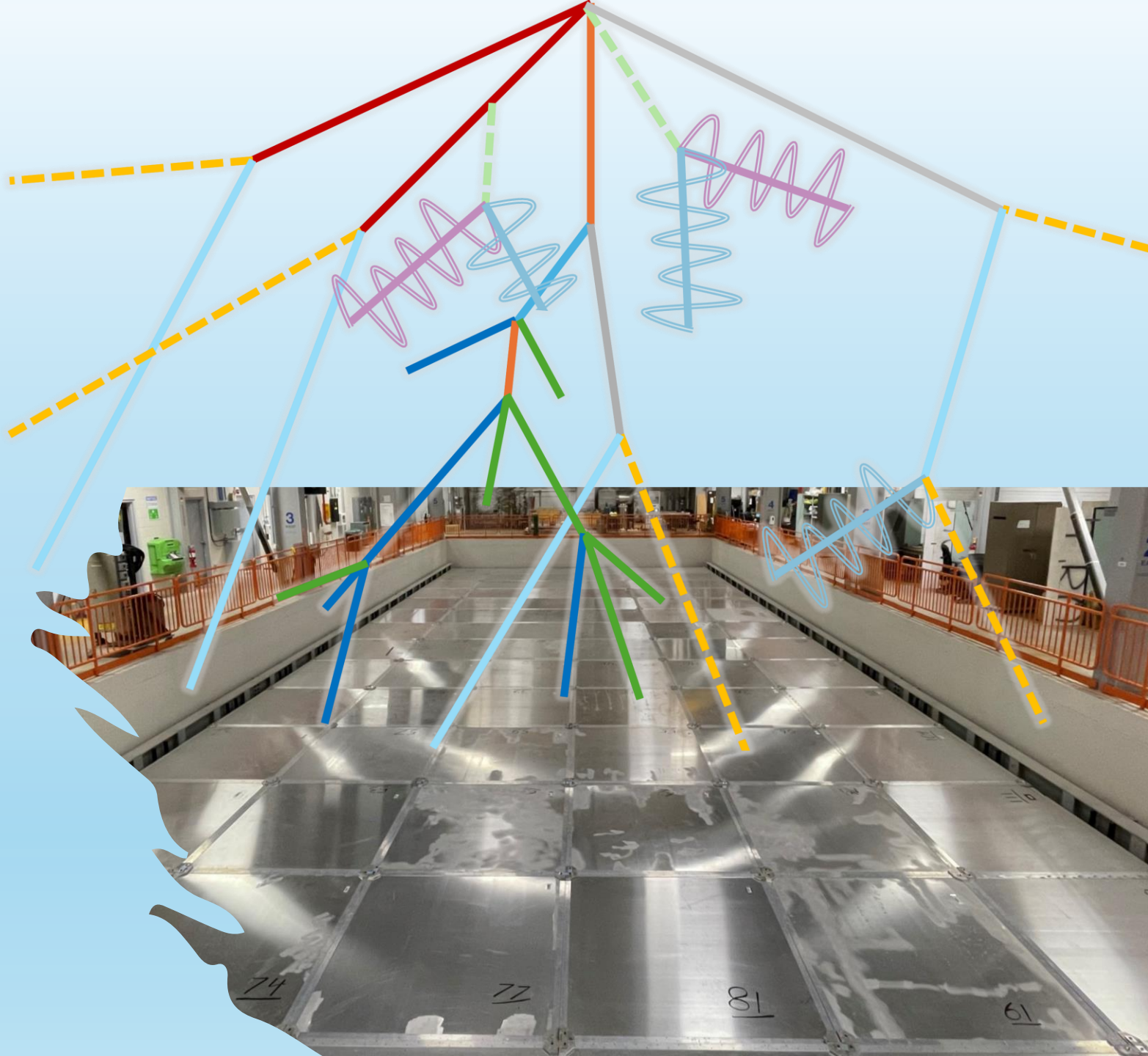
Cosmic Ray Rejection

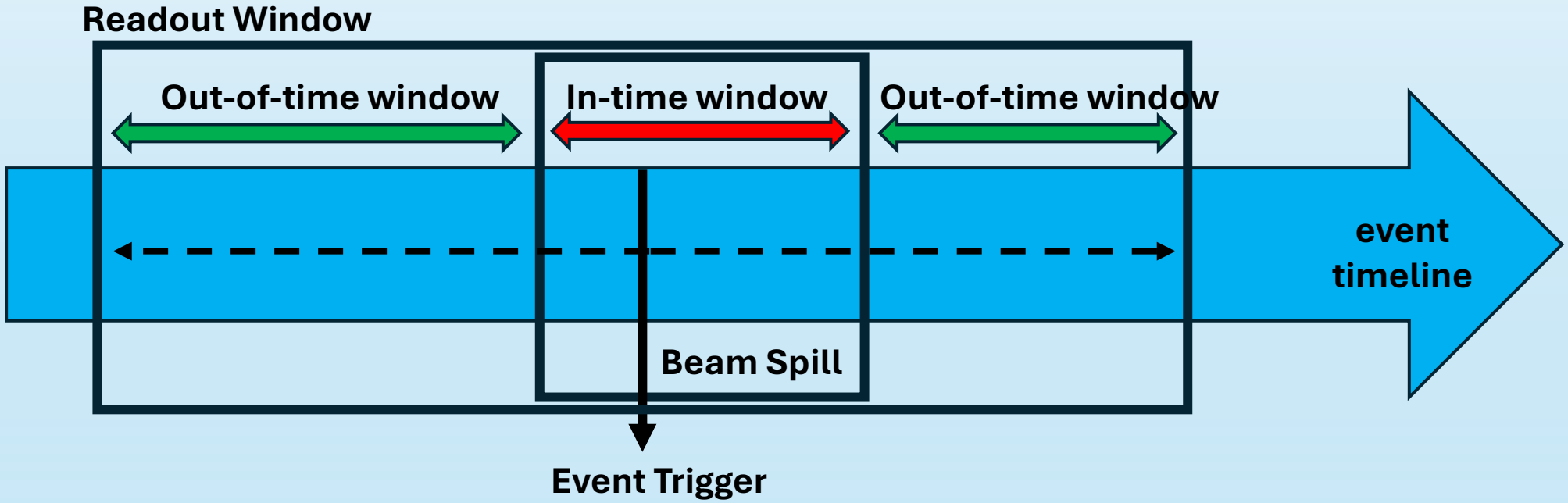
ICARUS Collaboration Meeting

Monday October 14th 2024

Francesco Poppi (INFN Bologna)
on behalf of the Neutrino Identification and Background Rejection WG



Cosmic interactions in ICARUS



In-(beam)-time cosmics:

- Cosmic particles entering in the TPC in time with the beam spill.
- Can determine an event trigger.

Out-of-(beam)-time cosmics:

- Cosmic particles entering in the TPCs out of the beam spill.
- Can be fully reconstructed if within 300 microseconds from the event trigger.

Cosmic Background:

ICARUS is located at shallow depth, exposed to a large cosmic ray activity.

The combined analysis of the different ICARUS sub-detectors (TPC, PMT and CRT) sets a cosmic-free background goal in sight.

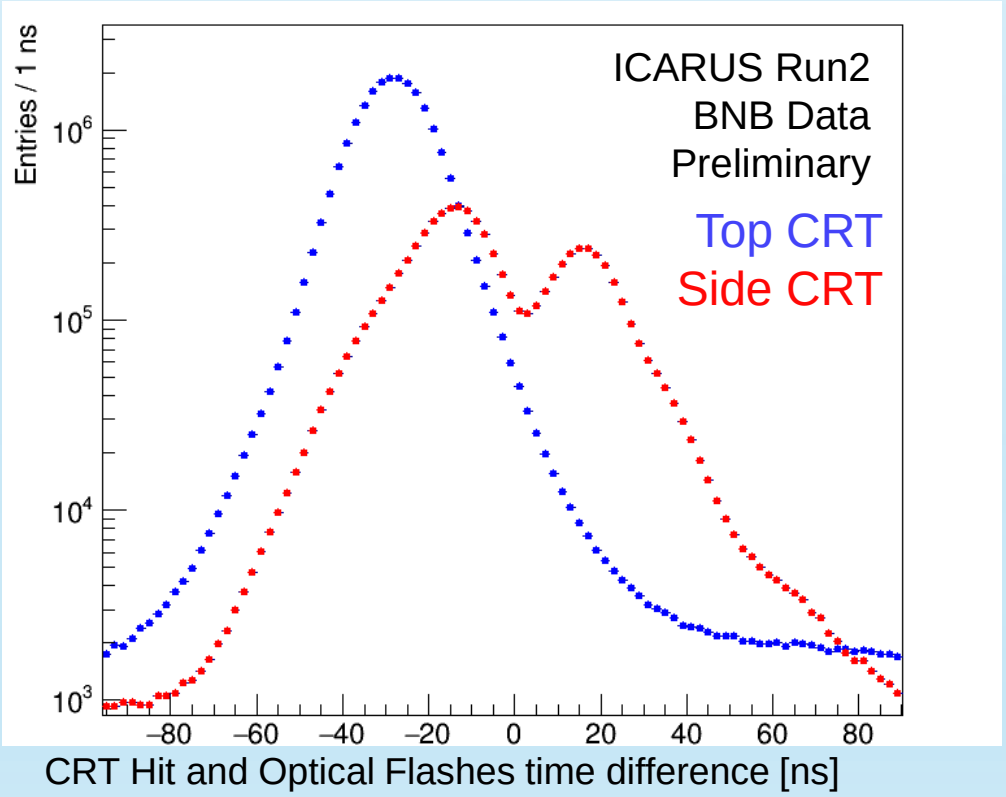
Some of the tools are already available, some are about to be released:

- Flash Barycenter matching (**available**);
- CRT-PMT matching* (**available**);
- CRT-TPC matching* (**available very soon**);
- Triple Matching* (**available soon**).
- (Light-based bunch structure selection (**partly available**).)

