}{All\ selected} \approx 81\%$$

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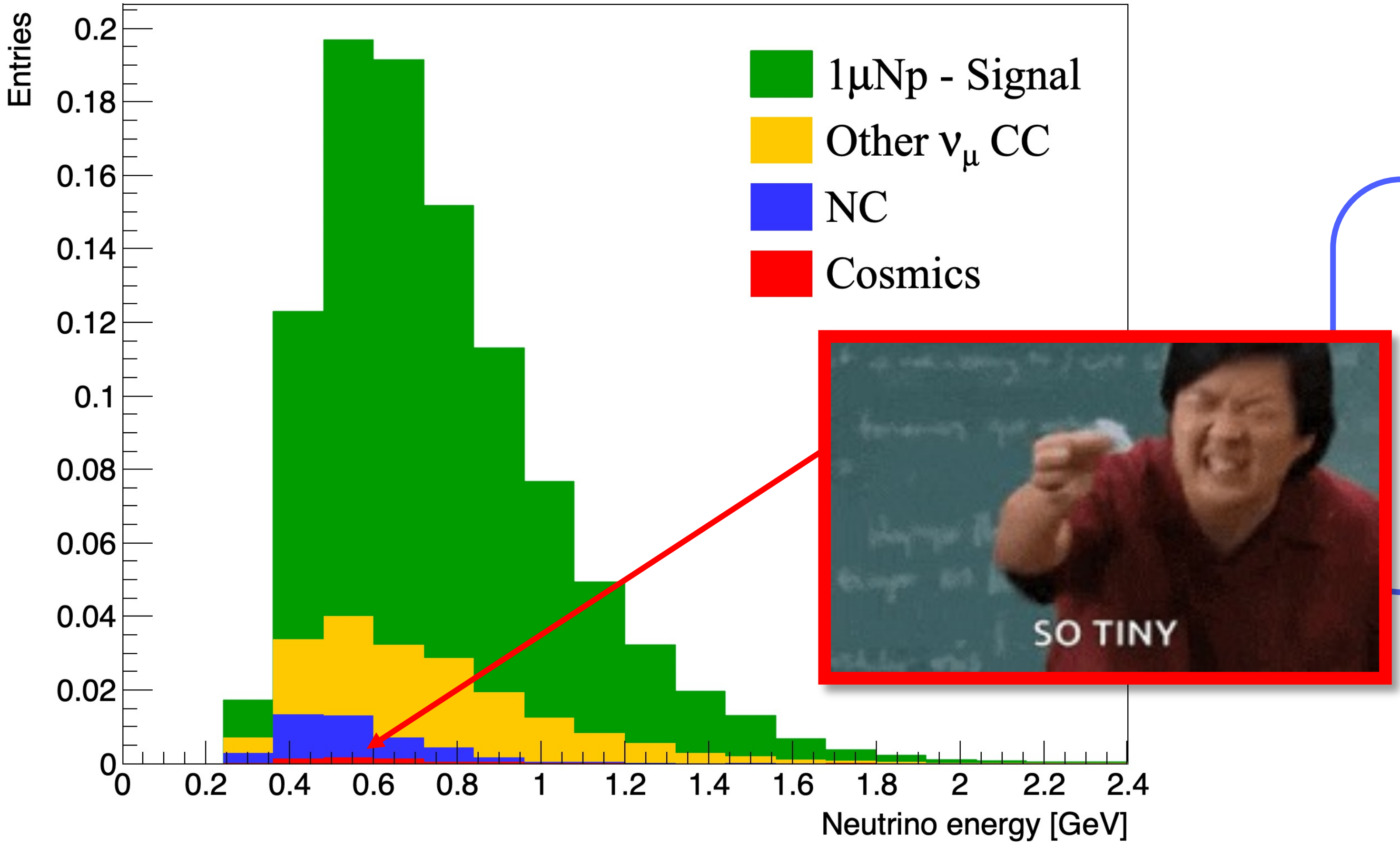

