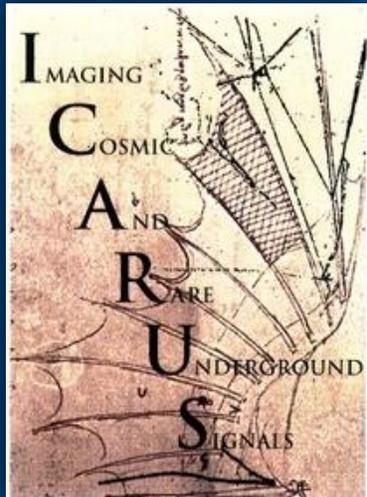


The cosmogenic background rejection of the ICARUS detector at Fermilab

F. Poppi
(INFN Bologna)
On behalf of the ICARUS Collaboration

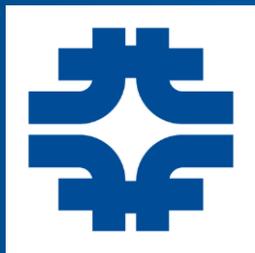
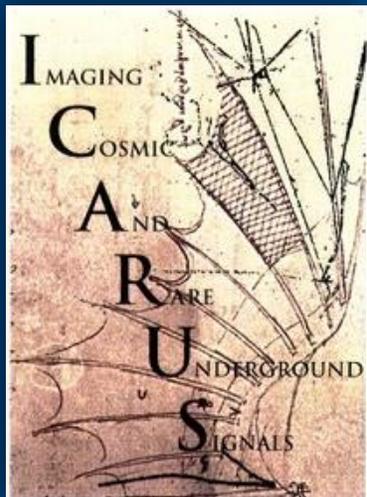


Neutrino Telescope
XX International Workshop on Neutrino Telescope
Venezia, October 24th 2023

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**More From ICARUS:
Maria ([Icarus Analysis](#))
Filippo (SBN program at
Fermilab, Wednesday Plenary)**



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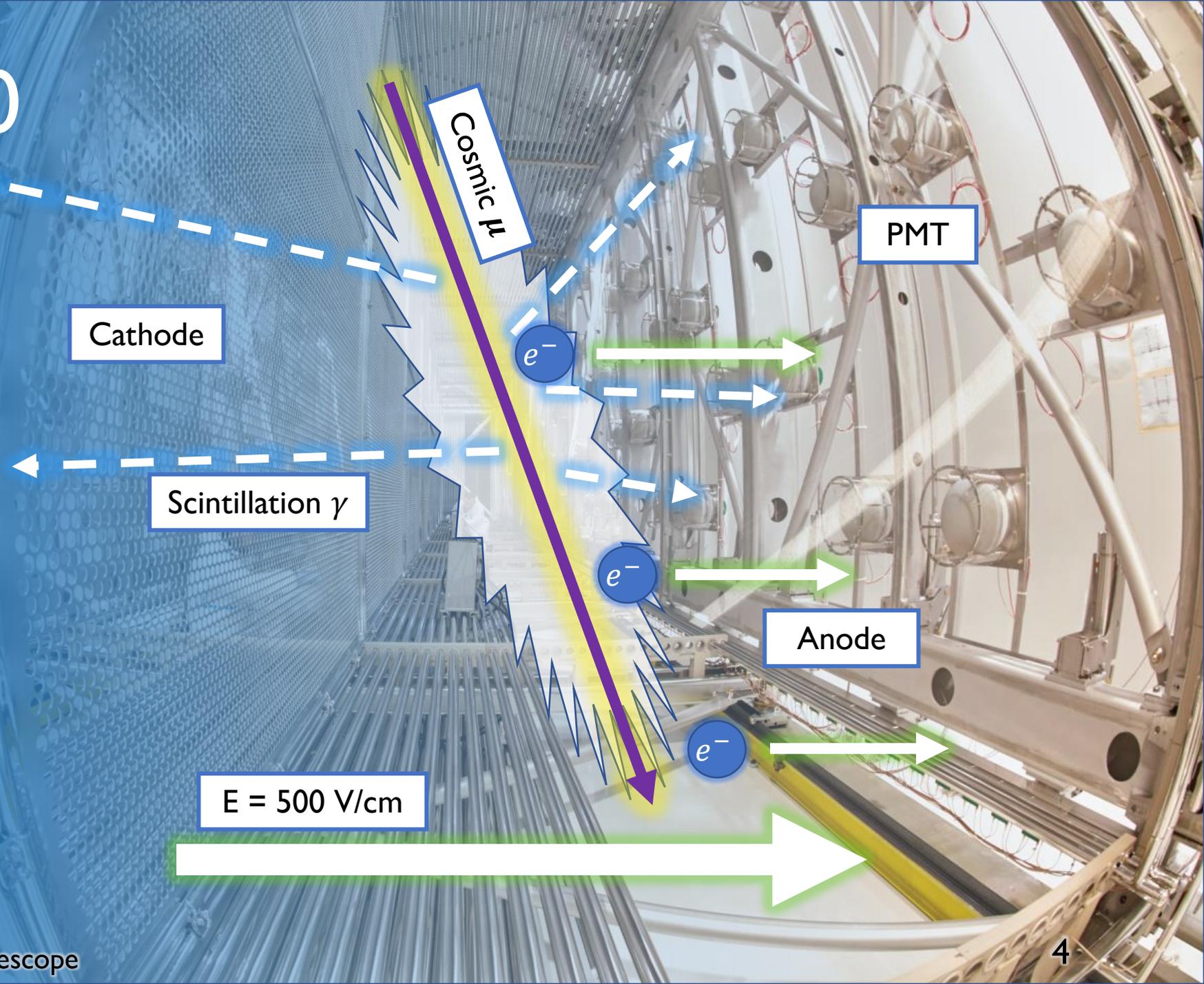
ICARUS T600

- Pioneer of the LArTPC technology.
- Total mass of 760 LAr tons.
- Two modules:
3.6 m X 3.9 m X 19.9 m,
total of 53248 wires.
- Max drift time of 0.96 ms.
- Photon Detection System (PDS) composed of 360 PMTs.



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Cosmic background

ICARUS is located at shallow depth and exposed to a large cosmic activity:

- **In-time:** cosmic particles entering the detector during the beam spill.
- **Out-of-time:** cosmic particles crossing the detector during the ~ 1 ms drift time.

$\sim 1 \nu$ every 180 (53) spills* for BNB (NuMI)
 ~ 1 cosmic μ every 55 (6) spills* for BNB (NuMI)

To suppress the cosmic background, ICARUS is surrounded with an external **Cosmic Ray Tagger system (CRT)** below a 3 m concrete overburden.

