Scintillation light detection in the long-drift ProtoDUNE-DP liquid argon TPC

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Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

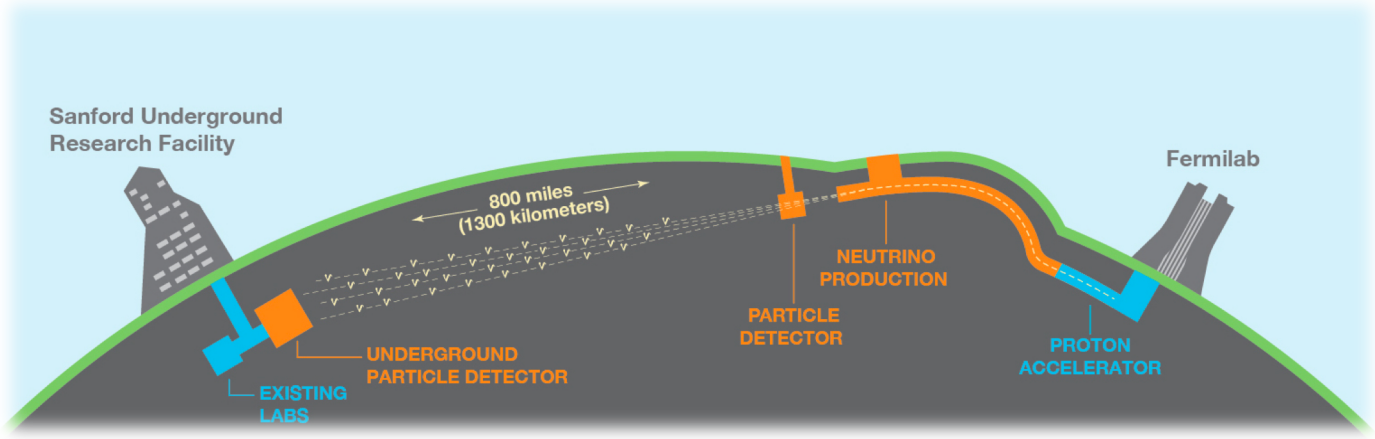
DUNE

Deep Underground Neutrino Experiment (DUNE)

DUNE aims at answering fundamental questions related to:

- The matter-antimatter asymmetry - neutrino oscillations & mass ordering
- The Grand Unification of forces - nucleon decay searches
- The supernova explosion mechanism - supernova neutrino detection

EPJC 80 (2020) 978
EPJC 81 (2021) 322
arXiv:2008.06647

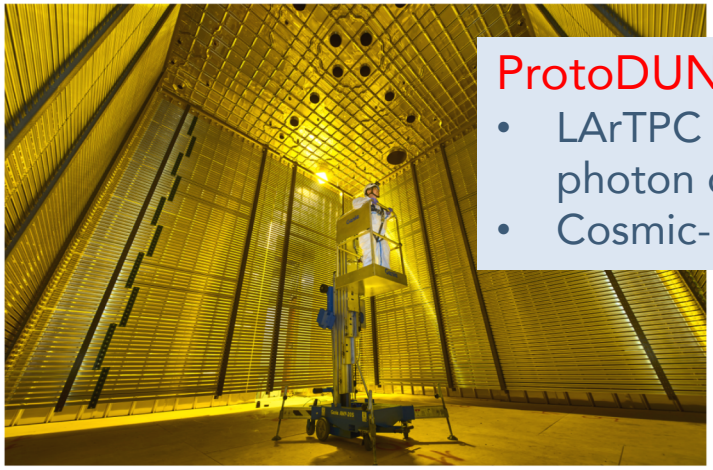


- New neutrino (ν_μ or $\bar{\nu}_\mu$) beam facility at Fermilab (LBNF), US
- A highly capable Near Detector at Fermilab to measure the unoscillated neutrino spectrum and flux constraints
- 4 x 10 kton (fiducial) LArTPC modules deep underground at SURF (Lead, SD, 1300 km baseline)

JINST 15 (2020) T08008
JINST 15 (2020) T08010

ProtoDUNEs at CERN

Construction and operation of 1 kton-scale prototypes at CERN, critical to demonstrate viability of LArTPC technology, and that the DUNE Collaboration can implement a major construction activity.