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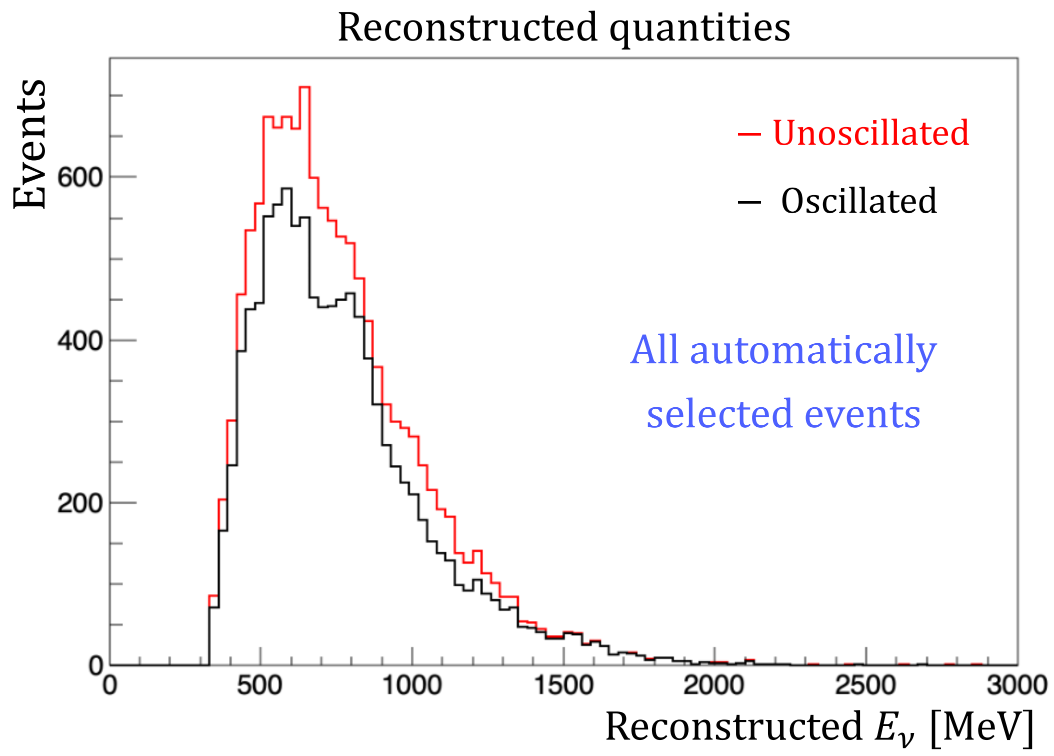
Oscillation hypothesis

- The ultimate goal of the event selection is to provide an oscillation measurement
- Example of a **hypothetical** ν_μ disappearance assuming $\sin^2 2\theta_{\mu\mu} = 0.36$, $\Delta m^2_{41} = 7.3$ eV^2 (Neutrino-4 results)

