The BiPo-3 detector for the measurement of ultra high radiopurities in Tl-208 and Bi-214 of thin materials

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On behalf of the SuperNEMO Collaboration

The BiPo-3 detector for the measurement of ultra high radiopurities in Tl-208 and Bi-214 of thin materials

- Description of the BiPo-3 detector
- Background measurement
- Validation of the detection efficiency with a calibrated Al. Foil
- Results of the measurement of the first ββ SuperNEMO ^{82}Se foils

Objective of the BiPo-3 detector

Measure the purity in ^{208}Tl and ^{214}Bi of the SuperNEMO source foils

SuperNEMO required radiopurity of the enriched ^{82}Se foils (40 mg/cm^2)

^{208}Tl < 2 μBq/kg and **^{214}Bi < 10 μBq/kg**

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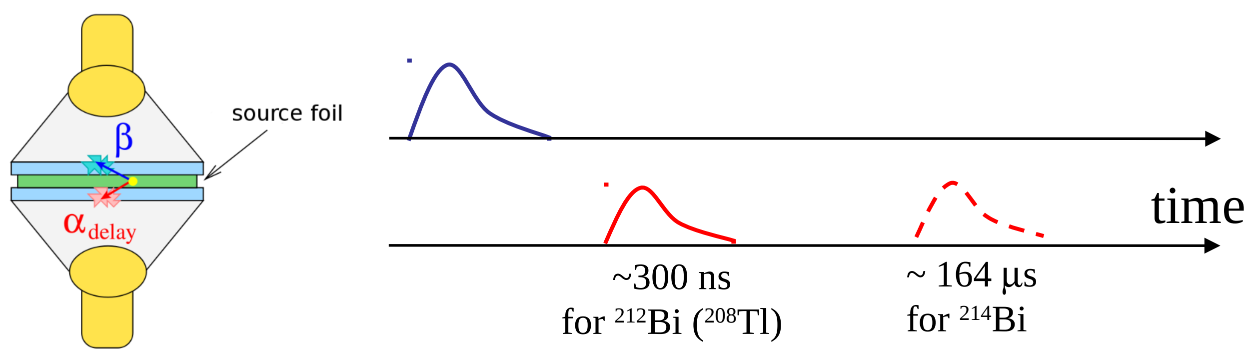
Detect the BiPo decay cascade: β + delayed α

Sandwich of two low radioactive thin polystyrene scintillators (2 x 300 x 300 mm)

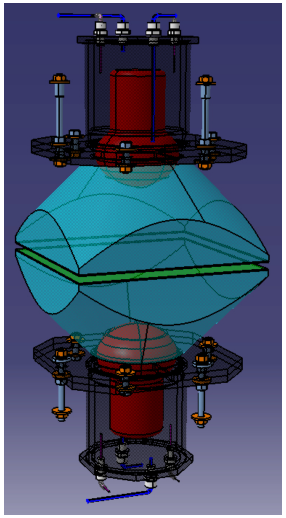
Time topology signature: 1 prompt hit (β) + 1 delay hit (α) and no coincidence

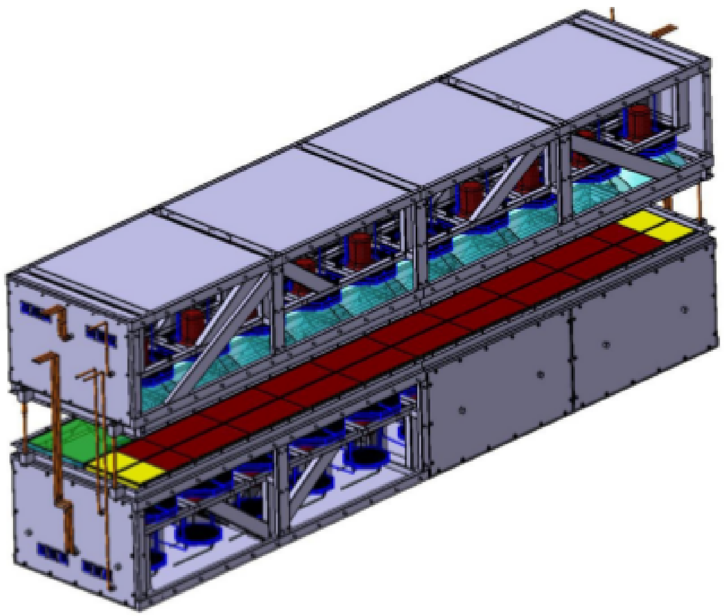


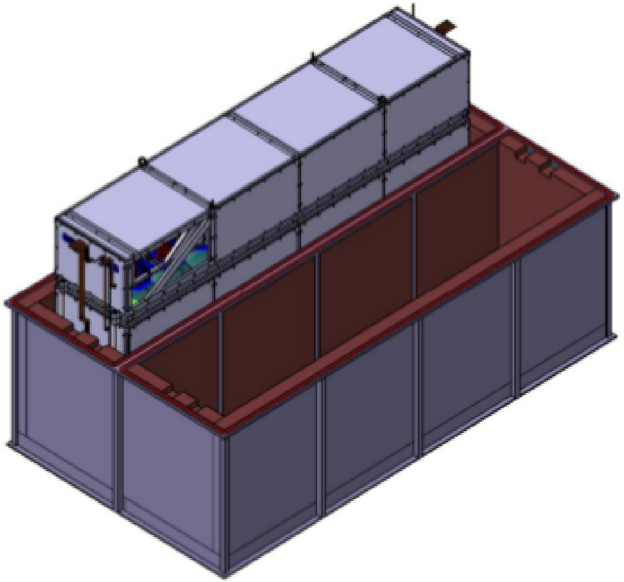
The BiPo-3 detector

Canfranc Underground Laboratory (Spain)

- BiPo-3 composed of two modules
- Each module :
  - 2×20 polystyrene scintillators
  - coupled to 5 low radioactive PMTs
  - scint. : $300\times300\times3$ mm^3
  - 200 nm ultrapure Al on scint. Surface
- Total active area of BiPo-3 (two modules)
  $S = 2\times1.8 = 3.6$ m^2







The BiPo-3 detector

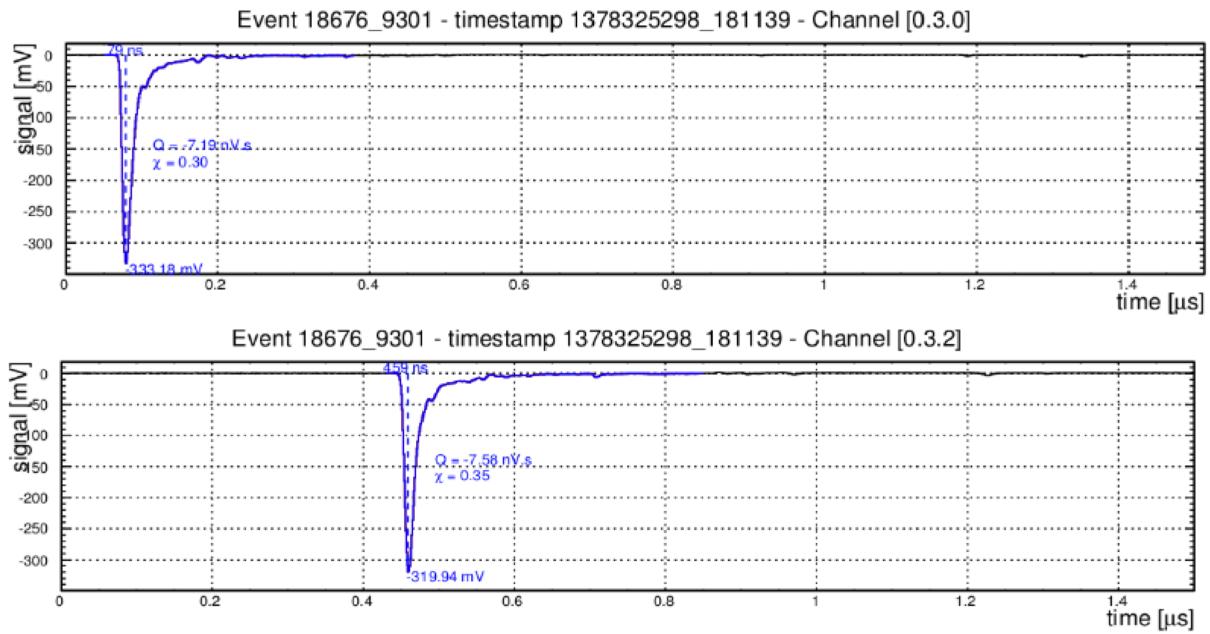
Canfranc Underground Laboratory (Spain)

Installation of the sample foils
In the clean room in Canfranc

A BiPo-3 module inside the low radioactive shield : 10 cm lead in a Radon-tight tank

BiPo-212 event

- Back-to-back event
- E(prompt)> 200 keV
- E(delay) > 100 keV
- Delay time
  20 ns < Δt < 1420 ns
- Coinc. signal with prompt e^{-}
  Ampl < 3 mV (~ 2 p.e.)
- Pulse Shape Criteria on Q/A



PMT signal recorded with MATACQ VME digitizer board (LAL & IRFU)

