

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

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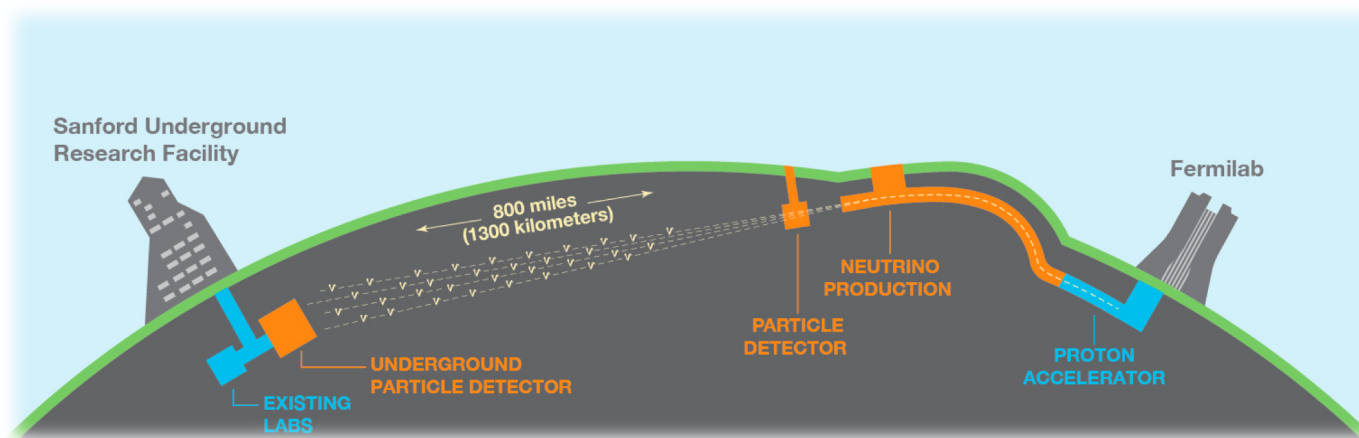
TIPP 2021

May, 26th 2021

Deep Underground Neutrino Experiment (DUNE)

DUNE aims at answering fundamental questions related to:

- The matter-antimatter asymmetry - neutrino oscillations & mass ordering [EPJC 80 \(2020\) 978](#)
- The Grand Unification of forces - nucleon decay searches (BSM Physics) [EPJC 81 \(2021\) 322](#)
- The supernova explosion mechanism - supernova neutrino detection [arXiv:2008.06647](#)



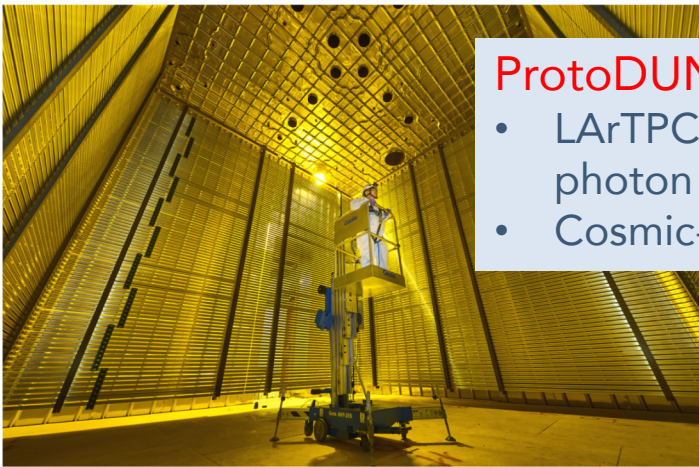
- New neutrino (ν_μ or $\bar{\nu}_\mu$) beam facility at Fermilab (LBNF), US
- A highly capable Near Detector at Fermilab to measure the unoscillated neutrino spectrum and flux constraints
- 4 x 17 kton LArTPC modules deep underground at SURF (Lead, SD, 1300 km baseline)

[JINST 15 \(2020\) T08008](#)

[JINST 15 \(2020\) T08010](#)

