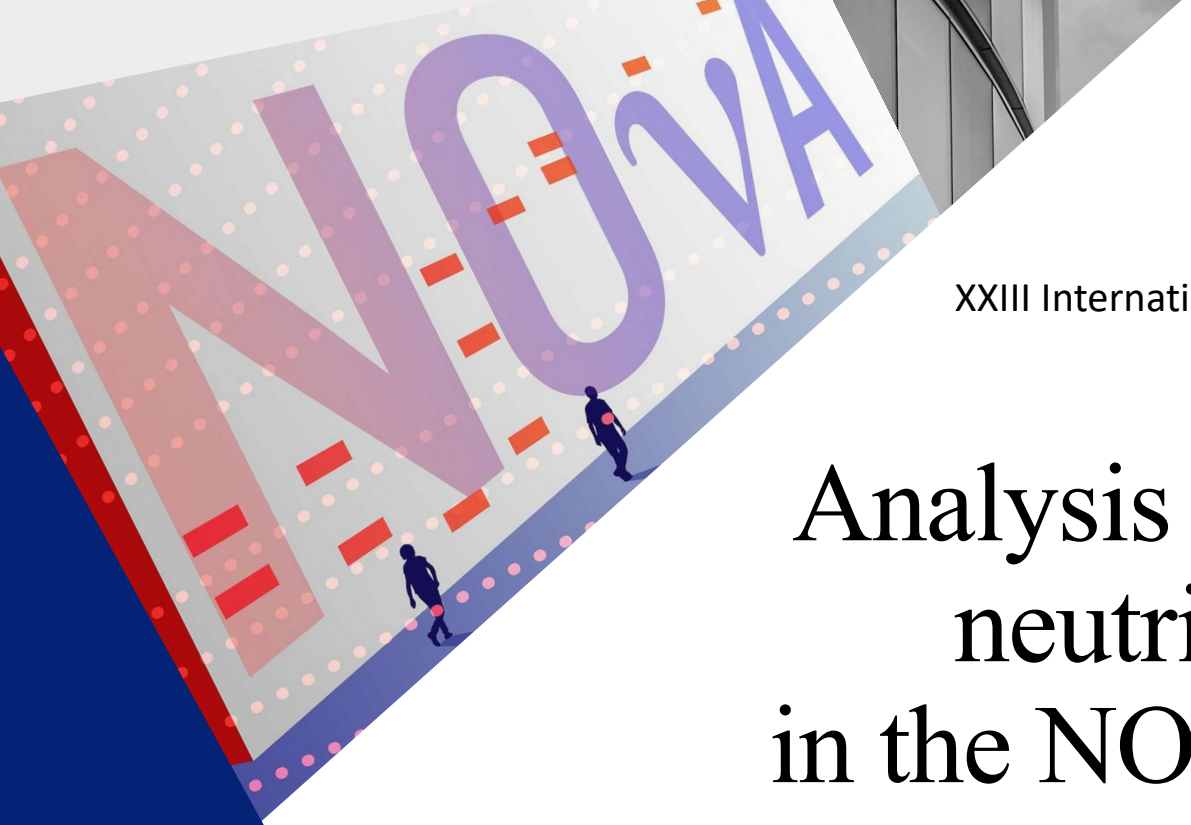


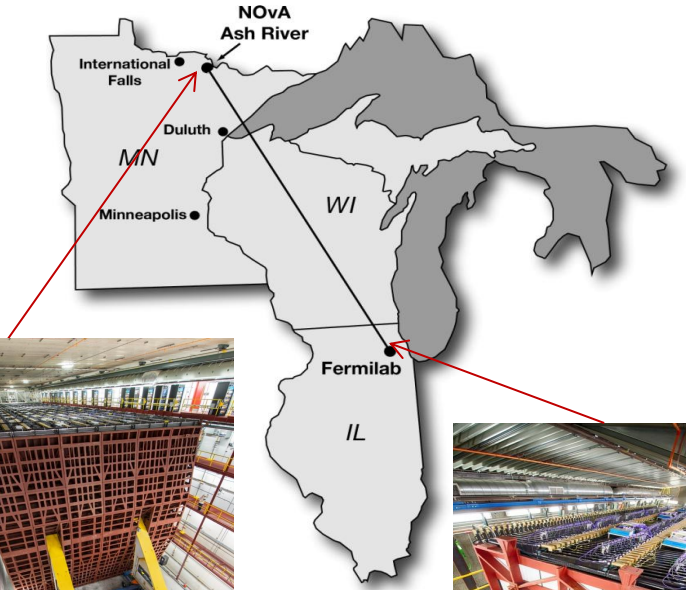

Quarks-2026
XXIII International Seminar on High-Energy Physics

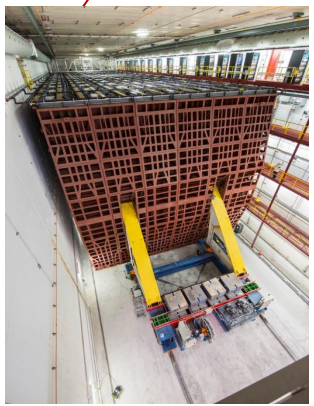
# Analysis of atmospheric neutrino interactions in the NOvA far detector

Aleksandra Ivanova, PhD student at MIPT

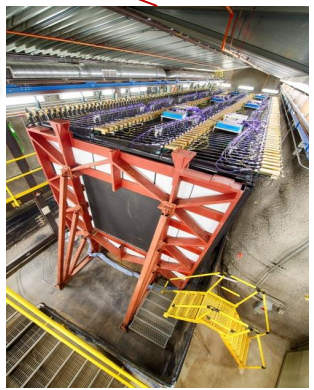
Atmospheric neutrinos are nature’s gift to physicists: a free, high-energy neutrino source. But in the NOvA experiment, this gift has been sitting unopened for 10 years – until now...

# The NOvA Experiment



*Far detector (FD)*



*Near detector (ND)*

- **N**uMI **O**ff-Axis $\nu_e$ **A**ppearance
- 14 mrad off-axis beam