→ 4 channels, 2.5ms time window, 1 GS/s high sampling rate

→ 12-bit amplitude resolution

→ 1 Volt amplitude dynamic range

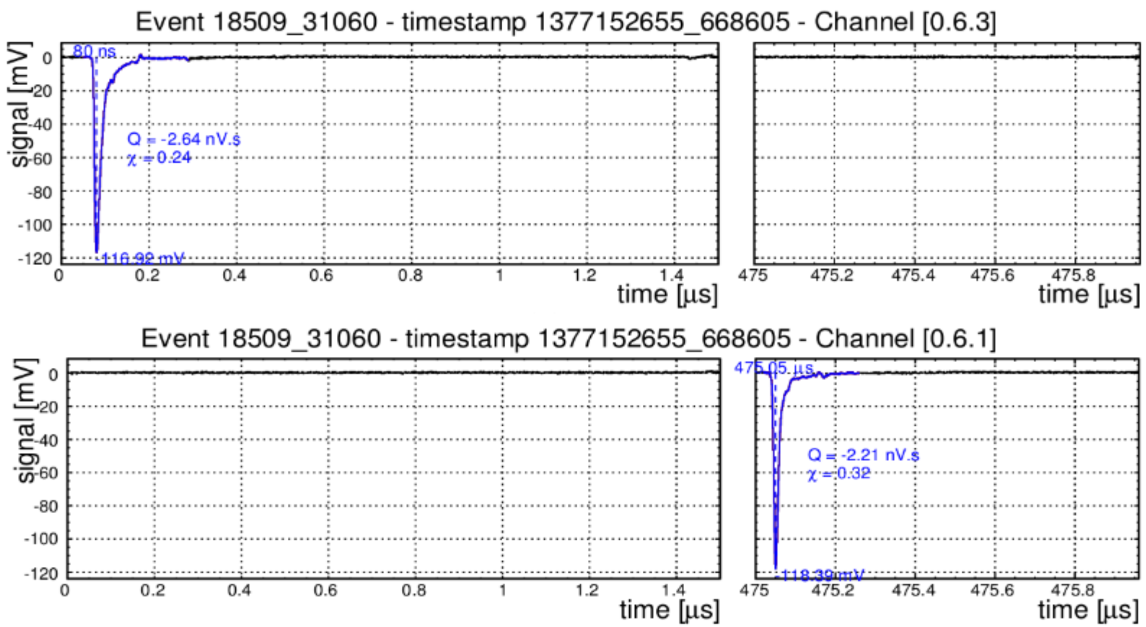
→ Electronic noise ~ 250 µV (r.m.s.)

BiPo-214 event

2nd delayed trigger up to 1 ms for BiPo-214 detection (10 μs dead time)

BiPo-214 event selection:

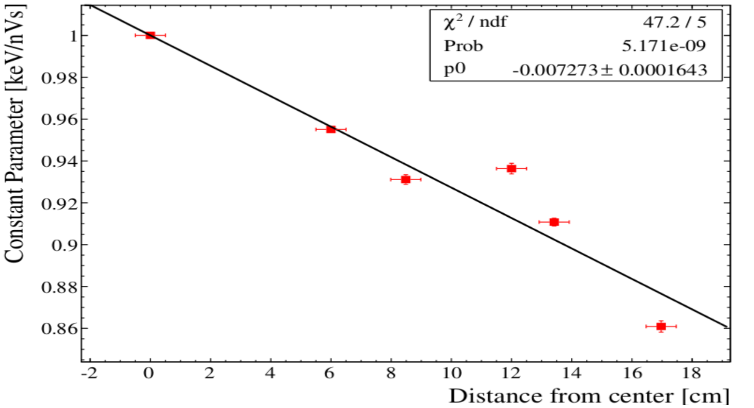
- Back-to-back event
- E(prompt)> 200 keV
- E(delay) > 300 keV
- Delay time
  10 μs < Δt < 1000 μs
- Coinc. signal with prompt e⁻
  Ampl < 3 mV (~ 2 p.e.)
- Pulse Shape Criteria on Q/A



Energy Calibration

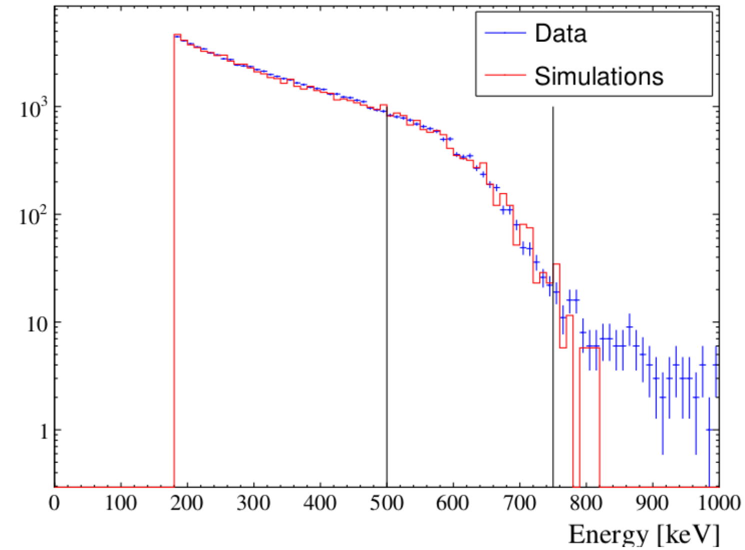
Surface Uniformity of the scintillators :

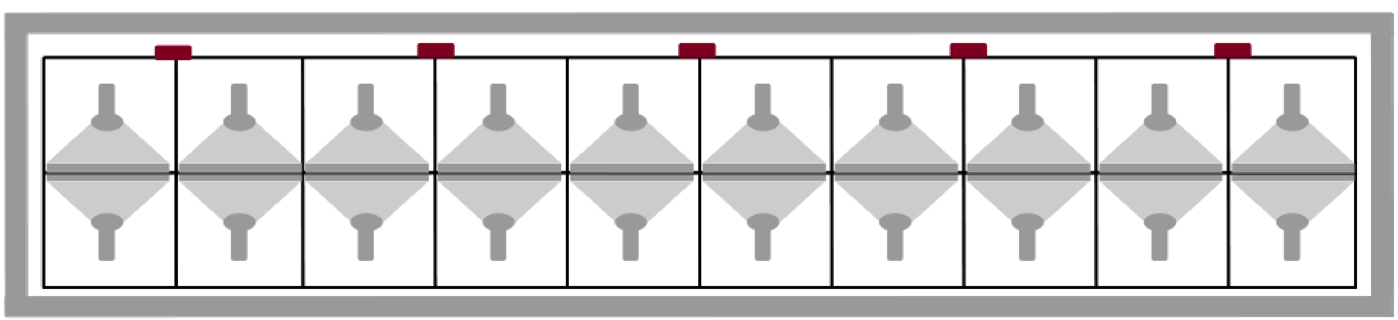
The surface response of each Scintillator+PMT has been measured with an ^{241}Am α source in Orsay
→ Decrease of about 15% in the light collection observed when the α source is moved from the center to the edges of the scint.



Absolute energy calibration:

Absolute energy calibration of the BiPo-3 detector is performed everytime a new measurement of a new sample is starting
→ 5 ^{54}Mn g sources deposited on the top of the BiPo-3 module
→ Compton edge used to calibrate in energy



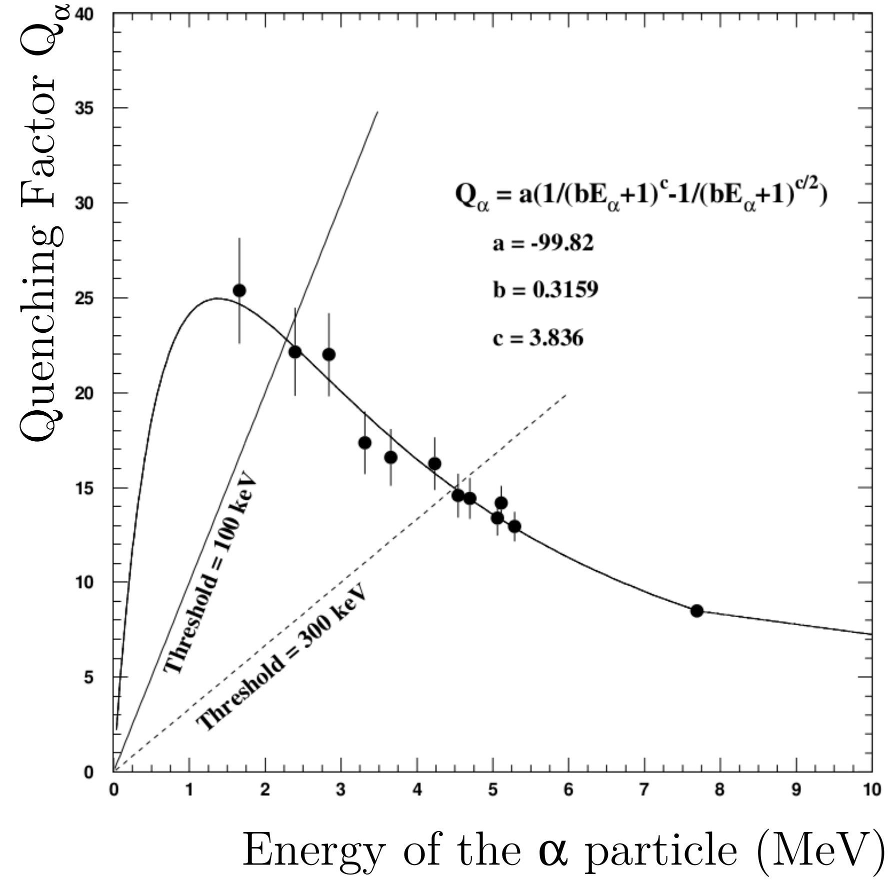


Quenching for α particle

Quenching factor Q_α =

$$\frac{\text{Light yield produced by e-}}{\text{Light yield produced by } \alpha \text{ of same energy}}$$