ProtoDUNE 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



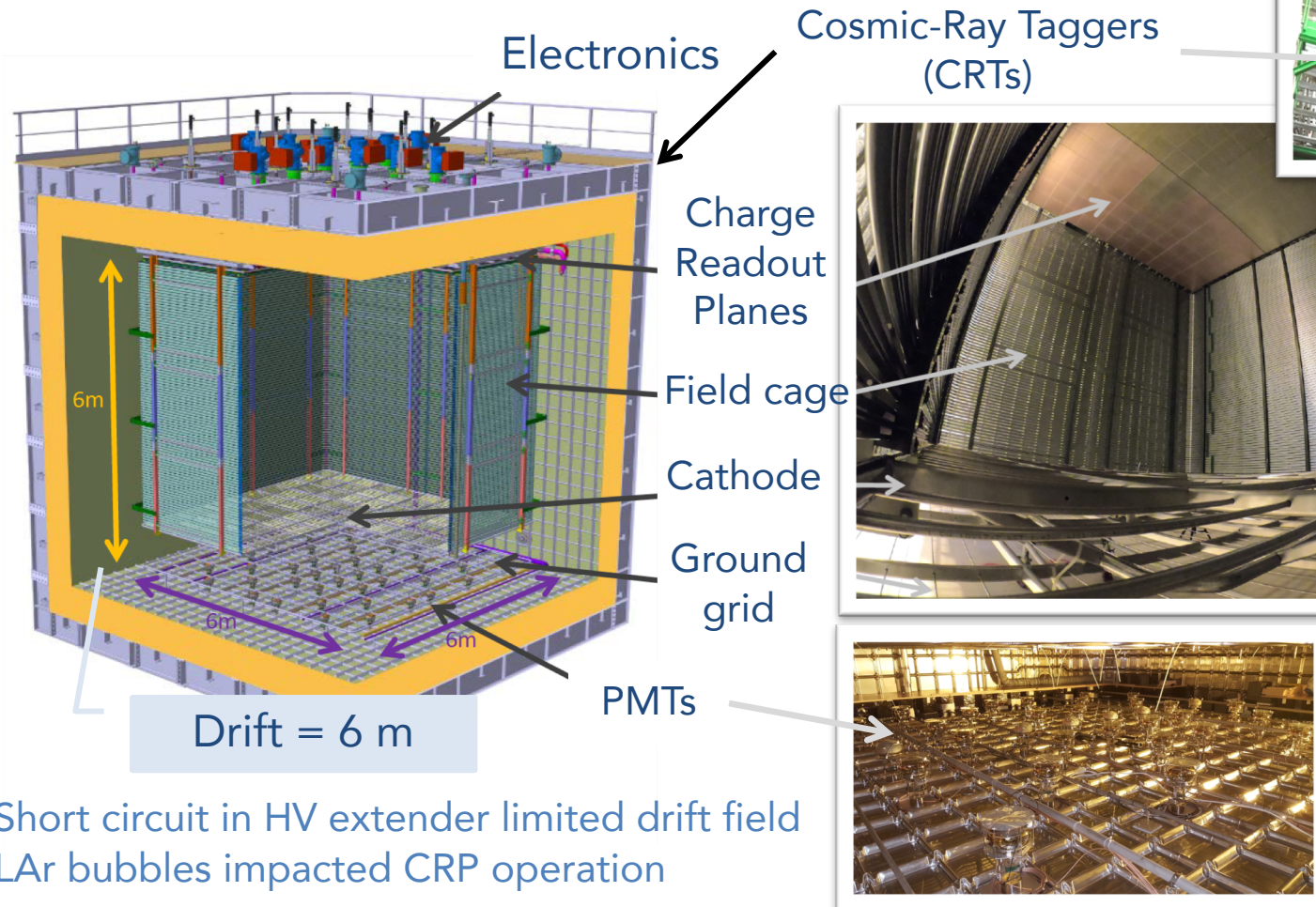
ProtoDUNE Single Phase

- 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](https://arxiv.org/abs/1409.4405)

6x6x6 m³ (300 ton active volume) DP LArTPC



Operation
at CERN
2019-2020

Photon Detection System (PDS)

36 8" cryogenic photomultipliers (PMTs)

[JINST 13 \(2018\) T10006](#)

[JINST 15 \(2020\) P09023](#)

