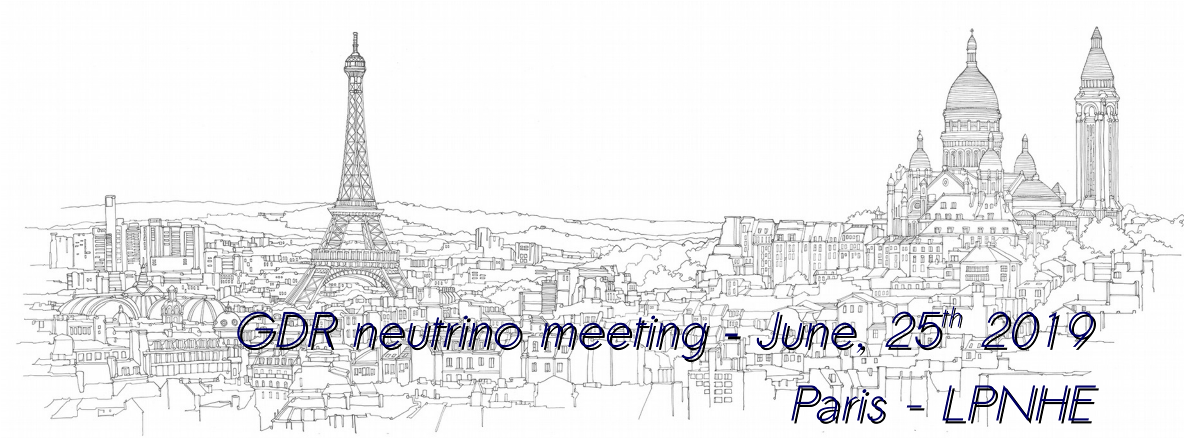
LIGHT PRODUCTION AND PROPAGATION ANALYSIS IN A LIQUID ARGON DUAL-PHASE TPC DEMONSTRATOR

CHIARA LASTORIA (CIEMAT)



GDR neutrino meeting - June, 25th 2019

Paris - LPNHE

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
LAPP
Laboratoire d'Annecy-le-Vieux de Physique des Particules
LPNHE
PARIS

Outline

1. Introduction to the Liquid Argon dual-phase technology
2. Toward giant dual-phase detectors
3. Description of the 4-tonne demonstrator
4. Main results from the light analysis in the demonstrator

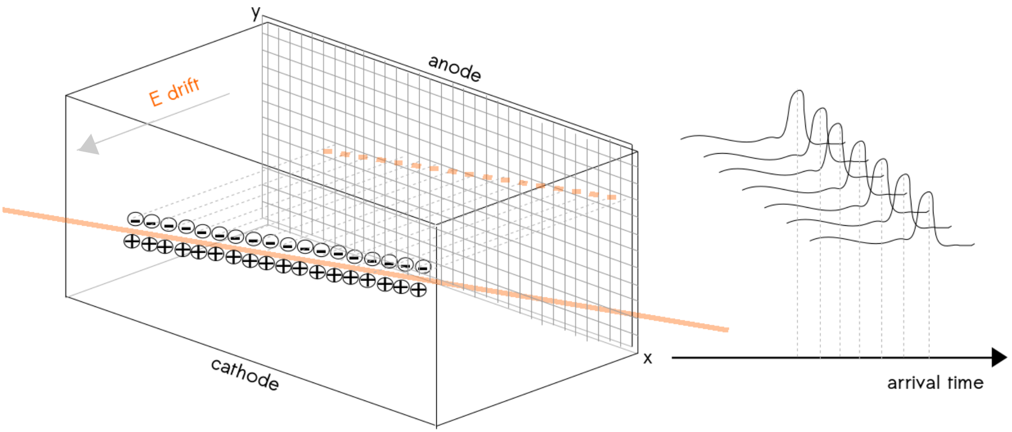
Liquid Argon Time Projection Chamber (TPC)

:> one active volume of Liquid Argon (LAr), **single-phase**

:> energy lost by a crossing particle ionizes Ar atoms

:> drift field applied allow electron drifting and collection

- 2D track trajectory projection in the xy plane (segmentation of the anode ↔ track resolution)
- **3D track reconstruction** including arrival time measurement
- **particle identification** from dE/dx measurement (calorimetry)



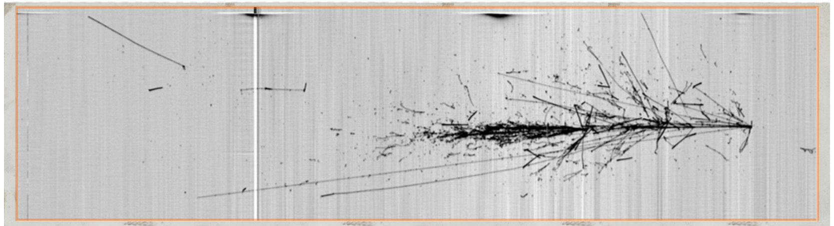
why Argon?

:> **advantages**

- can be found in nature (~1% of atmosphere)
- it is dense (1.4 g/cm^3) and inert
- large dieltectric rigidity
- good purification

:> **drawbacks**

- intrinsic presence of radioactive isotopes (Ar^{39}, Ar^{40}, Ar^{42})

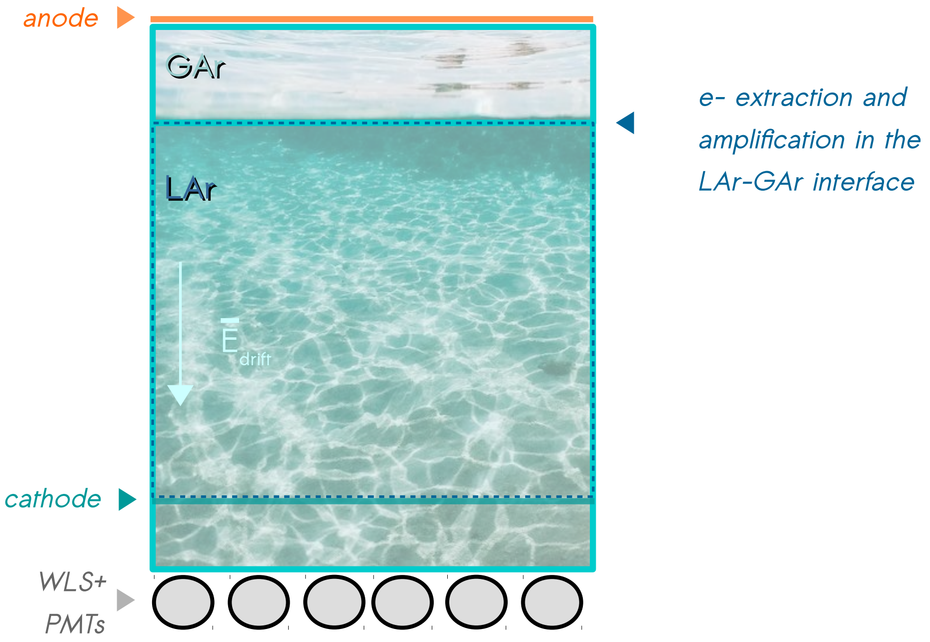


Neutrino interaction with LAr (event from Icarus T600 detector)

Dual phase technology

:> argon vapour (GAr) on the top of the LAr phase, **dual-phase**

- vertically drift of the e- from ionization
- extraction and amplification of e- in the GAr phase



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- vertically drift of the e- from ionization
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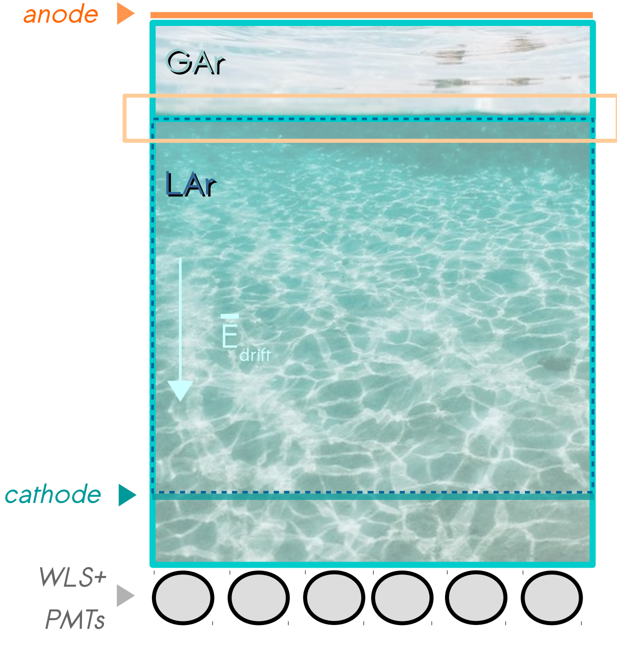
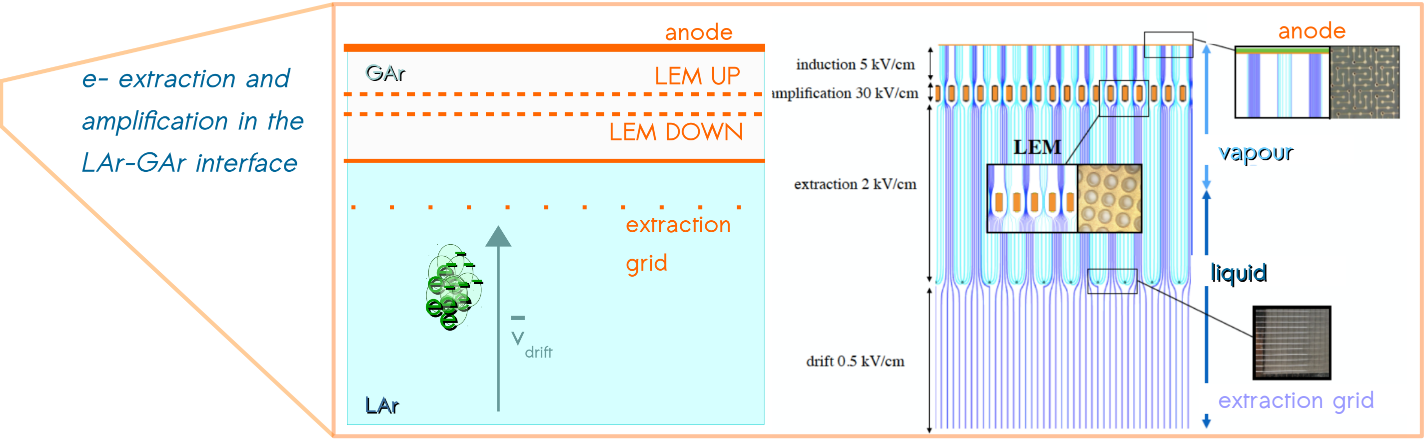
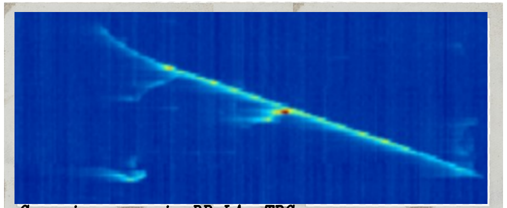
:> Charge signal
- extraction grid allow e- access to the GAr phase
- Large Electron Multipliers (LEMs) holes amplify the n. of e- extracted
- e- collection in the anode plane (track trajectory reconstruction)







Crossing muon in DP LAr-TPC (event from 4 tonne demonstrator)

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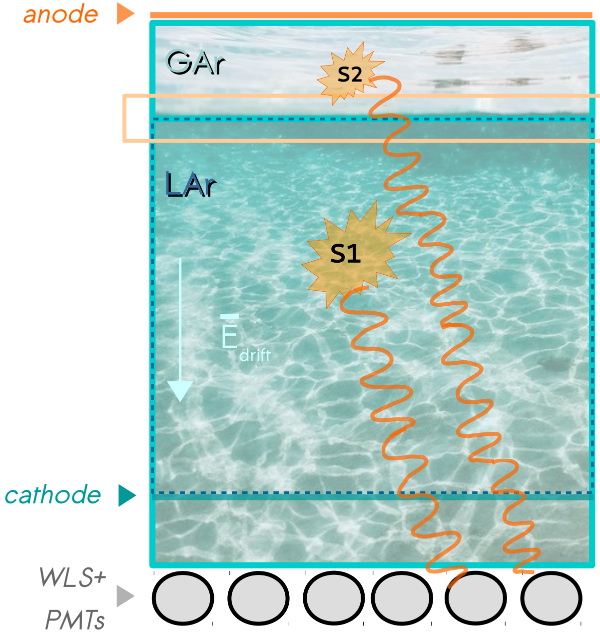
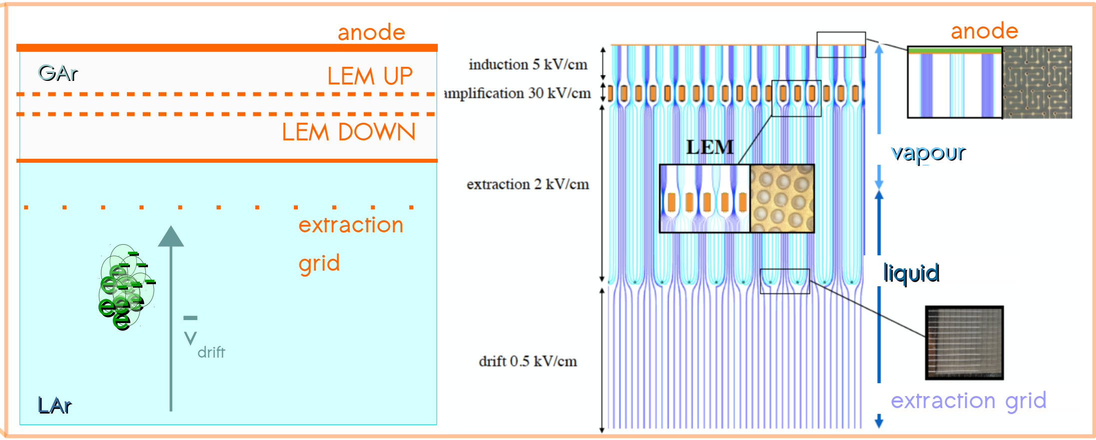
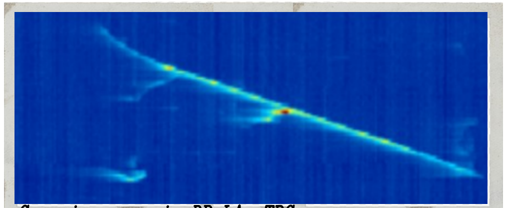


e- extraction and amplification in the LAr-GAr interface



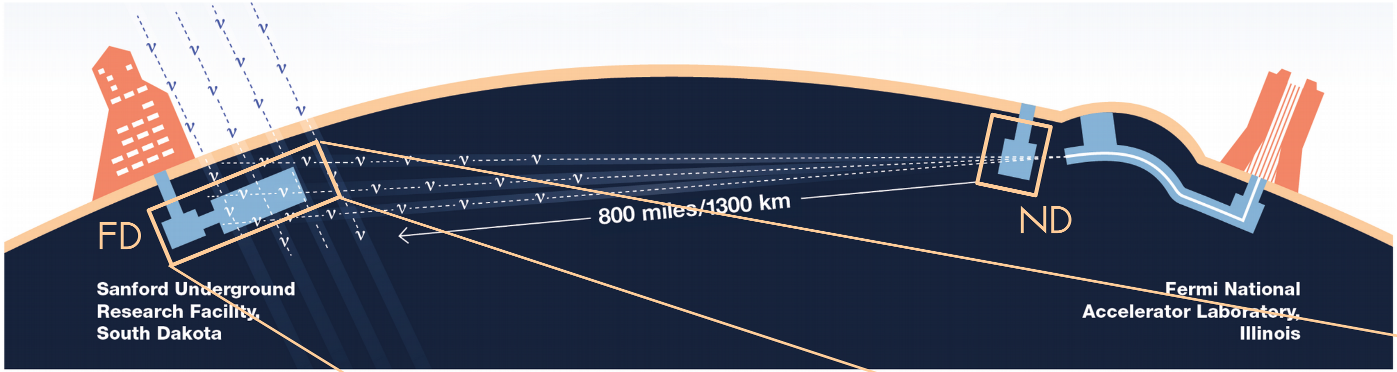
:> **Light signal**, two benchmark signals in the VUV spectrum:

- prompt scintillation light (S1)
- electro-luminescence light continuum (S2)



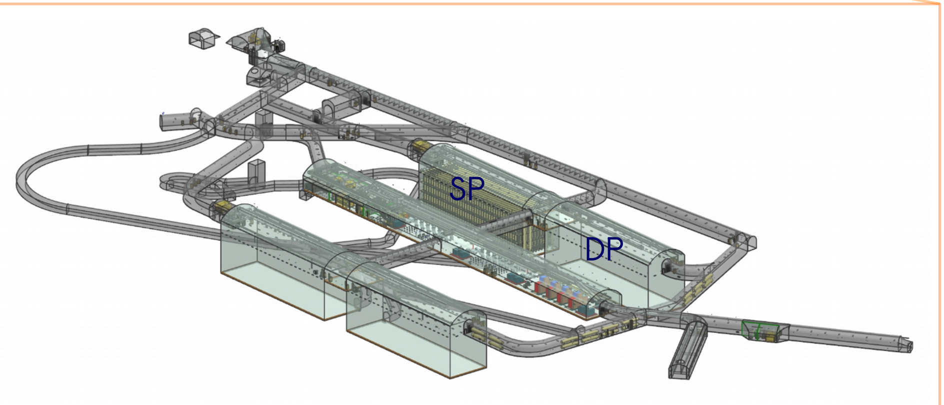
Crossing muon in DP LAr-TPC
(event from 4 tonne demonstrator)

Deep Underground Neutrino Experiment (DUNE)



- :> muon neutrino beam
- :> Near Detector (**ND**) at FermiLab
- :> Far Detector (**FD**) at SURF laboratory

- :> 4x**10kton** LArTPC modules in the FD
- :> 3D track reconstruction at high resolution
- :> sensitivity to low energetic events
- :> both SP and DP are foreseen
  - first module will be SP
  - at least one module is expected to be DP
  - open to other possibilities for the other two modules
- :> **demonstrate the two technologies at such large scale is crucial!**
  - prototypes @ CERN



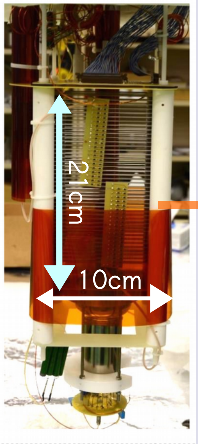
Toward bigger detectors

:> the staged approach
from R&D to the large scale

"3 liter"

- small setups for R&D

@ CERN, (2010~2014)

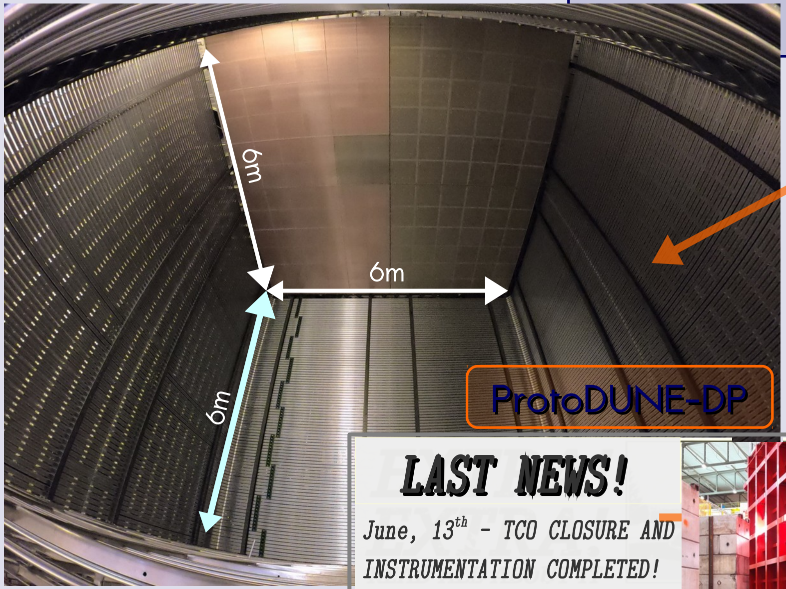


- first DP LAr-TPC at ton scale
- cosmic muons

@ CERN, bld. 182 (2014~2017)

- DP LAr-TPC ~300 ton
- cosmic muons and test beam

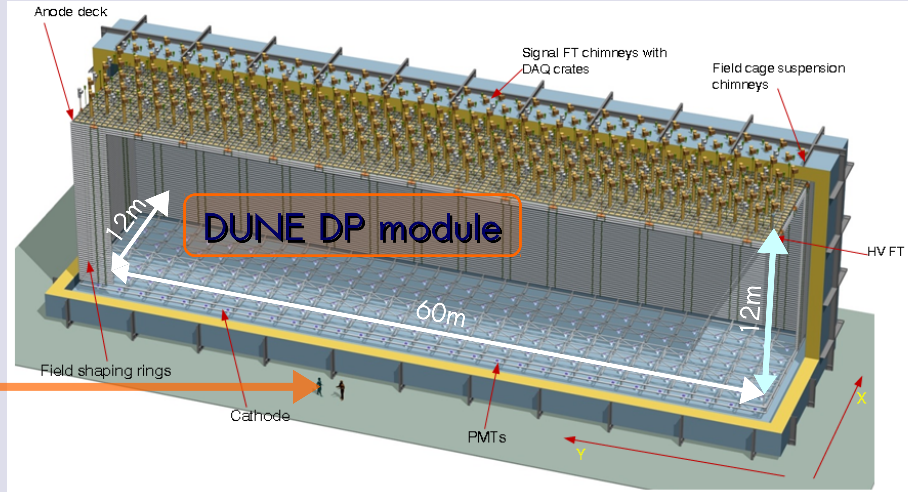
@ CERN, EHN1 (2016~2019)



LAST NEWS!

