# “ALL RUNS” SCINTILLATION TIME PROFILE FIT ANALYSIS AND SYSTEMATICS

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*3x1x1 light data-MC meeting*

*December 18th , 2019*

# Introduction

:> starting point: "good runs" list

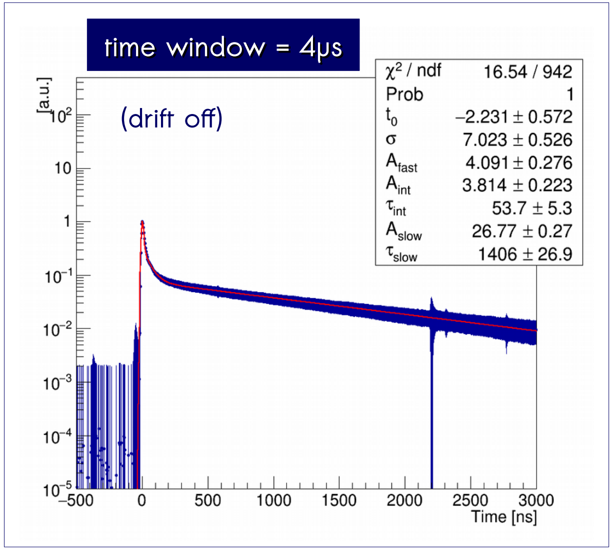
- only runs with stable fields condition (drift, extraction, induction and amplification)
- minimum initial number of events (1000 ev)
- minimum number of averaged waveforms (10 waveforms)

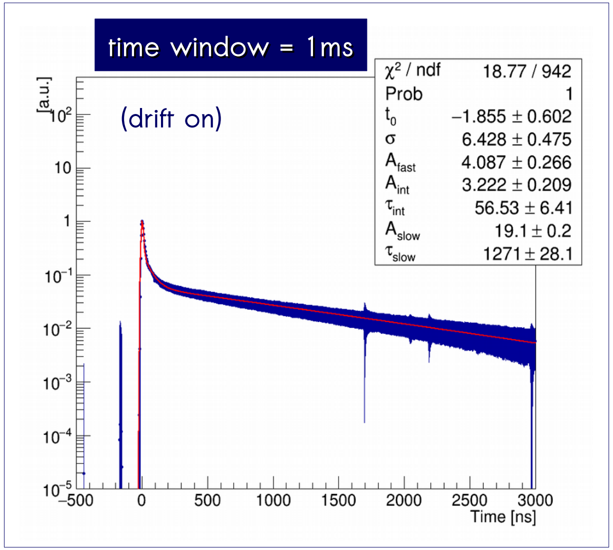
:> runs with both acquisition windows (4us, 1ms) are included

- fitted with the same model in the same range: **gaussian convoluted with three exponentials up to 3.5us**
  → **"phenomenological" model**, that adequately reproduce our data in this range (Ai are normalization constants, not directly connected with the probability of de-excitation from the single or triplet state)
- study with the toy MC showed that best result is obtained from a **$\mathcal{L}$ikelihood** fit instead of a $\chi^2$ fit
  → the $\chi^2$ fit is used only when the $\mathcal{L}$ikelihood fit fails and additional systematic uncertainties are added (more details in next slides)
- due to the digitization sampling (4ns) the tau fast is kept fixed at 6ns
  → more details will be given discussing the systematics

:> in runs with **amplification** (**1ms** acq.wind.) av. wave. only from ev. with $T_{S2,start} > T_{S1} + 4\mu s$

- in runs with **4us** acq. wind. Included only runs with ampl<=18.0kV/cm but (more details will be given discussing the systematics)



# Outline

:> NO DRIFT FIELD

- monitoring of LAr purity → connection of the tau slow value measured in the 3x1x1 and amount of impurities
- measurement of the tau intermediate
- measurement of the ratio (Af+Ai)/As
  - → comparison with other experiments
  - → comparison with f90 factor distribution

:> EFFECT OF THE DRIFT FIELD ON THE SCINTILLATION LIGHT

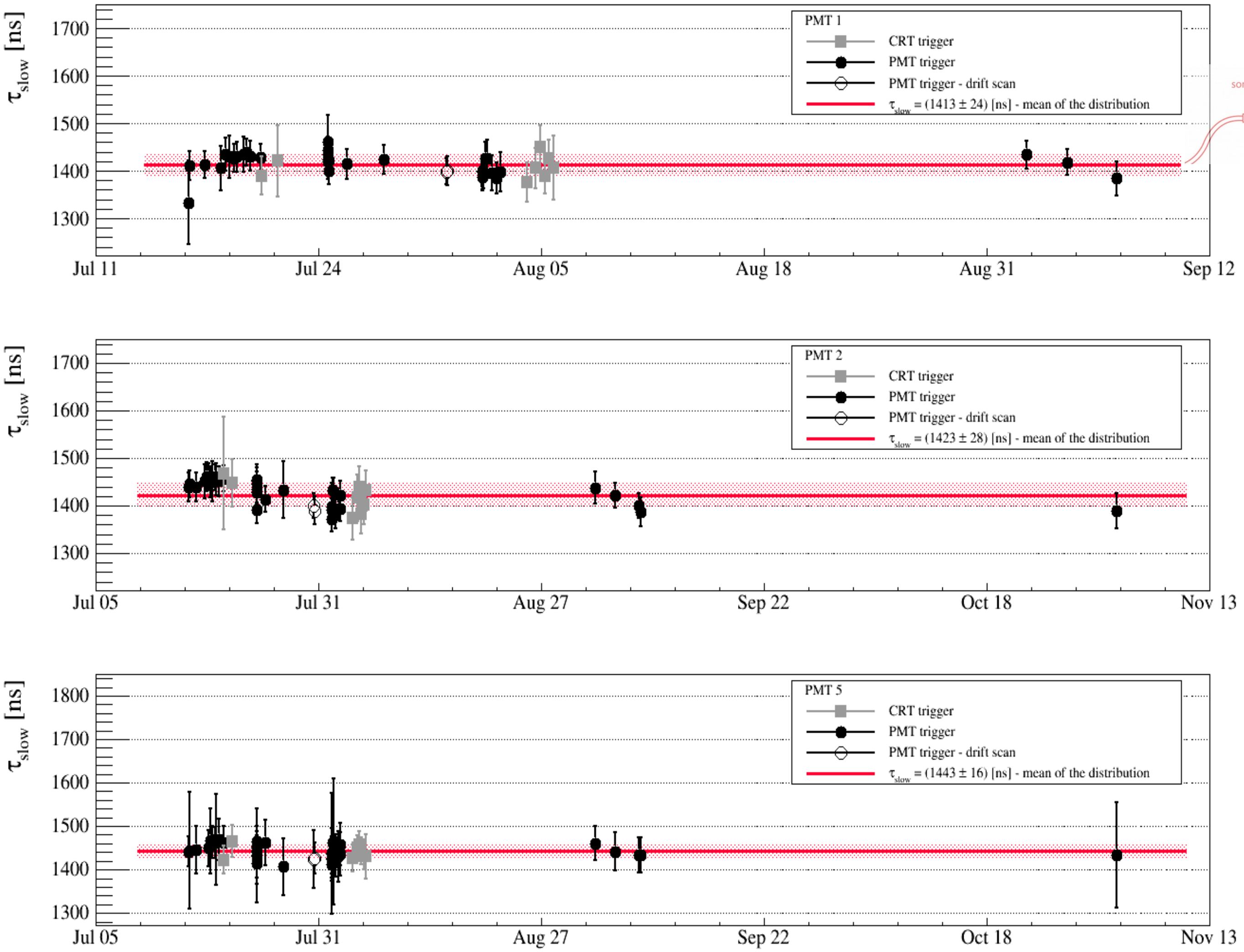
- dependence of relative probability amplitudes and ratio (Af+Ai)/As with the drift field
  - → comparison with f90 factor distributions
- dependence of the tau slow with the drift field
- absence of dependence of the tau intermediate with the drift dield

:> MAIN SOURCES OF SYSTEMATIC UNCERTANTIES

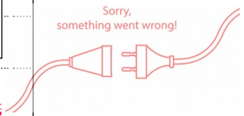
# Tau slow (E=0) vs time - monitoring of LAr purity

NB

SYSTEMATIC UNCERTANTIES NOT INCLUDED YET




*cable broken, PMT disconnected up to the end of the 3x1x1 op.*




:> the red line is the mean of the tau slow distribution obtained from all the plotted runs (the red band is the 1σ error)

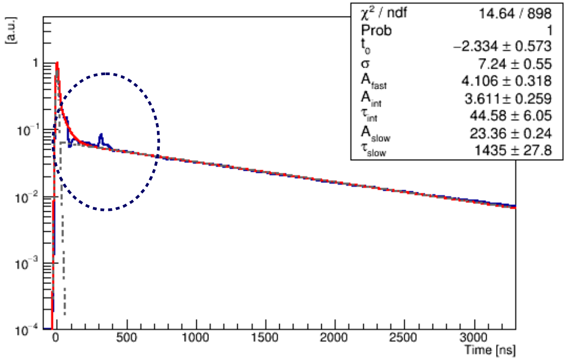
:> agreement within 1σ error among the three channels

| | $\tau_{slow}$ |
|---|---|
| PMT 1 | 1413 ± 24 |
| PMT 2 | 1423 ± 28 |
| PMT 5 | 1443 ± 16 |

