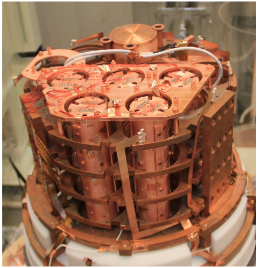
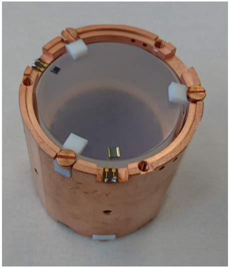
Final results from the CUPID-Mo experiment

Toby Dixon on behalf of the CUPID-Mo collaboration

IJCLab/ Université Paris-Saclay/ CNRS

March 2023





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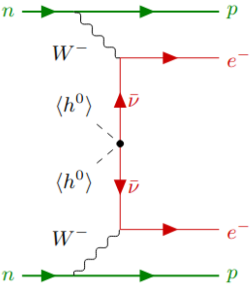
$0\nu\beta\beta$ decay creation of matter

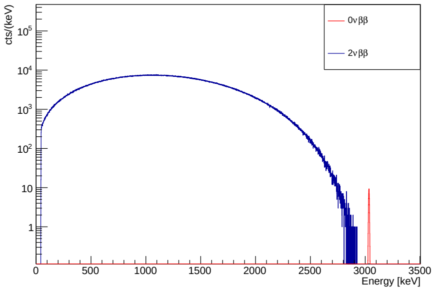
- Neutrino oscillations show neutrinos have mass, nature of this mass unknown
- Neutrinoless double beta decay, or *creation of electrons*, can probe Majorana nature of neutrinos,

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

- **Lepton number violation, clear evidence of BSM physics**
- Monoenergetic peak at the total energy of the decay $Q_{\beta\beta}$

$$(T_{1/2})^{-1} = \overbrace{g_A^4}^{\text{hadronic}} \times G \times \underbrace{|\mathcal{M}|^2}_{\text{nuclear}} \times \overbrace{\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}}^{\text{neutrino}} + \text{higher order}$$

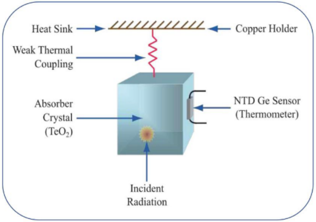




From CUORE to CUPID

- Bolometers [1] powerful tool to study $0\nu\beta\beta$
- CUORE stably operates 988 TeO_2 bolometers
- Background dominated by α particles
- CUPID will remove α background using Lithium Molybdate (LMO) bolometers

CUORE ^{130}Te
pure thermal detector
(bolometer)

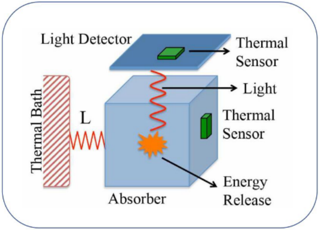


No PID
Q = 2527 keV **< 2615 keV**

PID → remove α

higher Q → remove γ

CUPID ^{100}Mo
heat + light
(scintillating bolometer)

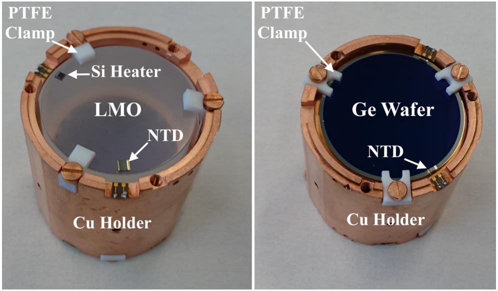


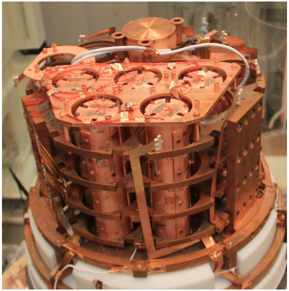
^{100}Mo **Q-value: 3034 keV**: β/γ background significantly reduced

[1] or cryogenic calorimeters

The CUPID-Mo experiment

- First demonstrator experiment of this technique using Lithium Molbydate (LMO) enriched in ^{100}Mo
- 20 LMO bolometers + 20 Ge Light Detectors (LDs)
- Operated in EDELWEISS cryostat (LSM)

