Imaging Cosmic And Rare Underground Signals

Study of cosmic rays in the ICARUS-T600 detectors

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on behalf of the ICARUS Collaboration

Padova University, Physics and Astronomy Department and INFN – Sezione di Padova

Intense
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101003460, 101081478

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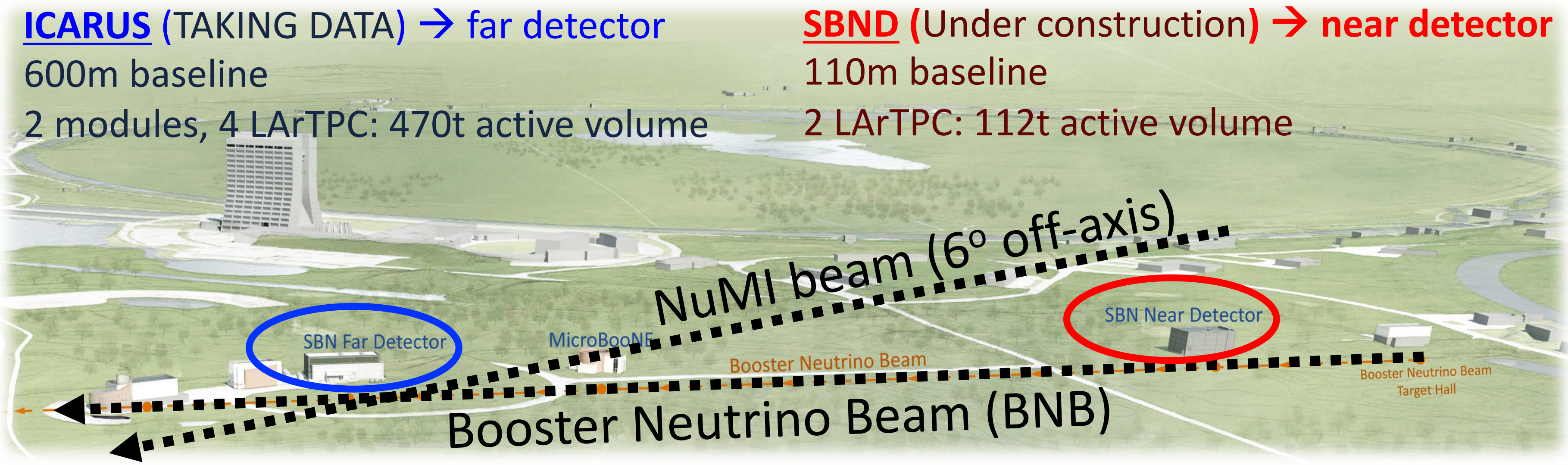
Outline

- SBN program at Fermilab
- ICARUS detectors system
- Preliminary study on cosmics rays light signal

Short-Baseline Neutrino Program at Fermilab

See D. Mendez 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 to confirm/rule out previous anomalies from past experiments;
- **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.

Phys. Rep. 928:1-63 (2021); Ann.Rev.Nucl.Part.Sci. 69 363-387 (2019)

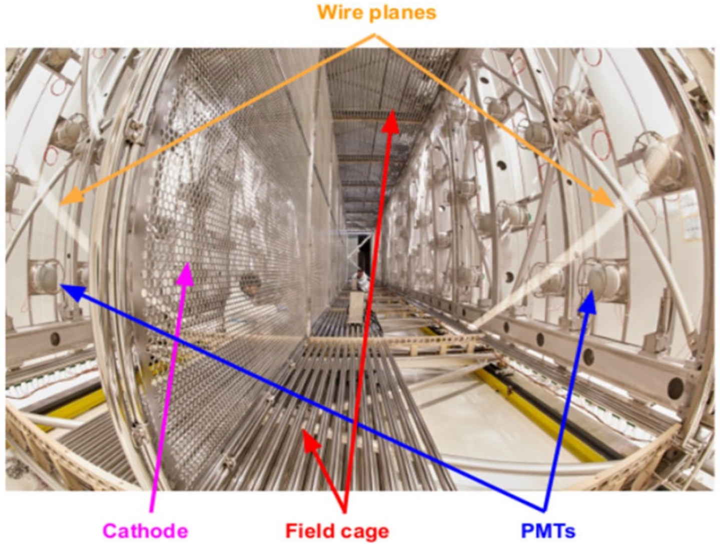
ICARUS detectors system

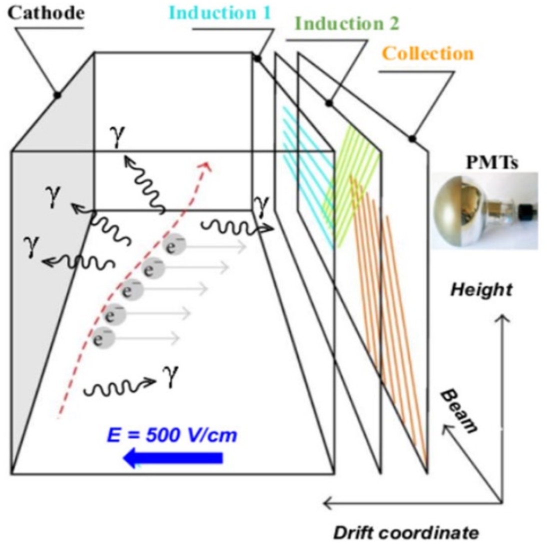
See D. Mendez talk for more details

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).

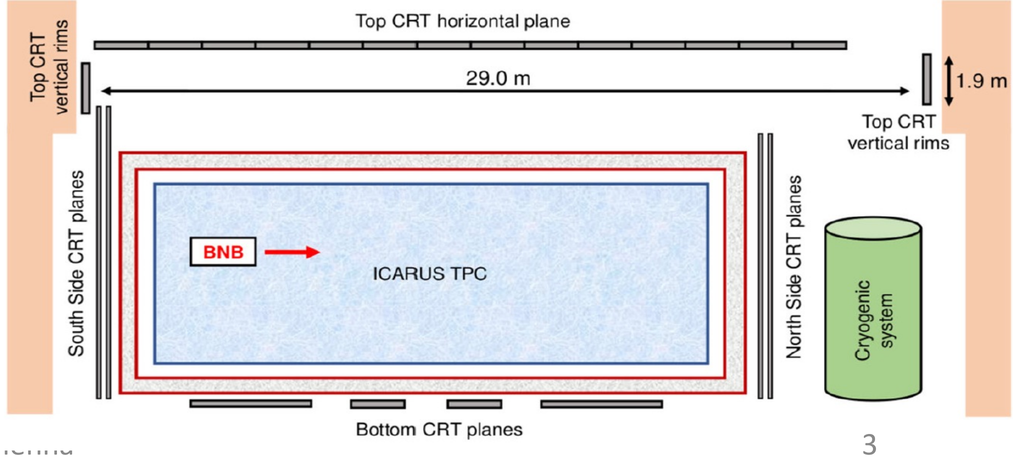
ICARUS T600 → two identical cryostats

- **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*.



Eur. Phys. J. C 83:467 (2023)

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.

Eur. Phys. J. C 83:467 (2023)

8” Hamamatsu R5912-MOD

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

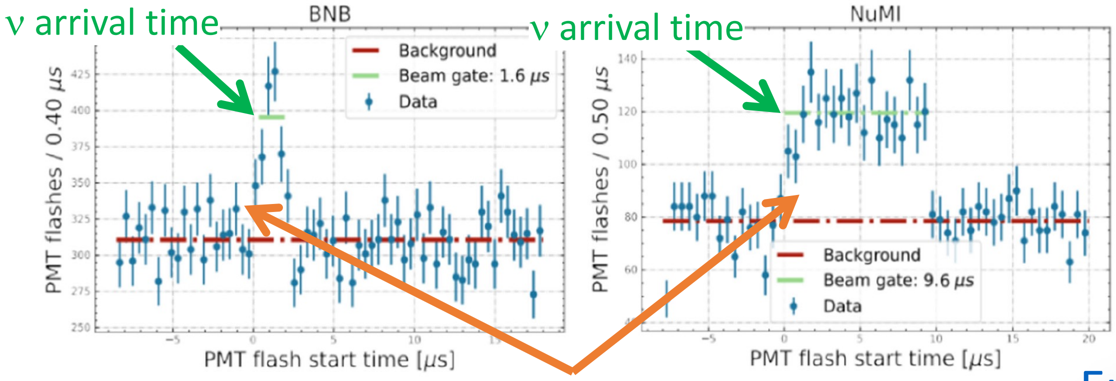
Trigger system and PMT data acquisition

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.

