Development of a high pressure single-anode radial TPC for the search of 2β0ν decays

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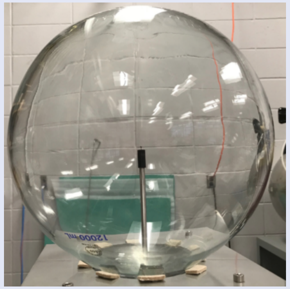
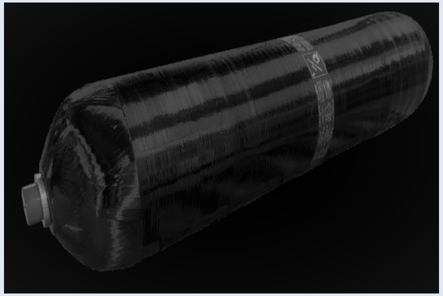
The R&D R2D2 (Radial Detectors for Rare Decays) collaboration

(Expertise from NEMO, NEWS-G, and many other experiences…)

LP2iB, Univ. Bordeaux, CNRS/IN2P3, Fr
CPPM, Univ. Aix-Marseille, CNRS/IN2P3, Fr
IRFU, CEA, Univ. Paris-Saclay, Fr
LSM, Univ. Grenoble-Alpes, CNRS/IN2P3, Fr
School of Physics and Astronomy, University of Birmingham, UK
SUBATECH, IMT-Atlantique, Univ. Nantes, CNRS/IN2P3, Fr





2β0ν decay

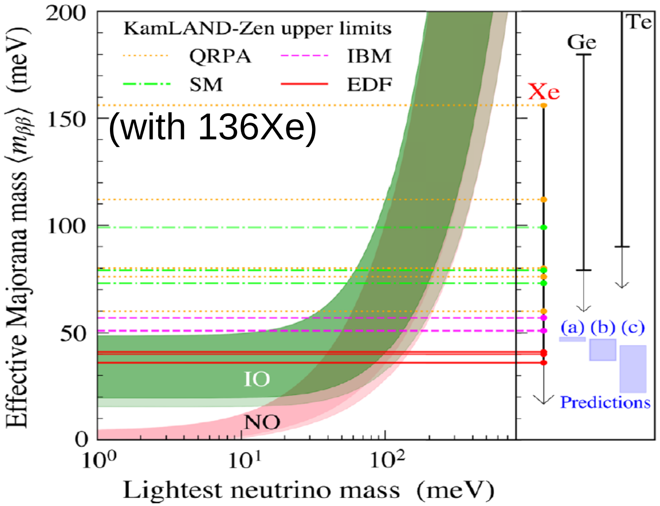
If neutrino is a Majorana particle => $\nu = \bar{\nu}$

- Neutrino mass explained with the existence of a heavy right-handed Majorana ν (seesaw mechanism)
  => Matter-antimatter asymmetry (Leptogenesis scenario) : $N \rightarrow l^- + H \neq l^+ + H$
- => 2β0ν can occur (chirality is not conserved):
  $(A, Z) \rightarrow (A, Z+2) + 2e^- + Q_{\beta\beta} = M(A,Z) - M(A, Z+2)$

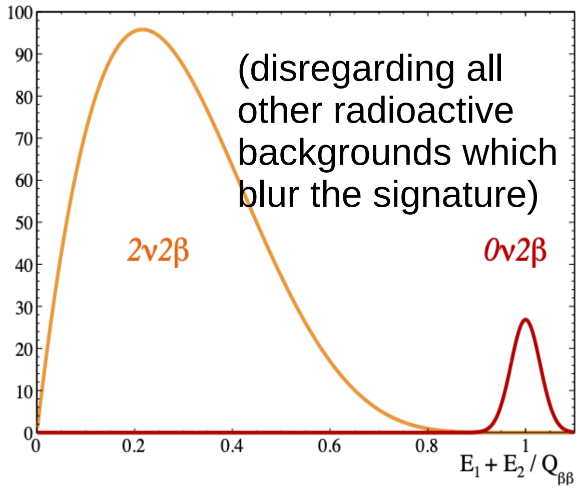
$$\Rightarrow \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu\beta\beta} \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2 \qquad m_{\beta\beta} = \sum U_{ei}^2 m_i$$

Inverse of half-life | Phase-space | Nuclear matrix element | Effective Majorana mass

Current lower limit of half-lifetime
=> 2.3×10^{26} year
=> Neutrino effective mass ($m_{\beta\beta}$): 36-156 meV



Energy spectrum

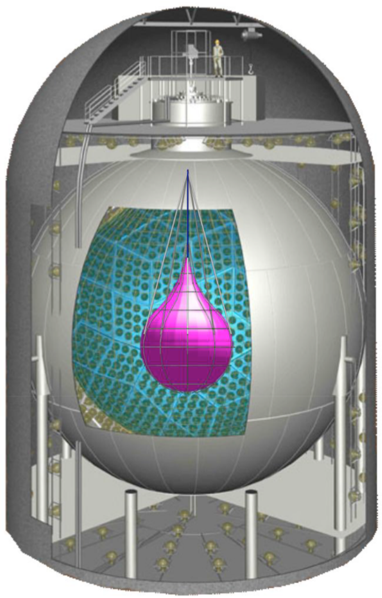


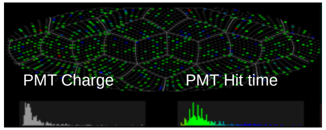
Current methods

for the search for rare (DM, 2β0ν, ν–physics) low-energy (~ MeV) Interactions with liquids or gases

Single-phase liq. TPC

Borexino-like: KamLandZen, (Juno)…





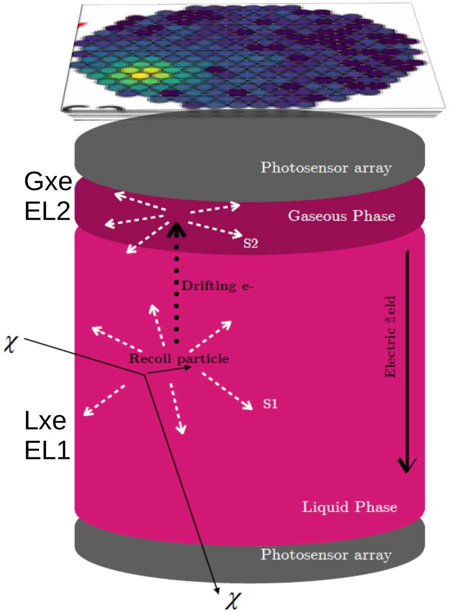
Calorimetry

ΔE/E > 7% FWHM

Dual-phase liq./gas TPC

Xenon-like, LZ, Panda4, Darkside, Exo...

(Darwin, nExo (Liq. phase + primaries e)...



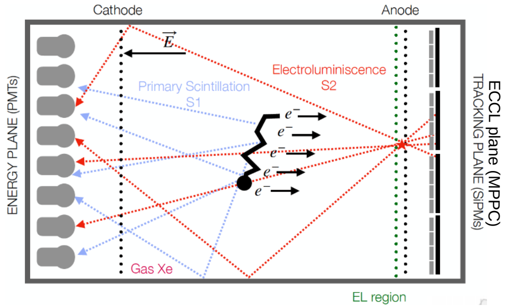
Calorimetry

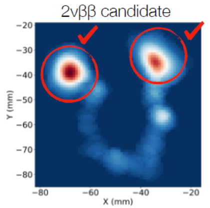
+ localization

ΔE/E ~ 2% FWHM

High pressure Xe gas TPC

Next, Axel, Panda-X3...