* BNB spill = $1.6 \mu\text{s}$
NuMI spill = $9.6 \mu\text{s}$



Cosmic background

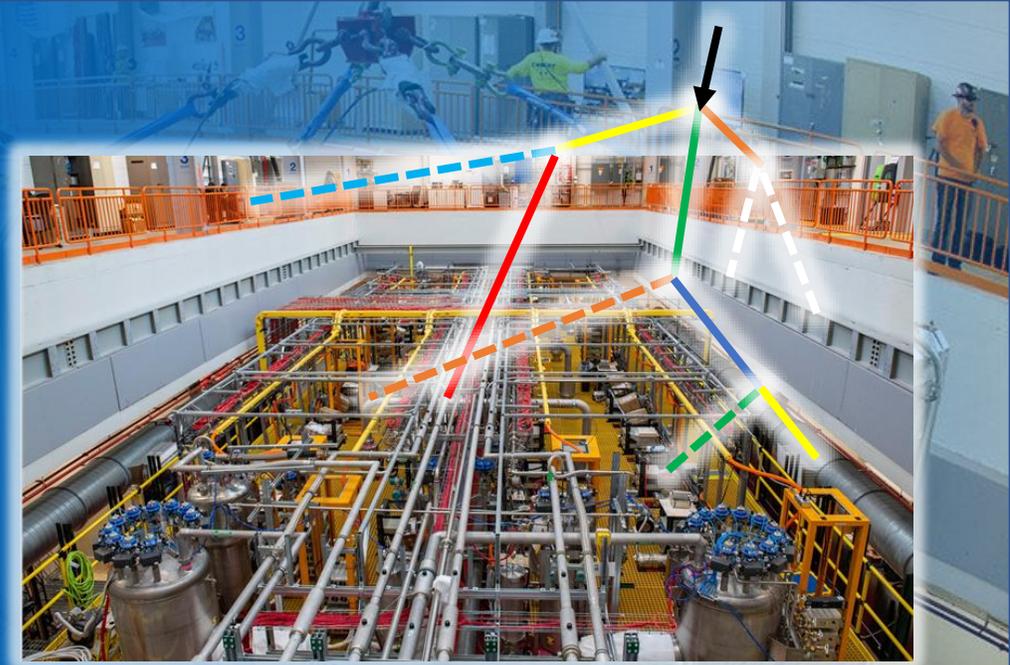
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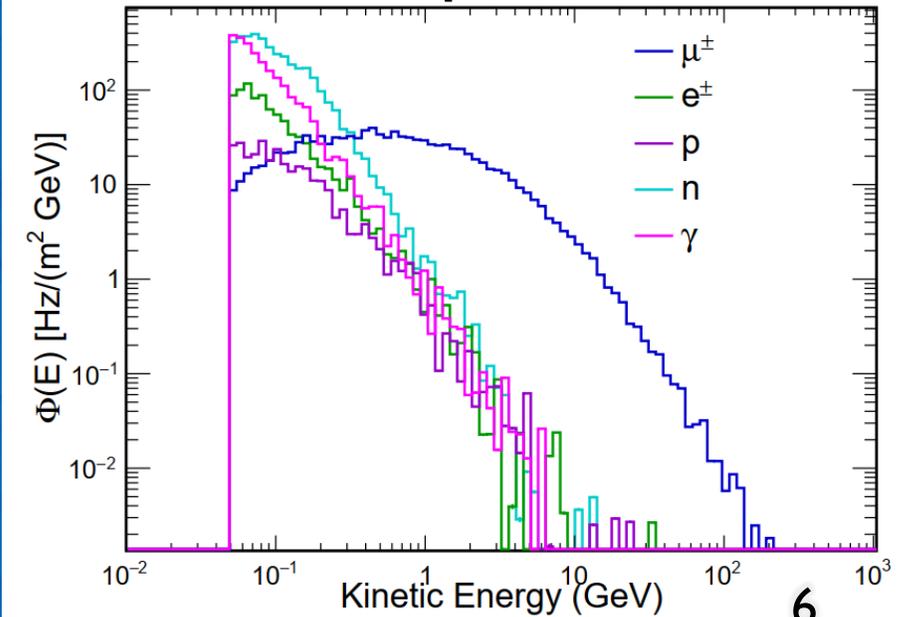
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Flux of cosmic particles at surface



The concrete overburden



- The soft electro-magnetic component is almost fully suppressed.
- The hadronic component is highly suppressed.
- The overburden reduces the dominant muon flux by a quarter.

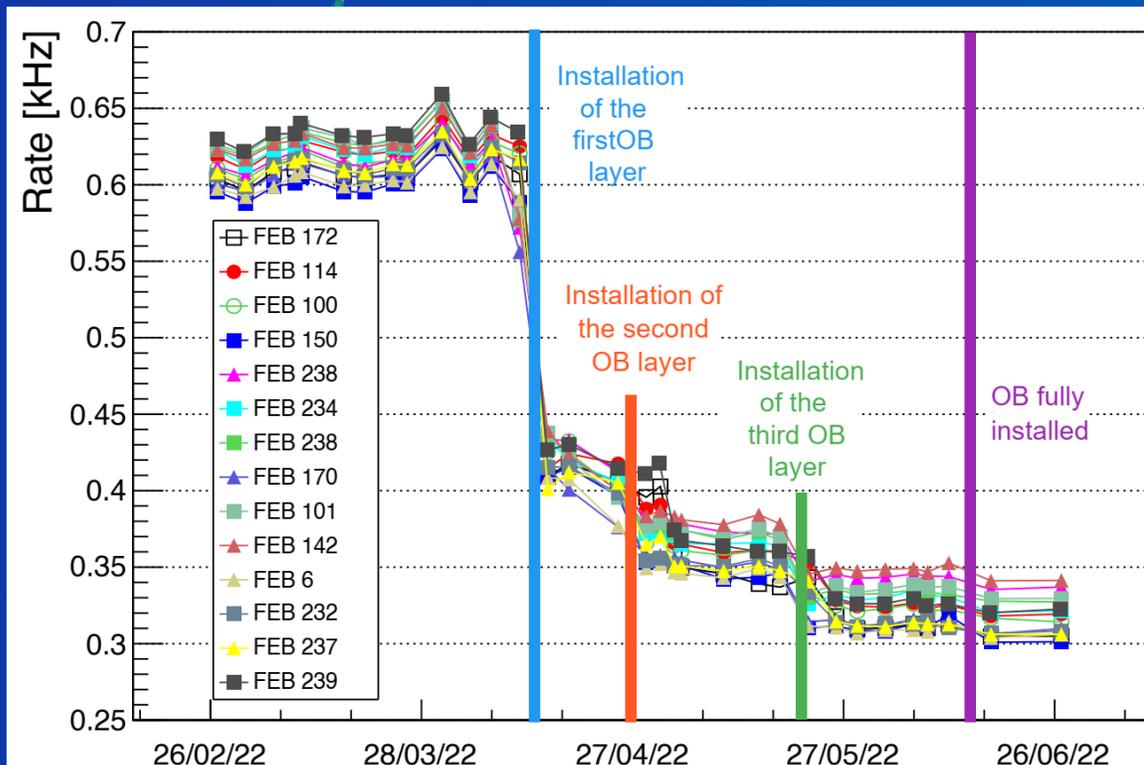


Simulated cosmic particles rate with/without the overburden

Particle	Without OB [Hz]	With OB [Hz]	Reduction
μ^\pm	~17100	~12800	~1.34
p	~50	0.1	> 500
γ	~100	$\ll 0.1$	> 3500
n	~1400	6.8	> 200