***Discussed in this presentation**

CRT-PMT Matching:

- The timing resolution of the CRT (~ns) and the PMT (<ns) systems and their synchronization by means of global event trigger allows to associate each reconstructed optical flash with one or more CRT hits using only timing information.
- The relative time difference allows to determine the direction of the «interaction»:
  - **Entering:** CRT Hit – Flash Time difference **<0** [ns];
  - **Exiting:** CRT Hit – Flash Time difference **>0** [ns].
- The random association between CRT hits and optical flashes was evaluated: <1%.



CRT-PMT Matching: in-time cosmics

- The majority of ICARUS triggered events are due to cosmic particles.
- By focusing the CRT-PMT analysis to only in-(beam)-time flashes, we can evaluate the origin of the triggered event ahead of the TPC reconstruction.
- The comparison between off-beam and on-beam data shows neutrino induced excess in the percentage of flash not matched with any CRT hit.

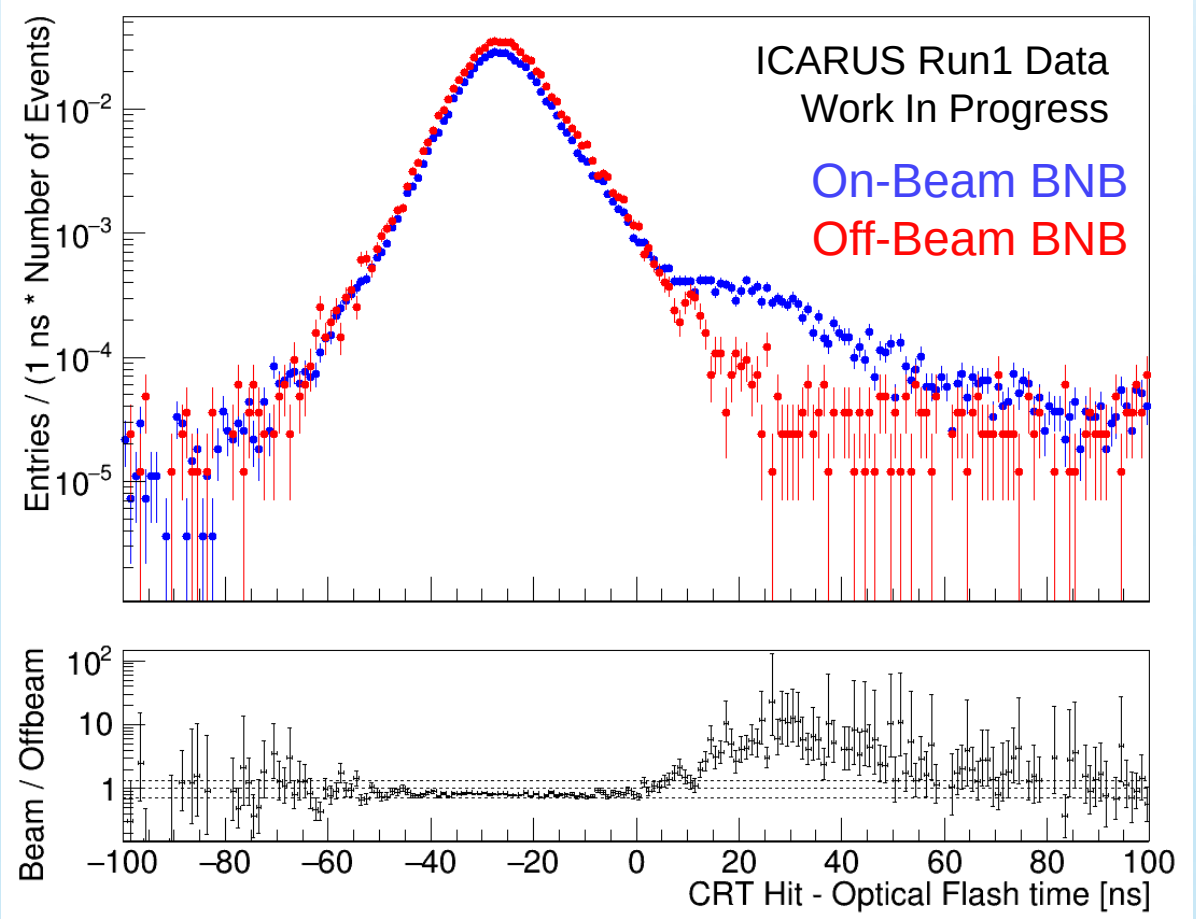
1 ν every **180** / **53** spills for **BNB** (1.6 μs) / **NuMI** (9.6 μs)

1 cosmic μ every **55** / **6** spills for **BNB** (1.6 μs) / **NuMI** (9.6 μs)

Classification	NuMI [%]		BNB [%]	
	OnBeam	OffBeam	OnBeam	OffBeam
No CRT match	39.0	12.7	32.4	12.3
1 Entering from Top	34.4	62.8	46.5	63.4
1 Entering from Side	10.7	10.5	8.5	10.5
1 Entering from Top 1 Exiting from Side	2.5	4.7	3.6	4.8
1 Exiting from Top	2.0	0.5	1.3	0.5
1 Exiting from Side	5.6	1.9	2.5	1.8
Others	5.8	6.9	5.3	6.7

CRT-PMT Matching: in-time cosmics

- The CRT-PMT matching can be also used to select an enriched sample of not fully contained neutrino interactions.
- Comparing the time differences between Top CRT and Flashes for Off-beam and On-beam shows an excess in the population of flashes followed by Top CRT hits.