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

- *in beam spills w/o any request on the PMT signals*
- *outside of the beam spills*



Beam event excess visible in PMT light signals

- **Trigger rate ~0.7 Hz** (0.3, 0.15 and 0.25 Hz for BNB, NuMI and off beam respectively) setting the **PMT's threshold at 13 ph.e.**
- **Trigger efficiency** is now **under investigation** on data (>90% above E_{dep} ~ 100 MeV)

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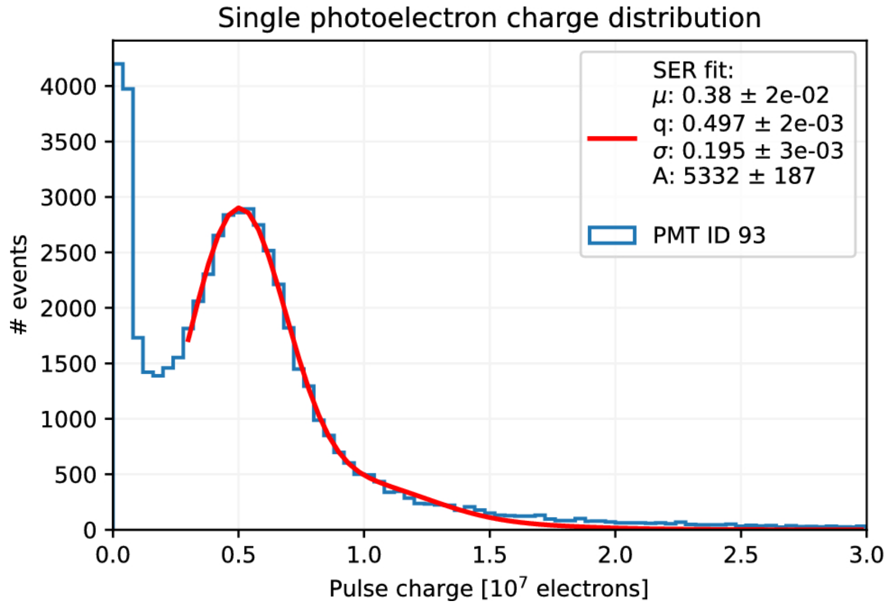
Study of light signal from cosmic muon
Monte Carlo simulation

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.**



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

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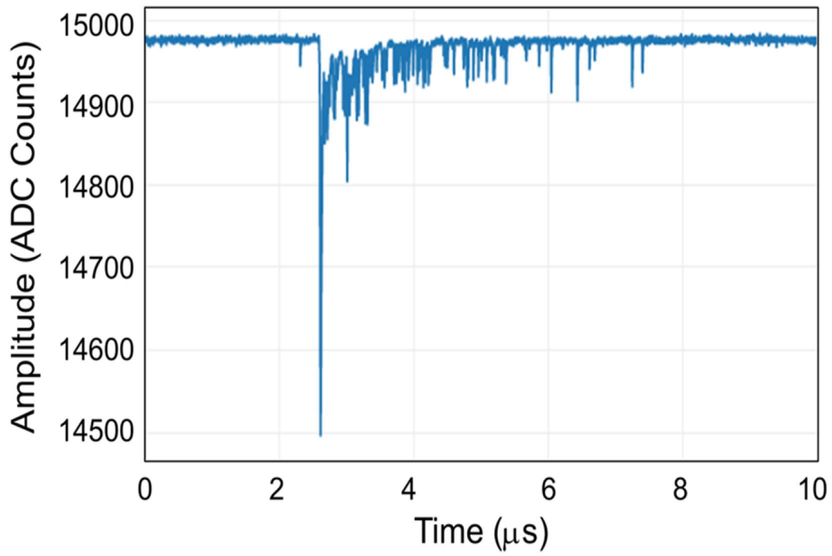
Study of light signal from cosmic muon
Number of photoelectron



PMT signal as recorded by the light detection system electronics.

[Eur. Phys. J. C 83:467 (2023)]

The **number of photoelectron** (*n. ph.e.*) is determined independently for each PMT signal (both in DATA and MC):

- **AREA** of the signal:
  1. Subtraction of the **baseline**;
  2. Signals are **discriminated against a fixed level**;

  $\Longrightarrow$ **AREA** = $\sum_i V_{i,ADC}$ (in ADC counts)

- **CHARGE** = F_E · AREA
  → F_E depends on the electronics characteristics, and allows to convert the stored AREA (ADC unit) in charge:

  $$F_E = \frac{k_{ADC \to V} \cdot \Delta t}{R} = \frac{0.122\ mV/ADC \cdot 2ns}{50\Omega}$$

$$\boldsymbol{n.ph.e.} = \frac{CHARGE}{e\ (= 1.6 \cdot 10^{-19} C)} \cdot \frac{1}{GAIN} = \frac{1}{e} \cdot \frac{1}{GAIN} \cdot F_E \cdot AREA$$

Preliminary study of light signal: comparison MC vs. DATA

Samples and selections

Analyzed samples:

- Reconstructed **DATA** → cosmic muons entering the TPC;
- Reconstructed **MC** → in time (with beam) single cosmic muons.

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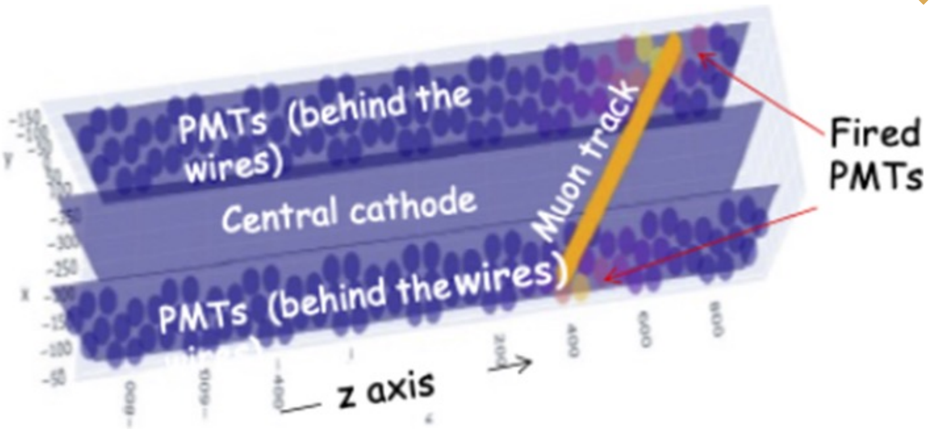
→ Selections:

- **Tracks** (ionizing particle within LArTPC):
  ⇢ passing through the cathode and fully detected in the TPC in order to measure the time of the ionizing particle crossing the cathode (t_{track})
  ⇢ longer than 50 cm.