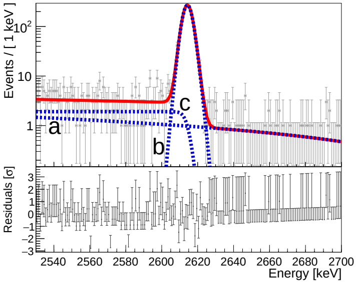


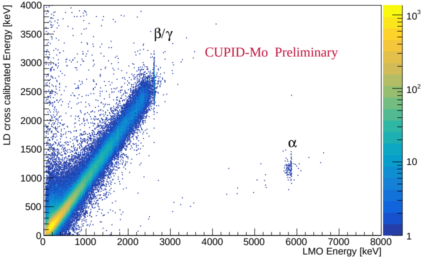


CUPID-Mo performances

- Performance close to the CUPID goals reached
  - **Energy resolution**: $\sim 7.4 \pm 0.4$ keV FWHM at 3034 keV
  - **Crystal radiopurities**: $< 0.5\mu\mathrm{Bq/kg}$ for ^{228}Th and ^{226}Ra
  - α**-particle rejection**: $> 99.9\%$ rejection
  - **Selection efficiency**: ~ 90 %

Technology chosen for CUPID





1. *Main* $0\nu\beta\beta$ analysis
2. Topological searches exploiting multi-detector events
3. Studies of the $\beta\beta$ spectral shape

$0\nu\beta\beta$ analysis

Trigger, Amplitude
Optimal Filter

→

Calibration
U/Th source

→

PSD
Remove pileups using PCA method

↓

Light Detector cut
Remove alpha particles

↓

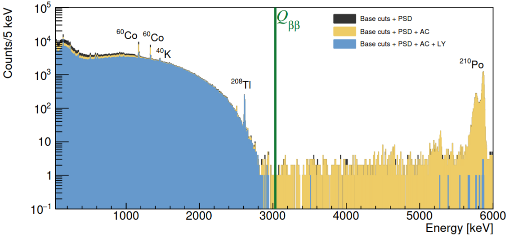
Coincidence
Select events with energy deposition in only one crystal

←

Estimate energy resolution, bias and efficiencies

←

Bayesian counting analysis for 0νββ limit



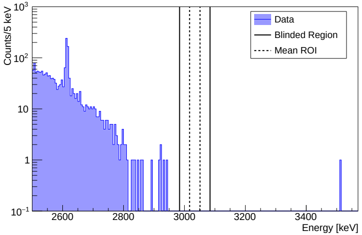
Limit on $0\nu\beta\beta$ half-life

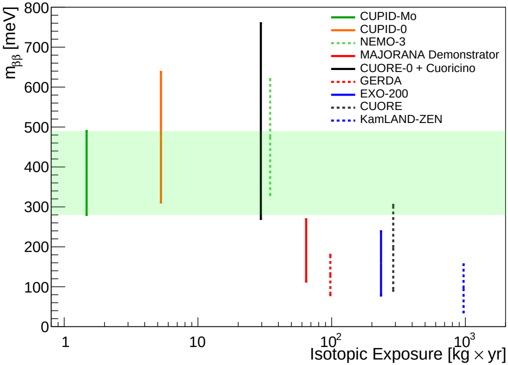
- After unblinding 0 events observed in ROI
- Leads to a limit:

$$T_{1/2}^{0\nu}(^{100}\text{Mo}) > 1.8 \times 10^{24} \text{ yrs } 90\% \text{ c.i.}$$

- Under light Majorana neutrino exchange model:

$$\langle m_{\beta\beta} \rangle < 280 - 490 \text{ meV}$$



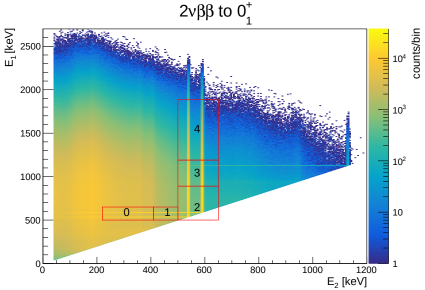


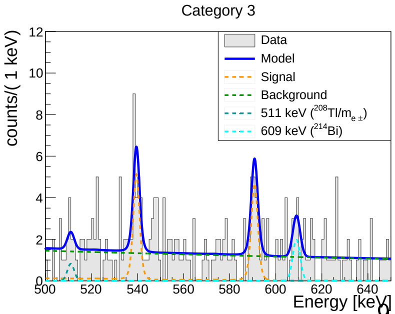
Most stringent limits for ^{100}Mo

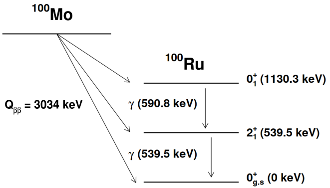
EPJC 82, 1033 (2022)

