Event filtering in the ICARUS T600 detector for the Short-Baseline Neutrino Experiment at Fermilab

NO1 Seminar

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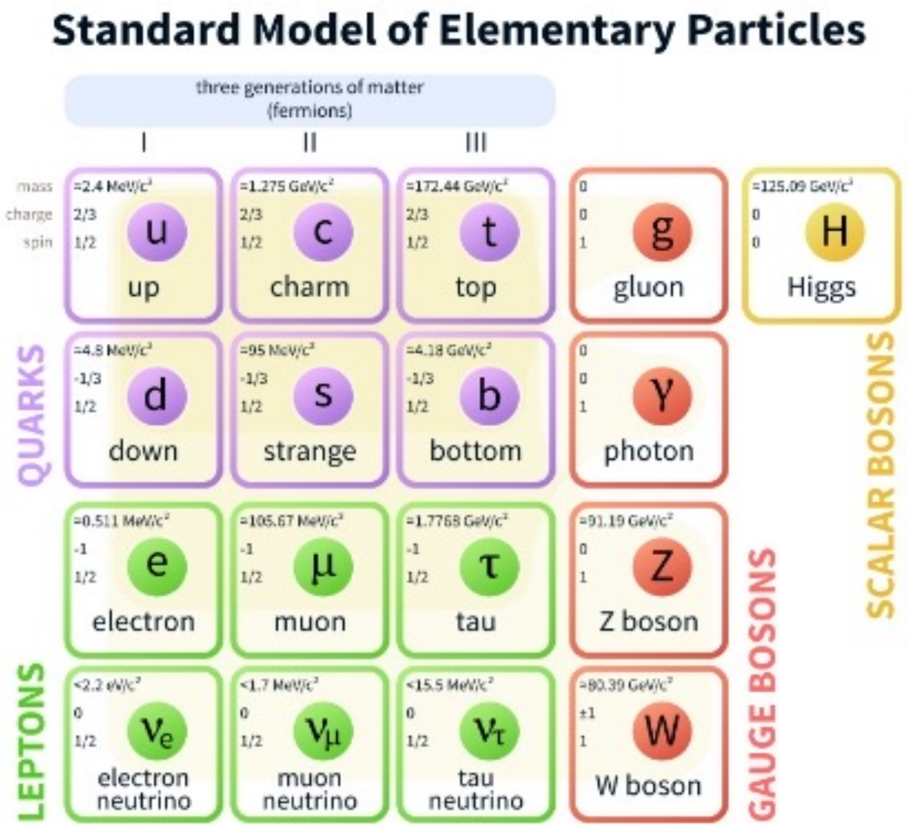
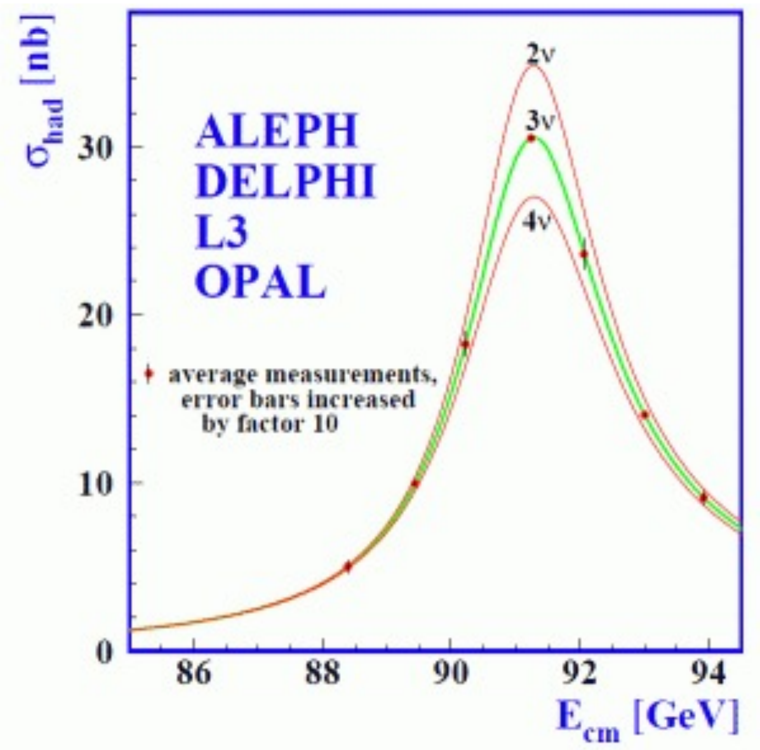
13.04.2021

Outline

1. Neurino oscillations and searches of sterile neutrinos
2. Short Baseline Neutrino Experiment at Fermilab
3. Liquid Argon Time Projection Chambers
4. Status of the SBN detectors
5. MicroBoone data taking status
6. ICARUS T600 detector
7. ICARUS detector subsystems and satus update
8. Event rates at the ICARUS detector
9. Event filtering in ICARUS using PMTs
10. Conclusions and Outlook

Few words about neutrinos





The SM assumption about zero mass of neutrinos in contradiction with the observations of neutrino oscillations in various experiments.

Number of neutrino flavours (light and coupling to the Z): 2.9840 $\pm$ 0.0082

2015 Nobel Prize in physics: Super-Kamiokande $(\nu_\mu \to \nu_\tau)$ and SNO $(\nu_e \to \nu_{\mu,\tau})$


Takaaki Kajita


Arthur B. McDonald

Oscillations – description for 3 flavour states and 3 neutrino mass states

- Oscillations for the three neutrino flavours are a well-established experimental fact.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix},$$

- But some experiments indicate the possibility of additional types of neutrino from beyond the SM.

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

Source: 10.1007/JHEP09(2020)178

Additional area of neutrino oscillations?

LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

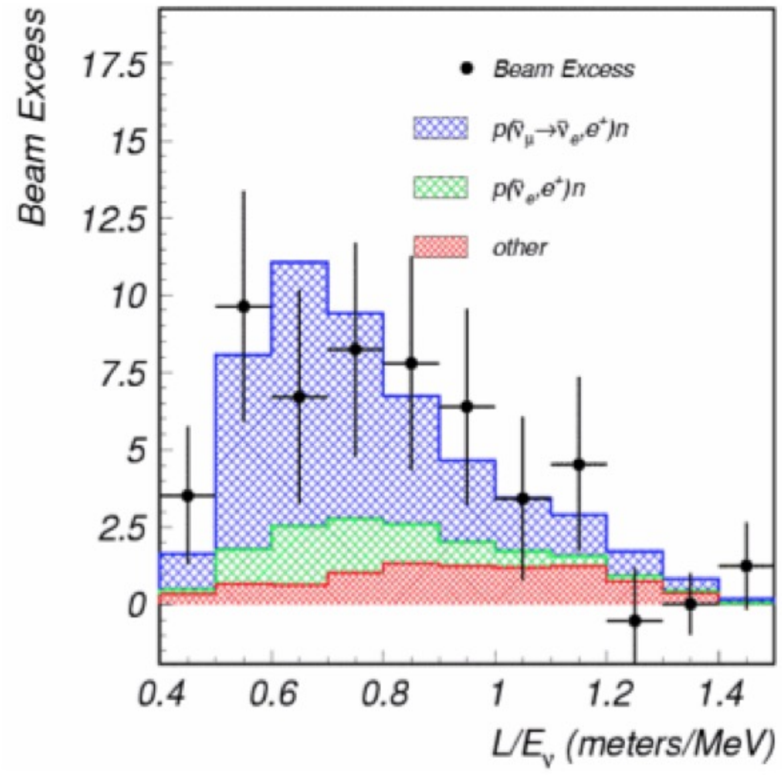
- Data taken in 1993 – 1998
- Measurement $\bar{\nu}_\mu$ of the decay: $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ from $\pi^+ \rightarrow \mu^+\nu_\mu$.
- Observed excess of $\bar{\nu}_e$ at 3.8σ.
- This leads to Δm^2 within the range from $0.2eV^2$ to $2eV^2$ for transitions $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ due to oscillations between active neutrinos and another kind of neutrino(s) called sterile neutrino(s).

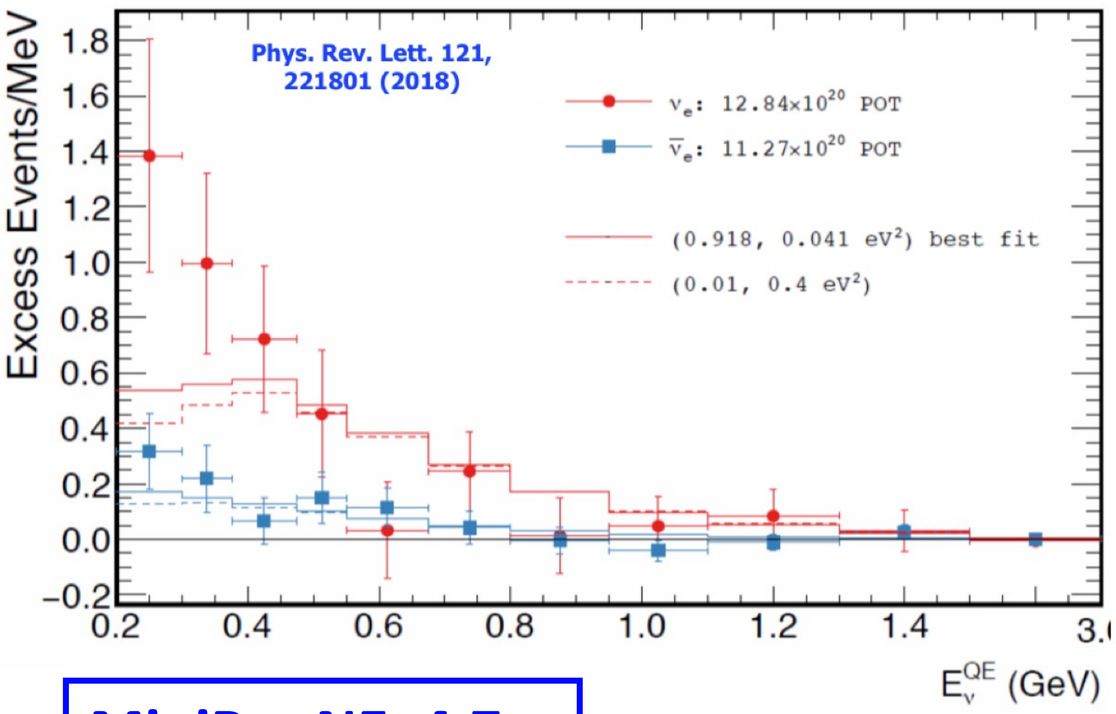
MiniBooNE: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

- Data taken in 2002-2017, altogether 11.27×10^{20} POT $\bar{\nu}_\mu$ beam and 12.84 $\times\, 10^{20}$ POT ν_μ beam.
- Best fit with a 2-flavour model for $\Delta m^2 = 0.041\ eV^2$ and $sin^2 2\theta = 0.918$.

Additional area of neutrino oscillations?

- The LSND and MiniBooNE experiments indicate that.





MiniBooNE: 4.7 σ
LSND: 3.8 σ
Both: 6.0 σ

Sterile neutrinos

Experiment	Type	Channel	Confidence level (σ)
LSND	DAR accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$	4.7
GALLEX/SAGE	Source: e^-	$\nu_e \to \nu_x$	2.9

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_s\rangle \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* & U_{e4}^* & \cdots \\ U_{\mu1}^* & U_{\mu2}^* & U_{\mu3}^* & U_{\mu4}^* & \cdots \\ U_{\tau1}^* & U_{\tau2}^* & U_{\tau3}^* & U_{\tau3}^* & \cdots \\ U_{s1}^* & U_{s2}^* & U_{s3}^* & U_{s4}^* & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ \vdots \end{pmatrix}$$

