Bolometric measurement of the 2νββ decay of ^{100}Mo with an array of $ZnMoO_4$ bolometers @ LNGS

Claudia Tomei - INFN Roma - on behalf of

L. Cardani[1, 2], L. Gironi[3, 4,*] N. Ferreiro Iachellini[4], L. Pattavina[5], J.W. Beeman[6], F. Bellini[1, 2], N. Casali[5], O. Cremonesi[4], I. Dafinei[2], S. Di Domizio[7], F. Ferroni[1, 2], E. Galashov[8], C. Gotti[4], S. Nagorny[5], F. Orio[2], G. Pessina[4], G. Piperno[1, 2], S. Pirro[4], E. Previtali[4], C. Rusconi[4], C. Tomei[2], and M. Vignati[2]

[1] *Dipartimento di Fisica, Sapienza Università di Roma, Roma I-00185, Italy*
[2] *INFN- Sezione di Roma, Roma I-00185, Italy*
[3] *Dipartimento di Fisica, Università di Milano-Bicocca, Milano I-20126 - Italy*
[4] *INFN - Sezione di Milano Bicocca, Milano I-20126 - Italy*
[5] *INFN - Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila) I-67010 - Italy*
[6] *Lawrence Berkeley National Laboratory, Berkeley, California 94720 - USA*
[7] *Dipartimento di Fisica, Università di Genova and INFN - Sezione di Genova, I-16146 Genova - Italy and*
[8] *Department of Applied Physics, Novosibirsk State University, Novosibirsk 630090 - Russia*

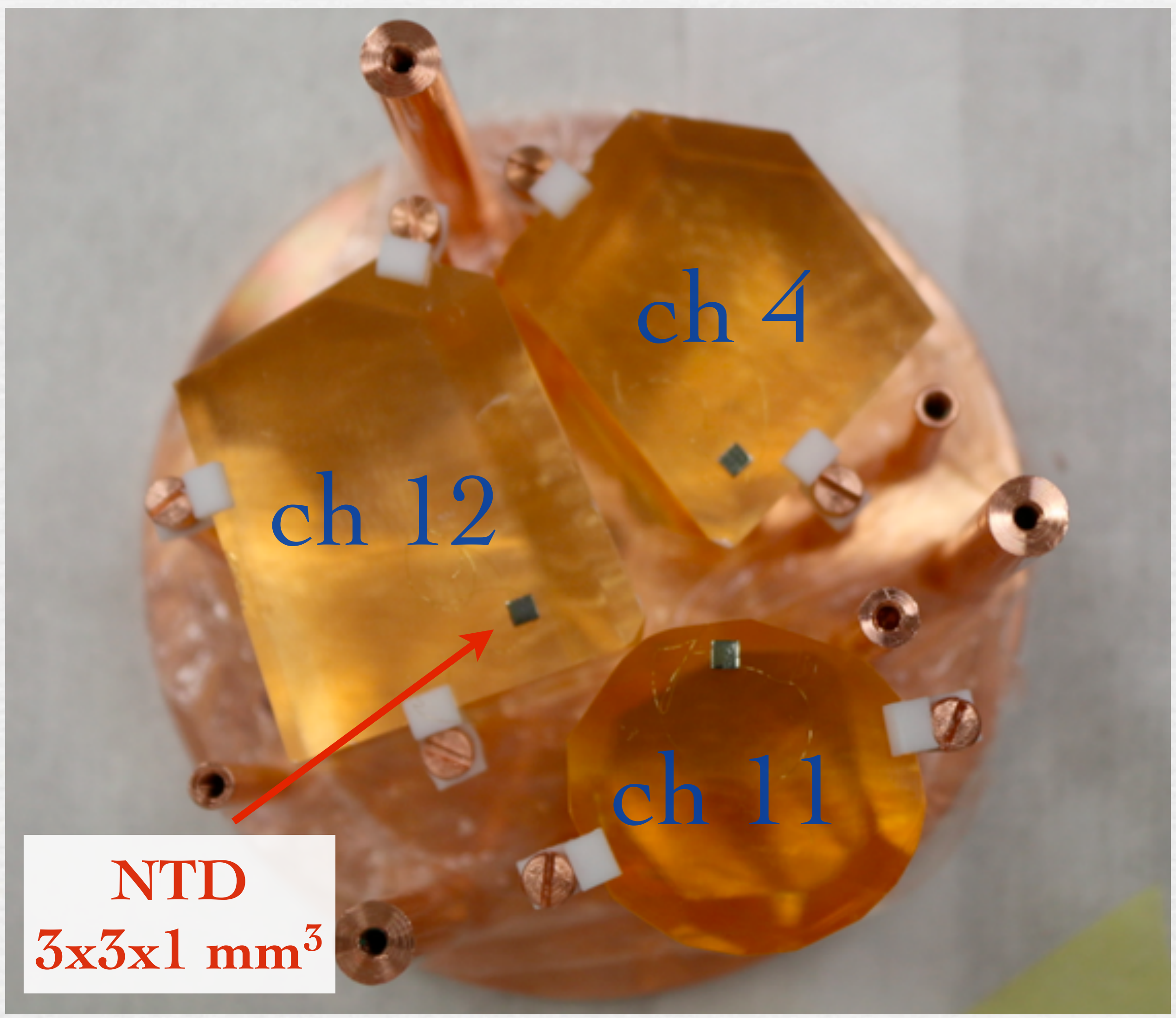
Outline

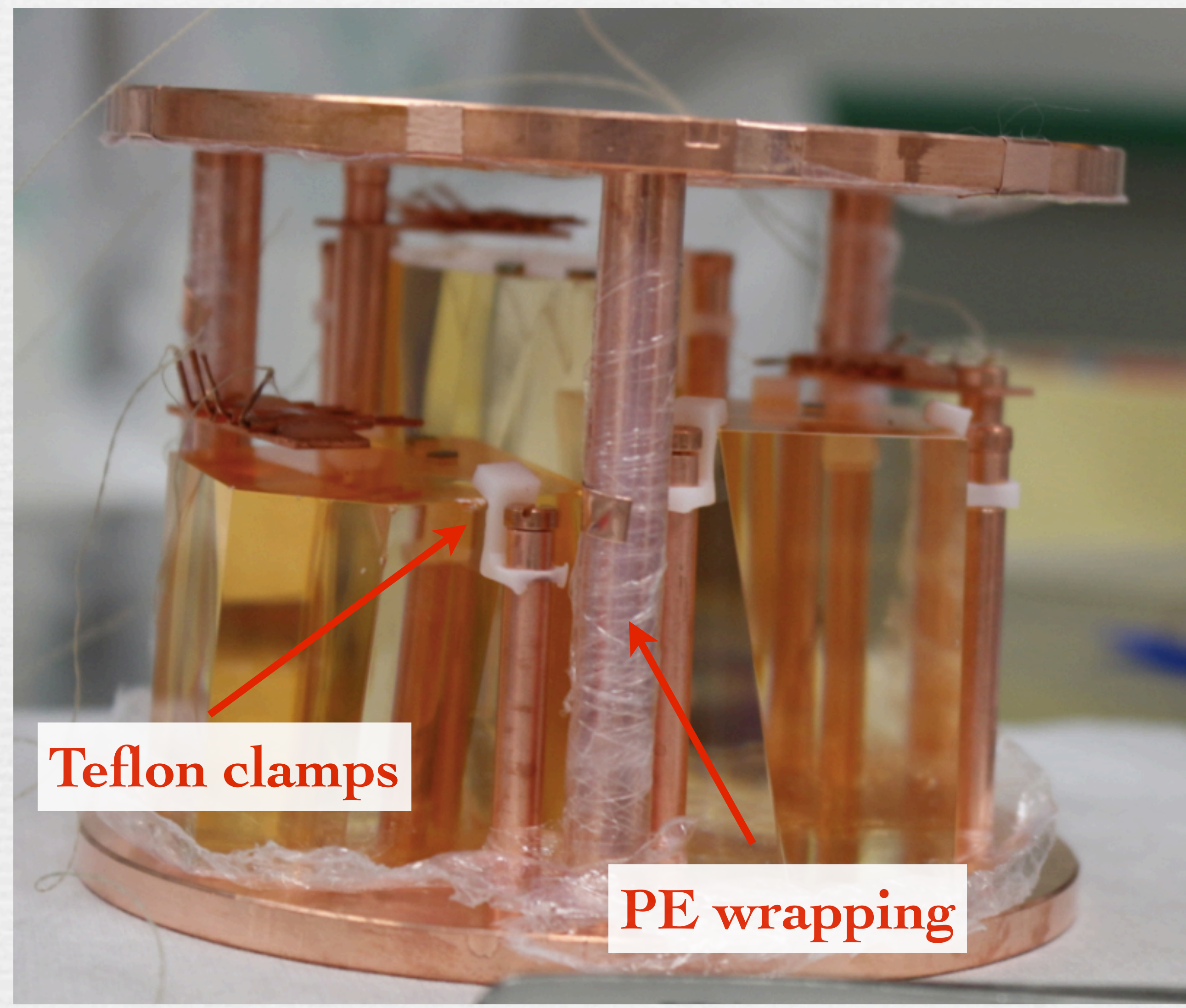
- Description of the experimental setup;
- Data analysis;
- General performances of the detectors;
- Bolometric measurement of the $2\nu\beta\beta$ decay of ^{100}Mo.