$<\tau_{slow, NB}>$ = (1426 ± 40) ns

# Tau slow (E=0) vs time - monitoring of LAr purity

PB

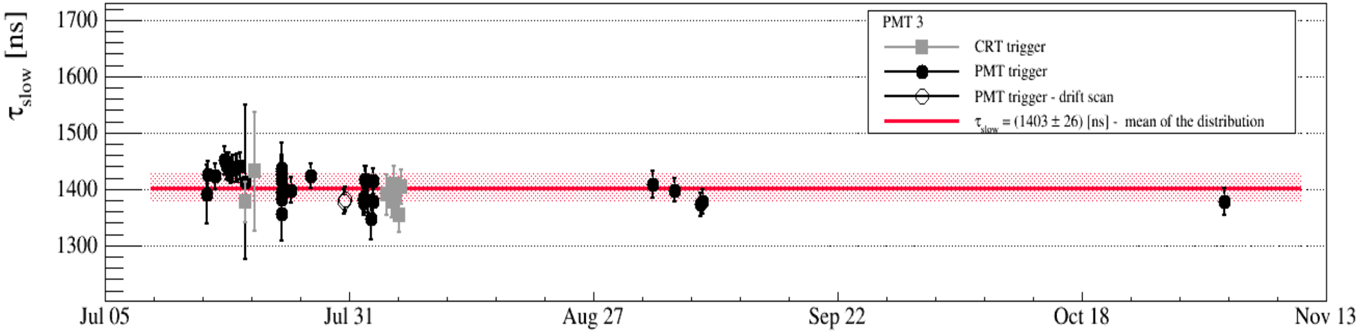


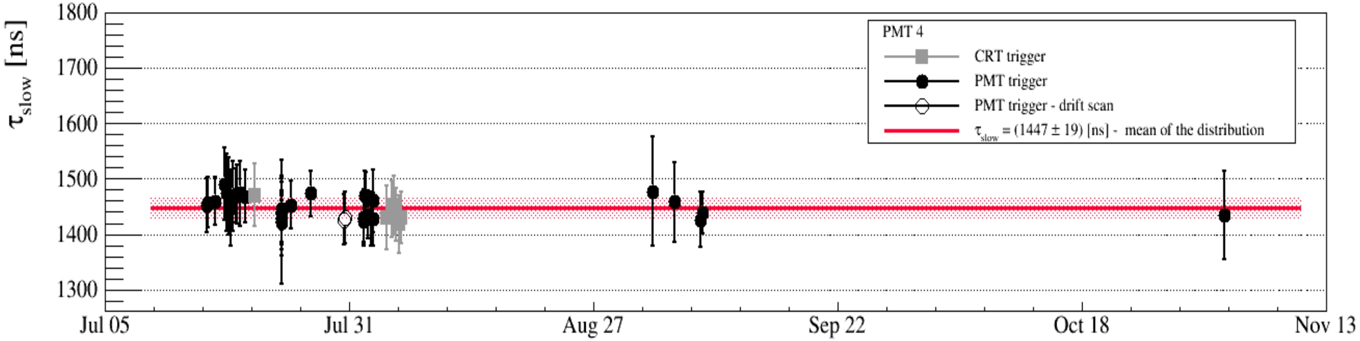

:> PB PMTs show consistent results with the NB PMTs

→ same stable trend of the tau slow is monitored

:> unfortunately, because of the presence of the reflections they cannot be included for the following analyses

SYSTEMATIC UNCERTAINTIES NOT INCLUDED YET




:> the red line is the mean of the tau slow distribution obtained from all the plotted runs (the red band is the 1σ error)

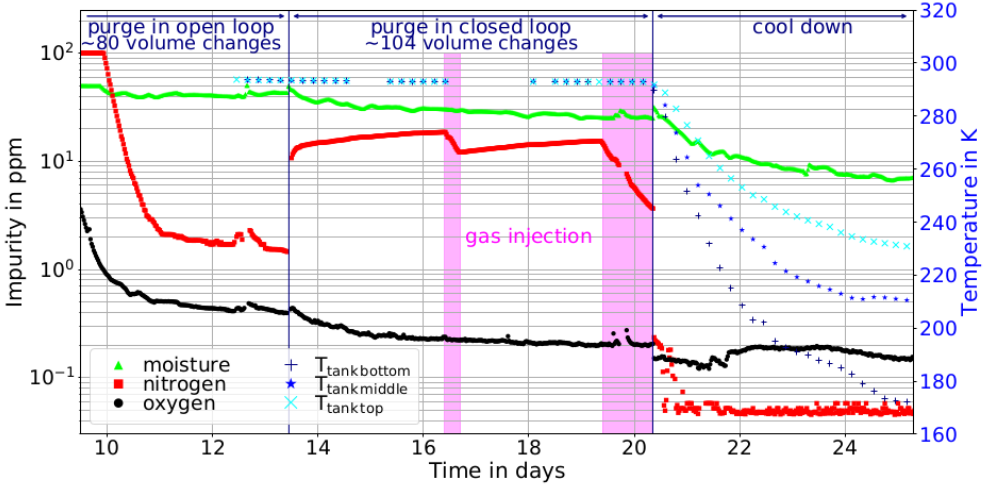
:> agreement within 1σ error among all the channels

| | $\tau_{slow}$ |
|---|---|
| PMT 1 | 1413 ± 24 |
| PMT 2 | 1423 ± 28 |
| PMT 3 | 1403 ± 26 |
| PMT 4 | 1447 ± 19 |
| PMT 5 | 1443 ± 16 |

# Comparison with the impurities measured by gas tracers

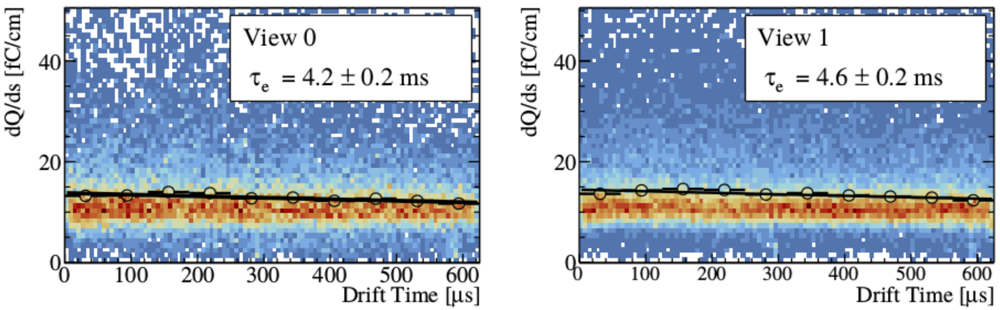
*info extracted from 3x1x1 technical paper*

:> in the 3x1x1 the amount of impurities has been monitored during the purge and cool down phases by three residual **gas trace analysers** (RGTA) for $O_2$, $N_2$ and $H_2O$ → lower minimum detected 50 ppb, 10 ppb, 10 ppb respectively




| instrument | upper detection limit | lower detection limit | number of ranges | precision at lowest range | provider |
|---|---|---|---|---|---|
| Oxygen | 23% | 50 ppb | 10 | ±100 ppb | AMI (2001 R series) |
| Nitrogen | 200 ppm | 10 ppb | 2 | ± 20 ppb | Gow-mac (1200 series) |
| Moisture | 50 ppm | 10 ppb | 2 | ± 20 ppb | Gow-mac (1402 series) |

:> the small amount of $O_2$ confirmed by the charge measurements

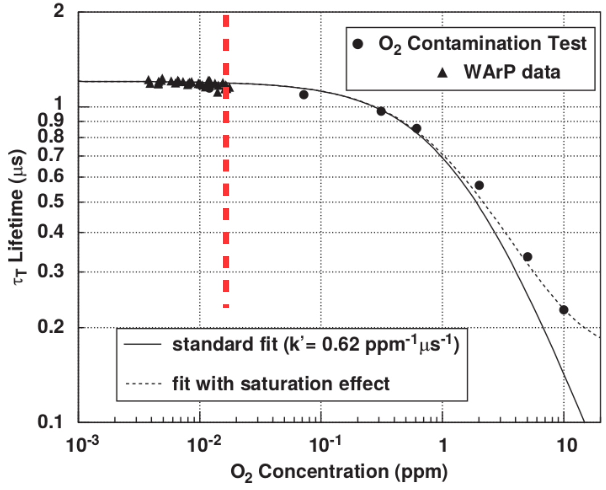


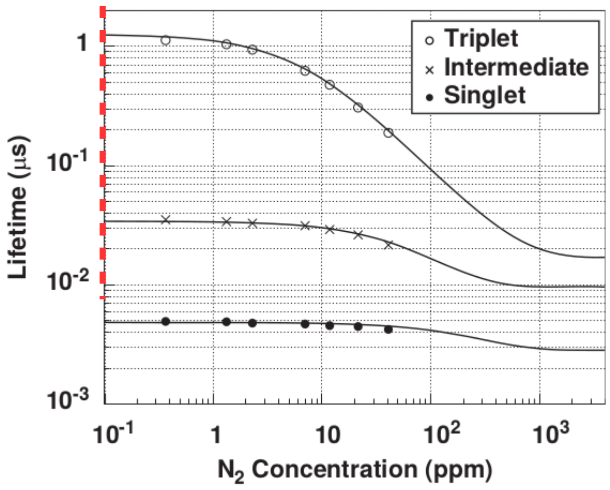
# Comparison with the impurities measured by gas tracers