Topological searches: Decays to excited states

- Useful to constrain nuclear physics models
- Can be sensitive to different exotic physics
- $\beta\beta$ accompanied by γ, often have energy deposit in multiple detectors
- Simultaneous fit to the γ lines for various patterns of energy deposition
- One example fit shown







Phys.Rev.C 107 (2023) 2, 025503

Decays to excited states

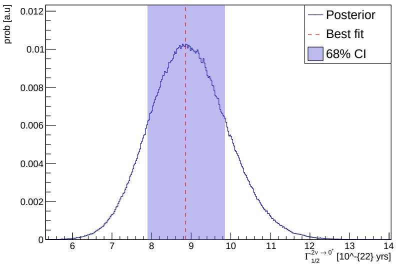
Phys.Rev.C 107 (2023) 2, 025503

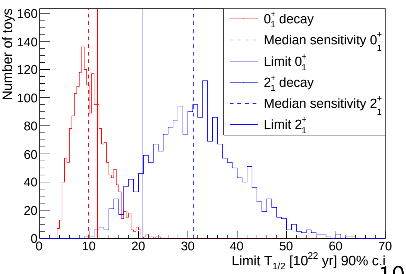
- Bayesian analysis including systematics leads to:

$$T_{1/2}(2\nu \to 0_1^+) = 7.5 \pm 0.8\ (\text{stat.})^{+0.4}_{-0.3}\ (\text{syst.})\ \times 10^{20}\ \text{yrs}$$
$$T_{1/2}(2\nu \to 2_1^+) > 4.4 \times 10^{21}\ \text{yrs}\ (90\%\ c.i.)$$
$$T_{1/2}(0\nu \to 0_1^+) > 1.2 \times 10^{23}\ \text{yrs}\ (90\%\ c.i.)$$
$$T_{1/2}(0\nu \to 2_1^+) > 2.1 \times 10^{23}\ \text{yrs}\ (90\%\ c.i.)$$

New measurement and most stringent limits on other processes

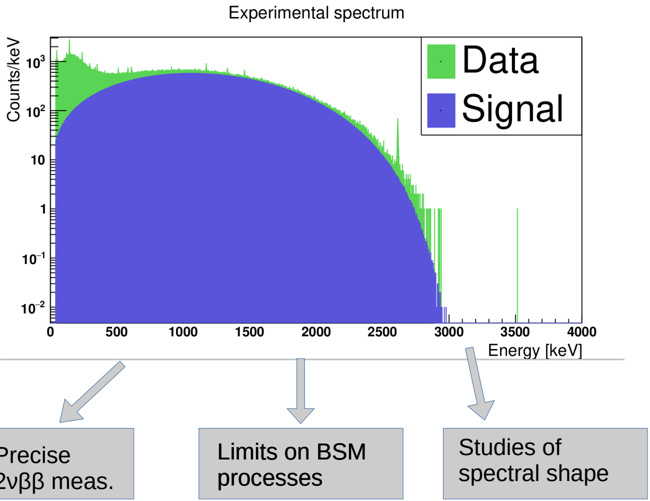
- Sensitivity extracted with toy MCs, compatible to observed limits





$2\nu\beta\beta$ spectrum

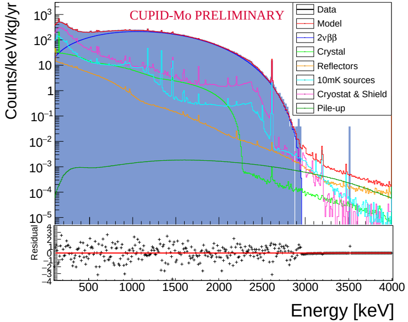
- CUPID-Mo background suppression leads to very clean $2\nu\beta\beta$ spectrum
- Almost background free spectra in range 1-3 MeV
- $> 1 \times 10^6$ $2\nu\beta\beta$ events

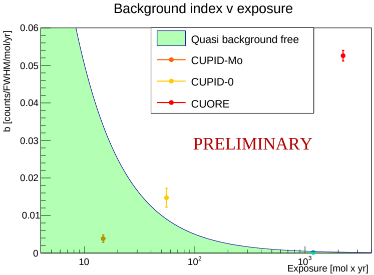


Background model

NEW!