Experimental setup

3 detectors for a total mass of 811 g

Crystals grown at NIIC, Novosibirsk (Russia) using the low-thermal-gradient Czochralski technique. Starting materials: high purity ZnO (Umicore) and MoO_3 (NIIC).

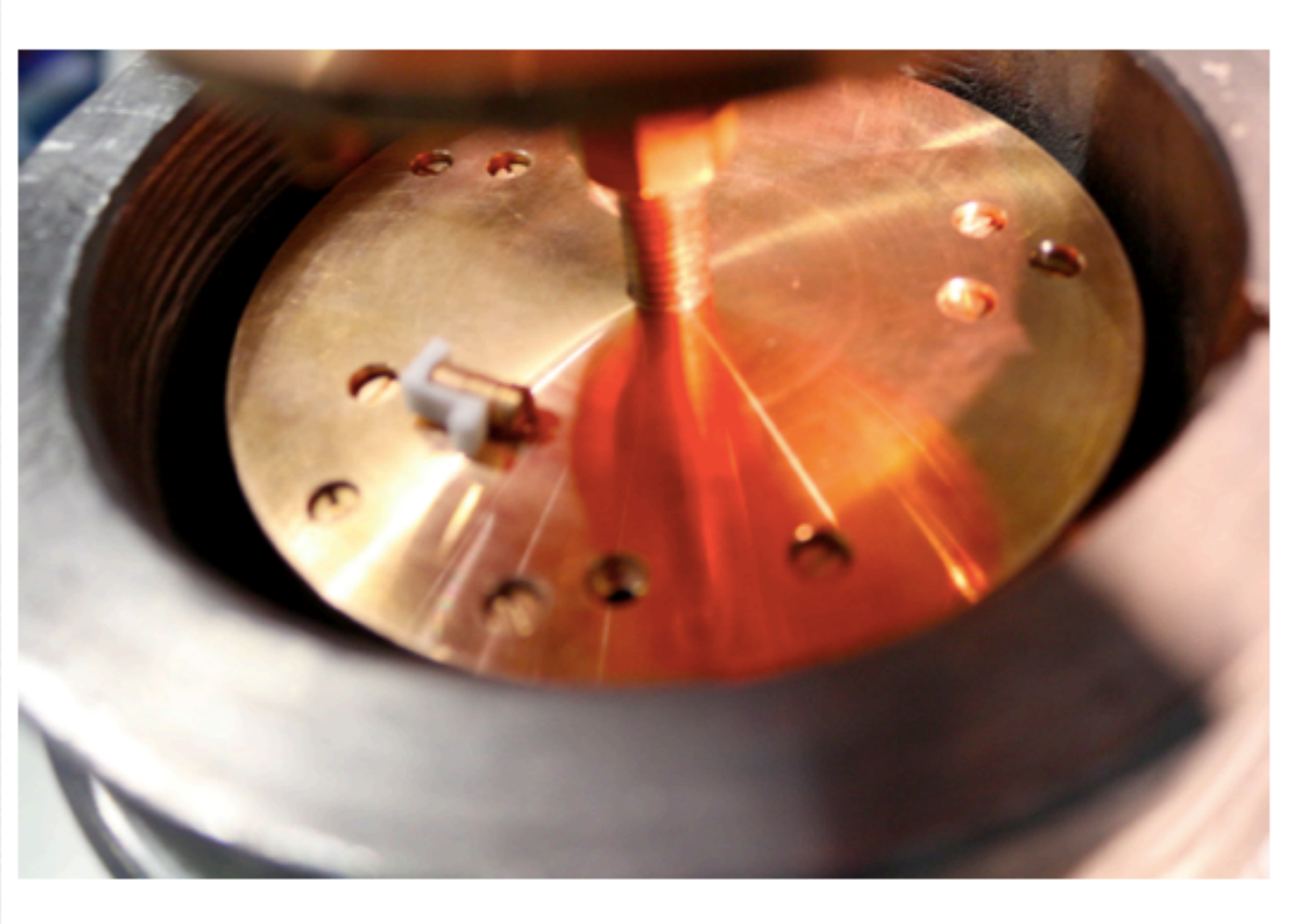




ch12 already operated in a previous run, results published in [J. Beeman et al., EPJ C 72 (2012)]

Experimental setup

- Ancient roman lead shield to reduce gamma radioactivity from outer cryostat shields and lab environment;
- Mounted in Hall C cryostat @ LNGS (INFN);
- T ~ 10 mK;
- No light detectors.

