Light signal study of cosmic rays in the ICARUS detectors

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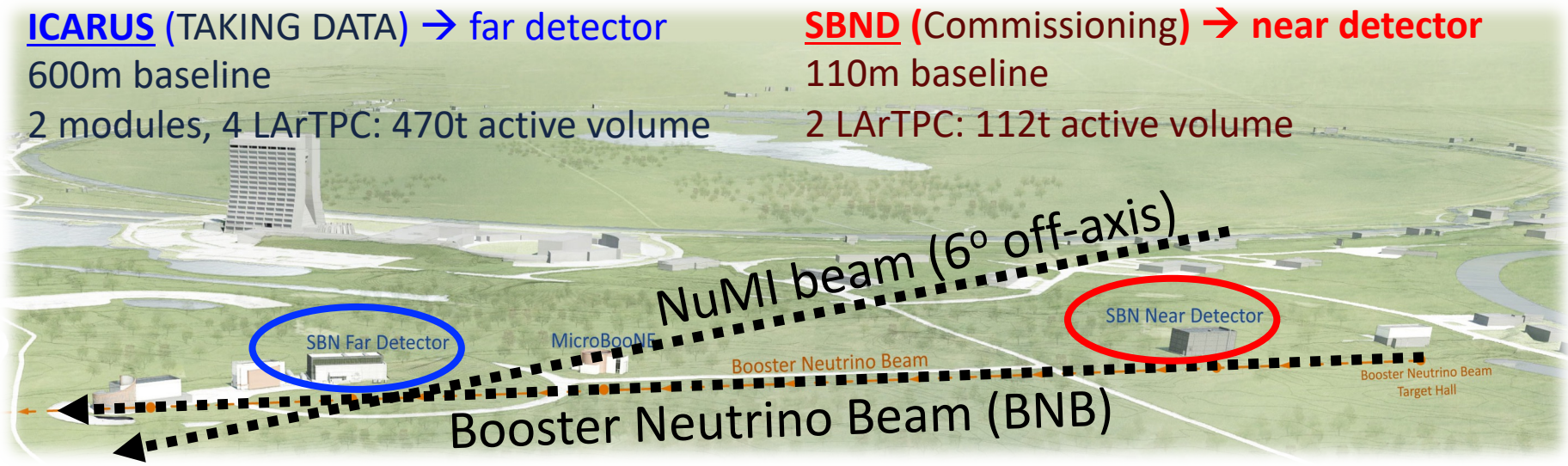
on behalf of the ICARUS Collaboration

H2020, M. Sklodowska-Curie
R&I No. 822185, 858199,
101003460, 101081478

Short-Baseline Neutrino Program at Fermilab

See L. Di Noto talk for more details



- **LAr-TPC** located **on-axis** of the **Booster Neutrino Beam** (BNB)
- **Searching for sterile-ν oscillations** both in **appearance** (ν_e) and **disappearance** (ν_μ) channels comparing the neutrino events collected by near and far detectors;
- **High-statistics ν-Argon cross-section measurements and event identification/reconstruction studies**:
  - ~10^6 events/y in SBND ~< 1 GeV from BNB;
  - ~10^5 events/y in ICARUS ~> 1 GeV from **NuMi** off-axis beam.