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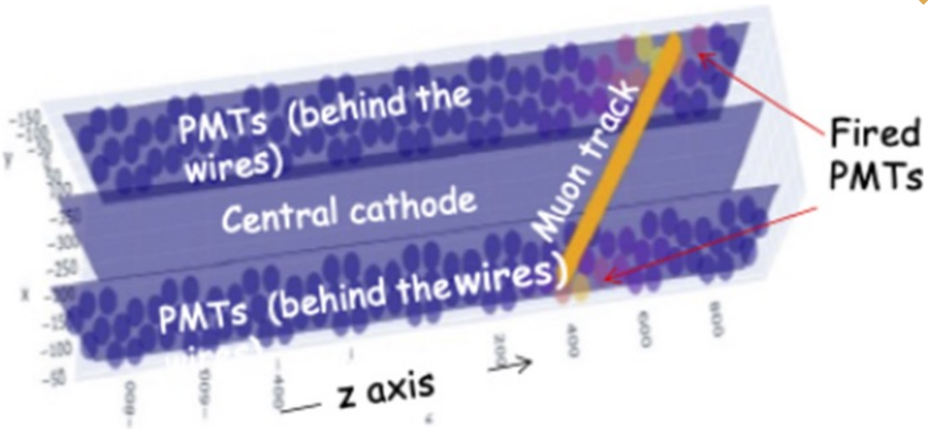
- **Tracks** (ionizing particle within LArTPC):
  ⇢ passing through the cathode and fully detected in the TPC in order to measure the time of the ionizing particle crossing the cathode (t_{track})
  ⇢ longer than 50 cm.
- **Flashes** (time-coincident (within ~1μs) ph.e. signals across multiple PMTs aiming for the reconstruction of an interaction).
  The first fired PMT provides the flash time (t_{flash}).
  ⇢ in coincidence with track:
  - time difference: $\Delta t = t_{track} - t_{flash}$ ($\lesssim 4\ \mu s$)
  - barycenter difference: $\Delta z = z_{track} - z_{flash}$ (< 30 cm)



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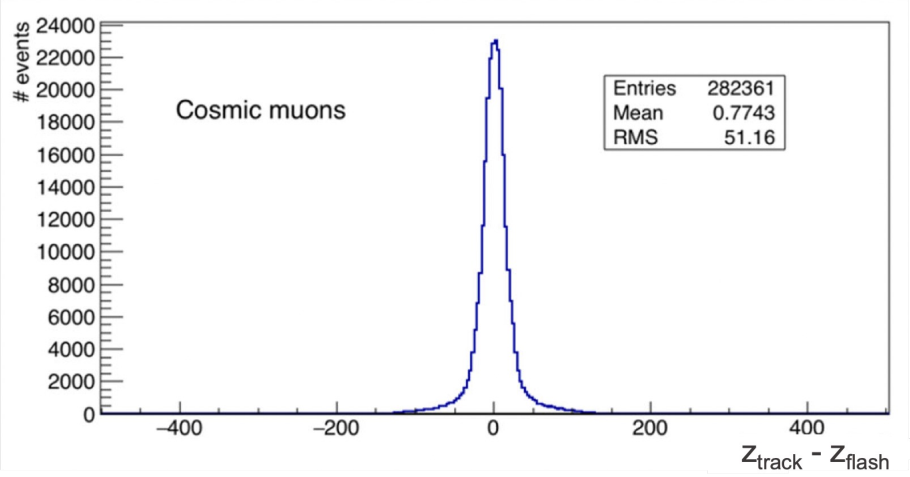
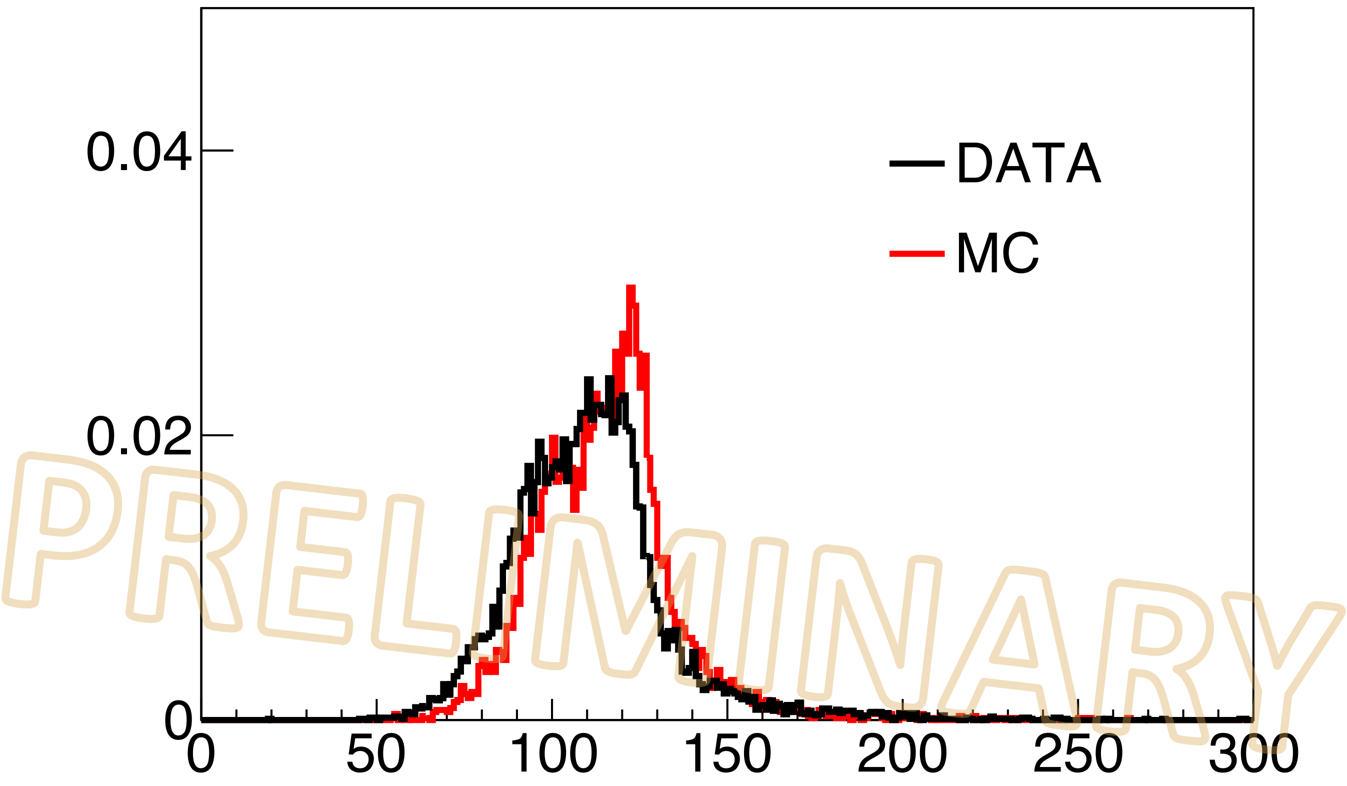
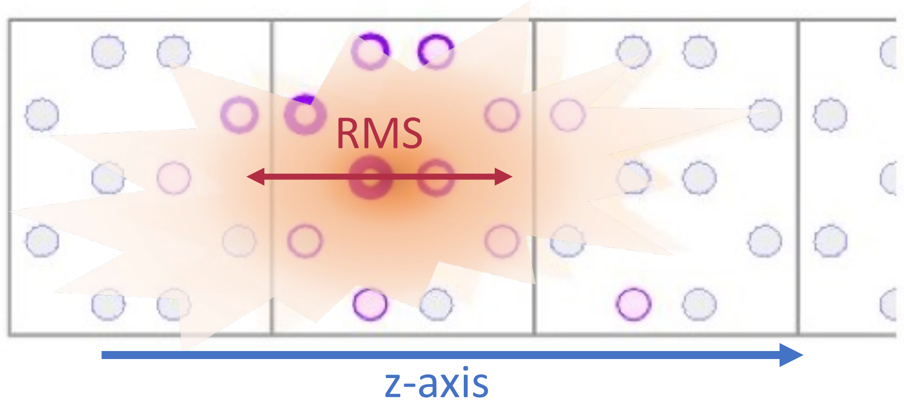


