Towards a neutrino analysis in the ICARUS detector

Probes Annual General Meeting

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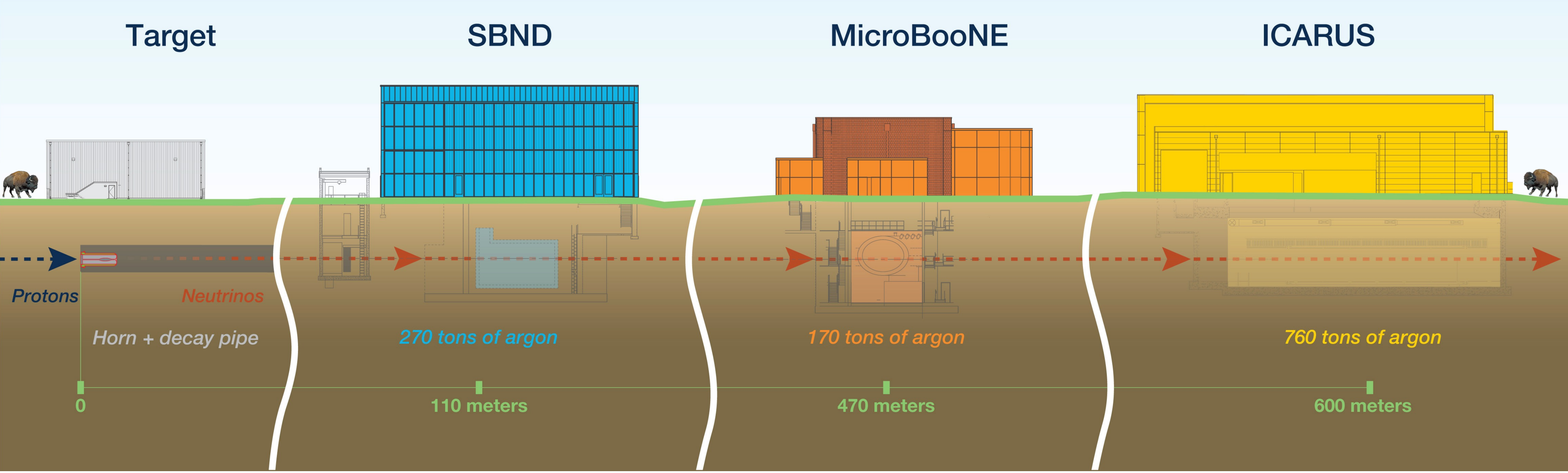
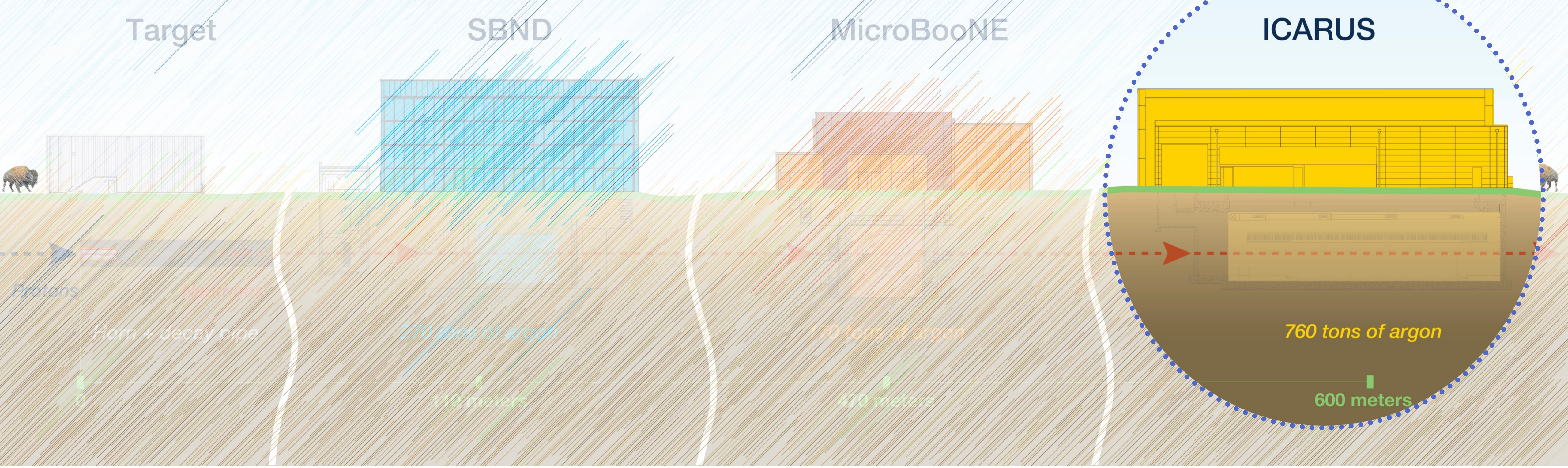
27th Nov 2025

