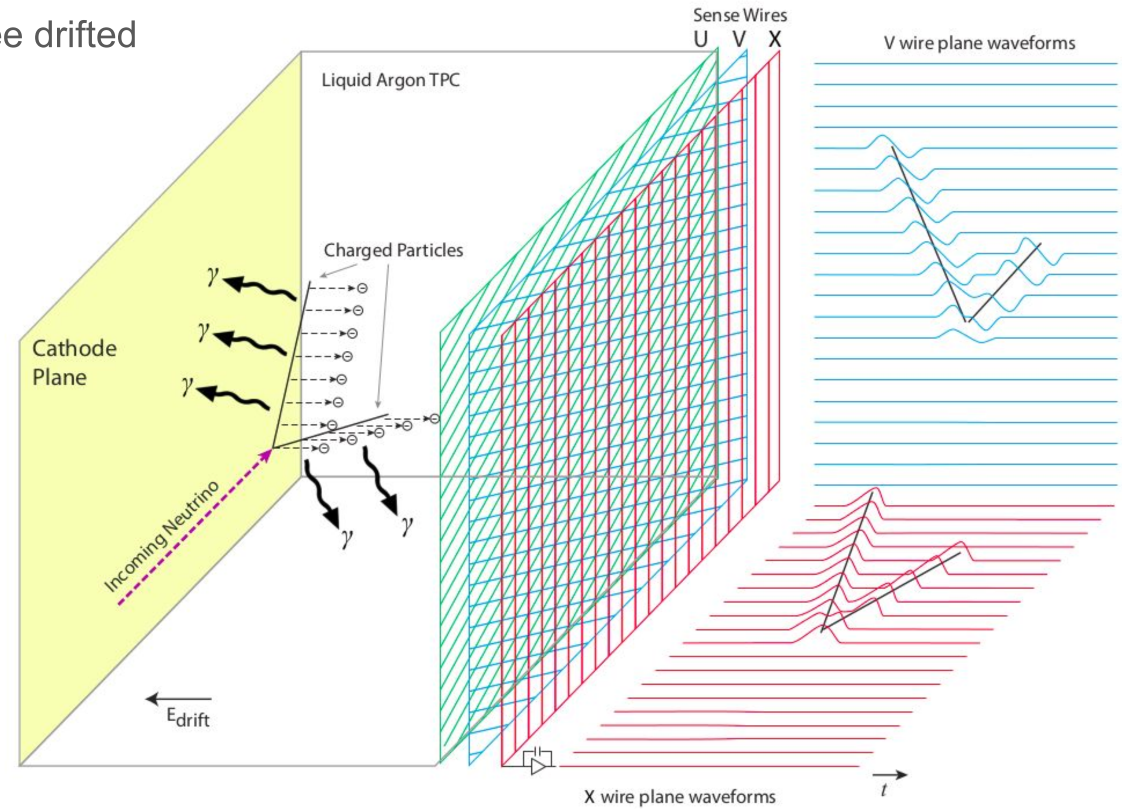
Light simulation and Analysis

Henrique Souza

APC - 19/04/2023

Motivation

- The LArTPC is characterized by the free drifted electrons signal and light emission
- The detection of scintillation light can provide the absolute time (T0) of events and internal triggering for non beam events
- **Besides,** light signals can improve position, time and energy resolution. Improve particle identification (PID) and improve background rejection by the proper fidualization of the detector.



Overview

- Liquid argon scintillation
  - Mechanism
  - Composition and time response
  - Propagation
- Detection
  - Description of DUNE’s photon detectors: X-Arapuca
- Simulation
  - How is the light simulation implemented
- Analysis
  - Where to find data real data and its structure

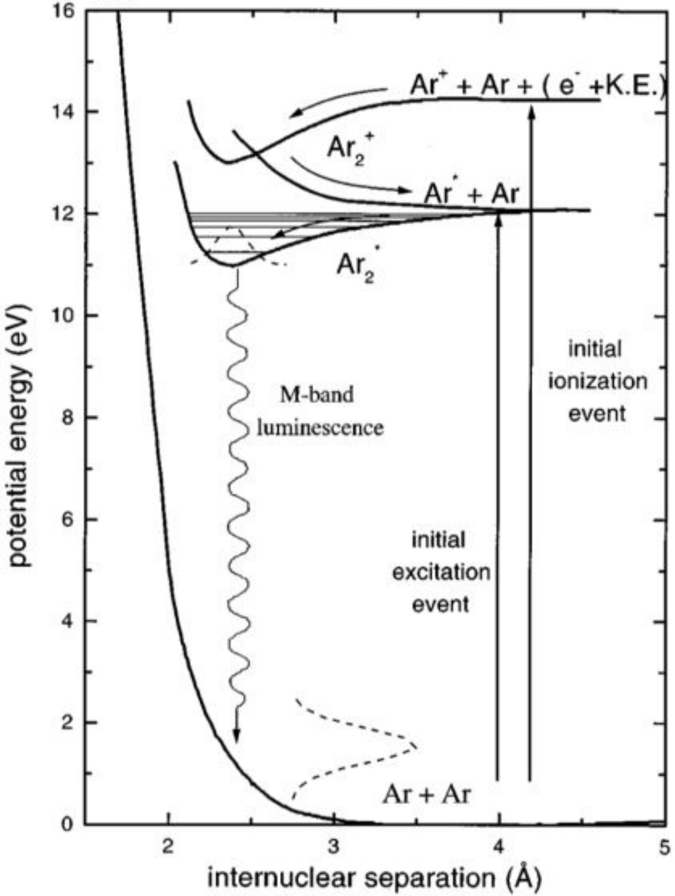
Disclaimer: many of these slides were possible from past slides, specially this presentation from Andrzej Szelc and thanks to Laura Paulucci for sending support material.

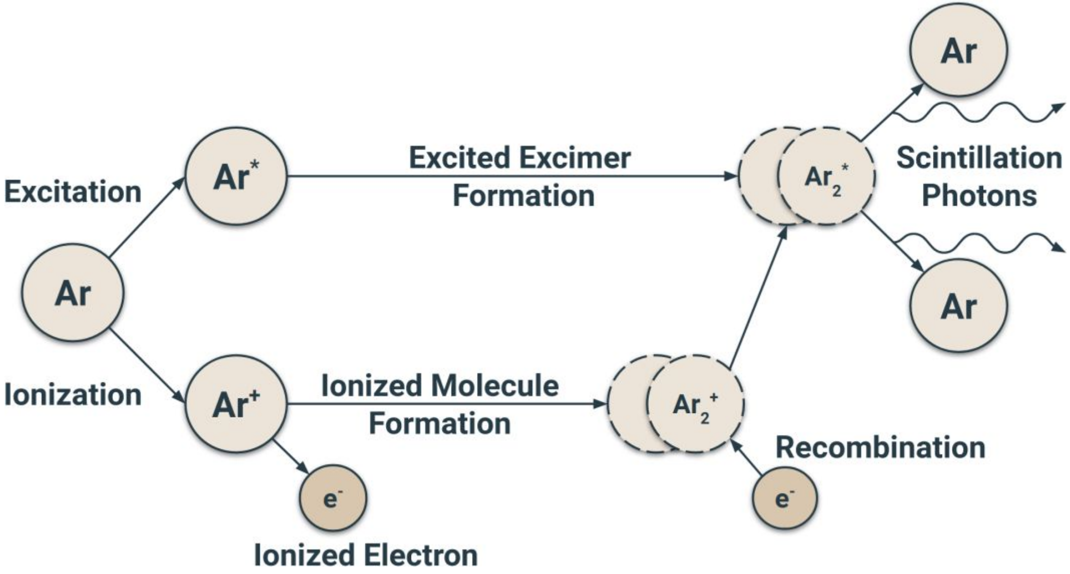
Liquid argon scintillation

- Mechanism of light production
- Time components
- Scintillation yield
- Electric field
- Light propagation

Mechanism

Ph. Rev. B 56 (1997), 6975

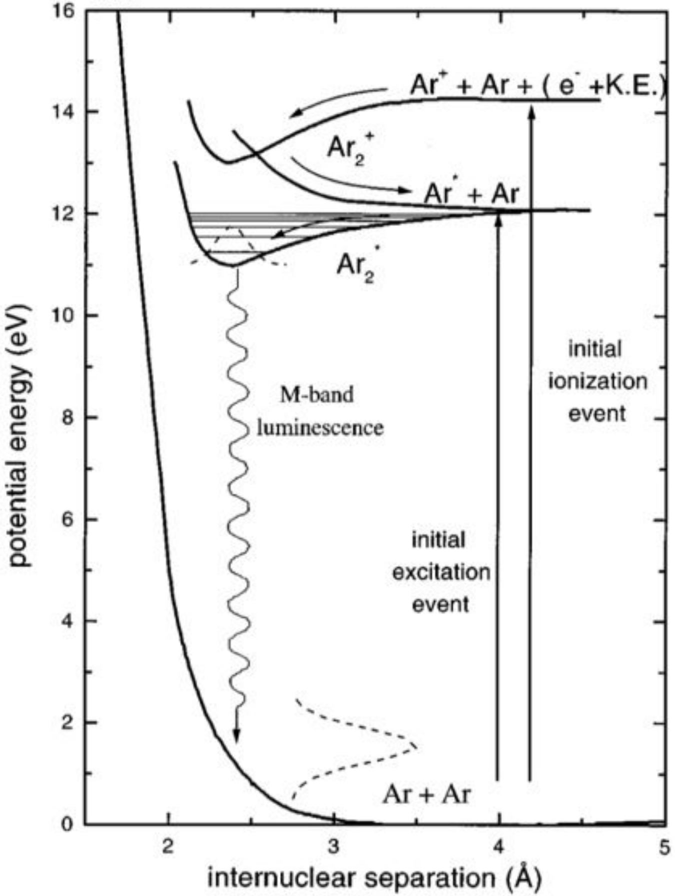




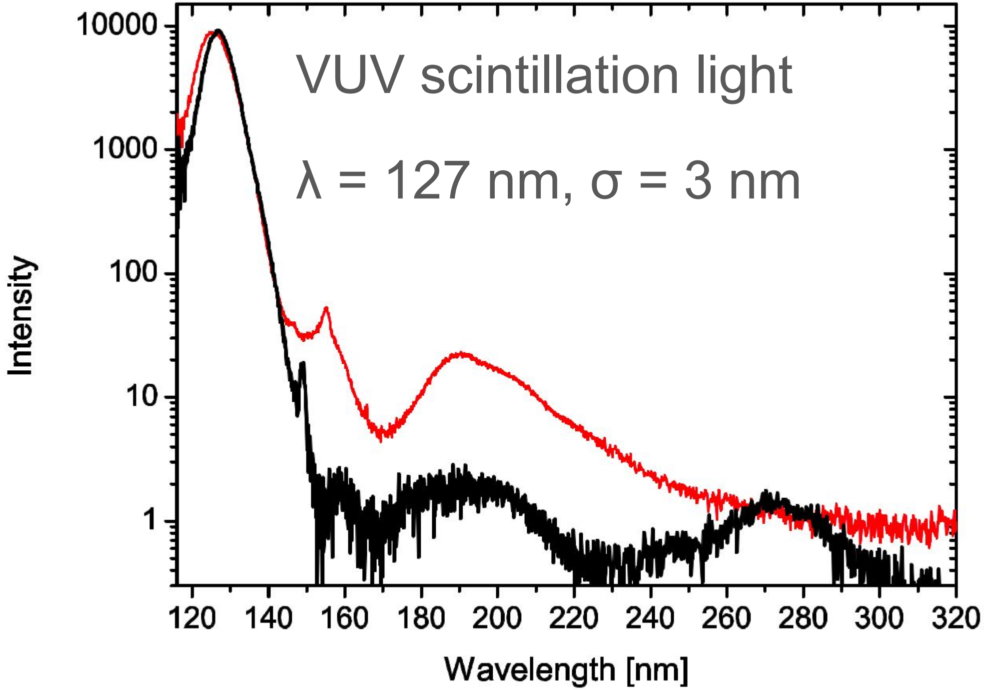
Ar^*_2 should be de-excited to the ground state by emitting a Vacuum ultraviolet (VUV) photon

Mechanism

Ph. Rev. B 56 (1997), 6975

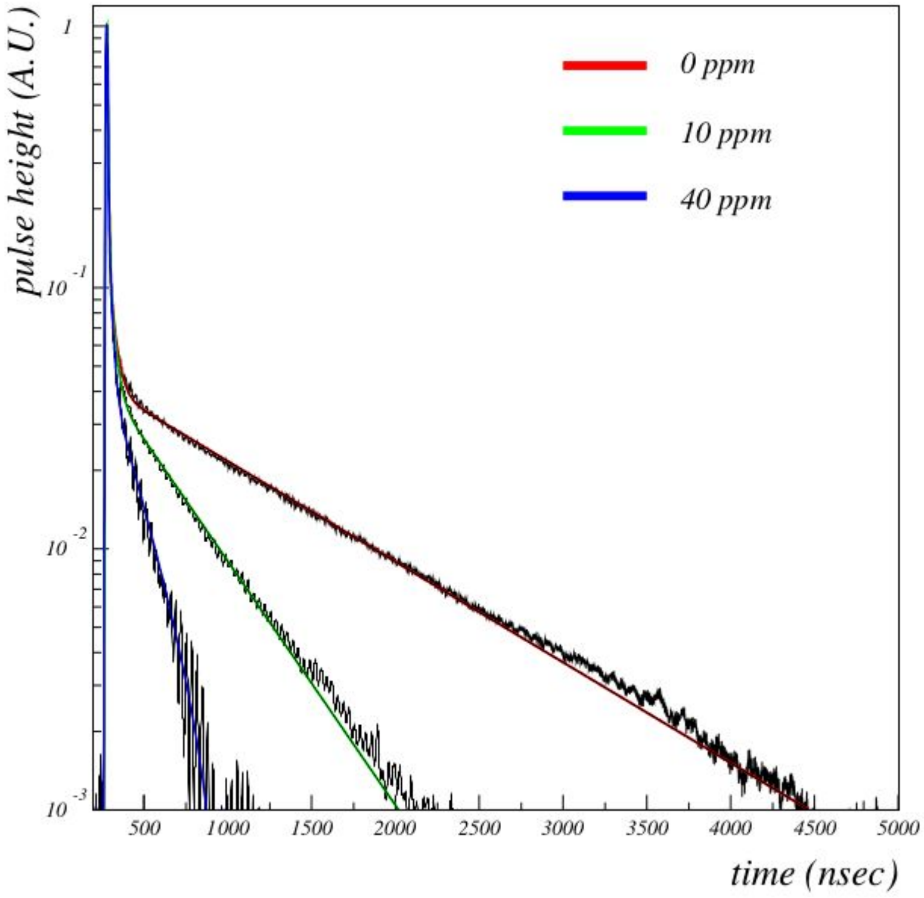


T. Heindl *et al* 2010 *EPL* **91** 62002

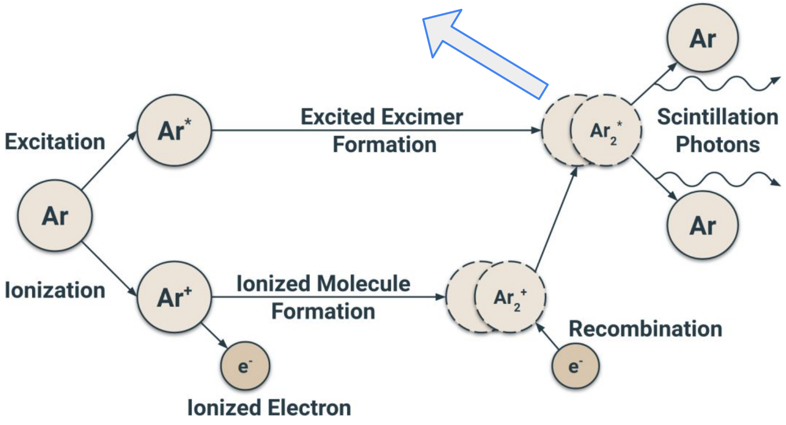


Time components

R Acciarri *et al* 2010 *JINST* **5** P06003



Singlet or triplet state



$$I(t) = A_S \exp\left(-\frac{t}{\tau_S}\right) + A_T \exp\left(-\frac{t}{\tau_T}\right)$$

$$\tau_S = 6 \text{ ns}$$

$$\tau_T = 1600 \text{ ns}$$

Scintillation time and yield

Composition of fast/slow (singlet/triplet) depends on particle Linear Energy Transfer (LET).

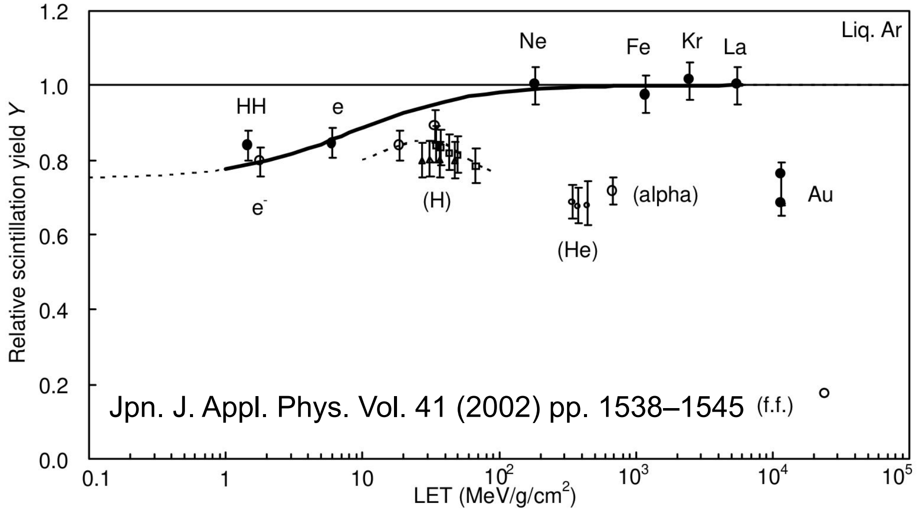
Muon/e$^-$: 23 % (fast) and 77% (slow)

Alphas: 77 % (fast) and 23 % (slow)

TABLE I. Decay times for the fast τ_S and the slow τ_T components of luminescence from liquid argon. The intensity ratios I_S/I_T of the fast component to the slow component are also shown. F.F. stands for fission fragments. All decay times are in nsec.

