ICARUS optical reconstruction: status and perspectives

ICARUS Collaboration Meeting

Fermilab, October 14th 2024

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on behalf the ICARUS Optical Reconstruction WG

Thanks Magda, Matteo and Vanessa for their excellent work and for providing slides!

The way we were in April CM

- A lot of work still needs to be done. Some highlights:
- Run2:
  - investigation of scintillation simulation
  - investigation of light propagation
  - ultimately, fix to light simulation

From G. Petrillo’s outlook

- Run3:
  - finalisation of PMT synchronisation
  - tuning of reconstruction
  - integration of the new PMT response into simulation
  - assessment of trigger efficiency and charge/light matching in simulation
  - in general: understand how to best exploit the interaction timing tool

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    - finalisation of PMT synchronisation (M. Vicenzi)
    - tuning of reconstruction
    - integration of the new PMT response into simulation (M. Vicenzi)
    - assessment of trigger efficiency and charge/light matching in simulation
    - in general: understand how to best exploit the interaction timing tool (M. Diwan, M. Vicenzi)

    - RUN2-RUN3 comparison (M. Cicerchia, V. Brio, C. Petta)

Study of light signal: RUN3 vs. RUN2

- First studies of light signals (amplitude and light yields) of **RUN3** (runs: 11816 + 11813) and its **comparison with RUN2** (run: 9435) by Magda Cicerchia.

- Main results:

  - Similar amplitude (as expected)
  - RUN3 is almost half of RUN2 in light yields' variables (integral, number of ph.e., …)

- More info in: DocDB: 36185-v1, 36368-v1, 36960-v1

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Selection of the tracks: cathode crossing vertical tracks with a $|t_0| < 350\mu s$
$y_{start} > 125$ $y_{stop} < -175$; $20 < |z_{start} - z_{end}| < 130$ cm; $20 < |x_{start} - x_{end}| < 130$ cm|z-barycenter of tracks| < 500 cm
Selections of flashes (OptFlash) in coincidence with tracks:
barycenter $\Delta z < 50$cm & in time $\Delta t = |t_0 - t_{flash}| = [2 , 8]$ (RUN2) and = [-3, 3] (RUN3) ⇢ |z-barycenter of flash| < 500 cm.

Selections of the *brightest signals* (OptHits with highest amplitude) in coincidence with tracks:
only the first flash associated to the track is considered and the first OptHit for each channel is recognized in each TPC side:

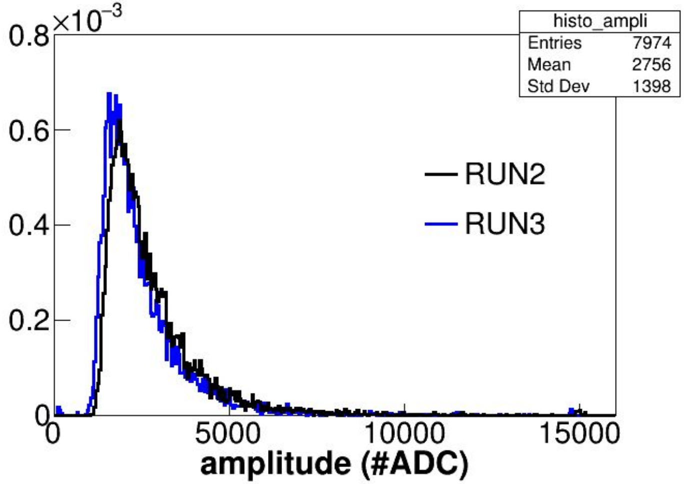
- The 10 ophits with the highest amplitude are selected;
- The 10 ophits with the highest integral are selected;