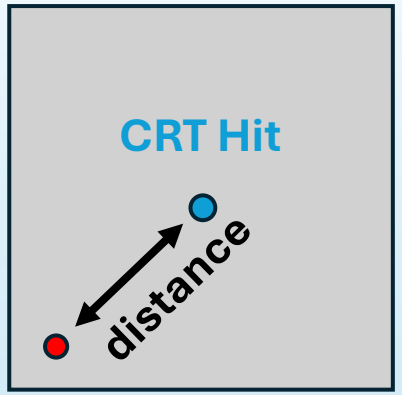


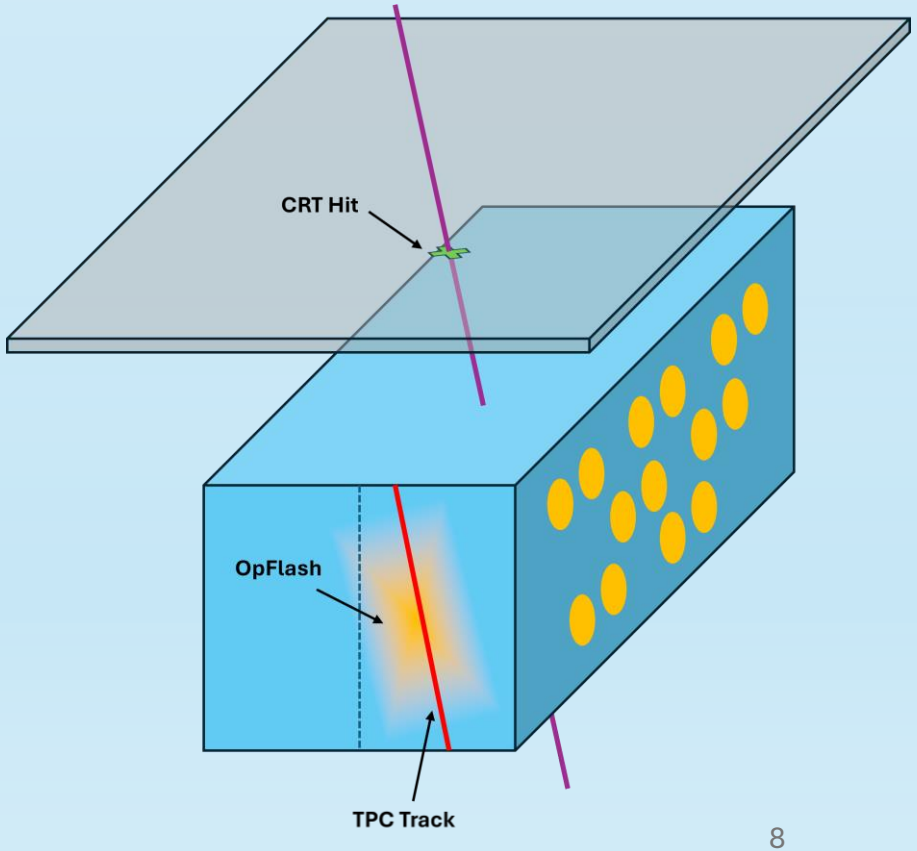
CRT-PMT Matching: summary

- The CRT-PMT matching analysis result is already available for analyzers.
- It is currently included in BNB analysis as a selection cut: only the events where the triggering flash is not matched with any CRT hit are preserved (CRT Veto).
- NuMI analyses currently do not include CRT-PMT cuts, studies are ongoing. Different effects are expected due to different signal definitions.
- Recently a bug was found in the matching analysis, the bug does not affect the «CRT Veto» cut. A Pull Request to address the issue is imminent.
- Additionally, a Filter Module was developed to pre-select interesting events on disk, based on the output of the CRT-PMT matching result. The filter is not enabled, but it can be in case of need.

CRT-TPC Matching:

- Tracks are 3D-reconstructed from the combination of signals in the three different wire planes, but drift coordinates can only be determined from the interaction time.
- The matching between a TPC track and a CRT Hit is performed by:
  - reconstructing the drift coordinates of the track assuming the CRT Hit time;
  - the displaced tracks are linearly fitted (PCA) to evaluate the cosine directors.
  - extrapolating the displaced track to the CRT Hit plane and evaluating their relative distance.



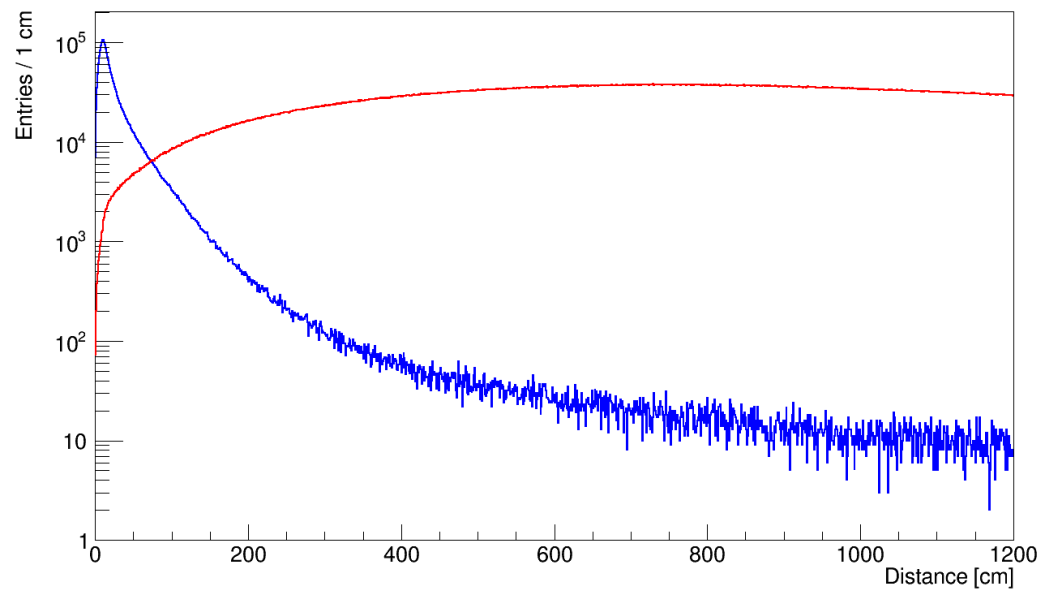


Developed by T. Boone and F. Poppi

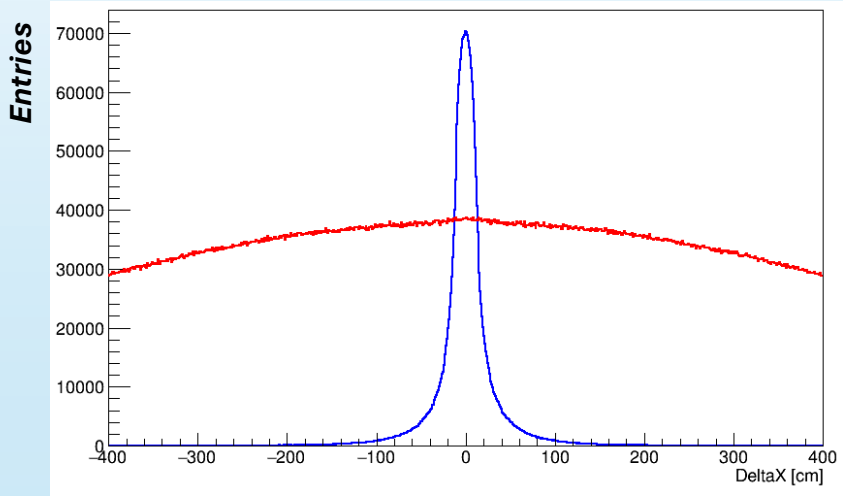
CRT-TPC Matching:

MC distributions of distances for **correct (Blue)** and **wrong (Red) associations**.
Correct is defined as TPC track and CRT hit associated with the same Geant4-ID; **Wrong** is a wrong association.

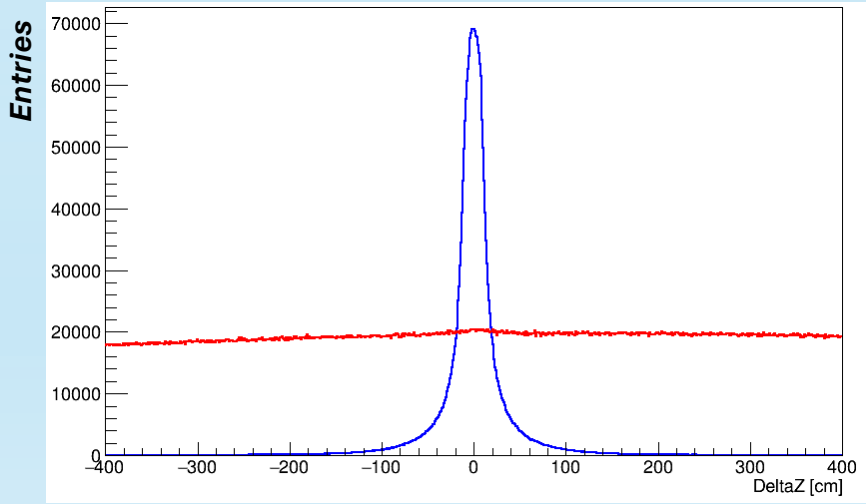
Top CRT Region 30 (Horizontal Plane): Distance



Top CRT Region 30 (Horizontal Plane): DX



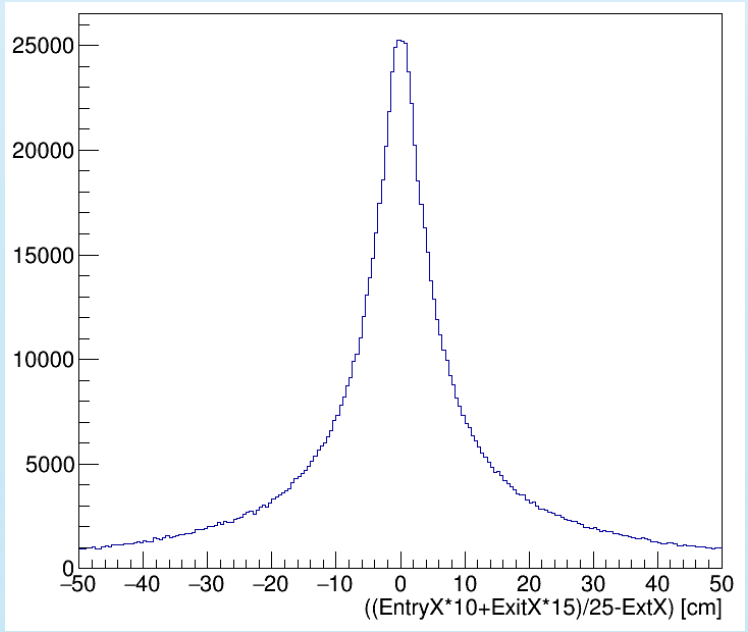
Top CRT Region 30 (Horizontal Plane): DZ