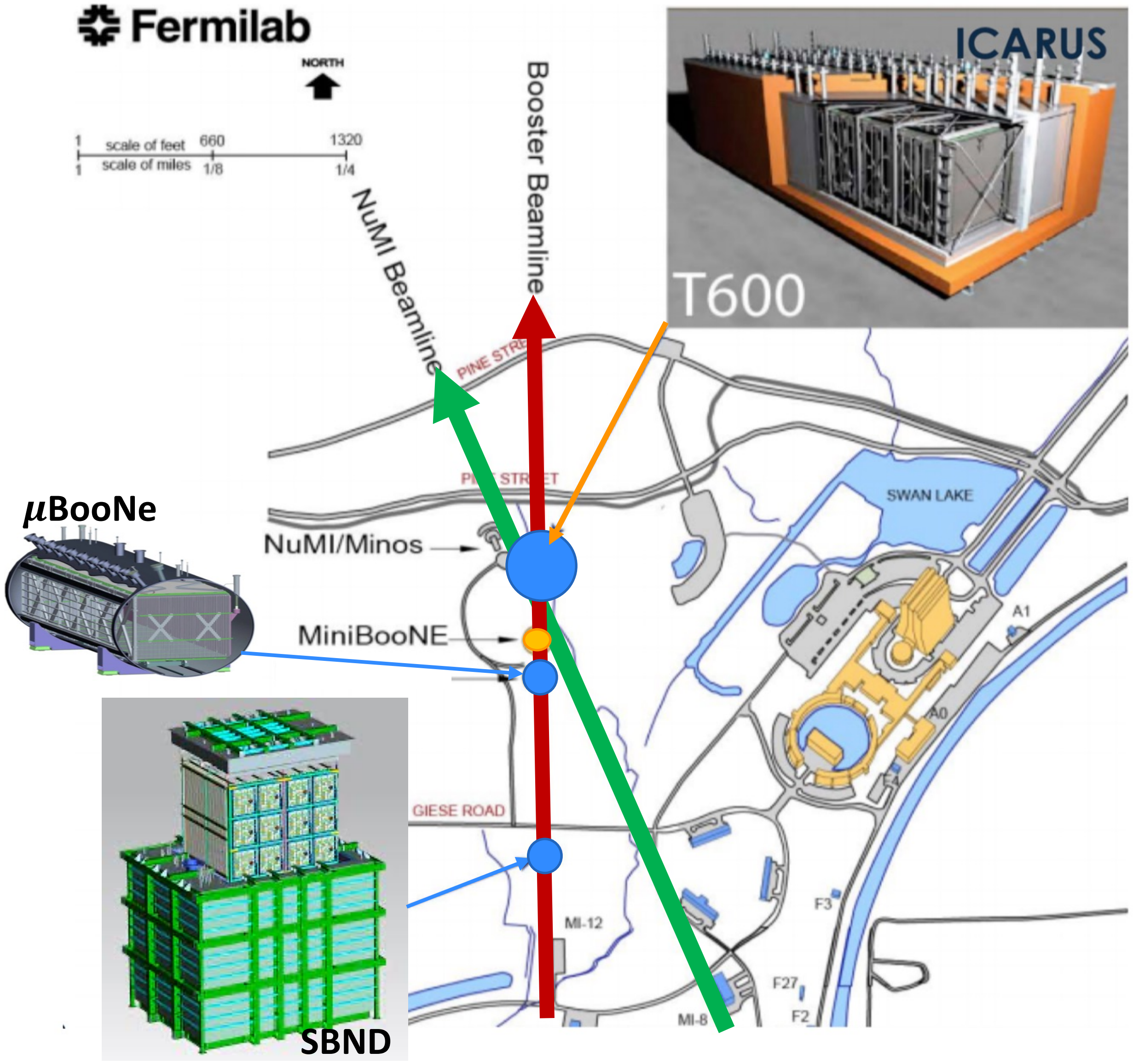
The mixing matrix for neutrinos can be extended with sterile neutrino(s).

ν_s can be detected by observing oscillations with active neutrinos.

Short-Baseline Neutrino Experiment at Fermilab

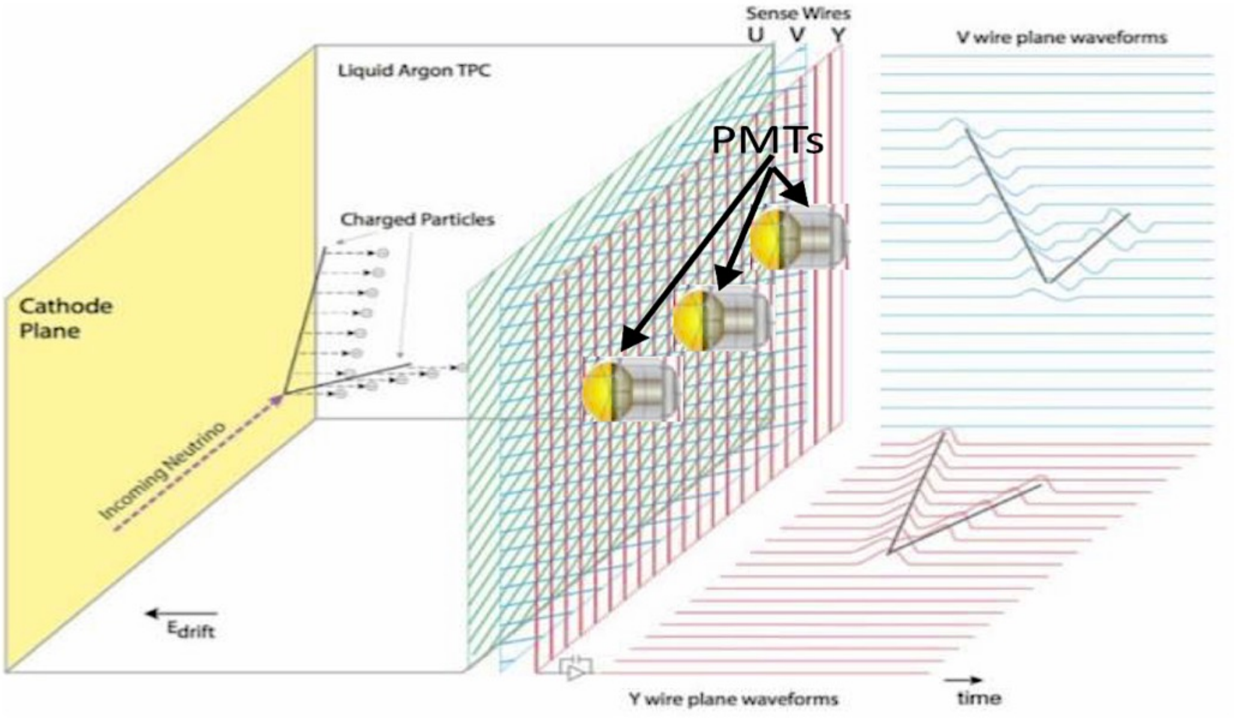
Purpose: final check of LSND and MiniBooNE observations.

- Short Baseline Neutrino experiment at Fermilab makes use of the well established Fermilab Booster Neutrino Beamline (BNB).
- Three liquid-argon time projection chambers located on the BNB beam.
- **All the three detectors are on the surface and thus are exposed to high cosmic background.**



Liquid Argon TPC detection technique

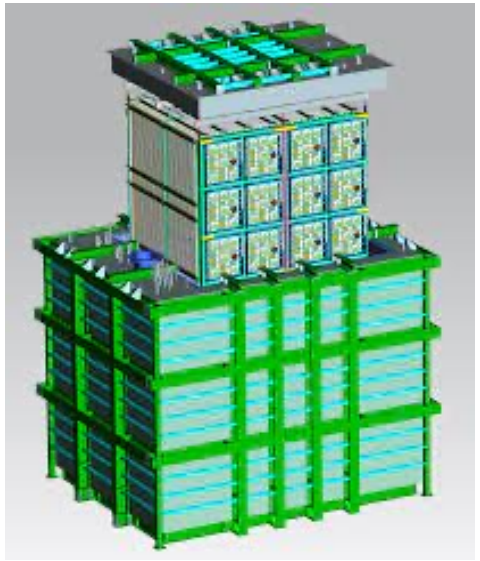
- **Possibility of light (fast signal) and charge (slow signal) detection** to obtain information on neutrino interaction time and 3D reconstruction of charged particles' tracks.
- **High spatial and energetic resolution,** which is required for studying details of the final states in neutrino interactions.
- **Possibility of building huge detectors** to compensate for very small cross-sections of neutrino interactions with matter



Detectors using the liquid-argon time projection technique: ICARUS, ArgoNeut, MicroBooNE, SBND, ProtoDUNE, DUNE.

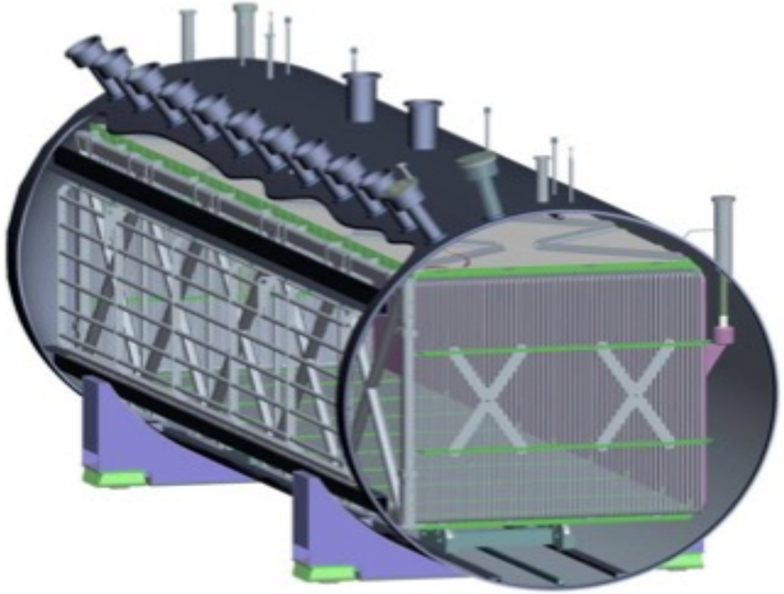
SBN Liquid Argon detectors

SBND



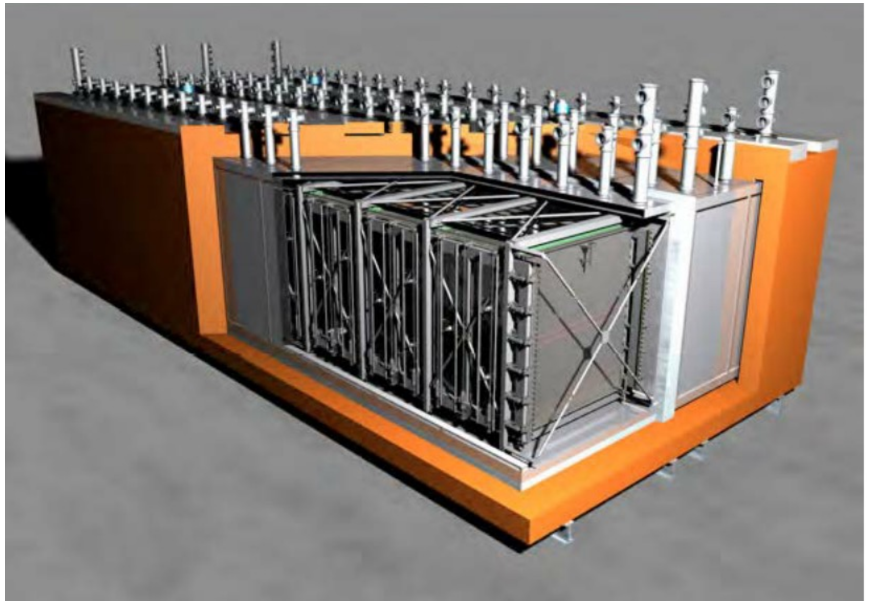
- 110 m from ν production
- 112 ton active volume
- 2×2.0 m drift length at 500 V/cm
- Cold analog and digital electronics
- 128 8” PMTs and scint. bars

μBooNE



- 470 m from ν production
- 85 ton active volume
- 2.56 m drift length at 500 V/cm
- Cold analog/warm digital electronics
- 32 8” PMTs and scint. nars

ICARUS



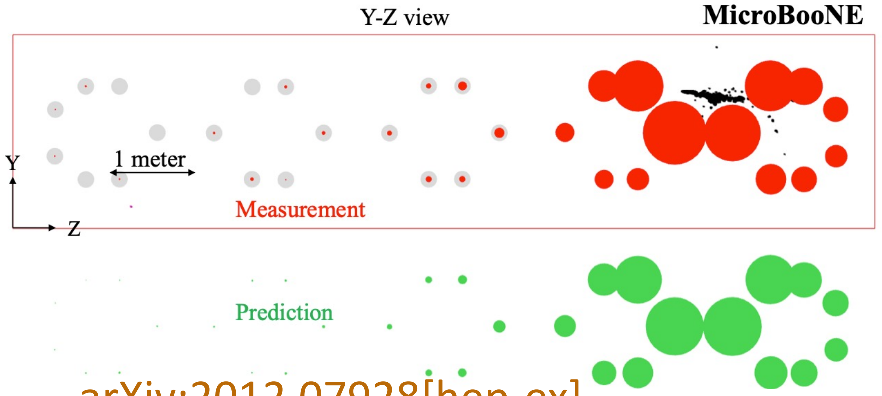
- 600 m from ν production
- 476 ton active volume
- 4×1.5 m drift length
- 75 kV HV
- 0.95 ms drift time at 500 V/cm
- Warm analog and digital electronics
- 360 8” PMTs and scint. nars

Status of the SBN detectors

- **SBND:**
  - The detector construction is well on its way, all the components ready for assembly and installation at Fermilab, the detector commissioning is planned for 2022.
- **μBooNE:**
  - First neutrino interaction observed in 2015.
  - Cosmic Ray Tagger (CRT) helps rejecting background since 2018.
  - Leading the way in mastering the challenging, but powerful LArTPC detector technology through the development of novel reconstruction and data analysis techniques.
  - Paving the way for the SBN program.
- **ICARUS:**
  - After an extensive refurbishing, ICARUS installation at FNAL in the SBN far site has been completed in 2018.
  - Cooling down, filling and cryogenic commissioning was completed in May 2020.
  - Detector filled with liquid argon and in stable operations at nominal drift field 500 V/cm since August 27th 2020.
  - **Observation of first neutrino interactions!**

