R2D2: An R&D program for the research of $2\beta0\nu$ decay with a SPC

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R2D2 collaboration

CENBG, Univ. Bordeaux, CNRS/IN2P3, Fr
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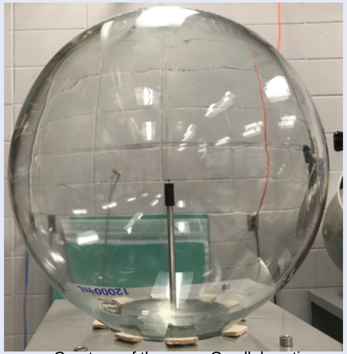
SUBATECH, IMT-Atlantique, Univ. Nantes, CNRS/IN2P3, Fr
-- also in NEWS-G

17 déc. 2021 - Université de Paris



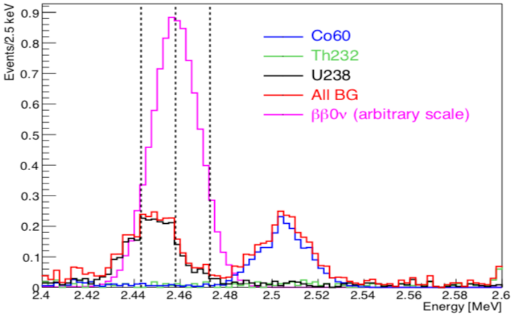
Courtesy of the news-G collaboration.

Motivations

NEWS-G showed that the **Spherical Proportional Counter (SPC)** is very attractive: (cf. Talk of Konstantinos, “Latest news from the NewsG experiment”, this conf.):

- Gain up to 10^4 .
- Low detection threshold (down to single electron).
- Good energy resolution (12% @ 2.6 KeV).
- Discrimination from surface and bulk interactions

Preliminary simulations indicated that **an SPC filled with pressurized 136Xe could be competitive for $\beta\beta0\nu$ decay searches** under some conditions .



JINST 13 (2018) no.01, P01009

The goal of the R&D project R2D2 (Rare Decays with Radial Detector) is to verify that these experimental constraints can be overcome :

Phase 1

- Energy resolution (requiring 1% FWHM @ $Q_{\beta\beta}$ of 2.458 MeV with 136Xe).
- Operation with Xe at high pressure.

and the scalability of such a detector:

Phase 2

- Up to a ton of Xe gas (1 m radius at 40 bars).
- With a extreme reduction of the radioactive background.

A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370

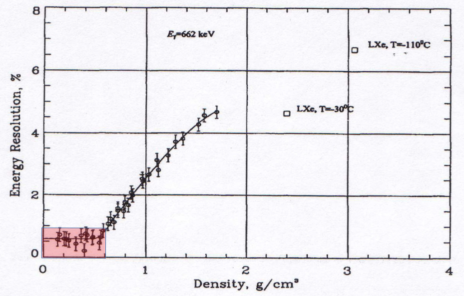


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma

Principle of the SPC

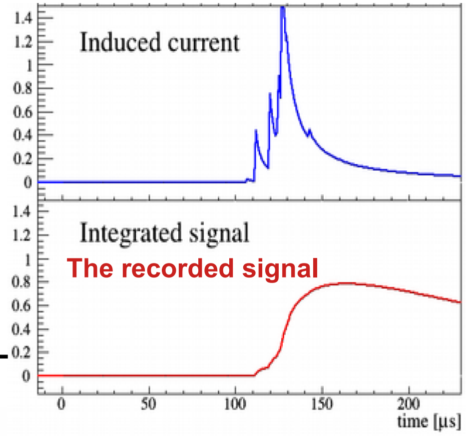
I. Giomataris, JINST 2008

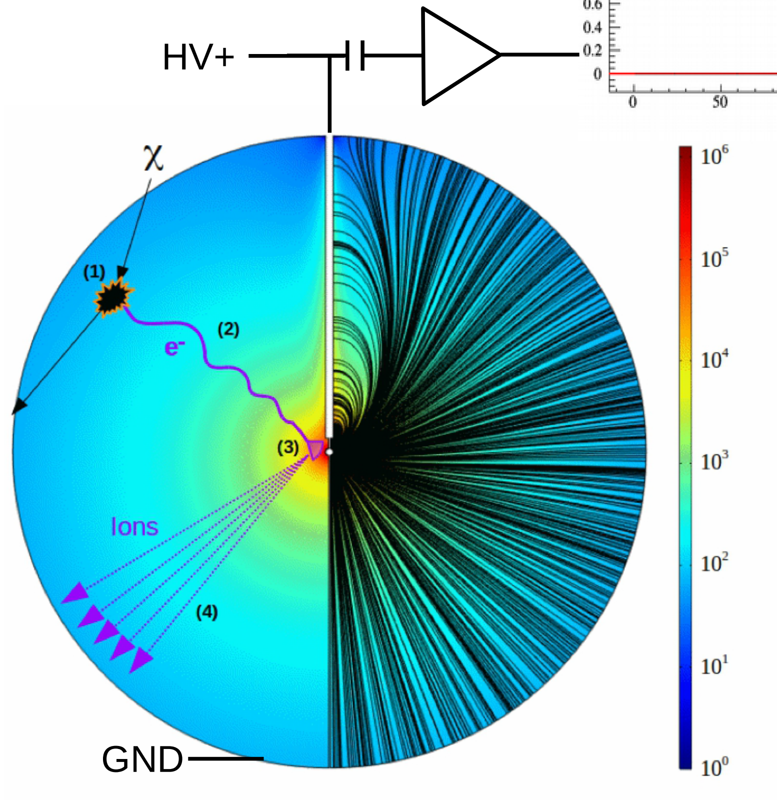
$C = 4\pi\varepsilon\rho < 1$ pF

$1/\rho = 1/r_a - 1/r_c$

$\rho \approx r_a$

$E(r) = V_0\, r_a/r^2$





Pros

- Simple mechanical structure (thin Cathode => low material budget => low radioactive background).
- Single channel FEE (advanced electronics + waveform signal processing).
- **An joker asset due to the gaseous medium => the possibility of recognition and localization of 2-tracks events.**

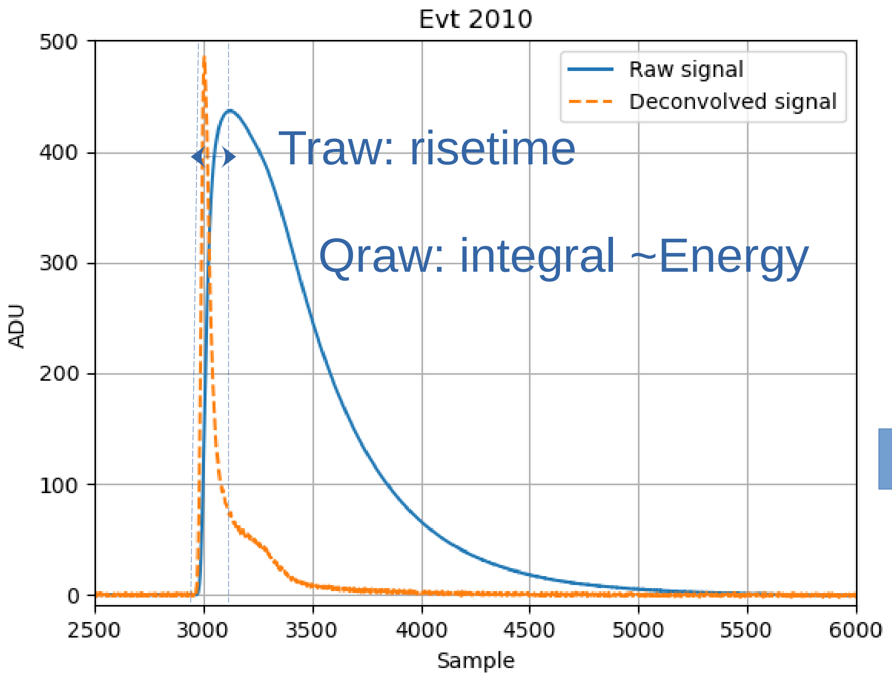
Cons

- Unknown polarization limit of the anode ball relative to the rod (pressurized gas)
- Need of excellent signal / noise

