PRODUCTION AND PROPAGATION OF THE SCINTILLATION LIGHT IN LAR-TPCS: FROM PROTOTYPES TO BIGGER DETECTORS

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OUTLINE

1. Motivation, the Deep Underground Neutrino Experiment
   - Light detection systems in the DUNE far detector modules
   - Detailed dscription of the WA105-DP demonstrator

   INTRODUCTION

2. Detailed analyses of the scintillation light signal in the WA105-DP demonstrator
   - Primary scintillation light
   - Secondary scintillation light

   PHYSICS RESULTS

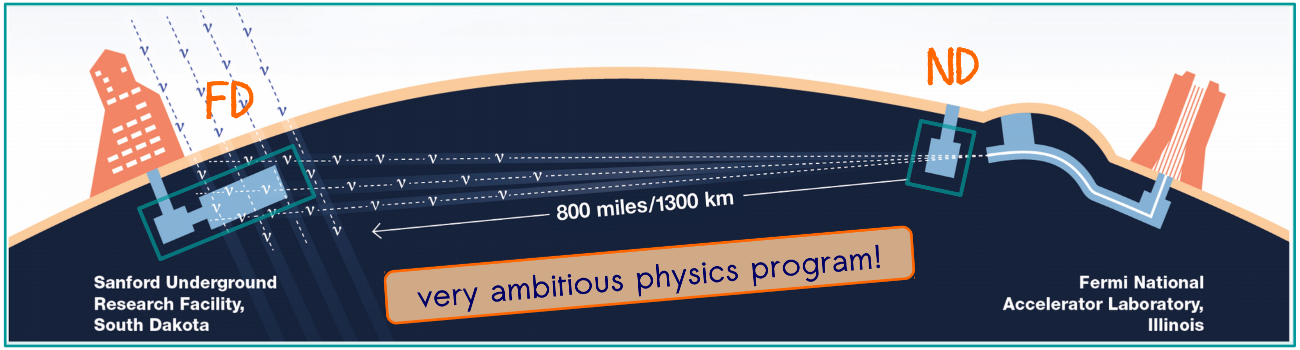
3. Outlook and comparison with bigger LAr-TPCs (ProtoDUNEs)

4. Summary

INTRODUCTION

WHY? → WHAT? → HOW?

THE DEEP UNDERGROUND NEUTRINO EXPERIMENT

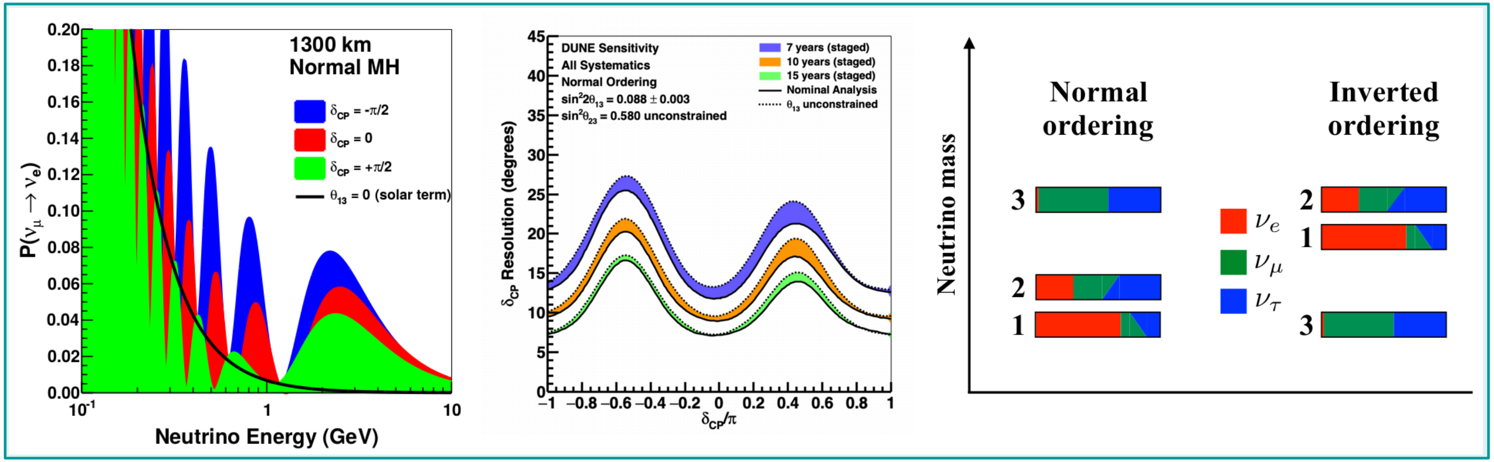


:> most powerful **(anti) ν_μ beam**

:> in the **USA** (31 countries, more than 1000 scientists)

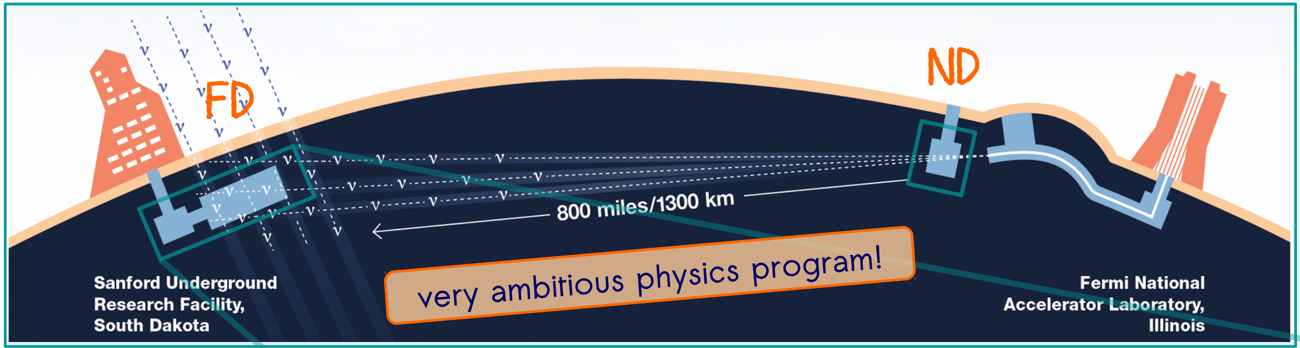
PHYSICS GOALS OF THE DUNE EXPERIMENT

- precise measurement of the **neutrino oscillation parameters**, **CP violation** sensitivity in the leptonic sector, **mass ordering**
- **non beam physics** (Supernovae neutrinos, solar neutrinos, proton decay searches, etc..)



for more details: J. Dawson seminar

THE DEEP UNDERGROUND NEUTRINO EXPERIMENT



:> most powerful **(anti) ν_μ beam**

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

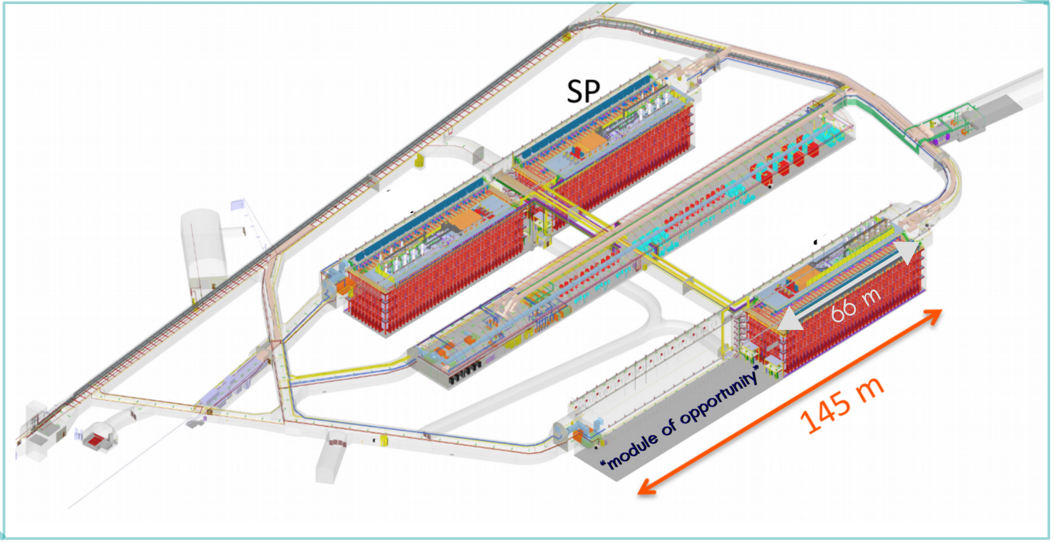
:> **Far Detector** (FD) at SURF laboratory

- operation of GIANT LAR-TPCS for neutrino detection

4 X 10 KTON LAR-TPC MODULES

- **single** (SP), **dual-phase** (DP) or other technologies
- 3D track reconstruction at high resolution
- none of them operated so far at such a giant scale!

building and operating smaller prototypes is crucial



ADVANTAGES OF USING ARGON

:> **noble gas**, third element most **abundant** gas in the atmosphere (~1%)

- **cheap** for using in big detectors

:> it is **dense** (1.4 g/cm^3) and **inert**

- **significant energy deposition** of crossing particles

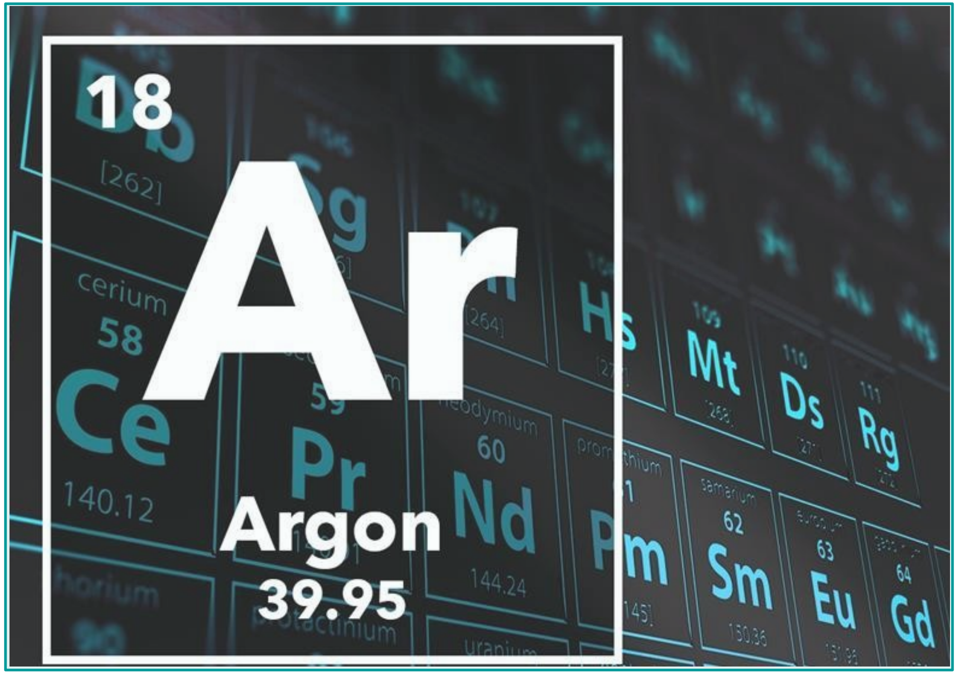
:> large **dielectric rigidity**,

- **high voltage** in **long drift paths**

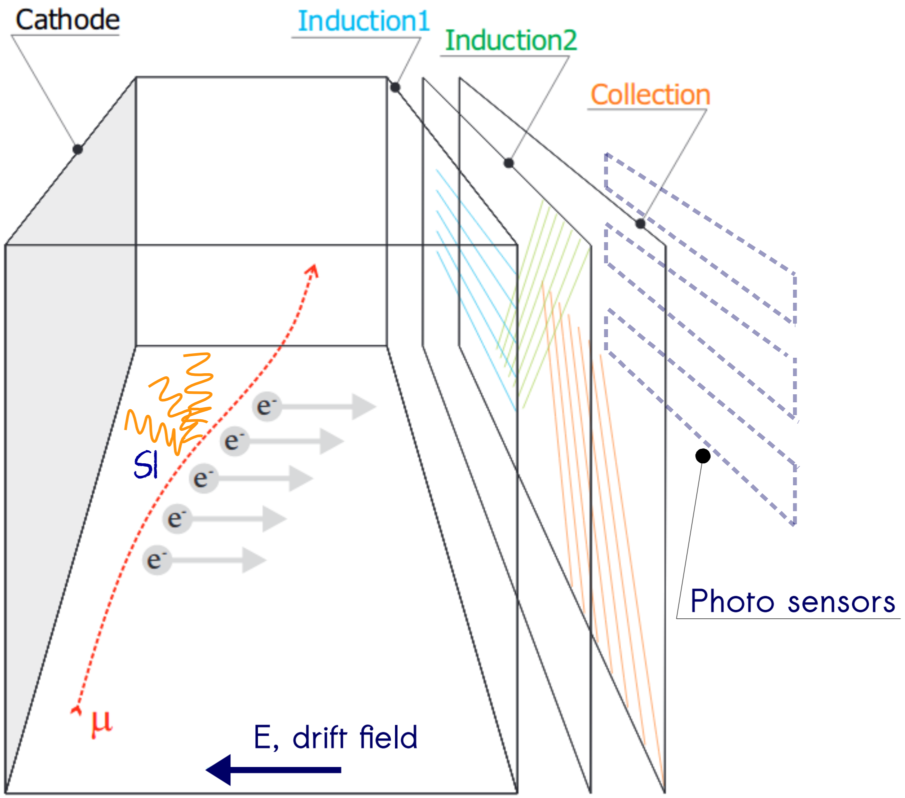
:> strong **scintillation power** (~5x10^4 photons/MeV)

- good **pulse shape discrimination**
- **transparent to its own scintillation light**

:> good **purification** by freezing out impurities from its liquid state



SP LAR-TPC WORKING PRINCIPLES



Picture adapted from B. Abi et al. JINST 15 T08008 (2020)

CHARGE:

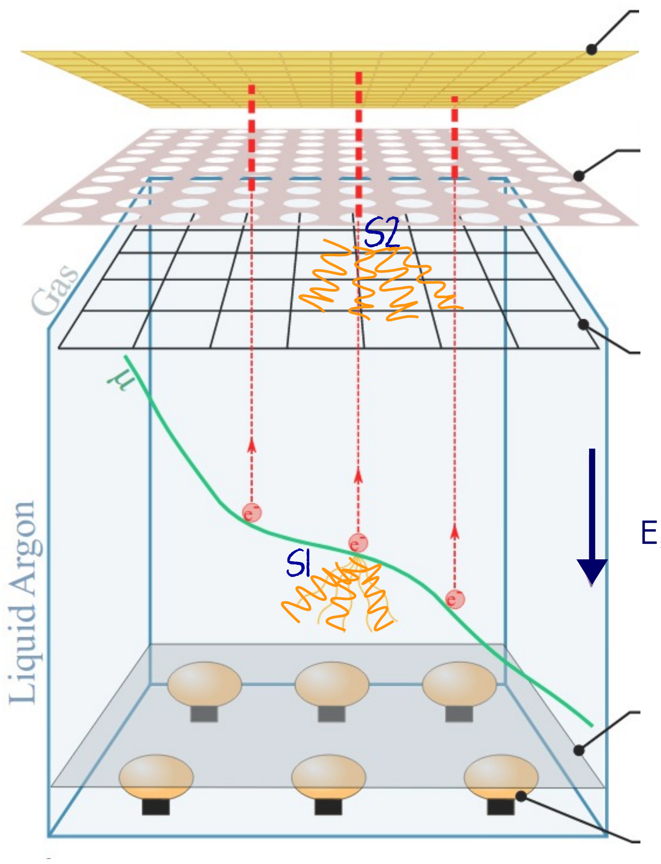
event reconstruction from **collecting** the **signal** in the **anode-plane**

LIGHT:

- scintillation light,

  t_0 time of the event

DP LAR-TPC WORKING PRINCIPLES



Picture adapted from B. Abi et al. JINST 15 T08008 (2020)

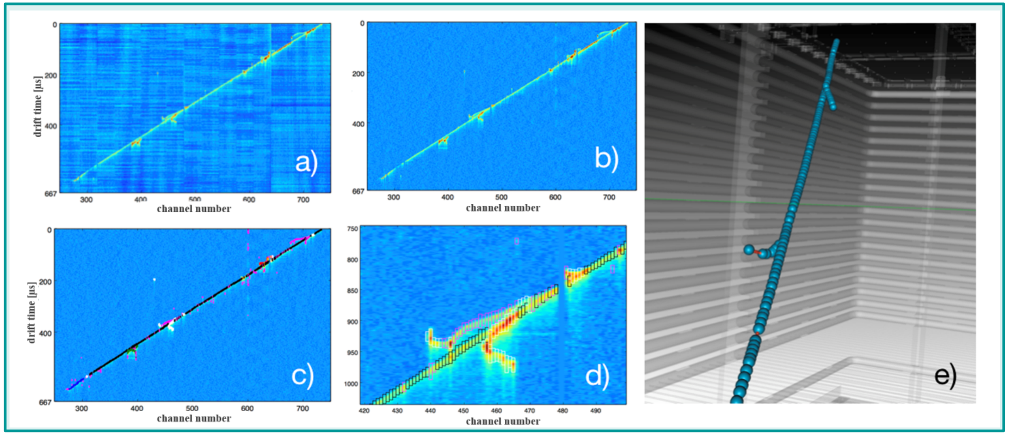
CHARGE:

event reconstruction from **collecting** the AMPLIFIED **signal** in the **anode-plane**

LIGHT:

- scintillation light (primary, **S1**) in the **LAr** phase, **t_0 time of the event**
- secondary scintillation light (**S2**) in the **GAr** phase, **proportional to ionization charge**

LAR-TPC WORKING PRINCIPLES

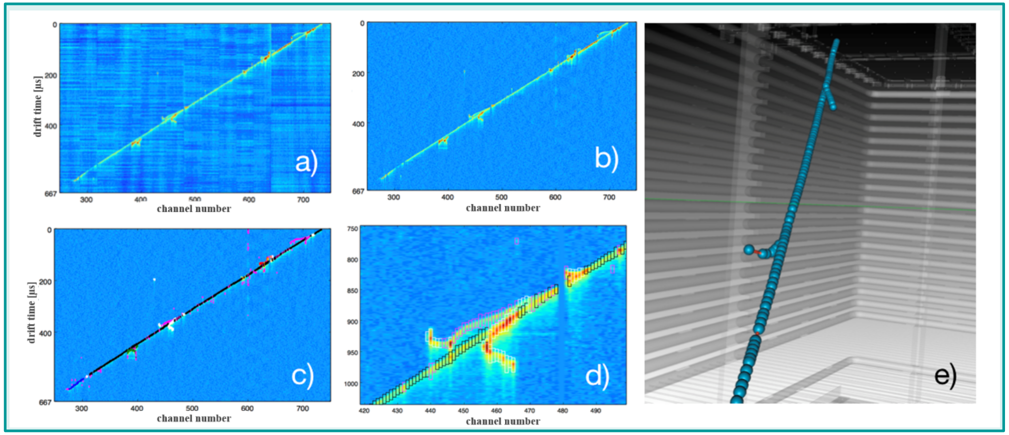


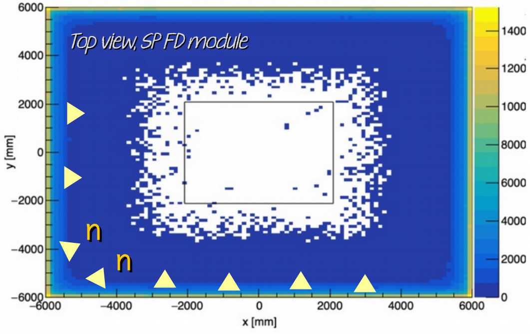
CHARGE:

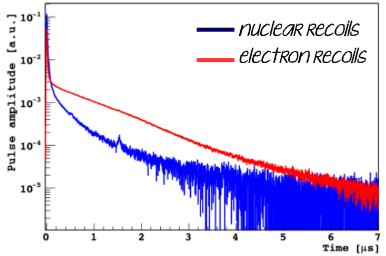
- event reconstruction reaching a mm-SCALE PRECISION
- excellent track-vs-shower separation

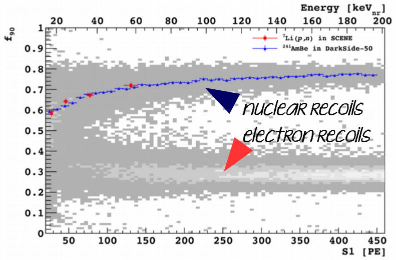
Pictures from:
- Charge, WA105 Coll., arXiv:2104.08227 (2021)

LAR-TPC WORKING PRINCIPLES









Pictures from:
- *Charge, WA105 Coll., arXiv:2104.08227 (2021)*
- *Light, C. Jackson, CPAD Workshop (2021)*
  C. J. Martoff, PoS (EPS-HEP2017) 074

CHARGE:

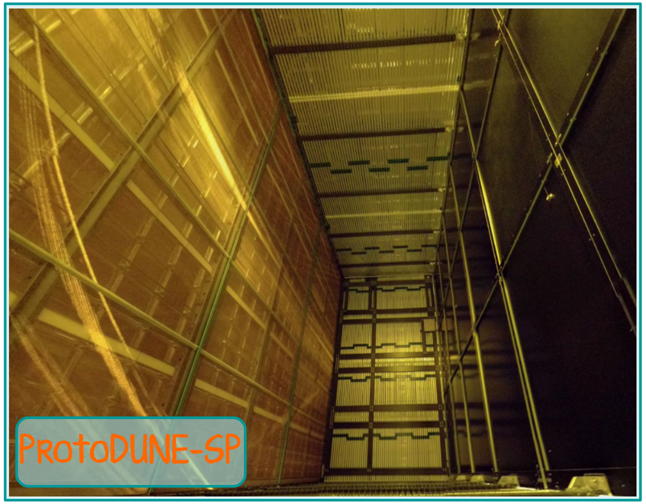
- **event reconstruction** reaching a **mm-SCALE PRECISION**
- excellent **track-vs-shower separation**

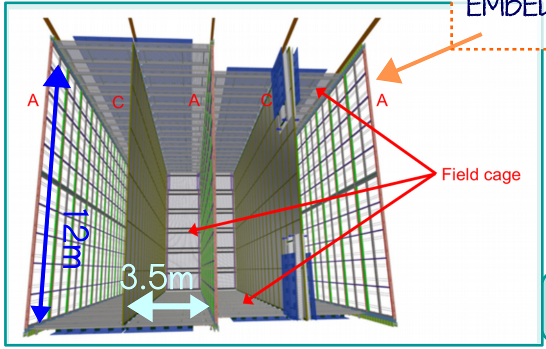
LIGHT:

- additional **calorimetric measurement**
- **improved bkg suppression**, systematic uncertainties
- more important for **NON-BEAM EVENTS** **reconstruction** (e.g. proton decays, supernovae neutrinos, etc..)