:> the effect of the presence of ($O_2$, $N_2$) on the $\tau_{slow}$ are given in [8], [9], [10]

→ for $[O_2]$<10 ppb no effects on the $\tau_{slow}$ are expected

→ for $[N_2]$<100 ppb no effects on the $\tau_{slow}$ are expected




:> the effect of the presence of $H_2O$ has been studied only in GAr → for concentrations lower then 10 ppb, no effects are expected [12]

The average value obtained from the NB PMTs $<\tau_{slow, NB}>$ = (1426 ± 40) ns is consistent with all this information

:> this value is also in **agreement** within the errors with the other values reported in literature [1], [2], [3]

# Tau intermediate

:> tau intermediate distribution obtained including all the runs collected in absence of drift field

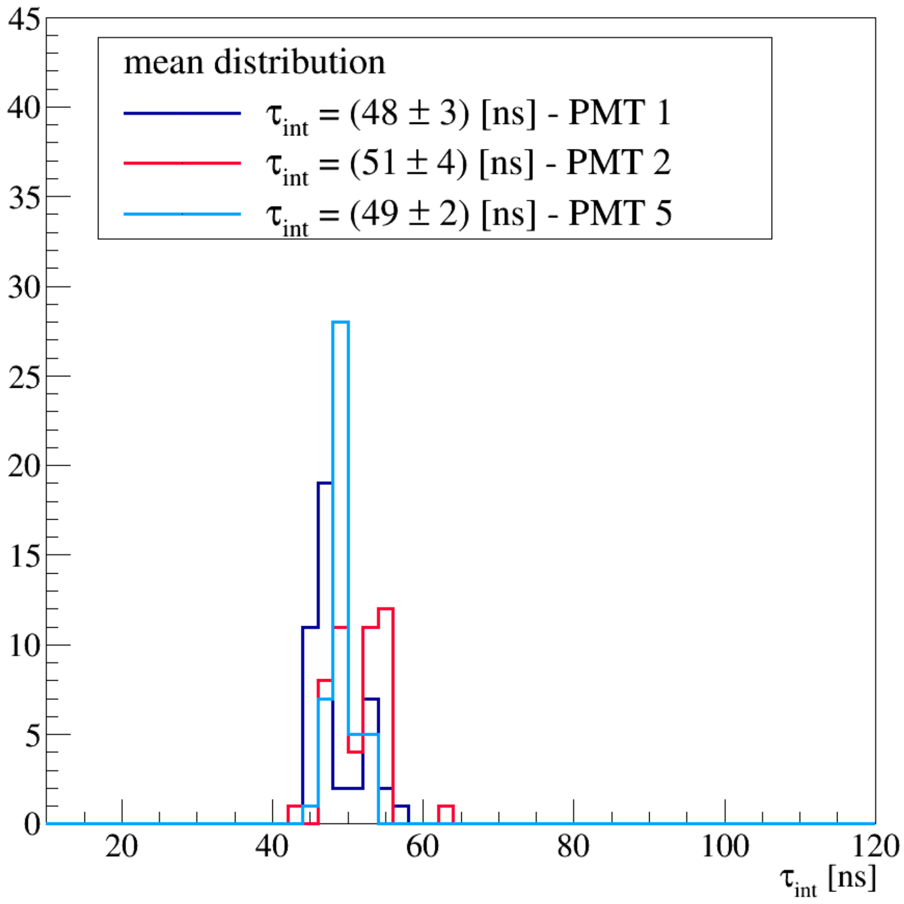
→ the error for each value corresponds to the σ of the distribution

| | $\tau_{int}$ |
|---|---|
| PMT 1 | 48 ± 3 |
| PMT 2 | 51 ± 4 |
| PMT 5 | 49 ± 2 |

$\langle \tau_{int,\ NB} \rangle = (49.3 \pm 5.4)$ ns

:> tau intermediate has been measured by other experiments [1], [2], [3], [8], [9], [10], [12] using different models, not always the value is given with the errors, its value spans from 20 ns up to 130 ns

→ **our value is in agreement with the value given in [12]**, the model used in [12] is different from our model



# Ratio (Af+Ai)/As and $f_{90}$ factor

:> the ratio between the probability of Ar de-excitation from the singlet or the triplet state ($I_S/I_T$) is directly connected with the nature of the particle excited Ar atoms and it can be used for particle identification

→ not always the value reported for this ratio is given with the errors

→ for the electrons, 0.26 [13], 0.3 [1], 0.35 [8] and **as a function of the particle energy** from (0.391 ± 0.012) to (0.282 ± 0.009) in **[2]**

:> with our model we do not have direct access to this information; despite that the ratio **(Af+Ai)/As**, defined from the normalization constants obtained from the fit, **is in the range** of values measured **(0.26; 0.39)**

| | (Af+Ai)/As - CRT | (Af+Ai)/As - PMT |
|---|---|---|
| PMT 1 | 0.2681 ± 0.0010 | 0.2889 ± 0.0026 |
| PMT 2 | 0.2747 ± 0.0082 | 0.2910 ± 0.0028 |
| PMT 5 | 0.2840 ± 0.0061 | 0.2830 ± 0.0040 |

$<(Af+Ai)/As_{NB}> = (0.2816 \pm 0.0048)$ ns

# Ratio (Af+Ai)/As and $f_{90}$ factor

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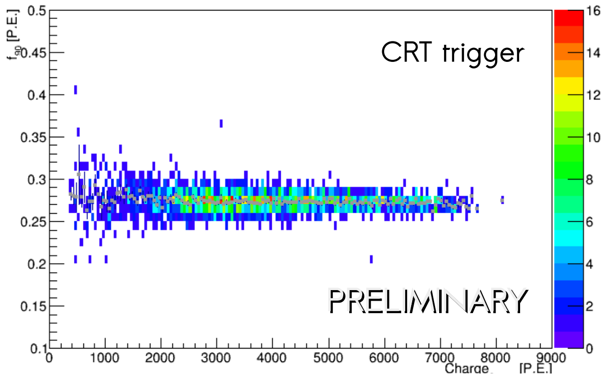
:> with our model we do not have direct access to this information; despite that the ratio **(Af+Ai)/As**, defined from the normalization constants obtained from the fit, **is in the range** of values measured **(0.26; 0.39)**

:> the empirical **$f_{90}$ factor** that can be computed event by event, give similar information

→ for the **electrons** [5], [6], [7] **f90 ~0.3**

→ for the **muons** [3] **f90 in the range (0.31; 0.39)**, no error discussion or plot shown




| | (Af+Ai)/As - CRT | (Af+Ai)/As - PMT |
|---|---|---|
| PMT 1 | 0.2681 ± 0.0010 | 0.2889 ± 0.0026 |
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| PMT 5 | 0.2840 ± 0.0061 | 0.2830 ± 0.0040 |

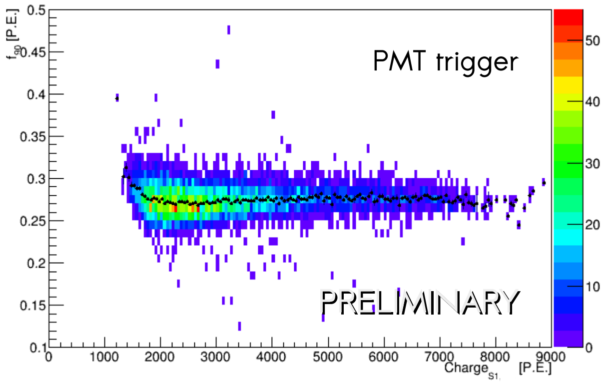
<(Af+Ai)/As$_{NB}$> = (0.2816 ± 0.0048) ns

$$f_{90} = \frac{\int_{t_0}^{t_*} light(t)}{\int_{t_0}^{t_f} light(t)}$$

, $t_0 = (T_{S1} - 40)$ns,

, $t_* = (T_{S1} + 90)$ns

$t_F = (T_{S1} + 3500)$ns.