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

Short-Baseline Neutrino Program at Fermilab



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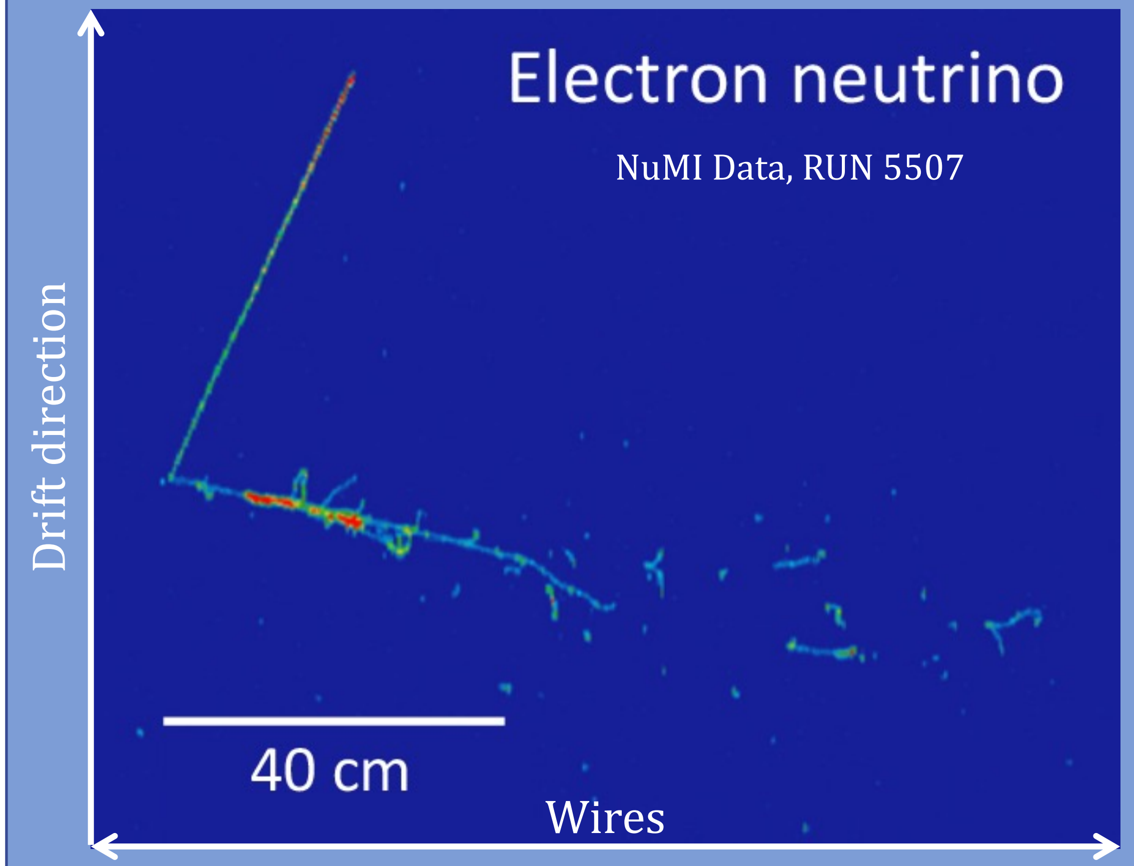
From images to physics