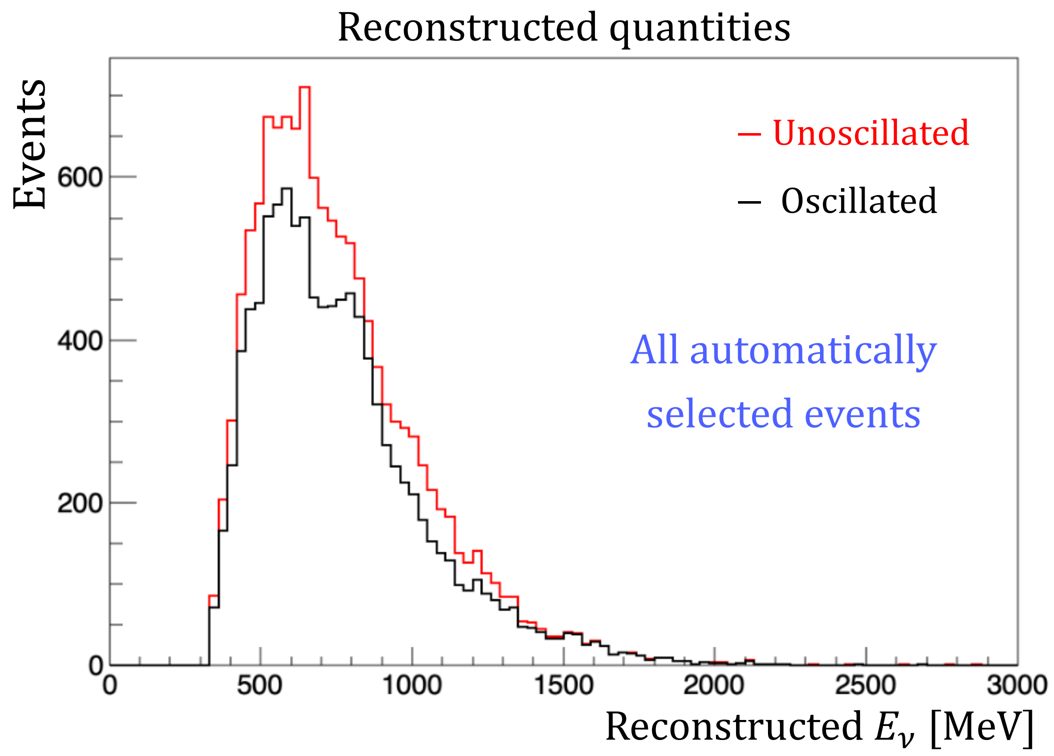


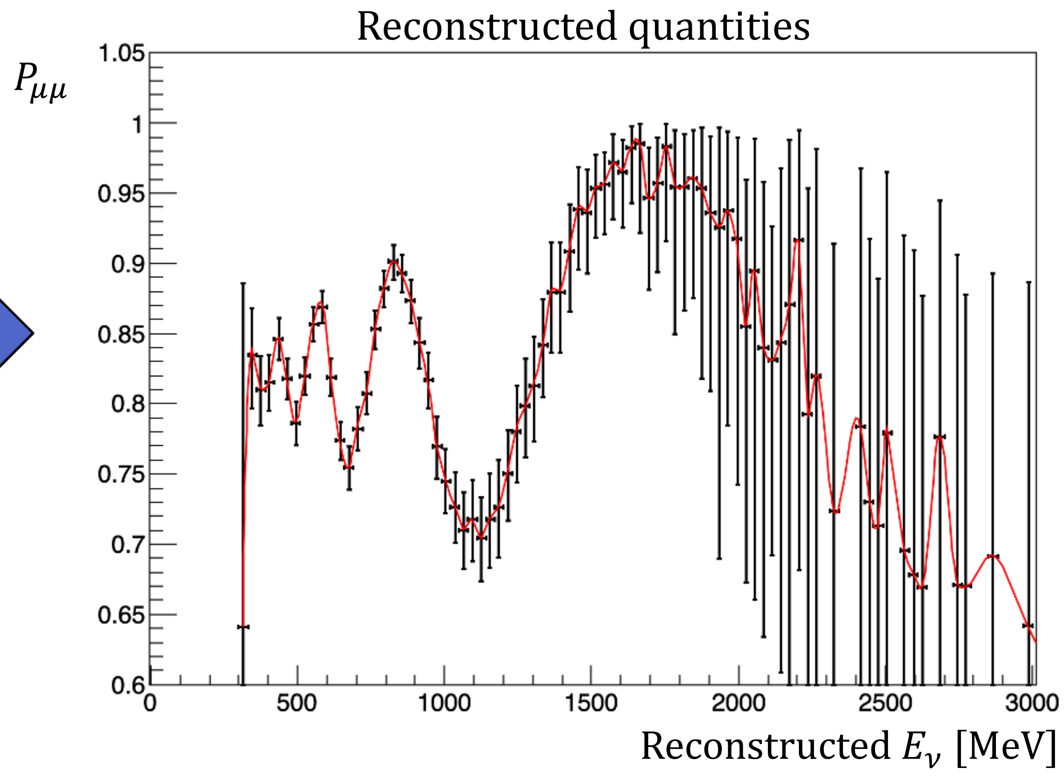
$$P(\nu_\mu \longrightarrow \nu_\mu)_{SBL} \simeq 1 - \sin^2 2\theta_{\mu\mu} \sin^2 1.27 \frac{\Delta m^2_{41} L}{E_{\nu_\mu,true}}$$

with $E_{\nu_\mu,true}$ and L the true baseline

Oscillation hypothesis

- The survival probability is obtained dividing the oscillated energy spectrum with respect to the unoscillated one