Wavelength-shifter:
PEN / TPB coating on PMT

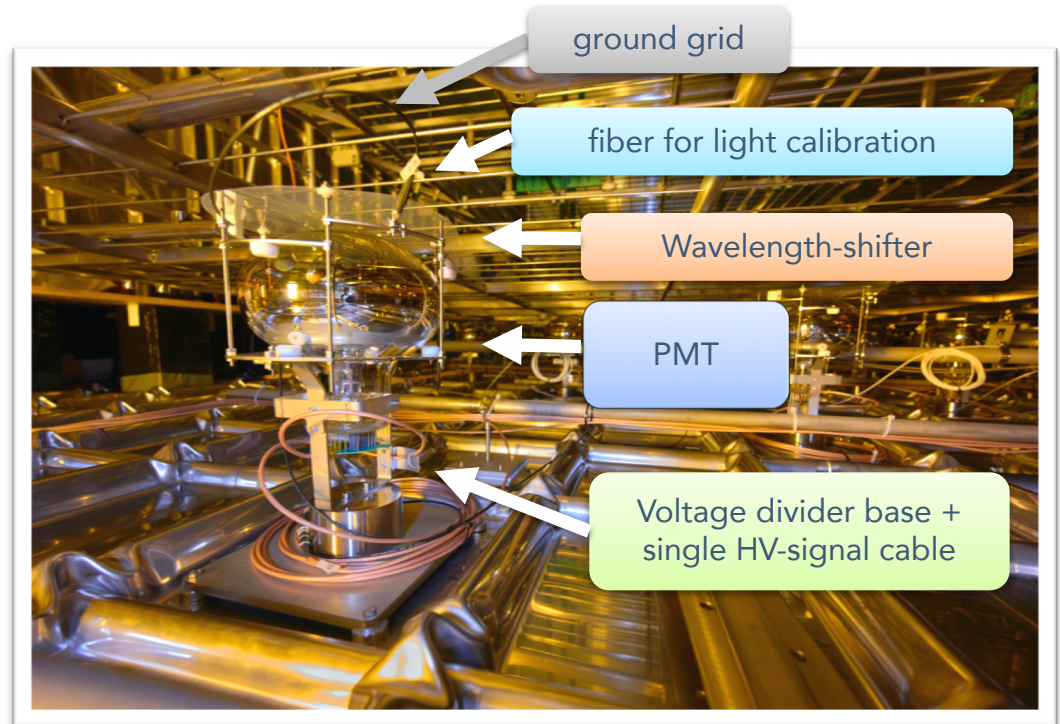
Voltage divider base +
single HV-signal cable +
splitter (external)

Light calibration system:
LED (external) & fiber based
[JINST 14 \(2019\) T04001](#)

DAQ system (external)
[arXiv:2103.02415](#)

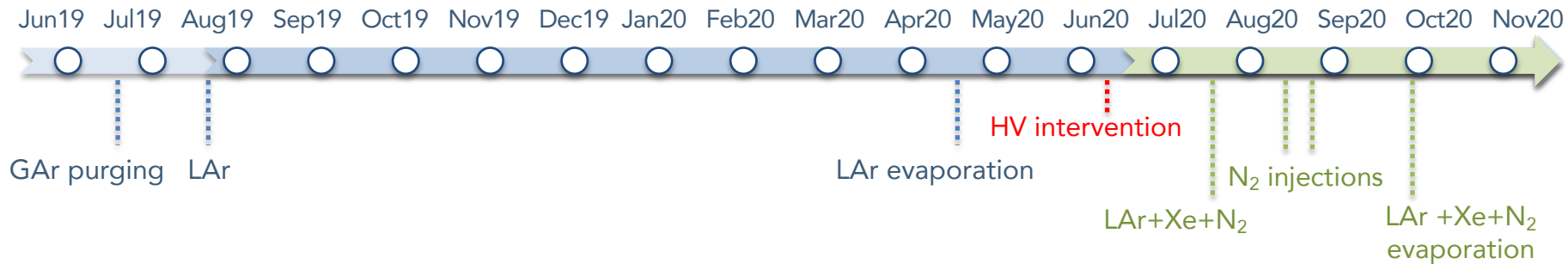
LAr scintillation light (VUV, 127 nm)

- 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.
- Data taken in **different liquid conditions**:

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

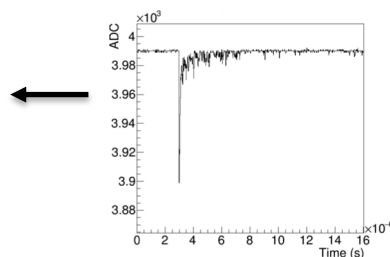
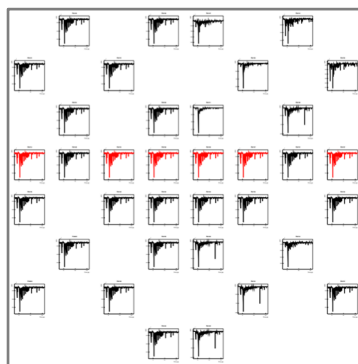
- PMTs switched on-off ~daily to allow cameras and purity monitor operation.
- Data taken in various trigger modes (130.7M events, 675 h) with and w/o drift field:

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).

Event example (36 waveforms)

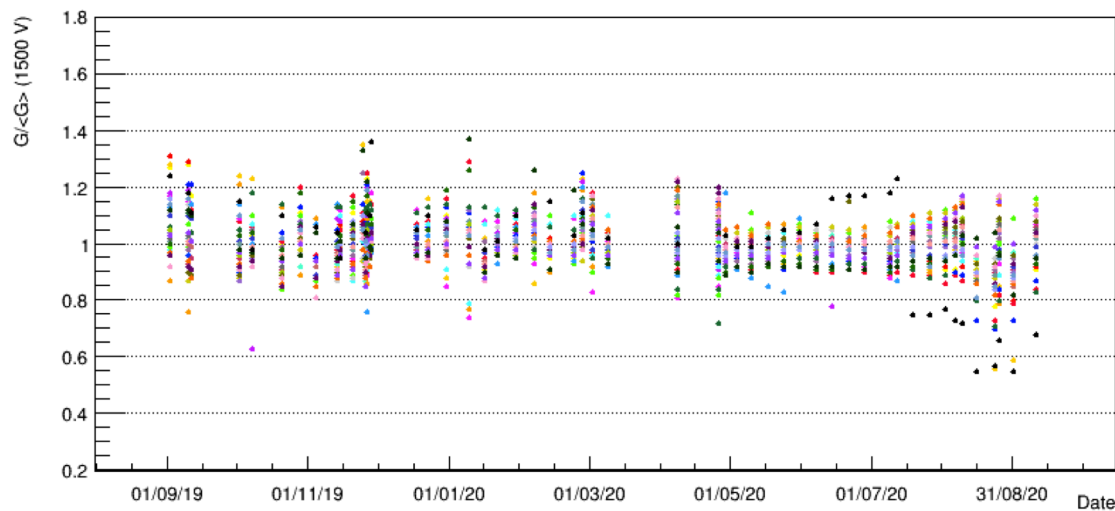
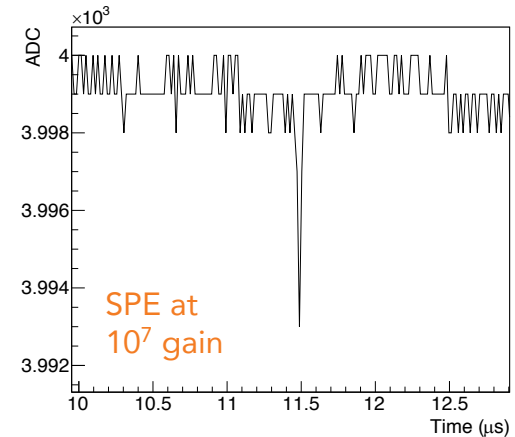
TPB PMTs
PEN PMTs



Single PMT waveform
(zoom)

PDS performance

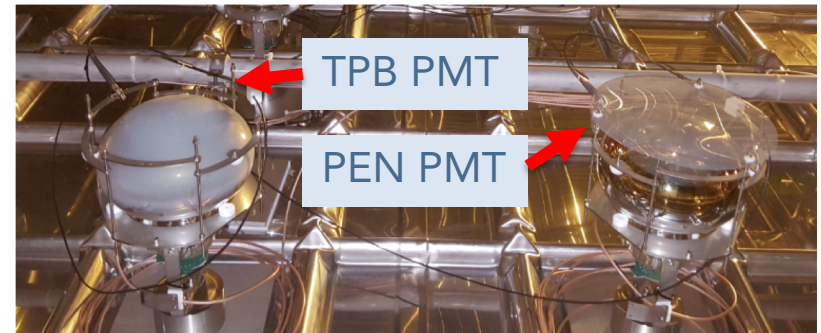
- Time accuracy among the PMTs for the same event better than 16 ns measured.
- Remarkable low noise in baseline (0.6 ± 0.1 ADC).
- Single photo-electron characterization (amplitude, width) as a function of gain. $S/N > 11$ at 10^7 gain.
- PMTs calibrated weekly to determine the PMT gain and measure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