Signal & Observables

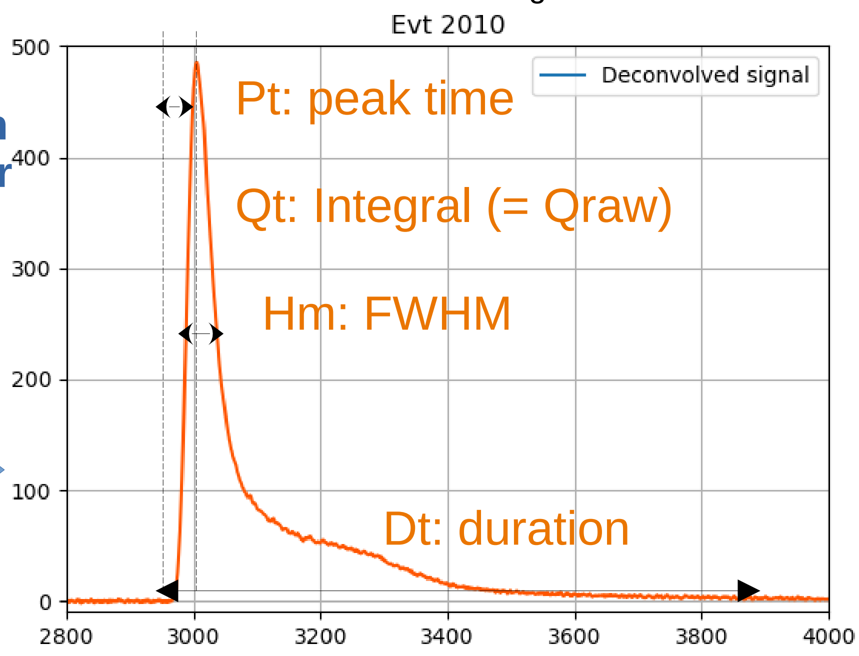
To achieve very high precision measurements, use of signal processing becomes essential

Raw signal (ArP2@200mb, 210 Po source, Sampling 2 MHz)



Deconvolution of the amplifier RC + Numerical filtering

Deconvolved signal

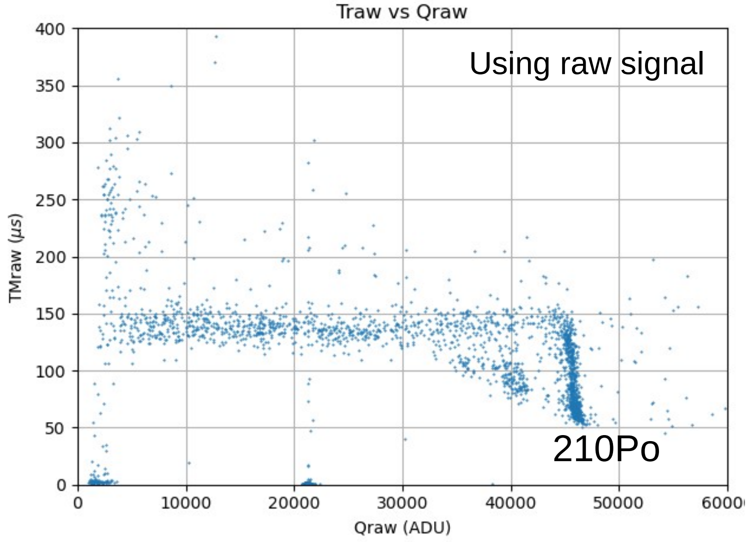


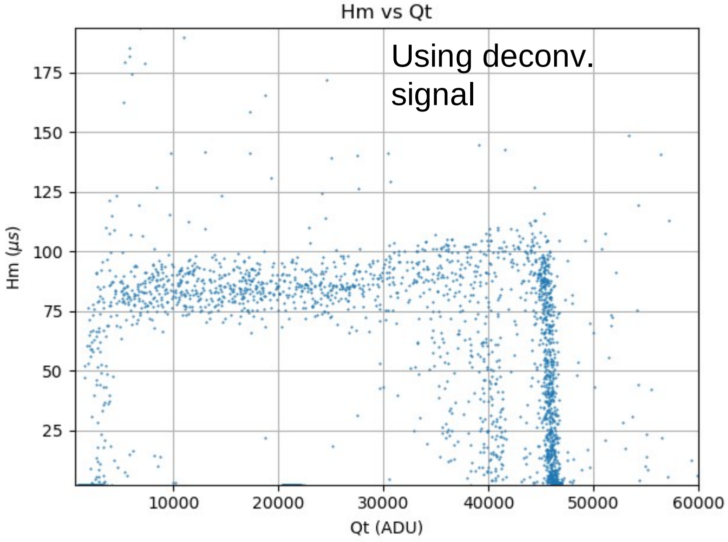
=> The maximum of the deconv. signal corresponds to the maximum of the energy deposition.

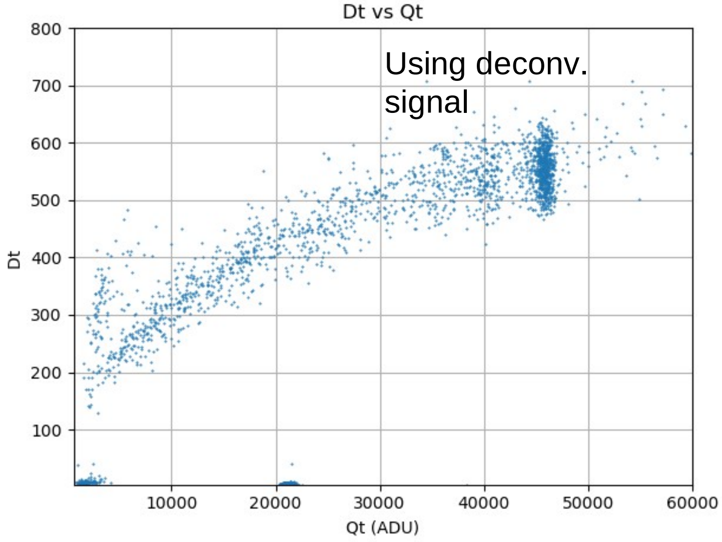
(Raw and deconvolved waveforms have different noise or information contents.)