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The ICARUS detectors system

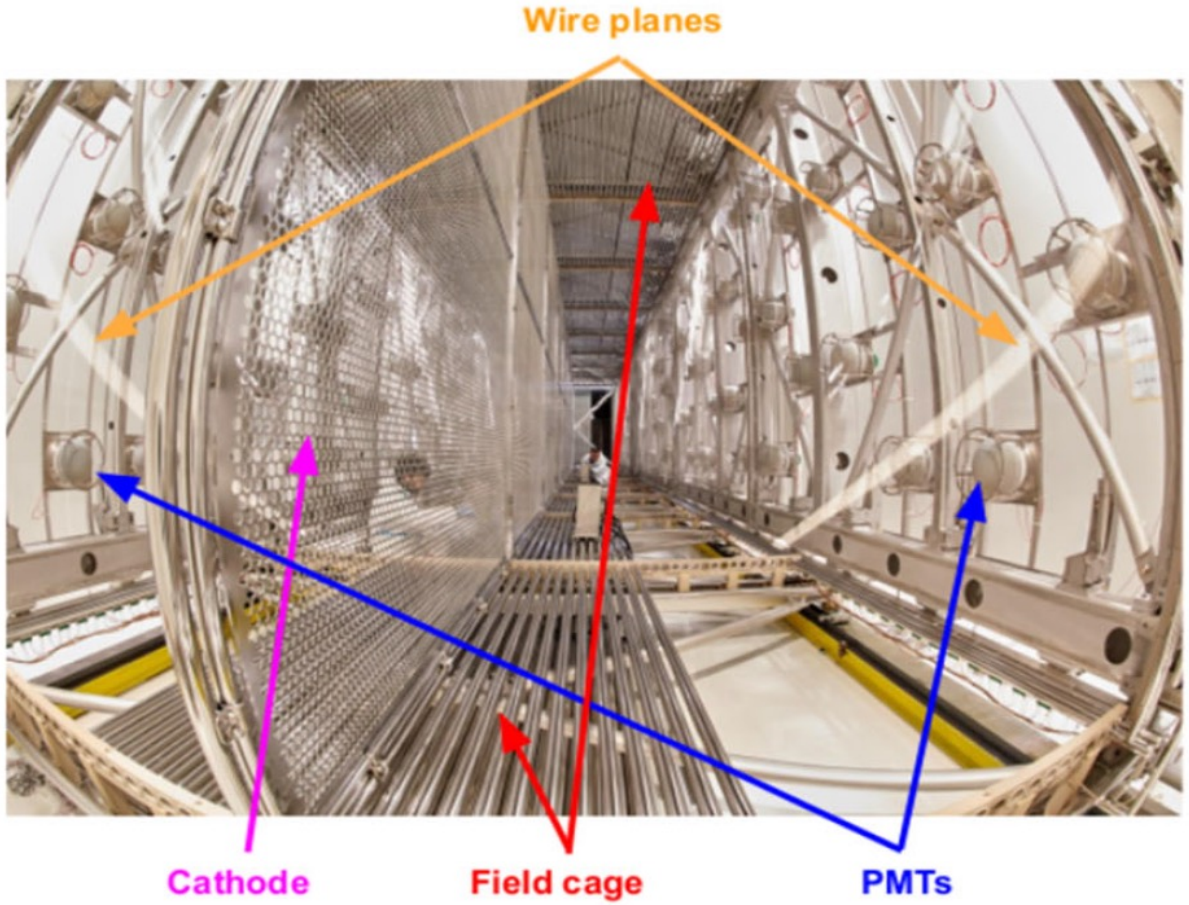
See L. Di Noto talk for more details

Liquid Argon Time Projection Chambers (LArTPC) are *high granularity continuously sensitive self-triggering* detectors with *3D imaging and calorimetric reconstruction* capabilities of events with complex topologies **ideal for ν-physics** (proposed by C. Rubbia in 1977).

ICARUS T600 → two identical cryostats

- **two LArTPC** per cryostat with a **common cathode** (E_{drift} = 500 V/cm);
- **3 "non-destructive" readout wire planes** with different orientation **(0°, ±60°)** continuosly read the ionization electrons (t_{drift} ~ 1ms, v_{drift}~1.6 mm/ms);
- **90 PMTs per TPC** located **behind the wires** to collect scintillation light and provide the interation time and the detector trigger.

➢**Cosmic Ray Taggers** surrond the cryostats, *tagging incoming cosmics with ~95% efficiency*.



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Scintillation light detection system

360 PMTs (8” Hamamatsu coated with TPB) installed **behind the TPC wire planes** (5% coverage, 15 ph.e./MeV) **allowing to**:

- Precisely **identify the interaction time of ionizing events** in the TPC (*time resolution ~ns*).
- **Localize events** in the PMT plane (**spatial resolution <50 cm**).
- Roughly **determine the event topologies** for fast event selection.
- **Generate a trigger signal** for readout with a sensitivity to low energy events (~100 MeV).

The system was completed in 2019 and activated after the LAr filling in 2020.