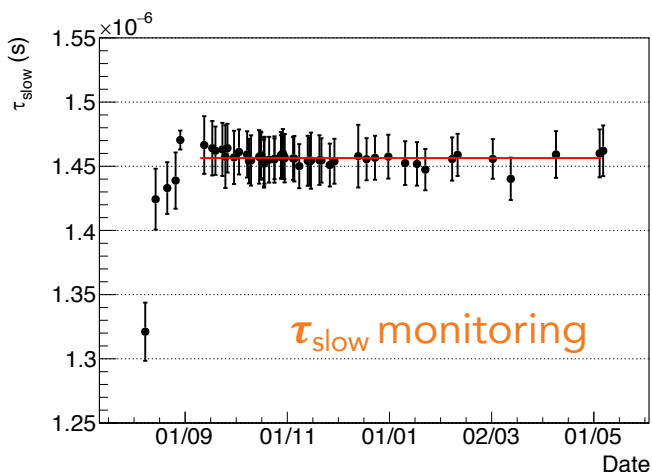
- Wavelength shifting required as PMTs are not sensitive to LAr scintillation light in VUV.
- Two methods in ProtoDUNE-DP:
 - PMTs covered with **PEN foils**, a novel thermoplastic simple to install.
 - **TPB coated** in a dedicated set up directly over the PMT glass.
- Experimental data: **S1 charge (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.



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

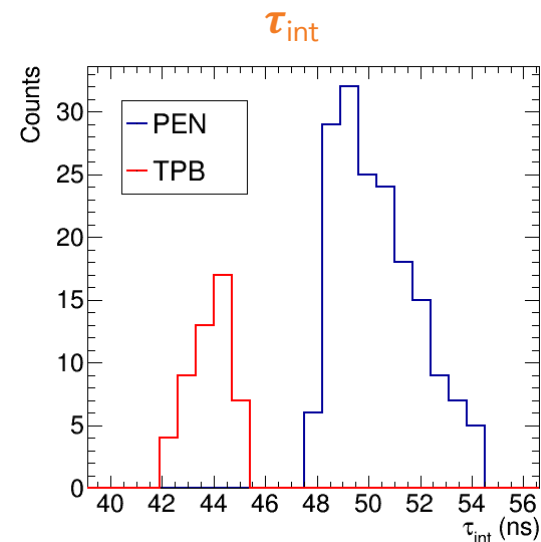
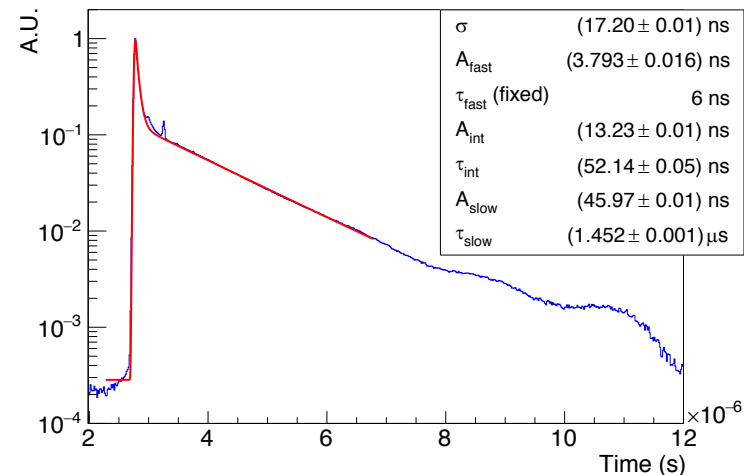
LAr scintillation time profile

- 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} : $1.45 \pm 0.2 \mu\text{s}$, monitored regularly indicating LAr purity at ppb level.



