Impact of xenon doping in the scintillation light in a large liquid-argon TPC

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"la Caixa" Foundation
GOBIERNO DE ESPAÑA
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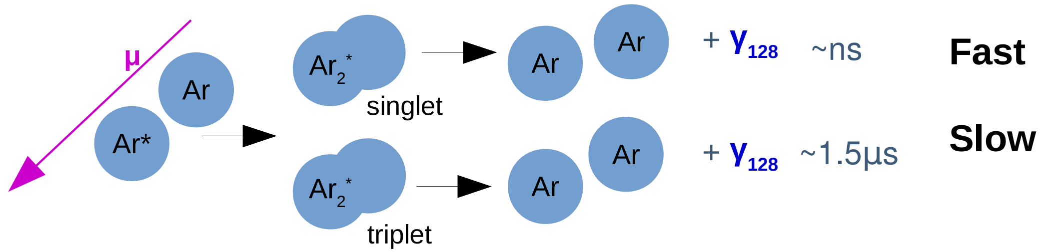
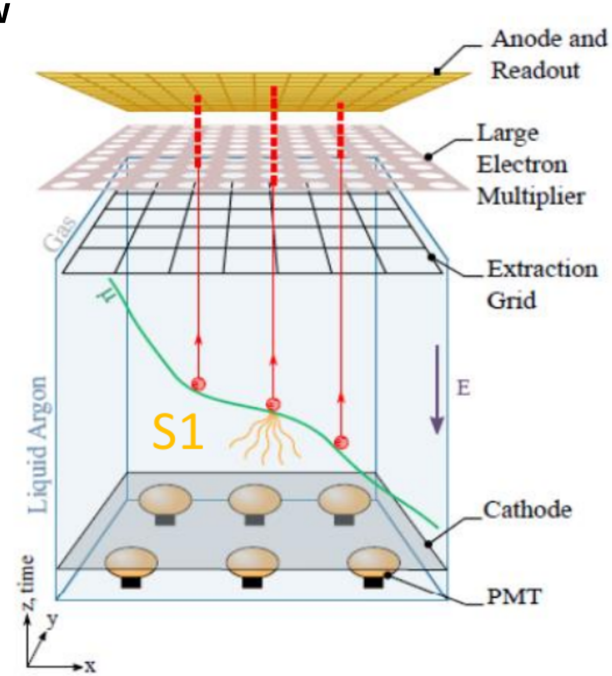
DUNE

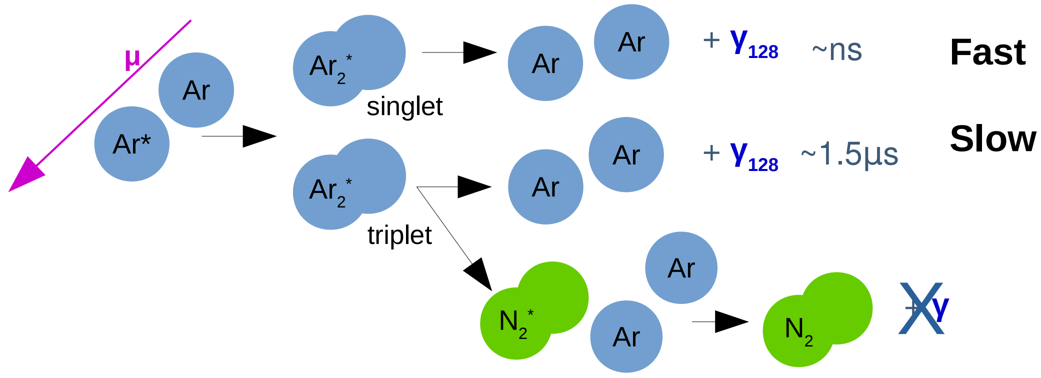
Scintillation light in a LAr-TPC





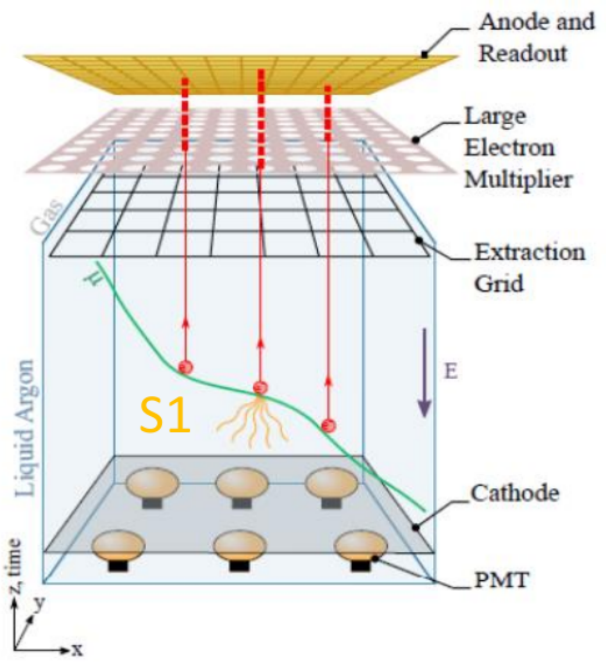
- In liquid argon, crossing particles produce ionization electrons and **scintillation photons**.
- Light detection is important in a LAr-TPC:
  - It provides the **timing**, and a **trigger.**.
  - It improves the **calorimetric reconstruction**.
- In a LAr-TPC **ionization electrons are drifted** (~ms) and extracted to reconstruct the track. They recombine producing more photons if no field is present.

Scintillation light in a LAr-TPC



- A high purity is required since long-life triplet-state can be **quenched by impurities** like N_2, reducing the light production [1].
- Also N2 impurities absorbe photons during propagation [2]:

[N2]	Absorption length	Attenuation at 5 m
ppb	1.8 km	0%
2 ppm	30 m	15%
5 ppm	12 m	35%

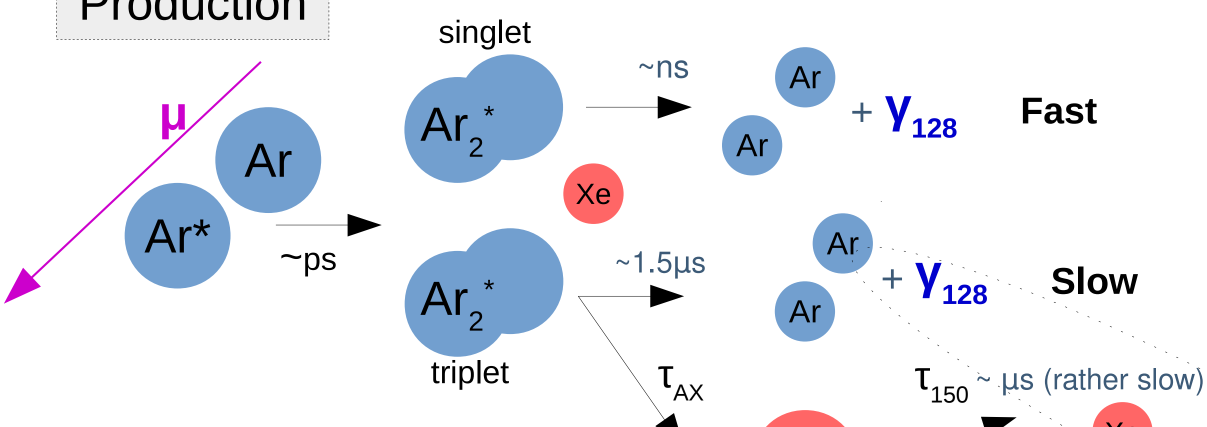


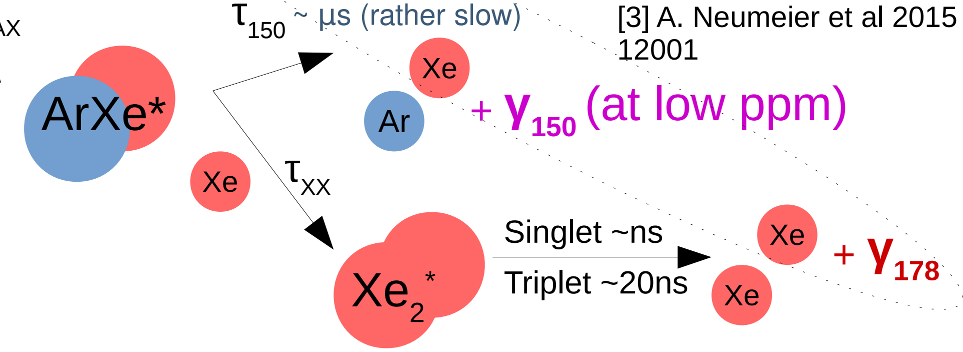
[1] R Acciarri et al 2010 JINST 5 P06003

[2] B J P Jones et al 2013 JINST 8 P07011

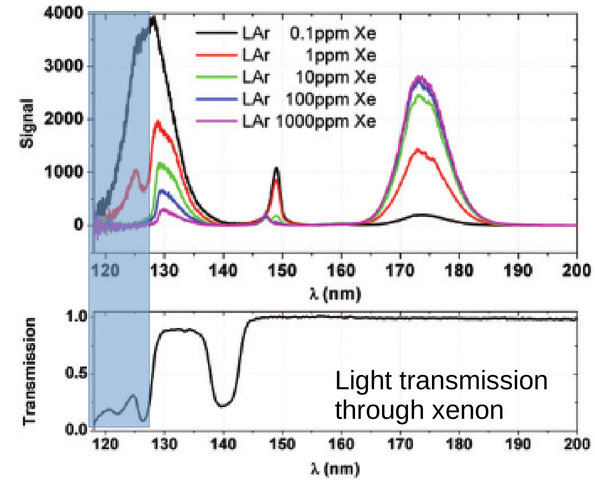
How does xenon affect the production and propagation of photons in LAr?