The concrete overburden

Top CRT horizontal modules rate during overburden installation

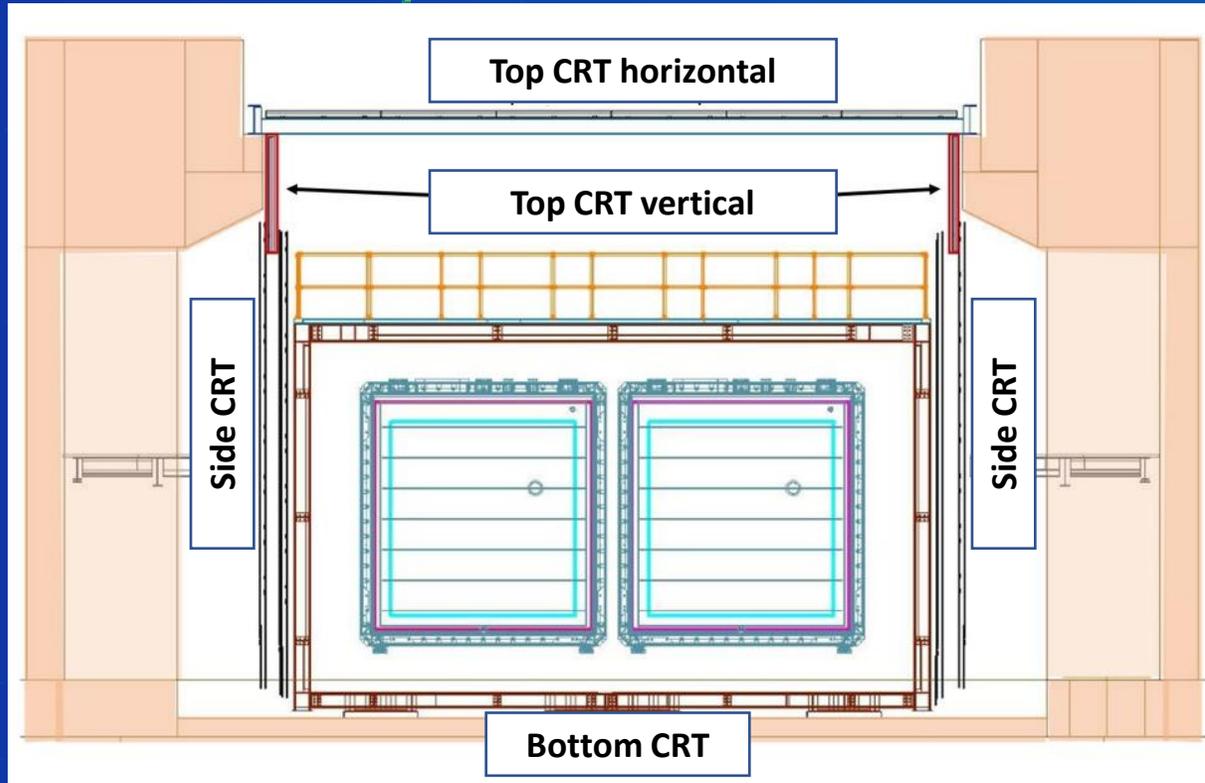


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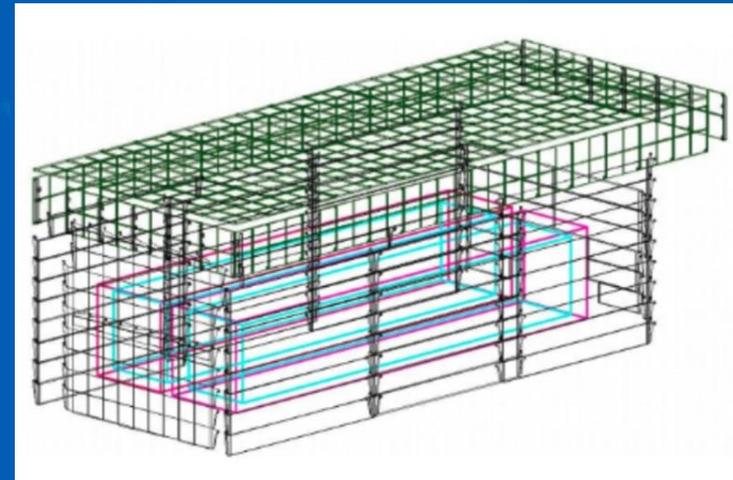
Simulated cosmic particles rate with/without the overburden

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The cosmic ray tagger

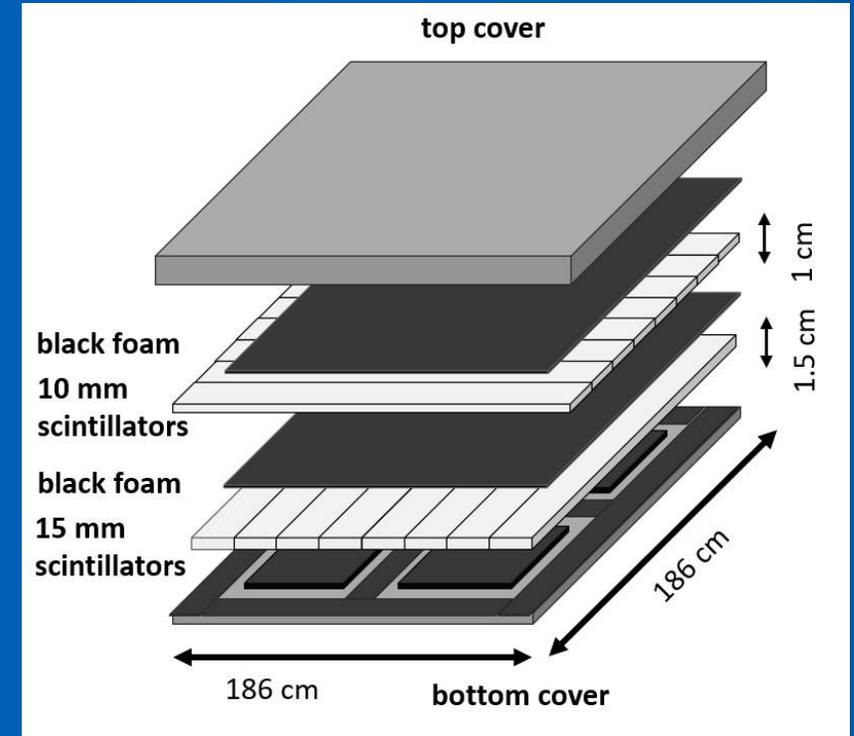
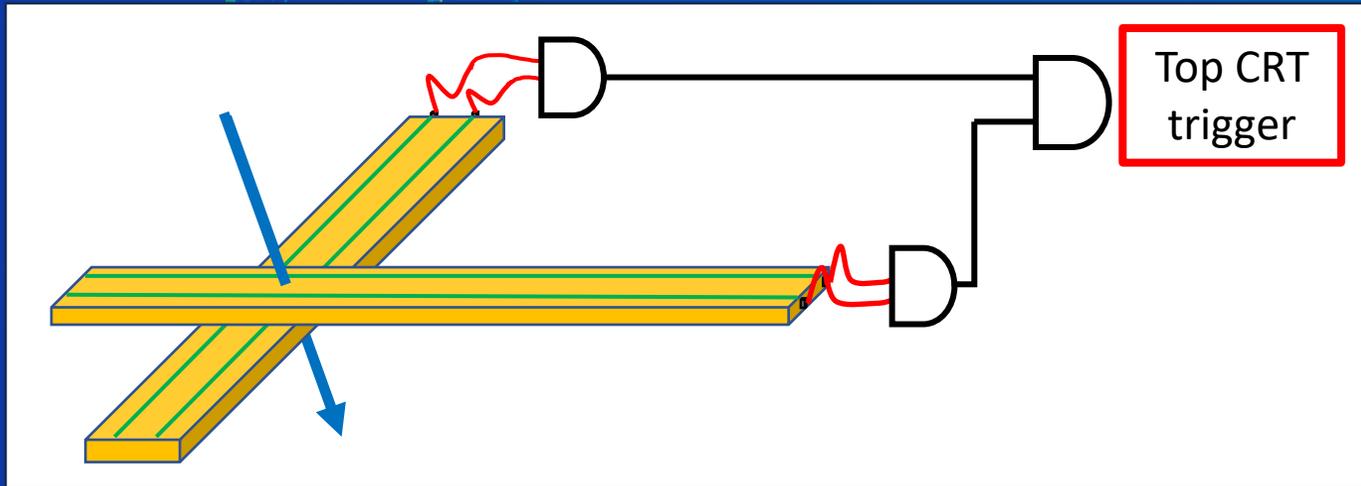