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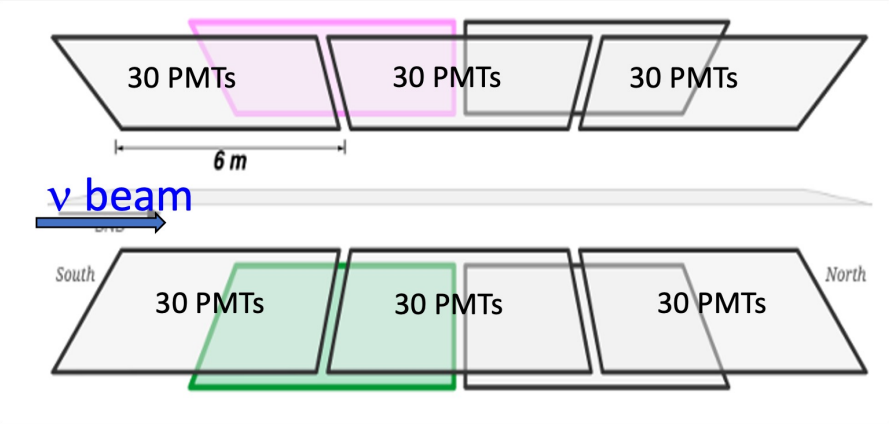
8” Hamamatsu R5912-MOD

The new ICARUS PMTs mounted behind the wires of one TPC.

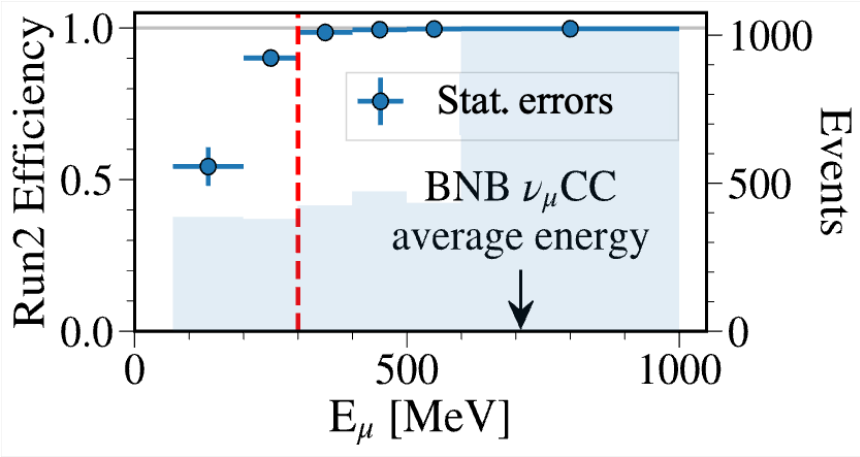
Trigger system

ICARUS main trigger signal is generated by the presence of **light signals from PMTs in coincidence with BNB (1.6 μs) and NuMI (9.6 μs) beam spills** defined using the Early Warning signals of proton beam extractions:



- Beam events are **collected requiring at least 5 fired PMT pairs** (Mj = 5) inside one of 6 m longitudinal slices equipped with 30+30 opposite PMTs;
- PMT and CRT **signals also recorded in 2 ms around the trigger to recognize cosmics** crossing LAr-TPCs in 1 ms e^- drift time.

ICARUS work in progess
Courtesy of R. Triozzi (INFN PD)



Additional triggers (*primitives*) to detect cosmic rays for calibration and background studies for the ν-oscillation searches.

- *minimum-bias triggers without requesting scintillation light a priori (**MinBias**)* → provide the sample for trigger efficiency study (trigger emulation starting from PMT waveforms)

Study of light signal from cosmic muon
data sample

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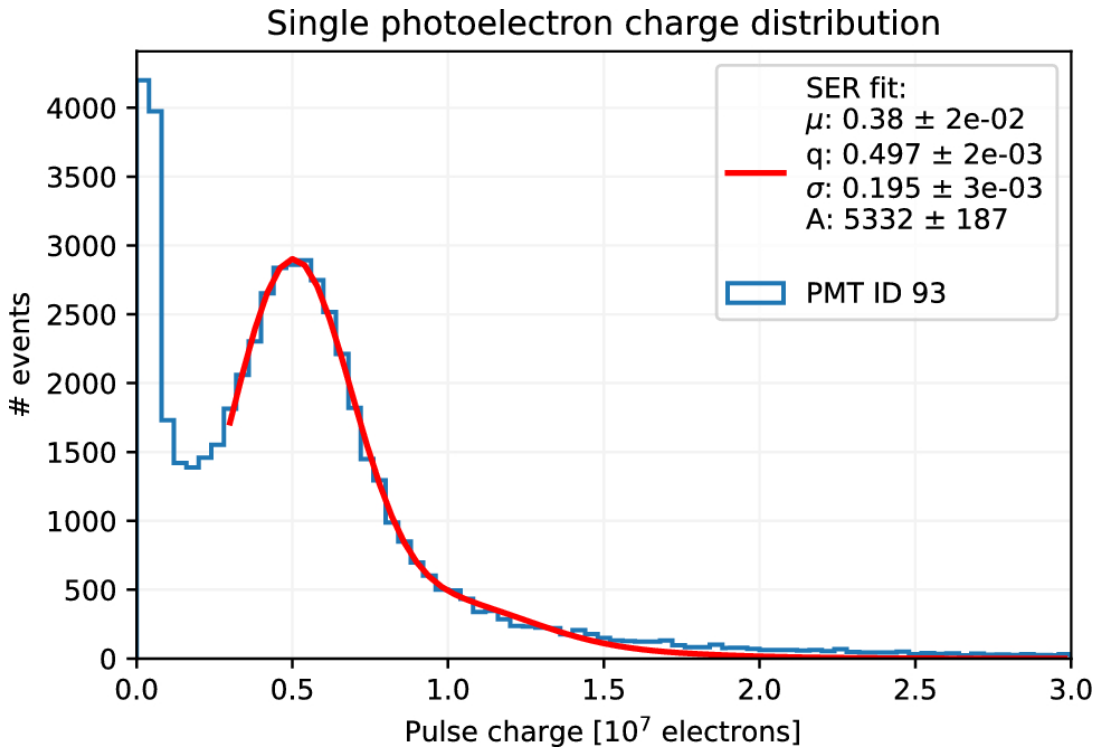
The studied data sample is a single run (9435) of about 15 k-events from the RUN2 collected with BNB majority.

