WISArD Collaboration Meeting, March 22, 2021

WISArD 2019 campaign
&
beta backscattering tests at CENBG

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Outline

Two main topics will be covered:

A **WISArD campaign (CERN, July 2019)**

→ runs taken with different radioactive sources (multiple α-source, β-sources)

→ data analysis & G4 simulations

- VALIDATION AND CONSTRAINT OF GEANT4 SIMULATIONS
- ACCURACY IN REPRODUCING OVERALL SPECTRA

B **β-backscattering tests (CENBG, 2020-2021)**

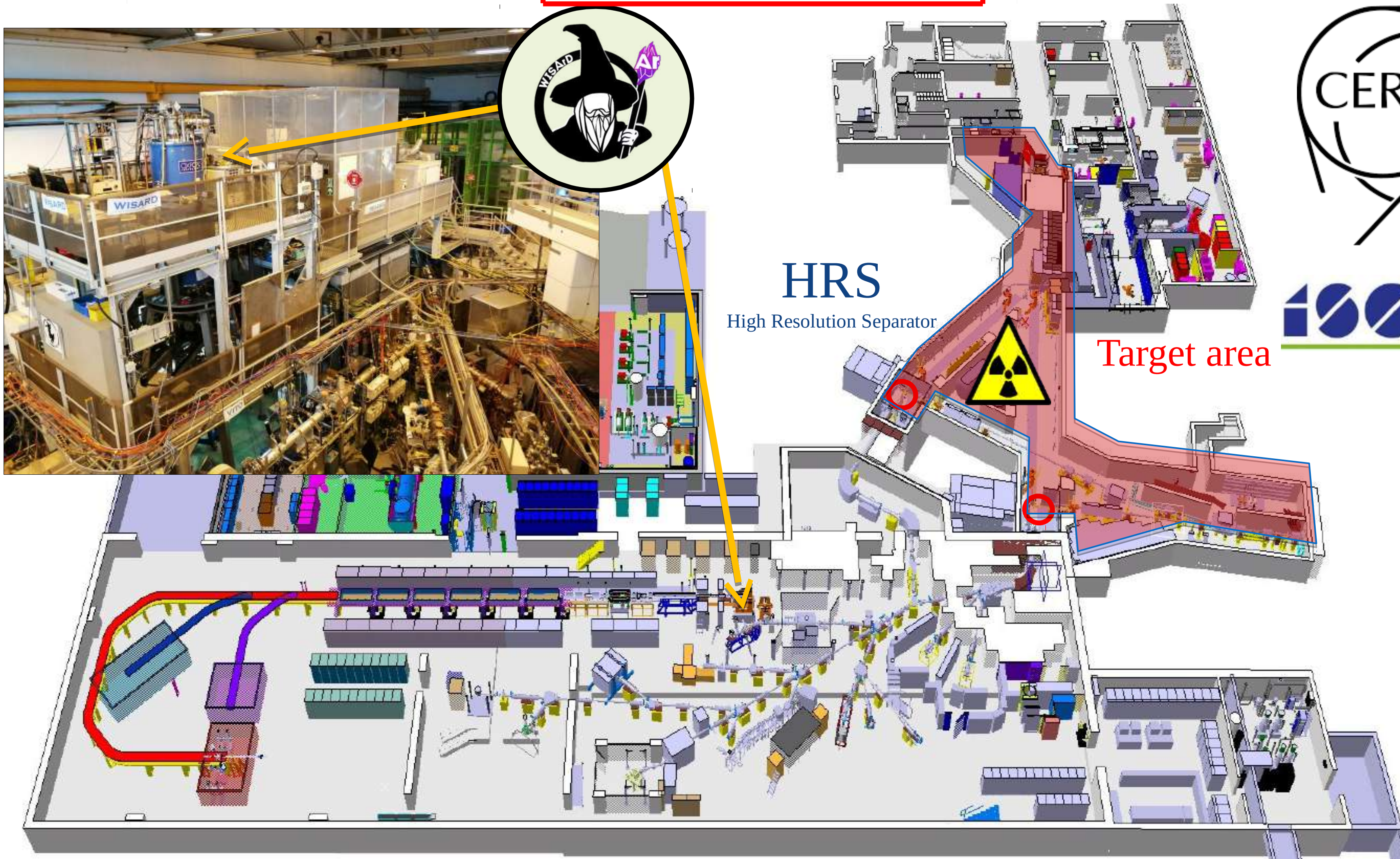
→ overview on tests performed in early 2020

→ new tests currently being performed

- feasibility study through G4 simulations
- current data taking

→ further studies & perspectives

WISArD campaign – CERN (2019)



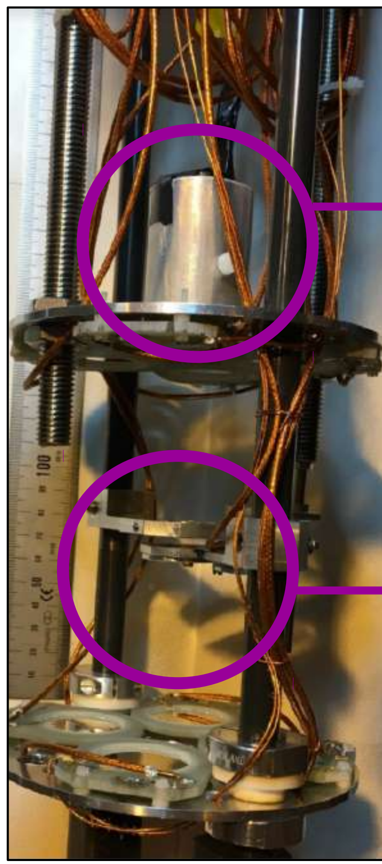
María J G Borge and Klaus Blaum, J. Phys. G: Nucl. Part. Phys. 45 (2018) 010301

WISArD campaign – experimental set-up

Same experimental set-up used for the WISArD proof-of-principle experiment:

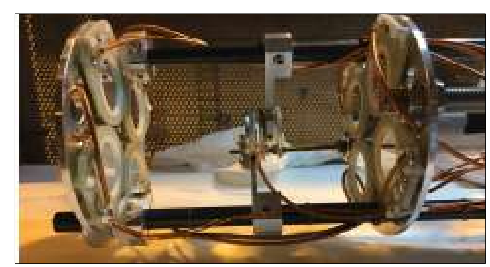
- **8 silicon detectors** (Ø = 3 cm, t = 300 μm) → α-particle detection
- **1 plastic scintillator** (Ø = 2 cm, l = 5 cm) + **1 SiPM** → β-particle detection

ISOLDE hall, CERN



WISArD detectors

β-detector: scintillator + SiPM



Source support + detector planes

WISArD campaign – experimental set-up

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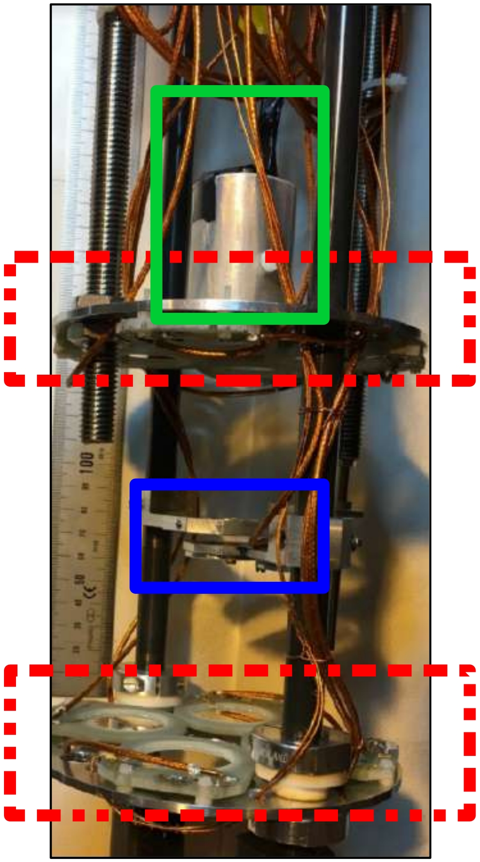
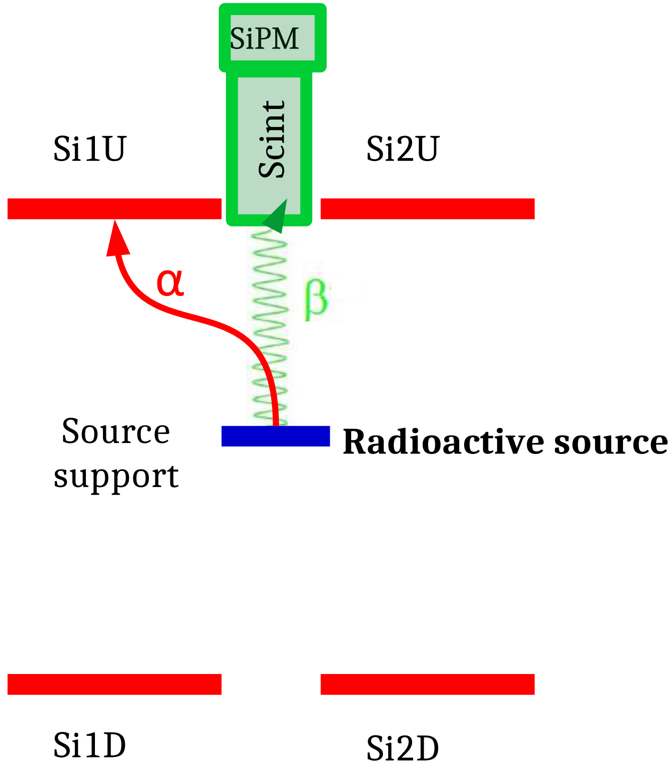


WISArD detectors



WISArD campaign – experimental campaign

From July 1st- July 10th 2019 (~130h of data acquisition) 36 runs were acquired:

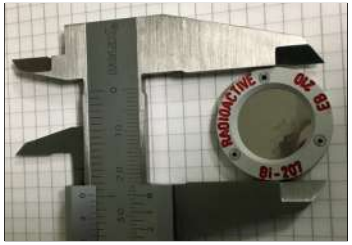
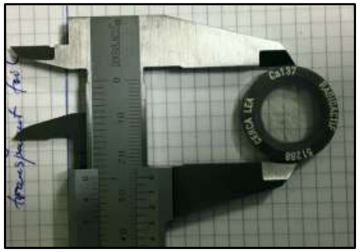
Multiple-α source

- 4-α source (A = 4.6 kBq) → 7 runs
  → ^{148}Gd, ^{239}Pu, ^{241}Am and ^{244}Cm

Electron converted/β-sources

- ^{207}Bi source (A = 20.9 kBq) → 13 runs
- ^{137}Cs source (A = 36.8 kBq) → 8 runs
- ^{133}Ba source (A = 592.8 kBq) → 8 runs

DIFFERENT B FIELD INTENSITIES
[0 , 6] T

Commercial calibration sources @ ISOLDE/CERN

Source	Run number	B (T)
^{207}Bi	1, 2, 3, 4, **5**, 6, 7, 8, 9, 10, 11, 12, 13	0, 4, 6, 0.3, **0.4**, 1, 2, 1.5, 1, 0.5, 0.2, 0.1, 0
^{137}Cs	**14**, **15**, **16**, 17, 18, 19, 20, 21	**4**, **4**, **0**, 2, 0, 1, 0.5, 0
4-α	22, 23, 24, 25, 26, 27, 28	0, 6, 4, 2, 1, 0.5, 0
^{133}Ba	29, 30, 31, 32, 33, 34, 35, 36	0, 0, 6, 4, 2, 1, 0.5, 0

Runs summary scheme

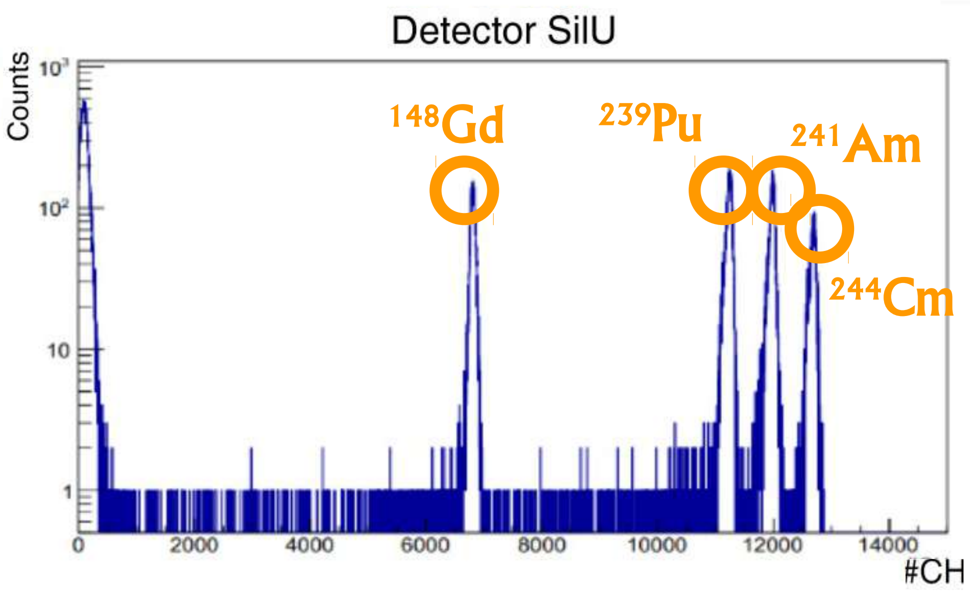
WISArD campaign – multiple α-source

7 runs in total

each run → 7 ADC spectra ≡
7 silicon detectors active at the moment of the data taking (Si4D disconnected)

each ADC spectrum → 4 main energy α-peaks

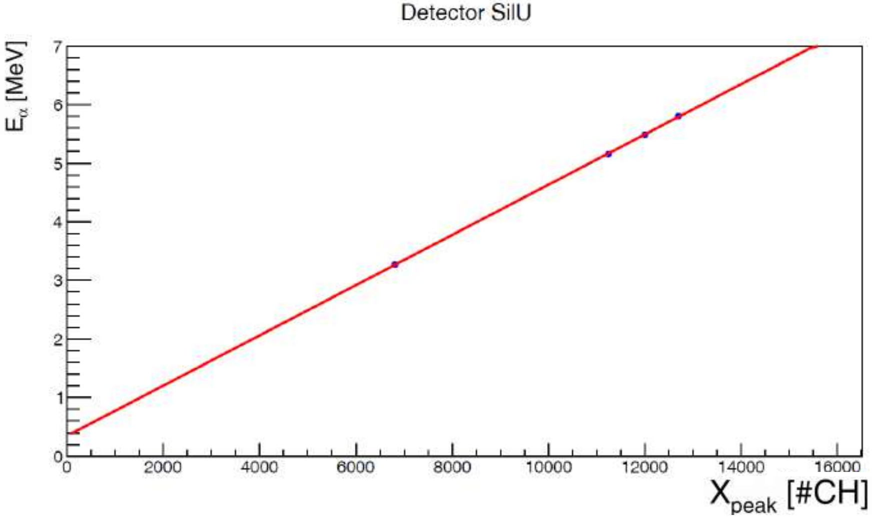
<u>Example: run 26, SiUp, B = 1 T</u>

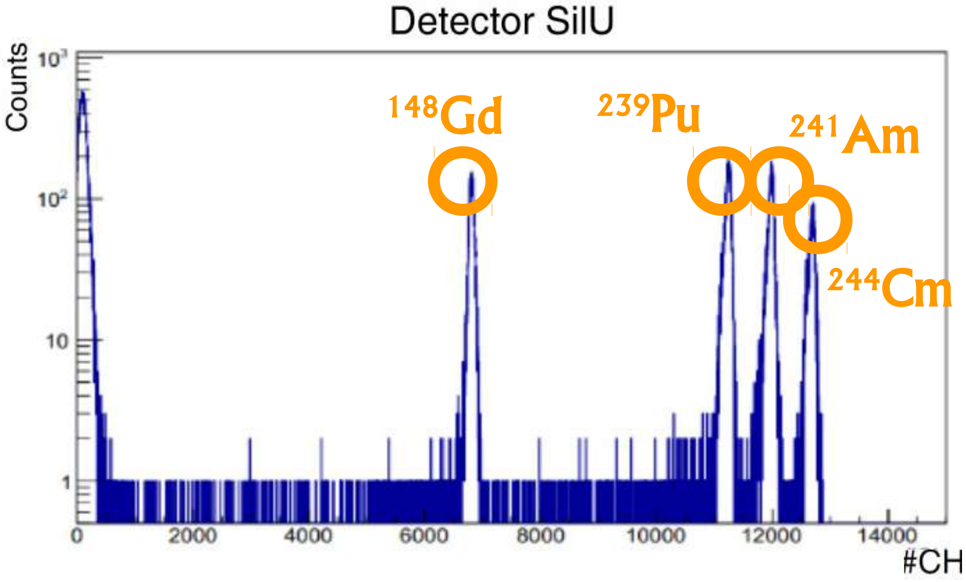


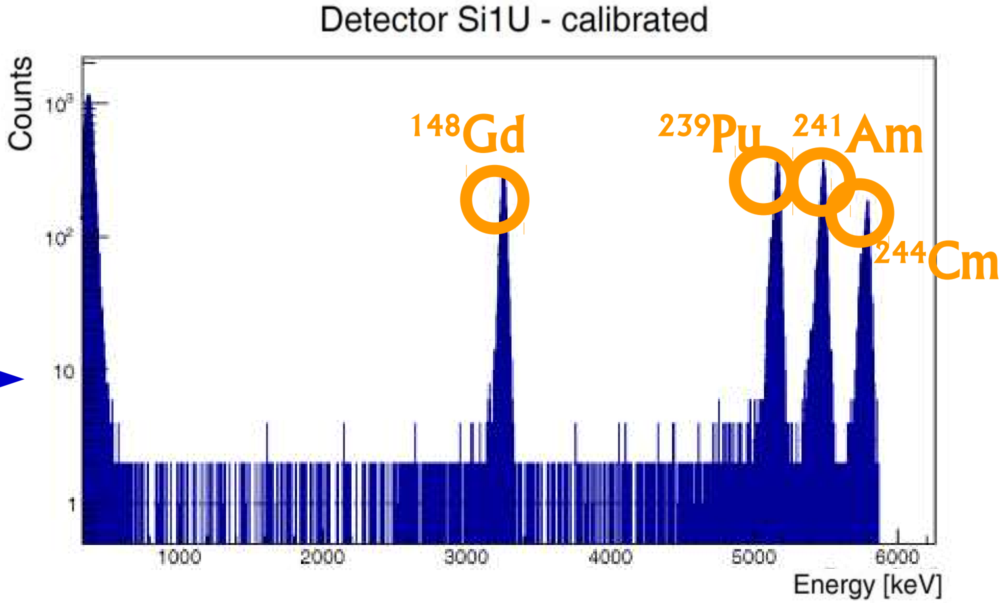
WISArD campaign – multiple α-source

DATA ANALYSIS

1. **Energy calibration (for all detectors and all runs)**
   → in all cases resulted perfectly linear







