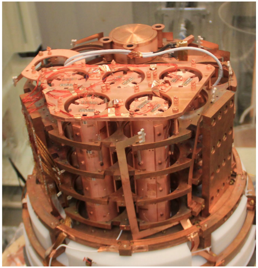
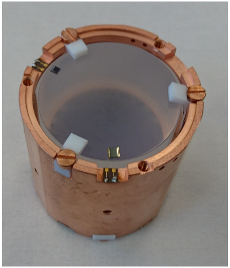
New results from the CUPID-Mo experiment

Toby Dixon on behalf of the CUPID-Mo collaboration

IJCLab/ Université Paris-Saclay/ CNRS

June 21 2023





$0\nu\beta\beta$ decay

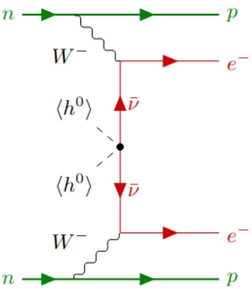
- Two-neutrino double beta decay ($2\nu\beta\beta$) rare SM process
- Neutrinoless double beta decay ($0\nu\beta\beta$) can probe Majorana nature of neutrinos,

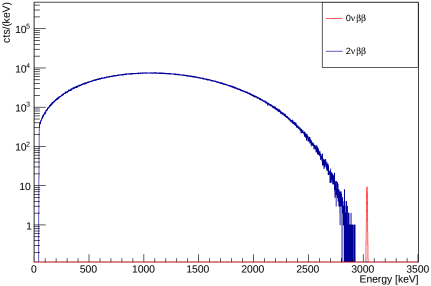
$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

- **Lepton number violation, clear evidence of BSM physics**
- For $0\nu\beta\beta$:

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

- Monoenergetic peak at the total energy of the decay $Q_{\beta\beta}$

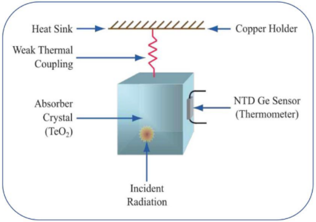




From CUORE to CUPID

- 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)

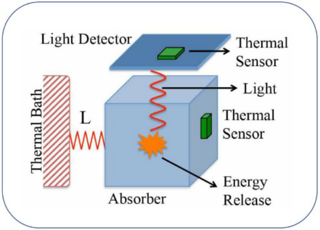


No PID
Q = 2527 keV **< 2615 keV**

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

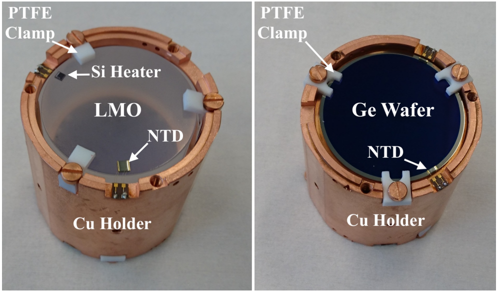
---

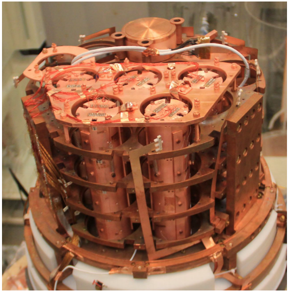
[1] or cryogenic calorimeters

The CUPID-Mo experiment

EPJC 80 (2020) 1, 44

- 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,France) in 2019-2020
- Performance close to the CUPID goals energy resolution, crystal radio-purity and α particle rejection





CUPID-Mo Analysis channels

1. *Main* $0\nu\beta\beta$ analysis
2. Information on backgrounds for CUPID
3. $2\nu\beta\beta$ studies to constrain nuclear models and help solve the problem of "g_A quenching"
4. Other Beyond Standard Model (BSM) searches