- **2 GeV** peak energy
- Measuring $\nu_\mu$ ($\overline{\nu}_\mu$) disappearance and $\nu_e$ ($\overline{\nu}_e$) appearance
- Two detectors:

  - **Near detector** (ND, 300 tons) at a distance of 1 km from target in Fermilab

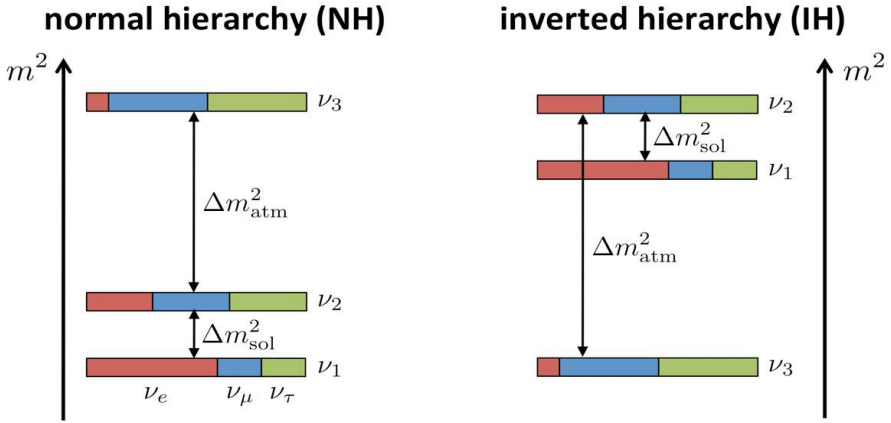
  - **Far detector** (FD, 14 kilotons) at a distance of 810 km, in Ash River, MN
- PVC tubes filled with **liquid scintillator** based on mineral oil

# NOvA Physics Goals

- Determination of the neutrino mass hierarchy
- Determination of the $\theta_{23}$ octant and refinement of $\theta_{13}$
- Constraining the CP-violating phase $\delta_{cp}$
- Measuring of neutrino cross-sections

