Tagging cosmic ray background in the Icarus detector

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Final Report, Summer Students at Fermilab program

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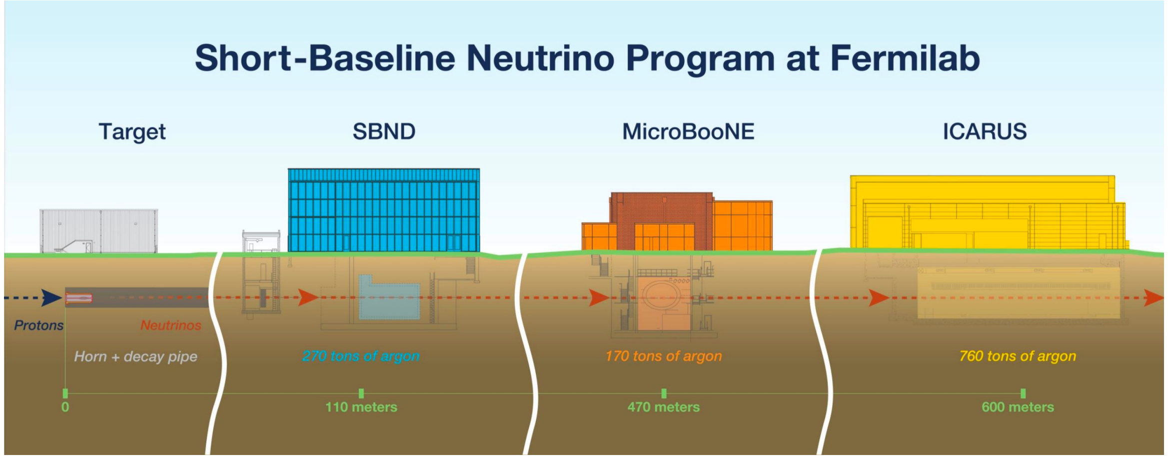
The Sort Baseline Neutrino program (SBN)

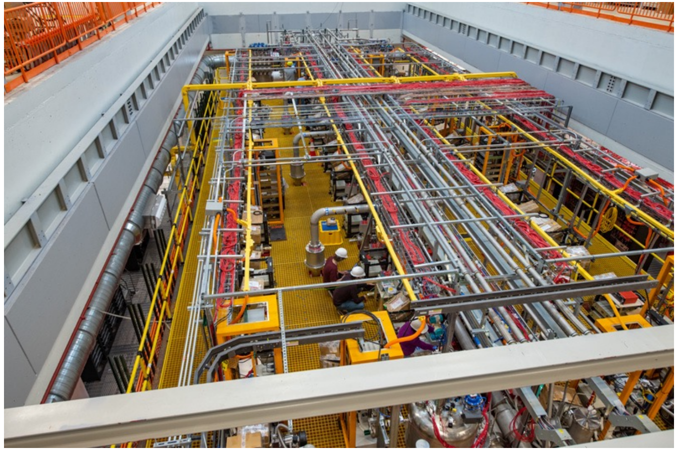
- Main aim: solving the remaining sterile neutrino oscillation anomalies.
- Three LArTPC-based detectors with baselines between 100 and 600 m, allowing to:
  - reach excellent neutrino identification to reduce the backgrounds.
  - reduce the systematics to the % level.
- The detectors will operate on neutrinos from the BNB (on-axis) and NuMI beams (used by Icarus for Neutrino-4 investigation).



Cutaway scheme of the neutrino beamline and of the SBN detectors.

The ICARUS detector

- Refurbished at CERN between 2016 and 2018.
- Neutrino events collected since the end of March 2021 from both beams.
- Four LarTPCs, two in each of the two cryostats (476 tons of active LAr volume):
    - Timing resolution of ~1 ns.
    - Spatial resolution of ~50 mm.
- Newly installed Cosmic Ray Tagger system to mitigate the cosmic ray background.



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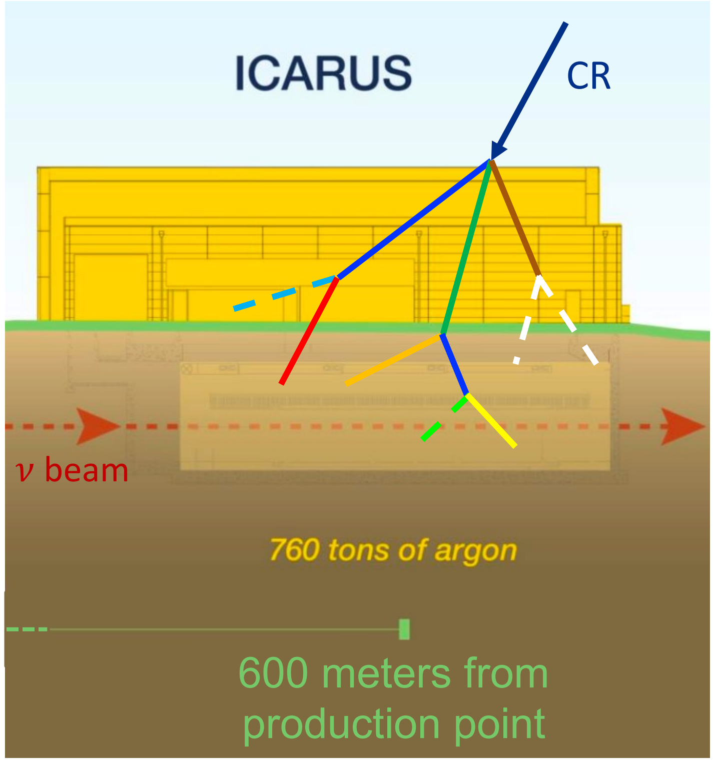
The Cosmic Background at ICARUS

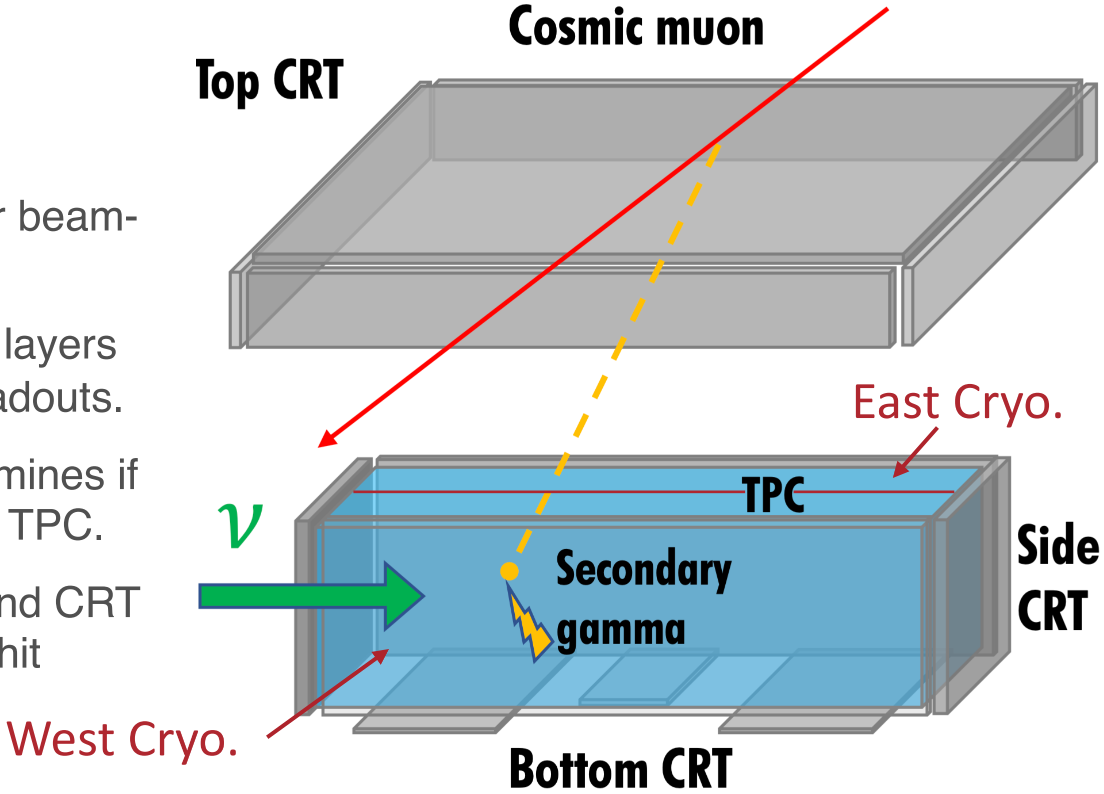
- ICARUS will be exposed to a huge Cosmic ray activity (11 kHz rate):
  - In-time activity: particles entering the detector during the **Beam Spill**.
  - Out-of-time activity: particles entering the detector during the **drift time**.
- CR background will be mitigated as much as possible by:
  - A 3 m concrete overburden (6 m water equivalent)
  - Coverage of the detector by **Cosmic Ray Tagging (CRT) modules**: Side and Top CRT systems are currently in operation.



Cutaway of the ICARUS detector showing Cosmic Ray (CR) activity.

The CRT system

- Capable of tagging 95% of cosmic or beam-induced muons.
- Both Top and Side CRTs use double layers of scintillator detectors with SiPM readouts.
- CRT Hit – PMT flash matching determines if the muon was exiting or entering the TPC.
- Consistent timing between all TPC and CRT elements must be achieved to allow hit matching and CR discrimination.