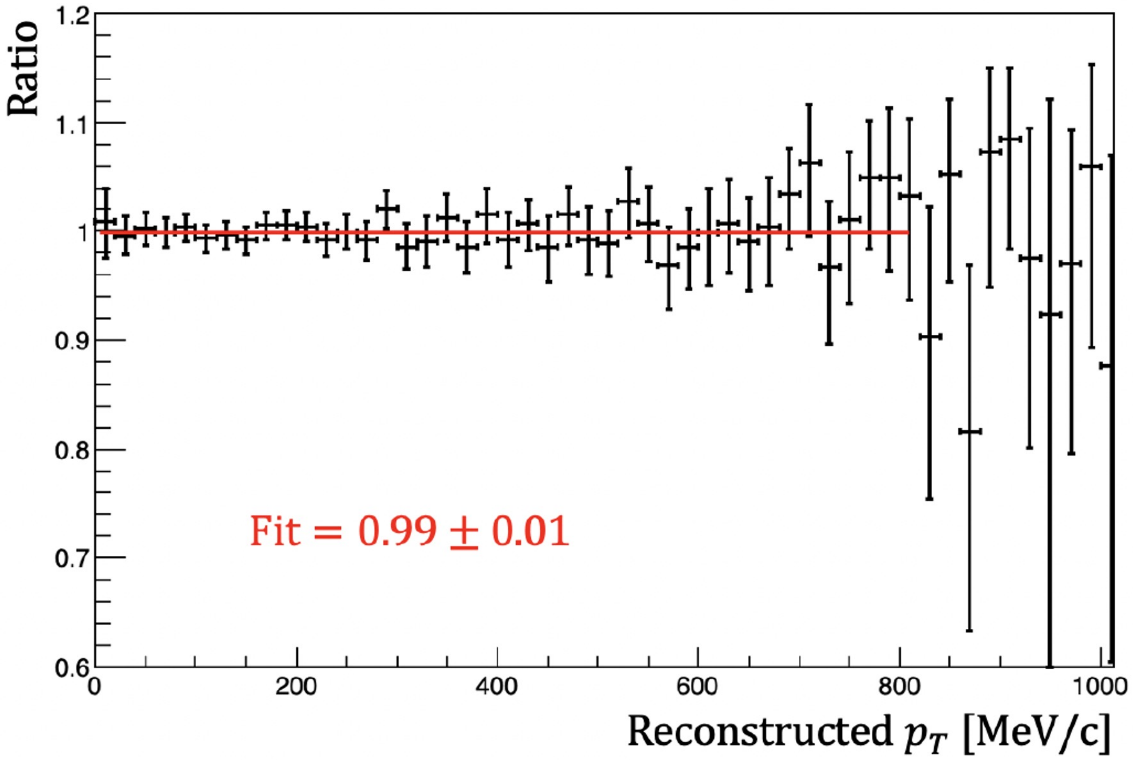


*Only statistical errors are shown

Oscillation hypothesis

- The transverse momenta was also studied showing that it is **not** affected by the mixing of sterile-active neutrino