June, 13th - TCO CLOSURE AND INSTRUMENTATION COMPLETED!

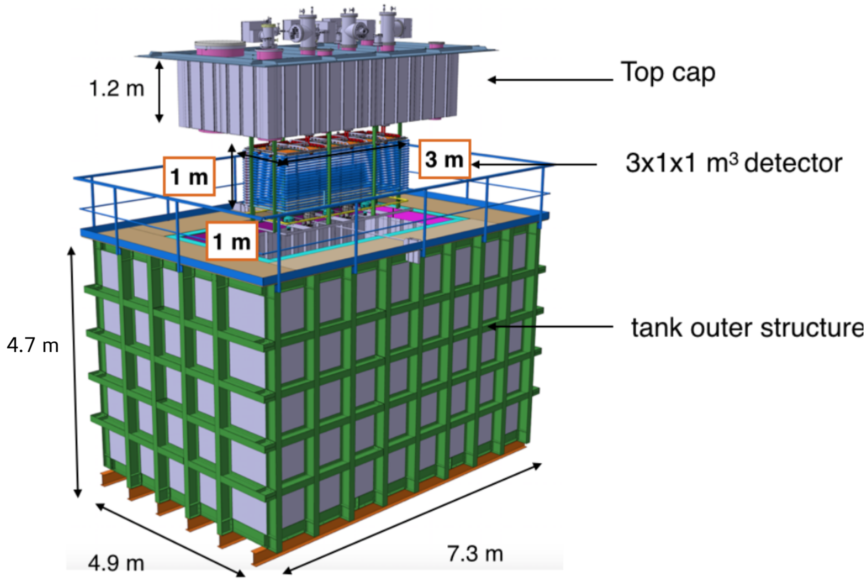
more info in Dominique's talk!



The 4 tonne demonstrator detector

:> data collection period:
May-Nov. 2017

:> exposed to **cosmic muons**



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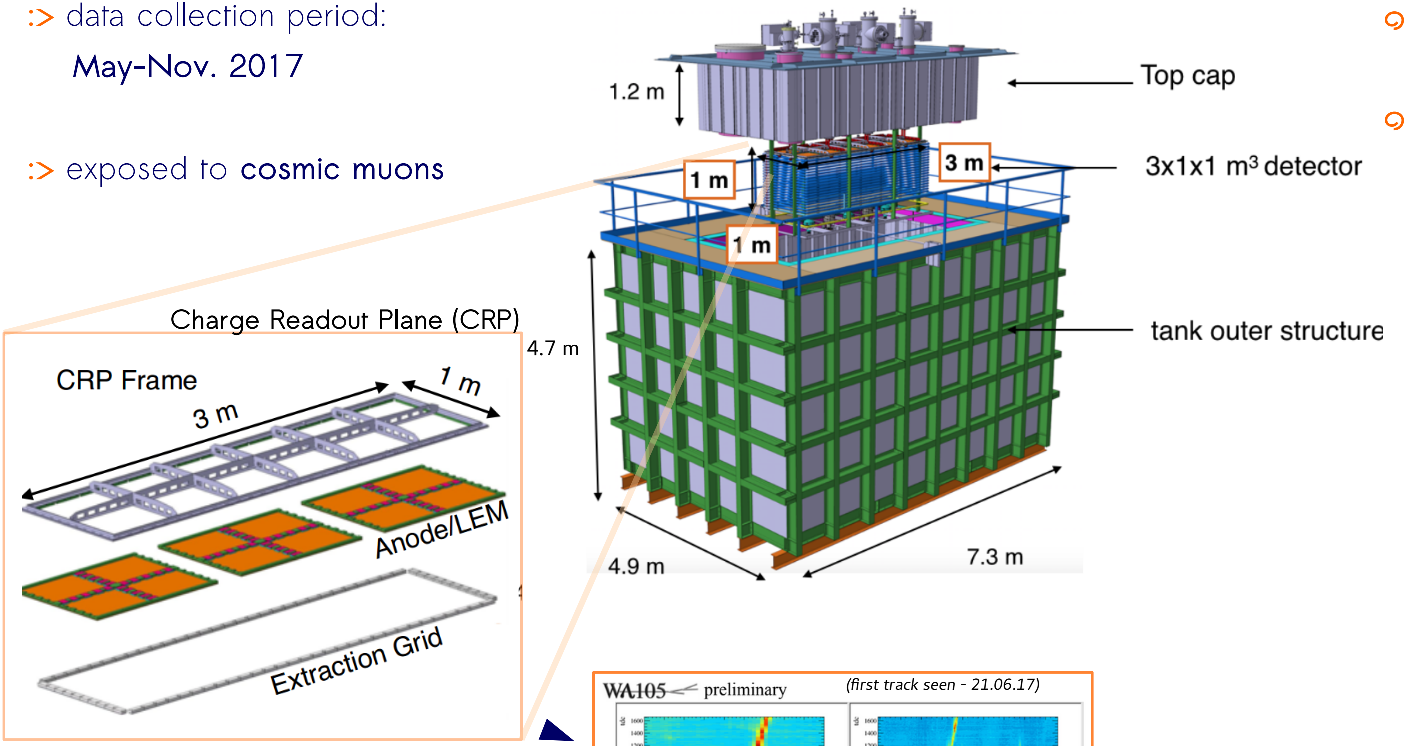

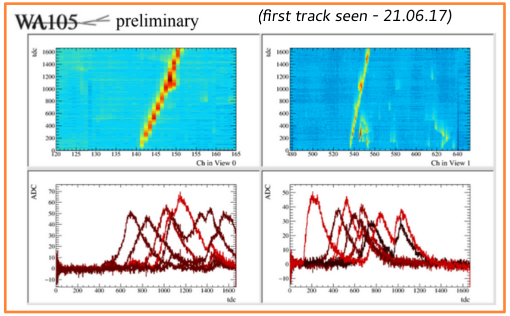

:> 3x1x1 technological milestones:

- extraction of ionization charge over $3m^2$ area
- amplification in pure Ar vapor by combined operation of multiple 50×50 cm^2 LEMs
- readout of the signal on two collection planes with strips (up to 3m length)

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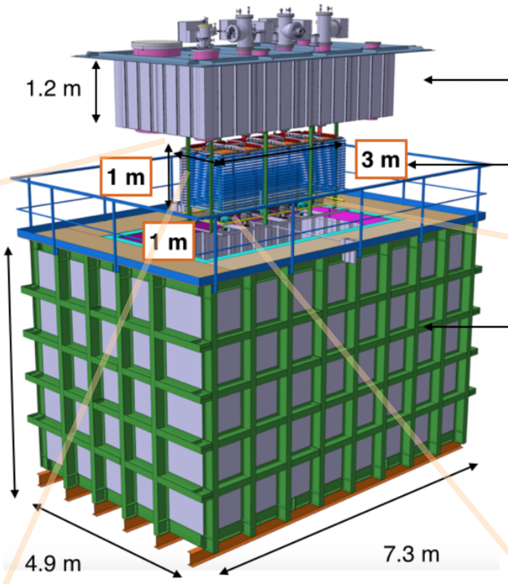
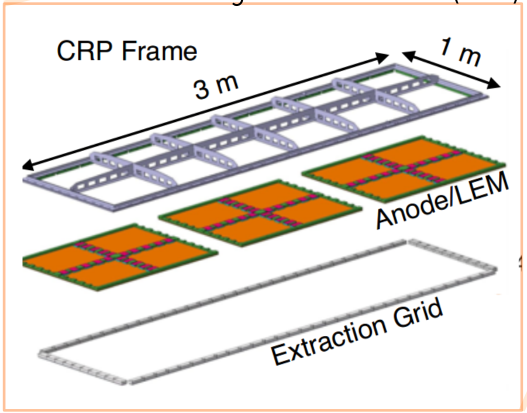
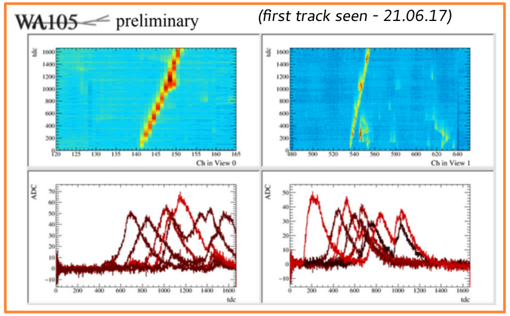
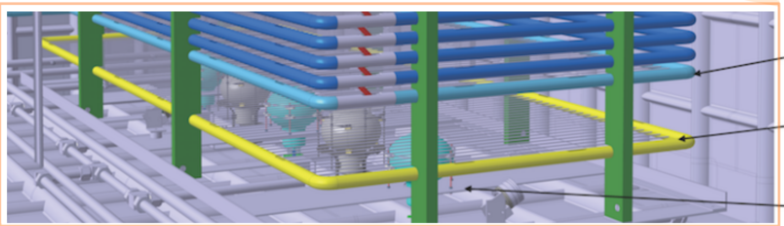


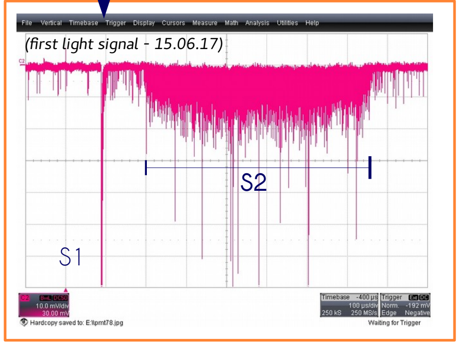






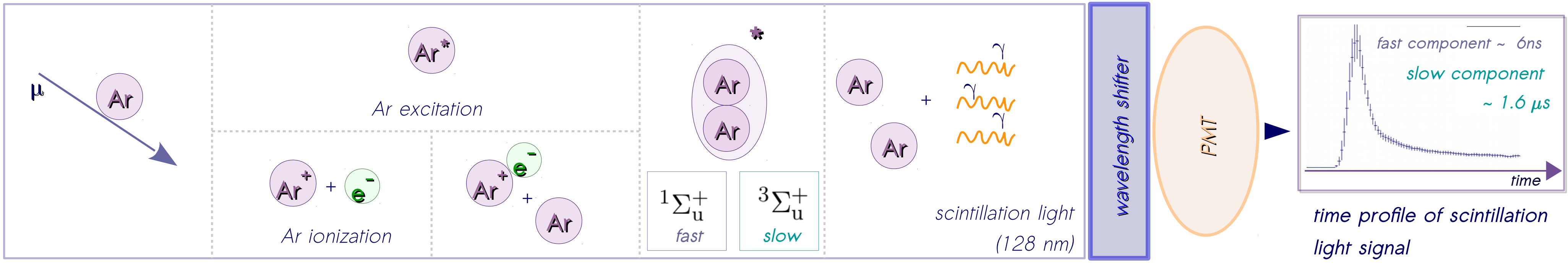
prompt scintillation light (S1)

electro-luminescence light continuum (S2)



The scintillation light signal

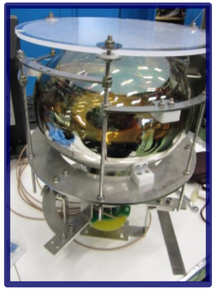
:> scintillation emission mechanism, two contributions in LAr: self-trapped excitation luminescence and recombination luminescence



The light detection system of the 4 tonne demonstrator

:> five R5921-02Mod PMTs by Hamamatsu (8 inch) with different configurations:

- 2 TPB(*) coating (direct coating ◯, TPB on PMMA plate ◎)



(*) tetraphenyl-butadiene

The scintillation light signal

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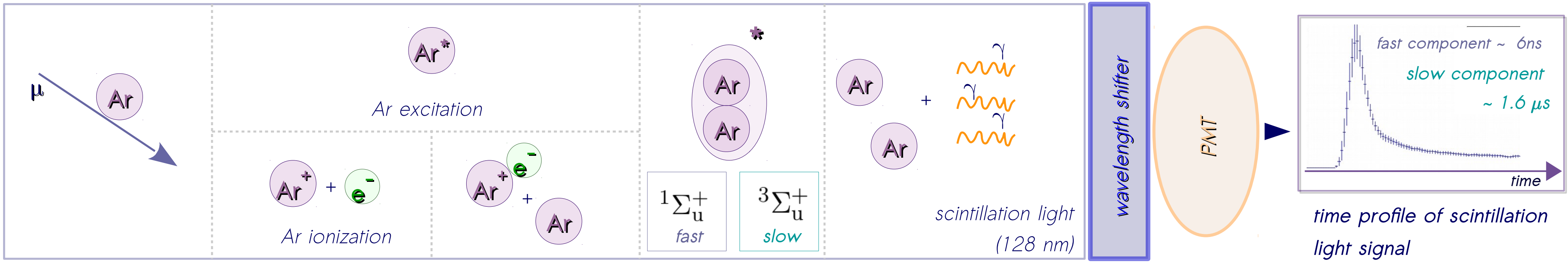

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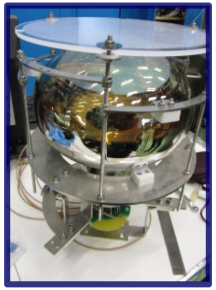
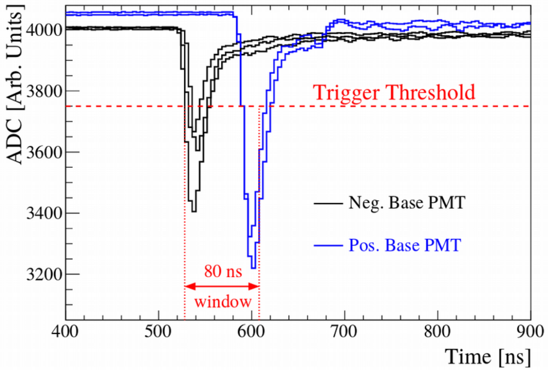
- 2 bases configurations (positive ⊕ or negative ⊖ polarization)



PMT trigger

5 fold coincidence in a time window over a fixed threshold



Typical triggered event rate ~3 Hz (~3*10⁶ of triggered ev.)

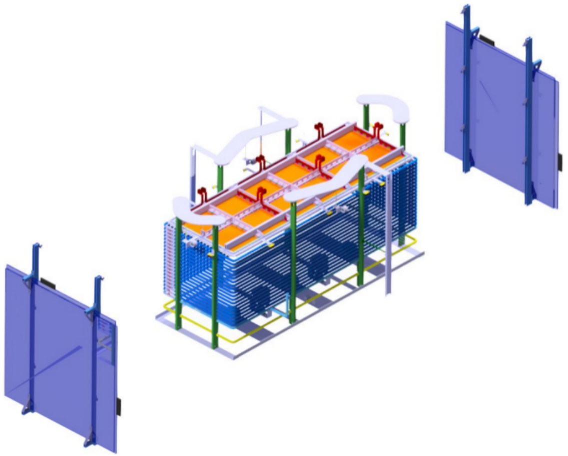
(*) tetraphenyl-butadiene

Cosmic Rays Taggers (CRTs)

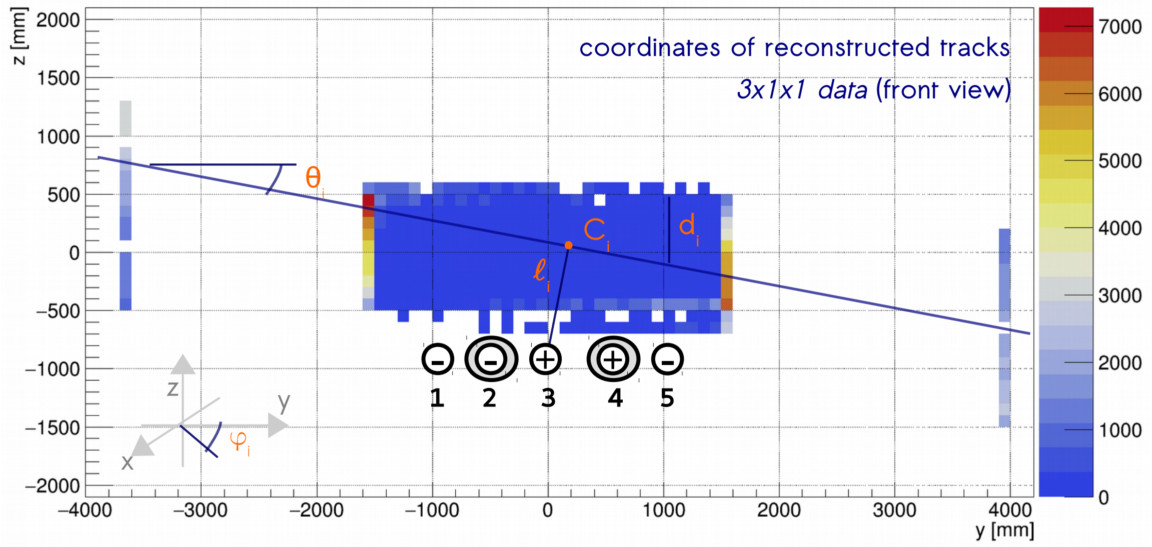
:> 4 modules of scintillators made by 16 strips per module (2 modules per side, 1.8m x 1.8m each)

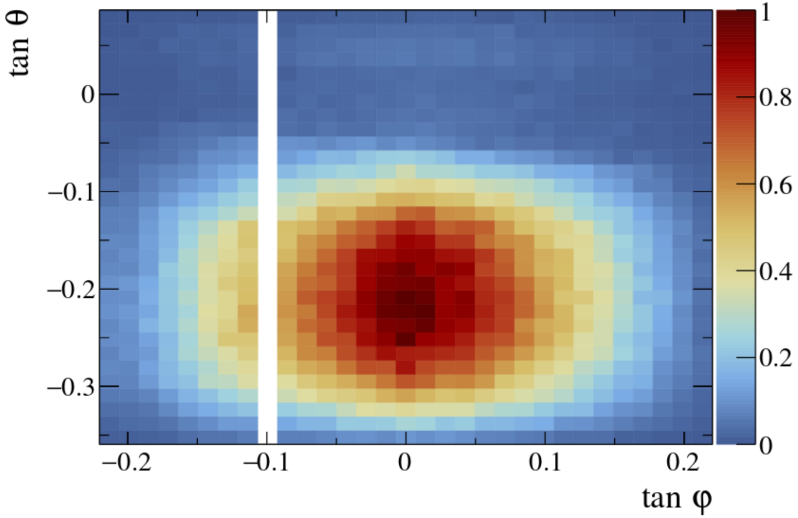
→ each strip is read by 2 optical fibers connected to 2 SiPMs

:> **direct geometrical track reconstruction** for the triggered event (only one muon, no multiple tracks)