Tracking chamber

+ calorimetry

ΔE/E ~ 1% FWHM (Next)

Trend is to larger, heavier and complex detectors ! Are there other ways ?

Partition of energy resolution

Assuming for each effect an equivalent charges fluctuation σ_L described by a Fano-like factor F_L :

=> $\sigma_L = (F_L * E/W)^{1/2}$

=> $\Delta E/E$ (FWHM) = σ_L * 2.35 / n

For Xe gas
(with F = 0.13, Q = 2.48 MeV, W = 21.9 eV)
=> $n = Q/W = 1.13 \times 10^5 \bar{e}$
=> $\sigma_n = (F*E/W)^{1/2} = 121 \bar{e}$ rms
=> $\Delta E/E$ (FWHM) = $(F*W/E)^{1/2}$ * 2.35 = 0.25%

=> Is there "a best method" ?

Would there be other important parameters ?

Merit of a experiment = $\frac{\text{Reached cross section}}{\text{Detector mass}}$

=> see last results of Damic…

Fluctuation sources	Fano-like factor (Contribution to energy resolution in % FWHM)	
Number of primary $\bar{e}$ (Fano factor)	0.13 (gas) (0.25 %) 0.05 - 0.1 (liq.) (0.015%)	inevitable (Ionization mode)
EL conversion	0.12 (0.22 %)	
Avalanche	0.6 – 0.8 (0.6 – 0.7 %)	In gas (proportional mode)
Double-phase detection	0.2	Charge extraction, ph scattering
Detection inefficiency	0.15 (0.25 %)	(Pixelation, threshold...)
Electric field drift effects	0.12 (0.2 – 0.3 %)	(W, field homogeneity)
Others	0.2 – 0.4	Electronics noise, ballistic deficit, calibration, non linearity….

R2D2 approach

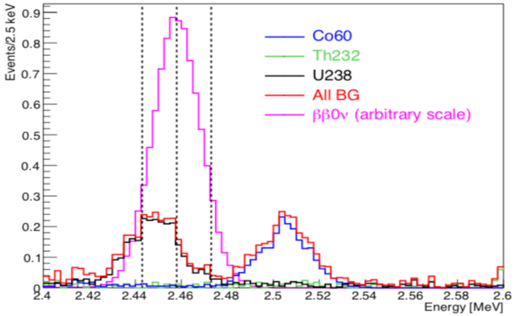
1) **Main objective: Reduction of the near background**
   => Use of the simplest and lightest possible structure in terms of mechanics and sensor

   2) **Energy resolution of 1% FWHM at $Q_{\beta\beta}$ of 2.458 MeV of 136Xe**

      3) **Track localization**

      4) **2-tracks recognition (NEMO)**

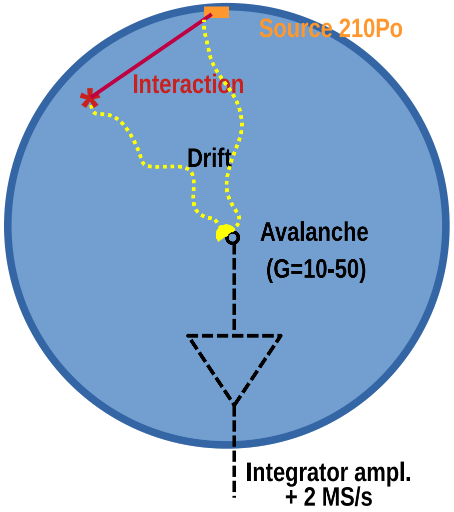
   } **Additional background rejection**



Preliminary simulations indicated that an SPC filled **with pressurized 136Xe** could provide appealing performances (JINST 13 (2018) no.01, P01009)

=> A single anode radial TPC at high pressure:

- Signal of charges only
- No cryogenic
- Scalability up to 1 ton of Xe gas at 40 bars => 0.5-1 m radius detector (1-2 m^3)



Studied configurations in R2D2

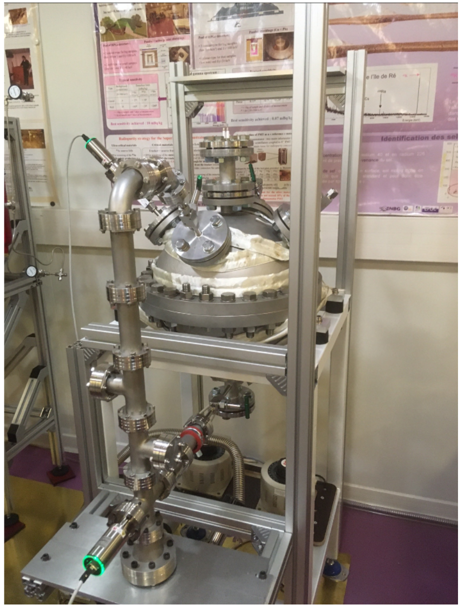
- SPC (Spherical Prop. Counter) - $1/r^2$ field
- CPC (Cylindrical Prop. Counter) - 1/r field
- Proportional / ionization modes
- Point-like / long tracks (function of pressure)

Detectors setup

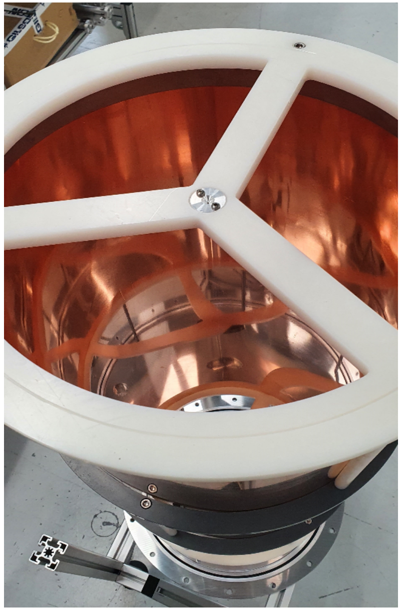
Test facility @ Bordeaux

(No radio-purity required & ArP2 gas mainly used at this stage of the R&D)

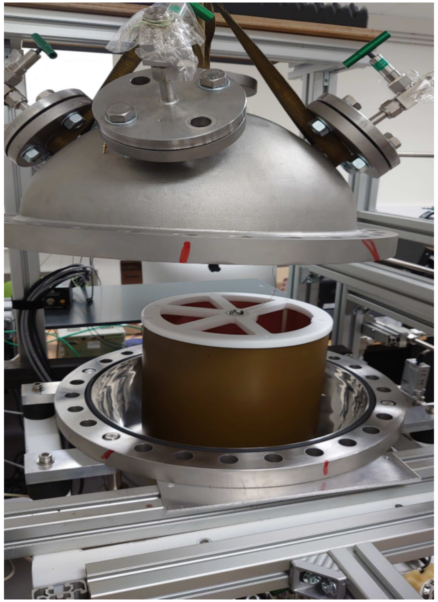
SPC-1 (2018)
D = 0.4 m
r_{ball} = 1 mm
(1 bar)