- A 4π coverage of the detector with Cosmic Ray Tagger modules (CRT): **Bottom CRT, Side CRT** and **Top CRT**.
- The Top CRT alone intercepts **80%** of the incoming cosmic ray flux.
- The external CRT system will provides spatial ($\sim\text{cm}$) and timing ($\sim\text{ns}$) coordinates of the track crossing point.



The Top CRT

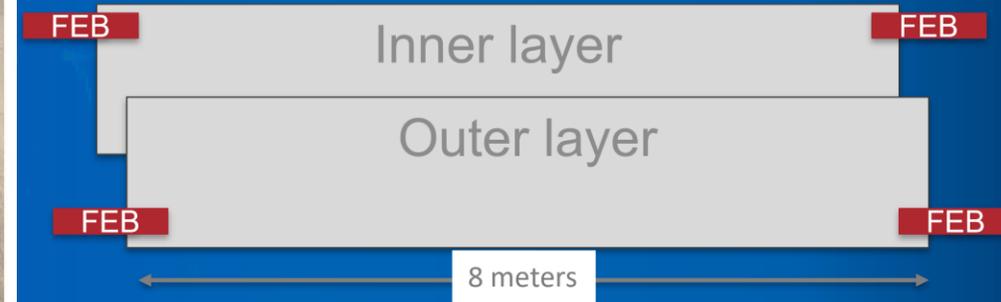
- Hodoscope modules: 2 orthogonal layers of eight 23 cm wide scintillator strips.
- Scintillation light collected by two WLS fibres readout at one end by one SiPM each.
- Auto-trigger provided by coincidence signals in both scintillation layers.



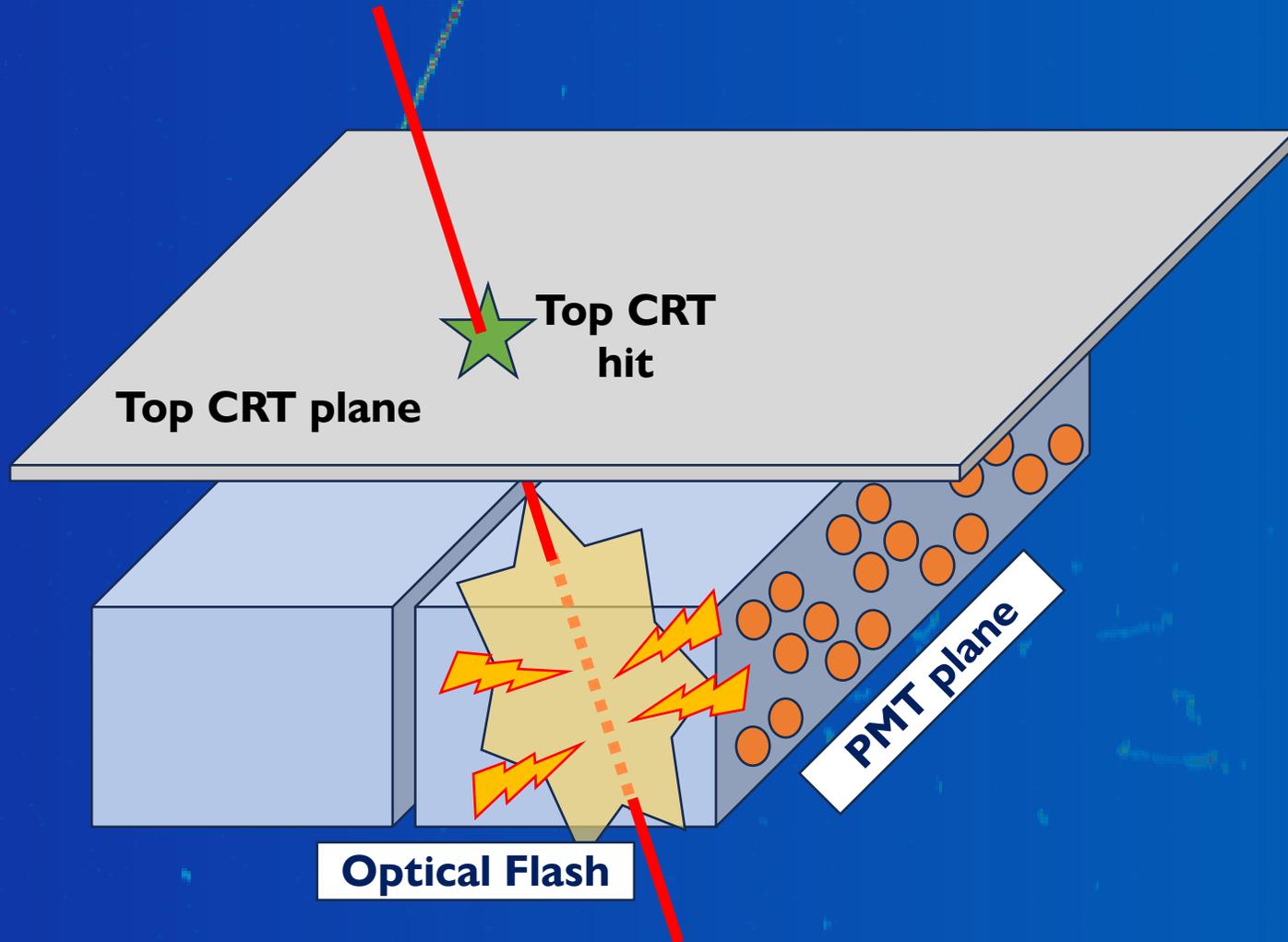
The Side CRT



- Modules repurposed from the MINOS experiment.
- Double parallel layer configuration, with the exception of the upstream wall (two perpendicular layers).