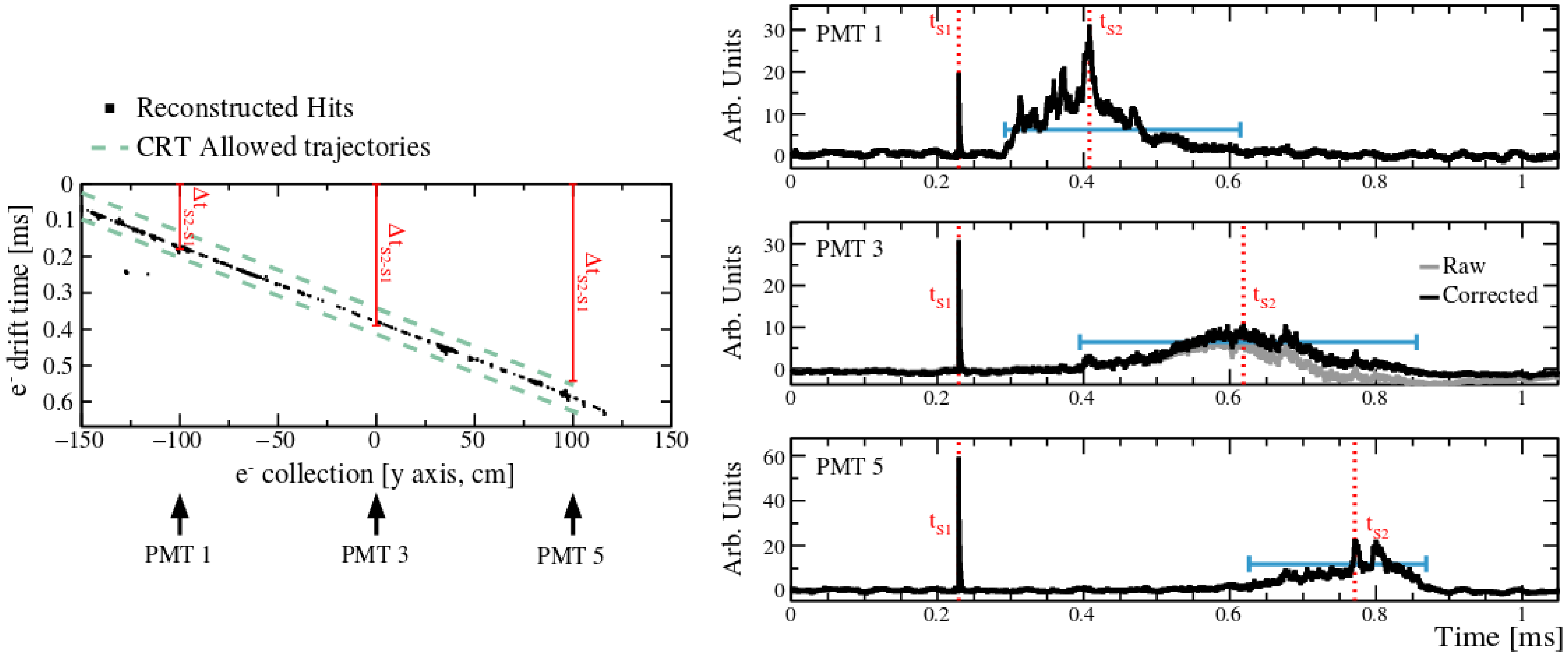


Typical triggered event rate ~ 0.3 Hz *(~7*10⁵ of triggered ev.)*





A real event reconstructed in the 4 tonne demonstrator

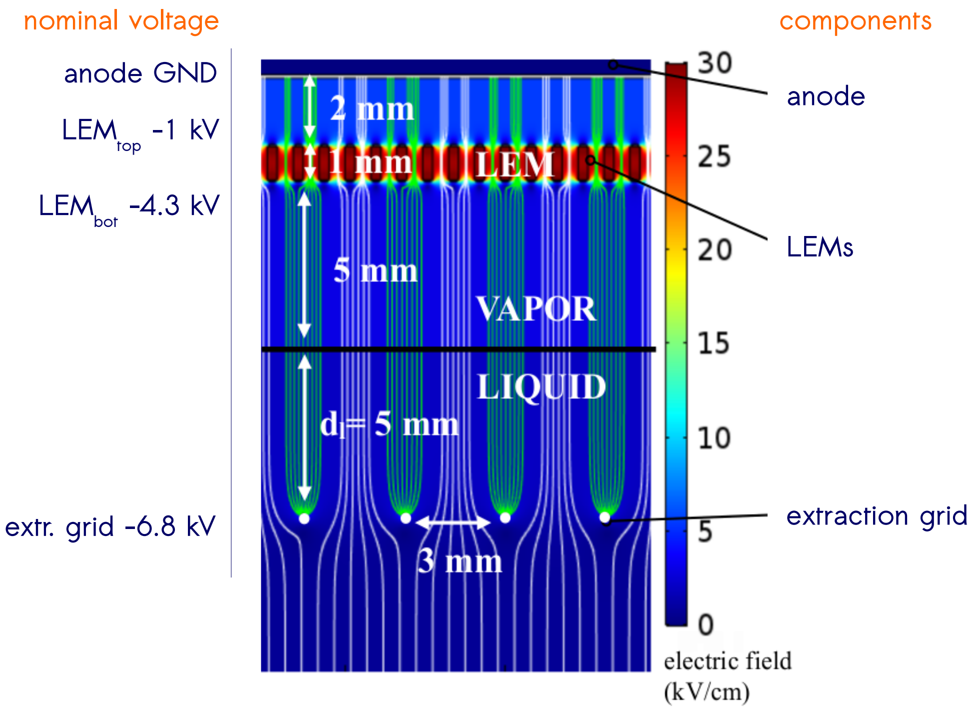


Data taking conditions

:> Different detector configurations has been investigated

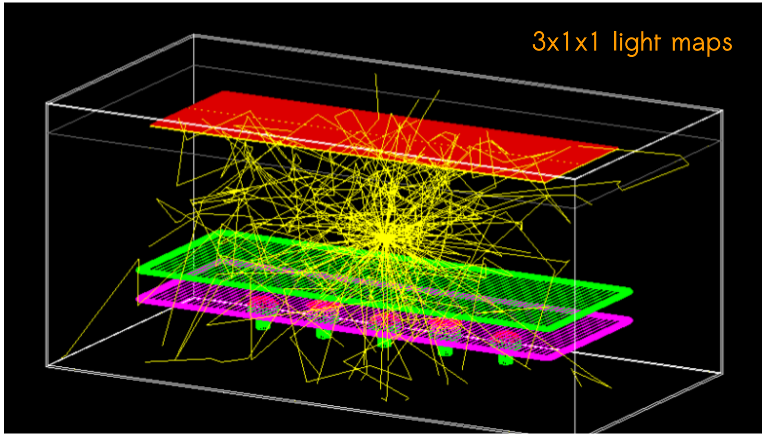
- a lot of data available at 0 kV/cm
  - → characterization of the scintillation light
  - → study the Rayleigh scattering (CRT reconstruction and data-MC comparison)
- a **dedicated drift field scan** with PMT trigger (no charge information available)
- different drift, extraction, amplification fields
  - → study of the scintillation light vs drift field
  - → study of electron luminescence light

:> Limitation by the maximum voltage applied to the grid (lower G_{eff} reached than the nominal)



	nominal	achieved
drift field	0.5 kV/cm	[0.3; 0.7] kV/cm
extraction field	2 kV/cm	2kV/cm (with -5 kV at extr.)
amplification field	33 kV/cm	limitation by grid
induction field	5 kV/cm	limitation by grid

The light Monte Carlo simulation



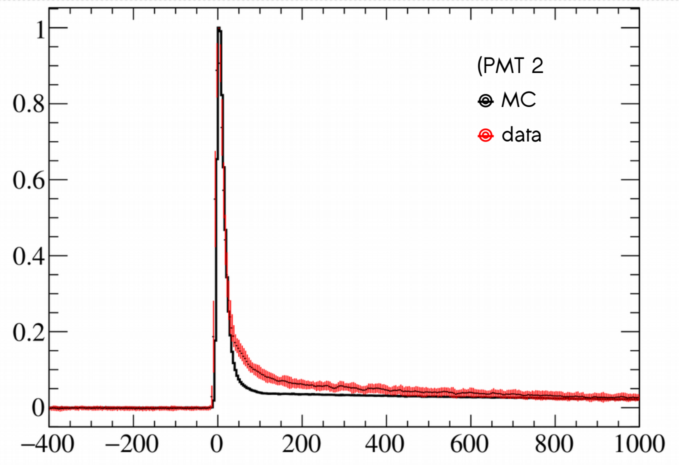
:> **events generation** following the CRT geometry based on 3x1x1 data

:> **light propagation** of the 3x1x1detector through the **light maps** (LightSim software)

- light maps for **LAr** and **GAr** phases
- 3x1x1 light maps available for **different Rayleigh scattering length** (20cm, 55cm, 163cm)
- λ_{abs} = 30 m

:> **PMT response** from 3x1x1 data **included** in the MC simulation,
final average waveform is (S1+ S2) ⊗ PMT response

average waveform (sim. of PMT response)

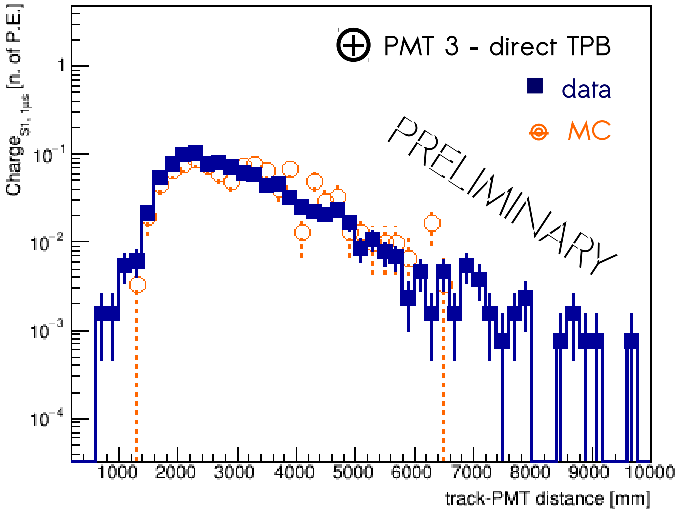


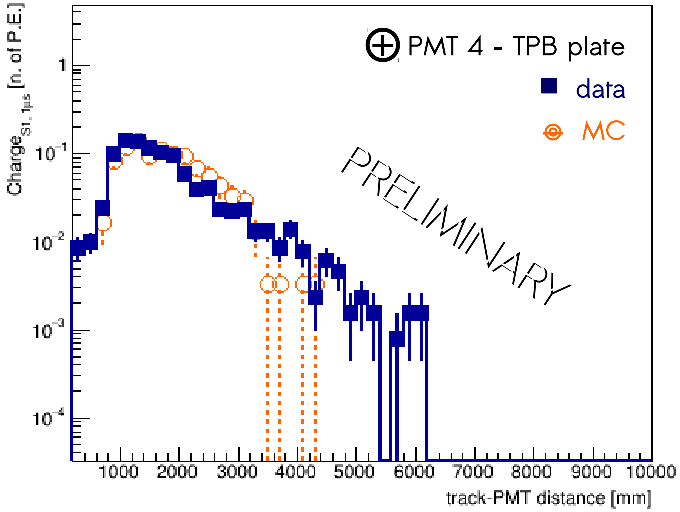
Data-MC comparison - scintillation light

References:
E. Grace, J, Nikkel, arXiv:1502.04213v2
B. J. P. Jones et al., arXiv:1306.4605v2

:> comparison between data and MC has been performed for **Rayleigh scattering length = 55 cm** and λ_{abs} = 30 m

- the collected charge distribution comparison shows quite good agreement
  (PMTs with different TPB coating configuration but same base)

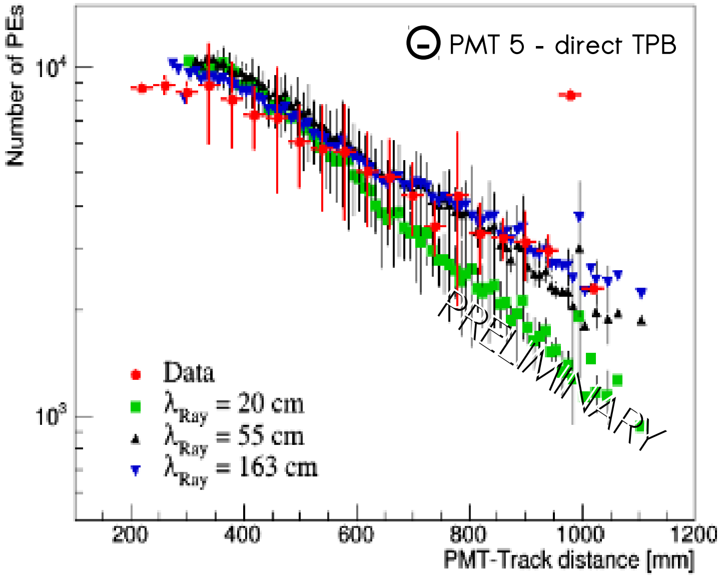




The Rayleigh scattering length

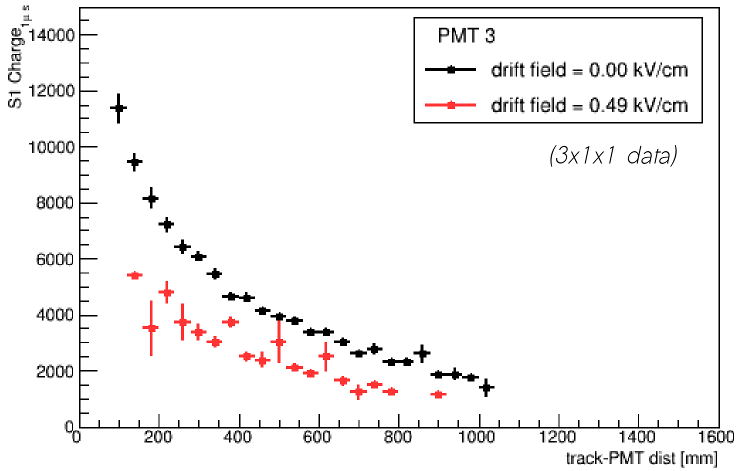
:> comparison of **different Rayleigh scattering length** values 20cm, 55cm, 163cm (λ_{abs} = 30 m)

- found **better agreement** for a Rayleigh scattering length **between λ_{Ray} = 55cm and λ_{Ray} = 163cm**



The scintillation light signal

:> the **recombination factor** has been studied for all the CRT runs available



good agreement among the five PMTs

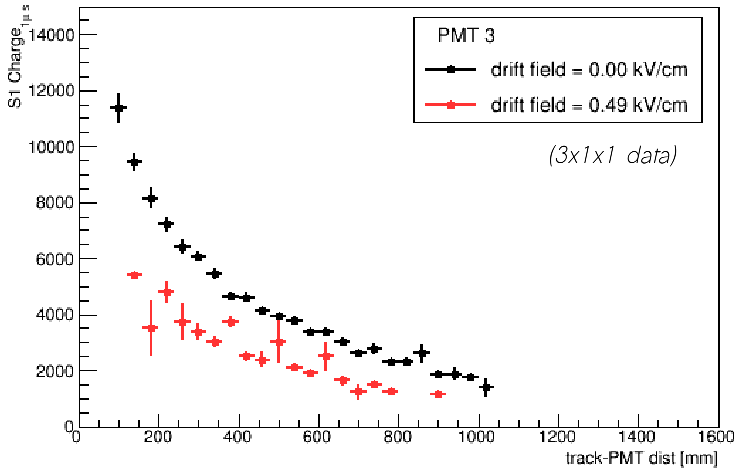
(agreement within 3%)

The scintillation light signal

References:
S. Kubota et al., Phys. Rev., vol. B20, pp. 3486-3496, 1979

:> the **recombination factor** has been studied for all the CRT runs available (**Birks' law curve**)

- the relative n. of P.E. has been calculated at the different drift field values - j index in the formula



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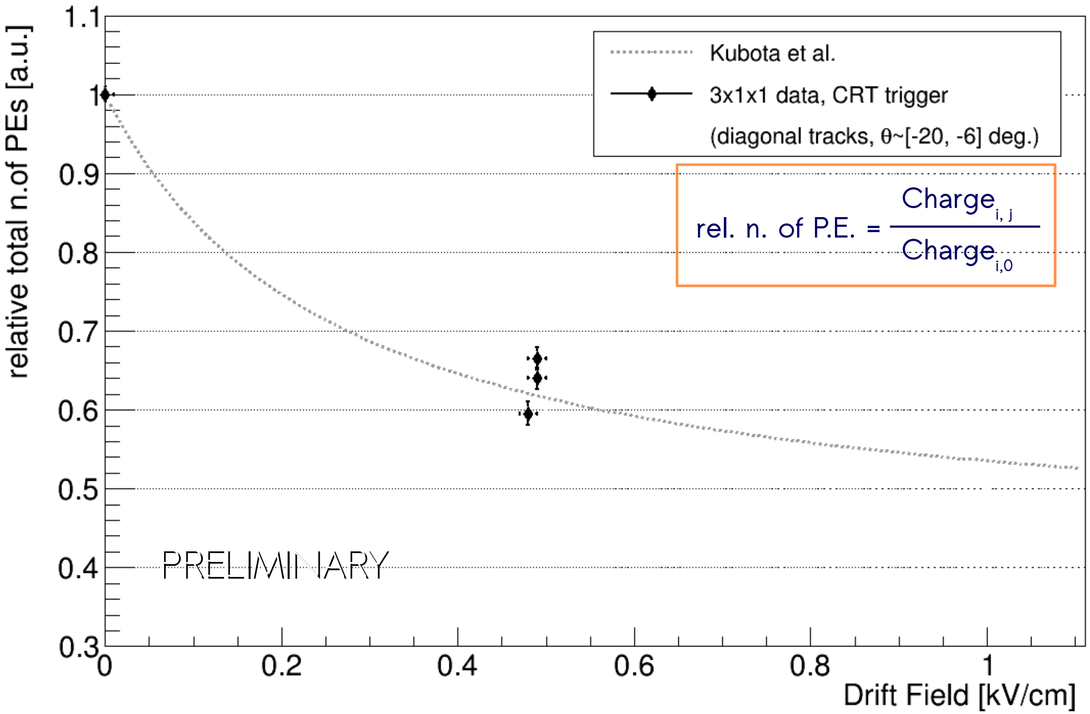
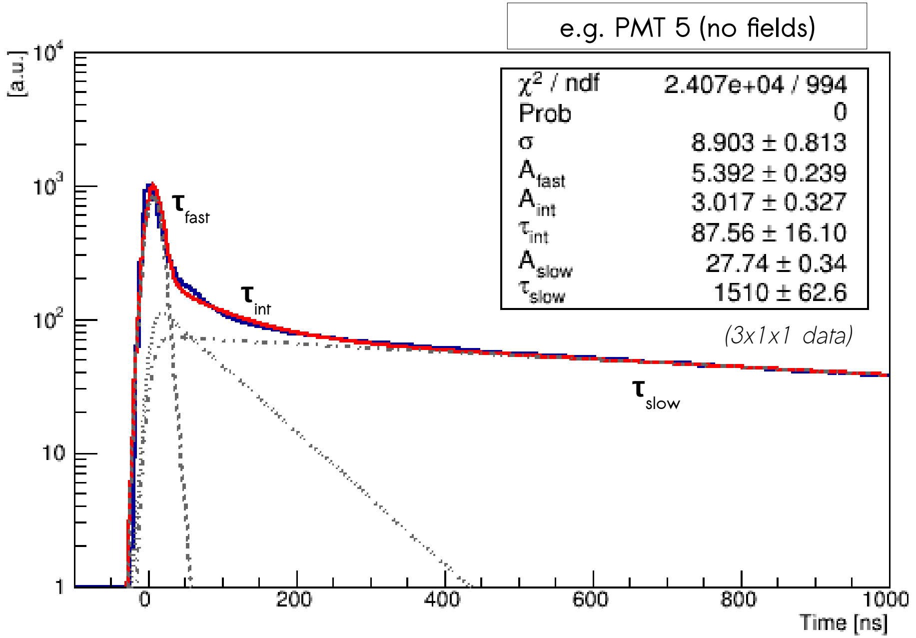


$$\text{rel. n. of P.E.} = \frac{\text{Charge}_{i,j}}{\text{Charge}_{i,0}}$$

- measured ~40% of recombination for drift field = 0.5 kV/cm (good agreement with Kubota measurements)

The scintillation light signal

References:
E. Segreto, arXiv:1411.4524v2
R. Acciarri er al, JINST 5 P06003



:> Fit function:

convolution of a gaussian with three exponentials

$$G(t-t_0, \sigma) \otimes \sum_i (A_i / \tau_i)^* \exp(-(t-t_0)/\tau_i)$$

- model the **detector response** to the triggered particles **(gaussian function)**
- fast and slow components fitted by **two exponentials**
- an intermediate exponential to improve the fit in the **fast/slow transition region**
- Ai, **relative amplitudes** → ΣiAi = integral of the average waveform

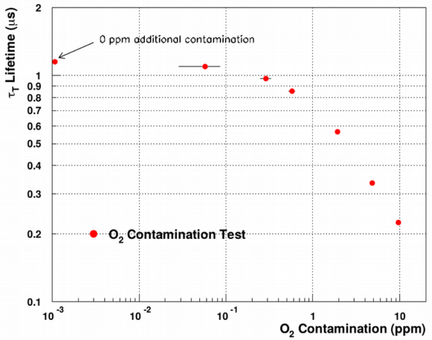
:> intermediate component not expected from Ar atoms de-excitation but measured by all LAr-TPC experiments

:> possible origins of the intermediate component:

- due to the presence of TPB
- instrumental effects

The scintillation light signal

References:
R. Acciari et al., JINST 5 P05003
doi:https://doi.org/10.1016/j.nima.2009.03.142
B. Aimard et al., arXiv:1806.03317