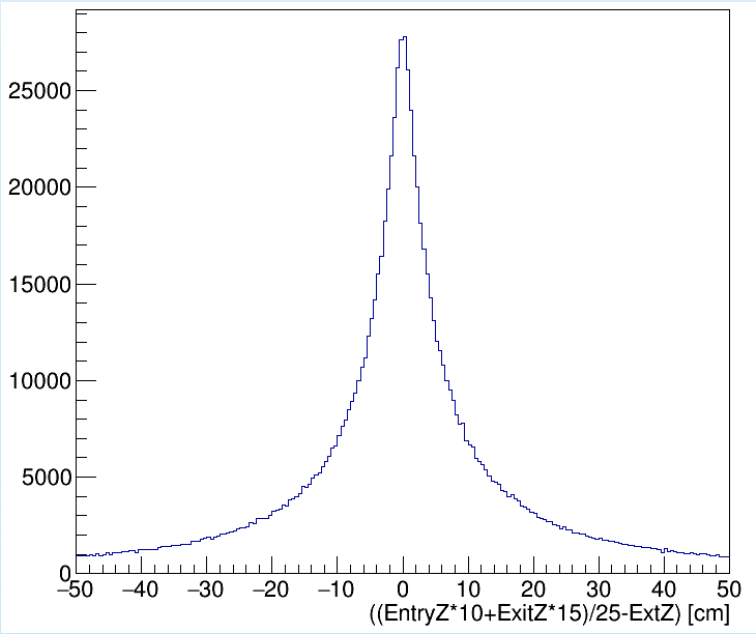
CRT-TPC Matching: extrapolation resolution

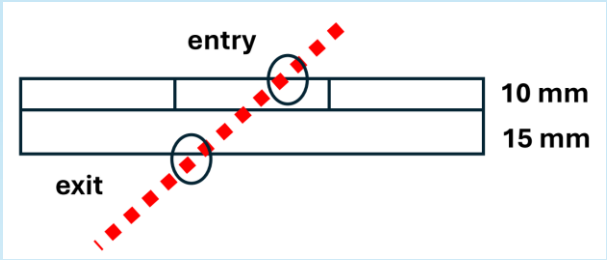
- The resolution of the extrapolation algorithm was evaluated by comparing the extrapolated track crossing point in the CRT Hit plane and the MC truth.
- This exercise was performed for the Top CRT. The residual **FWHM** is **8.5 cm** along Z and **10.5 cm** along X.

Truth crossing X – Ext crossing X (Top CRT)



Truth crossing Z – Ext crossing Z (Top CRT)





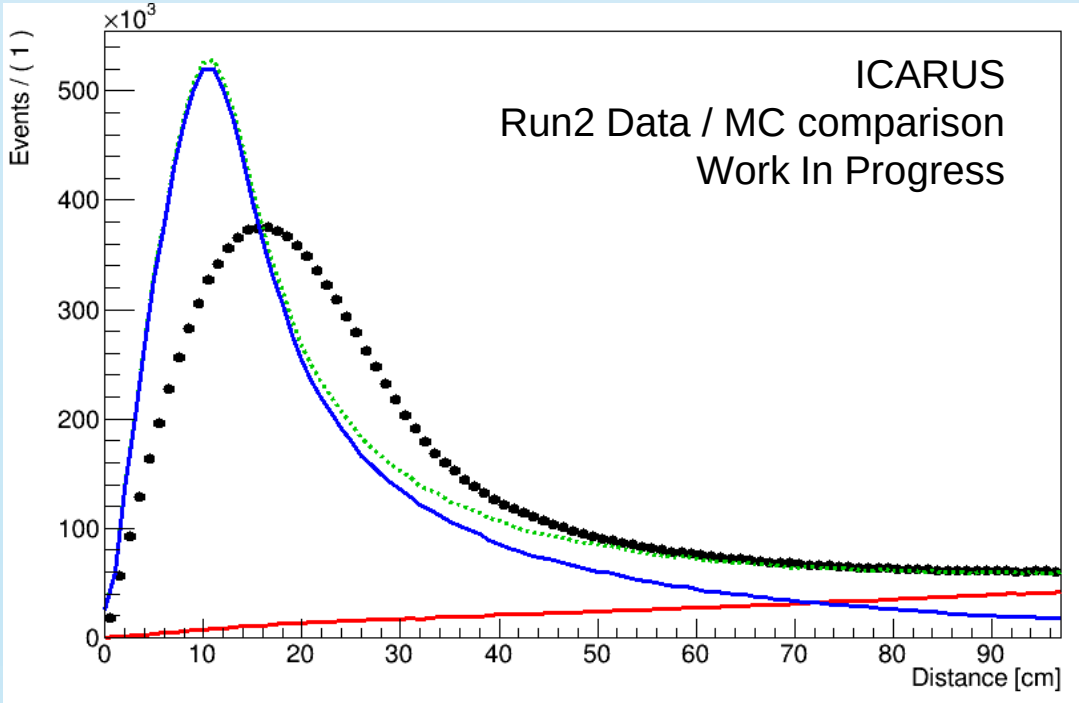
CRT-TPC Matching: data misalignments

- The reconstructed CRT Hit position relies on the CRT modules position in the nominal ICARUS geometry. No geometrical survey was performed following the Top CRT installation, therefore misalignments are expected.

- Misalignments due to installation show up when doing data (misaligned) and MC (aligned) comparisons.

- **Data** from Run2 BNB Majority (**black**) was fitted with **MC Correct*** (**Blue**) plus **MC Wrong*** (**Red**) **model** (**green**).

Top CRT Region 30 (Horizontal Plane): Distance



***Correct** is defined as TPC track and CRT hit associated with the same Geant4-ID; **Wrong** is a wrong association.

CRT-TPC Matching: data aligments

- The data-MC misalignments show a clear disagreement along the Z directions, but other effets (e.g. small rotations, shrinkage, offsets, ...) cannot be excluded.

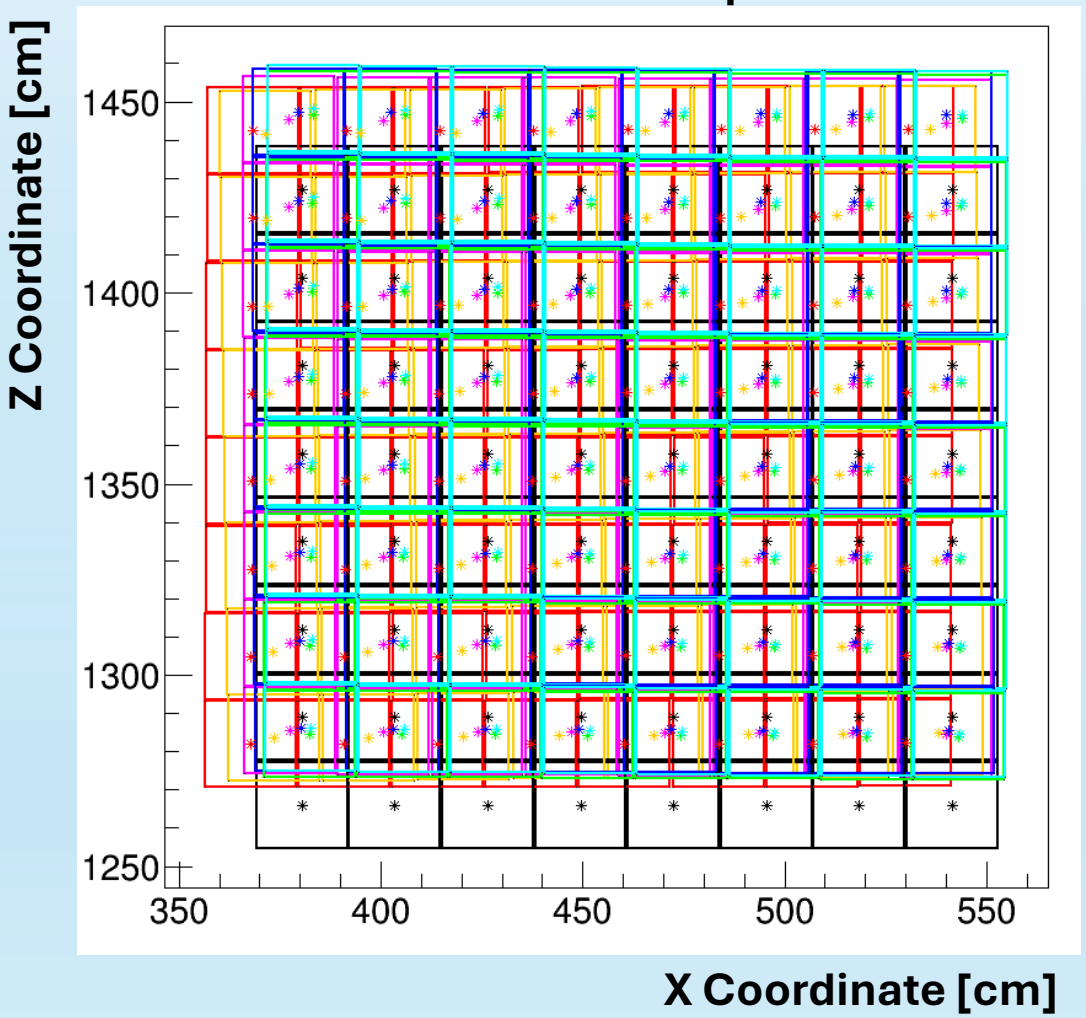
- In order to address the alignment of the Top CRT to the different TPCs, a dataset of run-2 Top CRT matched tracks was obtained. The alignment dataset was used to evaluate affine transformation parameters (2 offsets, 2 angles and 2 scale changes) per each module.

