Status of ICARUS optical detector simulation

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⇐ still low-res logo

In this talk

What is in this talk:

- description of the status of simulation of ICARUS optical detector
- description of the status of simulation of ICARUS trigger

What is *not* in this talk:

- optical detector reconstruction
- optical detector measurements from test stand and ICARUS *(G.L. Raselli)*
- optical detector calibration *(C. Farnese)*
- trigger hardware design and status *(A. Guglielmi)*

My purpose: highlight the parts that are still incomplete.

Simulated samples relevant to trigger studies

neutrino interactions in active volume (only in one module or with expensive filter):
neutrinos from BNB and from NuMI

cosmic rays (expected interaction rate is 11 kHz): being regenerated

beam halo (beam neutrinos interacting upstream): do we have it simulated?

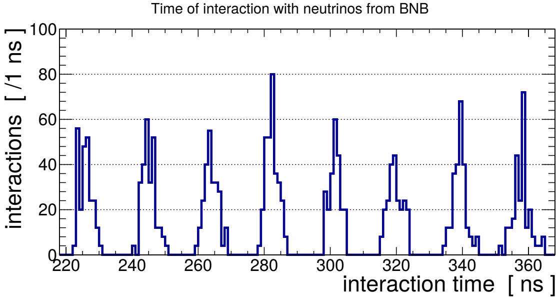
radioactivity only ^{39}Ar so far, with DUNE argon settings, expected 1.15 decays/BNB spill (somehow lower than observed at CERN test stand)
to be superimposed to the above

(see in appendix for the configuration file names)

Neutrino beam simulation

- neutrino flux impinging the detector is simulated both for BNB (< 1 s/event) and NuMI off-axis (> 60 s/event)
- (post-talk editing) ... but the simulation is evidently bugged
- beam figures are a bit of a moving target... current simulation:

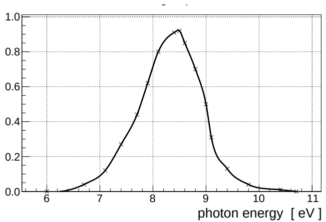
	BNB	NuMI
flux type	neutrinos	hadrons
POT/spill	$5 \cdot 10^{12}$	$6 \cdot 10^{13}$
spill duration	1.6 µs	9.6 µs
batches/spill	1	6+6
buckets/batch	81	
bucket distance	18.8 ns	
bucket FWHM	$\approx$ 2 ns	$\approx$ 0.75 ns



Detail of BNB proton bucket timing (shown 8 out of 81).

Optical simulation in liquid argon

- energy deposited in liquid argon is simulated by GEANT4
- scintillation photons are generated isotropically, at an average rate depending only on the type of ionising particle (expect $\mathcal{O}\left(40 \cdot 10^3\right)$ photons/centimetre)
- scintillation time is split into a fast and a slow component
- no medium saturation, no Cherenkov light is simulated



Scintillation spectrum (both slow and fast component). (nice, but LArSoft does not use it and generates all photons at 128 nm, 9.7 eV)

fast	6 ns
slow	1.59 µs

Scintillation time constants.

	γ/MeV	fast/total
p, $\pi^\pm$, $\mu^\pm$	19200	0.29
$K^\pm$	24000	0.23
α	16800	0.56
others	20000	0.27

Scintillation photons per deposited energy and fast component fraction, per ionising particle type.

Rumor I heard many months ago: NEST collaboration is working to an update for liquid argon, which will include ionisation/scintillation correlations.

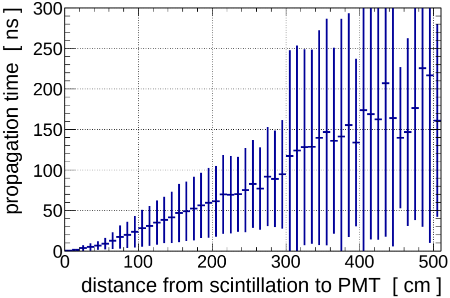
Propagation time

fast	6 ns
slow	1.59 µs

Scintillation time constants (again).