SPC-2 (2021)
D = 0.4 m
r_{ball} = 1 mm or 3 mm
(40 bar)



CPC-20 (2022)
L x D = 1 x 0.37 (m)
r_{wire} = 20 μm
(1 bar)



CPC-50 (2023)
L x D = 0.27 x 0.27 (m)
r_{wire} = 50 μm
(40 bar)

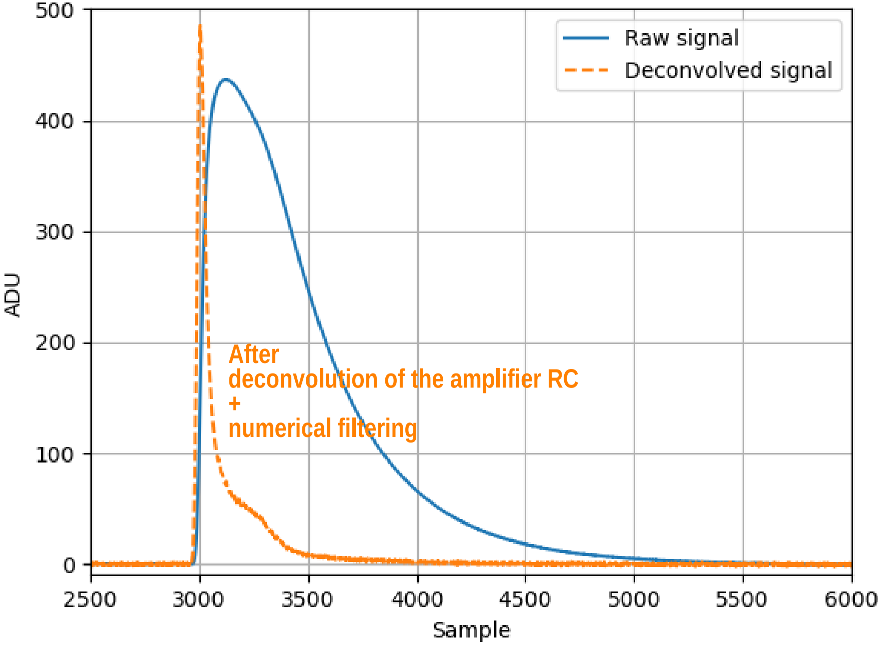
Used with cathodic HV bias

Amplifier positioned outside the tank (cables)

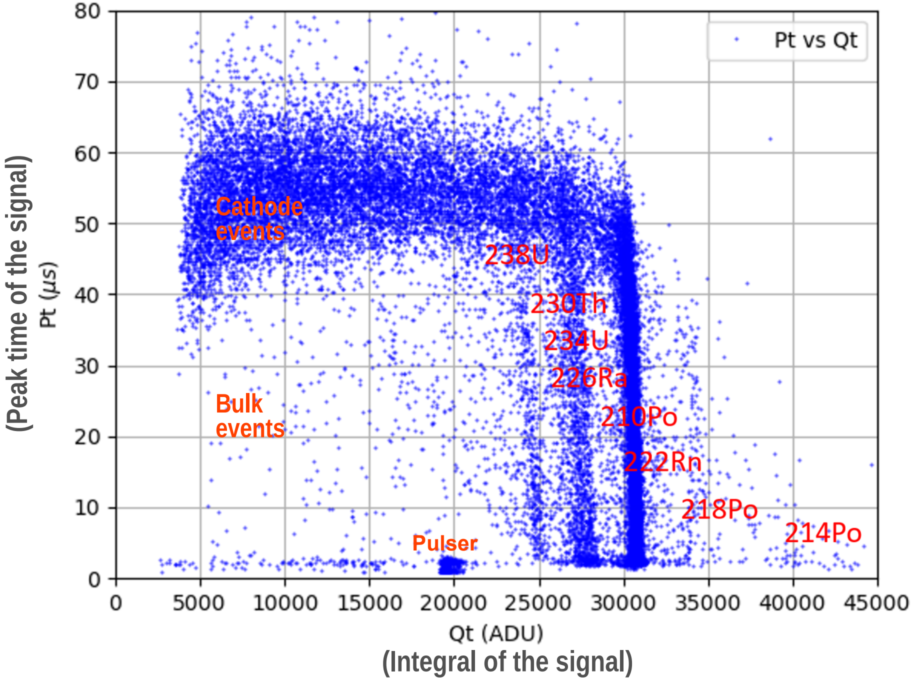
Signal treatment

To achieve very high precision measurements (with a single waveform) numerical signal processing becomes essential (even under excellent Signal / Noise conditions)

(SPC - ArP2@200mb, 210 Po source, Sampling 2 MHz)
Track length ~17 cm



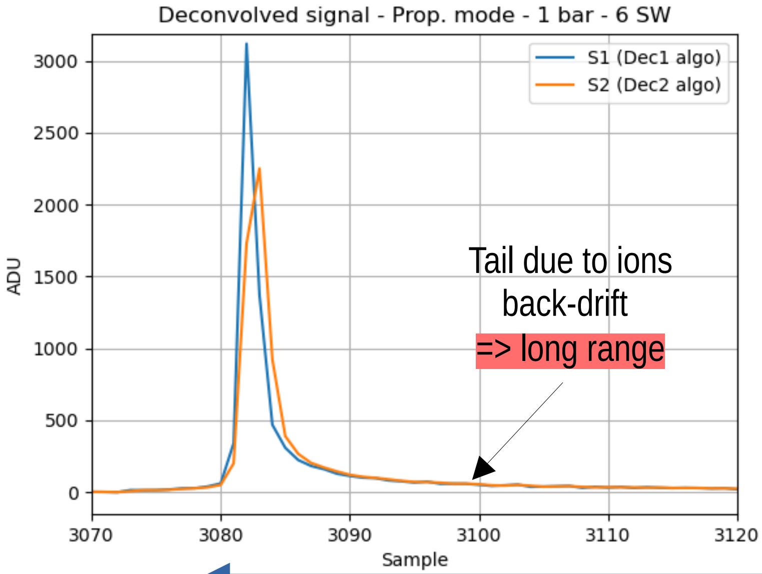
Using observables Pt and Qt of the deconvolved signals

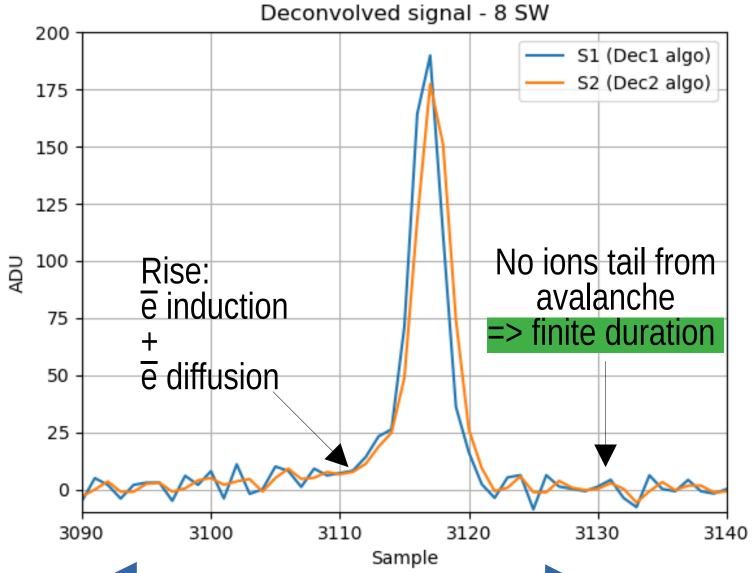


=> This processing allows to extract novel information on the interaction in the gas