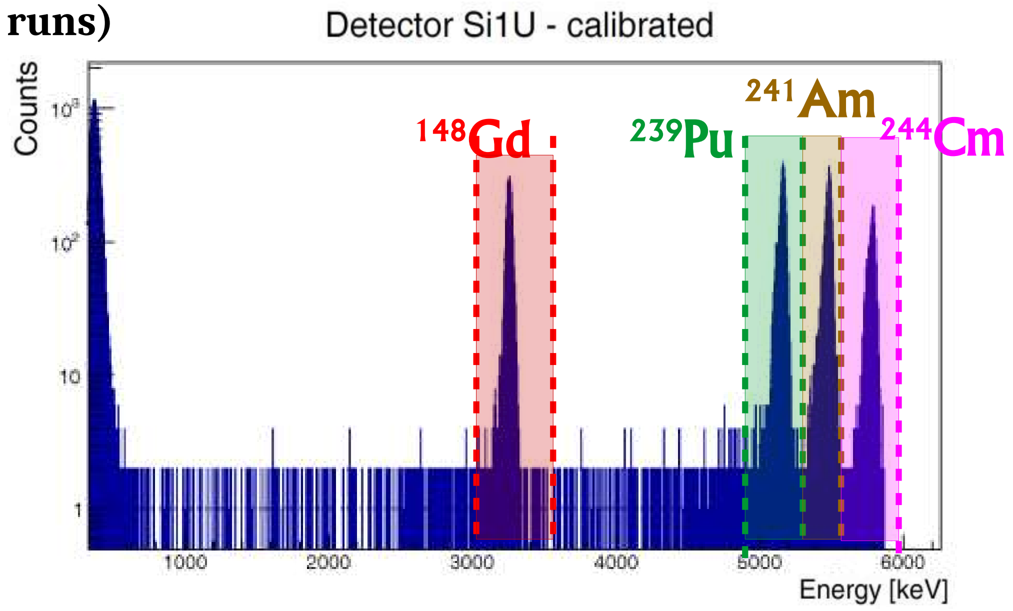
WISArD campaign – multiple α-source

DATA ANALYSIS

1. **Energy calibration (for all detectors and all runs)**
   → in all cases resulted perfectly linear

2. **Computation of α-detection efficiencies (for all peaks, all detectors and all runs):**

$$\epsilon_p^{det,run} = \frac{N_p^{det,run}}{\Delta t_{run}}$$



by using the following integration windows:

Peak n.	Source	Energy [keV]	Lower limit [keV]	Upper limit [keV]
1	^{148}Gd	3271	3100	3400
2	^{239}Pu	5156	5000	5300
3	^{241}Am	5486	5300	5600
4	^{244}Cm	5805	5600	5950

Table 2: Summary of the correspondence between α-peaks and the lower and upper integration limits used for the determination of the detection efficiencies.

WISArD campaign – multiple α-source

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1. **Energy calibration (for all detectors and all runs)**
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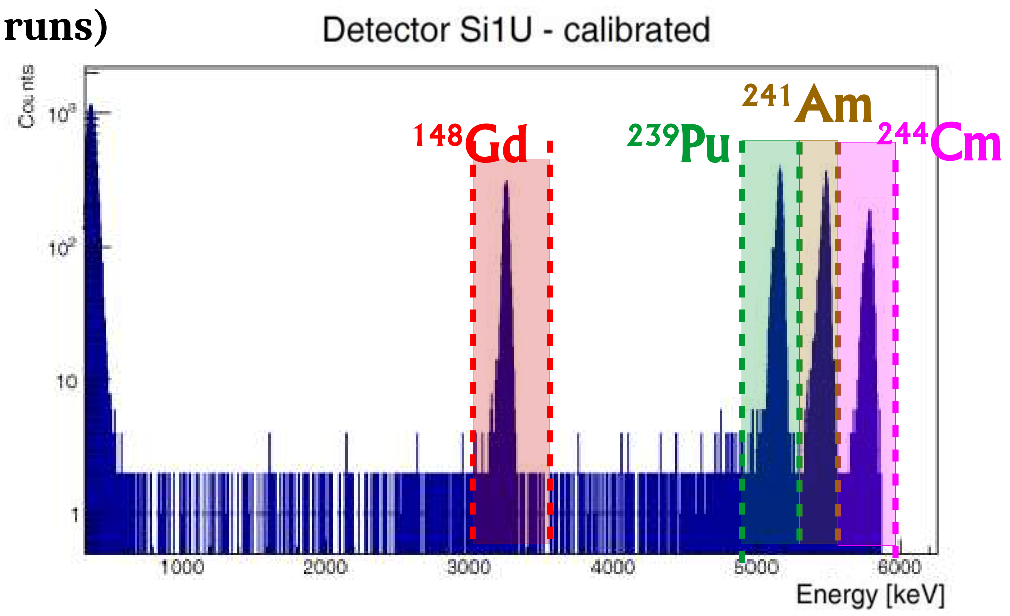


2. **Computation of α-detection efficiencies (for all peaks, all detectors and all runs):**

$$\epsilon_p^{det,run} = \frac{N_p^{det,run}}{\Delta t_{run}}$$

3. **Normalization of detection efficiencies to B = 0 T:**

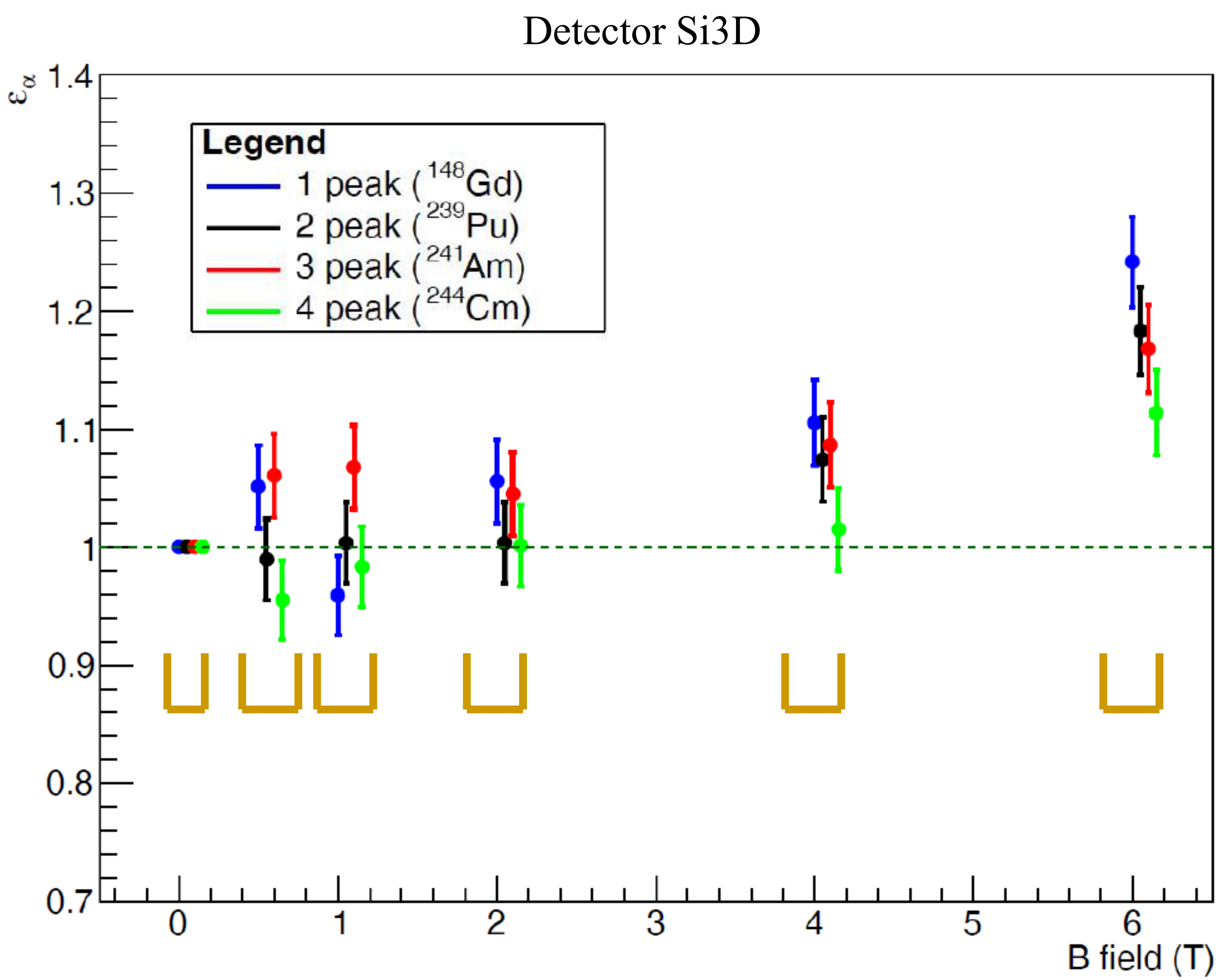
$$\epsilon_{NORM}^{det,run} = \frac{\epsilon_p^{det,run}}{\epsilon_{det,B=0T}}$$

WISArD campaign – multiple α-source

DATA ANALYSIS

Normalized experimental detection efficiencies have been determined for all peaks, all detectors and all runs

Example:
Si3D,
all peaks,
all B field values tested



WISArD campaign – multiple α-source

DATA ANALYSIS

Normalized experimental detection efficiencies have been determined for all peaks, all detectors and all runs

Example:
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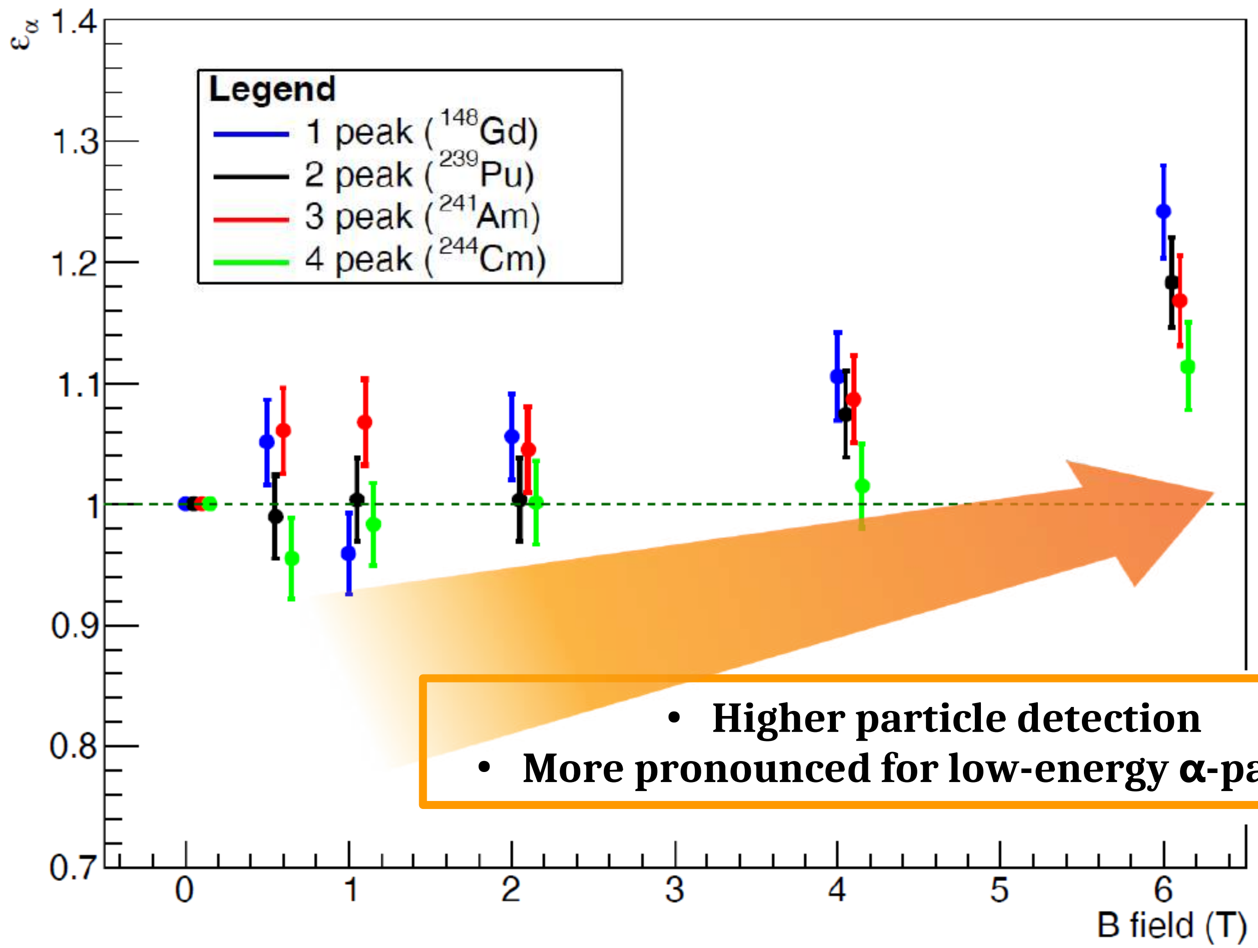
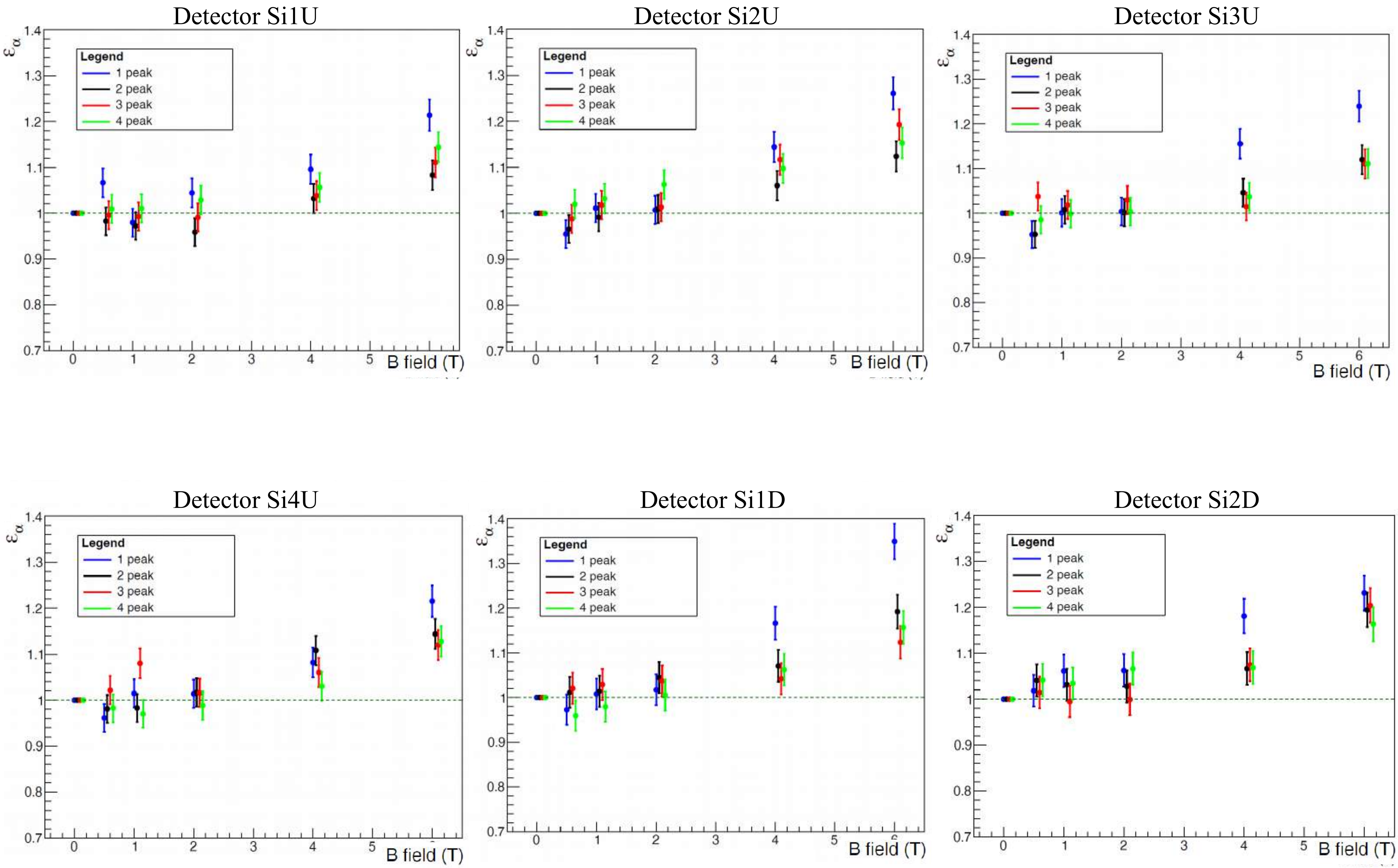
Detector Si3D



- **Higher particle detection**
- **More pronounced for low-energy α-particles**



Detector Si1U
Detector Si2U
Detector Si3U
Detector Si4U
Detector Si1D
Detector Si2D
ε_α
Legend
1 peak
2 peak
3 peak
4 peak
B field (T)