CRT-PMT matching



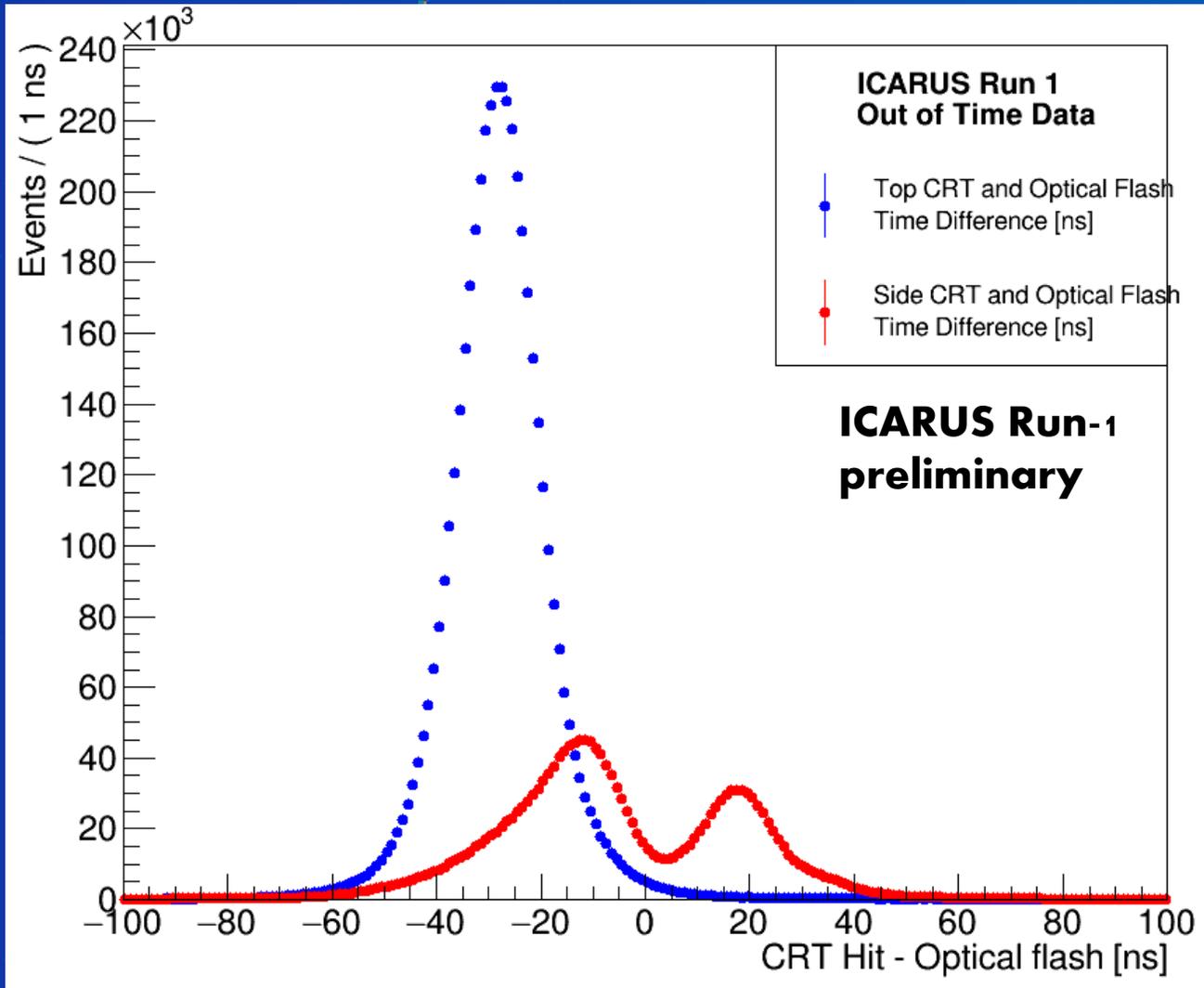
- CRT-PMT matching performed by associating an Optical Flash with one or more CRT hits only if the relative time difference is within 100 ns:

$$\Delta t = T_{CRT} - T_{OPFlash}$$
$$|\Delta t| < 100 \text{ ns}$$

- An hit is preliminarily defined **Entering** if $\Delta t < 0$ or **Exiting** if $\Delta t > 0$.

Note: OpFlash time is the reconstruction time of the PMT signal. Scintillation light propagation is not accounted for and it affects $\Delta t = T_{CRT} - T_{OPFlash}$ evaluation.

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CRT-PMT matching: offbeam data

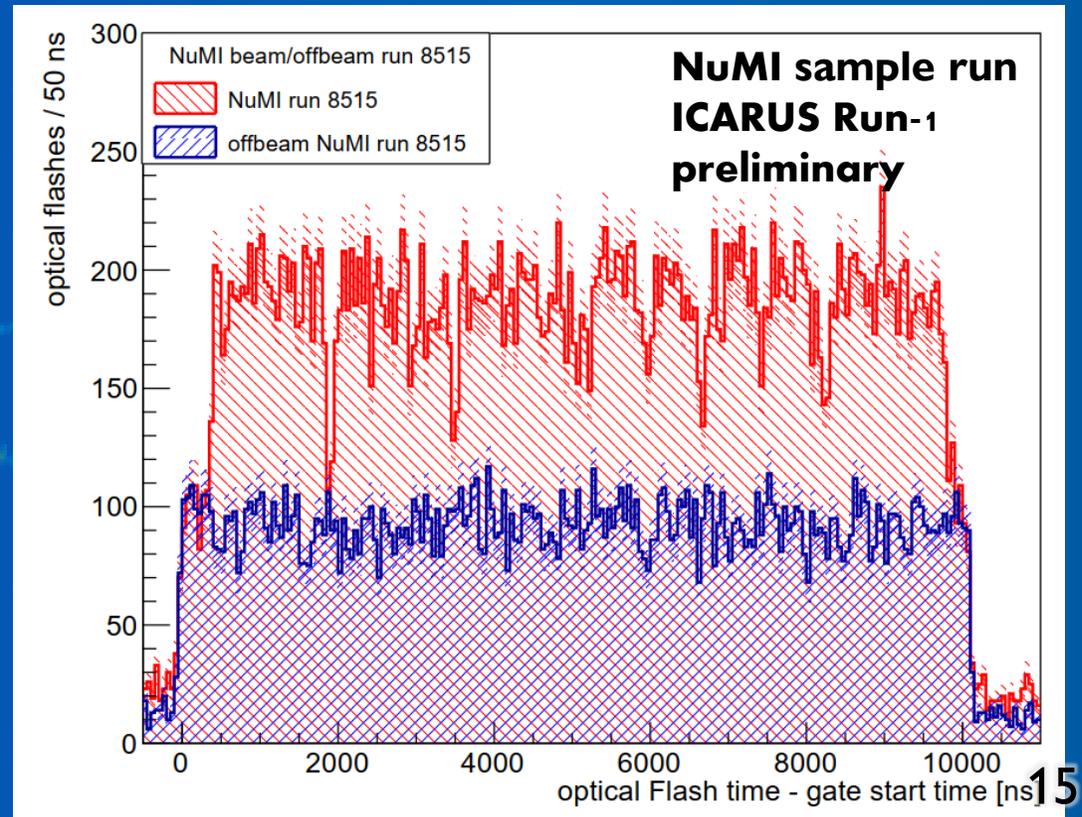
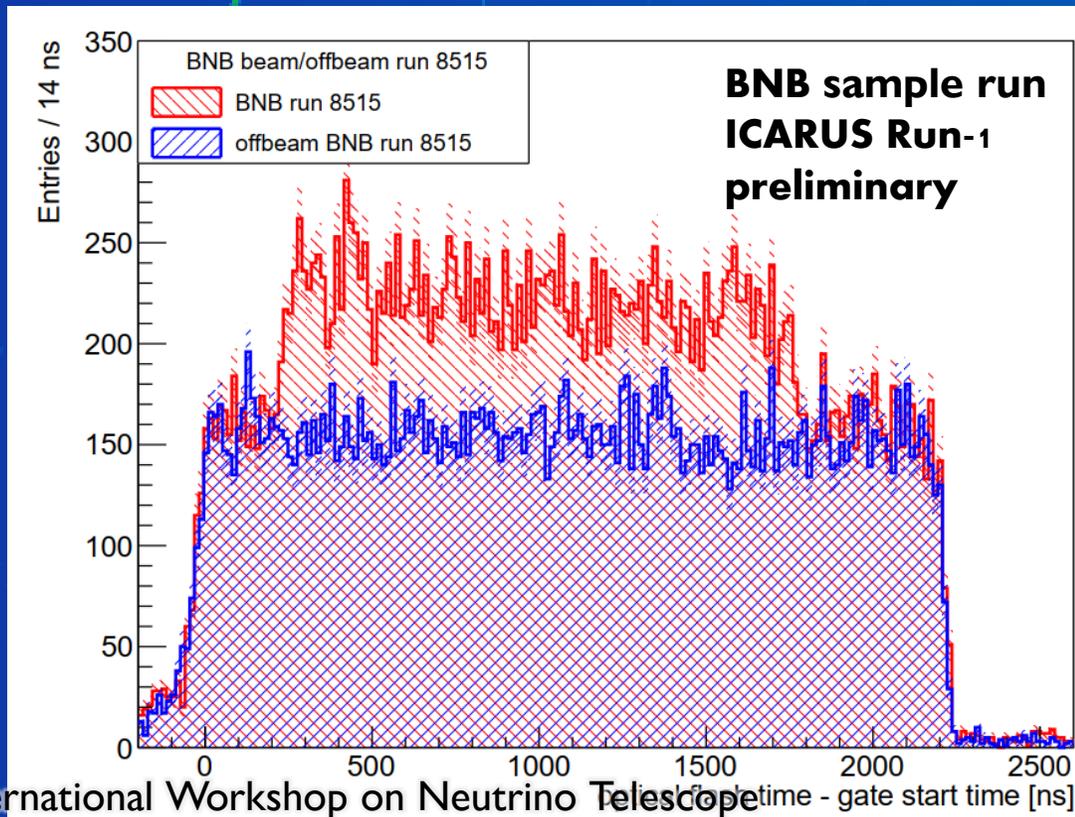
Classification	Entries	%
No CRT match	235266	12.51
1 Entering from Top	1157004	61.51
1 Entering from Side	209791	11.15
1 Entering from Top 1 Exiting from Side	86035	4.57
1 Exiting from Top	15489	0.82
1 Exiting from Side	38243	2.03
Others	139088	7.39