TOWARD DUNE FD MODULES STRATEGY

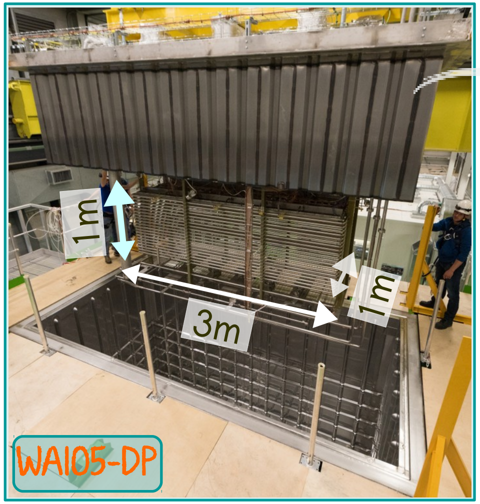
:> in the past, SP LAr-TPCs already used in several other experiments for studying neutrino physics

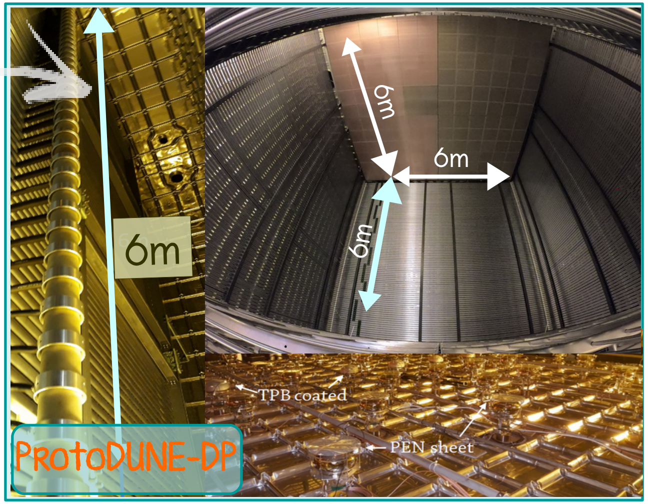


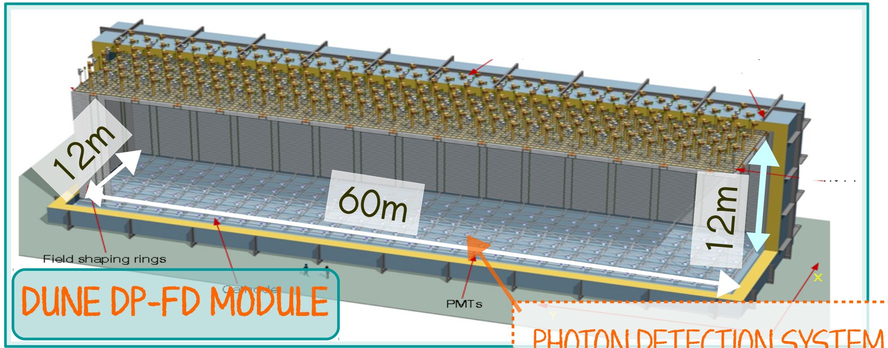


PHOTON DETECTION SYSTEM
EMBEDDED IN THE ANODE PLANES

DUNE SP-FD MODULE



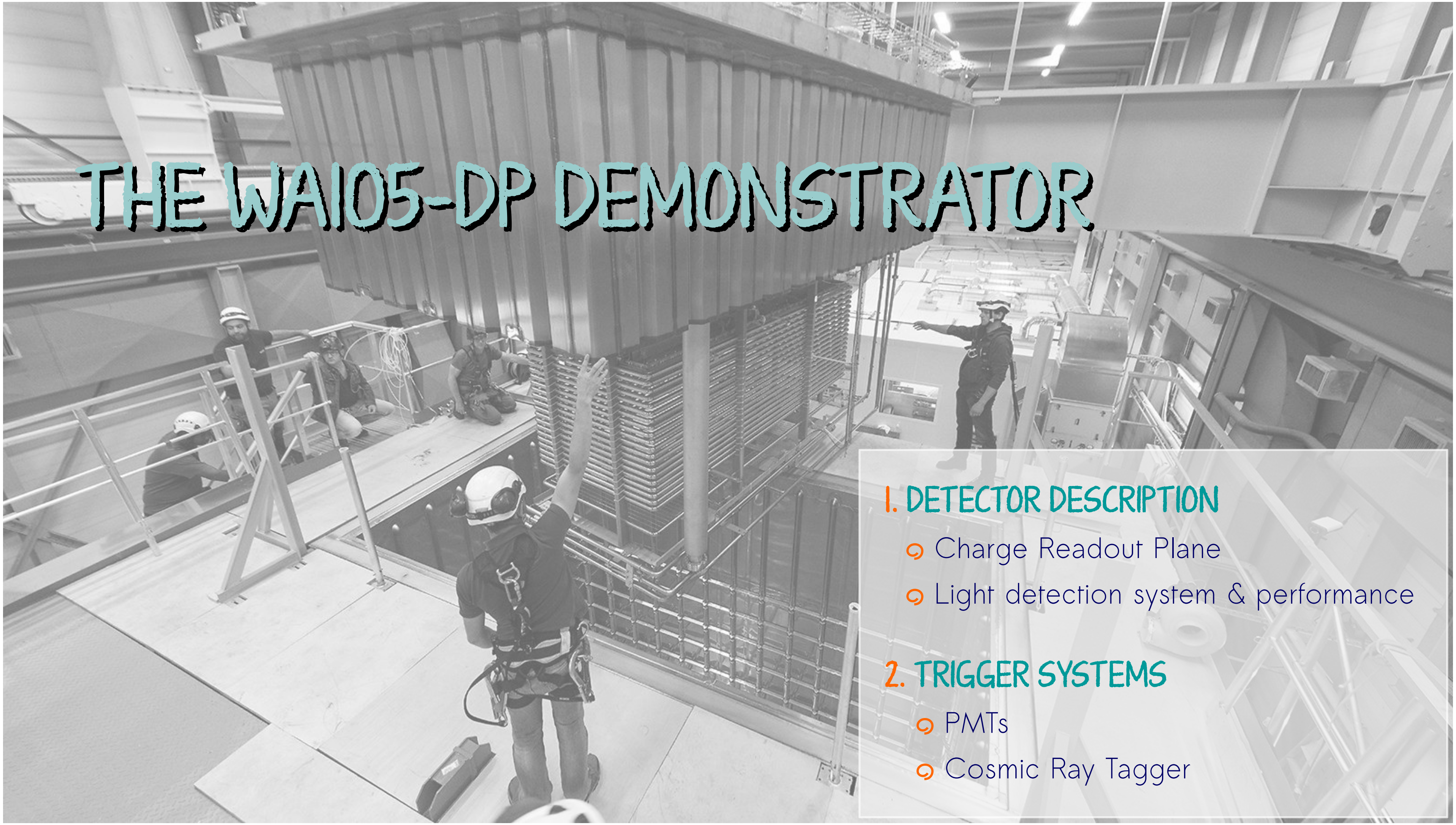




?

PHOTON DETECTION SYSTEM
ON THE CRYOSTAT FLOOR

THE WA105-DP DEMONSTRATOR

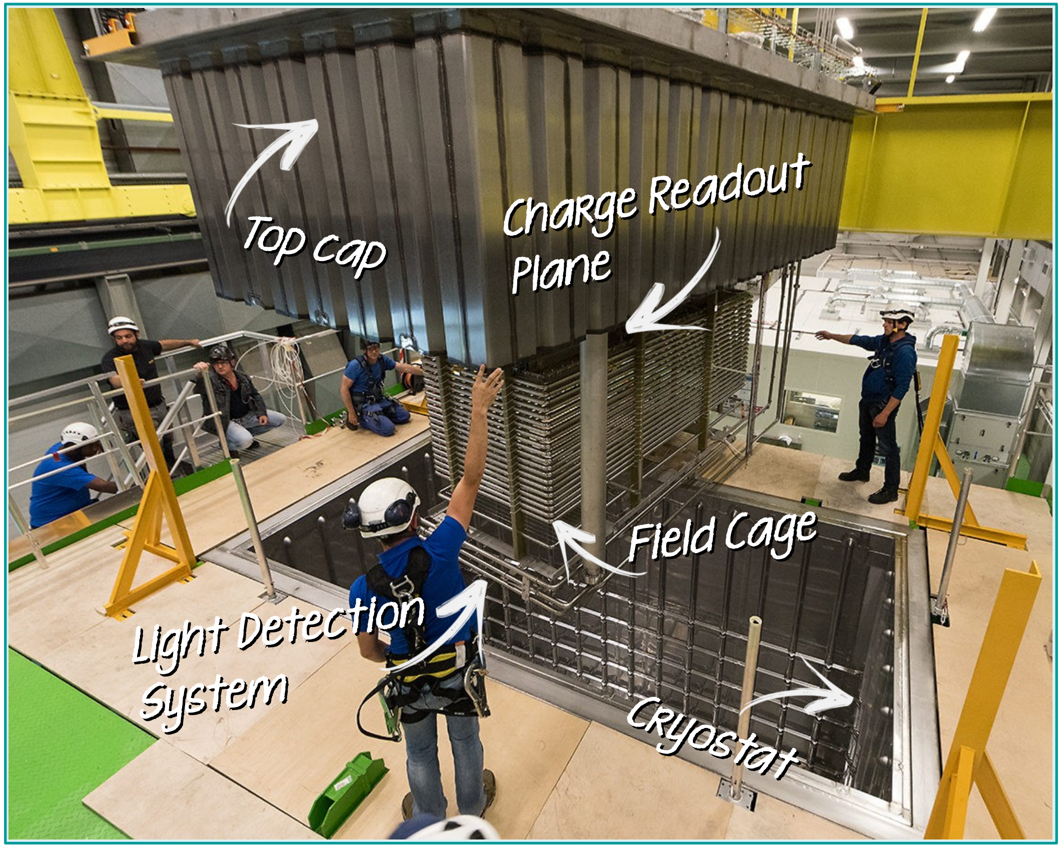


1. DETECTOR DESCRIPTION
   - Charge Readout Plane
   - Light detection system & performance
2. TRIGGER SYSTEMS
   - PMTs
   - Cosmic Ray Tagger

THE WA105-DP DEMONSTRATOR

:> Building 182, at CERN (10 countries, more than 100 scientists)

:> **Exposed to cosmic muons** (March-November, 2017, 9 months of operation)



3x1x1 m^3 FIDUCIAL VOLUME (~ 4.2 TONS)

Four main components

- cryostat (stable T_{LAr} = 87 K)
- Charge Readout Plane
- Field Cage
- Light Detection System

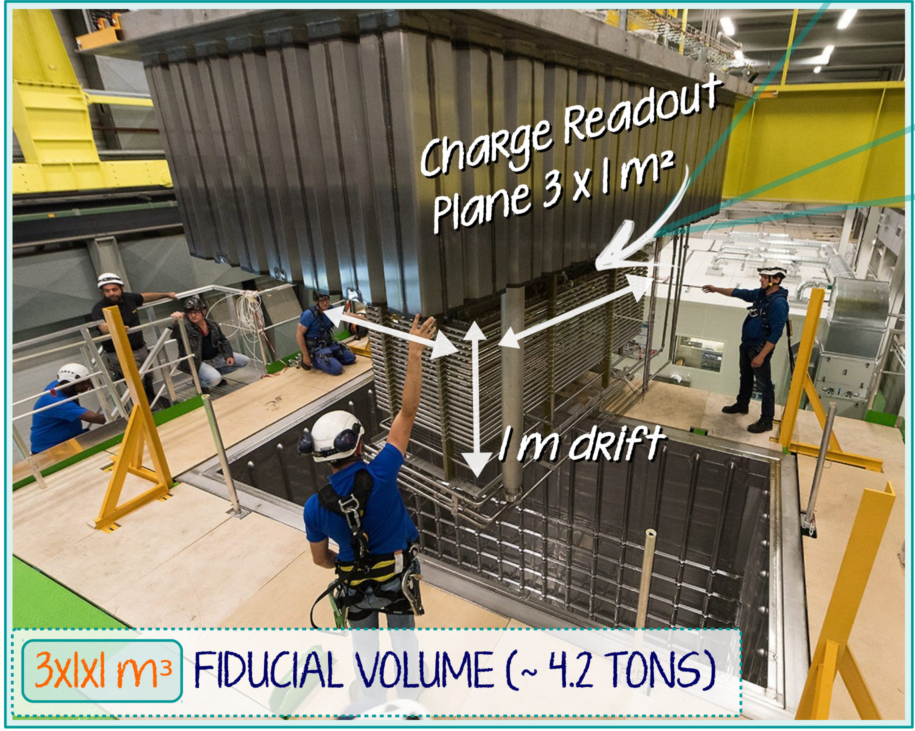
for more details: B. Aimard et al. [JINST 13 P11003] (2018)

THE WA105-DP DEMONSTRATOR: CHARGE READOUT

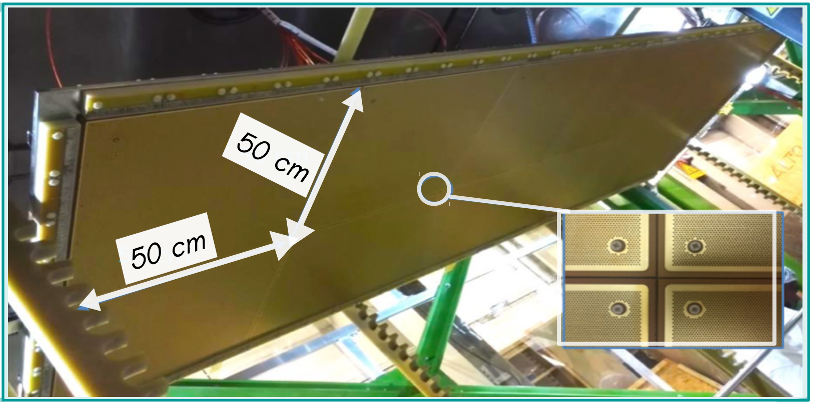
:> Charge Readout Plane (CRP):

independent structure from the field cage

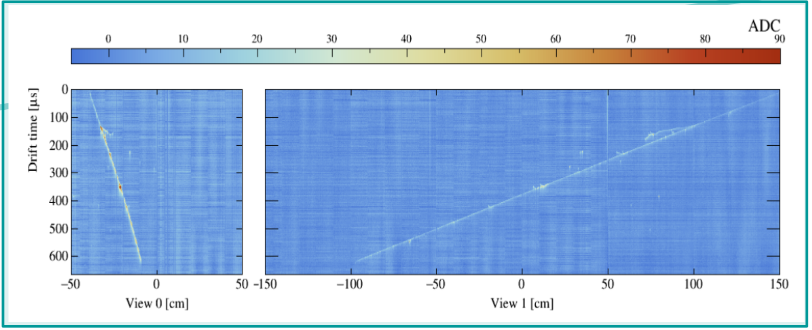
for more details: WA105 Coll., arXiv:2104.08227 (2021)



3x1x1 m³ FIDUCIAL VOLUME (~ 4.2 TONS)



CRP (BOTTOM VIEW)



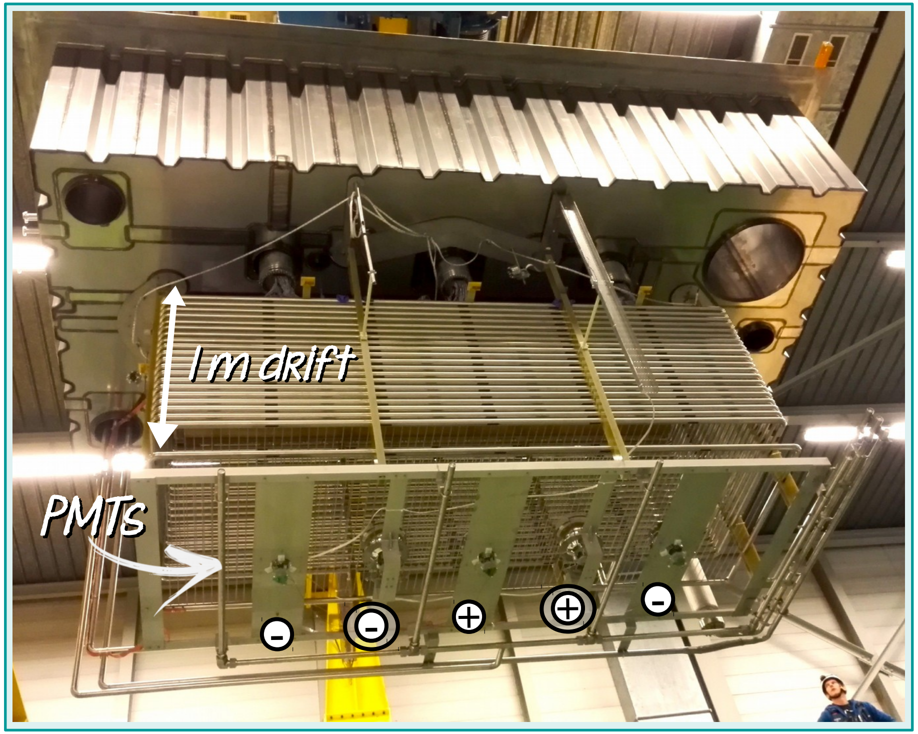
EVENT RECO

TECHNOLOGICAL MILESTONES

- **extraction** over **3m²** area
- **amplification** by combining **multiple 50×50 cm² LEMs** (12 units)
- **readout two collection planes** with strips (**up to 3m** length)

Array of **five cryogenic R5921-02Mod Hamamatsu PMTs** (8 inches):