→ Quenching factor has been measured with a test bench in Orsay

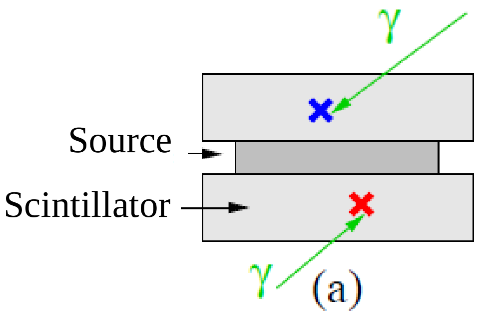


Systematic uncertainty on the BiPo efficiency dominated by the energy calibration and α quenching factor uncertainty

→ Syst. Error estimated by Monte-Carlo ~ 20 %

Background Measurement

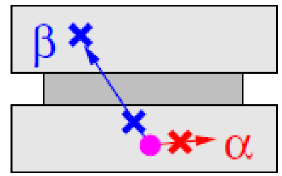
Origin of the background



Random coincidence
(e^- Compton from ext. γ)

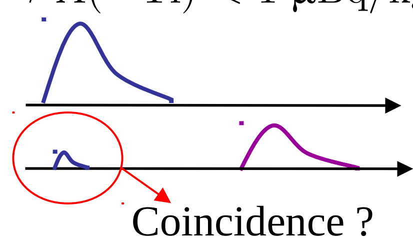
Low counting rate
Low bkg detector &
Low radioactive shield
Running in LSC Canfranc

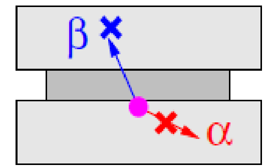
Flat distribution
of the delay time Δt



Bulk
contamination

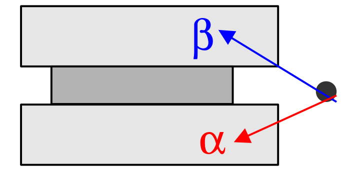
Low energy threshold to reject coincidence
$\rightarrow$ 10 keV ~ 100 μm
Radiopure scintillator
$\rightarrow$ A(^{208}Tl) < 1 μBq/kg





Surface
contamination

Ultra high surface radiopurity
No Radon and Thoron between scintillators
$\rightarrow$ A(Rn)<20μBq/m^3
(if gap=100μm)



External
Radon

Pure N2 flushed inside the detector

exp(-Δt)
E(α) totaly contained

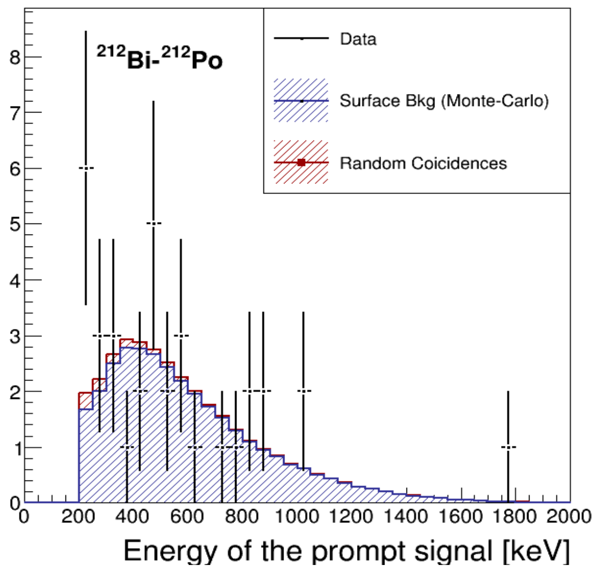
^{212}BiPo

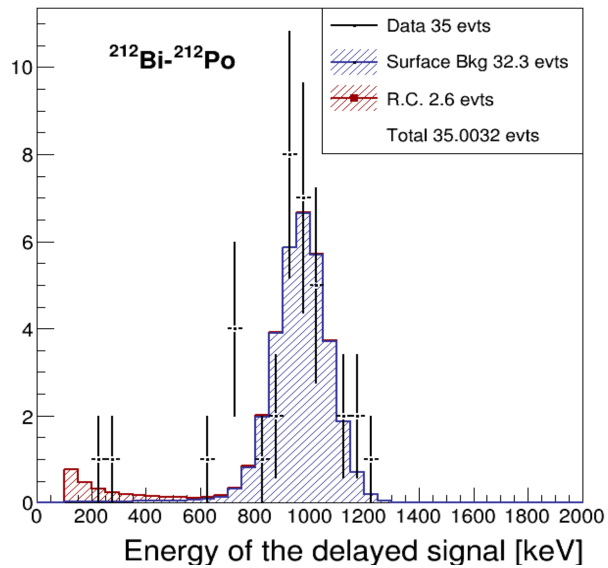
Measurement of the BiPo-3 background

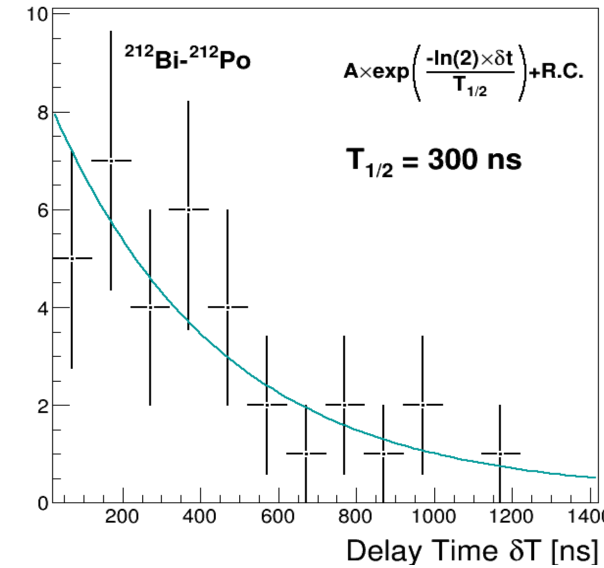
Three background measurements have been performed

Detector closed without any foil : $\varepsilon(^{212}\text{BiPo}) = 28.9\ \%$

⇒ A total of 35 ^{212}BiPo events observed after 229 days × 3.13 m² scint.







- Bkg due to ^{208}Tl contamination on the surface of the scintillators :

  $\boldsymbol{A(^{208}\text{Tl}) = 1.0 \pm 0.2\ \mu\text{Bq/m}^2}$ **scint.**

  ~ 1 ^{212}BiPo cts/month per BiPo-3 module, with the screening (~0.4) of a sample
- **Random coincidences are negligible**
- **Bkg ~ 0 if one requires E(delay α) < 700 keV**

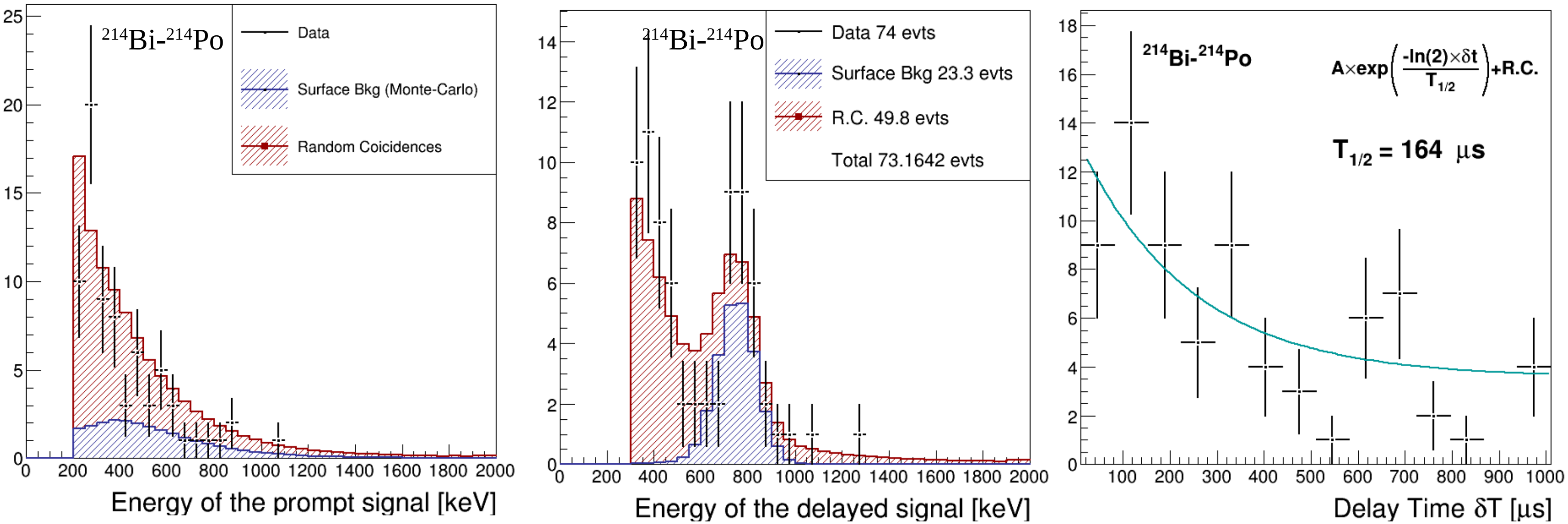
Measurement of the BiPo-3 background

The results of the three bkg measurements are compatible

	Duration (days)	Scintillator surface area (m^2)	^{212}BiPo candidates	$\mathcal{A}(^{208}Tl)$ $\mu Bq/m^2$ scint. [90% C.L.]
Module 1 Initial shield	79.5	2.70	9	0.9 ± 0.3
Module 1 Final shield	47.9	3.24	7	1.0 ± 0.4
Module 2 Final shield	101.6	3.42	19	1.2 ± 0.2
Total	229	3.13	35	1.0 ± 0.2

Measurement of the BiPo-3 background

A total of 74 ^{214}BiPo candidates observed after 184 days $\times$ 3.13 m^2 scint.