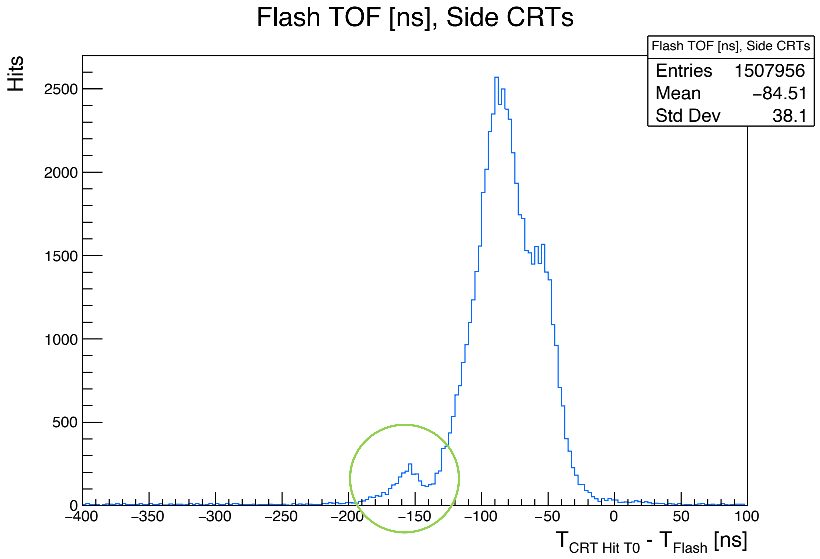
Cutaway scheme of the ICARUS TPCs and CRT system modules.

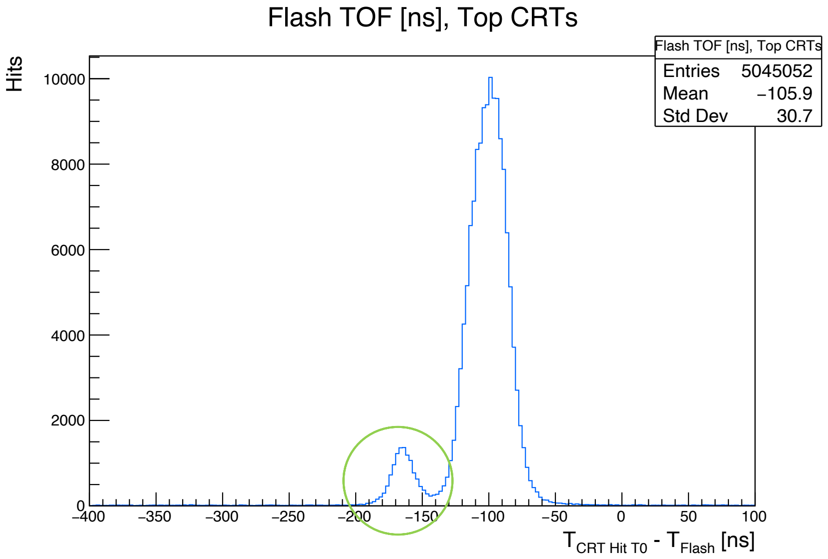
Activities by the end of August

- I had been working on the analysis of the CRT timing using ICARUS run data to gain an understanding of:
  - The design of the CRT system and of potential sources of delay.
  - The quantities at play in timing measurements (T0, T1, trigger time, gate start time…).
  - The processing and analysis procedures and the structure of the data.
- I obtained the relevant distributions for timing for a sample of 16419 NuMI beam events from run 8530 of ICARUS (July 3^{rd}-5^{th} 2022) and compared them to previous results with BNB event datasets.
- Performed a measurement of the delay of the T1 reset signal along the distribution path for the East and West Side CRT Timing Distribution Units (TDU).

Time of Flight distributions

- 16419 NuMI beam events from run 8530.
- Obtained the ToF distributions for the Side and Top CRTs: $ToF = T_{Hit} - T_{Flash}$.
- Double peak for the Side CRT and Single peak for Top CRT are expected due to event topology.
- Smaller highlighted peaks are possibly due to wrong calibration of some channels in the East cryostat.





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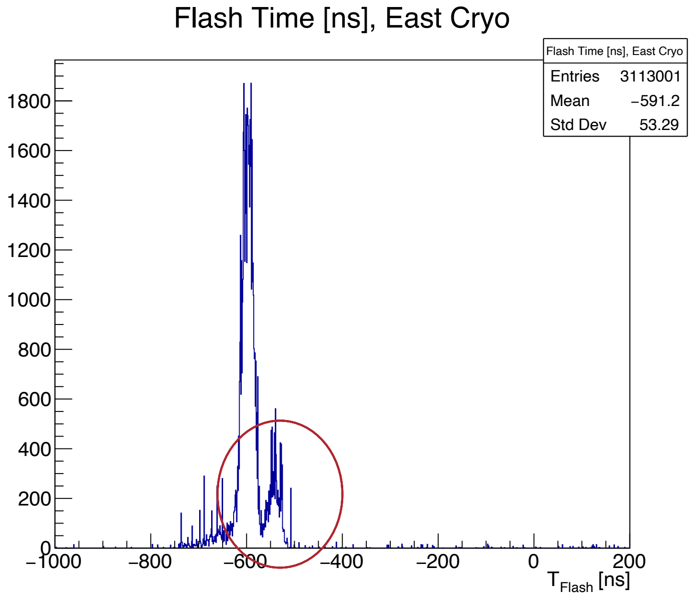
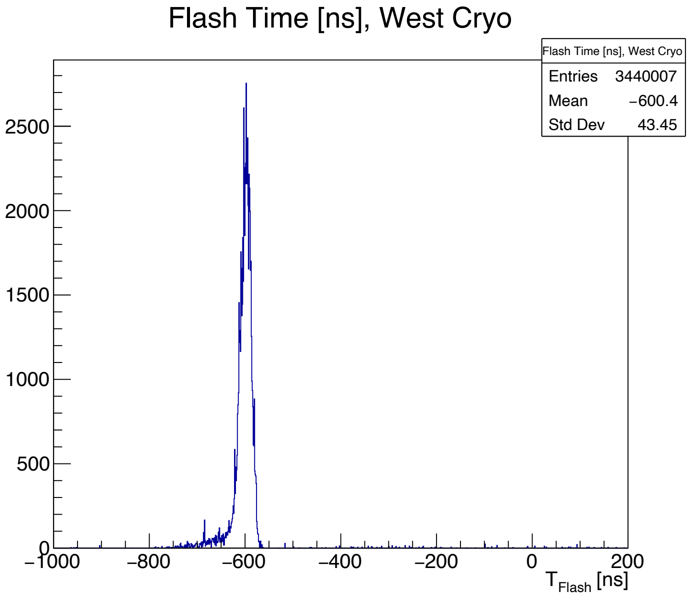
On the ToF distributions

- The Flash time distributions for the East and West Cryostats were obtained.
- The East Cryostat shows a secondary peak, believed to be the origin of the previous peaks.
- The discrepancy might be due to the wrong calibration of some channels in the East cryostat.