The time of arrival at the PMT is: $t = t_0 + \Delta t_s + \Delta t_p$

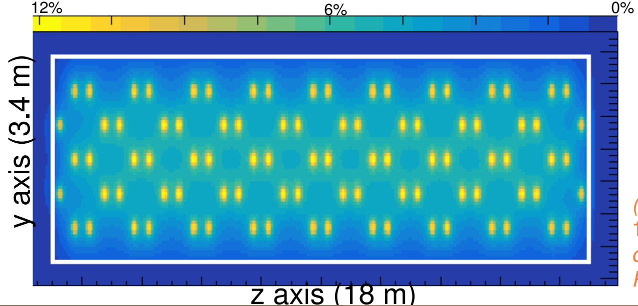
- t_0 energy deposition time, given by GEANT4
- Δt_s scintillation time, extracted with timing show in the table
- Δt_p propagation time to get to the PMT
  - dominated by scattering in argon
  - a parametrisation was adapted from SBND



Average propagation time (Δt_p). Error bars represent RMS.

Visibility mapping

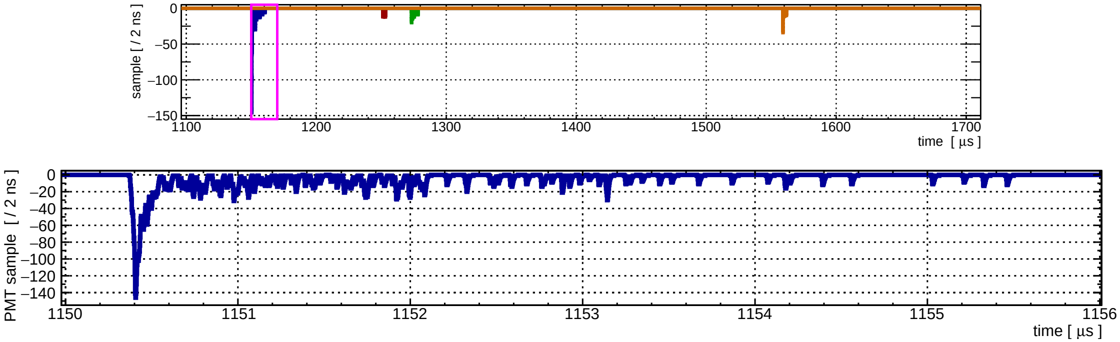
- we simulated a map of the fraction of scintillation photons reaching each PMT from anywhere in the active volume
- it covers the full active volume, $3.0 \times 3.4 \times 19\ \mathrm{m}^3$, for 180 PMT of one T300 module
- volume is diced in $(5\ \mathrm{cm})^3$ cubes (it sums up to 385 million entries)
- the same map is used for both T300 modules
  (saves the memory for 385 more million entries)
- the map also includes PMT quantum efficiency (7%)



Fraction of light collected by the optical detector (fraction of light, originating from a $150 \times 5 \times 5\ \mathrm{m}^3$ volume aligned along drift direction, arriving at the surface of any of the PMT's)

PMT digitisation

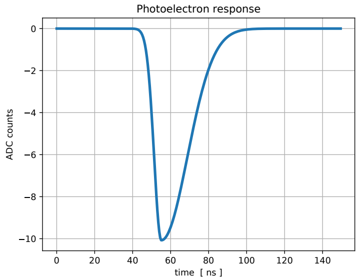
- digitisation via CAEN V1730B: 2 ns sampling, 12 – 24 ns trigger
- zero-suppressed waveforms with variable length acquired during TPC readout window (threshold: currently 10 ADC counts for all channels)
- ... except that 20 µs of waveform at beam gate is always simulated



One simulated waveform (no noise). Top: all unsuppressed time range; different colors represent distinct acquired waveforms; 20 µs after beam gate opening (magenta box) are always acquired. Bottom: detail of the main waveform.