Preliminary study of light signal: comparison MC vs. DATA

Comparison of light signal extension along the beam direction



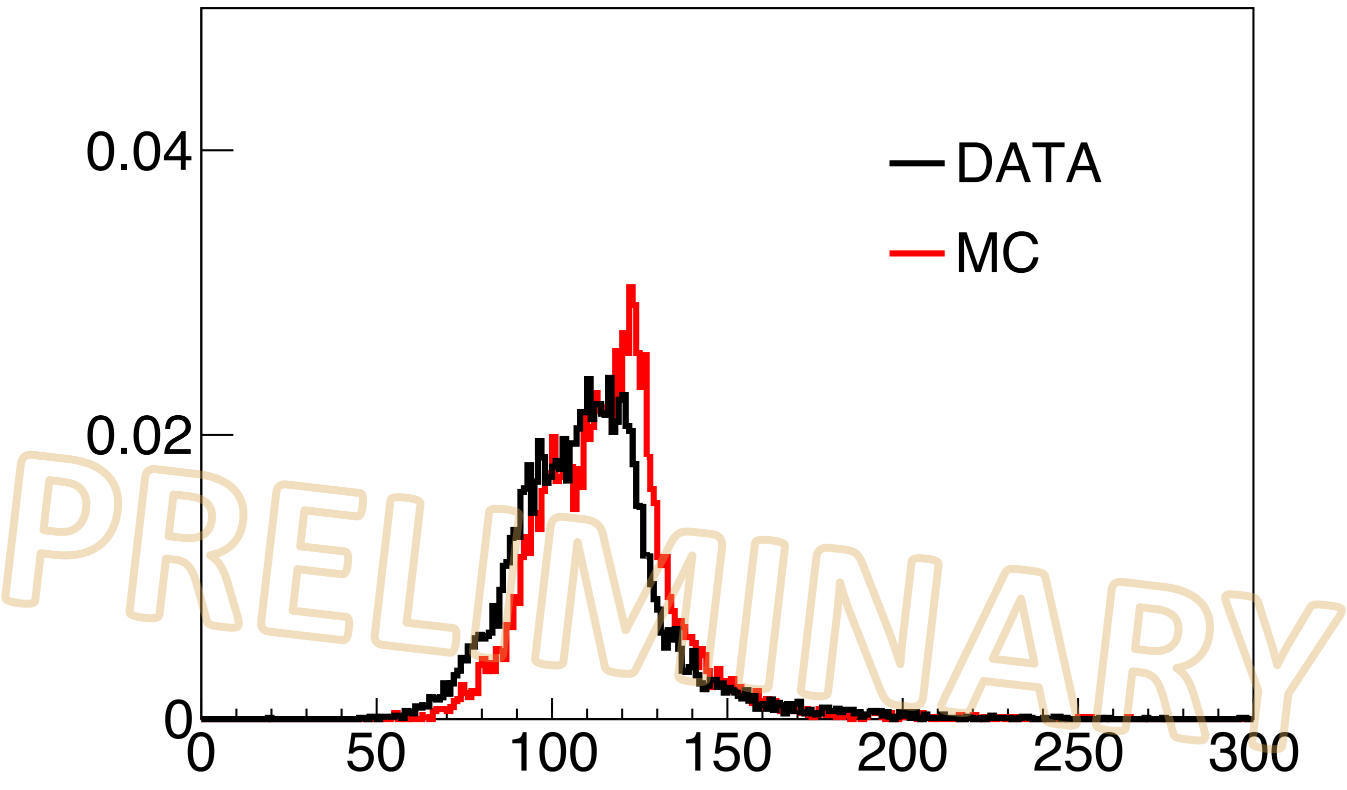
z-distribution of RMS spatial extension of the light flash *(cm)*



For each light flash, the position of its barycenter and its **RMS spatial extension along the beam axis z** are determined accounting for the number of **collected ph.e. on each fired PMT**.

Preliminary study of light signal: comparison MC vs. DATA

Comparison of light signal extension along the beam direction



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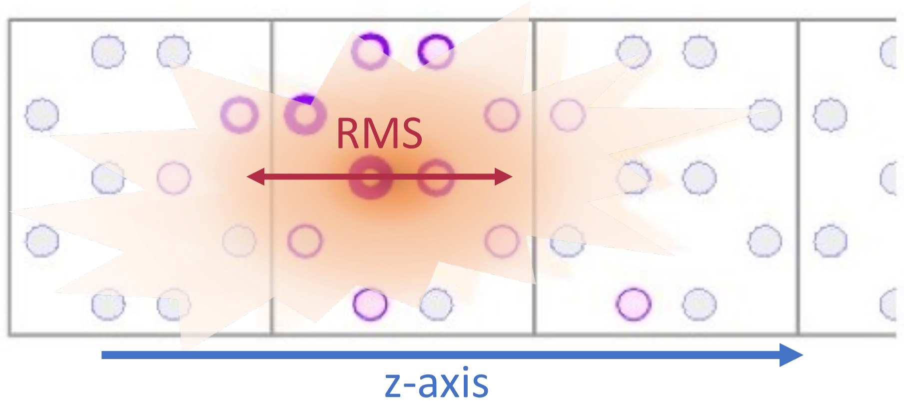


For each light flash, the position of its barycenter and its **RMS spatial extension along the beam axis z** are determined accounting for the number of **collected ph.e. on each fired PMT**.

Good agreement of **MC** prediction on the scintillation light extension with **DATA**.

Preliminary study of light signal: comparison MC vs. DATA

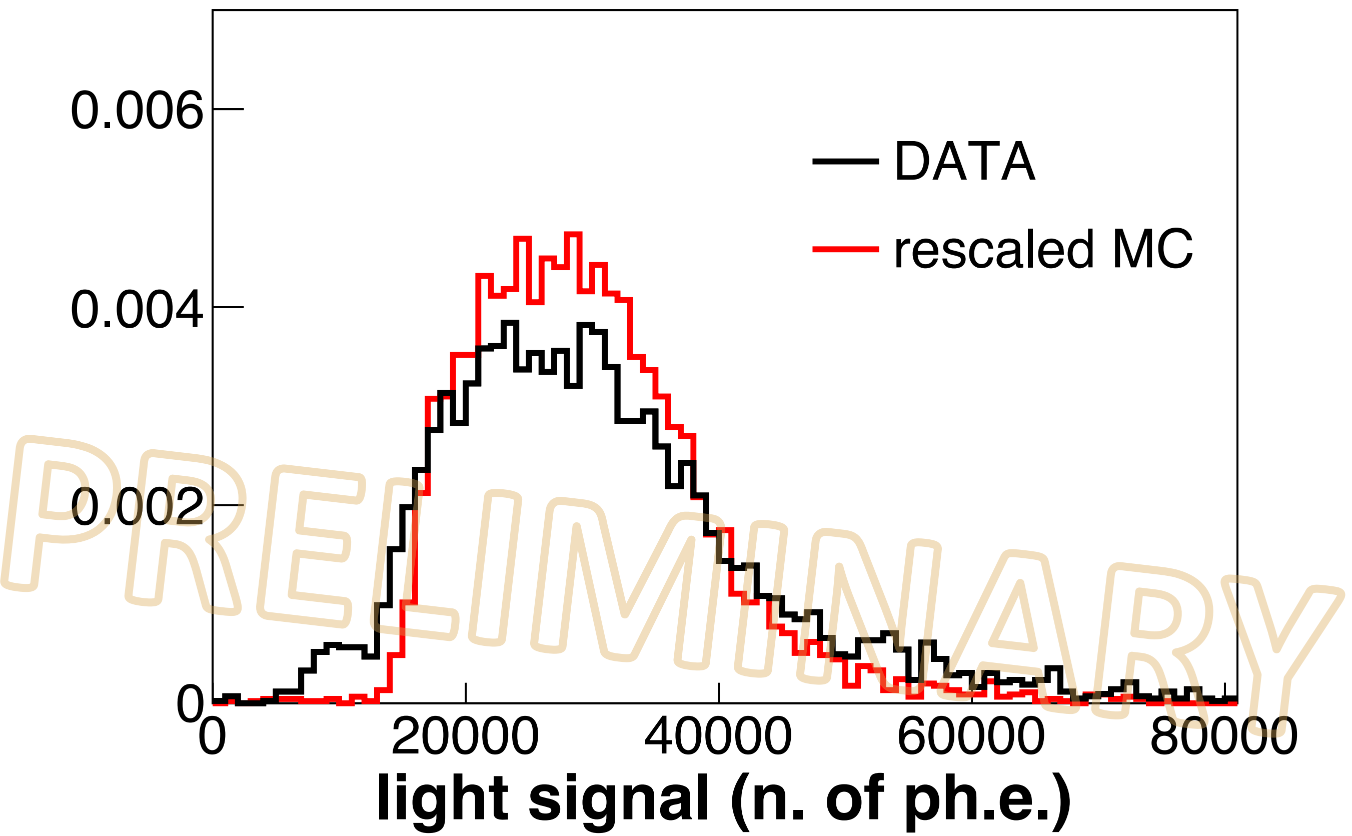
Rescaling of the MC light signal (ph.e.)