Recostructed modules coordinates:

Nominal Z/X

Aligned to East CC
Aligned to East EE
Aligned to East EW

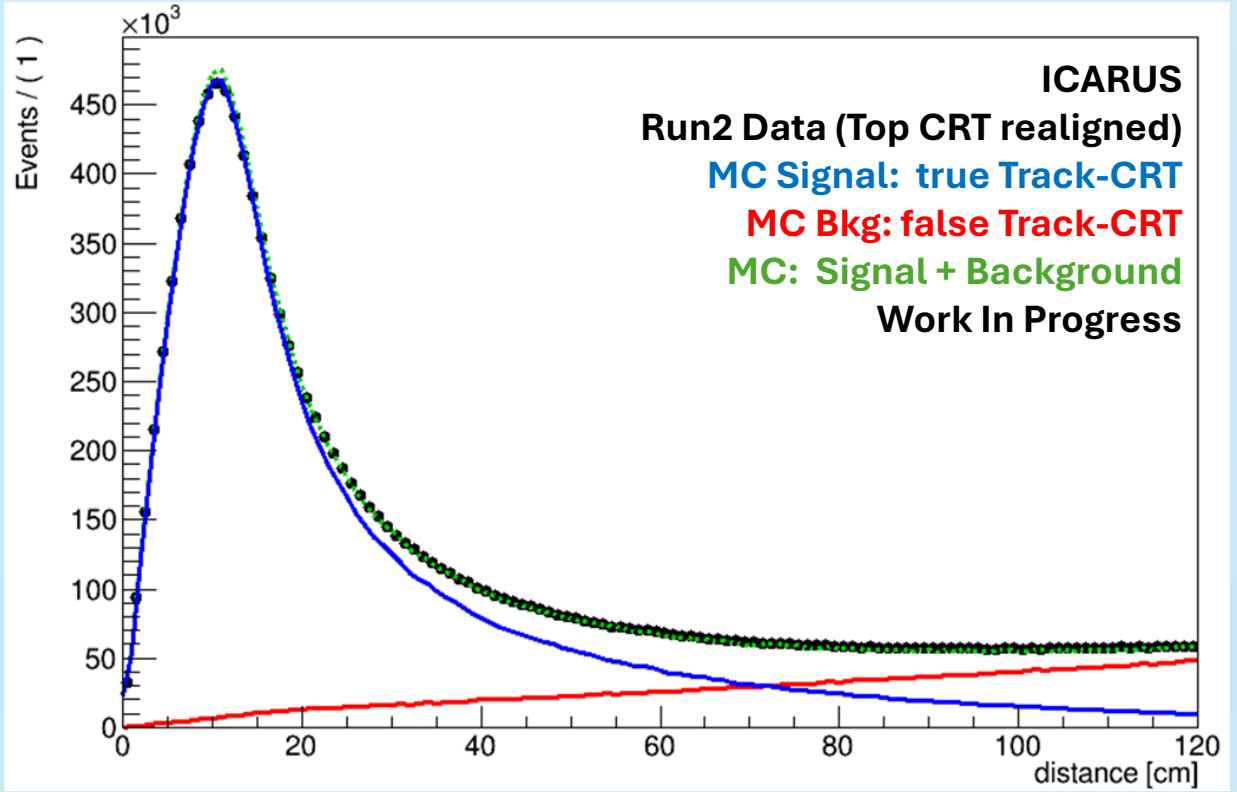
Aligned to West CC
Aligned to West WE
Aligned to West WW



CRT-TPC Matching: data aligments

- To test the alignment, the Top CRT Hits – Extrapolated track distance was re-evaluated after the application of the affine transformation.
- Data and MC comparison shows excellent agreement after alignment.
- The Top CRT alignment work is still ongoing, it needs to be re-evaluated after Run 3 processing and the transformation consistency has to be checked.

Top CRT Region 30 (Horizontal Plane): Distance



CRT-TPC Matching: selection efficiency

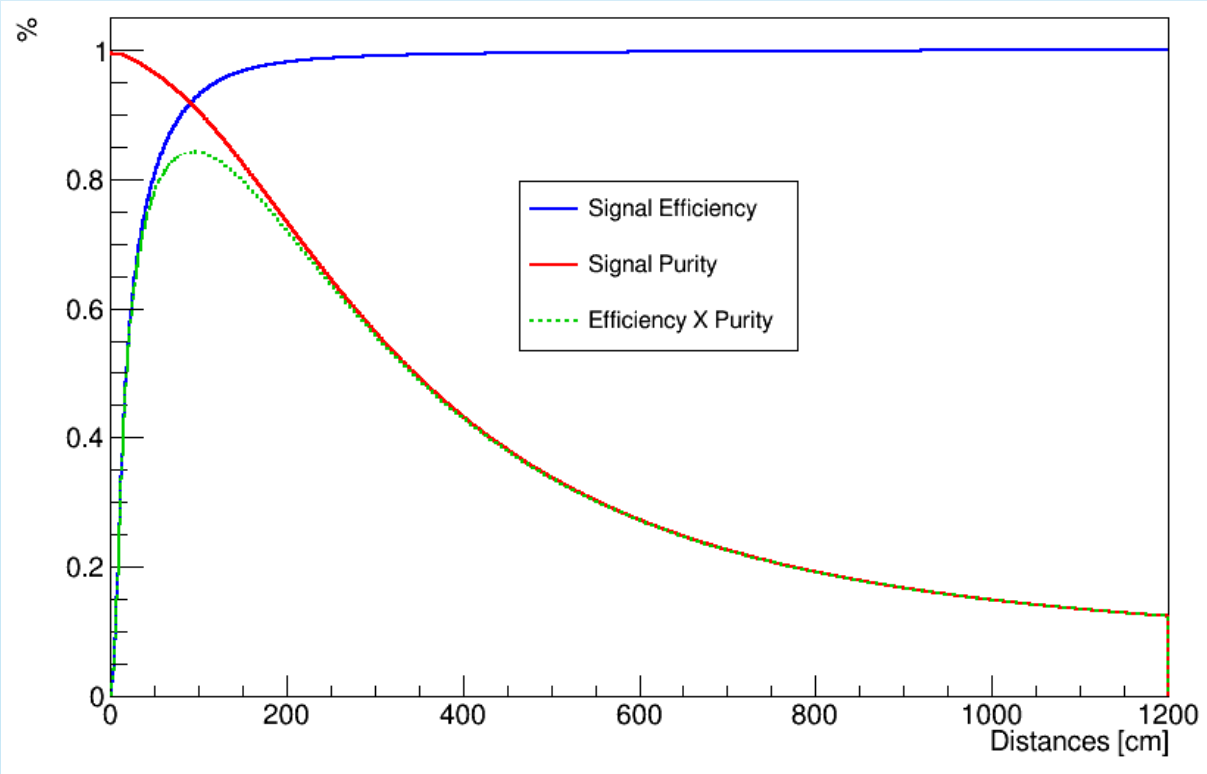
- The good Data/MC agreement corroborates the possibility to use properly scaled MC to evaluate efficiency and purity of the CRT-TPC matching as a function of distance variable.

- Some minimal quality cuts are considered in this analysis:
  1. track Length > 40 cm;
  2. number of good track hit points > 5;
  3. time compatibility of track and CRT Hit.

- A 95 cm cut on the distance variable results in efficiency of 92.3% and purity of 91.2%.

- With a 40 cm cut: efficiency > 79% and purity > 97.5%.