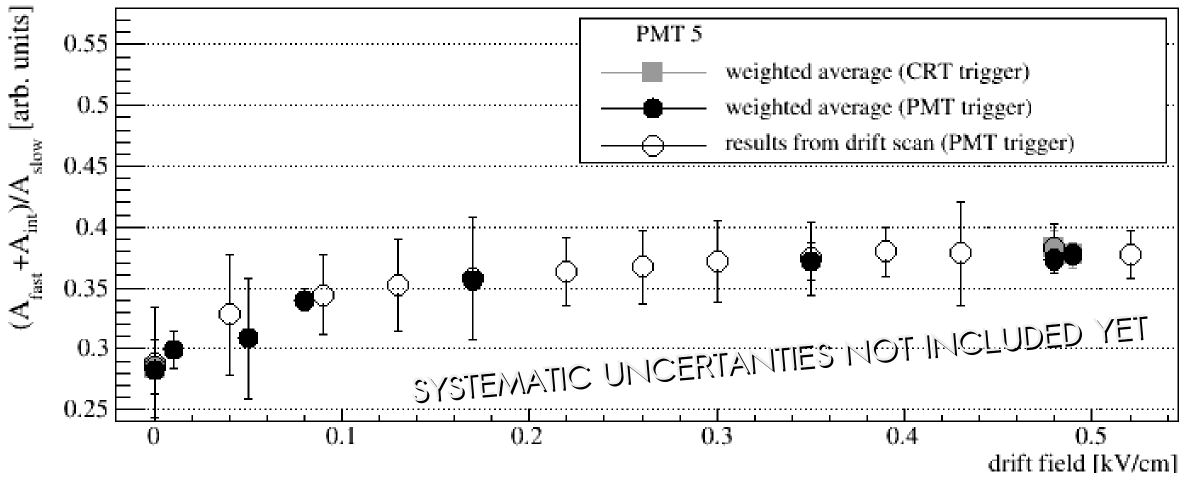

:> on average, **(Af+Ai)/As** ratio is **in agreement with** the value of the **f90 factor**

# Effect of the drift field on the scintillation light

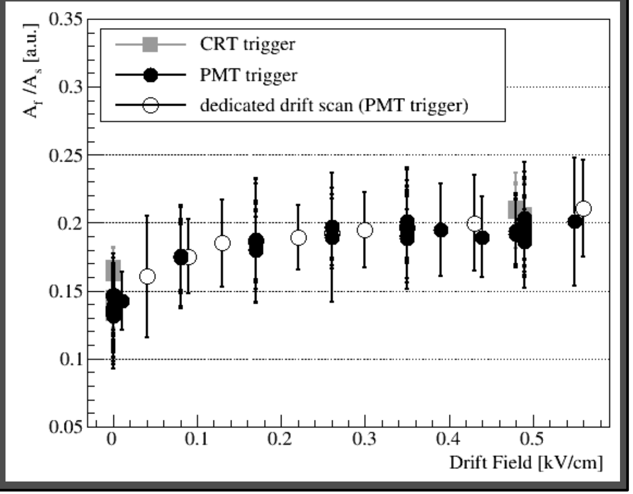
:> (Af+Ai)/As increases as a function of the drift field

→ results from CRT tr., PMT tr. or dedicated drift field scan are analyzed separately

→ **each point** at each value of the drift field is the **weighted average** of all the results available to take properly into account the error corresponding to each run




Reminder of previous result




*the Af/As ratios are in bkp slides*

# Effect of the drift field on the scintillation light

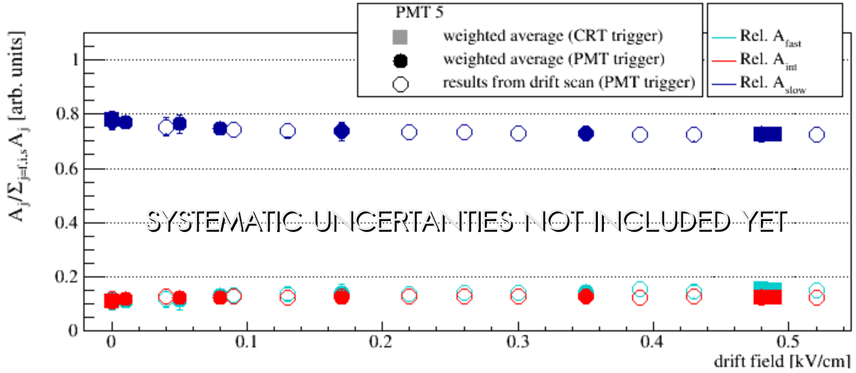
:> a statistically significant increasing of **(Af+Ai)/As** as a function of the drift field is confirmed

→ at higher field, a discrepancy between CRT and PMT not covered by the error bar is visible in PMT1 (but it is in PMT2 or PMT5)

→ it seems to be related with the track direction in CRT trigger (hyp.: attenuation due to the Rayleigh Scattering?)

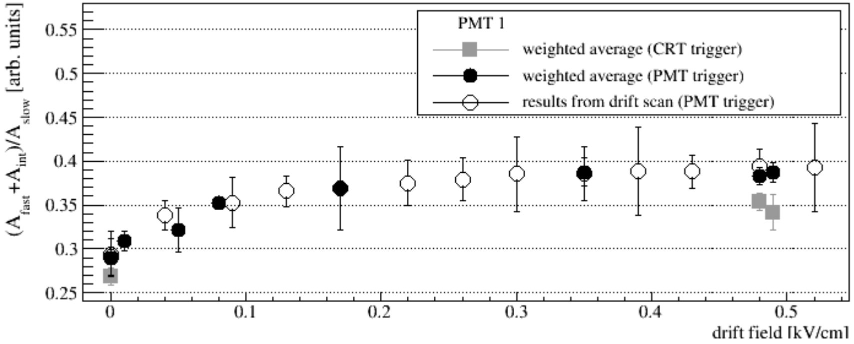
:> the same trend is observed considering the ratio Af/As

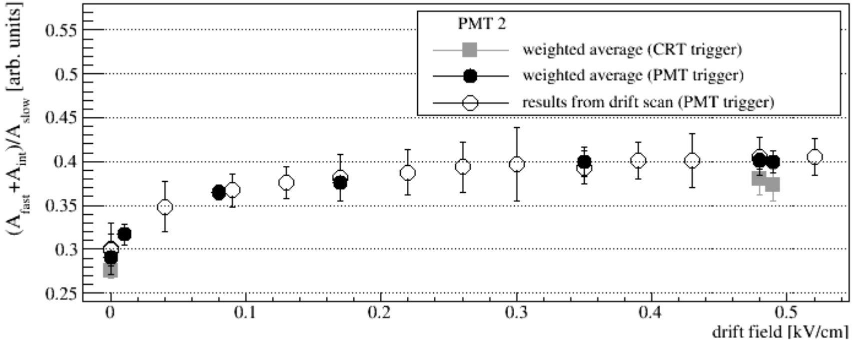
→ the relative contribution of Ai is not affected by the drift field