- 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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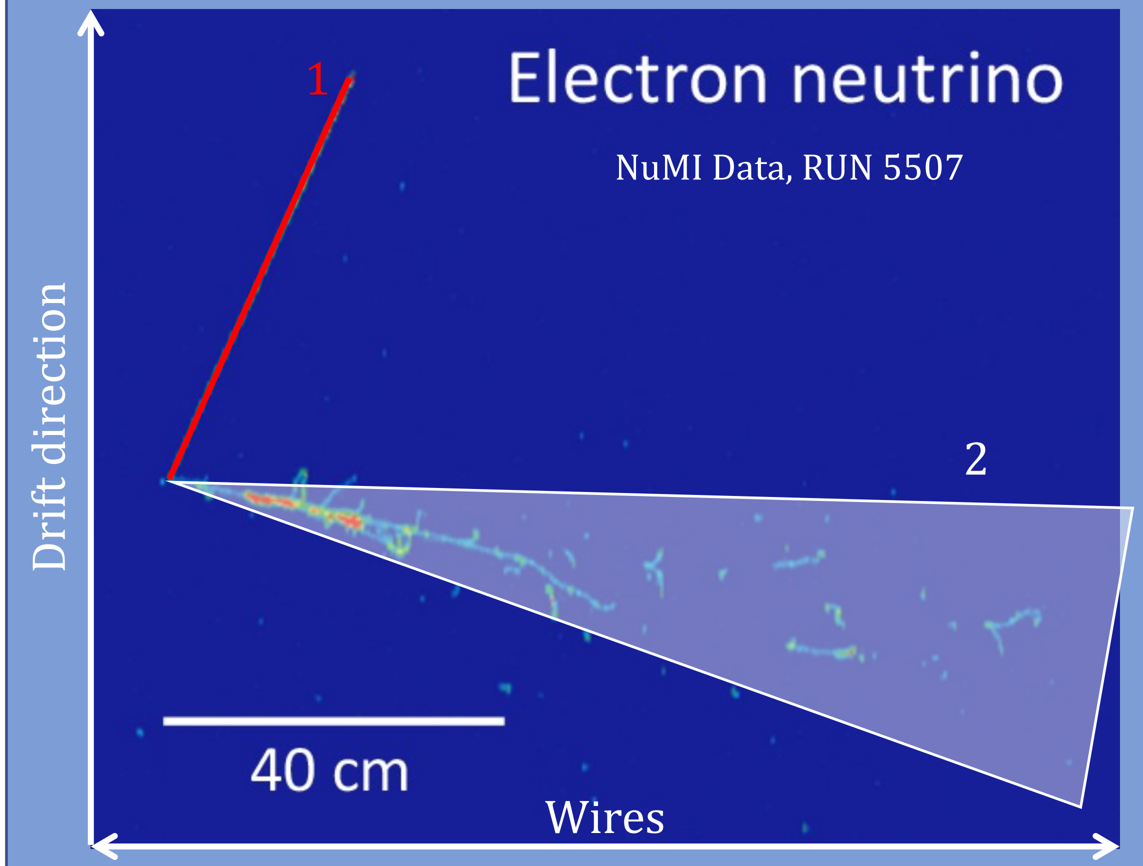

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Due to the large amount of data to analyse, an automated solution is mandatory

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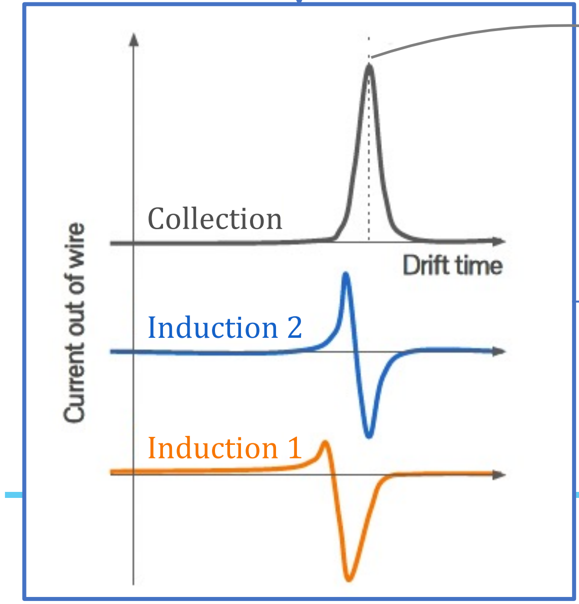
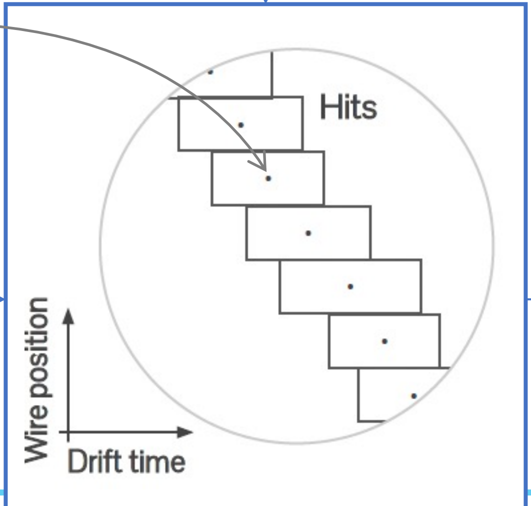
The reconstruction pipeline