RUN2:
December 22 - July 23

- BNB (FHC) positive focusing: 2.05 x 10^{20} PoT
- NuMI (FHC) positive focusing: 2.74 x 10^{20} PoT

BNB main trigger for RUN2:
>90% efficiency for E_{dep} >200 MeV



Example of a typical single photo-electron (ph.e.) charge distribution

Study of light signal from cosmic muon
Monte Carlo simulation

Scintillation photons (both from neutrino interaction and from cosmics):

1. **generated** from energy deposition and particle type;
2. **propagated through LAr** → all information of photons (location, time, …) reaching each PMT are stored exploiting a lookup tables (*photon library*) previously computed;
3. photon by photon the **single photon response** is added;
4. also **noise** is simulated and added to the simulated waveforms;

→ if this signal exceed ~ 0.6 ph.e. **threshold** on a channel, the **waveform** is recorded inside **4 µs window.**

The simulation has been tuned to data modifying the light simulation's parameters related to the gain and to the QE

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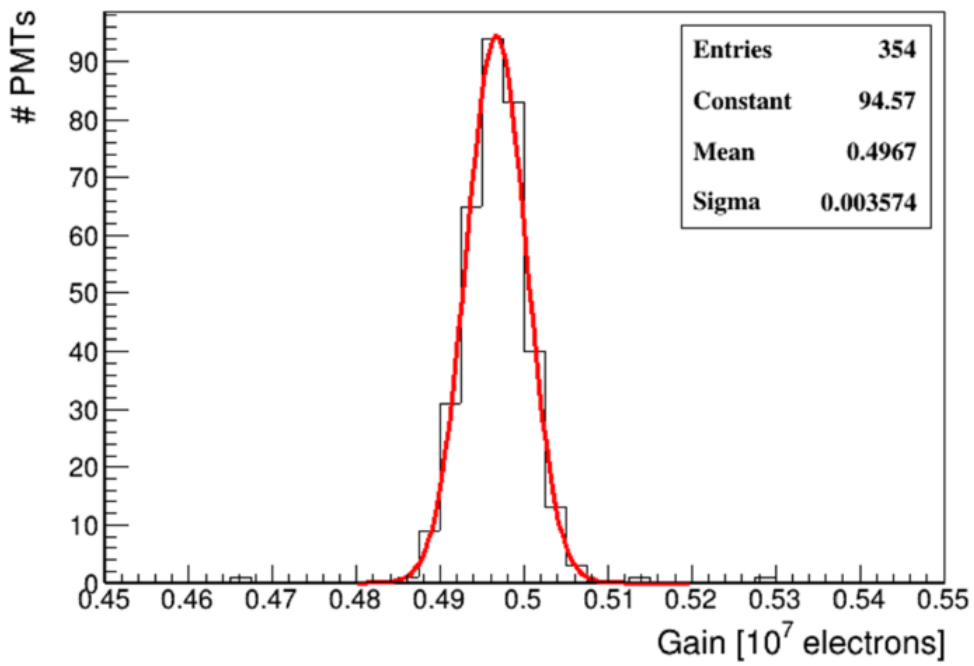
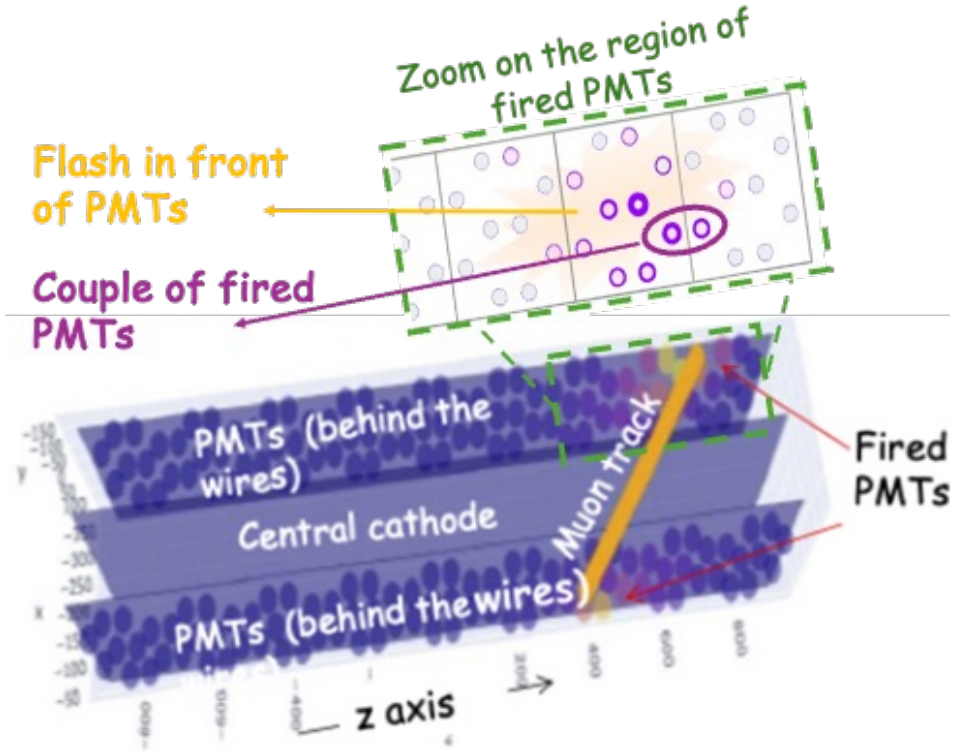


Gain distribution for 354 PMTs after the fine-tuning equalization. The automatic procedure was not applied on 6 PMTs (not present in the plot) that were manually calibrated.

Study of light signal: tuning MC light signal to data

Samples' selection: the brightest light signal

- **Tracks** (ionizing particle within LArTPC):
  ⇢ vertical, passing through the cathode and fully detected in the TPC (completely under control in time and position).



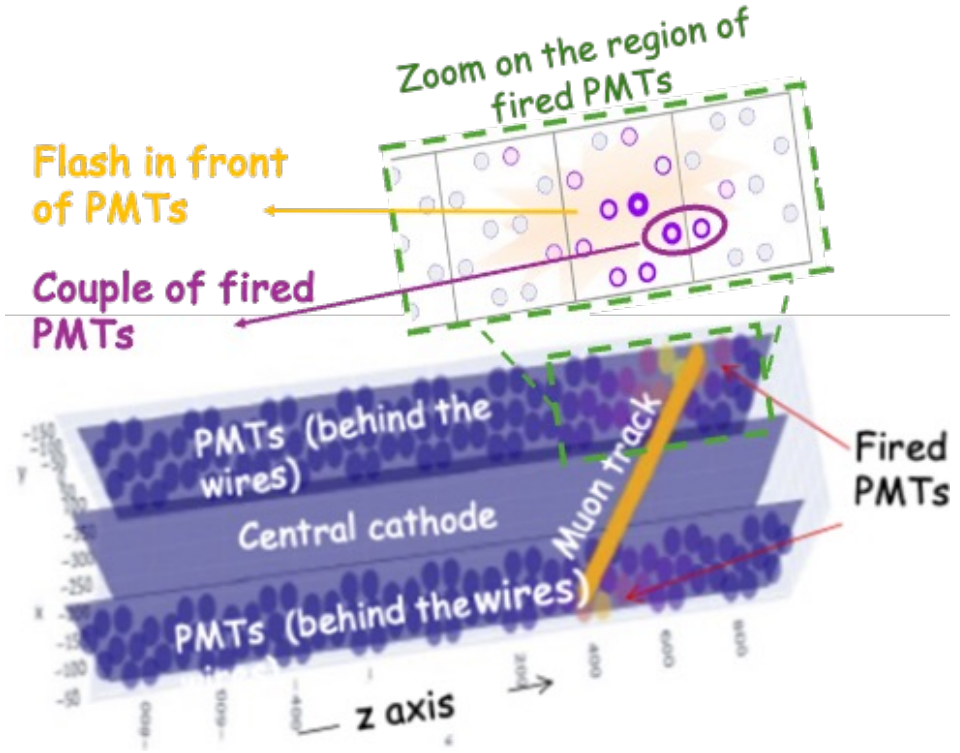
The PMTs associated with a cosmic ray muon crossing the cathode