Particle	τ_S	τ_T	I_S/I_T	Reference
Electron	6.3 ±0.2	1020±60	0.083	Kubota *et al.*[a]
	(5.0 ±0.2)	(860±30)	(0.045)	(E =6 kV/cm)[a]
	4.6	1540	0.26	Carvalho and Klein[b]
	4.18±0.2	1000±95		Keto *et al.*[c]
		1110±50		Suemoto and Kanzaki[d]
	6 ±2	1590±100	0.3	This work
α	~5	1200±100		Kubota *et al.*[e]
	4.4	1100	3.3	Carvalho and Klein[b]
	7.1±1.0	1660±100	1.3	This work
F.F.	6.8±1.0	1550±100	3	This work

Ph. Rev. B 27 (1983), 5279



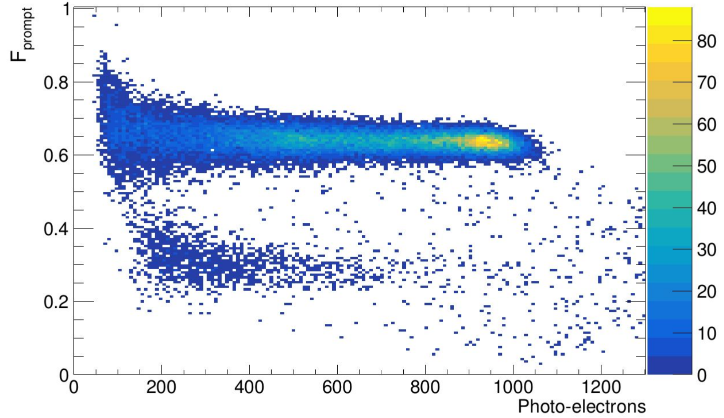
Jpn. J. Appl. Phys. Vol. 41 (2002) pp. 1538–1545

Scintillation yield also depend on LET.

Muon/e$^-$ ~ 0.8

Alphas ~ 0.7

Scintillation time and yield



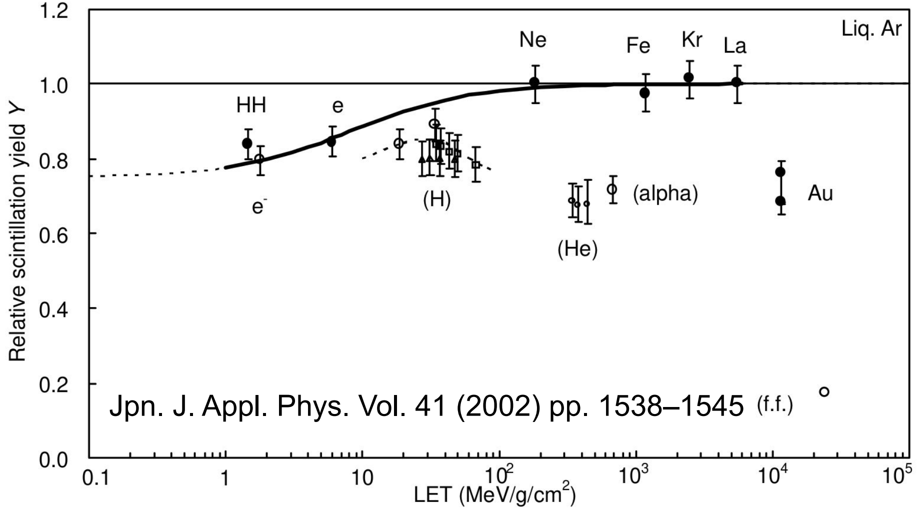


TABLE I. Decay times for the fast τ_S and the slow τ_T components of luminescence from liquid argon. The intensity ratios I_S/I_T of the fast component to the slow component are also shown. F.F. stands for fission fragments. All decay times are in nsec.

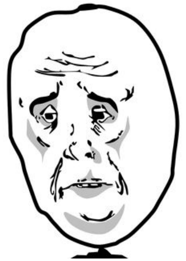
Particle	τ_S	τ_T	I_S/I_T	Reference
Electron	6.3 ±0.2	1020±60	0.083	Kubota *et al.*[a]
	(5.0±0.2)	(860±30)	(0.045)	(E = 6 kV/cm)[a]
	4.6	1540	0.26	Carvalho and Klein[b]
	4.18±0.2	1000±95		Keto *et al.*[c]
		1110±50		Suemoto and Kanzaki[d]
	6 ±2	1590±100	0.3	This work
α	~5	1200±100		Kubota *et al.*[e]
	4.4	1100	3.3	Carvalho and Klein[b]
	7.1±1.0	1660±100	1.3	This work
F.F.	6.8±1.0	1550±100	3	This work

Ph. Rev. B 27 (1983), 5279

Scintillation yield also depend on LET.

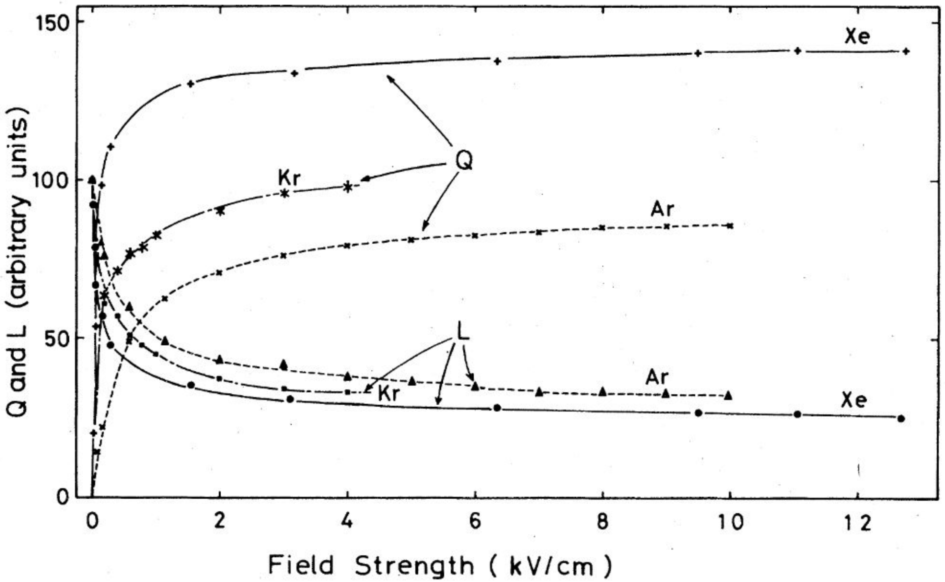
Muon/e$^-$ ~ 0.8

Alphas ~ 0.7

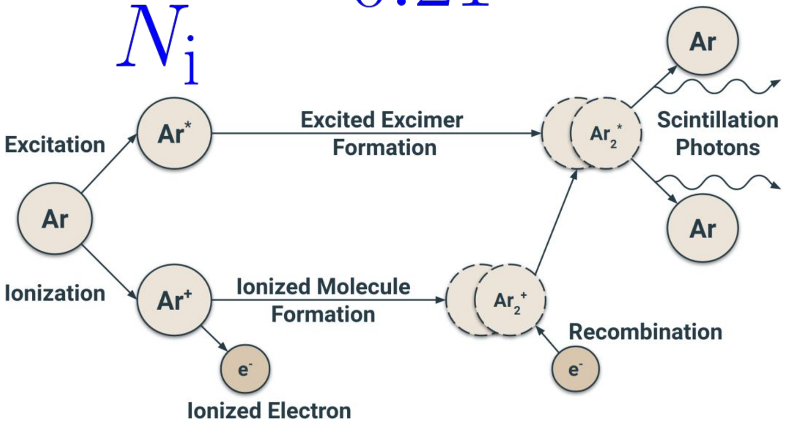


Electric field (simplified model)

Phys. Rev. B 20, 3486



$$\frac{N_{\mathrm{ex}}}{N_{\mathrm{i}}} \sim 0.21$$



$$Q = N_e = N_{\mathrm{i}} R_C$$

$$L = N_\gamma = N_{\mathrm{ex}} + N_{\mathrm{i}}(1 - R_C)$$

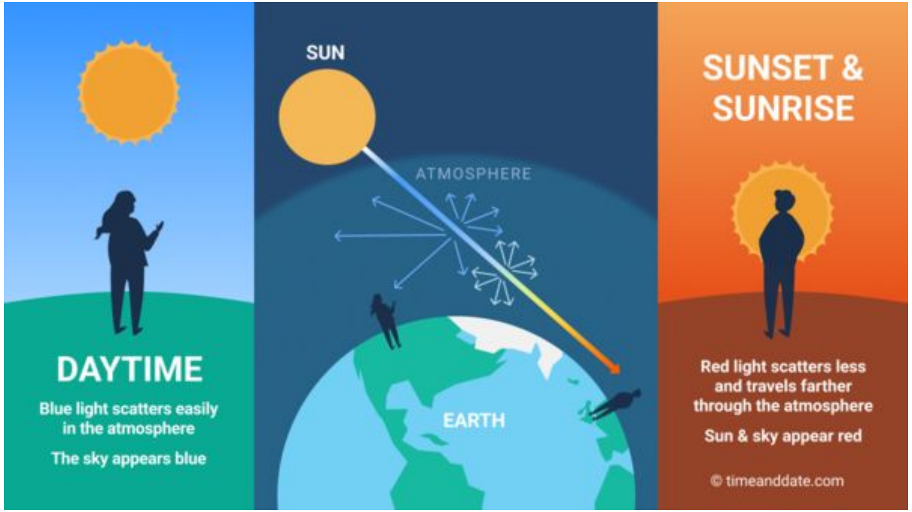
$$Q + L = N_{\mathrm{ex}} + N_{\mathrm{i}} = \Delta E / W_\gamma$$ 19.5 ± 1 eV

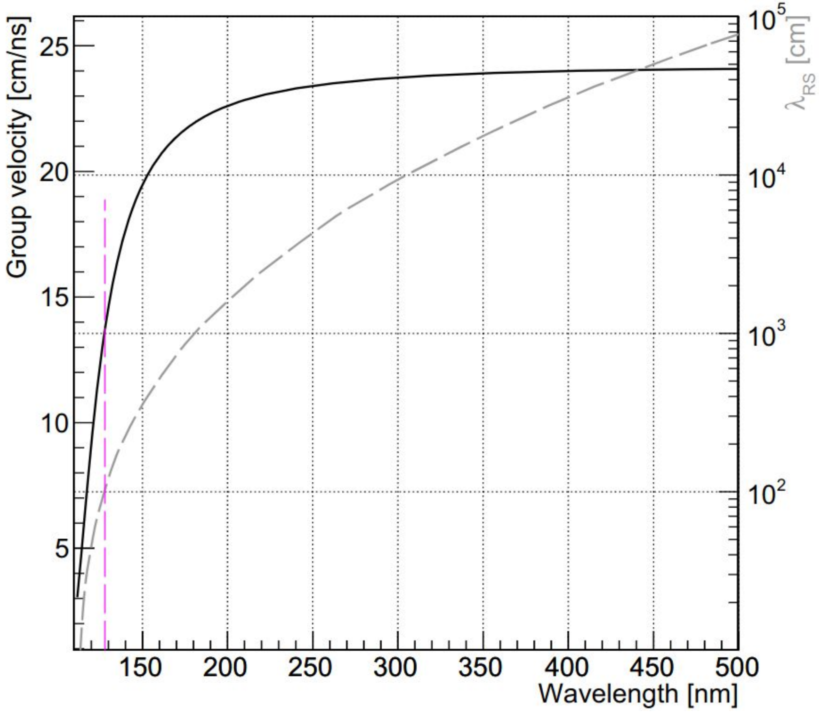
At 500 V/cm we have about 60% of light. For muons, this corresponds to 24,000 photons/MeV

(See backup for estimating number of photons)

Light propagation

- Pure LAr is transparent to its own scintillation radiation
  - Attenuation is given by an exponential with decay length of ~20 m (3 ppm N_2)
- During propagation through LAr VUV photons may undergo elastic interactions on Ar atoms ⇒ **Rayleigh scattering**





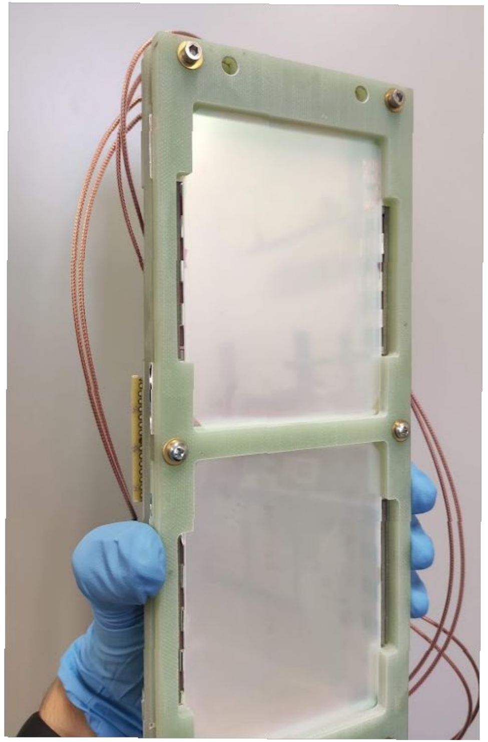
Eur. Phys. J. C 81, 349 (2021)

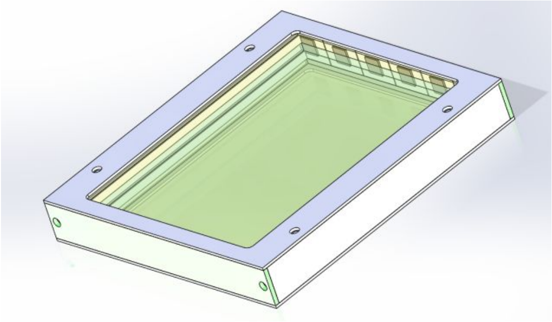
Detection

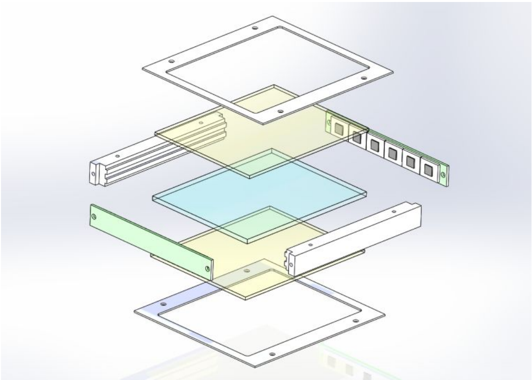
- Photon detection system (PDS) motivation
- X-Arapuca working principle

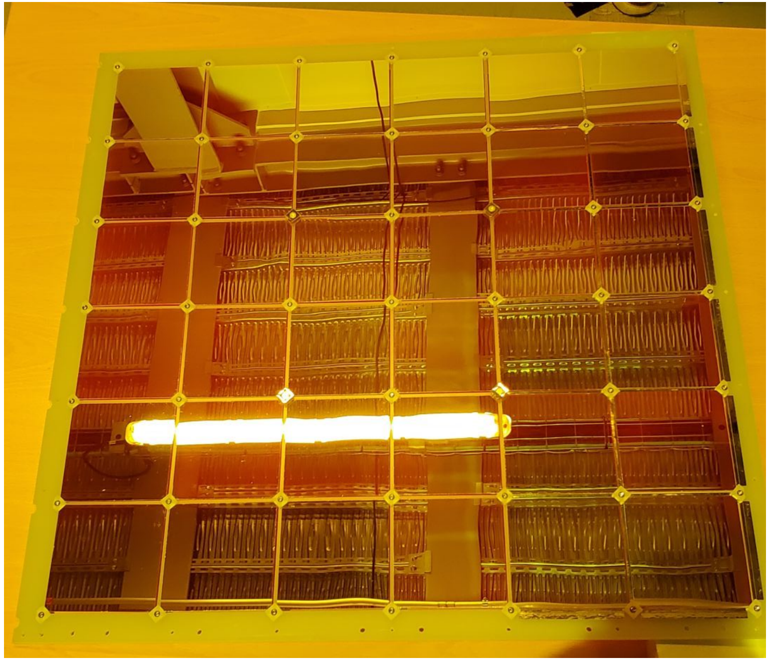
Photon Detection system - PDS

- Detecting 127 nm light is challenging. Besides, HD and VD requires that the photon detectors must have no more than 2 cm in thickness