ICARUS Run-1 preliminary – Cosmics only sample

- Matching algorithm was studied on a cosmics only sample acquired during the ICARUS Run-1 (summer 2022).
- ~2 milion optical flashes were selected to characterize the matching algorithm.
- 61.5% (11.2%) of the optical flashes were preceeded by one Top (Side) CRT Hit.
- 12.5% of the optical flashes were not matched with any CRT Hit: CRT acceptance/inefficiencies or not-matchable optical flash (e.g. slow scintillation light component with $1.6 \mu\text{s}$ lifetime).

CRT-PMT matching: on-beam

- By narrowing down the selection to the acquisition-triggering flash, the CRT-PMT matching based classification can be exploited to determine whether or not an event was likely triggered by a cosmic particle.
- A sample on-beam run (2-3 days of data taking) was studied to determine the Event Selection capabilities of the matching algorithm.



CRT-PMT matching: BNB

**BNB Beam gate:
1.6 us**

Classification	BNB		Offbeam BNB	
	Entries	%	Entries	%
No CRT match	8154	32.4	2185	12.3
1 Entering from Top	11700	46.5	11219	63.4
1 Entering from Side	2144	8.5	1851	10.5
1 Entering from Top 1 Exiting from Side	916	3.6	852	4.8
1 Exiting from Top	329	1.3	85	0.5
1 Exiting from Side	621	2.5	324	1.8
Others	1325	5.2	1180	6.7

- On-beam/off-beam data shows a significant increment of optical flashes not matched with any CRT Hit, in agreement with fully contained neutrino induced activity.
- A rejection of >65 % of the on-beam BNB sample can be performed without the need of reconstructing the TPC signals.
- Additionally, also the optical flashes followed by CRT hits increases, in agreement not-fully contained neutrino induced activity.