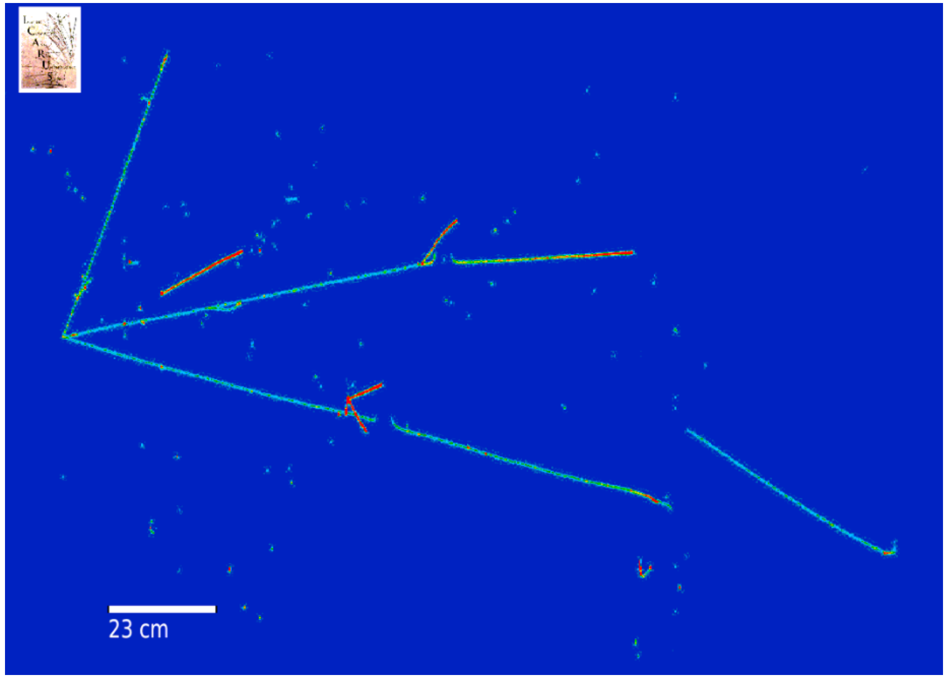
Can be exploited without inferring any neutrino oscillation property



*Only statistical errors are shown

Cross checks with data

- Data efficiency and purity were evaluated with Run 9435 ($\sim 2\times10^{18}$ POT)
- All candidates automatically selected were visually scanned to obtain the purity of the selection ~ 84%



- The selection efficiency was evaluated with an unbiased scanned sample using half of the entire Run 9435
  - 100 1μNp were chosen as a reference

The developed automatic selection identified 48 of them, reporting an Efficiency of 48%

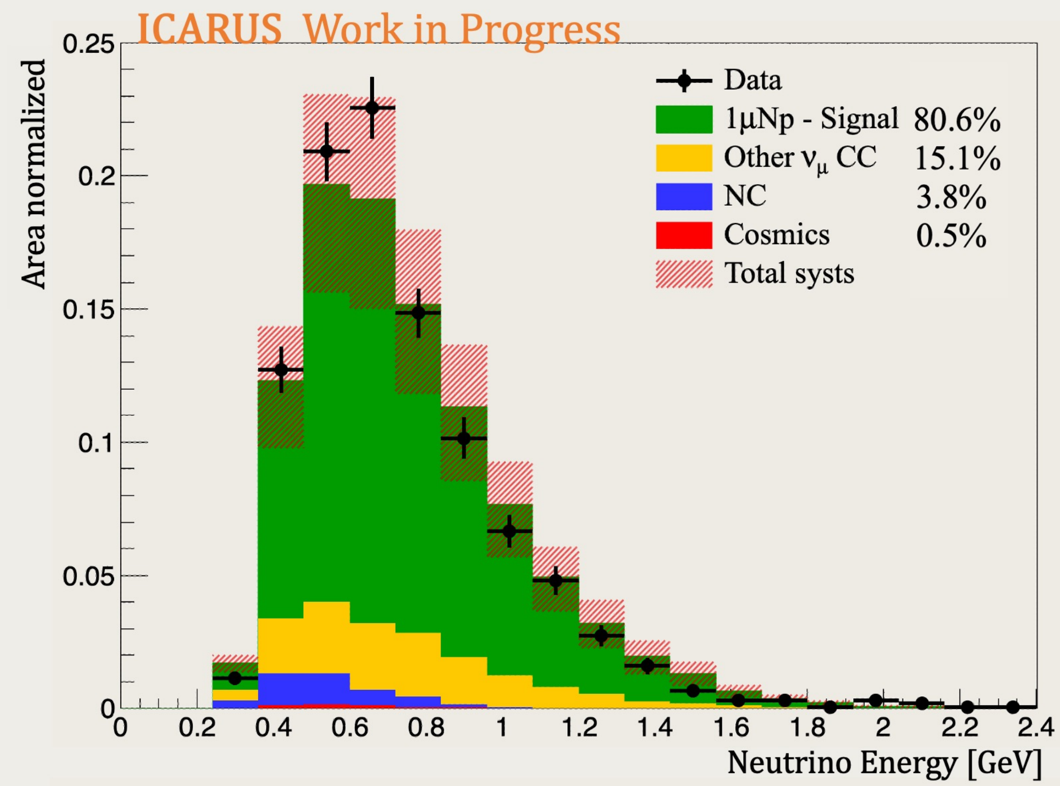
- MC study: ~ 48% Efficiency and ~ 81% Purity