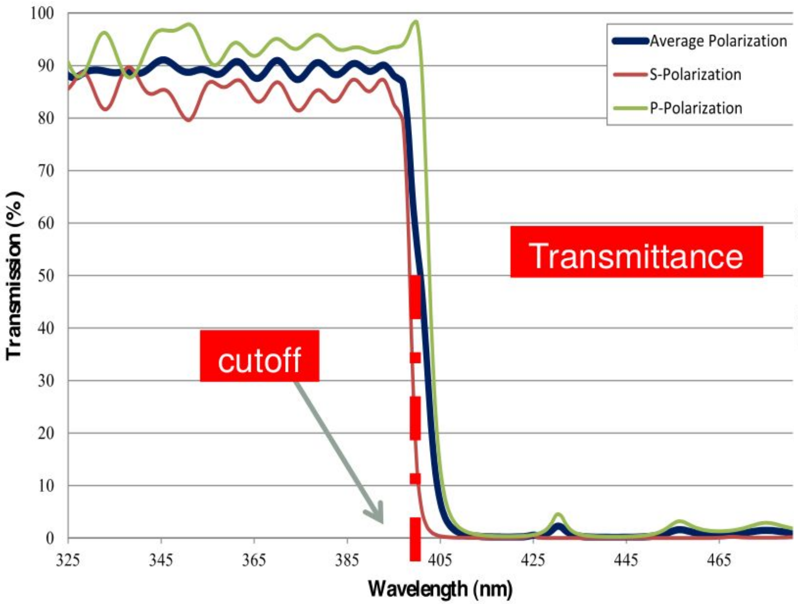


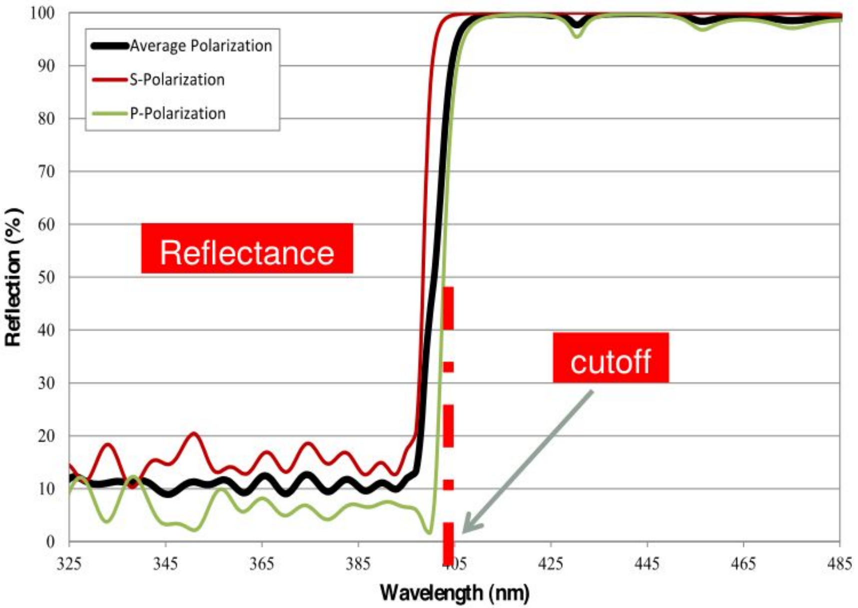






X-Arapuca - Working principle



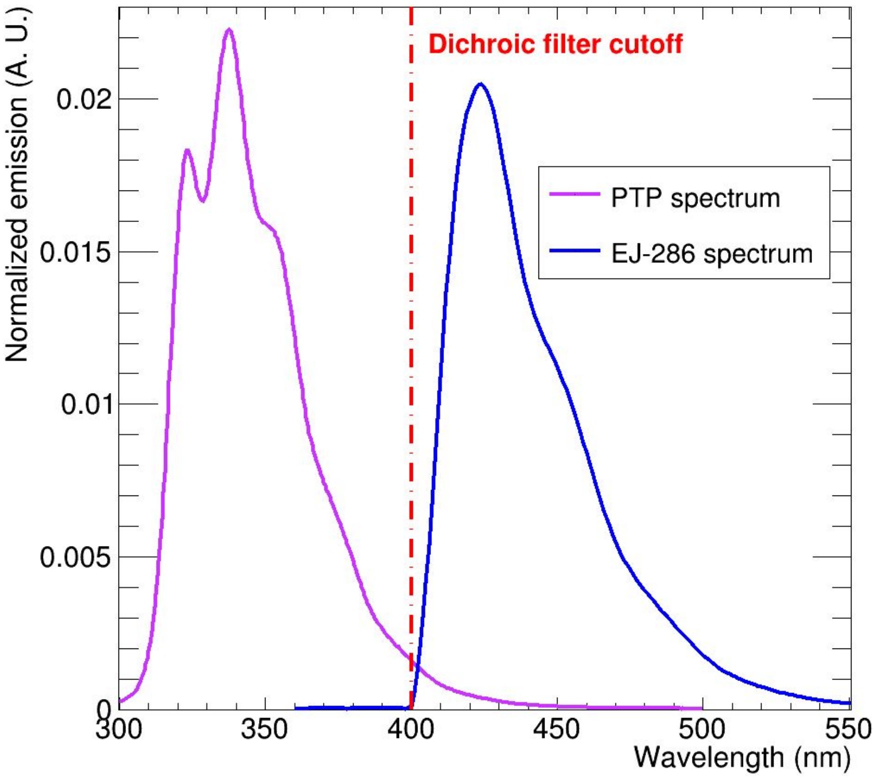


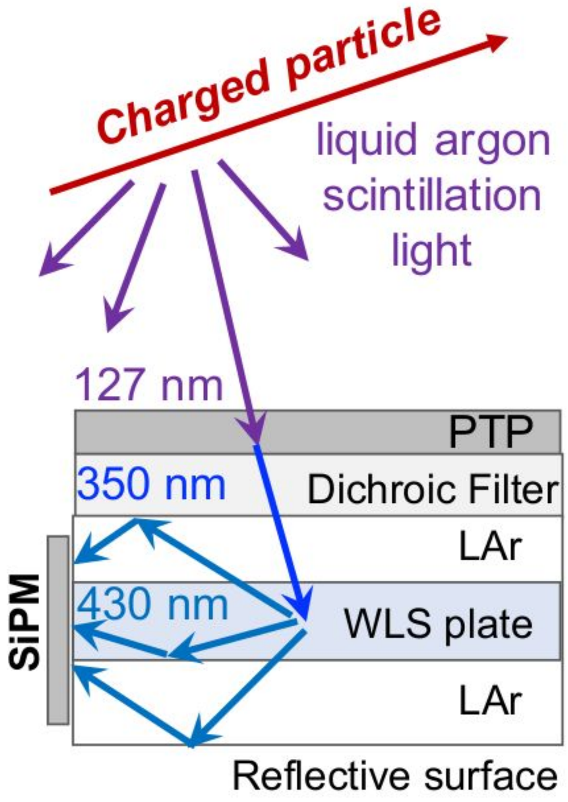
A.A. Machado and E. Segreto 2016 *JINST* **11** C02004

- The device makes use of a dichroic filter in combination with two wavelength shifters (WLS)

X-Arapuca - Working principle

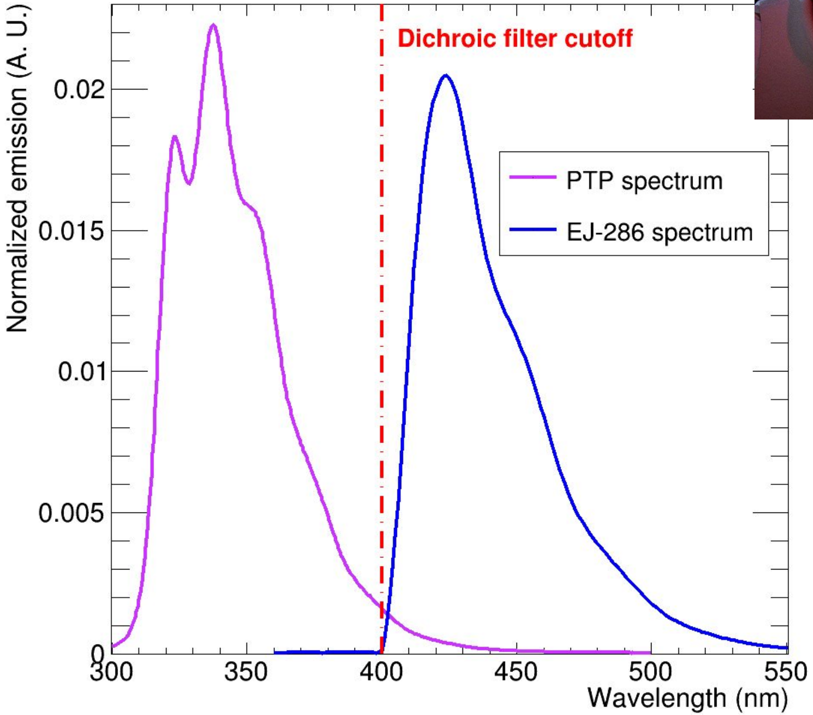
PTP → p-Terphenyl
SiPM → Silicon photomultiplier

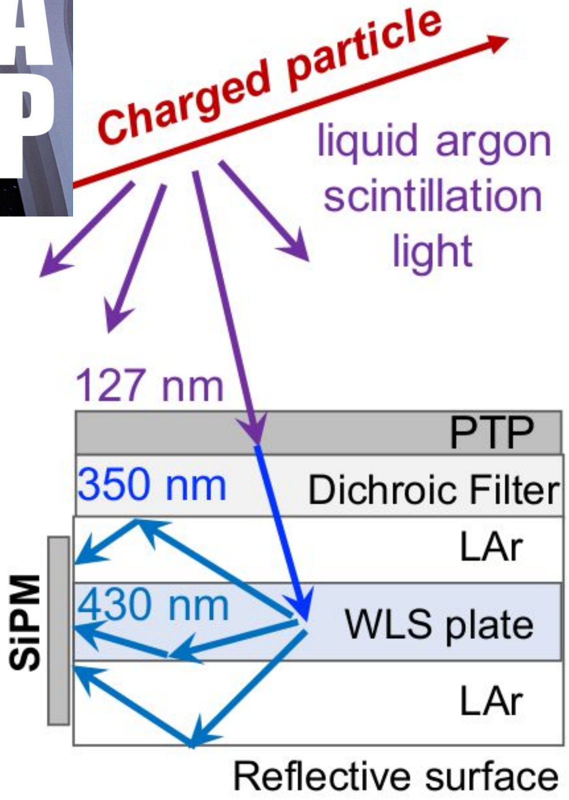




X-Arapuca - Working principle

PTP → p-Terphenyl
SiPM → Silicon photomultiplier



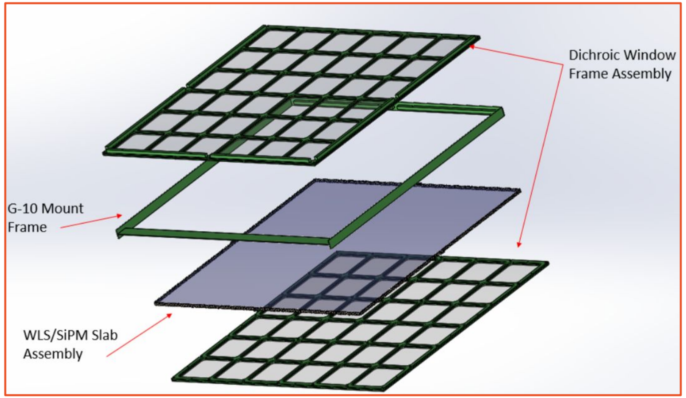


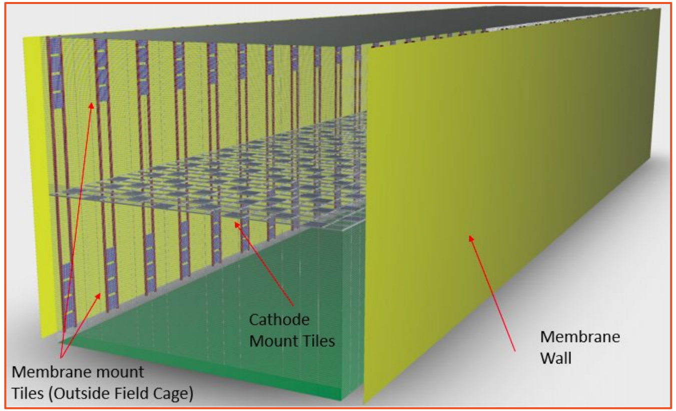
Photon Detection system - PDS

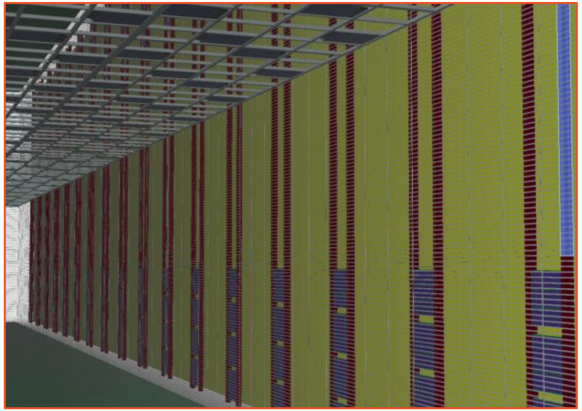
- The PDS is based on the X-Arapuca device

- A total of 2 x 80 Silicon Photomultipliers (SiPMs) per module
- 2x36 dichroic filters coated with pTP

- These devices are installed on the Cathode at -300 kV
    - Power supply and signal must be transmitted over non-conducting materials (not this talk)



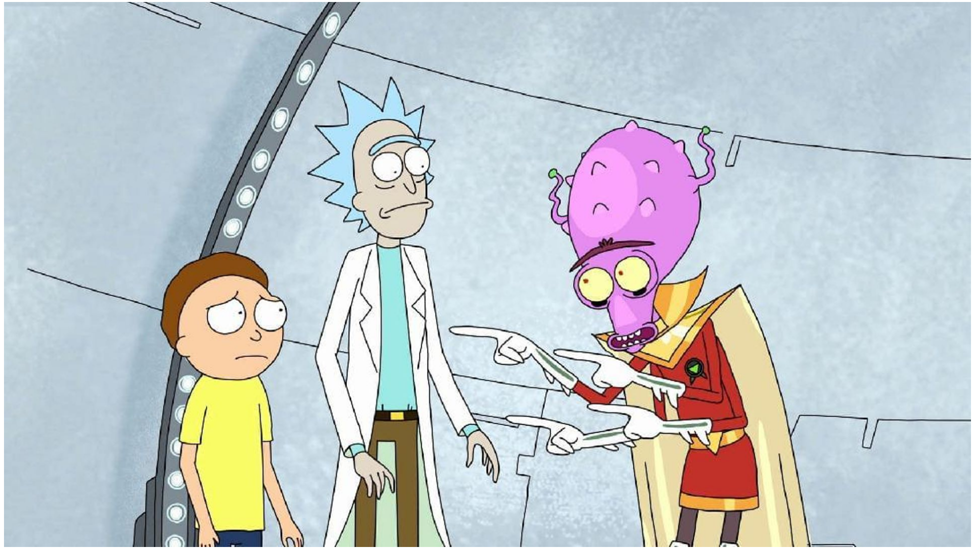




Simulation

- What about the simulation?

- It takes into account everything said up to here:
    - Emission spectrum
    - Time response
    - Scintillation yield
    - Propagation
    - Detection

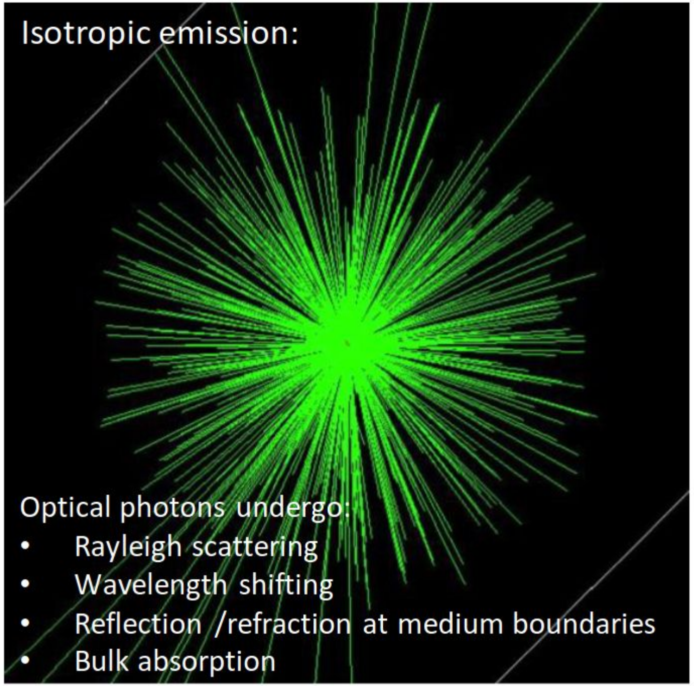


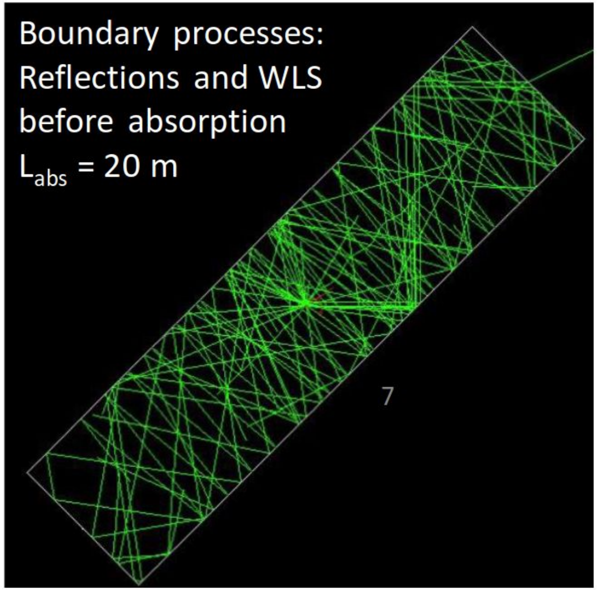
Simulation

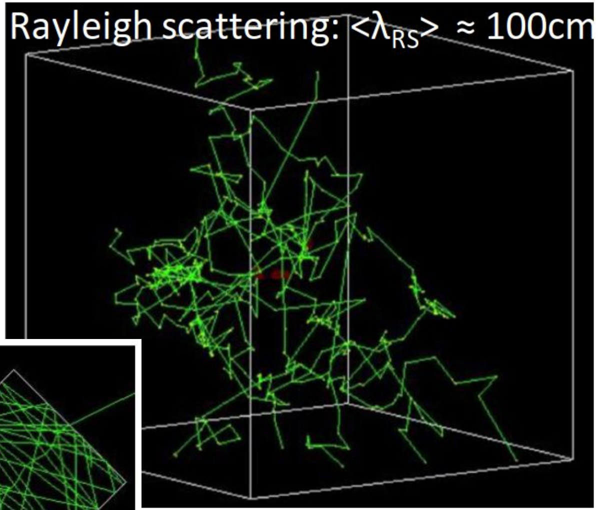
- Different modes of simulation
  - Full optical simulation (extremely slow)
    - Requires definition of all optical properties
  - Fast optical simulation (faster, but less precise)
    - Still need to run full optical at least once
    - Majority of optical properties "burned in"
    - Semi-analytic and optical library