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

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



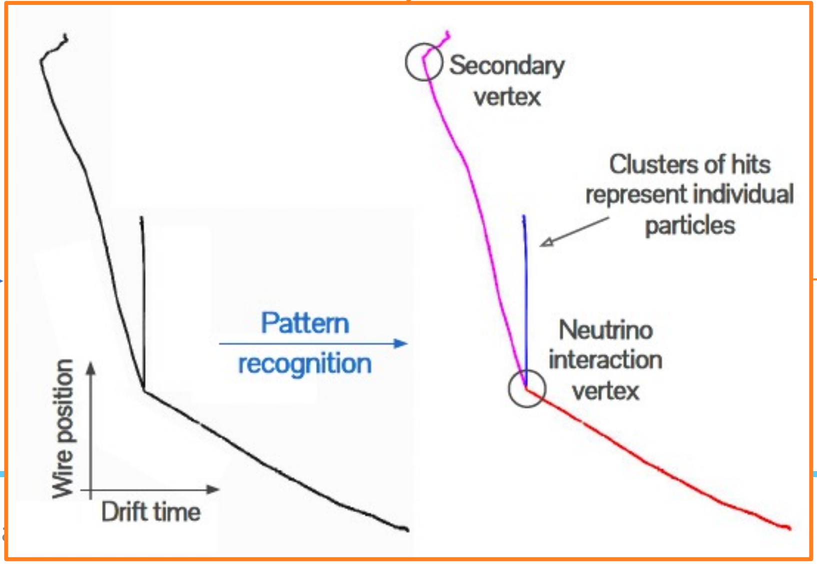
Hit finding
- Gaussian hits
- Cluster 3D



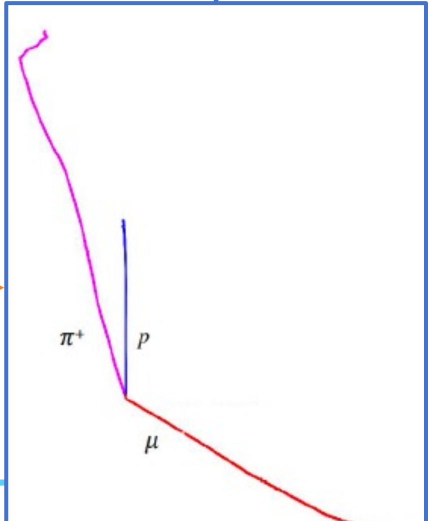
*hit: identified signal induced by a track on a wire.

Pattern recognition
- Pandora Algorithm

[software development toolkit]



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



From scanning to automatic selection

- Due to the large number of collected events an automatic procedure to select 1μNp candidates is mandatory

- **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
  - $\geq$ 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

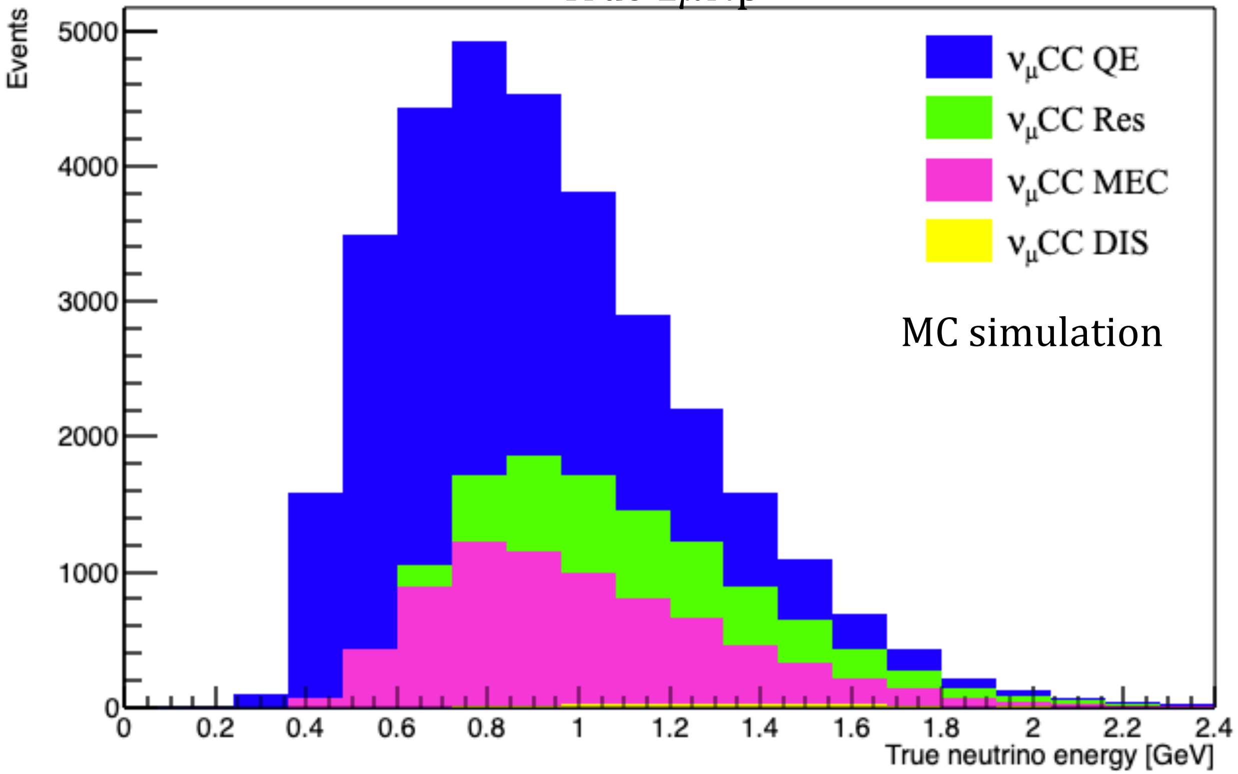
*50 MeV proton ≈ 2.3 cm length

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	$\mathbf{2.5 \times 10^{20}}$ **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	$\sim$ **32.3k**