μBooNE data taking status

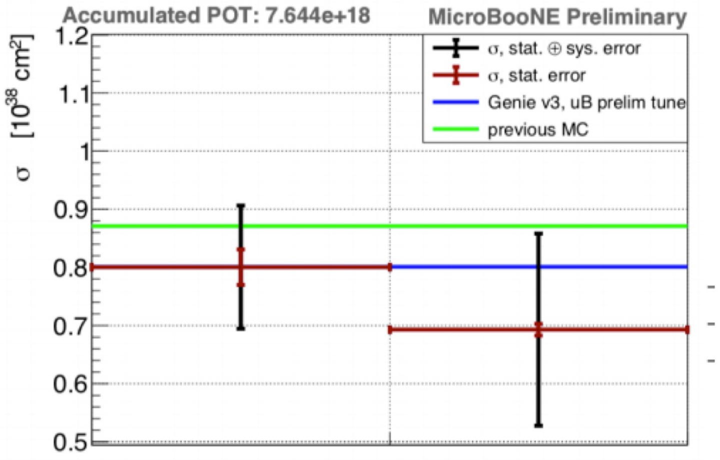
- Better understanding of LArTPC, energy reconstruction and improvements of the simulation models.
  - Improved signal processing.
  - New methods for TPC/PMT matching.
  - Cosmic rejection.
  - Data driven based detector uncertainties.



arXiv:2012.07928[hep-ex]

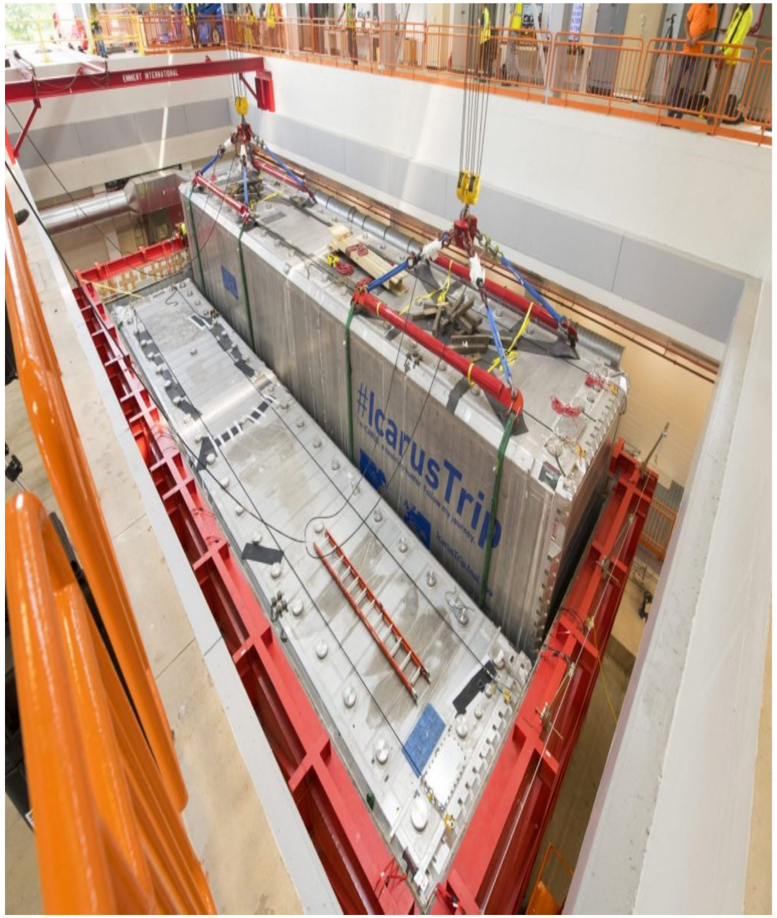
- Series of cross section measurements
  - Cross section measurements on Argon are vital for SBN and DUNE.
  - Inclusive results stand in reasonable agreement with various event generator predictions, except that for very forward going leptons Exclusive results show differences at specific regions of phase-s
  - Initial studies show for the first time a good agreement between data on Argon and a tune based on Carbon!

Improved systematics CCν_μ inclusive:
Phys. Rev. Lett. **123**, 131801, MICROBOONE-NOTE-1069-PUB

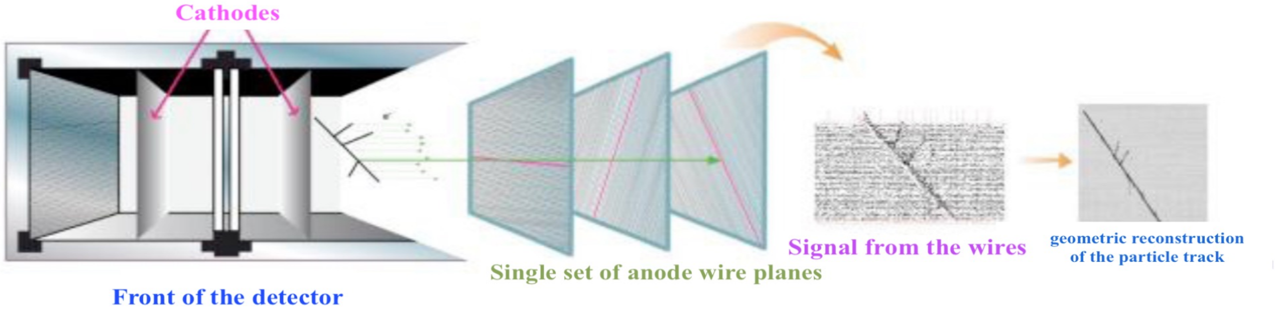


Current measurement Previously published measurement

ICARUS T600 detector



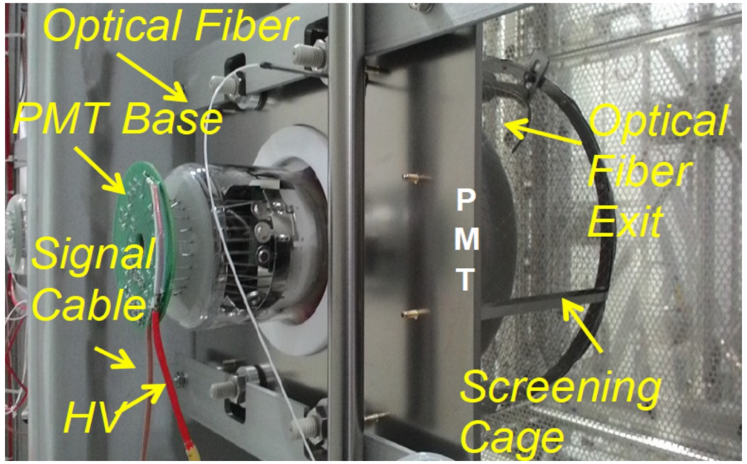
- Two identical modules adjacent to each other
- Dimensions of one module: 3.6 m × 3.9 m × 19.9 m
- Each module contains two time projection chambers which have a common cathode.
- HV: 75 kV
- Maximum electron drift length: 1.5 m
- Maximum electron drift time: ~1 ms (500 V/cm)

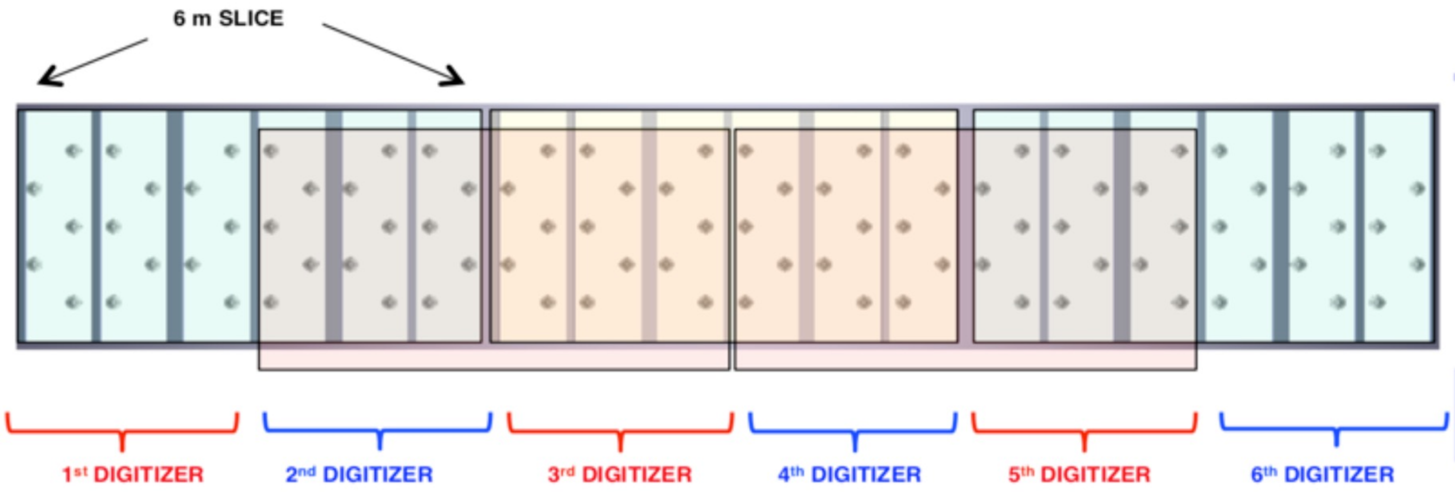


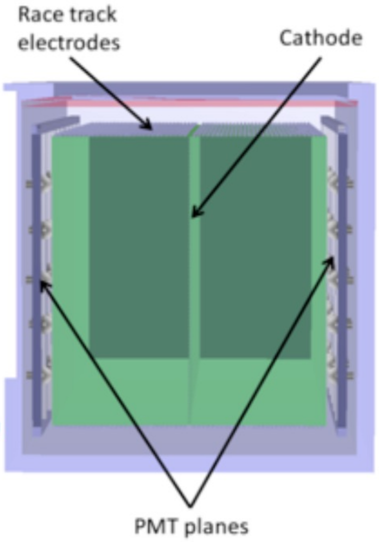
The PMT light collection system

The ICARUS PMT system is dedicated to perform three tasks:

- the identification of the time of occurrence (t_0) of each interaction,
- the generation of a light-based trigger signal,
- the initial recognition of event topologies for the fast event selection.



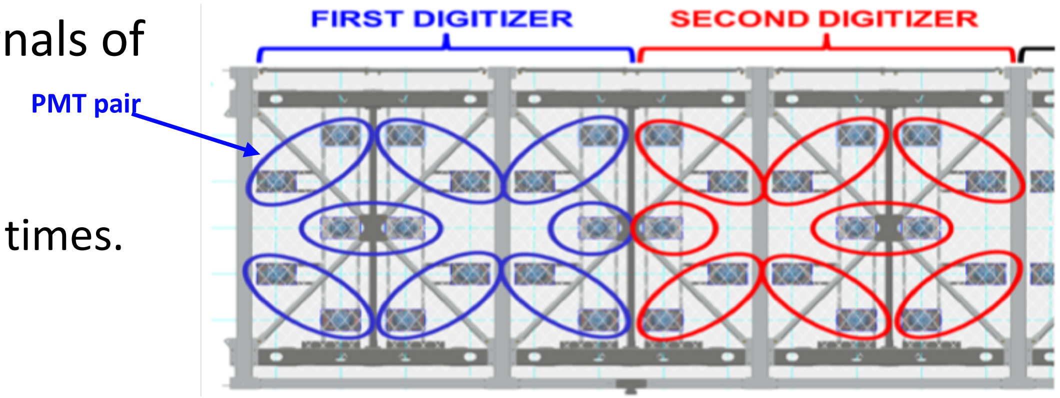


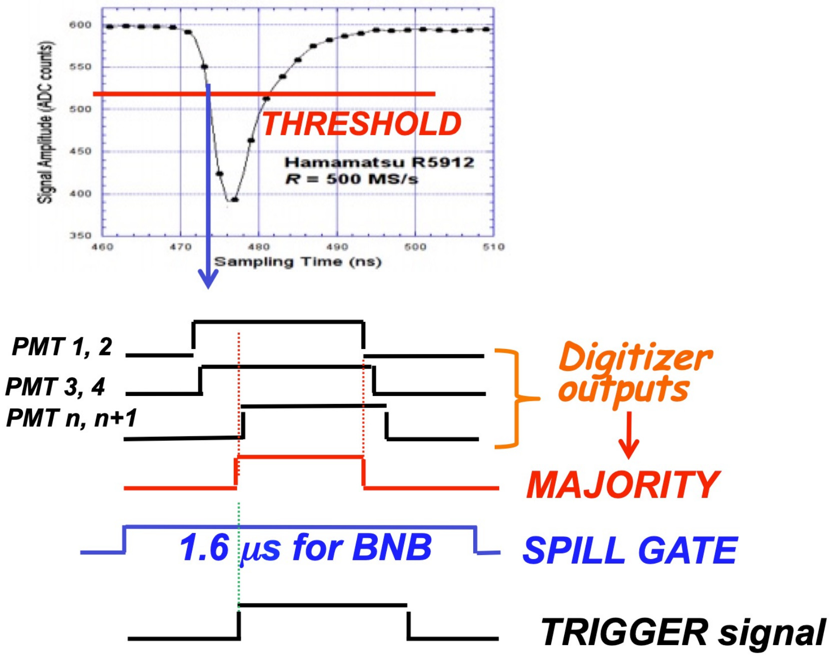


- PMT data taking is proceeding.
- A preliminary calibration is ongoing.