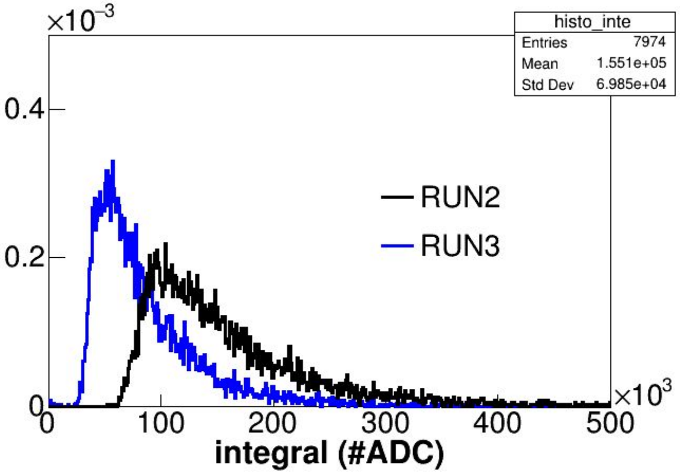
In addition, for each selected track, the sum of the integrals of all the OpHits in all the flashes associated to the track is calculated.

Light signal study for *brightest signals*

RUN2 (9435) vs. RUN3 (11813+11816) – amplitude and integral

DocDB: 36368-v1





Similar behavior and peak's values for the amplitude

RUN3's integral peak is ~ half of the RUN2 ones

Courtesy M. Cicerchia

Light signal study for *cathode crossing tracks*

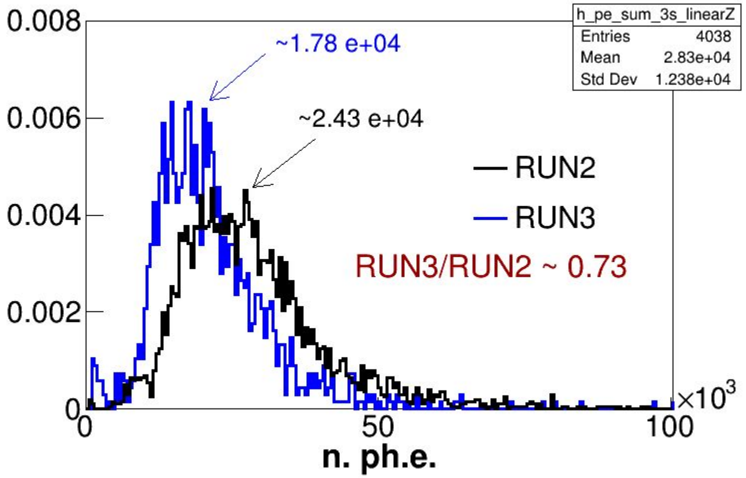
RUN2 (9435) vs. RUN3 (11813+11816) – number of ph.e.

DocDB: 36960-v1

Selection of the tracks: cathode crossing tracks with a $|t_0| < 300\mu s$
longer than 50 cm
⇢ |z-barycenter of tracks| < 500 cm

Selections of flashes (OptFlash) in coincidence with tracks:
in barycenter $\Delta z < 30cm$ & in time $\Delta t = |t_0 - t_{flash}|$ = [2 , 8] (RUN2) and = [-3, 3] (RUN3)
⇢ |z-barycenter of flash| < 500 cm.

Courtesy M. Cicerchia



Light signal study for *single OpHits*

RUN2 (9435) vs. RUN3 (11813+11816) – amplitude

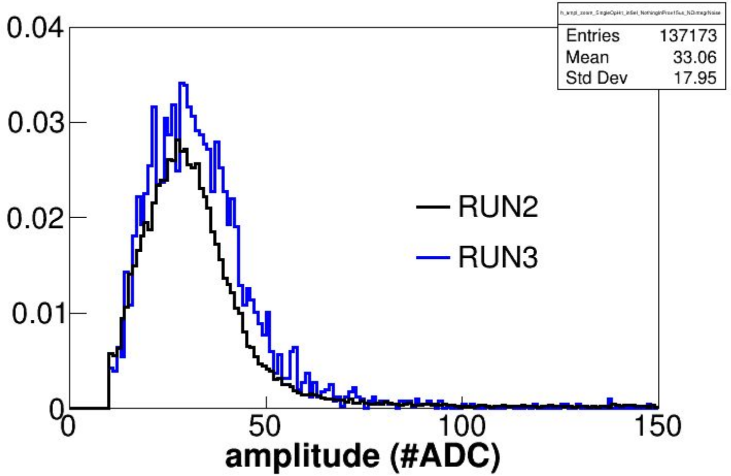
DocDB: [36960-v1]

Selection of the tracks: cathode crossing tracks with a $|t_0| < 300\mu s$
longer than 50 cm
⇢ |z-barycenter of tracks| < 500 cm

Selections of flashes (OptFlash) in coincidence with tracks:
in barycenter $\Delta z < 30$cm & in time $\Delta t = |t_0 - t_{flash}| = [2, 8]$ (RUN2) and $= [-3, 3]$ (RUN3)
⇢ |z-barycenter of flash| < 500 cm.