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

Average time profile



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:

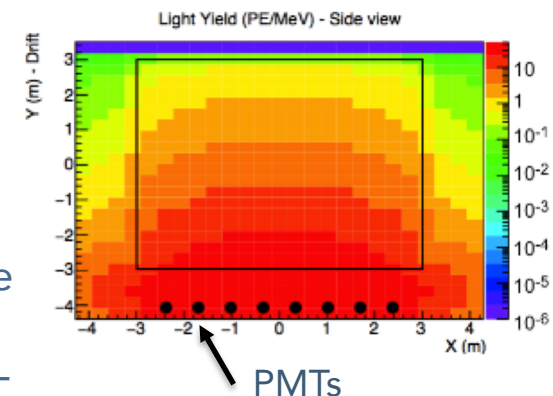
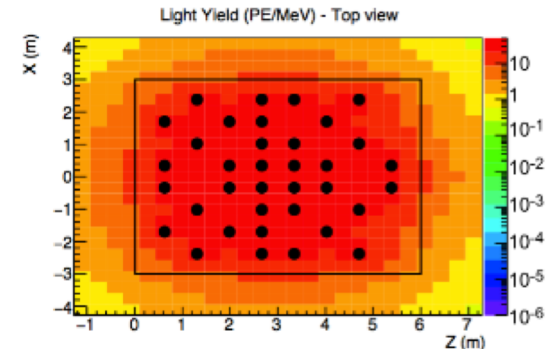
Parameter	Value
Absorption length	20 m
Rayleigh scattering length	99.9 cm*; 61 cm
VUV reflectance	26% Al & stainless steel; 0%
Voxel size	0.34 x 0.32 x 0.34 m ³

* Default values

Photon libraries: photon visibility and propagation time per voxel.

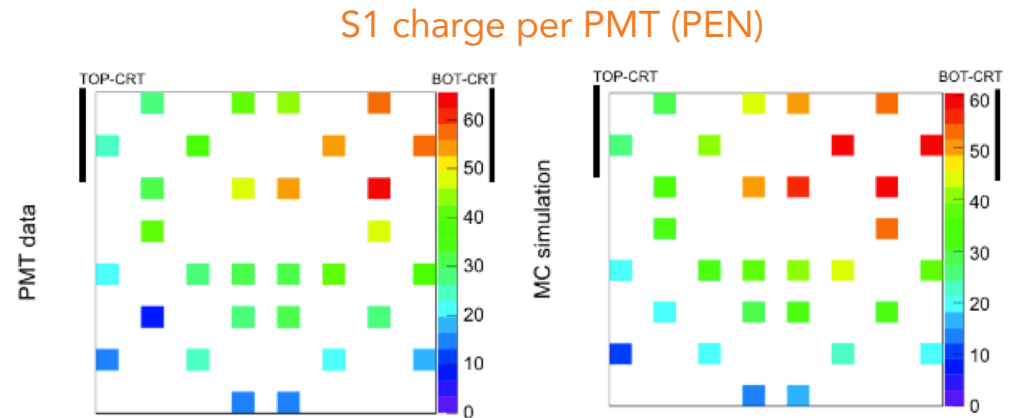
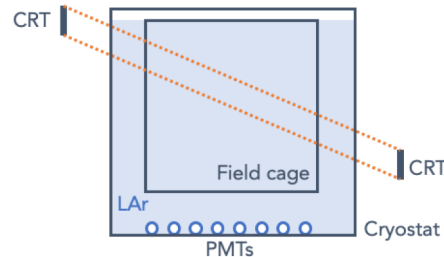
- PMT response simulated producing a waveform per PMT.