ProtoDUNE Dual Phase

- LArTPC 6 m vertical drift + charge amplification in gas Ar + photon detection system
- Cosmic-muon data in 2019-2020

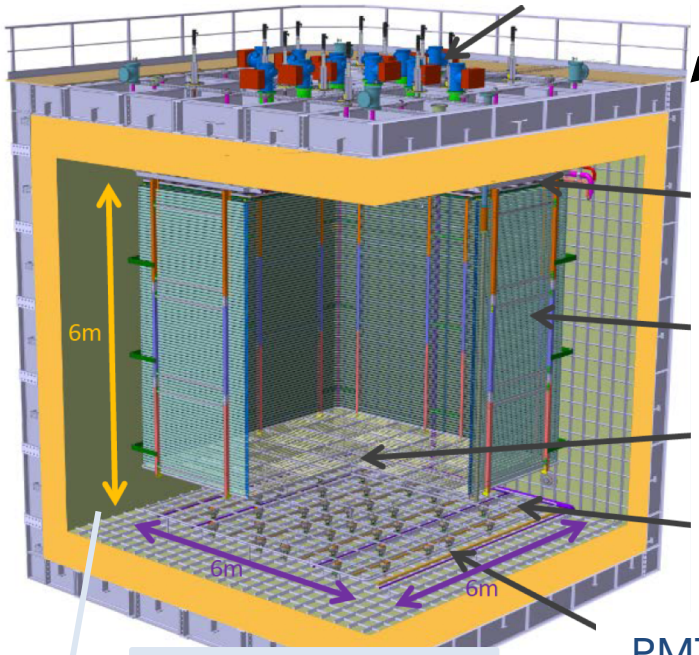
ProtoDUNE Single Phase

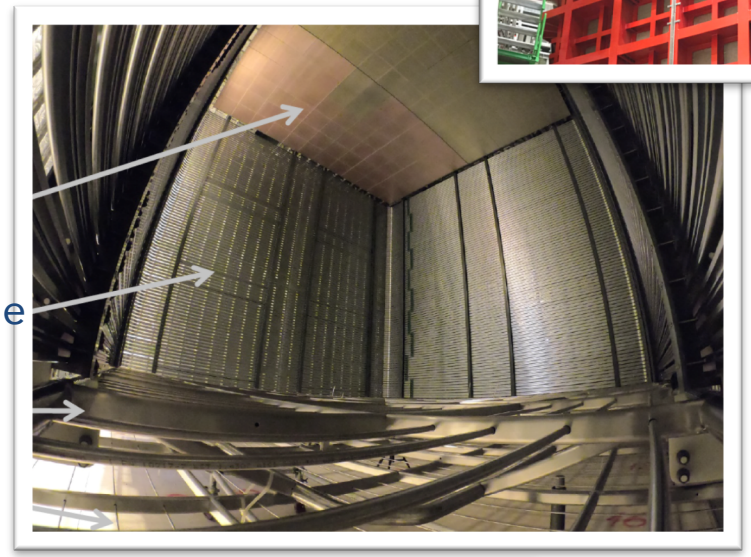
- LArTPC 3.6 m horizontal drift + photon detection system
- Beam data taken in 2018 & cosmic-muon data in 2018-2020 JINST 15 (2020) 12
- ProtoDUNE-SP Phase II in 2022

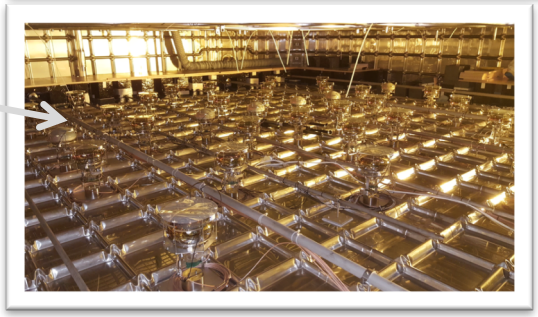
ProtoDUNE Dual Phase

TDR: arXiv:1409.4405

6x6x6 m^3 (300 ton active volume) DP LArTPC







Operation at CERN 2019-2020

Short circuit in HV extender limited drift field
LAr bubbles impacted CRP operation

Photon Detection System (PDS)

36 8" cryogenic photomultipliers (**PMTs**)
JINST 13 (2018) T10006
JINST 15 (2020) P09023