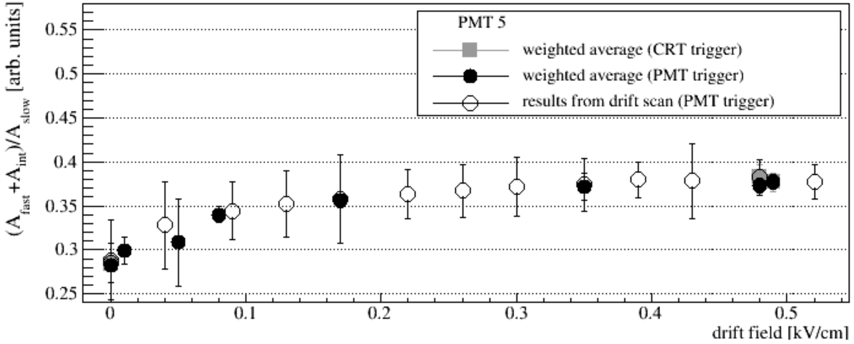



(E~0.5 kV/cm) $<(Af+Ai)/As_{NB}> = 0.3783 \pm 0.0221$

:> the increasing of the ratio $<(Af+Ai)/As_{NB}>$ at~0.5kV/cm is +34%



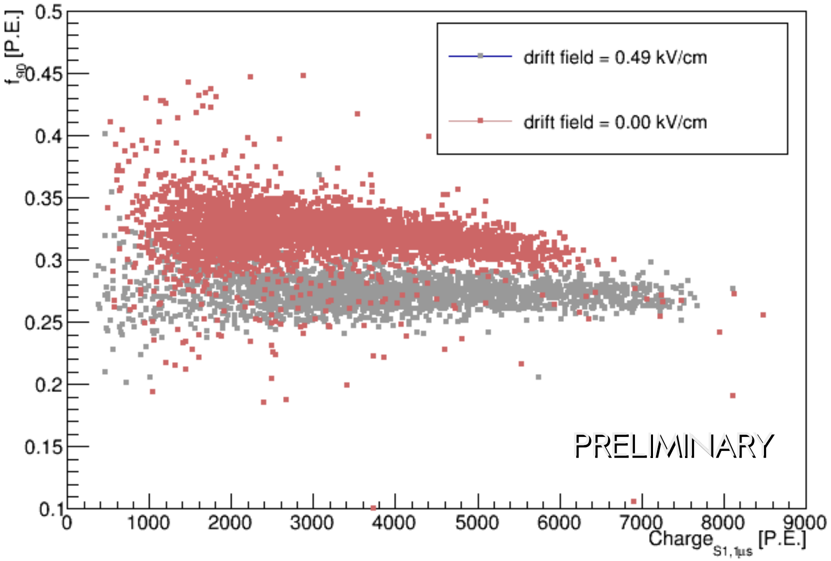



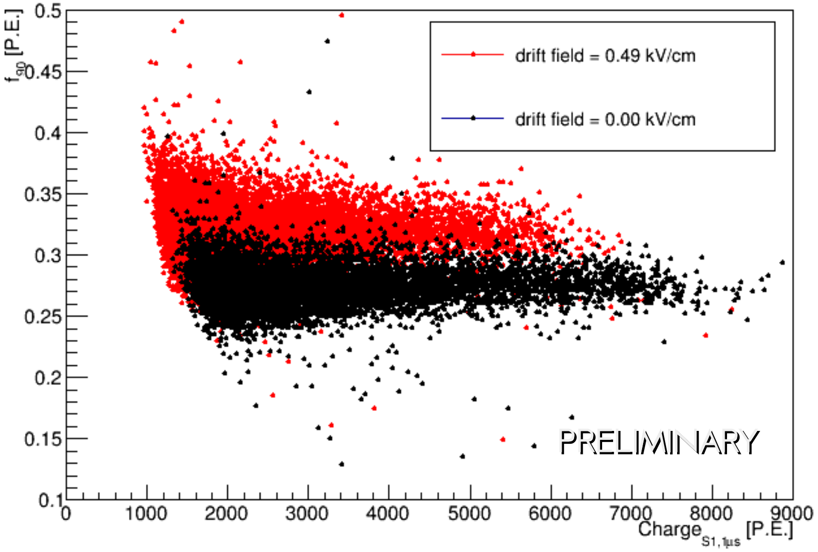

SYSTEMATIC UNCERTANTIES NOT INCLUDED YET

# Effect of the drift field on the scintillation light

:> $f_{90}$ factor

→ similar effect of the drift field is observed: increasing with the field both in CRT and PMT runs



# Effect of the drift field

:> decreasing of the tau slow for higher drift field applied

→ no dependence with the trigger systems (data from CRT or PMT trigger are in agreement within the errors)

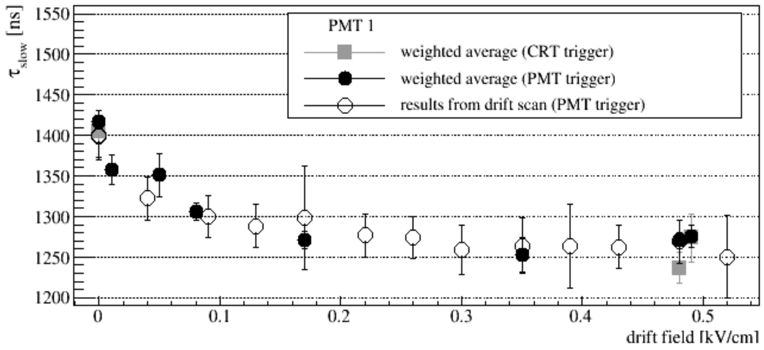
→ in PMT1 and PMT2 the decreasing is statistically significant

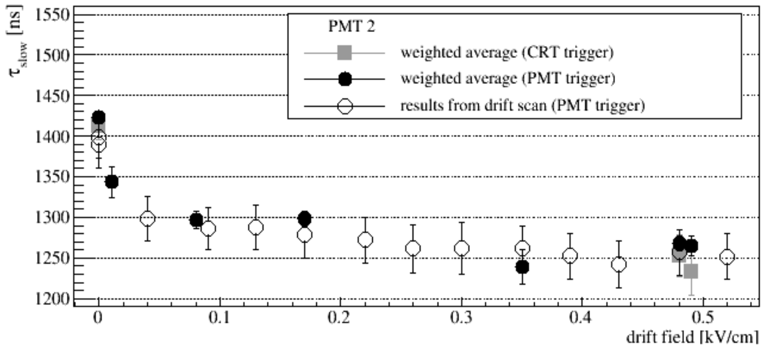
| | $\tau_{slow}$ (E~0.5 kV/cm) |
|---|---|
| PMT 1 | 1267 ± 7 |
| PMT 2 | 1262 ± 7 |
| PMT 5 | 1304 ± 8 |

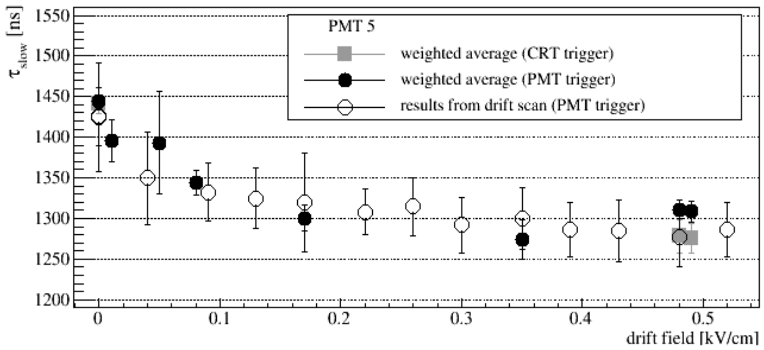
$<\tau_{slow, NB}>$ = (1278 ± 13) ns

:> the decreasing of the $<\tau_{slow, NB}>$ at ~0.5kV/cm is -10%

→ if we don't propose an hypothesis for that, I'm not sure that evaluate this decreasing is meaningful



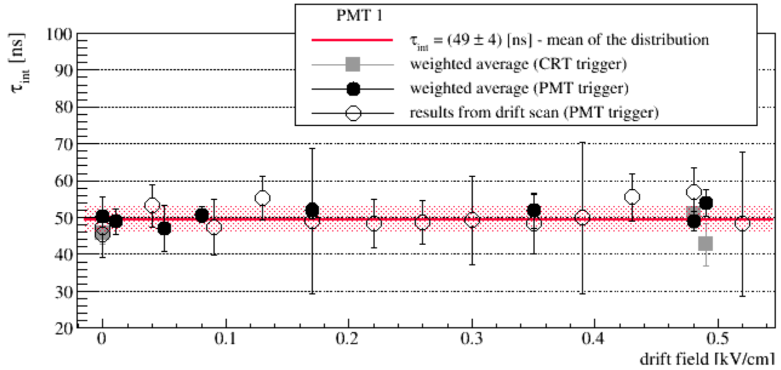

SYSTEMATIC UNCERTANTIES NOT INCLUDED YET

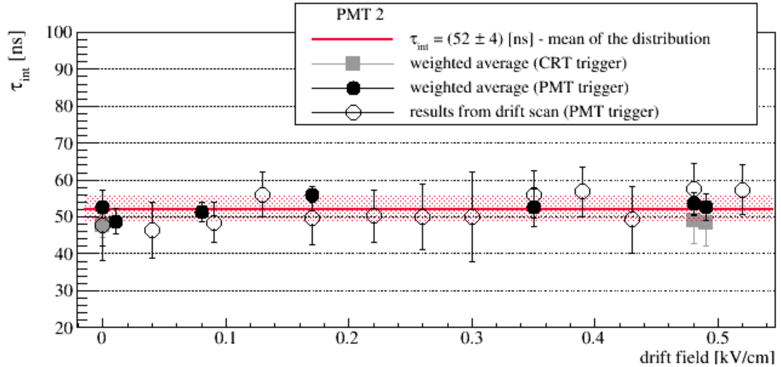
# Effect of the drift field

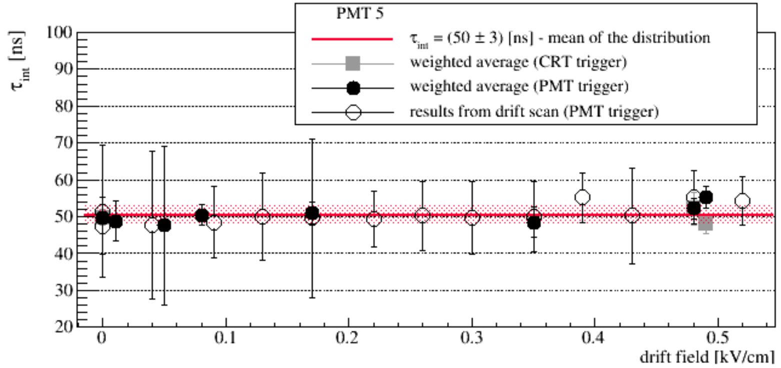
:> no statistical variation of the tau intermediate due to the presence of the drift field is observed

| | $\tau_{int}$ |
|---|---|
| PMT 1 | 49 ± 4 |
| PMT 2 | 52 ± 4 |
| PMT 5 | 50 ± 3 |

$\langle\tau_{int, NB}\rangle$ = (50.3 ± 6.4) ns




SYSTEMATIC UNCERTAINTIES NOT INCLUDED YET

# Main sources of systematic uncertainties

:> Performing a $\chi^2$ **fit when the $\mathcal{L}$ikelihood fit fails**

→ comparison of the mean value of each parameter distribution obtained from the runs without drift and amplification fields

→ from the Toy MC it is expected an effect (more details <u>here</u>)