:> underneath the cathode

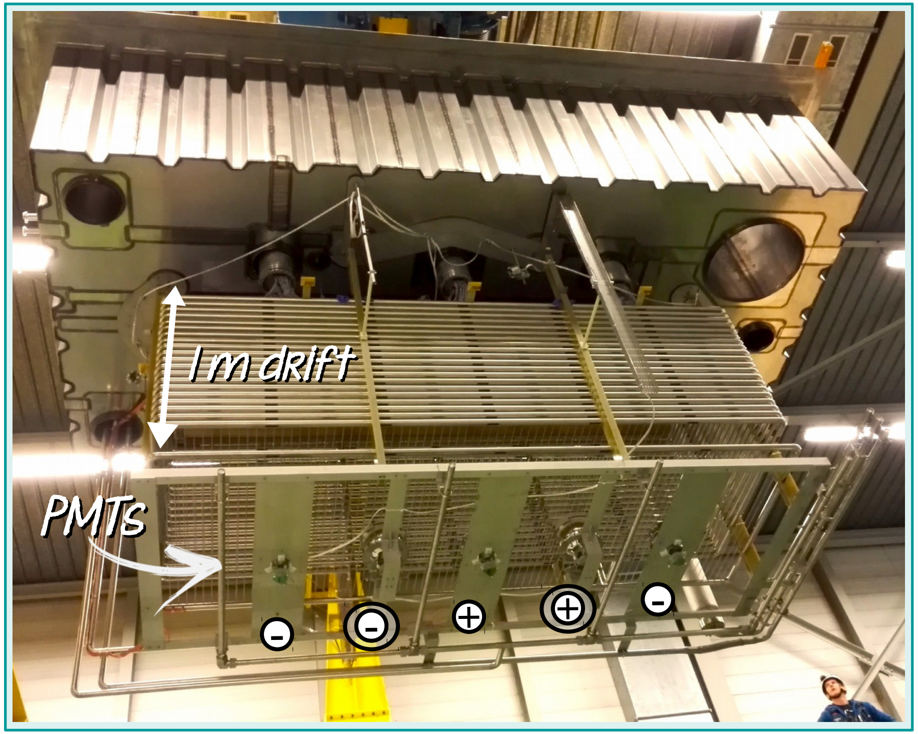


THE WA105-DP DEMONSTRATOR: LIGHT DETECTION SYSTEM

Array of **five cryogenic R5921-02Mod Hamamatsu PMTs** (8 inches):

:> underneath the cathode

:> different configurations (PMT base, wavelength shifter)

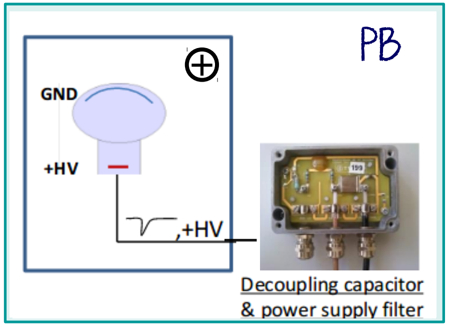


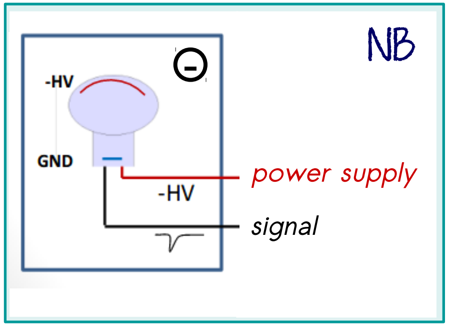
2 TPB COATING OPTIONS

(*) TetraPhenyl-Butadiene

(**) Poly(Methyl-MethAcrylate)

2 BASE CONFIGURATIONS





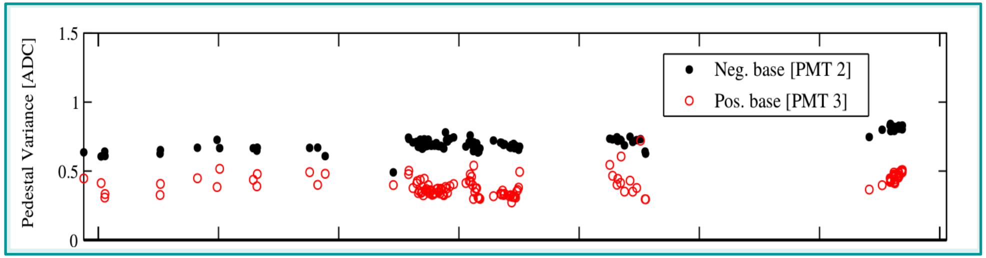
- one cable, signal splitter outside the cryostat
- two different cables

LIGHT DETECTION SYSTEM PERFORMANCE

for more details: B. Aimard et al., JINST 16 P03007 (2021)
D. Belver et al., JINST 13 T10006 (2018),
and in bkp slides

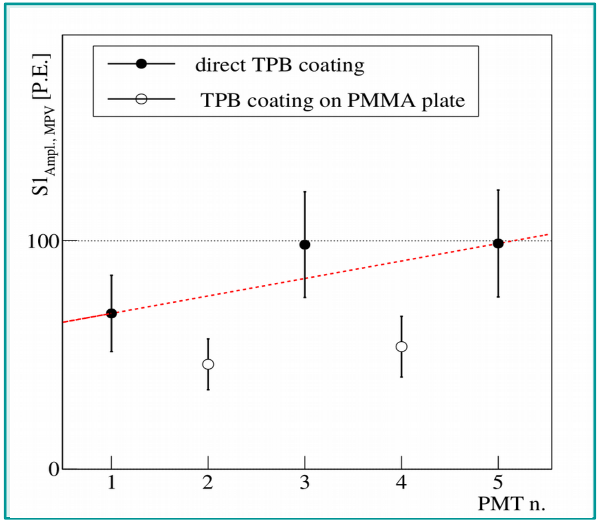
BASE CONFIGURATION

- base design and cabling costs
- PMT response linearity
- PMT pedestal stability



TPB OPTIONS

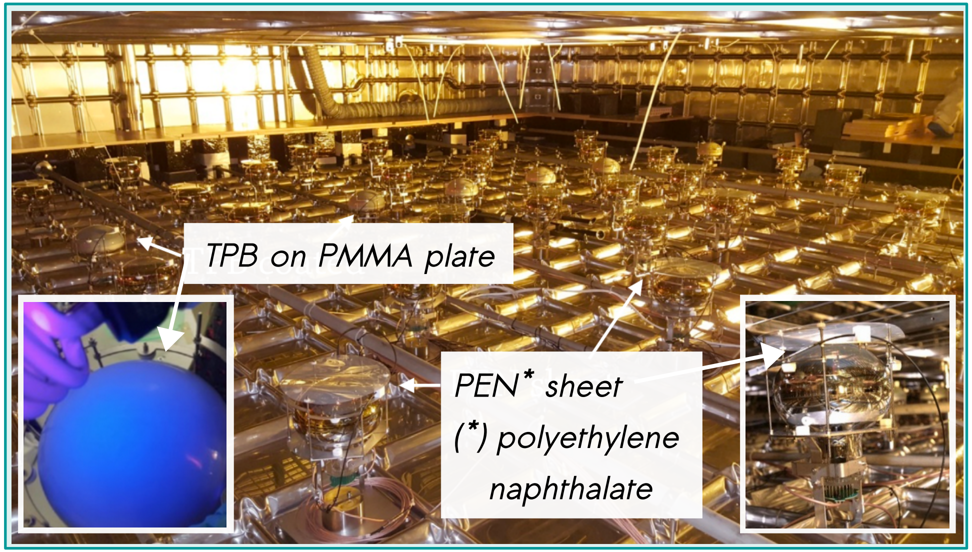
- wider geometrical acceptance
- minimization of light absorption



POSITIVE BASE

DIRECT TPB COATING

baseline design for PROTODUNE-DP DETECTOR

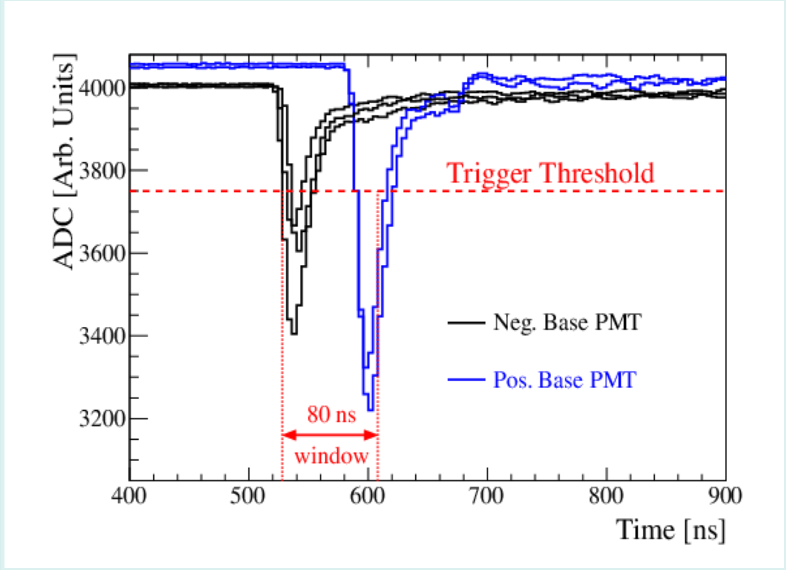


36 PMTs, in a *non-uniform* layout for optimizing coverage of light produced at the side of the detector

PMT TRIGGER

:> **5-fold coincidence** of the **prompt scintillation signal** over a **fixed ADC threshold, within 80 ns time window**

TRIGGER RATE ~3 HZ

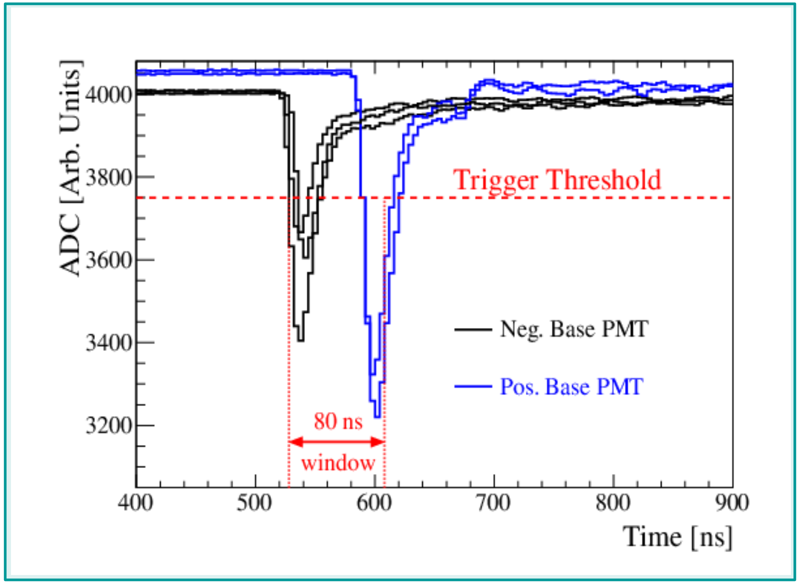


TRIGGER SYSTEMS

PMT TRIGGER

:> **5-fold coincidence** of the **prompt scintillation signal** over a **fixed ADC threshold, within 80 ns time window**

TRIGGER RATE ~3 HZ



COSMIC RAY TAGGERS (CRT) AS EXTERNAL TRIGGER

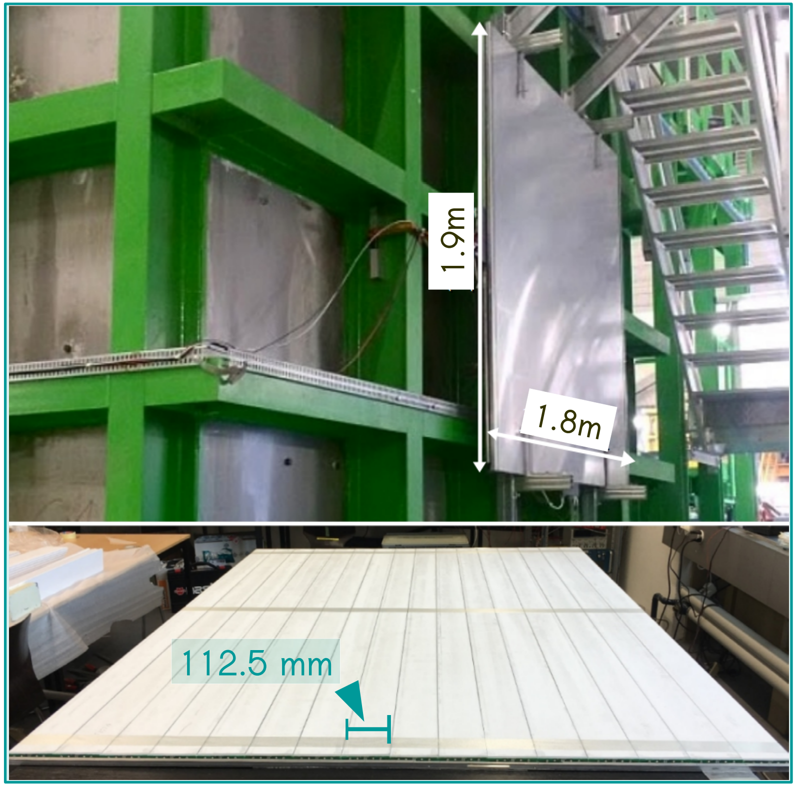
:> 4 modules of **plastic scintillators** (2 modules/side)

- 16 strips (112.5 mm width) per module

:> **4-fold coincidence among the 4 CRT panels**

- at least a signal must be detected in one strip/panel

TRIGGER RATE ~0.3 HZ



CRT RECONSTRUCTION OF MUON-LIKE EVENTS

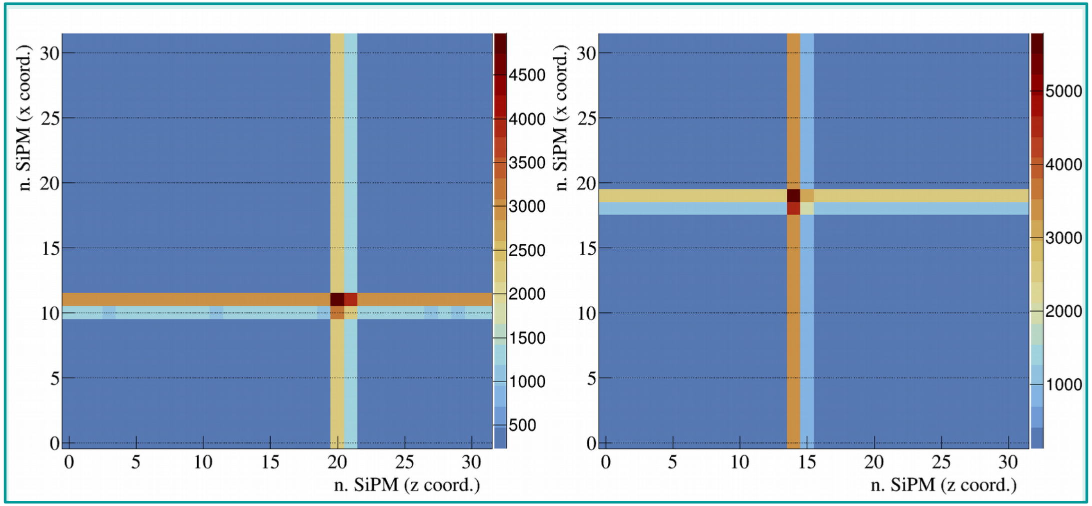
ALWAYS AVAILABLE, **independently from the drift field** conditions and track **reconstruction in the anode-plane**

:> **CRT panels** allow having a **good topology reconstruction of the muon tracks crossing the detector**

- **CRT** and **PMT DAQs information** (stored separately) are **matched** (ms precision)

CRT RECONSTRUCTION

:> requirement of **unambiguous track reconstruction:** only 1 hit per panel ↔ only one muon per event)



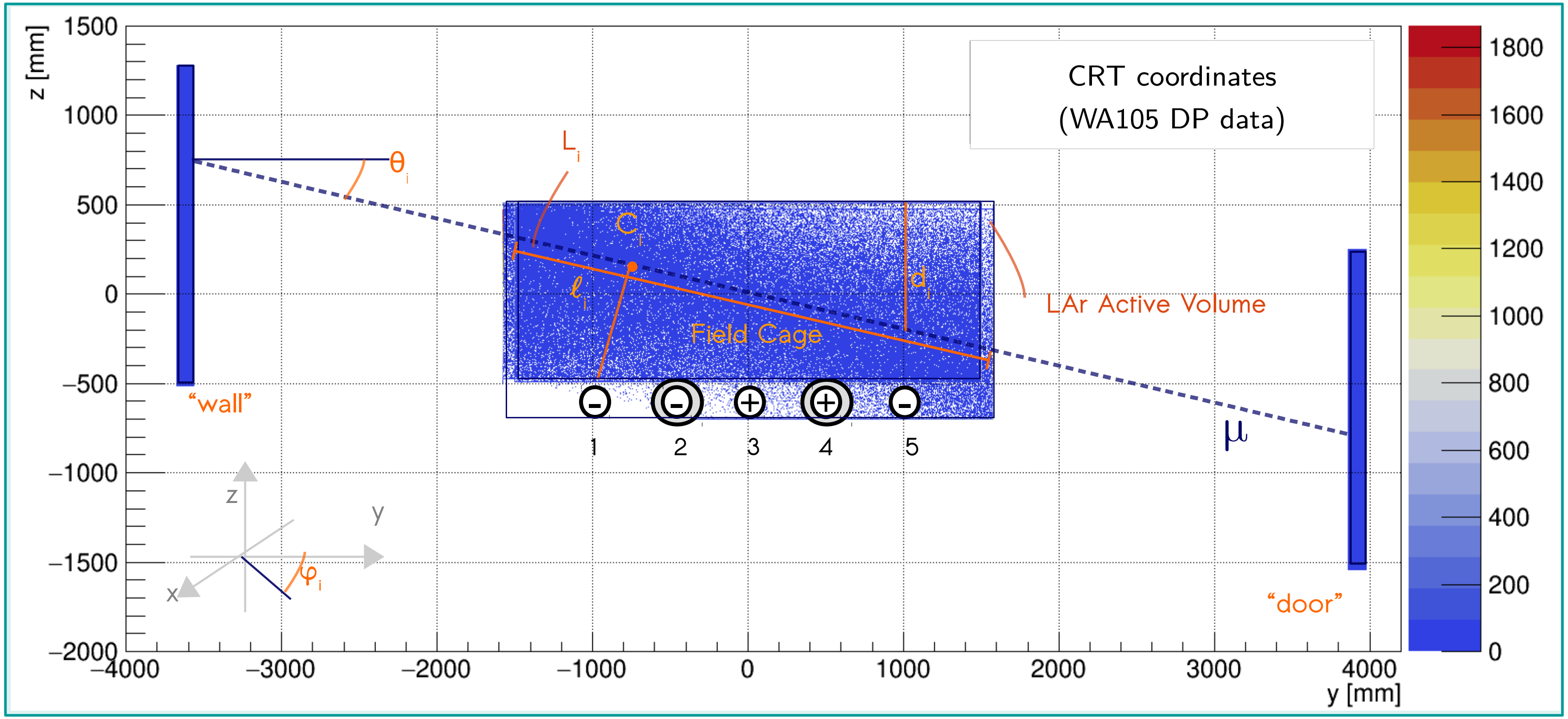
- only single COSMIC MUON track

& OTHER CUTS, FOR CLEANING THE **MUON-LIKE EVENT SELECTION**

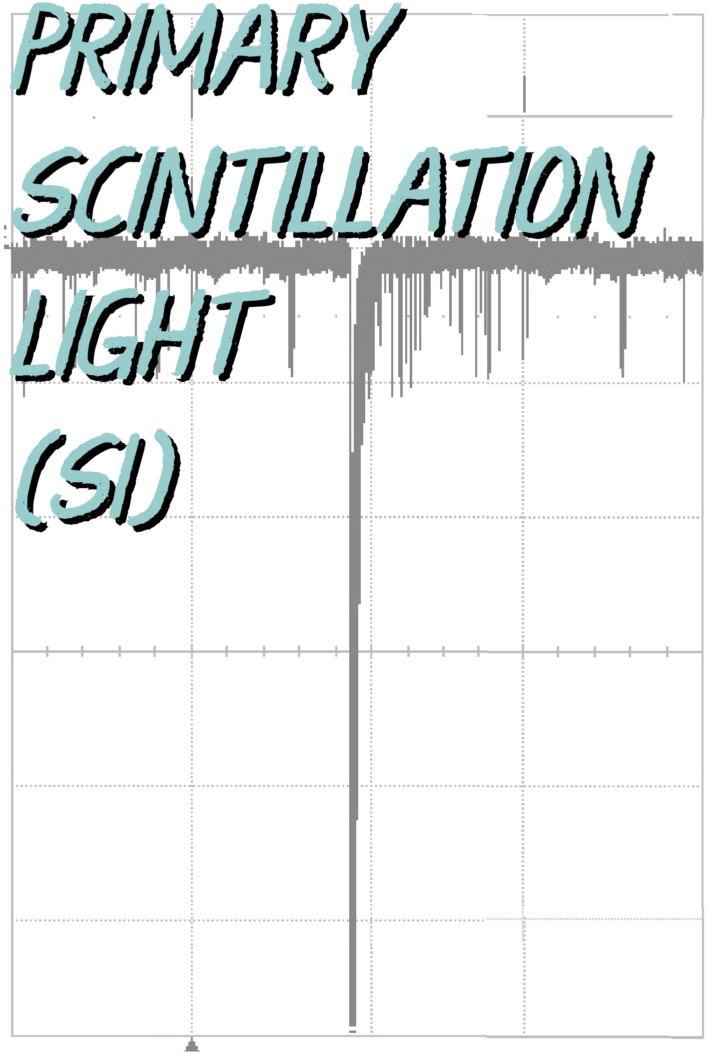
- quality cuts for an optimized PMT and CRT response
- geometrical cuts relative to the 3D CRT track reconstruction