- Two components of background for BiPo :
  - Surface contamination on the scintillator (~25.9%)

    ***A*(^{214}Bi) = 1.8 ± 0.4 μBq/m² scint.**

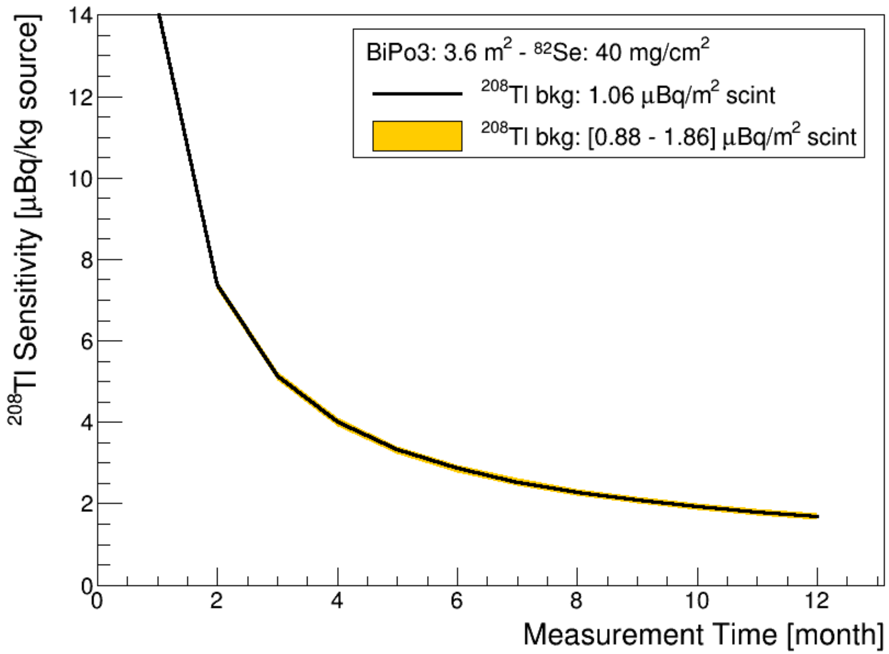
    ~ 1.7 ^{214}BiPo cts/month per BiPo-3 module with the screening (~0.4) of a sample
  - Random Coincidences (~70%)

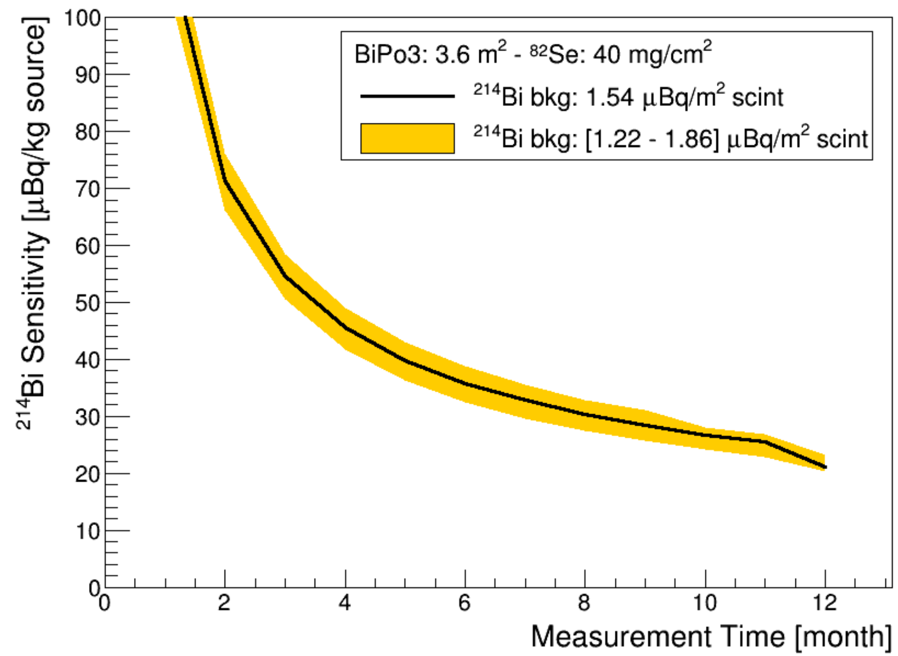
    ~ 9 R.C./month and per BiPo-3 module

- The results of the three bkg measurements are compatible
- E(delay α) > 300 keV in order to reject external Radon bkg

Expected sensitivity Of the BiPo-3 detector

Assuming SuperNEMO Se-82 foils (40 mg/cm^2)





With 6 months of measurement

A(^{208}Tl) < 3 µBq/kg (90 % C.L.)

A(^{214}Bi) < 22 µBq/kg (90 % C.L.)

Validation with a calibrated Aluminium foil

Calibrated Aluminium Foil

Two geometries measured in //
→ 1 single foil e= mm installed in a half of the detector
→ 2 superimposed foils installed in the 2nd half

Aluminium foil measured by HPGe :
A(BiPo-212) = 109 ± 2 (stat) ± 8 (syst) mBq/kg
A(BiPo-214) = 13.2 ± 2.6 (stat) ± 1.0 (syst) mBq/kg

Validation of the BiPo-3 efficiency with a calibrated aluminium foil

Thickness = 85 μm, Mass = 224 g

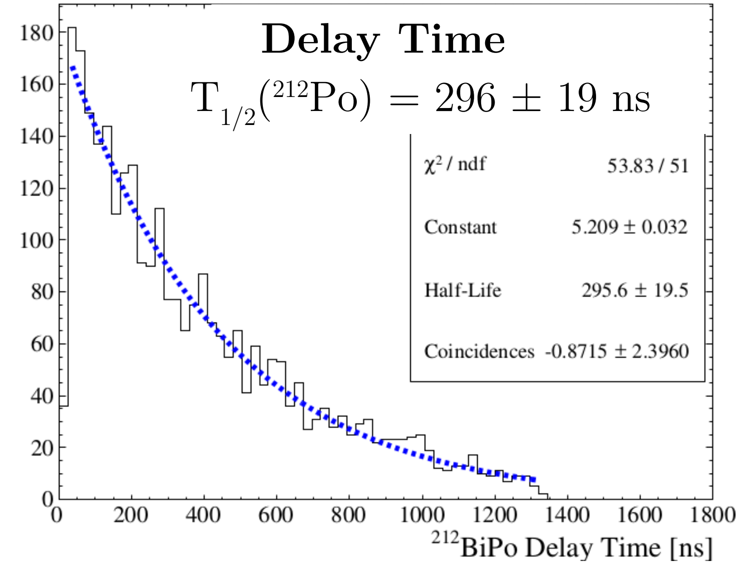
^{212}Bi – ^{212}Po

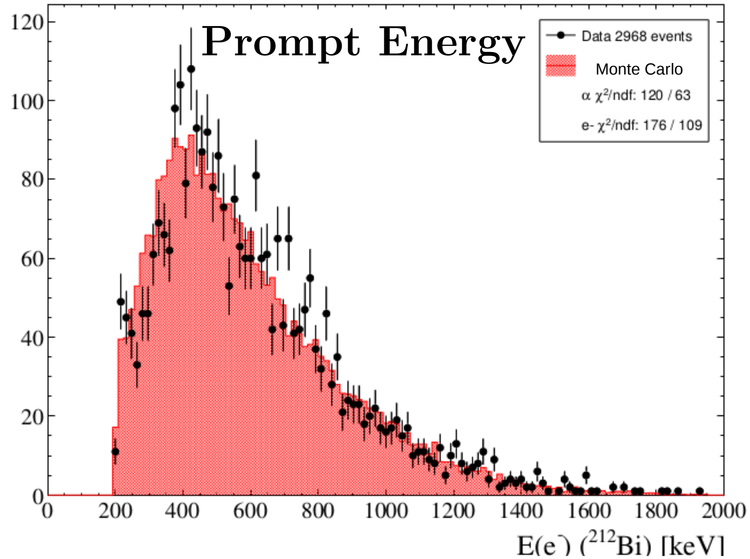
HPGe: A(^{208}Tl) = 61 ± 5 (syst) mBq/kg