WISArD campaign – multiple α-source

G4 SIMULATIONS

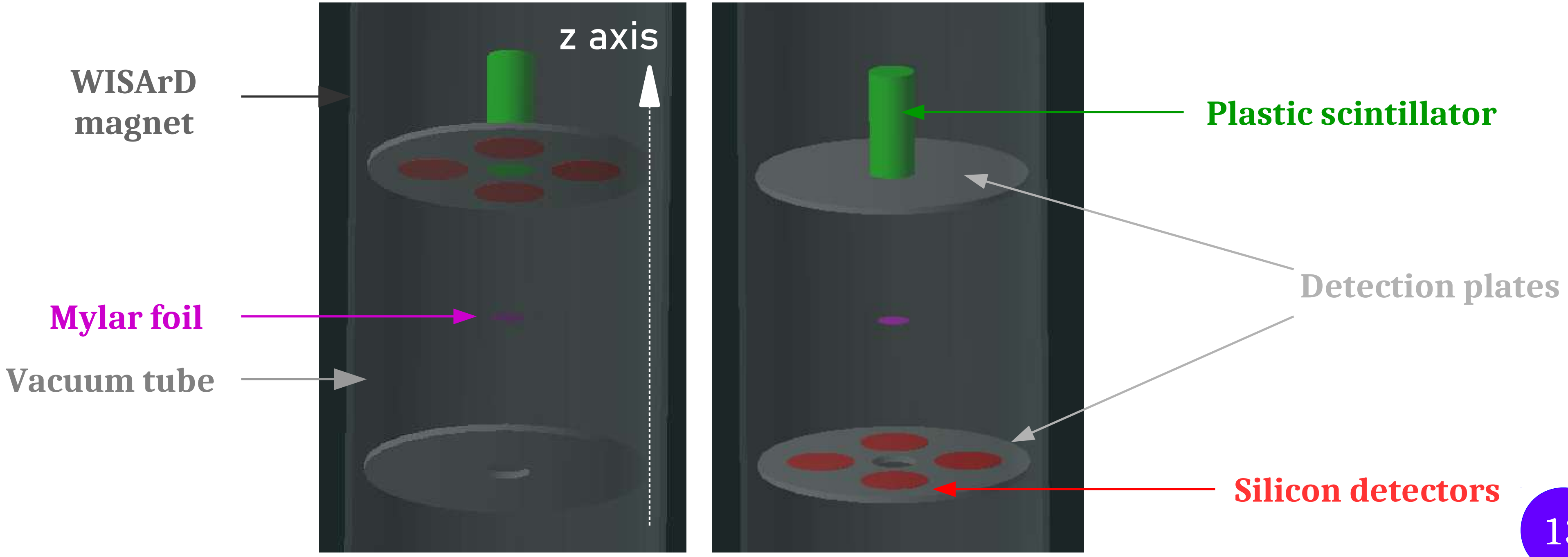
1. WISArD detection set-up implemented

→ detectors, main supports, WISArD magnet

2. Radioactive sources coded

→ r = 2 mm, decay libraries based on ENSDF

→ *emstandard_opt4* PhysicsList, per-decay simulations



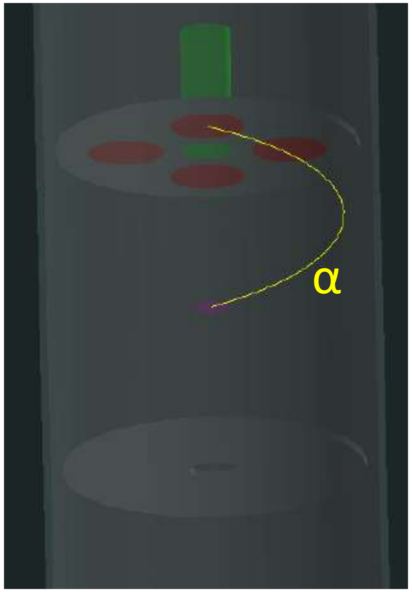
WISArD campaign – multiple α-source

G4 SIMULATIONS

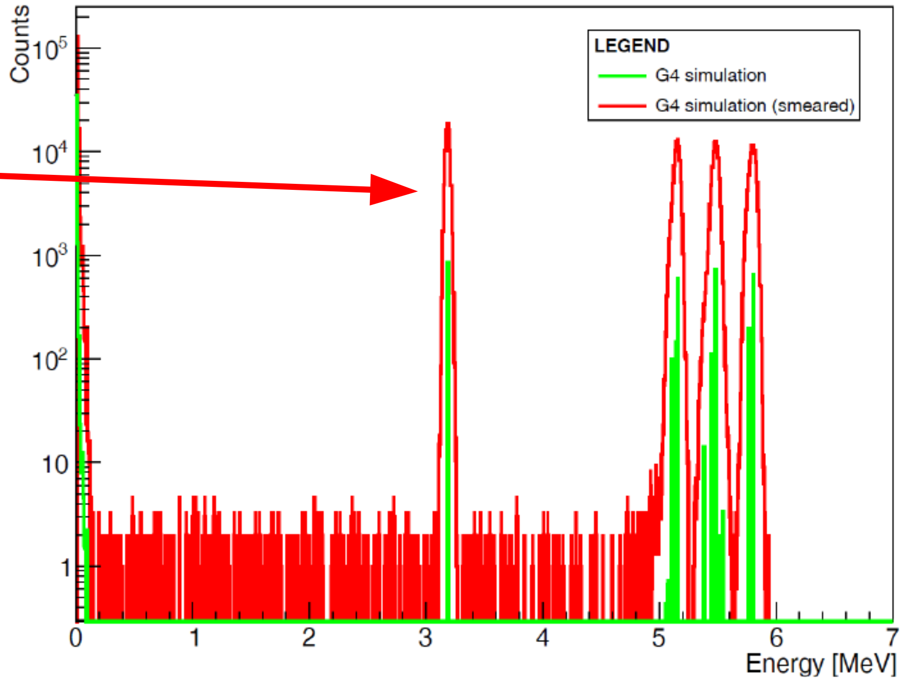
1. **WISArD detection set-up implemented**
   → detectors, main supports, WISArD magnet

2. **Radioactive sources coded**
   → r = 2 mm, decay libraries based on ENSDF
   → *emstandard_opt4* PhysicsList, per-decay simulations

3. **Magnetic field implementation**



G4 simulations
smeared
with the
detector resolution



WISArD campaign – multiple α-source

G4 SIMULATIONS

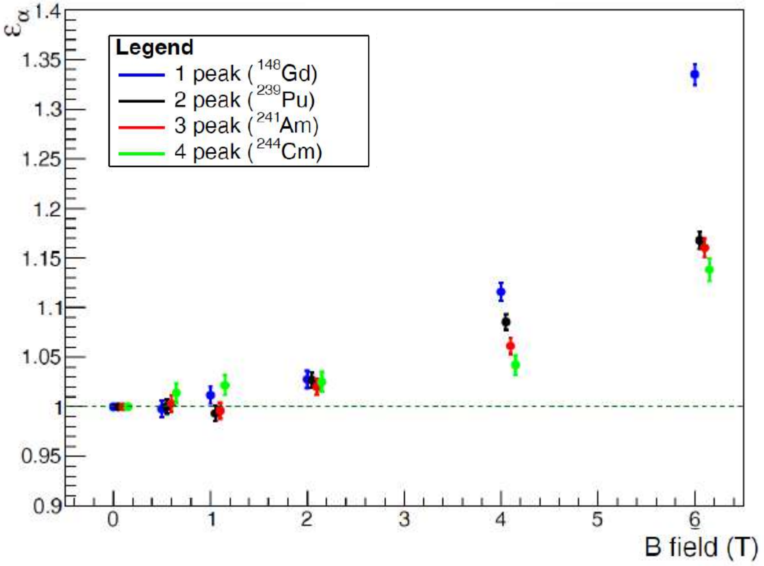
A. **All α-sources at all B field intensities have been simulated**
→ 7 source positions simulated ($\Delta x_0 \pm 2$ mm) → systematic errors

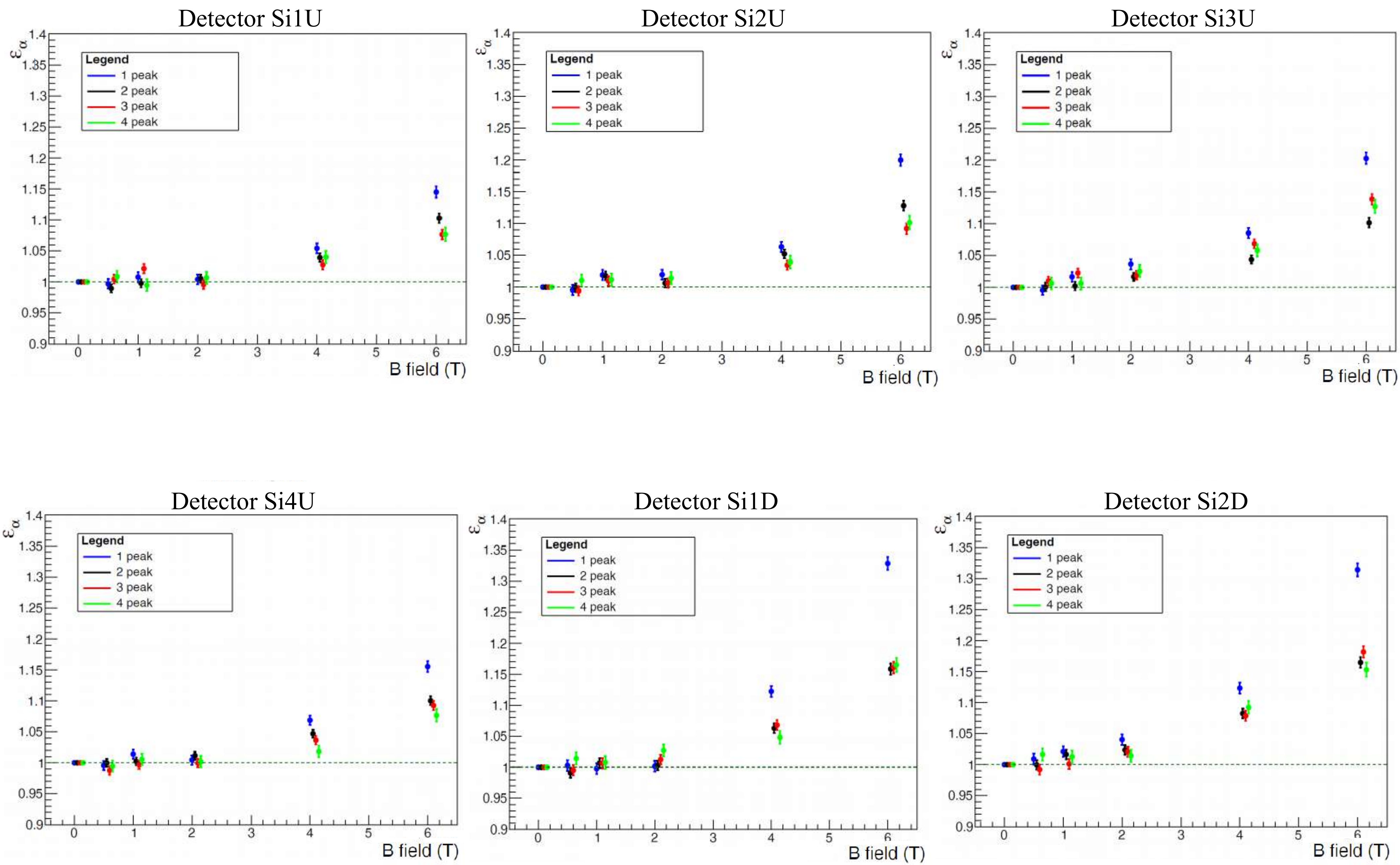
B. **Simulated runs built to reflect the experimental runs**
→ 4 individual α-source simulations have been summed up to a single run

C. **Simulated runs analyzed with the same method applied for the experimental ones**
→ determination of normalized detection efficiencies (for all detectors and all runs)

Detector Si3D

Example:
Si3D,
all peaks,
all B field values tested



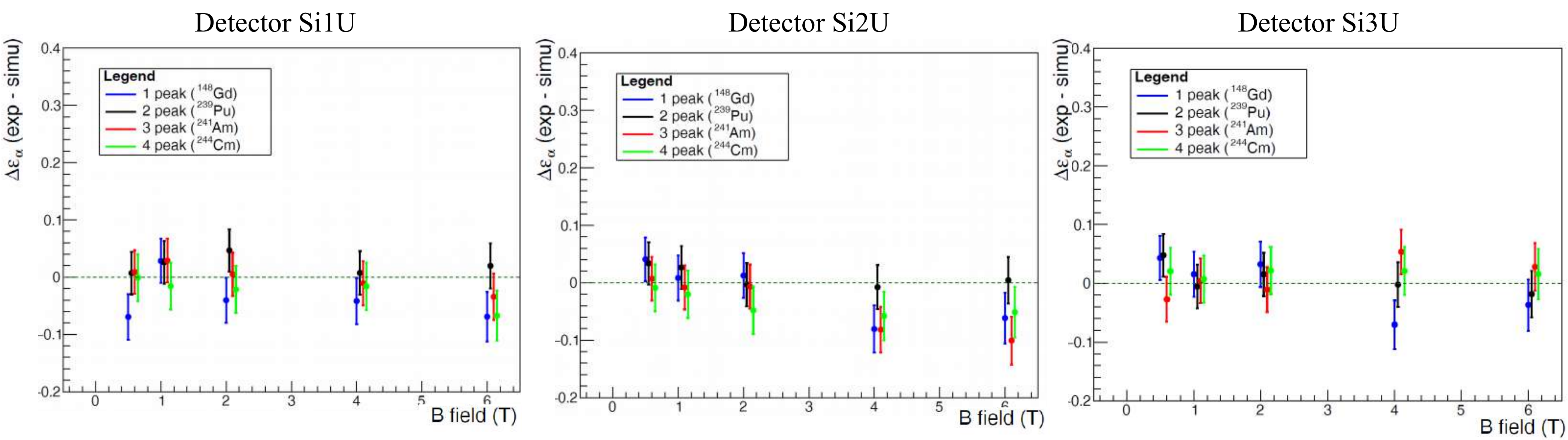

Detector Si1U
Detector Si2U
Detector Si3U
Detector Si4U
Detector Si1D
Detector Si2D
Legend
1 peak
2 peak
3 peak
4 peak
ε_α
B field (T)

WISArD campaign – multiple α-source

DIFFERENCES BETWEEN EXPERIMENTAL AND SIMULATED DETECTION EFFICIENCIES

- <u>Excellent agreement</u> between experimental and simulated results
  - ⟶ for all energies and at all B field intensities
  - ⟶ almost all values compatible with zero within the only statistic error bar (1σ)
  - ⟶ differences up to a 9.34% ± 4.87% (stat.) ± 4.67% (syst.)

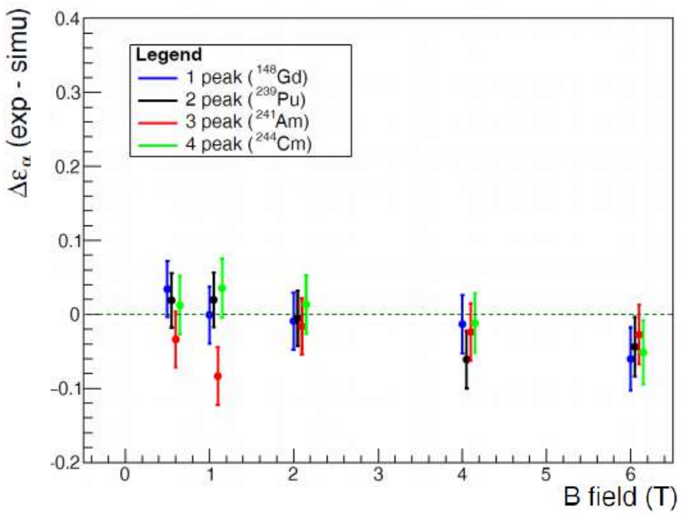
- Crystalline and quantitative <u>indicator to proceed and evaluate β-particle spectra reproduction</u>