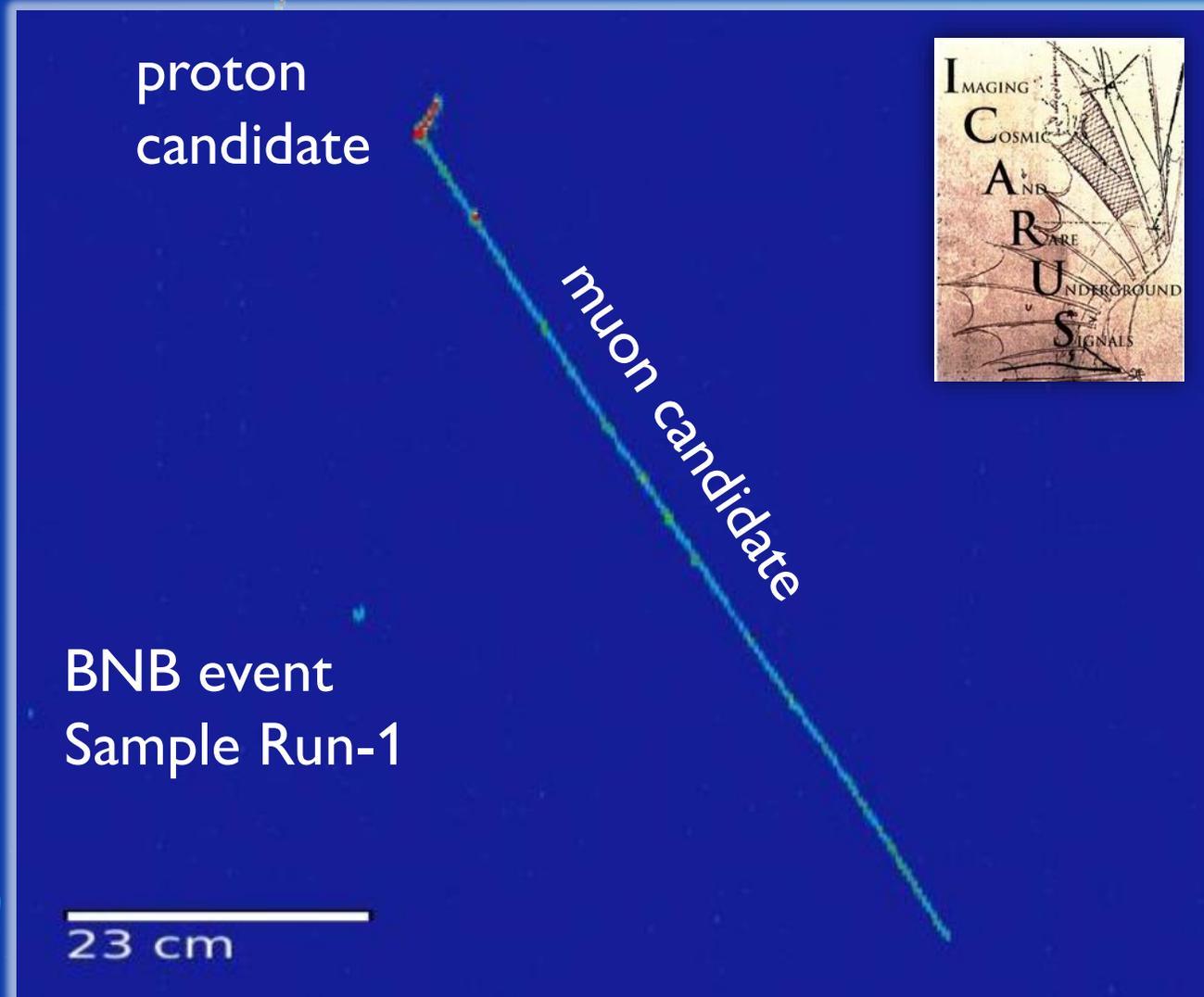
CRT-PMT matching: NuMI

NuMI Beam gate:
9.6 us

Classification	NuMI		Offbeam NuMI	
	Entries	%	Entries	%
No CRT match	13933	39.0	2257	12.7
1 Entering from Top	12281	34.4	11154	62.8
1 Entering from Side	3826	10.7	1856	10.5
1 Entering from Top 1 Exiting from Side	899	2.5	839	4.7
1 Exiting from Top	721	2.0	85	0.5
1 Exiting from Side	1992	5.6	333	1.9
Others	2035	5.7	1232	6.9

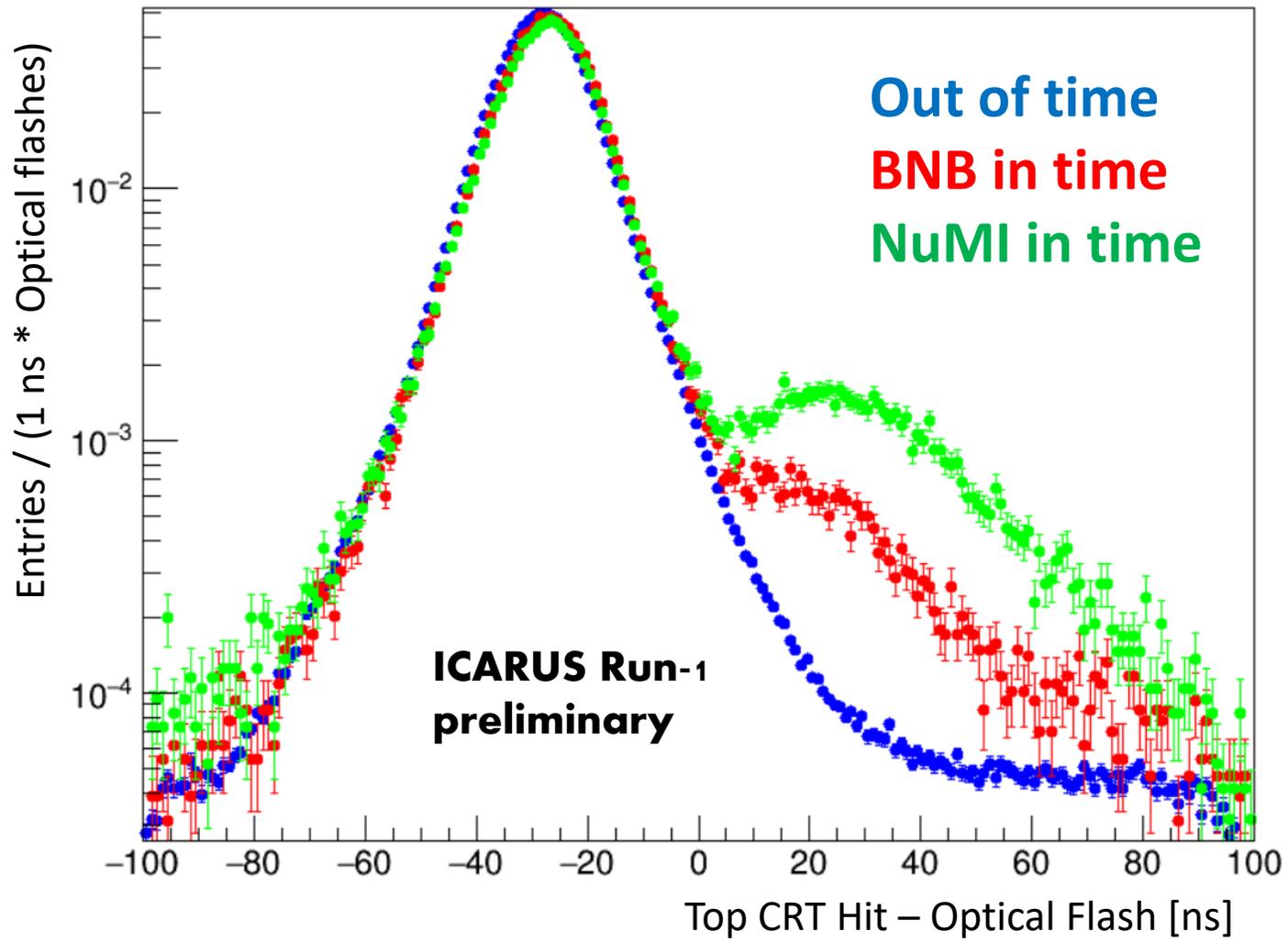
- On-beam/off-beam data shows a significant increment of optical flashes not matched with any CRT Hit, in agreement with fully contained neutrino induced activity.
- A rejection of >60 % of the on-beam BNB sample can be performed without the need of reconstructing the TPC signals.
- Additionally, also the optical flashes followed by CRT hits increases, in agreement not-fully contained neutrino induced activity.

CRT-PMT matching: selection of fully contained interactions



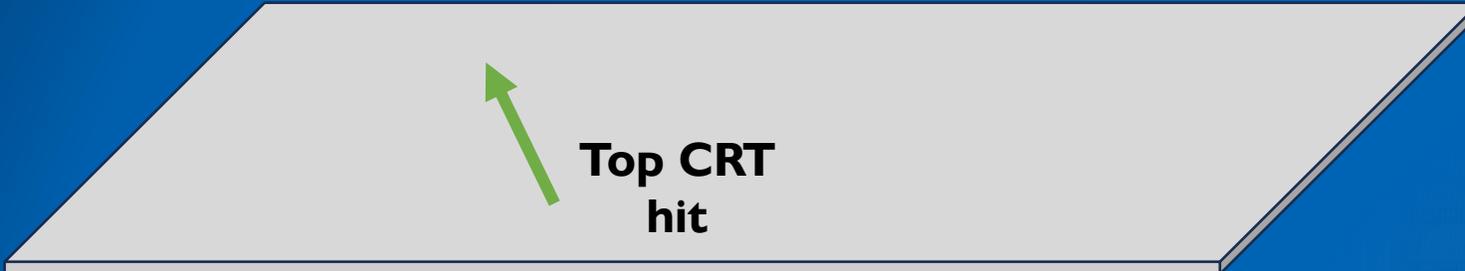
Example of QE-like muon neutrino CC candidate with a triggering flash not associated with any CRT hit.