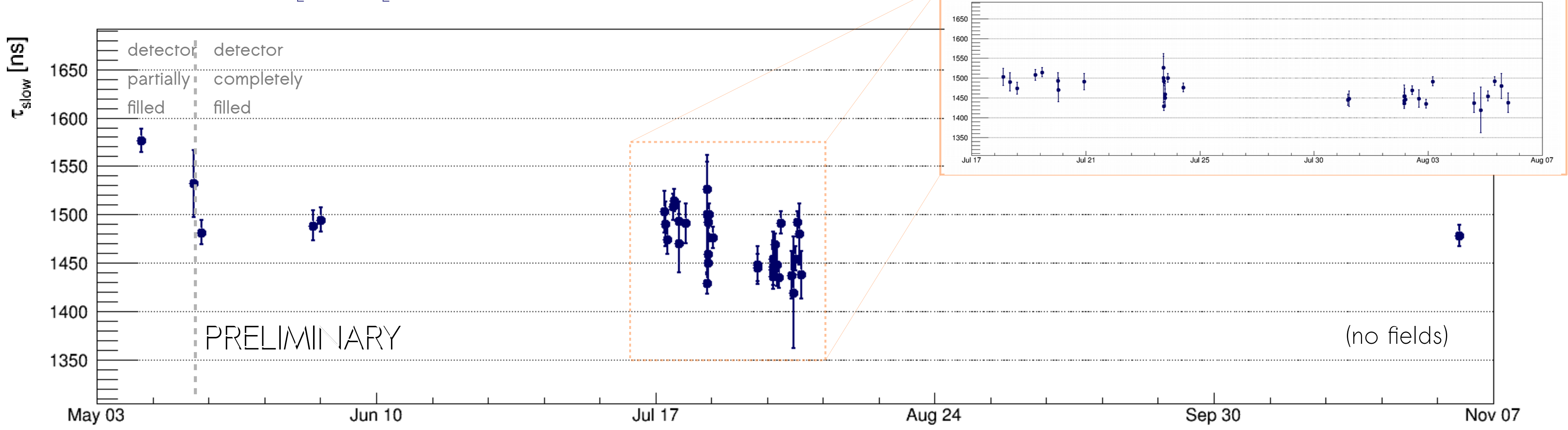


:> **monitoring of the LAr purity** through the τ_{slow}

- each point is the average among the tau slow obtained from NB-PMTs
- the error takes into account the estimated error from the fit and the dispersion among the channels

:> τ_{slow} almost constant during all the data taking

(very small amount of O_2 and N_2 impurities < ~ppm from the beginning)

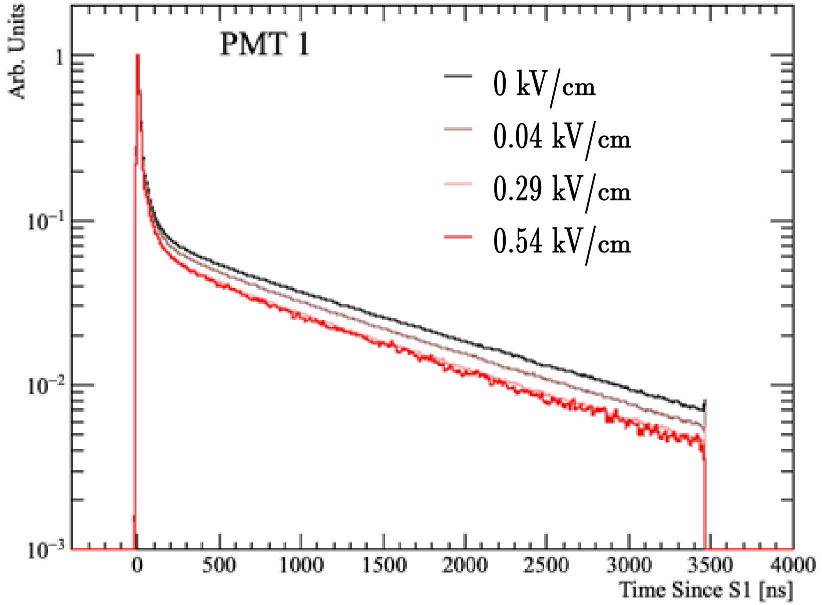


a decreasing of the LAr purity can be detected monitoring the τ_{slow}

The scintillation light signal

:> study of the **effect of the drift field** on the scintillation light signal with the **dedicated drift field scan**

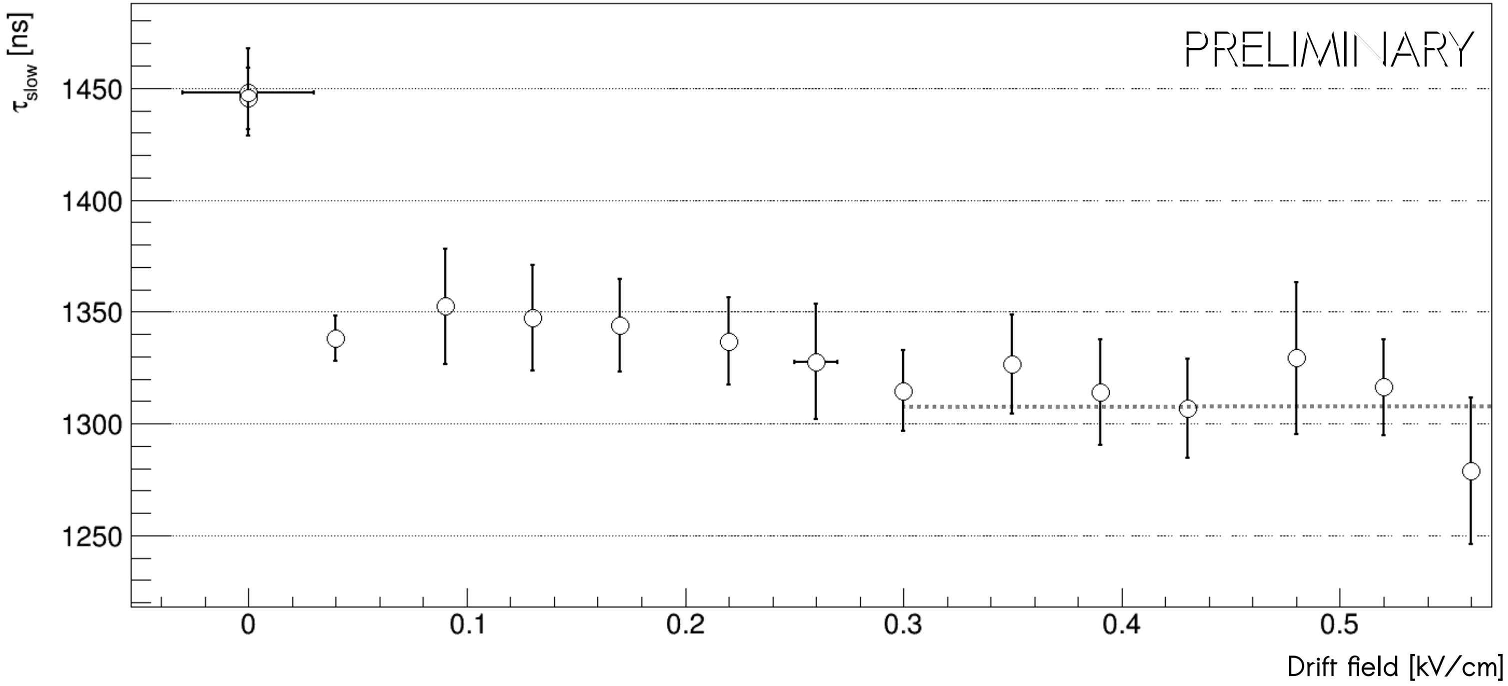
- evident difference in PMT waveform shape
- investigation with a detailed analysis of the scintillation light signal



The scintillation light signal

:> decreasing of the τ_{slow} due to the increasing of the drift field

- drift field acts like a quenching
- phenomenon not well documented in literature

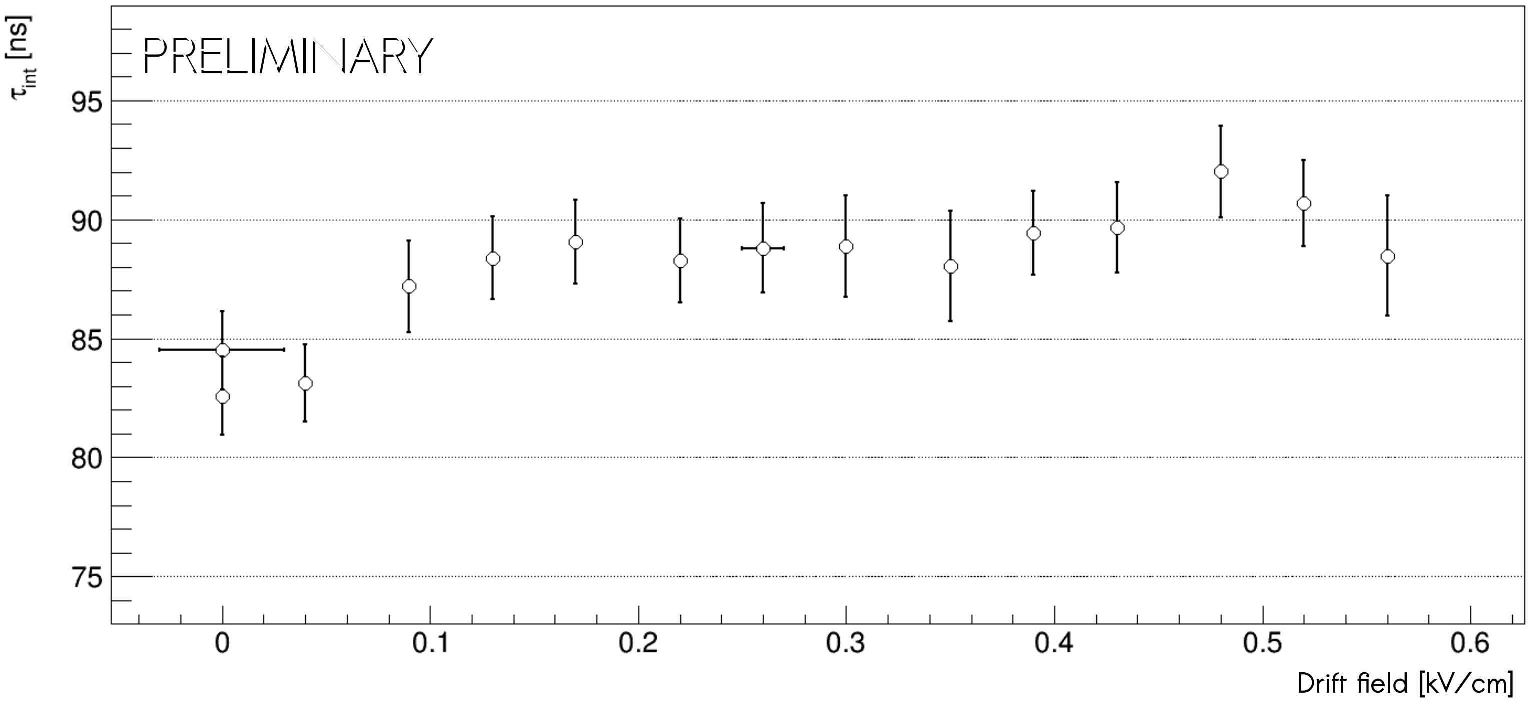


$\tau_{slow,0.5}$ = (1310,1 ± 7,4) ns
(at 0,5 kV/cm, ~11% lower than at 0 kV/cm)

The scintillation light signal

:> study of the **intermediate component**, τ_{int} as a function of the drift field

- **no** clear **dependence** with the **drift field** and on the **trigger condition**



The scintillation light signal

:> **measurement of the relative amplitudes** Rel. Ampl. i = $\frac{Ai}{\Sigma iAi}$

- dependence with the drift field

:> measured the ratio A_{fast}/A_{slow} **as a function of the drift field**

- **dependence with the trigger conditions** (under study)

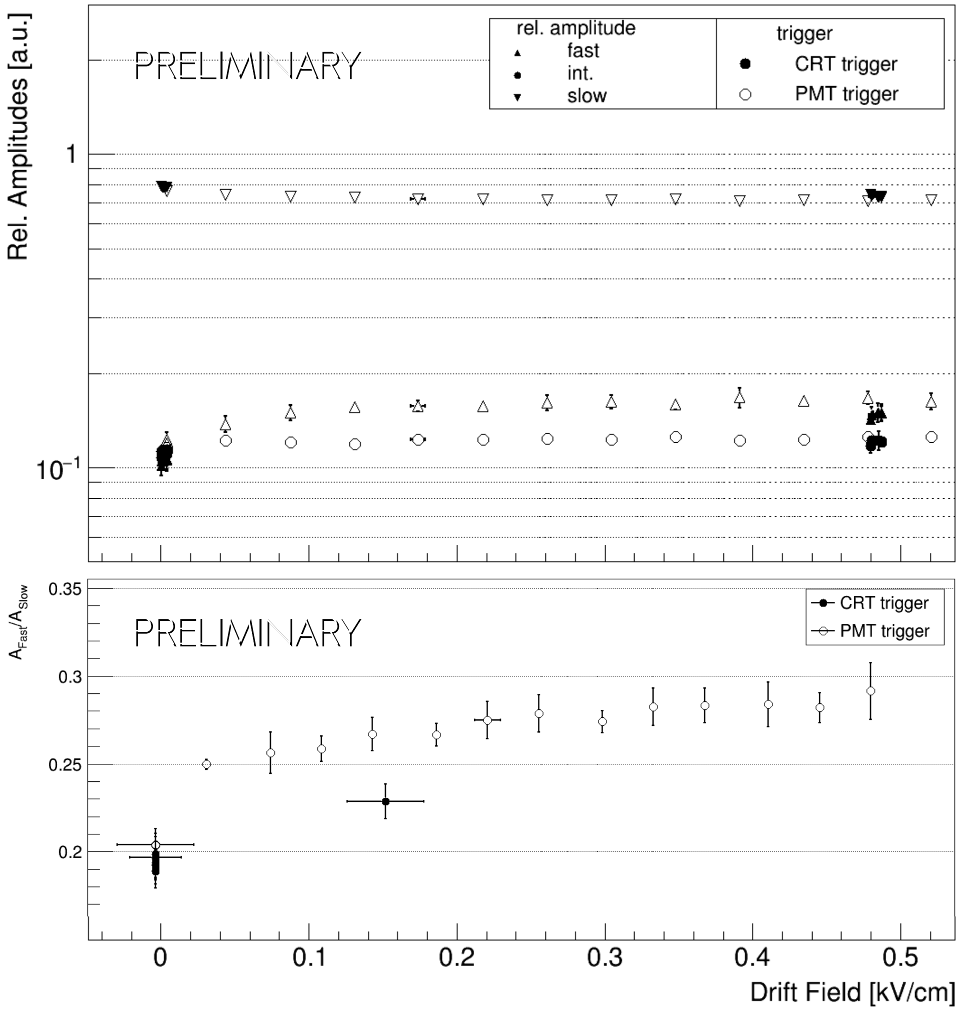
  A_{fast}/A_{slow} lower for particles triggered by CRT w.r.t. particles triggered by PMT

  (hyp.: PMT trigger select more energetic particles due to the threshold - under further investigation)

- **dependence with the drift field,**

  A_{fast}/A_{slow} increases at higher drift field

  (opposite behaviour found in literature - still under study)



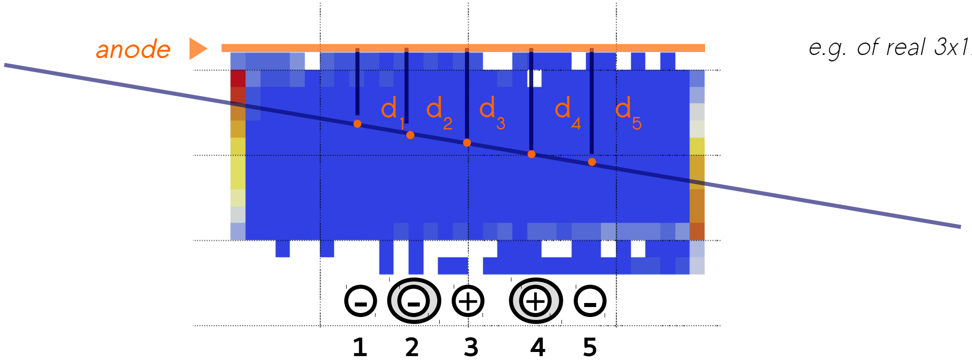
References:

S. Kubota et al., J . Phys. C : Solid State Phys., Vol. 11, 1978

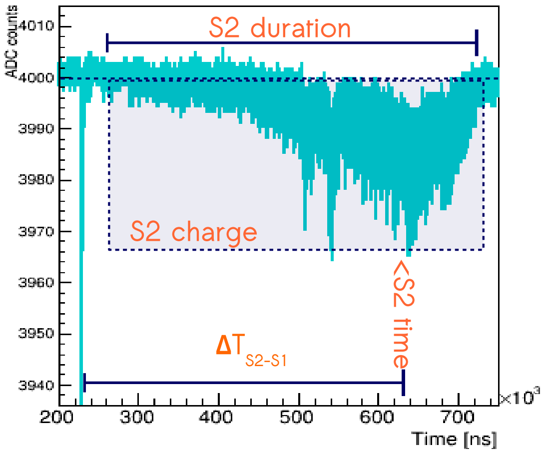
R. Acciarri er al, JINST 5 P06003

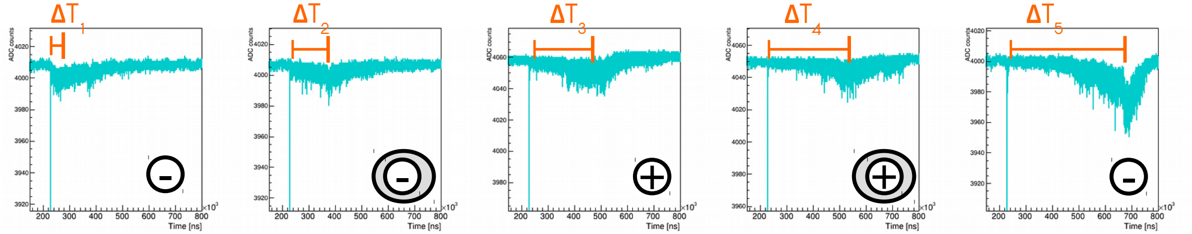
The electro-luminescence light signal

:> developed a dedicate algorithm to characterize S2 signal



e.g. of real 3x1x1 event





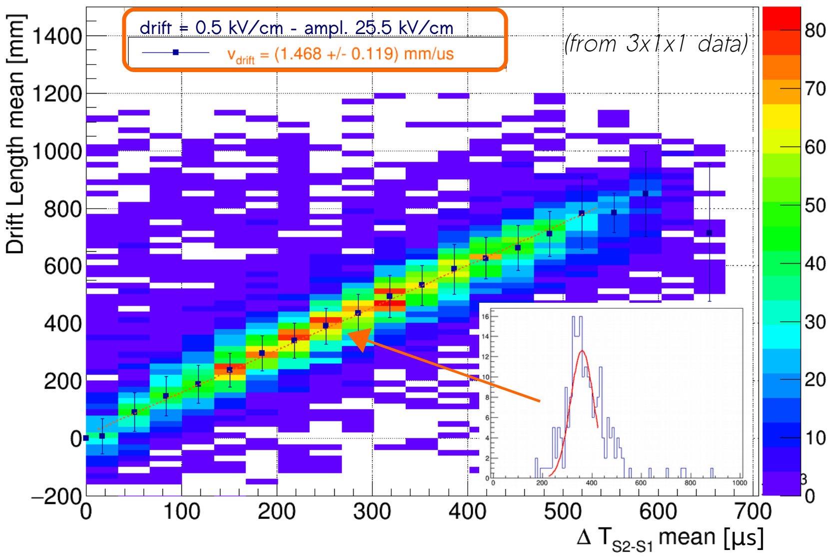
- **S2 time,** time distance $\Delta T_{S2\text{-}S1}$ between S2 and S1 peaks and **S2 duration** (related with track topology)
- integrated **S2 charge**

:> electro-luminescence gain, important parameter not measured yet and related with the S2 light intensity

$$G_{el} = \frac{\text{n. of S2 generated } \gamma}{\text{extracted e- in the GAr phase}}$$

Measurement of the drift velocity

:> global measurement by the 5 PMTs

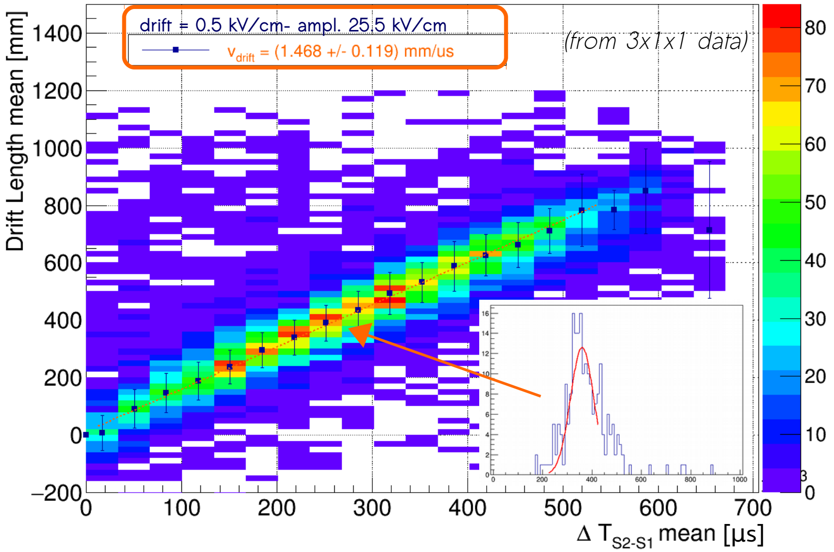


gaussian fit on each slice of 25us (error bar from fit)