:> **Fixing tau fast parameter = 6ns**

→ if it is kept free, the value found from the fit is ~10 ns (Lippincott found a similar value using a two expo model, most of all the other results given in the literature gave a value in the range (4.5; 7) ns)

→ this effect can be evaluated from an ***optimization grid*** done with the **toy MC**

→ a similar study is done for the **correlation** between $\sigma$ and $\tau_{fast}$, since its pull distribution is the only one that shows an evident bias

:> **Decreasing of the range fit from 3.5us up to 2.5 us in runs with amplification and 4us time acquisition window** (In this case it is not possible to look for S2 starting time position)

→ the S1 signal reaches the pedestal ~ 10us, if we fit up 10us, the three exponential model is no longer valid since in the NB PMTs an additional tail is visible that can be fitted by a 4$^{th}$ exponential (Whittington measured in three over the four light guide installed in the TallBo setup)

→ in our data, the 4$^{th}$ component is not so clearly visible in the PB PMTs

# Typical relative error assigned to the fit parameters

:> in the Table is reported the typical relative error of each fit parameter

→ for the PB PMTs are shown only the values related with the parameters not affected by the reflections

$$\frac{\Delta\mu\ [\%]}{\mu} = \frac{\text{mean of } \Delta\mu}{\text{mean of } \mu}$$

| | PMT1 | PMT2 | PMT3 | PMT4 | PMT5 |
|---|---|---|---|---|---|
| $\Delta t_0/t_0$ | ~31 | ~29 | ~24 | ~37 | ~36 |
| $\Delta\sigma/\sigma$ | ~13 | ~10 | ~10 | ~15 | ~14 |
| $\Delta\tau_{Int}/\tau_{Int}$ | ~15 | ~13 | --- | --- | ~17 |
| $\Delta\tau_{Slow}/\tau_{Slow}$ | ~3 | ~2 | ~2 | ~4 | ~4 |
| $\Delta A_f/A_f$ | ~13 | ~11 | --- | --- | ~16 |
| $\Delta A_i/A_i$ | ~10 | ~9 | --- | --- | ~11 |
| $\Delta A_s/A_s$ | ~1 | ~1 | --- | --- | ~2 |

# Systematics (based on data)

:> comparing the mean value of the distribution obtained from a likelihood or a $\chi^2$ fit for all the parameters

:> in the Table is reported the discrepancy coming from performing a $\chi^2$ fit w.r.t the likelihood fit

$$\Delta\mu\ [\%] = \frac{(\mu_{\chi^2} - \mu_{\mathcal{L}})}{\mu_{\mathcal{L}}}$$

:> the **systematic uncertainty** is reported in the last column

→ for the PM PMTs are reported only the parameters that are not affected by the reflections

| | PMT1 | PMT2 | PMT3 | PMT4 | PMT5 | syst. unc. (conservative) |
|---|---|---|---|---|---|---|
| $\Delta t_0$ | -17.84 | -11.37 | -15.88 | -5.58 | -10.74 | 18% |
| $\Delta\sigma$ | +9.35 | +6.71 | +6.95 | +3.79 | +4.44 | 9% |
| $\Delta\tau_{Int}$ | +12.12 | +10.16 | --- | --- | +7.80 | 12% |
| $\Delta\tau_{slow}$ | -0.66 | -0.03 | +0.54 | -0.51 | -1.09 | 1% |
| $\Delta A_f$ | +6.34 | +3.37 | --- | --- | +3.63 | 6% |
| $\Delta A_i$ | -6.74 | -6-62 | --- | --- | -7.98 | 8% |
| $\Delta A_s$ | -3.62 | -0.68 | --- | --- | -3.26 | 3% |
| % of runs obtained from $\chi^2$ fit → | 35% | 53% | 75% | 33% | 30% | |

the result obtained from the Toy MC is available here

# Systematics (based on toy MC)

:> From the toy MC, the sigma pull distribution is the only one that shows a bias

:> Goal: study the origin of its shift

→ *optimization grid* considering different input for the sigma and the tau fast

→ parameters input:

ped = 0 ns [fixed]

t0 = random(0,4) ns

$\sigma$ = {3., 4., 5., 6., 7., 8.} ns

$\tau_{fast}$ = {5., 6., 7., 8., 9., 10.} ns [fixed]

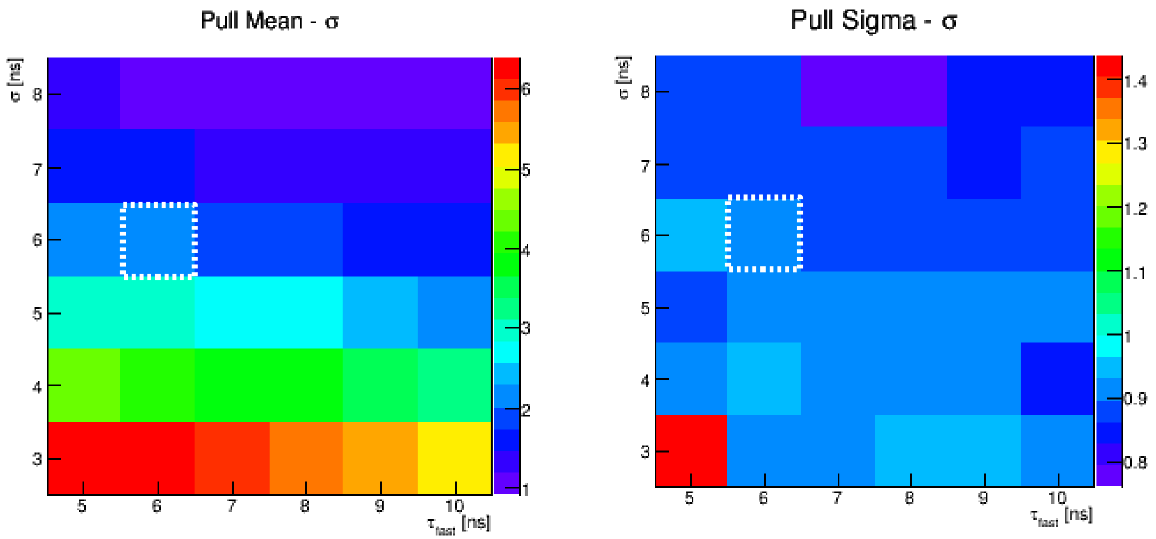
$\tau_{int}$ = 50 ns

$\tau_{slow}$ = 1400 ns

$A_{fast}$ = 0.11

$A_{int}$ = 0.11

$A_{slow}$ = 0.78




:> from the datasheet info, $\sigma$ is expected to be ~3ns

:> the decreasing of the mean of the $\sigma$ pull distribution for higher input values of $\tau_{fast}$ and $\sigma$ in the toy MC, confirms that the higher value measured is due to the 4ns sampling of the waveforms

# Systematics (based on toy MC)

:> To evaluate the **choice of keeping $\tau_{fast}$ = 6 ns fixed**

→ *optimization grid* considering different input for $\tau_{fast}$ and $\tau_{int}$

→ parameters input:

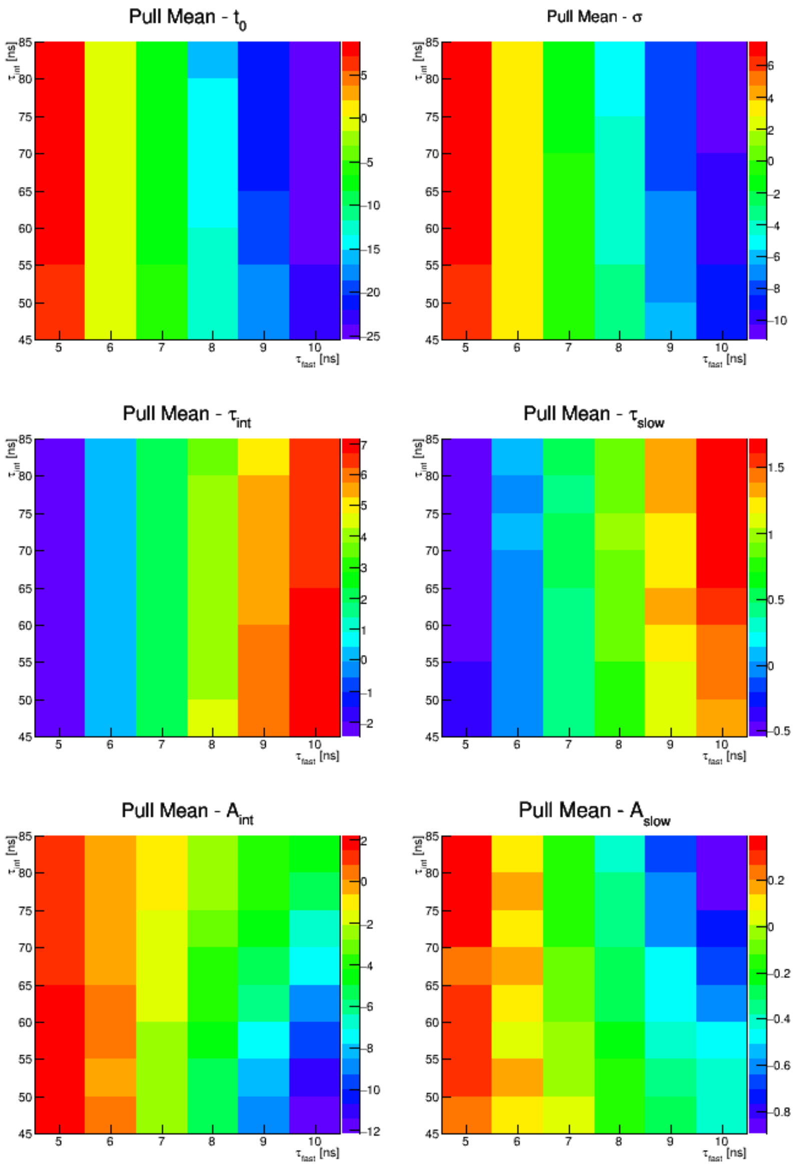
$\tau_{fast}$ input = **6 ns** and it is kept fixed at the following values {5., 6., 7., 8., 9., 10.} ns