ICARUS trigger system

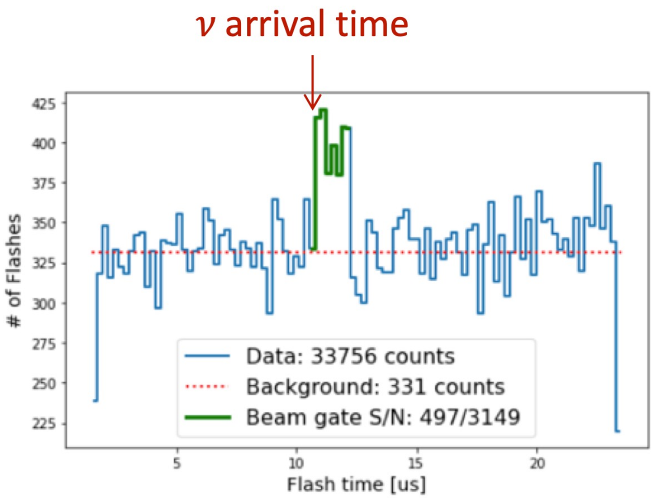
- The trigger hardware takes the combined discriminated signals of paired PMTs.
- The combination is done using either AND or OR logic:
  - AND - both PMTs have signals above threshold at overlapping times.
  - OR - at least one PMT has signal above threshold.





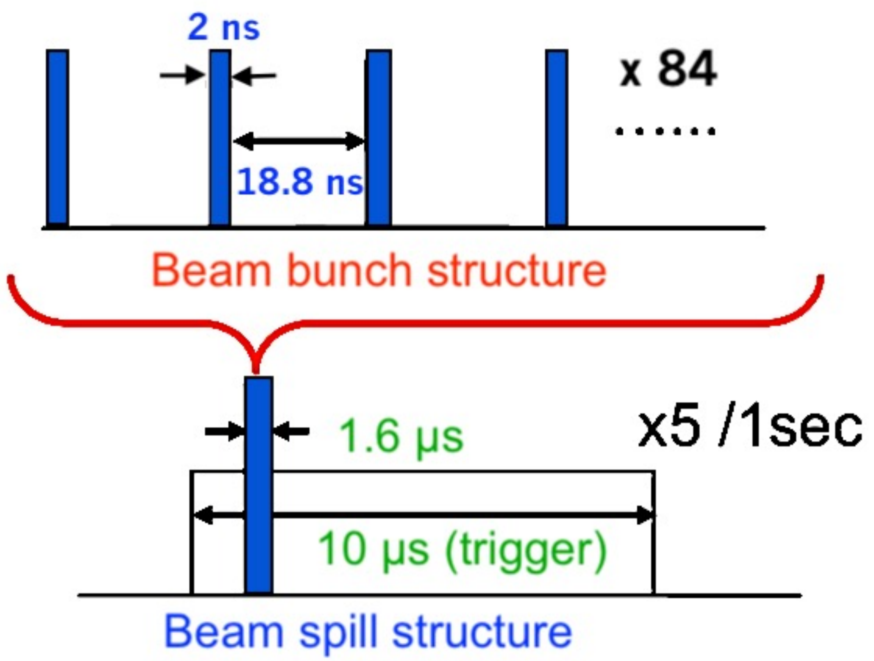
The commissioning of the Trigger system is proceeding in parallel to the PMT signals equalization and timing calibration.

Excess of PMT light flashes over the cosmic background rate at the beam expected time.



ICARUS event rates

1. BNB: 5×10^{12} POT/spill extracted in $\sim1.6\ \mu s$, 5 Hz repetition rate
   - **1 in-spill physical event over 35 spills (~ 0.15 Hz) expected inside ICARUS (E >100 MeV).**



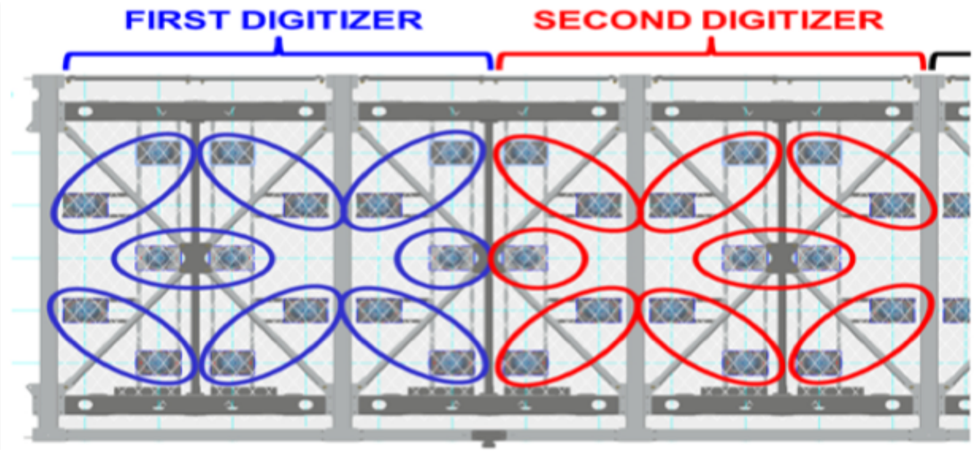
2. Within the BNB spill window we expect over three times more cosmic ray backgrounds than neutrino interactions.
3. NuMI: 6×10^{13} POT/spill extracted in $\sim9.5\ \mu s$, 0.75 Hz repetition rate
   - **1 in-spill physical event over ~ 5 spills (~ 0.17 Hz) expected inside ICARUS.**

Mitigation of the cosmic background in the ICARUS

- By a twofold strategy which includes:
  - 3 m concrete overburden.
  - realization of ~4 π Cosmic Ray Tagger detector encapsulating the TPCs.
- CRT surrounds the cryostat with two layers of plastic scintillators (~1000 m^2) .
- However, software reduction of the background is also needed, especially now due to the delays in installation of the top CRT and concrete overburden installation.

Event filtering in ICARUS using PMTs

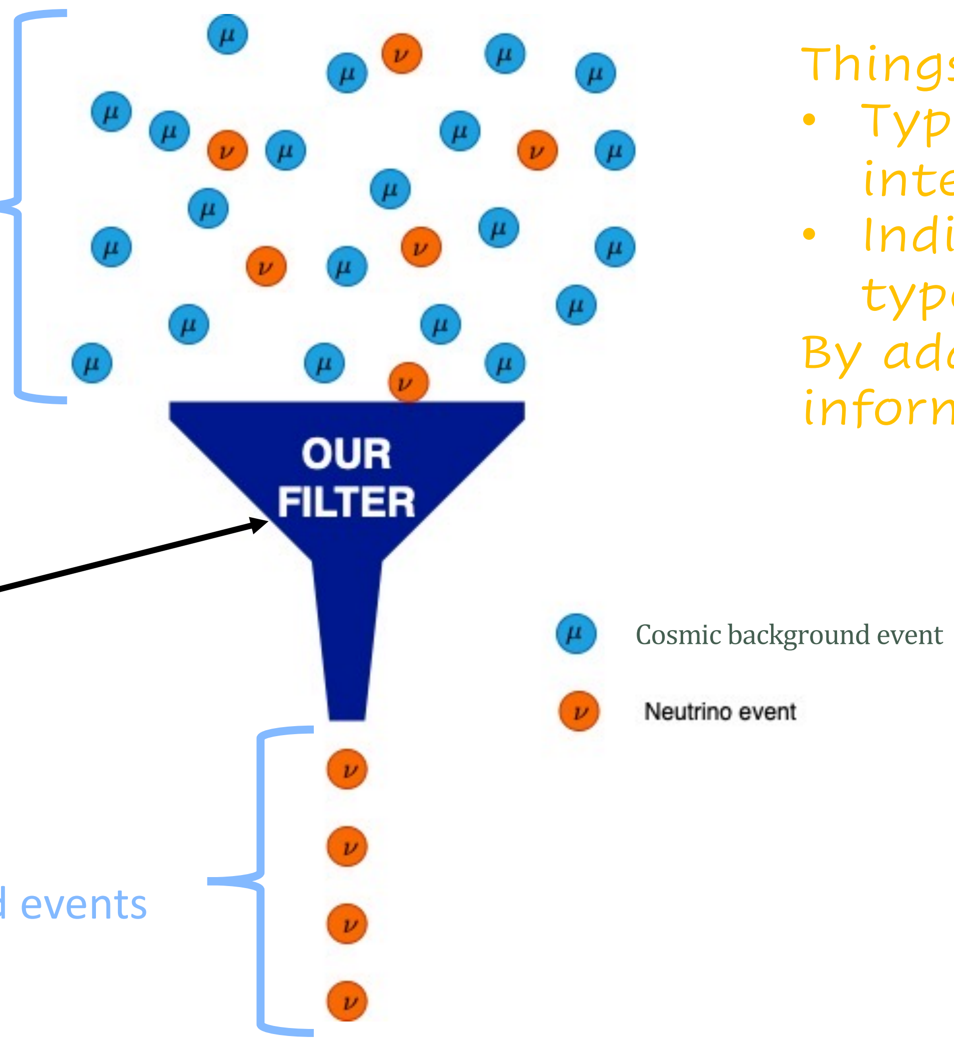
Goal: Reduce the cosmic background in the beam trigger window using the information available from the PMTs



1. Following the ICARUS trigger, PMT signals are considered per pair of PMTs using AND/OR logic patterns.
2. Paired PMT signals are then converted into 3D images using:
   - the 3D position of each pair as the point halfway between them
   - the number of times each pair surpassed the threshold in the trigger
   - the first opening time of the trigger gate after applying the beam gate coincidence
3. The 3D images are used to train the convolutional neural network (CNN) to separate cosmic background events from neutrino interactions.

How does it work?

Our input: events converted into 3D images using paired PMT signals



ML algorithms

Output: classified events

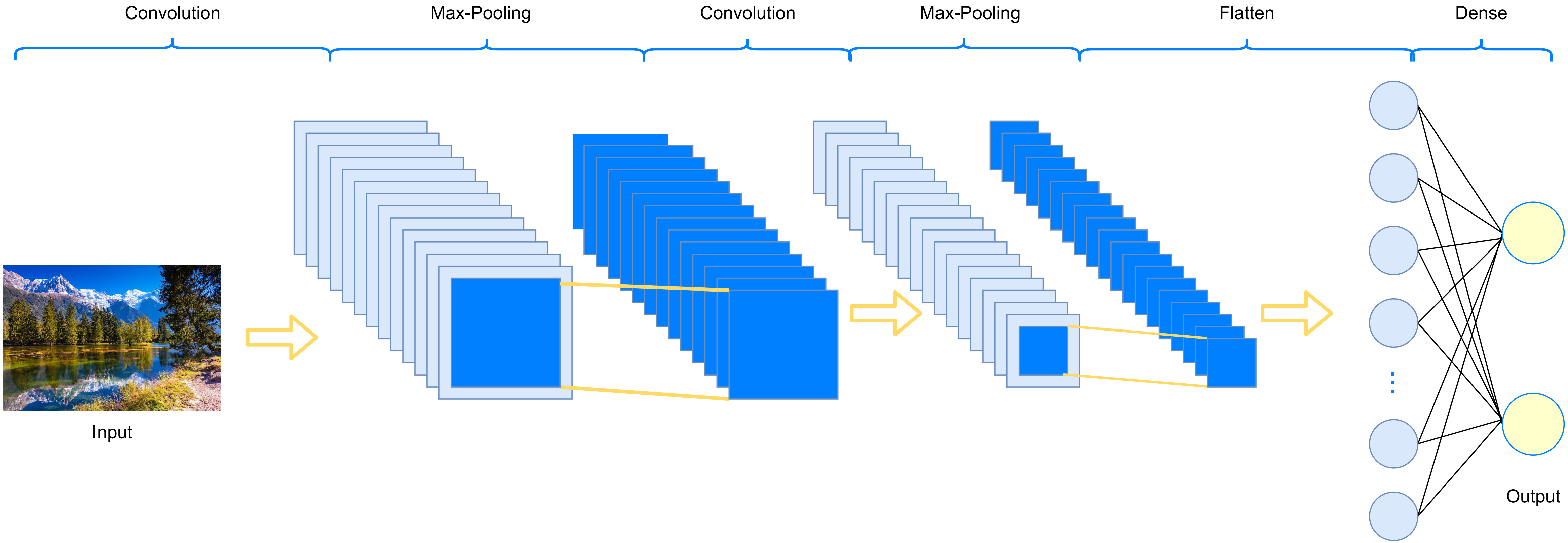
Things we could classify:

- Type of neutrino that interacted
- Individual particle types

By adding the TPC information to our input

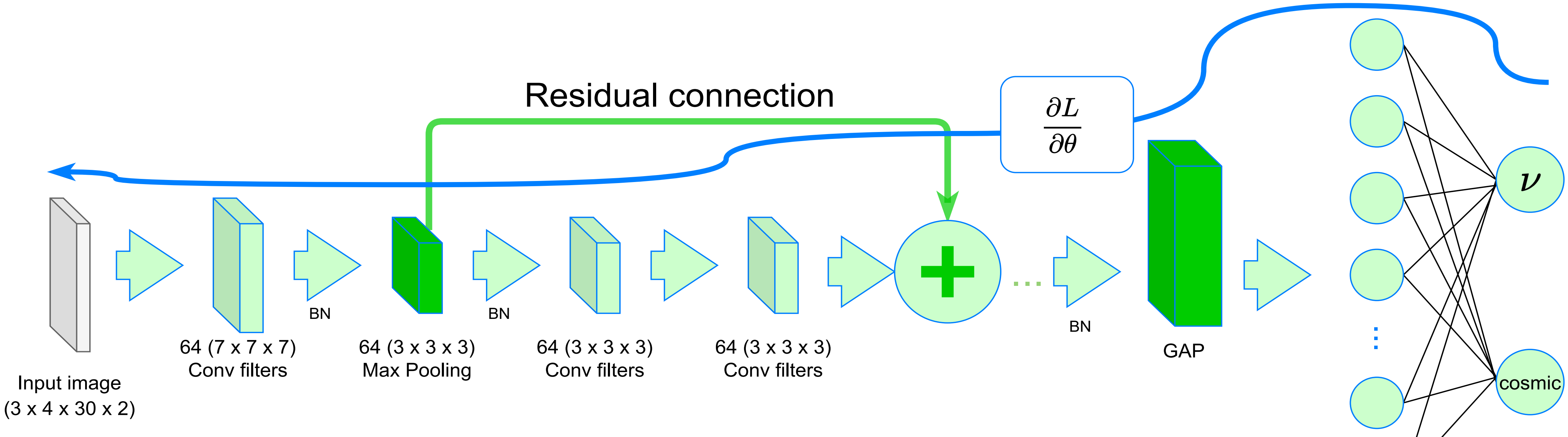
Convolutional Neural Network

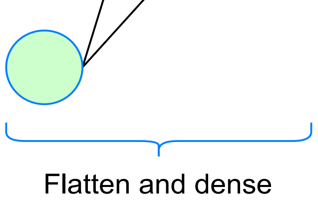
Goal: to extract features from the images that allow to classify them in some way

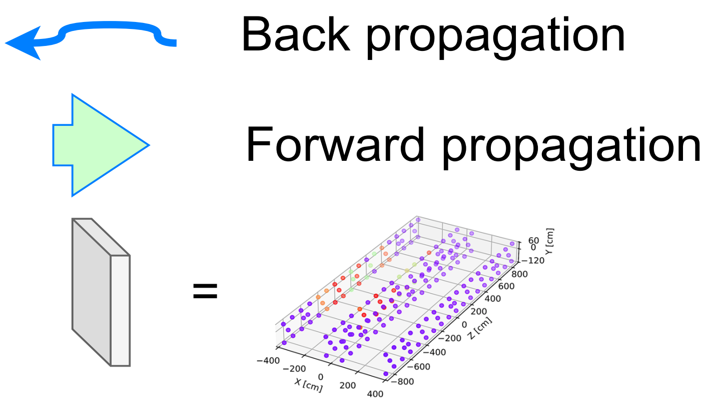


One huge advantage of using CNNs: no need to do a lot of pre-processing on images.

Our network architecture



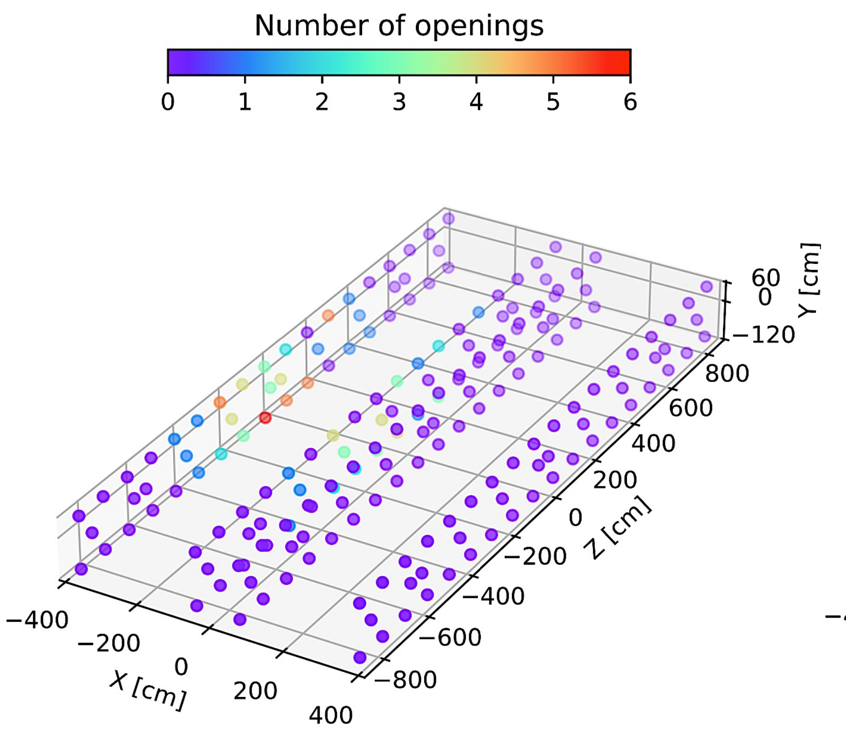




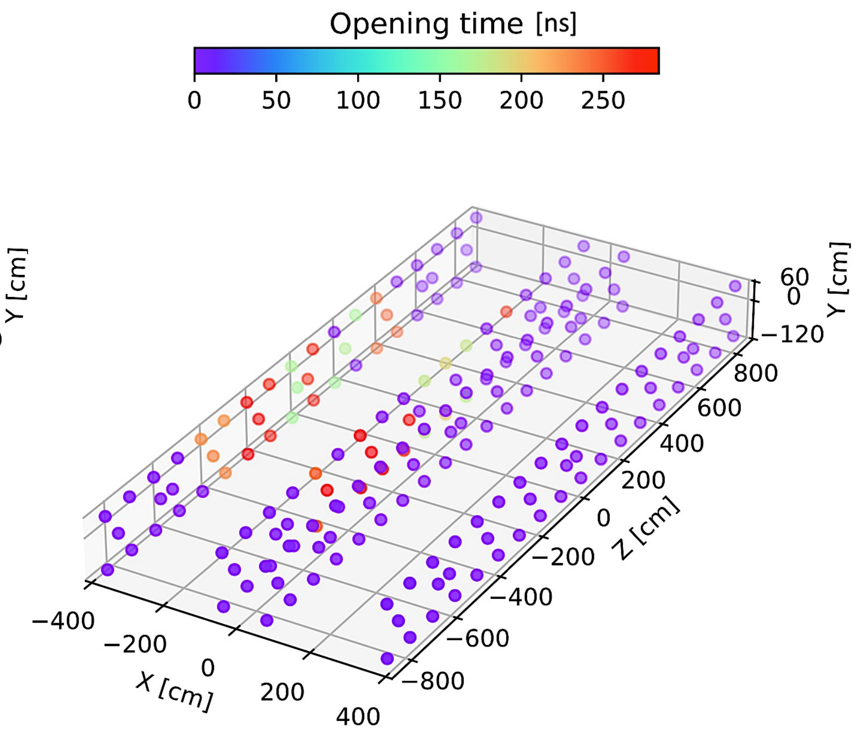
- Architecture: 3D ResNet
- Parameters: 33,185,473

Visualisation of the images used to train our convolutional neural network

The images represent the whole ICARUS detector volume with light detection system, where each circle corresponds to one PMT pair following the trigger pairing scheme.



runNo: 4386, subRunNo: 1,
eventNo: 2655, prediction: 0.32



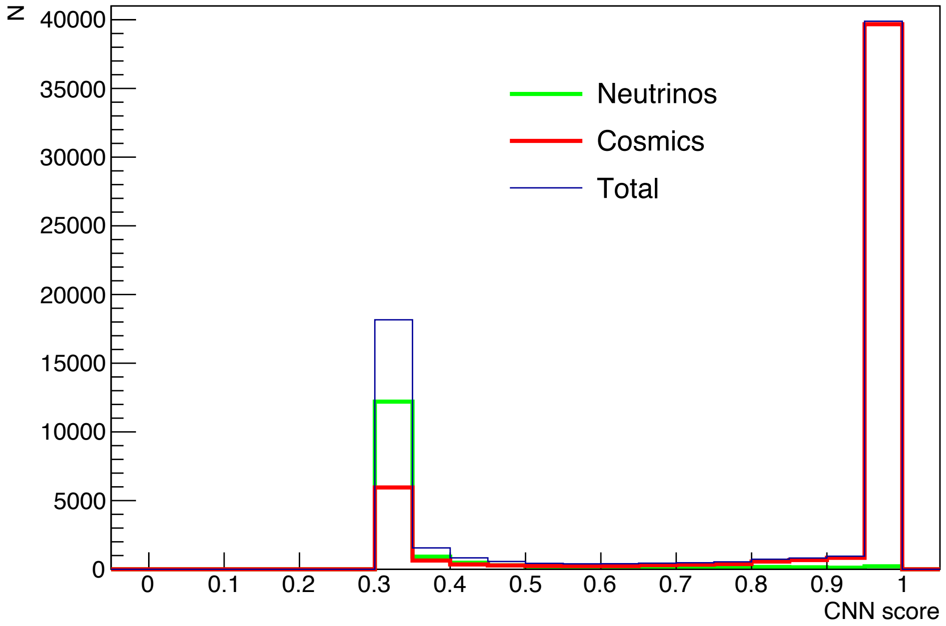
runNo: 4386, subRunNo: 1,
eventNo: 2655, prediction: 0.32

CNN-based event filtering in ICARUS using PMTs

- In the BNB trigger window the cosmic background is reduced from 77% to 34% whilst the total neutrino interaction selection efficiency is 91% (the efficiency for CC_{incl} = 96%).
- Many of the rejected neutrino interactions are NCQE events which leave only a recoil nucleon(s) inside the detector.
- Further separation of the relatively small remaining background can be done in higher level analyses.

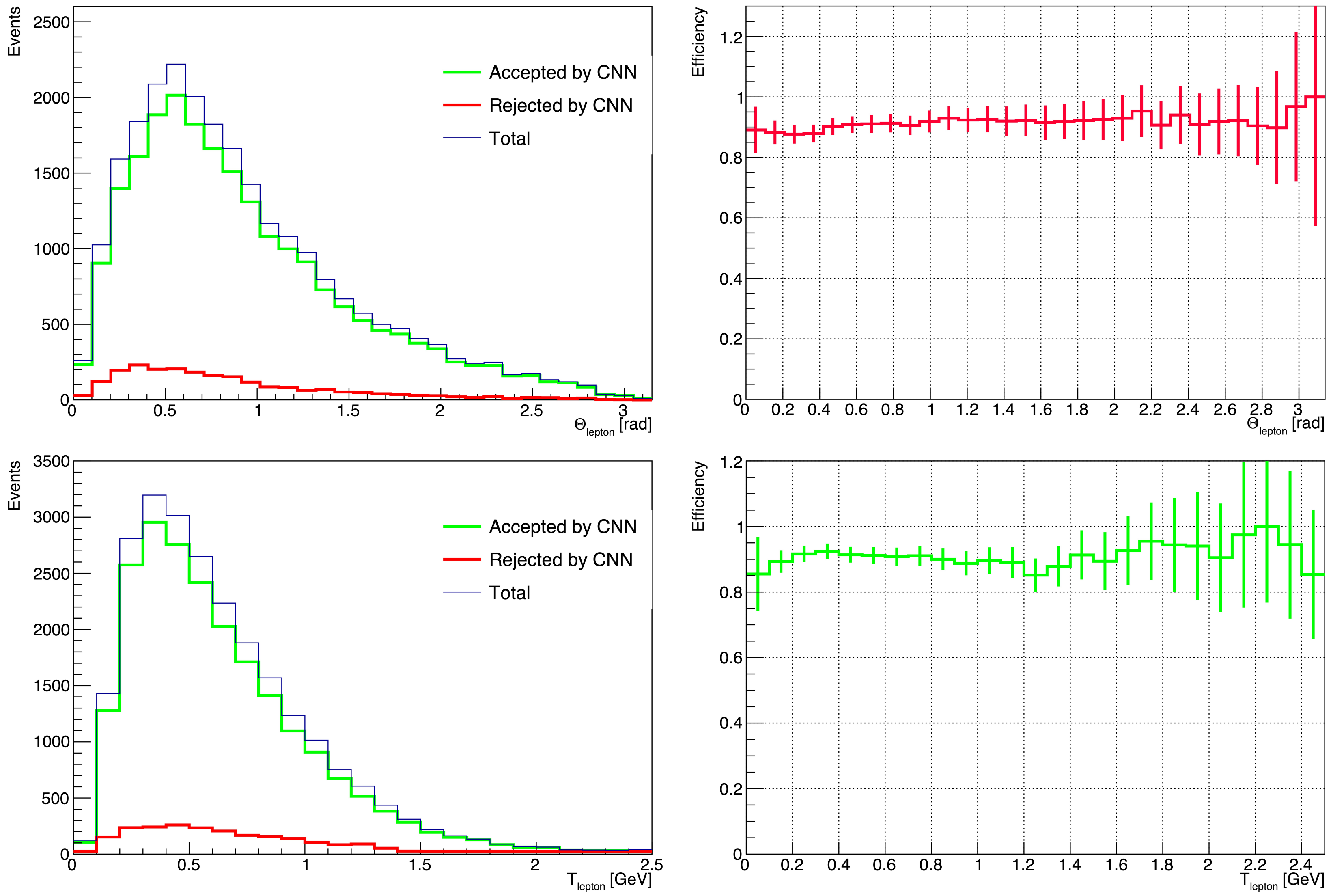
$$\mathcal{E} = \frac{\#\nu_{\text{predicted\_as\_}\nu}}{\#\nu \text{ in test sample}} = 91\%$$

$$\mathcal{P} = \frac{\#\nu_{\text{predicted\_as\_}\nu}}{\#\text{events}_{\text{predicted\_as\_}\nu} \text{ in test sample}} = 66\%$$