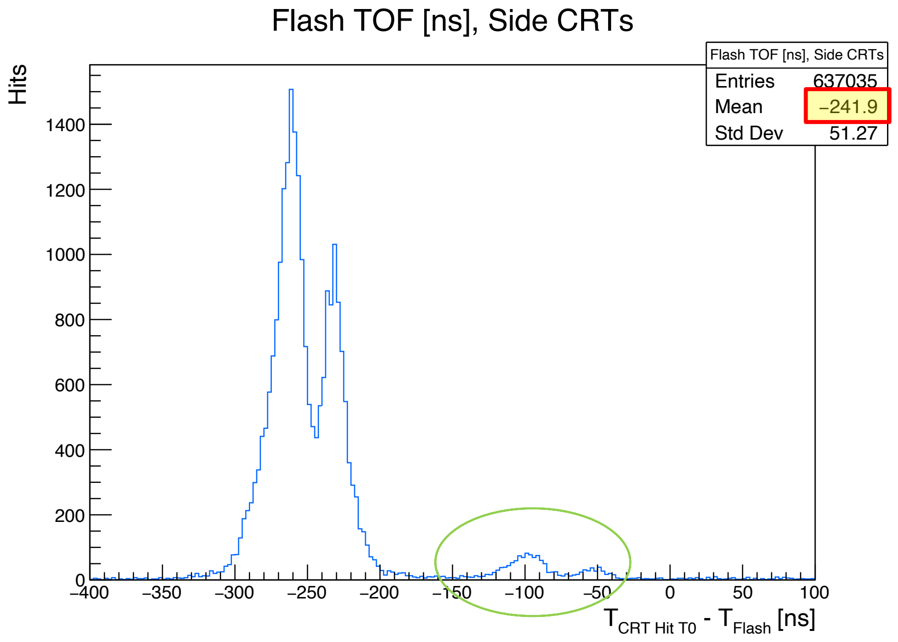


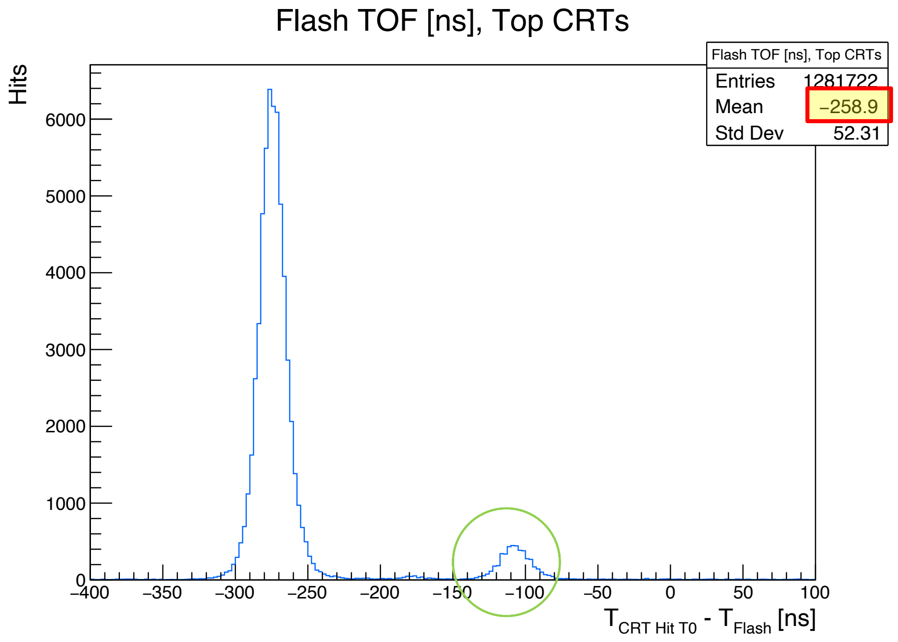


Follow-up and new activities

Follow-up on the CRT timing measurements

- Updated timing corrections were released in the past few days, including the PMT channel corrections.
- Subset of the same NuMI beam events from run 8530 of ICARUS (July 3rd-5th 2022).
- Work is still ongoing to implement the updates: local Icaruscode install (v09_58_02_01) does not pick up the corrections.





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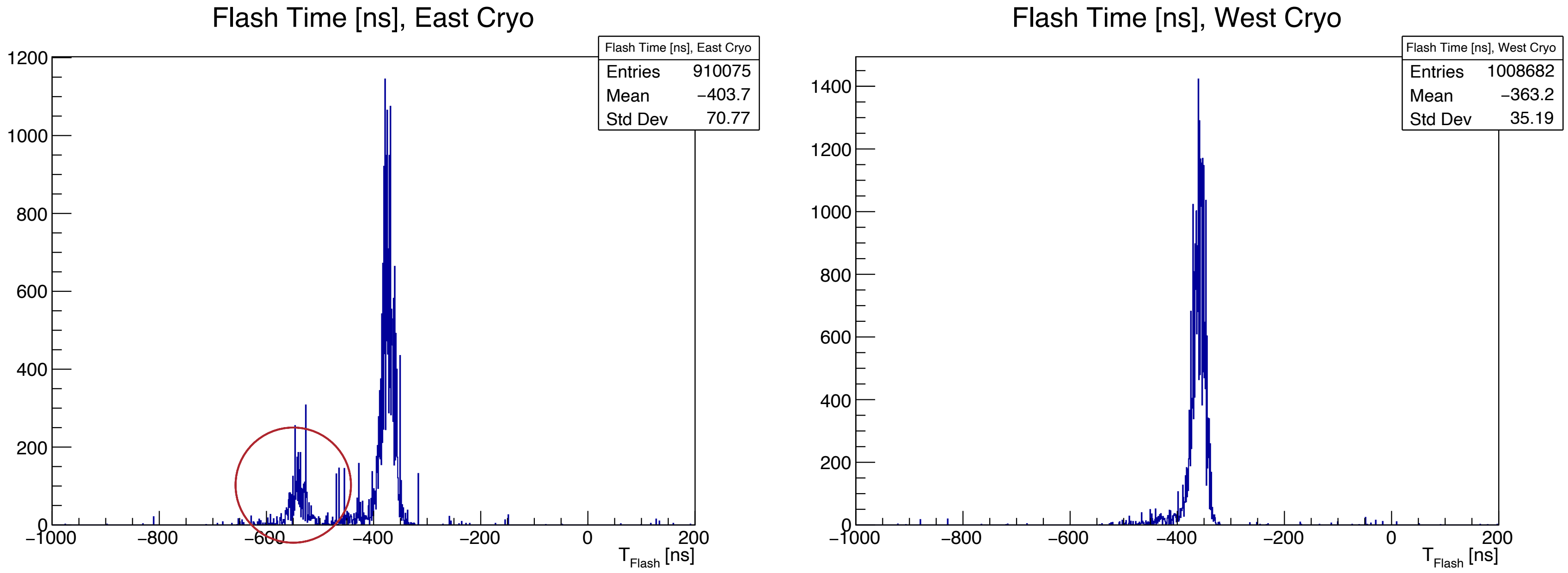
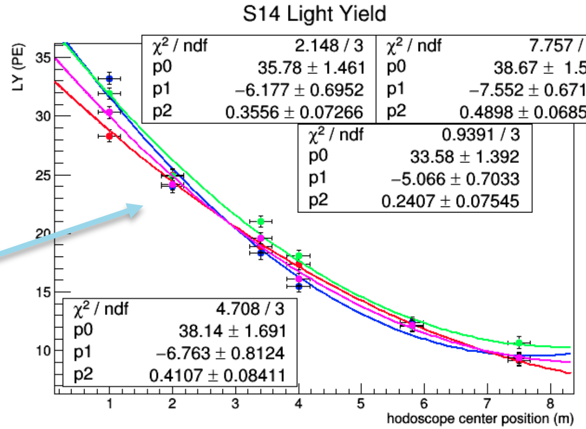
Follow-up on the CRT timing measurements (2)

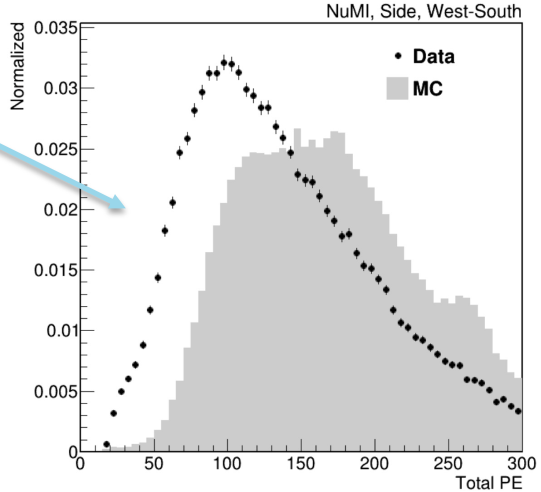
- Again Flash time distributions for the East and West Cryostats were obtained.
- The East Cryostat shows a secondary peak, believed to be the origin of the previous peaks.
- The discrepancy might be due to the wrong calibration of some channels in the East cryostat.

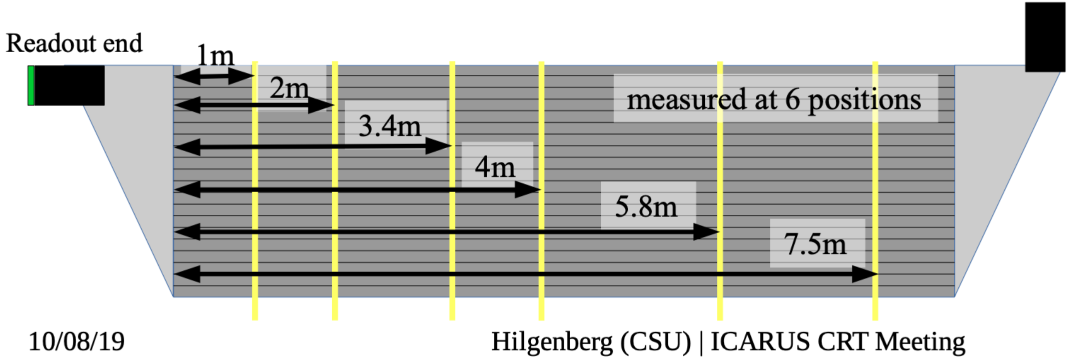


Light yield calibration of the Side CRT

- The response in photons (Pe) wrt. the z coordinate of the hit must be calibrated for consistent MC.
- Data from a test-stand have been used so far:
  - Pe vs. z response for a single end of the module.
  - Quadratic decrease with the distance from the readout.
- But the MC Pe distributions do not match exactly the data.







