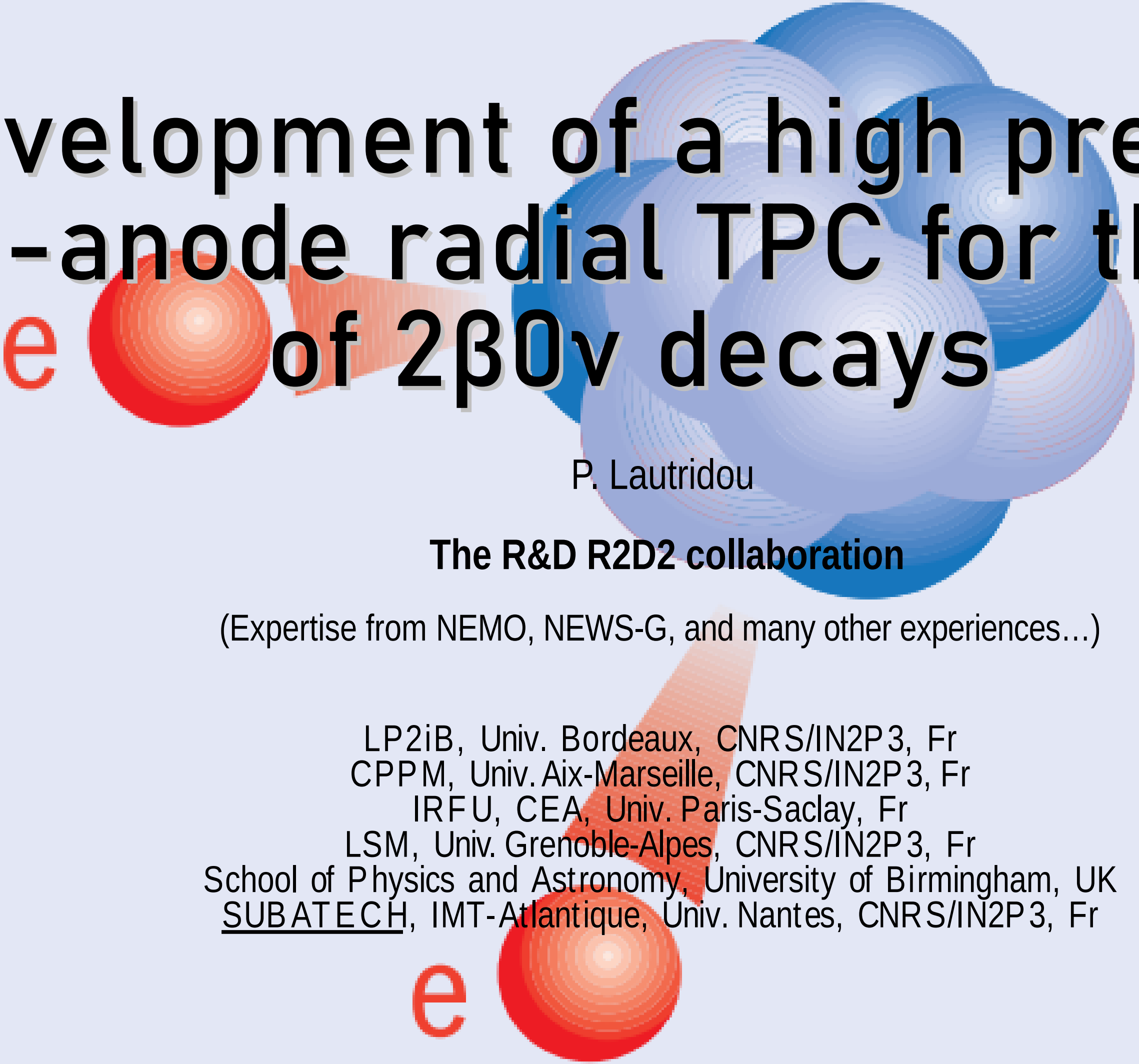


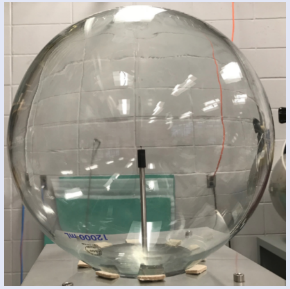
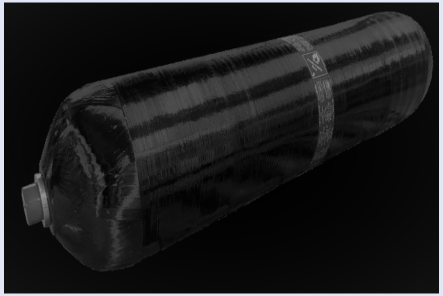
Development of a high pressure single-anode radial TPC for the search of 2β0ν decays

P. Lautridou

The R&D R2D2 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 (1)

Standard Model doesn't include mass term for ν ,
ν flavor oscillations indicate that ν are massive (but of low mass)…

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

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

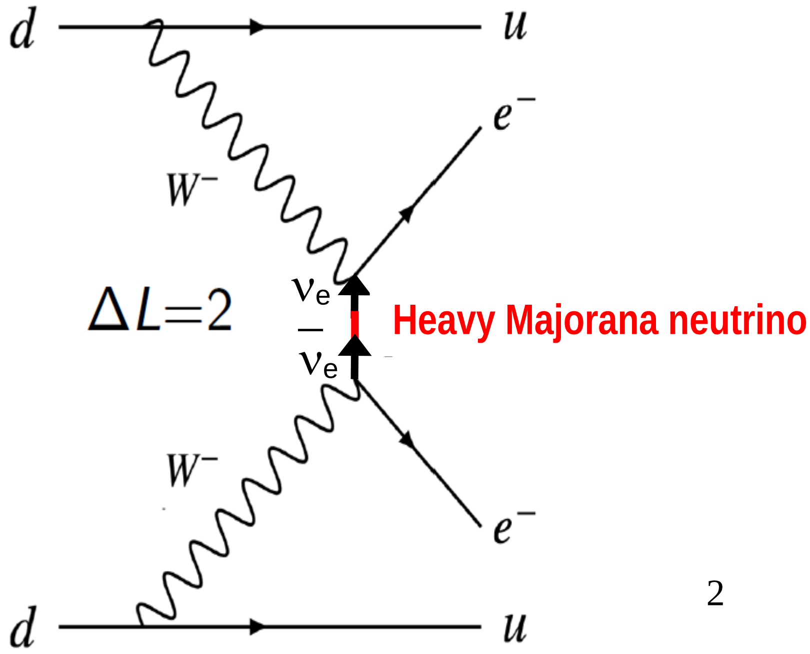
$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

Inverse of half-life

Phase-space

Nuclear matrix element

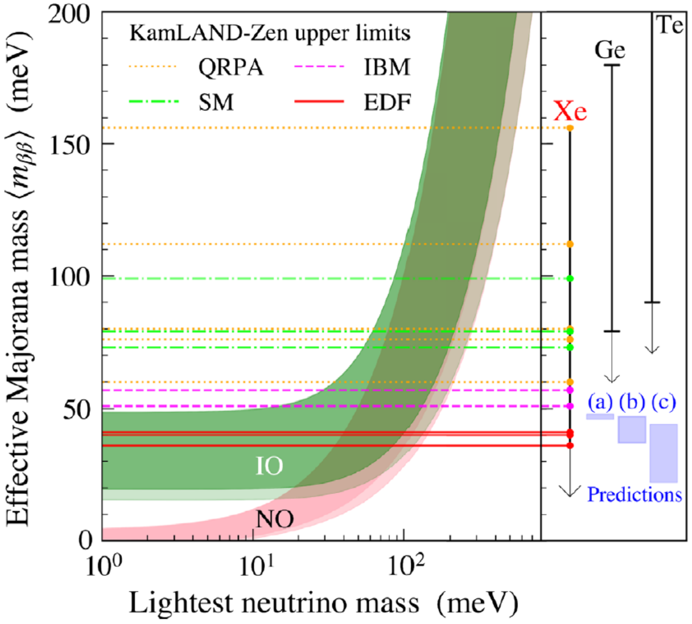
Effective Majorana mass



2β0ν decay (2)