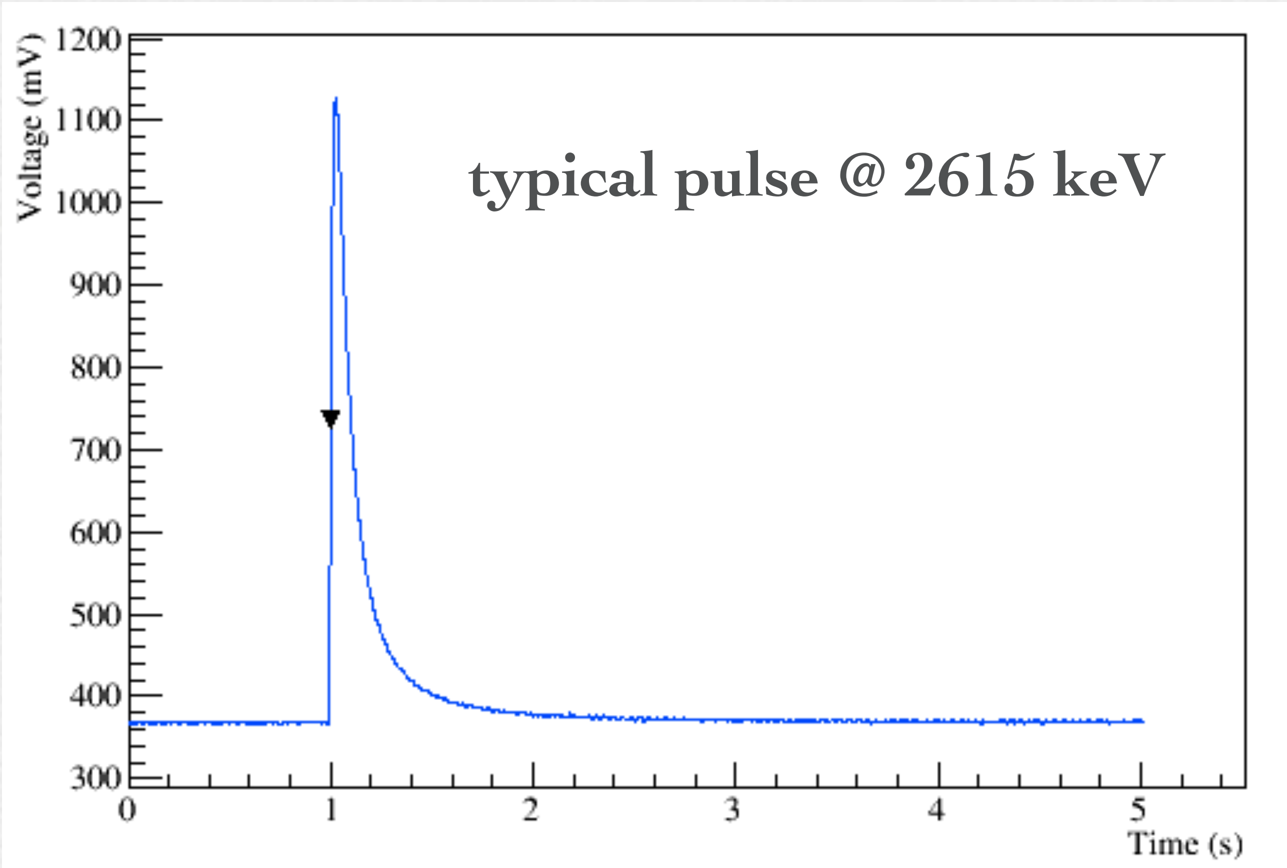


Data taking and analysis

Background	898.51 h
^{232}Th Calibration	173.96 h
^{40}K Calibration	19.58 h

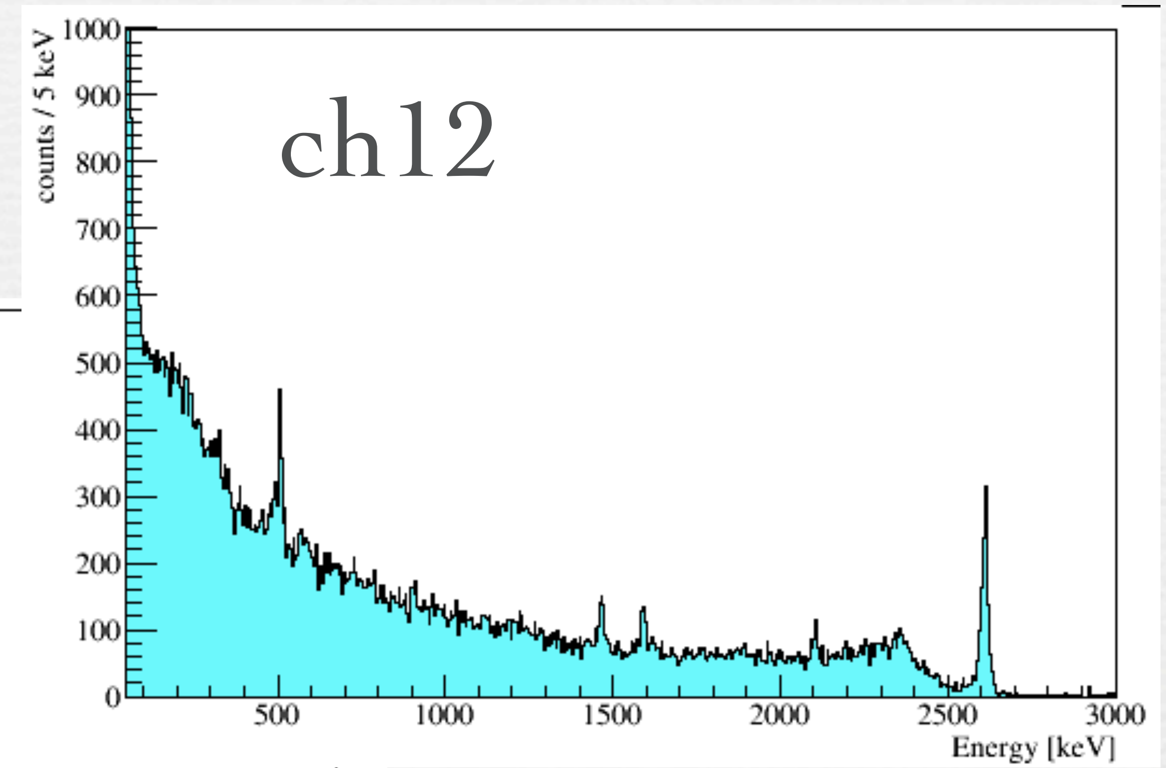
Data analysis chain

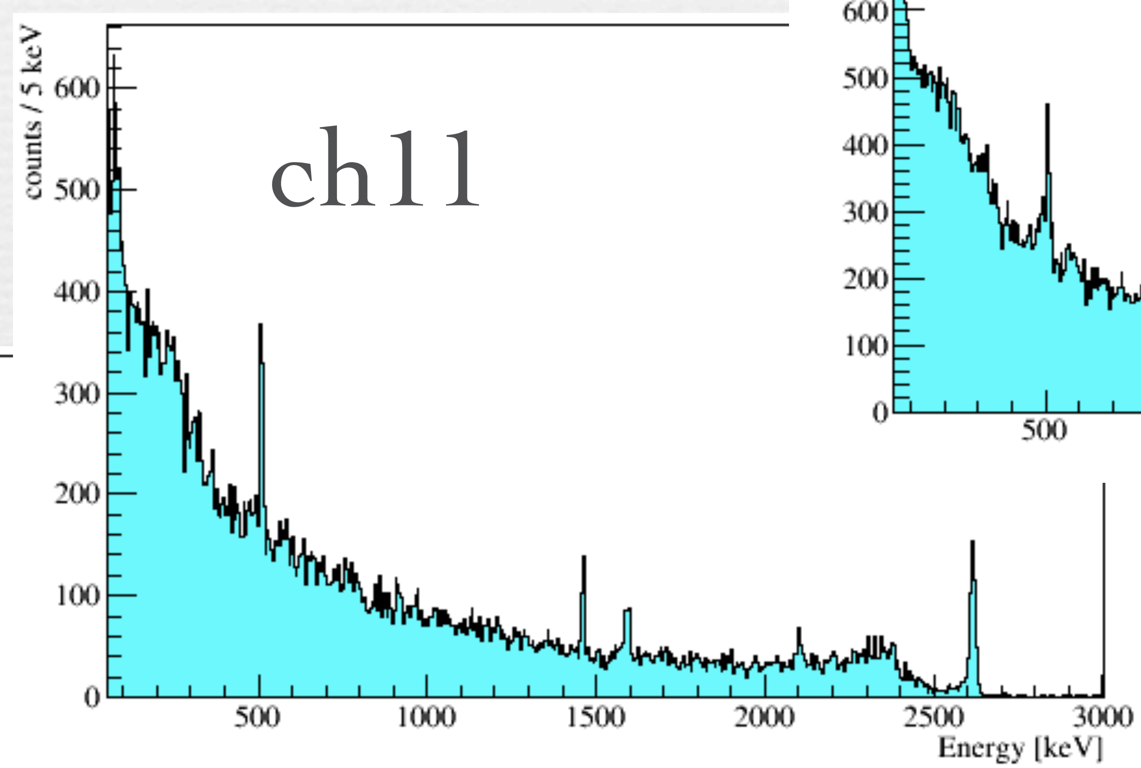
- Pulse amplitude and shape parameters estimation (OF)
- Energy calibration
- PSA cuts
- Evaluation of coincidences

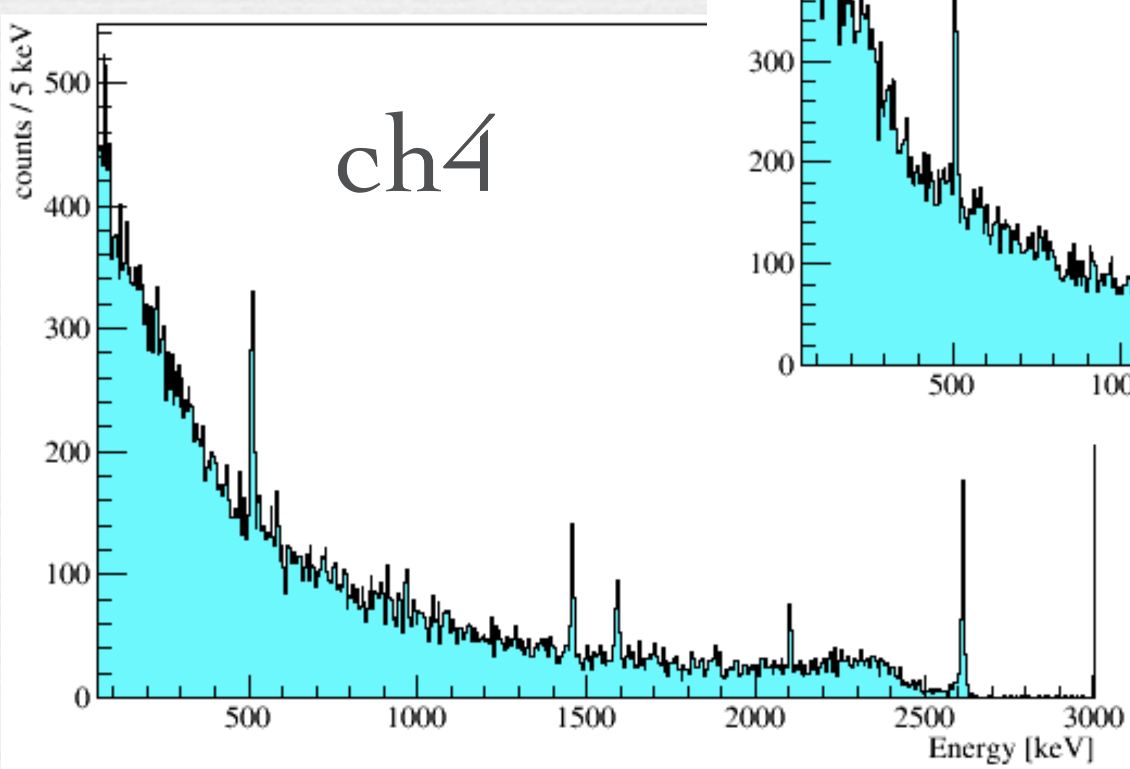


Energy calibration

Calibration function: 2nd order polynomial with zero intercept







Residuals on thallium peaks < 2 keV (<1 keV on 2615 keV)