Study of light signal: tuning MC light signal to data

Samples' selection: the brightest light signal

- **Tracks** (ionizing particle within LArTPC):
  ⇢ vertical, passing through the cathode and fully detected in the TPC (completely under control in time and position).

- **Flashes** (collection of light signals in the time window of 40 ns in at least 5 PMT):
  - ⇢ only the first flash in coincidence (in time and in barycentre along the beam direction) with selected tracks was considered;
  - ⇢ the first optical hits (i.e. light signal) looking along the time for each PMT are recognized
  - ⇢ the 10 optical hit with the highest amplitude are selected: brightest signals.

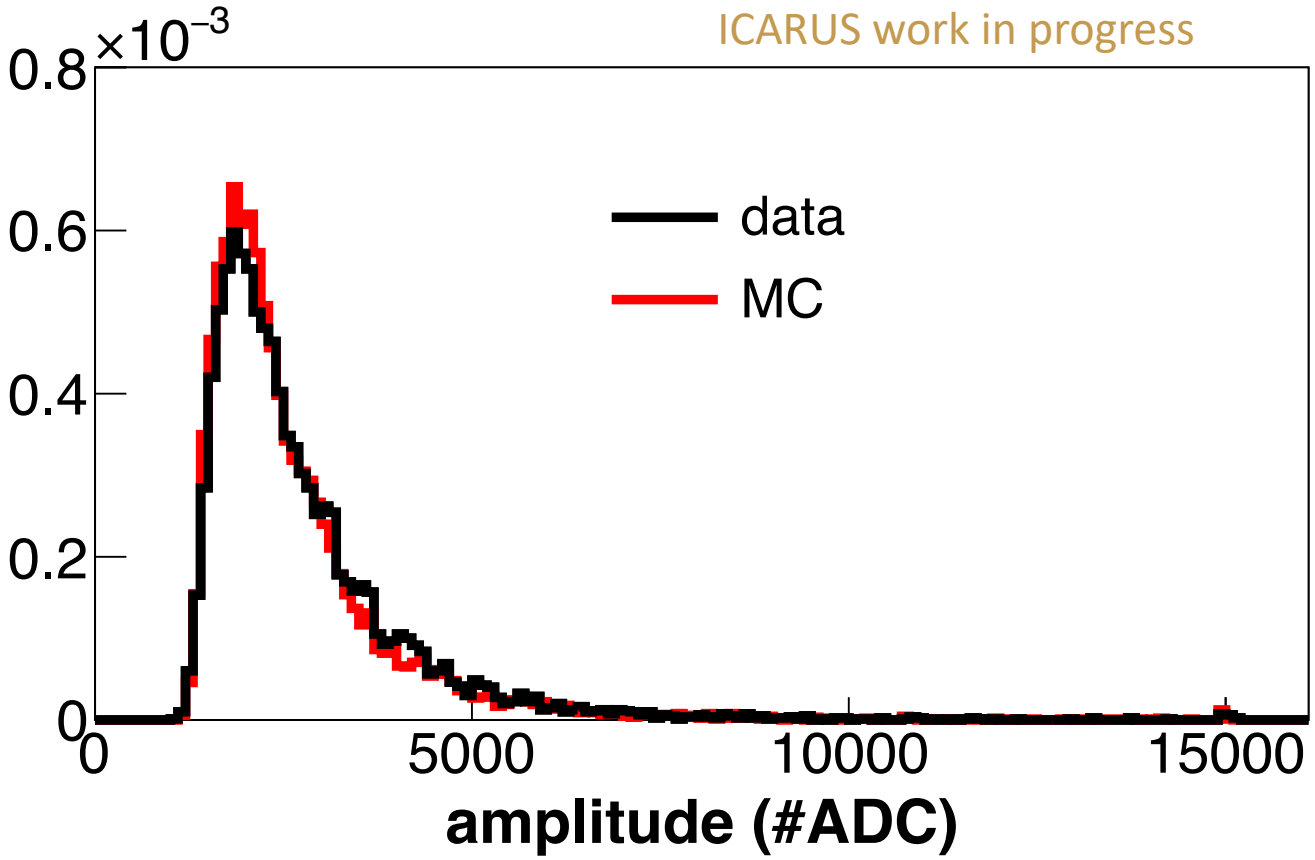


The PMTs associated with a cosmic ray muon crossing the cathode