PMT digitisation (II)

- each converted photoelectron contributes to the waveform
  - response shape is fixed, not reflecting our measurements
  - perfect linearity assumed, saturation not enabled
- base amplitude is about 10 ADC counts, varied according to gain fluctuations ($\approx 20\%$)
  - $\rightarrow$ also gain fluctuations do not implement latest ICARUS measurements
- PMT dark current noise available ($1 - 10$ kHz), but usually disabled (not very relevant anyway)
- electronics noise available but unpractically slow
- signal attenuation and reshaping due to cable should be included in single photoelectron response



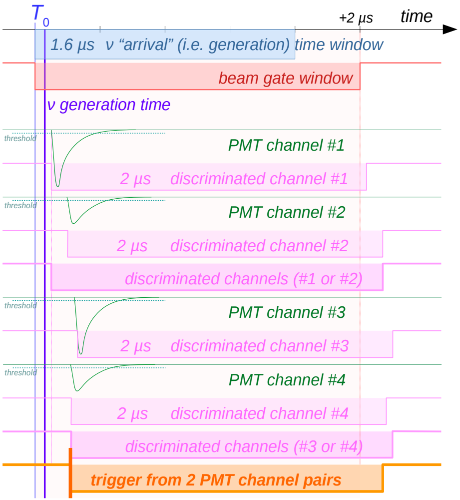
transit time	55.1 ns
rise time	3.8 ns
decay time	13.7 ns
amplitude	-10.07 ADC#

Simulated response to the single photoelectron.

Trigger simulation

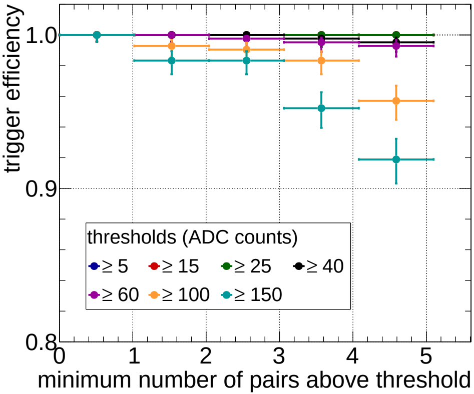
The (crude) trigger simulation:

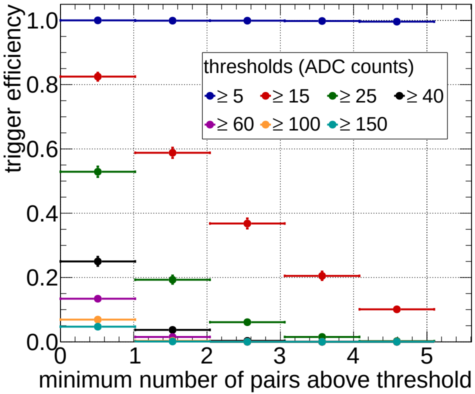
- beam gate is "generated" at time T_0
- a PMT-beyond-threshold "gate" is simulated for each PMT channel (resolution: 8 ns)
  - the gate opens when a single sample of the digitised optical waveform goes beyond PMT threshold
  - each gate is 2 µs long
- pairs of PMT channels are combined (AND/OR)
- if a channel's trigger gate overlaps the beam gate, that channel contributes to the trigger



Trigger: minimum number of firing channels, anywhere

- trigger efficiency on BNB Ar $+ \nu \to \ell + X$ interactions simulated on PMT waveforms
- OR-paired channels as function of PMT threshold (color coded)
- vs. min. number of channels beyond threshold (“majority”) anywhere in the detector





Trigger efficiency on charged current BNB neutrino interactions (left) and ^{39}Ar (right).