Production





Emmission spectrum in xenon-doped LAr



[3] A. Neumeier et al 2015 EPL 109 12001

- Fast component remains at 128 nm.
- Slow component transferred to 178 nm.

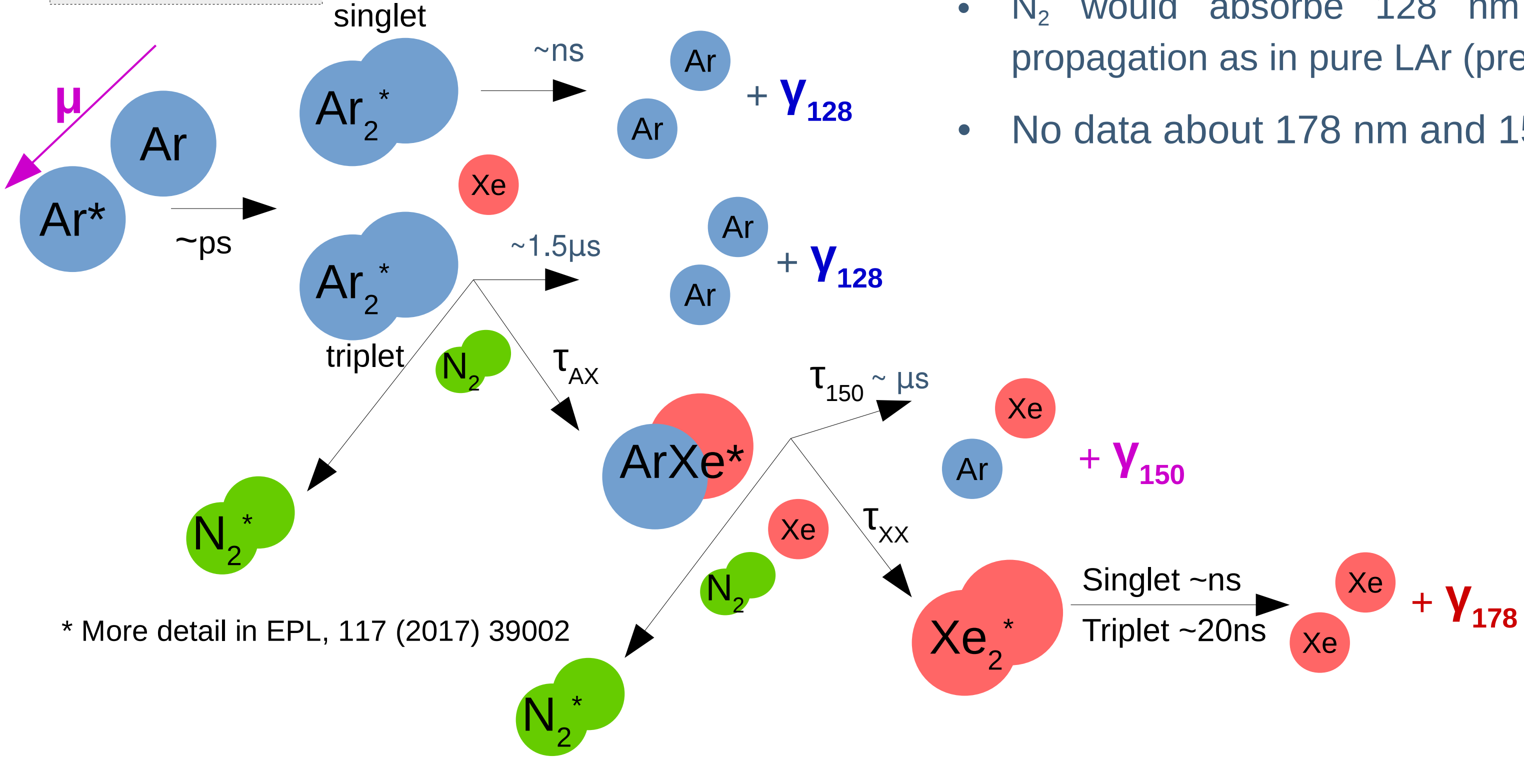
Propagation

- Xenon absorbes the 128 nm photons during propagation, no absorption at 178 nm and 150 nm photons [3].
- Larger Rayleigh scattering length for 178 nm photons (~9m vs 1m for 128 nm photons) → More collection at large distances [4].

[4] M. Babicz et al 2020 JINST 15 P09009

How does nitrogen affect the production and propagation of photons in xenon-doped LAr?

Production quenching



* More detail in EPL, 117 (2017) 39002

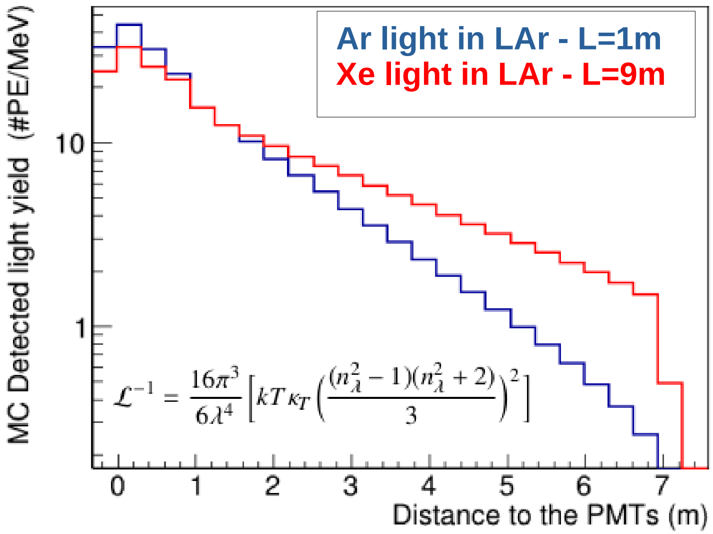
Propagation

- N_2 would absorb 128 nm photons during propagation as in pure LAr (previous slides).
- No data about 178 nm and 150 nm photons.

Why using Xe-doped LAr in a LAr-TPC?

- An increase in the detected light is expected:
  - **Better detection uniformity:** There is an increase in the collection at large distances, due to the larger Rayleigh scattering length for xenon light.
  - **Light production recovery in case of an N_2 contamination**.
  - Typically photosensors are more sensitive to 178 nm photons.
- Posible limitations:
  - **Xenon absorbes the fast signal**, this could compromise the trigger capabilities.
  - Also, the larger Rayleigh scattering would **reduce the light collection at short distances** (see plot at x=0 m).

Simulated light yield for 128 nm and 175 nm photons in ProtoDUNE-DP



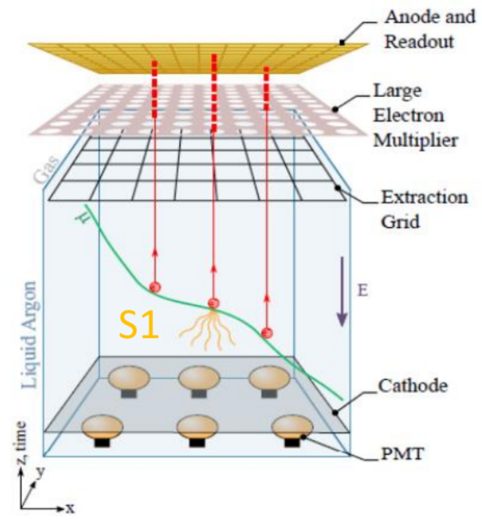
[2] M. Babicz et al 2020 JINST 15 P09009

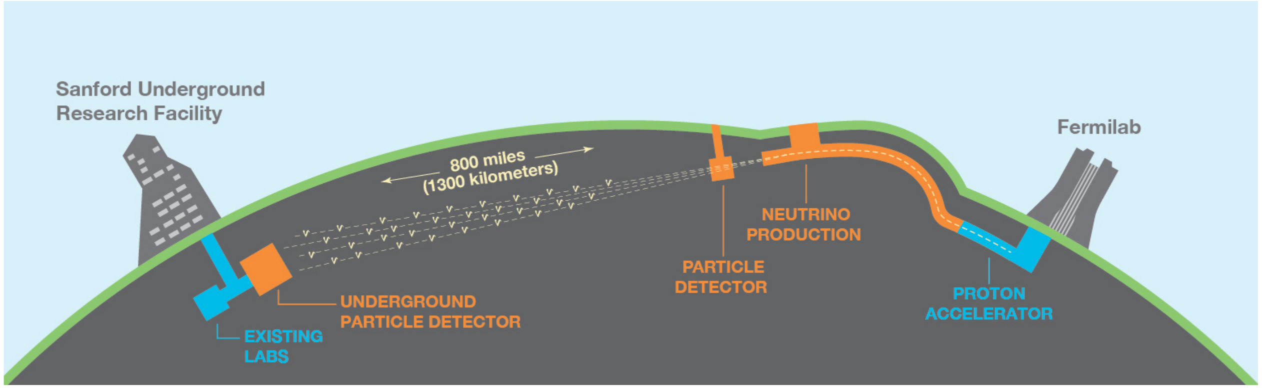
Deep Underground Neutrino Experiment

- DUNE is a long-baseline neutrino oscillation experiment. It will detect a beam of neutrinos produced 1,300 km away.
- It has a rich physics program:

  - **CP violation** and **neutrino mass** ordering using neutrino oscillations.