Wavelength-shifter:
PEN / TPB coating on PMT

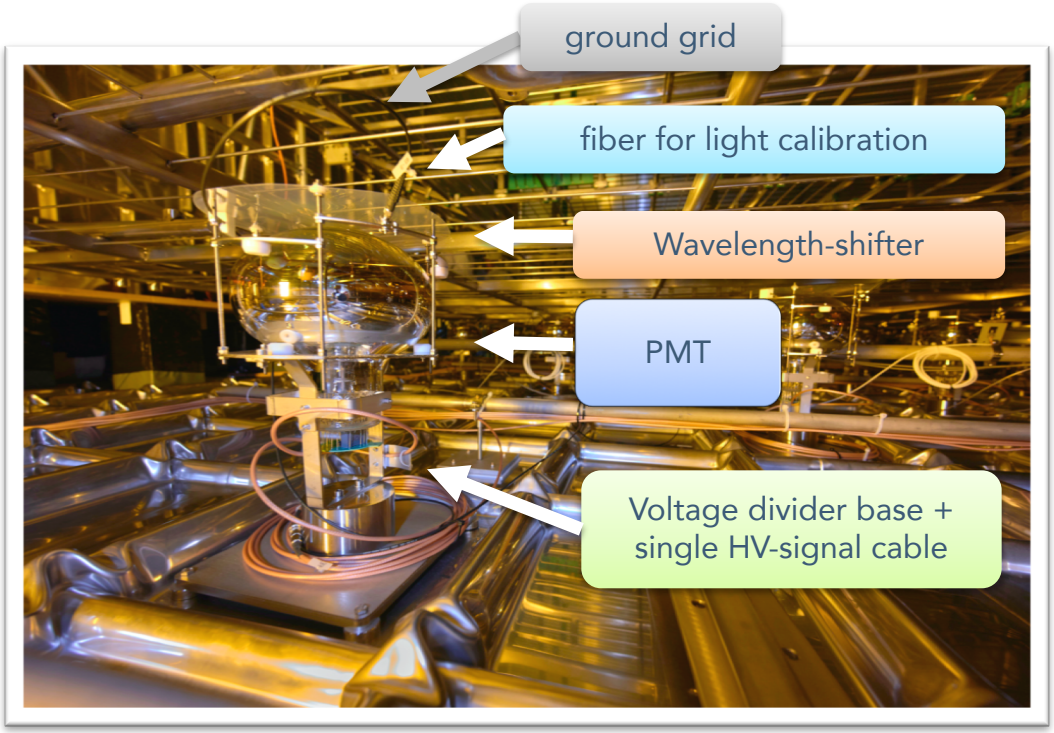
Voltage divider base + single HV-signal cable + splitter (external)

Light calibration system:
LED (external) & fiber based
JINST 14 (2019) T04001

DAQ system (external)
arXiv:2103.02415

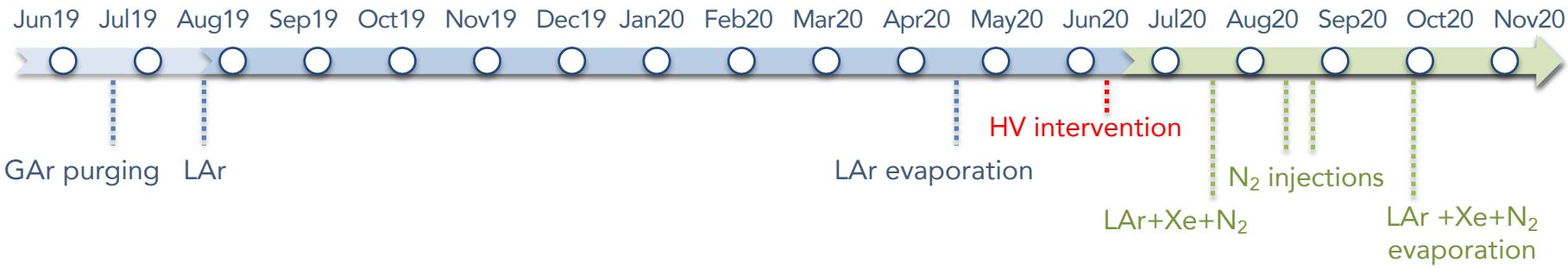
LAr scintillation light (VUV, 127 nm)

- S1: Singlet (τ_{fast}, 6 ns), triplet state (τ_{slow}, 1.6 μs)
- S2: electroluminescence from GAr (100's μs - ms)



ProtoDUNE-DP PDS operation at CERN

- Cosmic-muon data taken with the PDS from June 2019 to November 2020 (18 months):



- The PDS has operated in stable conditions all the time.
- PMTs switched on-off ~daily to allow cameras and purity monitor operation.
- Data taken in different liquid conditions:

Situation	[Xe] (ppm)	[N_2] (ppm)
LAr	0	0
LAr + Xe + N_2	5.8	1.7
1st N_2 injection	5.8	2.7
2nd N_2 injection	5.8	4.7

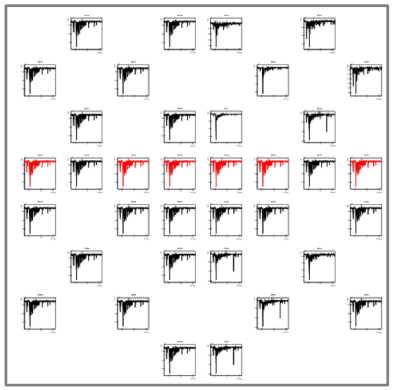
This talk is focused on the LAr operation, for Xe doping results, see talk by J. Soto: Impact of xenon doping in the scintillation light in a large liquid-argon TPC

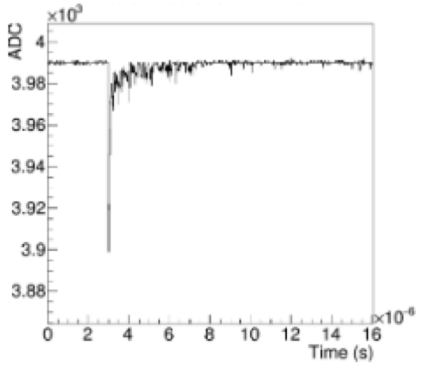
ProtoDUNE-DP PDS operation at CERN

- Data taken in various trigger modes (130.7M events, 675 h) with and w/o drift field:

Trigger	Rate	Goal	# of events (M)	Time (h)
PMT trigger	Hz-kHz	PMT coincidence over a threshold	85.3	96
CRT-trigger	0.3 Hz	muon-track selection	0.6	515
Calibration	1 kHz	PMT gain determination	30	42
Random trigger	Configurable	background and muon studies	14.7	21

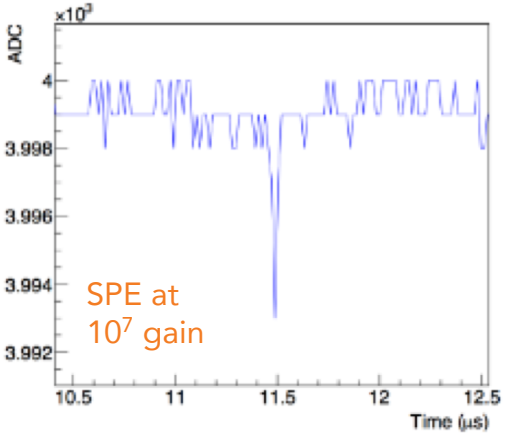
- Each event contains the information of 36 individual PMT waveforms (16 ns sampling, configurable acquisition window, 2 Vpp dynamic range).

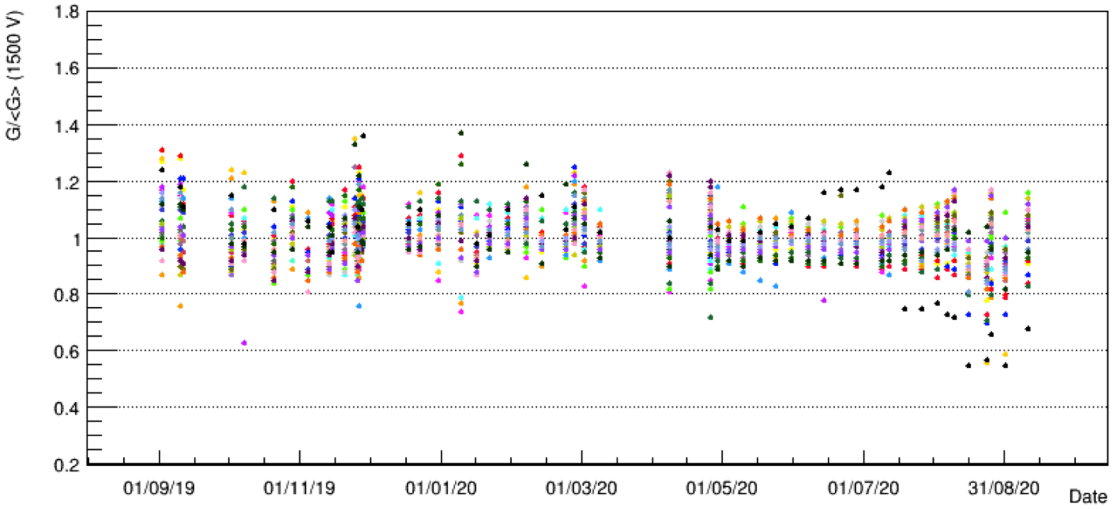




PDS performance

- Time accuracy among the PMTs for the same event better than 16 ns measured.
- Remarkable low noise in baseline (0.6 ± 0.1 ADC).
- Single photo-electron characterization (amplitude, width) as a function of gain. S/N > 11 at 10^7 gain.
- PMTs calibrated weekly to determine the PMT gain and measure light collected in PE.

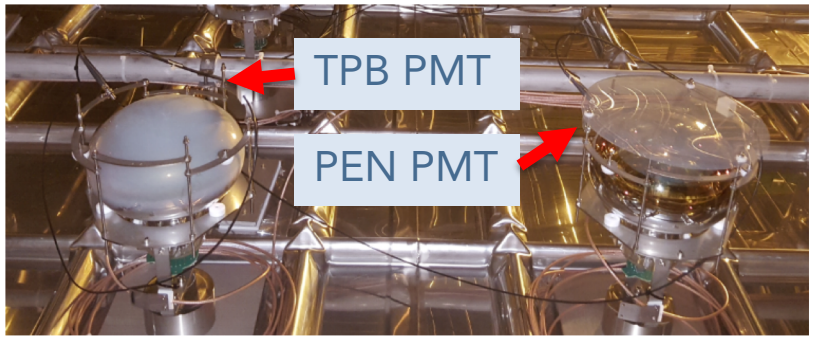




PMT gain stable despite PMTs are switched on daily. (9% gain STD at 1500 V, average 36 PMTs)

Wavelength shifting: PEN & TPB

- Wavelength shifting required as PMTs are not sensitive to LAr scintillation light in VUV.
- ProtoDUNE-DP has two different methods:
  - PMTs covered with PEN foils, a novel thermoplastic simple to install.
  - TPB coated in a dedicated set up directly over the PMT glass.