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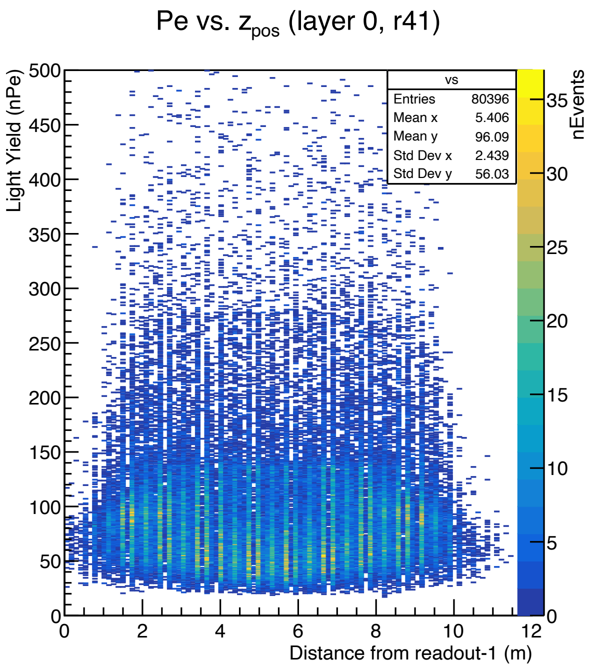
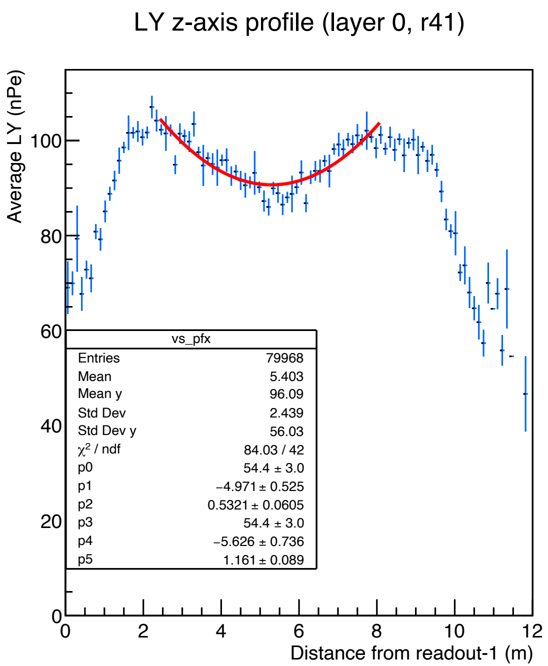
Light yield calibration of the Side CRT

- A calibration measurement using run data would be preferable.
- Two readouts are active in this case.
- The $Pe(z)$ profile of a CRT module can be fitted as a sum of parabolas $Pe(z) = P_1(z) + P_2(8m - z)$.





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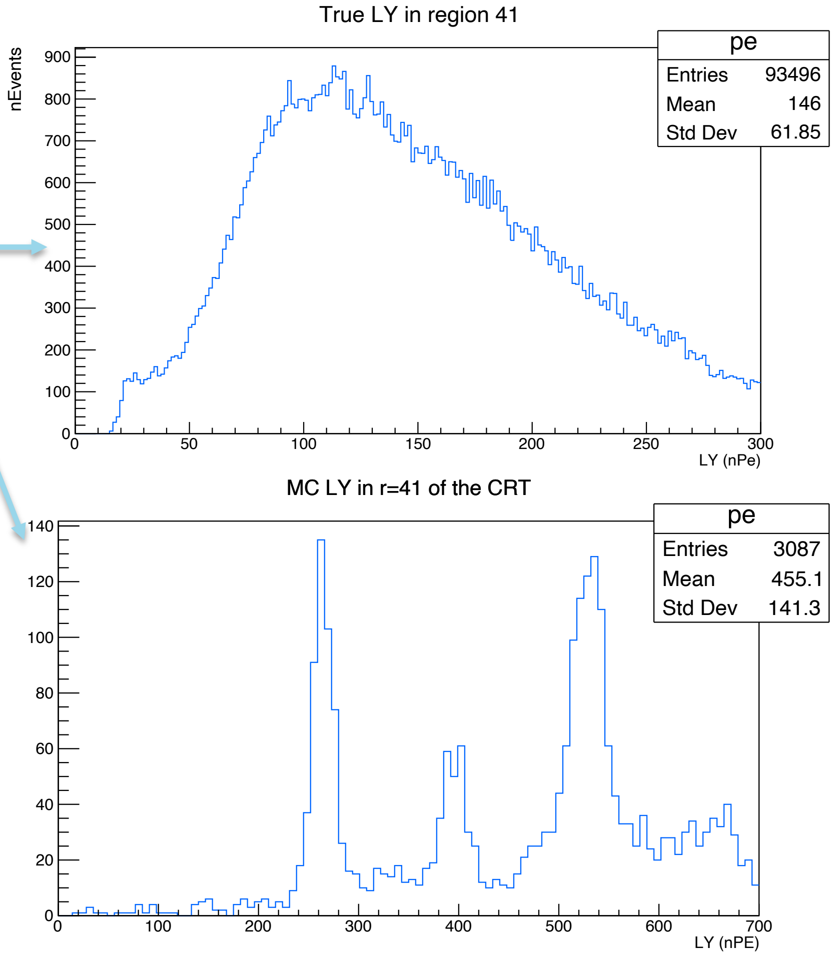
Light yield calibration of the Side CRT

- The double fit parameters so far worsen the adherence of the MC to the true distributions.
- Possible improvements might come from:
  - Using a dataset of cathode-traversing muon hits (direction constraint).
  - Fitting the separate contributions of the SiPMs.
- Work is still ongoing to understand the best approach to follow.
- If sorted out, calorimetric information may be extracted from the side CRTs.



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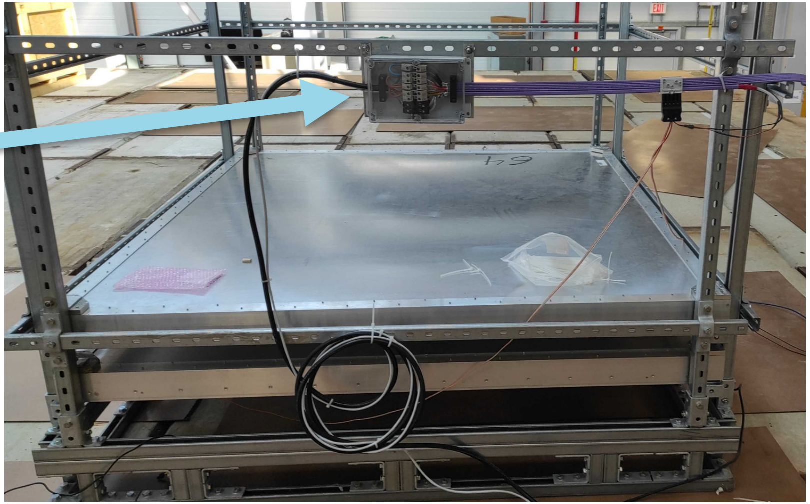
Setup of a Powerline for the Spare Top CRT modules

- Two spare Top CRT modules have been installed above the overburden.
- There they will collect Cosmic ray data.
- They will serve as a test bed for new firmware and other software.



- I participated in the building of a powerline to connect them to the common power supply on the mezzanine level.

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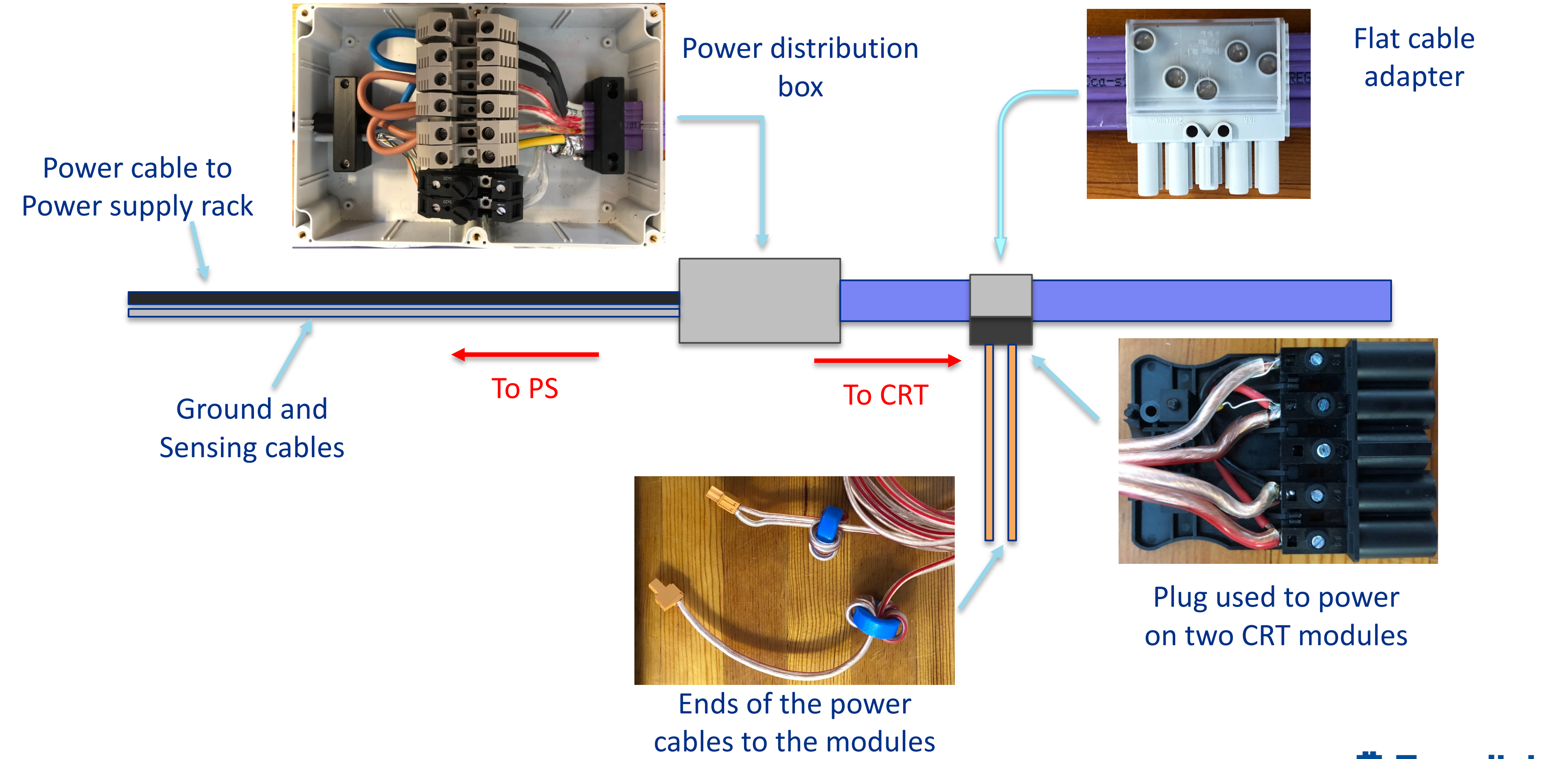
Scheme of the Spare CRT powerline



Summary

- The three SBN detectors will perform a world-leading search for eV-scale sterile neutrino.
- ICARUS installation at FNAL in the SBN far site has been completed: second full time (24/7) neutrino beam run started on June 9th 2022.
- The CRT system of ICARUS will be crucial to mitigate the Cosmic Ray event background.
- Consistent timing between the CRT modules and the TPCs must be achieved to allow event reconstruction and cosmic ray discrimination.
- Work is still ongoing to measure all the delays along the distribution path and implement the timing corrections and other calibrations to the analysis.