True 1μNp

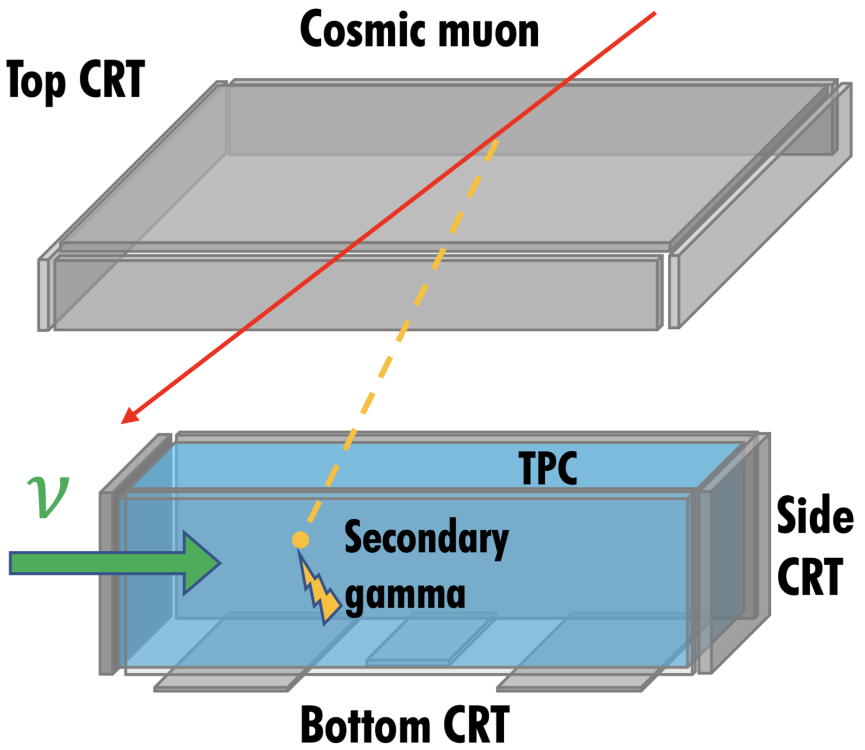


Automatic selection of $1\mu Np$ contained events

- 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

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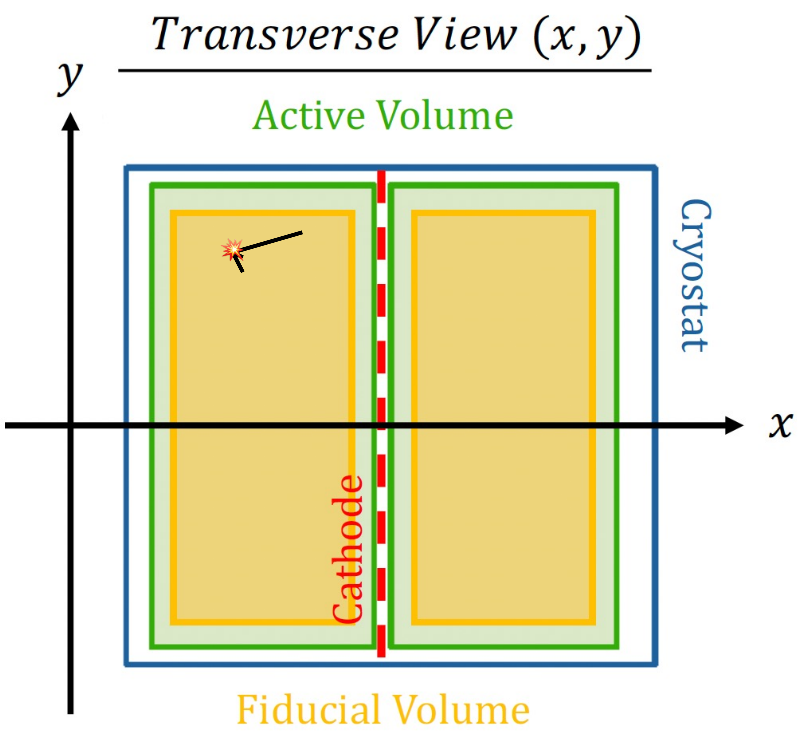
1. CRT Veto: no CRT-PMT in-time matching inside the 1.6 μs beam spill
2. Events with reconstructed vertex inside fiducial volume