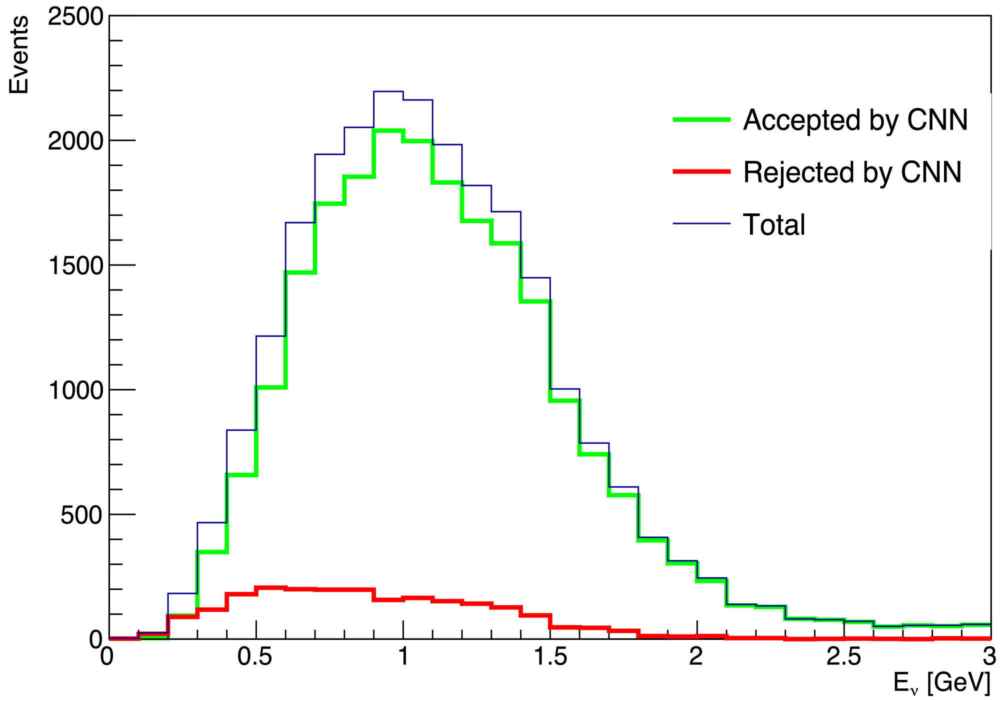
CNN score = the probability of an event having a particular label (ν or cosmic background event)

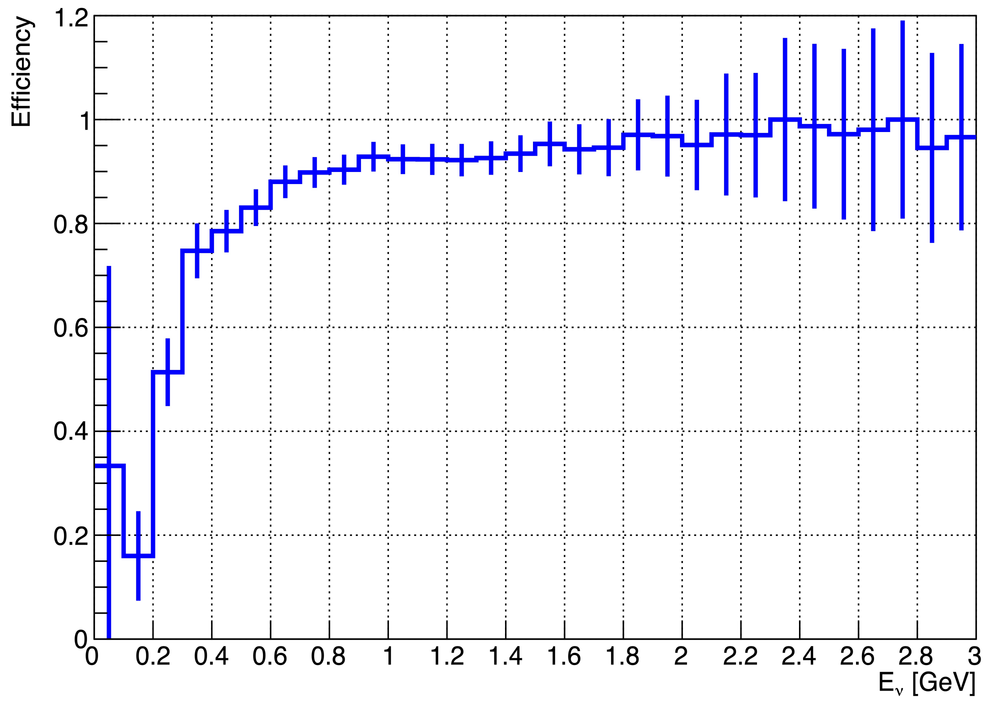
CNN performance w.r.t the outgoing lepton kinematic variables



- High and flat neutrino selection efficiency with respect to both: the outgoing lepton angle end energy.
- The classification is almost not biased by neither the outgoing lepton angle nor by the outgoing lepton energy.

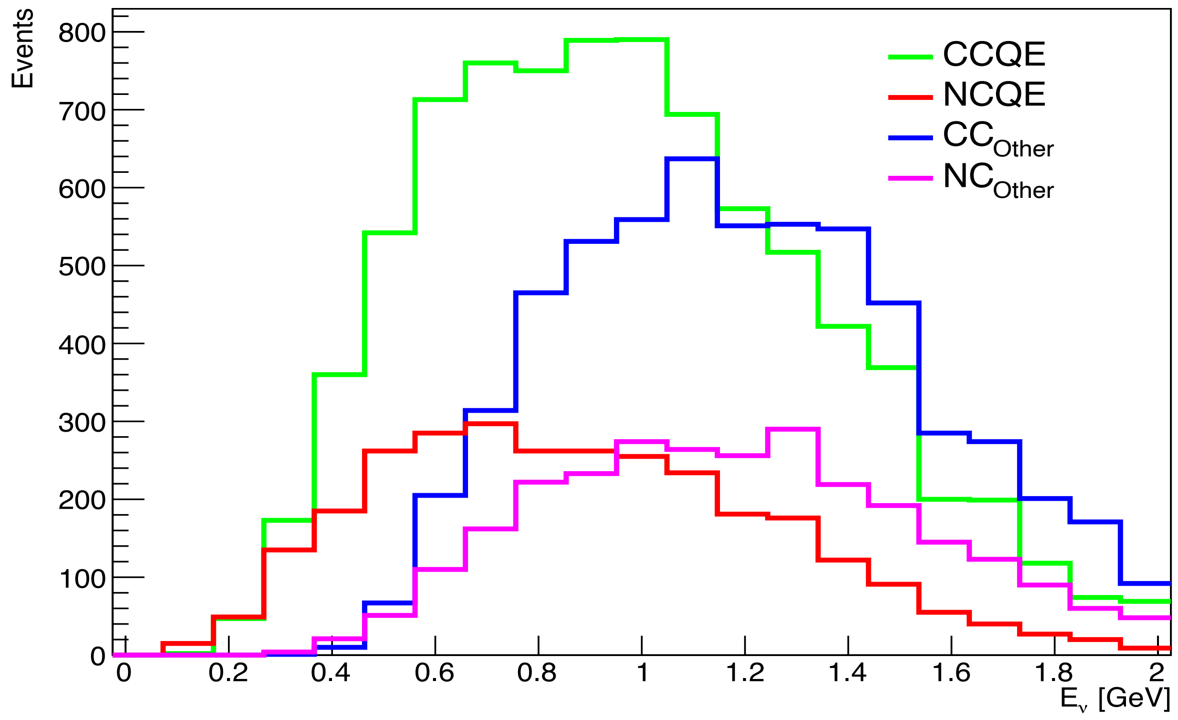
CNN performance w.r.t neutrino energy

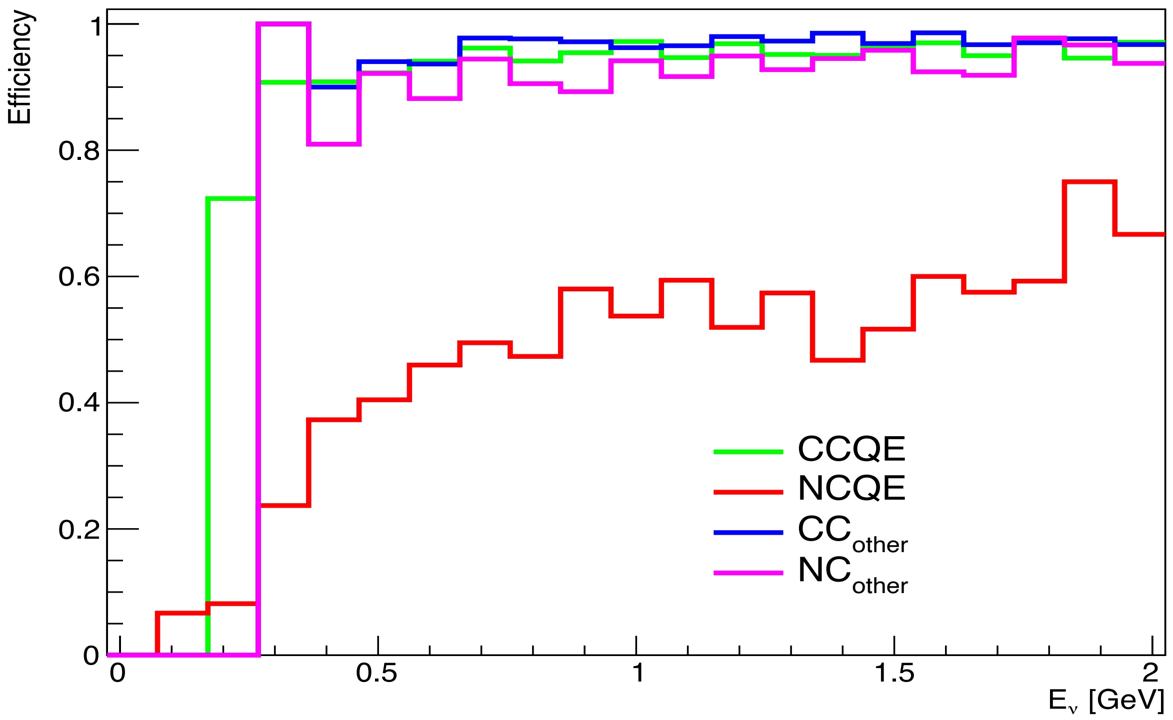




- There is a larger rejection of events at low neutrino energy, which stems from a small efficiency for NCQE interactions (which can leave only a recoil nucleon(s) inside the ICARUS detector).

Closer look to neutrino selection efficiency





- The efficiencies for the CCQE, CC_{other} and NC_{other} are above 90% starting form energy above 0.3 GeV while the efficiency for NCQE events are much lower.

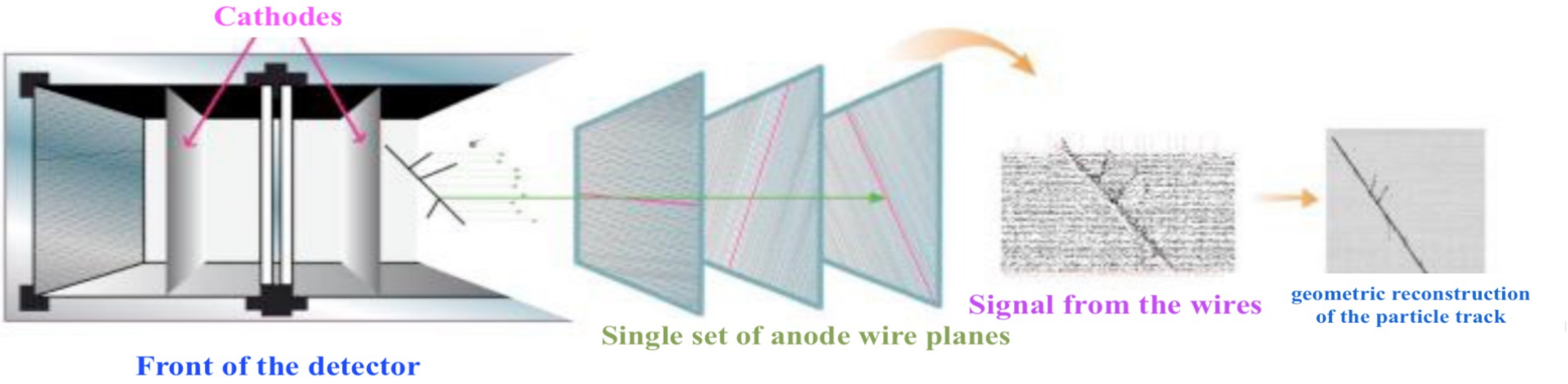
Conclusions and Outlook

1. The SBN experiment should finally clarify the anomalies observed by LSND and MiniBooNE.
2. The ICARUS trigger system is extremely important for the detector operation on a surface with a large cosmic muon background.
3. Even within the short BNB neutrino production window, cosmic events outnumber neutrino interactions by more than three to one.
4. A machine learning based event filter to separate neutrino interactions from cosmic backgrounds has been developed using the PMT system timing information only.
5. Current ICARUS simulation shows that the CNN-based event filter successfully rejects the vast majority of cosmic background while being very efficient for the selection of neutrino interactions.
6. The filter does not restrict the kinematic phase space of neutrino interactions.
7. Ongoing studies are further reducing the reliance of ICARUS simulation through adversarial training using real data.
8. Once finished, the event filter output will become the input to a future higher level analyses.
9. One of the future improvements includes adding the TPC information to the input image.

