The Bayesian software for the $0\nu\beta\beta$ CUORE analysis

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NEUTRINO 2020
XXIX INTERNATIONAL CONFERENCE ON NEUTRINO PHYSICS

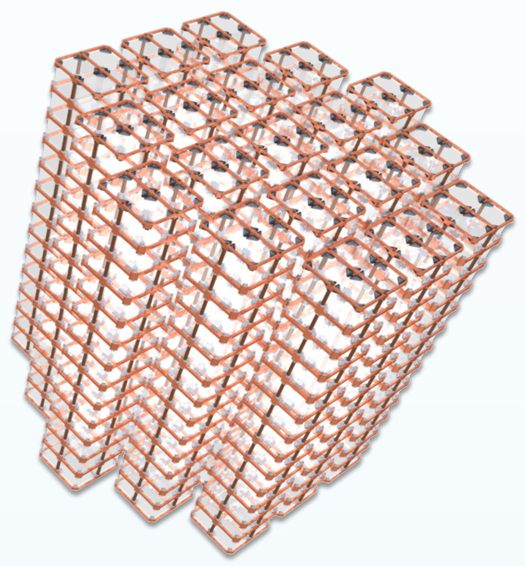
Istituto Nazionale di Fisica Nucleare

CUORE is a tonne-scale cryogenic experiment located at LNGS exploiting bolometric technique to search for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{130}Te. Here we present a thorough description of the software for the $0\nu\beta\beta$ fit that was developed for the last data release. It is based on BAT (the Bayesian Analysis Toolkit) and follows a Bayesian statistical approach. We show how the model is implemented, the treatment of systematics and the interpretation of results.

1 The CUORE experiment for the $0\nu\beta\beta$ search

Neutrinoless double beta decay ($0\nu\beta\beta$) is a hypothesized 2nd order nuclear transition in which two electrons and no neutrinos are released. Even if extremely rare ($\tau > 10^{24}$ years), its observation would be an indication of new physics beyond the Standard Model. In fact, it is a lepton number violating process and the simplest scenario includes massive Majorana neutrinos.

The Cryogenic Underground Observatory for Rare Events (CUORE) [1] is a bolometric experiment whose primary goal is the search for $0\nu\beta\beta$ of ^{130}Te ($Q_{\beta\beta} = (2527.518 \pm 0.013)$ keV).



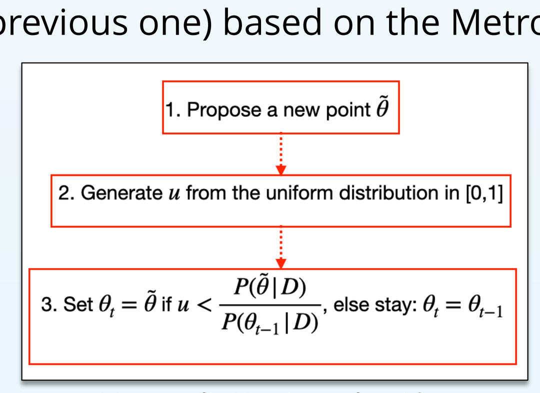
- Detector: 988 TeO_2 crystals, active mass ~742 kg (^{130}Te is ~206 kg)
- Resolution: the design is 5 keV FWHM at $Q_{\beta\beta}$
- Expected background: 0.01 counts/keV/kg/yr at $Q_{\beta\beta}$
- Sensitivity: $S^{0\nu}_{T_{1/2}} = 9 \cdot 10^{25}$ yr (90% C.L.) in 5 years data taking
- Located underground at LNGS
- ~10 mK operating temperature in a cryogen free ^{3}He/^{4}He dilution cryostat