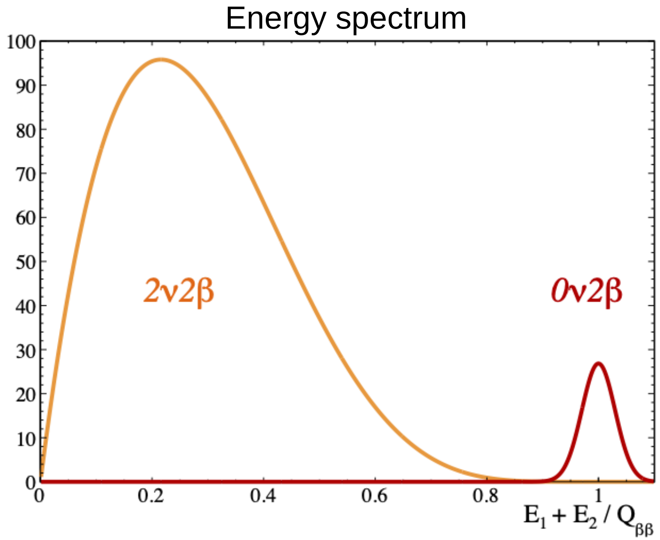
A worldwide competition / collaboration with dozens of projects developed in more than 50 years

The current lower limit of half-lifetime has been obtained with 136Xe with the KamLAND-Zen experiment (2022):
=> 2.3×10^{26} year (90% C.L.)
=> Neutrino effective mass ($m_{\beta\beta}$) upper limit: 36-156 meV



The experimental challenge

- Requires a huge mass of isotopes



- Search for a peak at the $Q_{\beta\beta}$ ….
in a very important background: U and Th decay chains, cosmics, 2β2ν decays.

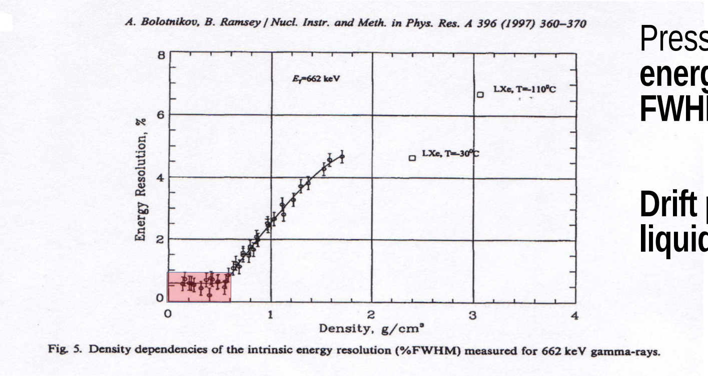
=> Good energy resolution
=> Search for 2 opposite tracks

Motivations

NEWS-G showed that the **Spherical Proportional Counter (SPC)** is very attractive: (cf. Conf. ICHEP2022, UCLA-DM2013, TMEX2023, Blois2022….)

- 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

For *ββ0ν* decays



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

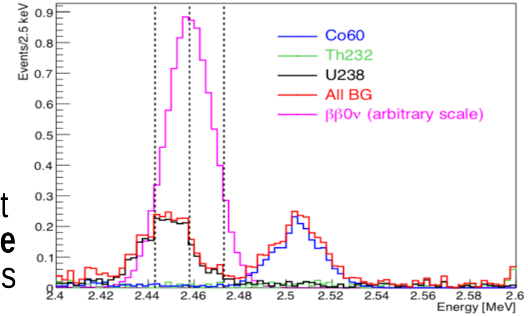
Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

Pressurized Xenon would allow a **energy resolution of 0.6 % FWHM up to 50 bars**

+

Drift performances in gas and liquid based TPCs

Our preliminary simulations indicated that an SPC filled **with pressurized 136Xe** could provide appealing performances



JINST 13 (2018) no.01, P01009

Provided that the experimental constraints can actually be overcome:

- Energy resolution of 1% FWHM @ $Q_{\beta\beta}$ of 2.458 MeV .
- Operation with Xe at 40 bars.

that the scalability of such a detector is possible:

- Up to a ton of Xe gas (~ 1-2 m^3 at 40 bars).

and that an extreme reduction of the radioactive background can be achieved.

Our approach

1) **A central concern: the reduction of the near background**
=> Use of the simplest and lightest possible structure in terms of mechanics and sensor.
=> A single anode radial TPC at high pressure (no cryogenics)

2) **Energy resolution of 1% FWHM**

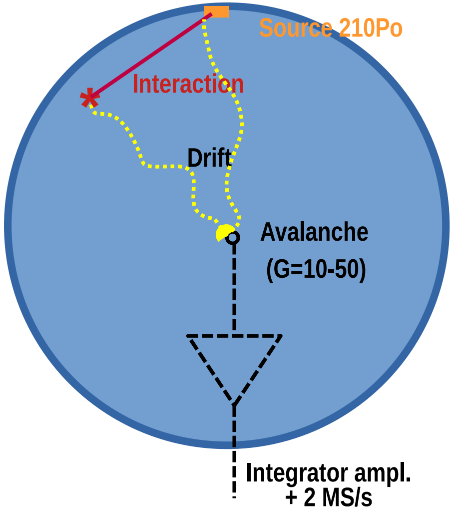
3) Track localization
4) 2-tracks recognition (for the background and function of pressure for 2β)

Additional assets for background rejection

Studied configurations

- 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)

(Final objective is 0.5 m in radius and 40 bars of Xe)

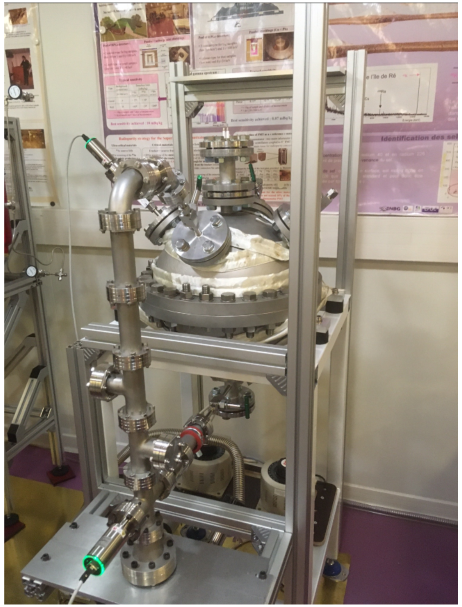


Detectors setup

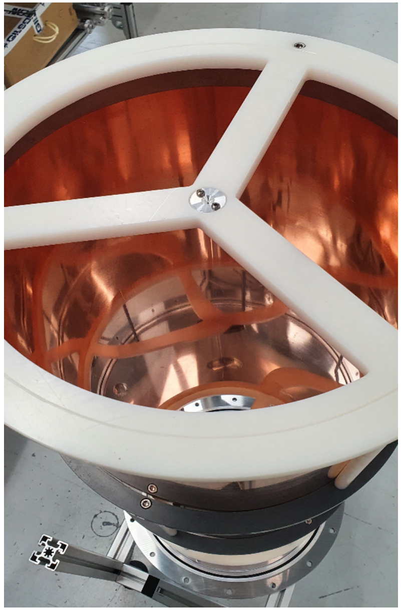
Test facility @ Bordeaux

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

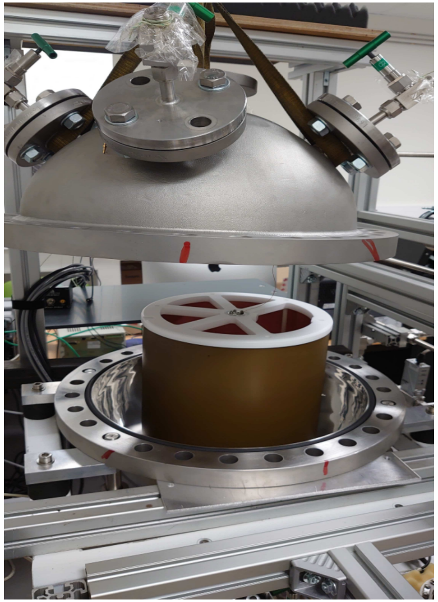
SPC-1 (2018)
D = 0.4 m
r_{ball} = 1 mm
(1 bar)