Selections of the *single Ophits*:
there are no other optcal hits in the previous 15 us

Courtesy M. Cicerchia



Similar peak values for the amplitude, but different shapes

Study of light signal: PMT waveforms

- Updated studies of the PMT waveform shape in **RUN2** (run: 9435) by Vanessa Brio and Catia Petta.

- Main results:

    - Good understanding of RUN2 Monte Carlo. Better understanding of RUN2 data w.r.t. April Collaboration Meeting.
    - Extraction of the time constants for scintillation in LAr from data.

- RUN2 sample: same selection used by Magda as previously shown to extract the average PMT waveform from data and Monte Carlo.

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- RUN2 sample: same selection used by Magda as previously shown to extract the average PMT waveform from data and Monte Carlo.

➔ *Selection of the 12 brightest PMTs for each flash;*

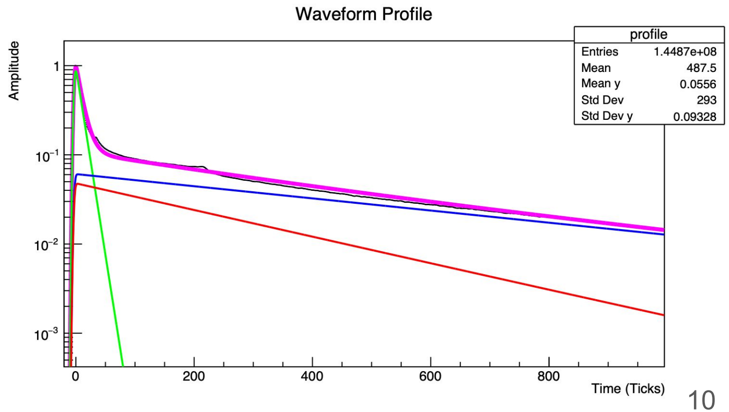
➔ *Alignment of all waveforms at t0=0;*

➔ *Normalization of the aligned waveforms;*

➔ *Study/fit of the average waveform;*

➔ *Comparison Data - MC.*

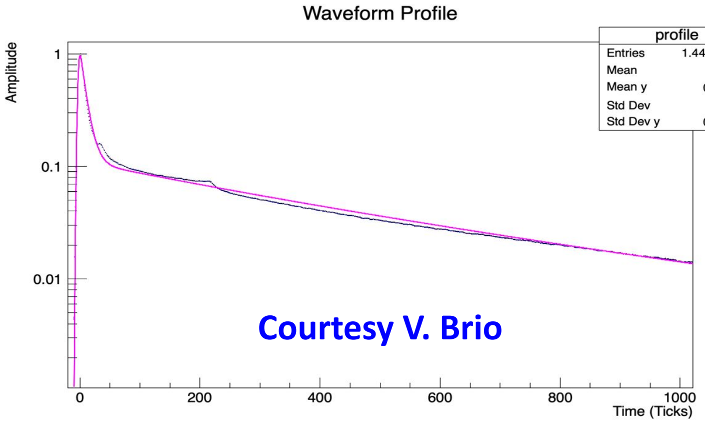
Courtesy V. Brio



PMT waveforms: RUN2 data

Old fit function:

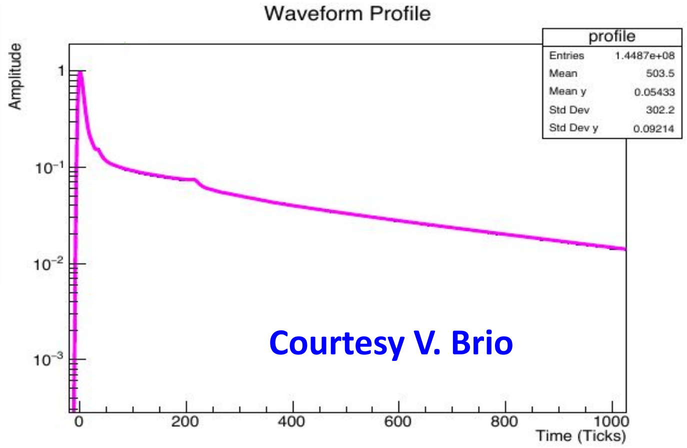
$$f(t) = \sum_{j=f,i,s} \frac{A_j}{2\tau_j} \exp\left[\frac{1}{2}\left(\frac{\sigma}{\tau_j}\right)^2 - \left(\frac{t-t_m}{\tau_j}\right)\right]\left[1 - \text{erf}\left(\frac{1}{\sqrt{2}}\left(\frac{\sigma}{\tau_j} - \frac{(t-t_m)}{\sigma}\right)\right)\right]$$



T Fast [ns]	T Interm [ns]	T Slow [ns]	% Fast	% Slow+ Interm
19 ± 0.5	555 ± 10	1275 ± 1	20%	80%

New fit function:

Old fit function convoluted with RUN2 Single Photoelectron Response (SPR)



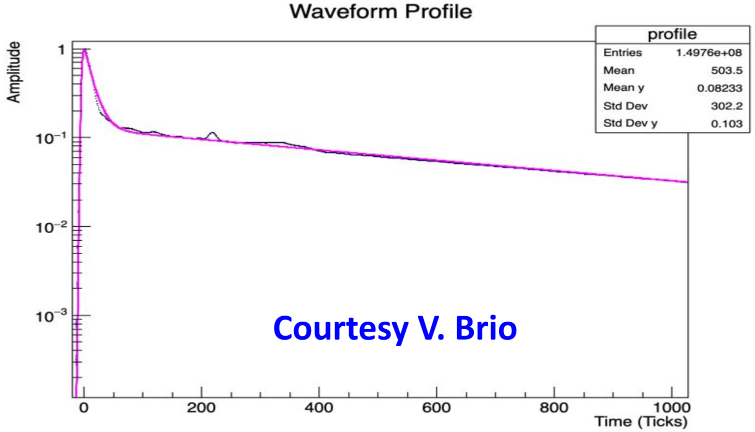
T Fast [ns]	T Interm [ns]	T Slow [ns]	% Fast	% Slow	%Interm
9.5 ± 0.1	127 ± 0.4	1310 ± 0.3	29.5%	61.5%	9%

- New fit: tau fast closer to the expected value of 6 ns. Slow/fast ratio closer to 3.
- Tau slow smaller than 1.6 us though. Intermediate component small, but present.

PMT waveforms: RUN2 Monte Carlo

Old fit function:

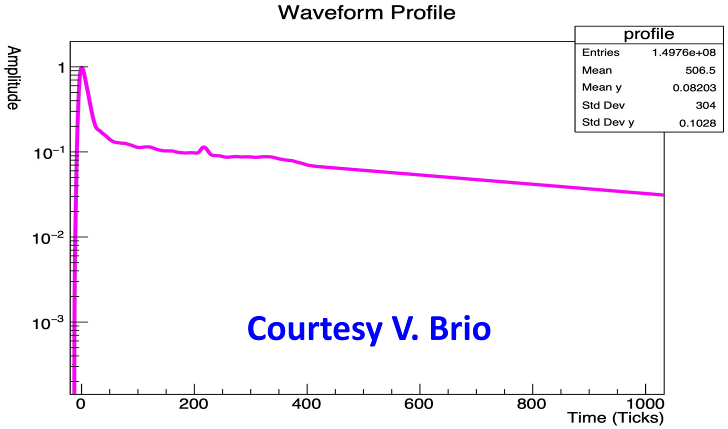
$$f(t) = \sum_{j=f,i,s} \frac{A_j}{2\tau_j} \exp\left[\frac{1}{2}\left(\frac{\sigma}{\tau_j}\right)^2 - \left(\frac{t-t_m}{\tau_j}\right)\right]\left[1 - \mathrm{erf}\left(\frac{1}{\sqrt{2}}\left(\frac{\sigma}{\tau_j} - \frac{(t-t_m)}{\sigma}\right)\right)\right]$$