5 Statistical approach: MCMC principle and BAT

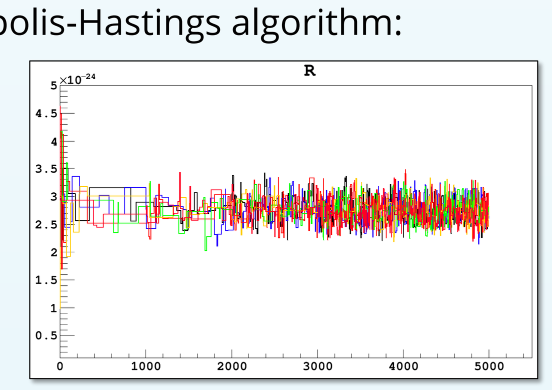
- Bayesian approach: our aim is to estimate ^{130}Te $0\nu\beta\beta$ rate ($\Gamma_{0\nu\beta\beta}$)

Bayes theorem $$P(\vec{\theta}|\vec{E}) = \frac{\mathcal{L}(\vec{E}|\vec{\theta}) \cdot \pi(\theta)}{\int_\Omega \mathcal{L}(\vec{E}|\vec{\theta}) \cdot \pi(\vec{\theta})\, d\vec{\theta}}$$

- Fit code developed using BAT (*The Bayesian Analysis Toolkit* [3]): numerical implementation with Markov Chain Monte Carlo (MCMC, a *random walk* in the parameters space - each state depends only on the previous one) based on the Metropolis-Hastings algorithm:



Metropolis Hastings algorithm



MC sampling: signal rate vs chain iteration

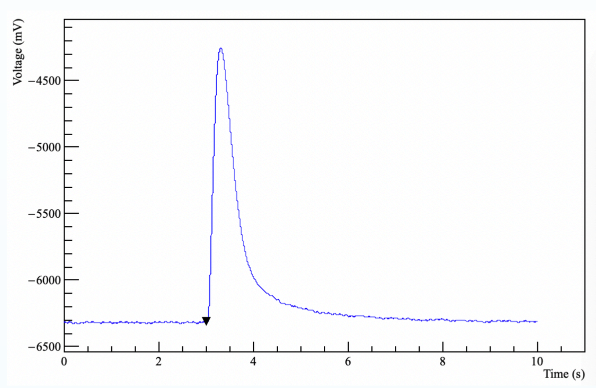
- We set a multivariate proposal function to perform the Markov Chain sampling and once it reaches the end, we use *Minuit* to identify the exact location of the maximum of the posterior distribution.
- To evaluate how the systematics affect the result we release the $\Gamma_{0\nu\beta\beta} > 0$ constraint allowing negative values for the rate and refer to the global mode (i.e. maximum of the posterior) extracted by Minuit. We restrict to the physical range to identify ^{130}Te $0\nu\beta\beta$ decay rate.

References

1. D. R. Artusa, F. T. Avignone III, O. Azzolini et al. [CUORE collaboration], Advances in High Energy Physics (2015) 879871
2. D. Q. Adams et al. [CUORE collaboration], *Improved Limit on Neutrinoless Double-Beta Decay in 130Te with CUORE*, Phys. Rev. Lett. 124, 122501 (2020)
3. https://bat.mpp.mpg.de/

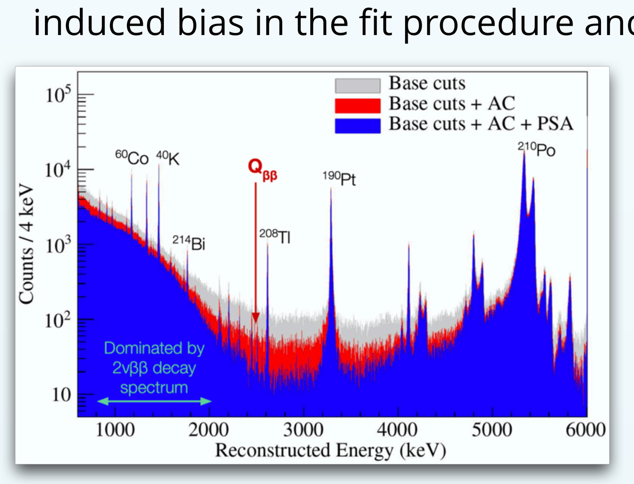
2 From raw data to the finalized ROI spectrum