  - **Proton decay** searches, **neutrino astrophysics** and physics **Beyond Standard Model** searches.
- **4 x LArTPCs** of 12x12x60 m^3 17kton of liquid argon each.

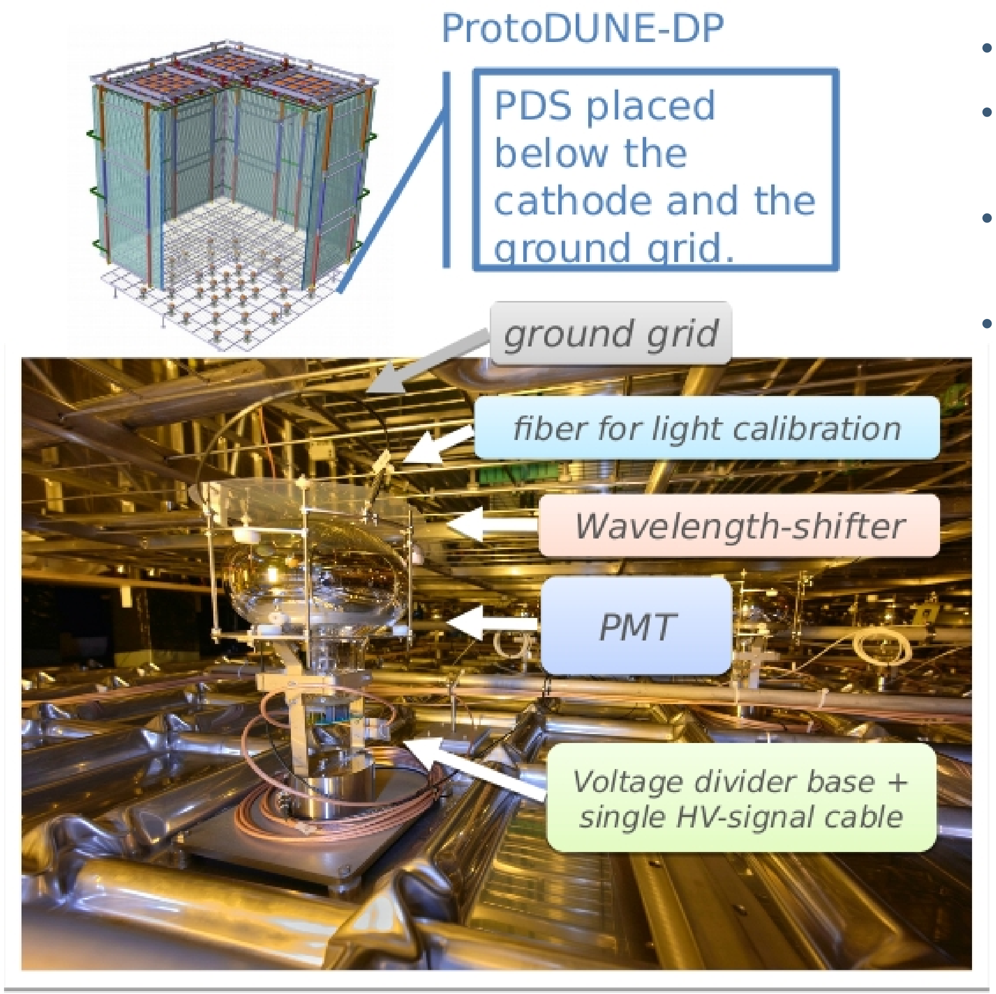




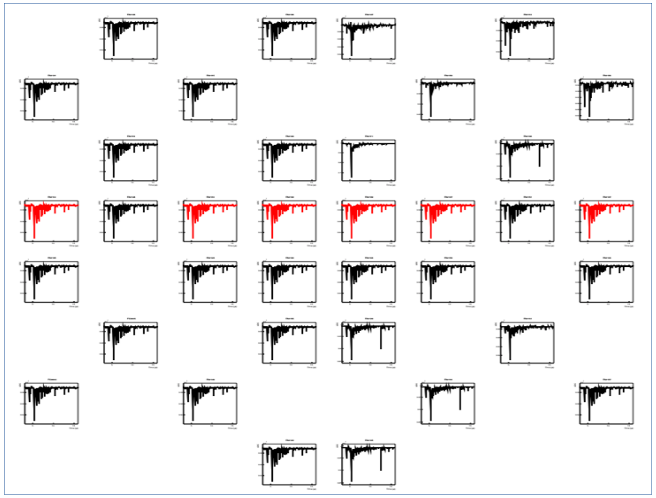
ProtoDUNE DP (CERN):

- 750 ton of Ar.
- Argon gas layer in the top where the charge signal is extracted, amplified and collected.
- The largest Dual-Phase TPC ever built: 6x6x6 m^3

Photon detection in ProtoDUNE-DP



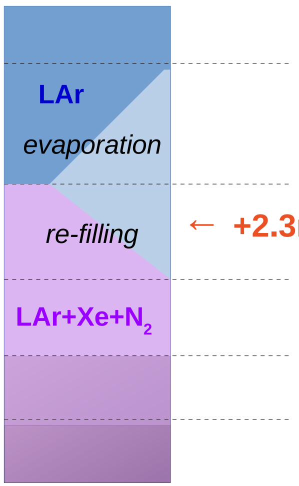
- Placed at CERN Neutrino Platform.
- 36 8'' Hamamatsu PMTs placed at the bottom.
- 6 PMTs coated with TPB or 32 with a PEN foil on top, to shift the wavelenght of the photons.
- One year of cosmic data with LAr, from summer 2019 to 2020.
- For pure LAr results see talk by C. Cuesta: https://indico.cern.ch/event/981823/contributions/4293608/



Typical event of a crossing muon on the 36 PMTs. TPB-coated PMTs in red.

Summary of the ProtoDUNE-DP xenon program:

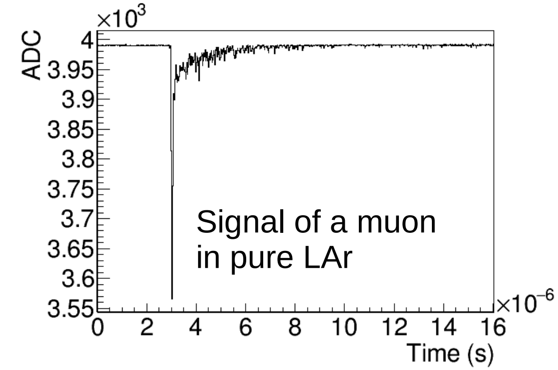
After the operation with pure liquid argon, the detector was refilled with a mitxure of **LAr+Xe+N_2**. Data were taken during all the process.

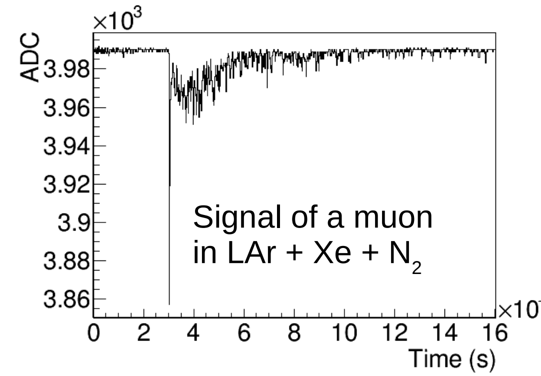


- May 6th – Evaporation starts (liquid argon level at 7.4m).
- July 22nd – Re-filling starts (level at 5.1m).