T Fast [ns]	T Interm [ns]	T Slow[ns]	% Fast	% Slow+ Interm
28 ± 0.2	979 ± 22	1592 ± 0.3	15%	85%

New fit function:

Old fit function convoluted with RUN2 Single Photoelectron Response (SPR)



T Fast [ns]	T Interm [ns]	T Slow[ns]	% Fast	% Slow	%Interm
14.6 ± 0.1	494 ± 0.5	1589 ± 0.2	23.9%	76%	0.1%

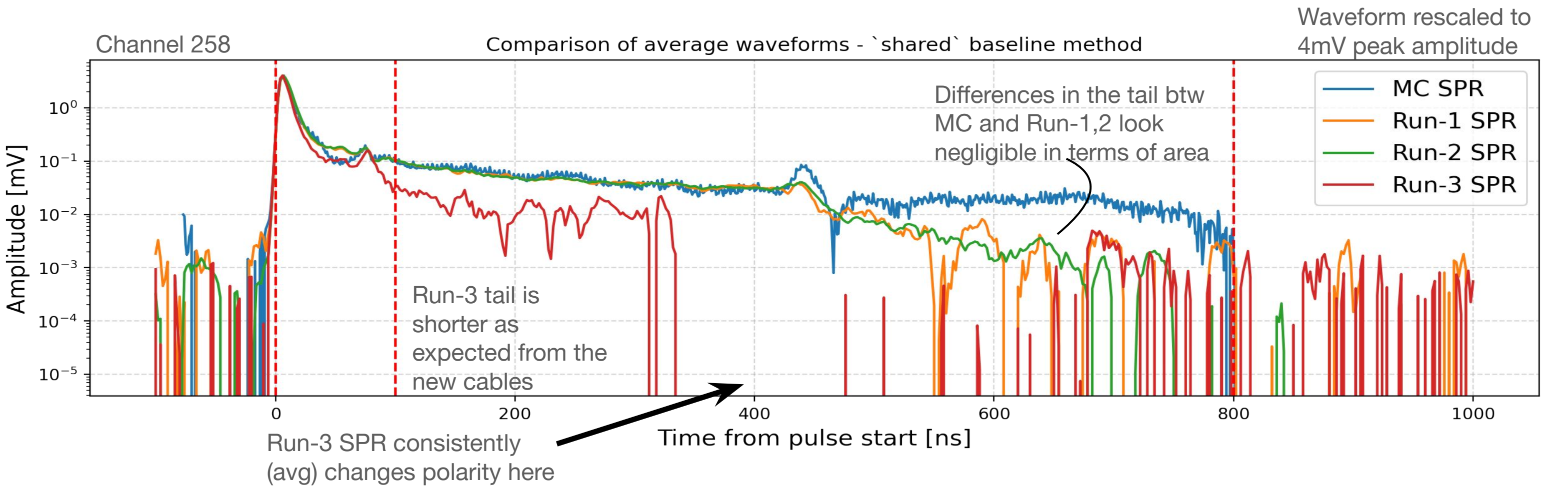
- New fit: MC tau fast improved, but still larger than data. Slow/fast ratio closer to 3.
- Tau slow ~ 1.6 us as expected and no interm. component: this is consistent since we do not simulate it!

Data-driven SPR for Run-1,2,3

- The SPR function is **extracted from data by averaging ~4k laser pulses** and then **rescaling its amplitude to the single-PE level**, also extracted from data**.** Laser pulses are <100 ps long, so the assumption is that all ph.e. are stacked on top of each other and linearity holds (shape can be rescaled).
    - Run-1,2 MC uses SPR from channel 258 taken with the scope (1ns sampling).
- Given the new cables, the **Run-3 SPR was extracted from digitized laser data**. Similarly, older laser runs were compared to the MC SPR to check for the possible source of MC vs data discrepancy.