Matching Efficiency and Purity (Top CRT only)



signal=*distance between CRT Hit and extrapolated track from same particle at truth level.*
background=*distance between CRT Hit and extrapolated track from different particles at truth level.*

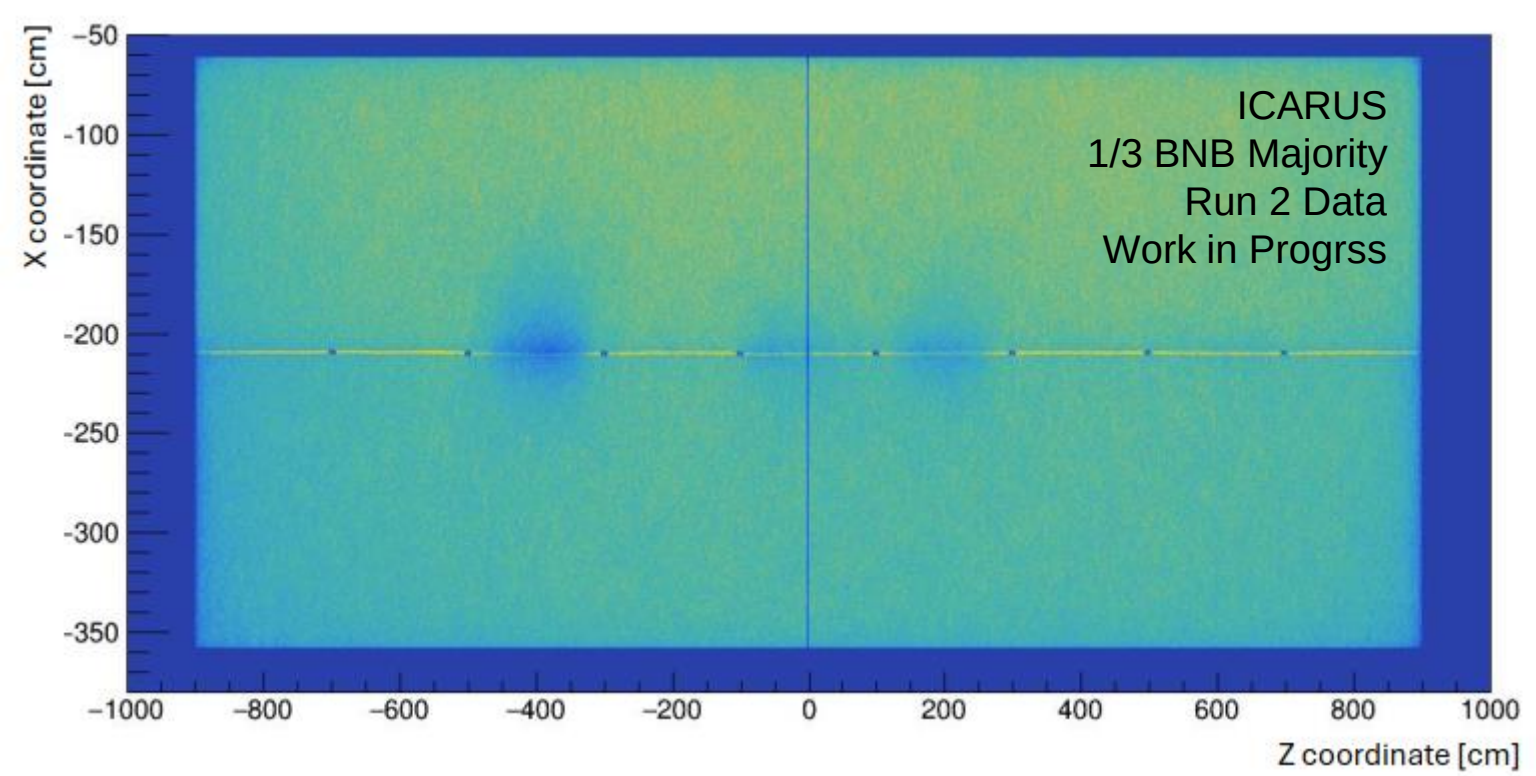
CRT-TPC Matching: some applications

- A CRT-TPC matching with high purity can be extremely useful for calibration purposes, mapping the whole drift coordinates with high statistics.

- Some application have been presented at the Calibration WG meeting and could be exploited for evaluation of Data/MC systematic differences.

- More studies are ongoing and will be performed once CRT-TPC matching will be available for the whole collaboration.

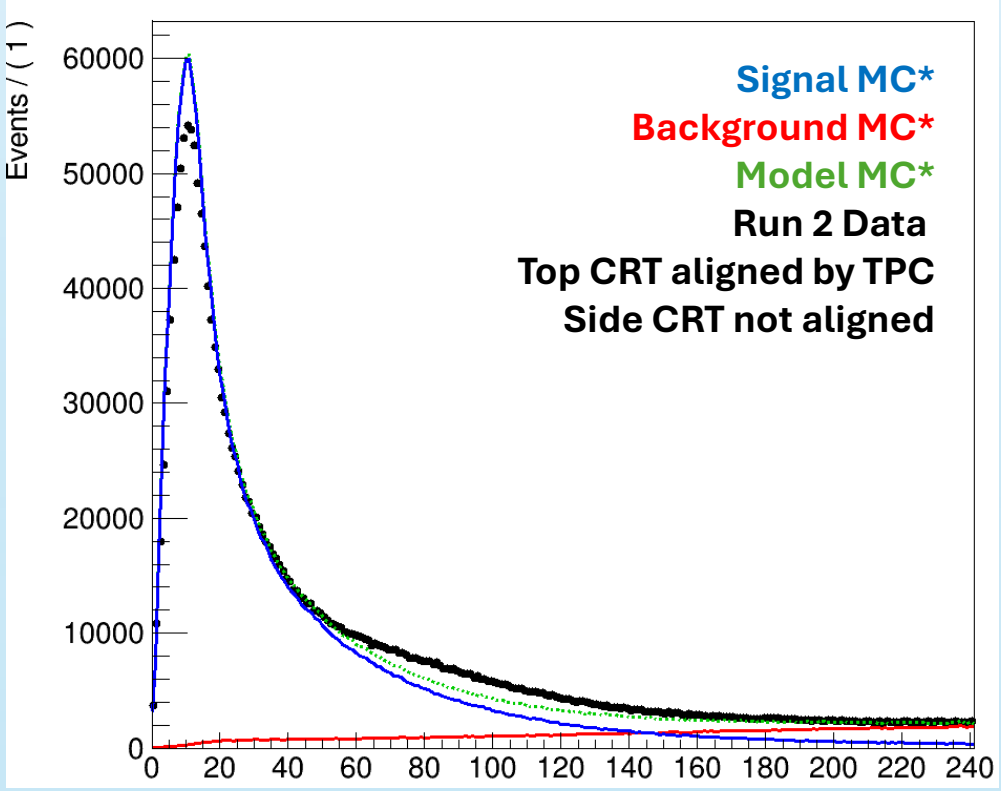
TPC tracks hit points distribution in the XZ plane



CRT-TPC Matching: Top+Side CRTs

- So far, CRT-TPC matching distributions only included Top CRTs because following alignment it shows very good Data/MC agreement.
- Side CRT Hits have bigger data/MC differences which seem specific of the different walls.
- During the summer, a measurement campaign was performed by Anna on the Side CRT hardware, which will allow to improve the Side Hit reconstruction and its agreement with MC.