At moment, several factors are **under study**:

- *quantum efficiency* at LAr temperature
- *effects of the refraction* index of LAr
- *reconstruction artifacts*
- …

⇣

In the meanwhile, the **MC signal is rescaled to** the same average value as measured in **DATA** by fitting the ph.e. curve.



Preliminary study of light signal: comparison MC vs. DATA

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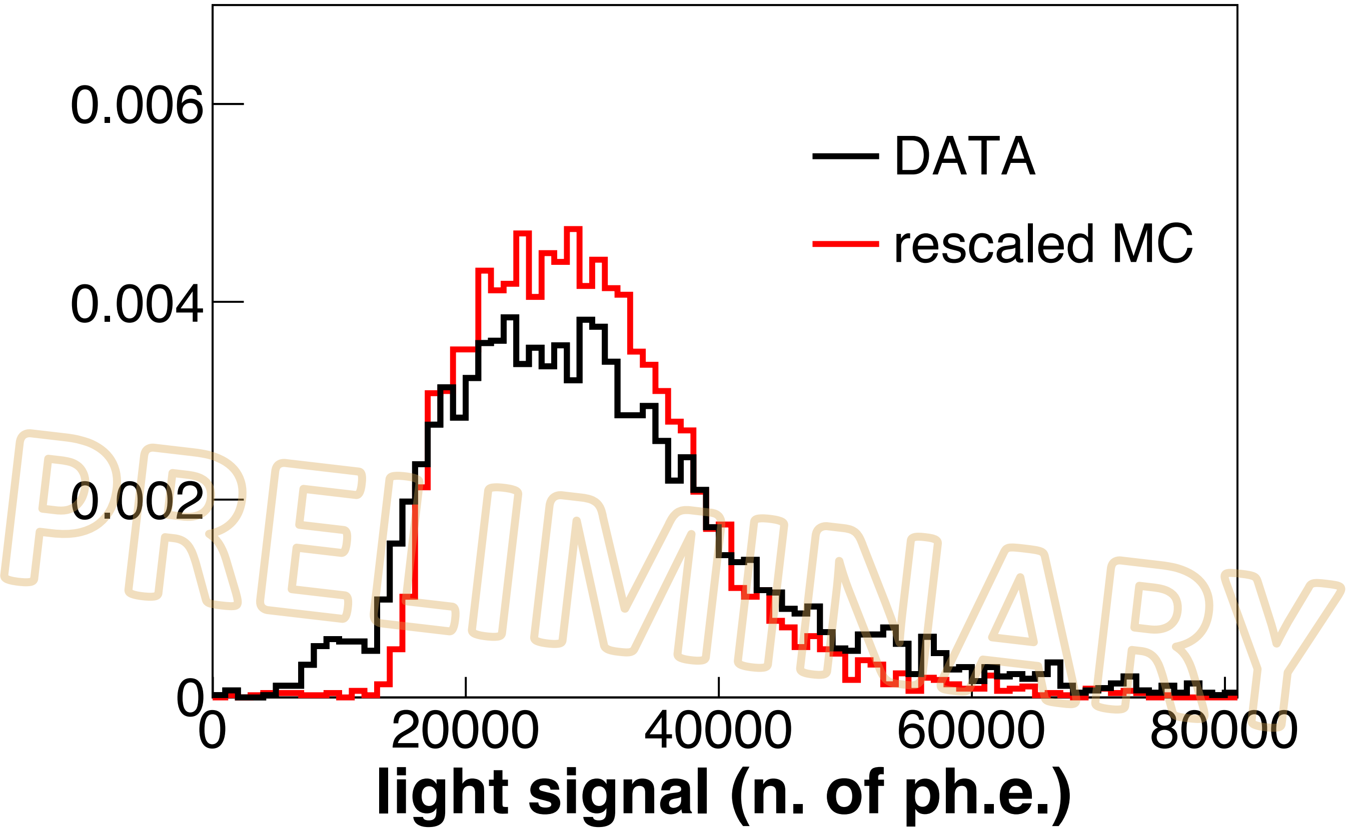
⇣

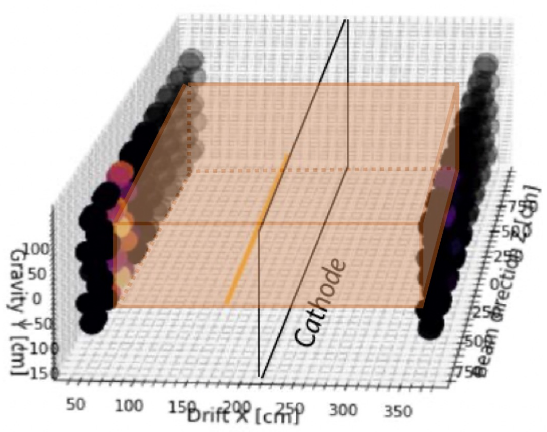
This allows to **open the possibility to study** with rescaled MC the **features of events associate with light** *to be later applied to event's selection.*



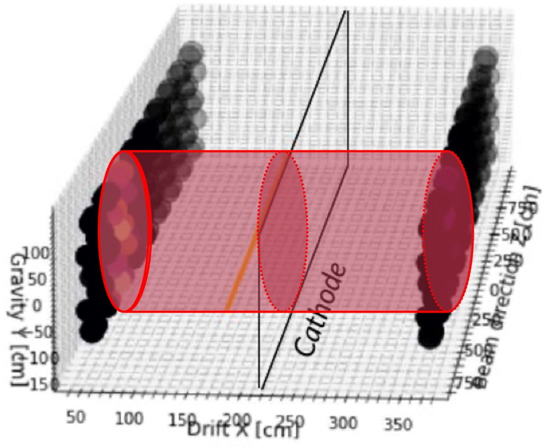
What's next…

- **Deeper analysis** on selected detector regions (i.e. center, boundary, close to the fired PMTs, far from the to the fired PMTs, …)
  - **First check**: focus on events far from detector boundary (i.e. trigger threshold, boundary acceptance, …) to be independent to reconstruction.
- **Deeper analysis** selecting specific tracks inclination (i.e. vertical, horizontal, …) and length.
- **Check and measure of the relevant parameters of scintillation light** production and collection by PMTs in order to improve the MC simulation.

Example (sketch) of detector's region selection



Center of the detector: far from the boundary!



Close to the fired PMTs

Summary

The preliminary study of LIGHT SIGNAL related to cosmics muon in the LArTPC is presented.

- The **MC** simulation of the **light signal extension along the beam direction** for cosmic muon is **well describing** the **collected DATA**.

- Relevant parameters in the optical simulation of the scintillation light, which affects the signal detected by PMTs are still under study.

- A **preliminary rescaling** of light simulated by **MC** to the collected DATA is applied **to study the features of events associate with light** in order **to develop event selection criteria and analysis**.