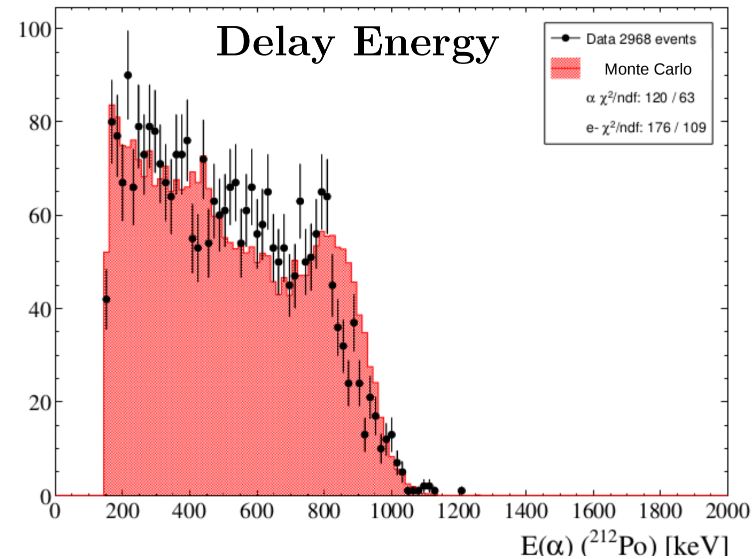
2968 ^{212}BiPo events in 24.1 days

Monte-Carlo: ε(^{212}BiPo) = 5.3 %

⇒ BiPo : A(^{208}Tl)= 67 ± 5 (syst) mBq/kg







Validation of the BiPo-3 efficiency with a calibrated aluminium foil

Thickness = 85 μm, Mass = 224 g

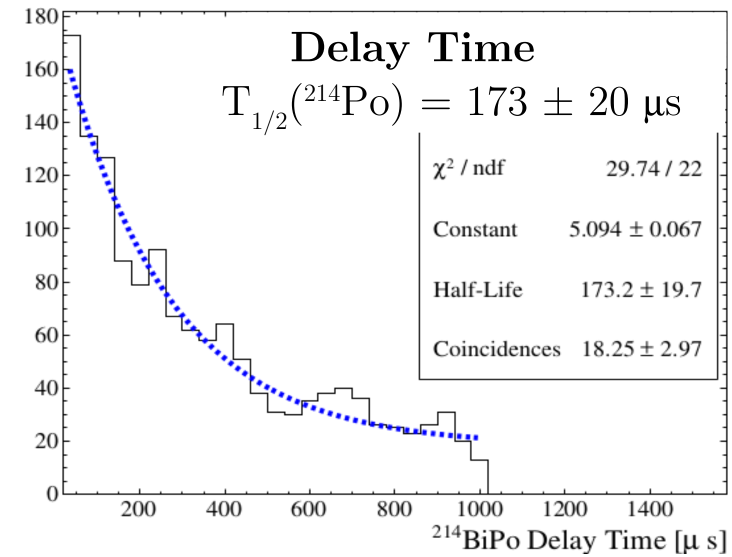
^{214}Bi – ^{214}Po

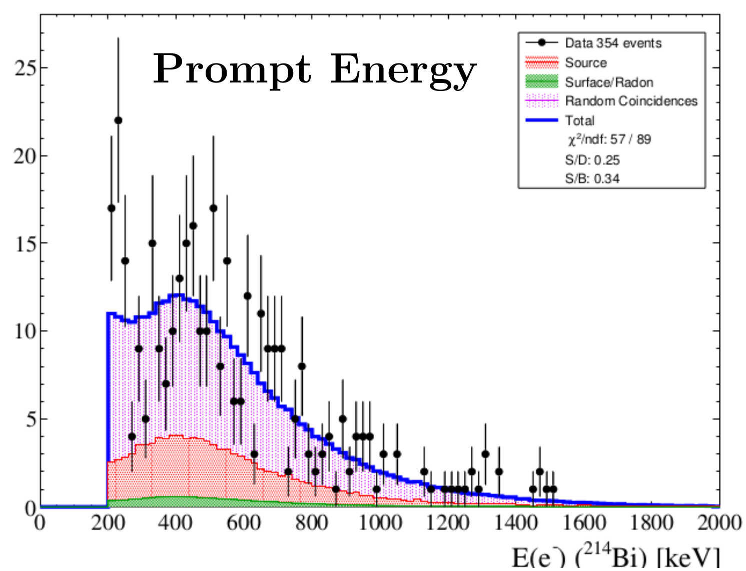
HPGe: A(^{214}Bi)=13.2±2.6(stat)±1.0(syst) mBq/kg

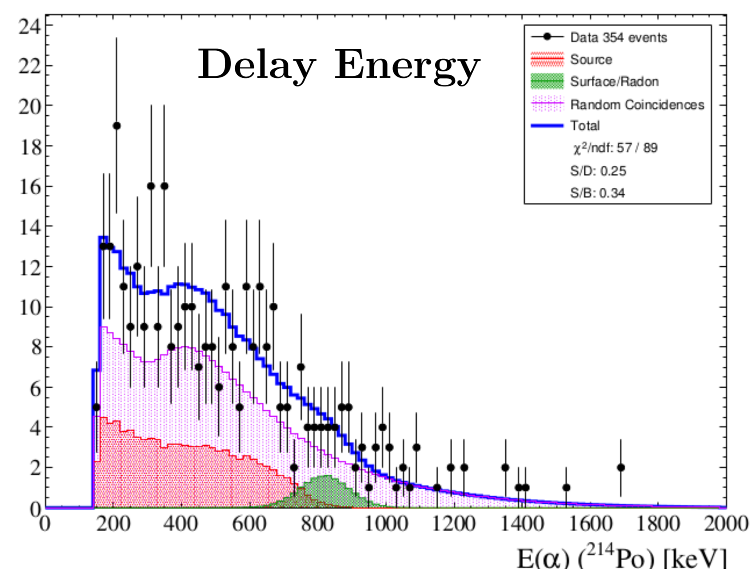
354 ^{214}BiPo events in 11.9 days

Monte-Carlo: ε(^{212}BiPo) = 3.3 %

⇒ BiPo : A(^{214}Bi)= 12.7 ± 2.1(syst) mBq/kg

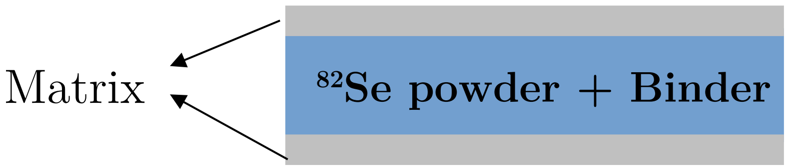






First results
Of Supernemo samples
Measurements

Samples for the SuperNEMO ^{82}Se foil



Binder → PVA
→ Nylon mesh

Matrix → Irradiated mylar e=12μm
→ Nylon mesh

All the different components have been measured separately with BiPo

Sample	T_{obs} (days)	Mass (g)	Surface Scint. (m^2)	Expected Background	Observed Events	$\epsilon(^{212}$BiPo) (%)	$\mathcal{A}(^{208}$Tl) (90% C.L.)
Mylar $200^* < E(\alpha) < 800$keV	76.5	108.1	1.62	0.5	1	5.5	< 49 μBq/kg
Irrad. Mylar $100 < E(\alpha) < 800$keV	44.4	200	3.06	0.5	10	5.9	$[62 - 200]$ μBq/kg
PVA $100 < E(\alpha) < 800$keV	137.2	210	1.8	0.9	0	3.0	< 12 μBq/kg
Nylon Mesh $E(\alpha) > 100$keV	110.6	70.6	1.44	18.0 ± 5.3	96	9.1	$[222 - 407]$ μBq/kg

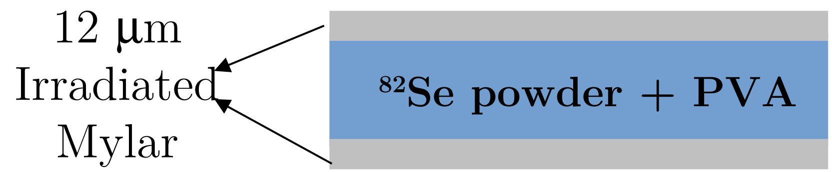
$E(\alpha) < 800$ keV allows to reject most of the surface background
**$E(\alpha) > 200$ keV for Mylar measurement due to a anormal bkg at lower energy during this period*

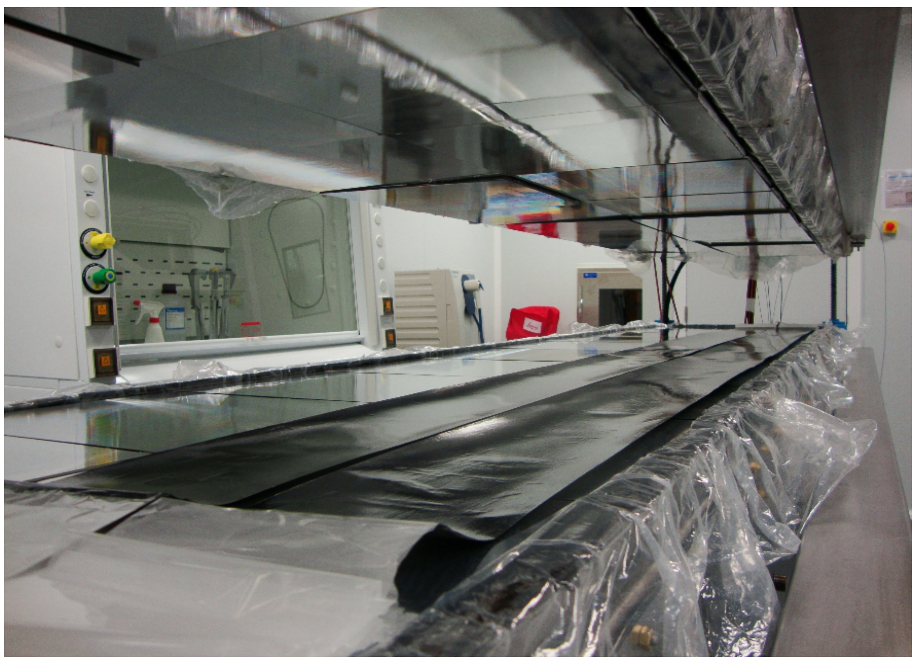
BiPo-214 results not yet validated...