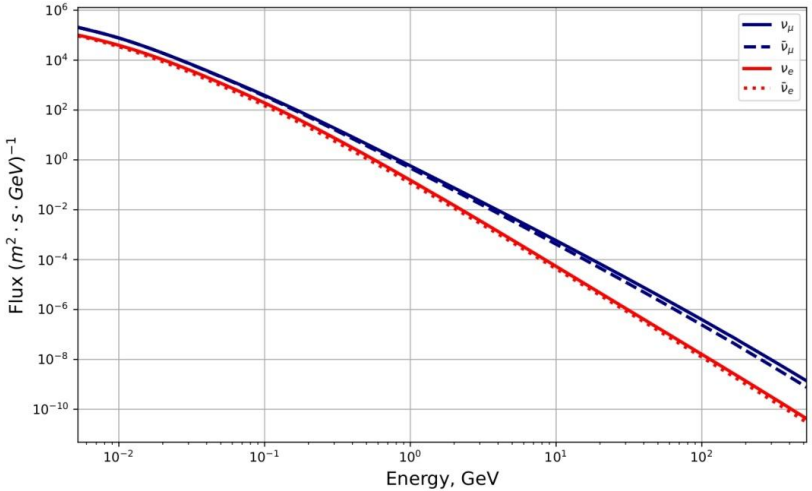
} Primary analysis of accelerator neutrinos

- Searching for sterile neutrinos and other exotic physics...



# Atmospheric Neutrinos

- This study will improve the **precision of oscillation parameter** measurements in NOvA
- Atmospheric neutrinos are a **background** for many additional physics topics, including:
  - Searches for dark matter particles
  - Studies of proton decay
  - Detection of the cosmic-ray Moon shadow

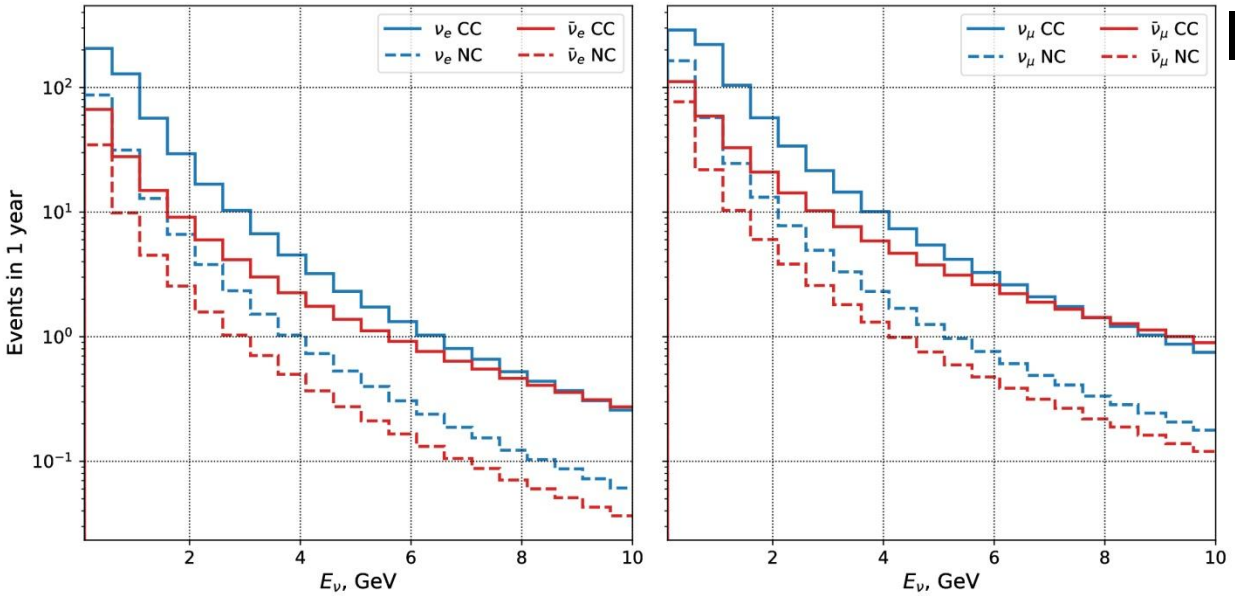



*Theoretical atmospheric neutrino flux [1] as a function of energy*

- This work will enable **stricter tests** of various hypotheses, including the possible existence of sterile neutrinos and non-standard interactions