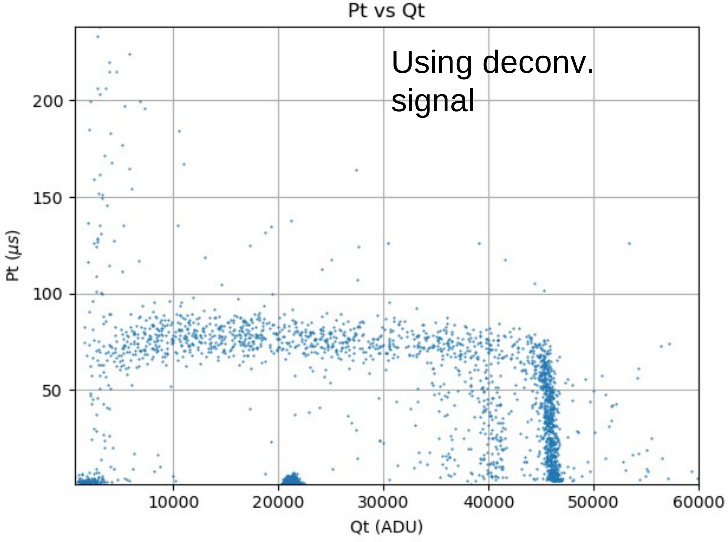
Event features

(ArP2 @ 200 mb, 210Po source)









R2D2 setup

JINST 16 (2021) 03, P03012

First step:

Optimization of a first small prototype

- **In terms of signal/noise and E-resolution**
- **Working with pressures of 200 to 1100 mb** (because the high pressure certification was not obtained).

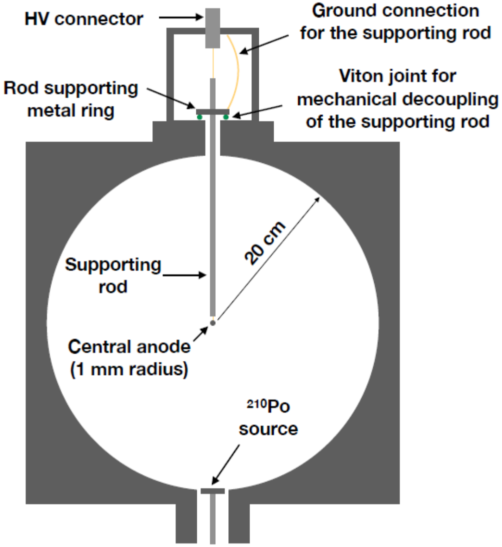
Detector parameters:

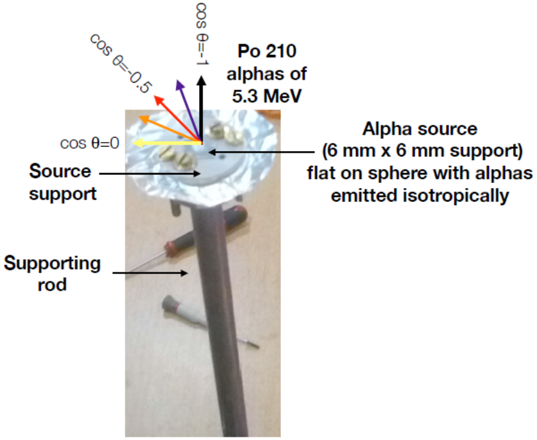
- Detector built in Aluminum **(no-radio purity need at this stage).**
- Stringent requirements on sealing (avoid external contamination).
- **Operation @ moderate gain ~ 50.**

Gas: Argon P2 (98% Ar, 2%CH4) (easiest using)

Source: 210Po source (α of 5.3 MeV)

=> Maximum track lengths of 3 to 17 cm depending of the gas pressure (from 1 bar to 0.2 bar).





Second step:
Add of a light detector

- **To study the possibility of trigger using primary photons emitted by pure noble gas.**
- **To look for correlations between the detected photons and the SPC observables.**

One SiPM was added to detect the scintillation light:

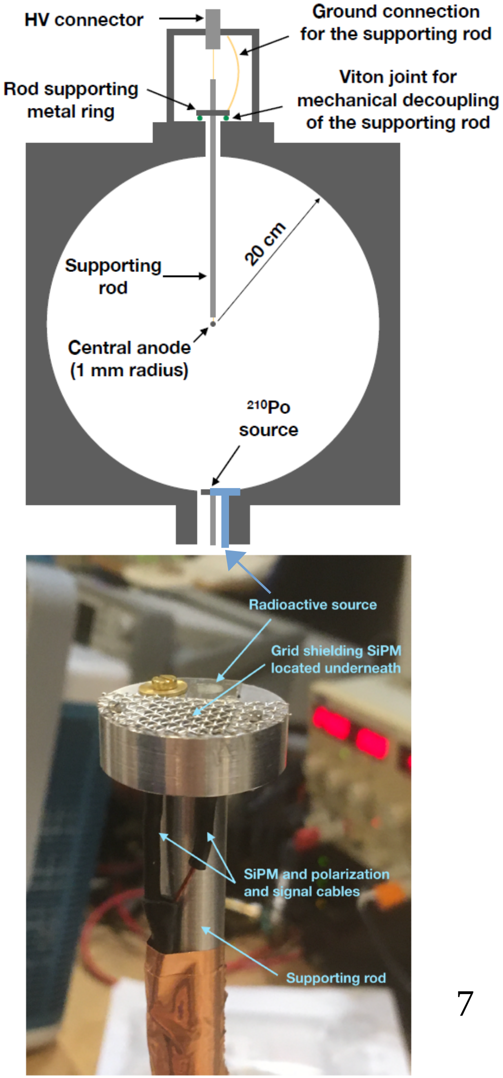
(Hamamatsu: 6x6 mm^2 , 14% QE at 128 nm)
- Addition of a metal grid to protect against the leakage electric field of the SiPM.

Gas: Use of pure Ar (purity 99.9999%) @ 1.1 bar (2200 V)

- **but we weren't able to control the purity after filling.**

- Suitable operation conditions were only achieved at 1 bar (primary ionization detected near the SiPM).

- **FEE of the SiPM induced noisier conditions for the SPC.**

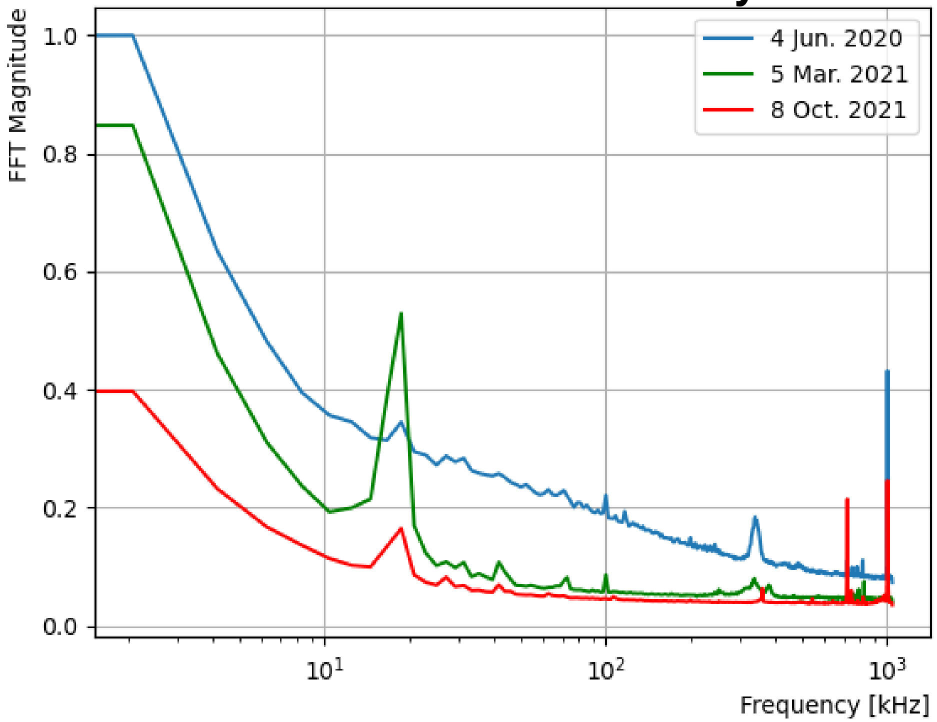


Results

Noise improvement

- Use of a custom charge pre-amplifier OWEN (limited bandwidth, t_r ~100 ns).
- Use of very low noise power supplies(~mV_{pp} of ripple for HV).
- Optimization of the sensor geometry
- Optimization of connections & groundings.
- Reduction of the acoustic vibrations.
- Survey of the gain stability vs room temperature

Noise evolution over 1.5 years



=> Drastic reduction of the noise figure.
(A background task in continuous improvement...)