Detected light per voxel for the default photon library

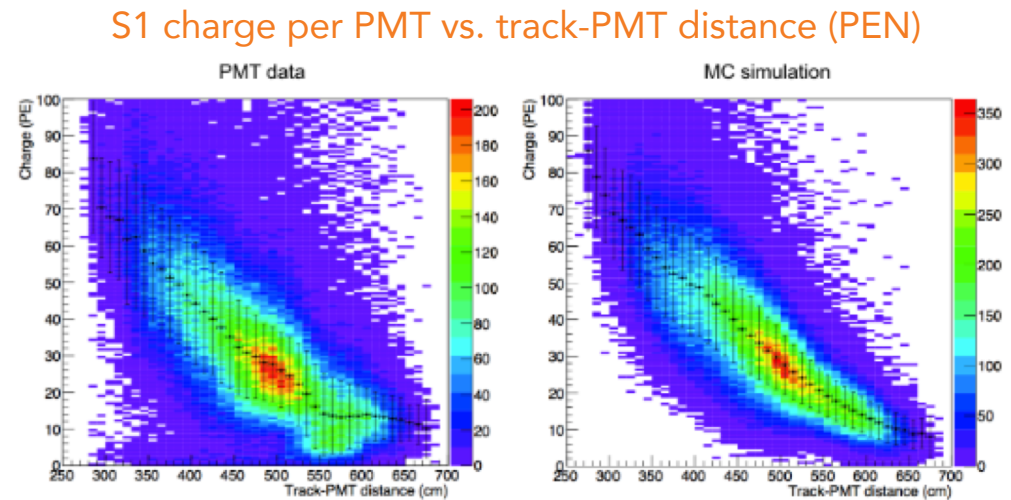


LAr light study with cosmic-muon data

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

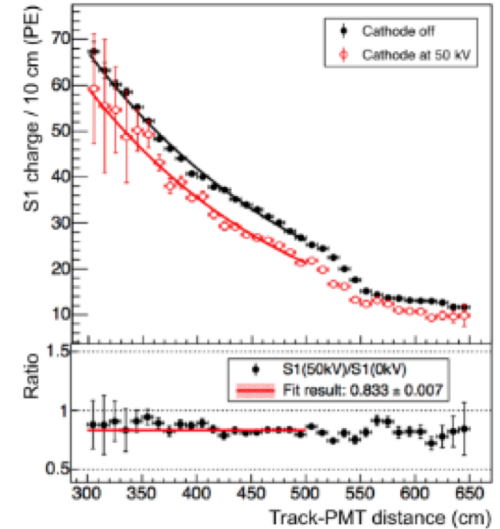
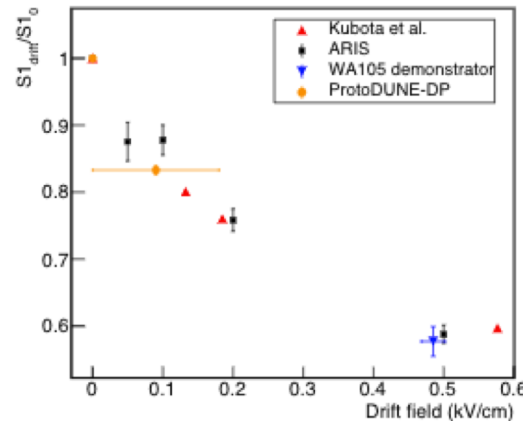
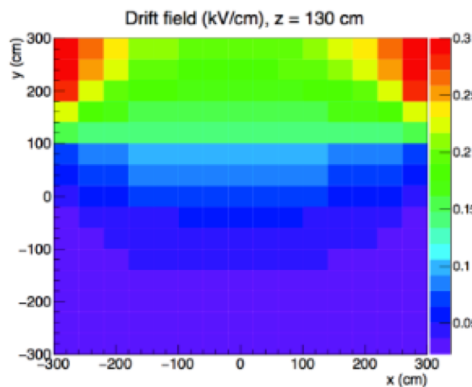


- S1 charge per PMT follows the expected pattern.
- Study of collected S1 light per PMT vs. minimum distance from the muon to the PMT for data and simulation.
- High energy events (>100 PE) and low energy background (relevant at >5 m) not included in simulation.
- Data-MC match within 10%.



Light production in LAr

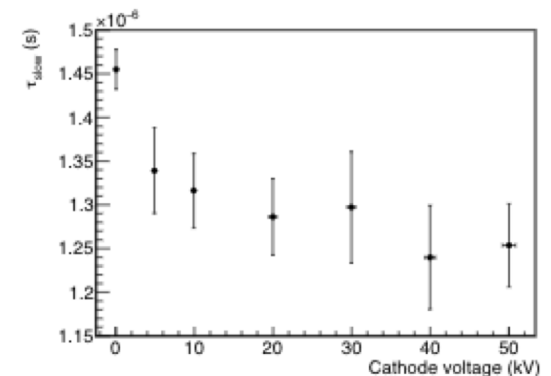
- S1 light yield reduction with drift field (17% at 50 kV) caused by the suppression of the electron-ion recombination.
- Considering average drift field (0.9 kV/cm), Birk's law is verified.