SBN-docdb-35672

Courtesy M. Vicenzi

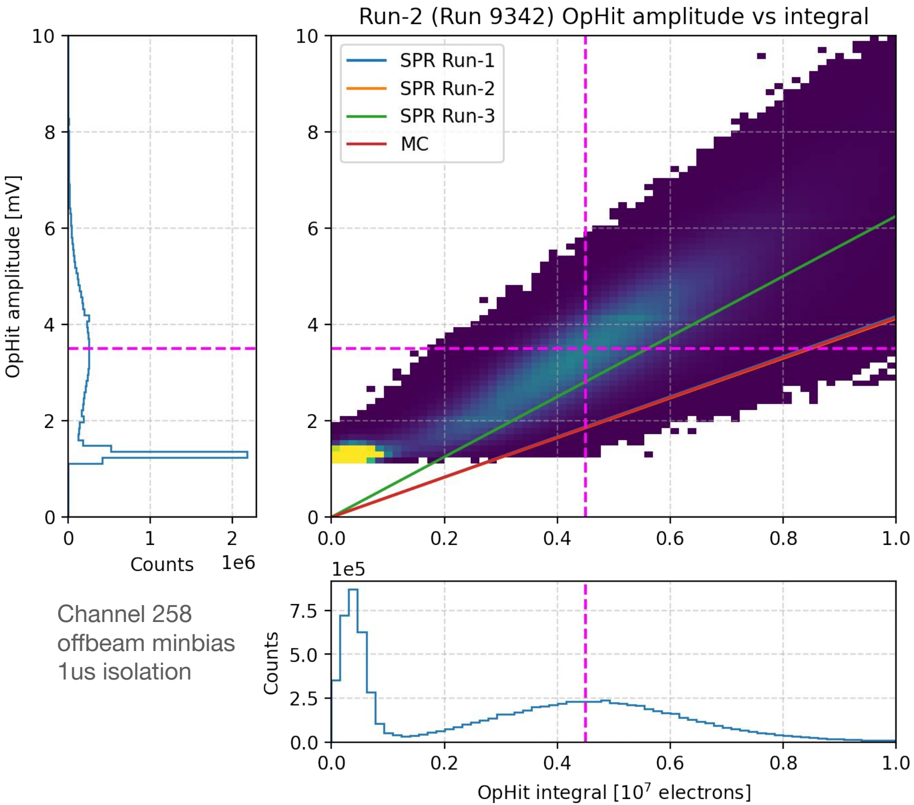


SPR vs single Ph.e. OpHit

SBN-docdb-35672

- The single Ph.e. level is determined using **small and isolated (1us) OpHits in minbias data**.
- The distribution of amplitude and integral are fitted to find the **single Ph.e. amplitude** and the **gain** (=charge collected from a single Ph.e.)
- Discrepancy found comparing the **expected scaling between peak amplitude and area** from the SPR and the actual OpHit distribution in all Run-1,2,3.
  - Setting the SPR to the same OpHit amplitude in data (~3.5 mV) does not yield the same area/gain.
- The **source of the disagreement** is being investigated as well as its effects on Data vs MC comparison.
  - SPR is integrated between 0-800ns, while OpHits have dynamic integration windows.