Measurement of the first SuperNEMO ^{82}Se foil

Two ^{82}Se Strips installed mid-August 2014
in half of a BiPo-3 module
- Se+PVA: 13.5 x 270 cm2 each foil
- 39.1 mg/cm2 and 36.5 mg/cm2
- Total Mass Se+PVA ~ 300 g

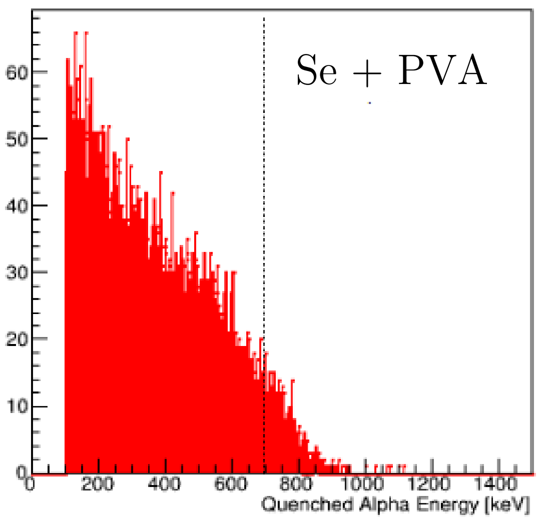
Second half of the BiPo-3 module
used to control the background

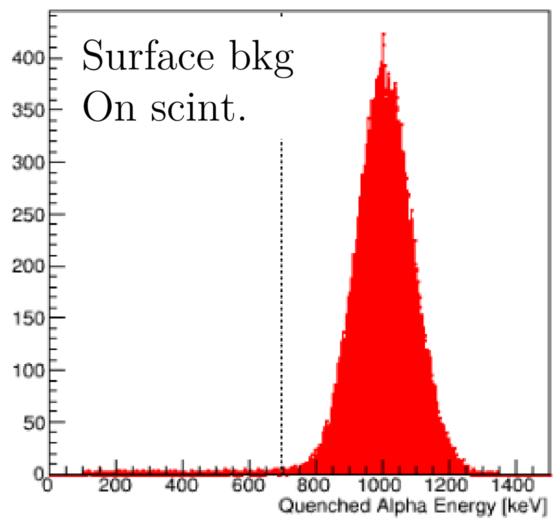


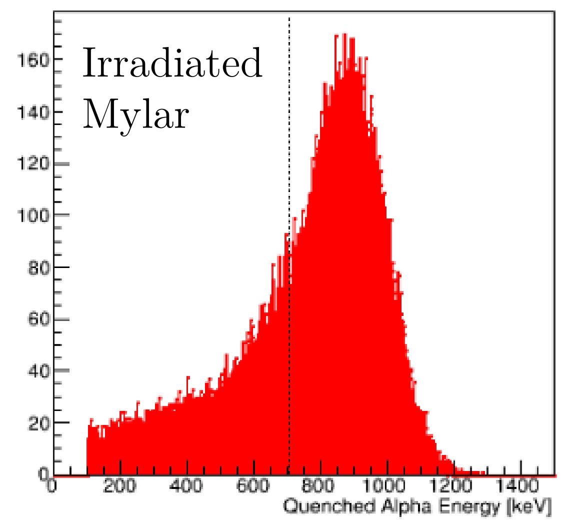


^{82}Se foil
Monte-Carlo Simulation BiPo-212

Energy spectrum of the delayed α calculated by Monte-Carlo
→ E(a) < 700 keV allows to reject surface bkg and most of the BiPo events from irradiated mylar







^{212}BiPo efficiency calculated by Monte-Carlo

Criteria	^{82}Se+PVA	Irrad. Mylar	Surface Bkg
$E(\alpha) > 100$ keV	2.9%	9.3%	12.1%
$100 < E(\alpha) < 700$ keV	2.8%	3.4%	0.15%

^{82}Se foil $\rightarrow$ Results BiPo-212

- Mass ^{82}Se+PVA = 226 g
- Mass irradiated mylar = 22 g
- Surface scintillator = 1.33 m^2
- Tobs = 130.6 days

Criteria	Expected Surf. Bkg	Expected Irrad. Mylar	Total Exp. Bkg	Observed Events
$E(\alpha) > 100$ keV	3.2 ± 0.9	$[2.5 - 8.0]$	$[4.8 - 12.1]$	3
$100 < E(\alpha) < 700$ keV	0.04 ± 0.01	$[0.9 - 3.0]$	$[0.9 - 3.0]$	0

E(α) < 700 keV allows to reject most of the surface bkg and part of the irradiated mylar contamination

Using Feldman-Cousins
(n_{obs}=0; n_{bkg}=0.9)

A(^{208}Tl) <13 μBq/kg (90 % C.L.)

Control of the Background
(2nd halh of the module without any sample)

Duration: 104 days
Surf. Scint. = 1.26 m^2

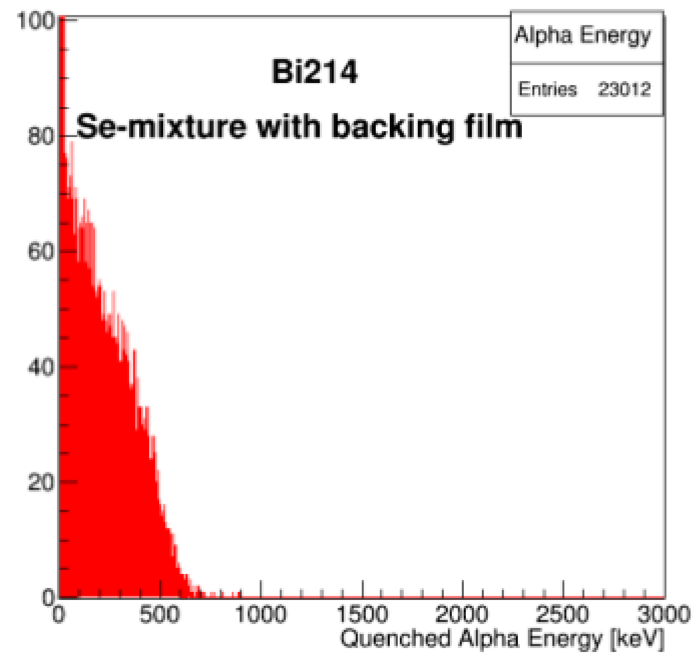
Criteria	Expected Surf. Bkg	Observed Events
$E(\alpha) > 100$ keV	5.8 ± 1.2	5*

* all the events with 800<E(α)<1200 keV as expected for surface events

^{82}Se foil
Monte-Carlo Simulation BiPo-214

Criteria	Se+PVA	Surface background	Irradiated mylar
300 keV$<E_{delay}<$ 600 keV	0.56 %	0.25 %	3.1%

- The irradiated mylar reduces the BiPo-214 detection efficiency
- Without mylar → (Se+PVA) detection efficiency = 2.1 %
- E(α) < 600 keV reject almost all surface bkg



^{82}Se foil $\rightarrow$ Results BiPo-214

- Mass ^{82}Se+PVA = 184 g
- Mass irradiated mylar = 17.8 g
- Surface scintillator = 1.08 m^2
- Tobs = 91.9 days

Detected events	Random Coincidences	Exp. backg surf events	Exp.backing-film events	Total exp. back events
9	5.9±1.7	0.07[0.05-0.09]	4.7[2.7-7.2]	10.7[7.0-14.9]

Using Feldman-Cousins
(n_{obs}=0; n_{bkg}=7) → **A(^{214}Bi) <1015 µBq/kg (90 % C.L.)**

Without mylar (**ε**=2.1%) and with the full surface area of the BiPo-3 detector (mass×4), the sensitivity after 91.9 days would be A(^{214}Bi) < 68 mBq/kg)

Control of the Background
(2nd halh of the module without any sample)

Duration: 62.2 days
Surf. Scint. = 1.26 m^2

	Expected Bkg	Observed Events
$E(\alpha) > 700$ keV $\Longrightarrow$ Surf. Bkg	3.2 ± 0.6	2
$E(\alpha) < 700$ keV $\Longrightarrow$ Rand. Coinc.	6.8 ± 1.0	7

Conclusions

- Full BiPo-3 detector running in Canfranc LSC since 2013
- Ultra low background in ^{208}Tl and ^{214}Bi has been measured at several periods
- BiPo efficiency validated with a calibrated Aluminium foil
- First SuperNEMO foils measured since Aug. 2014

  Preliminary results:

  Se+PVA $A(^{208}\mathrm{Tl}) < 13\ \mu\mathrm{Bq/kg}$ (90 % C.L.)

  $A(^{214}\mathrm{Bi}) < 1.0\ \mathrm{mBq/kg}$ (90 % C.L.)

- The BiPo-3 detector has become a « generic » detector

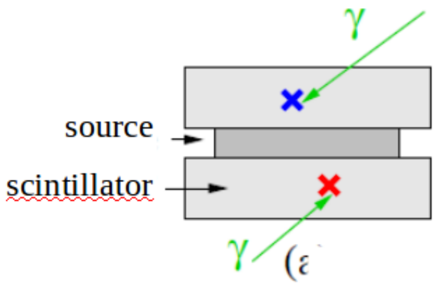
  $\rightarrow$ Other samples have been already measured
  - Polyethylene for CUORE
  - Reflecting film (Vikuiti) for bb experiments with scintillating bolometers
  - Wafers for Micromegas TPC developped by Zaragoza Univ.

- Article in preparation

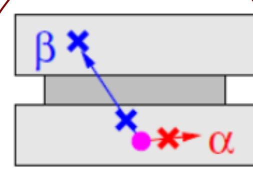
BACKUP

Improvement of the background rejection induced by the bulk contamination in scintillators

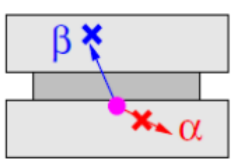
The detection of a small signal in coincidence with the prompt β signal allows to reject a BiPo-decay induced by a bulk contamination in scintillators and close to the surface



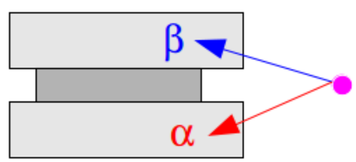
Random coincidence
(e^- Compton from ext. γ)