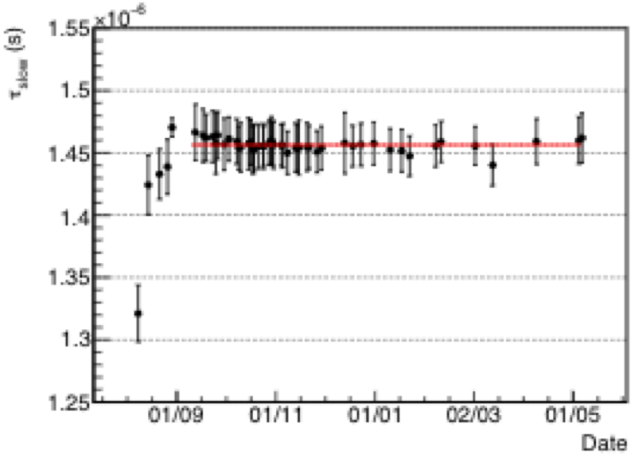


- Experimental data: S1 charge (PE) collected by PEN PMTs is 25% the charge collected by TPB PMTs in a controlled event population (50-200 PE average, PMT trigger data).
- From the experimental data the relative wavelength shifting efficiency of both materials is 0.35, estimated taking into account the geometrical differences between both systems:
  - There are less photons arriving to the TPB than to the PEN, as PEN has both faces exposed to LAr (x0.69).
  - 50% (25%) of the photons re-emitted by the TPB (PEN) reach the PMT.

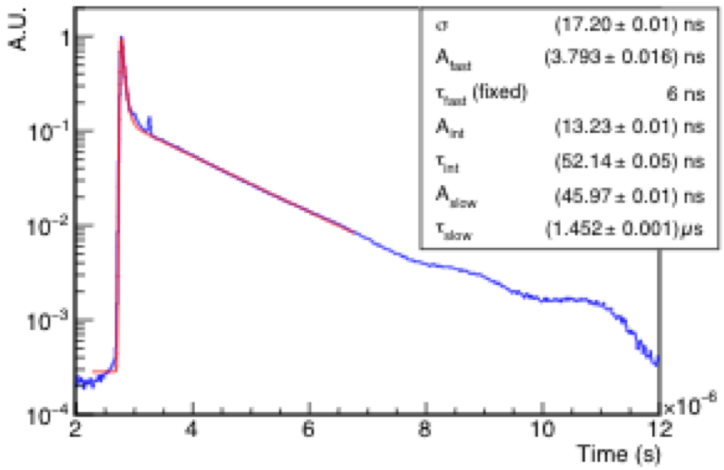
Parameter	Factor
S1 charge (PE) collected by PEN PMTs / TPB PMTs in ProtoDUNE-DP	0.25
Relative WLS efficiency PEN / TPB	0.35

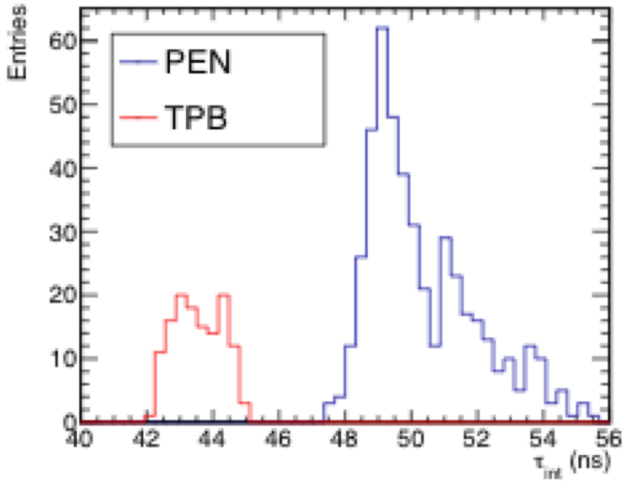
LAr scintillation time profile

- Muon-like events with no drift field applied (full recombination of e^-).
- Average time profile: convolution of 1 gaussian with 3 exponential decays:
  - τ_{fast}: fixed to 6 ns.
  - τ_{slow}: 1.45 ± 0.2 µs, monitored regularly indicating LAr purity at ppb level.



  - τ_{int}: clear difference between PEN and TPB PMTs pointing to delayed emission in the WLS.