We split the acquisition in datasets (~1-month data taking). Each dataset is bookended by 2 calibrations: the former to identify the relationship amplitude-energy, the latter to verify the detector stability. We refer to intermediate runs devoted to $0\nu\beta\beta$ search as *physics* runs.
The analysis we present here includes 7 datasets (372.5 kg · yr of TeO_2).
A single CUORE event is a 10-s window in which a signal trigger fired. We use a trigger algorithm based on the optimum filter technique to increase SNR and reduce energy thresholds. Pre-trigger gives us a measurement of the bolometric temperature, pulse amplitude is proportional to the energy released. We perform data analysis with a custom-made software.



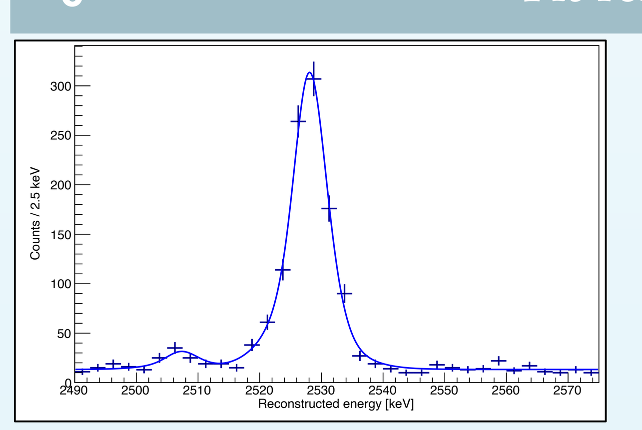
The event reconstruction includes:
- amplitude evaluation
- Thermal gain correction
- Energy calibration.

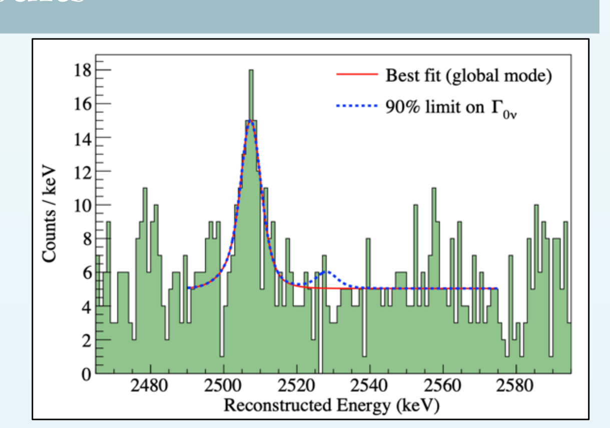
All events selected at this stage pass *Base cuts* (grey spectrum).
We expect a $0\nu\beta\beta$ event in the same crystal in which decay occurred in ~88% of the cases (i.e. *containment* efficiency). Therefore, we apply an anticoincidence cut (referred to as *AC* in the plot below) to reject background events, i.e. energy depositions above threshold in multiple crystals within ±5 ms window. We require the shape of each pulse to be consistent with that of a true signal event. Thus, we build an event sample characterized by 6 shape parameters using γ lines from ^{40}K and ^{60}Co and we discard all the outliers. Data selected by this additional *PSA cut* are highlighted in blue in the spectrum below [2]. Finally we blind events in the region of interest (~100 keV around $Q_{\beta\beta}$) to avoid human-induced bias in the fit procedure and results.



We evaluate the overall signal efficiency combining the effects of the analysis cuts and the containment efficiency (i.e. the probability to detect $0\nu\beta\beta$ decay as a single crystal event) that we extract from the Monte Carlo simulation of our detector.

6 Fit results





Left: Blinded fit on all datasets combined. *Right*: ROI spectrum with best-fit curve overlaid (red) and best-fit curve with the $0\nu\beta\beta$ rate fixed to the 90% C.I. limit.