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)
$r_{wire} = 20\ \mu m$
(1 bar)



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

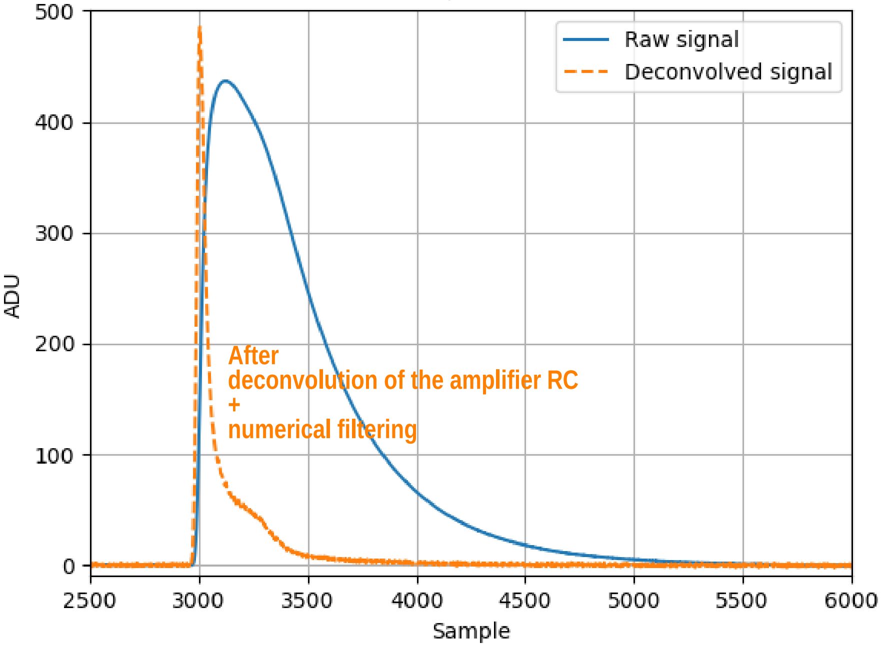
Amplifier positioned outside the tank (cables)

Used with cathodic HV bias

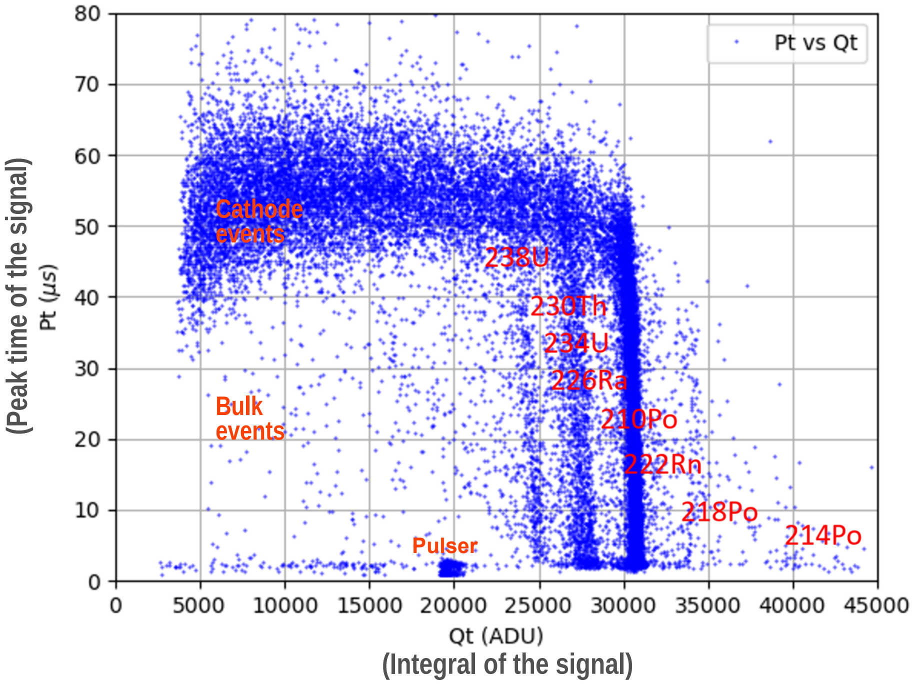
Signal treatment

**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

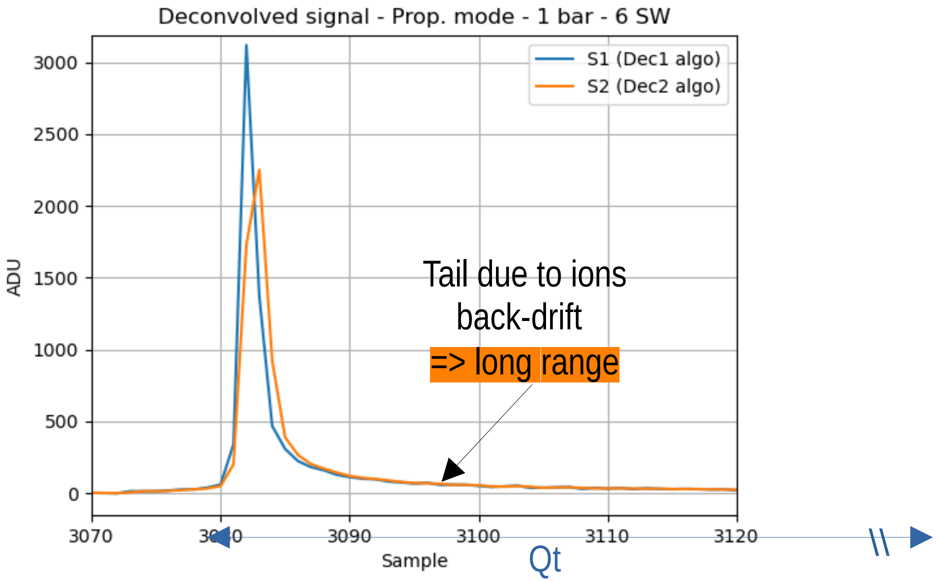


=> Processing allows to extract new information

Ionization / proportional signals

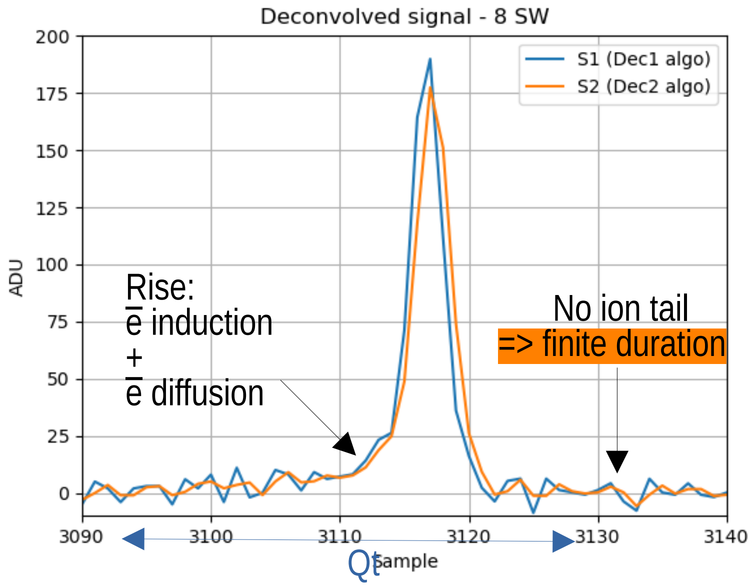
Constraints in HV, Ion space charge, gain fluctuation, quenching….