Cosmic-muon light simulation

- LArSoft toolkit designed for LAr neutrino experiments
- ProtoDUNE-DP detailed geometry
- Cosmic-induced particles based on CORSIKA
- Muons crossing CRT panels simulated
- Photon propagation in LAr:

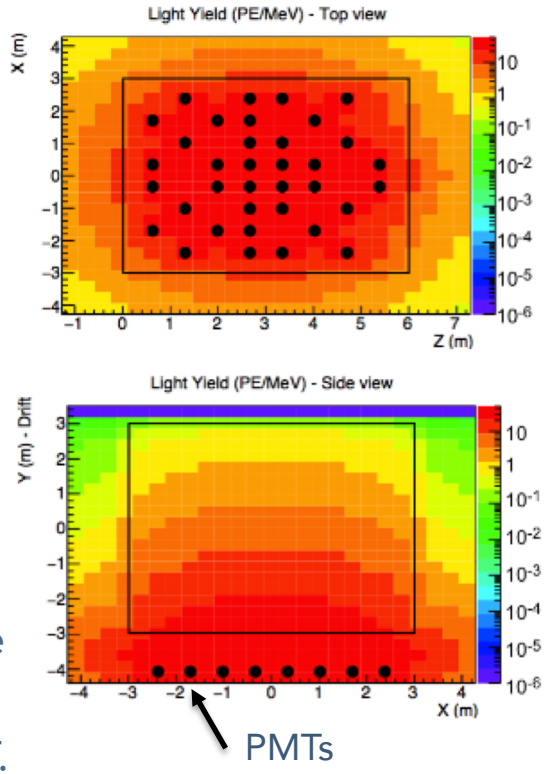
Parameter	Value
Absorption length	20 m
Rayleigh scattering length	99.9 cm*; 61 cm
VUV reflectance	26% Al & stainless steel; 0%
Voxel size	0.34 x 0.32 x 0.34 m^3

* Default values

Photon libraries: photon visibility and propagation time per voxel.

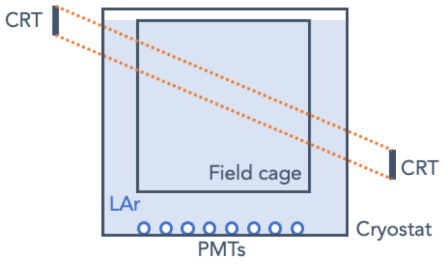
- PMT response simulated producing a waveform per PMT.

Detected light per voxel for the default photon library



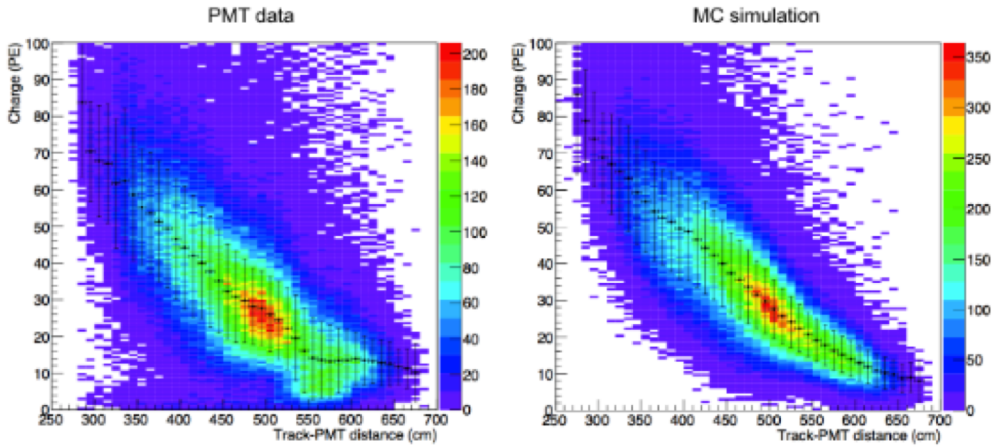
LAr light study with cosmic-muon data

- CRT-trigger events with known topology (diagonal muon tracks).

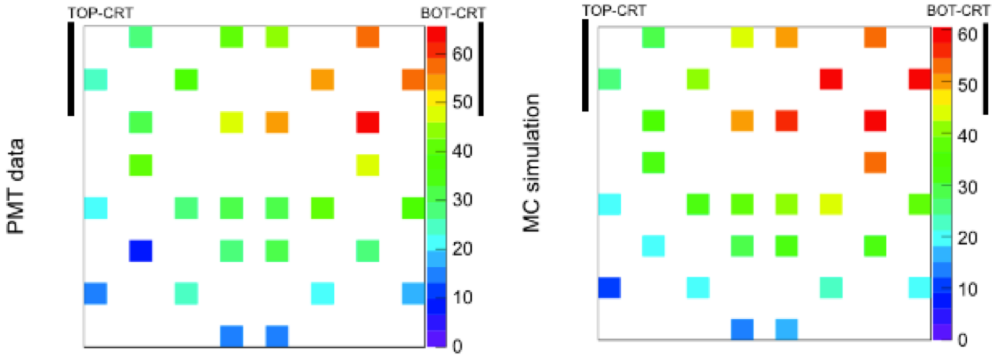


- Study of collected S1 light per PMT vs. minimum distance from the muon to the PMT for data and simulation.
- S1 charge per PMT follows the expected pattern.
- Analysis focused on PEN PMTs.
- High energy events (>100 PE) and low energy background (relevant a >5 m) not included in simulation.
- Data-MC match within 10%.