Ionization / proportional signals

CPC-50 - Deconvolved signal - ArP2 - 1 bar – 210 Po - Track length ~3 cm





Qt

Qt

Proportional mode

- High S/N
- High HV
- Long duration of integration can alter E-Resolution (LF noise)
- Possible ion space charge effect (counting rate)

Ionization mode

- Low S/N
- Low HV
- Use pure noble gases without quencher
- Duration almost independent of the gas nature

Energy resolution (1)

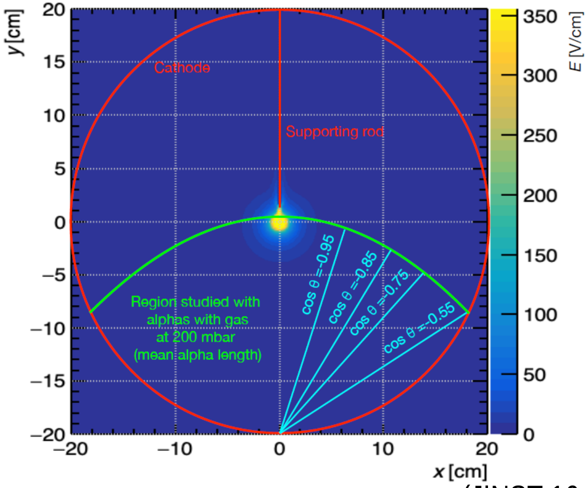
What energy resolution could be achieved for a detector larger than an few cm ?
(cf. Bolotnikov et al., NIM A 396 (1997) 360-370: 0.6% FWHM below 50 bars of Xe)

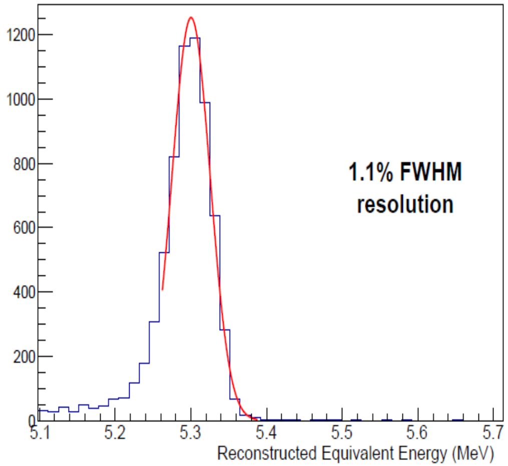
With ArP2 gas, we explored the SPC response from 0.2 bar to 1.1 bar ie. 17 and 3 cm track lengths (Proportional mode with identical gains).

=> Resolutions of 1.1 to 1.2 % FWHM were obtained.

=> Similar results were obtained with the CPC.

SPC – 0.2 bar - ArP2 - Prop. Mode - 210Po source





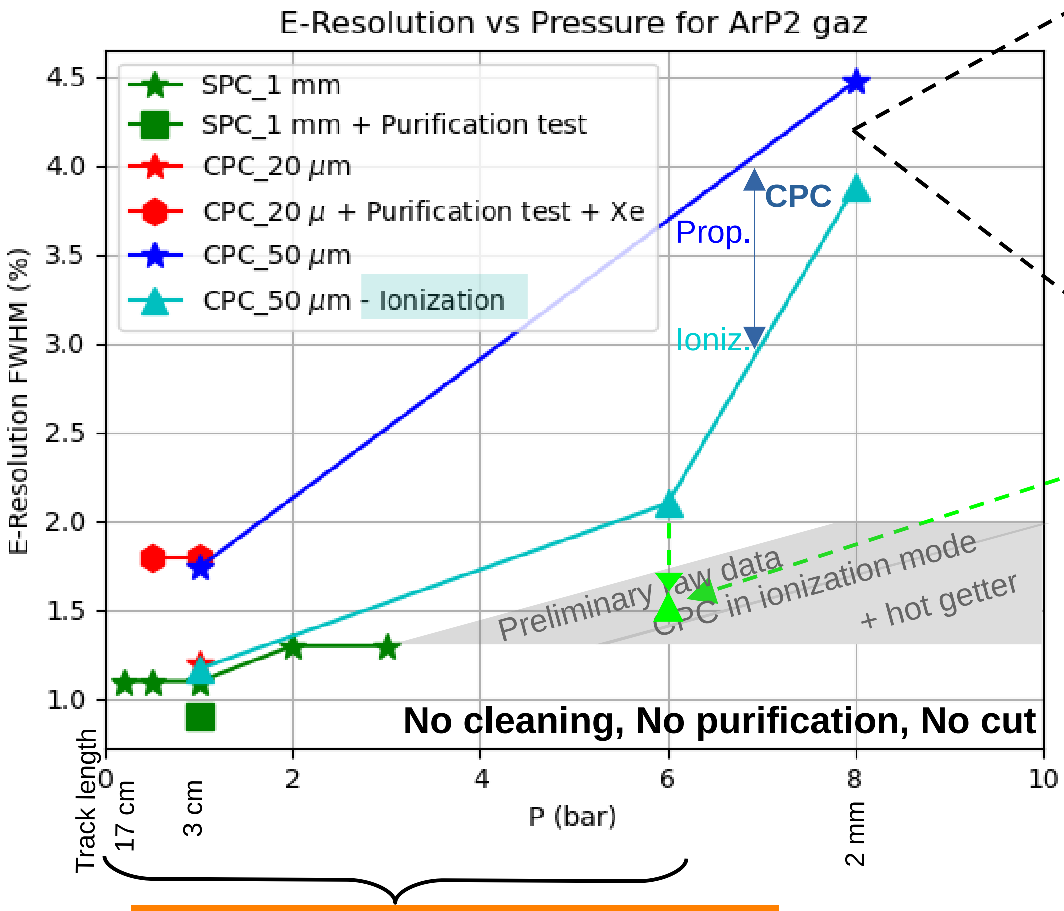
(JINST 16 (2021) P03012)

=> Track direction doesn't affect energy resolution.

=> Track length doesn't affect the energy resolution.

(Contribution of the source and the electronic was estimated to account for 0.6%).

Energy resolution (2)



Validate the detection principle

Same number of primaries => suggests a gas purity effect.

Use of a gas filtration system becomes essential.

=> Since July 2022, use of a circulating pump and 2 cold getters => spring: ▲ 2.2 % (6 bars).

=> In may 2023: upgrade with a hot getter => in test => today: ▲ 1.5 % (6 bars).

Other strong improvements expected in resolution (> 1 %):

- Use of spark discharge purifier if an additional cleaning is required;
- FEE optimization (in board FEE);
- Optimization of processing for ionization.