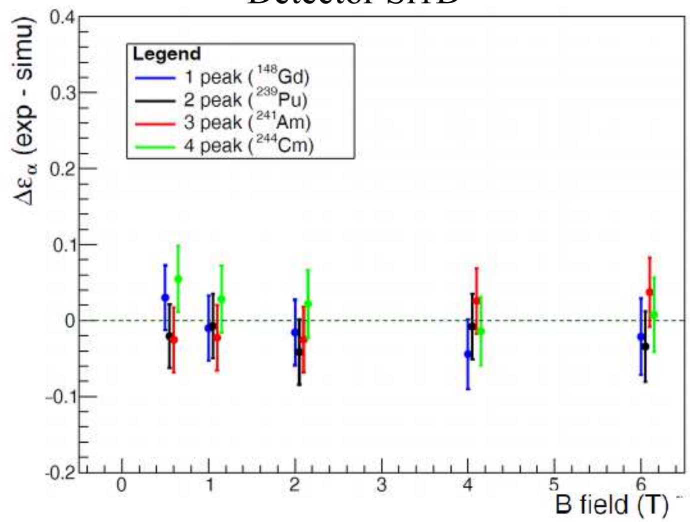
WISArD campaign – multiple α-source

DIFFERENCES BETWEEN EXPERIMENTAL AND SIMULATED DETECTION EFFICIENCIES

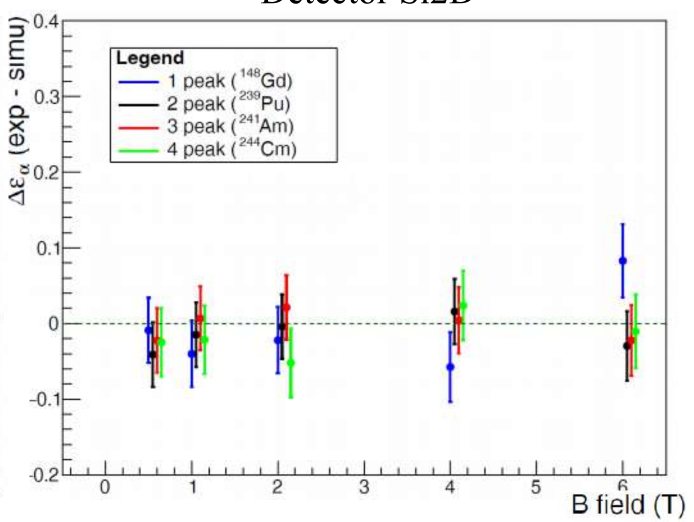
Detector Si4U



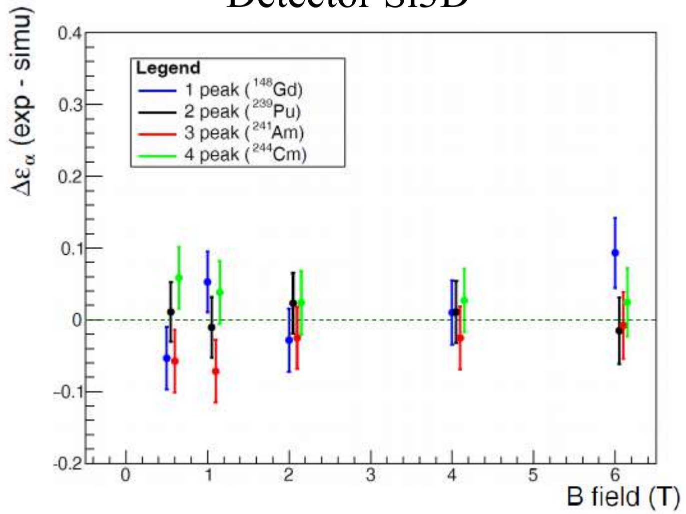
Detector Si1D



Detector Si2D



Detector Si3D



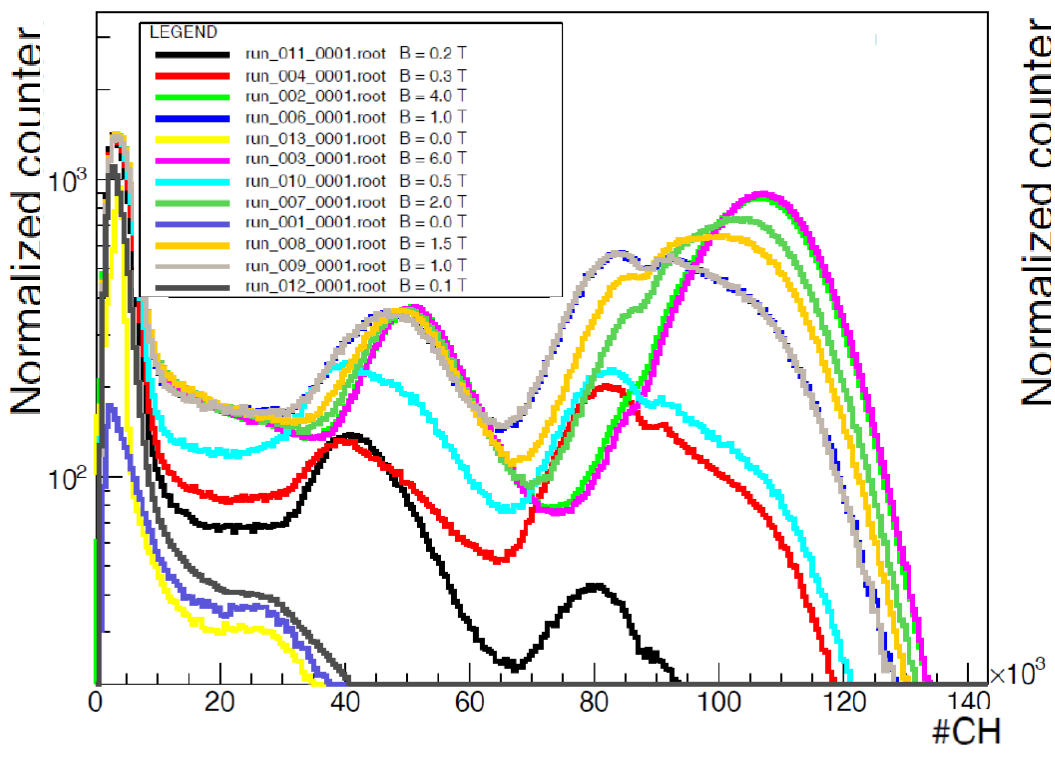
WISArD campaign – β-sources

DATA ANALYSIS

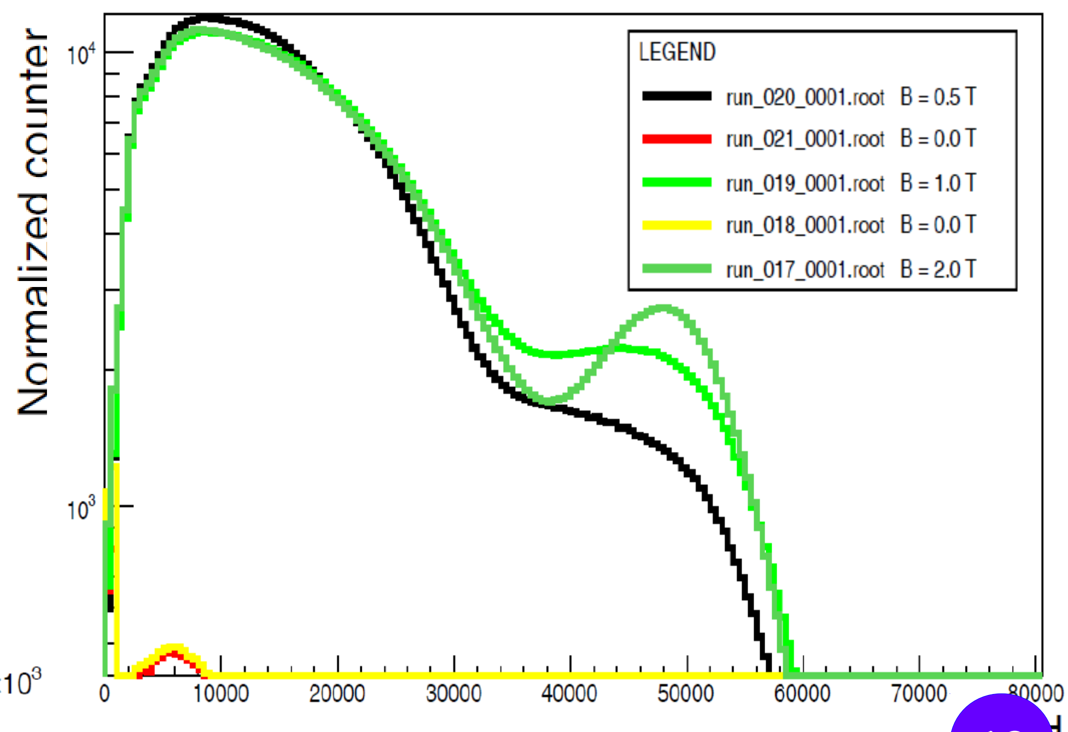
Runs with different electron-converted sources were acquired:

- each run → three QDC spectra: **[-10, 250]**, [-10, 50] and [-10, 1200] **ns**
- ^{207}Bi source, ^{137}Cs source and ^{133}Ba source

Runs taken with source of ^{207}Bi with QDC1: [-10, 250] ns



Runs taken with source of ^{137}Cs with QDC1: [-10, 250] ns



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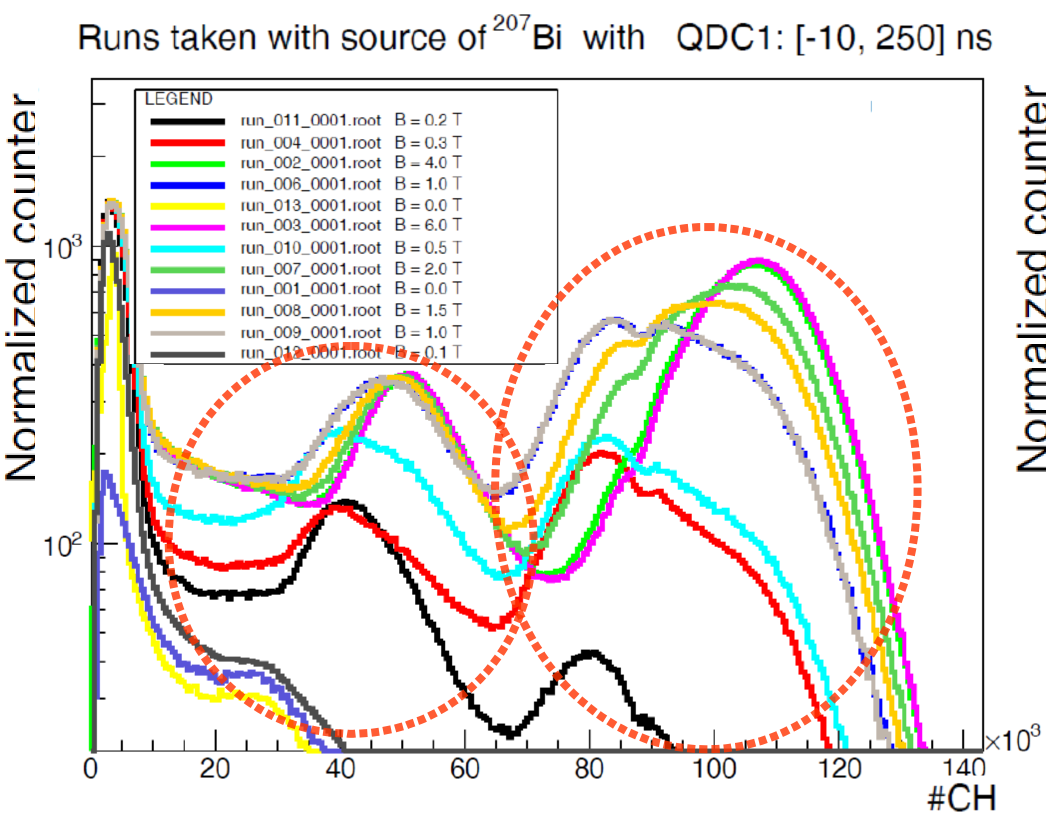

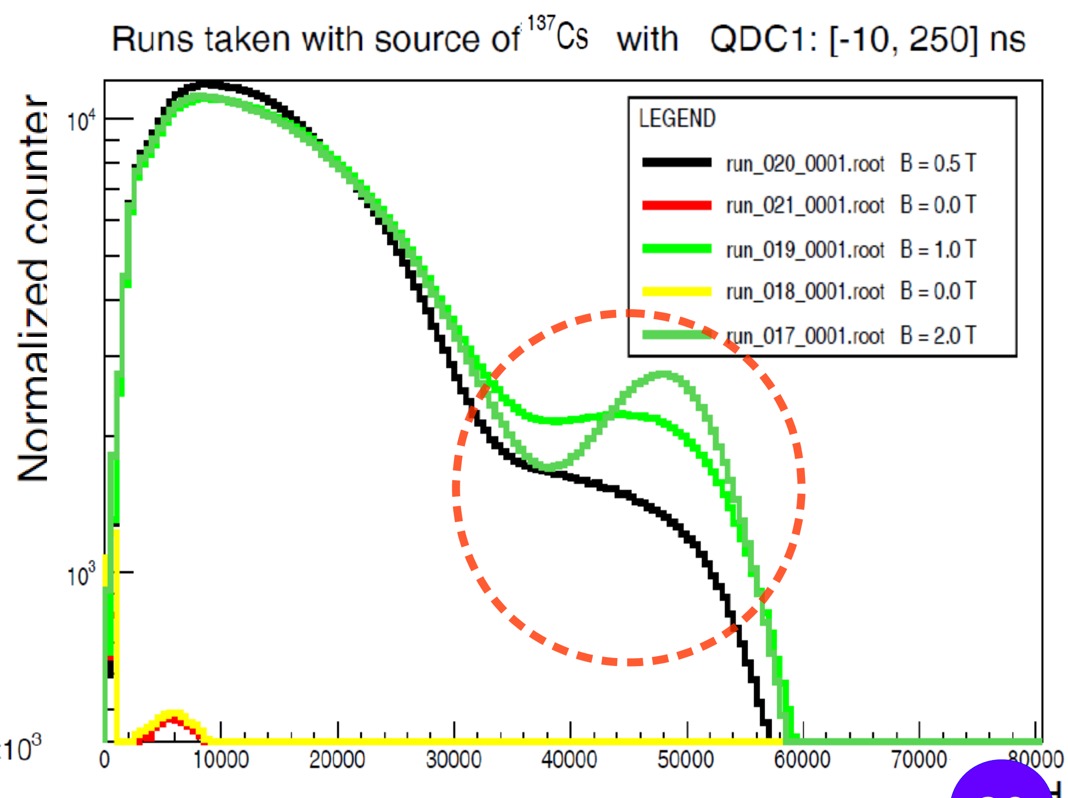

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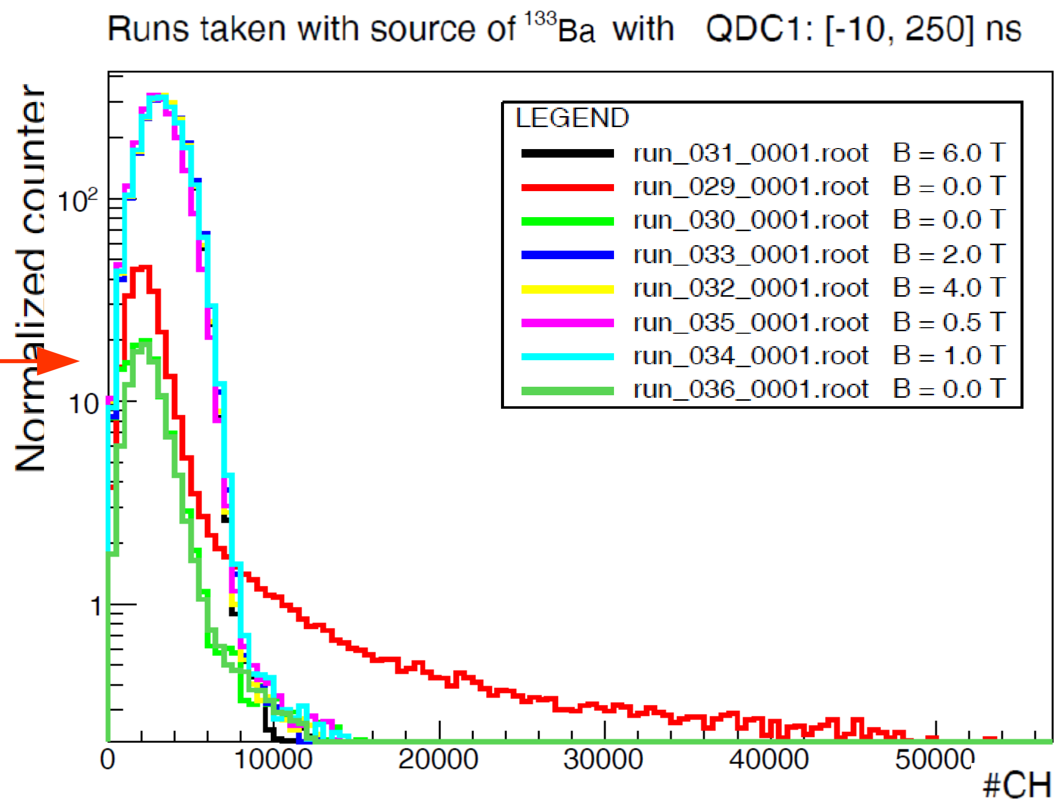
excluded from the analysis

2.1 Electron Capture Transitions

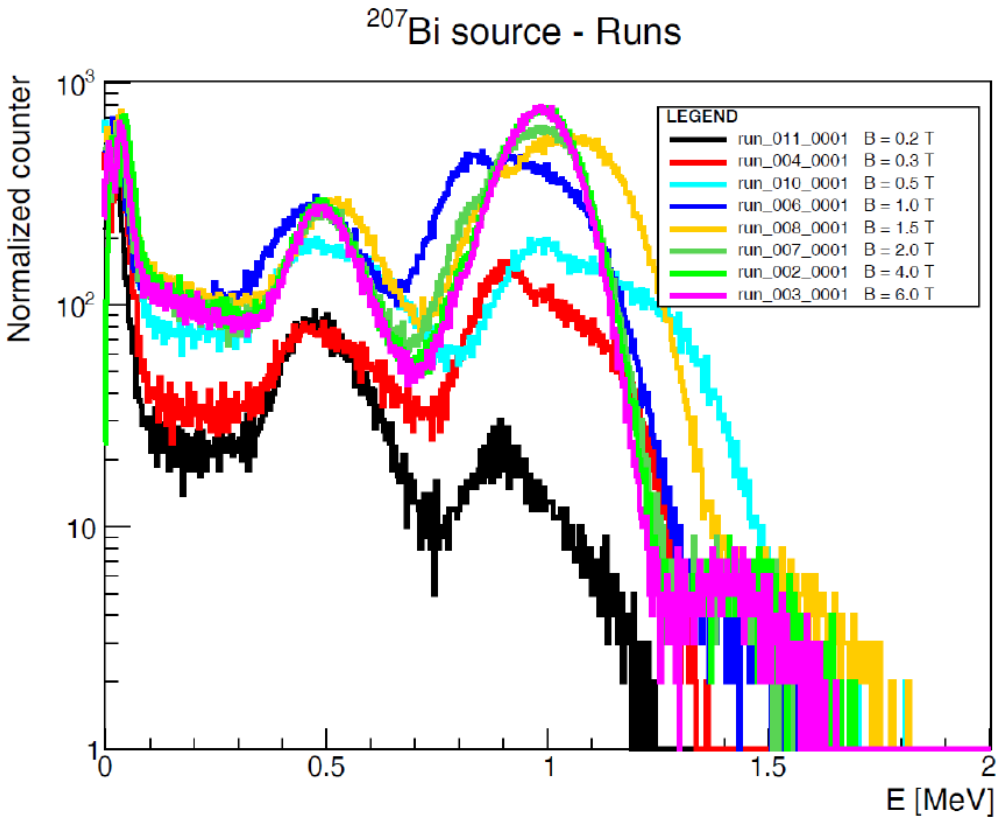
	Energy (keV)	Probability (%)	Nature	lg ft
$\epsilon_{0,4}$	80,3 (10)	85,41 (53)	Allowed	6,63
$\epsilon_{0,3}$	133,5 (10)	14,46 (51)	Allowed	8,03
$\epsilon_{0,2}$	356,7 (10)	<0,3	2nd Forbidden	>10,6
$\epsilon_{0,1}$	436,3 (10)	<0,7	2nd Forbidden	>10,9
$\epsilon_{0,0}$	517,3 (10)	<0,0005	Unique 2nd Forbidden	>13,9