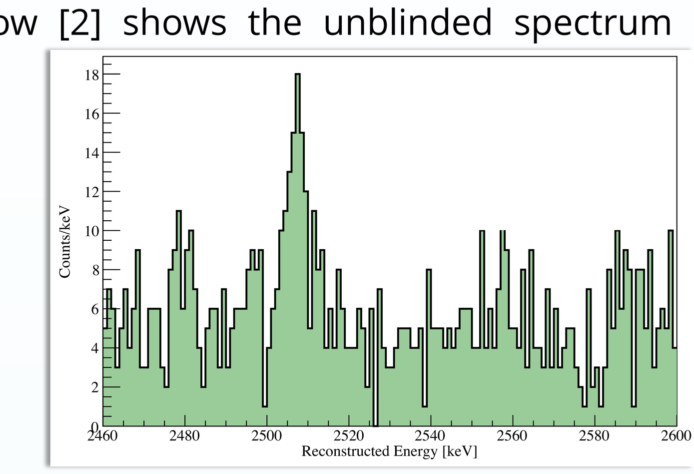
We find no evidence of neutrinoless double beta decay. Thus, we set a limit on ^{130}Te $0\nu\beta\beta$ decay half-life, $\boldsymbol{T^{0\nu}_{1/2} > 3.2\, 10^{25}}$ **yr (90 % C.I.)**. Repeating the fit without signal component, we evaluate the average background contribution $\mathrm{BI} = (1.38 \pm 0.07) \cdot 10^{-2}\ \mathrm{counts/(keV \cdot kg \cdot yr)}$.

Parameter [dim]	Effect on the rate global mode
^{130}Te Q-value [keV]	0.02%
^{130}Te isotopic fraction	0.02%
Containment efficiency	0.01%
Analysis cut efficiency I	0.01%
Analysis cut efficiency II (PSA)	0.04%
Energy scale bias [keV]	0.02%
Energy resolution scaling	

Including all the nuisance parameters we yield a 0.4% weaker limit on ^{130}Te $0\nu\beta\beta$ half-life. The pulse shape (PSA) analysis efficiency has the strongest effect on $\hat{\Gamma}_{0\nu\beta\beta}$.

3 Final ROI spectrum and model

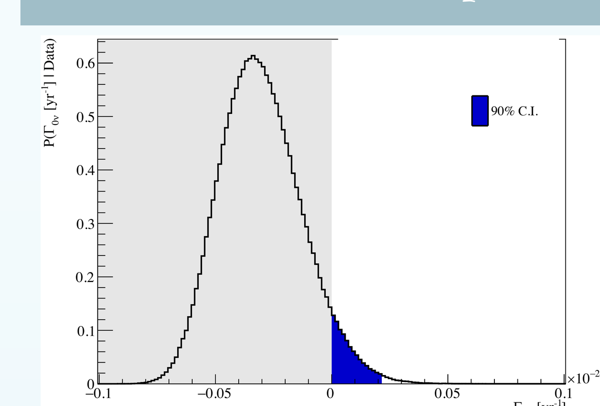
The plot below [2] shows the unblinded spectrum in the region of interest:



Besides the signal peak at $Q_{\beta\beta}$, we include the following contributions:
- the ^{60}Co sum line at 2505.7 keV
- a flat background mainly induced by degraded α particles and ^{208}Tl 2615 keV γ events undergoing multiple Compton scatterings.

We find an additional structure with a significance ≥ 2σ at ~2480 keV. As none of the hypothesized explanations was satisfactory, we decided to restrict the fit range from [2465,2575] to [2490,2575] keV.
We model the detector response (*Line-shape*) to a monochromatic peak with the sum of 3 Gaussian components, by fitting the 2615 keV ^{208}Tl line in calibration. To evaluate possible shifts in the peak position and how the energy resolution scales at $Q_{\beta\beta}$, we fit the most prominent γ lines in physics data. We treat both the peak position bias and the resolution scaling energy dependence as a quadratic function of energy.