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



Tail due to ions back-drift

=> long range



Rise:
$\bar{e}$ induction
\+
$\bar{e}$ diffusion

No ion tail

=> finite duration

Proportional mode

- High S/N
- Long duration of integration can alter E-Resolution (impose to control the LF noise)

Ionization mode

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

Energy resolution (1)

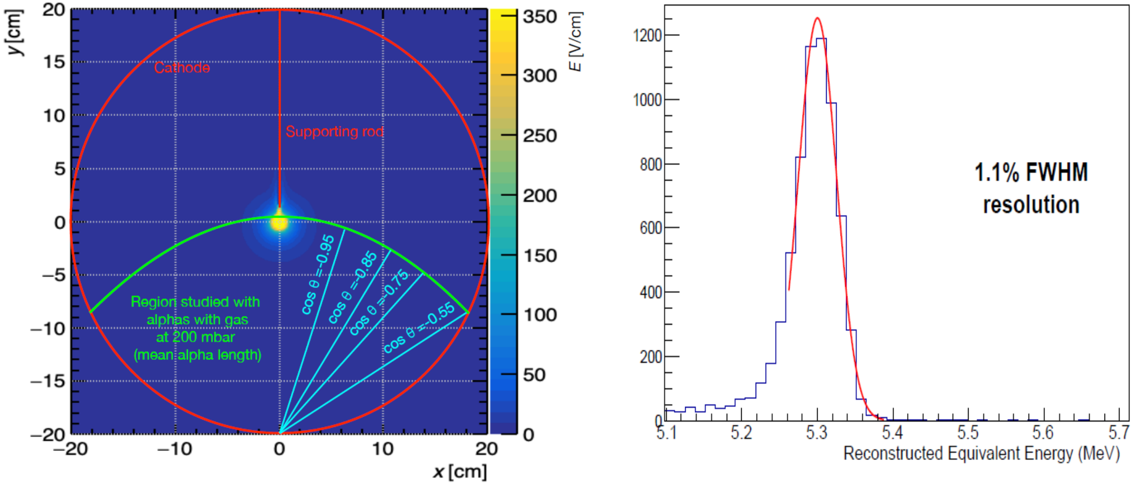
What energy resolution could be achieved for a detector larger than an few cm ?

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

In proportional mode
=> 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



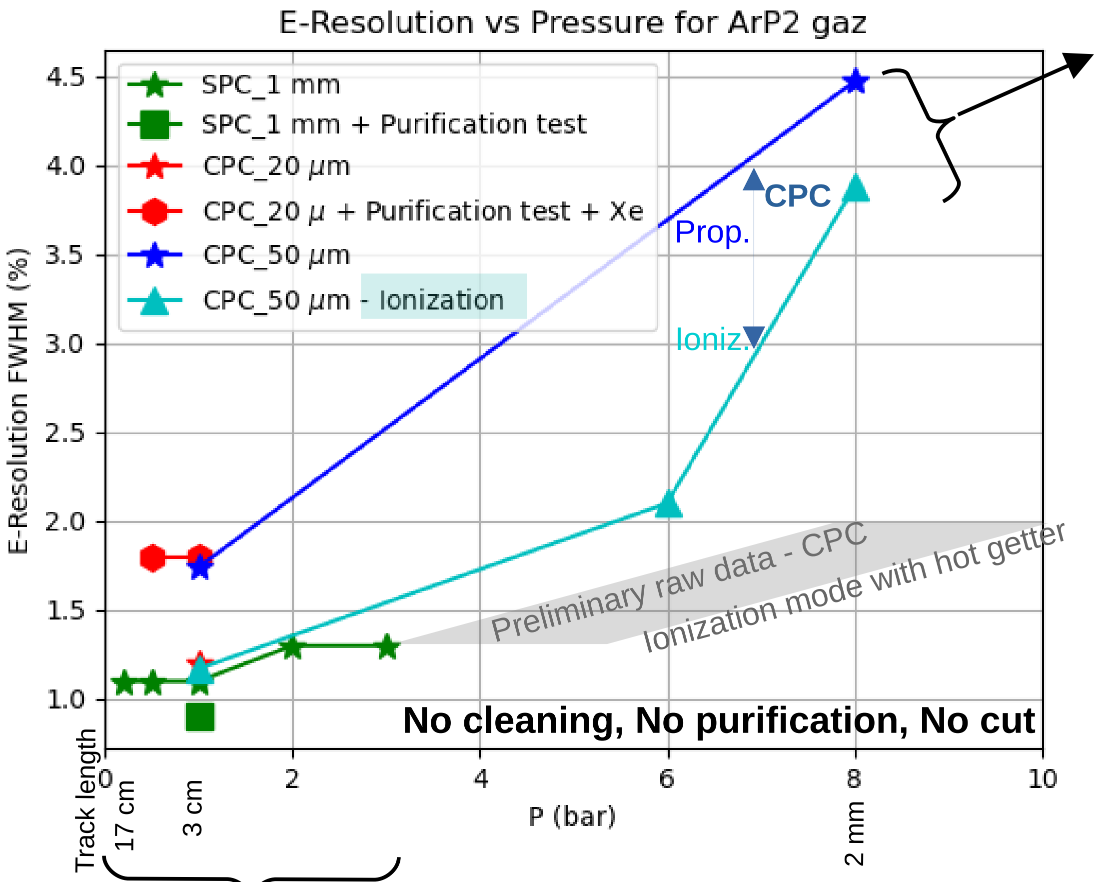
(JINST 16 (2021) P03012)

=> 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

Since the number of primaries is the same, the high pressure degradation suggests a gas purity effect.

At this stage of R&D (with pressure rise),
The use of a clean detector and a gas filtration system become essential to improve the energy resolution.

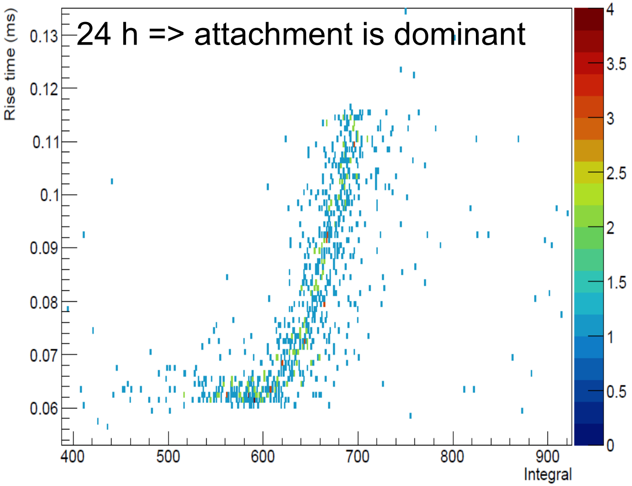
Another strong improvement in resolution (> 1 %) is also expected by FEE optimization (in board FEE).

Preliminary tests with Xe

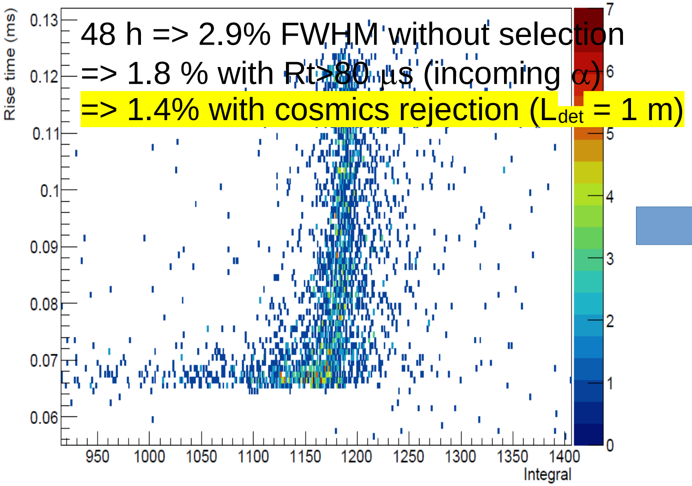
Our first system was based on a circulating pump and 2 cold getters to trap electronegative molecules in Xe (July 2022).

CPC-20 – Raw signal (no signal processing) - Xe - 1 bar - 1200 V - Prop. Mod - ^{210}Po source

After filling (during some hours)
=>
No observed source signal (except cosmic tracks)



24 h => attachment is dominant



48 h => 2.9% FWHM without selection
=> 1.8 % with Rt>80 µs (incoming α)
=> 1.4% with cosmics rejection (L_{det} = 1 m)

Upgrade of the system adding a hot getter

It is in test, but for now, resolution results are not stable (▭ in previous slide)

Additional system ? use of spark discharge purifier ?