S1 charge per PMT vs. track-PMT distance

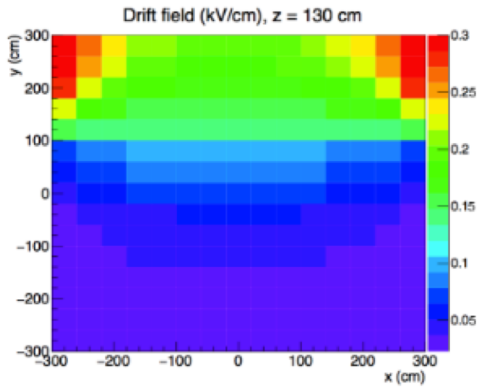


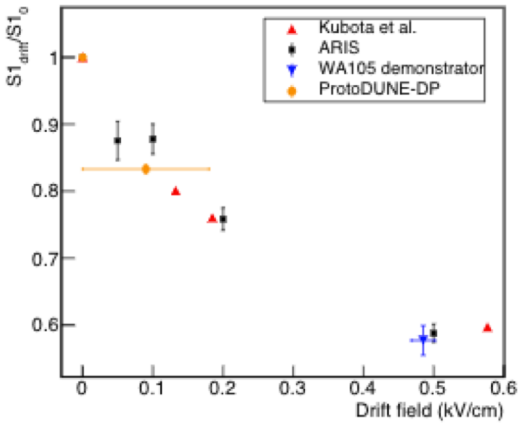
S1 charge per PMT

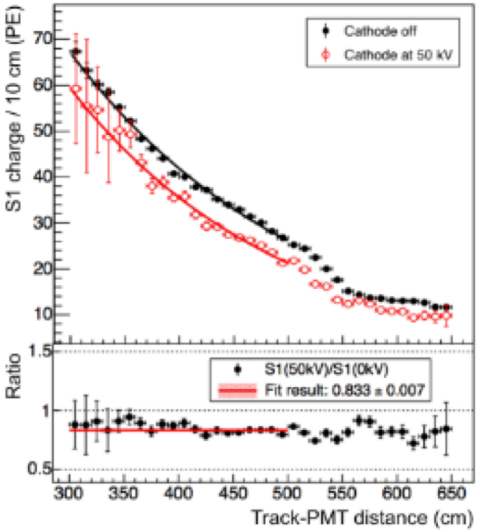


Light production in LAr

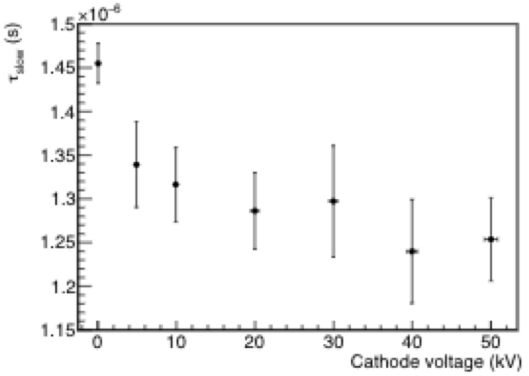
- S1 light yield reduction with drift field (17% at 50 kV) caused by the suppression of the electron-ion recombination.
- Considering average drift field (0.9 kV/cm), Birk's law is verified.







- Observation of τ_{slow} decrease with drift field as first shown the 3x1x1 m^3 DP LAr demonstrator*. Attributed to the quenching of the long lived triplet states through the self-interaction with other triplet states or through the interaction with molecular Ar^+_2 ions**.

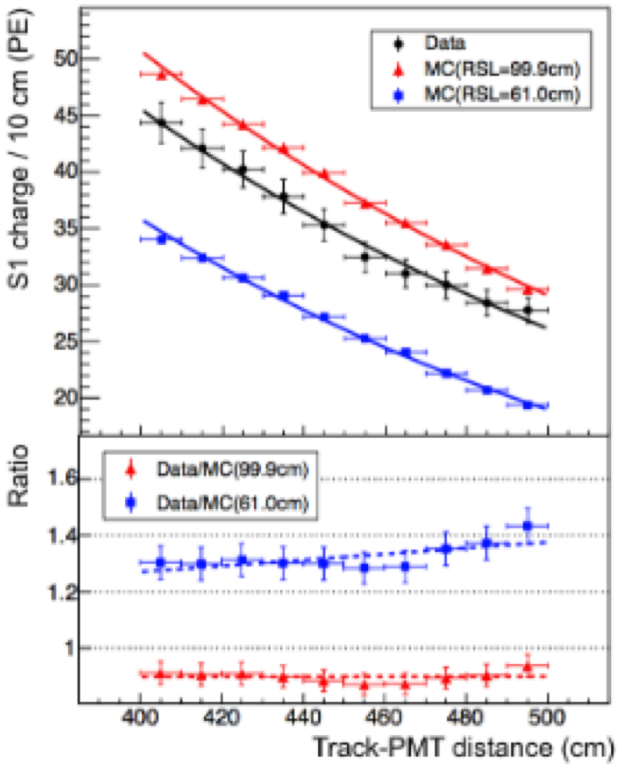


[* JINST 16 (2021) P03007]
[** PRD 103 (2021) 043001]

Light propagation in LAr

- ProtoDUNE-DP, the longest drift-distance LAr TPC ever operated → unprecedented study of the light propagation.
- Evaluation of the simulated Rayleigh scattering length.
  - Better agreement between data and the 99.9-cm MC sample than with the 61.0-cm value.
  - Light will undergo Rayleigh scattering before being deeply attenuated due to absorption by LAr impurities or detector elements (excellent LAr purity & large free LAr volume).
- Study of the VUV-photon reflections comparing simulations:
  - 26% reflectivity for VUV light in the field cage (Al) and in the cryostat walls, cathode and ground grid (stainless steel)
  - Full light absorption in all components.