- To exploit the $2\nu\beta\beta$ spectrum a background model is needed
- Data fit to sum of MC simulations
- Features of experimental data well reconstructed





$b = 3.8 \pm 1.0 \times 10^{-3}$ cts/FWHM/mol_{iso}/yr

- Important inputs to CUPID background budget measured

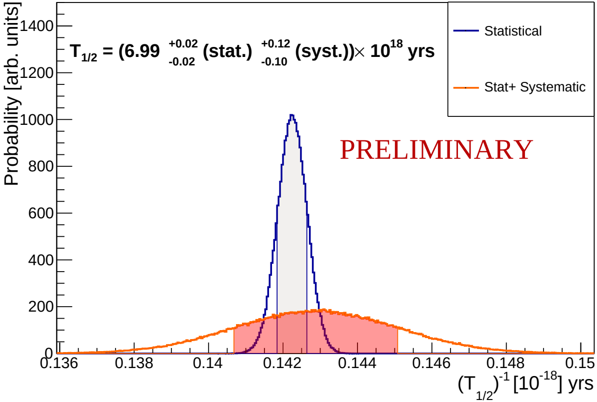
The lowest ever background index in a bolometric $0\nu\beta\beta$ experiment

$2\nu\beta\beta$ to ground state measurement

NEW!

- Bayesian analysis computes $2\nu\beta\beta$ posterior distribution
- Systematic uncertainties related to energy reconstruction, theoretical spectral shape, binning, model choice and selection efficiencies considered

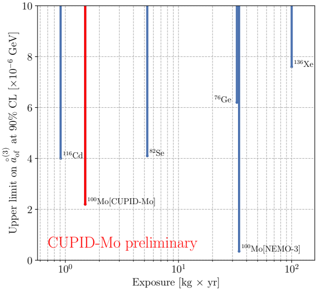
The most precise measurement of $2\nu\beta\beta$ decay in any isotope

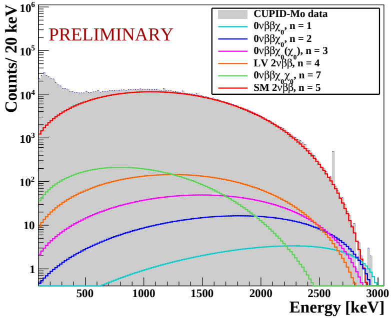


Spectral shape - Lorentz Violation and Majorons

NEW!

- BSM physics processes can distort the $2\nu\beta\beta$ spectrum
- Search for $2\nu\beta\beta$ with LV and $0\nu\beta\beta$ with Majorons
- LV parameterised by $a_{of}^{(3)} = C \times \Gamma_{LV}/\Gamma_{SM}$





Process	Limit [10^{21} yrs] (90% c.i.)
$\beta\beta\chi_0$ (n=1)	2.1
$\beta\beta\chi_0$ (n=2)	4.5
$\beta\beta\chi_0(\chi_0)$ (n=3)	1.4
$\beta\beta\chi_0\chi_0$ (n=7)	0.5

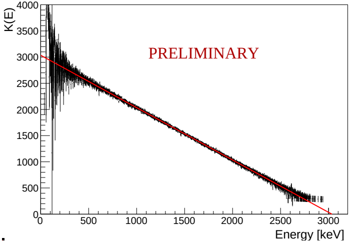
Strongest limit on LV for this technique despite small exposure

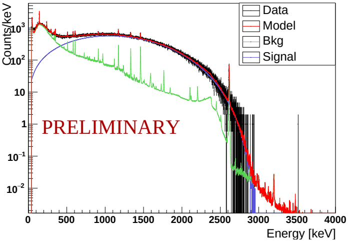
Measurement of $Q_{\beta\beta}$

NEW!