*[1] M. Honda et al., Phys. Rev. D 92, 023004 (2015)*

# Expected Number of Interactions in the NOvA FD



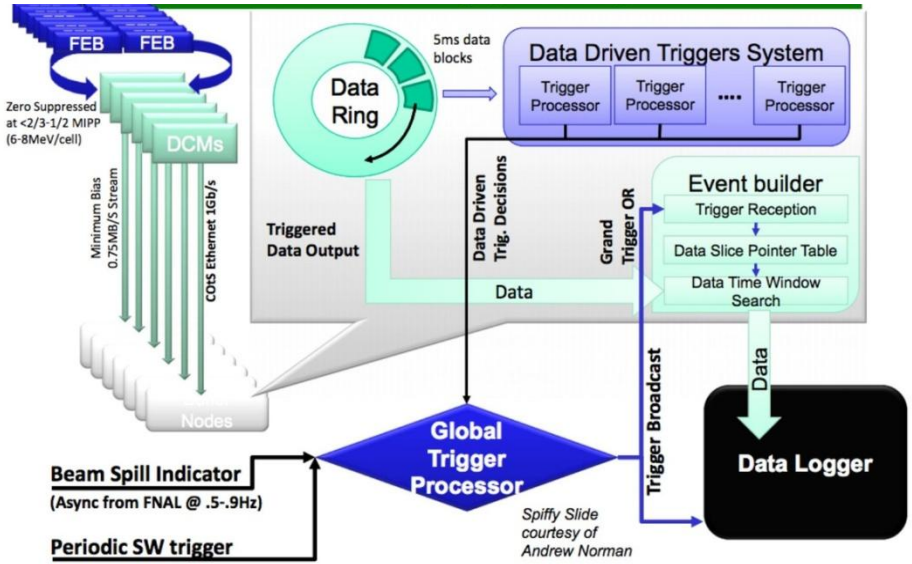

*Number of interactions in the NOvA far detector as a function of neutrino energy for $\nu_e$ (left) and $\nu_\mu$ (right) atmospheric neutrinos. Estimation based on atmospheric neutrino flux calculations [1]*

Events = flux * cross-section * $N_A$ * mass/Molar-mass * time

flux — neutrino flux
cross-section — cross-sections from GENIE
$N_A$ — Avogadro's number
mass — detector mass
Molar-mass — molar mass of FD NOvA substance
time — registration period (1 year)


*[1] Honda M., Sajjad Athar M., Kajita T., Kasahara K., Midorikawa S. At-mospheric neutrino flux calculation using the NRLMSISE-00 atmosphericmodel // Phys. Rev. D. — 2015. — V. 92, no. 2. — P. 023004.*

# Software Trigger System in NOvA




*Data Acquisition System in NOvA*

- Main analysis selects events that are time-coincident with the beam
- For other physics tasks, a software trigger system — **Data Driven Triggers (DDT)** — is used
- All data are written to a circular buffer and processed by algorithms that save the necessary events for offline analysis
- Existing triggers were evaluated for the analysis of atmospheric neutrinos using already collected data

- However, NOvA currently **do not have** a **dedicated trigger** for atmospheric $\nu$ selection

# Selection Efficiency for Signal and Background Data

**The signal dataset** (40k events, GENIE) was processed by all DDT algorithms

| Trigger ID* | N of events | Efficiency |
|---|---|---|
| UPMU | 7 | 0.07 % |
| CONTAINED | 6 | 0.06 % |
| NNBAR | 1145 | 11.45 % |

The overall efficiency: 11.6%

**UPMU**: upward-going muons from neutrinos
**CONTAINED**: upward-going muons from neutrinos (contained in detector)
**NNBAR**: neutron–antineutron oscillations