Outlook

- a lot of PMT simulation details need to be finalised
  - → simulation of electronics noise
  - → adoption of latest measurements from ICARUS and CERN test stand
- need to scratch our head on how to validate with data as much as we can
- trigger studies ongoing; priority toward:
  - simulation of triggers relevant to purity and first calibration
    - any cosmic ray
    - cosmic ray crossing both anode planes
  - simplest triggers for neutrino events
  - then: localisation of the event
  - precision timing for coincidence with beam structure

Joint discussion on PMT, trigger and DAQ!!! (yep, parallel to software's)

Time	Friday (tomorrow), 9:00 – 11:00
Fermilab	Refuge Chamber meeting room, WH13SW
Zoom ID	6509263088
Topics	see/add topic in shared document

Thank you for your attention

main (recent) contributors to PMT/trigger simulation work:
M. Diwan, A. Falcone, C. Farnese, D. Gibin, W. Ketchum,
A .Menegolli, A. Palazzo (SLAC summer student), G. Petrillo,
and others that I am for sure forgetting to list...

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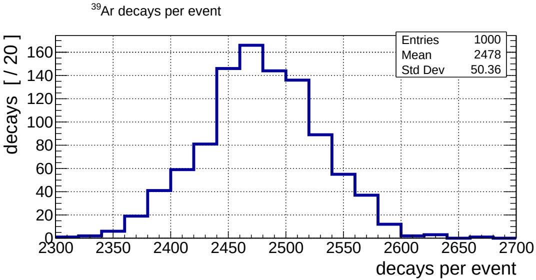
(additional material follows)

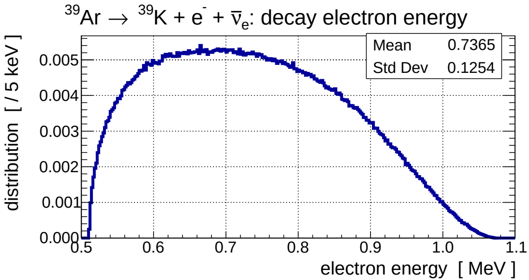
Event generation job configuration

The following configuration files are available in icaruscode `v08_30_00_01` :

- neutrino interactions on a single module: `simulation_genie_icarus_bnb.fcl` (BNB), `simulation_genie_icarus_numi.fcl` (NuMI)
- cosmic rays `prodcorsika_standard_icarus.fcl`
- beam halo ?
- radioactivity `prodbackground_Ar39_icarus.fcl`

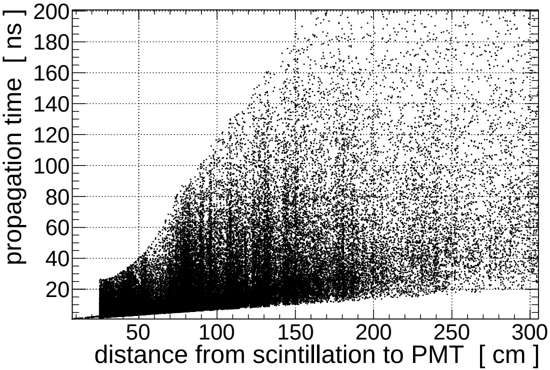
Radioactivity in argon





- simulated by: `prodbackground_Ar39_icarus.fcl`
- set to $1.41 \cdot 10^{-3}$ Bq/cm^3, averages 1.15 decays in the detector every 1.6 µs (in the left plot, an “event” lasts 3.3 µs)

Transportation time: detail

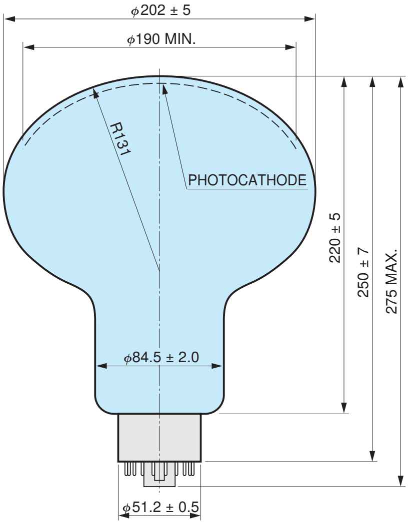


- imported by A. Falcone and A. Menegolli from D. Garcia-Gamez work (SBND)
- simple parametrisation when closer than 25 cm to the PMT
- always much larger than just $\Delta t = d/(c/n)$ (refraction index $n \approx 1.5$)