- Brief description of LArSoft output

Full optical light simulation



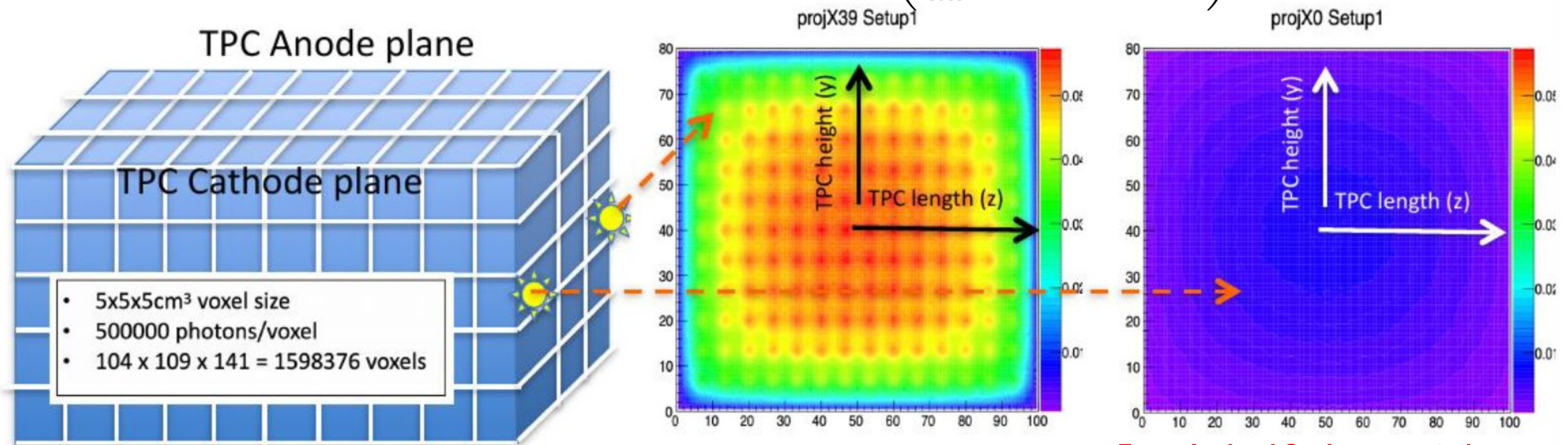




From Andrzej Szelc presentation

Fast optical model: Optical Library

$$\langle N \rangle_{\text{Det-hits}} = \left(\frac{dE}{dx} \times \text{Length}_{\text{step}} \right) \times \text{LY} \times \text{visibily}^{\text{Det}}_{\text{step}}$$

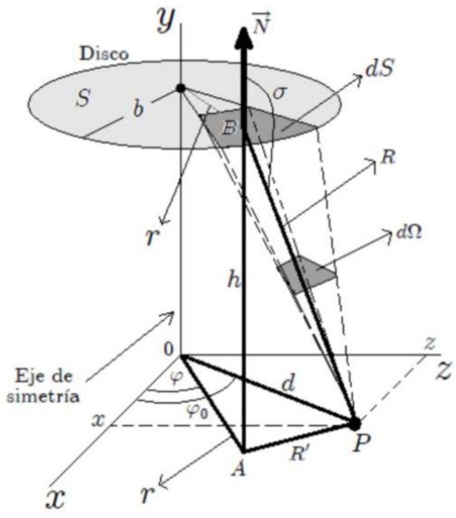


From Andrzej Szelc presentation

- Resolution depends on voxel sizes:
  - granularity effects at short distances
- Optical library size scales with detector size and number of photon detectors
  - Difficult to get working in DUNE

Fast optical model: Semi-Analytic

From Andrzej Szelc presentation



$$\Omega = h \int_0^{2\pi} \int_0^{b} \frac{r}{[h^2+r^2+d^2-2rd\,\mathrm{Cos}(\varphi_o-\varphi)]^{3/2}} dr d\varphi$$

Eur. Phys. J. C 81, 349 (2021)

- Given a dE/dx in a point (x, y, z) we want to predict the number of hits in our optical detector (x_i, y_i, z_i)
- Isotropic scintillation emission makes the problem "almost" geometric

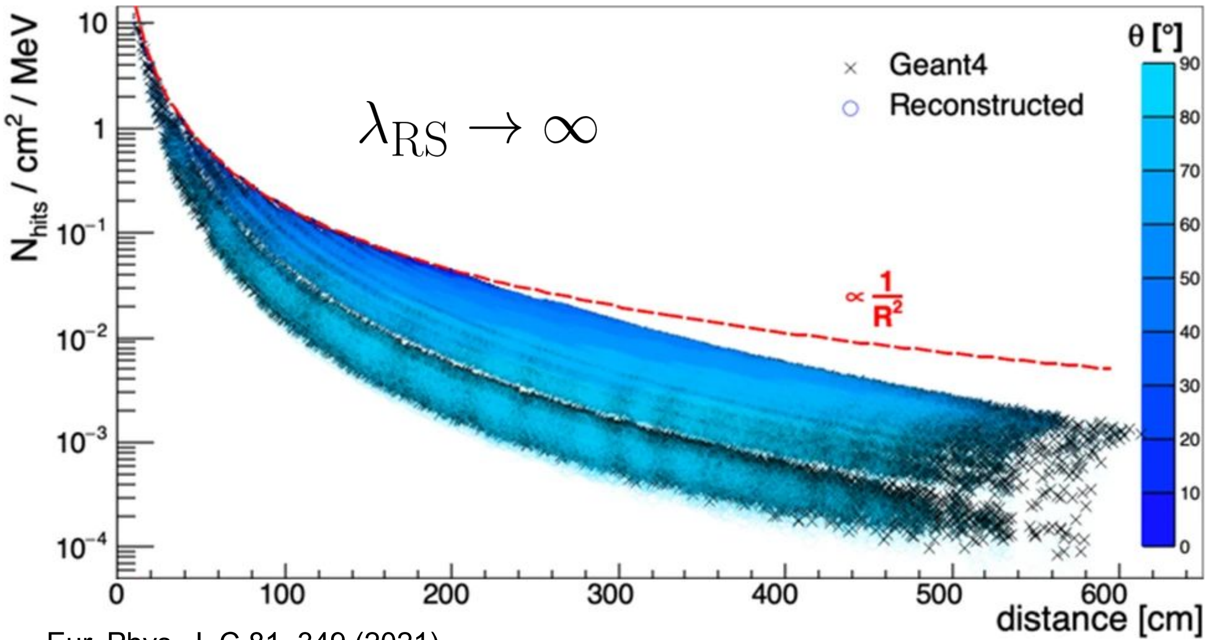
$$N_\Omega = e^{-\frac{d}{\lambda_{\rm abs}}} \times \Delta E \times S_\gamma(\mathcal{E}) \times \frac{\Omega}{4\pi}$$

$\lambda_{\rm abs}$ = LAr absorption

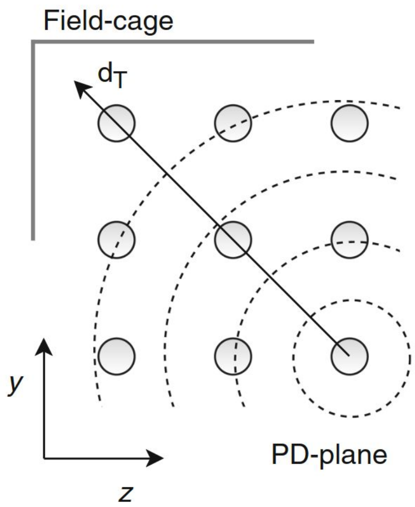
$S_\gamma(\mathcal{E})$= Scintillation Yield as function of electric field

ΔE = Energy deposited

Fast optical model: Semi-Analytic



Eur. Phys. J. C 81, 349 (2021)



In the DUNE-like geometry, energy depositions are spaced in approximately 25 cm steps in the drift direction and 100 cm steps in d_T

λ_{abs} = LAr absorption

$S_\gamma(\mathcal{E})$= Scintillation Yield as function of electric field

ΔE = Energy deposited

$$N_\Omega = e^{-\frac{d}{\lambda_{abs}}} \times \Delta E \times S_\gamma(\mathcal{E}) \times \frac{\Omega}{4\pi}$$

Fast optical model: Semi-Analytic

- Implementation of Rayleigh scattering
  - Correction using Gean4 simulation

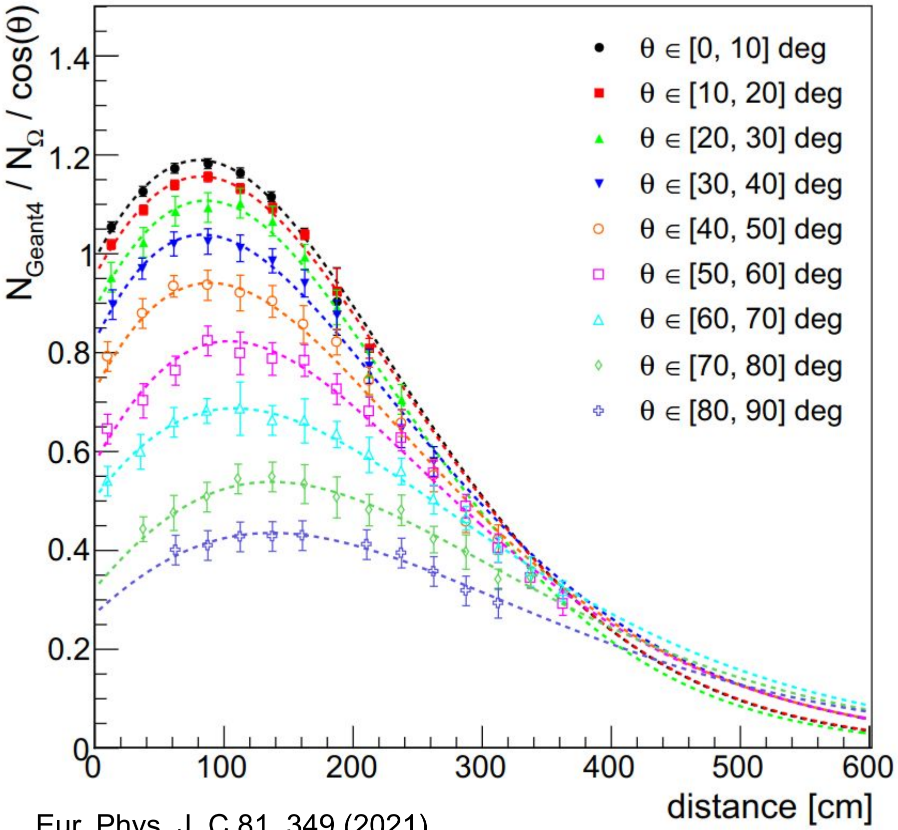
- Correction for detector size and geometry (not included here)

Gaisser–Hillas (GH) functions:

$$GH(d) = N_{\max} \left(\frac{d - d_0}{d_{\max} - d_0} \right)^{\frac{d_{\max} - d_0}{\Lambda}} e^{\frac{d_{\max} - d}{\Lambda}}$$

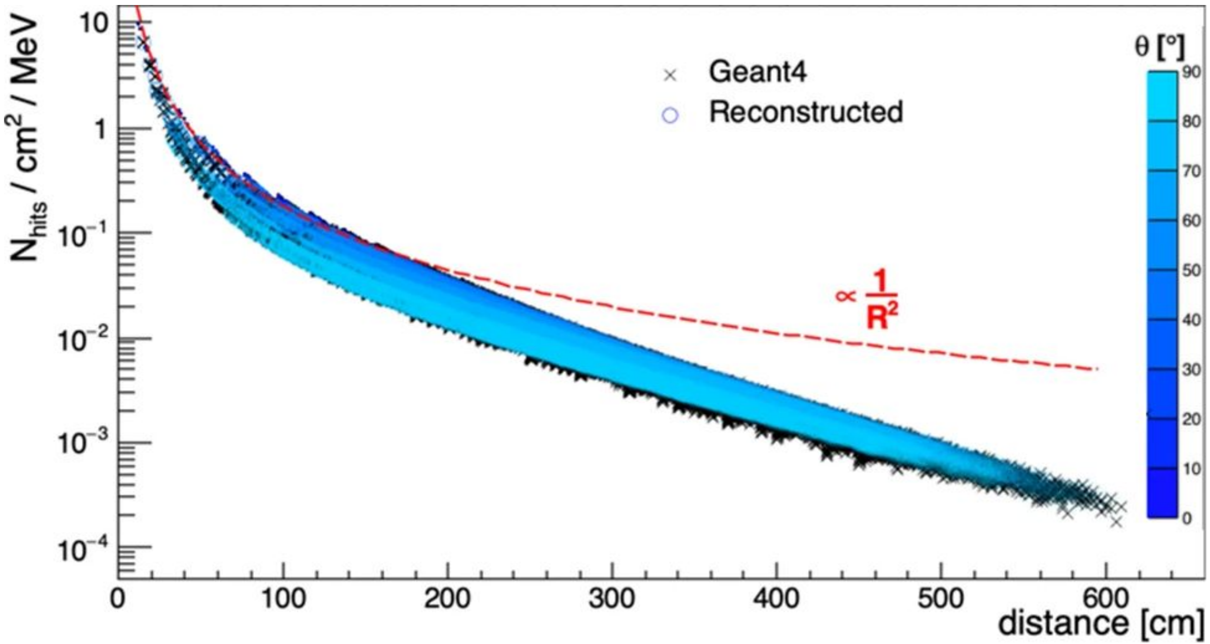
"where N_{max} is the maximum of the function located at a distance d_{max}, and d_0 and Λ are parameters describing the width of the distribution"

$$N_\gamma = N_\Omega \times GH'(d, \theta, d_T)/cos(\theta)$$



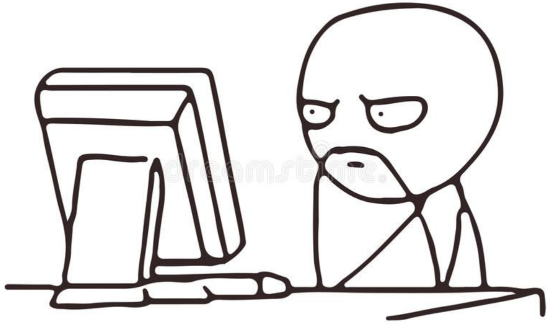
Eur. Phys. J. C 81, 349 (2021)

Fast optical model: Semi-Analytic



Eur. Phys. J. C 81, 349 (2021)

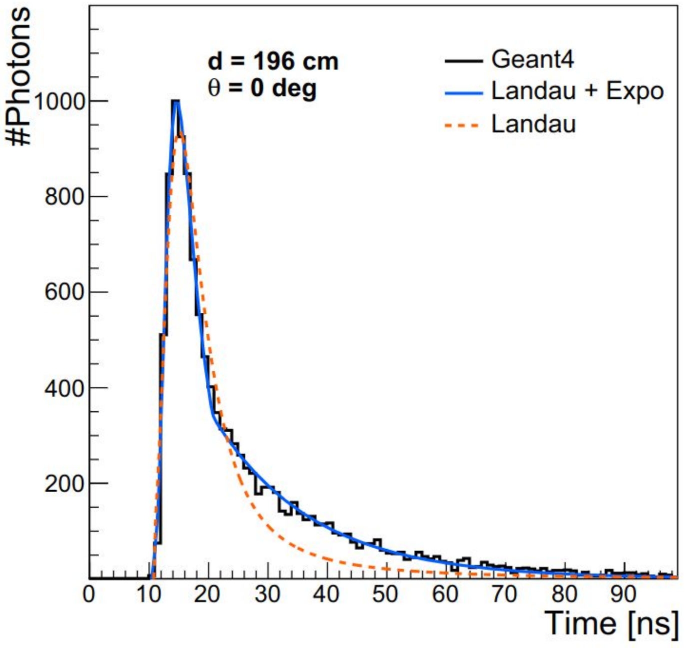
One thing is still missing



$$N_\gamma = N_\Omega \times GH'(d, \theta, d_T)/cos(\theta)$$

Time structure of detected signals

Eur. Phys. J. C 81, 349 (2021)



Example of the distribution of direct photons arrival times due to only transport effects

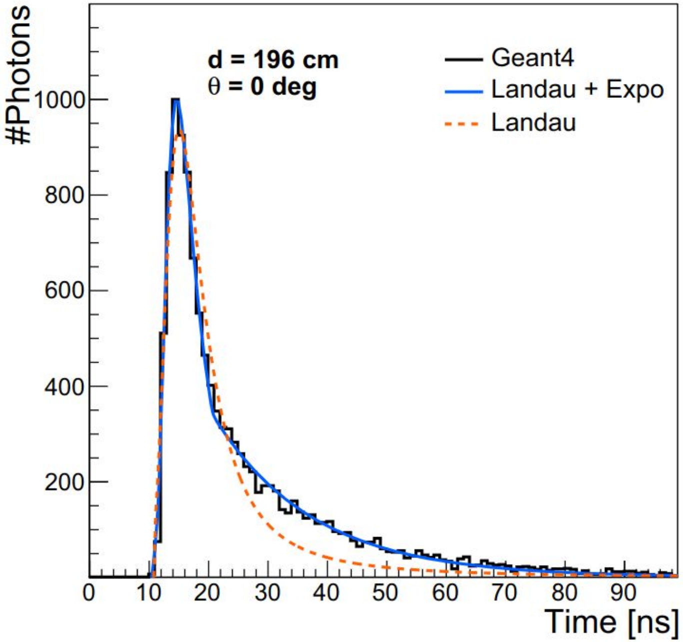
- Empirically described by a Landau and exponential for all emission points

$$t_t(x) = \underbrace{N_1 \frac{1}{\xi} \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} e^{\lambda s + s \log s}\, ds}_{Landau} + \underbrace{N_2\, e^{\kappa\, x}}_{Exponential}$$

“where λ = x−μ/ξ , with μ and ξ commonly referred as the landau most probable value and width parameters respectively, κ is the slope of the exponential and N1 and N2 are normalisation constants.”