Track localization

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

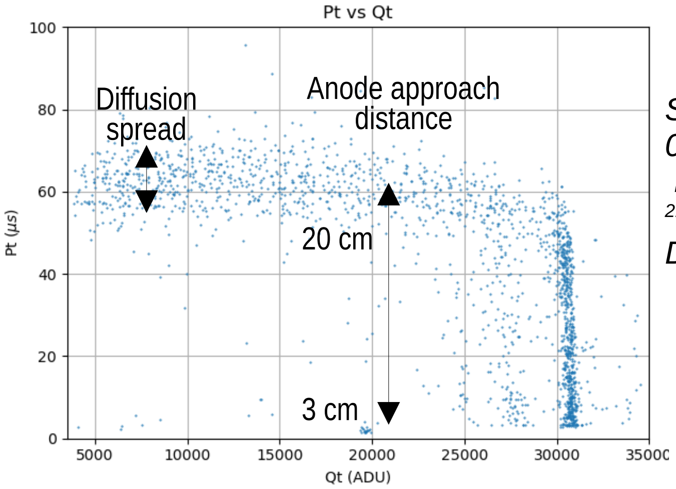
- The minimal distance of energy deposition relative to the anode.
- The diffusion of the primaries during their drift.

=> We assumed that Pt was related to distance in a simple relationship like:

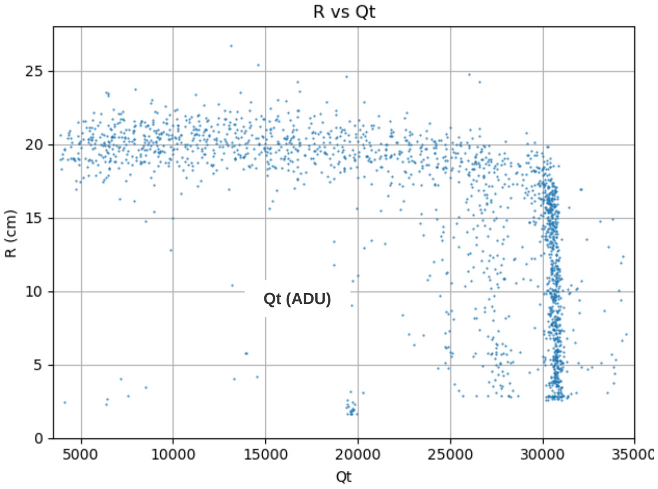
$Pt = Pt_{max} * (R/R_{max})^{\alpha}$

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



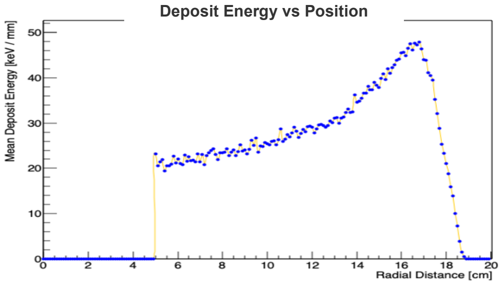
SPC – ArP2 - 0.2 bar - 800 V - Prop. Mode - ^{210}Po source - Deconv. signal

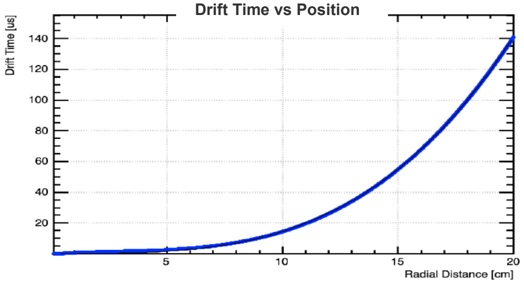


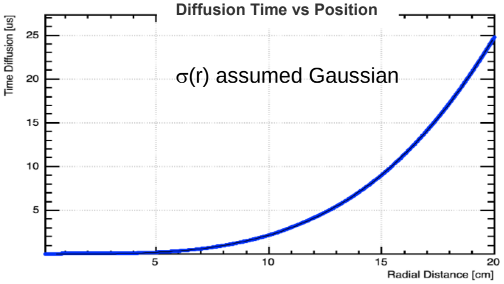
LTPC 2021, J. of Phys. Conf. Series 2502 (2023) 012006

Simulations

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



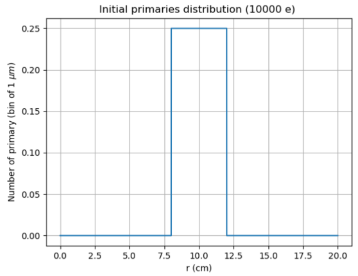




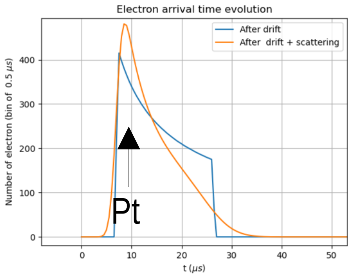
They depend
on the
operating
conditions.

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

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

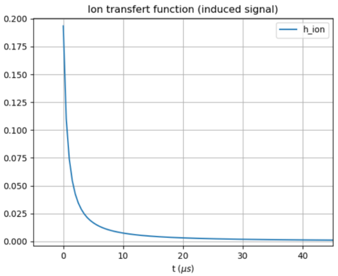


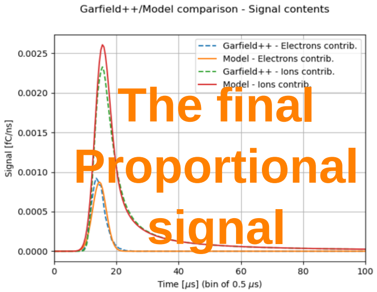
After
transport
+ diffusion
of the $\bar{e}$



The ionization signal

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



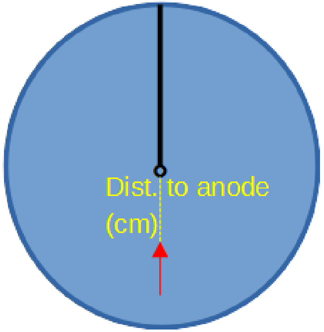


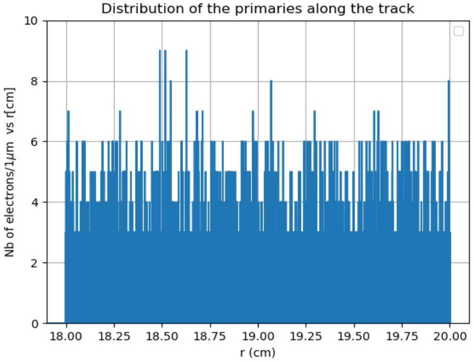
The final Proportional signal

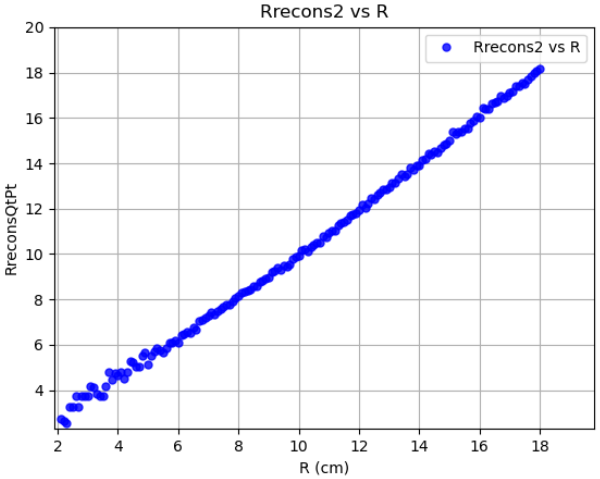
=> First result of the simulation: Pt is a relevant observable for the localization.