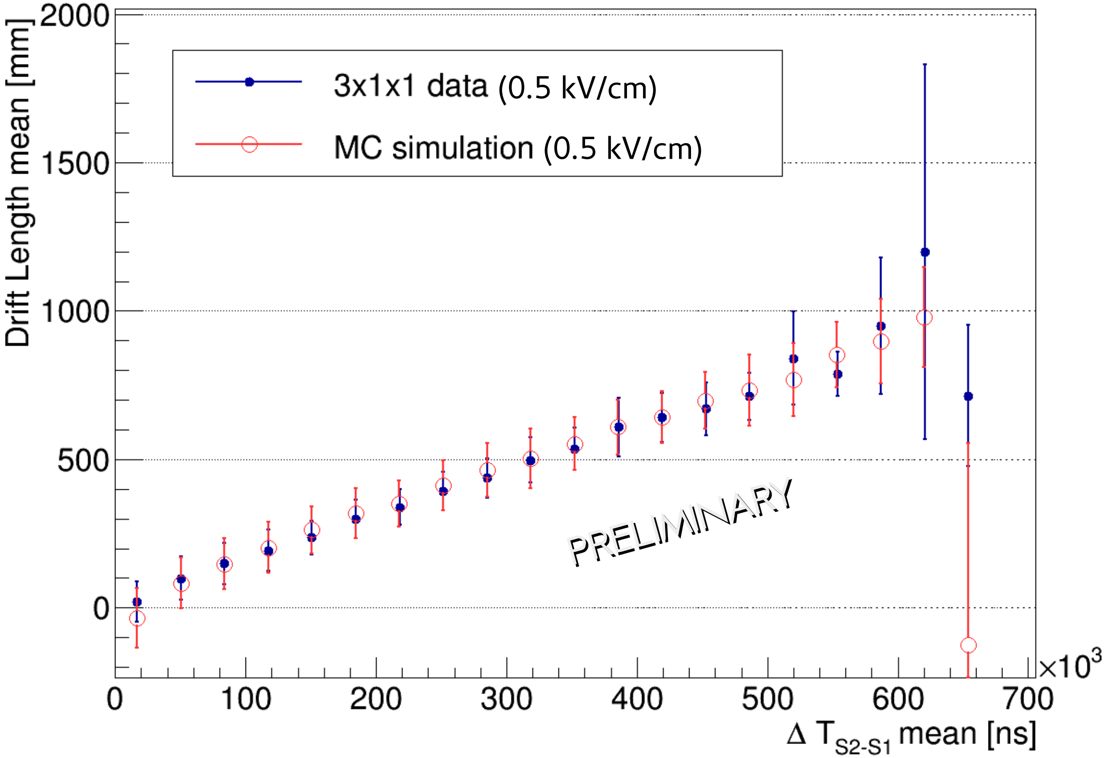
0.5 kV/cm drift	3x1x1 data
drift velocity	1.468 ± 0.119 mm/μs

Measurement of the drift velocity

:> global measurement by the 5 PMTs



gaussian fit on each slice of 25us (error bar from fit)

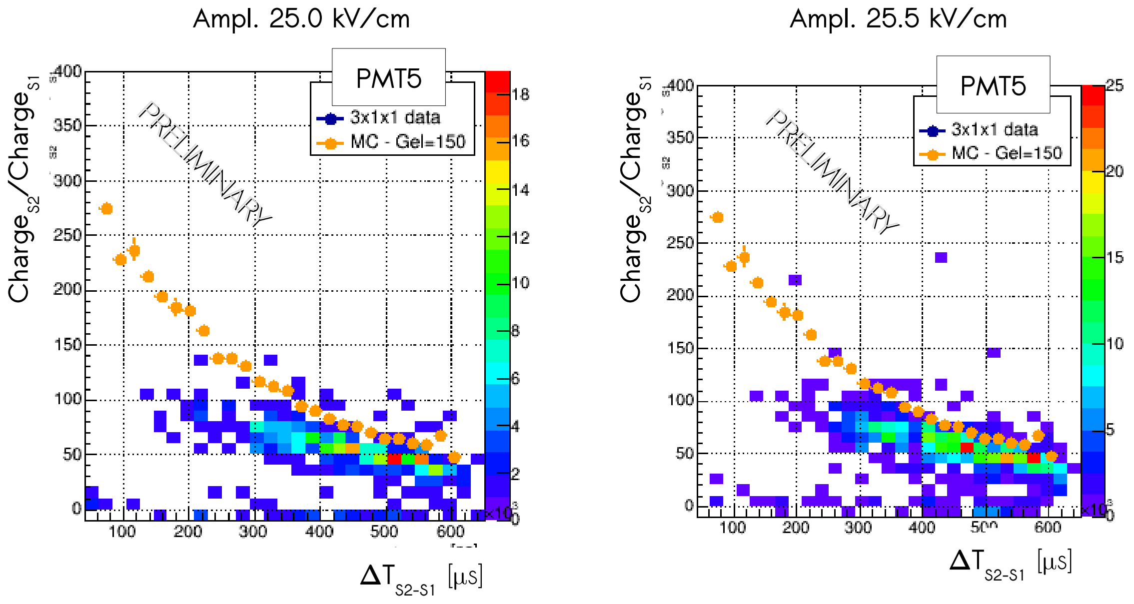


0.5 kV/cm drift	3x1x1 data	MC
drift velocity	1.468 ± 0.119 mm/μs	1.496 ± 0.131 mm/μs

the data-MC comparison shows a good agreement (within 2%)

The electro-luminescence light signal

:> preliminary studied of the electro-luminescence gain



:> still in early stage complicated by the presence of different contribution mixed together

- there are still other contributions that must be tested (e.g. Rayleigh scattering, e- diffusion, ...)

Conclusions

A lot of analysis have been performed and interesting results on the light production and propagation have been found

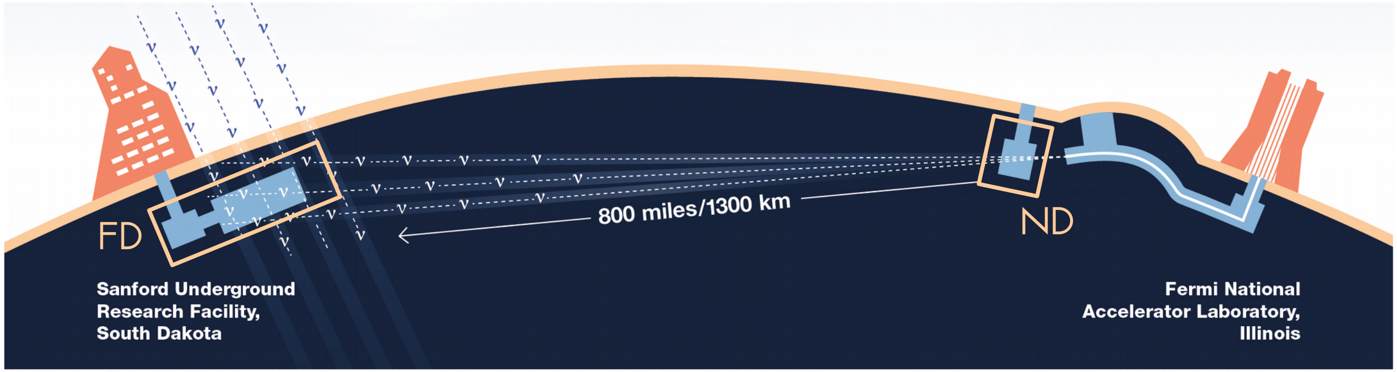
:> preliminary analysis that combine charge and light are ongoing

:> paper in preparation

:> more results from ProtoDUNE-DP

Backup slides

Deep Underground Neutrino Experiment (DUNE)



:> muon neutrino beam

:> Near Detector (**ND**) at FermiLab

:> Far Detector (**FD**) at SURF laboratory

:> Physics goals:

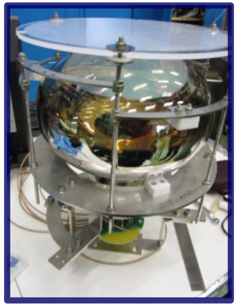
- measurement of neutrino flux in the FD (1300km away from ND)
  - → neutrino oscillation parameters from muon beam
  - → neutrino mass ordering
  - → CP violation phase in the leptonic sector

- sensitivity to non beam searches
  - → proton decay
  - → atmospheric neutrinos
  - → Super-Nova explosions

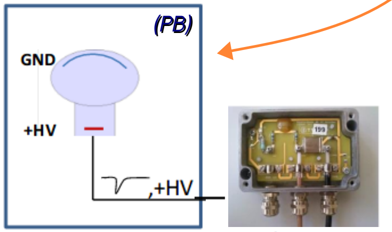
The light detection system of the 4 tonne demonstrator

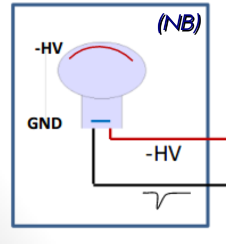
:> five R5921-02Mod 8" PMTs by Hamamtsu with different configuration:

- 2 TPB(*) coating (direct coating ○ , TPB on PMMA plate ◎)



- 2 bases configurations (positive ⊕ or negative ⊖ polarization)

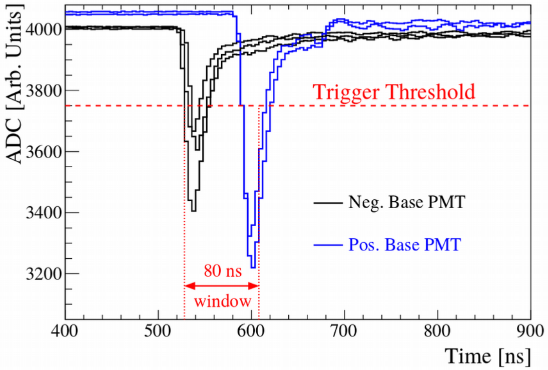




only one cable for power supply and signal

PMT trigger

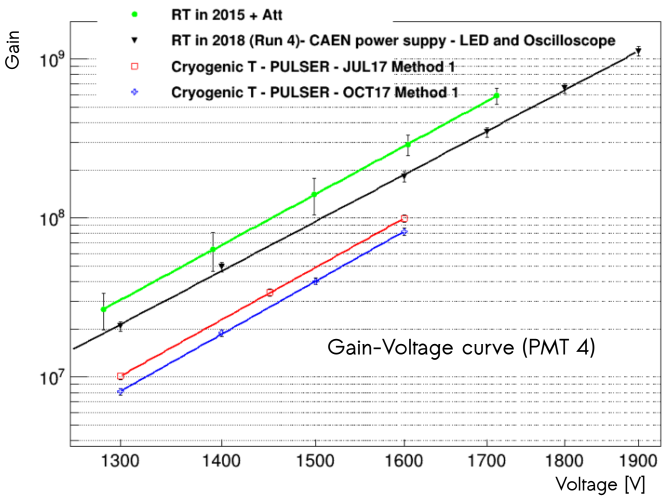
5 fold coincidence in a time window



Typical triggered event rate ~3 Hz *(~3mln of triggered ev.)*

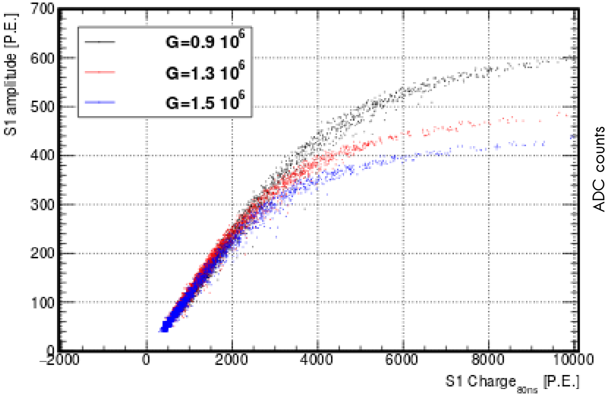
PMT characterization in the 3x1x1 detector

:> **PMT gain calibration** with dedicated random trigger runs

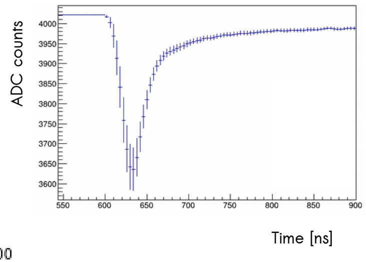


:> **PMT response characterization:**

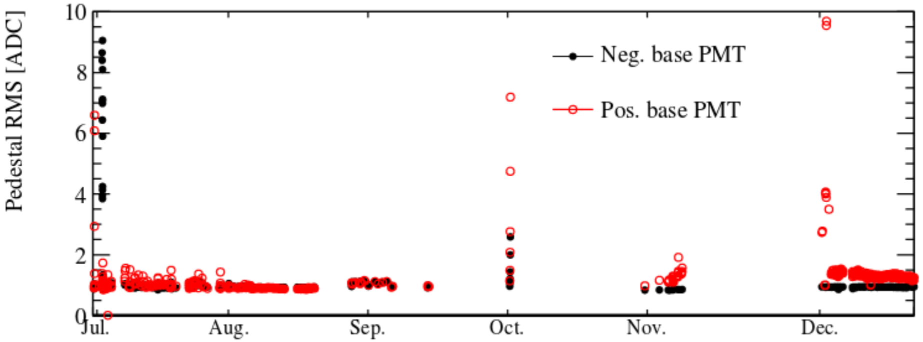
- saturation observed when a huge number of P.E. is collected in a short time (events removed)



typical PMT waveform

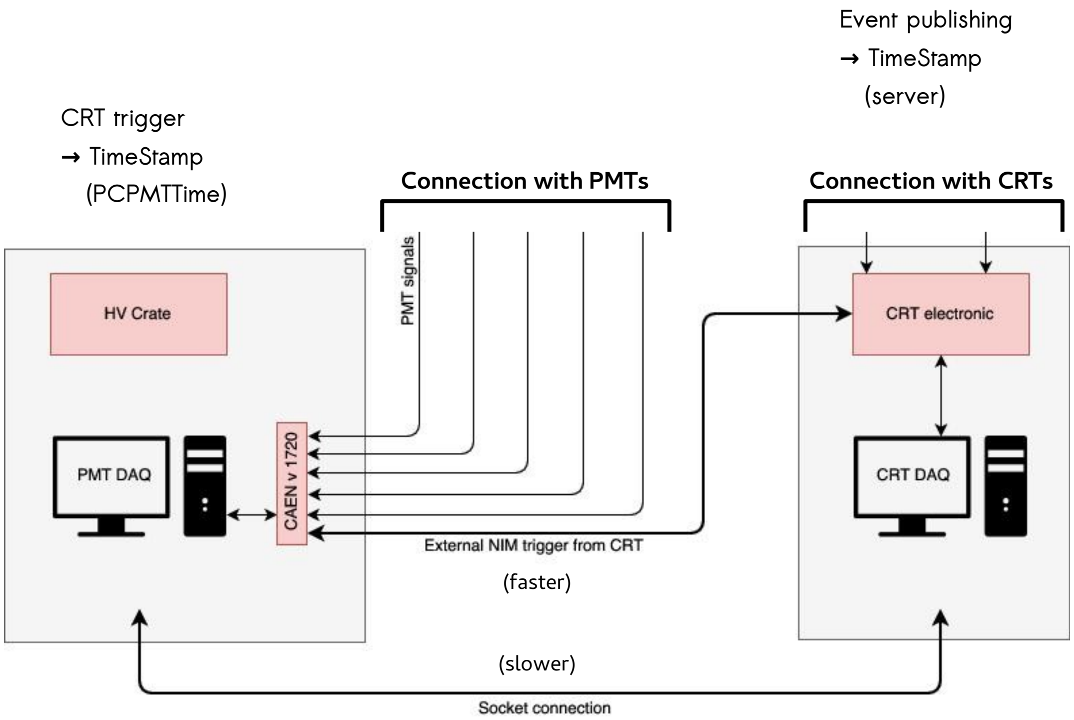


:> **PMT noise stability** monitored looking at the Pedestal RMS



CRT-PMTDAQ communication

- CRT trigger is created upon 4-fold coincidence among the 4 CRT panels (at least one strip per panel)
- CRT-DAQ publishes the event information on a ZMQ server
- PMTs are ridden-out upon receiving the external trigger from the CRTs
- PMT-DAQ query the ZMQ server to retrieve the event which generated the trigger



CRT-PMT DAQ times matching

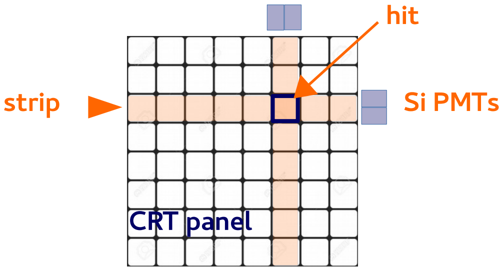
- CRT server pulled each 1s (max 10 events stored in the buffer)
- off-line matching of the events closest in time at the ms level

Muon selection in CRT analysis

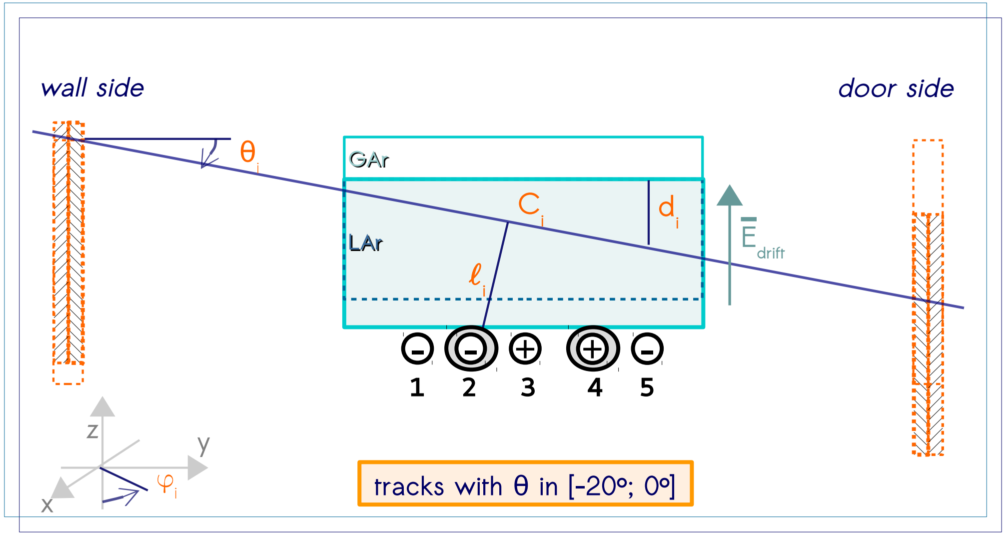
:> CRT and PMT information are matched within ms precision

:> from CRT panels it is possible to reconstruct a track if the trigger signal *fired* only 1 hit per panel (= only two strips with signal in SiPM)

:> CRT panels allow to have a good topology reconstruction of the muon tracks crossing the detector



CRT reconstruction



:> from CRT information it is possible to define:

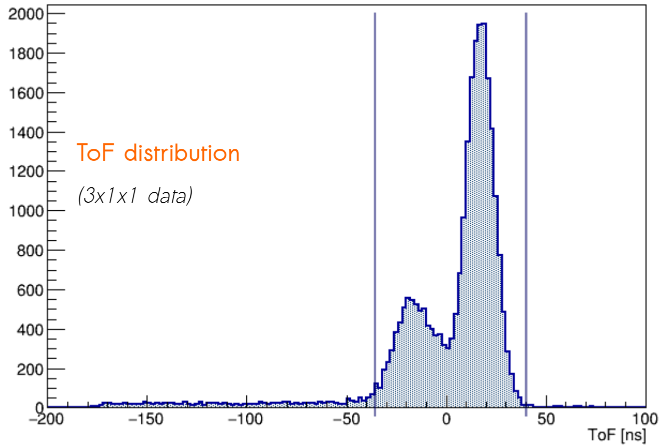
- the coordinates in the *door* and *wall* sides (x_{door}, y_{door}, z_{door} and x_{wall}, y_{wall}, z_{wall})
- ℓ_i, the minimum approach distance of the tracks from the center of the surface of each PMT
- the coordinates of the closest point C_i
- d_i, the drift length calculated from extraction grid level
- track length
- Time of Flight (ToF), time difference between the CRT trigger on the *door* side panels and the *wall* side ones

Muon selection in CRT analysis

quality cuts

	analysis cuts
	CRT-PMT DAQ matched ev.
	CRT reco ev. (1 hit/panel)
	no ADC saturation
	no. PMT response saturation
	inside LAr active volume
no fake CRT tr.	minimum S1 ampl. (ch by ch)
good ToF	-40<ToF<40
min track length	L>3100 mm

analysis cuts



The scintillation light signal

:> scintillation emission mechanism, two contirbutions in LAr: recombination luminescence (A) and self-trapped excitation luminescence (B)