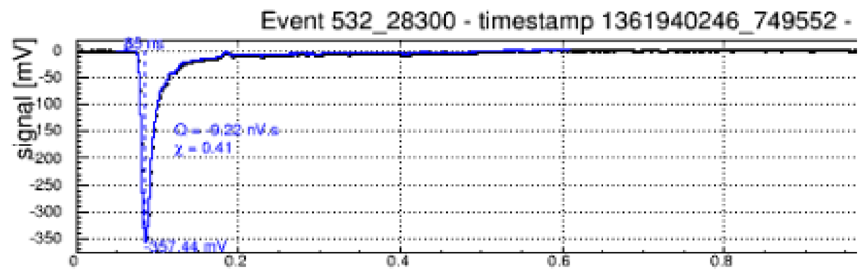
Bulk contamination
Scintillator

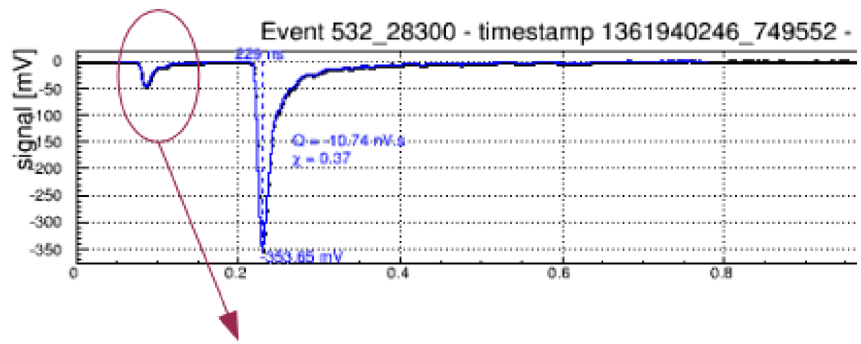


Surface contamination
^{238}U and ^{232}Th



External Radon





Coincidence with prompt signal

Lower is the threshold for coincidence, higher is the rejection

Background rejection by detecting coincidence signal

Radon deposited on the surface of the scintillators when the detector is opened in clean room (for sample insertion)

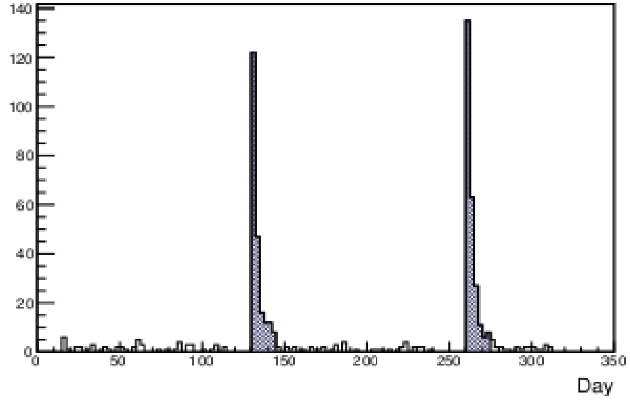
$$^{222}\mathrm{Rn} \xrightarrow{\alpha} {}^{218}\mathrm{Po} \xrightarrow{\alpha} {}^{214}\mathrm{Po} \xrightarrow{\beta} {}^{214}\mathrm{Bi}$$

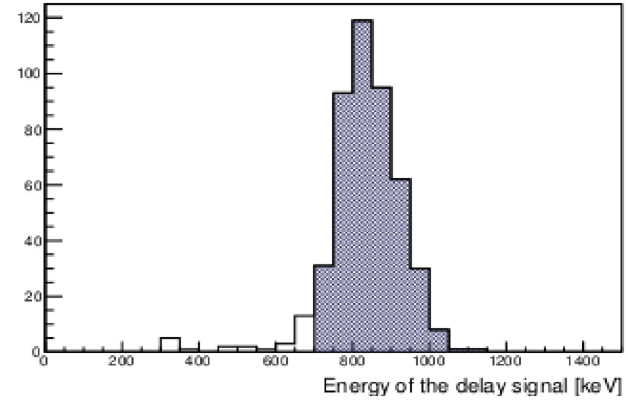
Energy recoil induced by the two successive α decays
$\rightarrow$ nucleus penetrates inside the plastic scintillator
$\rightarrow$ ^{214}Bi is not any more on the surface but is slightly inside the scintillator

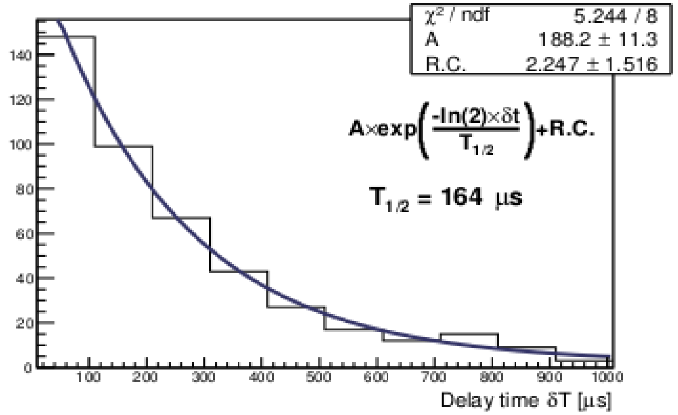
Bkg measurement with Radon

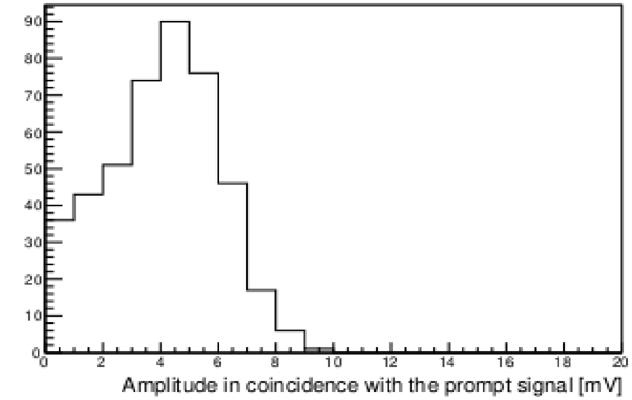
15 first days → **Radon deposited on the scintillators**

$E(\alpha) > 700$ keV
→ surface-like events









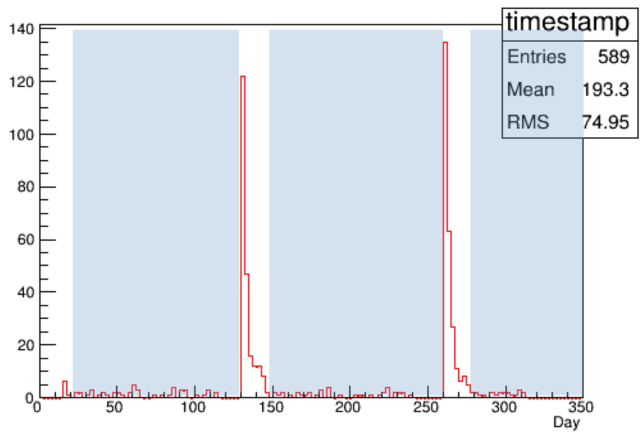
Delay time Δt in agreement with $T(^{214}Po)$=164 μs

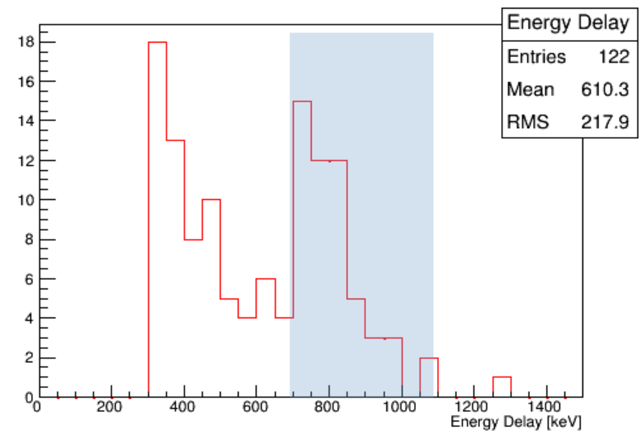
signal in coincidence with prompt β signal
→ **⟨Amplitude⟩ = 4 mV ~ 12 keV**

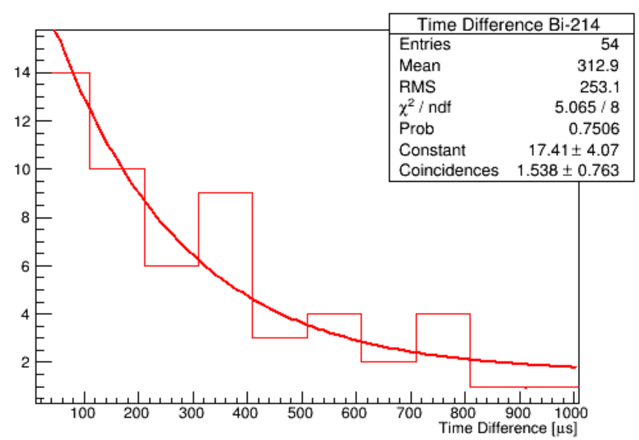
Bkg measurement without Radon

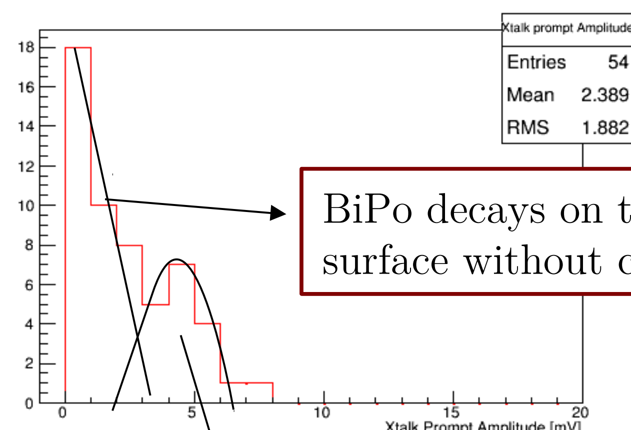
15 first days removed
→ **No more Radon**

E(α) > 700 keV
→ surface-like events









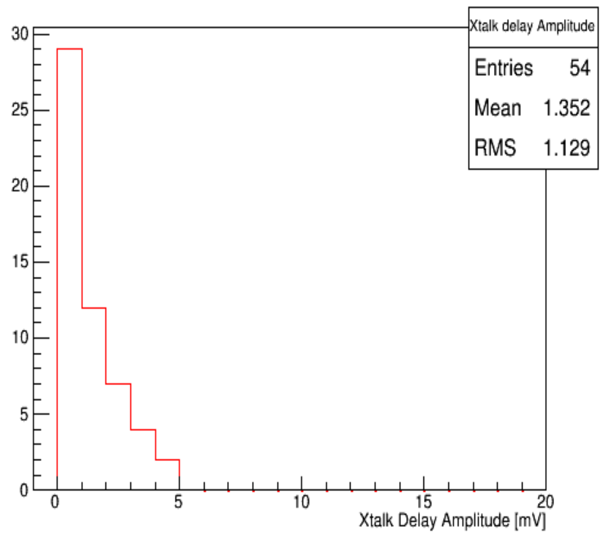
BiPo decays on the scintillator surface without coincidence signal

Residual BiPo decays from bulk contamination in scintillators with coincidence signal
→ rejected by requiring A(coinc.) < 3 mV

Which threshold to keep signal ?