Thank you for your attention!

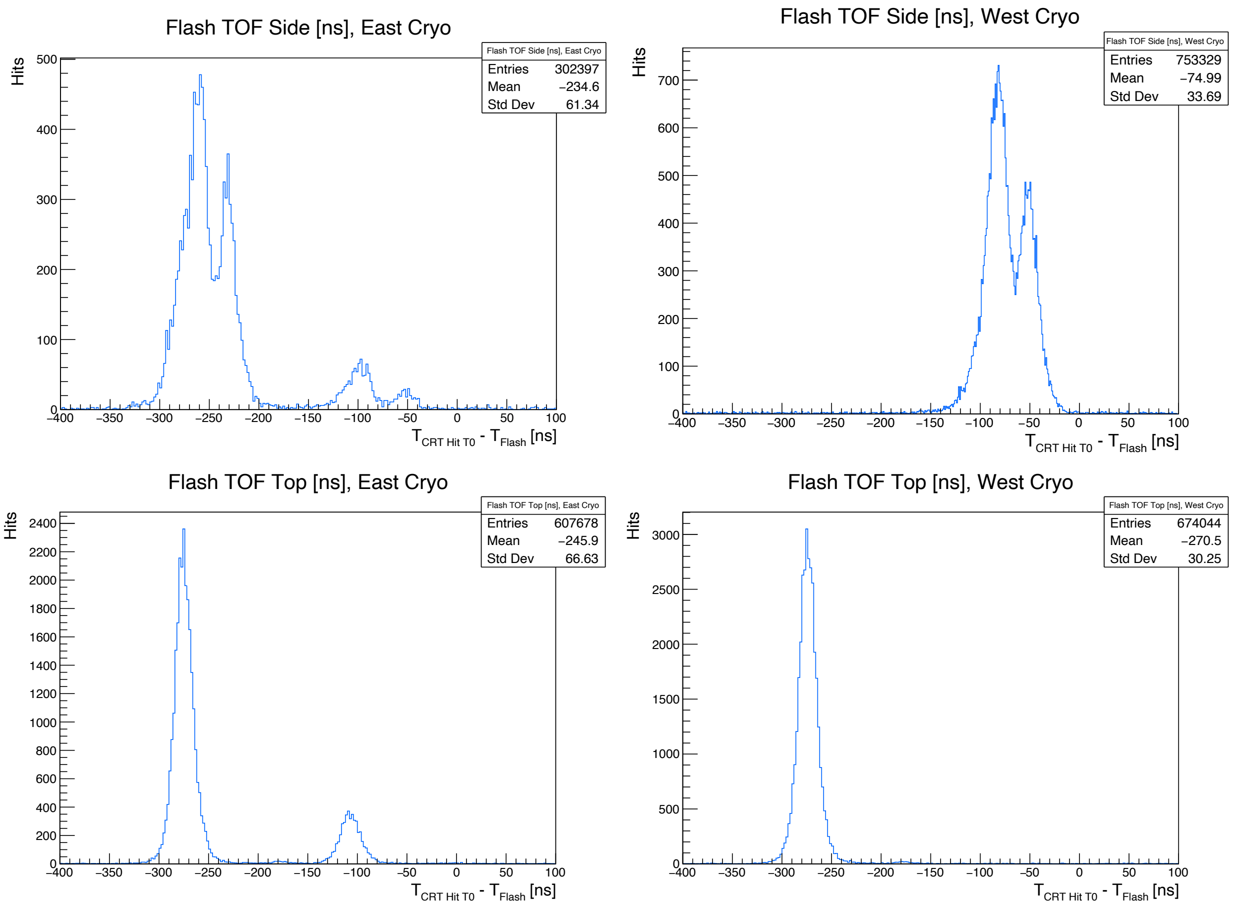
References

1. Giunti, Carlo, and Chung W. Kim, *Fundamentals of Neutrino Physics and Astrophysics* (Oxford, 2007; online edn, Oxford Academic, 1 Jan. 2010).
2. Betancourt Minerba, *ICARUS and the Fermilab Short Baseline Neutrino Program*, talk (Neutrino 2020, June 22- July 02, 2020).
3. F. Poppi, *ICARUS spreads its wings*, talk (FNAL 55° Annual Users Meeting).
4. SBND and MicroBooNe and Icarus Collaborations, Maurizio Bonesini(INFN, Milan Bicocca and Milan Bicocca U.) for the collaborations, *The Short Baseline Neutrino Program at Fermilab*, (Mar 11, 2022).
5. Angela Fava, *Status of the Icarus Detector*, talk (SBND Collaboration meeting 06/27/2022).
6. F. Poppi, *The Cosmic Ray Tagger system of the ICARUS detector at Fermilab*, talk (ICHEP 2022 41° International Conference on High Energy Physics, 07/08/2022).

Backup Slides

On the ToF peaks (1)

- The Side and Top CRT ToF distributions were plotted by separate TPC cryostat.
- The Side CRT show a double peak structure as it can act as both entry point and exit point for the particles.
- The Top CRT can only be an entry point.
- Only the hits with flashes in the East TPC show the additional peak.



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The search for sterile neutrinos

- RH neutrino fields are called sterile as they only interact gravitationally.
- Their number is not constrained by the Anomalies of the Standard Model → there could be more than 3.
- How to *observe* them: sterile neutrinos can couple to ordinary ones through the mass term

Mass Basis: $\nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4 \quad \nu_5 \quad \cdots$

Flavor Basis: $\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_{s_1} \quad \nu_{s_2} \quad \cdots$

ACTIVE STERILE

they give rise to a complicated mixing structure:

mixing $\Rightarrow \quad \nu_{\alpha L} = \sum_{k=1}^{N} U_{\alpha k} \nu_{kL} \qquad \alpha = e, \mu, \tau$

$N \geq 3$

no upper limit!

Past hints

- Flavour neutrinos could oscillate into sterile states ⟺ discrepancies in the number of observed neutrinos.
- Four anomalies have ben observed by Short Baseline experiments over the past 20 years.
- Explainable by sterile neutrino states driving oscillations at $\Delta m^2_{new} \simeq 1\ eV^2$ and small $\sin^2 2\theta_{new}$.

$$P^{SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Experiment	Type	Channel	Significance
LSND anomaly	DAR accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8 σ
MiniBooNE anomaly	SBL accelerator	$\nu_\mu \rightarrow \nu_e$	4.5 σ
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8 σ
GALLEX/SAGE anomaly	Source – e capture	ν_e disappearance	2.8 σ
Reactors anomaly	β decay	$\bar{\nu}_e$ disappearance	3.0 σ

Past Short-baseline neutrino anomalies.

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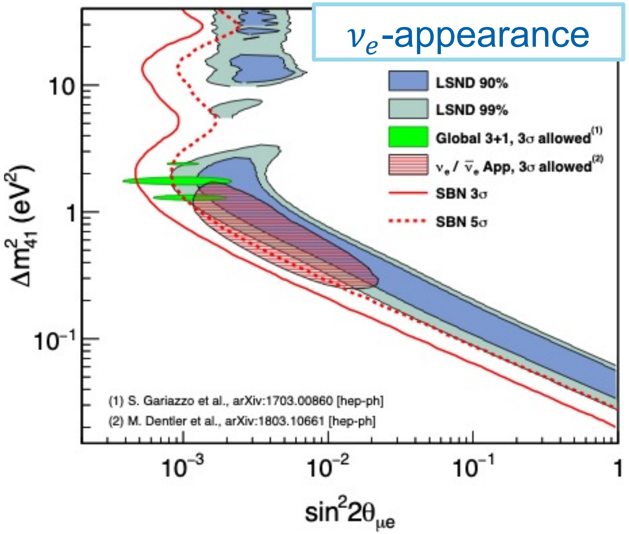
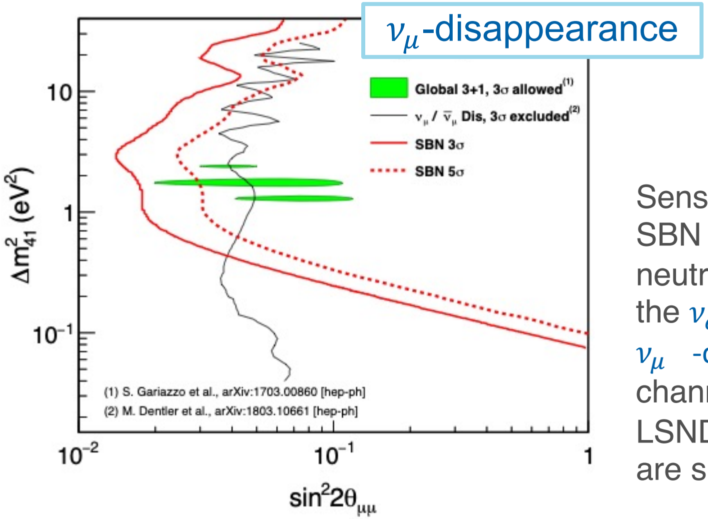
Sensitivity of SBN

- SBN will reach $> 5\sigma$ significances in the allowed parameter region with 3 yrs. of data taking (6.6×10^{20}POT).
- Searches for both ν_μ disappearance and ν_e appearance will be conducted.
- ICARUS alone could provide a complete verification of the oscillation claim by Neutrino-4 within 1 yr. using BnB and NuMI.