- Could be a systematic shift due to difference between γ events used for calibration and $\beta\beta$ signal
- Phase space given by $G = A(E)(Q - E)^5$
- Bayesian fit to the spectrum floating $Q_{\beta\beta}$
- Can be visualised by a Kurie plot

$$\boxed{Q_{\beta\beta} = 3038.4 \pm 1.5(\text{stat.}) \pm 7(\text{syst.})\ \mathrm{keV}}$$

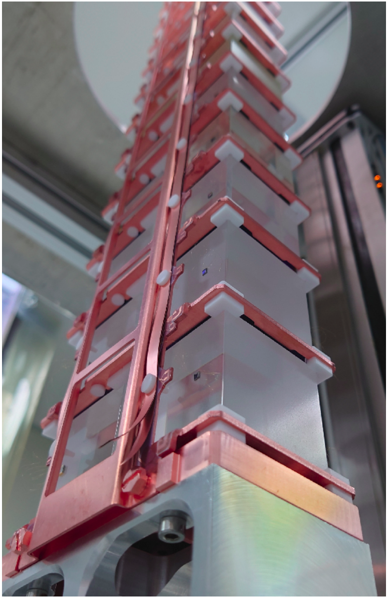




Prospects: CUPID and CROSS

- **CUPID**
- Next generation $0\nu\beta\beta$ experiment
- Builds on the experience of CUPID-Mo and CUORE
- $\sim$ 1500 LMOs and LDs
- Aim to fully cover the inverted hierachy regime
- Tests ongoing at LNGS and LSC

- **CROSS**
- Remove surface background using "surface sensitive bolometers"
- Also exploit higher sensitivity NTL light detectors
- Demonstrator with $\sim$ 50 crystals at LSC to start in 2024

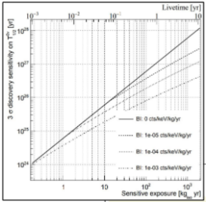


1. Performance close to CUPID goals
2. Lowest ever background index in a bolometric $0\nu\beta\beta$ decay experiment
3. New limits and measurements of $\beta\beta$ decays to ground and excited states
4. Limits on other BSM processes

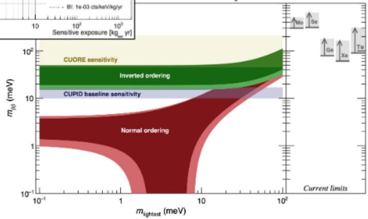
Thanks for your attention!

CUPID sensitivity

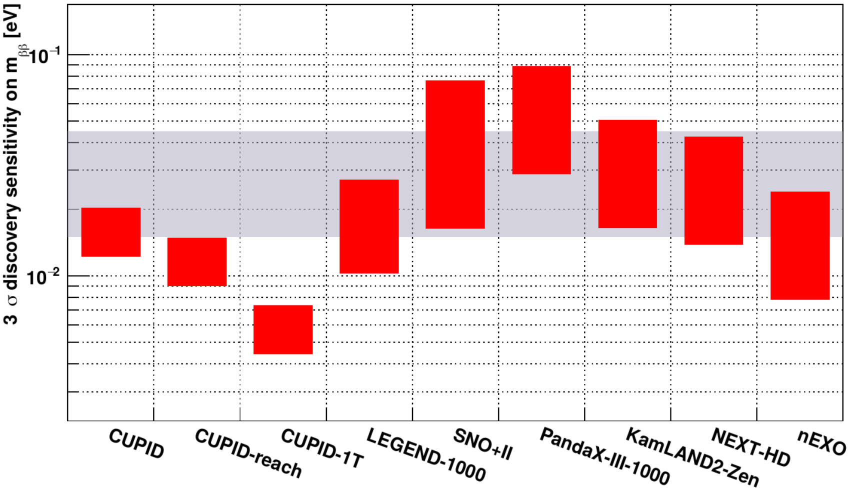
- 450 kg of LMO
- $T_{1/2} > 1.1 \times 10^{27}$ yr (3 σ)
- $\langle m_{\beta\beta} \rangle < 12 - 20$ meV



$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

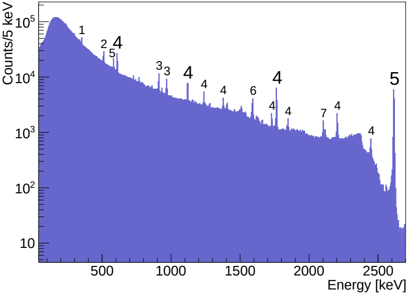


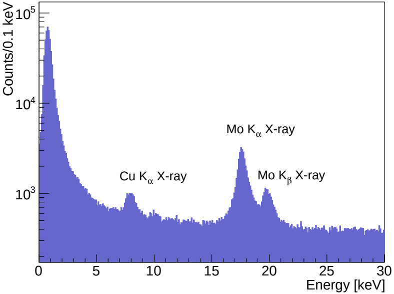
CUPID sensitivity-2



Data processing: Calibration / stabilisation

- Calibrate LMO using Th/U calibration source
- Correct for thermal gain variations with ^{208}Tl 2615 keV peak