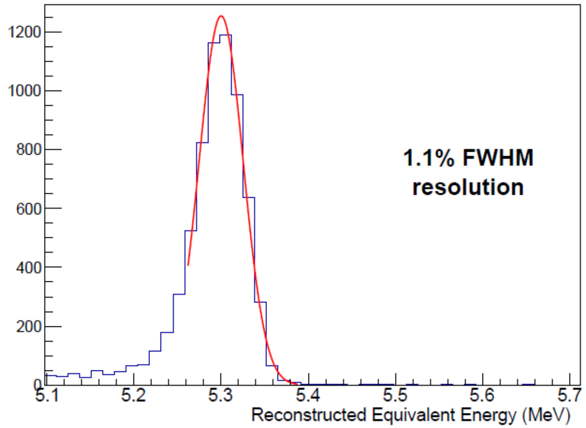
Results with ArP2 @ 0.2 – 1.1 bar
E-Resolution - Track length effects

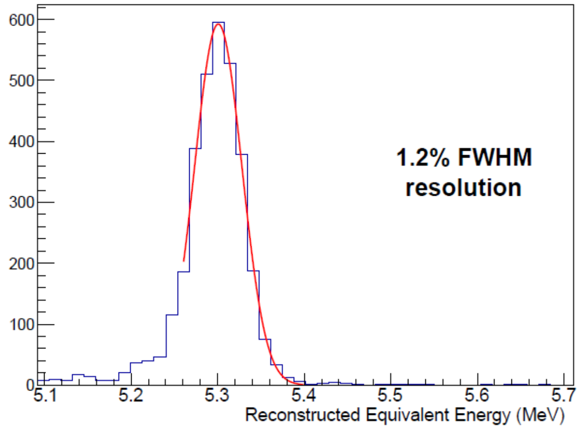
The first stage of R&D focused on the attainable energy resolution.

Detector response was explored at 0.2 bar (720V) and 1.1 bar (2000V) and with a same gain level.

=> Main difference: The α track length (17 cm vs 3 cm respectively).

Histograms of the observable Q converted into energy.





Source positioning not perfect => non-homogeneity of E field near the source => Degraded performances @ 1.1 bar with track length of 3 cm.

200mbar — Ar-P2 – 210Po source — 1100mbar

=> Track length and pressure do not (strongly) affect the energy resolution.

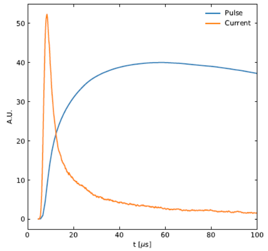
(Contribution of the source and the electronic was estimated to account for 0.6%).

Signal simulation

SPC Simulation based on

- Finite Elements Software: Ansys or Gmsh+Elmer.
- Geant44: simulation of primary interaction.
- Garfield++: simulation of gas, electrons transport and charge collection.
- Signal treatment.

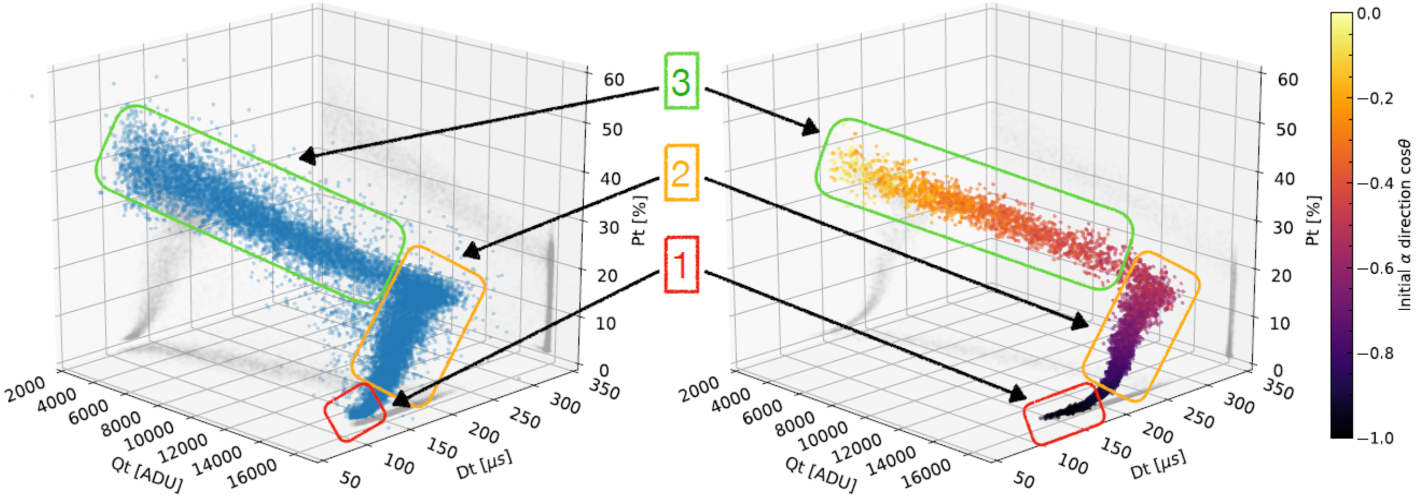
=> In continuous improvement



Cross-check data/simulation

Choice of the observables makes it possible to highlight the interaction topology.

=>3 regions in the following plots:
(1) Tracks toward the anode.
(2) Tracks at larger angles but contained in gas.
(3) Tracks hitting the cathode (loosing energy in it).