Time structure of detected signals

Eur. Phys. J. C 81, 349 (2021)



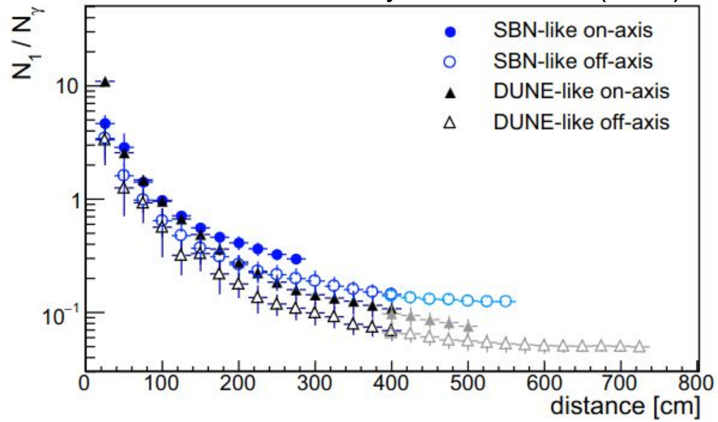
$$t_t(x) = \underbrace{N_1 \frac{1}{\xi} \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} e^{\lambda s + s \log s} \, ds}_{Landau} + \underbrace{N_2 \, e^{\kappa \, x}}_{Exponential}$$

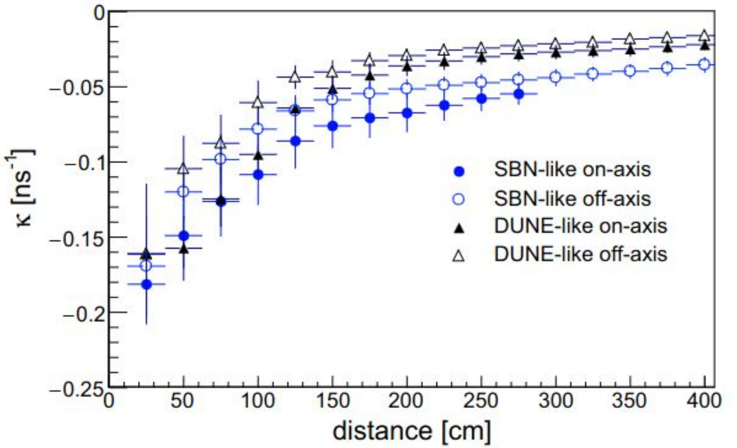
- [0, 45] on-axis

- [45, 90] off-axis

- Lighter grey and blue points are landau only approach

Eur. Phys. J. C 81, 349 (2021)

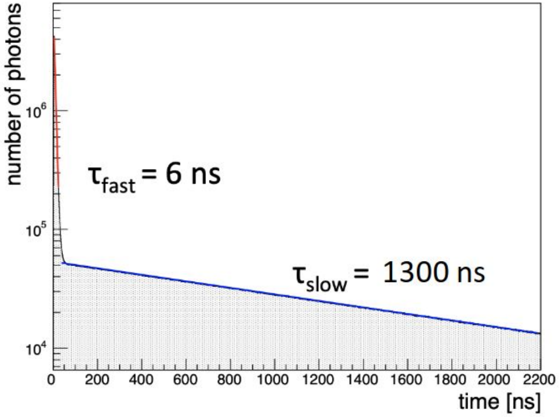




Time structure of detected signals

Scintillation (emission):

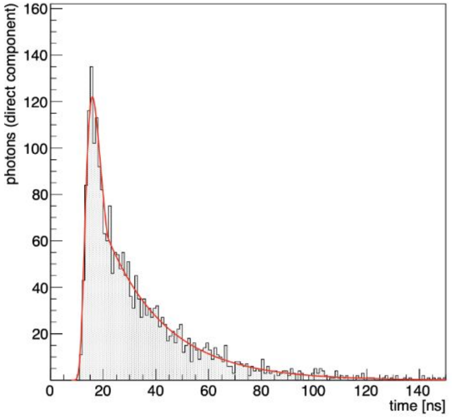
$0.3 \times \tau_{fast}(6\text{ ns}) + 0.7 \times \tau_{slow}(1300\text{ ns})$



+

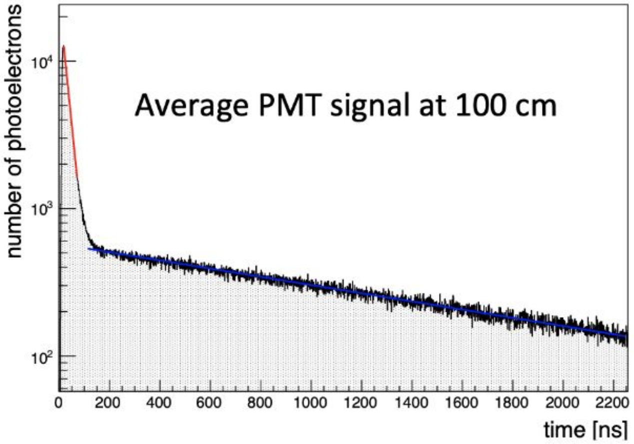
Propagation:

Direct transportation + Rayleigh Scattering



=

From Andrzej Szelc presentation

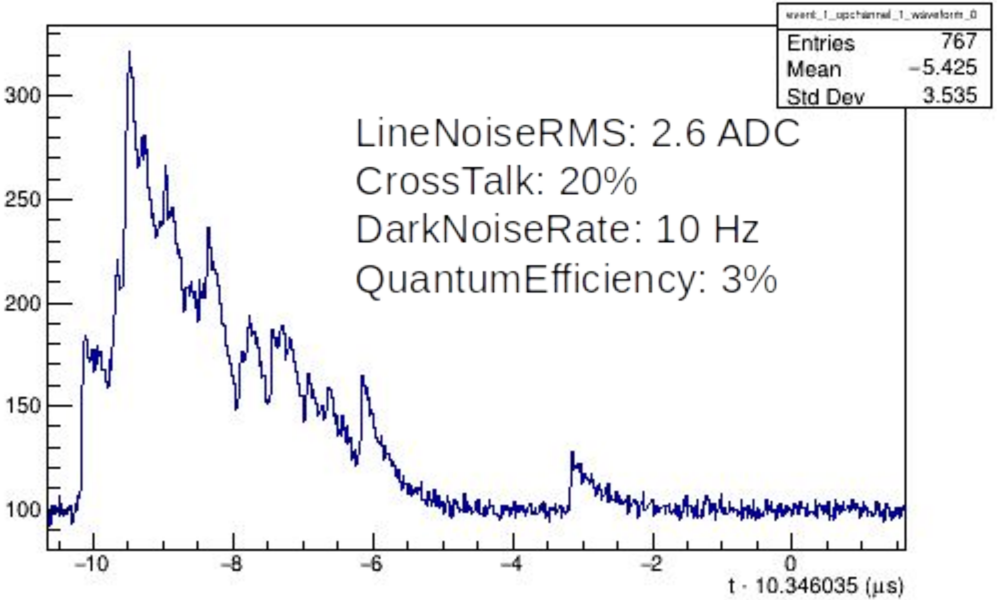


- The final time response of the detector will take into account:
  - Emission time
  - Propagation time

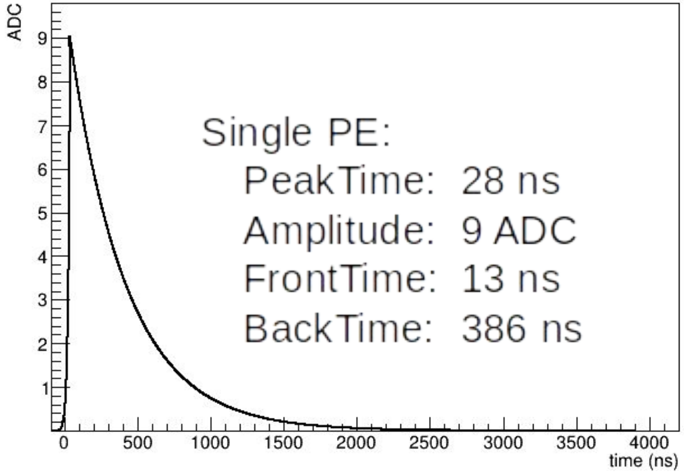
  - Wavelength shifter delay
  - Detector time

Time structure of detected signals

Time histogram of photons at each PD → Detector simulation → Simulated data



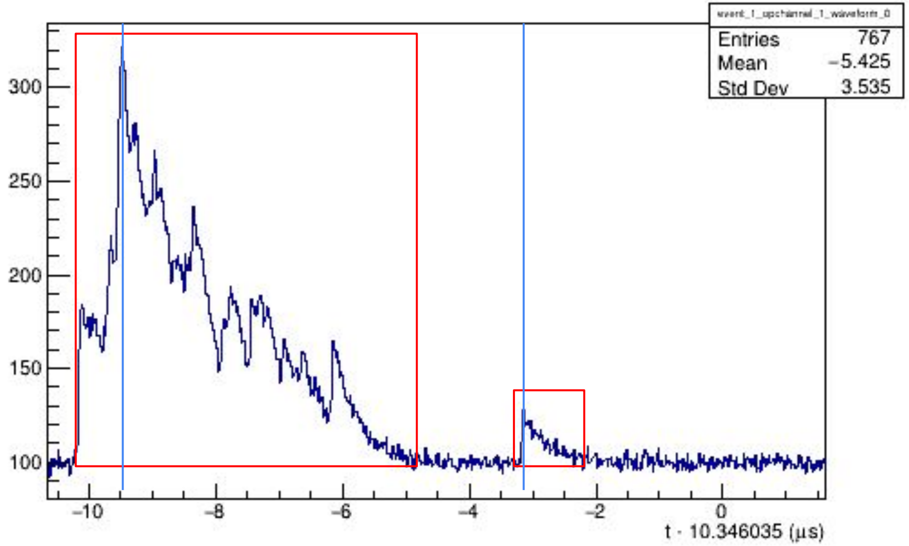
Courtesy of Laura Paulucci



Larsoft output

Reconstruction of events

Simulated data → **Reconstruction**



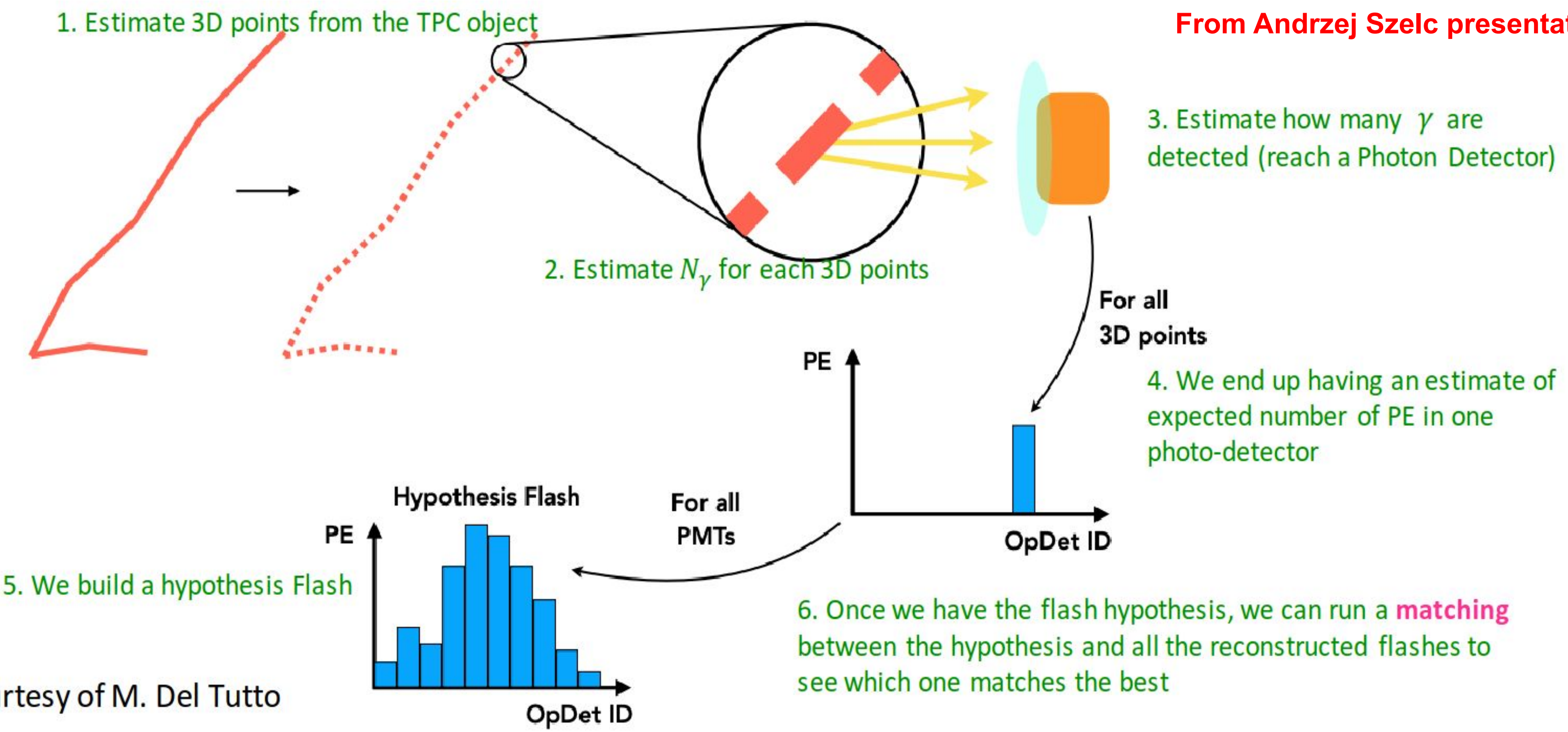
Courtesy of Laura Paulucci

Hit finding:

searches for peaks on individual waveforms channel-by-channel, identifying the time and the total amount of PEs

Reconstruction of events

From Andrzej Szelc presentation



Courtesy of M. Del Tutto

Analysis

- Where you can find some actual data
- The structure of this data
- Some of the main analysis performed up to now

Some actual data

- Since Dec. 2021 we have been collecting data with the coldbox.
    - Unfortunately, one need to understand the setup by asking / tracing back old slides as the configuration changed quite often there
    - Besides, there was no simulation implemented for the coldbox and, at this point, Module-0 will soon enough collect data to be analyzed.
        - However if anyone interest, please let me know :D
    - Nevertheless, the data of past coldbox runs can be found in lxplus: /eos/experiment/neutplatform/protodune/experiments/ColdBoxVD
    - I will quickly show how the data was collected and the main analysis up to now (if there is time hehe)
- Future data of Module-0
    - Where? Don't know
    - Format? Probably binary in similar way of what I am going to show now

Some actual data

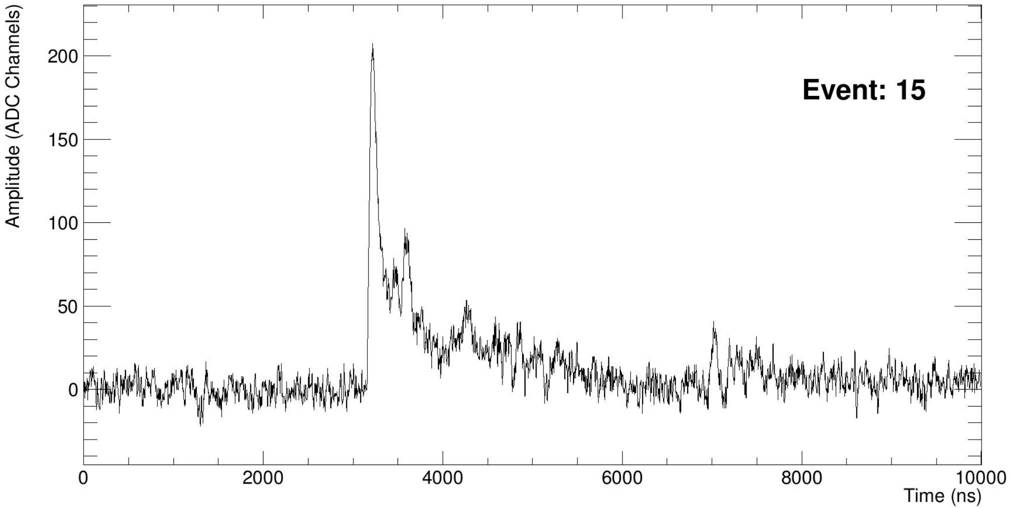
Data acquisition done with CAEN Digizer DT5730SB (2 Vpp 14 bits 250* MS/s):

- Data stored at lxplus:

  /eos/experiment/neutplatform/protodune/experiments/ColdBoxVD/

- To access data, please, register in the np-comp e-group:

  https://e-groups.cern.ch/e-groups/EgroupsSearchForm.do



Data format

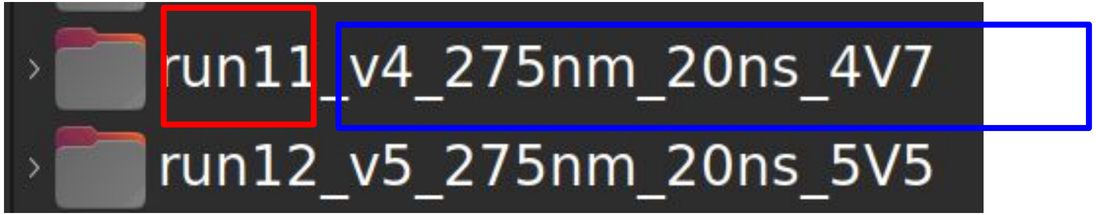
20220615_LED_calibration_cathode_off

run11_v4_275nm_20ns_4V7
run12_v5_275nm_20ns_5V5

Run folder with brief description
(README file available)

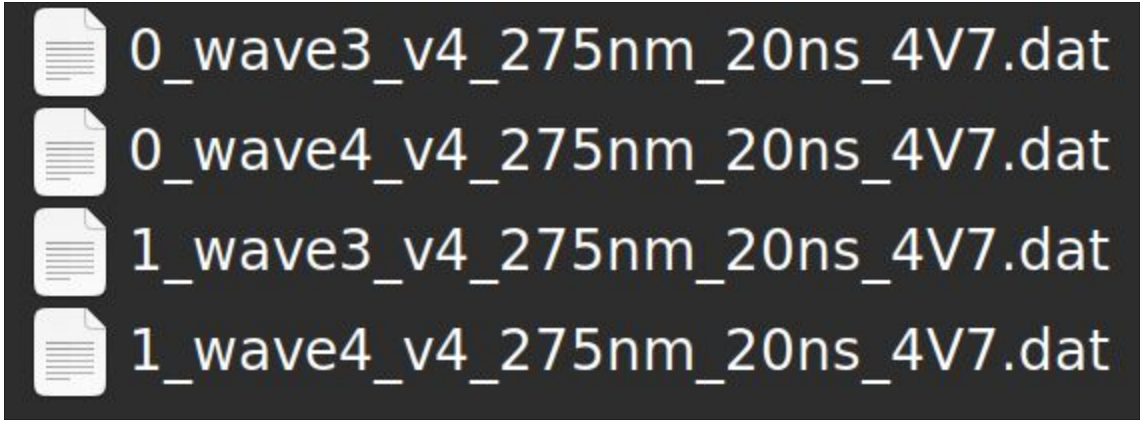
0_wave3_v4_275nm_20ns_4V7.dat
0_wave4_v4_275nm_20ns_4V7.dat
1_wave3_v4_275nm_20ns_4V7.dat
1_wave4_v4_275nm_20ns_4V7.dat