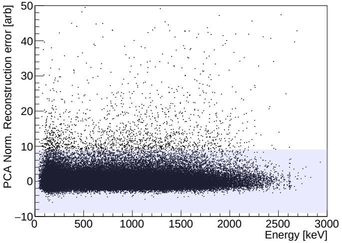


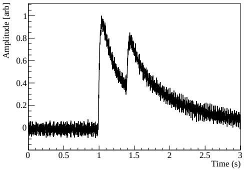
Data processing: PSD

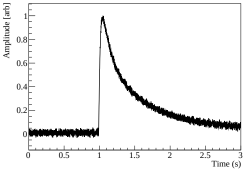
- Remove pileups and other superious events (eg noise spikes)
- Principle components trained on $2\nu\beta\beta$ events
- Reconstruct each pulse using first 6 components
- Define a reconstruction error:

$$R = \sqrt{\sum_i (x_i - \sum_k q_i w_{k,i})^2} \qquad (1)$$

- Normalise by the observed Median and MAD



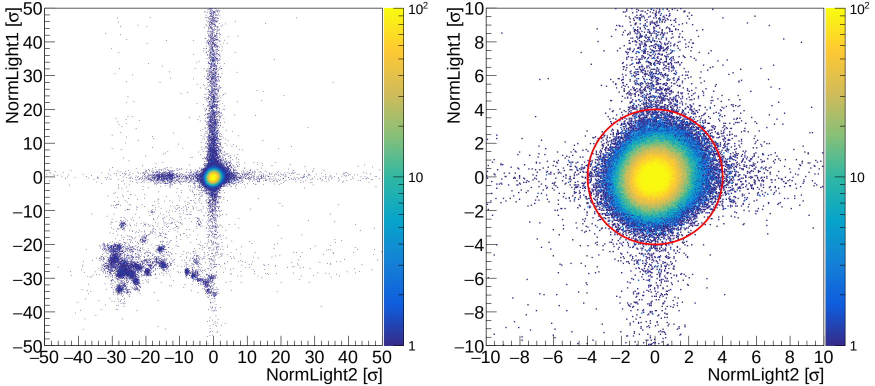




Data processing: LD cuts

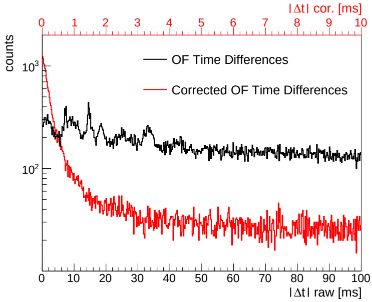
- Each detectors sees two LDs
- Combine the two pieces of information for a 2D cut
- LD energy centered and normalised based on energy resolution

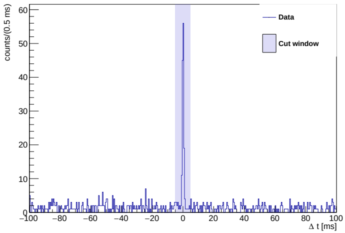
$$n_i = \frac{E_{i,\mathrm{LD}} - E_{i\mathrm{LD,exp}}}{\sigma_i(E)}$$

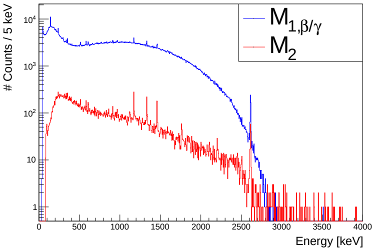


Data processing: Coincidences

- Fairly small range of e^- in LMO means $0(2)\nu\beta\beta$ signal is likely to reconstruct in one crystal ($\mathcal{M}_1$)
- Backgrounds can trigger multiple detectors
- Define *multiplicity* as number of detectors triggered with $E > 40$ keV in a window ± 10 ms
- Also remove events within ± 5 ms of a muon veto trigger