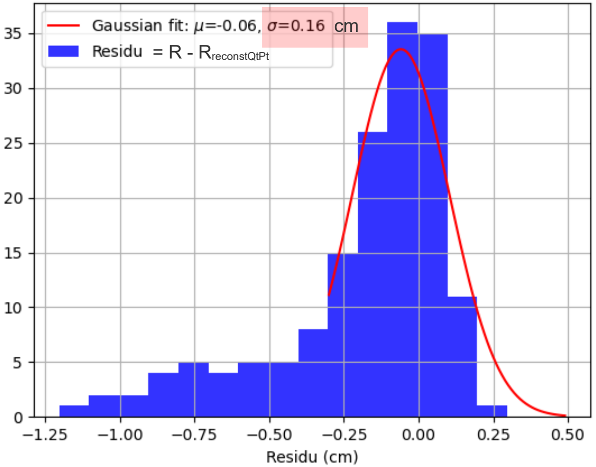
Radial localization

SPC simulation with
Track length of 2 cm - non-uniform ionization - 10000 e^-
- ArP2 gas - Prop. Mode (G=8)









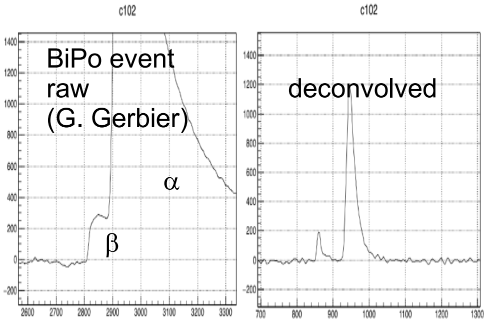
- Pt_{max}, Pt are deduced from plot (Qt, Pt)

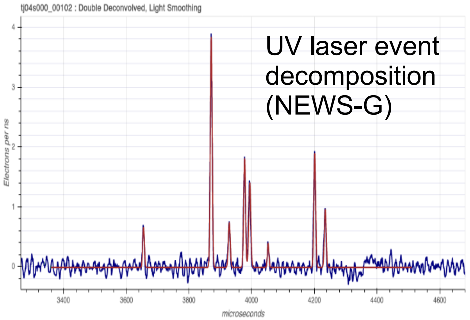
- $RreconsQtPt = r_{max} * (Pt / Pt_{max})^{1/a}$ is then compared to the initial distance R set for the simulated event through residues analysis

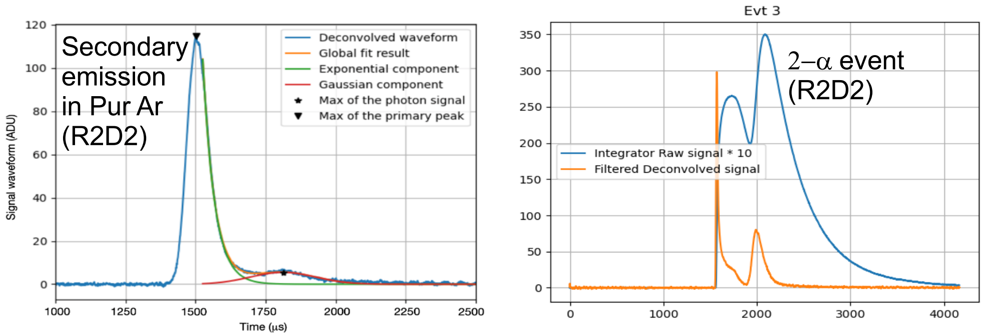
=> Second result of the simulation: A track localization can be obtained.

Multi-tracks recognition

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

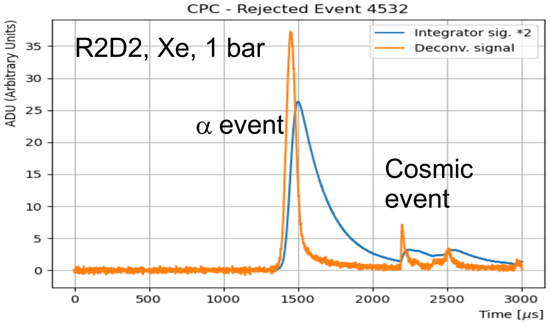






NIM A 1028 (2022) 166382

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



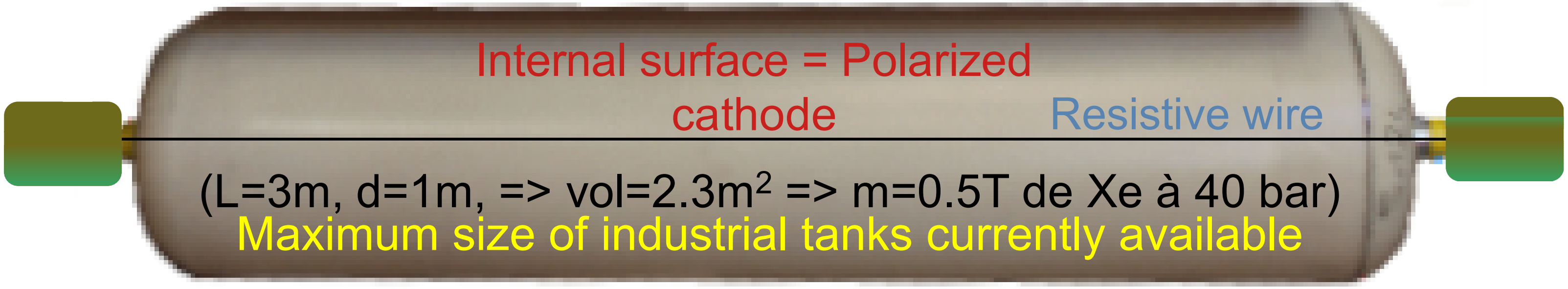
@ high pressure, except for cosmics, all interactions appear as point-like
=> recognition of the 2-tracks of 2β0ν decay can become very challenging !
=> can this set a limit in pressure ? (work is in progress...)

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



(L=3m, d=1m, => vol=2.3m^2 => m=0.5T de Xe à 40 bar)

Maximum size of industrial tanks currently available

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

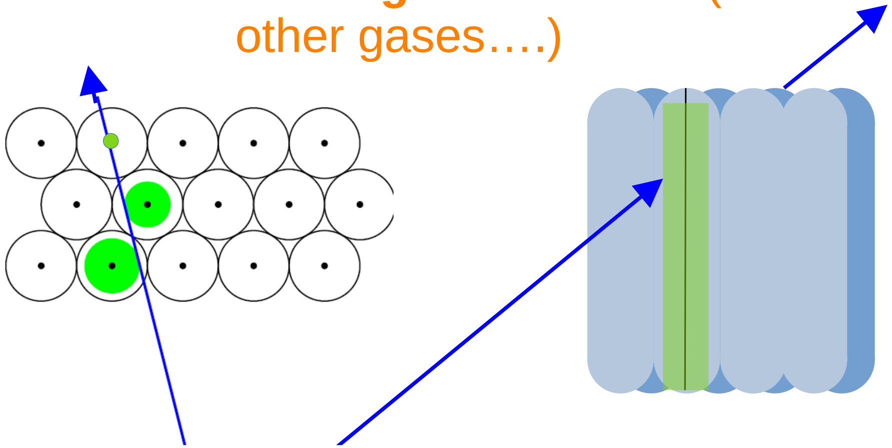
But many unknowns...: selection of radio-pure materials (NEMO expertise).

Backup design: a conventional open metallic tank.

Conclusion & Perspectives

- **Several results essential to the proof of concept have been aggregated, especially in terms of energy resolution and localization.**
- **For 2β0ν, CPC in ionization mode is currently our preferred option.**
- **A huge amount of work remains to be done to bring this concept to an operational scale (size, pressure, radio-purity, etc.).**

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



Source of radiation :
Reactors, Cosmics....
Particles detected :
α, β, γ, ν, μ, n....

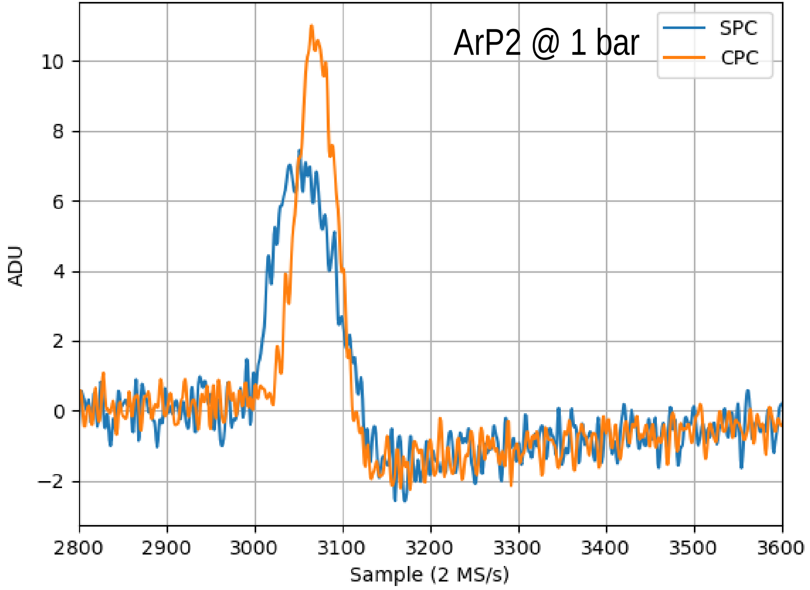
Tanks wall
(conceivable over hundreds of m)

and why not using liquids (ionization mode) ?