Courtesy M. Vicenzi



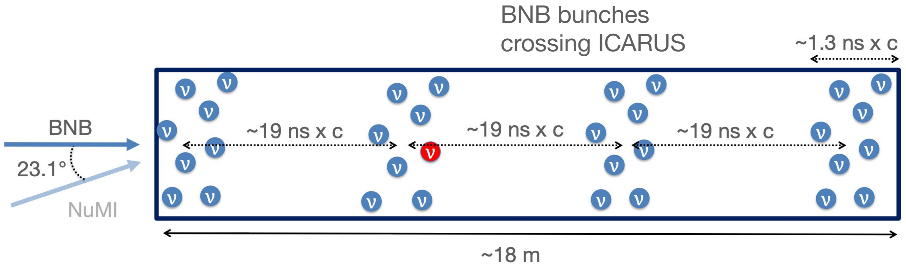
Event timing with light only

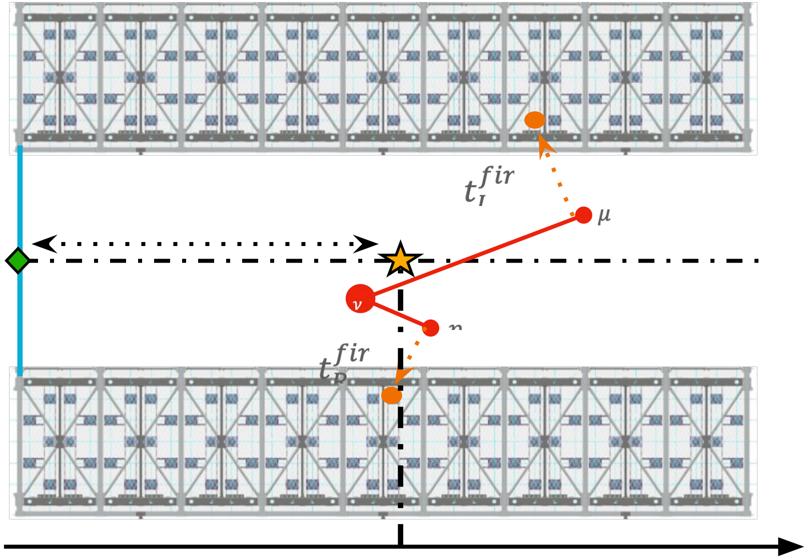
- Precise event timing allows to **tag neutrinos directly** by exploiting the known **time profile of the beam(s).** This builds upon our three-stage timing calibrations that bring the synchronization to O(300-500ps).

- Time and position of the scintillation events is reconstructed only with PMT data and synchronized with the beam timing. This procedure has allowed to reconstruct the **full ns-level time profile of both BNB and NuMI beams** with **only light information**.

  - The dependency on the (x,y) position is removed by taking the mean between the **first PMT times on opposite walls** of the module.

  - A **time-of-flight** (ToF) correction is applied using the barycenter of the flash of light.





“flash” z barycenter

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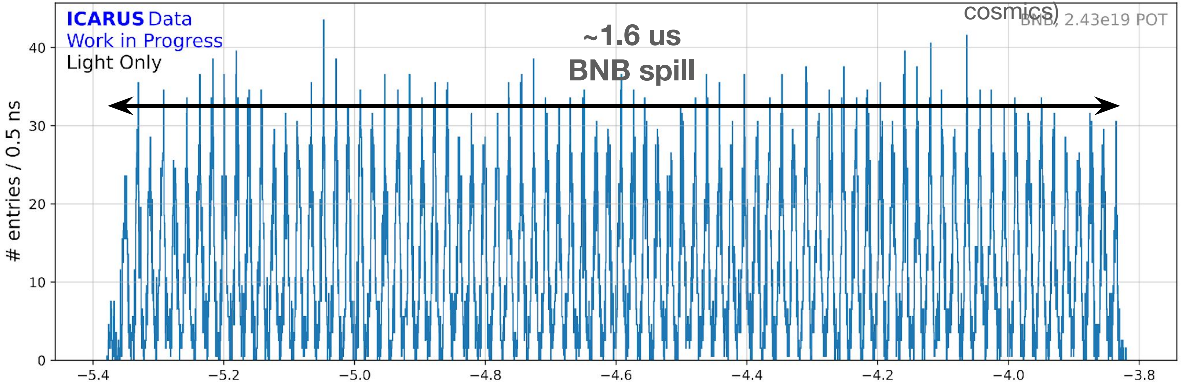
Beam structure

Courtesy M. Vicenzi

(After subtracting cosmics)