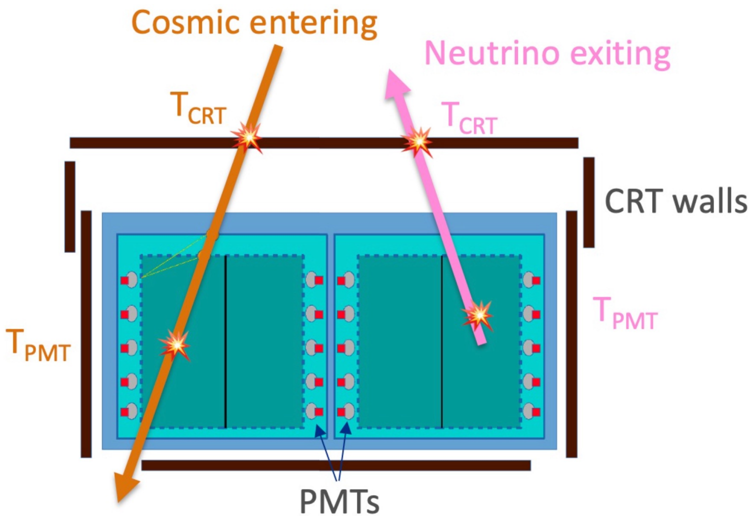




Sensitivity at 3σ and 5σ of SBN to light sterile neutrino oscillations for the ν_e-appearance (left) and ν_μ -disappearance (right) channels.
LSND preferred regions are shown in the left plot.

Matching CRT and TPC data

- The CRT data must be matched to TPC tracks to reconstruct the events.
- Tracks are matched to the closest CRT hit to their projections on the CRT planes, accounting for the drift time.
- Once the data are matched, CR and rock muons are distinguished from ν –interactions by the sign of the difference $T_{CRT\ hit} - T_{TPC\ flash}$.
- Consistent timing must be achieved across all detector elements for this to work.



Scheme of the CR/ν event discrimination criterion based on the Time of Flight.

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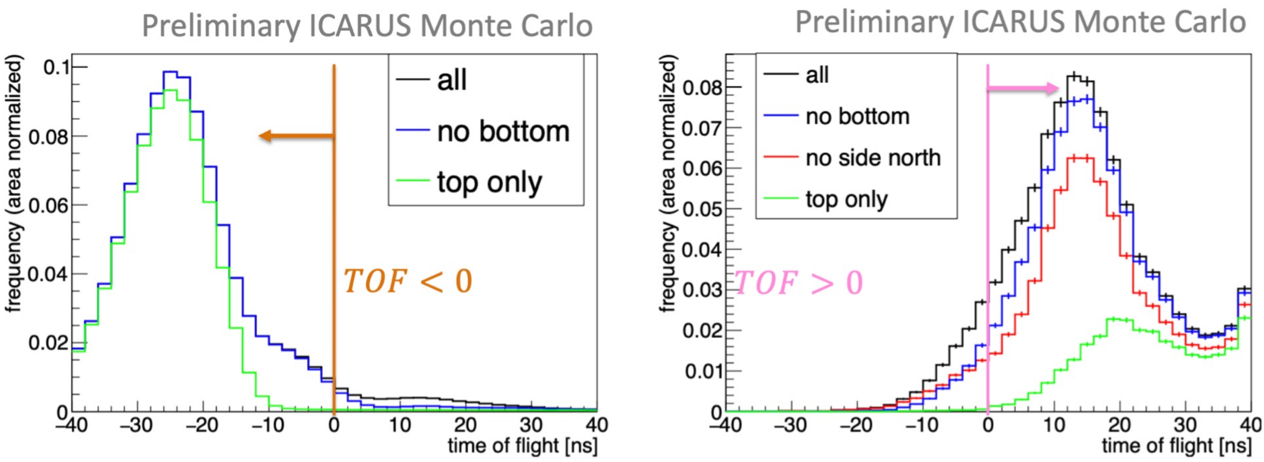
Expected ToF distribution

- Cosmogenic and rock muons will enter from the CRT and then traverse the TPCs → $ToF < 0$.
- Neutrino event particles will be produced inside the LAr volume and then reach the CRT → $ToF > 0$.

$$TOF = T_{CRT} - T_{PMT}$$



(a) Cosmogenic muons. (b) BNB ν_μ.

Simulated ToF distributions in ICARUS for Cosmogenic muon events and ν_μ −events from BNB [1].

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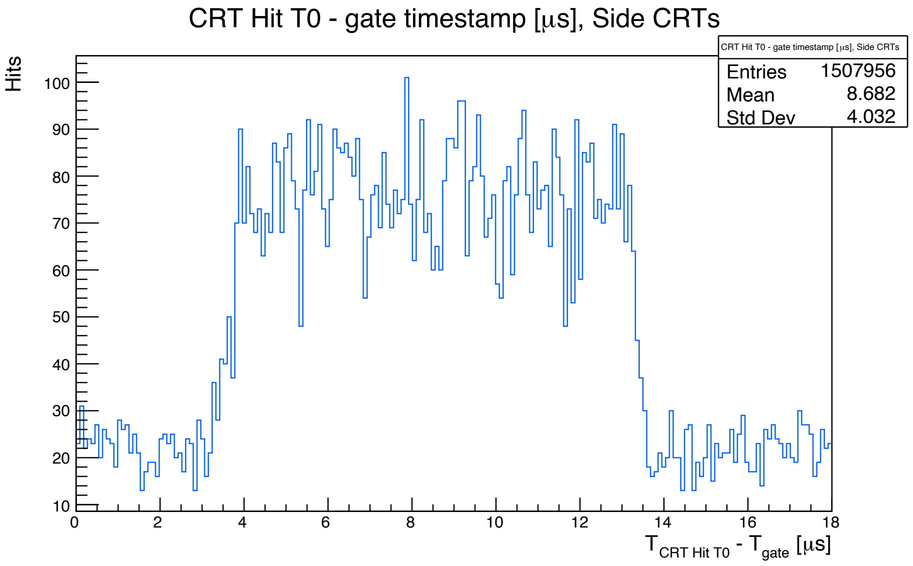
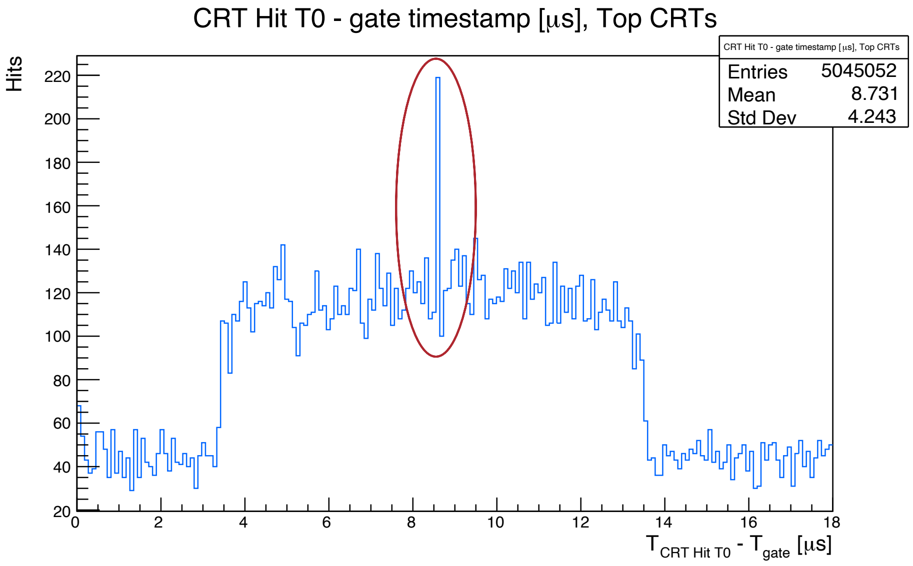
Excess CRT activity during the beam gate

- The excess of CRT hits due to cosmics in time with the beam spill gates is used to verify the correct timing.
- The peak width corresponds to that of the trigger gate for NuMI (12 μs).
- The origin of the highlighted peak in the Top CRT distribution is to be investigated.