Study of light signal: tuning MC light signal to data

Amplitude of the brightest light signal

Aiming to a good agreement between data and MC **amplitude** of the brightest light signals (samples completely under control) the MC simulation is tuned in gain and QE parameters.

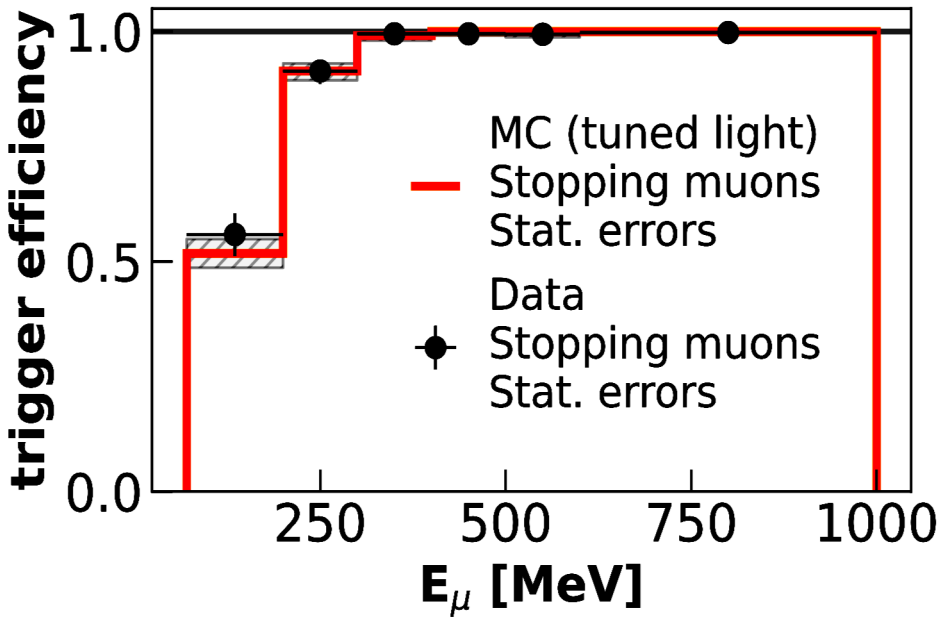


Validation with trigger efficiency
data vs. MC

The data **trigger efficiency** (Mj=5) for single tracks is well matched using data-based tuning of the MC parameters.

- Samples selections: unbiased sample of cosmics muon (single stopping muons) selected with CRT-PMT matching from MinBias runs (no request on scintillation light).
- The trigger logic software emulates considering the recorded PMT waveforms and reproducing the hardware PMT-majority trigger chain (Mj=5).