Pulse shape cuts

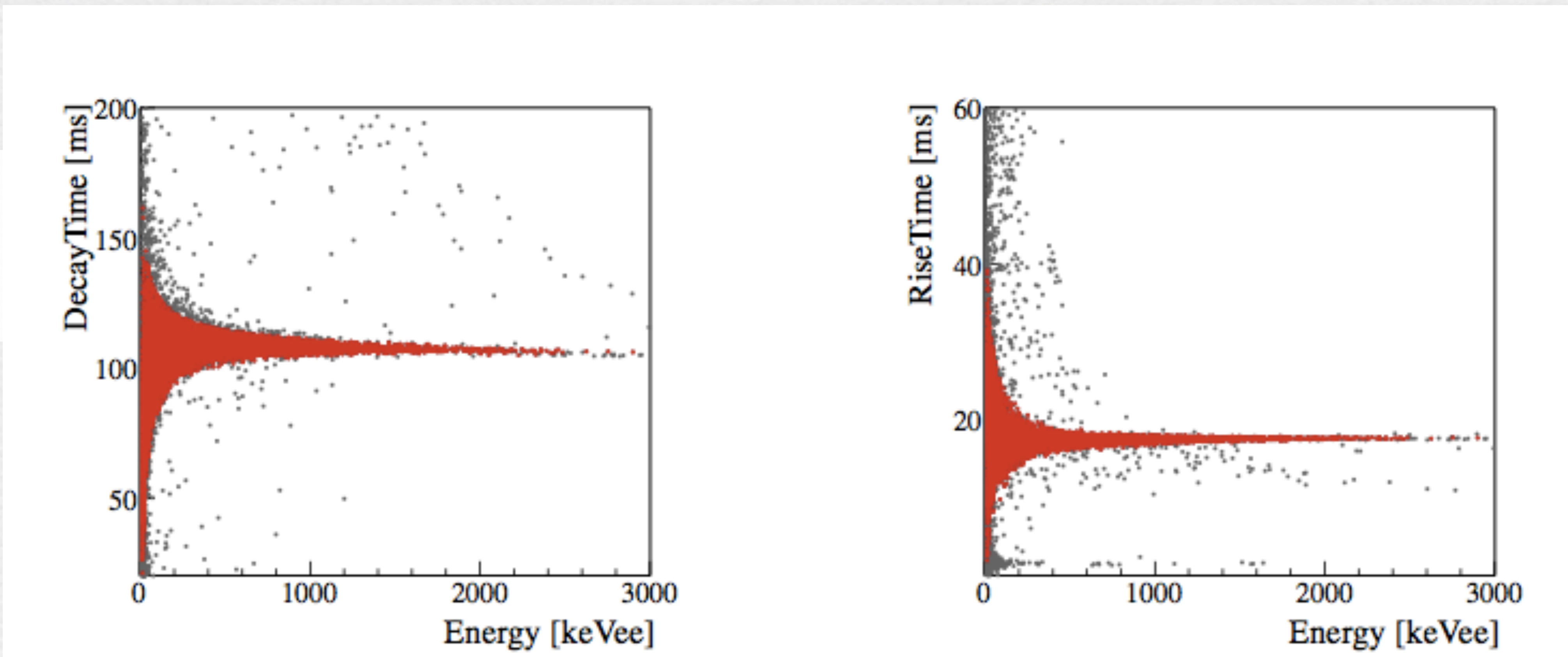
BaselineSlope: slope of the baseline evaluated on the pretrigger (~1s);

OF_RiseTime (OF_DecayTime): Rise (Decay) time of the OF filtered pulse, evaluated as time difference between the 10% and the 90% of the leading edge, and the time difference between the 90% and 30% of the trailing edge, respectively;

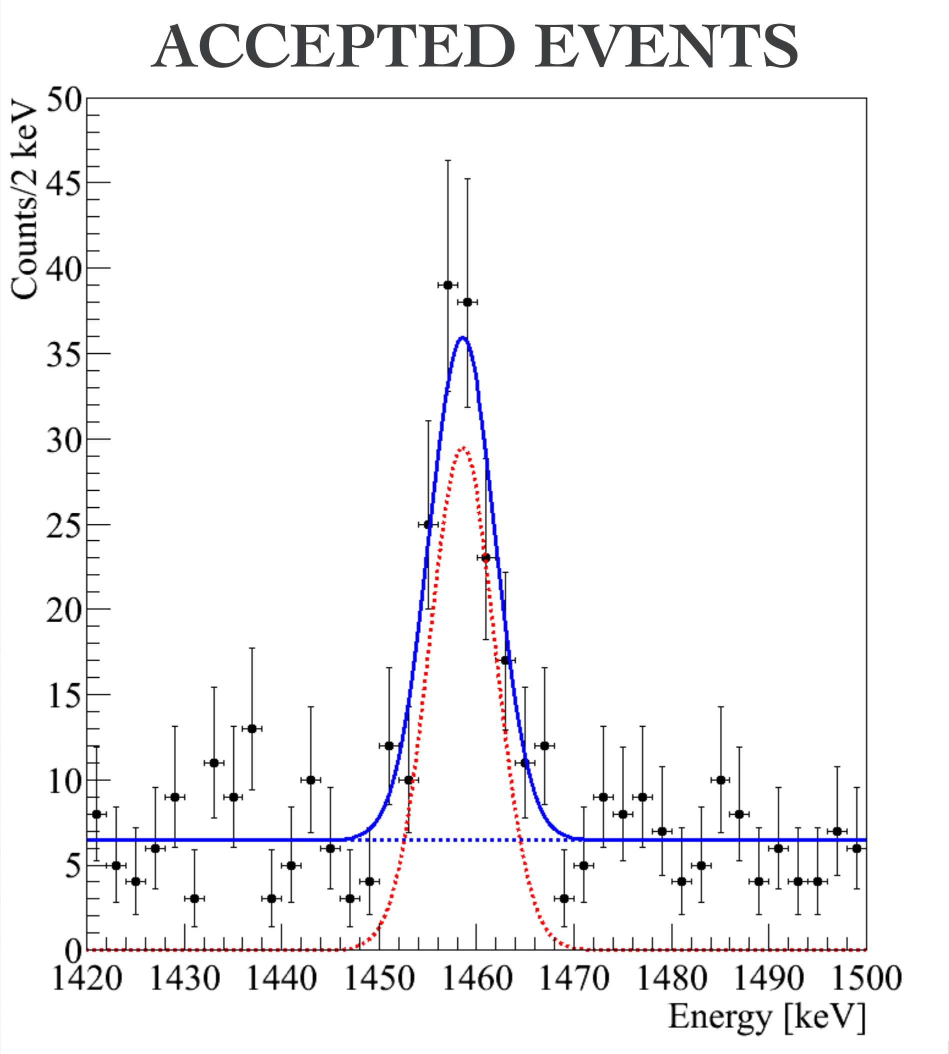
OF_TVR (OF_TVL): mean quadratic deviation of the OF filtered pulse from the OF filtered average detector response, evaluated on the right (left) side of the pulse with respect to the maximum.

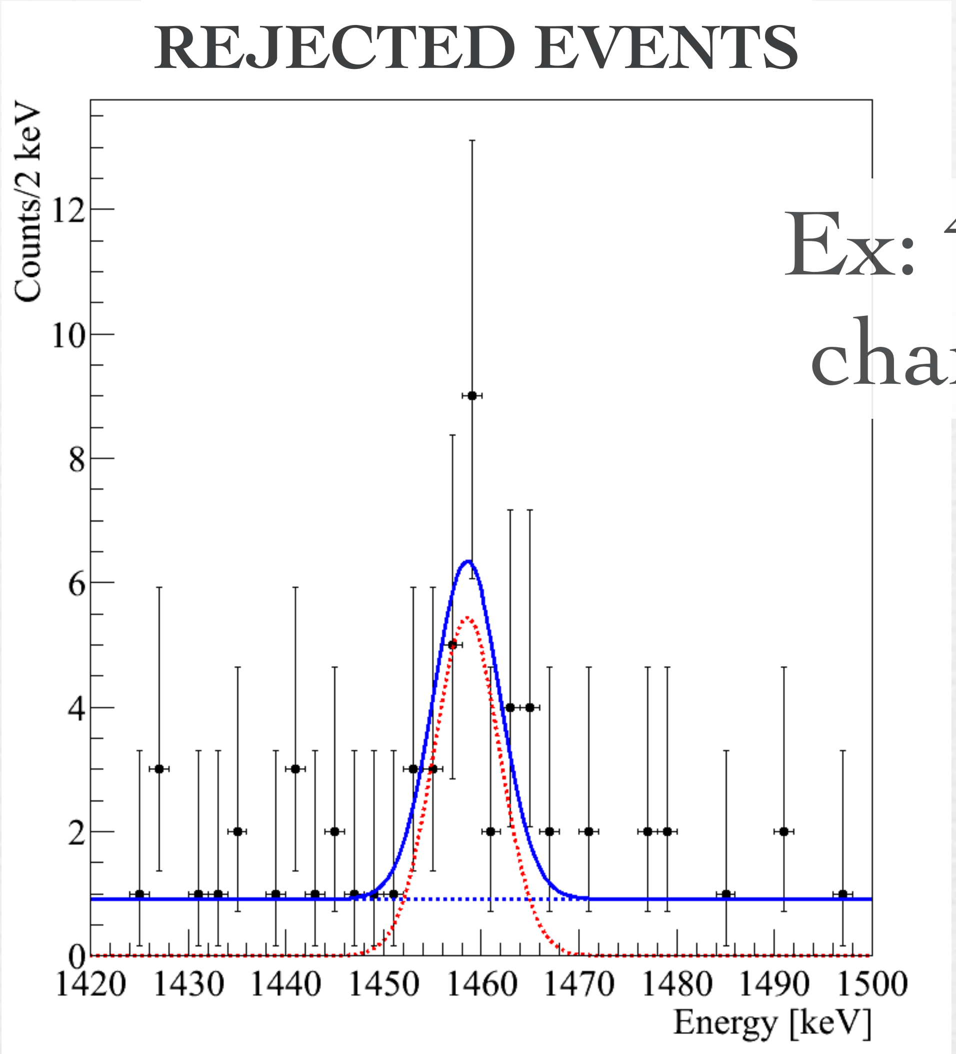
- Fit of the given shape parameter dependence on energy using calibration peaks
- Apply number-of-sigma cuts on normalized variables (no energy dependence)

Ex: RiseTime and DecayTime for channel 11



PSA cuts efficiency





Ex: ^{40}K for channel 4

The efficiency after the pulse shape cuts was evaluated for each crystal with a simultaneous fit on accepted and rejected events on the ^{228}Th and ^{40}K calibration lines.