Data

Ar-P2 - 200 mb – 720 V data
Gain = 50

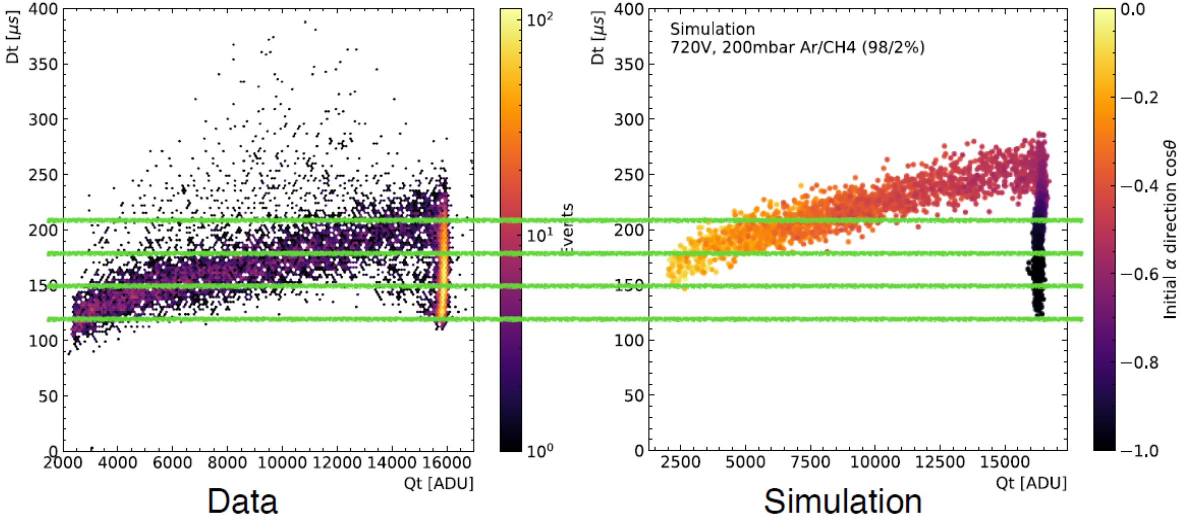
Simulation

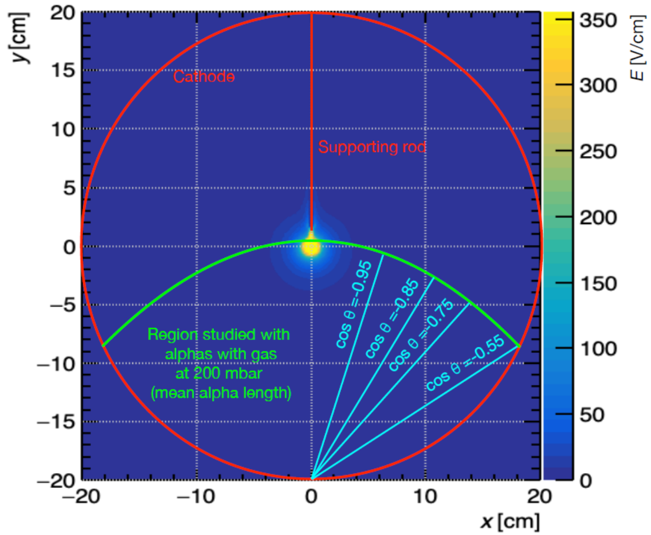
=> Good understanding of the topology of the events.

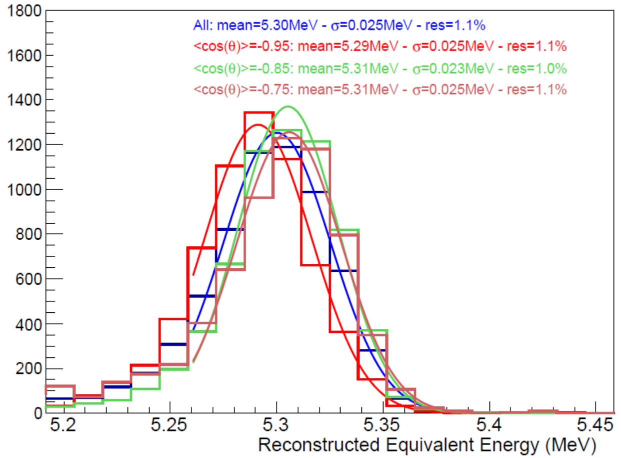
E-Resolution – Direction effects

Ar-P2 - 200 mb – 720 V data

Angle (direction) selections
defined from simulation.







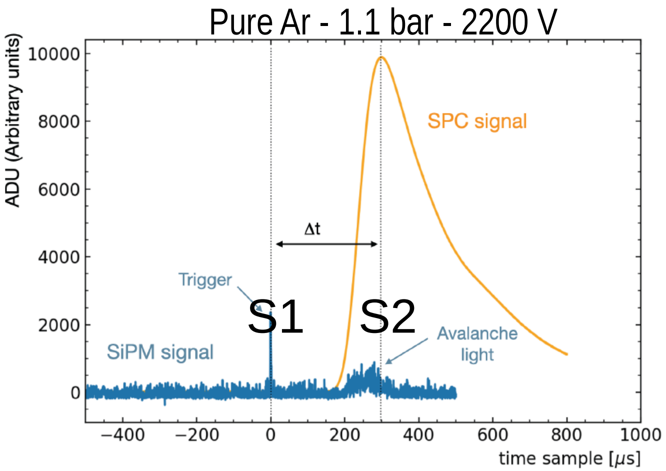
=> Track direction doesn't (strongly) affect energy resolution.

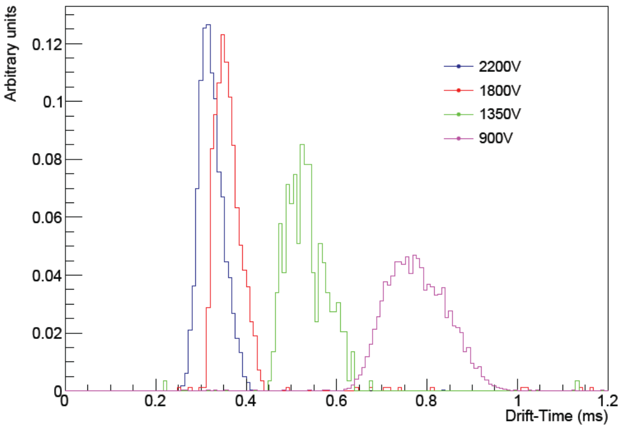
(ditto for volume effects - favorable effect of attachment near anode).

Results with pure Ar @ 1.1 bar
Exploitation of the SiPM signals

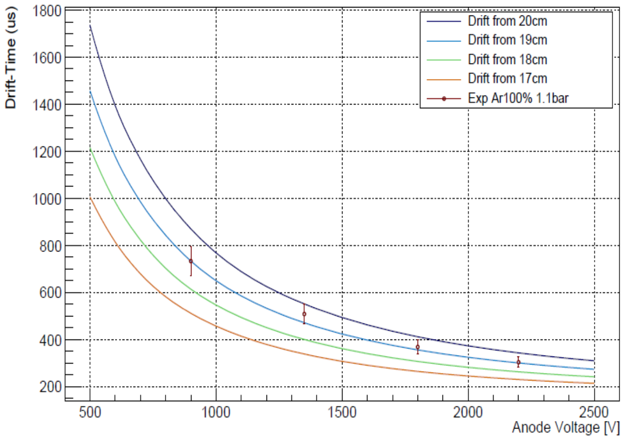
(Results submitted to NIMA)

Scintillation light was first used to estimate the drift-time in the detector





Drift time vs. anode HV



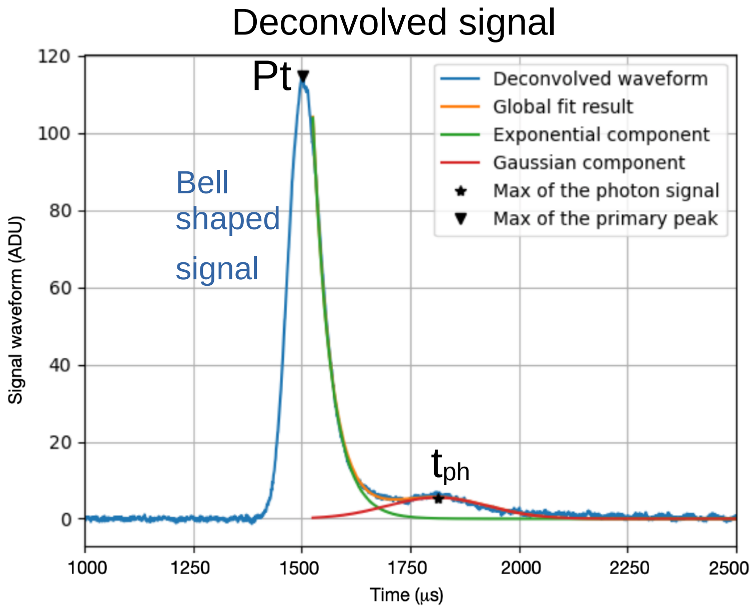
Drift time (Garfield++ simulations) vs. anode HV