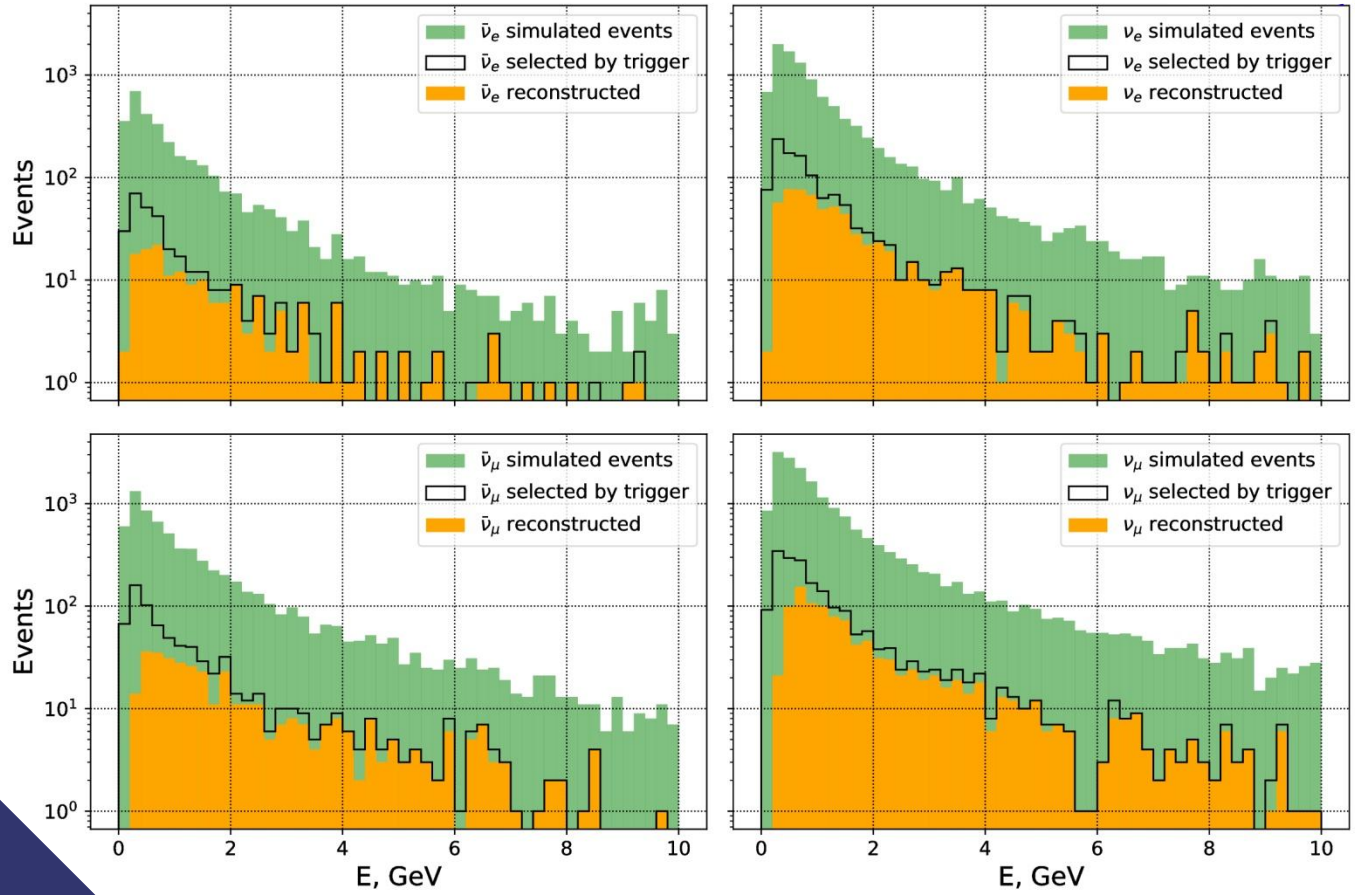
**trigger names for searching for different signatures*