CRT RECONSTRUCTION OF MUON-LIKE EVENTS

ALWAYS AVAILABLE, **independently from the drift field** conditions and track **reconstruction in the anode-plane**



PRIMARY SCINTILLATION LIGHT (S1)



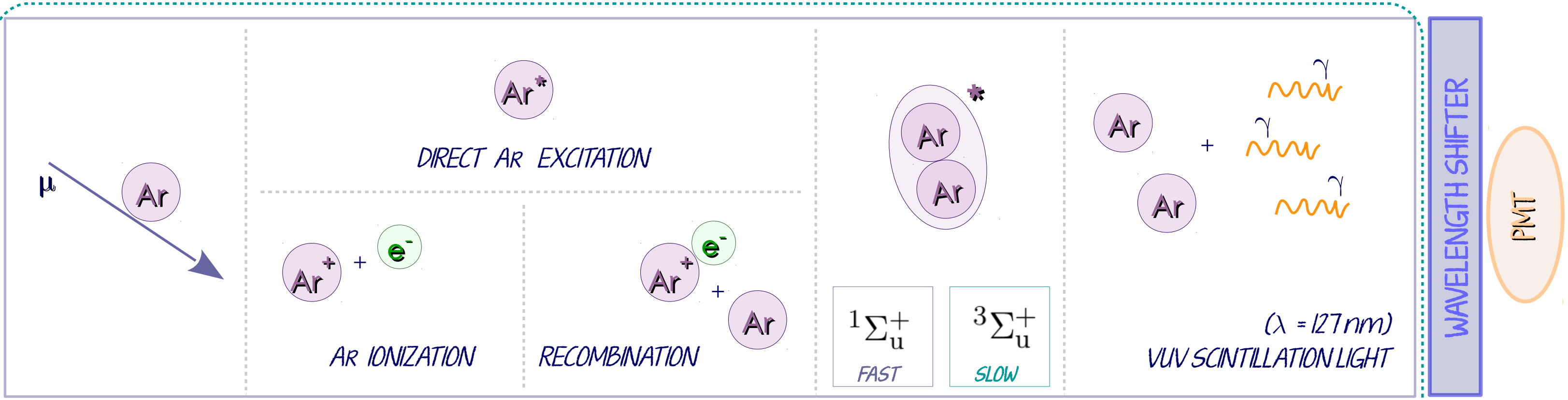
1. SCINTILLATION LIGHT PRODUCTION FROM COSMIC MUONS IN LAR

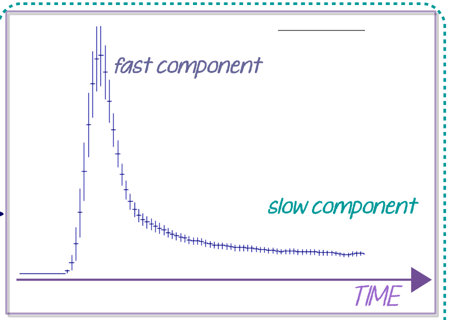
- study of the **LAr scintillation time profile**
- study of the **LAr purity**
- **impact** of the **drift field on the scintillation light** signal (**LAr recombination factor** and of the **recombination dynamics**)

2. SCINTILLATION LIGHT PROPAGATION IN LAR

- **evaluation** of the **Rayleigh scattering** through **data/MC comparison**

THE PRIMARY SCINTILLATION LIGHT SIGNAL (S1)





TIME PROFILE
OF SCINTILLATION LIGHT SIGNAL

$\tau_{fast} \sim$ ns

$\tau_{slow} \sim \mu$s

$$\ell(t) \sim \frac{A_s}{\tau_s} e^{-t/\tau f} + \frac{A_T}{\tau_T} e^{-t/\tau s}$$

scintillation emission mechanism, two contributions in LAr:

DIRECT EXCITATION $Ar^* + Ar \rightarrow Ar^*_2 \rightarrow Ar + Ar + \gamma$

RECOMBINATION $Ar^+ + Ar \rightarrow Ar^+_2 + e \rightarrow Ar^*_2 \rightarrow Ar + Ar + \gamma$

suppressed in **presence** of the **drift field**

dis-excitation probability from **singlet** (A_S) or **triplet** (A_T) states, in terms of A_S/A_T, **depend on the interacting particle**

(A_S/A_T~0.3 for e-, muons, etc...)

KNOWNS

..AND UNKNOWNS

- **two** characteristic **decay times** describing the LAr dynamics (τ_{fast}~ ns, τ_{slow}~ μs)

at least, an additional third **intermediate component** has been **experimentally measured**, BUT..

- ***origin?*** *most accredit hypothesis, WLS material*
- ***decay time?*** *so far, found in [34; 132] ns..*

- **probability of excitation** in the **singlet or triplet states** depending on the **particle nature** (used for particle identification)

Hints of **dependence on the drift field strength** of

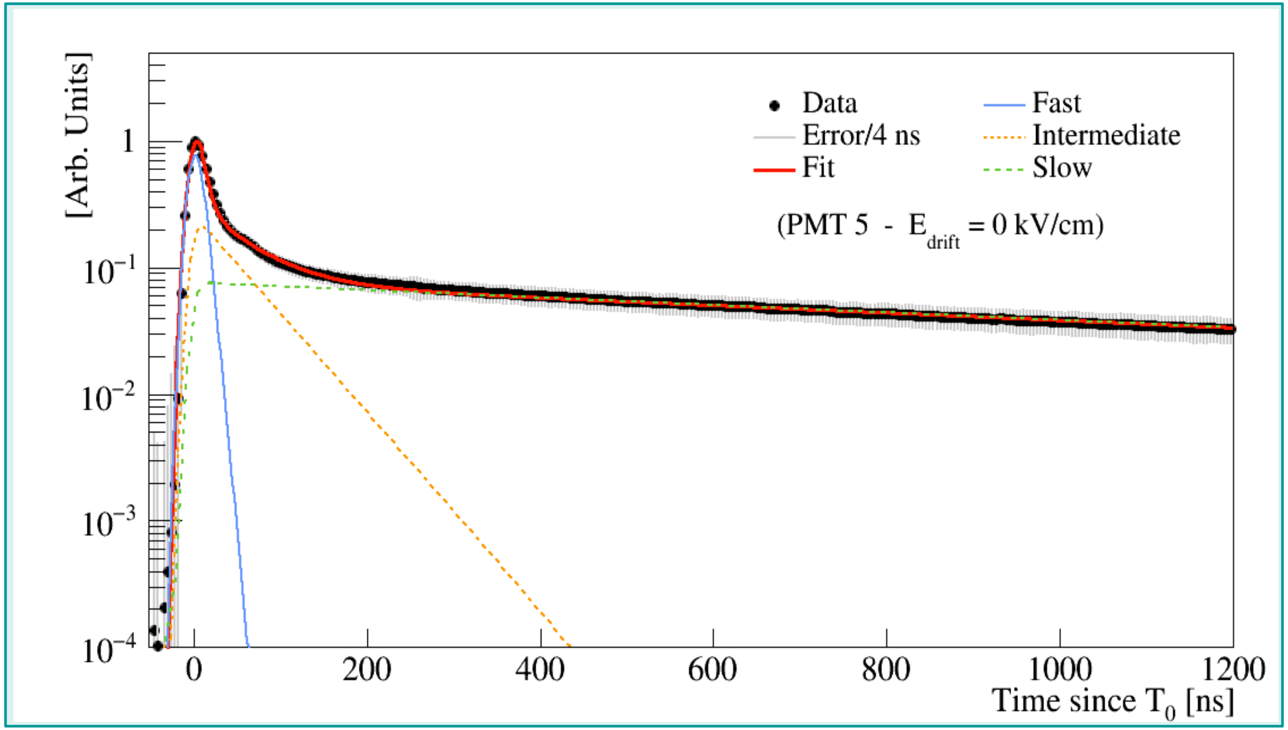
- ***dis-excitation probability****, why that?*
- *is the* ***LAr dynamic*** *affected? if so,* ***how?***

- **excimer formation** from either **direct excitation** or Ar_2^+-e^- pair **recombination**
  → **drift field, suppression of the recombination processes** and, in turn, **light yield decrease**

THE SCINTILLATION TIME PROFILE

:> In the WA105-DP demonstrator, **fit** of the **average waveform** to a **Gaussian function** (PMT response) **convoluted with** THREE **exponential functions:**

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



:> **Physical meaning** of **fit parameters**:

- t_0, S1 peak time
- σ
- $\tau_{j=fast,\ int,\ slow}$, decay times
- $A_{j=fast,\ int,\ slow}$, normalization constants

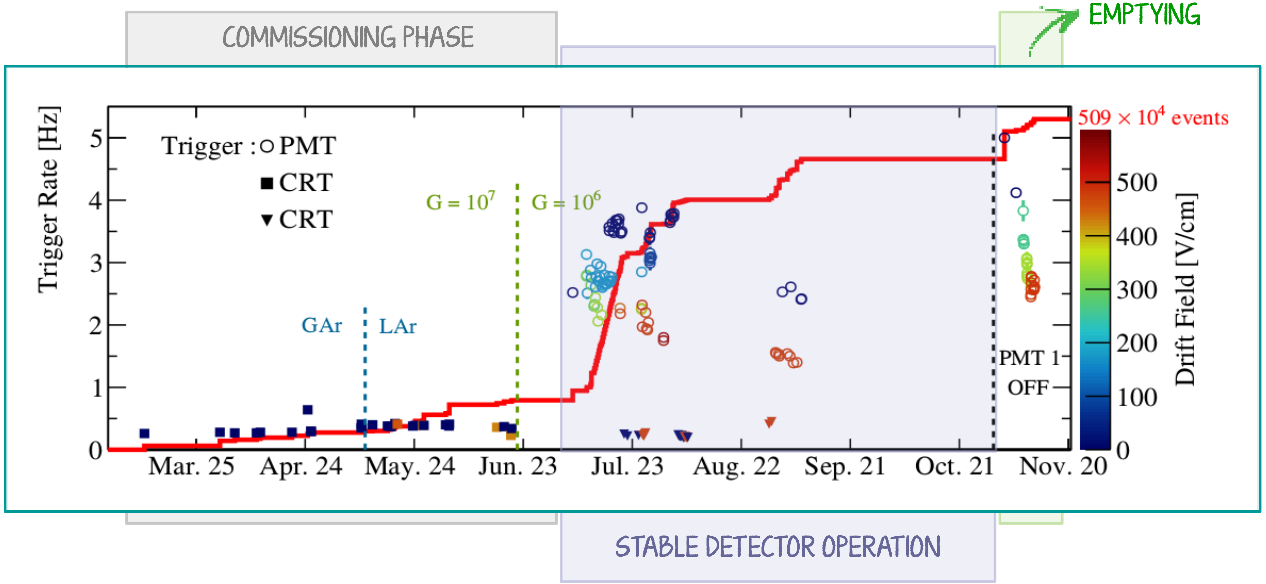
:> Obtained from the fit parameters:

- $A_{rel,j} = A_j / \Sigma_{j=fast,\ int,\ slow} A_j$, relative contribution to tot. scintillation light

FIT PROCEDURE AND SYSTEMATIC UNCERTAINTIES

:> general fit procedure, independent from trigger and electric field conditions (valid for any PMT in each run):

- **CRT trigger**, the MUON-LIKE EVENT SELECTION is applied
- **PMT self-trigger**, only **rejection of events saturating** the **ADC dynamic range** or the **PMT response**



MAIN OUTCOMES FROM DEDICATED TOY-MC

:> Effect of **parameters' correlation**

:> Limitation due to the **digitization sampling (4ns)**:

- τ_{fast} = 6ns [fixed]

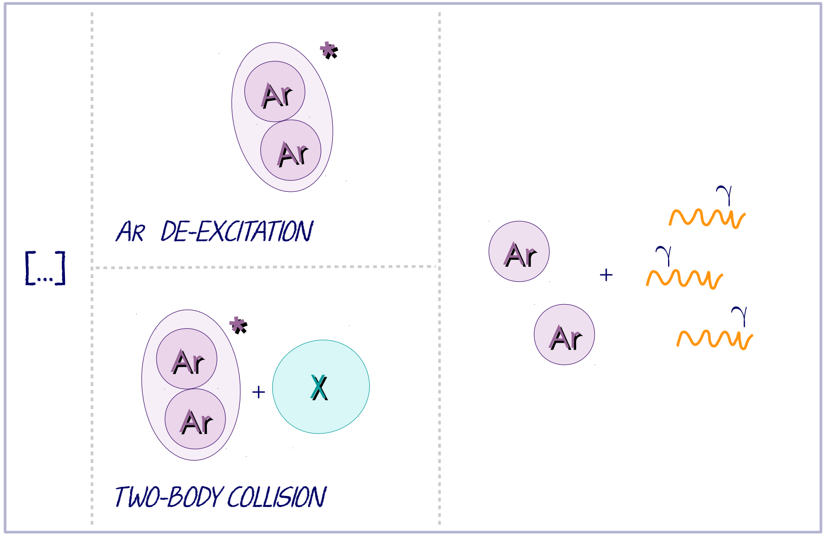
(influencing τ_{int} measurement)

:> all included in **systematic uncertainty, ∀ parameter**

for more details: C. Lastoria, Ph.D. thesis (2020) and in bkp slides

MONITORING OF THE LAR PURITY

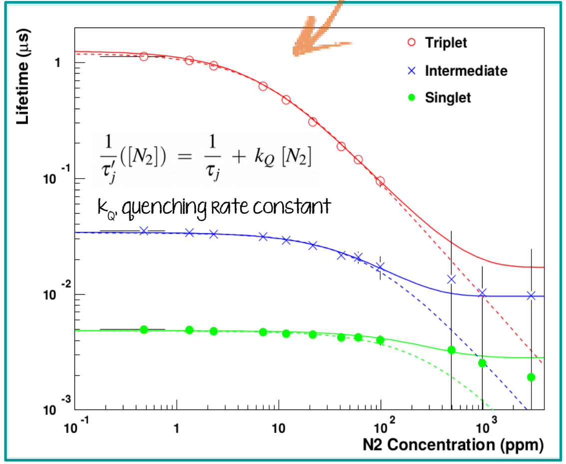
:> **Quenching** of the **light** in presence of **electronegative impurities**, τ_{slow} **most sensitive parameter**

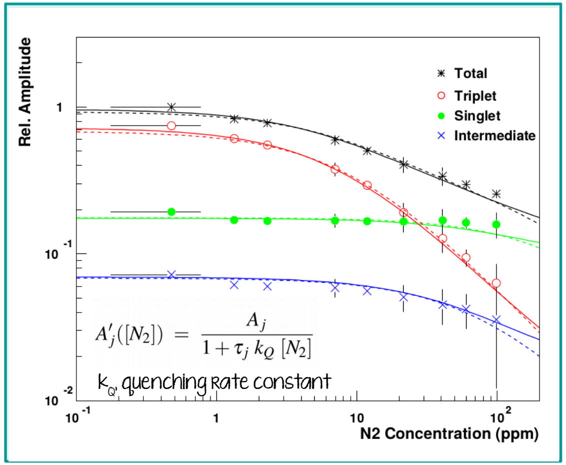


two processes in competition:

EXCIMER DIS- EXCITATION $Ar^*_2 \rightarrow Ar + Ar + \gamma$

TWO-BODY COLLISION $Ar^*_2 + X \rightarrow Ar + Ar + \gamma + X$





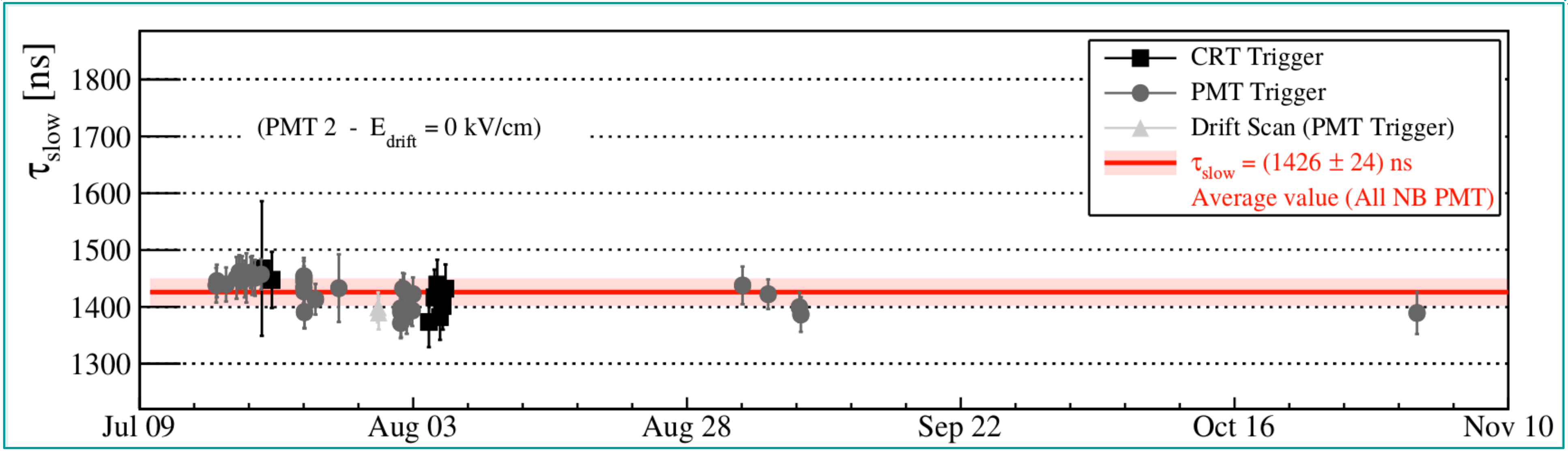
for more details: R. Acciarri et al., JINST 5 P06003 (2010)

MONITORING OF THE LAR PURITY

:> **Quenching** of the **light** in presence of **electronegative impurities**, τ_{slow} **most sensitive parameter**

:> On average, τ_{slow} = (1426 ± 24) ns, consistent with electron lifetime, τ_{el} > 4ms

for more details: B. Aimard et al. [JINST 13 P11003] (2018)



- GOOD AND STABLE LAR PURITY, during 5 month of stable detector operation
- **scintillation light analysis** from **all data** collected during stable detector operation

LAR SCINTILLATION TIME PROFILE (NO FIELDS)

- **observation** and **measurement** of the **intermediate component**:
  - → relative contribution to the total scintillation light, $A_{int} / \Sigma_{j=f,\,i,\,s} A_j$, $A_{int,rel}$ = 11%
  - → decay time, τ_{int} = (49.7 ± 3.0) ns

in agreement with other measurements

E. Segreto, Phys. Rev. C 91, 035503, (2015) τ_{int} = (49 ± 1) ns

- due to the delayed light re-emission of TPB molecules

LAR SCINTILLATION TIME PROFILE (NO FIELDS)