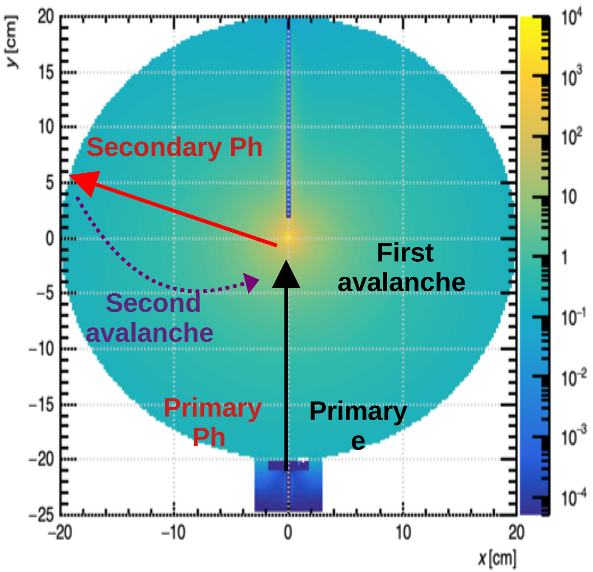
=> Good agreement between data and simulation

(Geometric acceptance of our light detector limited the study to the tracks directed towards the anode).

Associated SPC signals

=> The deconvolution method has allowed to access to fine details.





Modeling of the falling part of the deconvolved signal: Exponential (or SNIP) + Gaussian.

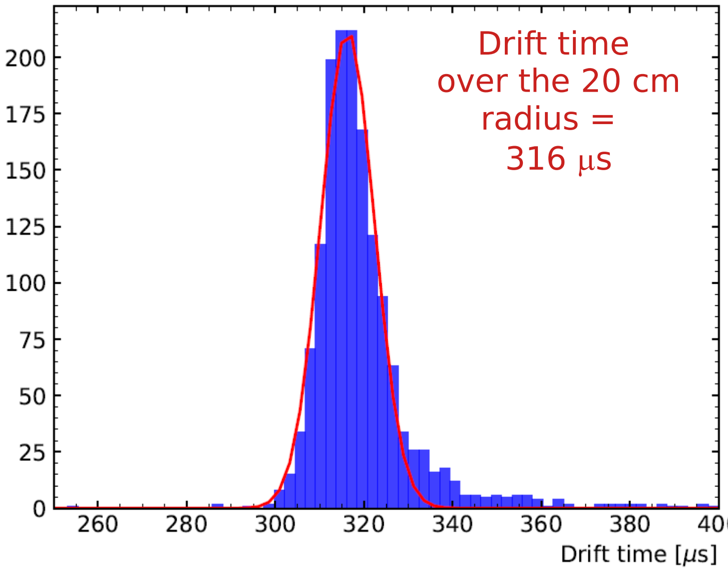
- Pt : time of the first avalanche (@max)
- t_{ph} : time of the photon signal (@max).
- Qt : Integral of whole signal.
- Q_{ph} : integral of the photons peak.
- Hm : FWHM of the first avalanche.
- σ_{ph} : width of the photon peak (σ).

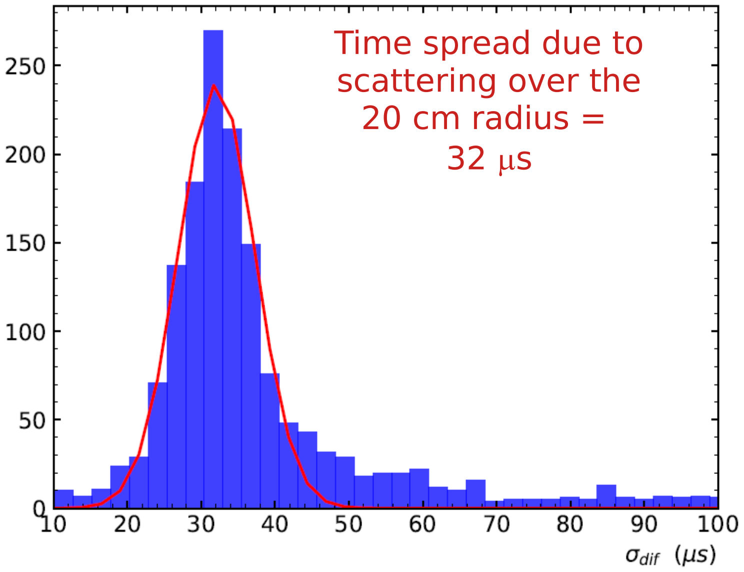
$t_{drift} = t_{ph} - Pt$

$\sigma_{dif}^2 = \sigma_{ph}^2 - (Hm/2.35)^2$

SPC drift time and diffusion time

Using only the SPC signal.

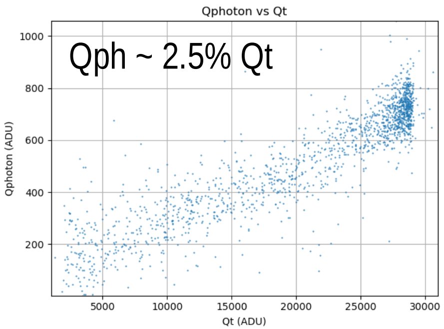




=> Maximum drift time deduced from SPC signal in good agreement with SiPM results.

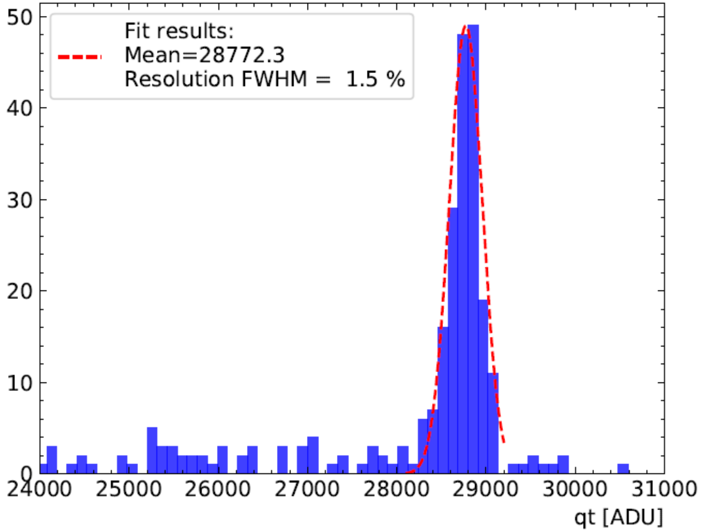
(σ_{diff} (and Q_{ph}) depends on the extraction method (the tail) within a factor 2 because the exponential and Gaussian functionals were probably not optimal).

E-Resolution – photons contribution

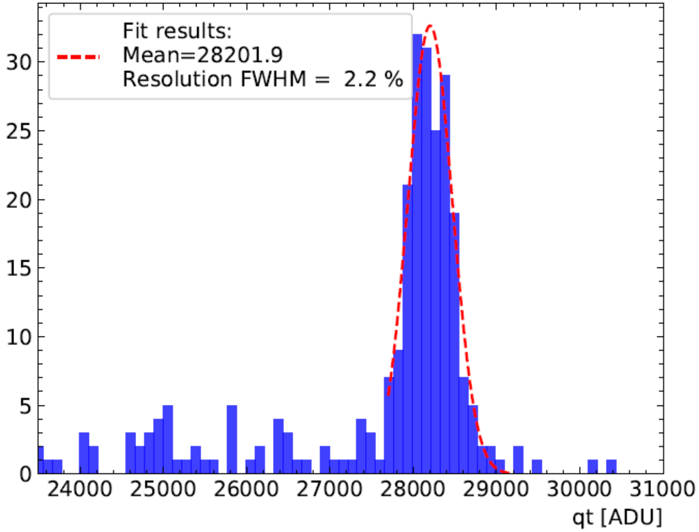


Energy resolution was studied with and without subtracting the photons contribution.