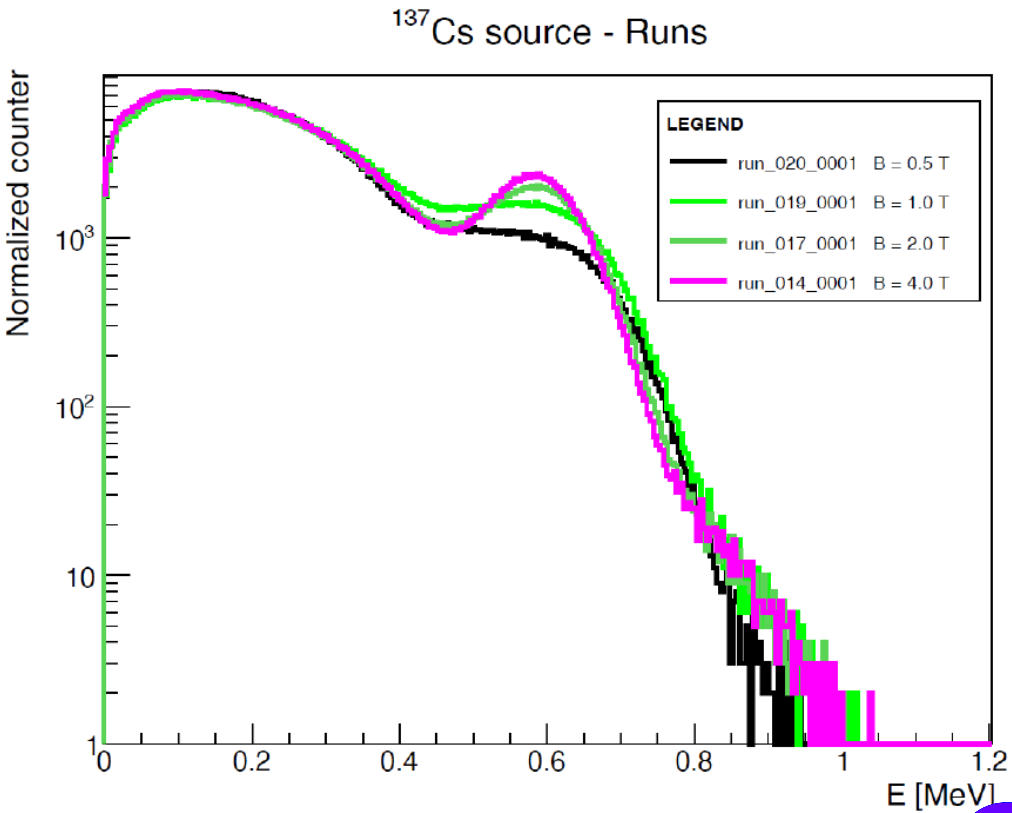


WISArD campaign – β-sources

DATA ANALYSIS

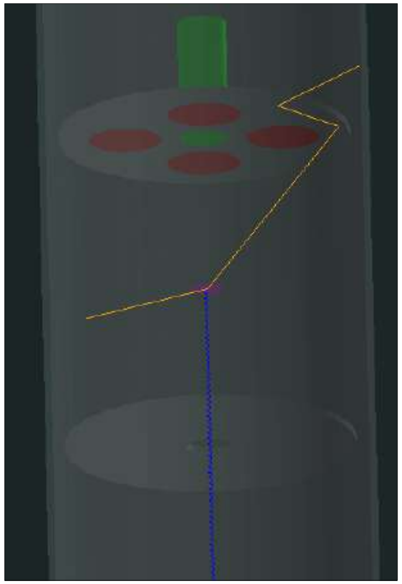
→ Subtraction of run at B = 0 T (for ^{207}Bi and ^{137}Cs runs respectively)
→ *Ad hoc* energy calibration for each run





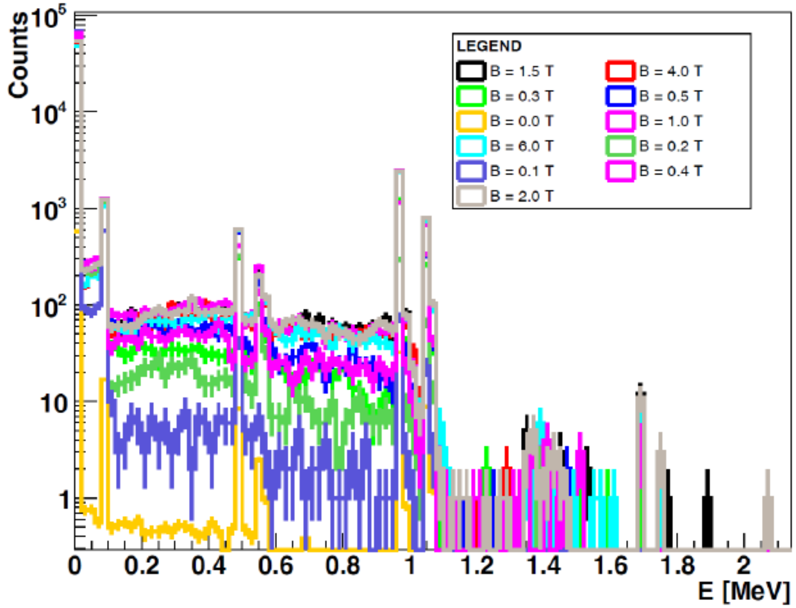
WISArD campaign – β-sources

G4 SIMULATIONS

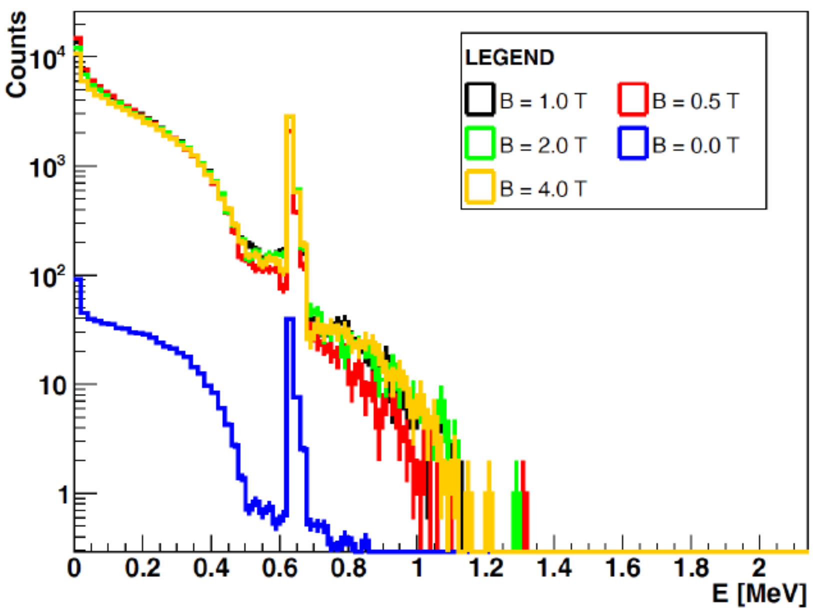


- ^{207}Bi and ^{137}Cs sources coded (*G4 General Particle Source*)
- Total energy spectra inside scintillator retrieved
- Each spectrum convoluted with the response function of the detector
  → extrapolated from exp. runs: $\sigma \propto \sqrt{E}$
- Subtraction of spectra at B = 0 T

^{207}Bi source



^{137}Cs source



WISArD campaign – β-sources

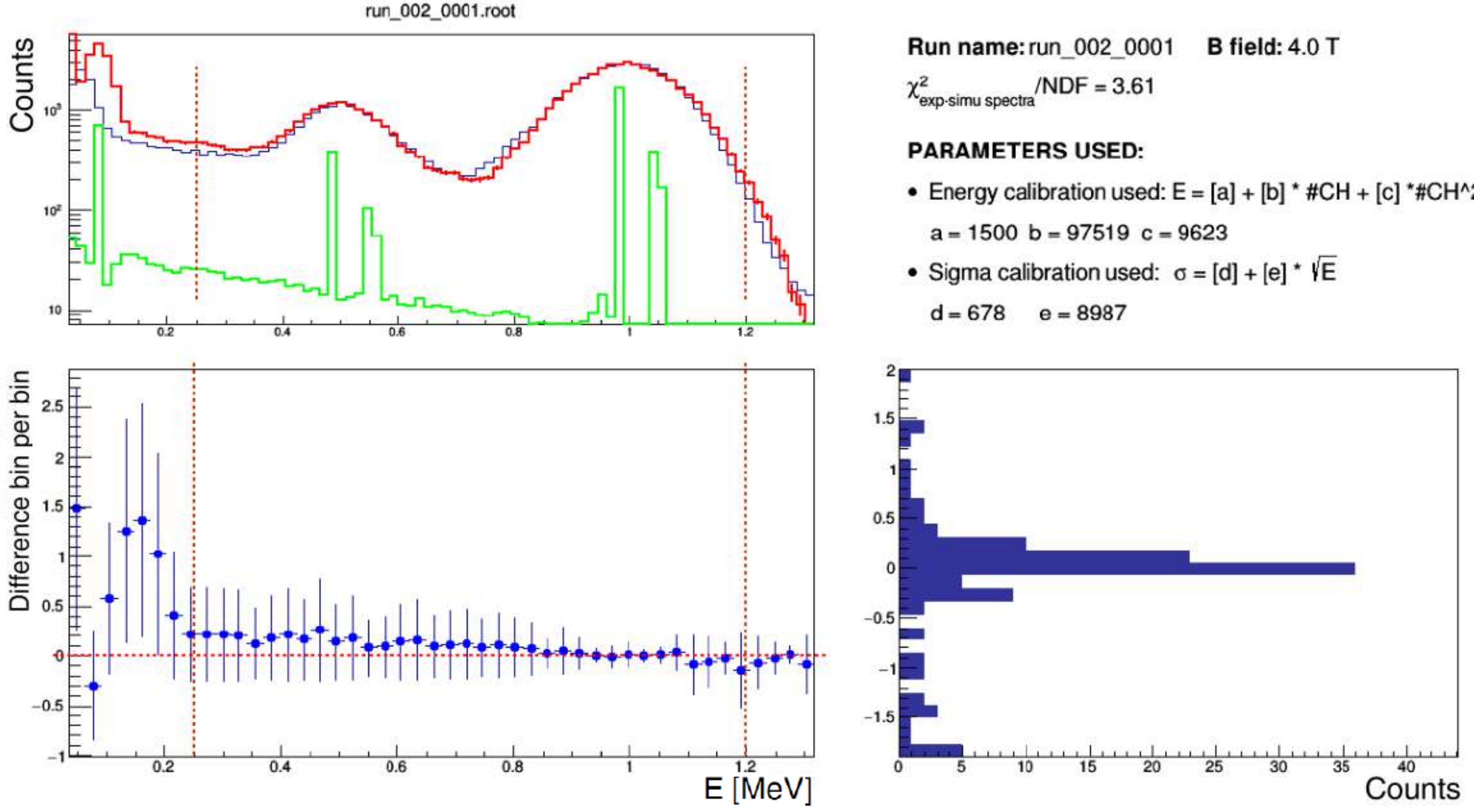
COMPARISON EXP/SIMU

- Exp/simulated runs superimposed
- Descend gradient algorithm to minimize the χ^2

  → best configuration in the 5-dimension parameter space:

$$E = \mathbf{a} + \mathbf{b} \cdot \#CH + \mathbf{c} \cdot \#CH^2$$
$$\sigma = \mathbf{d} + \mathbf{e} \cdot \sqrt{E}$$

Example:



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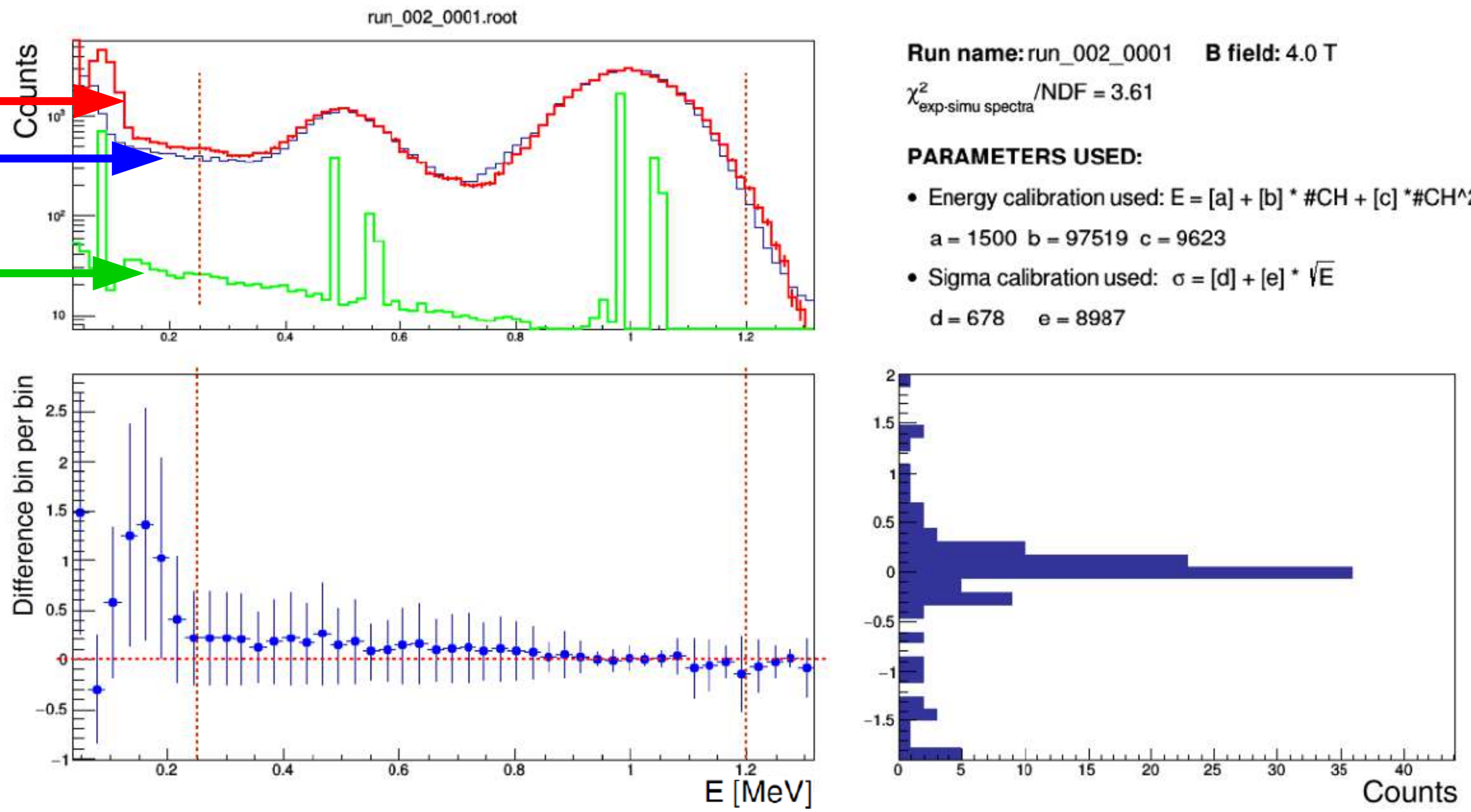
Example:

G4 smeared
Exp. run
G4 simulation (scaled)



WISArD campaign – β-sources

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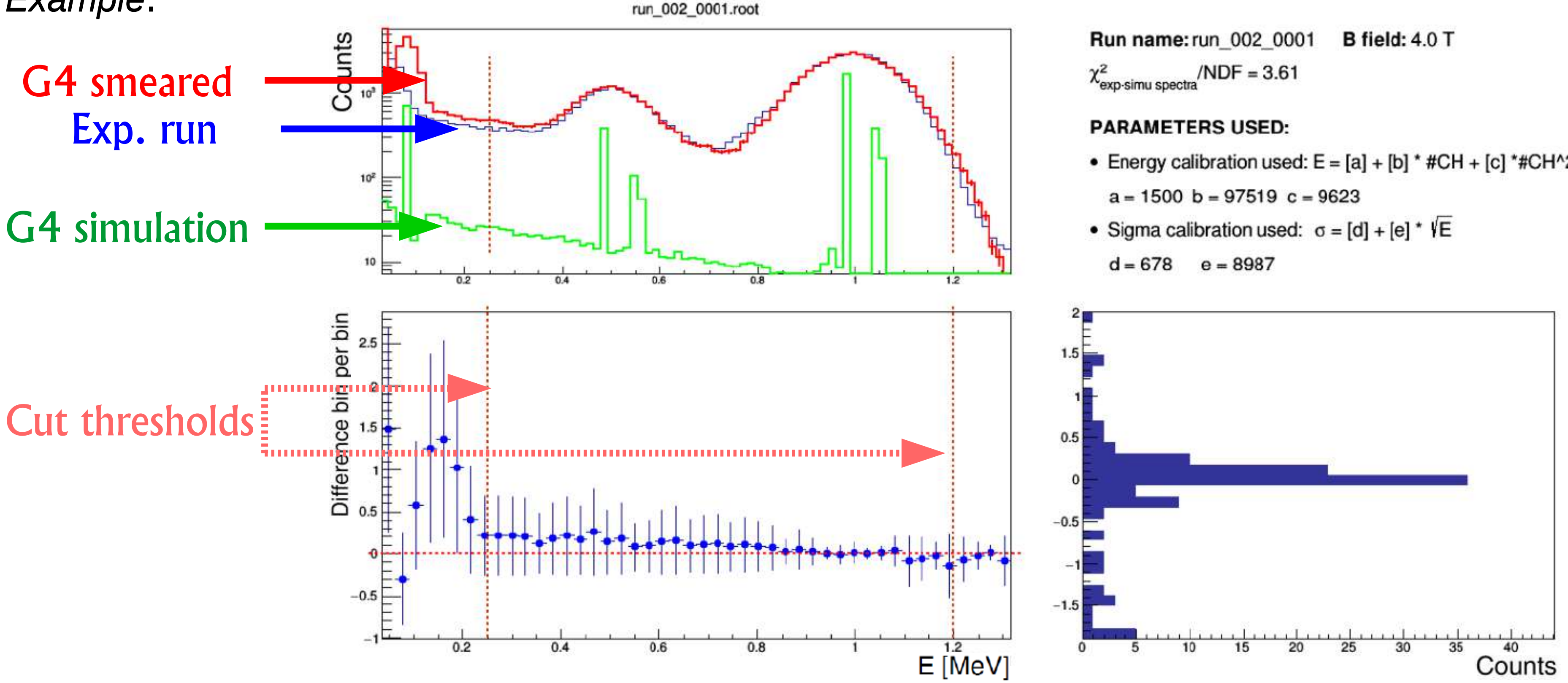