CRT-PMT matching: selection of not fully contained interactions

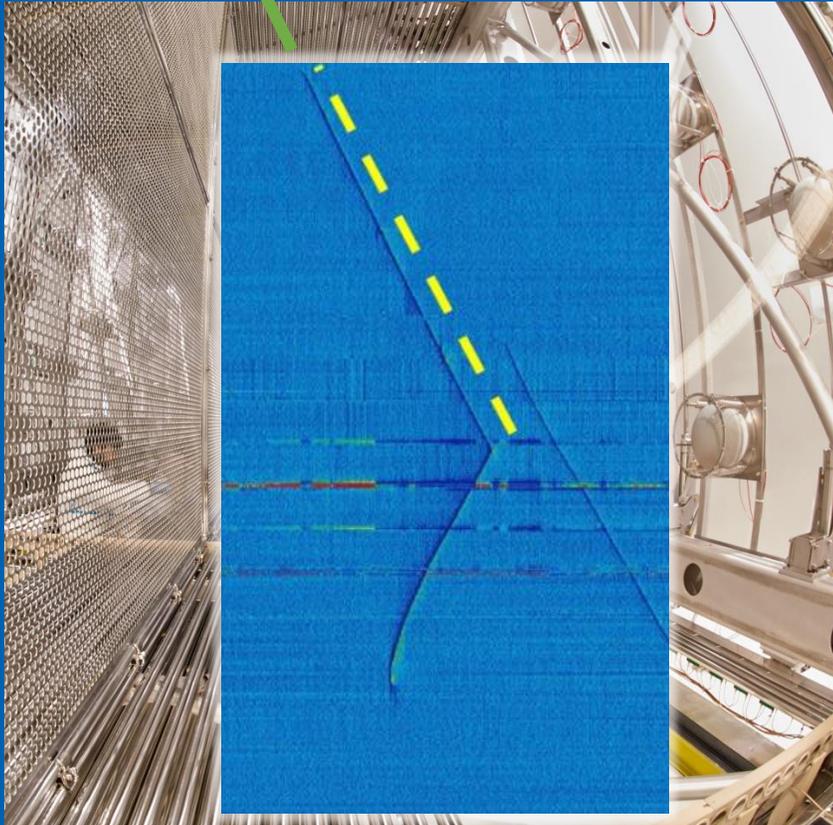


- On-Beam and Off-Beam data shows an excess of CRT hits following the in-time flashes.
- This sample of events is enriched with not fully contained neutrinos.

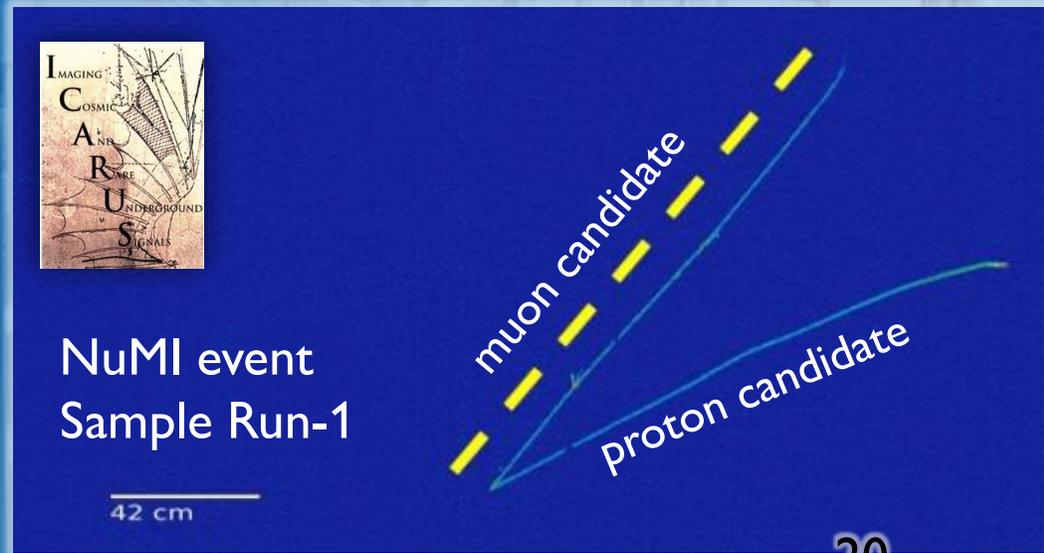
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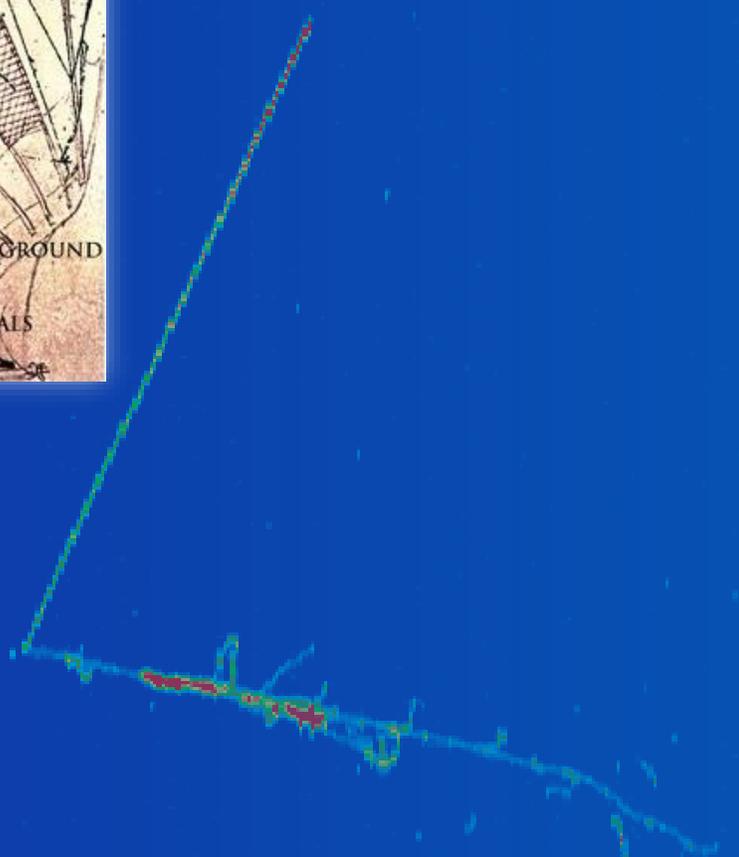
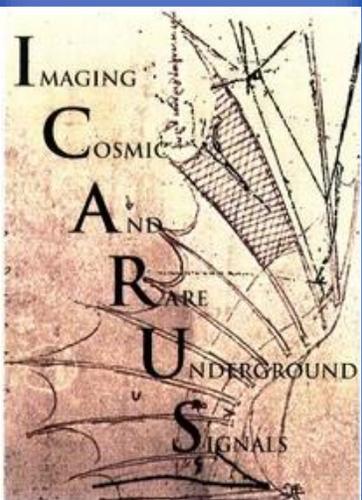



Beam direction



Summary

- ICARUS at FNAL is located at surface level thus exposed to a large cosmic ray flux.
- In order to mitigate as much as possible the cosmic induced activity, the detector is instrumented with an external cosmic ray tagging system (CRT).
- The CRT system when combined with the reconstructed TPC tracks and the Photon Detection System provides a unique tool to reject in-time and out-of time cosmic activity.
- By exploiting the CRT and PMTs \sim ns timing synchronization, it is possible to perform of rejection of cosmic-likely triggered events ahead of the TPC signal reconstruction.
- The application of a CRT-PMT based selection, for the channel of fully contained neutrino interactions would reject $> 65\%$ (60%) of the whole BNB (NuMI) sample.



Thank you!