With whole signal: ΔE/E = 1.5% FWHM



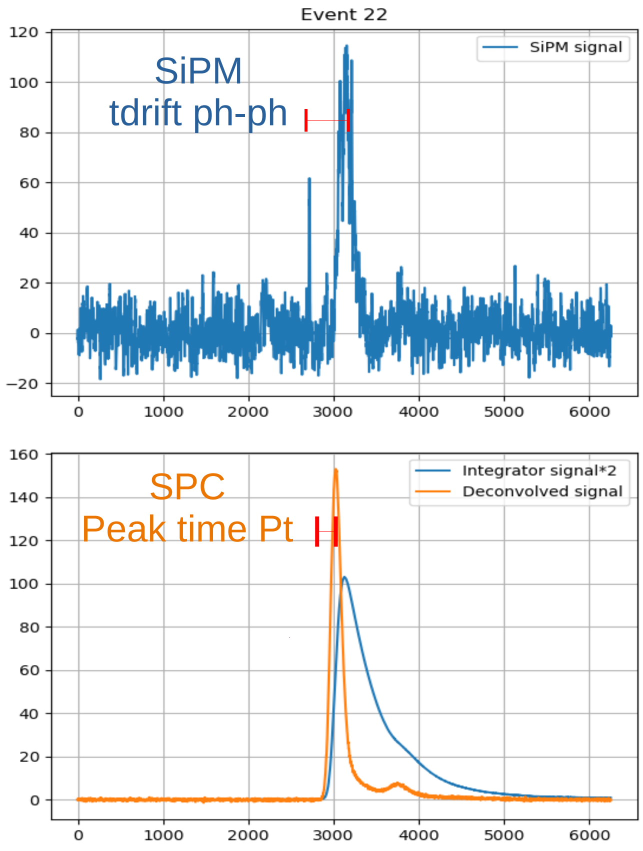
With photons removed: ΔE/E = 2.2% FWHM



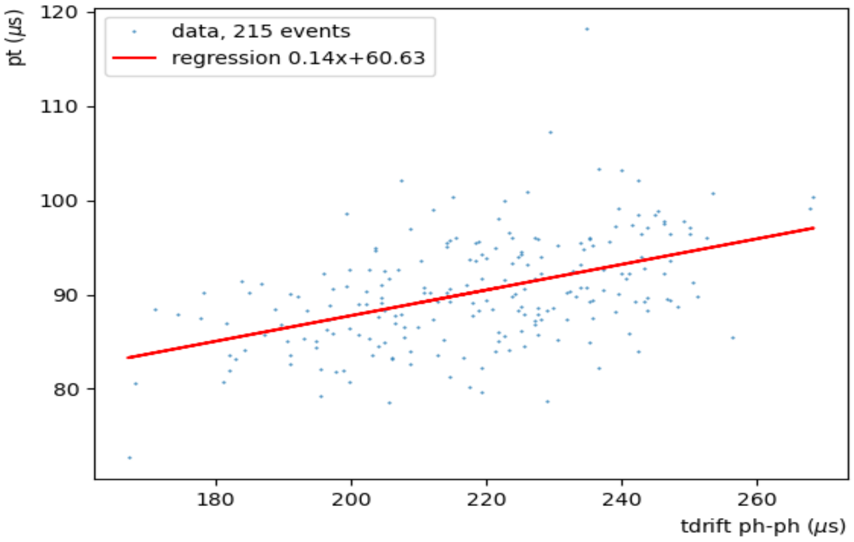
=> Contribution of photons does not seem to spoil energy resolution.

(but the noise induced by the SiPM slightly degraded the resolution)

Correlations between light & SPC observables



Pure Ar @ 1.1 bar – 210 Po source



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

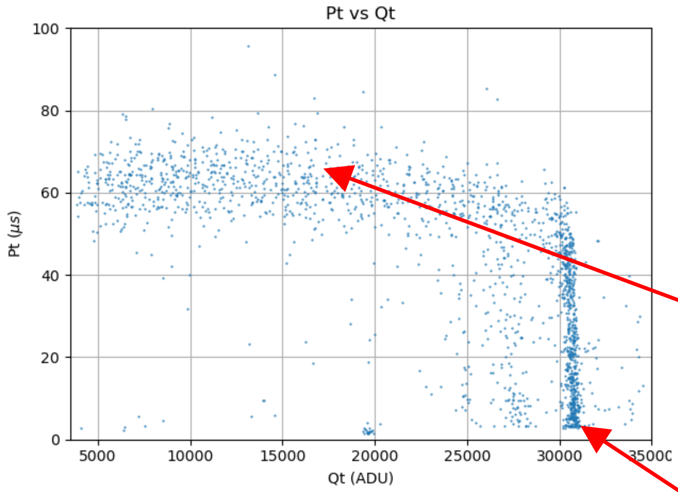
(It requires further studies but it is already encouraging given that the tracks are short: 3cm @ 1.1 bar).

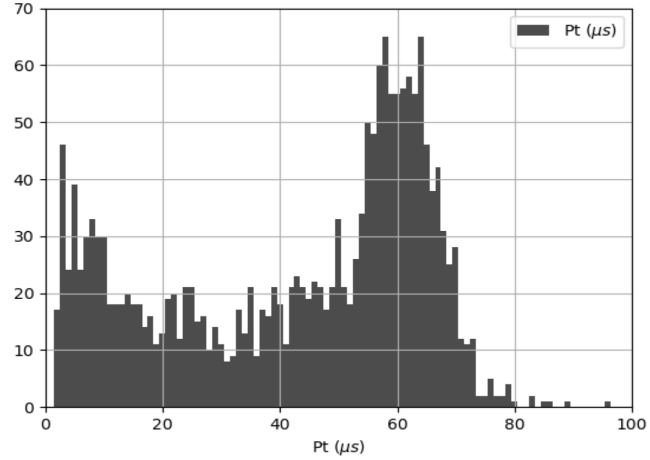
A way to bypass the use of the SiPM...