WISArD campaign – β-sources

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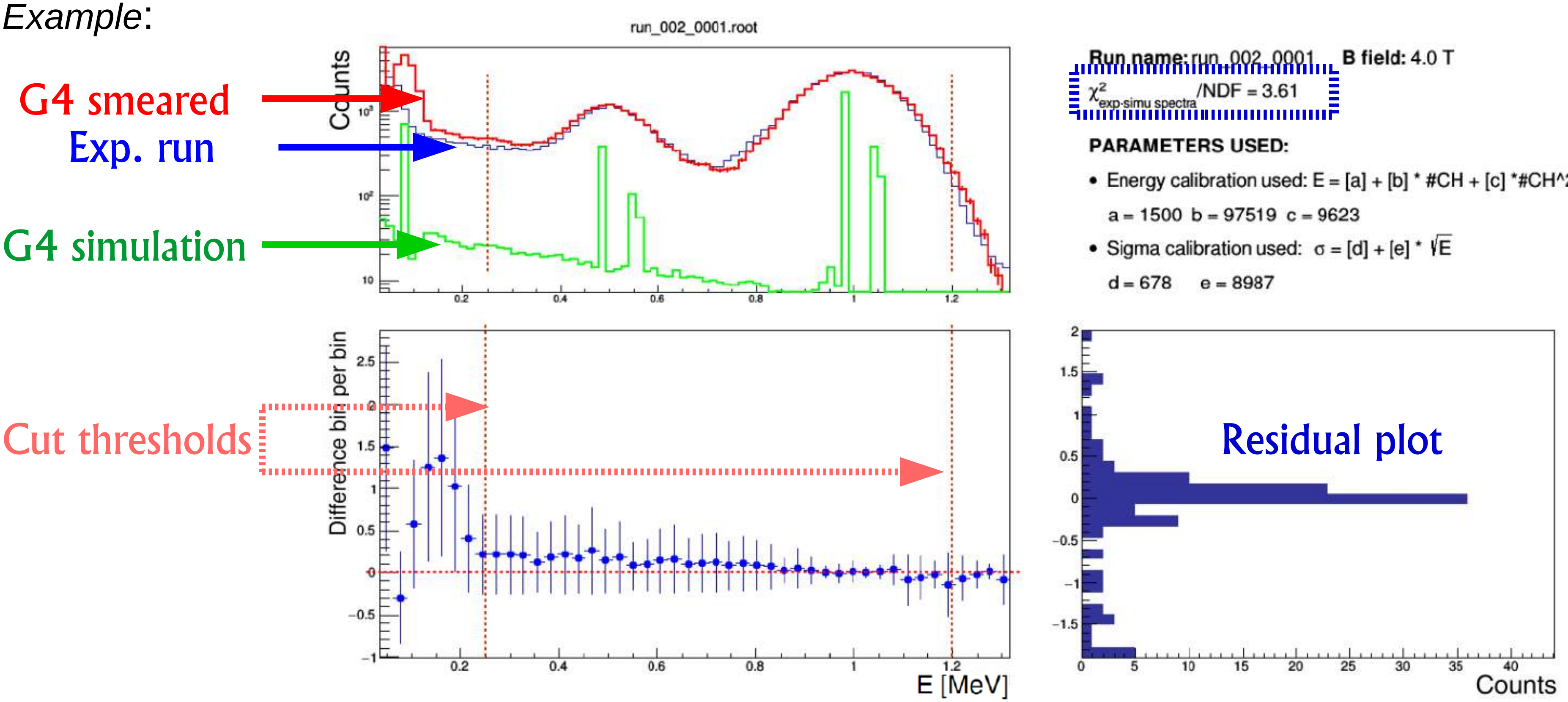


WISArD campaign – β-sources

COMPARISON EXP/SIMU

- Good agreement between experimental and simulated results

Run number	B field [T]	PhysicsList	$\chi^2_{exp-simu}$/NDF
11	0.2	GS	7.85
4	0.3	GS	3.49
10	0.5	GS	4.85
6	1.0	GS	9.51
8	1.5	GS	6.94
7	2.0	GS	5.85
2	4.0	GS	3.61
3	6.0	GS	5.54

- Similar results obtained for other *PhysicsLists* tested

emstandard_opt4

penelope

β-backscattering tests - CENBG

β-backscattering tests - Motivation

First results: error budget (November 2018) [1]

	Source	Uncertainty	$\Delta\tilde{a}_{\beta\nu}(10^{-3})$
background	false coinc.	8%	< 1
proton	detector calibration	0.2%	2
	detector position	1 mm	< 1
	source position	3 mm	3
	source radius	3 mm	1
	B field homogeneity	1%	< 1
	silicon dead layer	0.3 μm	5
	mylar thickness	0.15 μm	3
positron	backscattering	10%	15
	threshold	12 keV	8
total			19

OBJECTIVE:

characterization of backscattering of β's

- Lower detection threshold as a function of E_e and θ_{inc}
- Validation and constraints for GEANT4 simulations

HOW TO ACHIEVE IT:

- Different experimental set-up explicitly conceived for the study of β-backscattering
- Simulations varying input parameters in Geant4
- Study of the Geant4 goodness of description of β-backscattering

[1] V. Araujo-Escalona et al. arXiv:1906.05135 [nucl-ex]

β-backscattering tests - State-of-the-art

Different β-backscattering test benches to reproduce different relative angles between detectors and incoming particles:

Electron spectrometer (Nov. 2019 - ...)

data analyzed and compared with G4 simulations:

- fairly good agreement with the experimental data
- evaluation of backscattering coefficient @ E, θ_{inc}

PROS: → selection of monoenergetic e- beam
→ high intensity

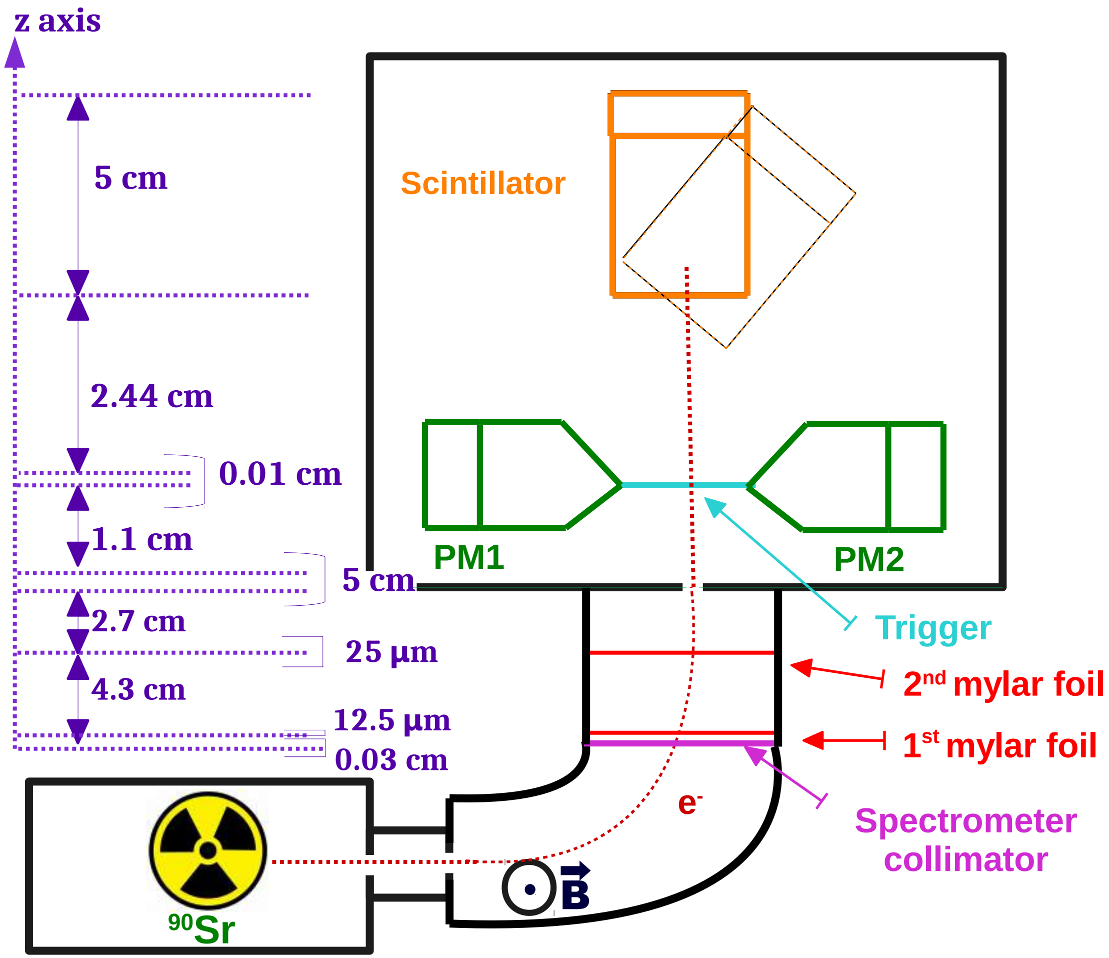
CONS: → measurements taken at atmospheric pressure

New dedicated set-up (ongoing)

- feasibility study through Geant4 simulations
- currently data taking

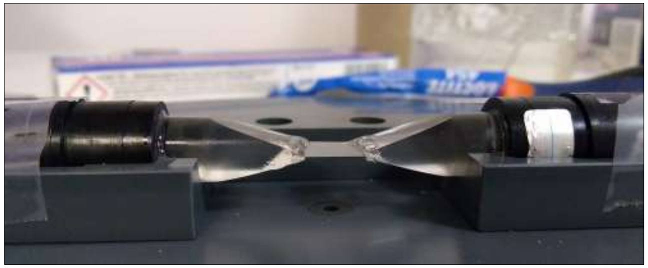
PROS: → measurements taken in primary vacuum
→ employment of radioactive sources

β-backscattering tests @ e- spectrometer



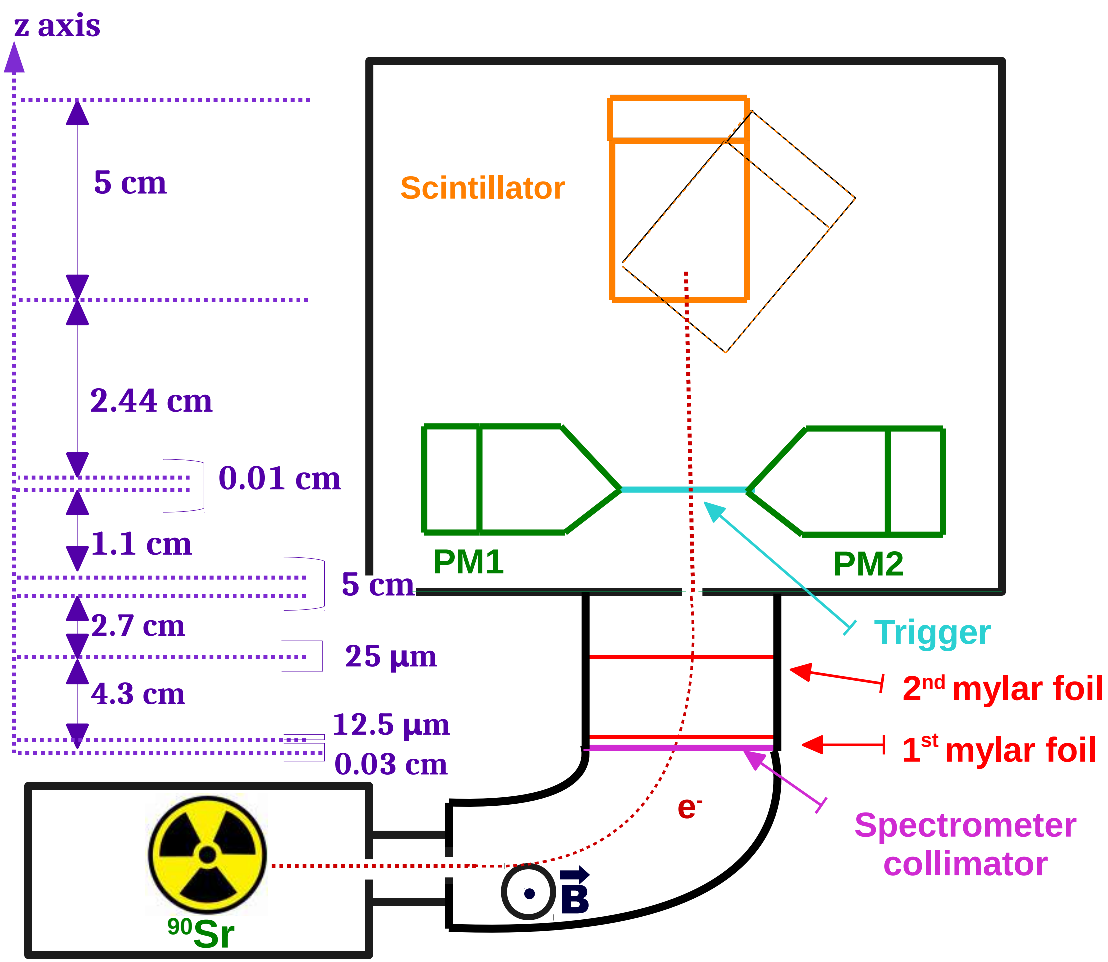
- <u>Source ^{90}Sr:</u>
  - $Q_{\beta}(^{90}Sr) = 0.55$ MeV → $Q_{\beta}(^{90}Y) = 2.3$ MeV
  - Monoenergetic electrons via B field
  - Collimator (radius = 0.2 cm)
  - $E_{e-} = 0.7 – 1.8$ MeV

- <u>Black box:</u>
  - Air (no vacuum)
  - Trigger on e-
    - plastic scintillator
    - 100 μm thickness
  - + 2 optical guides coupled with PMs



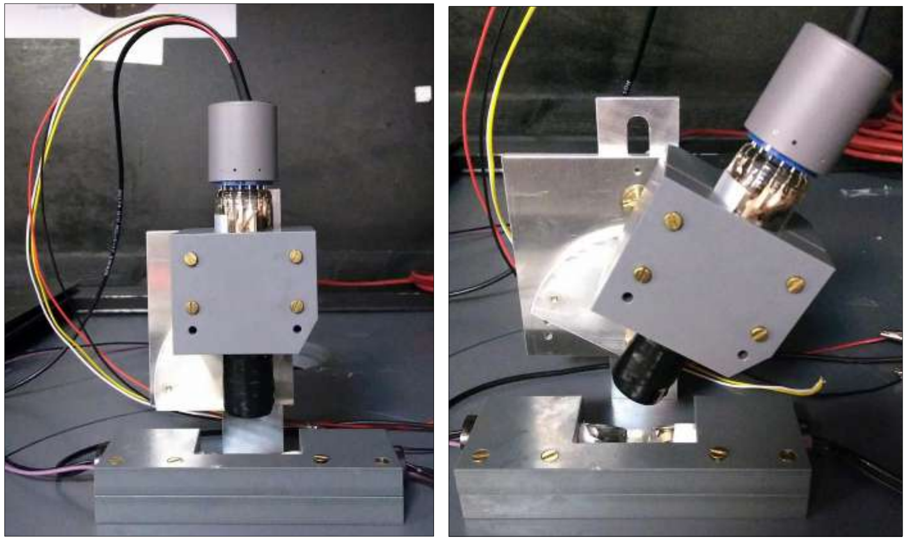
Electron trigger with optical guides and PMs

β-backscattering tests @ e- spectrometer



- <u>Black box:</u>
  - Plastic scintillator (rotatable)
    - radius = 1 cm
    - length = 5 cm

→ collecting data with different electron incident angles (θ = 0°, 20°, 40°)



Plastic scintillator fixed on a rotatable support

β-backscattering tests @ e- spectrometer

EXPERIMENTAL MEASUREMENTS

- 13 runs varying 0.7 MeV < E_e < 1.8 MeV at different incident angles with respect to the scintillator (0°,20°,40°)

DATA ANALYSIS

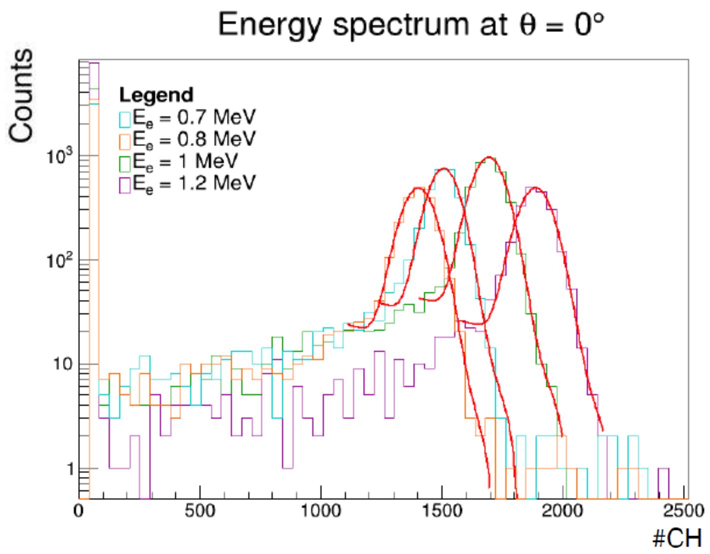
- Reconstruction of the ADC spectra
- Gaussian+background fits
  - → μ → energy calibration
  - → σ → used to apply resolution to G4 simulations