   To have a better control of the event reconstruction



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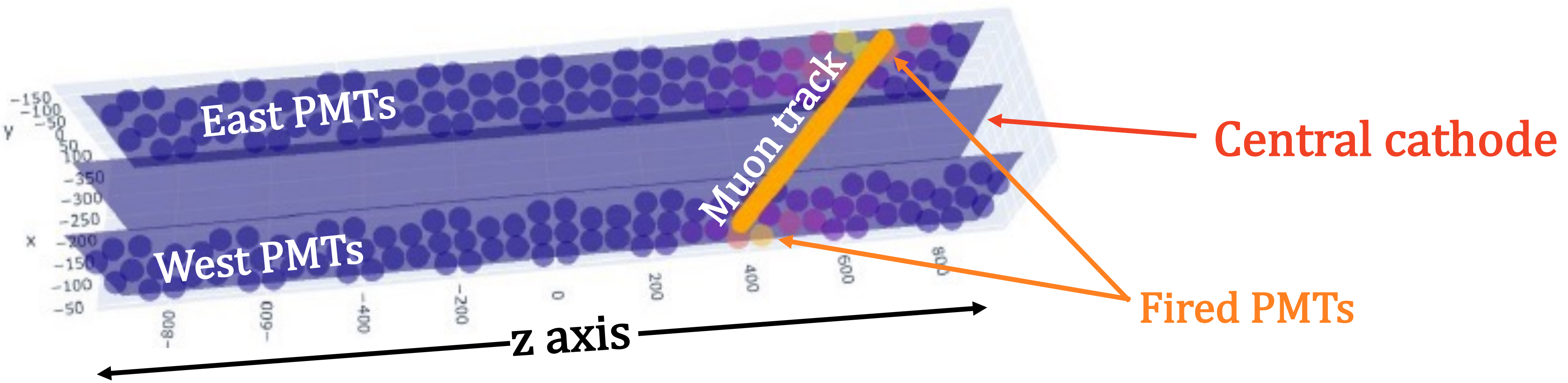
To define the region of interest where the event is located, effectively rejecting out of spill cosmic events



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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)

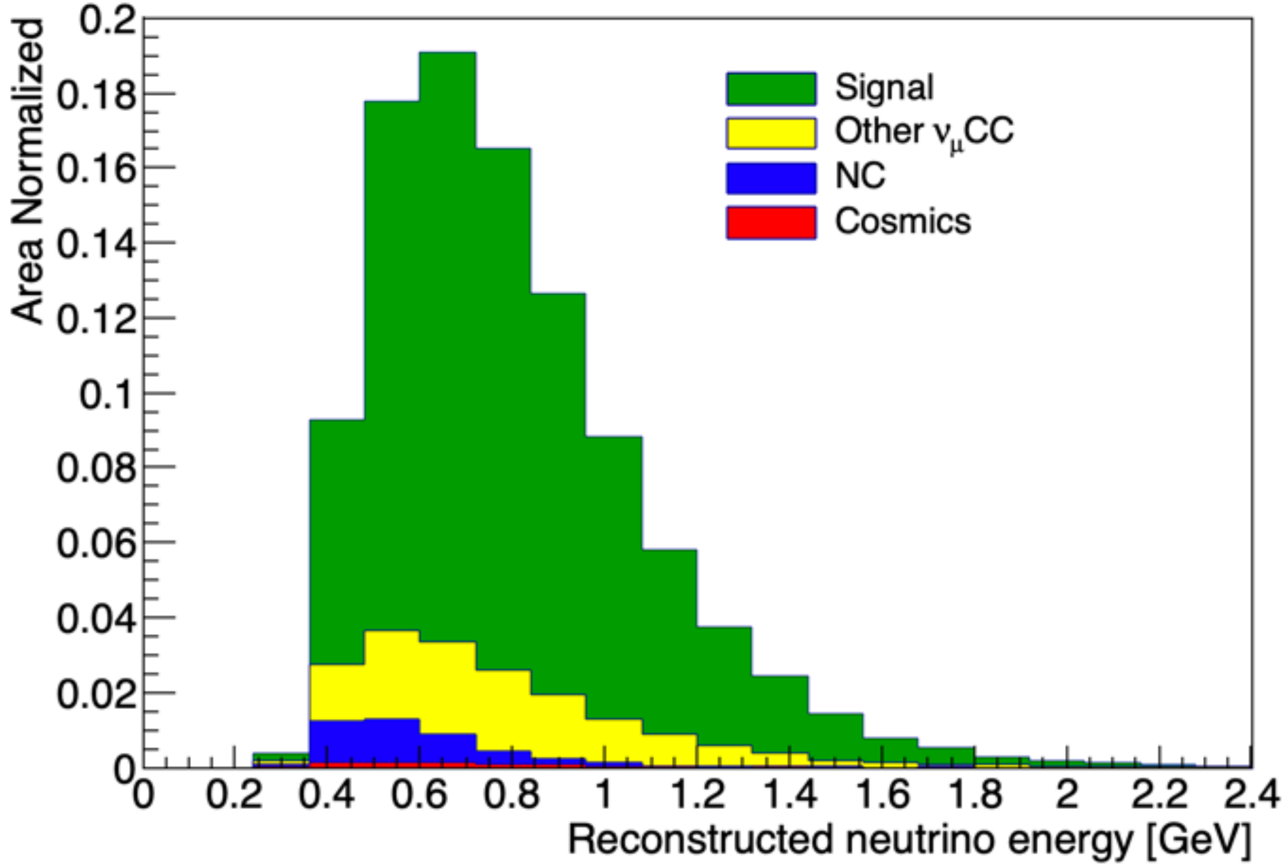
7. Proton identification: the remaining reconstructed tracks needs to be tagged as a proton candidates
   - Start point within 10 cm from the reconstructed vertex
   - At least 50 MeV of kinetic energy, range-based measurement
   - Tagged as a proton by the Particle identification tool