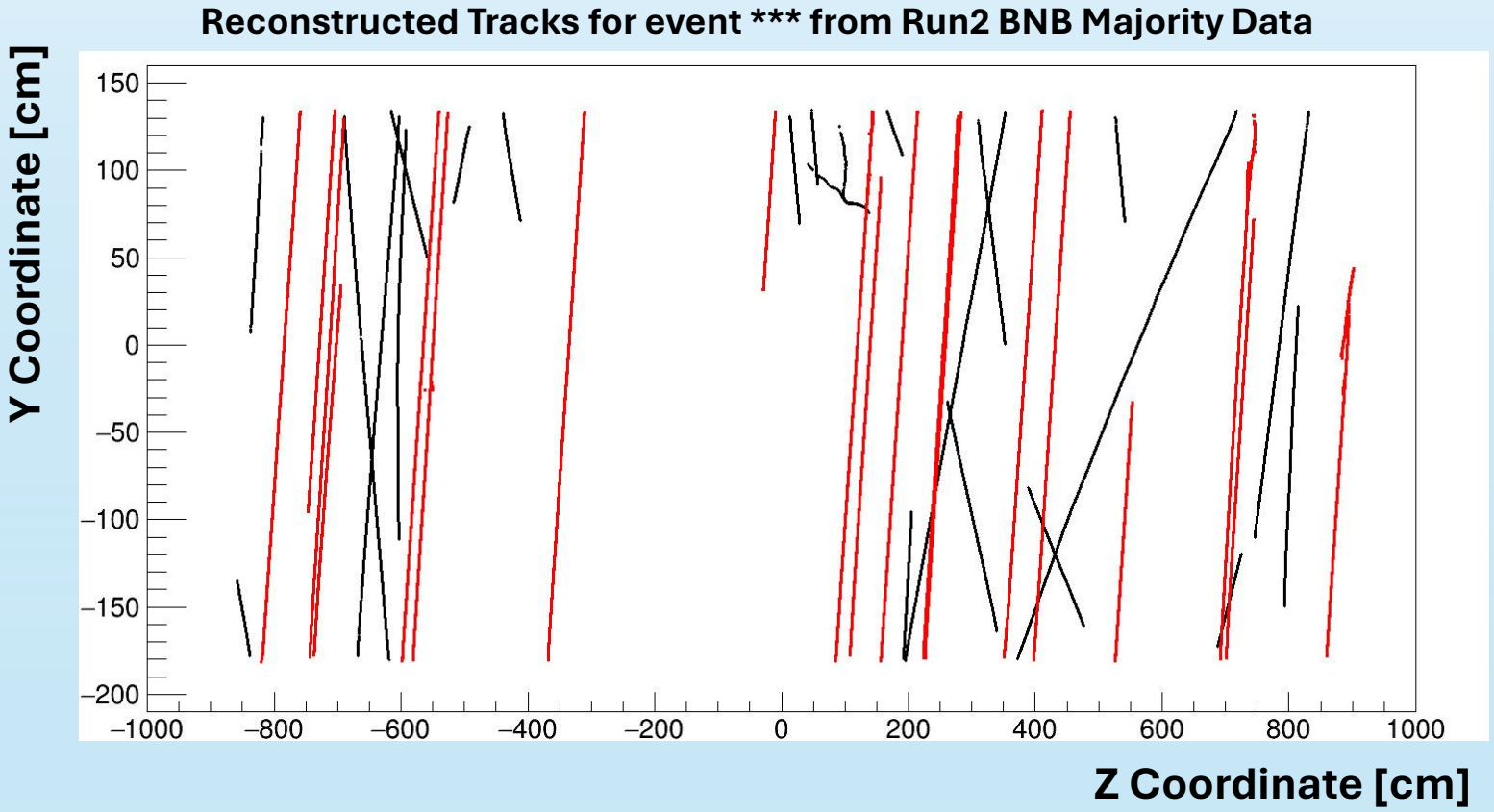
Top + Side CRT: Distance



***Signal** is defined as TPC track and CRT hit associated with the same Geant4-ID; **Background** is a wrong association.

CRT-TPC Matching: some applications

- As an exercise, the CRT-TPC matching was exploited to identify events with muon bundles.
- The selection was performed by looking for events with multiple tracks matched with different Top CRT Hits within 1 microsecond.
- Some of the selected events were visually studied to verify the selection.



Legend: ***Black*** *all track hit points;* ***Red*** *tracks matched with different Top CRT hits within 1microsecond.*

CRT-TPC Matching: next stpes

- The CRT-TPC matching algorithm was fully developed in ICARUSCODE, based on the previous work from Dr. T. Boone.
- CRT-TPC matching will include Side CRTs nontheless, but the best results are expected after Side CRT calibration and re-alignement.
- As a first step, the CRT-TPC matching will be soon included in the common code, a first pull request is expected this week. The pull request will include the matching algorithm and the construction of a T0-object based on the matching selection.
- Following the first step, discussion with Calibration experts are needed to include CRT-Tagged tracks in the calibration ntuples. The CRT-TPC matching will be included in the CAF files, and tested in the analysis framework.
- The CRT-TPC matching selection was tested on the events selected by Maria Artero‘s NuMu selected events on Run 9436, and <3% of the muon candidates where wrongly matched with a CRT Hit (<1% for Top CRT), but this study needs to be re-evaluated.

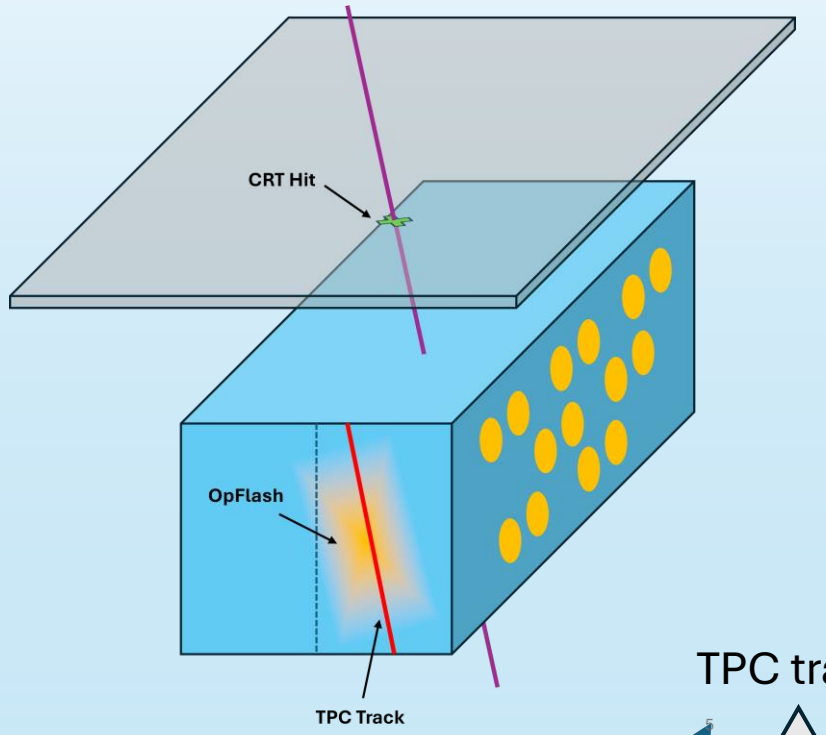
Developed by F. Poppi and R. J. Campos

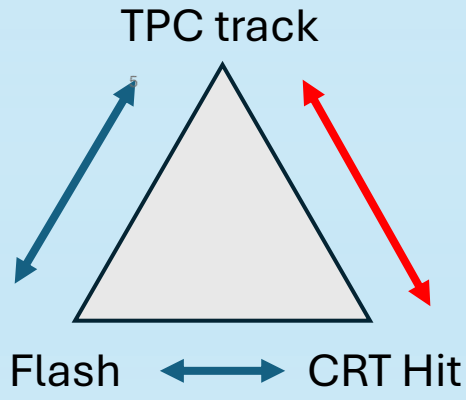
Triple Matching:

- A combination of all the already developed tools (Flash-barycenter matching, CRT-PMT matching and CRT-TPC matching) can be exploited to match a reconstructed TPC track with a timestamp (CRT or Flash) and determine the track direction from the CRT-PMT time difference.

- This combined multi-detector analysis («Triple matching») works by testing a reconstructed TPC track with an optical flash by means of their barycenter distances and the CRT hits already associated with that flash.

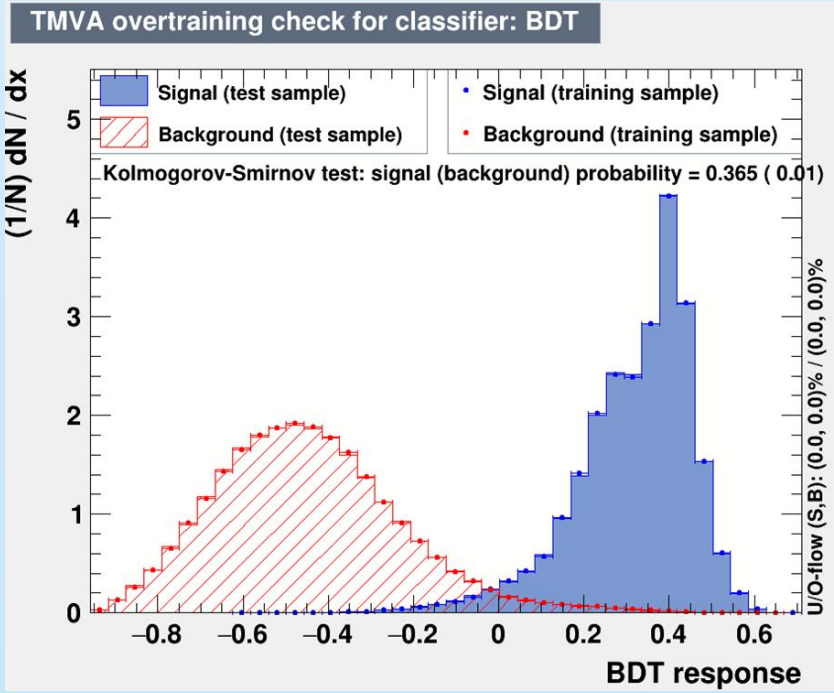
- The «triple-matching» was perfomed using a multi-variate approach (initially a Boosted Decision Tree) on several variables coming from CRT-TPC, CRT-PMT or Flash Barycenter related variables.





Triple Matching: first results…

- The Boosted Decision Tree training and analysis was performed by Ricardo Campos (Bologna Master Degree student) using the TMVA toolkit from Root.
- Initially a Boosted Decision Tree was trained on MC to classify **Signal** (correctly associated Track – Flash – CRT hit at truth level) and **Background** (random matches).
- The BDT was trained on several variables: *track length*, *track direction*, *drifted track Start/End*, *Flash time*, *distance between Charge-Light Barycenters*, *CRT-Extrapolation distances*, *flight length* and *CRT-PMT time difference/Flight length*.
- The results showed Signal classification efficiency and purity both 95%.