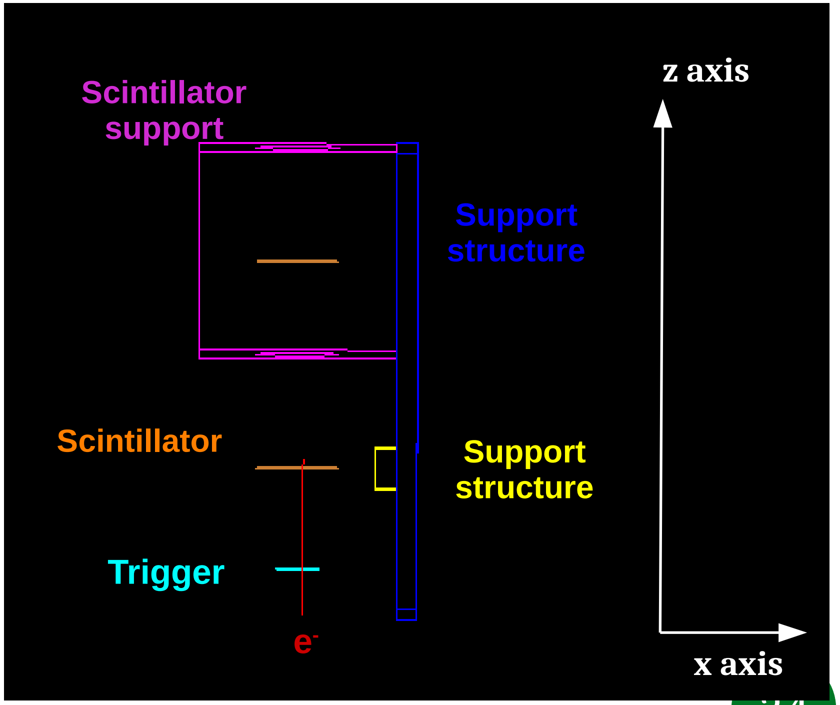
G4 SIMULATIONS

- Each run simulated by using 8 different *PhysicsLists*

COMPARISON EXP/G4 SIMULATIONS

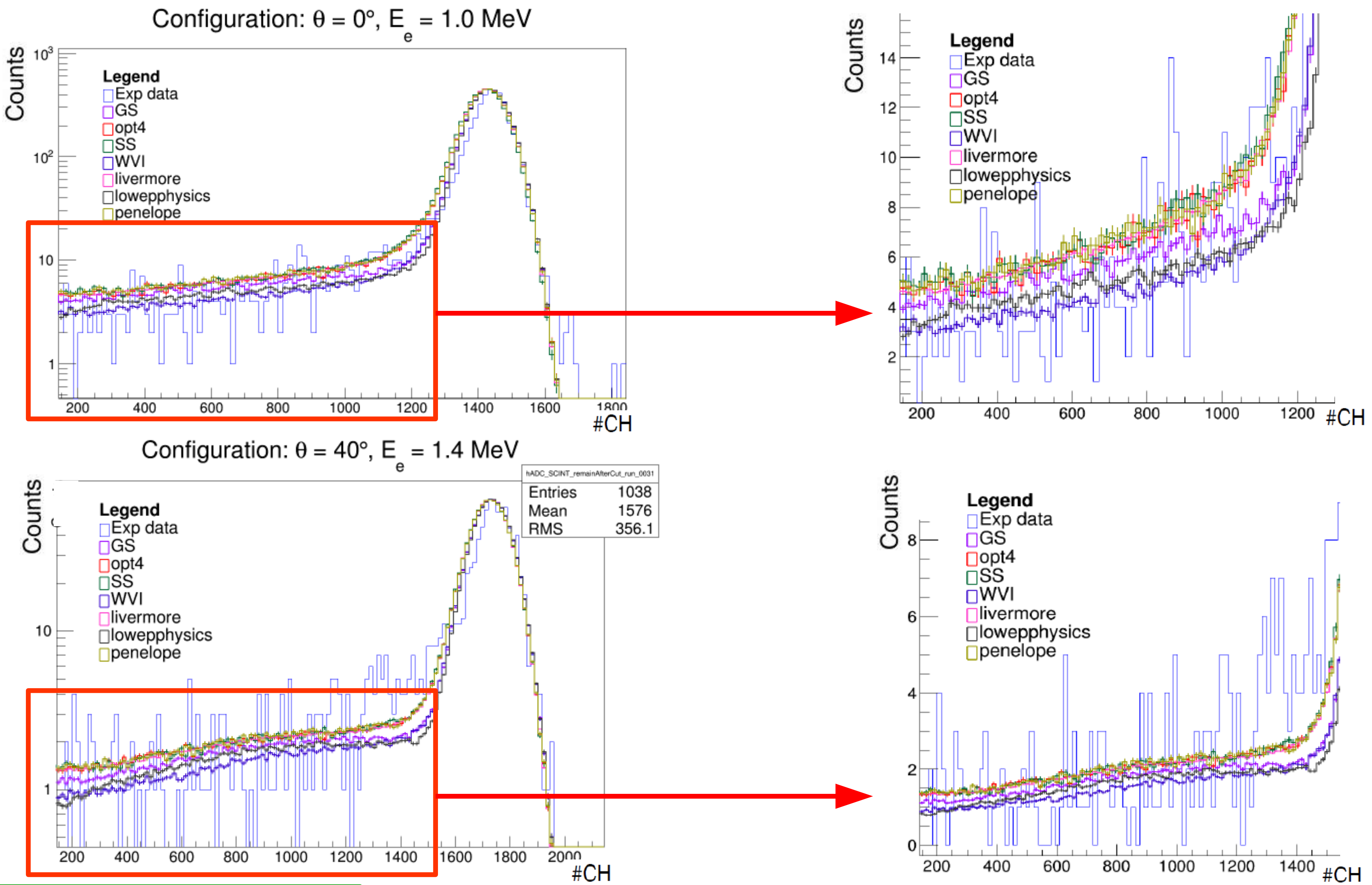
- β-backscattering coefficients computed (± stat. ± syst.)





β-backscattering tests @ e- spectrometer

EXAMPLES (LOWEST AND HIGHEST θ_{INC}):



QUALITATIVELY:

- GS and SS describe better the experimental spectra

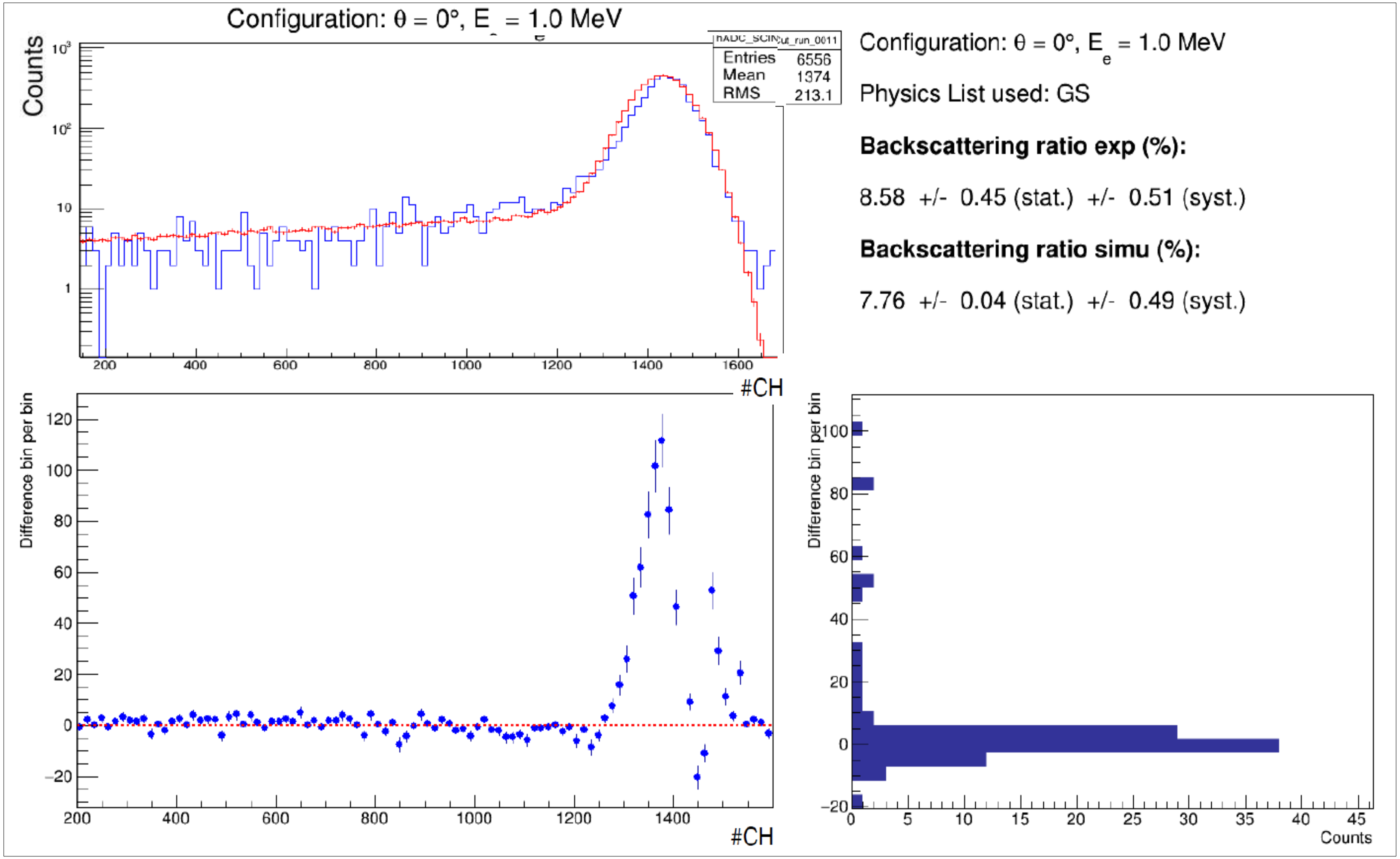
F. Cresto

β-backscattering tests @ e- spectrometer

QUANTITATIVELY:

→ **Residual plots**
→ **Backscattering coefficient experimental/simulated spectra**

<u>EXAMPLE:</u> E_e = 1 MeV, θ = 0°



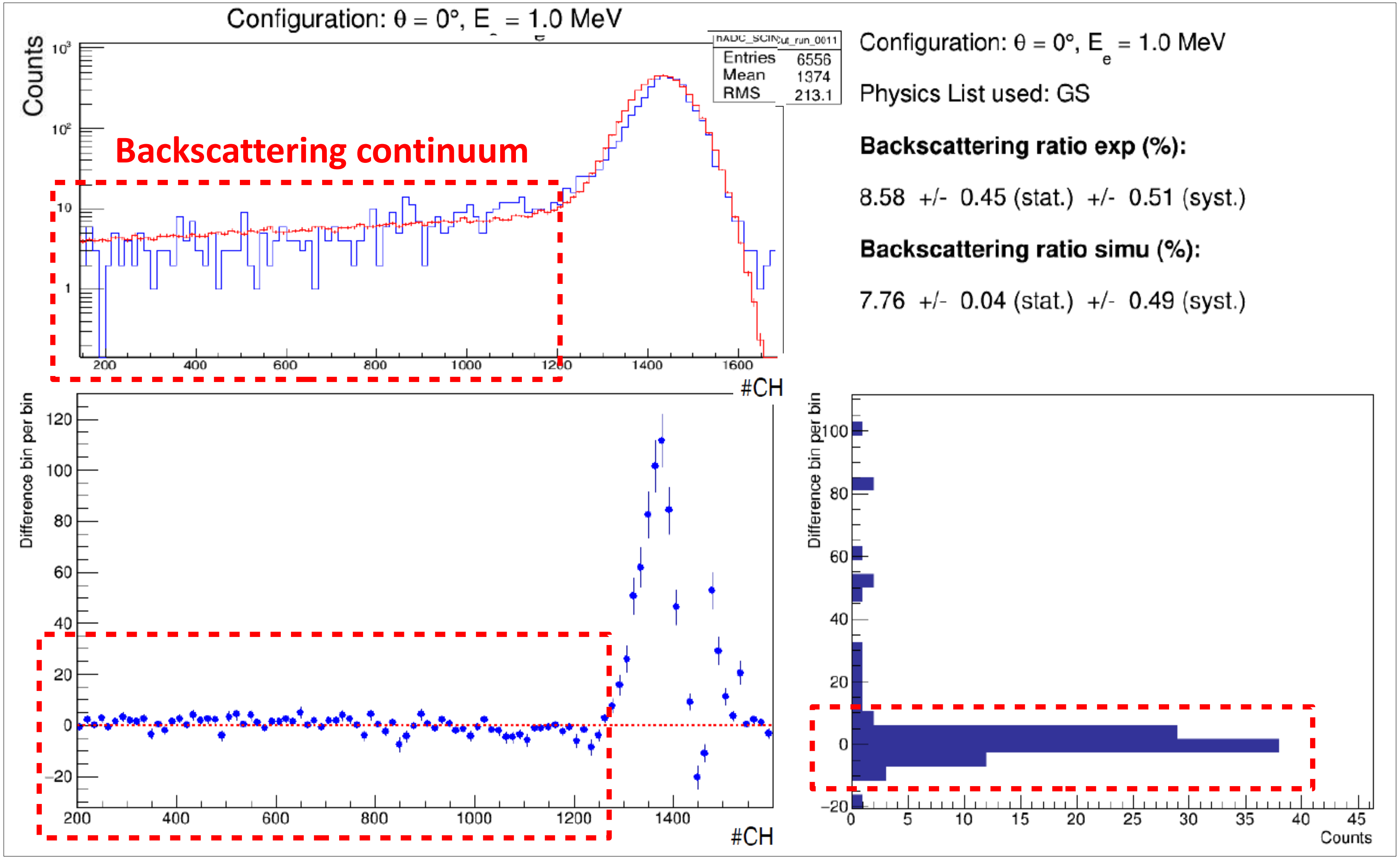
F. Cresto

β-backscattering tests @ e- spectrometer

QUANTITATIVELY:

→ **Residual plots**
→ **Backscattering coefficient experimental/simulated spectra**

EXAMPLE: E_e = 1 MeV, θ = 0°



β-backscattering tests @ e- spectrometer

QUANTITATIVELY:

→ **Residual plots**
→ **Backscattering coefficient experimental/simulated spectra**

- Qualitatively → best reproduction with GS and SS PhysicsList
- Quantitatively?

$E_e = 1.0$ MeV, $\theta = 0°$

Run name + PhysicsList	Backscattering coefficient (%) Value	Stat.	Syst.
hADC_SCINT_remainAfterCut_run_0011	8.58	0.45	0.51
run_0011_GS	7.76	0.04	0.49
run_0011_opt4	8.88	0.05	0.41
run_0011_SS	9.17	0.05	0.40
run_0011_WVI	6.40	0.03	0.61
run_0011_lowepphysics	6.84	0.03	0.57
run_0011_penelope	9.05	0.05	0.40

Exp. spectrum
Simu. spectrum

$E_e = 1.0$ MeV, $\theta = 20°$

Run name + PhysicsList	Value	Stat.	Syst.
hADC_SCINT_remainAfterCut_run_0013	9.87	0.48	0.44
run_0013_GS	9.23	0.04	0.42
run_0013_opt4	10.48	0.06	0.35
run_0013_SS	10.67	0.06	0.34
run_0013_WVI	7.82	0.04	0.50
run_0013_lowepphysics	8.39	0.04	0.47
run_0013_penelope	10.84	0.06	0.34

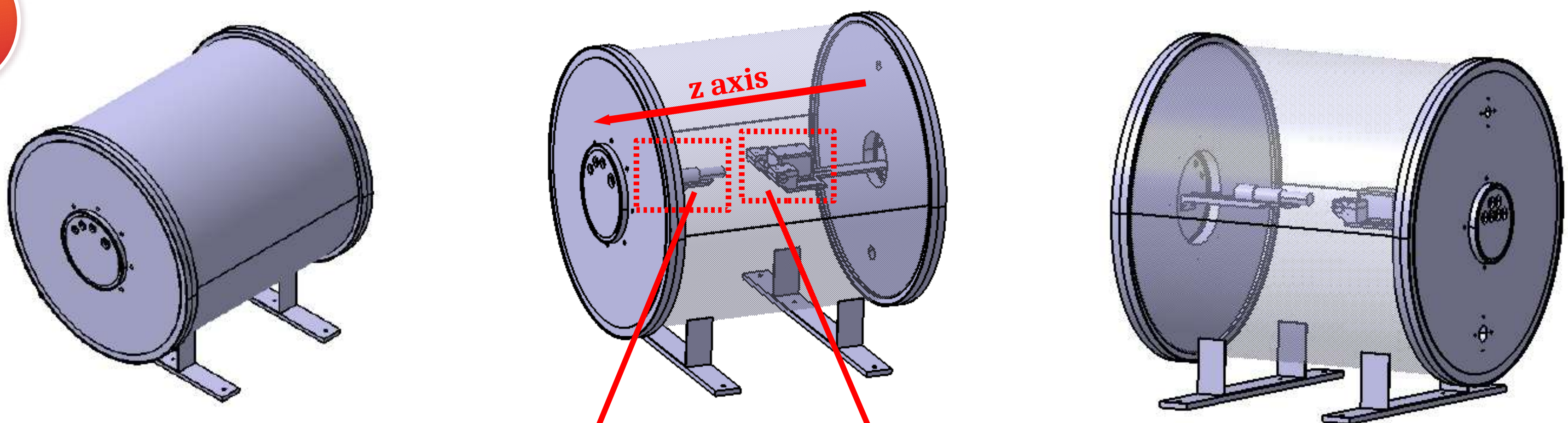
$E_e = 1.4$ MeV, $\theta = 40°$

Run name + PhysicsList	Value	Stat.	Syst.
hADC_SCINT_remainAfterCut_run_0031	17.14	1.40	1.14
run_0031_GS	13.75	0.05	1.38
run_0031_opt4	15.14	0.06	1.20
run_0031_SS	15.12	0.06	1.20
run_0031_WVI	11.93	0.04	1.62
run_0031_lowepphysics	12.89	0.05	1.50
run_0031_penelope	15.23	0.06	1.19

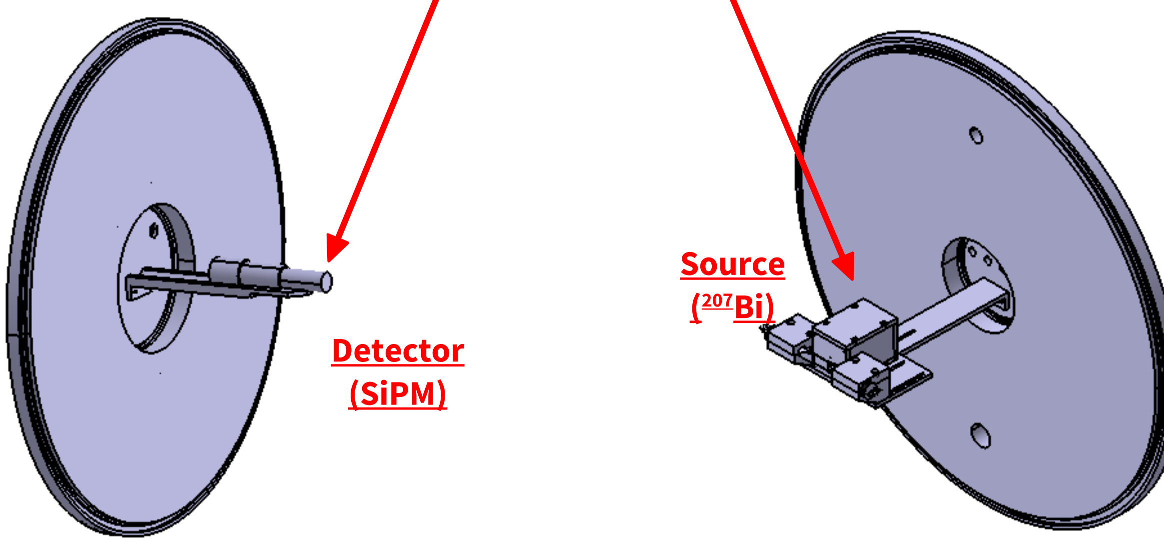
β-backscattering tests @ new set-up

Two different set-ups were originally conceived and simulated
in order to decide the final configuration