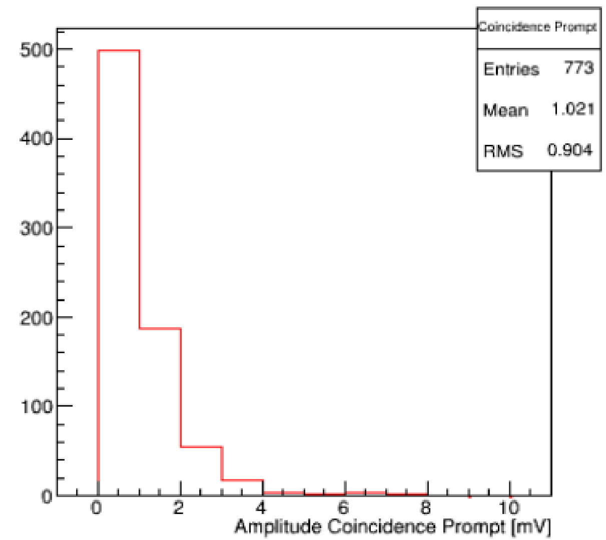
We need a coincidence threshold as low as possible
But possible optical cross-talk can mimick it
$\rightarrow$ Two analysis to measure the cross-talk

^{214}BiPo events from Bkg measurement
Amplitude coincidence with delay a signal



With signal ~ 1000 keV
Optical cross-talk < 3mV in ~ 90 %

^{212}BiPo events from Alu foil measurement
Amplitude coincidence with prompt b signal

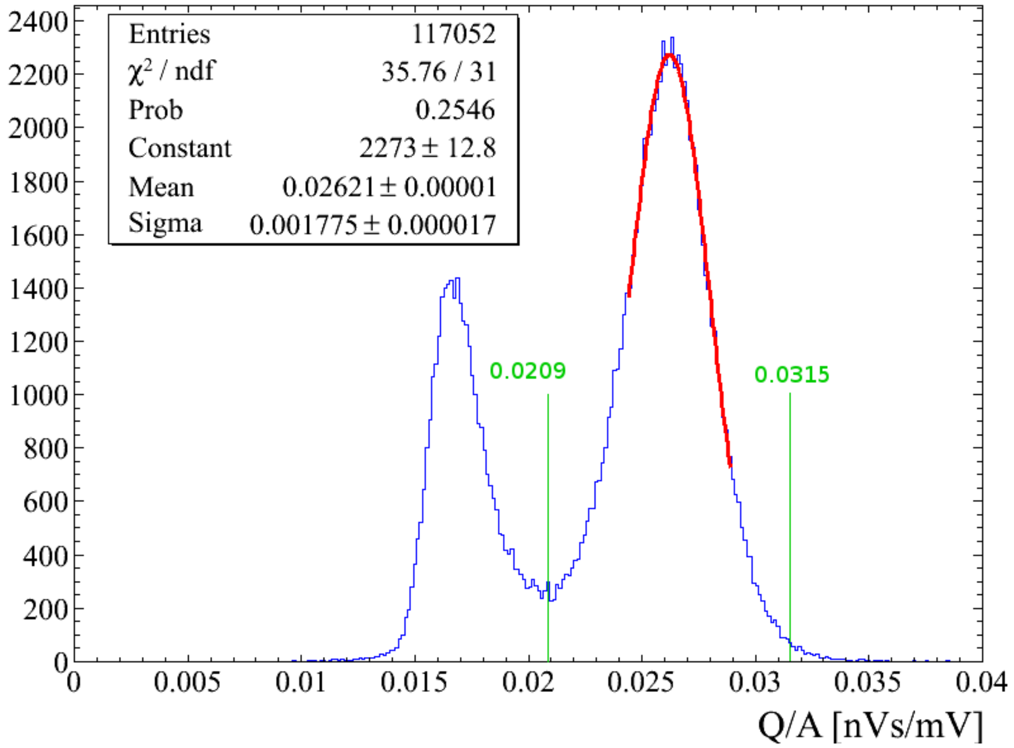


For 96 % of the BiPo decay from the foil
The coincidence with prompt < 3mv

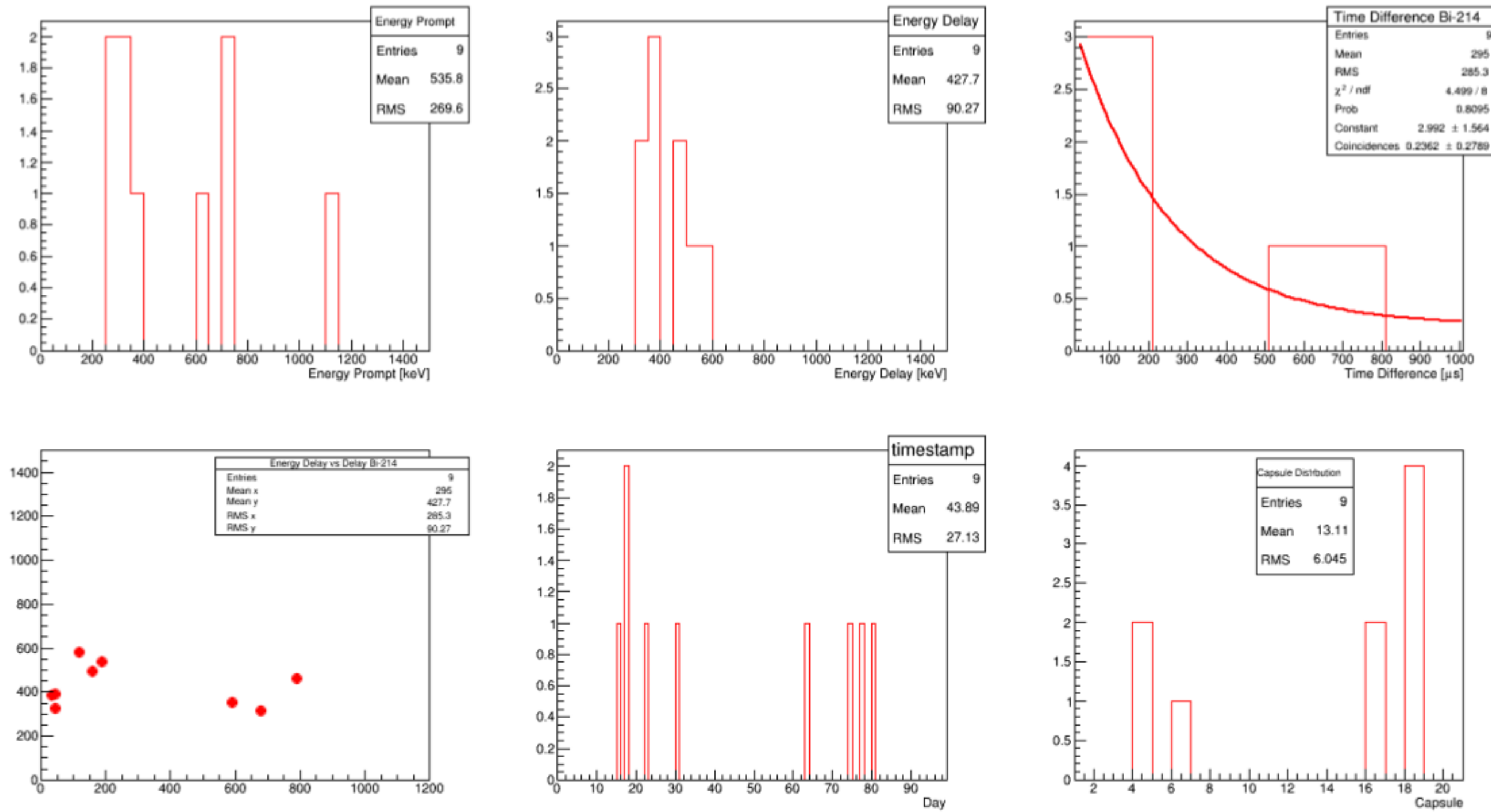
Criteria : Amplitude coincidence prompt < 3 mV

Pulse Shape Analysis

Noise rejection



Result Bi-214 (BiPo-214)



Criteria to select BiPo events

BiPo-212
Back-to-back events
E(prompt) $>$ 200 keV
E(delay) $>$ 100 keV
Delay Time : $20 < Dt < 1420$ ns
Pulse Shape Analysis Q/A
Amplitude coincidence $<$ 3 mV
3 first days of data are rejected

BiPo-214
Back-to-back events
E(prompt) $>$ 200 keV
E(delay) $>$ 300 keV
to reduce R.C. and ext. Radon
Delay Time : $10 < Dt < 1000$ μs
Pulse Shape Analysis Q/A
Amplitude coincidence $<$ 3 mV
3 first days of data are rejected