- **observation** and **measurement** of the **intermediate component**:
  - → relative contribution to the total scintillation light, $A_{int} / \Sigma_{j=f,\,i,\,s} A_j$, $A_{int,rel} = 11\%$
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in agreement with other measurements

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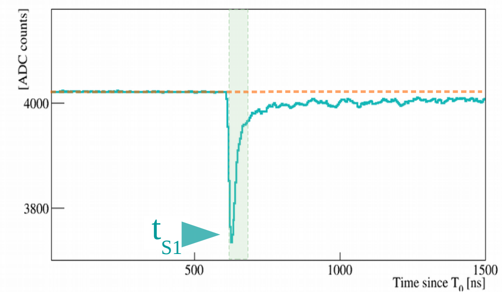
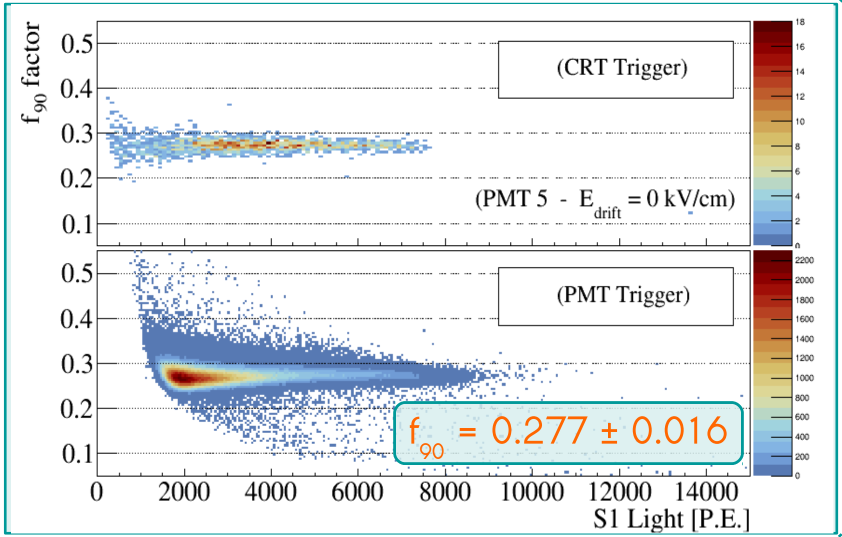
- due to the delayed light re-emission of TPB molecules

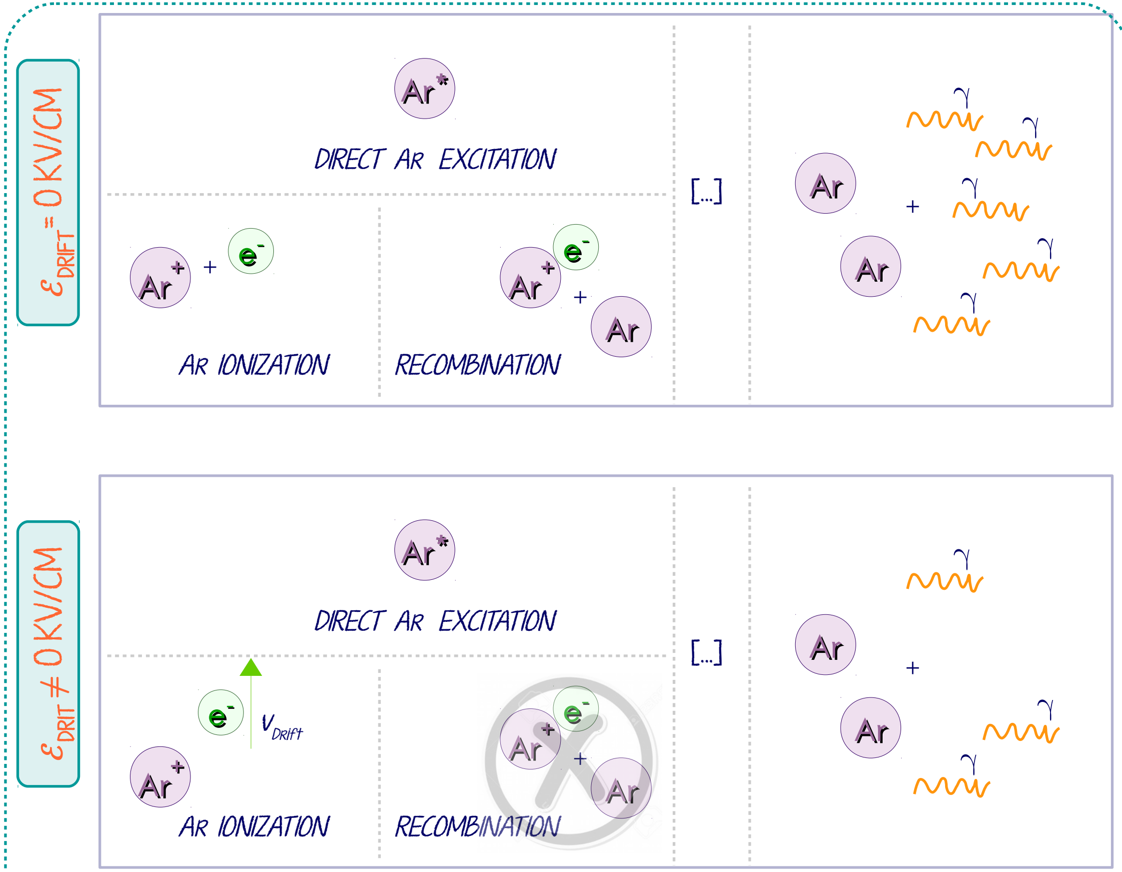
- for **cosmic muons**, FRACTION OF SINGLET OVER TRIPLET :
  - → expressed by the ratio $(A_f+A_i)/A_s$, $(A_f+A_i)/A_s = 0.284 \pm 0.020$
  - → empirical definition of prompt contribution to the total scintillation light, f_{90} **factor** = Σ_{90ns}Light/$\Sigma_{4\mu s}$Light (independent from parametrization)



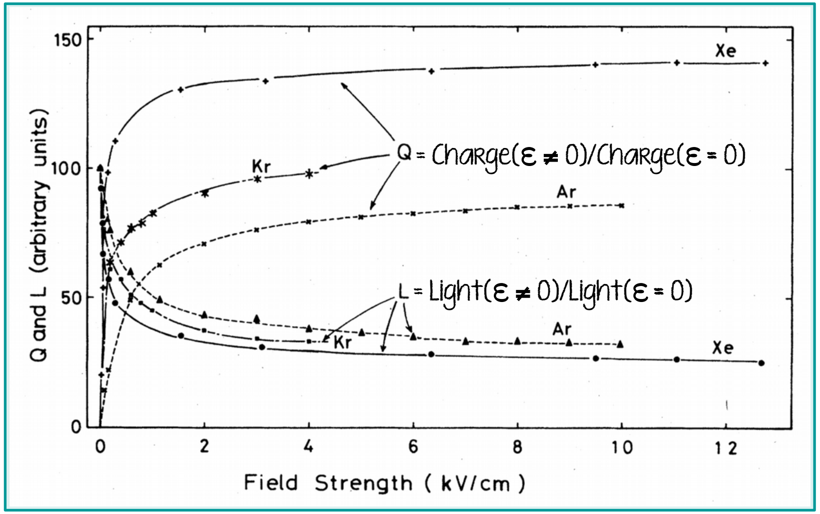


EFFECT OF THE DRIFT FIELD ON THE SCINTILLATION LIGHT

for more details: S. Kubota et al., Phys. Rev. B20, pp 3486-3496 (1979)
S. Amoruso et al., NIM in Phys. Res. A 516 (2004) 68-79



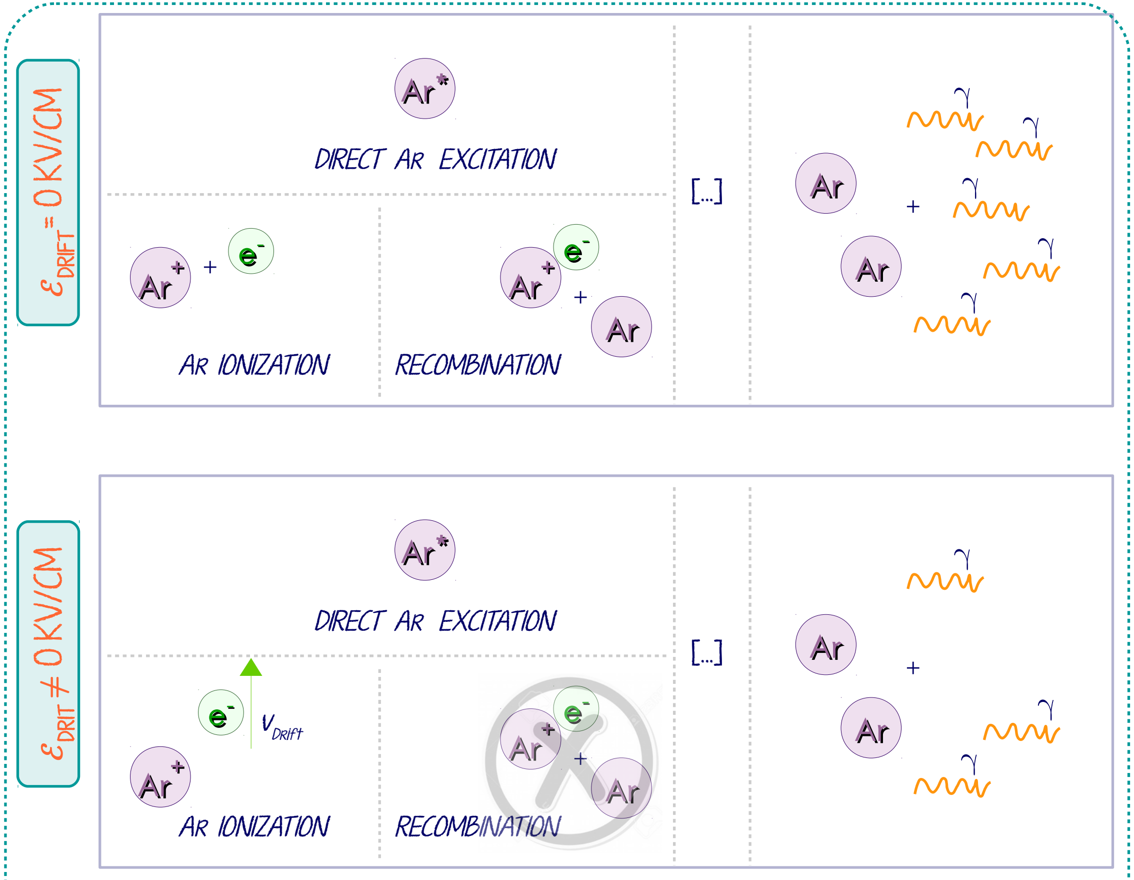
RECOMBINATION suppressed in presence of the drift field



Characteristic **Birks recombination constant**, k_ε(dE/dx) such that $R(\varepsilon) \sim A/(1+k_\varepsilon/\varepsilon)$

- in LAr, k_ε = (0.0486 ± 0.0006) kV/cm (g cm^{-2}/MeV), for cosmic muons at MIP

EFFECT OF THE DRIFT FIELD ON THE SCINTILLATION LIGHT



RECOMBINATION **suppressed** in **presence** of the **drift field**

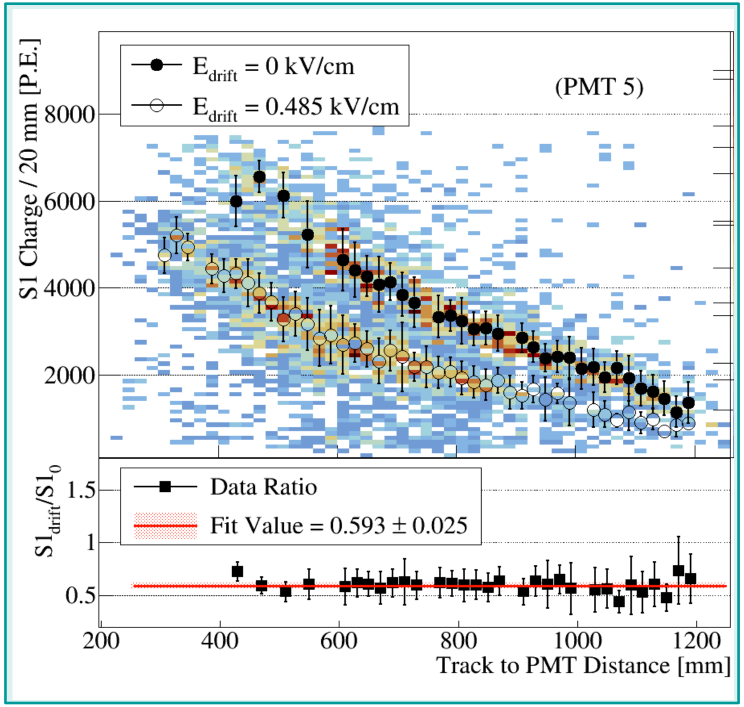
In the WA105-DP, $\mathcal{E}_{DRIT} \neq 0$ KV/CM

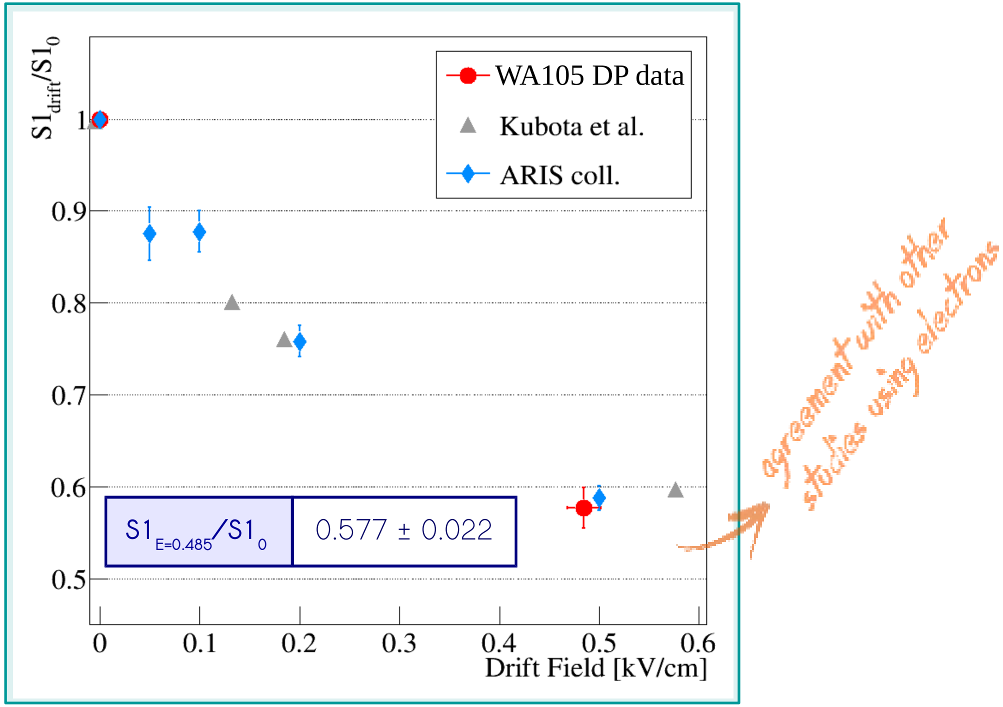
1. Considering the **total scintillation light**
   :> **LAr recombination factor** @ nominal TPC operation drift field **(~0.5 kV/cm)**

2. Considering the **scintillation time profile**
   :> **impact of the drift field on the:**
   - fraction of singlet and triplet, $(A_f+A_i)/A_s$ and relative amplitudes A_j, separately
   - **decay times** (τ_{int} and τ_{slow})

LAR RECOMBINATION FACTOR AT THE NOMINAL DRIFT FIELD

:> Selecting only CRT **muon-like tracks** crossing the TPC field cage volume





averaging results from the 5 PMTs, ~42% **of the light produced in absence of drift field comes from recombination**

DRIFT FIELD EFFECT ON THE SCINTILLATION TIME PROFILE

:> The **scintillation time profile** is **sensitive** to the **LAr conditions**

- few (and old) information investigating the LAr recombination dynamics
- suggestion of **drift field affecting the scintillation time profile**

Kubota et al., Phys.Rev. B 20, (1979)

	[Exc. + Recomb.]	[Exc.]
	E_{drift} = 0 kV/cm	E_{drift} = 6 kV/cm
A_S/A_T	(0.5 ± 0.2)	(0.36 ± 0.06)
τ_{slow}	(1020 ± 60) ns	(860 ± 30) ns

- big error in A_S/A_T ratio at 0 drift is due to the treatment of the intermediate component
- small value of the slow decay suggests a low control of electronegative impurities

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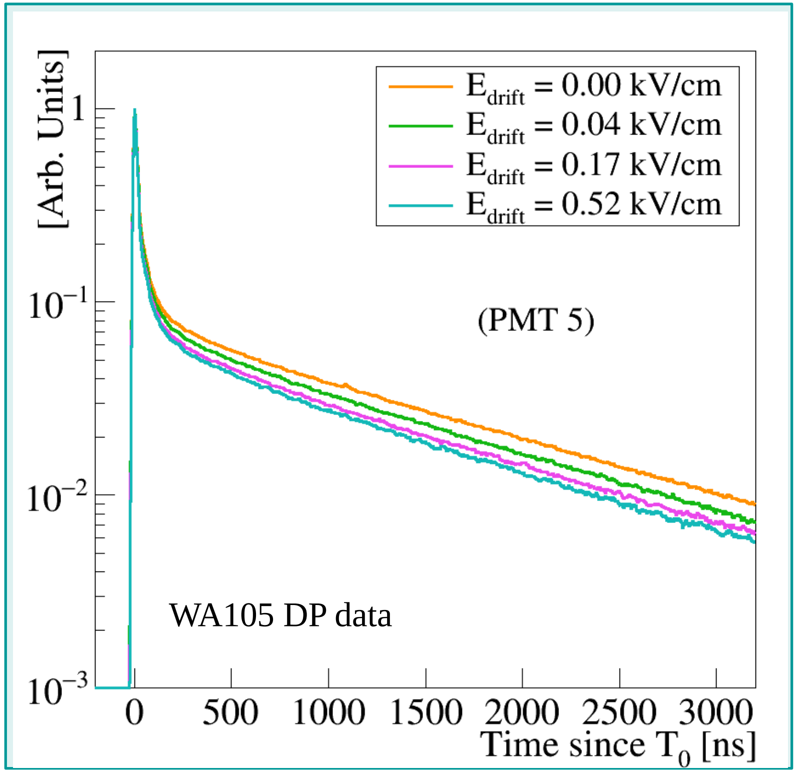


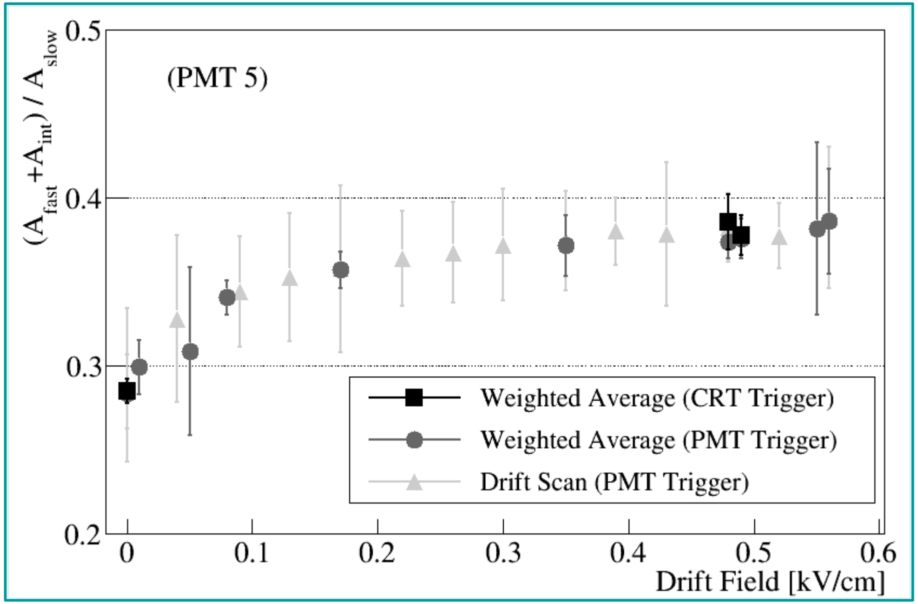
:> In the WA105-DP, several data collected in the (0, 0.56) kV/cm drift field range