Data format



Run number, it refers to the order in which data were taken

Some block of information relevant for that specific run.
A README file helps to understand this block of information



Data format

20220615_LED_calibration_cathode_off

run11_v4_275nm_20ns_4V7
run12_v5_275nm_20ns_5V5

0_wave3_v4_275nm_20ns_4V7.dat
0_wave4_v4_275nm_20ns_4V7.dat
1_wave3_v4_275nm_20ns_4V7.dat
1_wave4_v4_275nm_20ns_4V7.dat

X_waveY

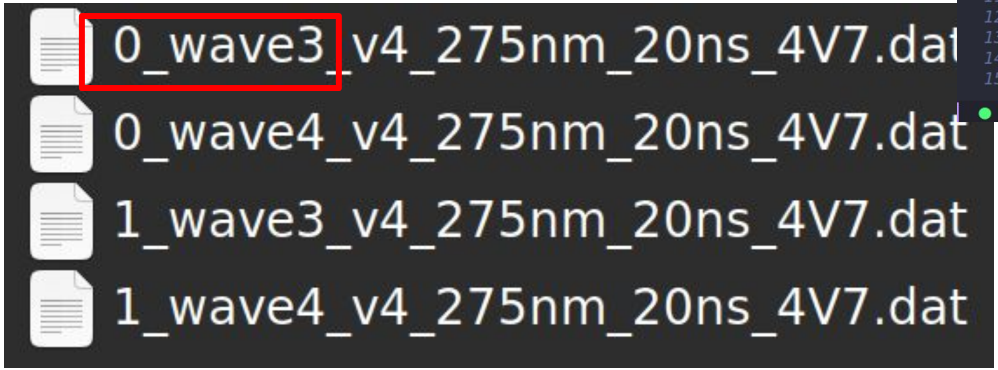
X are subruns with 10k events each
Y is the channel number

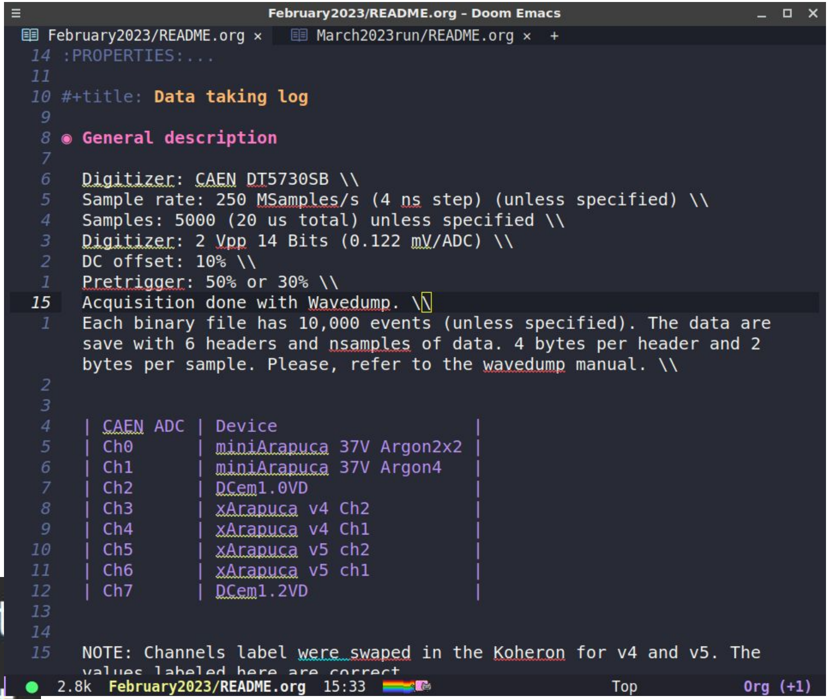
Data format

Example:
wave0: xArapuca A4ch2 (light blue fiber)
wave1: xArapuca A1ch1 (white fiber)
wave2: miniArapuca A4ch1 (green fiber)
wave3: miniArapuca A1ch2 (blue fiber)

X_waveY

X are subruns with 10k events each
Y is the channel number




February2023/README.org - Doom Emacs

February2023/README.org × March2023run/README.org × +

:PROPERTIES:...

#+title: **Data taking log**

* **General description**

Digitizer: CAEN DT5730SB \\
Sample rate: 250 MSamples/s (4 ns step) (unless specified) \\
Samples: 5000 (20 us total) unless specified \\
Digitizer: 2 Vpp 14 Bits (0.122 mV/ADC) \\
DC offset: 10% \\
Pretrigger: 50% or 30% \\
Acquisition done with Wavedump. \\
Each binary file has 10,000 events (unless specified). The data are save with 6 headers and nsamples of data. 4 bytes per header and 2 bytes per sample. Please, refer to the wavedump manual. \\

CAEN ADC	Device
Ch0	miniArapuca 37V Argon2x2
Ch1	miniArapuca 37V Argon4
Ch2	DCem1.0VD
Ch3	xArapuca v4 Ch2
Ch4	xArapuca v4 Ch1
Ch5	xArapuca v5 ch2
Ch6	xArapuca v5 ch1
Ch7	DCem1.2VD

NOTE: Channels label were swaped in the Koheron for v4 and v5. The values labeled here are correct

2.8k February2023/README.org 15:33 Top Org (+1)

Data format

Data is saved as binary (faster and lighter).
1 waveform consist of 6 headers and **n** samples

The HEADER is so composed (for all digitizer families except the 742 one):

4 bytes	<header0> Event Size (i.e. header + samples)
4 bytes	<header1> Board ID
4 bytes	<header2> Pattern (meaningful only for VME boards)
4 bytes	<header3> Channel
4 bytes	<header4> Event Counter
4 bytes	<header5> Trigger Time Tag
N * 2 bytes	<N samples>

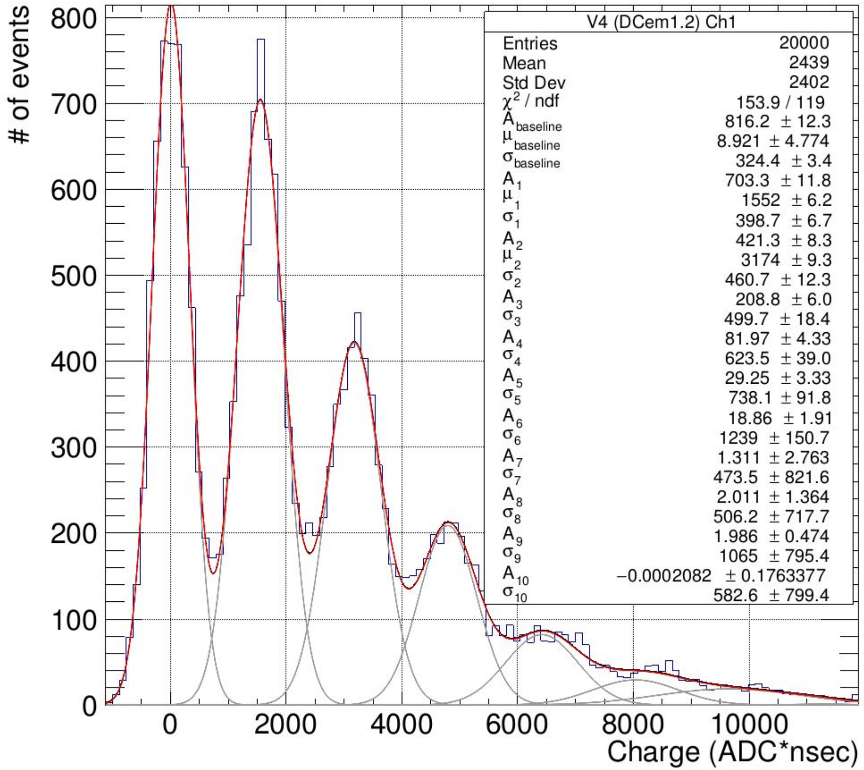
This number is given in bytes. So if we have 5000 samples, this number will be:

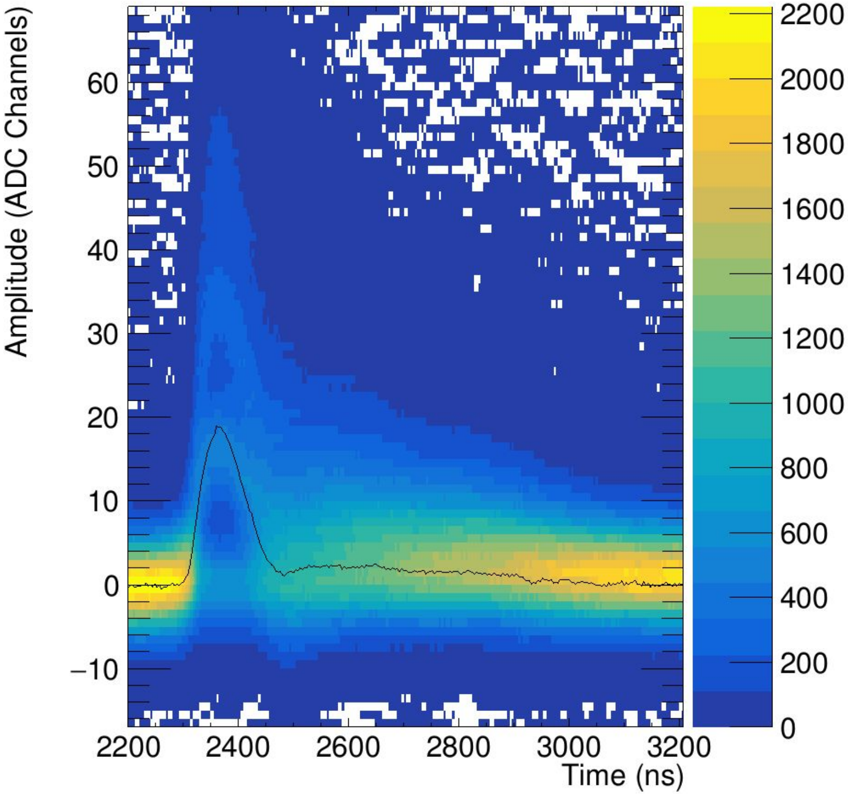
Headers = 24 bytes
+ samples = 5000*2
Total = 10024 bytes

Let me know if you need an example code to read the data with Root.

Main analysis up to now

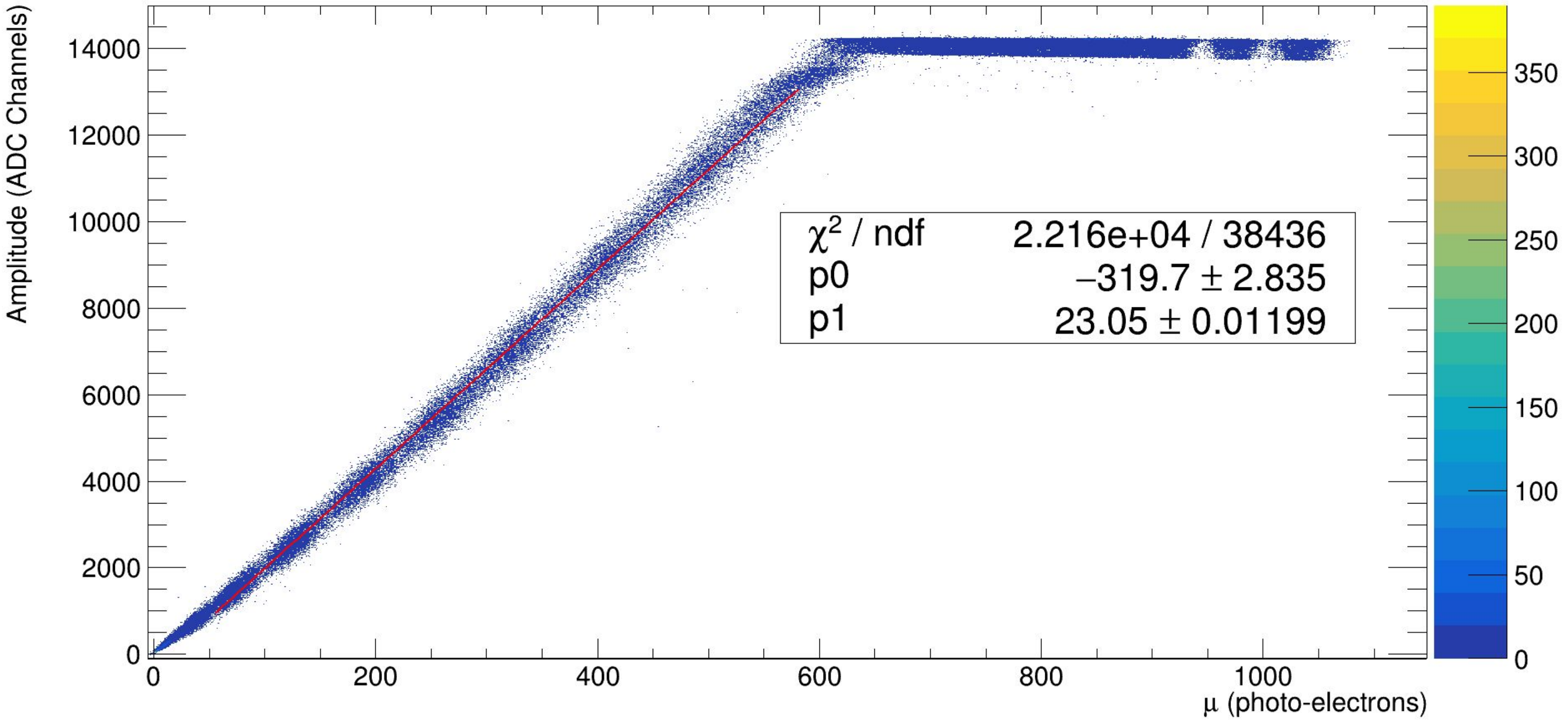
Single photo-electron (SPE): uses low intensity LED flashed of light to detect one or more photons. Which results in what we call `SPE spectrum`





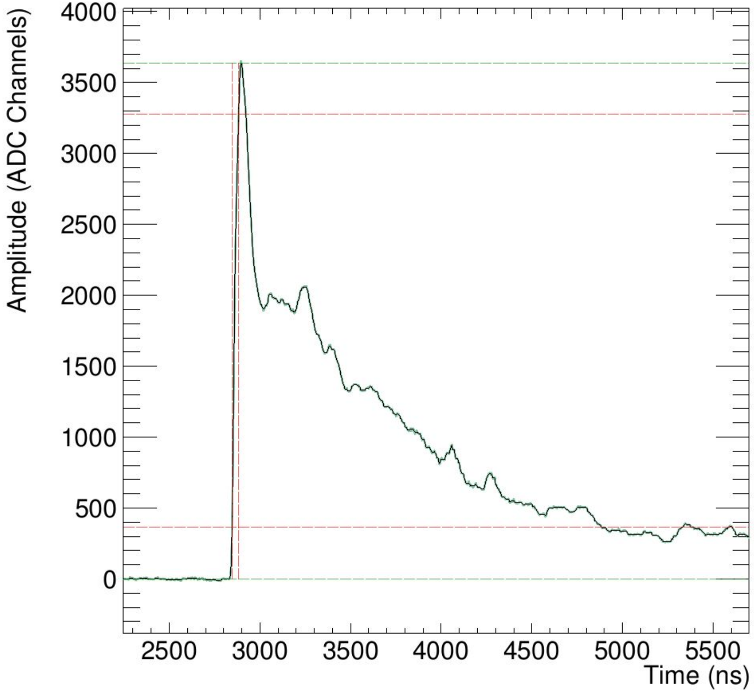
Main analysis up to now

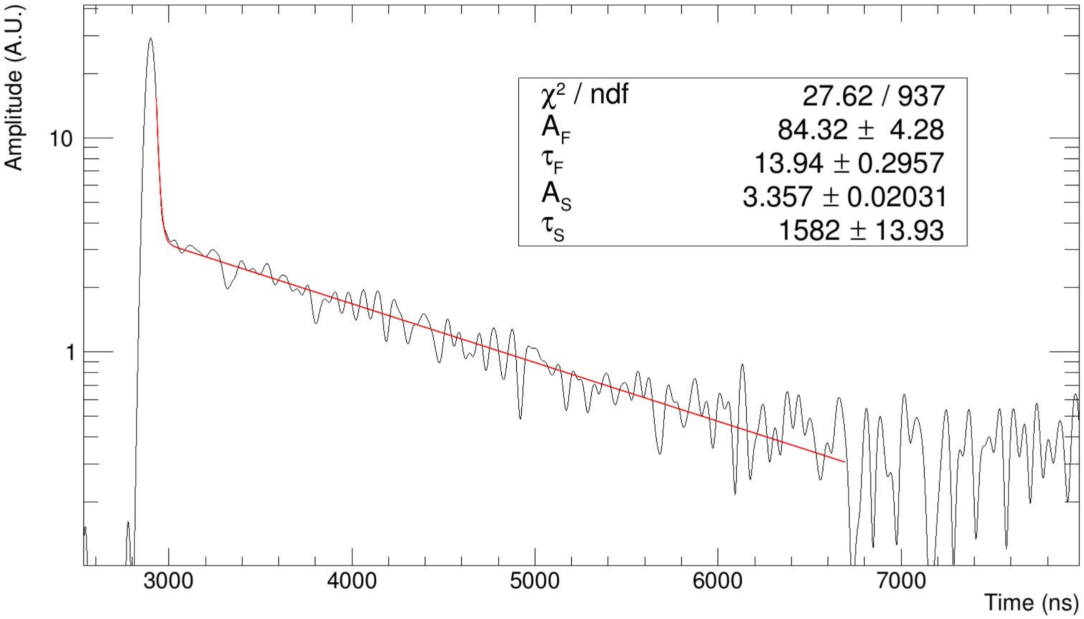
Linearity and dynamic range: uses LED to check linear behaviour of detector/electronics over the entire dynamic range of the device.