Track localization

Experimentally, the behavior of the observable Pt suggested that it depends on :

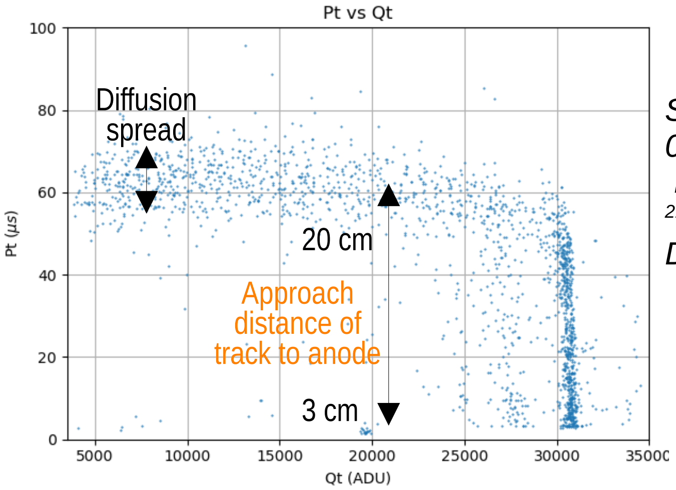
- The minimal distance of energy deposition relative to the anode.
- The diffusion of the primaries during their drift.

=> Hypothesis: Pt can be related to distance by a simple relation like:

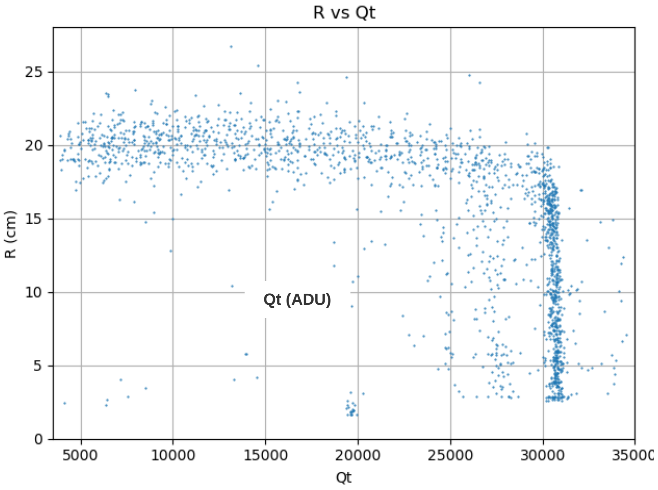
$Pt = Pt_{max} * (R/R_{max})^{\alpha}$

Inversion of this functional then made it possible to recover the distance of the track.

=> To verify this empirical interpretation, we developed a very simple macroscopic modeling of the signals



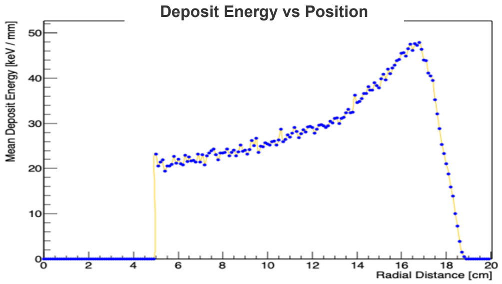
SPC – ArP2 - 0.2 bar - 800 V - Prop. Mode - ^{210}Po source - Deconv. signal

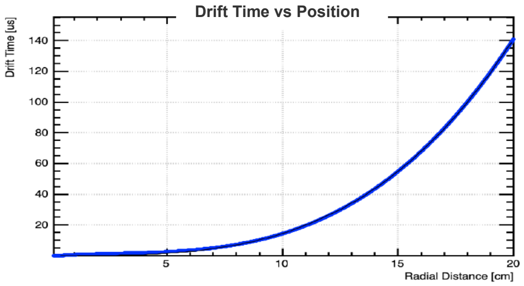


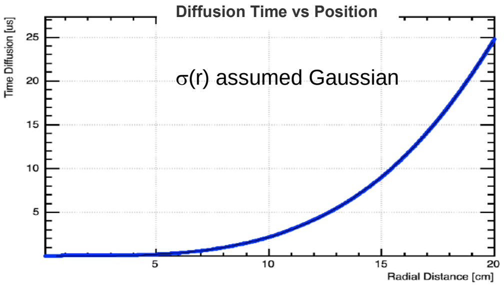
LTPC 2021, J. of Phys. Conf. Series 2502 (2023) 012006

Simulations

It uses outputs from (Geant4, Garfield, Magboltz) for the drift of the primary electrons.



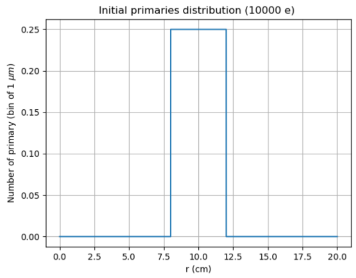




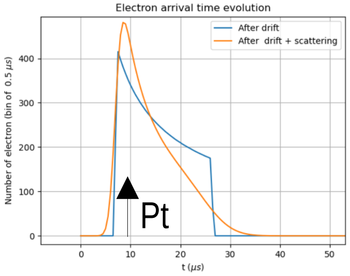
They depend on the operating conditions.

- The mechanisms of drift and scattering of the electrons are modeled by simple analytical functions as:

$T_{drift}(t) = t_{max} * (r/r_{max})^{\alpha}$, $\sigma_{diff}(t) = t_{max} * (r/r_{max})^{\beta}$ ….

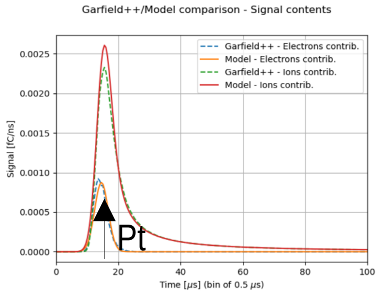


After transport + diffusion of the $\bar{e}$ in the non-uniform Efield



Ionization mode

For proportional: $\bar{e}$ signal is then convolved to the induction function of the ions.

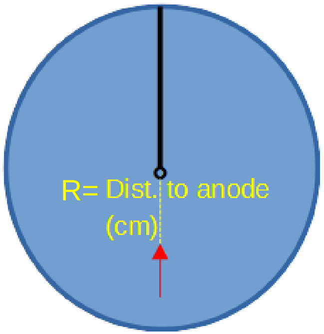


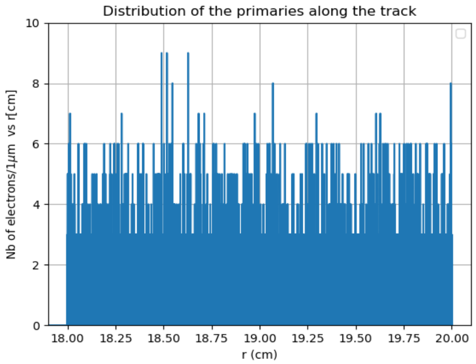
Proportional mode

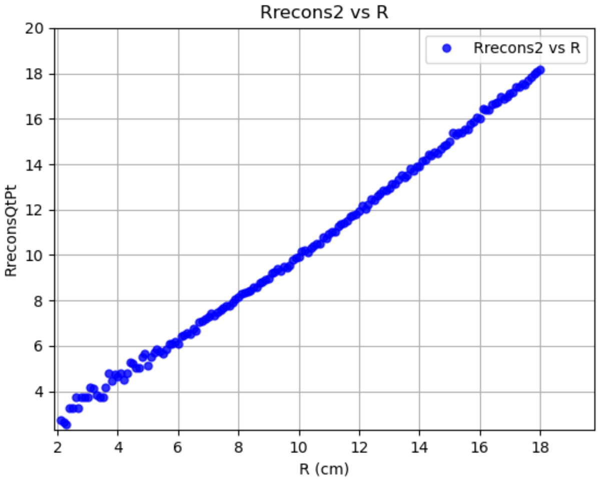
=> First result of the simulation: Pt is a relevant observable for the localization.