Backups

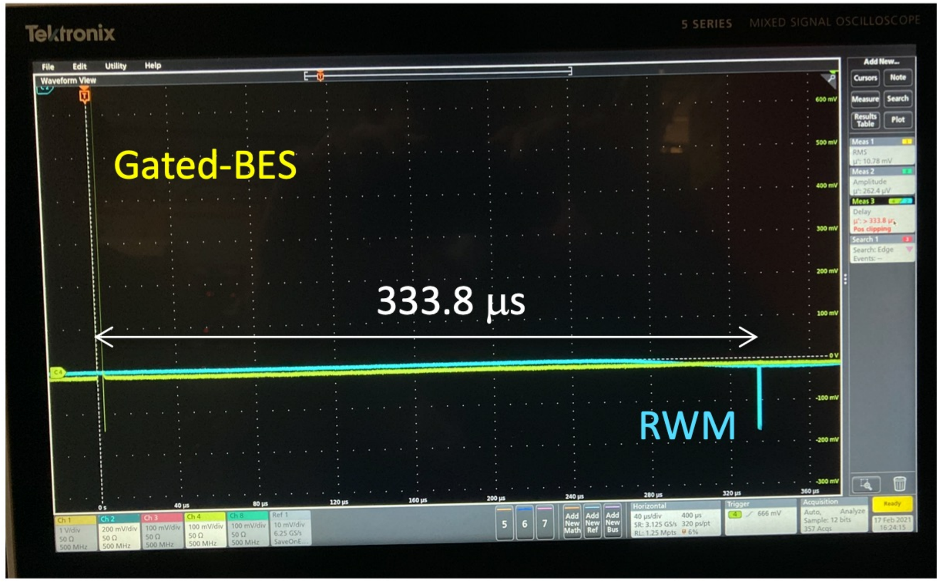
ICARUS T600 detector

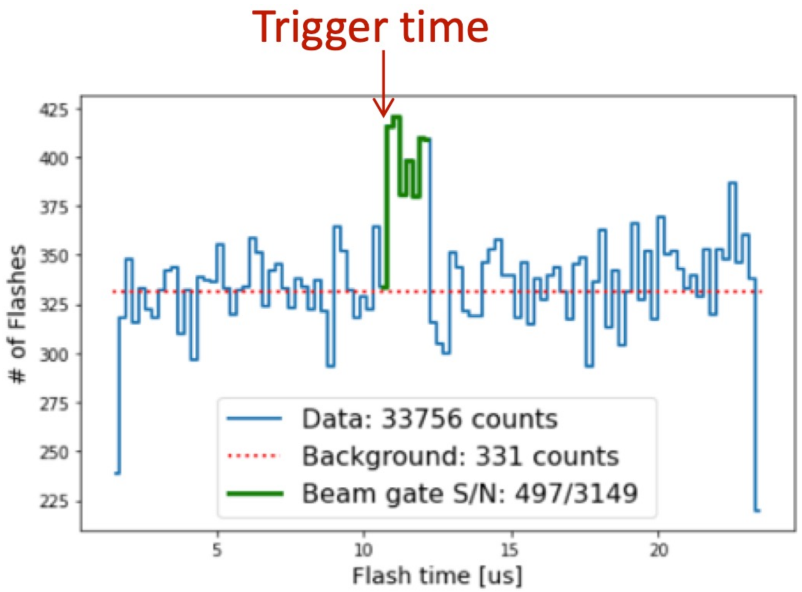
- There are four sets of three planes of anode wires (in total 53248 wires) and two cathode planes in the ICARUS T600 detector.
- In each set of three planes of anode wires, difference in inclination angles of wires of subsequent planes is 60° .
- Distance between wires: 3 mm, distance between planes: 3 mm.
- 360 8" PMTs placed behind the anode planes (90 PMTs per TPC).



ICARUS trigger system

- ICARUS has taken PMT data in and around the BNB beam spill arrival time in order to study beam profile and commissioning the trigger hardware
  - Running the trigger simulation over these data sets allows to study preliminary neutrino and background rates
  - Excess of PMT light flashes (>5 fired PMTs within 150 ns window in coincidence in both left and right TPCs) over the cosmic background rate at the expected time. – zbyt szczegolowo





The beam profile can be clearly seen by plotting the opening times of the simulated trigger gates.

ICARUS event rates

1. BNB: 5×10^{12} POT/spill extracted in $\sim1.6\ \mu s$, 5 Hz repetition rate
   - 1 neutrino interaction in the detector per 180 spills, i.e. 0.029 Hz.
   - 1 beam-associated event every 210 spills from beam halo/interactions in the material surrounding the detector, i.e. 0.025 Hz.
   - 1 in-spill cosmic event every 55 spills, i.e. 0.090 Hz.

1 in-spill physical event over 35 spills ($\sim$ 0.15 Hz) expected inside ICARUS (E >100 MeV).

2. NuMI: 6×10^{13} POT/spill extracted in $\sim9.5\ \mu s$, 0.75 Hz repetition rate
   - 1 neutrino interaction/15 spills, i.e. 0.050 Hz.
   - 1 beam halo event/15 spill, i.e. 0.050 Hz.
   - 1 cosmic event/10 spill, i.e. 0.075 Hz.

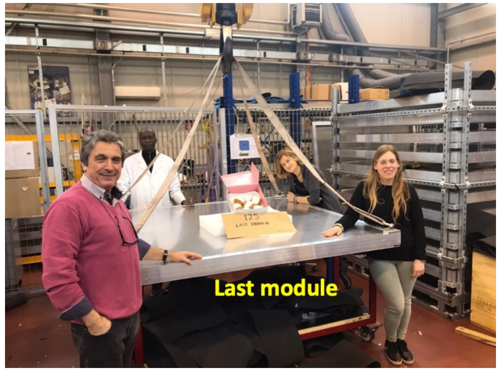
1 in-spill physical event over $\sim$ 5 spills ($\sim$ 0.17 Hz) expected inside ICARUS.

Cosmic Ray Tagger system

- CRT surrounds the cryostat with two layers of plastic scintillators (~1000 m^2)
- Provides spatial and timing coordinates of the track entry point
- Match reconstructed CRT hits to activity in the TPC
- Few ns time resolution allows measuring direction of incoming/outgoing particle propagation via time of flight
- Three subsystems providing ~95% tagging efficiency:
  - Bottom, side and top CRT
- Commissioning of the two walls with cosmic is ongoing

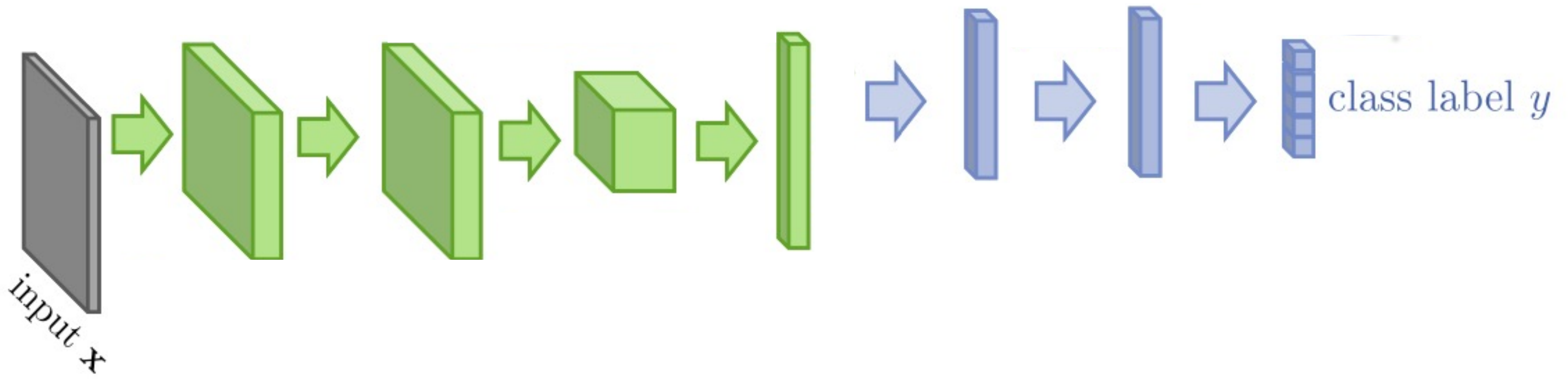
Bottom CRT: installed.

Top CRT: modules ready



Domain-Adversarial Neural Networks

- Neural network for classification.
  - I.e., neural network for neutrino vs cosmic prediction.



https://arxiv.org/abs/1505.07818

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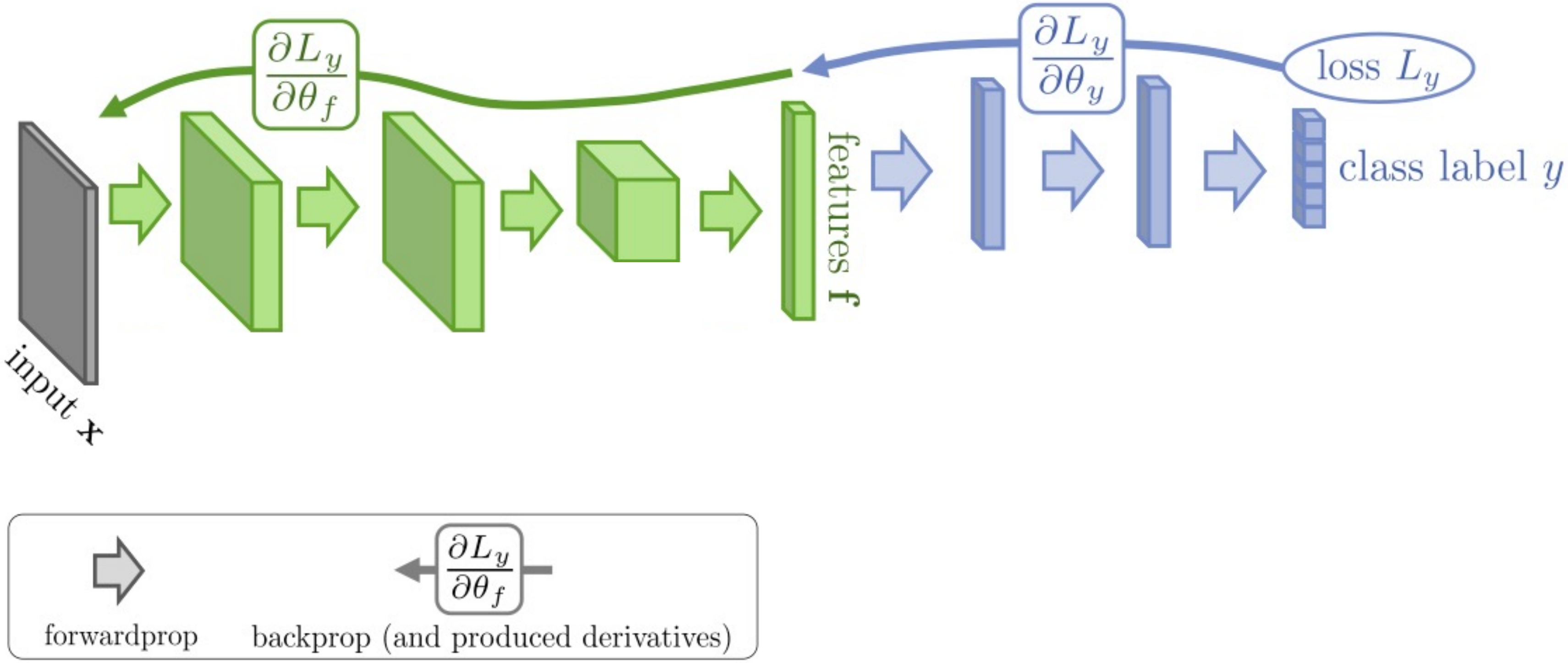
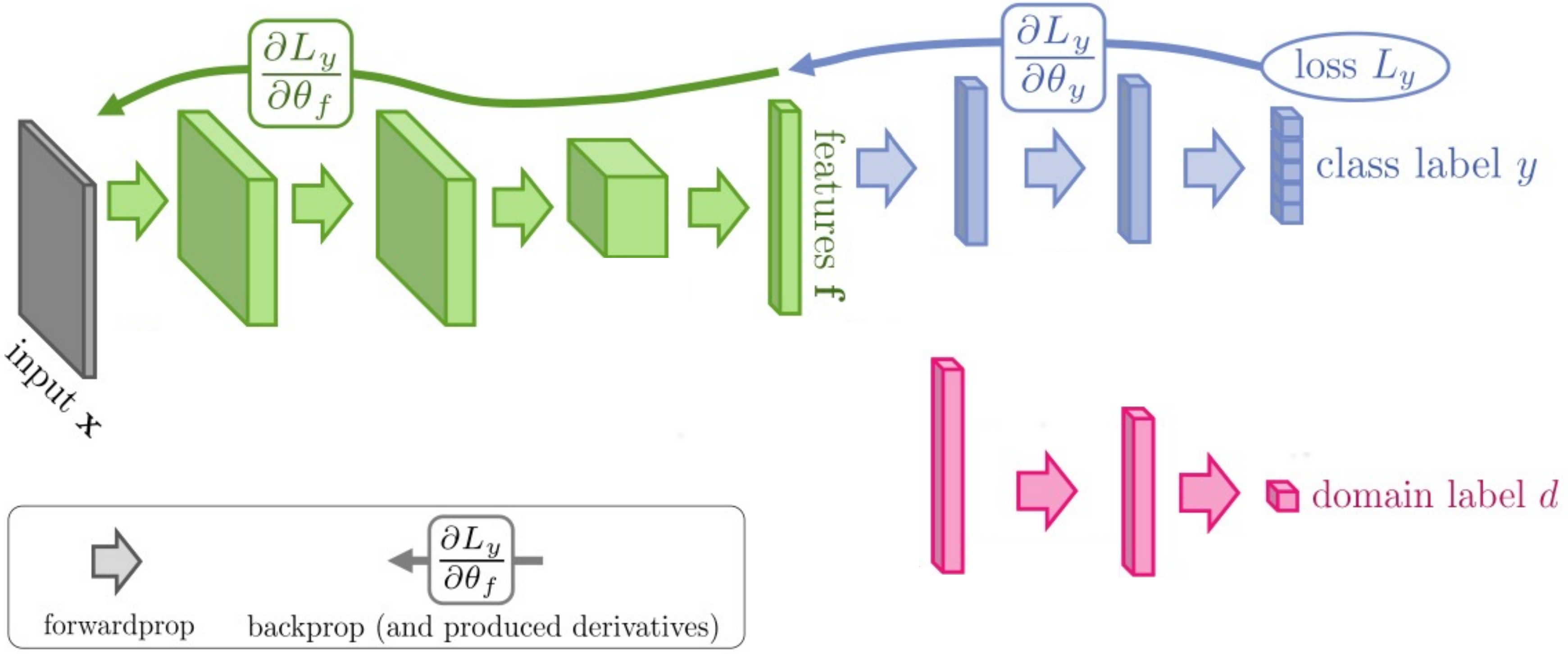