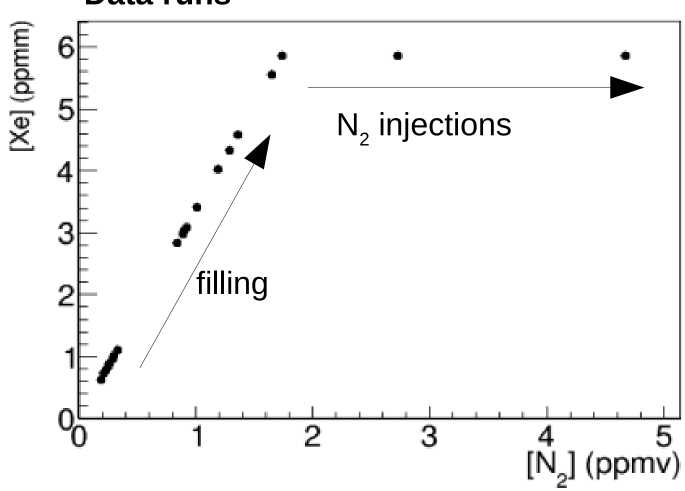
← **+2.3m of liquid**

- July 24rd – Re-filling ends (level at 7.4m)
- August 14th – 1st injection of N_2
- August 28th – 2nd injection of N_2.





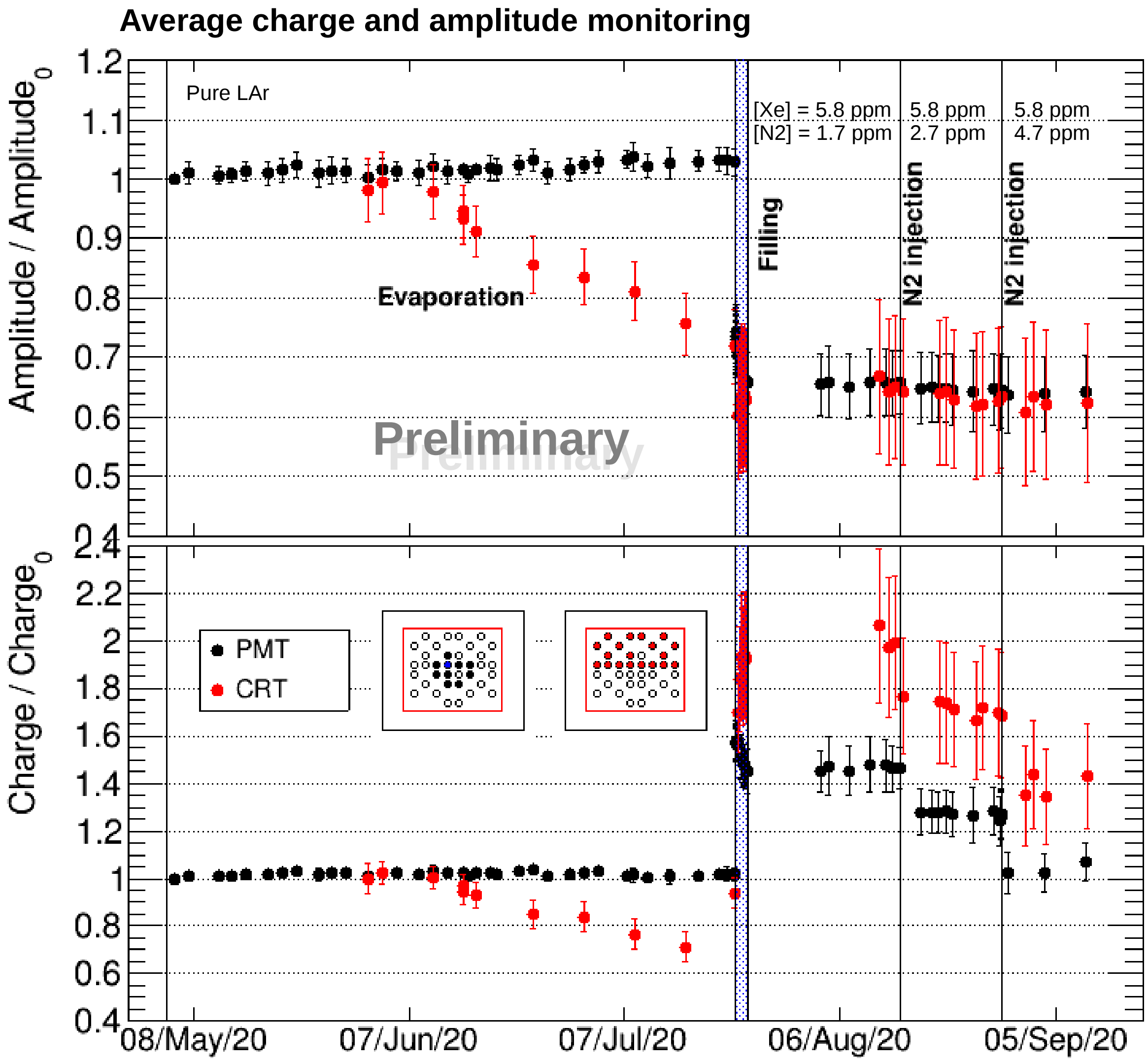
Data runs

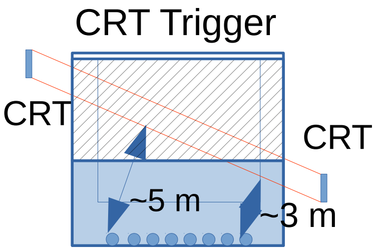


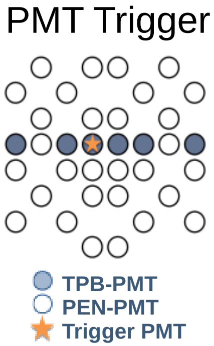
Situation	[Xe] (ppmm)	$[N_2]$ (ppmv)
LAr	0	0
LAr + Xe + N_2	5.8	1.7
1^{st} N_2 injection	5.8	2.7
2^{nd} N_2 injection	5.8	4.7

ProtoDUNE-DP results

Signal monitoring





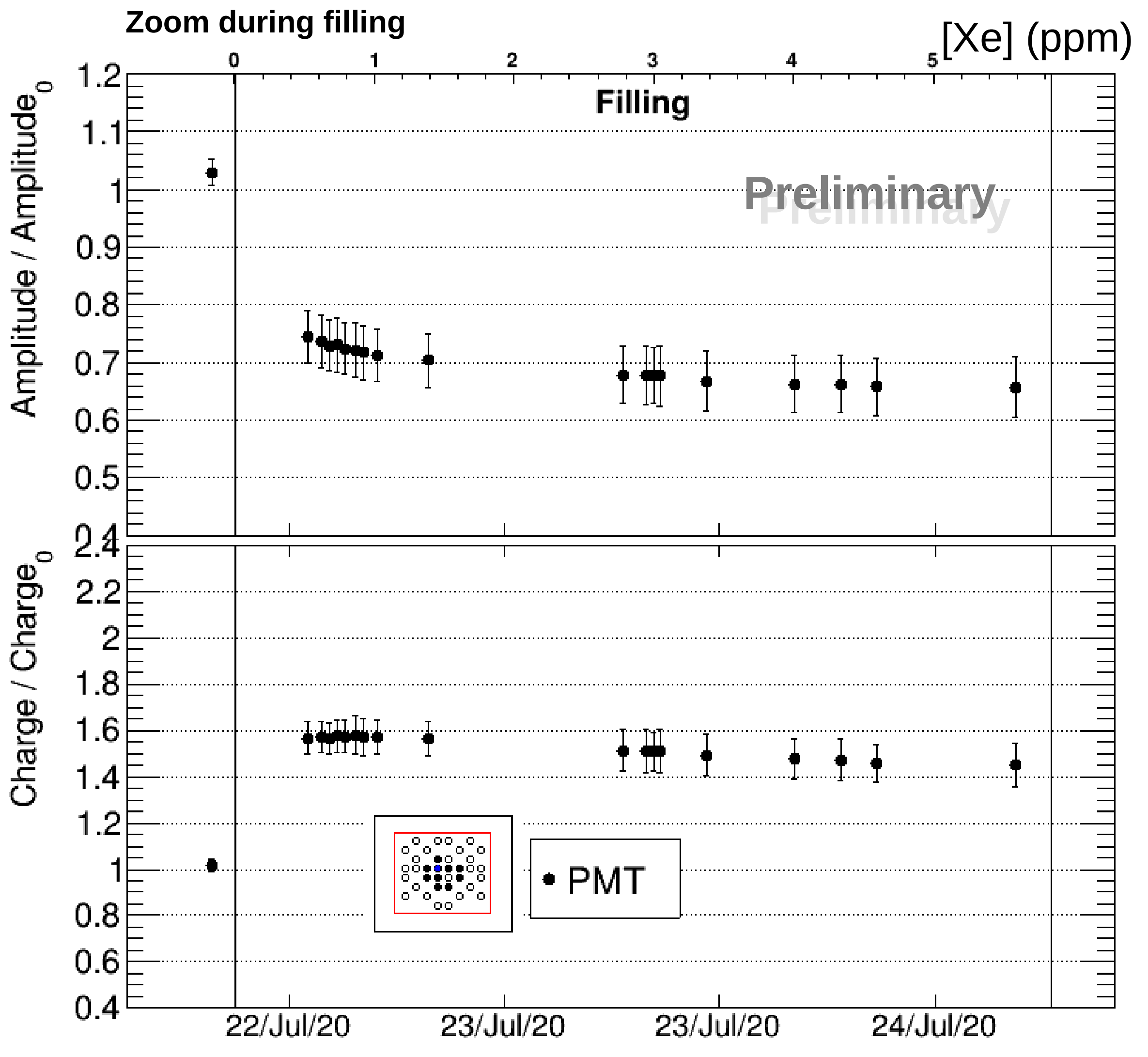


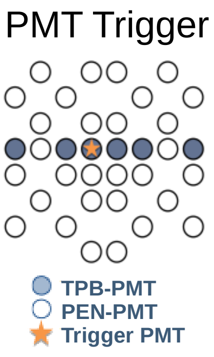
- 2 triggers:
  - PMT Trigger: Near tracks.
  - CRT trigger Far tracks.
- Amplitude is reduced 35% when adding xenon, and it is not affected by the nitrogen.
- A large increase of charge (x2) with xenon, and reduction with N_2, as expected.