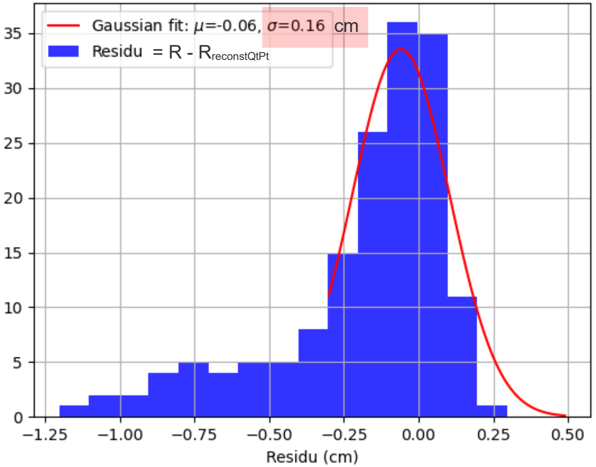
Radial localization

SPC simulation with
track length of 2 cm - non-uniform ionization (clusters) - 10000 e^- - ArP2 gas - prop. mode (G=8)







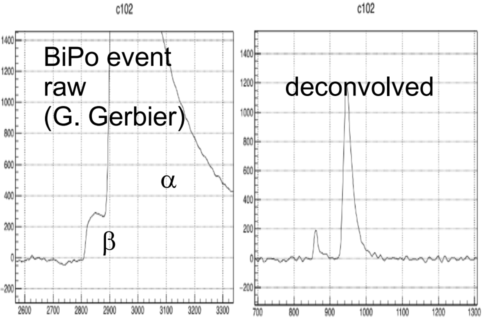


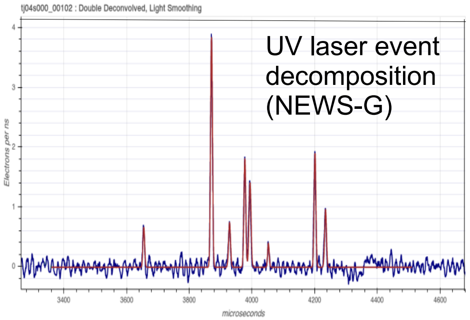
- Pt_{max}, Pt are deduced from plot (Qt, Pt)
- RreconsQtPt = $r_{max} * (Pt / Pt_{max})^{1/a}$ is then compared to the initial distance R set for the simulated event through residues analysis

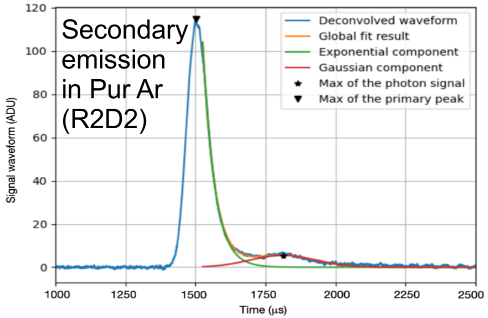
=> Second result of the simulation: A track localization can be obtained.

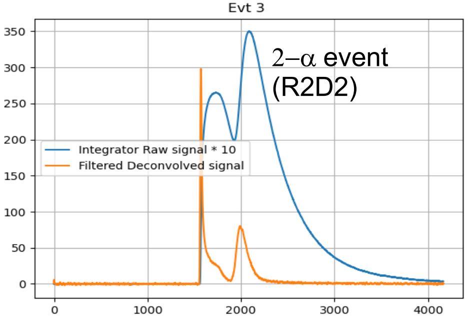
Tracks recognition

@ low pressure, this kind of detector allows to observe fine details about the interactions:

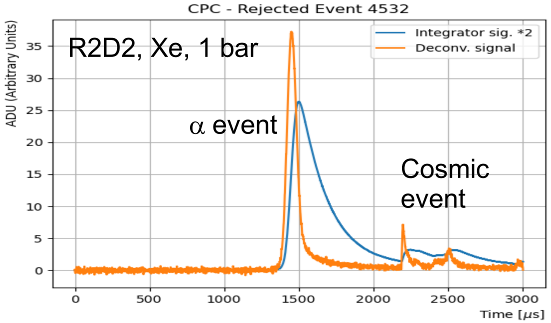








NIM A 1028 (2022) 166382



=> Efficient recognition of background events (Compton, cosmics, etc.) should be achieved.

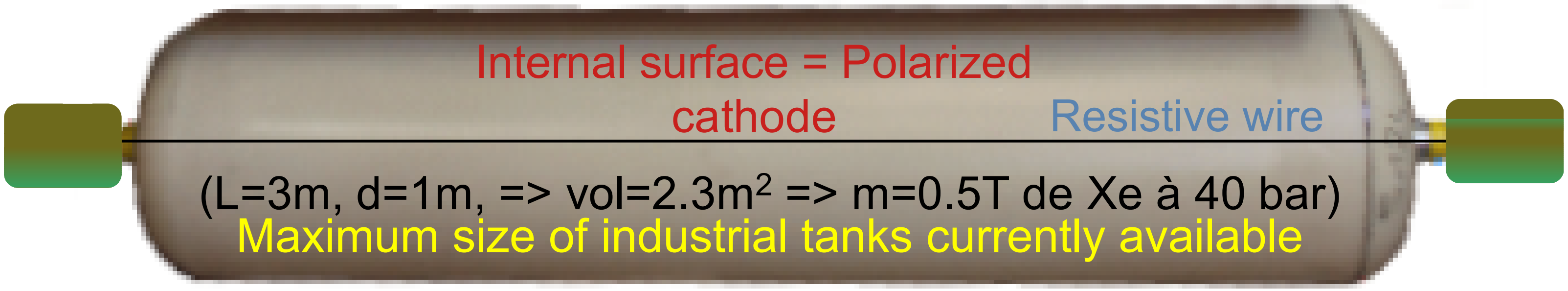
@ high pressure, except for cosmics, all interactions appear as point-like => recognition of the 2-tracks of $2\beta0\nu$ decay can become very challenging ! => can this set a limit in pressure ? (work is in progress...)

Next step considered

Cylindrical geometry is mostly use in industry.

=> A CPC based on composite tank technology (600 bars) developed for H_2 storage.

- Easy mass scalability up to tons.
- Low material budget (& cost).
- Low internal amount of metals to reduce Rn attachment (< 1 gram ?).
- Additional longitudinal localization by charge sharing on a resistive wire *(NIM A 492 (2002) 26–34)*
  => improvement of background rejection .