(A): |i> = Ar+, then $Ar^+ + Ar \rightarrow Ar^+_2$

$Ar^+_2 + e^- \rightarrow Ar^{**} + Ar$

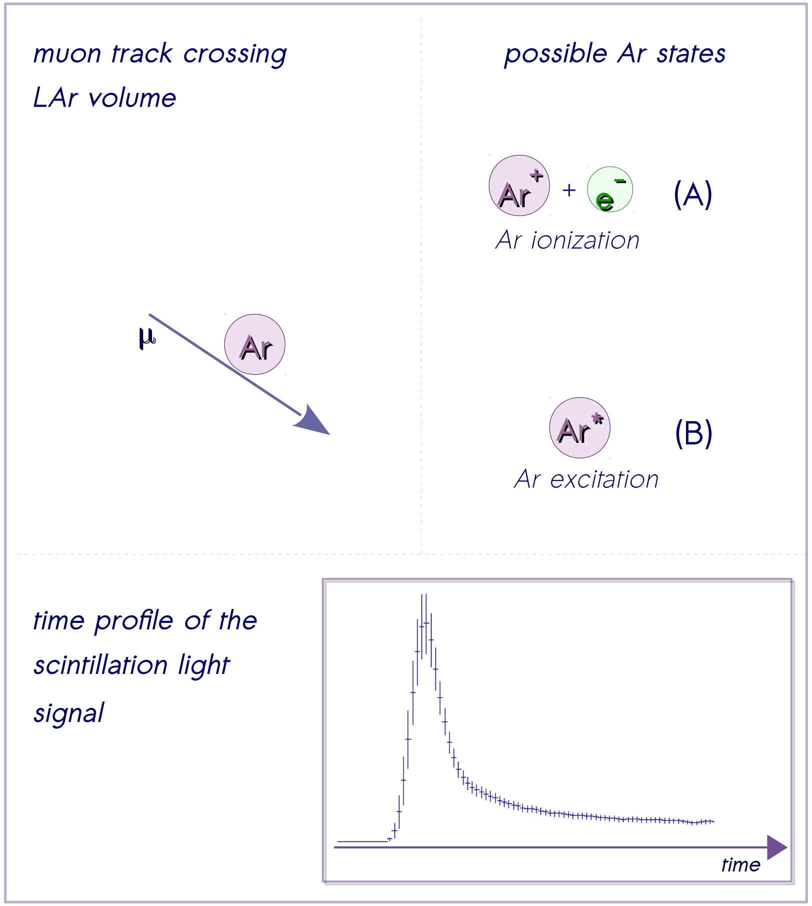
$Ar^{**} \rightarrow Ar^* + heat$

$Ar^* + Ar \rightarrow Ar^*_2$

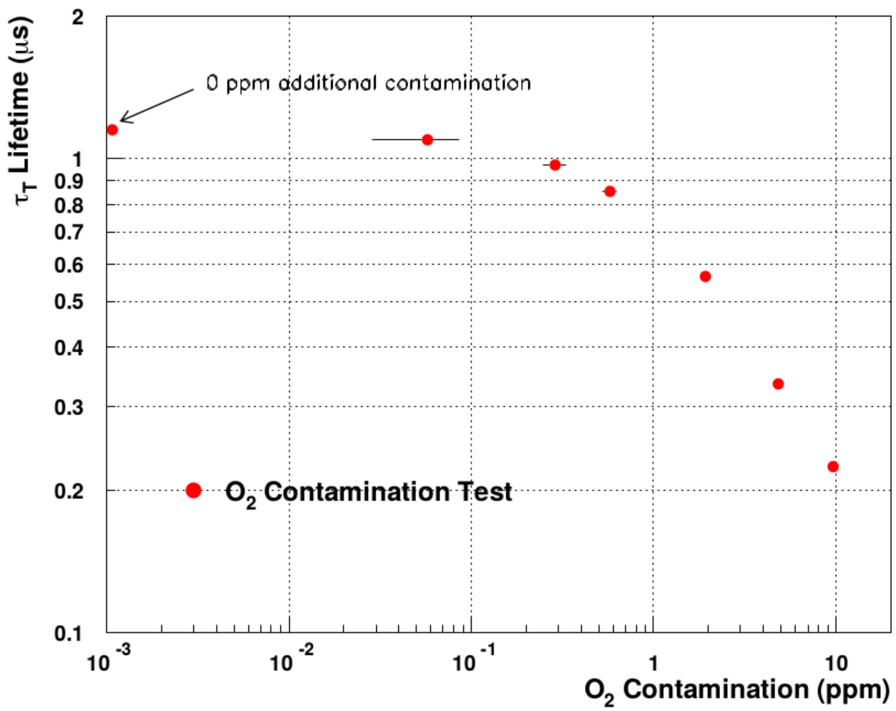
$Ar^*_2 \rightarrow Ar + Ar + h\nu$ (= scintillation light, γ)

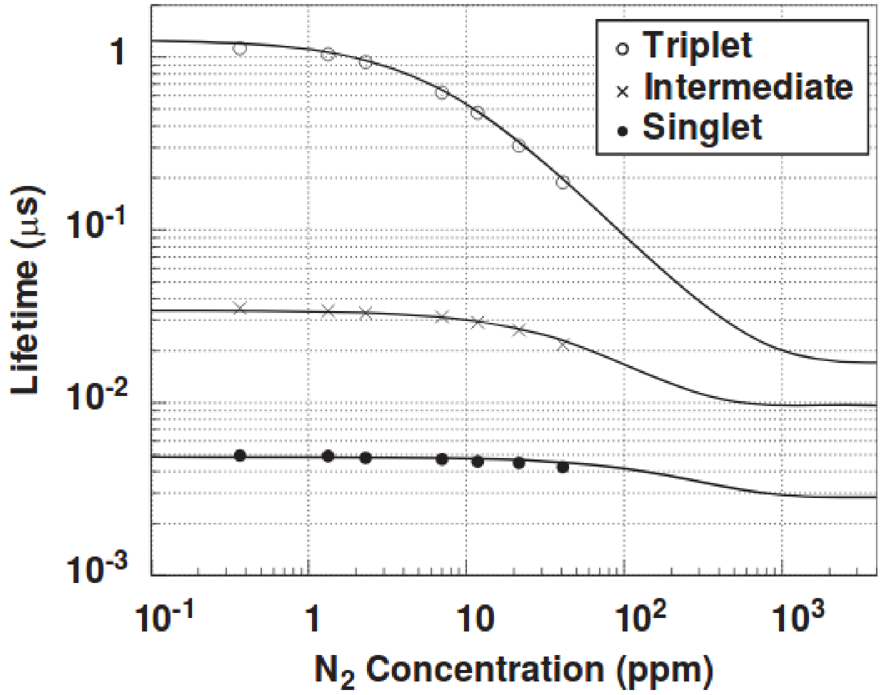
(B): |i> = Ar^*, then $Ar^* + Ar \rightarrow Ar^*_2$

$Ar^*_2 \rightarrow Ar + Ar + h\nu$ (= scintillation light, γ)



The scintillation light signal

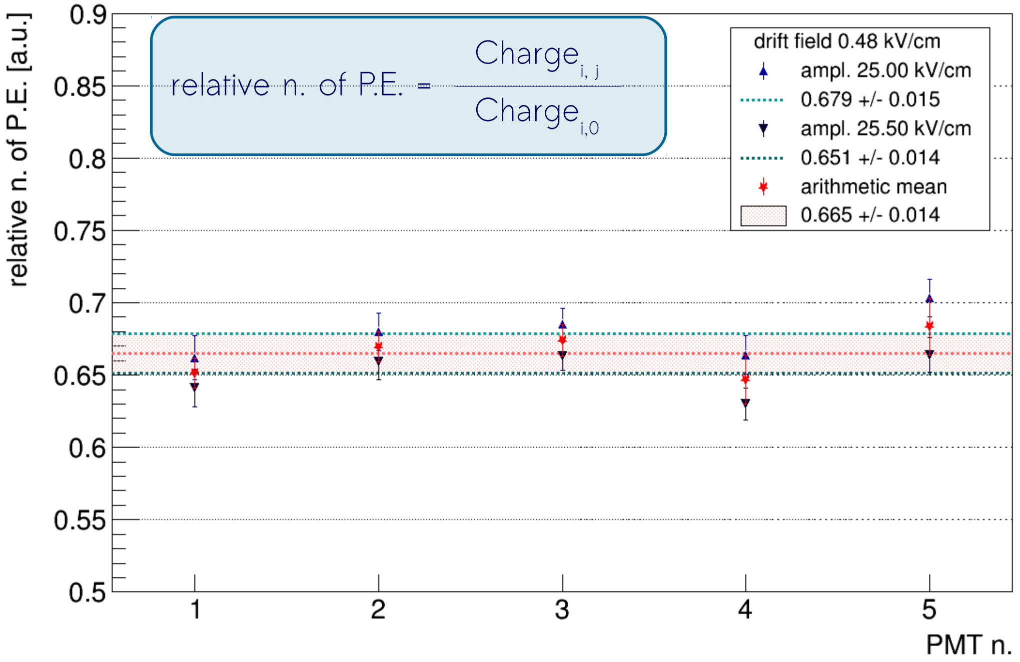




The scintillation light signal

:> Birk's law calculation has been studied for all the CRT runs available

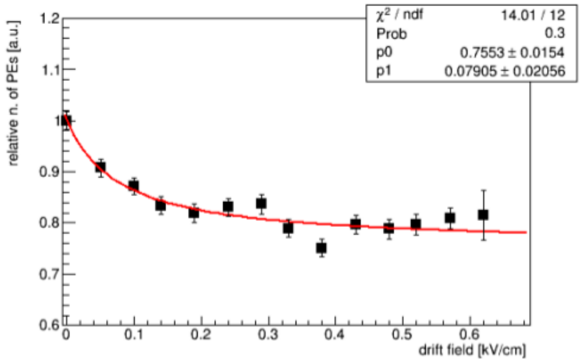
→ comparison among channels for runs at 0.48

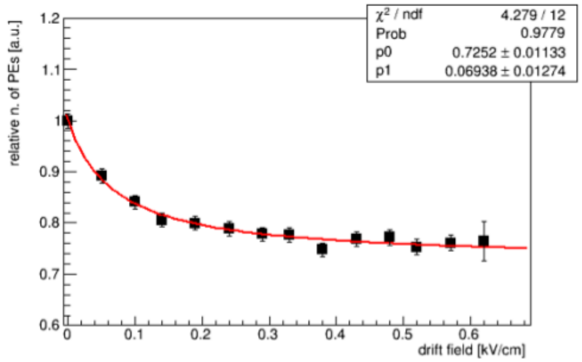


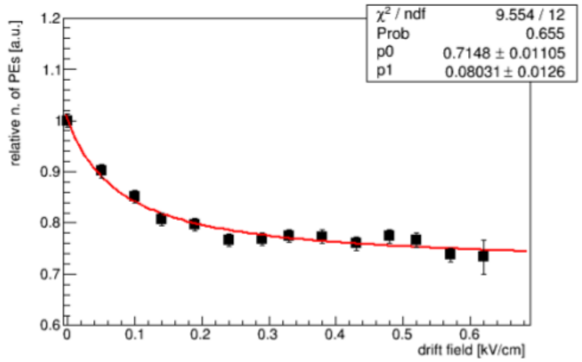
:> good agreement among the five PMTs (agreement within 3%)

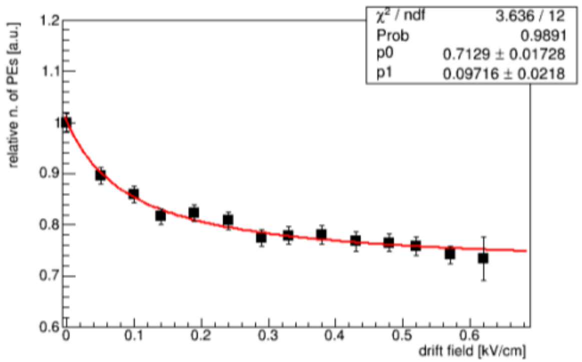
The scintillation light signal

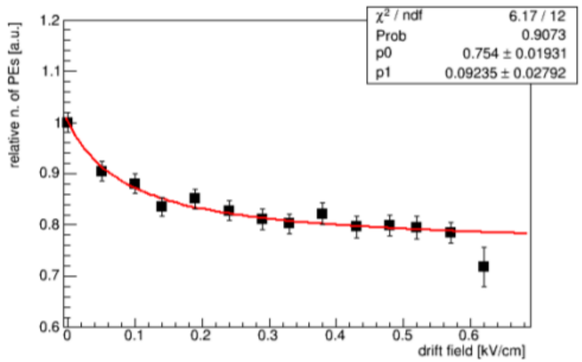
:> Birk's law calculation for runs triggered by PMTs











	p0 parameter
Ch0	0.76 +/- 0.02
Ch1	0.73 +/- 0.01
Ch2	0.71 +/- 0.01
Ch3	0.71 +/- 0.0.2
Ch4	0.75 +/- 0.02

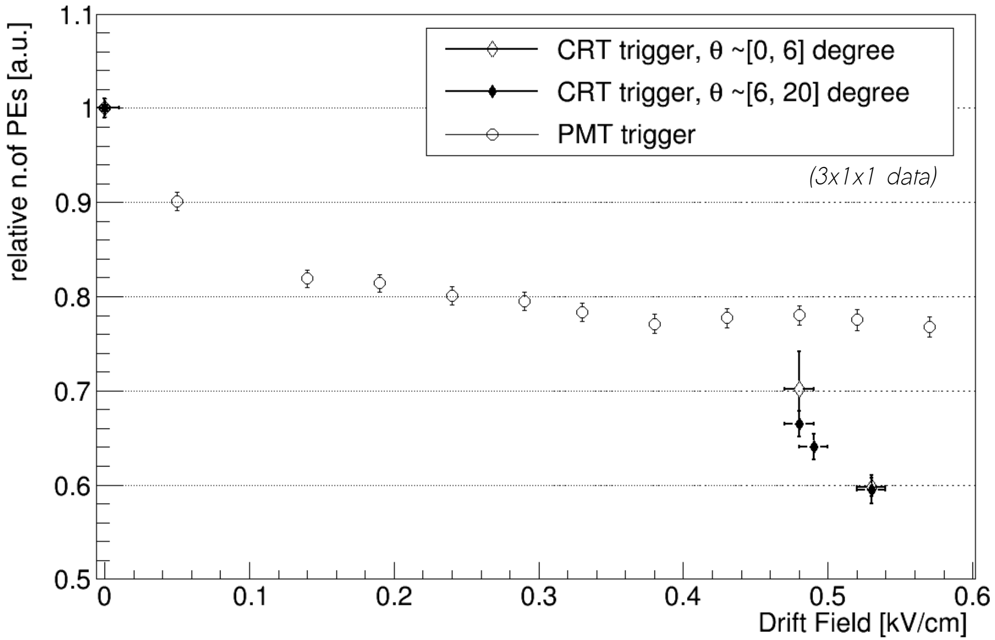
- reached the agreement among all channels: <p0> = 0.73 +/- 0.02 (preliminarily, ~27% of recombined charges)

The scintillation light signal

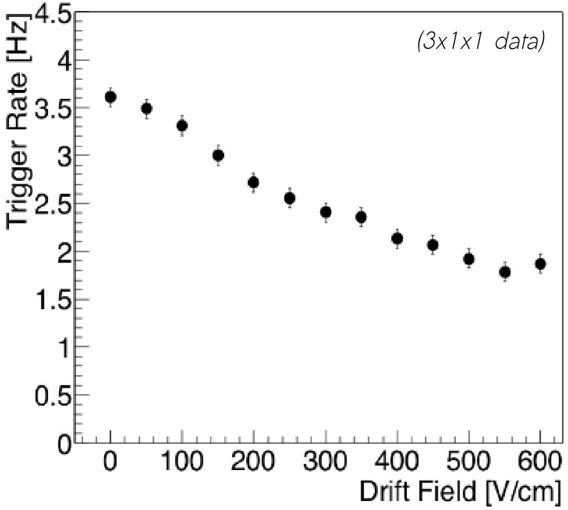
:> a drift scan was performed with PMT trigger and no charge collected

- Birk's law calculation has been studied
  - → good agreement among the 5 channels (within 3%)
  - → same threshold for all the drift field applied (increasing the drift field, lower energetic particles are lost)

- runs triggered by PMTs cannot be analyzed as the ones triggered by CRTs
  (if the light information is combined with charge information we can perform a similar analysis - studies on going)



Trigger rate vs drift field
(fixed threshold ~ 3775 ADC counts)



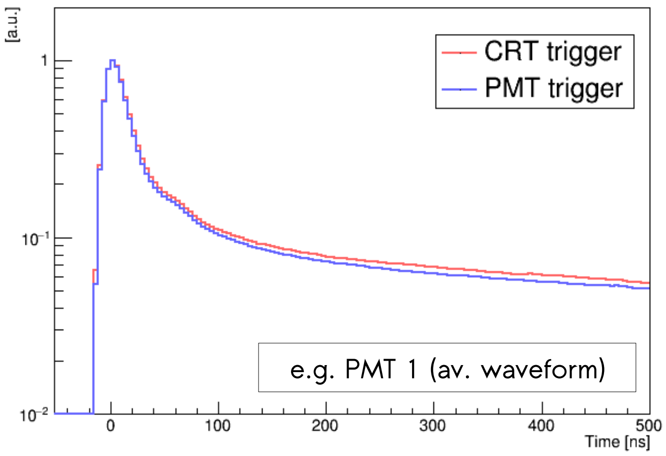
The scintillation light signal

:> study the fit on waveforms filled in different range of S1 amplitudes (using step of 200 ADC counts)

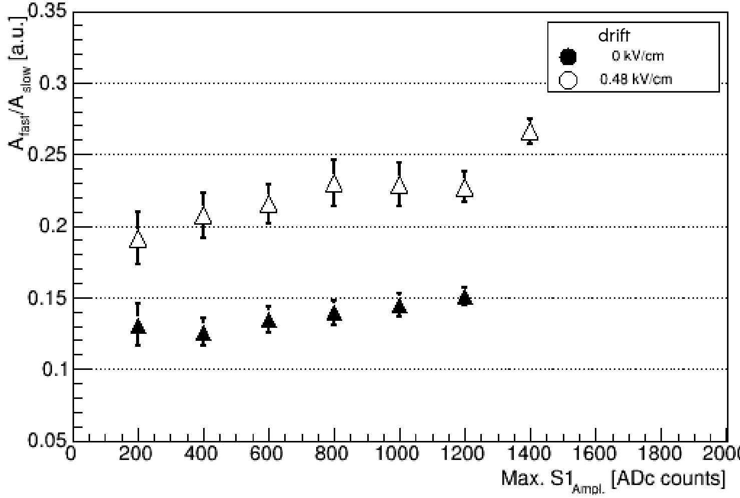
:> difference in the ratio A_{Fast}/A_{Slow} due to the trigger (with and without drift field)

- comparison between CRT and PMT trigger selection
  - → higher the S1 amplitude, higher the ratio (in CRT trigger)

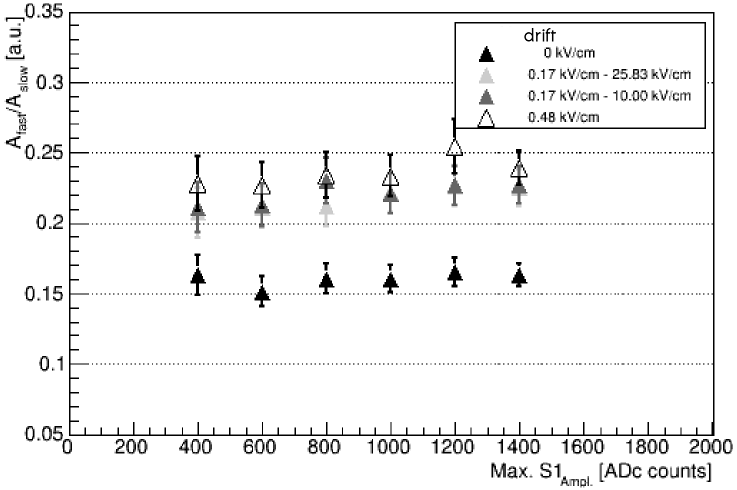
:> hint for explanation: dependence with the energy lost by the crossing particle (higher S1 amplitude, higher LET)