ICARUS work in progress



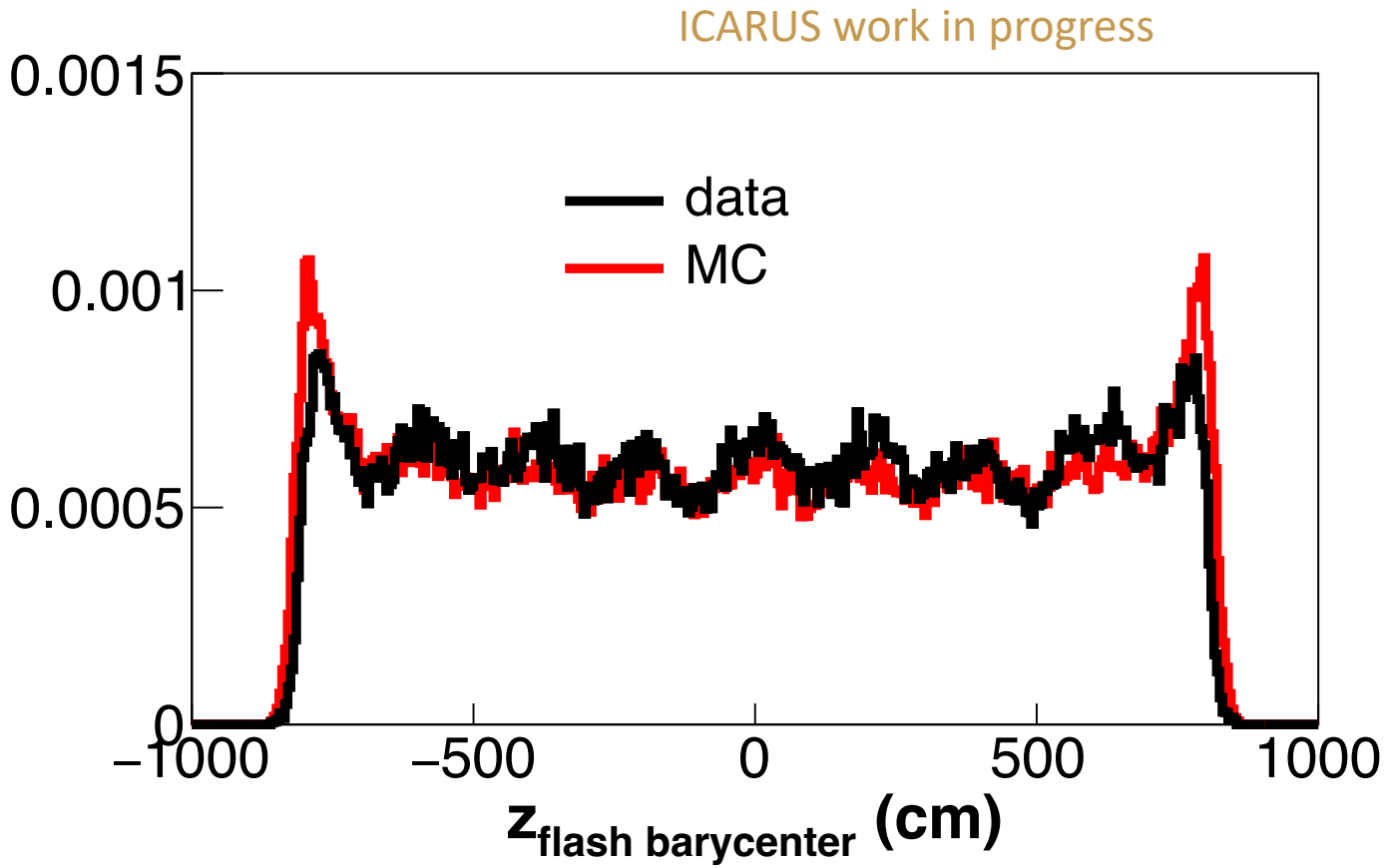
Comparison of trigger efficiencies (data vs. MC) for single tracks with majority 5 (Mj=5). Courtesy of R. Triozzi (INFN PD).

Validation with light position (barycentre along the beam direction)

data vs. MC

The data ***flash*** **barycentre along the beam direction** is quite well reproduced by tuned MC.

- Samples selections: all flashes.
- The barycentre along the beam direction of the flashes is used in the ICARUS analysis to match the *tracks* in TPC with the light signal (*flash*); the flash-time is assigned to the track if its time is unknow.



Summary

From the study of **brightest light signal** in coincidence with vertical cosmic rays, the gain and QE parameters of light **simulation are tuned** to well reproduce the data light amplitude.

Two **validations** confirm the data-tuning of MC:

- **trigger efficiency**;
- ***flash barycentre* along the beam direction**.

This effective MC is well suited to study and analyze with MC the neutrino interactions.

Summary

From the study of **brightest light signal** in coincidence with vertical cosmic rays, the gain and QE parameters of light **simulation are tuned** to well reproduce the data light amplitude.

Two **validations** confirm the data-tuning of MC:

- **trigger efficiency**;
- ***flash barycentre* along the beam direction**.

This effective MC is well suited to study and analyze with MC the neutrino interactions.

The study of light signal continue…

- to reduce the differences between data vs. MC (where it is possible)
- to evaluate the possible detector systematic effects of the light in the neutrino events selection.
  - ➢ a preliminary evalution shown that this systematic is low (few percent).

Stay tuned!

Thank you for your attention!

The ICARUS collaboration

12 INFN groups, 12 US institutions, CERN,
1 Mexican institution, 1 Indian Institution

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