Thank you for your attention!

The ICARUS collaboration

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

P. Abratenko[19], A. Aduszkiewicz[21], F. Akbar[23], M. Artero Pons[15], J. Asaadi[24], M. Babicz[2], W.F. Badgett[5], L.F. Bagby[5], B. Baibussinov[15], B. Behera[4], V. Bellini[7], O. Beltramello[2], R. Benocci[13], J. Berger[4], S. Berkman[5], S. Bertolucci[6], M. Betancourt[5], K. Biery[5], M. Bonesini[13], T. Boone[4], B. Bottino[8], A. Braggiotti[15], J. Bremer[2], S. Brice[5], V. Brio[7], C. Brizzolari[13], J. Brown[5], H. Budd[23], A. Campani[8], A. Campos[27], D. Carber[4], M. Carneiro[1], H. Carranza[24], D. Casazza[8], A. Castro[3], M. Cicerchia[15], S. Centro[15], G. Cerati[5], M. Chalifour[2], A. Chatterjee[26], D. Cherdack[21], S. Cherubini[11], N. Chitirasreemadam[25], T. Coan[18], A. Cocco[14], M. R. Convery[17], S. Copello[16], A. De Roeck[2], S. Di Domizio[8], D. Di Ferdinando[6], L. Di Noto[8], M. Diwan[1], S. Donati[25], J. Dyer[4], S. Dytman[22], S. Dolan[2], F. Dolek[27], L. Domine[17], R. Doubnik[5], F. Drielsma[17], C. Fabre[2], A. Falcone[13], C. Farnese[15], A. Fava[5], F. Ferraro[8], F. Garcia[17], C. Gatto[14], M. Geynisman[5], D. Gibin[15], A. Gioiosa[25], W. Gu[1], M. Guerzoni[6], A. Guglielmi[15], S. Hahn[5], A. Heggestuen[4], B. Howard[5], R. Howell[23], J. Hrivnak[2], C. James[5], W. Jang[24], L. Kashur[4], W. Ketchum[5], J.S. Kim[23], D.H. Koh[17], U. Kose[2], J. Larkin[1], G. Laurenti[6], G. Lukhanin[5], A. Maria[26], C. Mariani[27], C. Marshall[23], S. Martinenko[1], N. Mauri[6], A. Mazzacane[5], K.S. McFarland[23], D.P. Mendez[1], G. Meng[15], A. Menegolli[16], O.G. Miranda[3], D. Mladenov[2], A. Mogan[4], N. Moggi[6], N. Montagna[6], A. Montanari[6], C. Montanari[5,b], M. Mooney[4], G. Moreno Granados[3], J. Mueller[4], M. Murphy[27], D. Naples[22], M. Nessi[2], T. Nichols[5], S. Palestini[2], M. Pallavicini[8], V. Paolone[22], R. Papaleo[11], L. Pasqualini[6], L. Patrizii[6], G. Petrillo[17], C. Petta[7], V. Pia[6], F. Pietropaolo[2,a], F. Poppi[6], M. Pozzato[6], A. Prosser[5], G. Putnam[20], X. Qian[1], A. Rappoldi[16], R. Rechenmacher[5], L. Rice[22], E. Richards[22], F. Resnati[2], A.M. Ricci[25], A.Rigamonti[2], G.L. Raselli[16], M. Rosemberg[19], M. Rossella[16], C. Rubbia[9], G. Savage[5], A. Scaramelli[16], D. Schmitz[20], A. Schukraft[5], F. Sergiampietri[2], G. Sirri[6], J. Smedley[23], A. Soha[5], L. Stanco[15], J. Stewart[1], N.B. Suarez[22], H.Tanaka[17], M. Tenti[6], K.Terao[17], F. Terranova[13], V. Togo[6], D.Torretta[5], M. Torti[13], Y.T. Tsai[17], S. Tufanli[2], T. Usher[17], F. Varanini[15], S. Ventura[15], M. Vicenzi[1], C. Vignoli[10], B. Viren[1], D. Warner[4], Z. Williams[24], P. Wilson[5], R.J. Wilson[4], J. Wolfs[23], T. Wongjirad[19], A. Wood[21], E. Worcester[1], M. Worcester[1], M. Wospakrik[5], H. Yu[1], J. Yu[24], A. Zani[12], C. Zhang[1], J. Zennamo[5], J. Zettlemoyer[5], S. Zucchelli[6], M. Zuckerbrot[5]

1. Brookhaven National Lab., USA
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21. University of Houston, USA
22. University of Pittsburgh, USA
23. University of Rochester, USA
24. University of Texas (Arlington),USA
25. INFN Pisa and University, Italy
26. Ramanujan Faculty Phys. Res. India
27. Virginia Tech Institute

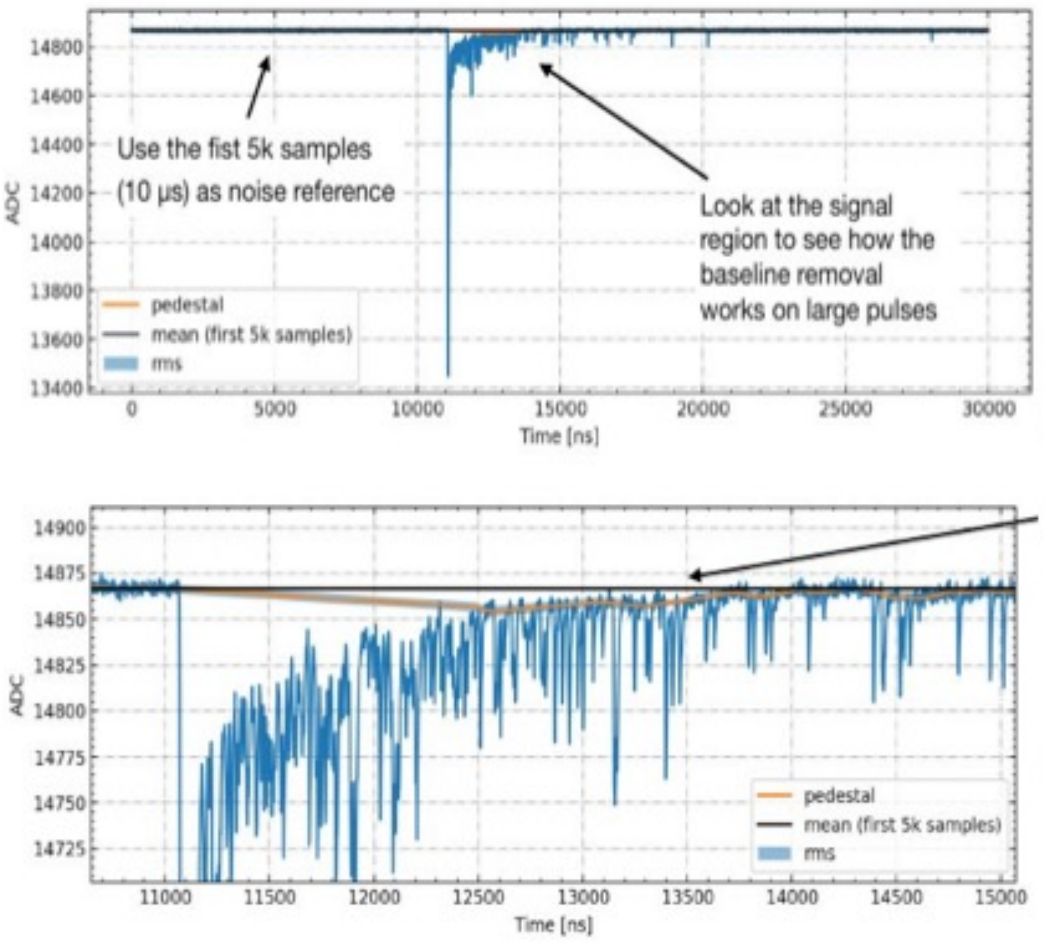
a. On Leave of Absence from INFN Padova
b. On Leave of Absence from INFN Pavia

Spokeperson: C. Rubbia, GSSI

SPARE SLIDES

Study of light signal (n.ph.e.)