1



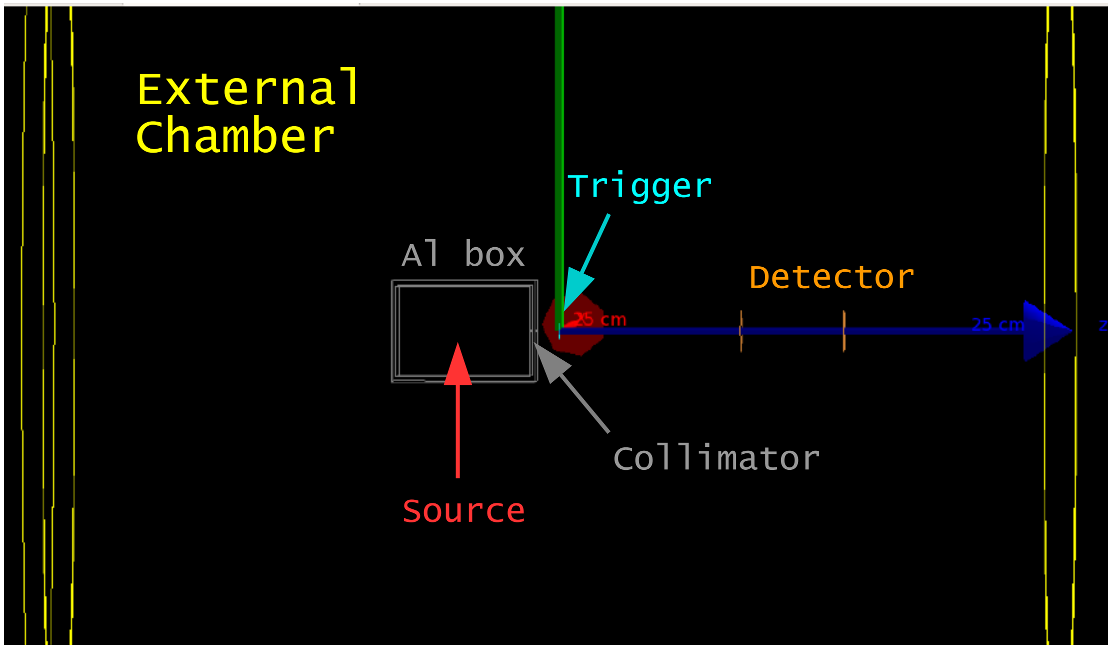
Detector collinear with the z axis for the time being (expected upgrade: rotation)



- Box of Al 5x5x5 mm
- Source may be placed at the different z positions
- Collimator r=1 mm
- **Trigger 200 um**
- **Vacuum**

β-backscattering tests @ new set-up

^{207}Bi source positioned at the **centre of the Al box**



DIMENSIONS:

→ Al box → thickness = 5 mm
→ **collimator → radius = 1 mm**
→ trigger → thickness = 200 um
→ detector → r = 1.5 cm, l = 5 cm

DISTANCES:

→ source – collimator = 4.6 cm (*)
→ collimator – trigger = 1.1 cm
→ **trigger – detector = 5.0 cm (*)**

(*) these distances can be varied in simulations

PROS:

→ incoming e- beam precisely collimated

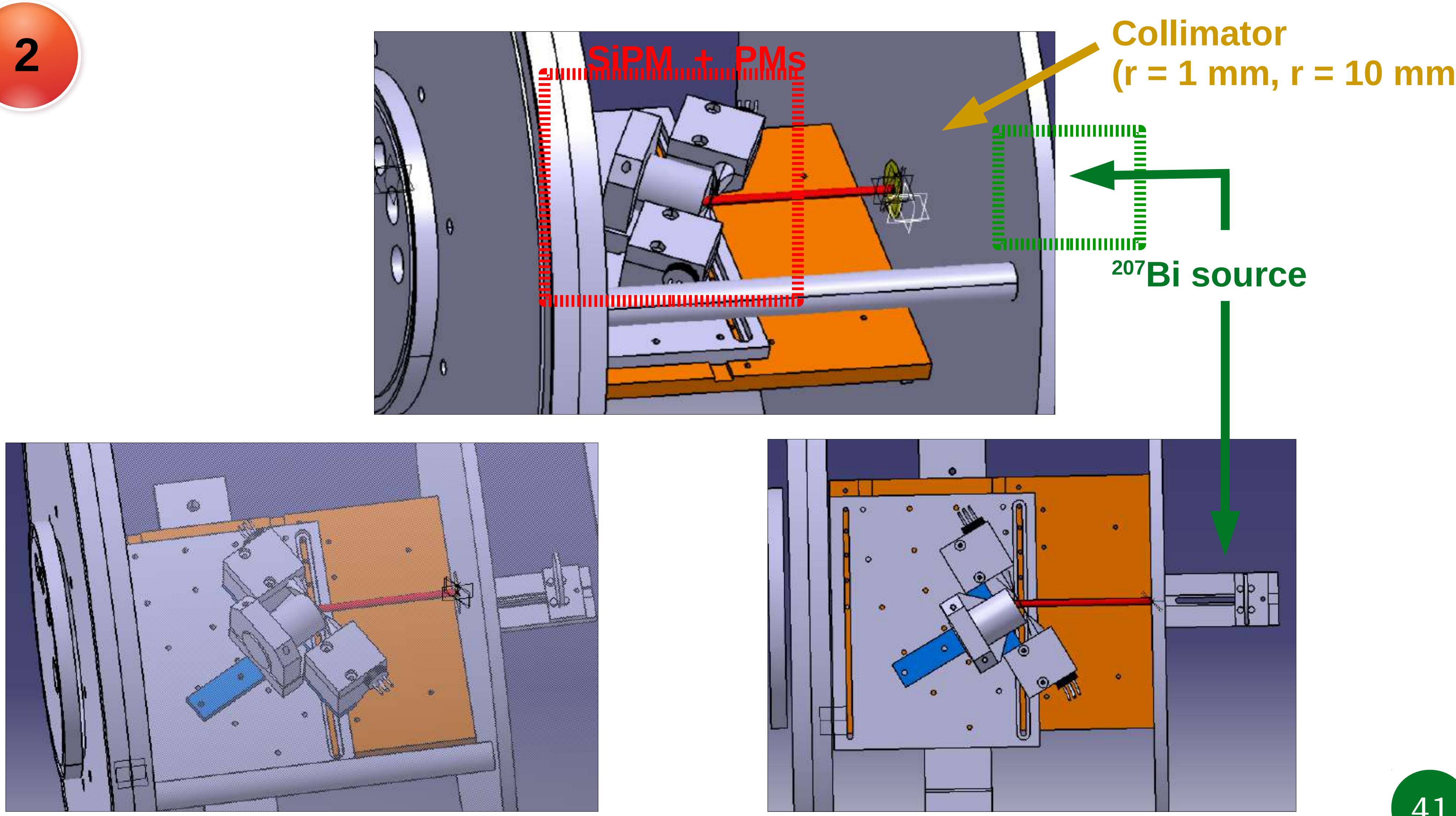
CONS:

→ solid angle too little
→ acquisition time to obtain reasonable e- spectra too long

β-backscattering tests @ new set-up

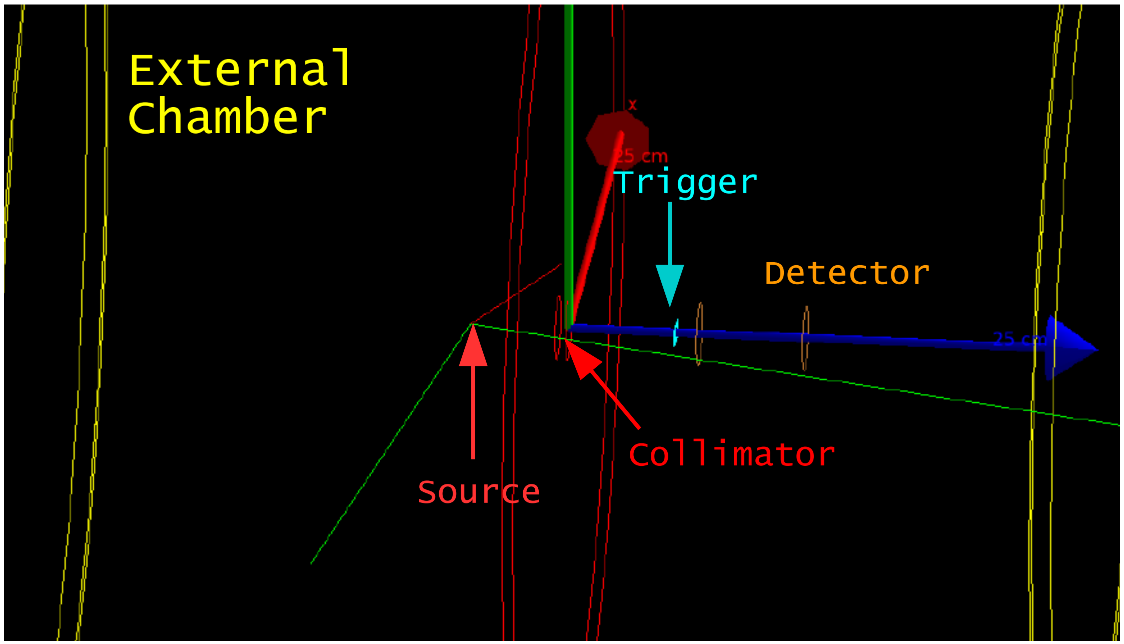
Two different set-ups were originally conceived and simulated
in order to decide the final configuration

2



β-backscattering tests @ new set-up

^{207}Bi source positioned **without the Al box**



DIMENSIONS:

→ **collimator → radius = 1.5 cm**
→ trigger → thickness = 200 um
→ detector → r = 1.5 cm, l = 5 cm

DISTANCES:

→ source – collimator = 3.0 cm (*)
→ collimator – trigger = 5.0 cm (*)
→ **trigger – detector = 1.1 cm**

(*) these distances can be varied in simulations

DIFFERENCES BETWEEN THE TWO SET-UPS:

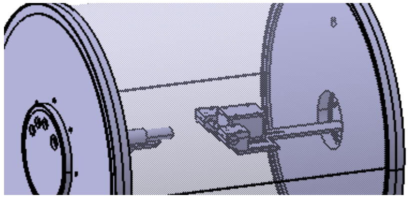
→ NO Al box
→ collimator with higher radius, as large as the external chamber
→ distance between trigger and detector fixed at the minimum value request from mechanical constraints

G4 simulations will allow to choose the best experimental configuration

β-backscattering tests @ new set-up

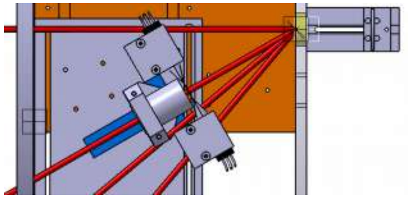
Simulations have been performed to choose the experimental set-up:

- $N_{\text{simulated events}} = 400\text{ M}$



FIRST SET-UP:

Dist deltaE-detector [cm]	N° incident e- on detector base (already triggered)	Peak of incident angle distribution [°]	N. retrodiff	Backscattering coeff. (%)
5.83	2069	9-12	39	1.88
8.83	1188	6-9	17	1.43



SECOND SET-UP:

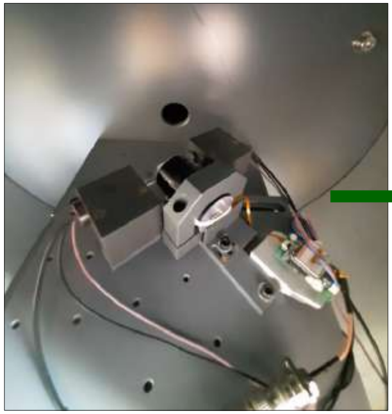
Rcoll [cm]	Dist source-coll [cm]	Dist coll-deltaE[cm]	N° incident e- on detector base (already triggered)	Peak of incident angle distribution [°]	N. retrodiff	Backscattering coeff. (%)
0.5	3.5	5	41690	6-9	737	1.77
1.5	3.5	5	41493	6-9	737	1.78
0.5	5.5	2	49505	6-9	1021	2.06
1.5	5.5	2	56233	6-9	1193	2.12
0.5	5.5	6	18409	6-9	343	1.86
1.5	5.5	6	18461	6-9	344	1.86

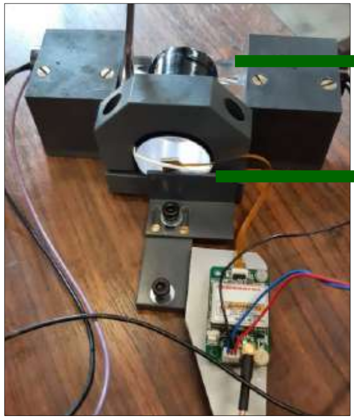
β-backscattering tests @ new set-up

Second experimental set-up realized and mounted (February 2021, CENBG):

→ possibility to maintain a collimated particle emission

→ sensibly higher data collection given the same source activity





Plastic scintillator (t = 1 mm)
+ 2 PMs

SiPM
(Hamamatsu , C13367-1350EA)

Current data taking:

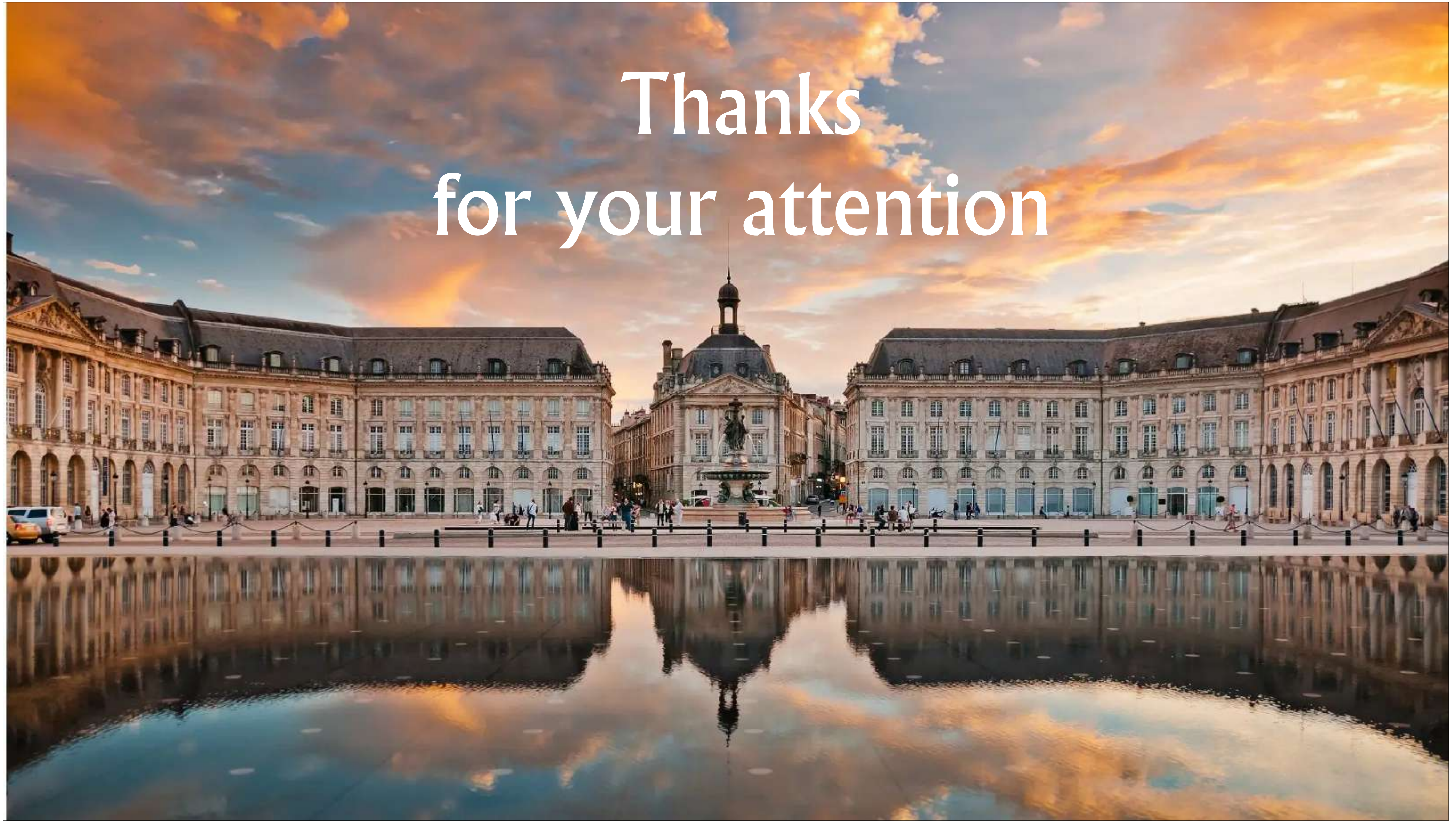
→ ^{207}Bi source (A = 148.7 kBq @ 01/02/2021)

→ old GANIL acquisition system

→ 28 runs being acquired (different θ, l):

13 runs with higher collimator radius (r = 1 cm)
+ 13 runs with lower collimator radius (r = 1 mm)
+ 2 runs of background

Additional runs will be acquired to get rid of the gamma contribution (Al shield, t ≈ 3 mm)


Thanks
for your attention