* error bars show the STD variation for the selected PMTs

ProtoDUNE-DP results

Signal monitoring



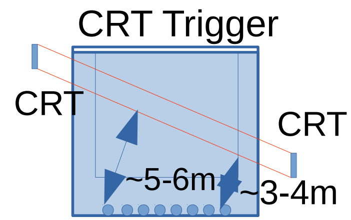


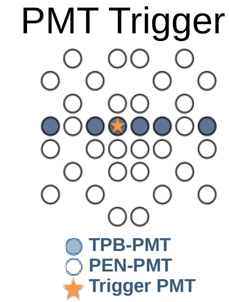
- Most of the amplitude reduction happened at the beginning of the filling, with the xenon concentration still very low (<1ppm).
- The charge increase is maximal at the lowest xenon concentration.

* Error bars show the STD variation for the selected PMTs.
* Filling flow was uniform during all the filling.

ProtoDUNE-DP results

Impact on the average signal





When adding Xe and N_2 (filling):

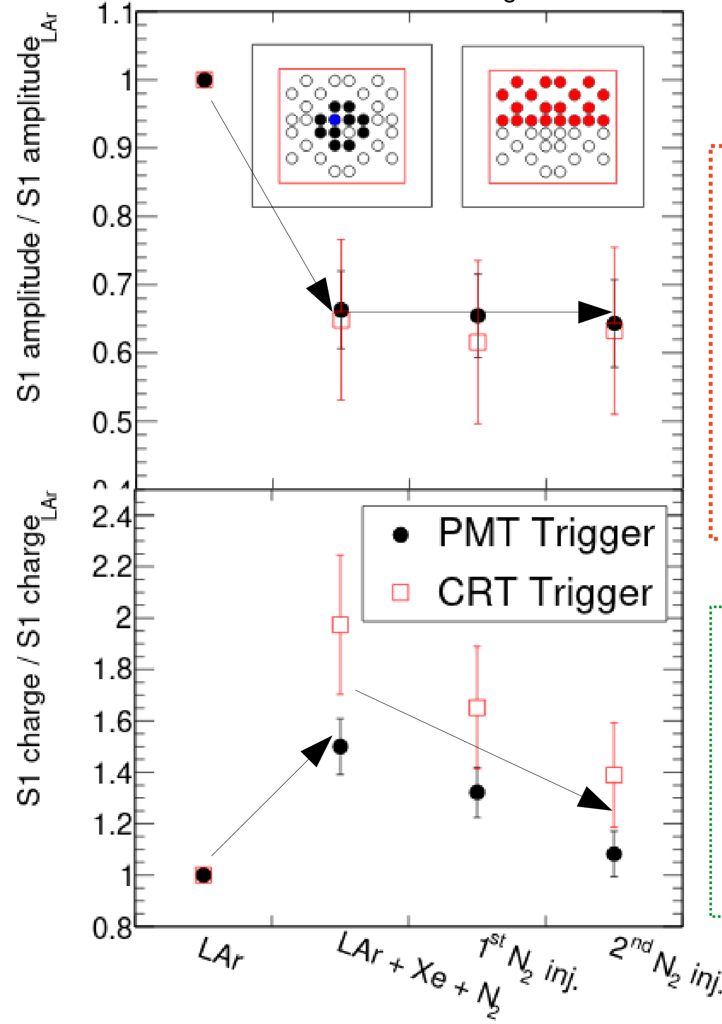
- We expect **a suppresion of the amplitude/fast component** due to the absorption of 128 nm photons by Xe and N_2.

  → We observe a **reduction of 35%** in both triggers.

- We expect a **larger increase of the collected charge on far tracks (CRT)** due to improved uniformity for 178 nm photons.

  → **60%** charge increase on **near tracks** (PMT), **100%** increase on **far tracks** (CRT).

Relative variation of the average signal detected at different triggers:
Error show STD variation among PMTs.



When adding N_2 only:

- We expect **a ~20% reduction of the amplitude/fast component on CRT tracks** due N_2 absorption of 128 nm photons.

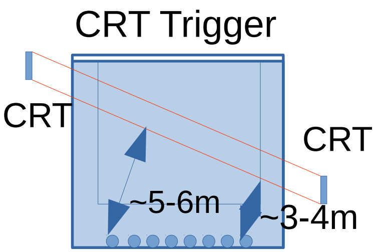
  → Unexpectedly the **amplitude is constant**.

- We expect **a reduction of the charge** due to the ArAr and ArXe quenching.

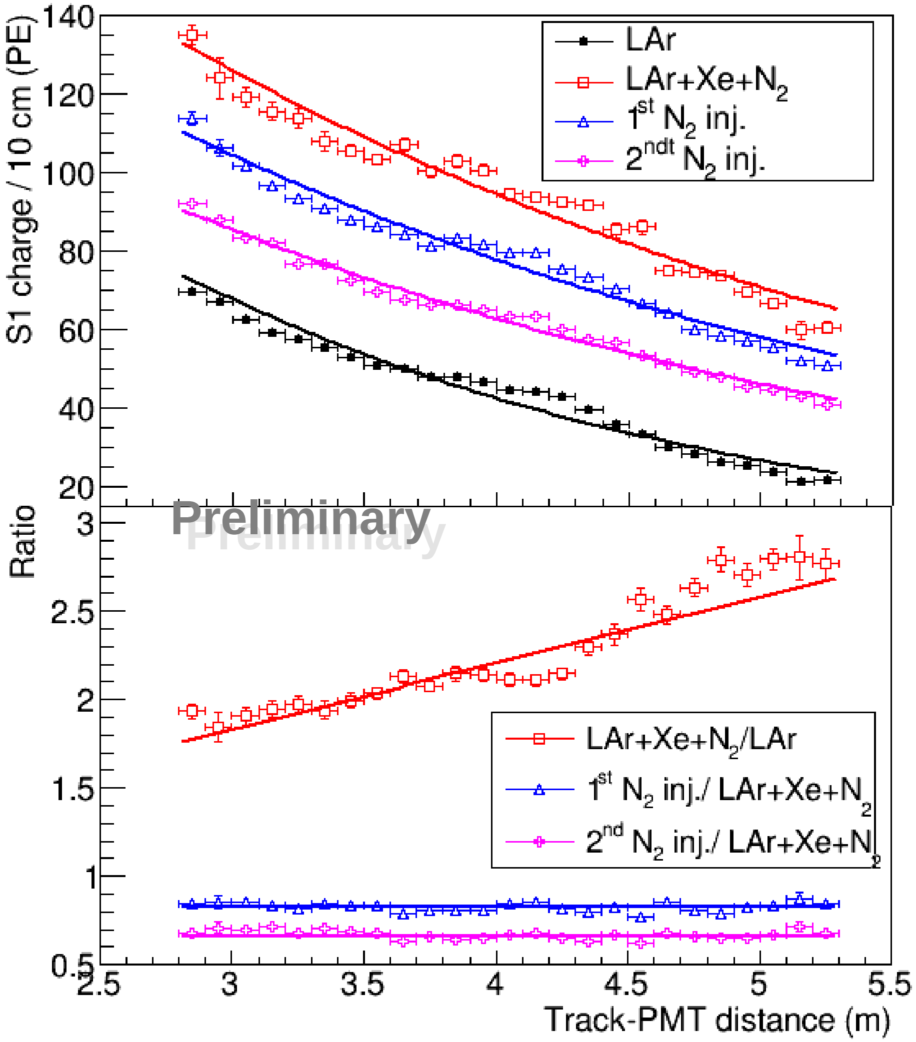
  → Charge is **reduced ~30%** on both triggers.