Selection of 1μNp contained events ready!

*50 MeV proton ≈ 2.3 cm length

Automatic selection of $1\mu Np$ contained events

MC simulation



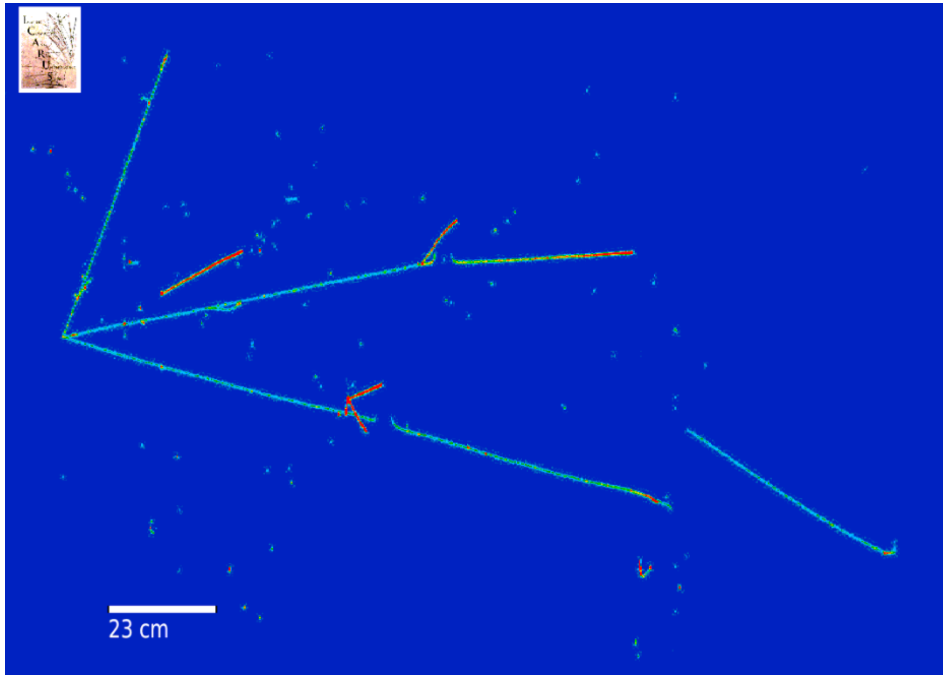
MC expectations

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

$$\text{Purity} = \frac{Selected\ signal}{All\ selected} \approx 82\%$$

Cross checks with data

- Data efficiency and purity were evaluated with Run 9435 ($\sim 2{\times}10^{18}$ 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 51 of them, reporting an Efficiency of 51%