- Observation of τ_{slow} decrease with drift field as first shown the 3x1x1 m³ 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**.

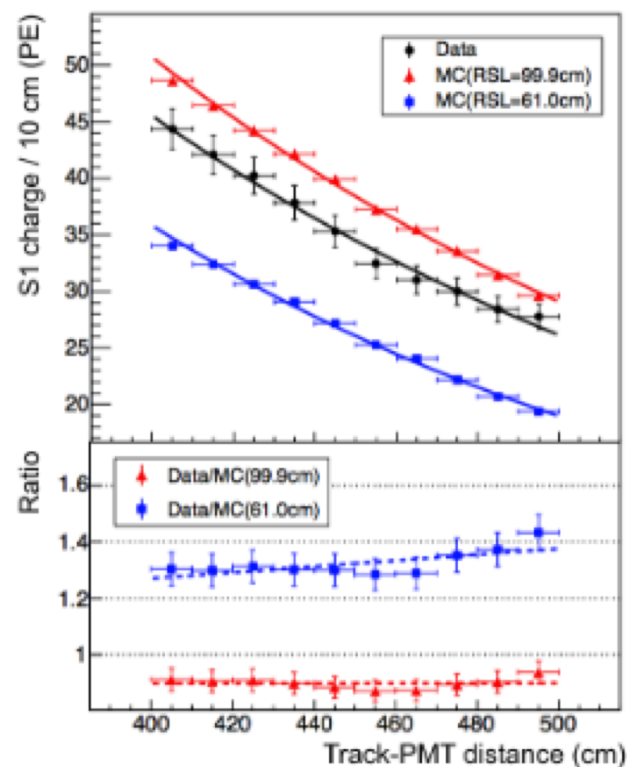
* JINST 16 (2021) P03007

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

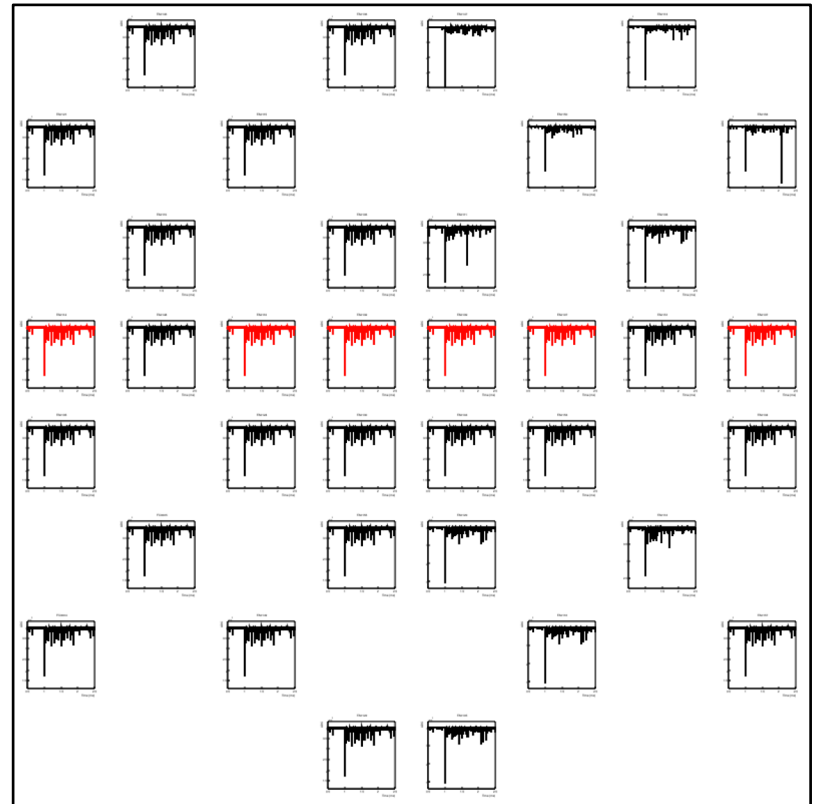


Parameter	λ_{att} (from fit)
Data	180 ± 17 cm
MC (RSL 99.9 cm)	180 ± 10 cm
MC (RSL 61.0 cm)	157 ± 8 cm

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 efficiency determined relative 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