THANK YOU FOR YOUR ATTENTION

Backup: SCP / CPC Features

Ionization mode



SPC is slower due to the lower E-field

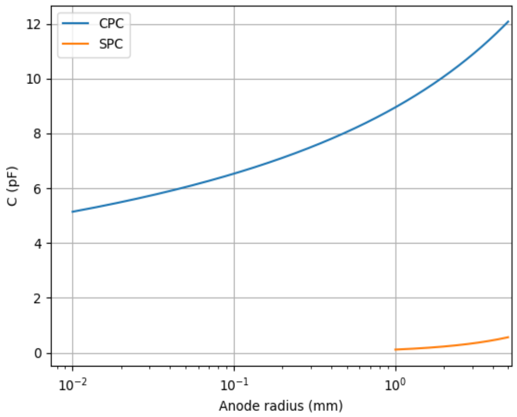
Pro (ionization)

- Low HV
- No field screening
- No ion tail (=>duration)
- No gain fluctuation

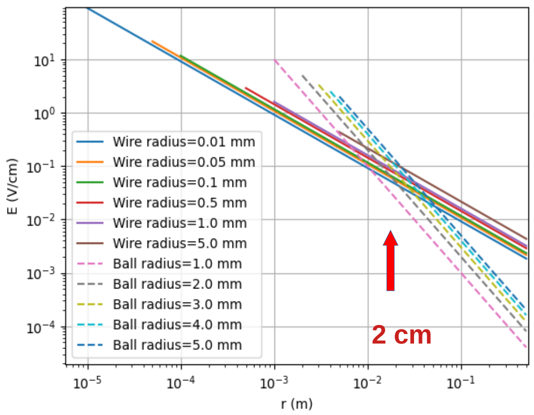
Cons (ionization)

- signal / noise

TPC capa vs Ranode for Rcathode = 0.5 m

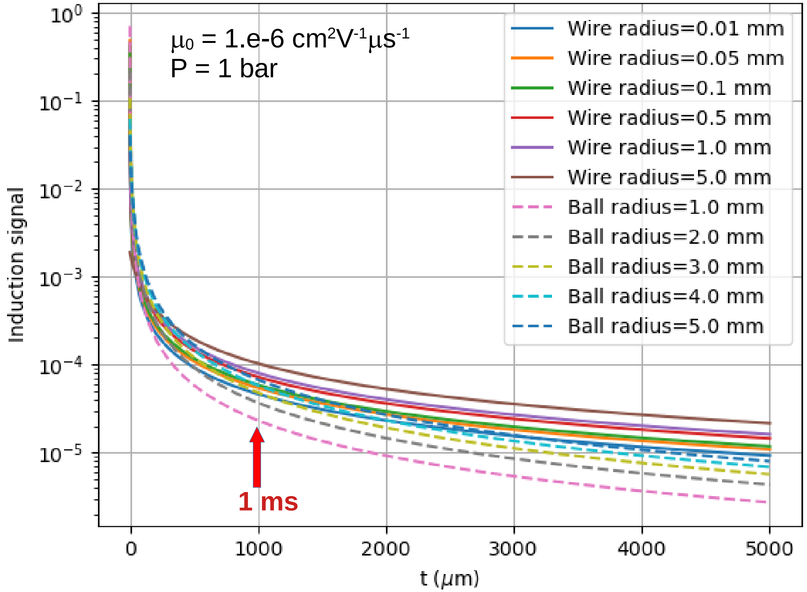


Electric field versus radius for Rcathode = 0.5 m & V0 = 1V



Proportional mode

Ion transfer function according to the anode radii

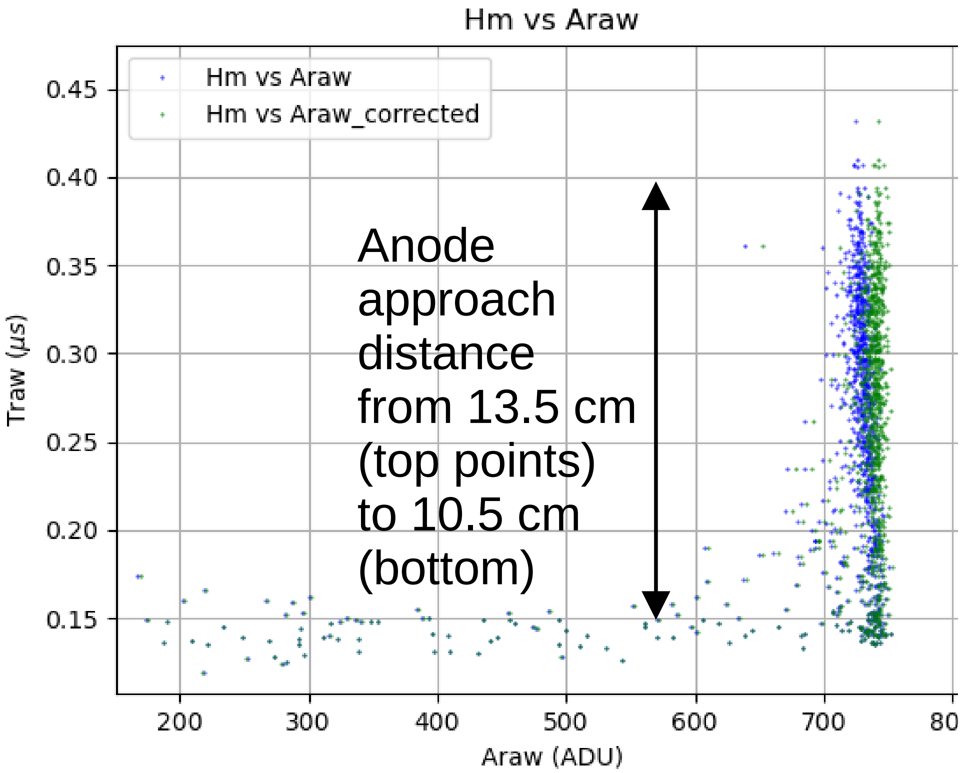


Ions mobility governs the signal duration.