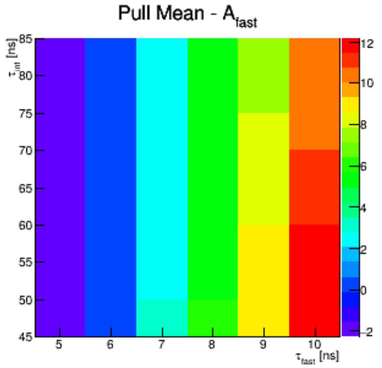
$\tau_{int}$ = {45., 50., 55., 60., 65., 70., 75., 80.} ns

:> The mean of the pull distributions is centered in 0 only if $\tau_{fast}$ is fixed for values in the range (5;7)ns for all the other values the bias is much stronger

→ $\tau_{fast}$ ~10ns retrieved in the data when it is kept free is an artifact of the 4ns sampling (similar to what happen for the $\sigma$ parameter)

:> proposal for the paper: fix $\tau_{fast}$ = 6ns is motivated by the 4ns sampling of the waveform and give a reference for this value (e.g. [Hitachi])



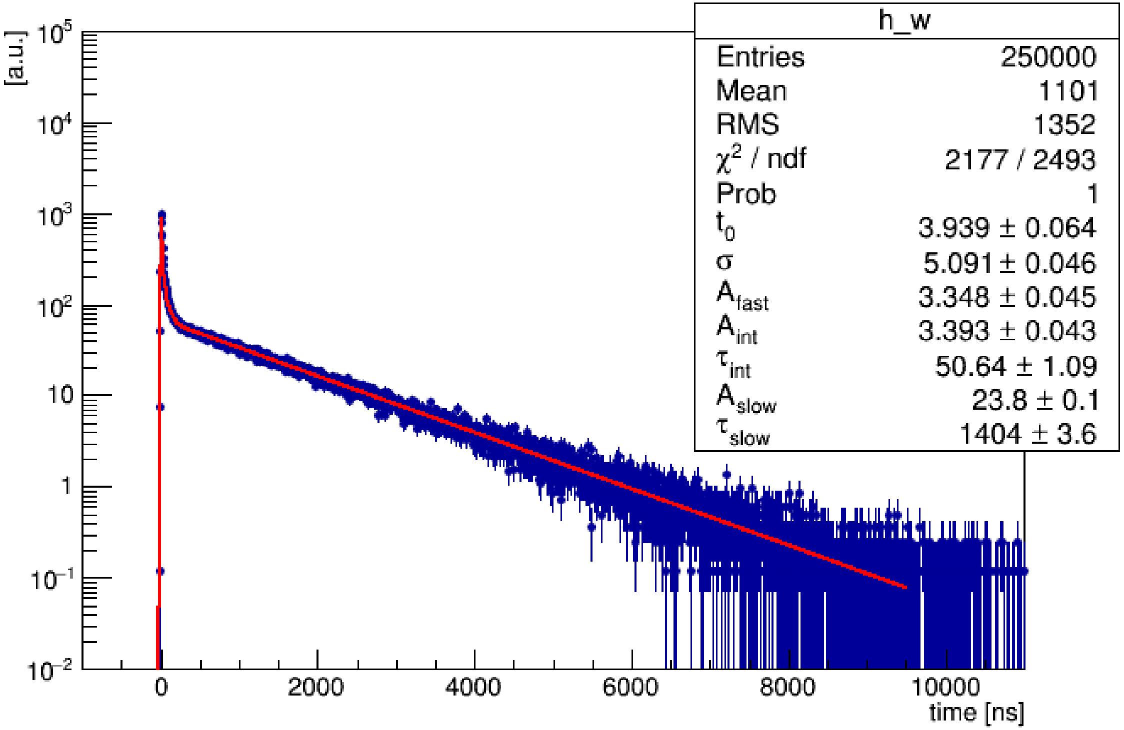

*the optimization grid for the sigma are in bkp slides*

# Systematics (based on toy MC)

:> the S1 duration is up to ~10us

- **goal:** take into account possible effect due to the decreasing of the fit range from **whole S1** (9.5μs) **up to 3.5μs (range used in the data), or 2.5μs**

- this effect tends to be covered by the errors:
  - → from the toy MC, no shift in the pull distribution
  - → from the data, tau int and tau slow parameters tends to be affected by this decreasing (presumably because of the 4th component, a preliminary check tends to show that the chi2/ndf fit value improves - more ongoing)



# Systematics (based on toy MC)

:> Toy MC generation:

→ nGenerations = 250000 entries

→ nIterations = 5000

→ parameters input: ped = 0 ns [fixed]

t0 = random(0,4) ns

sigma = 5 ns

tau fast = 6 ns [fixed]

tau int = 50 ns

tau slow = 1400 ns

a fast = 0.11

a int = 0.11

a slow = 0.78

| | fit range = 9.5 ns | fit range = 3.5 ns | fit range = 2.5 ns |
|---|---|---|---|
| t0 | Mean = 0.016 && σ = 0.92 | **Mean = 0.010 && σ = 0.92** | Mean = 0.019 && σ = 0.91 |
| σ | Mean = 2.803 && σ = 0.92 | **Mean = 2.822 && σ = 0.92** | Mean = 2.799 && σ = 0.91 |
| $A_{Fast}$ | Mean = 0.032 && σ = 0.82 | **Mean = 0.030 && σ = 0.84** | Mean = 0.033 && σ = 0.83 |
| $\tau_{Fast}$ | fixed | **fixed** | fixed |
| $A_{Int}$ | Mean = 0.025 && σ = 0.93 | **Mean = 0.024 && σ = 0.95** | Mean = 0.022 && σ = 0.93 |
| $\tau_{Int}$ | Mean = 0.019 && σ = 0.87 | **Mean = 0.009 && σ = 0.89** | Mean = 0.013 && σ = 0.86 |
| $A_{Slow}$ | Mean = 0.110 && σ = 0.58 | **Mean = 0.105 && σ = 0.68** | Mean = 0.098 && σ = 0.77 |
| $\tau_{Slow}$ | Mean = 0.017 && σ = 0.98 | **Mean = -0.010 && σ = 1.04** | Mean = -0.014 && σ = 0.97 |

:> the sigma of the pull distributions tends to be close one in most of the cases

:> except the case of the sigma parameter (already expected), all the pull distributions are centered in 0

:> the mean of all the pull distributions are always compatible with 0, no variation expected due to the range fit

# Systematics (based on data)

:> comparing the mean distribution value obtained fitting the scintillation time profile up to 2.5 us w.r.t the fit performed up to 3.5 us, the parameters whose variation is not within 1sigma are the tau intermediate and the slow

$$\Delta\mu\ [\%] = \frac{(\mu_{2.5us} - \mu_{3.5us})}{\mu_{3.5us}}$$

:> in the Table is reported the variation of the discrepancy of performing a fit up to 2.5 us w.r.t the fit performed up to 3.5 us for the 3 NB PMTs, the **systematic uncertainty** is reported in last column

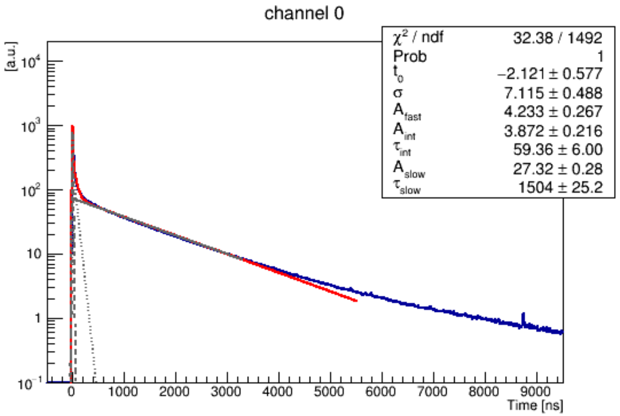
| | PMT1 | | PMT2 | | PMT5 | | |
|---|---|---|---|---|---|---|---|
| | $\chi 2$ | $\mathcal{L}$ | $\chi 2$ | $\mathcal{L}$ | $\chi 2$ | $\mathcal{L}$ | syst. unc. (conservative) |
| $\Delta\tau_{Int}$ | ---- | -4.48 | --- | -3.96 | -4.06 | -4.38 | 5% |
| $\Delta\tau_{Slow}$ | -2.41 | -3.61 | -3.68 | -2.91 | -2.87 | -3.50 | 4% |
| % of runs fitted in2.5 us → | 24% | | 23% | | 23% | | |