GOAL: **improve understanding of LAr recombination dynamics!**

DEPENDENCE OF THE $(A_F+A_I)/A_S$ RATIO

:> in contrast with literature, an INCREASING of $(A_f+A_i)/A_s$ **as a function of the drift field** is observed

- **clear trend, never reported before!** (robust against all the data analyzed)



- around +34% w.r.t. the value measured in absence of drift field, $(A_f+A_i)/A_{s\ @\ 0.5kV/cm} = 0.378 \pm 0.022$

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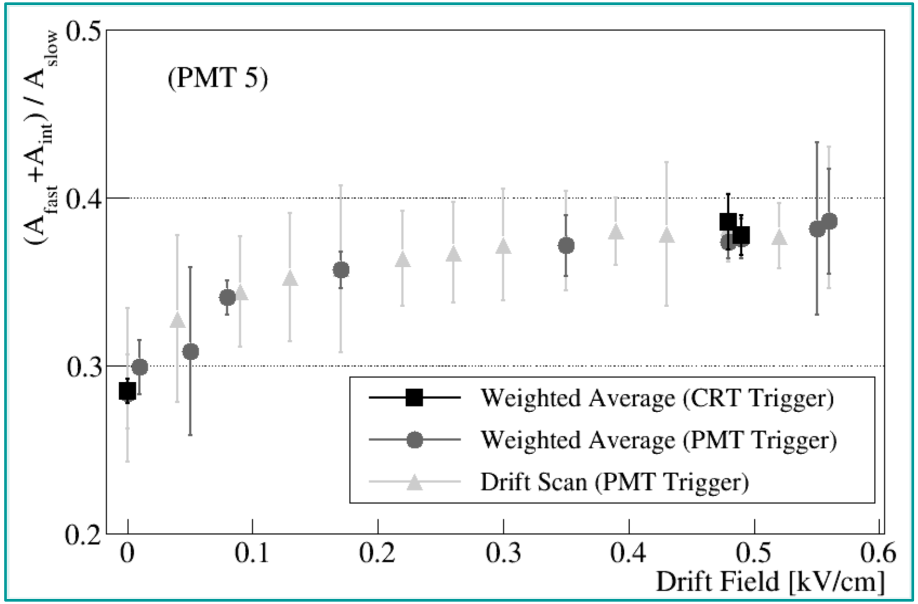
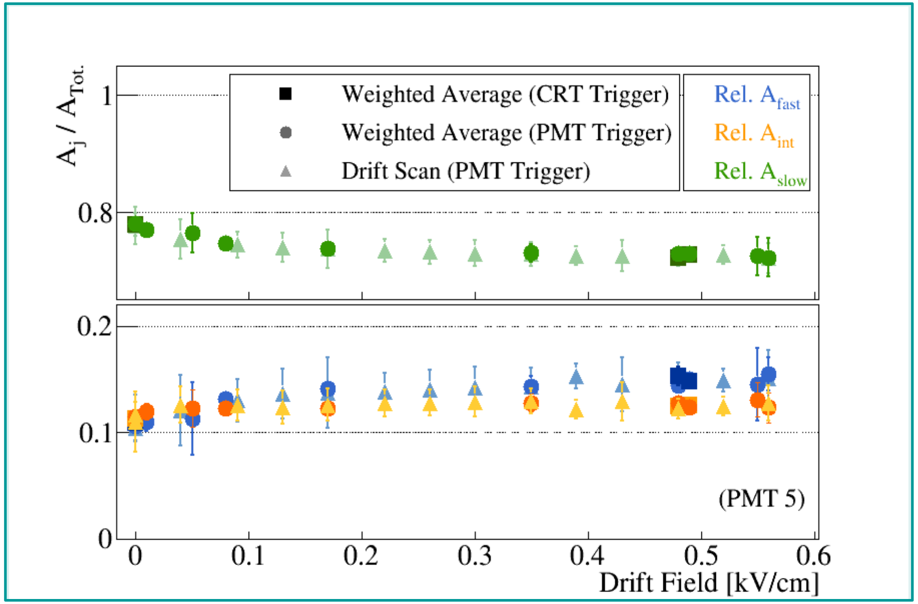




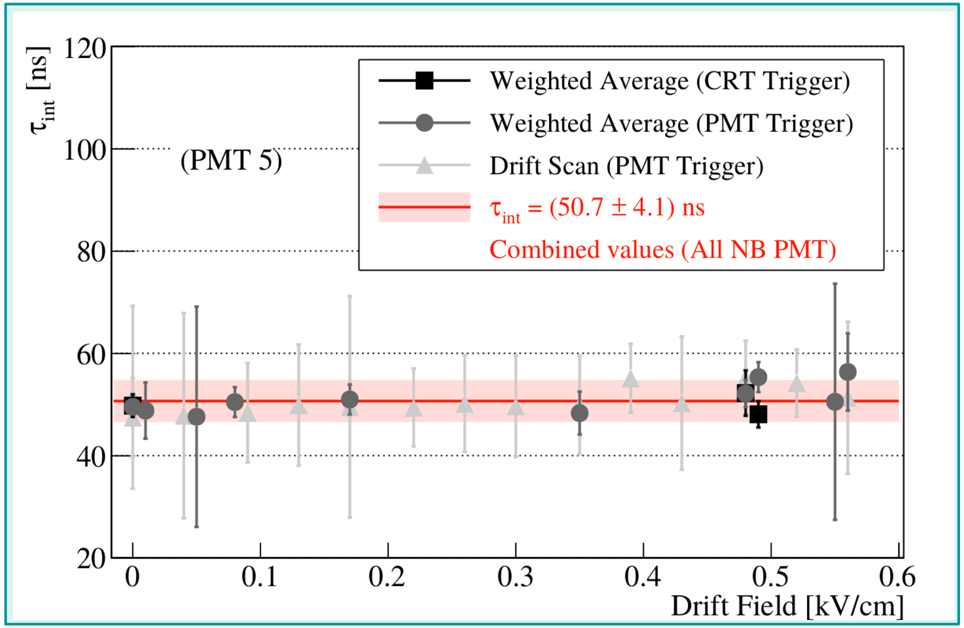
- around +34% w.r.t. the value measured in absence of drift field, $(A_f+A_i)/A_{s\ @\ 0.5kV/cm} = 0.378 \pm 0.022$

- **intermediate** relative contribution, $A_{rel,\ int,}$ **not affected** by the presence of the **drift field**

DEPENDENCE OF THE INTERMEDIATE DECAY TIME

:> **No variation** due to the **increasing strength** of the **drift field** is **observed** (never studied before!)

- combining all the data and all NB PMTs, τ_{int} = (50.7 ± 4.1) ns (fully in agreement with value at null drift field)

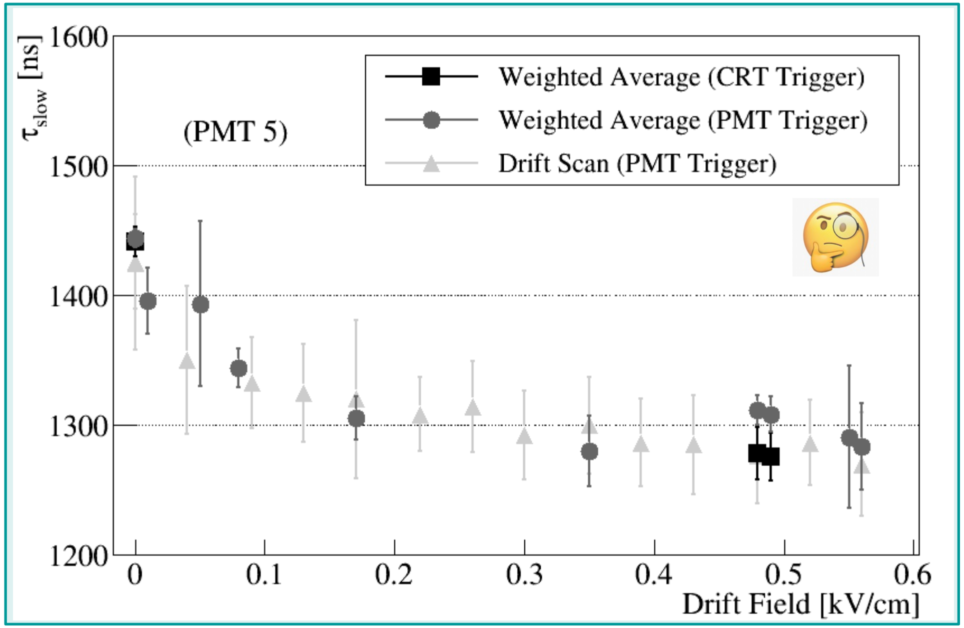


- together with the result on the relative **intermediate** amplitude, it **suggests** the **origin of the** intermediate component **independent from the LAr excitation mechanisms**

DEPENDENCE OF THE SLOW DECAY TIME

:> **Decreasing of the slow decay time with the drift field,** -10% than at null drift field

- such a CLEAR TREND HAS NEVER BEEN REPORTED BEFORE FOR LAr!
- **no dependence with the trigger conditions** (PMT trigger drift scan, duration < 2 hours)



- Robust, but **not explicable with the "classic" LAr dis-excitation model..**

ANY POSSIBLE ARTIFACT DUE TO THE FIT PROCEDURE HAS BEEN EXCLUDED!

for more details: C. Lastoria, Ph.D. thesis (2020) and in bkp slides

- Combining all the data and NB PMTs, at the nominal drift field, $\tau_{slow\ @\ 0.5kV/cm}$ = (1276 ± 44) ns

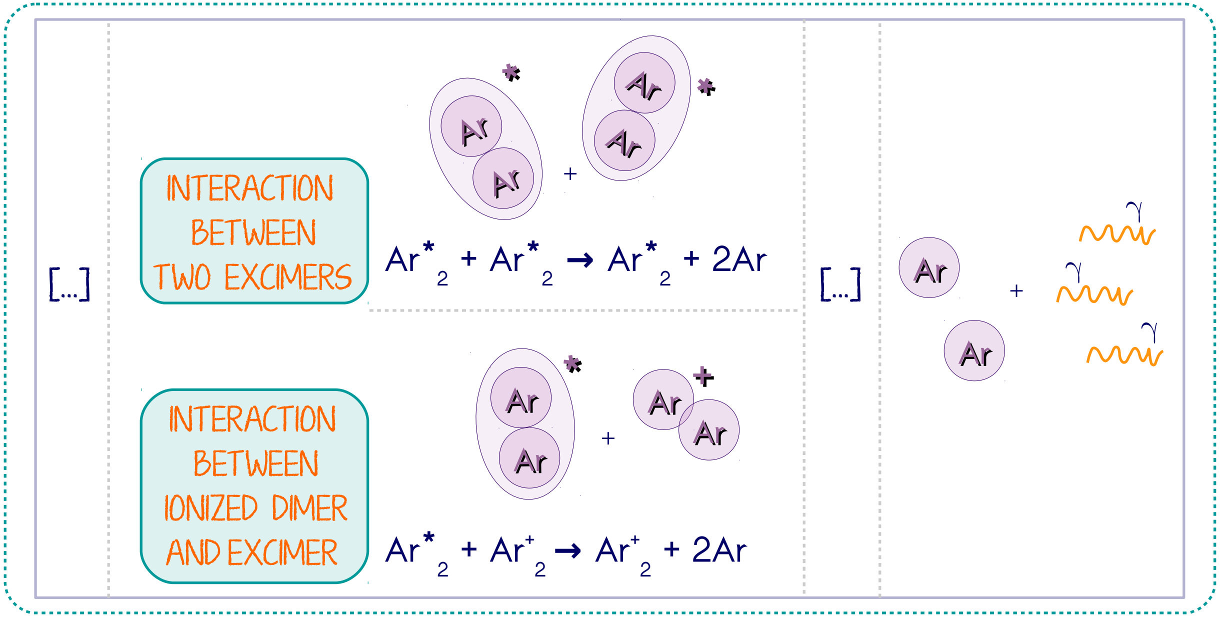
AN INTERPRETATION OF THE SLOW DECAY TIME DECREASING

*singlet state too fast for being affected

A very recent study PROPOSED an EXPLANATION for REPRODUCING THE WA105-DP DATA!

:> contribution of two additional processes quenching the triplet* state

E. Segreto, Phys. Rev. D 103, 043001 (2021)



The escaping probability of electrons from ions existing also at null drift field makes both processes always possible:

$$\ell(t) \sim \frac{A_s}{\tau_s} e^{-t/\tau_s} + \frac{A_T}{\tau_T} \frac{e^{-t/\tau_Q}}{1 + q\,\tau_Q\,(1 - e^{-t/\tau_Q})}$$

$q \sim N_0$, initial density of triplet states

$\tau_Q = 1/\lambda_Q$ and $\lambda_Q = \lambda_3 + k_0^+$,

with $k_0^+ \sim N_0^+$, initial density of ions

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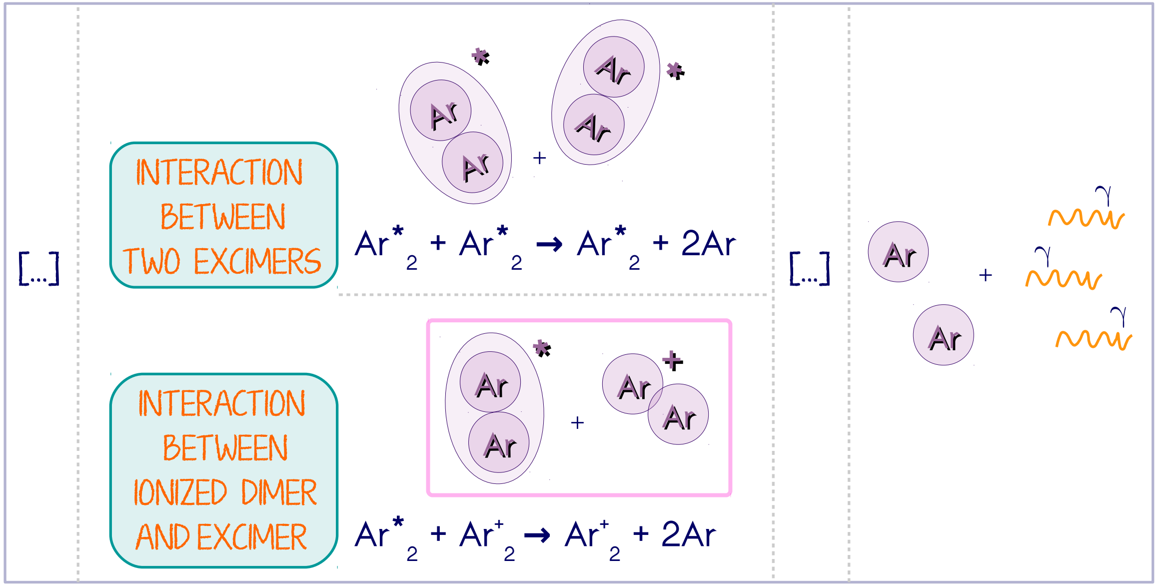
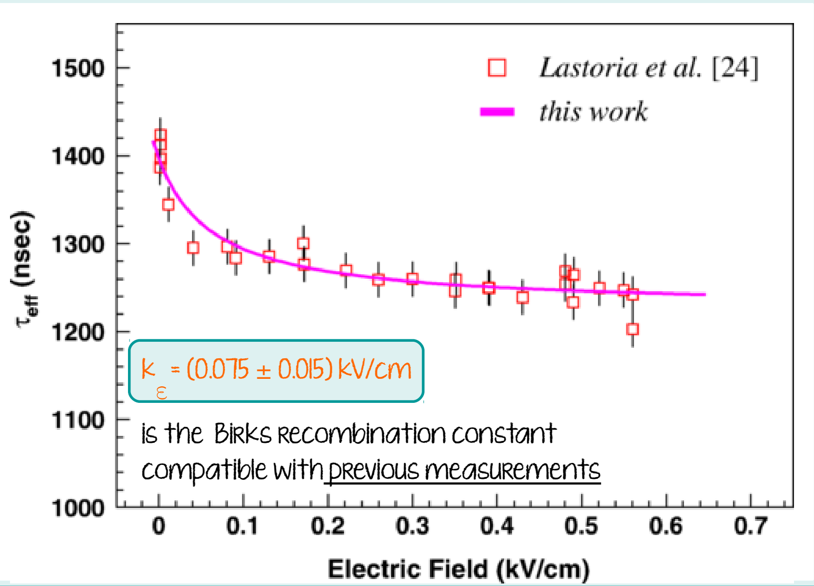


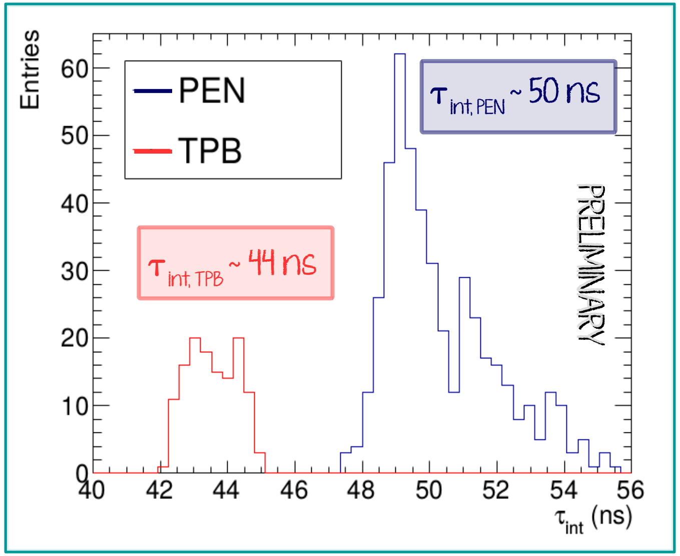


:> consequently, **slow decay time is an effective time, τ_{eff}**, and its **quenching** is nothing then else than the **measurement of the recombination process, k_ε, through the scintillation light**

$$\tau_{eff} \simeq \tau_q = \frac{1}{\frac{1}{\tau_3} + k_0^+ + \frac{k_0^+ A}{B(1+k\varepsilon/\varepsilon)}} = \frac{1}{\alpha + \frac{\beta}{1+k\varepsilon/\varepsilon}}$$

SIMILAR STUDIES PURSUED IN PROTODUNE-DP

:> Encouraging preliminary results come from the ongoing analyses:



- Dependence of the intermediate decay time with the wavelength shifter material

...paper in preparation!