=> Demonstrate the ability to instrument a tank (end-caps which hold the wire)...

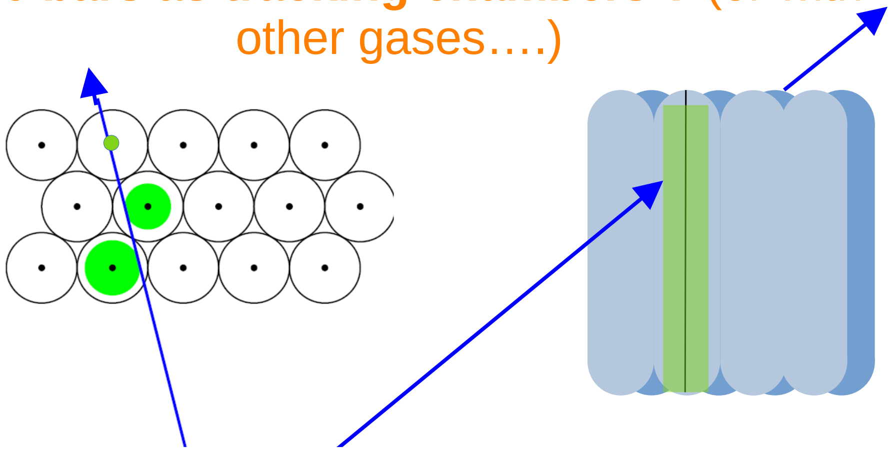
+ Selection of radio-pure materials (NEMO expertise).

Backup design: a conventional metallic tank.

Conclusion & Perspectives

- **The detection proof of concept is done.**
- **CPC in ionization or proportional modes may be used for $2\beta0\nu$.**
- **Next objective: build a one-ton gas demonstrator.**

Could we use industrial tanks with H2 at 600 bars as tracking chambers ? (or with other gases….)



Source of radiation :
Reactors, Cosmics....
Particles detected :
$\alpha, \beta, \gamma, \nu, \mu$, n....

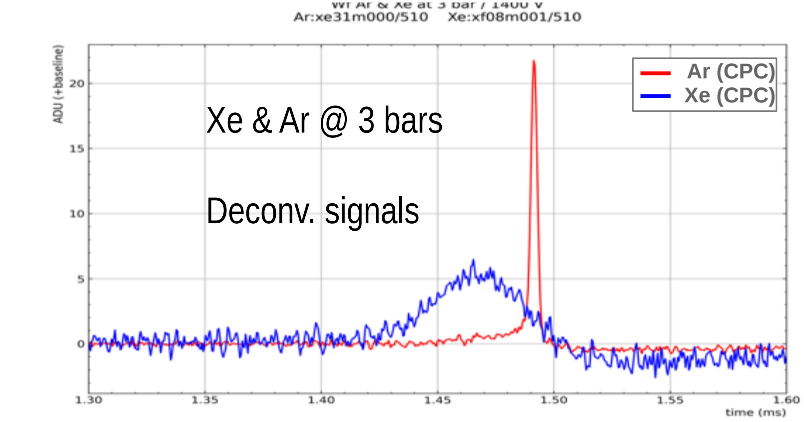
Tanks wall
(conceivable over hundreds of m)

and why not using liquids (ionization mode) ?

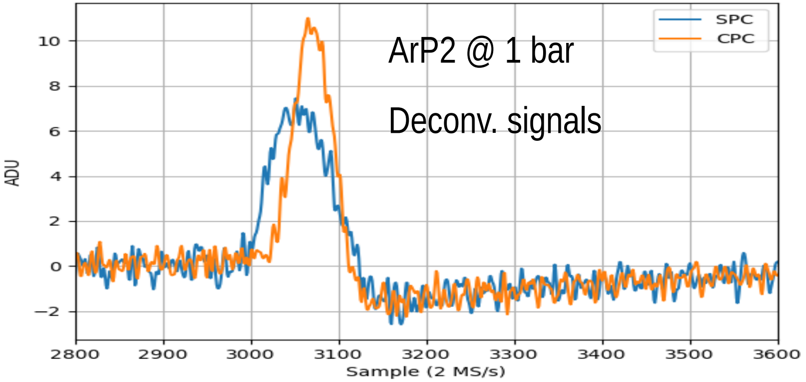
THANK YOU FOR YOUR ATTENTION

Backup: SCP / CPC Features

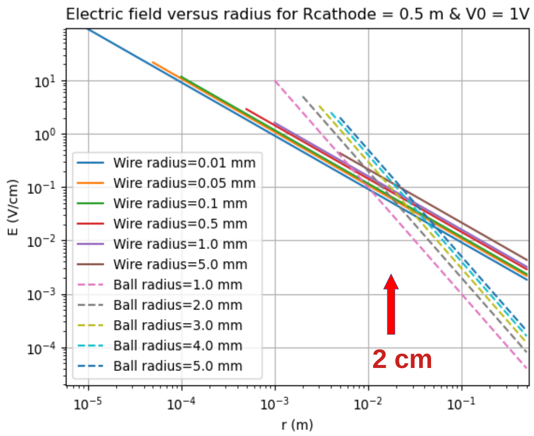
Ionization mode



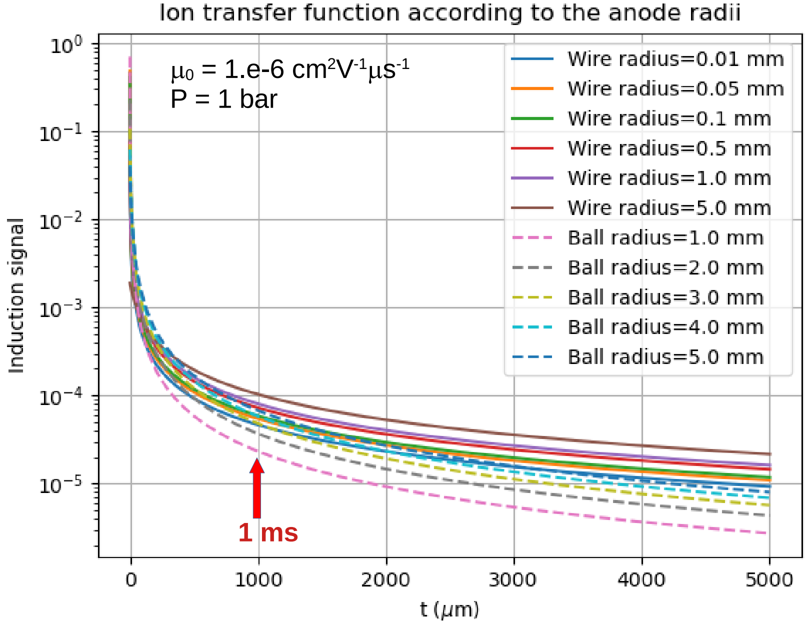
Xe gas is slower than Ar gas due to density