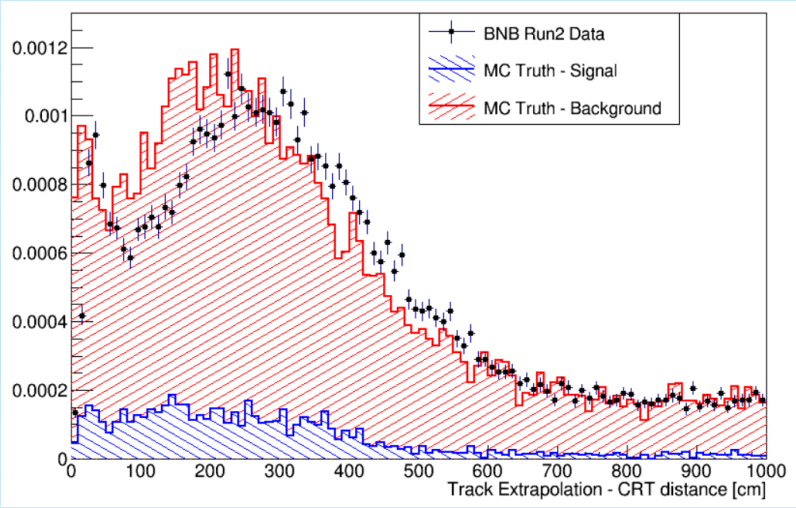


Signal *(correctly associated Track – Flash – CRT hit at truth level) and* ***Background*** *(random matches).*

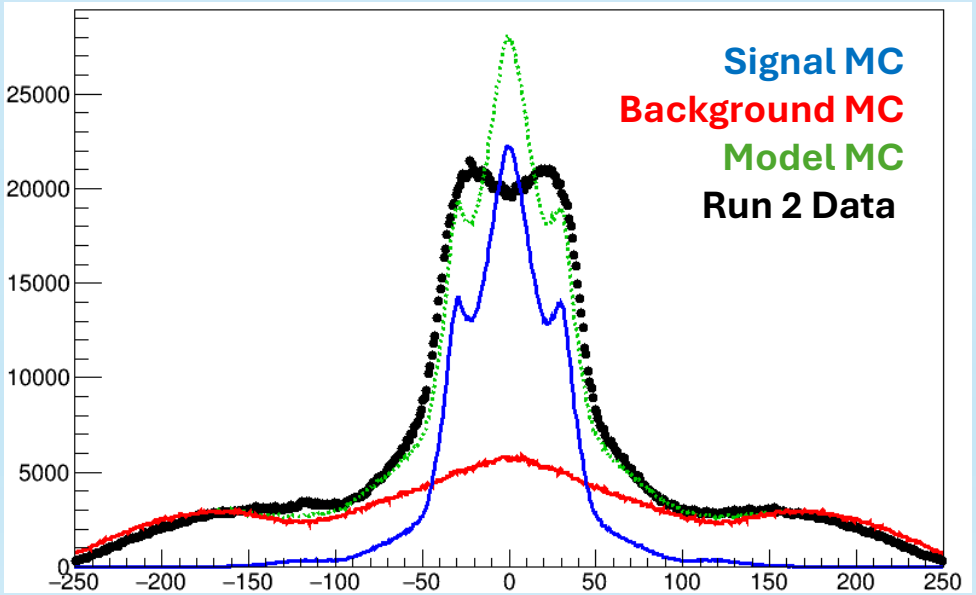
Triple Matching: … and hiccups.

- After the training of the BDT was performed and tested on MC, the algorithm was applied to Run2 BNB Majority data.
- Unfortunatly, some of the variables showed sub-optimal data-MC agreements (note, that the training was performed before the Top CRT alignment).

Side CRT: track extrapolation CRT distance



Charge-Light barycenter: Delta X



Triple Matching: Next steps

- The Triple Matching algorithm will soon be revised, a new Boosted Decision Tree (or Neural Network) will be trained on variables which show good data-MC agreement.
- The implementation of the Triple-matching algorithm «should» not take long: the analysis module has already been developed on icaruscode, and the outcome is expected to be similar to the CRT-TPC matching one.
- The timeline can vary on the needs of the collaboration: when is the next big production? Realistically: December.

Conclusion:

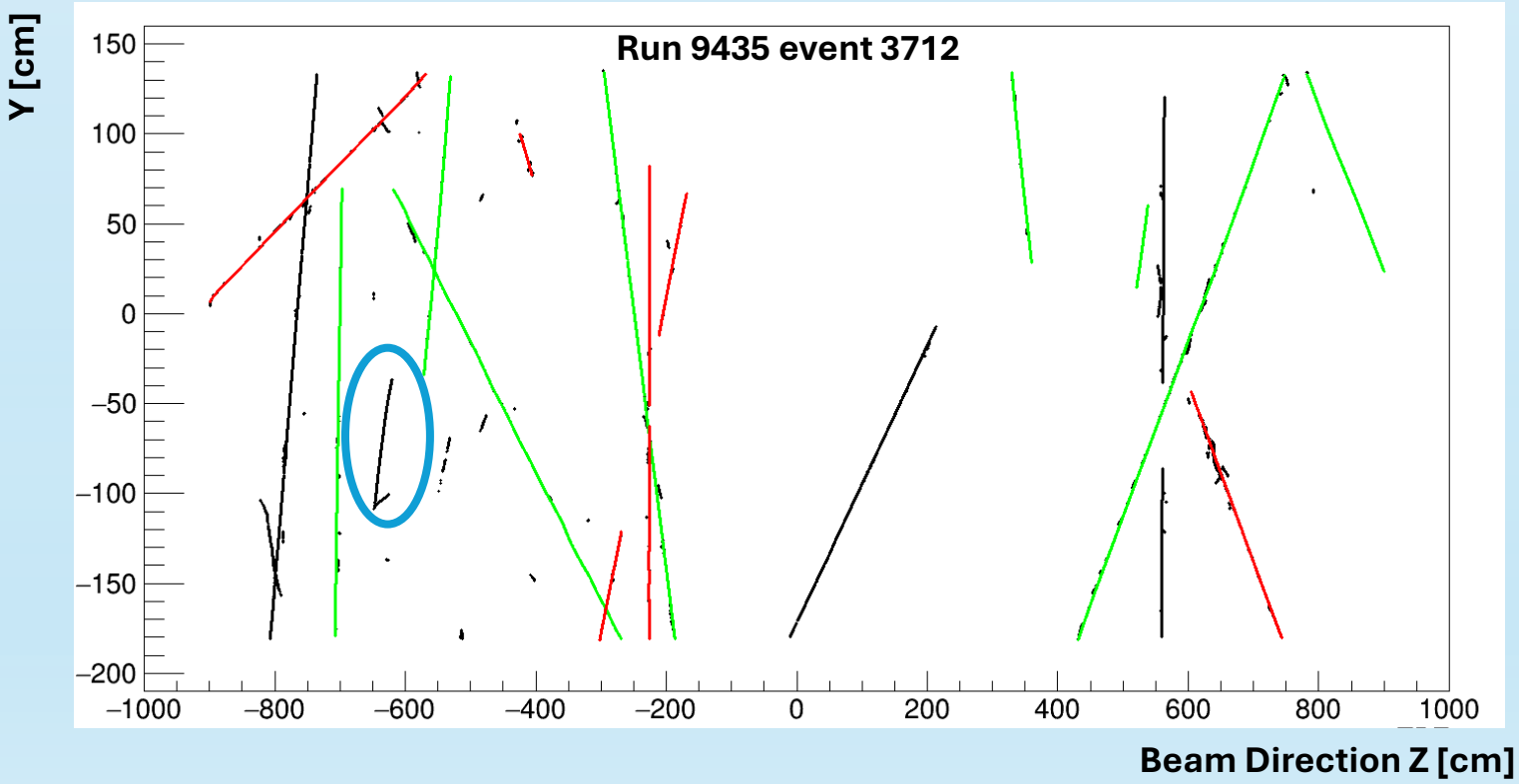
- Several cosmic identification tools have been developed and some of their possible applications have been presented.

- The different tools aim to address different cosmic background components:
  - CRT-PMT matching allows the rejection of the in-time cosmics;
  - Flash Barycenter matching selects slices which are compatible with the triggering flash;
  - CRT-TPC matching allows to assign a timing to tracks determined by out-of-time cosmic interactions;
  - Triple-matching would merge all these tools to determine TPC-Flash-CRT triplets.

- Some of these tools (CRT-PMT and Flash Barycenter) are already available for analyzers, the other tools will be soon included in icaruscode.

Thank you for the attention!

Example of how an ICARUS neutrino triggered event would look after CRT-TPC track rejection.



- **Green** Tracks are tracks matched with Top CRT Hits;
- **Red** Tracks are tracks matched with Side CRT Hits;
- **Black** are tracks not matched with any CRT.