Delayed coincidence

- Veto events likely orginating in Th/U decay chains

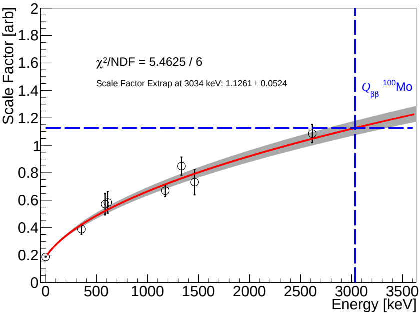
$$^{212}\text{Bi} \xrightarrow[\alpha(6207\ \text{keV})]{60.6\ \text{min},\ \ 35.9\%\ \text{BR}} {}^{208}\text{Tl} \xrightarrow[\beta^-(4999\ \text{keV})]{3.1\ \text{min},\ \ 100\%\ \text{BR}} {}^{208}\text{Pb}.$$

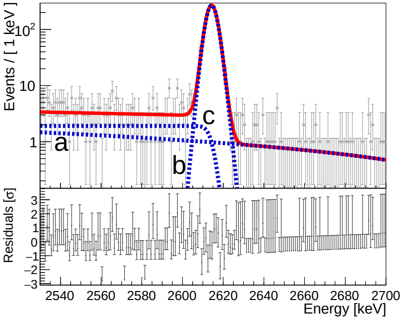
- Low CUPID-Mo radioactivity allows a novel cut on ^{214}Bi with a long dead time

$$\begin{aligned}
&^{222}\text{Rn} \xrightarrow[\alpha(5590\ \text{keV})]{3.8\ \text{day},\ \ 100\%\ \text{BR}} {}^{218}\text{Po} \xrightarrow[\alpha(6115\ \text{keV})]{3.1\ \text{min},\ \ 99.98\%\ \text{BR}} {}^{214}\text{Pb} \\
&^{214}\text{Pb} \xrightarrow[\beta^-(1018\ \text{keV})]{27.1\ \text{min},\ \ 100\%\ \text{BR}} {}^{214}\text{Bi} \xrightarrow[\beta^-(3269\ \text{keV})]{19.7\ \text{min},\ \ 99.98\%\ \text{BR}} {}^{214}\text{Po} \\
&^{214}\text{Po} \xrightarrow[\alpha(7834\ \text{keV})]{163.4\ \mu\text{s},\ \ 100\%\ \text{BR}} {}^{210}\text{Pb}
\end{aligned} \tag{1}$$

Energy resolution

- Estimate energy resolution using γ lines in background and calibration data

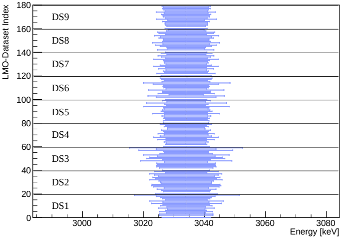


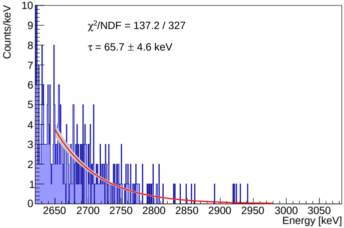


Bayesian counting analysis

- Counting analysis used to estimate $0\nu\beta\beta$ decay rate
- Exponential + linear model
- Binned fit with 3 bins (central and two sidebands)
- Optimized ROI on Ch-Ds basis

$$\lambda_i = \sum_{c=1}^{19}\sum_{d=1}^{9}(Mt)_{c,d}/Mt \cdot \left(\varepsilon_i(c,d)\cdot \Gamma^{0\nu}\frac{N_A \cdot \cdot \eta}{W} + \int_{E_{a,i}(c,d)}^{E_{b,i}(c,d)} f(E)dE\right). \tag{2}$$





$2\nu\beta\beta$ systematics

- Series of tests to constrain systematic uncertainties
- Dominant

Uncertainty	Posterior Distribution
Binning	Gaussian 0.3%
Energy Scale	Gaussian 0.1%
MC statistics	Gaussian 0.1%
Source location	Gaussian 0.8%
Model choice	Gaussian 0.2%
Bremsstralhung cross section	Gaussian 0.2%
Cut efficiency	Gaussian 1.2%
Isotope Abundance	Gaussian 0.2%
^{90}SrY	Uniform [0,+1.0%]