Main analysis up to now

Overall pulse shape: undershoot, overshoot, rise and fall time characterization of signals with LED and Cosmic (self-trigger data) data





If there is still time…

- Interesting past analysis with ProtoDUNE-SP

- Xenon doping

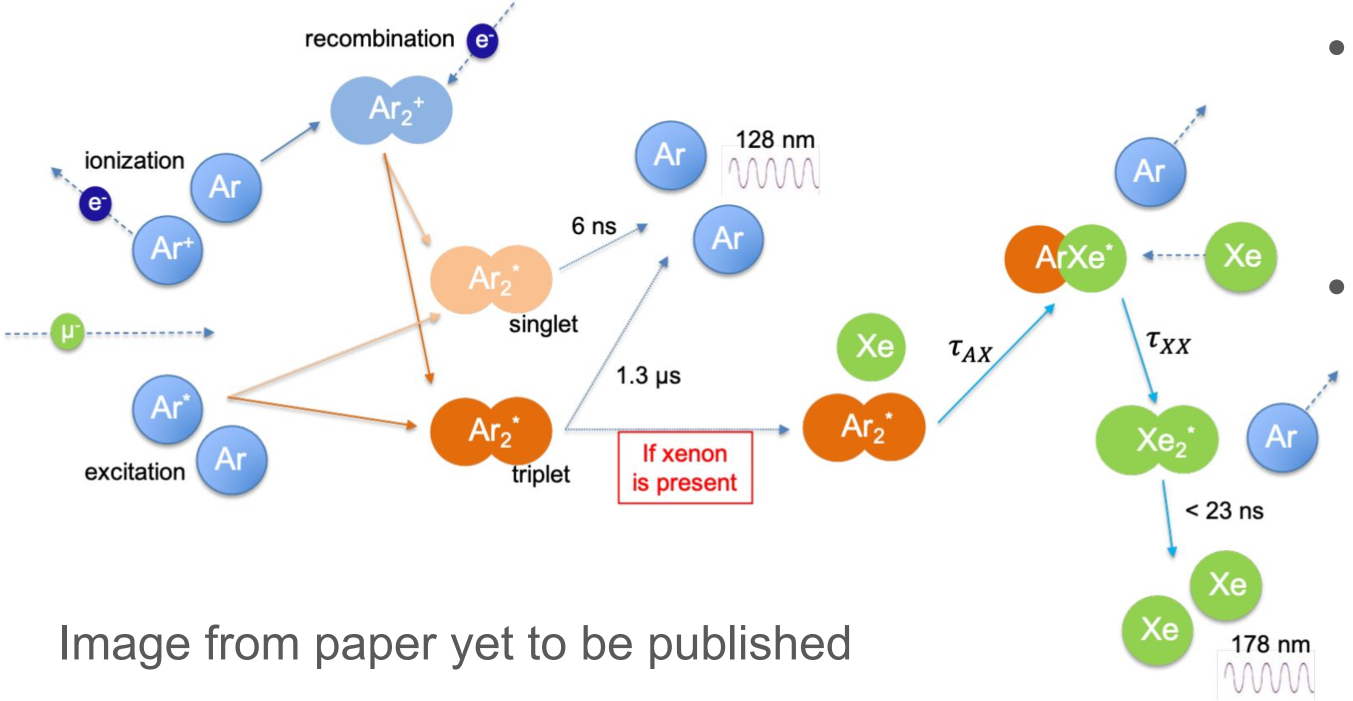
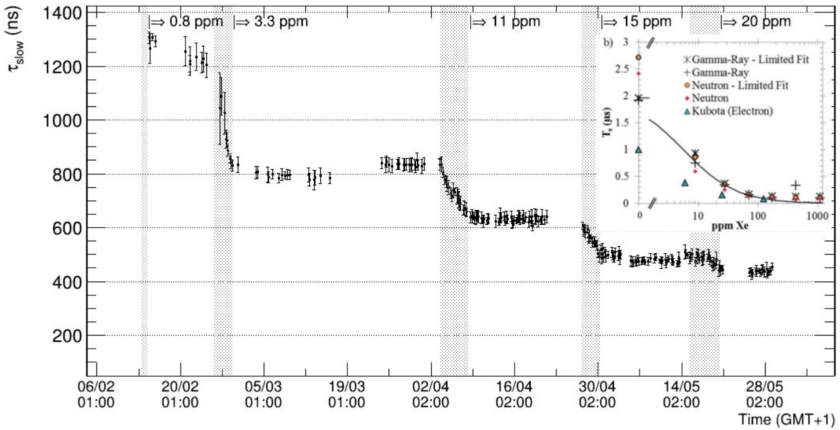


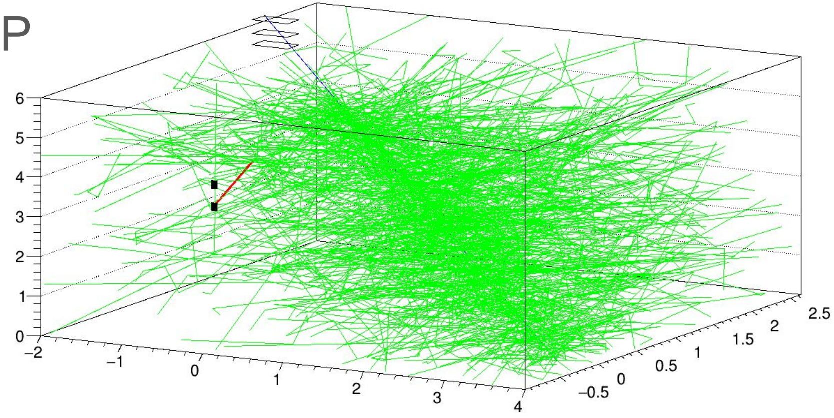
Image from paper yet to be published

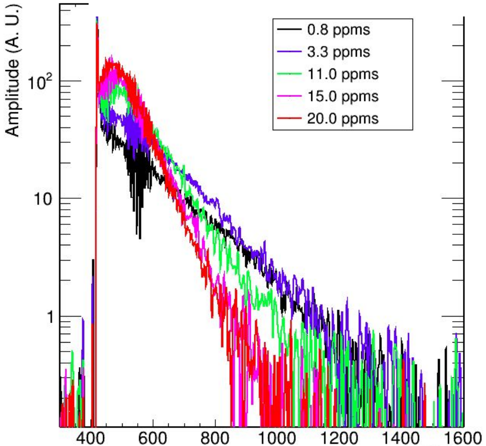
- Recover light that would be lost to nitrogen contamination
- Increase the wavelength of the photons:
  - Easier to detect
  - Higher Rayleigh scattering
- Possibly increase PID capability

If there is still time…

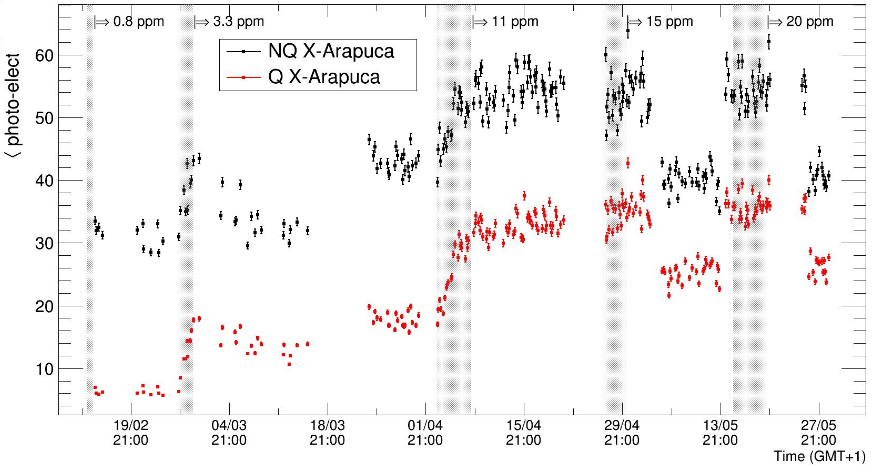
- Interesting past analysis with ProtoDUNE-SP





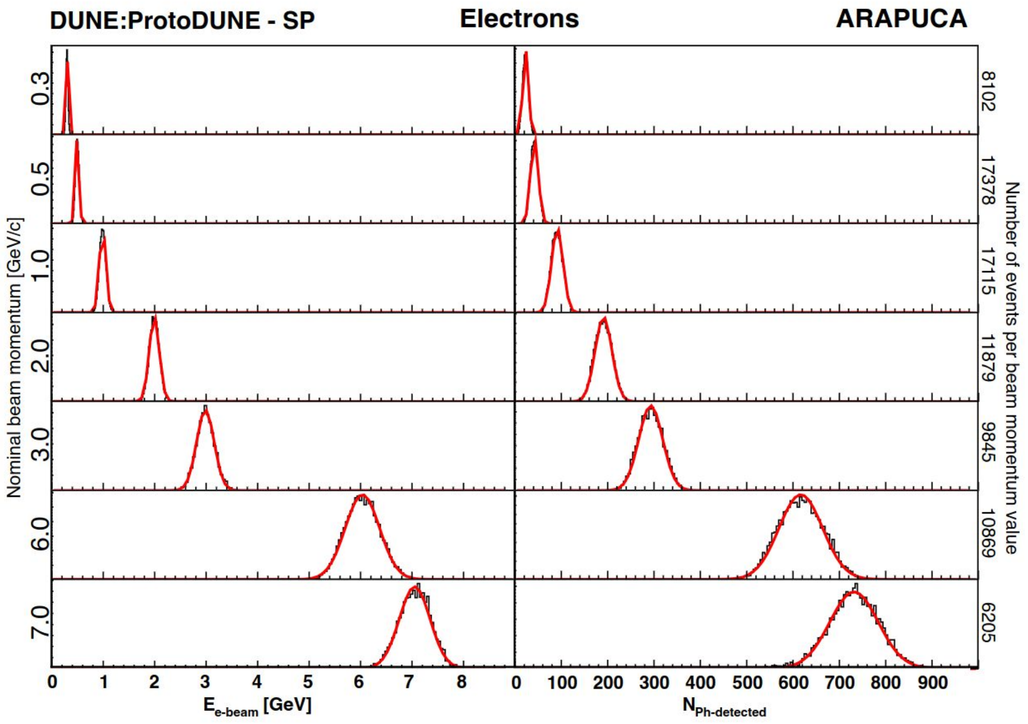


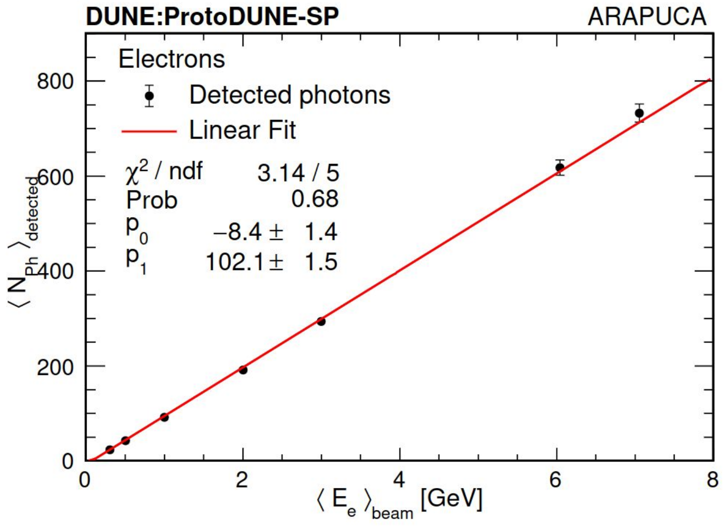
- Xenon doping



If there is still time…

- Interesting past analysis with ProtoDUNE-SP





B. Abi *et al* 2020 *JINST* **15** P12004

Thanks :D

Backup

Backup

- Estimating number of photons:

  Number of ionized atoms is proportional to the energy deposited (E_0) by the particle divided by the average energy expected per ion pair (W_I = 23.6 ± 0.3 eV):

  $$N_i = E_0 / W_l$$

  Assuming that all ionized and excited molecules will produce photons, we have:

  $$N_{ph} = N_i + N_{ex} = N_i \cdot (1 + N_{ex}/N_i) = E_0/W_l \cdot (1 + N_{ex}/N_i)$$

  And so:

  $$N_{ph} = \frac{E_0}{W_{ph}^{\min}} \quad \text{with} \quad W_{ph}^{\min} = \frac{W_l}{1 + N_{ex}/N_i} = 19.5 \pm 1.0 \text{ eV}$$

  So the maximum number of photons produced by MeV is simple 1MeV / 19.5 ~ 50×10^3 photons/MeV
  If you consider 0.8 factor for muons and 0.6 factor for Electric field, wth have the usual 24×10^3 photons/MeV

Backup

- Noble gas: electropositive and dielectric (low electron absorbance and high voltage allowed)
- High density
- High radiation length (allows good discrimination between electrons and photons and make it easier to retrieve neutrino vertex)
- Abundant in nature

https://arxiv.org/abs/2112.02967

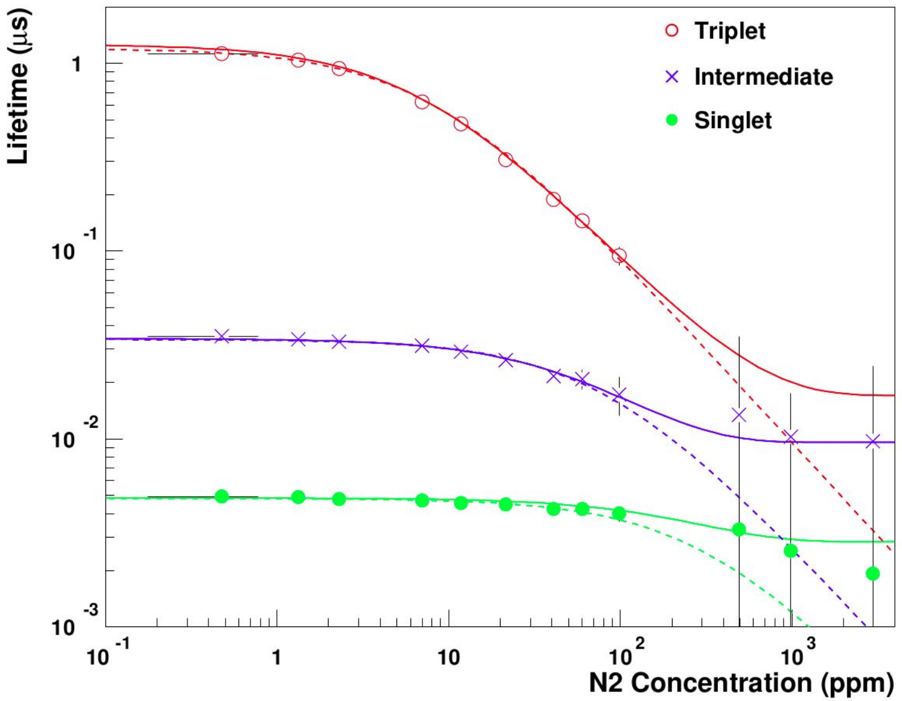
	Water	He	Ne	Ar	Kr	Xe
Boiling point [K] @ 1 atm	373	4.2	27.1	87.3	120	165
Density [g/cm^3]	1	0.125	1.2	1.4	2.4	3.0
Radiation length [cm]	36.1	755.2	24	14	4.9	2.8
Scintillation [γ/keV]	-	19	30	40	25	42
Scintillation λ [nm]	-	80	78	128	150	175
dE/dx [MeV/cm]	1.9	0.24	1.4	2.1	3.0	3.8
Abundance (Earth atm) [ppm]	25×10^3	5.2	18.2	9300	1.1	0.09
Electron mobility [cm^2/V·s]	-	<0.3	<0.01	~500	~1800	~2200

Backup

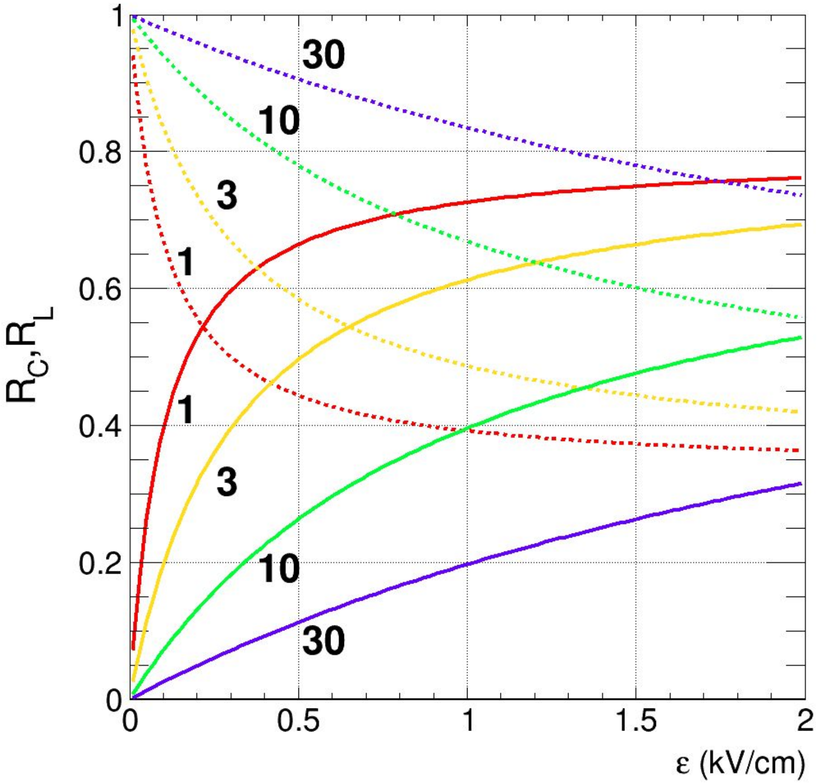
https://arxiv.org/abs/2112.02967

Mean energy loss (mip)	$\langle dE_{mip}/dx \rangle = 1.519$ MeV/(g/cm^2) [13]
Average energy for pair production (e^-, Ar^+)	$W_I = 23.6 \pm 0.3$ [45, 46]
Excited to ionized atoms ratio	$N_{ex}/N_i = 0.21$ [45, 48, 49]
γ emission spectrum	$\langle \lambda_{scint} \rangle = 127$ nm; $\sigma_{scint} \approx 3$ nm [57]
Decay time consntats	$\tau_S \sim 6$ ns; $\tau_T \sim 1600$ ns [37, 57]
Relative intensity	$A_S/A_T = 0.3$ for electrons and muons $= 1.3$ for alpha particles $= 3.0$ for neutrons [37, 59, 60]
Average energy for γ production	$W_{ph}^{min} = 19.5 \pm 1.0$ eV [45, 48, 49]
Light Yield [$\epsilon = 0$ V/cm] (ideal) [$\epsilon = 0$ V/cm] (mip) [$\epsilon = 500$ V/cm] (mip)	$Y_{ph}^{ideal} = 5.1 \times 10^4\ \gamma$/MeV $Y_{ph}^{mip} = 4.1 \times 10^4\ \gamma$/MeV $Y_{ph}^{mip} = 2.4 \times 10^4\ \gamma$/MeV [5, 48]
Rayleigh scattering length ($\lambda_{scint} = 127$ nm)	99.1 ± 2.3 cm [64]
Absorption length (for N_2 concentration < 5 ppm)	$L_A > 20$ m [65]
Refractive index	$n_{LAr} = 1.38$ [62]