Excess CRT activity for the Side CRT modules.



Excess CRT activity for the Top CRT modules.

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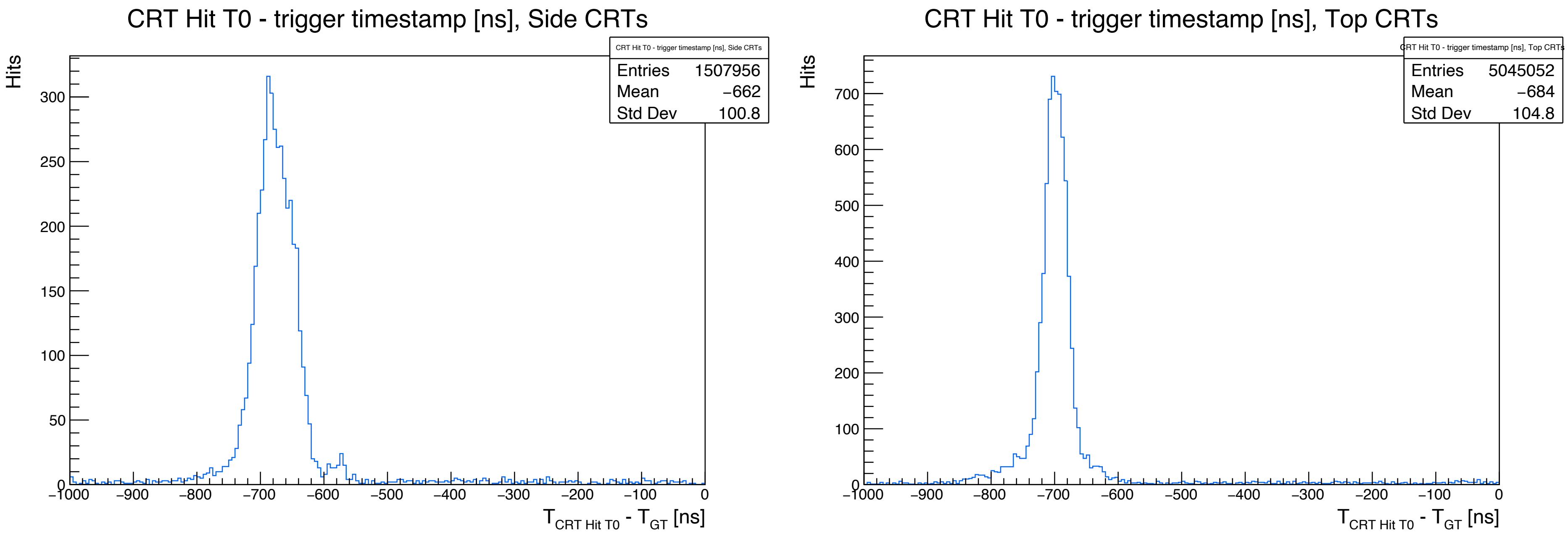
CRT Hit time distributions

- The CRT hit times are computed with respect to the global trigger time: $T_{Hit} = T0_{Hit} - T_{GT}$.
- The Side CRT distribution shows a second smaller peak, which must be investigated.
- Good agreement of the distributions with the analysis of BNB data: the in-time hit peak is visible.



On the ToF peaks (1)

- The Side and Top CRT ToF distributions were plotted by separate TPC cryostat.
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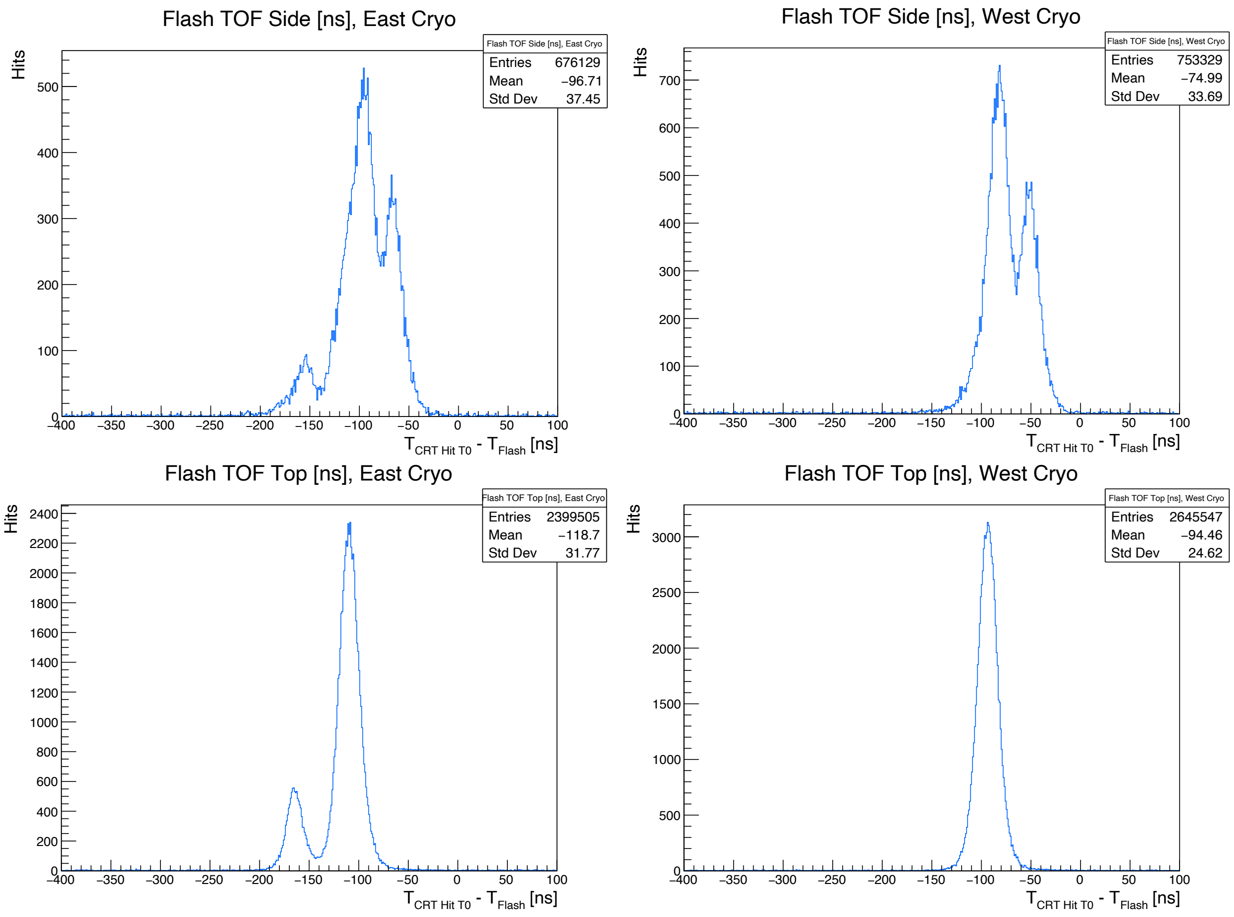
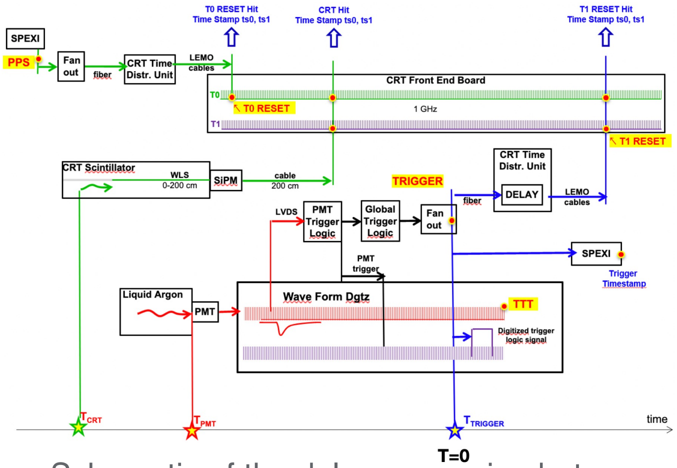


CRT timing

- The Front End Boards (FEB) of the CRT modules are instrumented with two independent counters/timing signals (with 1 ns precision):
  - T0, which is used to generate the global timing of hits and other signals.
  - T1, which is reset at the time a global trigger is generated by the trigger crate.
- Modelling the delays occurring across the systems is non-trivial but crucial.

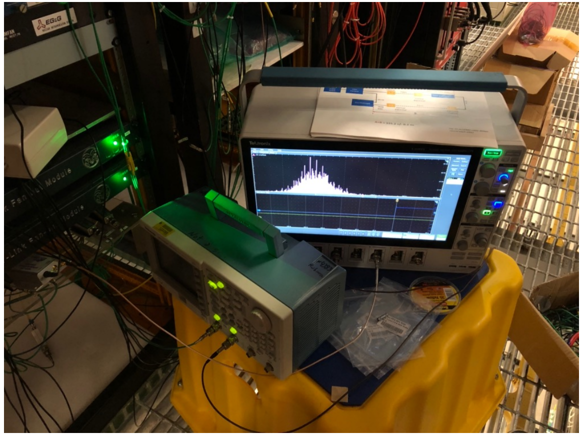
Picture of one of the FEBs used for the CRT system



Schematic of the delays occurring between Trigger, CRT and TPCs.