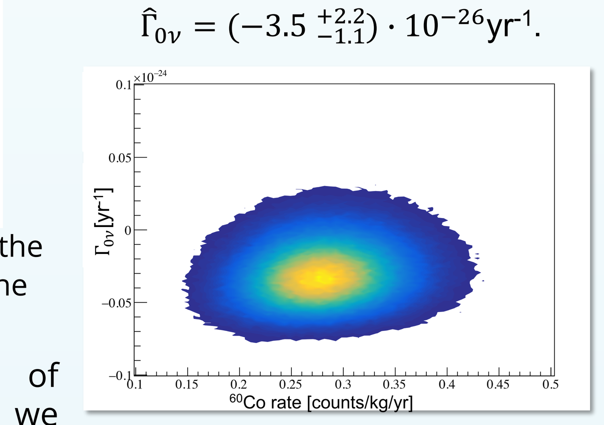
7 Posteriors: improved knowledge from the fit



$\Gamma_{0\nu\beta\beta}$ posterior with all the systematics for the fit on the physical range and on the full one ($\Gamma_{0\nu} < 0$ in grey). 90% C.I. shown in blue.

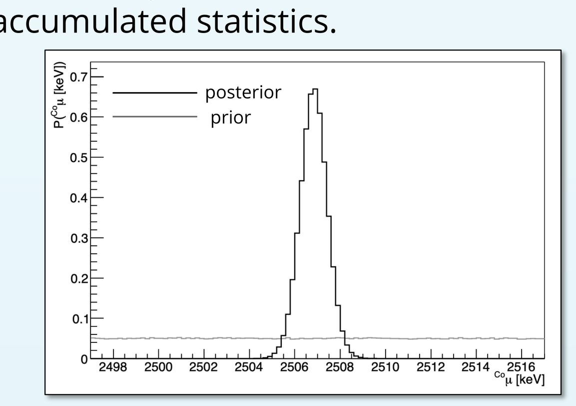
Allowing negative values for the signal rate, we observe a background under-fluctuation. The best fit (global mode) is:

$$\hat{\Gamma}_{0\nu} = (-3.5\ ^{+2.2}_{-1.1}) \cdot 10^{-26}\mathrm{yr}^{-1}.$$

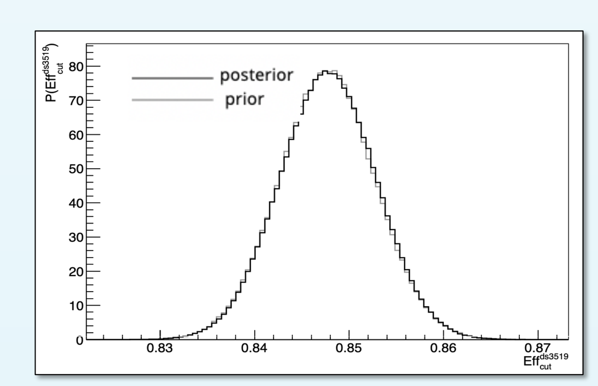


2-dimensional posterior distribution for $0\nu\beta\beta$ rate vs cobalt event rate

Comparing prior and posterior of statistical nuisance parameters we observe a major improvement. This is not the case for systematics as their uncertainty does not decrease with accumulated statistics.



^{60}Co sum-peak position probability distribution



Probability distribution of the Analysis cut efficiency I for the first dataset

9 Conclusion and perspectives

- CUORE proved the scalability of the bolometric technique and paved the way to the rare processes bolometric search
- Other interesting rare event searches ongoing
- Have a look at posters by G. Fantini (ID: #295 - *Search for double beta decay of ^{130}Te to the excited states of ^{130}Xe in CUORE*) and V. Dompè (ID: #146 – *Understanding the contributions to the CUORE background*) for further information on our activities!