https://arxiv.org/abs/1505.07818

Domain-Adversarial Neural Networks

- Add domain output.
  - E.g., MC vs data, real MC vs fake MC, etc.



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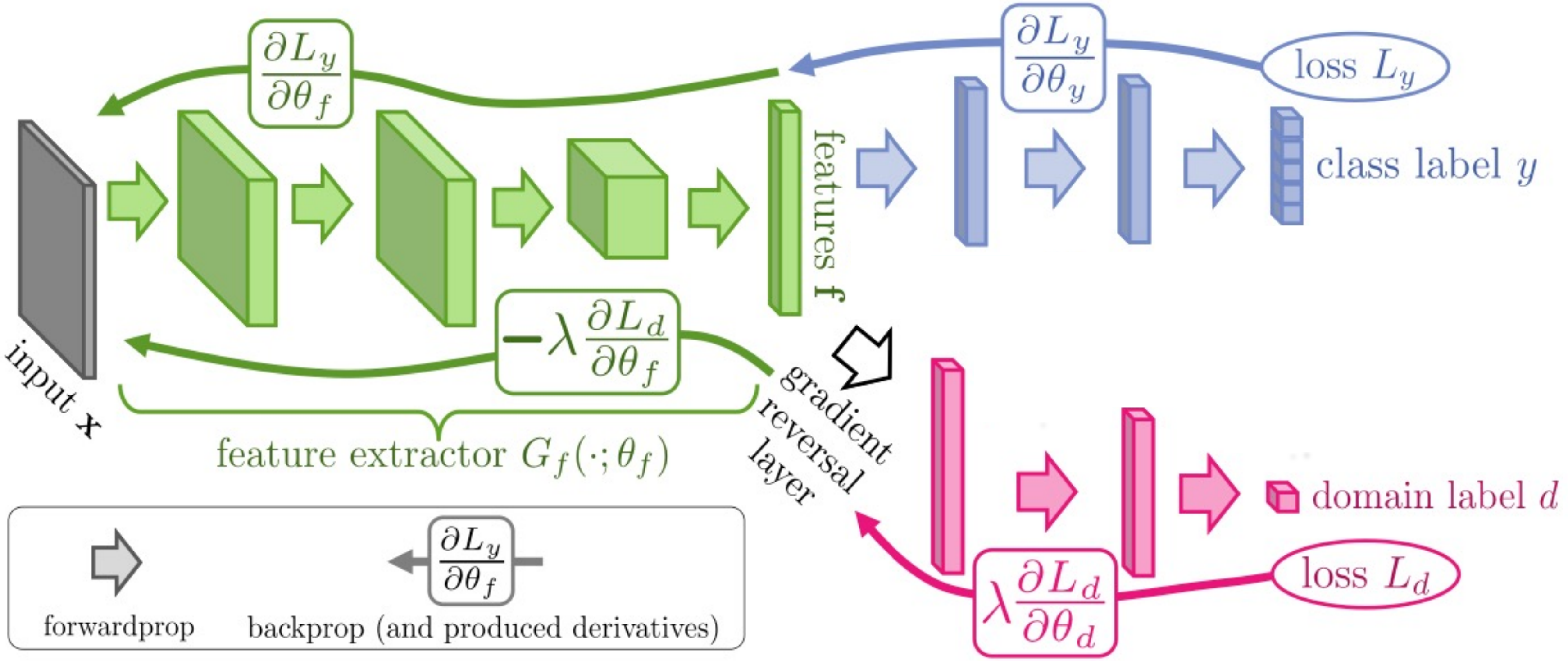
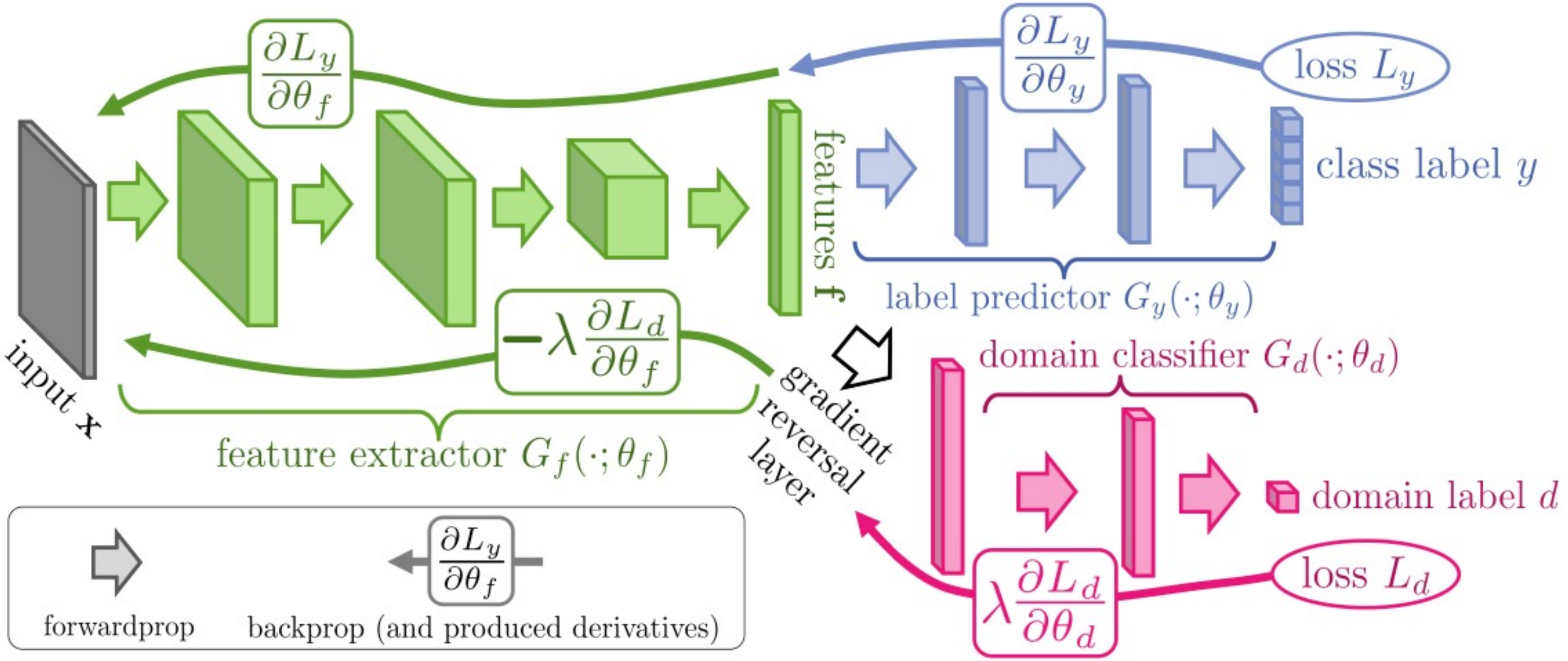


https://arxiv.org/abs/1505.07818

Domain-Adversarial Neural Networks

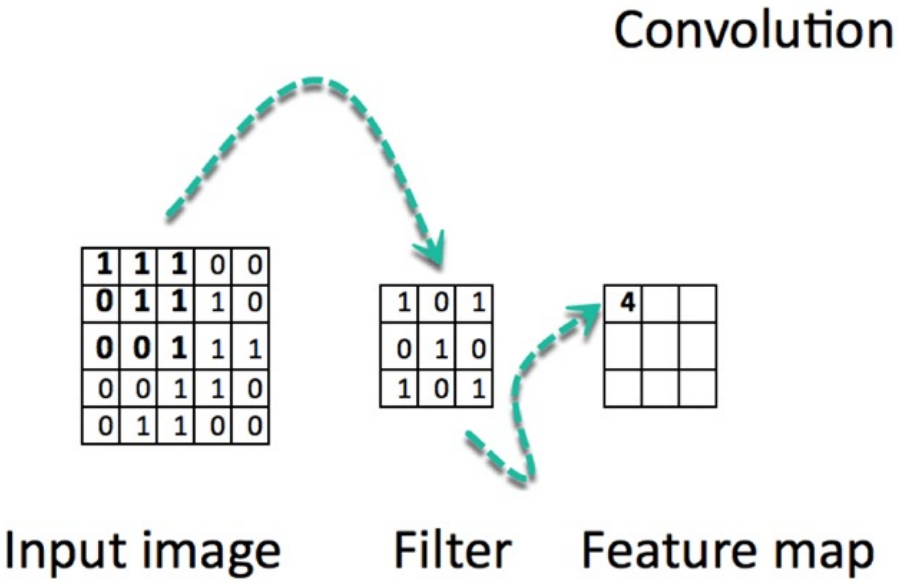
- Gradient reversal ensures that the feature distributions over the two domains are made similar (domain-invariant features).

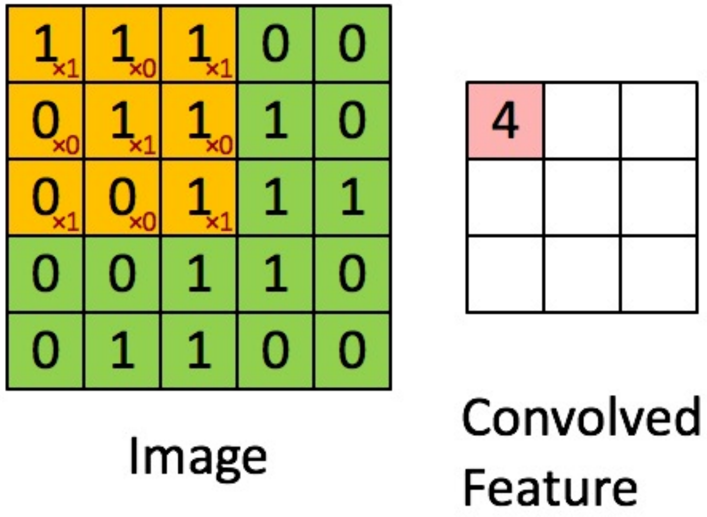


https://arxiv.org/abs/1505.07818

Convolution

- is a simple application of a filter to an input that results in an activation.
- Repeated application of the same filter to an input results in a map of activations called a feature map, indicating the locations and strength of a detected feature in an input, such as an image.





Images source

Max pooling

- The main purpose: reduce the dimensionality of the input.
- A standard way to pool the input image is to use the maximum value of the feature map.