ICARUS PMT of choice: Hamamatsu R5912

Information from Hamamatsu R5912 datasheet:

- diameter: 202 mm
- stages: 10 (box & line)
- typical gain: 10^7 (for applied voltage 1.5 kV)
- dynode constant *k*: 0.7–0.8 (from the handbook)
- distribution of potential: relative resistance (arbitrary units) between the 10 multiplication stages: 16.8 + 0.6, 3.4, 5.0, 3.33, 1.67, 1.0, 1.2, 1.5, 2.2, 3.0
- dark noise: 4 kHz typical, 8 kHz max
- electron transit time: 54 ns (FWHM: 2.4 ns)
- rise time: 3.6 ns
- peak/valley ratio (?): 2.8 (1.5 minimum)



Configuration of PMT digitisation simulation

PMT digitisation simulation settings (icaruscode `v08_30_00_01`):

```
opdaq: {
  TransitTime:        55.1       PulsePolarity:              -1
  ADC:                -11.1927   TriggerOffsetPMT:           -1150
  Baseline:           8000.0     ReadoutEnablePeriod:        3450
  FallTime:           13.7       CreateBeamGateTriggers:     true
  RiseTime:           3.8        BeamGateTriggerRepPeriod:   2.0
  MeanAmplitude:      0.9        BeamGateTriggerNReps:       10
  AmpNoise:           1.0        Saturation:                 300
  DarkNoiseRate:      1000.0     QE:                         0.07
  ReadoutWindowSize:  2000       FluctuateGain:              true
  PreTrigFraction:    0.25       module_label: "opdaq"
  ThresholdADC:       10         module_type: "SimPMTIcarus"
  PMTspecs: {
    DynodeK:              0.75
    VoltageDistribution: [ 17.4, 3.4, 5.0, 3.33, 1.67, 1.0, 1.2, 1.5, 2.2, 3.0 ]
    Gain:                 1e7
  }
}
```

Trigger: minimum number of firing channels, anywhere

- trigger efficiency on BNB Ar $+ \nu \rightarrow \ell + X$ interactions simulated on PMT waveforms
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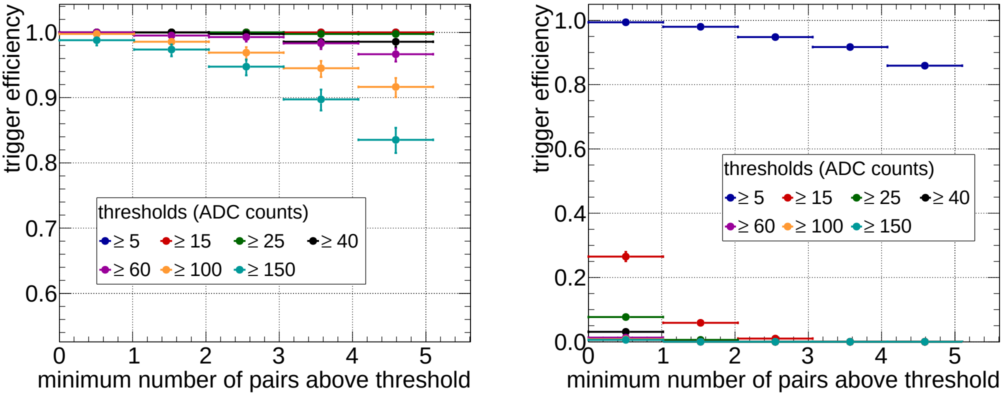

Trigger efficiency on charged current BNB neutrino interactions (left) and ^{39}Ar (right).