Backup

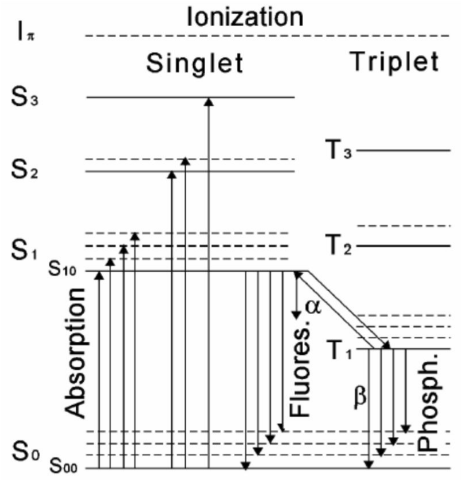


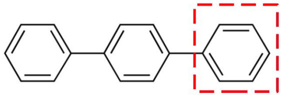
Triplet
Intermediate
Singlet
Lifetime (μs)
1
10 -1
10 -2
10 -3
10 -1
1
10
10 2
10 3
N2 Concentration (ppm)



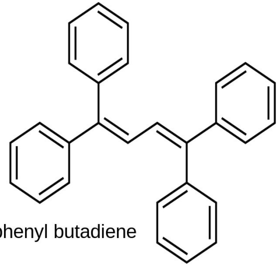
R_C,R_L
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
ε (kV/cm)
30
10
3
1
1
3
10
30

Backup

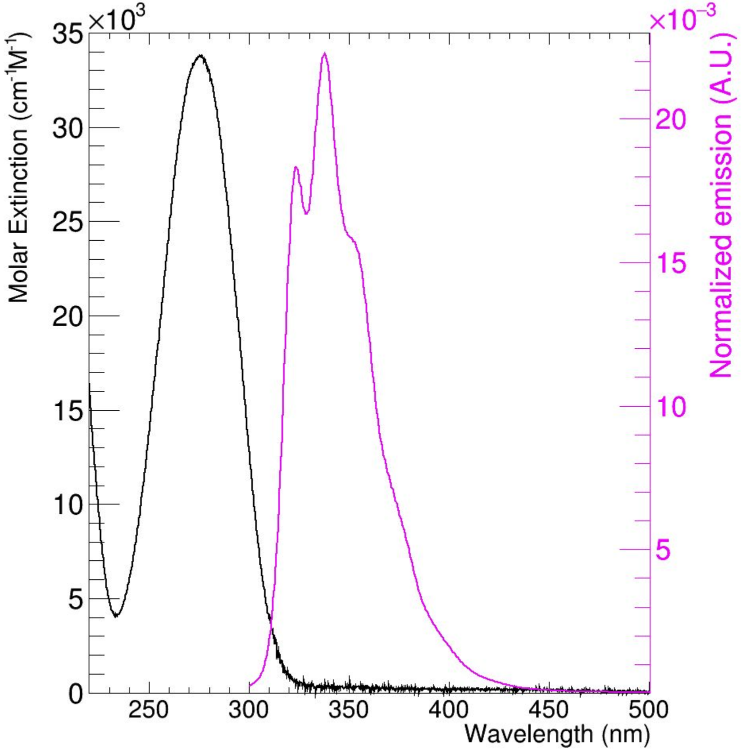


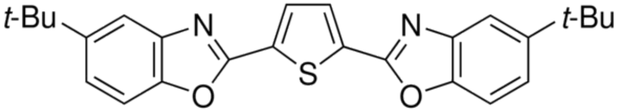


p-Terphenyl



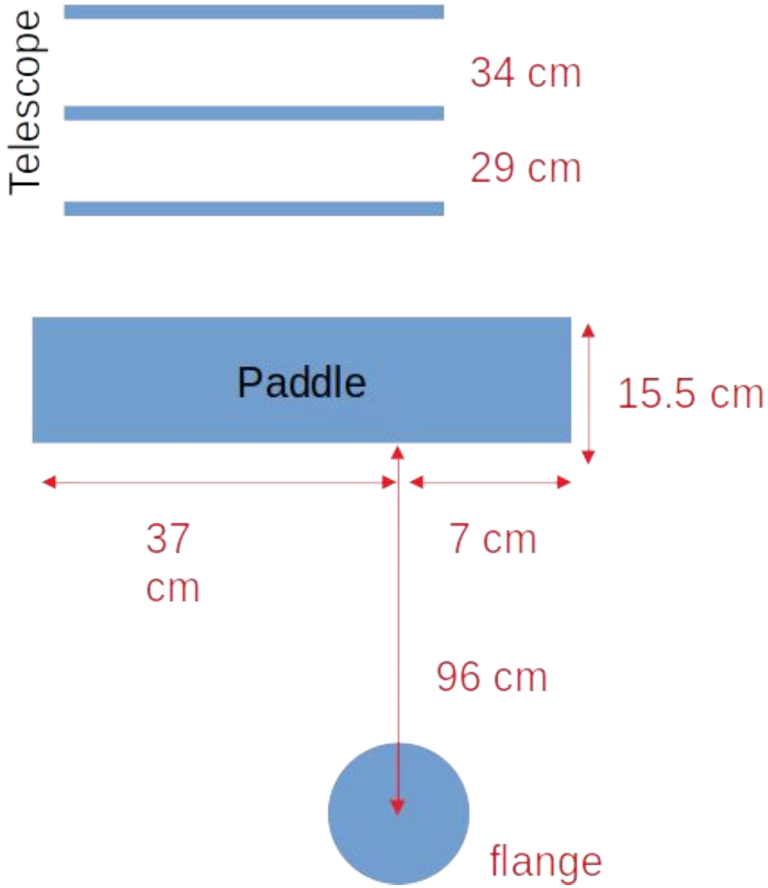
Tetra-phenyl butadiene

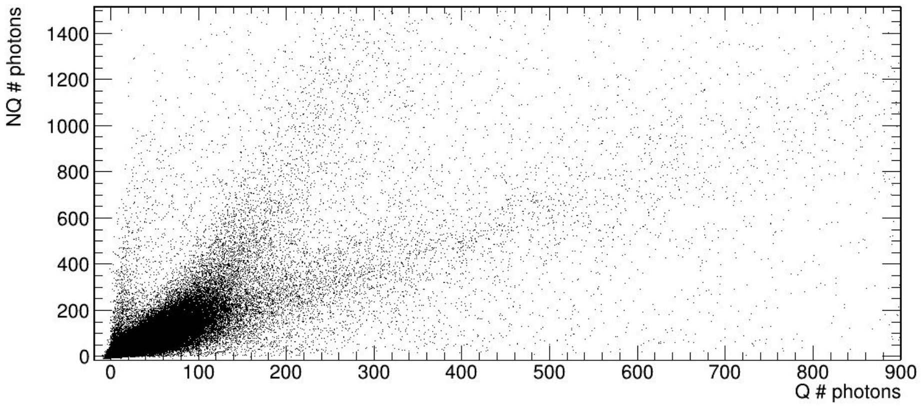


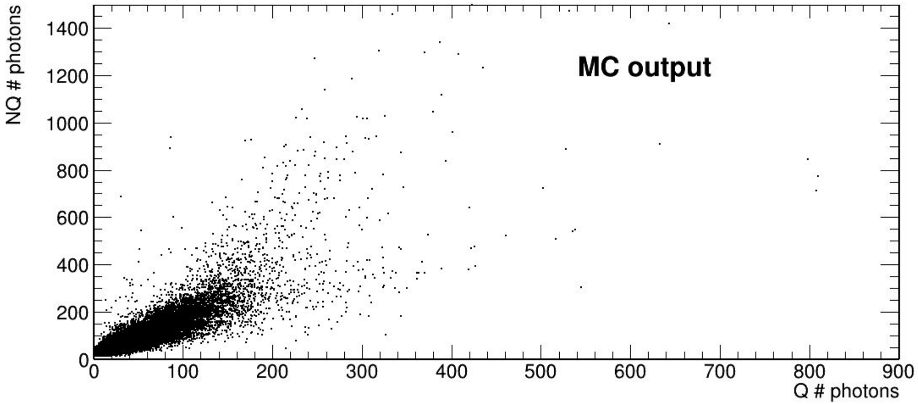


5-Bis(5-tert-butyl-benzoxazol-2-yl)thiophene (BBT).

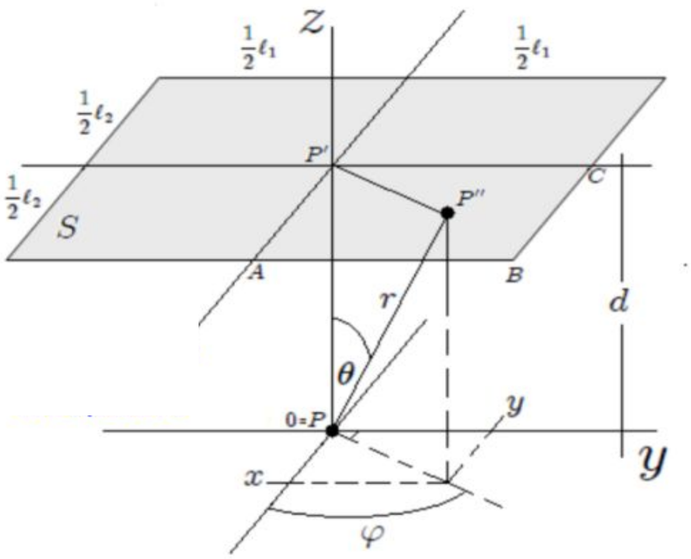
Backup


Telescope
34 cm
29 cm
Paddle
15.5 cm
37
cm
7 cm
96 cm
flange


NQ # photons
Q # photons


MC output
NQ # photons
Q # photons

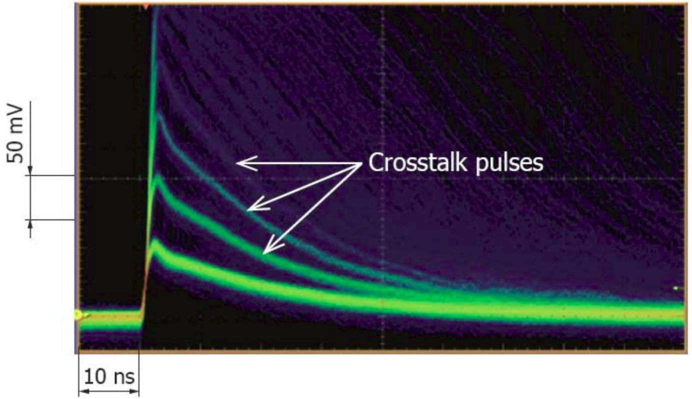
Backup

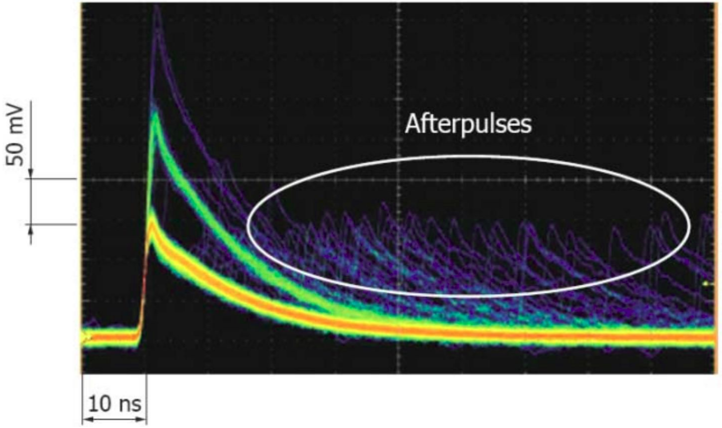


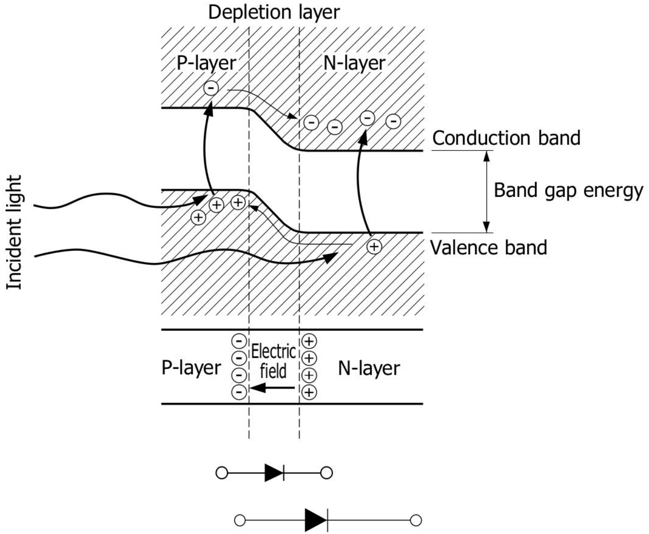
Courtesy of Laura Paulucci

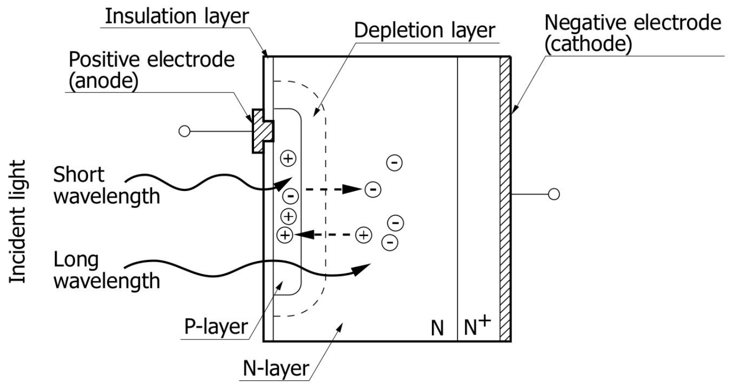
prod_muminus_0.1-5.0GeV_isotropic_dune10ktvd_1x8x14_gen_g4_detsim_reco.root
- RootFileDB;1
- MetaData;1
- FileIndex;1
- Parentage;1
- EventHistory;1
- Events;1
  - EventAuxiliary
  - art::TriggerResults_TriggerResults__Reco.
  - simb::MCTruths_generator__SinglesGen.
  - recob::OpHits_ophit10ppm__Reco.
  - sim::SimChannels_tpcrawdecoder_simpleSC_detsim.
  - sim::OpDetBacktrackerRecords_PDFastSimArExternal__G4.
  - sim::SimEnergyDeposits_IonAndScintExternal__G4.
  - sim::OpDetBacktrackerRecords_PDFastSimXeExternal__G4.
  - raw::RawDigits_tpcrawdecoder_daq_detsim.
  - sim::SimChannels_elecDrift__G4.
  - art::RNGsnapshots_rns__detsim.
  - recob::Wires_wclsdatanfsp_wiener_Reco.
  - sim::SimPhotonsLites_PDFastSimAr__G4.
  - art::RNGsnapshots_rns__G4.
  - raw::OpDetWaveforms_opdigi10ppm__detsim.
  - art::RNGsnapshots_rns__SinglesGen.
  - recob::OpFlashs_opflash10ppm__Reco.
  - sim::SimEnergyDeposits_IonAndScint__G4.
  - recob::OpFlashrecob::OpHitvoidart::Assns_opflash10ppm__Reco.
  - art::TriggerResults_TriggerResults__G4.
  - sim::OpDetBacktrackerRecords_PDFastSimAr__G4.
  - sim::SimEnergyDeposits_largeant_LArG4DetectorServicevolExternalActive_G4.
  - sim::OpDetDivRecs_sipmAr10ppm__detsim.
  - simb::MCParticles_largeant__G4.
  - sim::SimEnergyDeposits_largeant_LArG4DetectorServicevolTPCActive_G4.
  - sim::OpDetBacktrackerRecords_PDFastSimXe__G4.
  - sim::OpDetDivRecs_sipmXe10ppm__detsim.
  - sim::SimPhotonsLites_PDFastSimXeExternal__G4.
  - recob::Hits_gaushit__Reco.
  - sim::SimPhotonsLites_PDFastSimArExternal__G4.
  - sim::SimPhotonsLites_PDFastSimXe__G4.

Backup


50 mV
Crosstalk pulses
10 ns


50 mV
Afterpulses
10 ns


Depletion layer
P-layer
N-layer
Conduction band
Band gap energy
Valence band
Incident light
P-layer
Electric field
N-layer


Insulation layer
Depletion layer
Negative electrode (cathode)
Positive electrode (anode)
Incident light
Short wavelength
Long wavelength
P-layer
N-layer
N
N+