ProtoDUNE-DP results

Impact on the attenuation length



Average signal detected per PMT in CRT trigger tracks:



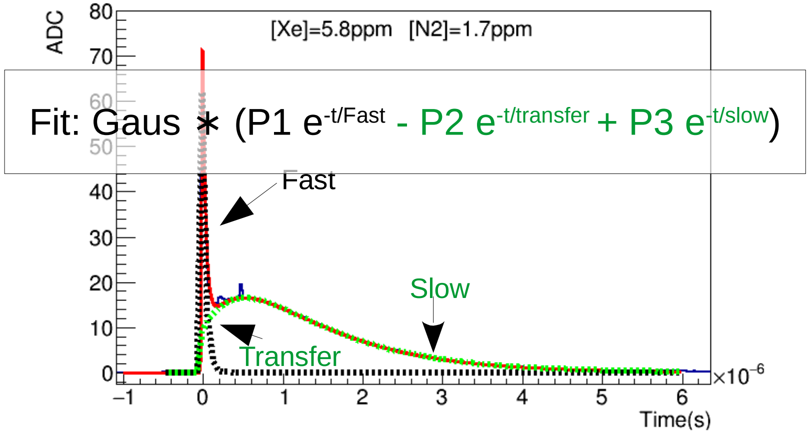
Preliminary

Situation	λatt (±10 cm)
LAr	215
LAr + Xe + N_2	350 (+60%)
1^{st} N_2 injection	340
2^{nd} N_2 injection	330

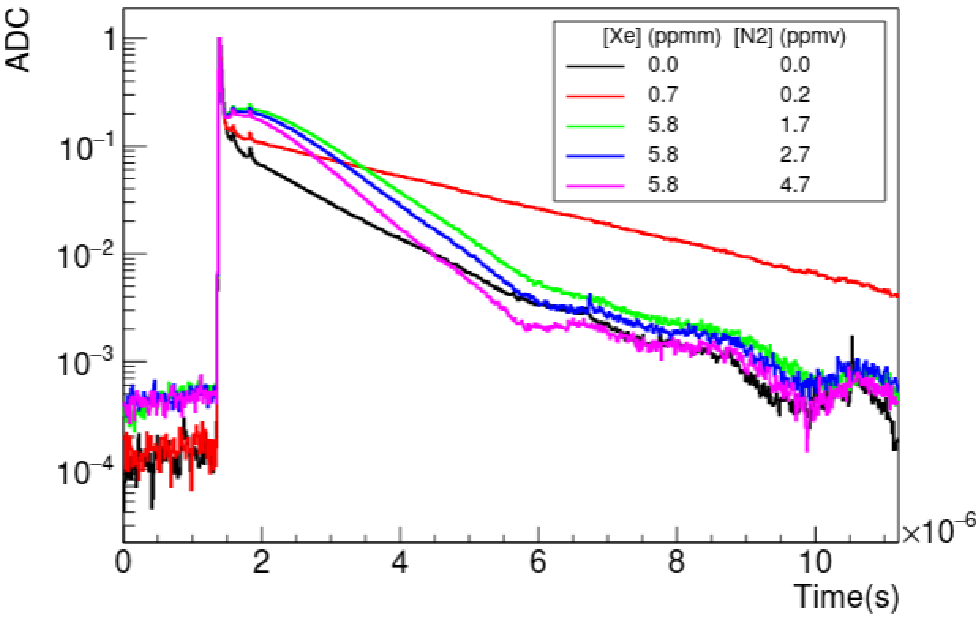
- The effective **attenuation length increases 60%** when adding xenon, while it remains after the injections of nitrogen.
- Small sensitivity to variations in the absorption length due to the N_2 injections (flat ratios in the bottom panel).

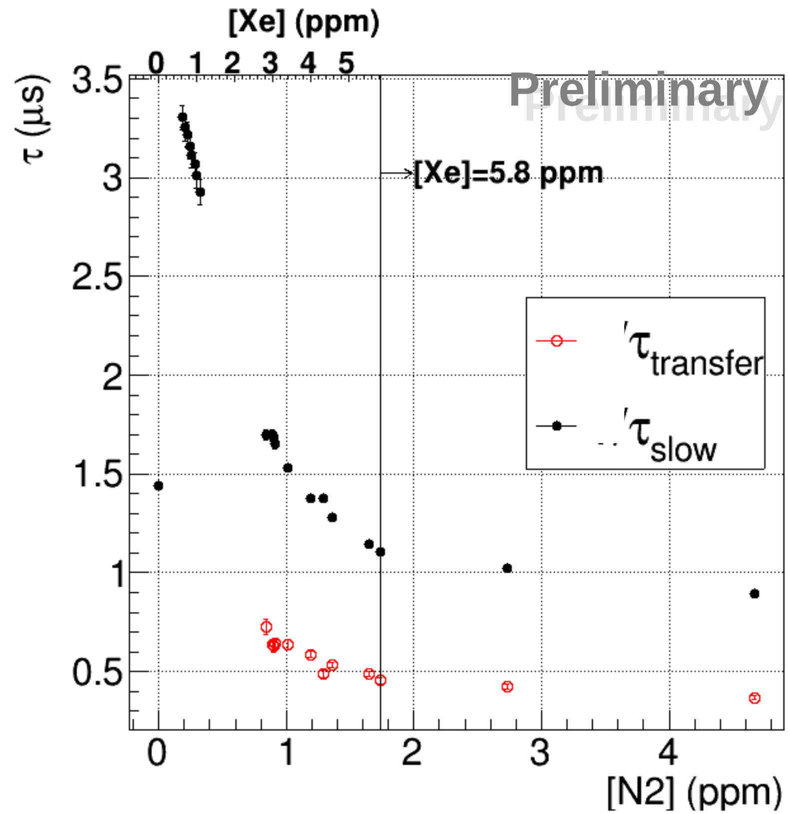
ProtoDUNE-DP results

Impact on the time profile



Average waveform at different concentrations



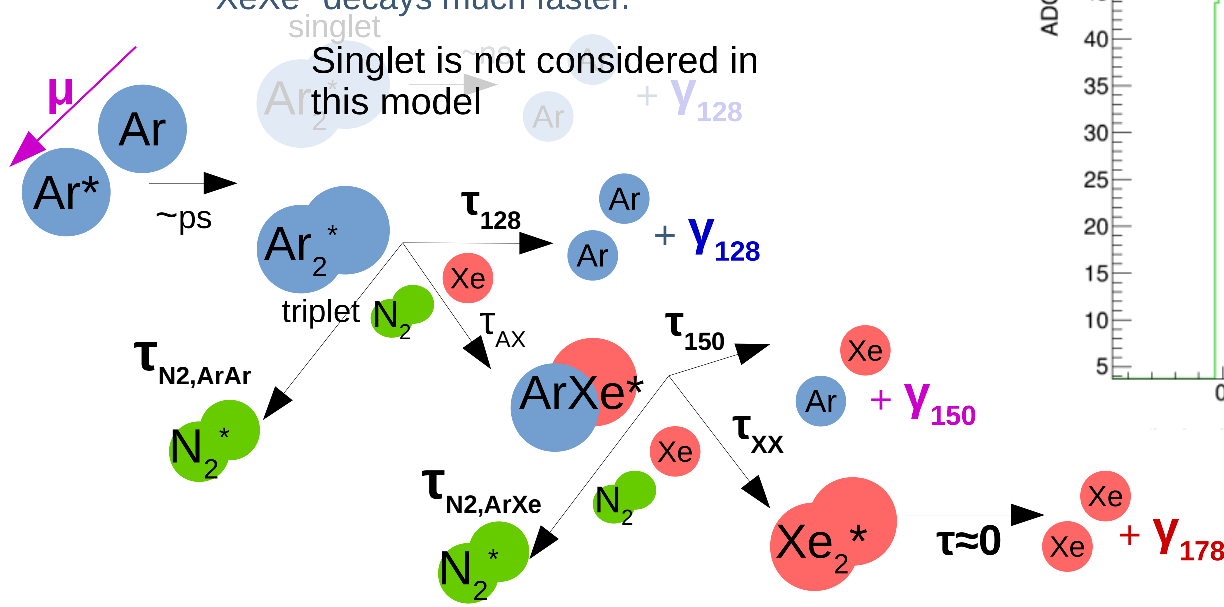


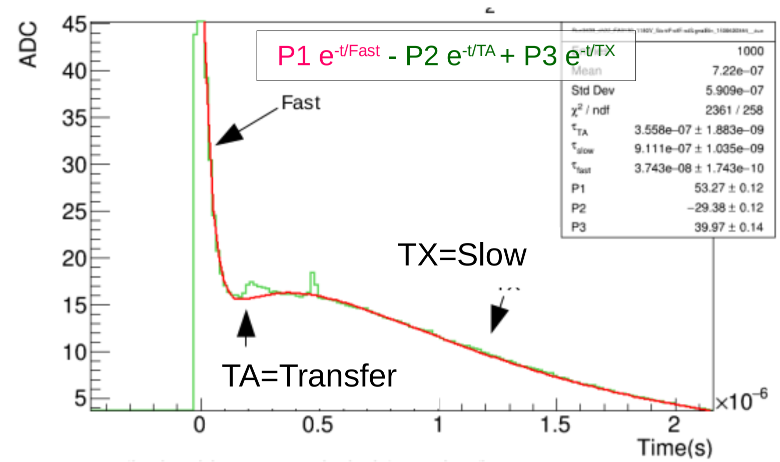
- Each average waveform is fitted.
- Fit parameters are shown in the right plot.