**The background sample** (10k events of 550 μs each, CRY) was processed by all DDT

| Trigger ID* | N of events | Efficiency |
|---|---|---|
| UPMU | 108 | 1.08 % |
| FASTMONO | 31 | 0.31 % |
| H_MU | 28 | 0.28 % |
| NNBAR | 25 | 0.25 % |
| CONTAINED | 21 | 0.21 % |
| ENERGY | 12 | 0.12 % |
| SLOWMONO | 6 | 0.06 % |

The overall selection efficiency: 2.3%

# Expected Spectrum of AtmoNu Using Existing Data

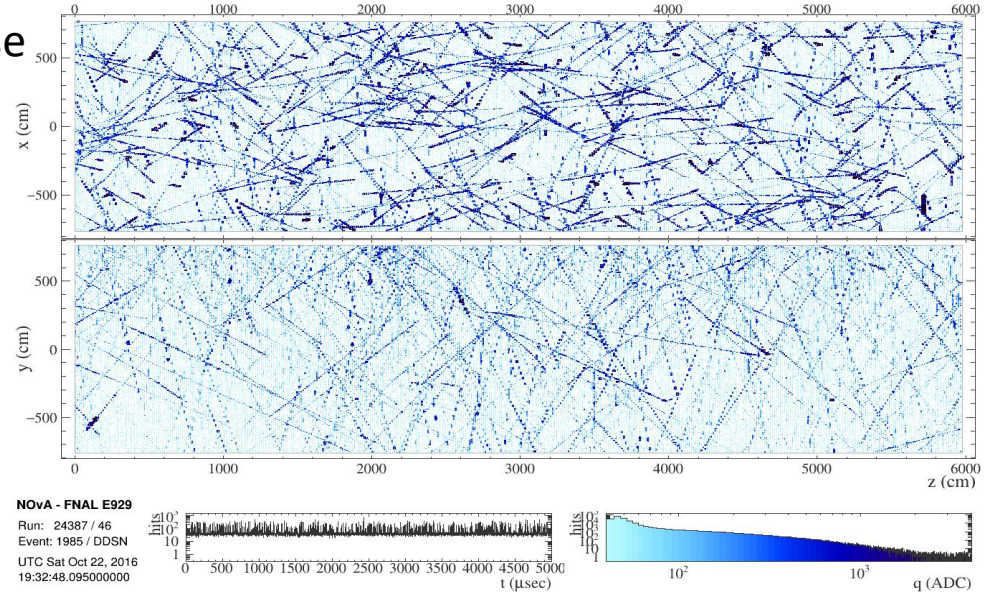



1. 40k events were simulated (9.2 years)
2. After selection by the "**NNBAR**" trigger ~ **11%** of events
3. After applying the standard reconstruction procedure to the "NNBAR" algorithm dataset ~ **6%**

(**~ 250 events per year**)

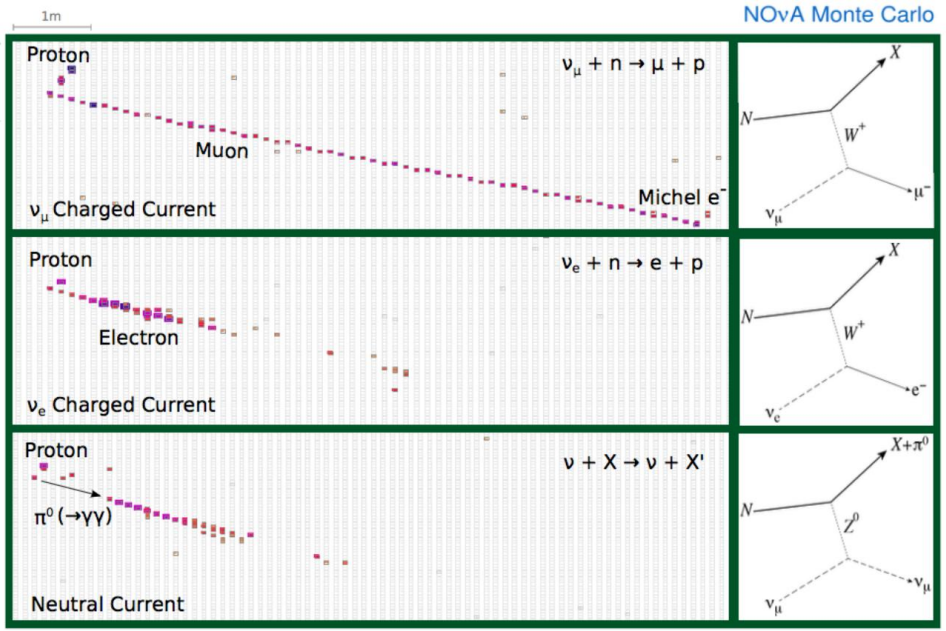
# Development of AtmoNu Selection Algorithms