Position reconstruction

(of the maximum of the deposited energy)

=> We go back to ArP2 @ 0.2 bar to benefit of longer tracks (17 cm)





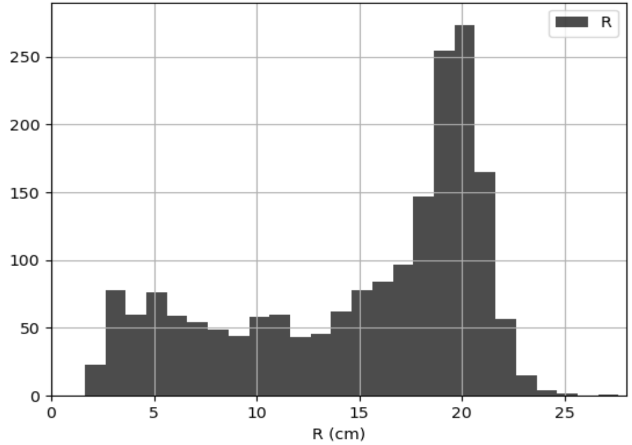
Empirical dependence:

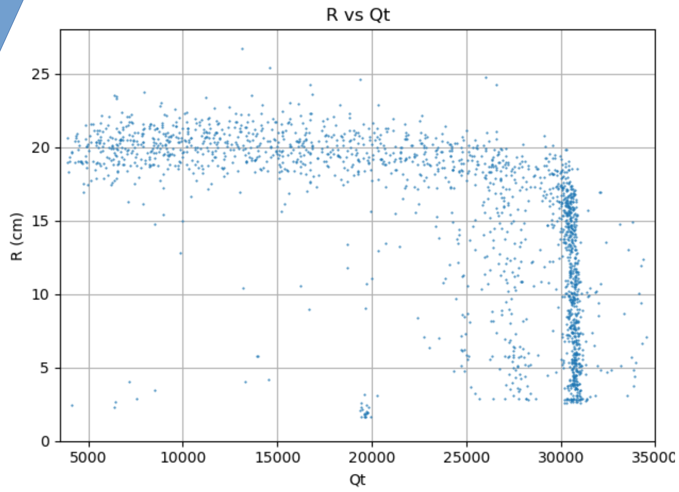
$$Pt = Pt_{max} * (R/R_{max})^{\alpha}$$

With R the distance to the anode

- Pt_{max} = maximum peak time (experimental value)
- R_{max} = maximum radius (det. Parameter)
- α = ($\alpha \sim 1.8$) fixed by the experimental value $Pt_{min} = 2.5$ μs) and simulation value $R_{min} = 3$ cm,

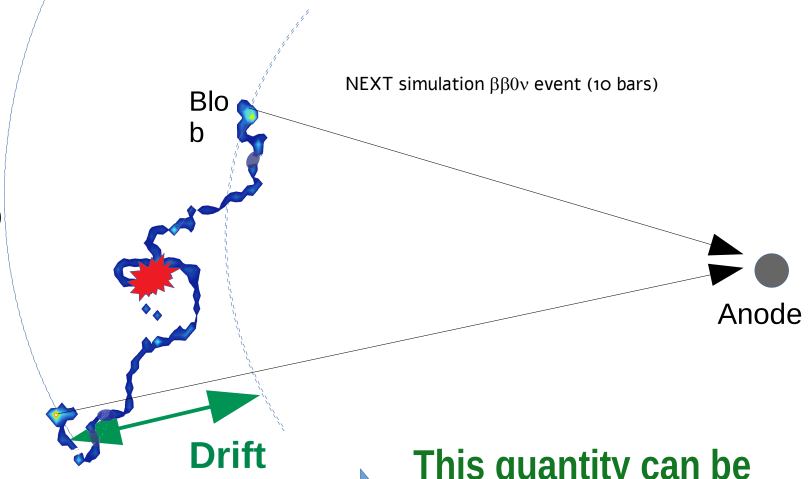
=> Work in progress





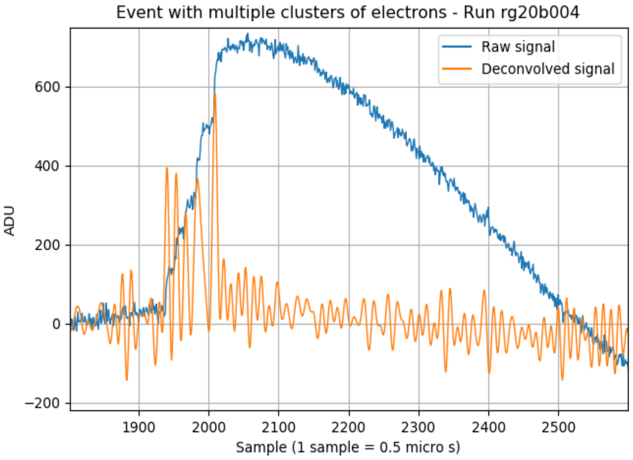
2-tracks recognition

Current scenario for 2β0ν search
(gas detector)



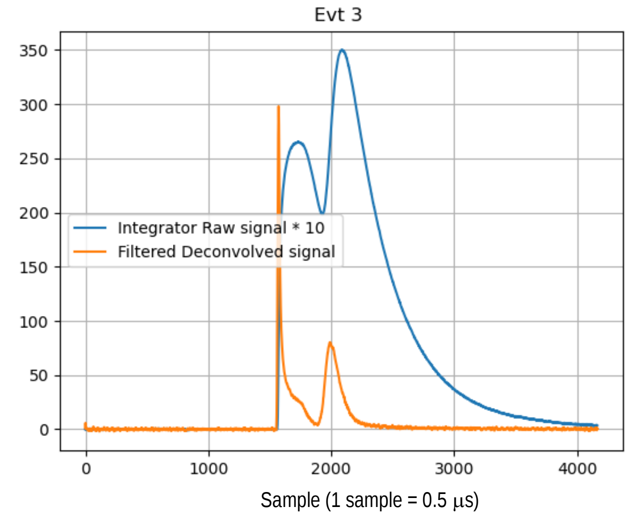
Drift Time Gap → **This quantity can be measured with the SPC**

With NEWS-G:
For dark matter search: detection + decomposition signals into single electrons routinely obtained
(time separation > 3*sampling period.)



Gas: He/CH_4

=> A preliminary basis to this possibility with R2D2:
2-tracks identification already obtained for 2-alphas events.



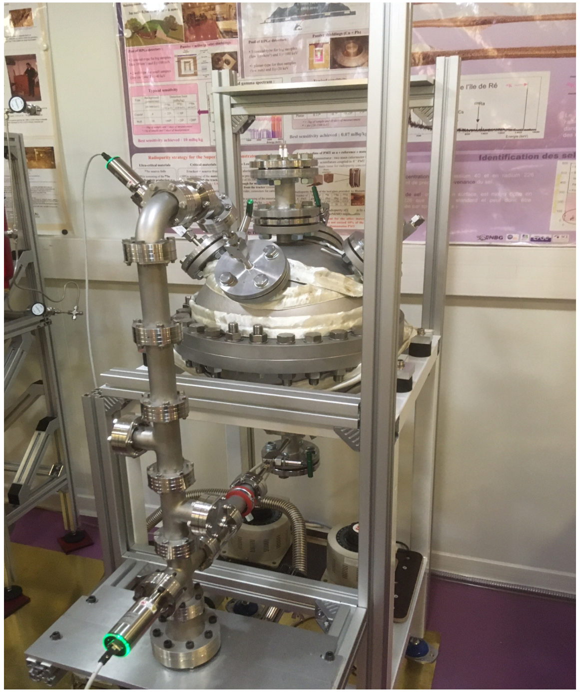
Conclusion

Very promising results were obtained with a single channel SPC at moderate pressure.
Its operation in stand-alone mode seems possible.

Many studies remain to be done...

- **Prototype-2 has been commissioned + finally certified for pressure of 40 bars !**
  (at least 10 bars are necessary to contain fully inside the volume β tracks of 2 MeV)
- We will start very soon the studies with pure Ar and pure Xe at high pressure

=> but for Xe: recuperation + gas filtering + re-circulating systems are needed (under construction).



If this step is successful, the roadmap could be :

- An almost "zero-background" demonstrator (50kg Xe Radio-pure detector allowing measurements with limits $m_{\beta\beta}$<160-330meV).
- A full scale experiment (1 ton Xenon, 1 m radius) covering the Inverse Hierarchy and reaching $m_{\beta\beta}$<m< 10 meV.

THANK YOU FOR YOUR ATTENTION

Signal features

(ArP2 @ 200 mb, 210Po)