The average values on the entire energy spectrum (511 keV - 2615 keV) are: 85±2%, 86±3%, 83±3% for the three crystals, respectively.

Coincidences

Standard coincidence window: 100 ms.

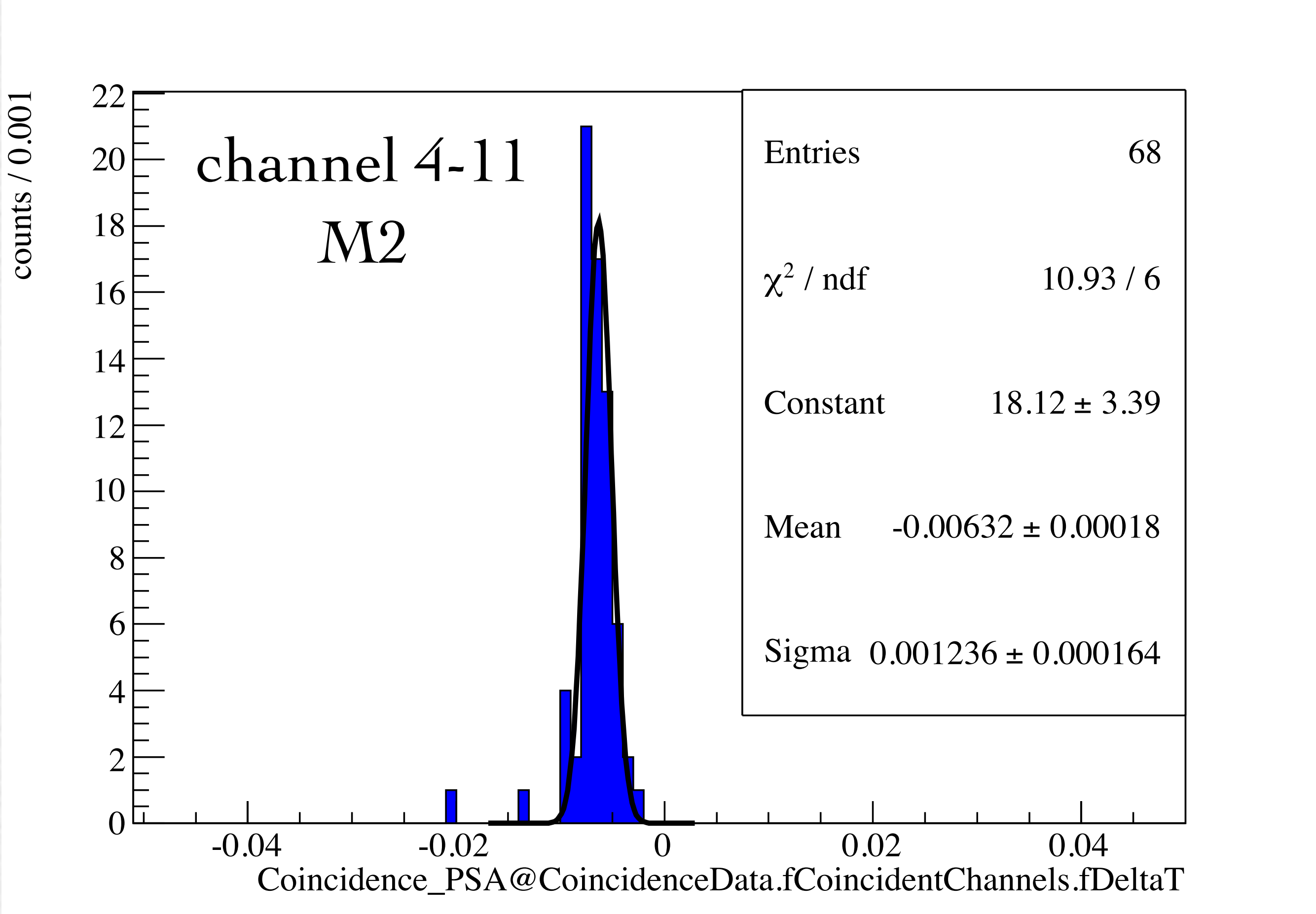
Ch	Rate before Cuts [mHz]	Rate after Cuts [mHz]
4	6.4	3.3
11	7.1	4.5
12	46	26

Channels	Random coincidence rate in 100 ms [Hz]
4/11	$1.5 \cdot 10^{-6}$
4/12	$9 \cdot 10^{-6}$
11/12	$1.3 \cdot 10^{-5}$

Optimized coincidence window: 25 ms.

To evaluate the optimal coincidence window we analyzed the distribution of the DeltaT in double coincidences with total energy @ 2615 keV for the 3 couples of channels.

With a much narrower coincidence window we can reject random coincidences.



General Performances

Crystal	mass [g]	R_{base} [MΩ]	A_S [μV/MeV]	$\sigma_{baseline}$ [keV RMS]	τ_R [ms]	τ_D [ms]
ch 4	235.2	37	53	1.89	19	138
ch 11	247.0	17	75	1.25	18	106
ch 12	328.8	40	116	5.46	30	116