4 Implementing the fit: Likelihood and parameters

We perform a Bayesian fit to the maximum posterior probability. We report the likelihood for a single bolometer: $f_{\beta\beta}$ (f_{Co}) indicates the three-Gaussian response function at $Q_{\beta\beta}$ (^{60}Co E_{sum}).

$$\mathcal{L}(E_i|\vec{\theta}) = \frac{e^{-\mu}\mu^n}{n!} \prod_{event\ i} \left[\frac{n_{\beta\beta}}{\mu} f_{\beta\beta}(E_i|\vec{\theta}) + \frac{n_{Co}}{\mu} f_{Co}(E_i|\vec{\theta}) + \frac{n_{bkg}}{\mu}\frac{1}{\Delta E} \right]$$
$$\mu = \bar{n} = n_{\beta\beta} + n_{Co} + n_{bkg},\quad \Delta E \text{ is the width of the fit region}$$

The table below includes the list of all the fit parameters. There are two blocks, the former contains statistical parameters (always enabled), the latter systematic effects that can be activated independently.

Parameter [dim]	Dependence	Prior distribution	Derivation method
Signal rate [1/yr]	Global	Flat	/
Cobalt rate [counts/(kg yr)]	Global	Flat	/
Cobalt position [keV]	Global	Flat	/
Background Index [counts/(keV kg yr)]	By Dataset	Flat	/
^{130}Te Q-value [keV]	Global	Gaussian	Literature
^{130}Te isotopic fraction	Global	Gaussian	Literature
Containment efficiency	Global	Gaussian	Monte Carlo simulations
Analysis cut efficiency I	By Dataset	Gaussian	Estimate from data
Analysis cut efficiency II (PSA)	Global	Flat	Estimate from data
Energy scale bias [keV]	By Dataset	Multivariate	Pol2 fit in physics data
Energy resolution scaling	By Dataset	Multivariate	Pol2 fit in physics data

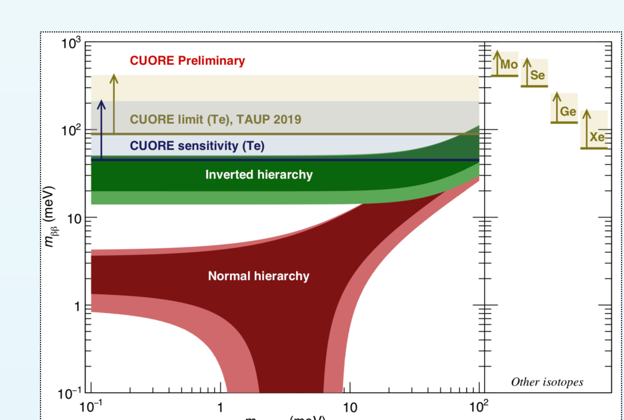
8 Updated results from CUORE

- No evidence of $0\nu\beta\beta$: we set a limit on ^{130}Te $0\nu\beta\beta$ decay half-life

$$\boldsymbol{T^{0\nu}_{1/2} > 3.2\, 10^{25}\ \mathrm{yr\ (90\ \%\ C.I.)}}$$

- We compute our exclusion sensitivity generating 10^4 pseudo experiments under the null hypothesis: flat background and ^{60}Co events obtained as the best fit results, we fit them with a positive signal rate and extract a median 90 % C.I. sensitivity of $\boldsymbol{1.7 \cdot 10^{25}}$ **yr**, the probability to get a stronger limit than $3.2 \cdot 10^{25}$ yr is 3%.
- If mediated by the light neutrino exchange, $0\nu\beta\beta$ rate can be related to the effective Majorana mass

$$\boldsymbol{\Gamma_{0\nu\beta\beta} = G_{0\nu}(Q,Z)\, |M_{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}}$$



where $G_{0\nu}(Q,Z)$ is the space phase factor, $M_{0\nu}$ indicates the nuclear matrix element, $m_{\beta\beta}$ the effective Majorana mass.
Assuming the light neutrino exchange, our limit on the effective Majorana mass is

$$\boldsymbol{m_{\beta\beta} < 75 - 350\ \mathrm{meV}}$$

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