- **Goal**: Develop a dedicated trigger to increase statistics and enable real data analysis
- The NOvA main data-taking period is planned to **conclude in 2027**
- **Main challenge**: Remove the secondary cosmic-ray background (~ 150k muons per second in FD)
- **Expected neutrino rate**: only 12 events per day




*Cosmic-ray background activity (per 550 μs)*

# Event Types in the Detector




*Example events from simulations of $\nu_e$ and $\nu_\mu$ interactions via CC and NC currents in the detector [2]*

**$\nu_\mu$ CC:**

- Long muon track
- $E_{event} = E_{\mu}^{track} + E_{hadronic}^{calor}$

**$\nu_e$ CC:**

- EM shower (lepton) + hadronic shower
- Final states with electron: nucleon / nucleon+π / hadron shower

**$\nu$ NC:**

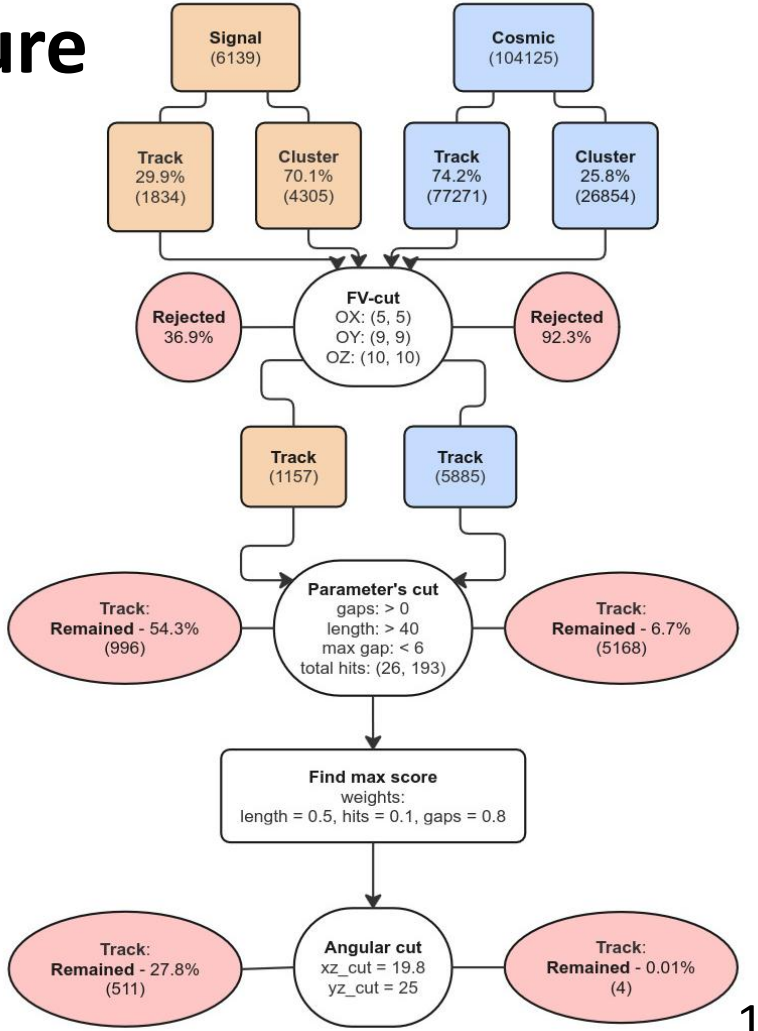
- Pions → hadronic or EM showers

[2] Catano-Mur Erika. Recent results from NOvA. 2022

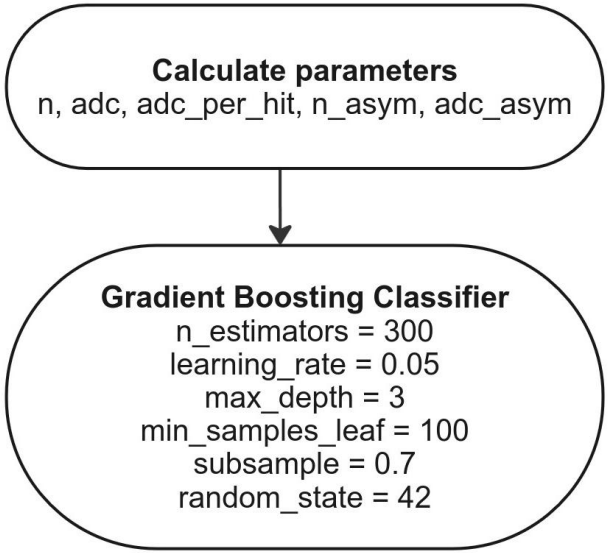
# Track Selection Procedure

- Track events are most often **muons**

- The procedure includes:
  - **Fiducial Volume (FV)** – interactions within the detector
  - Selection criteria on **parameters**:
  number of **gaps** in a track, track **length**, **maximum gap** between hits and **hits total number**
  - Selection **the best track** in an event using the **Score**:
    - Assigning weights to length, hits, and gaps
    - Selecting the maximum score
  - **Angular selection** – bg events are mostly vertical



# Non-Track Selection Procedure




$n$ – hits number
$adc$ – total signal amplitudes
$adc$ per $hits$ – average signal amplitudes per hit

$$n_{asym} = \frac{n_x - n_y}{n_x + n_y} \; ; \; adc_{asym} = \frac{adc_x - adc_y}{adc_x + adc_y}$$

- Examples of **non-track events** are electromagnetic showers, as well as neutral current (NC) events