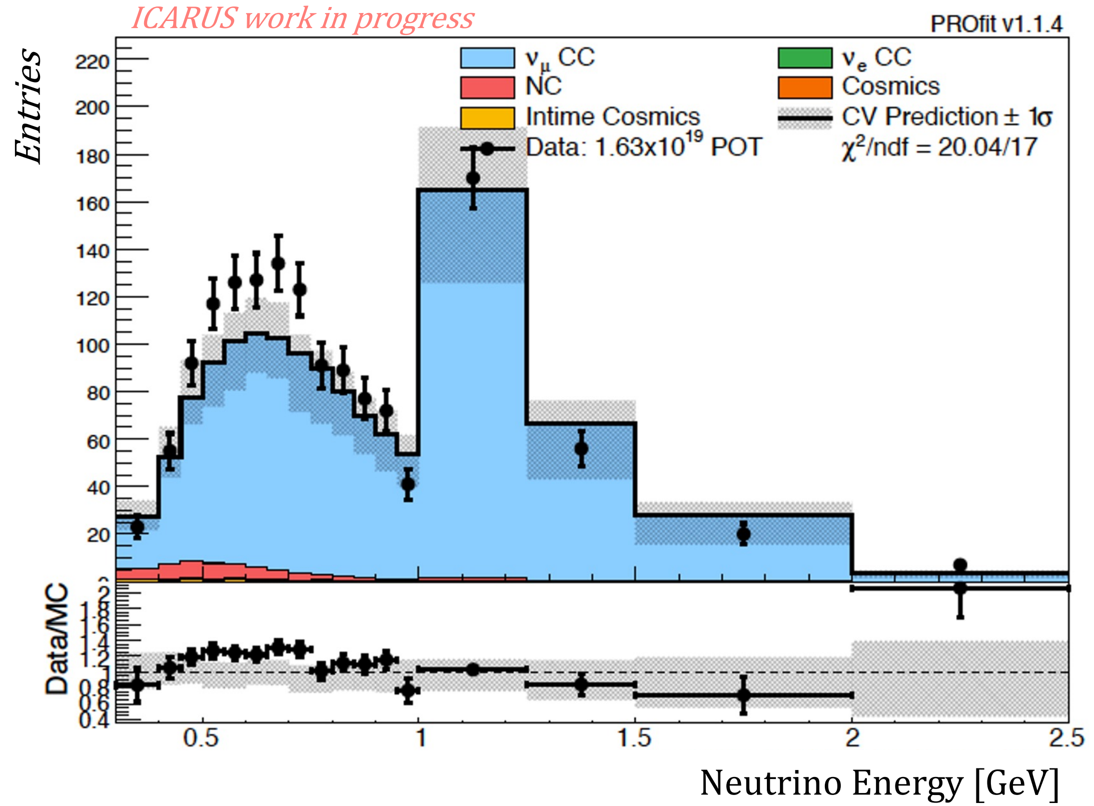
- MC study: ~ 48% Efficiency and ~ 82% Purity

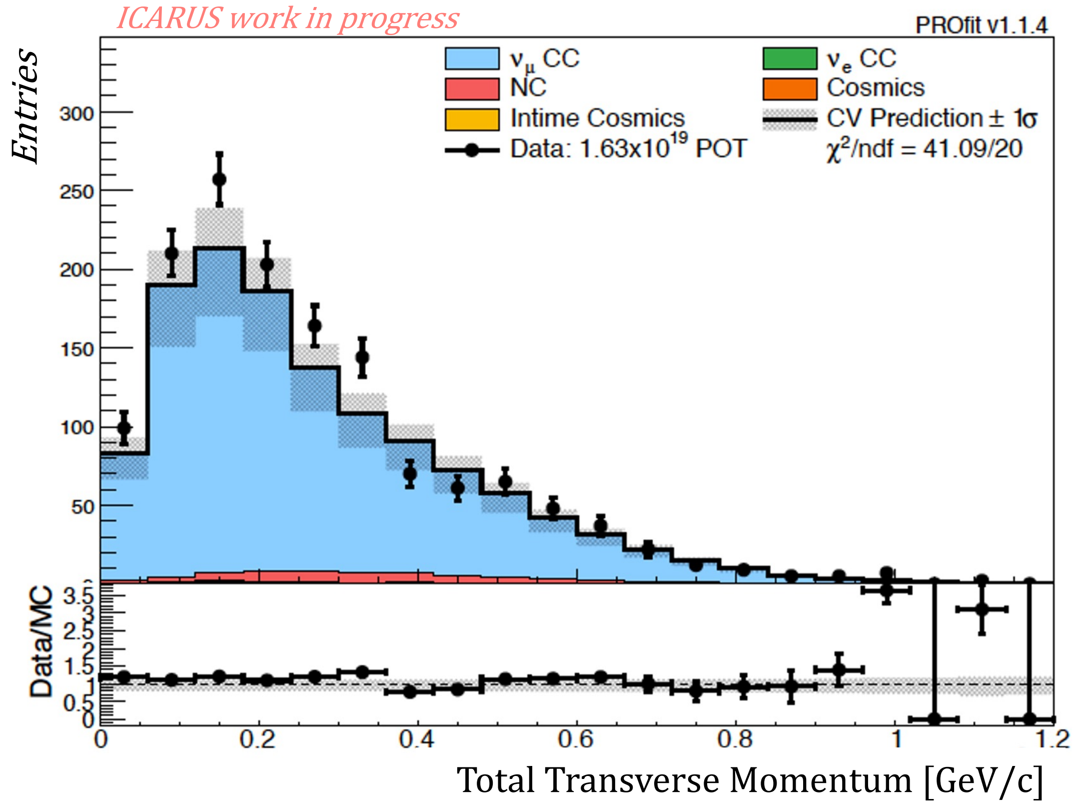
Data – MC comparison

- 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 full evaluation of systematic uncertainties





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  Good agreement for all studied variables