CRT trigger

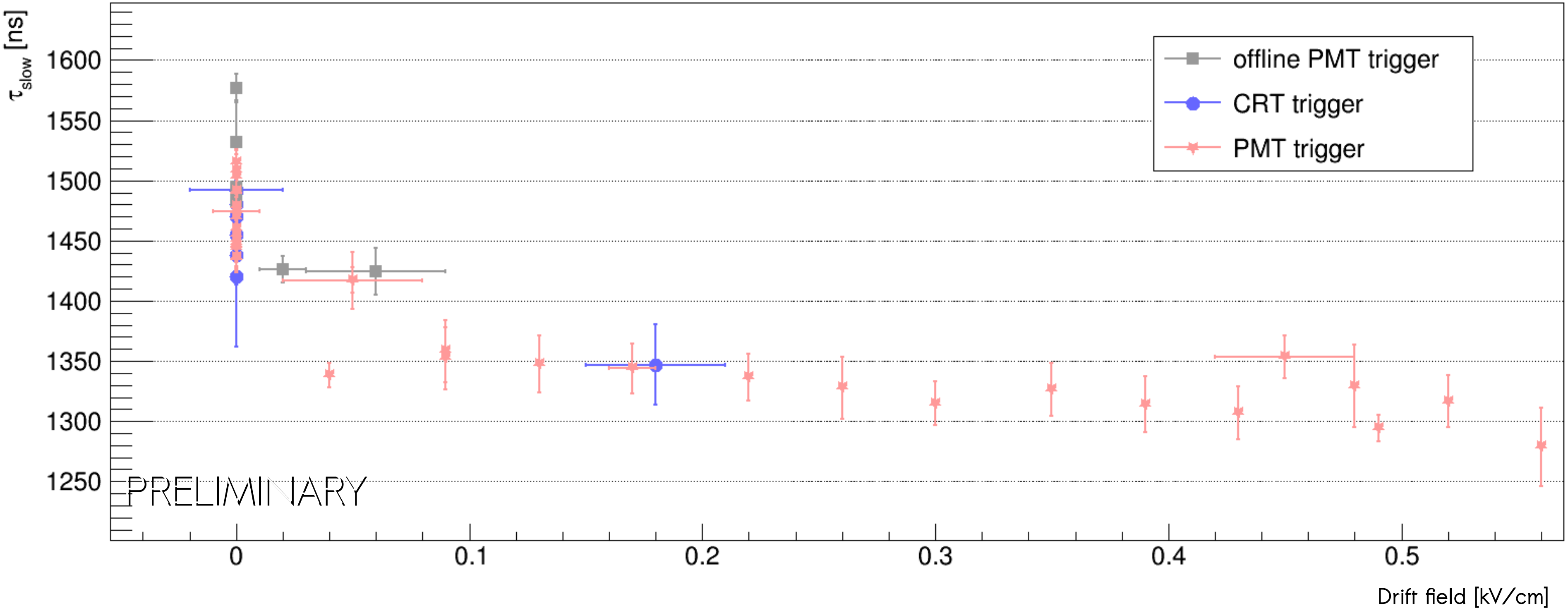


PMT trigger



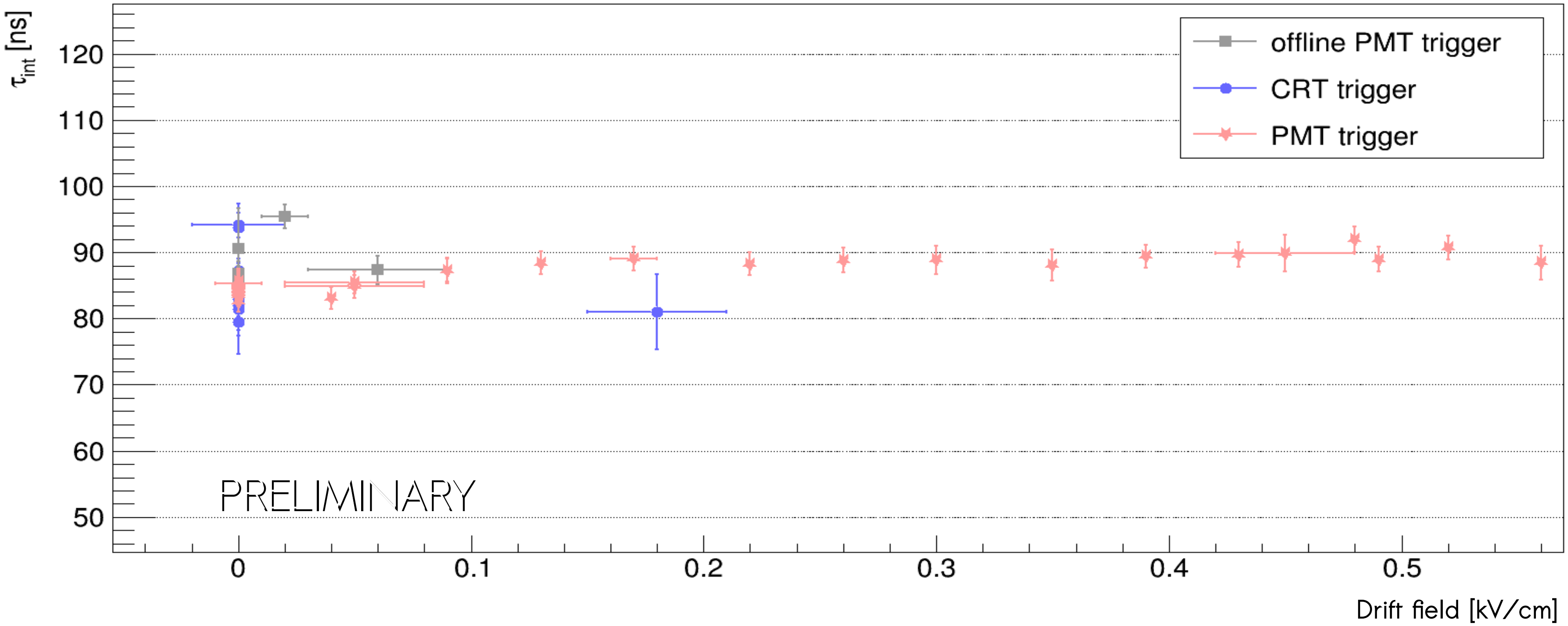
The scintillation light signal

:> decreasing of the τ_{slow} due to the increasing of the drift field

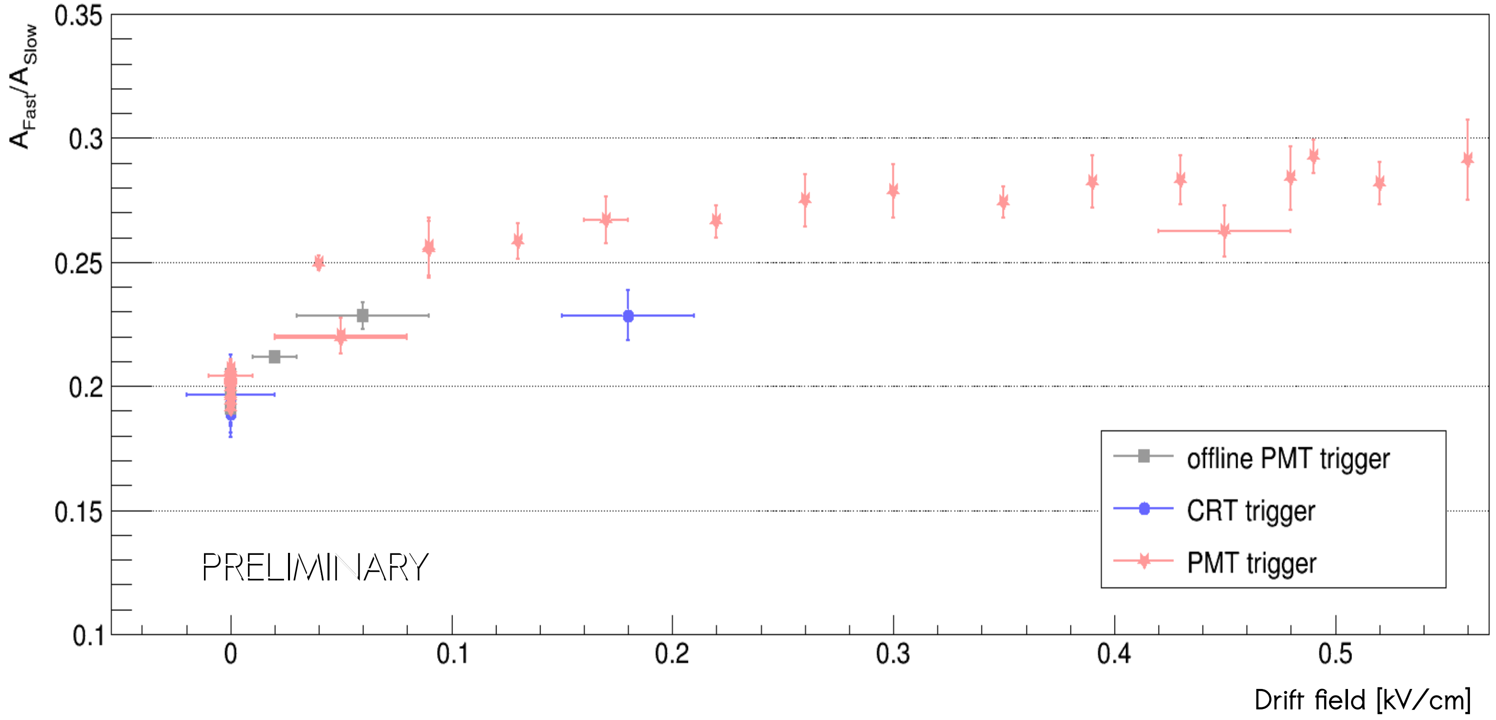


The scintillation light signal

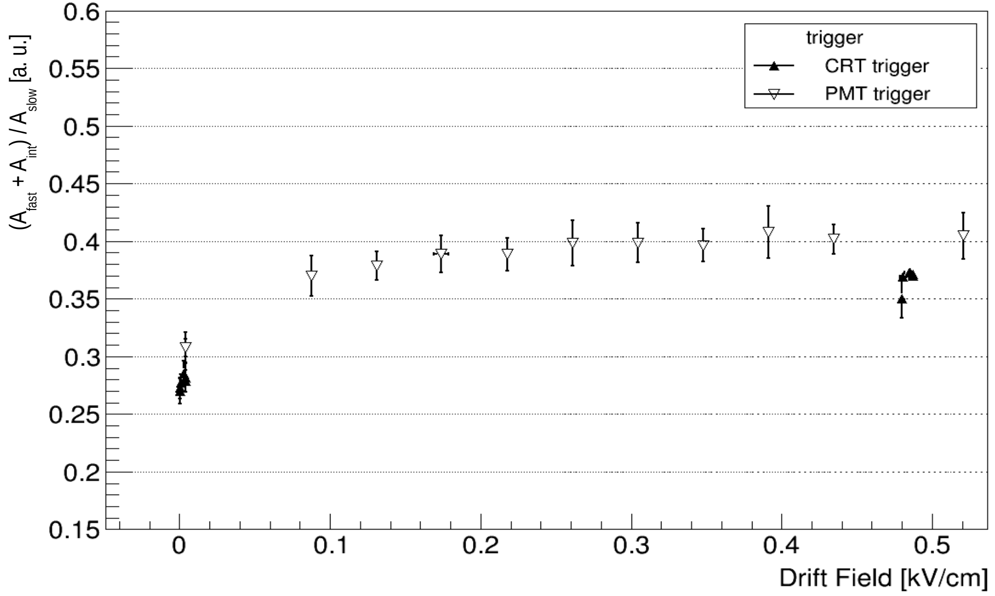
:> study of the **intermediate component**, τ_{int} as a function of the drift field

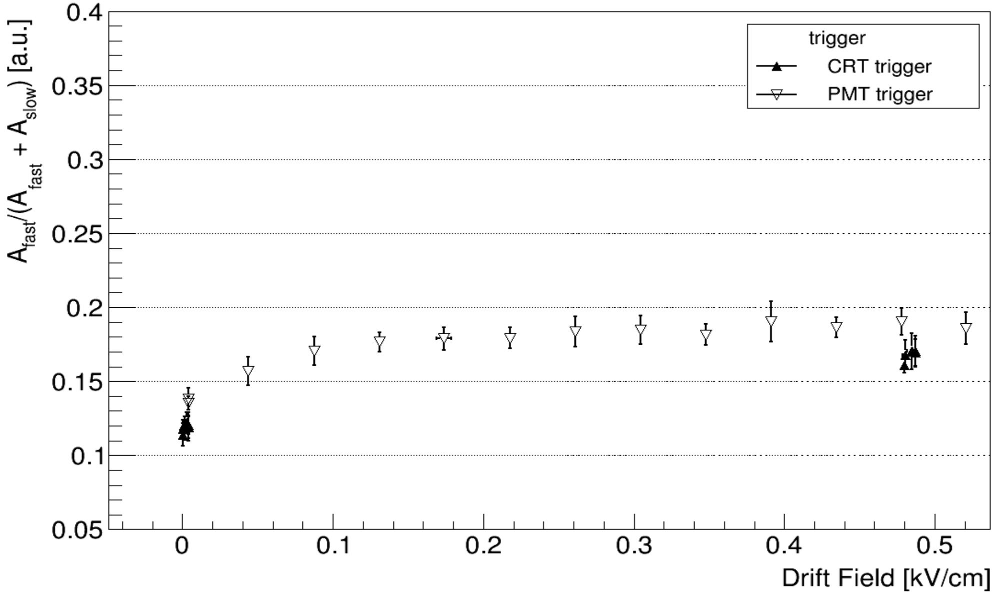


The scintillation light signal

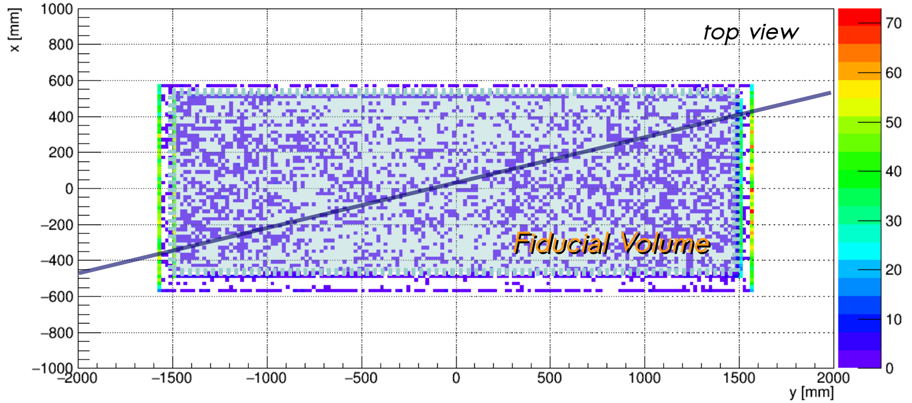


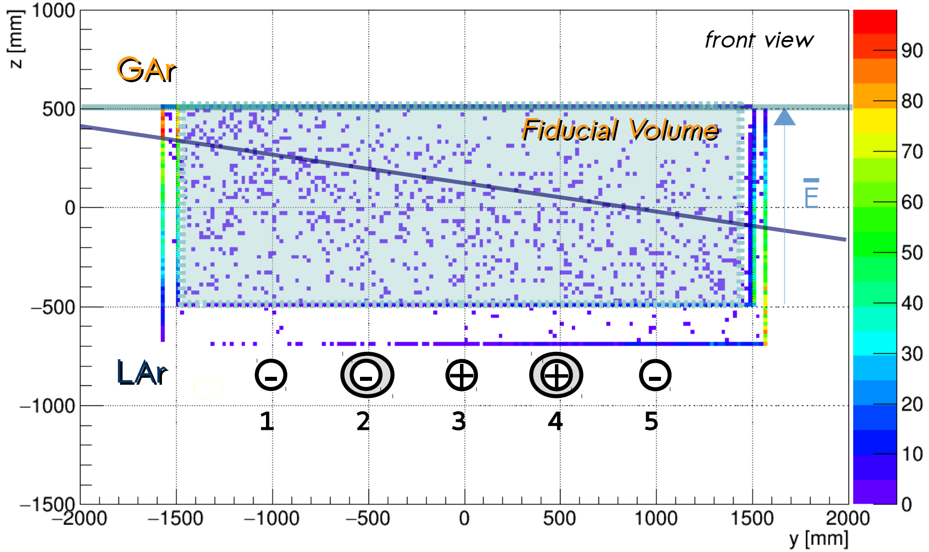
The scintillation light signal





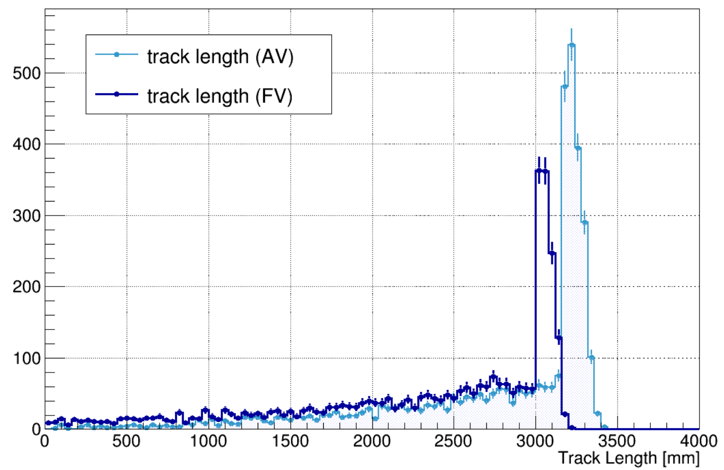
MC simulation





:> two volumes can be recognized:
→ LAr Active Volume
→ Fiducial Volume (FV, LAr volume under CRP surface)

:> only long tracks are accepted
→ in the S1 analysis, inside the AV
→ in the S2 analysis, inside the FV

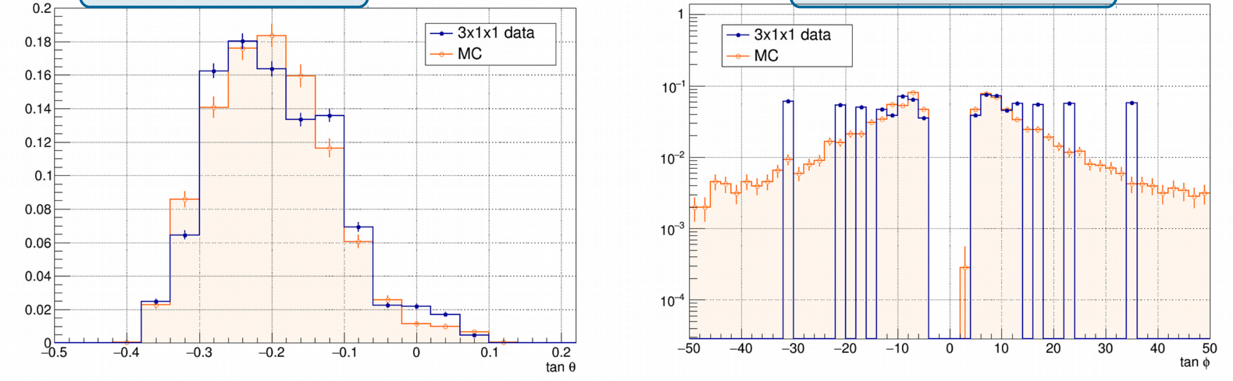


Data-MC comparison - geometric reconstruction

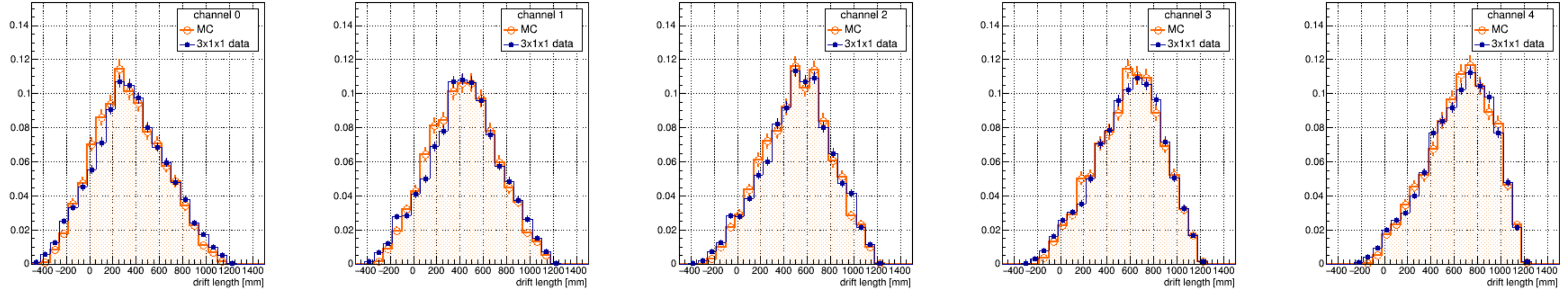
- geometric reconstruction

θ ∈ (-20; 6) degree

φ ∈ (-180; 180) degree



drift length



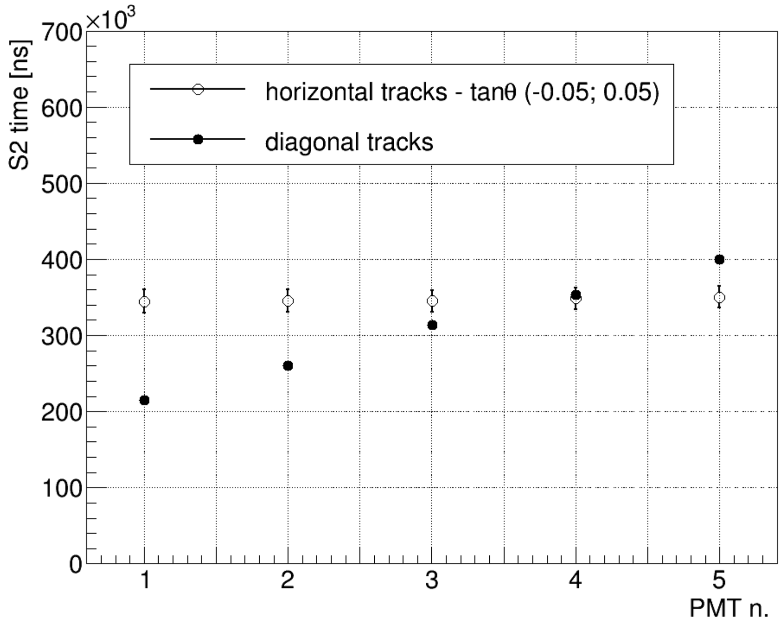
MC simulation

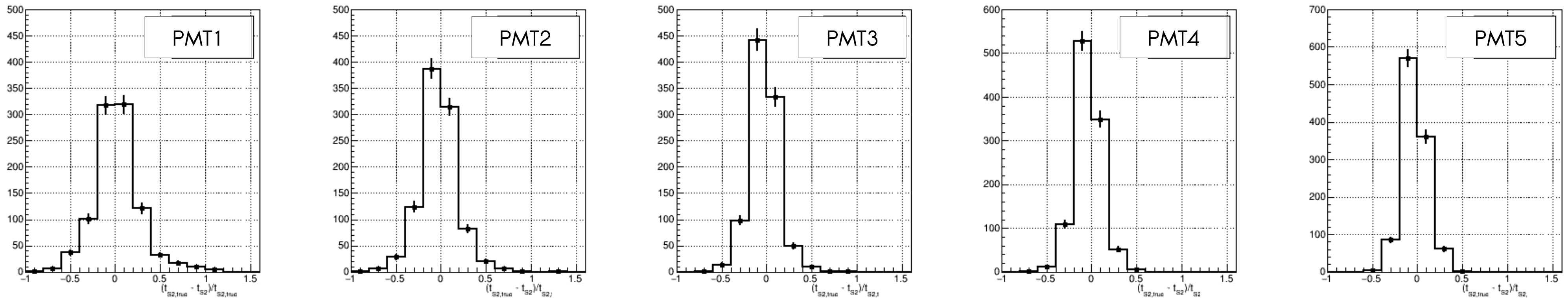
S2 time reconstruction

:> comparing the expected time ($t_{S2,true}$) with S2 time found with the algorithm