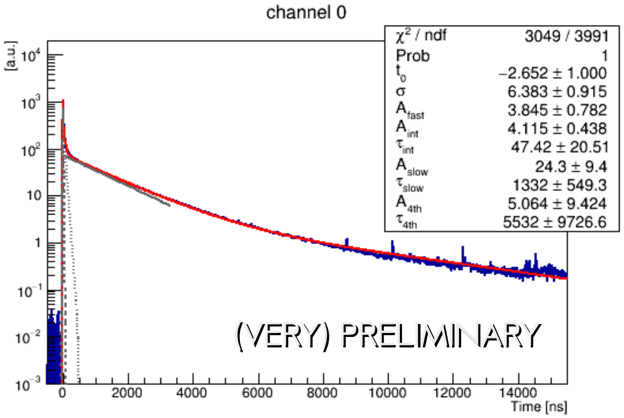
:> from the toy MC the decreasing of the fit range should not affect the fit results

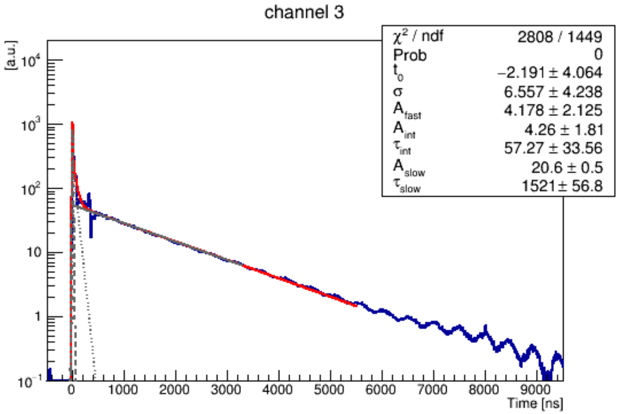
→ but a small shift is visible in the tau int and tau slow parameters

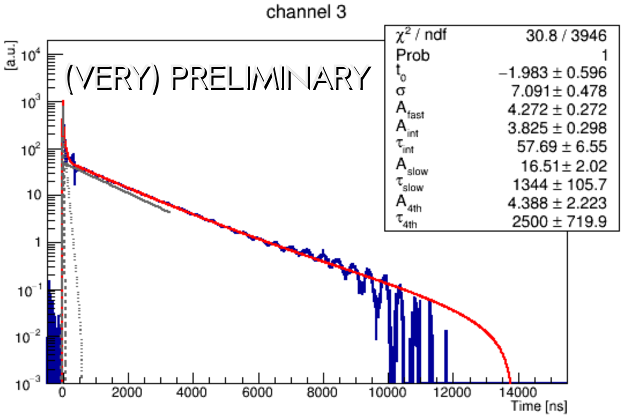
# Systematics

:> one explanation of the small shift measured in the tau int and tau slow parameters could be because in the 1ms runs (clearly evident in NB PMTs, not so evident in PB PMTs) the three exponential model does not adequately reproduce the data in the whole range and a **4th exponential is needed to fit the whole range** [3]



# Systematics

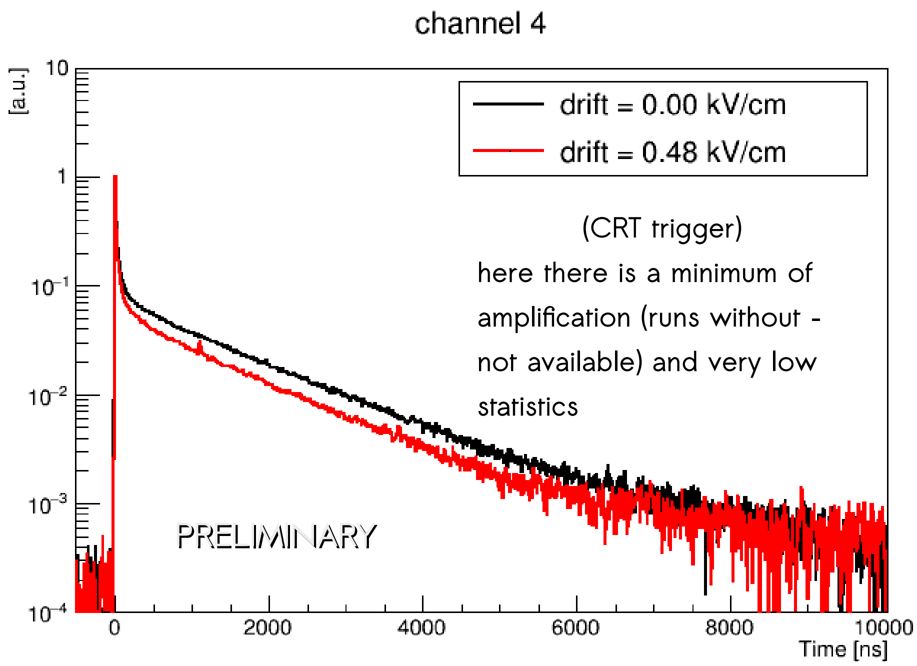
:> a detailed and conclusive study of the 4th component is complicated by the fact that we have very few runs taken without amplification with and/or without drift field

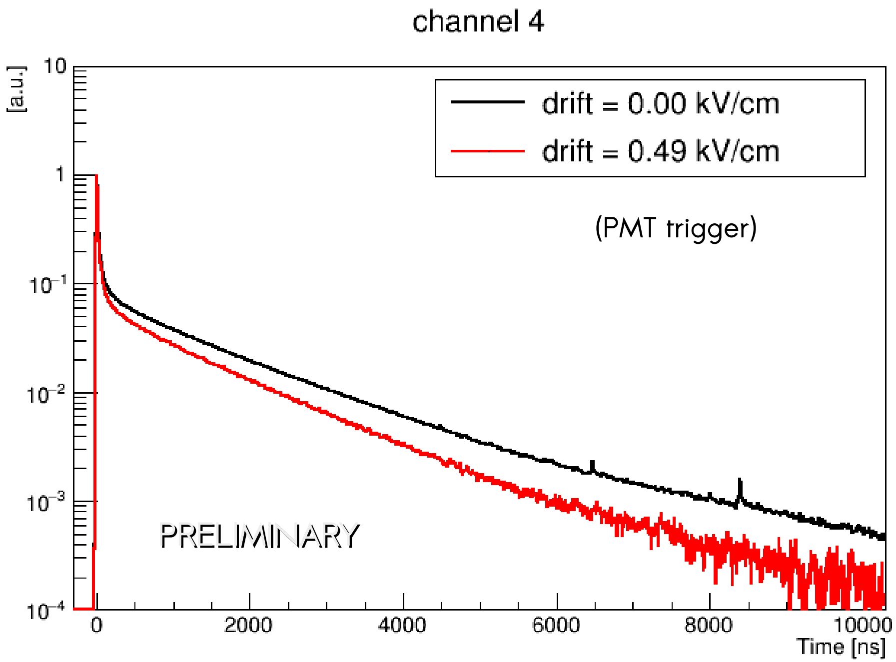
→ in presence of amplification field is too complicate disentangle the effect of the S2 contamination from a possible 4th component

→ additional complication is to separate it from pedestal fluctuations at the end of the S1 signal

:> despite that, there are few runs with and without drift field that can be compared

→ the effect of the drift field on the waveform is still visible



# Conclusions

:> the final summary of the results obtained from the scintillation light fit has been presented

:> the average value of the tau slow measured in absence of the drift field has been presented

→ it is consistent with the amount of impurities measured in the 3x1x1 (no significant variations during the demonstrator operation have been registered) and with values reported in literature **$<\tau_{slow,\ NB}>$ = (1426 ± 40) ns**

→ the presence of the drift field caused a decreasing of this value which is statistically significant

→ measurement of the **$<\tau_{int,\ NB}>$ = (50.3 ± 6.4) ns**, not affected by the drift field

→ study of the effect of the drift field on the relative amplitudes (Af, Ai, As) has been presented considering the ratio **(Af+Ai)/As** to include the contribution of the intermediate component

→ the drift field causes a statistically significant increasing of this ratio

→ the same effect has been confirmed considering the f90 factor measured event by event

→ in absence of drift field the value found in the 3x1x1 is **$<(Af+Ai)/As_{NB}>$ = (0.2816 ± 0.0048) ns** and it is consistent with the value obtained from the f90 distribution

:> the main sources of been **systematics** have been shown

→ for runs fitted with a $\chi 2$ fit, systematics uncertainties will be added

→ for runs taken with amplification field >18kV/cm with 4us time window, systematic uncertainties will be added due to decreasing of the range fit from 3.5 us → 2.5 us

→ from toy MC studies, the decreasing of the range should not affect the fit; a possible explanation for this effect can be found in the presence of a $4^{th}$ component visible in NB PMT after ~5us

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