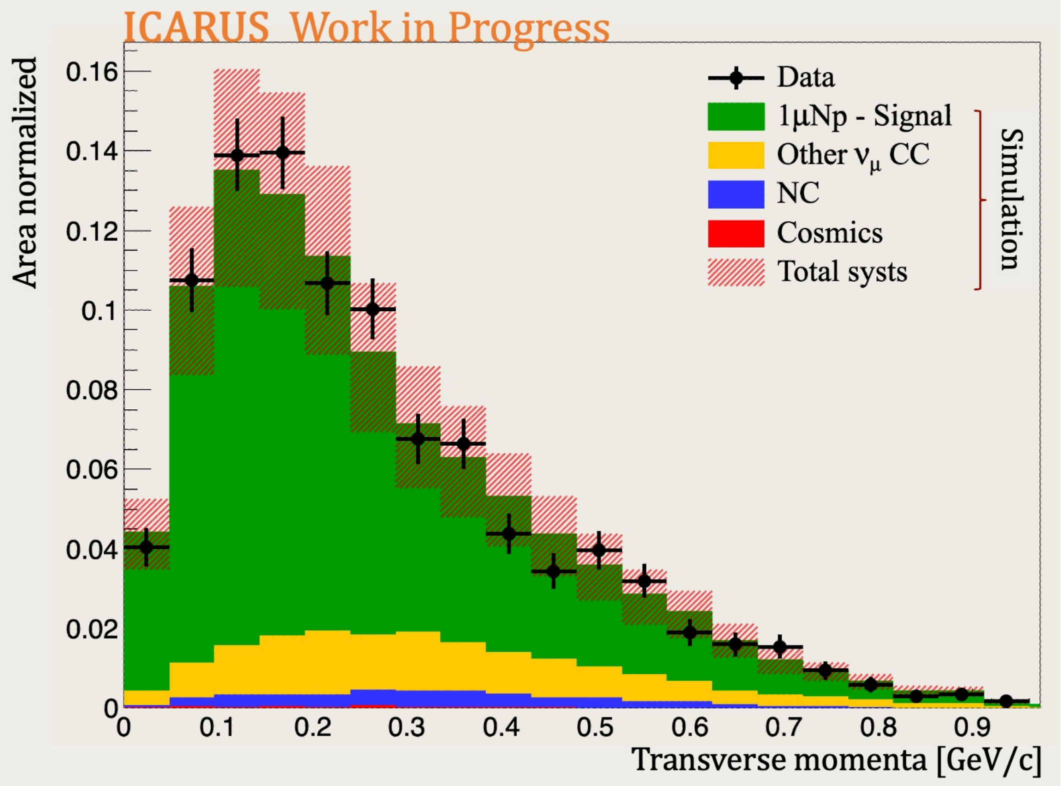
Data – MC comparison

- The automatic selection was applied to the whole MC sample and ~ 10% of total collected data