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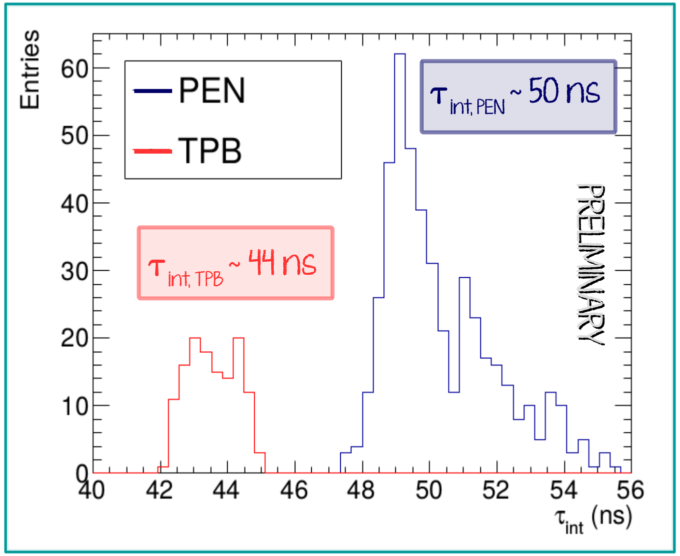

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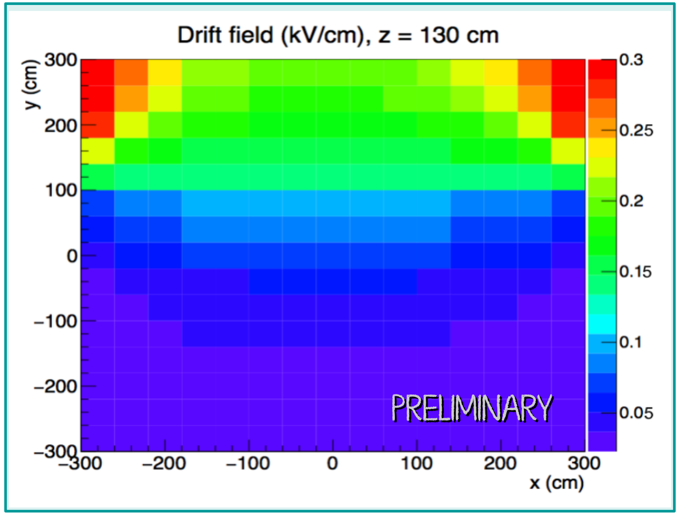
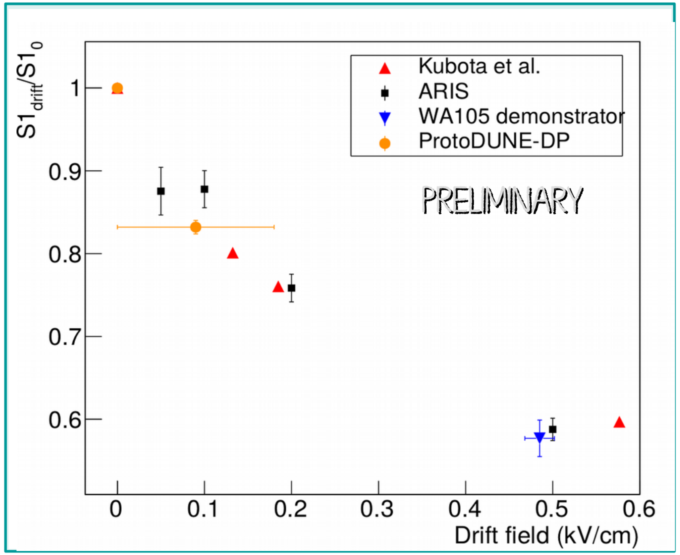


- Main difficult due to the inhomogeneity in the drift field



- Fair agreement with previous works

...paper in preparation!

TO KEEP IN MIND...

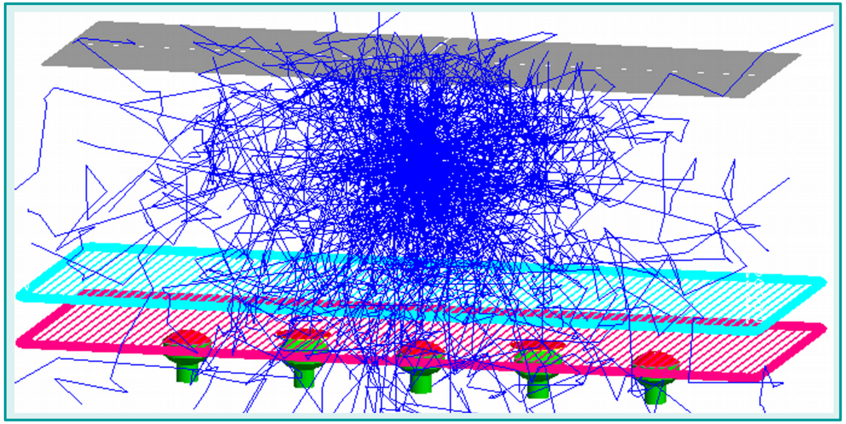
:> VUV light attenuation is affected by several factors: $\frac{1}{\lambda_{att}} \sim \frac{1}{\lambda_{Ray}} + \frac{1}{\lambda_{abs}}$

NEGLIGIBLE WITH A GOOD LAR PURIFICATION SYSTEM

:> In big LAr-TPCs, the impact of the Rayleigh scattering length can limit their operation

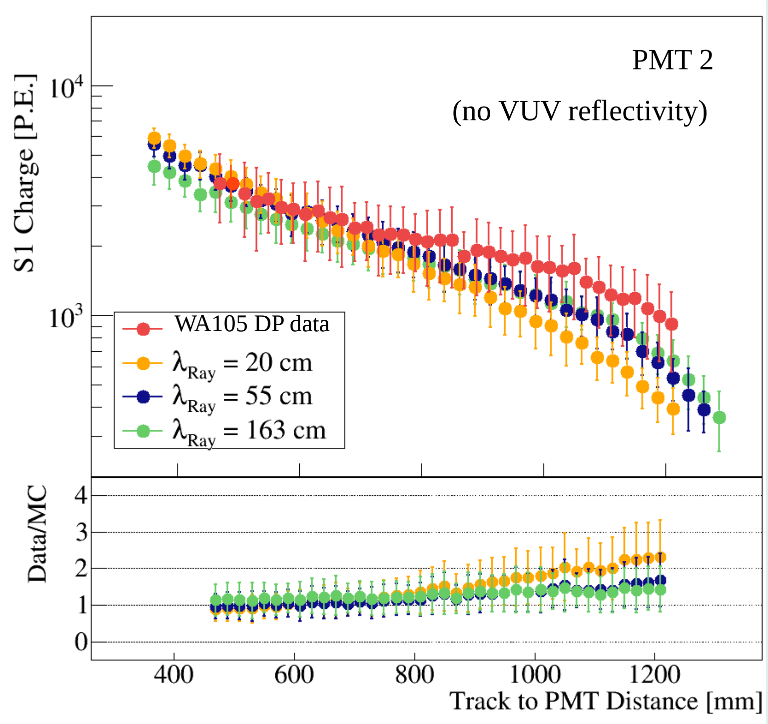
- controversial knowledge, **estimation** from **theoretical calculations** and **experimental measurements**

λ_{att}	(66 ± 3) cm	direct measurement
	(52 ± 7) cm	direct measurement
	[110; 163] cm	derived measurement
λ_{Ray}	90 cm	theoretical calculation
	(55 ± 5) cm	theoretical calculation
	(99.9 ± 0.8) cm	derived measurement



RAYLEIGH SCATTERING LENGTH AND OTHER FACTORS

:> Due to WA105 DP dimensions, data/MC ratio **compatible** with **both** λ_{Ray} = 55 cm and λ_{Ray} = 163 cm



RAYLEIGH SCATTERING LENGTH AND OTHER FACTORS

for more details: B. Abi et al., JINST 15 P12004 (2020)

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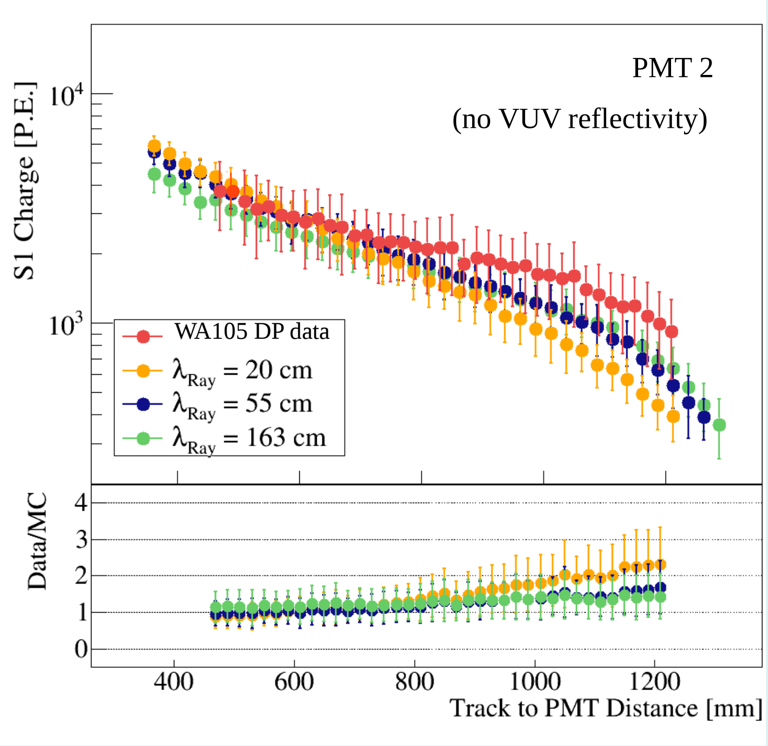
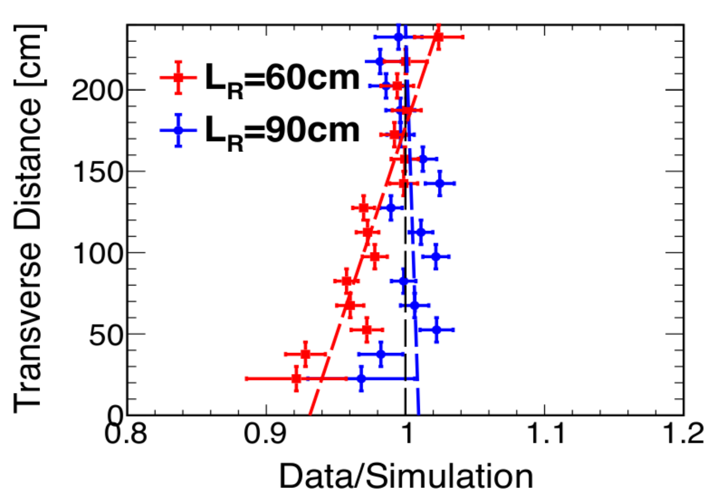
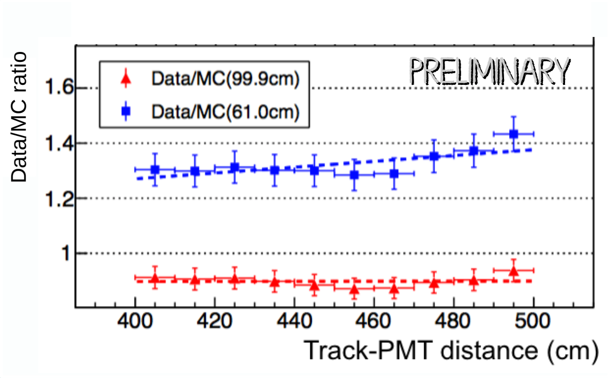


PROTODUNE-SP



- better data/MC agreement for λ_{Ray} = 90 cm

PROTODUNE-DP

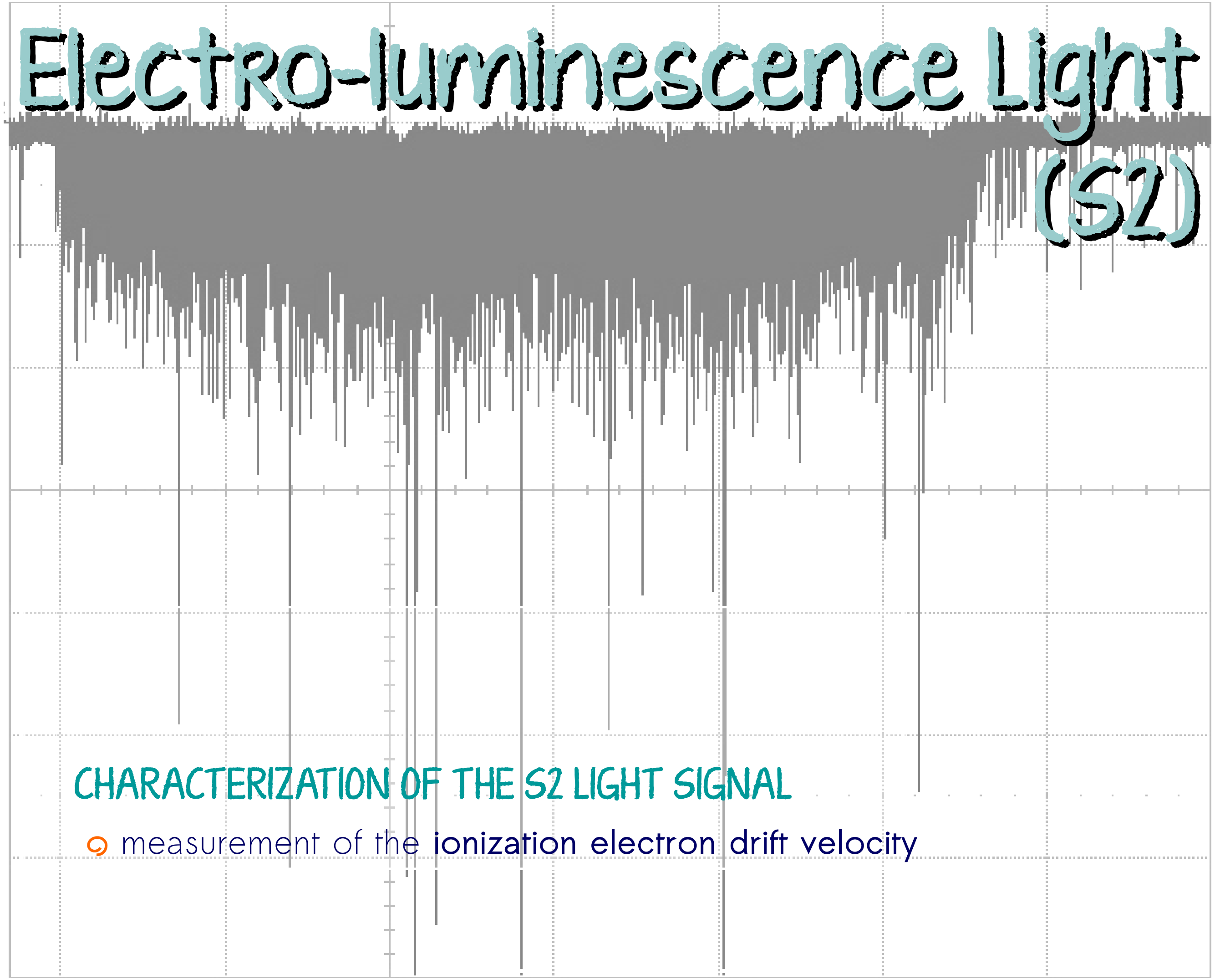


The more horizontal, the better:

- λ_{Ray} = 99.9 cm is preferred

...paper in preparation!

Electro-luminescence Light (S2)



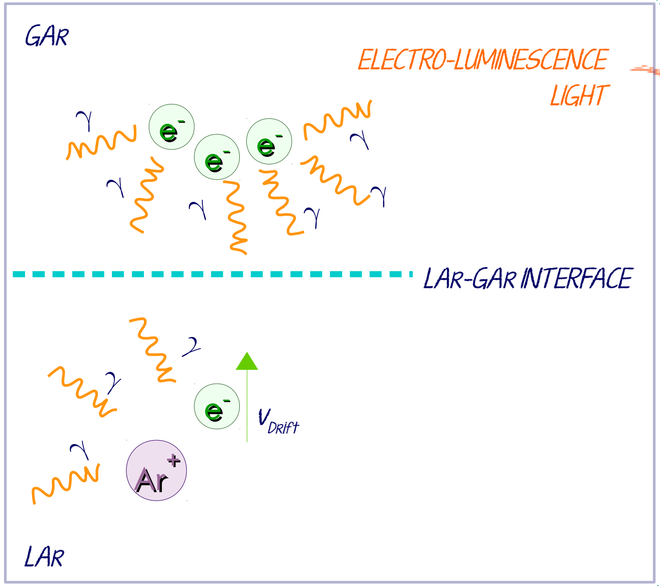
CHARACTERIZATION OF THE S2 LIGHT SIGNAL

- measurement of the **ionization electron drift velocity**

:> In DP LAr-TPC, the amplification mechanism in LEMs is a relatively innovative concept

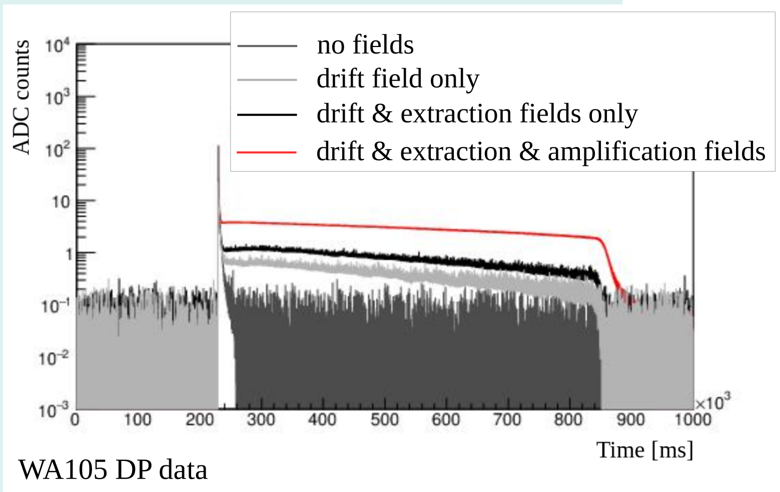
- **electro-luminescence light in GAr, both from the extraction and amplification in the LEMs holes**

under **strong electric fields** (≤ tens of kV/cm), **extraction** and **amplification** of ionization electrons take place in a **few mm space**



..TO BE CHARACTERIZED

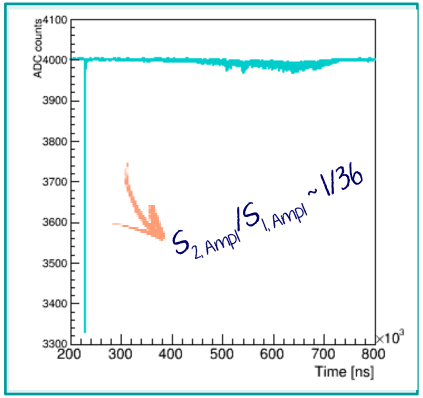
- *how the electro-luminescence light is affected?*



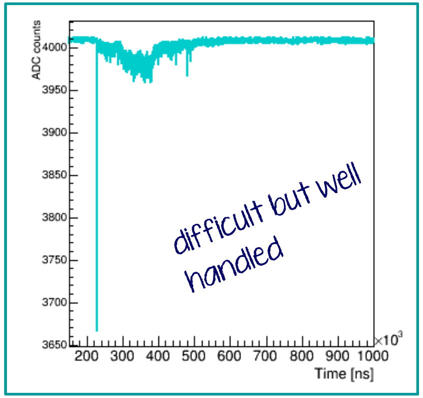
S2 SIGNAL RECONSTRUCTION ALGORITHM

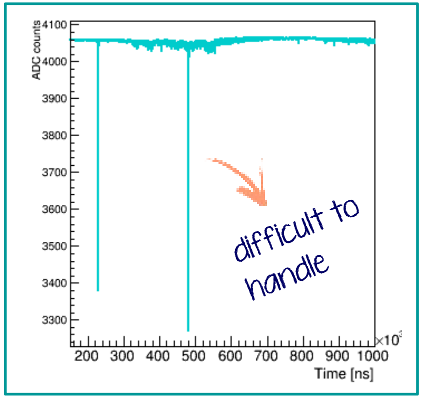
MAIN DIFFICULTIES IN THE RECONSTRUCTION:

- $S_{2,\ Ampl} << S_{1,\ Ampl}$
  typically, $S_{2,\ Ampl} < 40$ ADC



- S2 signal is not always clearly separated from S1 signal or it is contaminated by spurious S1 signals





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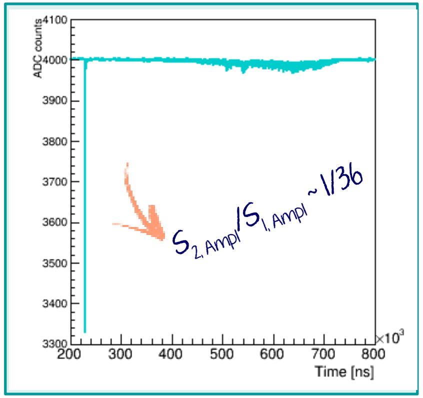