Measurement of the Side CRT T1 reset distribution path

- Measured the delay along the T1 distribution path for the East and West Side CRT Timing Distribution Units (TDU).
- The time delay introduced by the distribution path of T1 between two synchronous square waves was measured with an oscilloscope.
- The measured delays are being implemented in the analysis of the Side CRT.

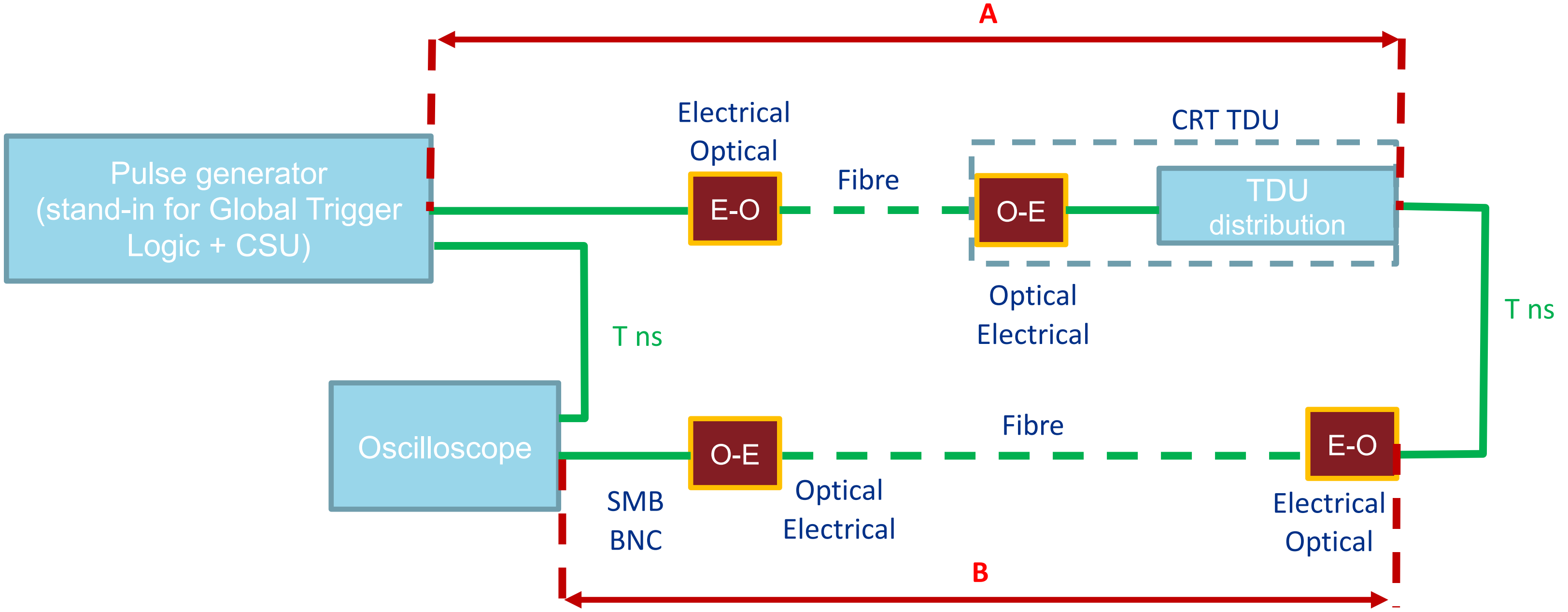


The oscilloscope and pulse generator used for the measurement

CRT side	T1 signal delay
Side CRT East	$204.2 \pm 0.2\ ns$
Side CRT West	$251.4 \pm 0.2\ ns$

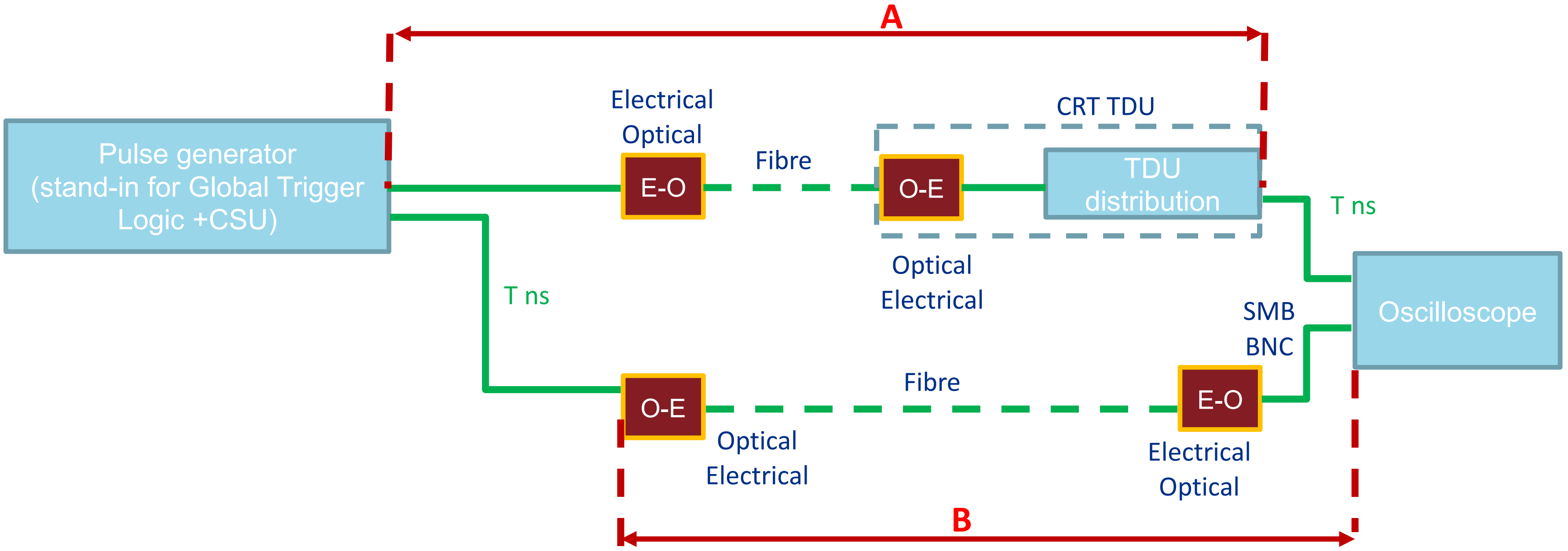
The measured T1 delay values

On the measurement of the Side CRT T1 delay (1)



- The output of the CSU fanout and that of the CRT TDU are on different floors.
- In order to measure the delay along the T1 distribution path (A) induced by the TDU, the delay along the path A+B (in the scheme above) was first measured.

On the measurement of the Side CRT T1 delay (2)



- The connection was then changed according to the scheme above, allowing to measure the difference A-B.
- The T1 delay A could then be computed as $A = [(A + B) + (A - B)]/2$

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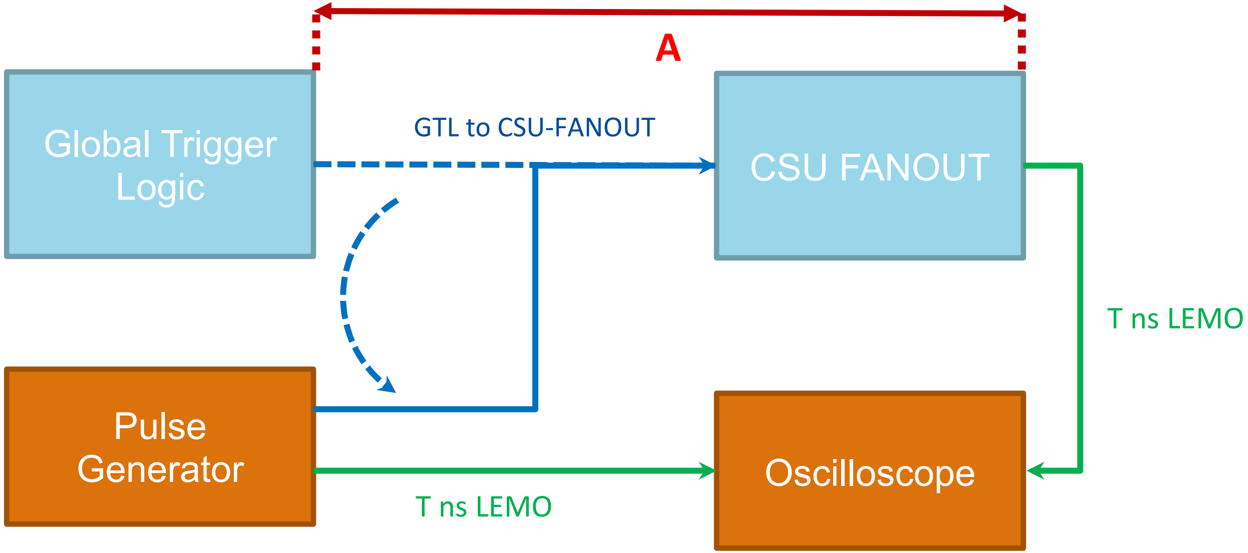
On the measurement of the Side CRT T1 delay (3)



- The measurement of the delay between GTL_{OUT} and $CSU\text{-}FANOUT_{OUT}$ (**A**) was performed separately.
- The delay of path **A** was measured through an oscilloscope by the time difference between two square waves, as the **LEMO cable** delays cancel out.