ProtoDUNE-DP results

Fitting to the scintillation model

- A simple model is proposed **to obtain the physical parameters (6 parameters)** of the scintillation.
- Approximations:
  - No xenon quenching on the singlet.
  - XeXe* decays much faster.





Rate of ArAr* disappearence:

$$\frac{1}{\tau_{TA}} = \frac{1}{\tau_{N2,ArAr}} + \frac{1}{\tau_{AX}} + \frac{1}{\tau_{128}} = k_{N2,ArAr}[N2] + k_{AX}[Xe] + \frac{1}{\tau_{128}}$$

Rate of ArXe* disappearance:

$$\frac{1}{\tau_{TX}} = \frac{1}{\tau_{N2,ArXe}} + \frac{1}{\tau_{XX}} + \frac{1}{\tau_{150}} = k_{N2,ArXe}[N2] + k_{XX}[Xe] + \frac{1}{\tau_{150}}$$

- **The time constants are extracted by doing a global fit to all the profiles at the different dopant concentrations.**

ProtoDUNE-DP results

Fitting to the scintillation model

Preliminary

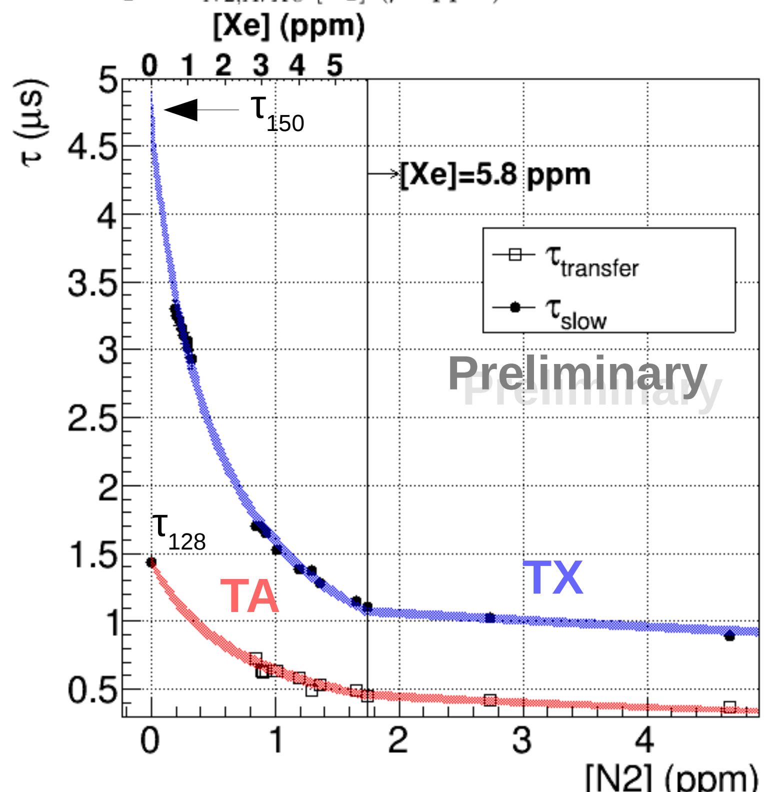
Process	Time	ProtoDUNE-DP results	Literature
$Ar_2^*(^3\Sigma_u^+) \rightarrow 2Ar + \gamma$ (128 nm)	τ_{128} (μs)	1.44	~ 1.5
$Ar_2^*(^3\Sigma_u^+) + Xe \rightarrow ArXe^* + Ar$	τ_{AX} [Xe] (μs ppm)	5.4 ± 0.3	
$ArXe^* \rightarrow Ar + Xe + \gamma$ (150nm)	τ_{150} (μs)	4.7 ± 0.1	
$ArXe^* + Xe \rightarrow Xe_2^*(^{1,3}\Sigma_u^+) + Ar$	τ_{XX} [Xe] (μs ppm)	9.2 ± 0.1	11.4 [Wahl]
$Ar_2^*(^3\Sigma_u^+) + N_2 \rightarrow 2Ar + N_2$	$\tau_{N2,ArAr}$ [N_2] (μs ppm)	4.1 ± 0.1	9.1 ± 0.1 [Acciarri]
$ArXe^* + N_2 \rightarrow Ar + Xe + N_2$	$\tau_{N2,ArXe}$ [N_2] (μs ppm)	20.3 ± 0.7	

The **model fits well the data**.

Some of the parameters are measured for the first time.

The **N_2 quenching on ArAr is much faster than the value in the literature.**

Transfer rate from ArXe to XeXe is not far from the literature.



Global fit ± σ in red and blue.
Points show the individual fit for each run.

Limitations:

- Valid at **low concentrations** (1-5 ppm)
- **Model approximations**: Fast component quenching not considered and XeXe decay instantaneous.
- **Limited sensitivity to TA** due to the overlapping fast signal and reflections.

Summary and conclusions

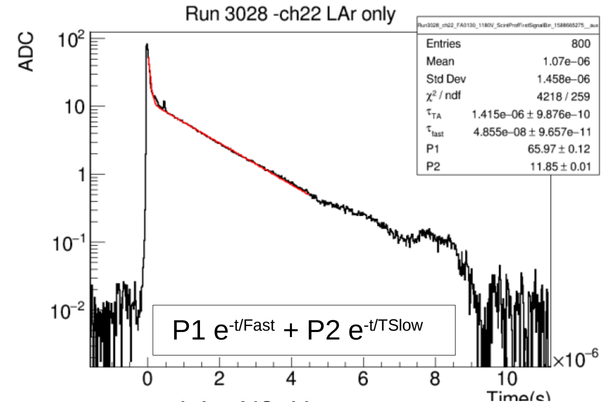
- Xenon-doping is a promising technique that would increase the light yield and improve the light detection uniformity for large Lar-TPCs, like DUNE.
- ProtoDUNE-DP took dedicated data with xenon-doped liquid argon, in the range of 0-5 ppm of xenon and nitrogen.
- **Collected light increases 100% for a diagonally crossing muon** in LAr+Xe(5.8ppm)+N_2(1.5ppm) w.r.t to LAr only.
- The **detection uniformity improves**, with an attenuation length 60% longer when adding xenon.
- The **light signal amplitude decreases** 35% in LAr+Xe(5.8ppm)+N_2(1.5ppm) w.r.t to liquid argon only. This could compromise the trigger capabilities.
- A model for the scintillation light production in xenon doped liquid argon with N_2 impurities has been proposed to measure the quenching constants.

Backup

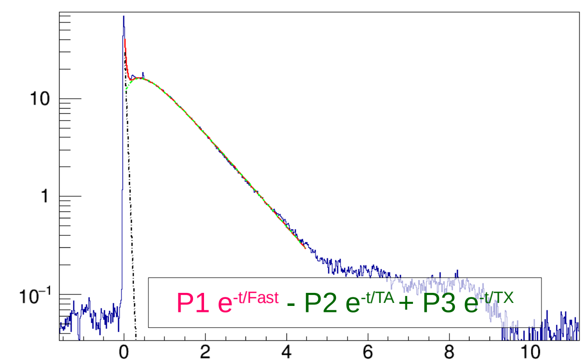
Scintillation model in LAr, Xe, N_2 mixtures

The scintillation time profile can be resolved. In this case, only for the triplet component:

	Process	Time	Value	
	$Ar_2^*(^3\Sigma_u^+) \rightarrow 2Ar + \gamma\ (128\ \text{nm})$	τ_{128}	$\sim 1.5\mu s$	(decay time)
	$Ar_2^*(^3\Sigma_u^+) + Xe \rightarrow ArXe^* + Ar$	τ_{AX}		(collision time)
Xe	$ArXe^* \rightarrow Ar + Xe + \gamma\ (150\text{nm})$	τ_{150}		
	$ArXe^* + Xe \rightarrow Xe_2^*(^{1,3}\Sigma_u^+) + Ar$	τ_{XX}		
	$Xe_2^*(^{1,3}\Sigma_u^+) \rightarrow 2Xe + \gamma\ (175\ \text{nm})$	τ_{175}	$\sim ns$	(Kubota, 1993)
N2 quenching	$Ar_2^*(^3\Sigma_u^+) + N_2 \rightarrow 2Ar + N_2$	$\tau_{N2,ArAr}$	$\frac{9\ \mu s\ \text{ppm}}{[N2]}$	(Acciarri, 2009)
	$ArXe^* + N_2 \rightarrow Ar + Xe + N_2$	$\tau_{N2,ArXe}$		(quenching time)



LAr+N2+Xe



Considering the processes collected in the table above, and their characteristic time decays (τ's), the concentration of Ar_2*, ArXe* and Xe_2*excimers (AA, AX and XX) is modelled as entangled stochastic processes:

$$\frac{dAA}{dt} = -\frac{AA}{\tau_{128}} - \frac{AA}{\tau_{N2,ArAr}} - \frac{AA}{\tau_{AX}} = -\frac{AA}{\tau_{TA}}$$
$$\frac{dAX}{dt} = +\frac{AA}{\tau_{AX}} - \frac{AX}{\tau_{150}} - \frac{AX}{\tau_{N2,ArXe}} - \frac{AX}{\tau_{XX}} = +\frac{AA}{\tau_{AX}} - \frac{XX}{\tau_{TX}}$$
$$\frac{dXX}{dt} = +\frac{AX}{\tau_{XX}} - \frac{XX}{\tau_{175}}$$

The total number of photons will be proportional to the sum of the time derivative of all the concentrations.