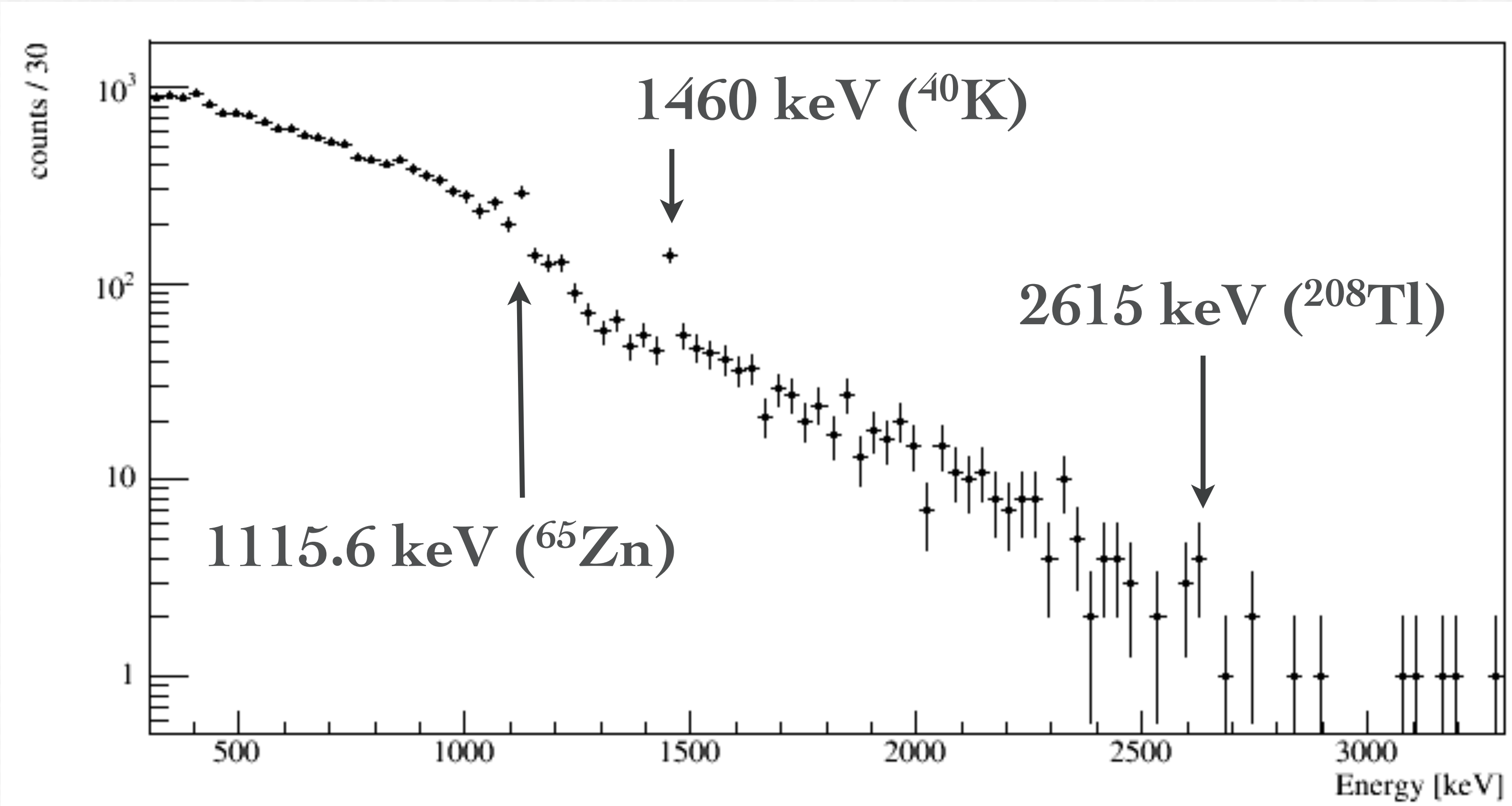
Energy Resolution

Peak	Energy [keV]	ch 4	ch 11	ch 12
Pb X-ray	74.2*	5.12 ± 0.64	4.35 ± 0.54	–
Pb X-ray	84.8*	5.12 ± 0.64	4.35 ± 0.54	–
	511	8.04 ± 0.65	9.32 ± 0.79	10.96 ± 1.47
^{40}K	1461	8.36 ± 0.93	6.45 ± 0.67	18.7 ± 3.03
^{208}Tl double escape	1593	9.96 ± 1.8	15.2 ± 2.1	14.4 ± 0.29
^{208}Tl single escape	2104	8.3 ± 3.7	17.8 ± 8.9	14.3 ± 28.6
^{208}Tl	2615	9.3 ± 1.3	16.0 ± 2.4	22.0 ± 2.3
^{210}Po	5400	8.39 ± 0.28	7.76 ± 0.19	19.7 ± 0.76

α/β discrimination by pulse shape

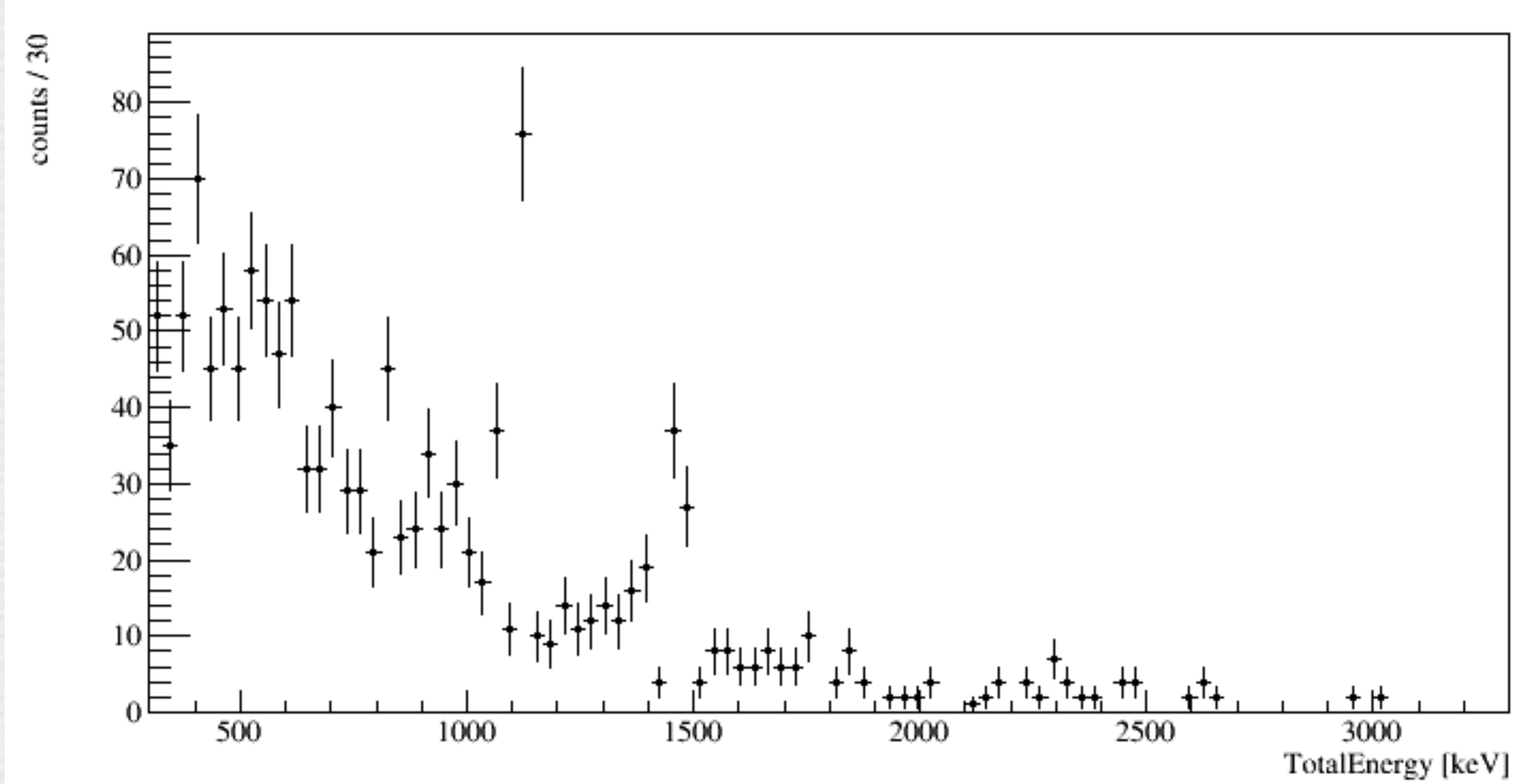
- The experimental conditions of this run did not allow to discriminate between α and β/γ events, as it is often the case with scintillating bolometers;
- The very low operating temperature of the cryostat resulted in a slower development of the thermal pulse with a subsequent loss of sensitivity on the small pulse shape differences between α and β/γ events due to the slow scintillation decay time.

Experimental spectra



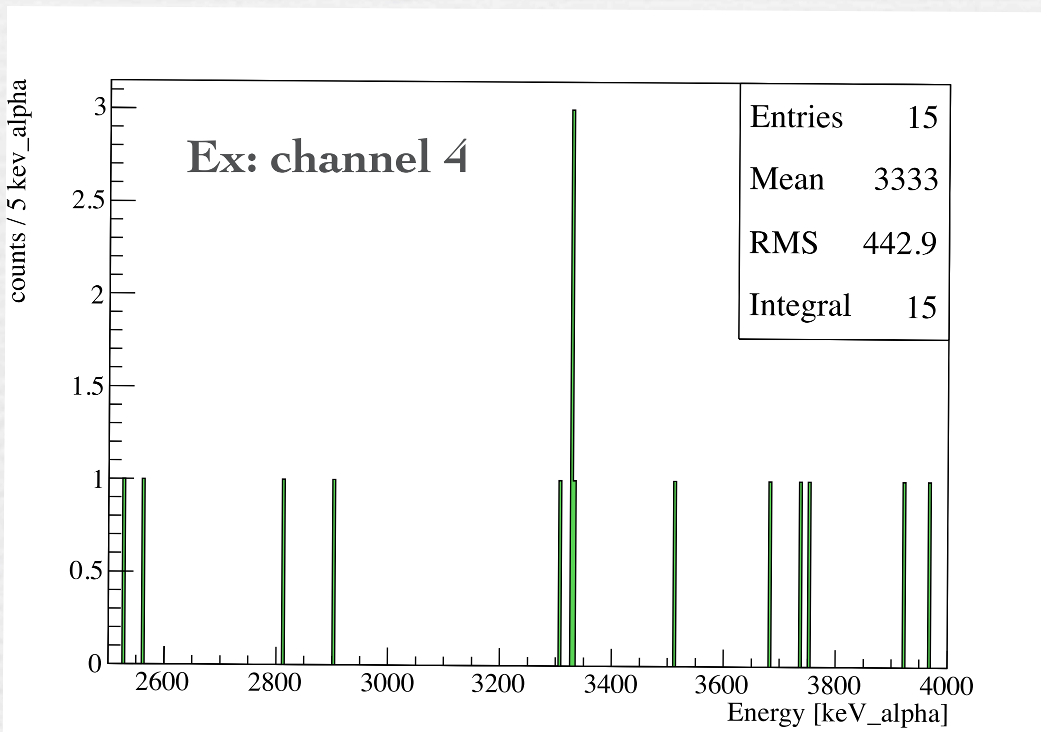
Multiplicity = 1

Multiplicity = 2
Total Energy



Alpha background

Since we can not rely on light detection or pulse shape for α discrimination, we see a contribution to the experimental spectrum from αs.



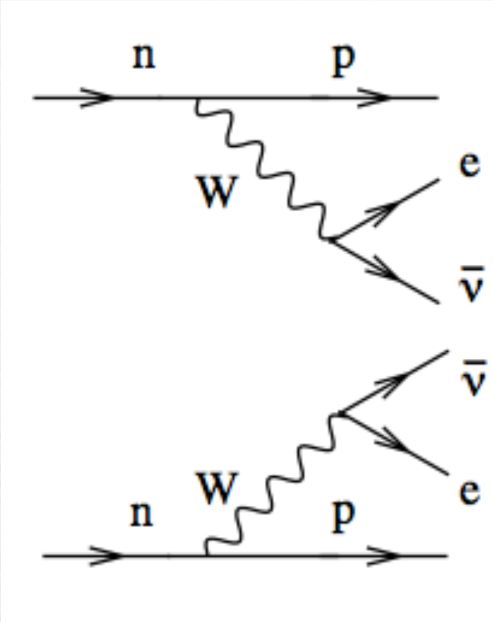
Channel	α bkg [counts/keV]
4	$7.6 \cdot 10^{-3}$
11	$2.6 \cdot 10^{-2}$
12	$2.5 \cdot 10^{-2}$

Evaluated above 2615 keV: (2700-4000)keV - excluding the energy region around ^{190}Pt decay - as a flat component to the background.