  >11 % of the light detected PMTs in the MC from reflected VUV-light in Al or stainless steel.

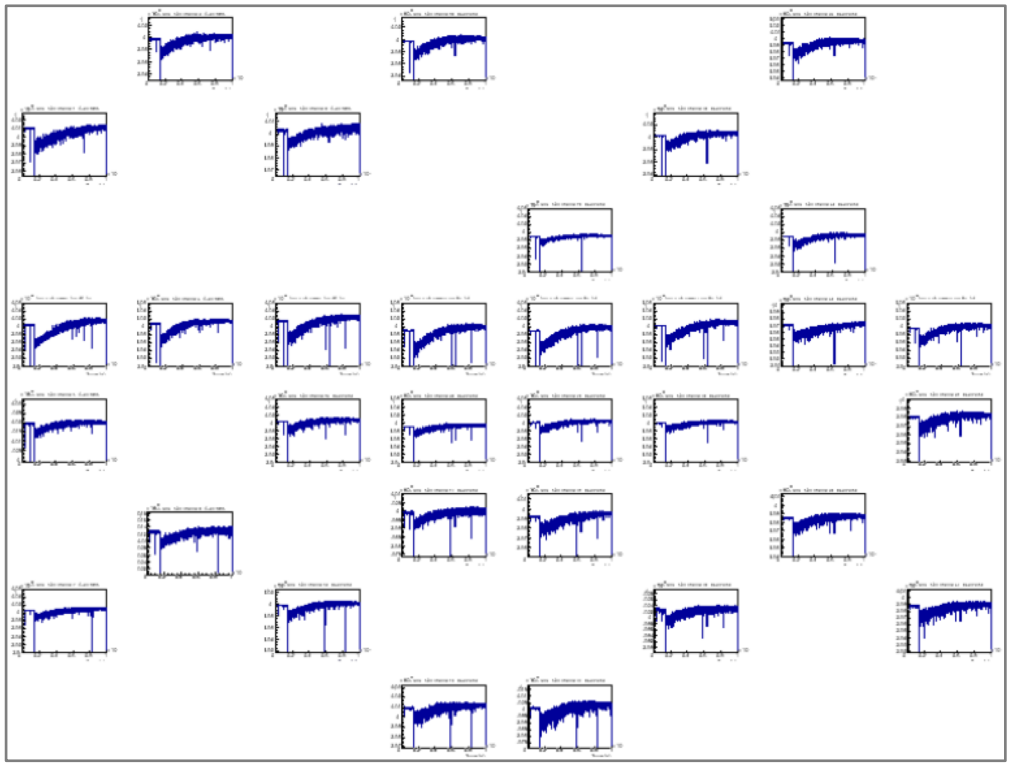


Parameter	λ_{att} (from fit)
Data	180 ± 17 cm
MC (RSL 99.9 cm)	180 ± 10 cm
MC (RSL 61.0 cm)	157 ± 8 cm

Electroluminescence light detection

- Effect on the SPE rate (background), computed from random-trigger data:
  - without S2: ~350 kHz (TPB PMTs), ~170 kHz (PEN PMTs)
  - with S2: ~2.5 MHz (TPB PMTs), ~1.1 MHz (PEN PMTs)

- S2 electroluminescence signals detected in all PMTs, corresponding to light 7 m away from PMTs.
- S2 provides information of the drifted e-, but ProtoDUNE-DP field limitations restricts the study.



Event example with S1+S2 signal

Conclusions

- We will learn a lot about neutrinos in the next decades and DUNE will be a crucial experiment as well as an enormous challenge.
- To demonstrate the technology, ProtoDUNE program running at the CERN Neutrino Platform.
- ProtoDUNE-DP operated in 2019-2020 at CERN with limited field conditions. PDS collected cosmic-ray data for 18 months in stable conditions with 36 PMTs operative.
- Validation of the PDS design for long drift LAr TPCs.
- Pioneering use of PEN as wavelength shifter and performance compared to TPB.
- Light production: Observation of light yield suppression with drift field due to recombination according Birk's law.
- The size of ProtoDUNE-DP, the longest drift-distance LAr TPC ever operated, allows for unprecedented results of the light propagation in LAr.
- Electroluminescence signal detected from 7 m in all PMTs.


Thanks