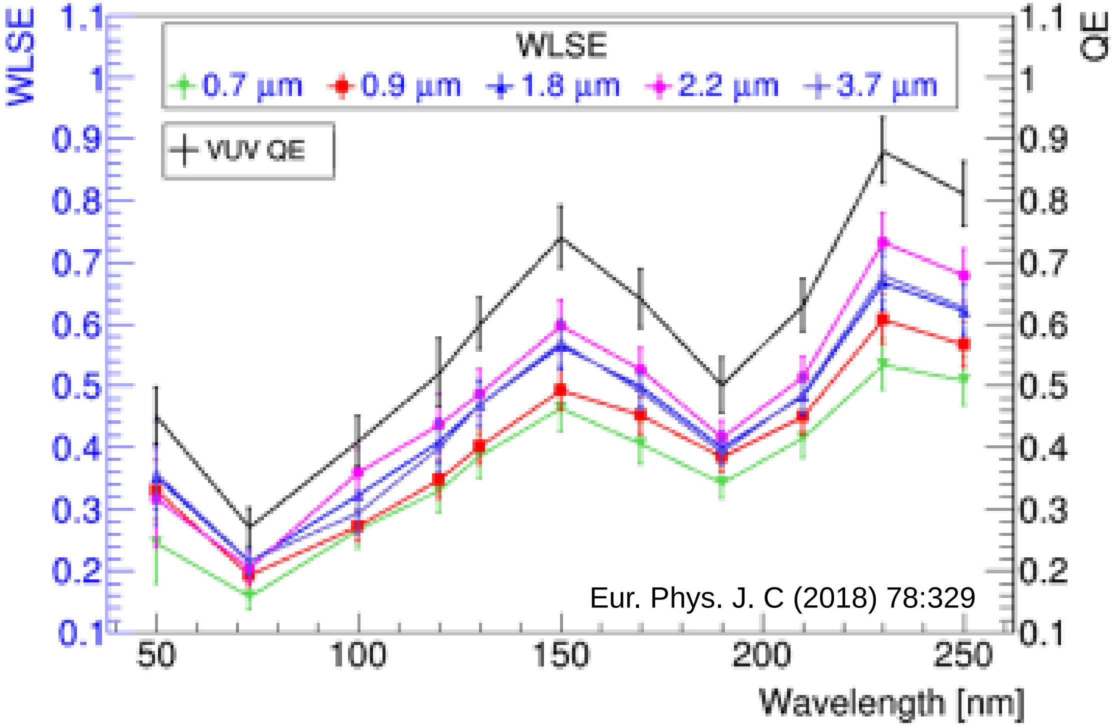
$$\frac{dAA}{dt}(128\ \text{nm}) + \frac{dAX}{dt}(150\ \text{nm}) + \frac{dXX}{dt}(175\ \text{nm}) \overset{\tau_{175} \ll \tau_{TA},\tau_{TX}}{\approx} -A_1 e^{-t/\tau_{TA}} + A_2 e^{-t/\tau_{TX}}$$

The scintillation time profile can be expressed as two exponentials, with the time decay depending linearly with the dopant concentration:

- τ_{TA} and τ_{TX} are the exponents we extract directly from the data:

$$\frac{1}{\tau_{TA}} = \frac{1}{\tau_{N2,ArAr}} + \frac{1}{\tau_{AX}} + \frac{1}{\tau_{128}} = A[N2] + B[Xe] + C$$
$$\frac{1}{\tau_{TX}} = \frac{1}{\tau_{N2,ArXe}} + \frac{1}{\tau_{XX}} + \frac{1}{\tau_{150}} = D[N2] + E[Xe] + F$$

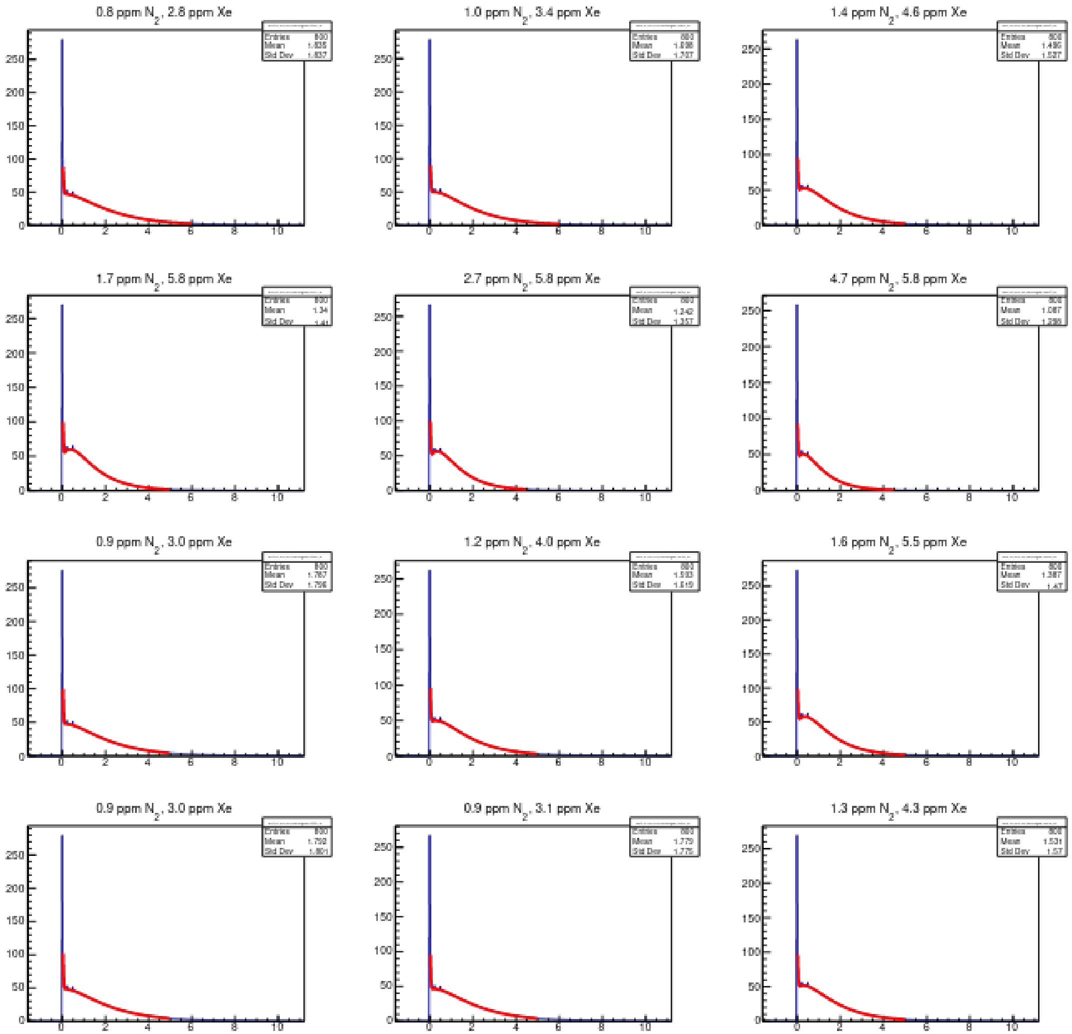
TPB wavelength-shifting efficiency vs wavelength

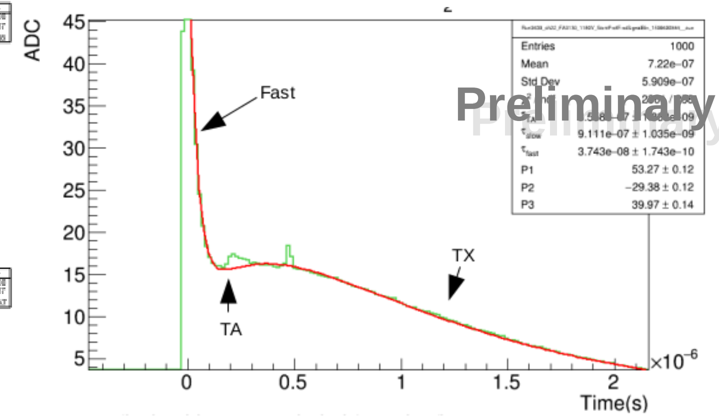


ProtoDUNE-DP results

Fitting to the scintillation model

Move to backup?





Warning: The fast component and the reflections limit the sensitivity to the TA

- Example of the global fit performed to a PMT.