$2\nu\beta\beta$ double beta decay

$2\nu\beta\beta$ is the rarest nuclear weak process experimentally observed.

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$



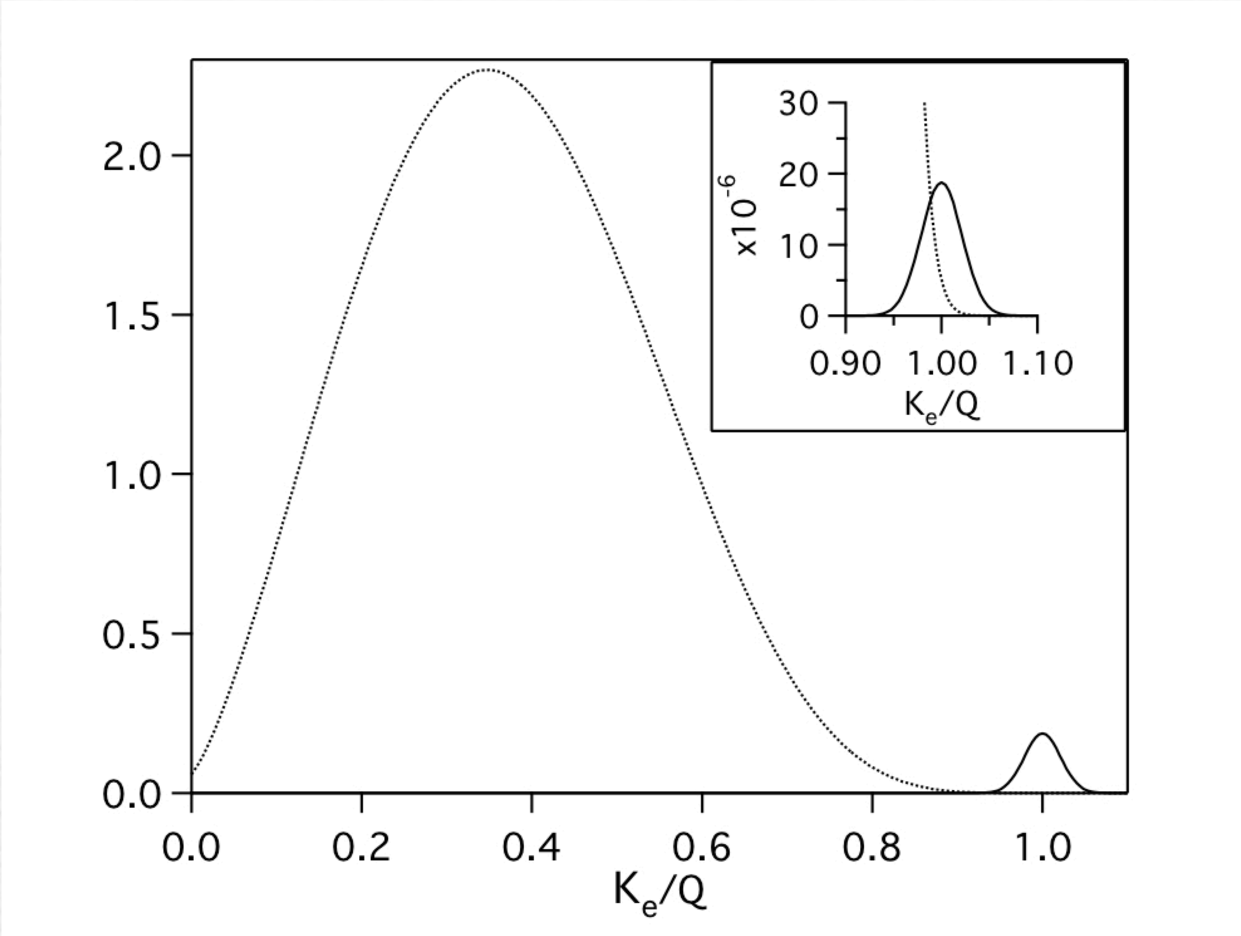
Detected so far for eleven nuclides, with half-lives in the range (10^{18} - 10^{24}) y .

The measurement of the half-life $T_{1/2}$ (2ν) has various interesting theoretical implications that are crucial for $0\nu\beta\beta$ search:

- derive constraints on the Nuclear Matrix Element (NME) of $0\nu\beta\beta$;
- test nuclear models.

$2\nu\beta\beta$ signature

- Detect the sum energy of the two emitted electrons;
- Continuous spectrum from 0 to the Q-value of 3034 keV;
- Needs to be disentangled from the various background sources;



- Most accurate measurement to date (from NEMO3): $T_{1/2} = 7.11 \pm 0.02(\text{stat.}) \pm 0.54(\text{syst.}) \cdot 10^{18}\,y$

^{100}Mo content of crystals

$$N(^{100}Mo) = N(Mo) \times i.a.(^{100}Mo) = N_{Avog} \frac{m_{crystal}\ [g]}{225.21\ [u.m.a.]} \times i.a.(^{100}Mo)$$

i.a. = 0.097 ± 0.002 (assuming natural isotopic abundance of ^{100}Mo)

	mass [g]	Mo atoms	^{100}Mo atoms	^{100}Mo mass [g]
ch 4	235.2 ± 0.1	$6.289 \cdot 10^{23}$	$6.056 \cdot 10^{22}$	10.03
ch 11	247.0 ± 0.1	$6.605 \cdot 10^{23}$	$6.360 \cdot 10^{22}$	10.53
ch 12	328.8 ± 0.1	$8.792 \cdot 10^{23}$	$8.467 \cdot 10^{22}$	14.02
Total ^{100}Mo mass				34.58

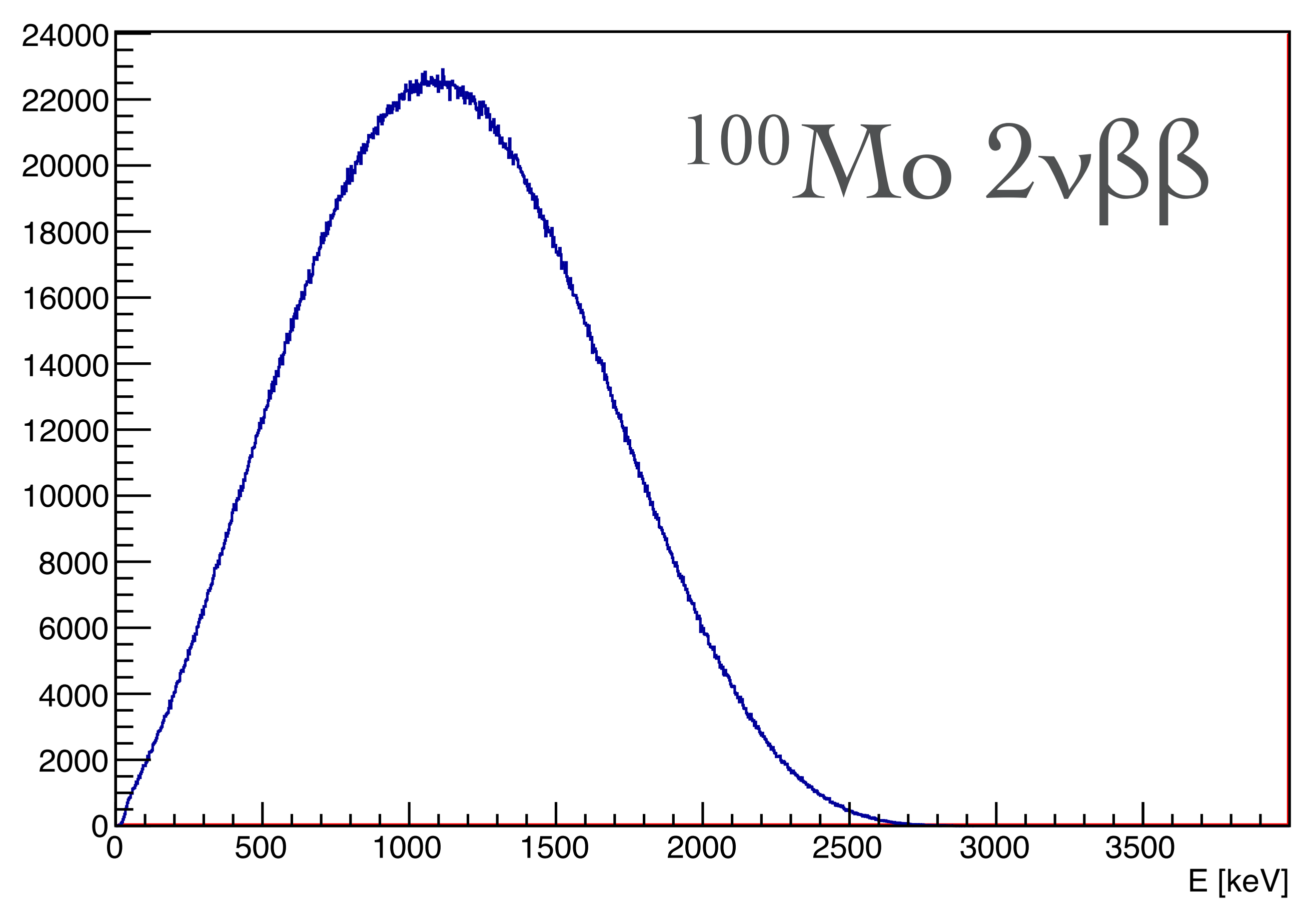
Total ^{100}Mo background statistics = 31.07 kg · hour ~ 1.3 kg · day