  To perform Data – MC comparison in accordance with the blinding policy

- Shape only analysis with systematic uncertainties





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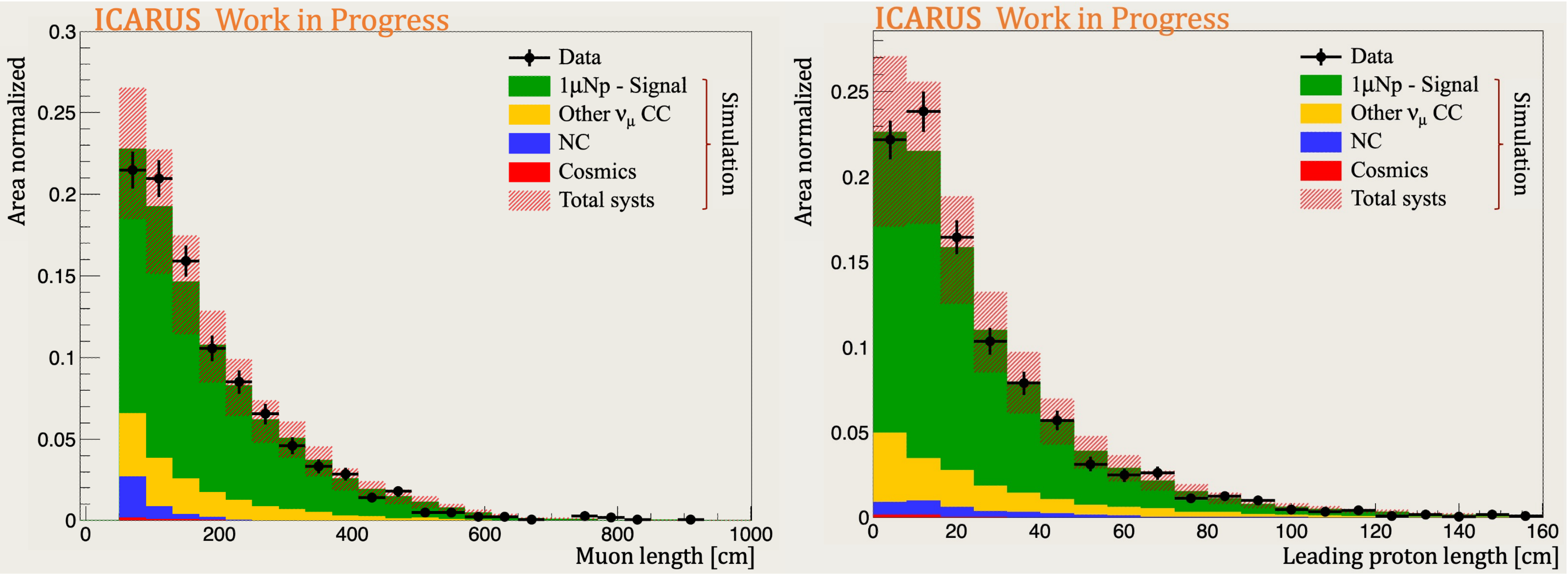


Conclusion and perspectives

- My thesis was intended to pave the way towards a BNB ν_μ disappearance analysis

  A first step to test the Neutrino-4 $\overline{\nu_e}$ oscillation hypothesis

1. ICARUS detector and reconstruction algorithms' performance validation

   Visual scanning campaign proving ICARUS capability to perform calorimetric studies, particle identification and kinematic reconstruction of contained $1\mu 1$p events

2. Development of an automatic selection to identify 1μNp events

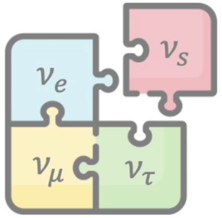
   Simulation studies were performed leveraging all 3 detector subsystems $\Longrightarrow$ achieving 81% purity and 48% efficiency

- Small **data** sample was used to estimate the sample purity ($\sim$ 84%) and selection efficiency ($\sim$48%)
- Data – simulation comparison showing reasonable agreement

  More statistics are needed together with a quantitative comparison

1μNp automatic selection ready to be used !

Conclusion and perspectives



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Thank you!

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