- The selection procedure consists of:
  - **Fiducial Volume (FV)** selection – interactions only within the detector
  - **Computing parameters**: $n$, $adc$, $adc$ per $hits$, $n_{asym}$, $adc_{asym}$
  - Applying the **Gradient Boosting Classifier algorithm** [3] to the computed values

[3] J.H. Friedman, Ann. Statist., vol. 29, no. 5, pp. 1189–1232 (2001)

# Selection Efficiencies

The selection procedure was applied to the **signal simulation** (sg) and **background** (bg), and previously collected **experimental data** (SNEWS). On April 27th, it was run on the detector!

**AtmoNu Trigger Rates**:

**Track procedure**

**Signal simulation** – 27.8%
**Bg simulation** – 4 Hz
**SNEWS** data – 8 Hz
**Online** detector data ~ 15 Hz

**Non-track procedure**

**Sg** – 28.6%
**Bg** – 12 Hz
**SNEWS** – 36 Hz
**Online** ~ 32 Hz

Expected number of events by the end of 2026 after trigger and reconstruction procedure ~ **300 events**


*Rate monitor on the detector*

# Summary

Results:

- Procedure has been developed to search for atmonu interactions in NOvA data using the **NNBAR** trigger algorithm
- Expected number of atmonu interactions in the NOvA FD is ~ **250 events per year**
- Dedicated algorithm for selecting atmonu (both **track** and **non-track** events) has been developed and implemented within the NOvA software framework
- Expected number of atmonu events using this algorithm is ~ **300 events** for 8 months

Plans:

- Perform **post-selection** of trigger events
- Analyze the **existing NNBAR** experimental data using the proposed procedure
- Build an **energy spectrum**
- Apply the procedure to calculate **neutrino oscillation parameters**