Global rate ($T_{1/2}$ from NEMO3) ~ 56 ev/day ~ 2000 ev for the total live time

Simulation

- Using a GEANT4-based Monte Carlo simulation of the experimental setup (crystals, assembly, shielding), we evaluated the spectral shape of the various component (signal + background) that are expected to contribute to the experimental spectrum of the three crystals;

- For $2\nu\beta\beta$ we used the non relativistic Primakoff-Rosen approximation for the Coulomb interaction between the nucleus and the outgoing electrons.



Background sources

- ^{65}Zn (T1/2 = 244.3 d, Q-value = 1351.9 keV): produced by activation from ^{64}Zn. Decays via EC (98.5%) or β+-decay (1.5%). The decay on the excited state of Cu (50.2%) generates a 1115.6 keV γ-ray.
  ^{65}Zn was generated as a uniform bulk contamination of the crystals.

- ^{210}Pb: belongs to the ^{238}U decay chain and is present as natural contaminant in almost every material.
  ^{210}Pb was simulated both in the bulk of the crystals and in the copper elements facing them.

- ^{40}K: decays via β-decay (89.3%, Q-value=1311 keV) or EC (10.7%, Q- value=1505 keV). Its presence is due to the natural radioactivity of the laboratory environment, to contaminations in the cryostat shields and in the crystals themselves.
  ^{40}K was simulated both in the bulk of the crystals and around them.

- ^{208}Tl: belongs to the ^{232}Th decay chain. Its presence is due to the natural radioactivity of the laboratory environment and to contaminations in the cryostat shields.
  The decays were simulated uniformly distributed around the experimental set-up.

Fit model

- Simultaneous, extended, unbinned, maximum likelihood fit (RooFit);
- Data are function of a continuous variable (E) and are divided into categories according to one or more discrete observables: crystal (C) and multiplicity (M);
- One or more fit parameters are shared among the categories: half-life $T_{1/2}$ (2ν);
- The categories are fitted simultaneously with the same fit function F.

Fit Function

$$F(E,C,M) = \Sigma_i N_i(C,M)\, B_i(E,C,M) + N_{sig}(C,M)\, S(E,C,M) + B_\alpha(C,M)$$

E = 300 - 3100 keV
C = 4,11,12
M = 1,2

i = ^{65}Zn, ^{210}Pb (bulk), ^{210}Pb (ext.), ^{40}K (bulk), ^{40}K (ext.), ^{208}Tl

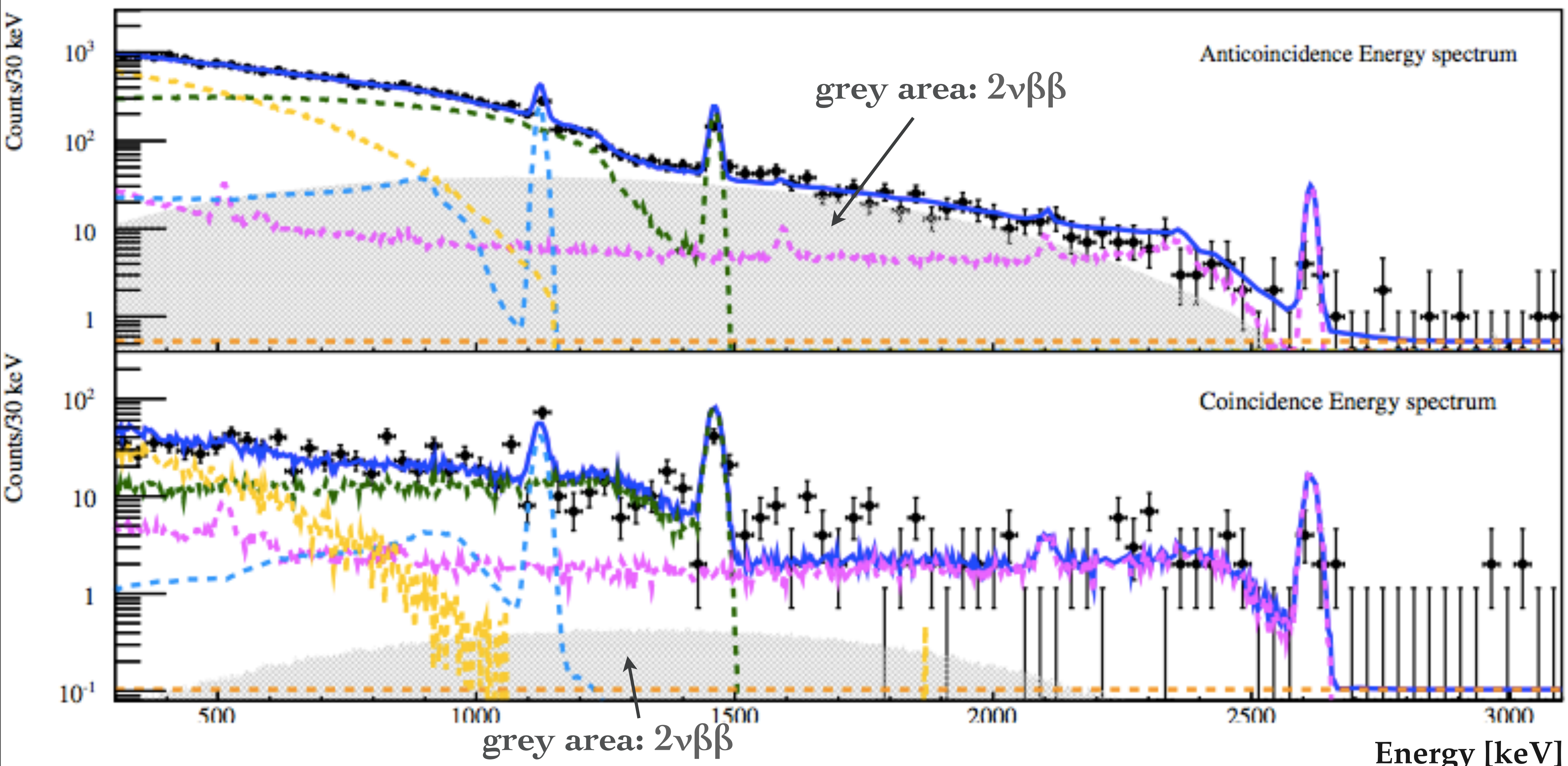
$B_i(E,C,M)$ = p.d.f. of the ith background source
$S(E,C,M)$ = signal p.d.f.
→ from MC

$B_\alpha(C,M)$ = flat alpha background (estimated from data)

$N_i(C,M)$ = number of events corresponding to the ith background source
$N_{sig}(C,M)$ = number of signal events

free parameters but ratio M1/M2 fixed by MC

Results



The best estimate of $T_{1/2}(2\nu)$ is:

$$T_{1/2} = 7.15 \pm 0.37 \text{ (stat.)} \pm 0.66 \text{ (syst.)} \cdot 10^{18} \text{ y}$$

Systematic error

Fit model: 2.2%

- We varied the energy threshold, the value of the flat α background and the order of interpolation of the simulated histograms used to model the shape of the signal and background components.

Monte Carlo: 7.1%

- uncertainty in the modeling of electromagnetic interactions in GEANT4 (5%)
- inaccuracy in the description of the geometry of the experimental setup (estimated as an additional 5%).

Others: 5.5%

- uncertainties in the evaluation of the pulse shape cuts efficiency (4.6%)
- uncertainty on the ^{100}Mo isotopic abundance (3.1%).

Total: 9.3%

Conclusions

- We operated successfully an array of three $ZnMoO_4$ bolometers @ LNGS;
- We performed the first bolometric measurement of the $2\nu\beta\beta$ decay of ^{100}Mo, based on an exposure of 1.3 kg · day of ^{100}Mo;
- The measured half-life of the decay is:
  $T_{1/2} = 7.15 \pm 0.37 \text{ (stat.)} \pm 0.66 \text{ (syst.)} \cdot 10^{18}$ y
  in good agreement with existing results from other kind of detectors.