Number of photoelectron: AREA of the light signal



Zooming on the signal region it appear evident how this algorithm smoothen out some tail removing part of the charge contained in it

If we integrate the charge between 10 μs to 24 μs we find the following:
- Total charge integral > 5 ADC (using **mean subtraction**) : **94764**
- Total charge integral > 5 ADC (using pedestal removal) : **84954**

Ratio is 89 %

The number of ph.e. is determined independently for each PMT signal (both in DATA and MC):

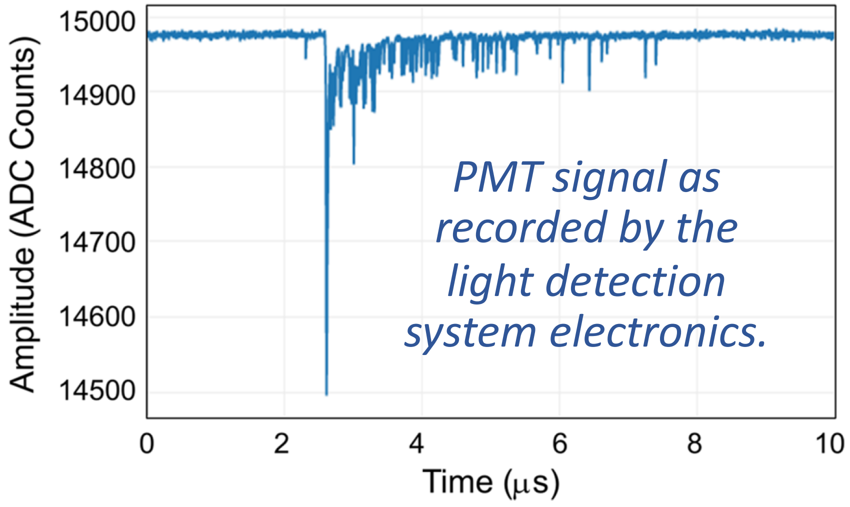
- **AREA** of the signal:
  1. Subtraction of the **baseline**;
  2. Signals are **discriminated against a fixed level**;

  $\Longrightarrow$ **AREA** = $\sum_i V_i \cdot k_{V \to ADC}$

  where:
  - i = index of sampling of the digitizer;
  - V = voltage read by the digitizer after the baseline subtraction.
-

Study of light signal (n.ph.e.)

Number of photoelectron



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  where:
  - i = index of sampling of the digitizer;
  - V = voltage read by the digitizer after the baseline subtraction.
- **CHARGE** = AREA · F_E
  - F_E depends on the electronics characteristics:

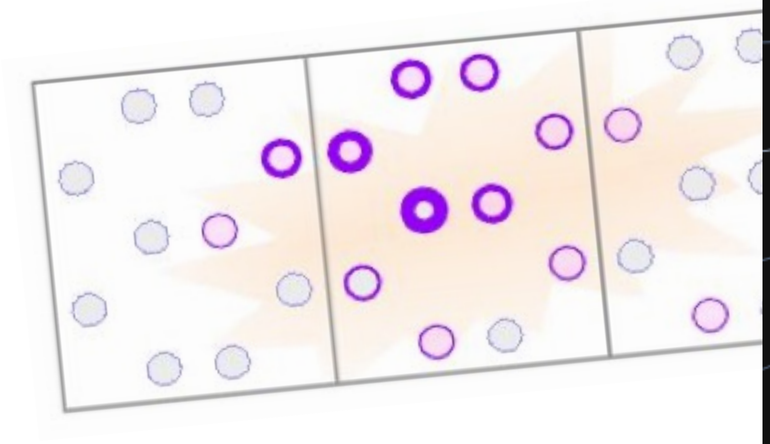
    $$F_E = \frac{k_{ADC \to V} \cdot \Delta t}{R} = \frac{0.122\ mV/ADC \cdot 2ns}{50\Omega} = \frac{0.122 \cdot 2 \cdot 10^{-12}}{50}\left[\frac{V/ADC \cdot s}{\Omega}\right]$$

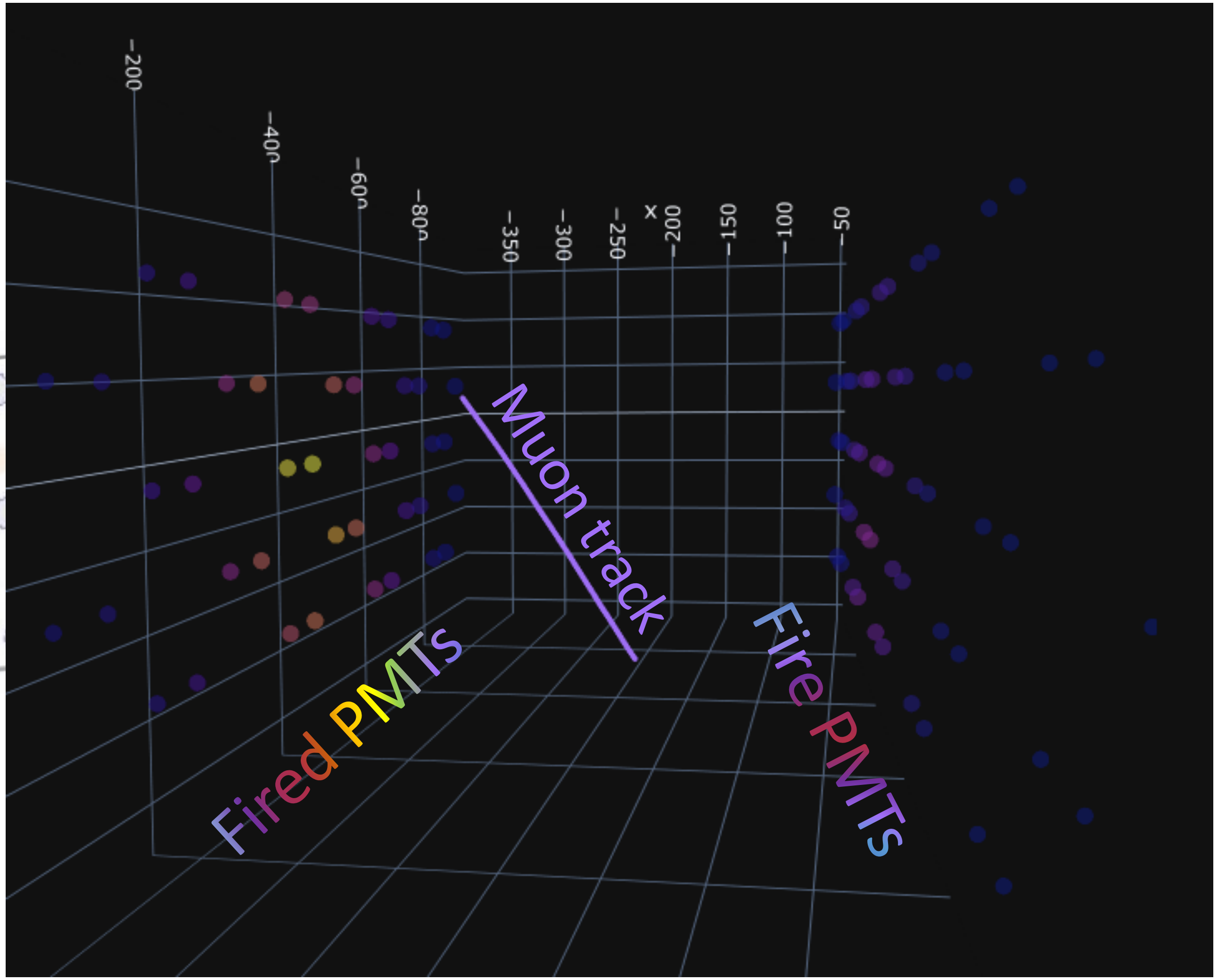
  where: R = 50 Ohm → standard impedance of our circuit.
- Photoelectron number (**n.ph.e.**) = CHARGE / e (=1.6·10^{-19} C).