SPC is slower than CPC due to lower E-field



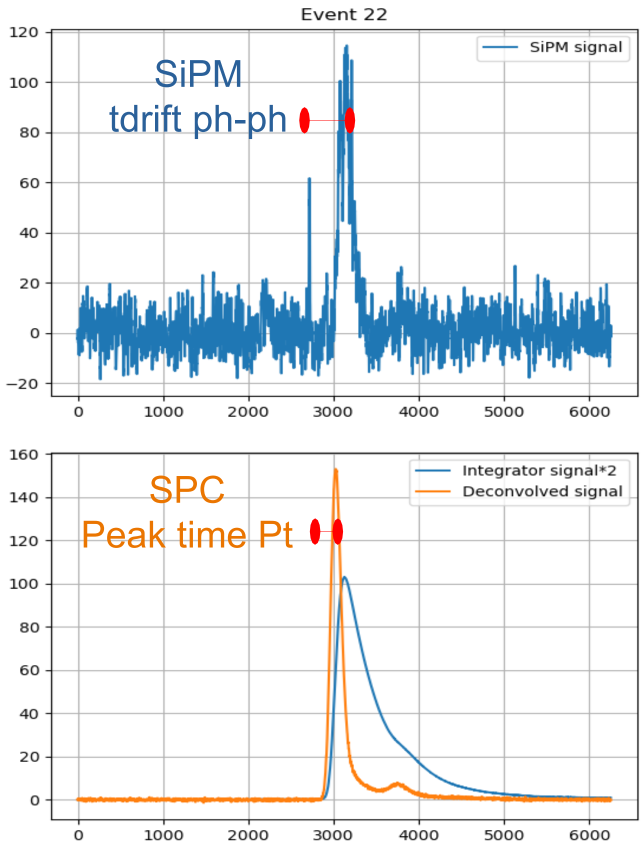
Proportional mode



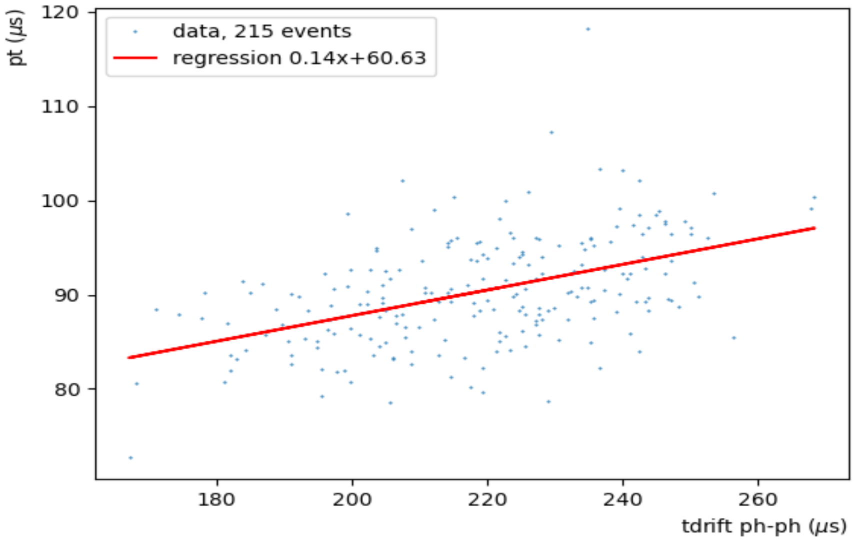
Ions mobility governs the signal duration.

CPC has faster but longer signal

Backup : Correlations between light & SPC signal



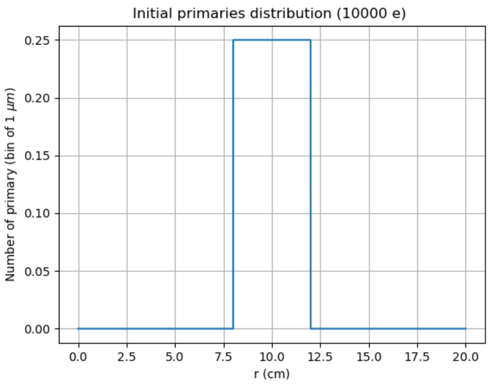
Pure Ar @ 1.1 bar – 210 Po source – Track length of 3 cm



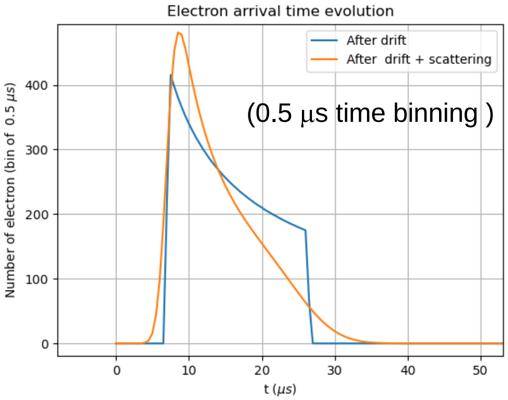
=> Correlation drift time (SiPM) - peak time (SPC) observed.

=> A way to bypass the use of the light emission...

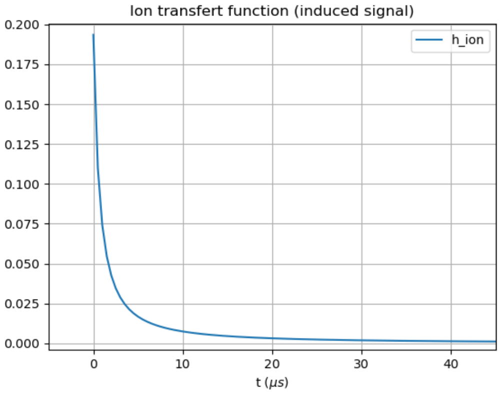
Backup: signal formation



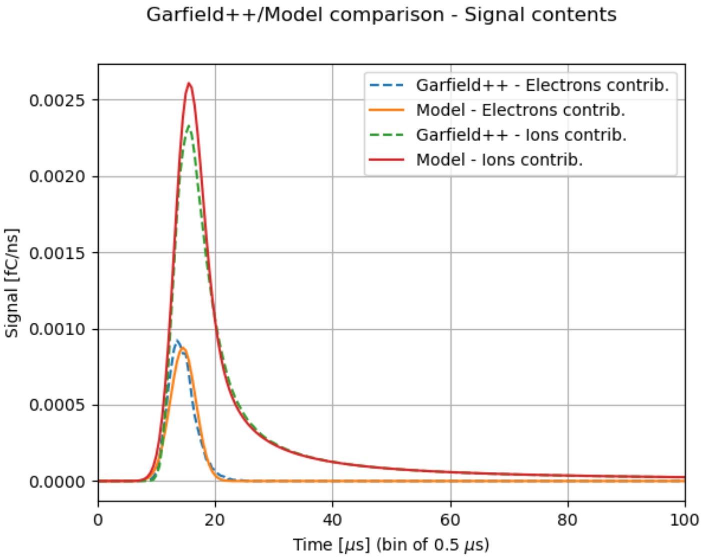
Transport and diffusion effects for primary electrons



Convolution of the final Electron arrival time distribution with the ion induction function h_ion(t)



Response with to a Dirac primary charge @ 10 cm *SPC ($r_{cathode}$=20 cm, r_{anode}=1mm) - Gas ArP2 - P=200mb - HV=700V, μ_0=1.e-6 Gain = 8*



Backup: Track distance sensitivity

CPC-50 - Deconvolved signal - ArP2 - 1 bar – 210 Po - Track length ~3 cm