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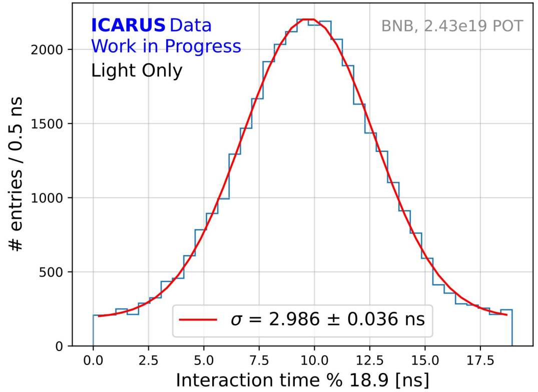
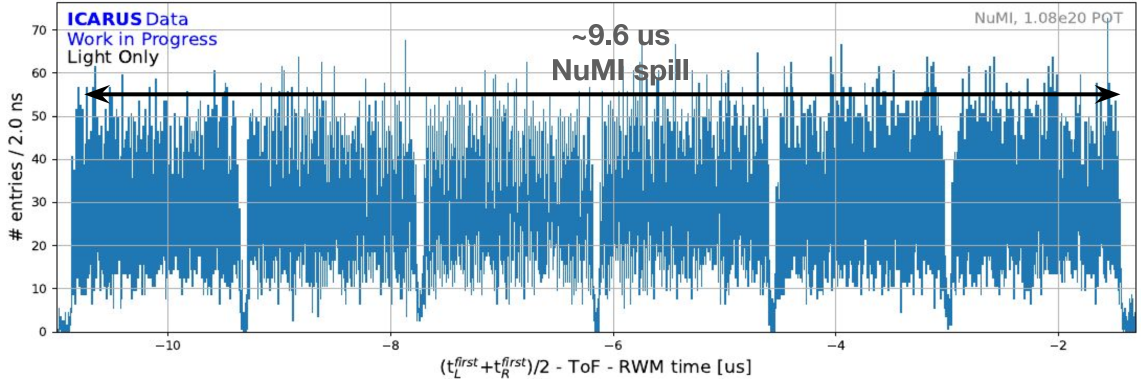
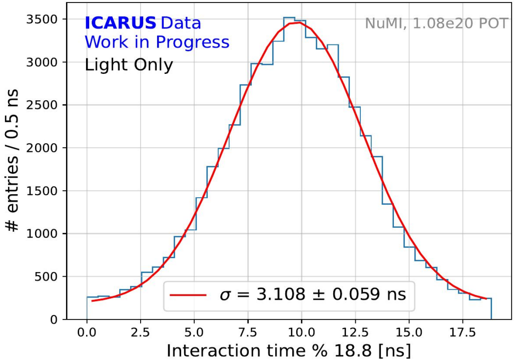
BNB intrinsic bunch width is $\sigma \sim 1.3$ ns



Courtesy M. Vicenzi





Beam timing as selection tool

- Beam structure: powerful tool for either neutrino selection (rejecting cosmic background) or neutrino rejection (BSM searches).

- Fully unbiased neutrino sample by looking at minimum bias data, being independent from reconstruction software trained on MC.

- Next: improve bunch resolution. The structure currently shows the expected spacing, but a larger bunch width (~ 3 ns) due to bias in the light-only determination of the ToF correction using the flash barycenter caused by different topologies + relative timing shifts from run to run over time (see SBN-docdb-36341).

- The first integration of this additional timing information into the reconstruction framework (calb_ntuples) has been completed with PR#751. Work in progress to add it into the CAF for event selection in a proper analysis flow.

Summary and perspectives

- Many of the recent activities within OpReco WG have been carried out to improve our understanding of PMT light signal in ICARUS through Data/MC comparison and RUN2/RUN3 comparison.

- Also timing is at a very good stage and it may be used now for event selection and cosmic background rejection profiting of the exploitation of the BNB/NuMI beam structures.

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- What next? Studies are already ongoing to get an energy calibration using ICARUS PMT light signals.

- Eventually: shall we use ICARUS as a self-compensating light calorimeter at the *o*(GeV) neutrino energy to be used in synergy with the LAr-TPC charge calorimetry? See for example the recent (last week!) arXiv:2410.04603

Thank you for your attention

The OpReco Working Group (apologies to whom I forgot to list!):

M. Betancourt, V. Brio, M. Cicerchia, S. Copello, M. Diwan, C. Farnese, A. Heggestuen, A. Menegolli, M. Mooney, V. Paolone, G. Petrillo, C. Petta, F. Poppi, S. Saha, S. Seo, J. Smedley, R. Triozzi, M. Vicenzi, J. Zettlemoyer

… and please more people are welcome!

Reports on the work in progress happen on Mondays, 11:00 am (FNAL time).
Quick communications occur via Slack channel #icarus-light-analysis.