Trigger: minimum number of firing channels, anywhere (signal)

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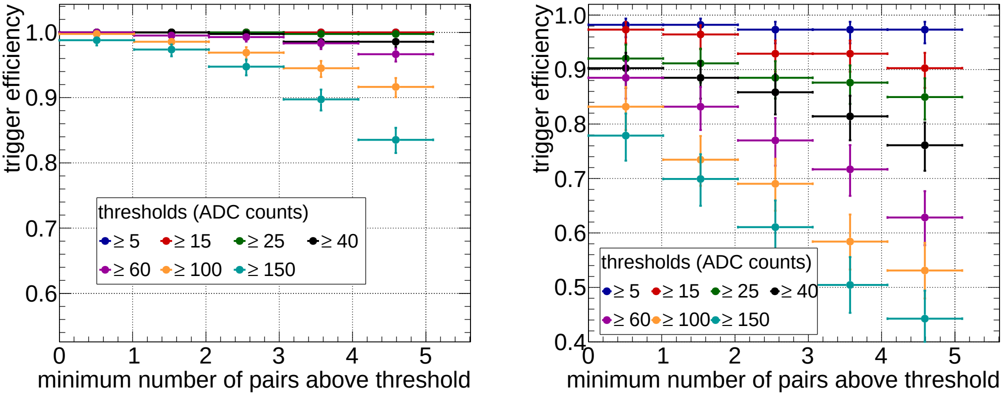

Trigger efficiency on charged (left) and neutral (right) current BNB neutrino interactions.

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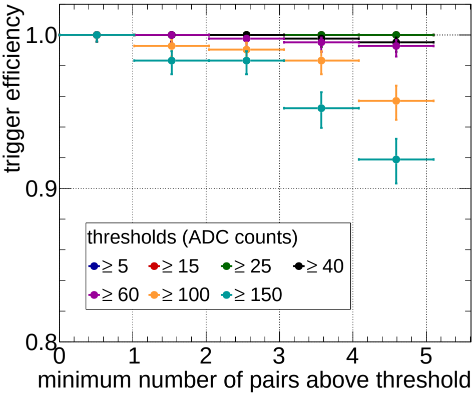

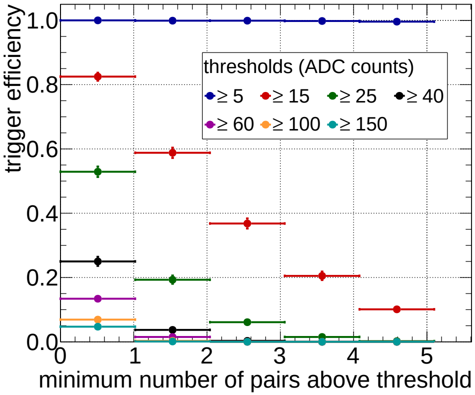

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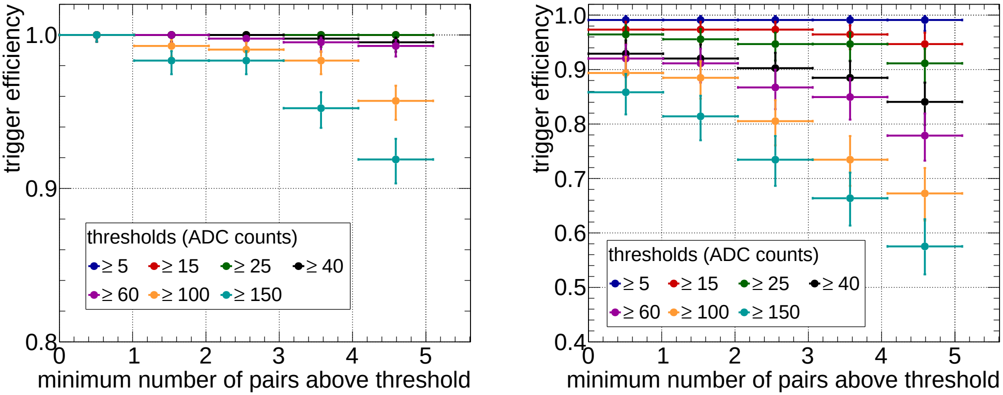

Trigger efficiency on charged (left) and neutral (right) current BNB neutrino interactions.