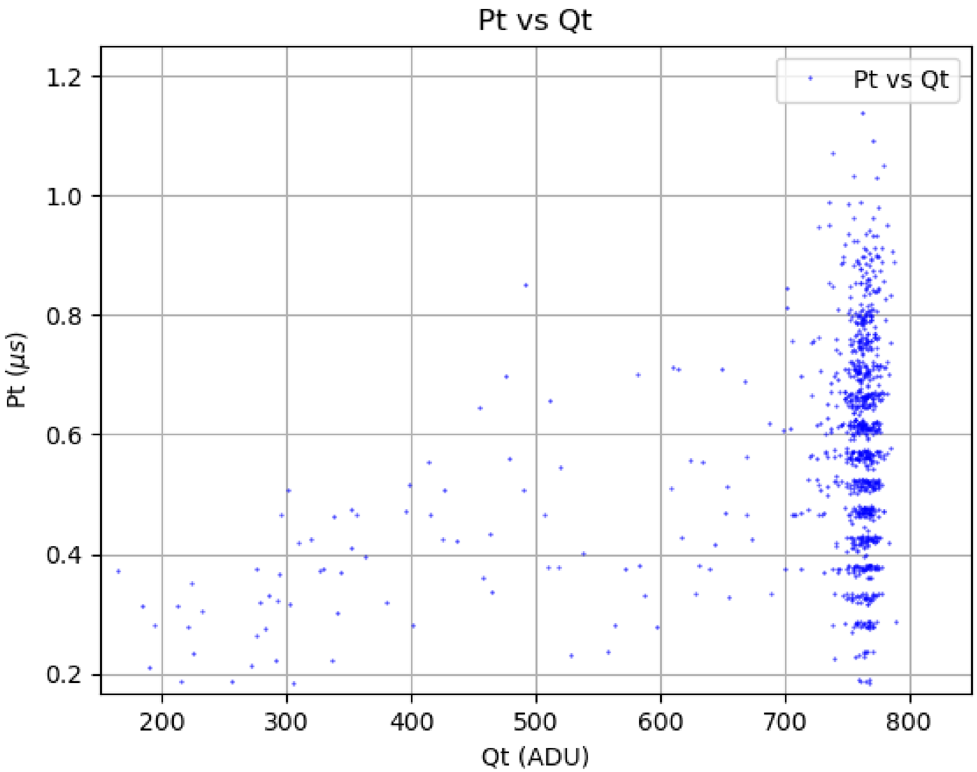
CPC has faster but longer signal

Backup: Track distance sensitivity

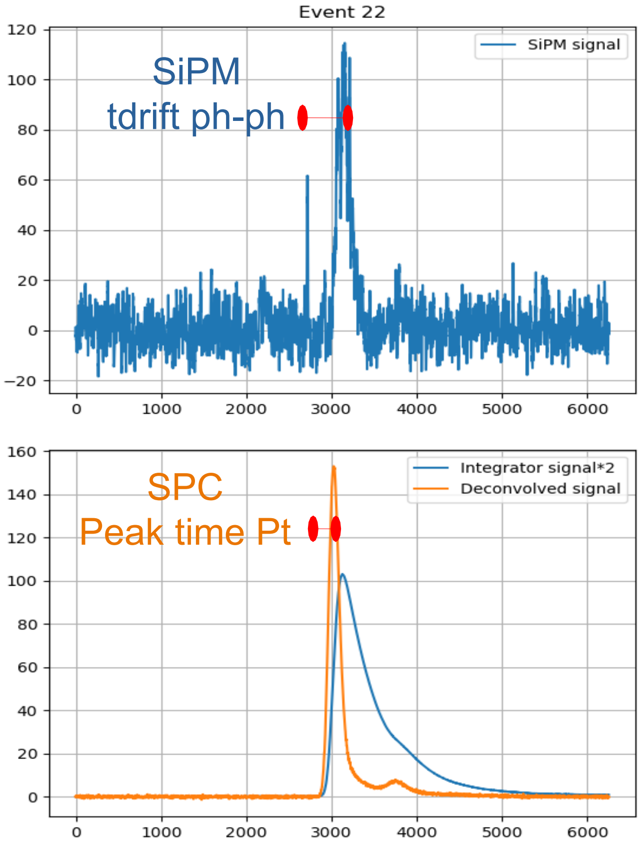
CPC-50 - Deconvolved signal - ArP2 - 1 bar – 210 Po - Track length ~3 cm



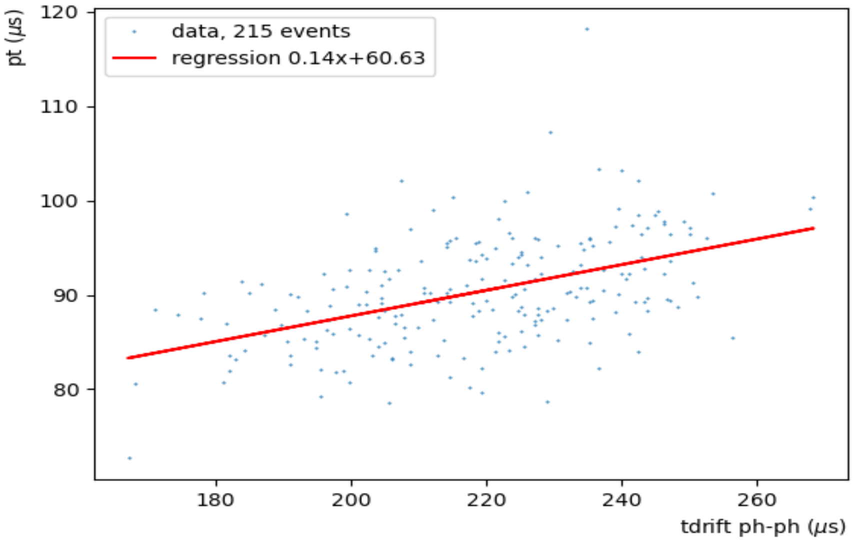
Anode approach distance from 13.5 cm (top points) to 10.5 cm (bottom)



Backup : Correlations between light & SPC signal



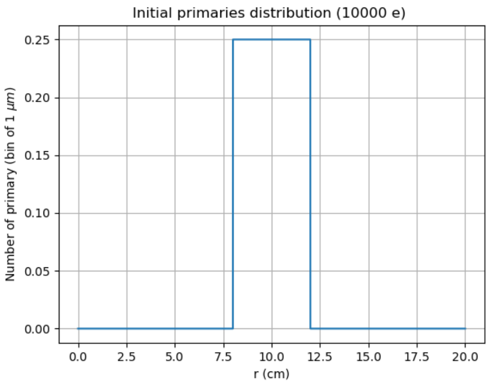
Pure Ar @ 1.1 bar – 210 Po source – Track length of 3 cm



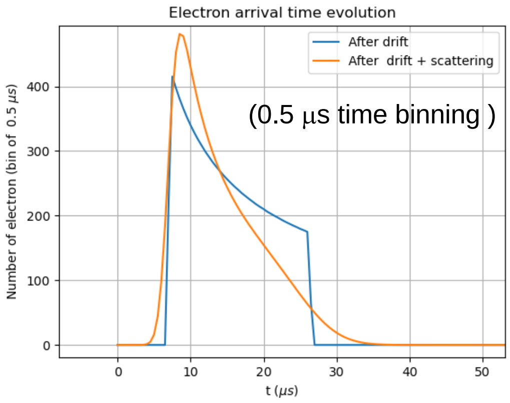
=> Correlation drift time (SiPM) - peak time (SPC) observed.

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

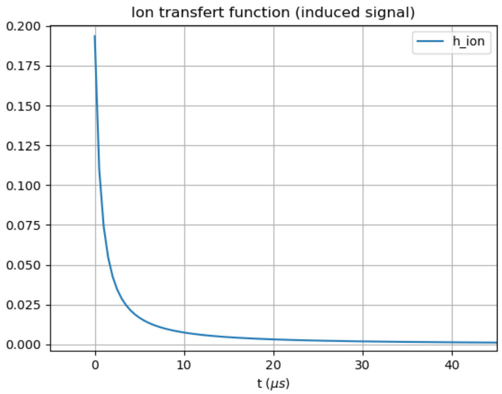
Backup: signal formation



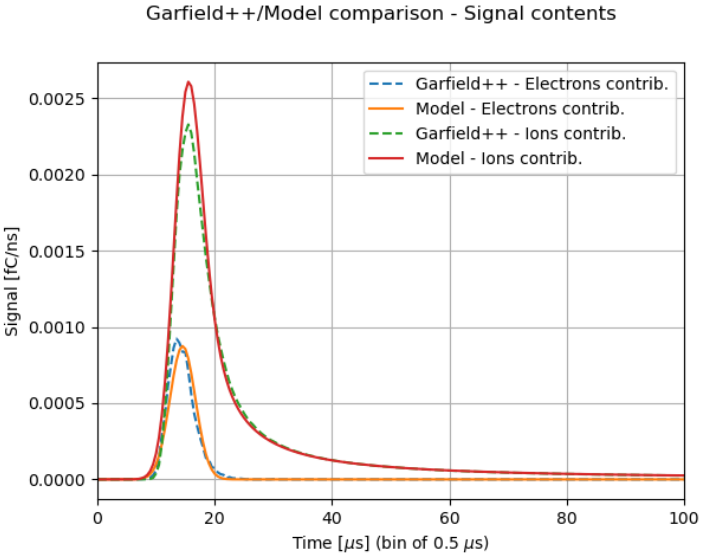
Transport and diffusion effects for primary electrons



(0.5 μs time binning)



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*