→ in each channel the distribution $(t_{S2,true} - t_{S2})/t_{S2,true}$ is symmetric and it is well centered in 0, σ~0.17, on average

:> S2 time reconstructed follow the expected behavior given the track geometry



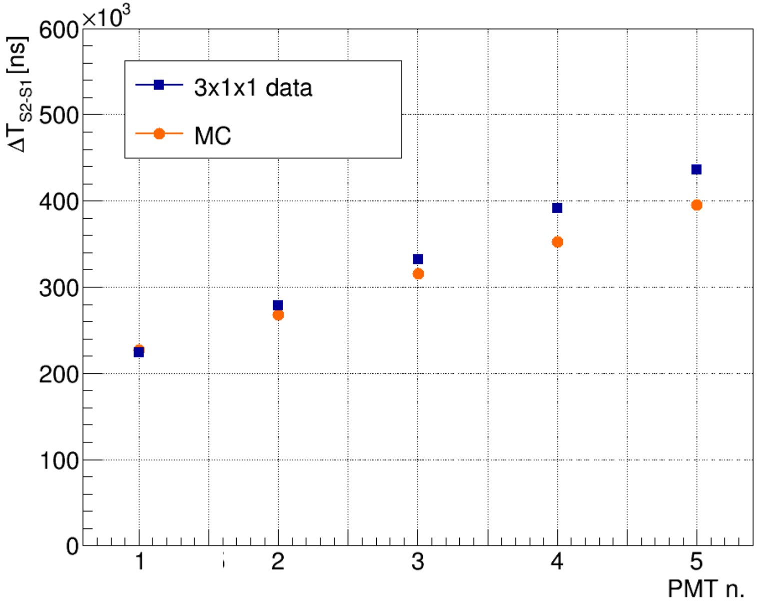


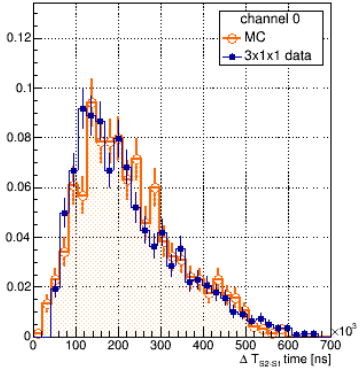
S2 algorithm performance, data-MC comparison

ΔT_{S2-S1} time

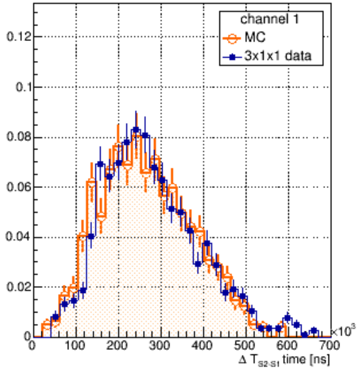
:> algorithm applied to the data and in MC
(drift field = 0.49kV/cm, ampl. field = 25.5 kV/cm)

:> quite good agreement in the comparison with the data
→ discrepancy in Ch3 and Ch4 where the drift length of the electrons is longer (under investigation)

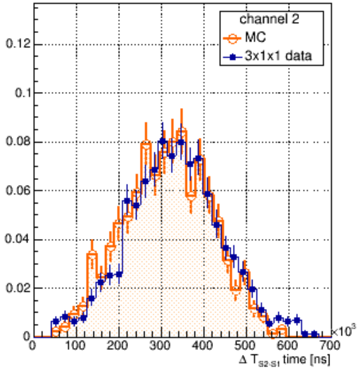




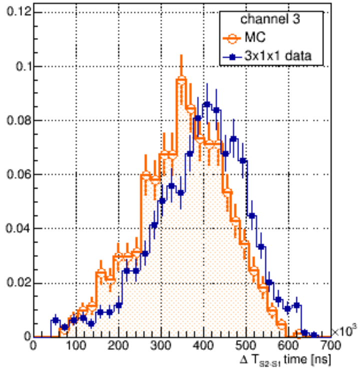
PMT1



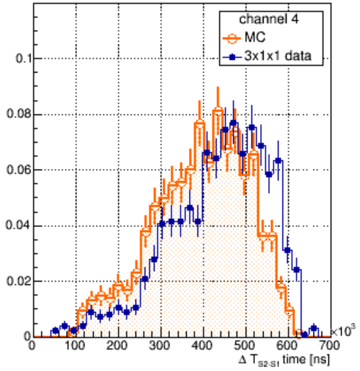
PMT2



PMT3



PMT4



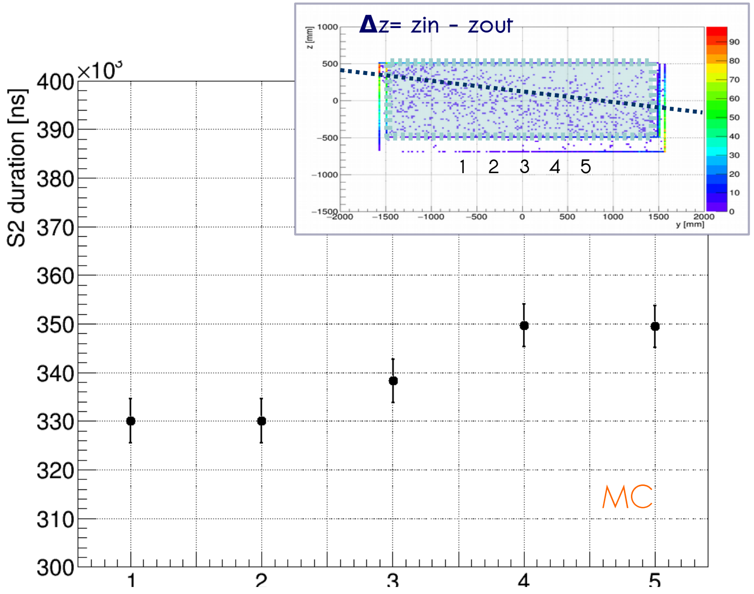
PMT5

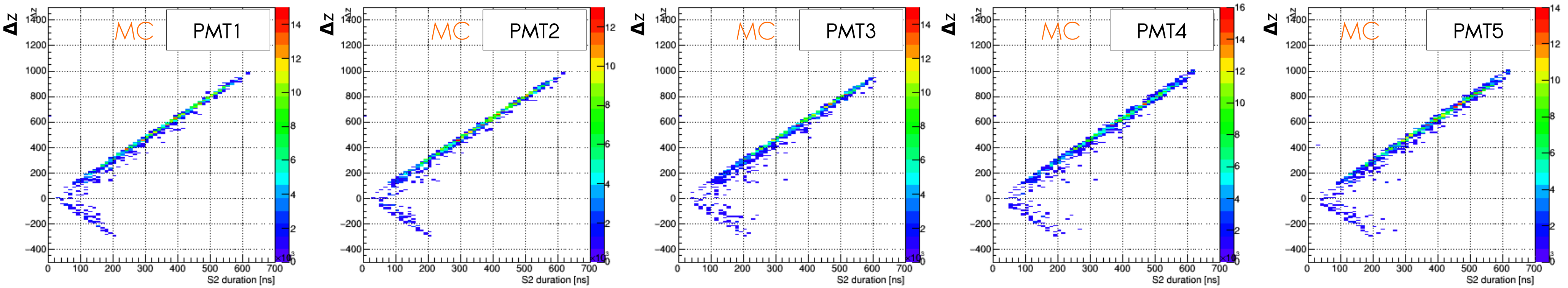
S2 algorithm performance, data-MC comparison

S2 duration

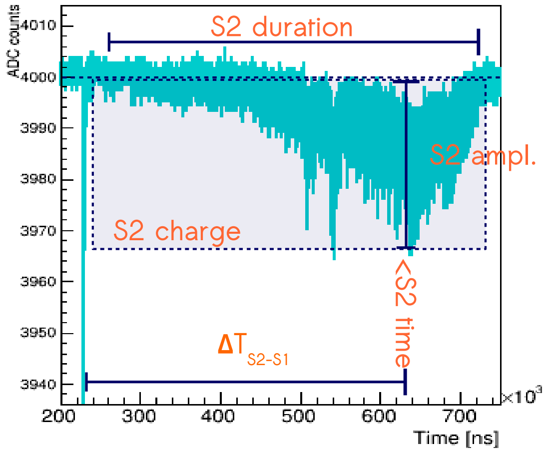
:> measurement of the S2 duration

→ more diagonal is the track and longer is expected to be the S2 signal



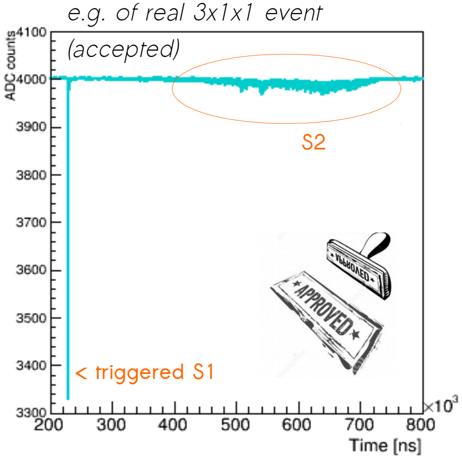


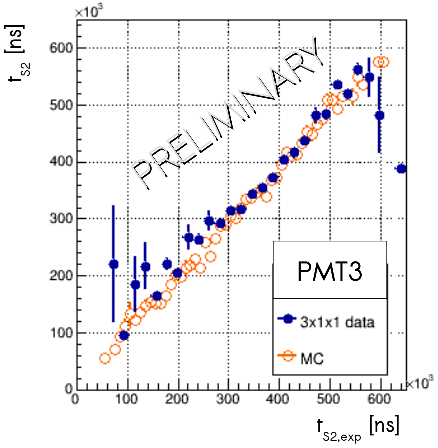
All other measurement and results from data-MC comp.

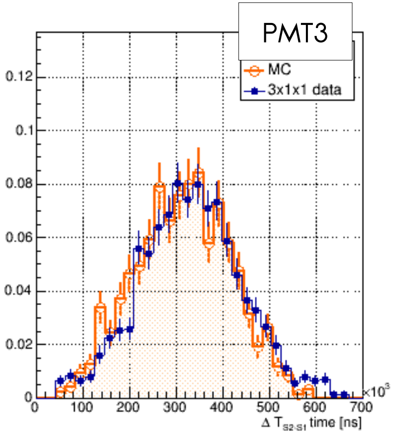


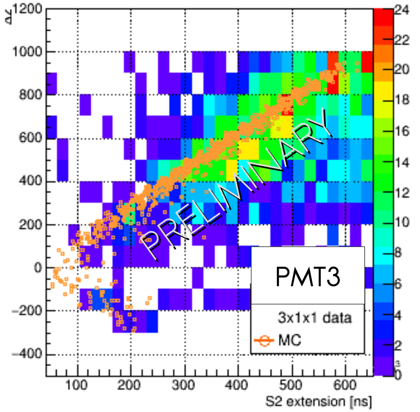
:> electro-luminescence gain 150 and 300 γ/e- isotropically generated and propagated

→ field lines studies favor lower gain and more focused production (on going studies)



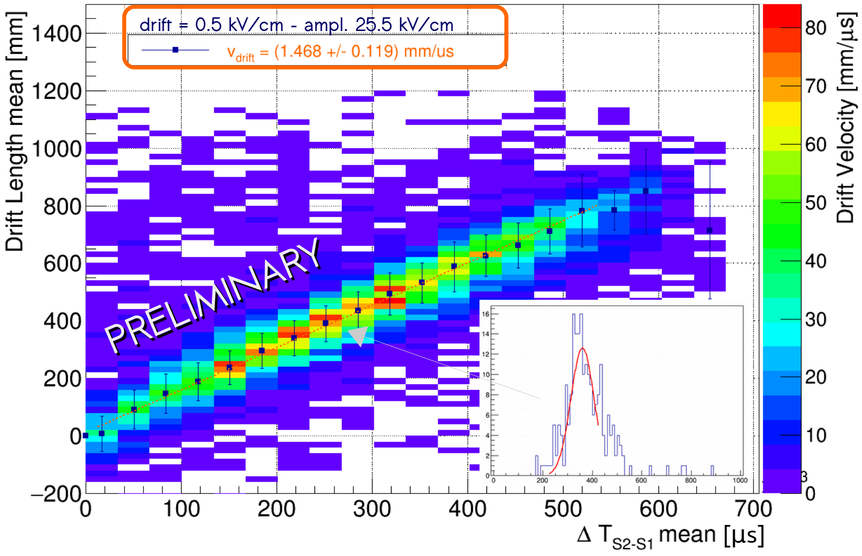




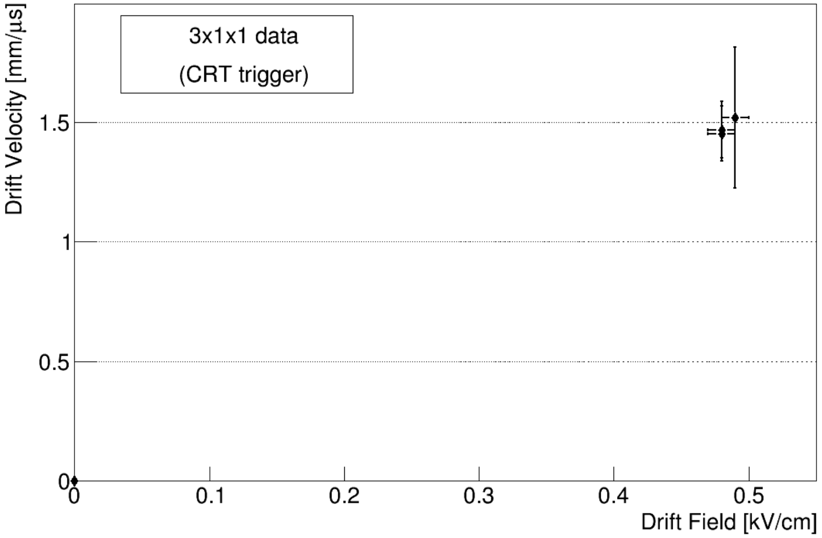


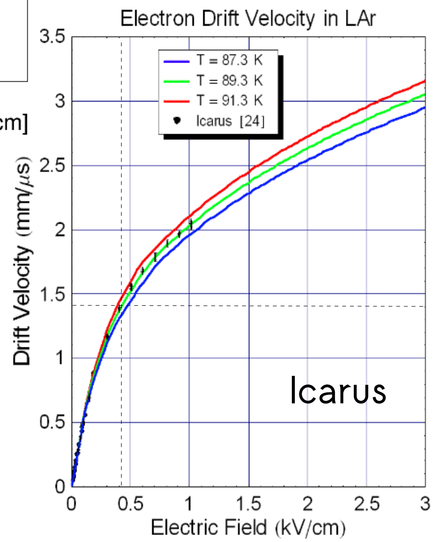
Drift velocity

:> the drift velocity has been calculated for the runs triggered by CRTs, due to the low statistic only two runs can be used



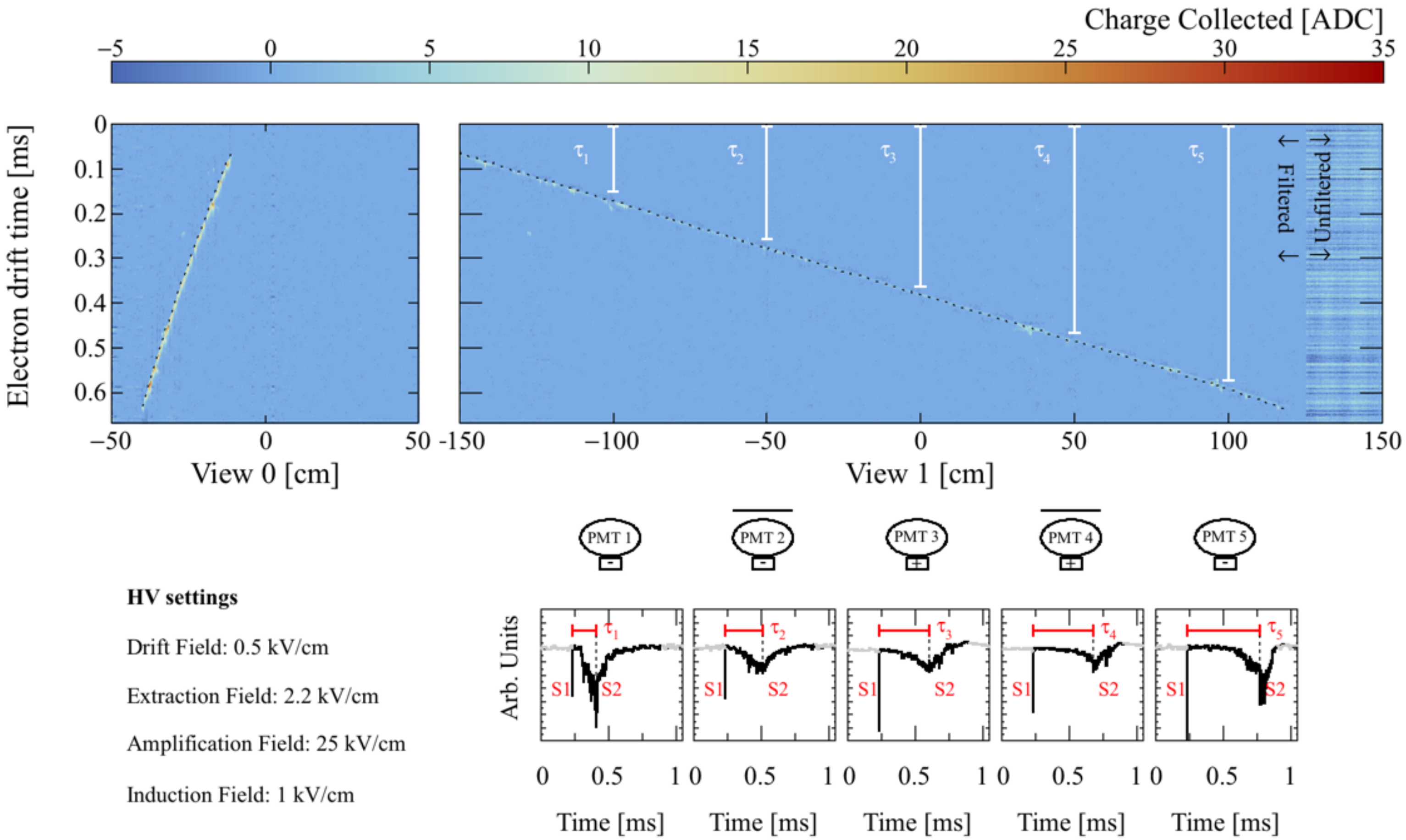
gaussian fit on each slice of 25us (error bar from fit)





:> quite good agreement with Icarus studies on the drift velocity depending on the temperature of the LAr (the LAr temperature in the 3x1x1 demonstrator was at 89 K)

Charge-Light analysis



HV settings

Drift Field: 0.5 kV/cm

Extraction Field: 2.2 kV/cm

Amplification Field: 25 kV/cm

Induction Field: 1 kV/cm

Some plot CRT-PMT like charge vs track-pmt dist?