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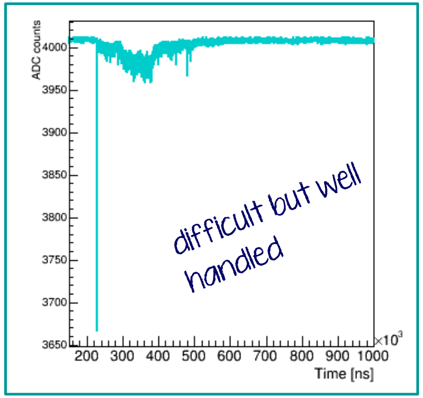
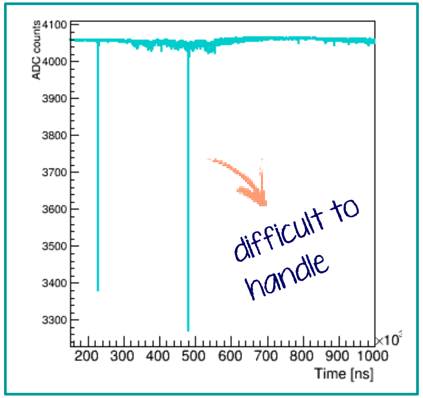
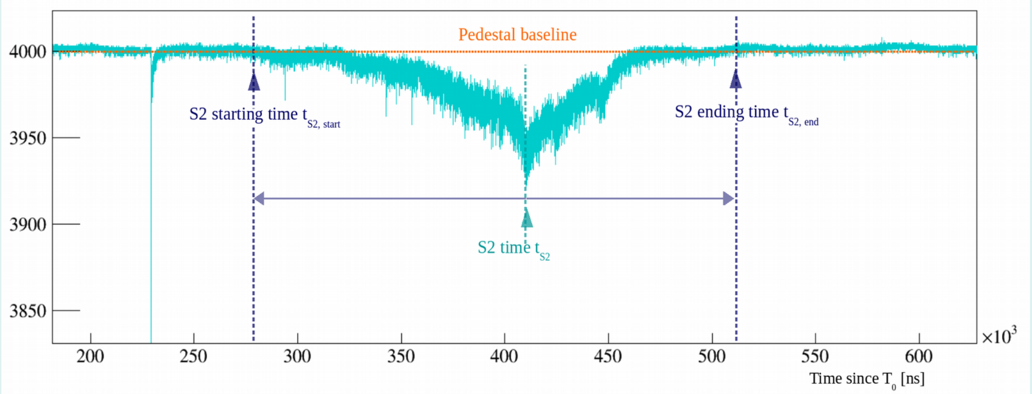




reconstruction of a real WA105-DP event (zoomed in y axis):
Drift = 0.49 kV/cm, $Extr_{GAr}$ = 2.14 kV/cm, Ampl. = 25 kV/cm, Ind. = 1kV/cm

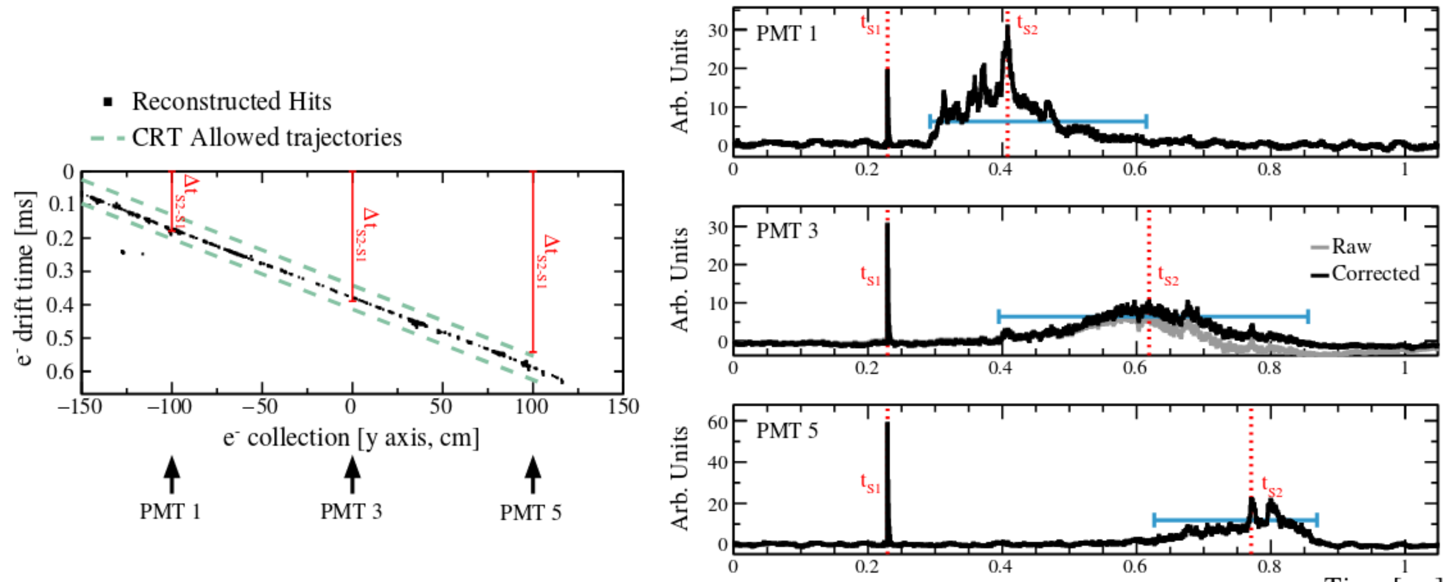


RECONSTRUCTED INFO:

- drift time, t_{S2} and S2 amplitude
- starting and ending time, time duration
- integrated charge

ELECTRO-LUMINESCENCE LIGHT FEATURES

- starting and ending time, **time duration** → related to the **track inclination with respect to the CRP plane**
- **integrated charge** → proportional to the **ionization charge signal**
- **drift time** → corresponds to the **arrival time of the electrons at the LEM holes**

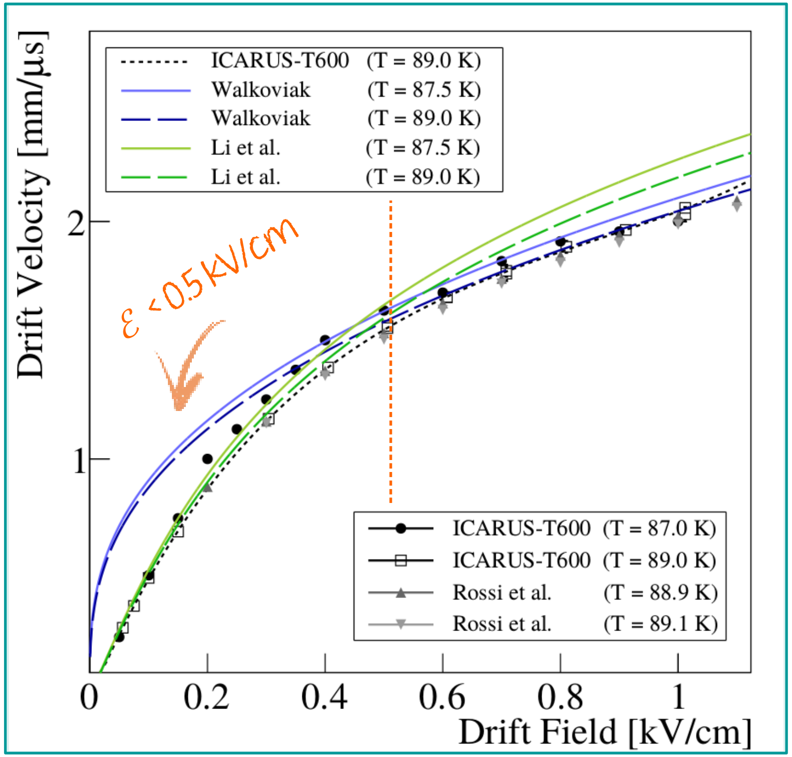


reconstruction of a real event: Drift = 0.49 kV/cm, $Extr_{GAr}$ = 2.14 kV/cm, Ampl. = 25 kV/cm, Ind. = 1kV/cm

ELECTRON DRIFT VELOCITY

:> Crucial parameter also for the track reconstruction in the anode-plane (it gives the **z coordinate of the event**!)

- difficult parametrization, v = v(T, ε), dependent on the LAr temperature and drift field strength



- Discrepancies between parametrizations and measurements are present

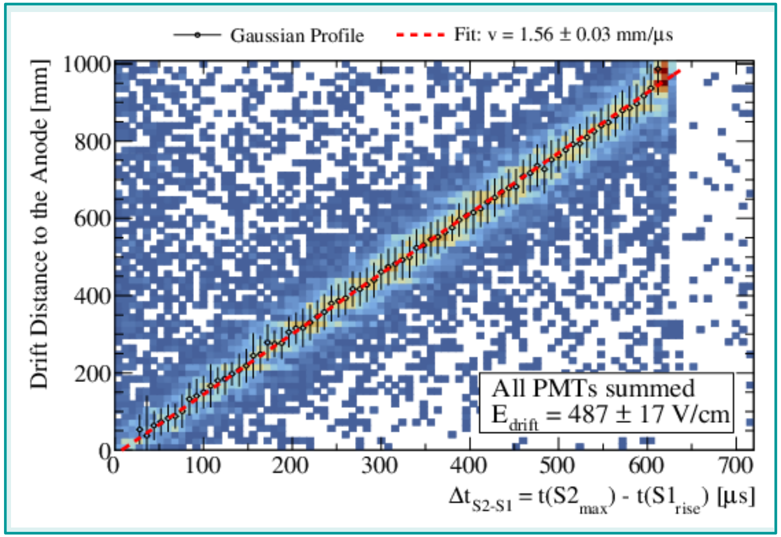
it is important to have other measurements!

MEASUREMENT OF THE DRIFT VELOCITY IN THE WA105-DP

:> **Two distinct analyses** that show a **good agreement**:

- **CRT selection:** drift length from CRT reconstruction and drift time from PMT waveforms

CRT ANALYSIS



- added **systematic uncertainties** due to the **width** of CRT strips

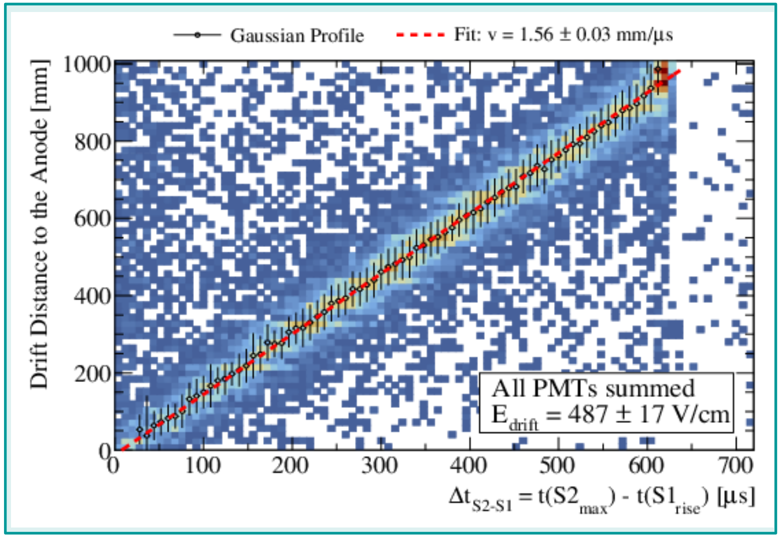
v_{drift} = (1.56 ± 0.03) mm/µs

MEASUREMENT OF THE DRIFT VELOCITY IN THE WA105-DP

:> **Two distinct analyses** that show a **good agreement**:

- **CRT selection:** drift length from CRT reconstruction and drift time from PMT waveforms
- **combining light and charge information**: considering $t_{S2,\ end}$ **signal** for **anode-to-cathode tracks** ($d_i \sim 1$m)

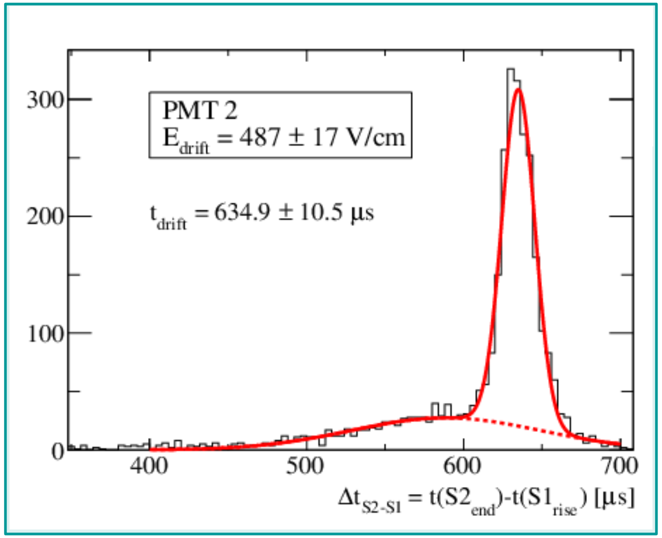
CRT ANALYSIS



- added **systematic uncertainties** due to the **width** of CRT strips

$v_{drift} = (1.56 \pm 0.03)\ \text{mm}/\mu\text{s}$

S2 ENDING TIME

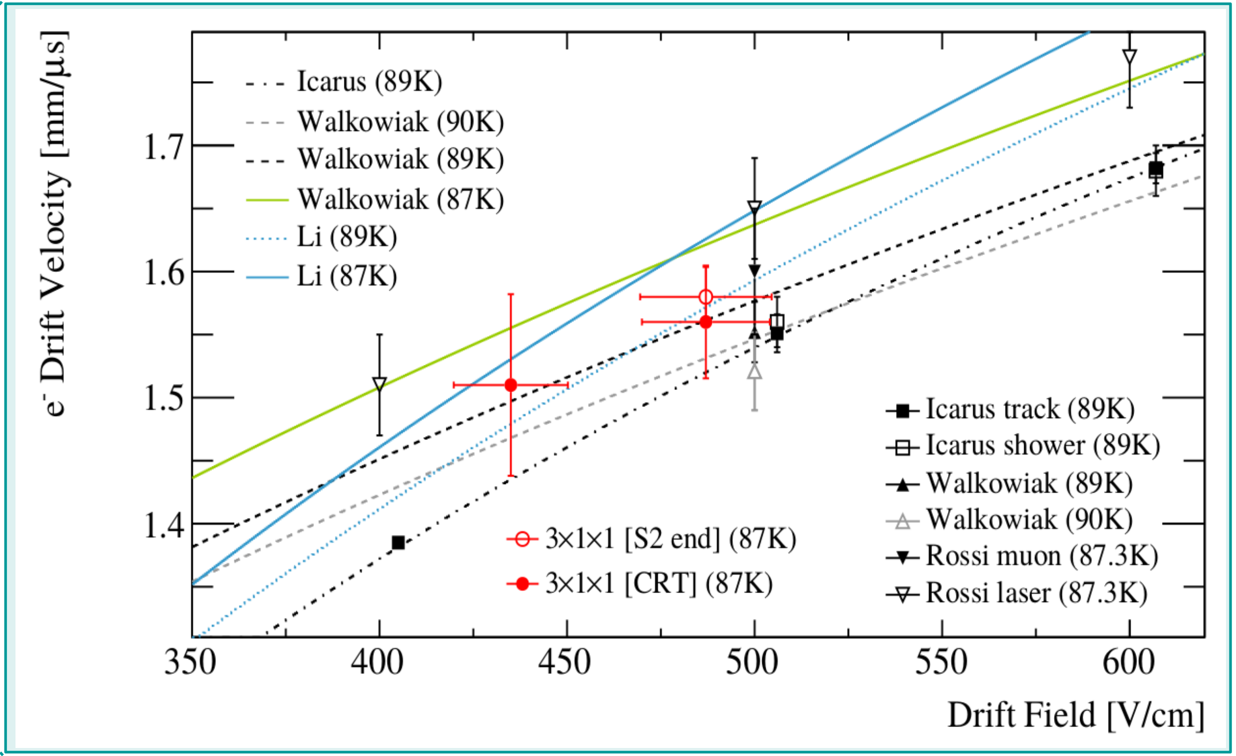


- assigned conservative error due to LAr surface position

$v_{drift} = (1.58 \pm 0.02)\ \text{mm}/\mu\text{s}$

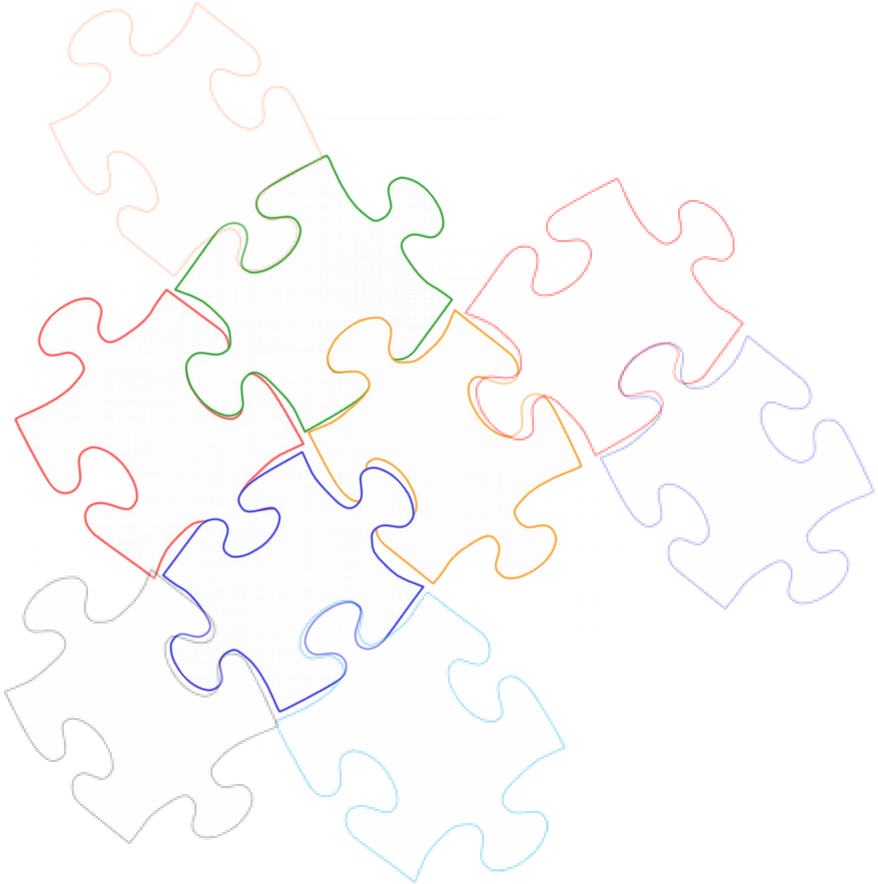
COMPARISON WITH OTHER MEASUREMENTS AND PREDICTIONS

:> Unfortunately only few data available, at 87 K in the (0.4; 0.5) kV/cm drift field range



- WA105-DP results are compatible (within two σ) with predictions

SUMMARY...



FINDINGS ON THE PRODUCTION MECHANISMS

PRESENCE OF INTERMEDIATE COMPONENT

:> Contributing with A_{int} ~ **11%** to the total scintillation light

:> **Not affected by the drift field strength**

- τ_{int} = (50.7 ± 4.1) ns

Reinforcing the HYPOTHESIS of not being related to LAr dis-excitation but the WAVELENGTH SHIFTER MATERIAL

:> Qualitatively confirmed by ProtoDUNE-DP analysis ($\tau_{int,TPB} \neq \tau_{int,PEN}$)

UNKNOWN PROPERTIES OF LAR

:> **Dependence of the LAr dynamics on the drift field**

- **Increasing** of the fraction of singlet over triplet ($\Delta(A_f+A_i)/A_{s,\,\mathcal{E}\neq 0}$ = **+34%**, at ~0.5 kV/cm)
- **Net decreasing** of the **slow decay time** ($\Delta\tau_{slow,\,\mathcal{E}\neq 0}$ = **-10%**, at ~0.5 kV/cm)

NEW MODEL, PROPOSED

Explained including **secondary scintillation mechanisms** neglected so far in the classical LAr scintillation model

interesting for general LAr TPC operation

..ON THE PROPAGATION

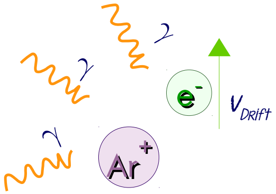
:> New models and additional measurements tend to confirm a higher value for the **Rayleigh scattering length** (CRITICAL PARAMETER FOR OPERATING BIG LAR-TPCS!)

- λ_{Ray} ~ (90; 100) cm

:> **From studying the electro-luminescence light** signal in the WA105-DP demonstrator, additional measurement of v_{drift} **measurement** at low drift field, $\mathcal{E}$~0.5 kV/cm

- v_{drift}~ 1.58 mm/μs

(CRITICAL FOR OBTAINING THE Z-COORDINATE OF THE RECONSTRUCTED TRACK!)



..thanks for your attention!