$$\boldsymbol{n.ph.e.} = \frac{CHARGE}{e} \cdot \frac{1}{GAIN} = \frac{1}{e} \cdot \frac{1}{GAIN} \cdot FE \cdot AREA = \frac{0.122 \cdot 2 \cdot 10^{-12}}{50} \cdot \frac{1}{1.6 \cdot 10^{-19}} \cdot \frac{1}{GAIN} \cdot AREA \left[\frac{\cancel{V}/\cancel{ADC} \cdot \cancel{s}}{\cancel{\Omega \cdot C}} \cdot \cancel{ADC}\right]$$

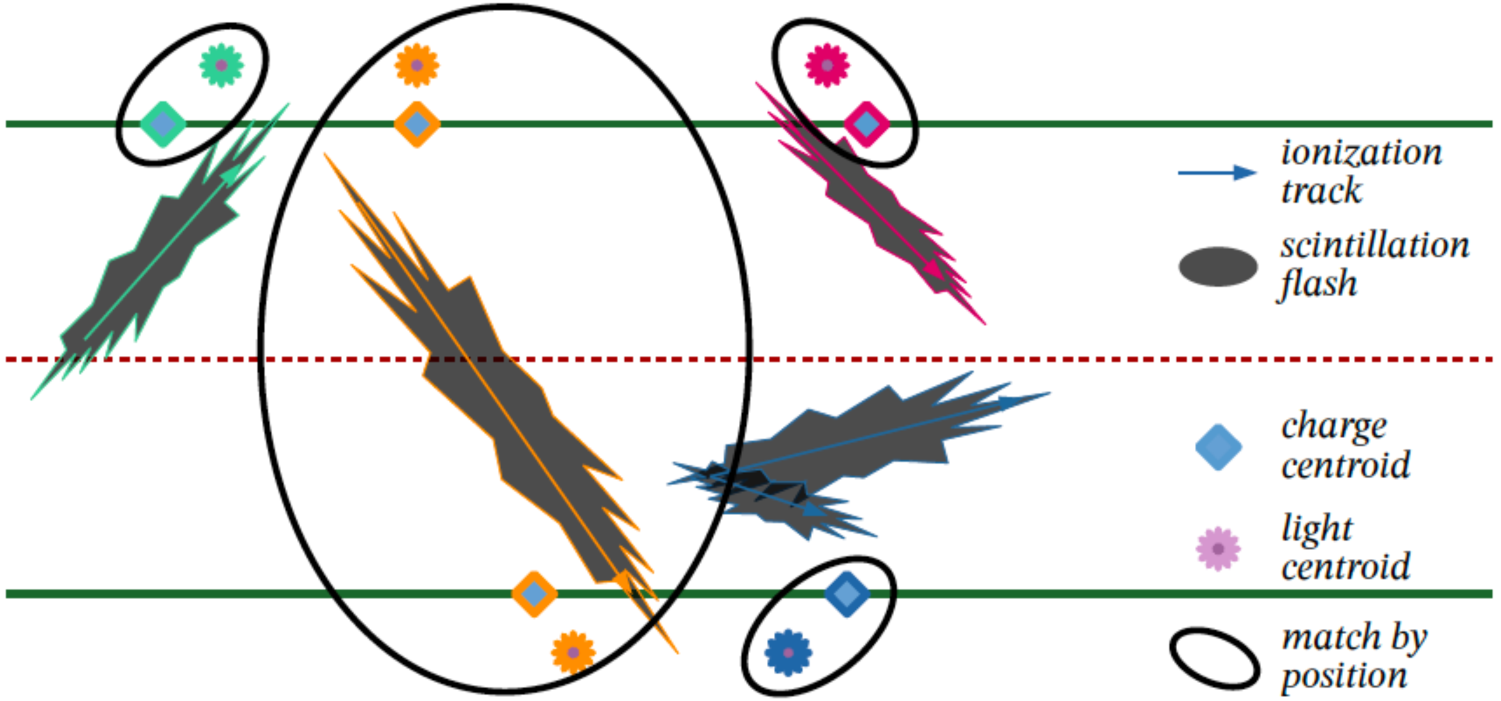
Light signal study:

Muon trajectory inside the TPC
→ light detected by PMTs





Light signal study:
Barycentre matching



1. **Reconstruction** of TPC tracks and PMT flashes;
2. **Compute the centroid** of each reconstructed **track** (within each TPC);
3. **Compute the centrois** of each reconstructed **flash** (within each TPC) at any time;
4. **Associate the two by proximity**.

Study of light signal:

Baricenter and width along beam axis

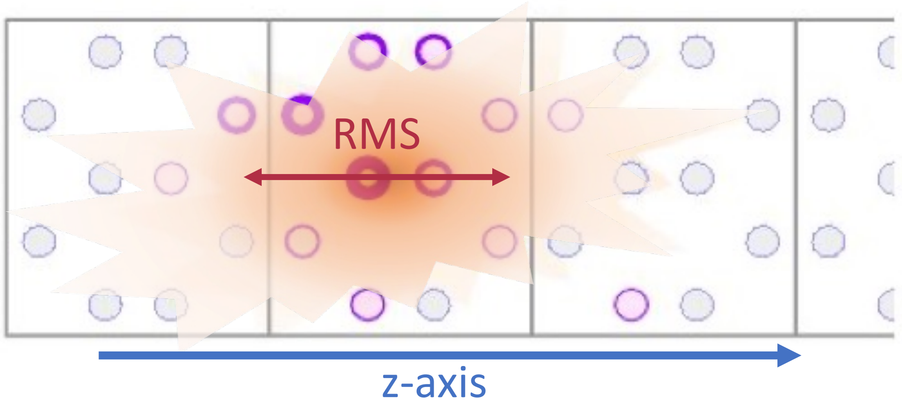
Baricenter along beam direction is the average of the fired PMT weigthed with the quantity of reconstructed ligth in each fired PMT:

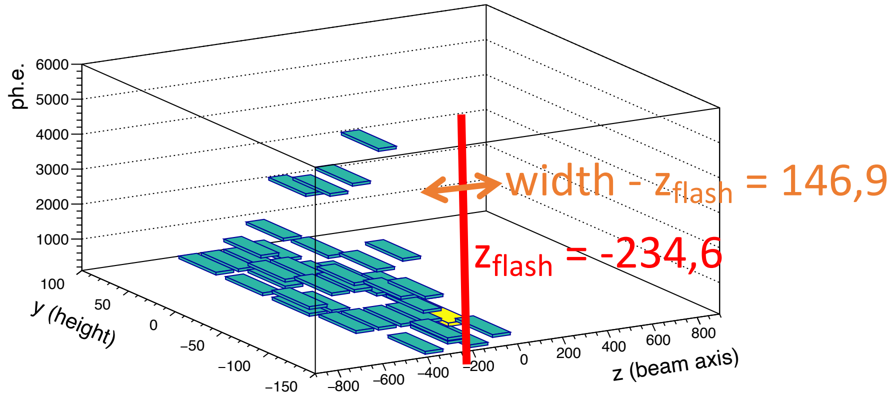
$$z_{flash} = \frac{\sum_{i = fired\ PMT} phe_i z_i}{\sum phe_i}$$

where z_i is the position of the fired PMT and w_i is the weight meaning the quantity of reconstructed ligth in each PMT.

Baricenter **width** along beam direction is the position **RMS of the fired PMTs, weigthed with the quantity of reconstructed light in each fired PMT**:

$$width_{flash} = \sqrt{\frac{\sum_{i = fired\ PMT} phe_i (z_i - z_{flash})^2}{\sum phe_i}}$$





Example: run 9435, event 18513, flash_id 0