$0\nu\beta\beta$ analysis

Trigger, Amplitude
Optimal Filter

Calibration
U/Th source

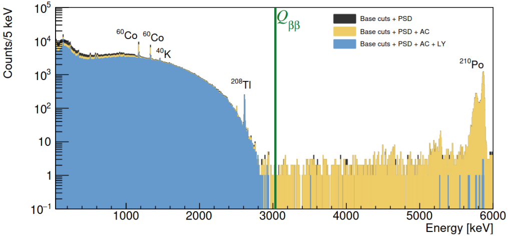
PSD
Remove pileups using PCA method

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



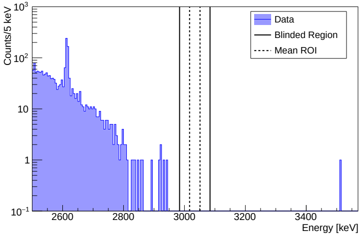
Limit on $0\nu\beta\beta$ half-life

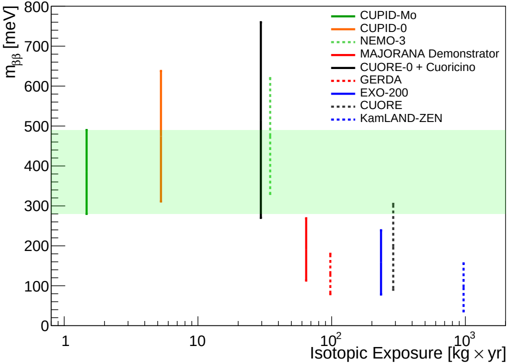
- After unblinding 0 events observed in ROI
- Leads to a limit:

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

- Under light Majorana neutrino exchange model:

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





Most stringent limits for ^{100}Mo

EPJC 82, 1033 (2022)

Nuclear matrix elements

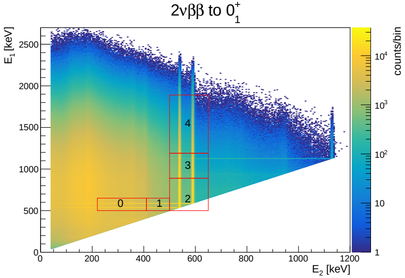
- Interpretation of $0\nu\beta\beta$ experiments relies on nuclear physics calculations
- Currently values only known with very limited precision

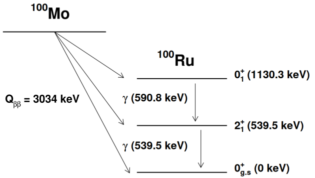
$$(T_{1/2})^{-1} \propto |M|^2 g_{A,\text{eff}}^4 \tag{1}$$

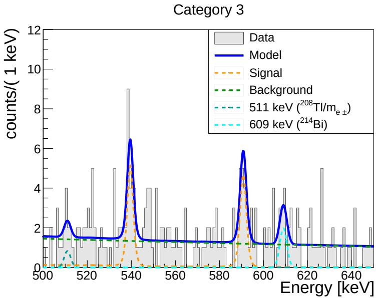
- Models generally tuned with $T_{1/2}$ for $2\nu\beta\beta$ to ground state
- Additional experimental data is needed to test the models and study the possible "quenching of g_A"
- We perform analysis to extract:
  1. Half-life to ground and excited states
  2. Information on spectral shape: **novel experimental observables based on an improved description of $2\nu\beta\beta$ decay**

Decays to excited states

- $\beta\beta$ 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

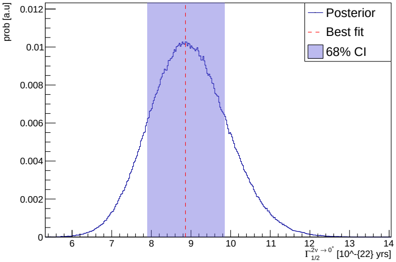
Phys.Rev.C 107 (2023) 2, 025503

- Bayesian analysis including systematics leads to:

$$T_{1/2}(2\nu \to 0_1^+) = 7.5 \pm 0.8\ (\text{stat.})^{+0.4}_{-0.3}\ (\text{syst.})\ \times 10^{20}\ \text{yrs}$$

- And the most stringent limits on other processes
- Extract $M_{2\nu} = \sqrt{1/(T_{1/2} \times G)}$

Additional information to test the nuclear models



	$\lvert M_{2\nu} \rvert$
Experiment	0.143 ± 0.008
Shell model (bare operator) [2]	0.395
Shell (effective operator)[2]	0.090
IBM-2 [3]	0.595
QRPA [4]	0.185

---

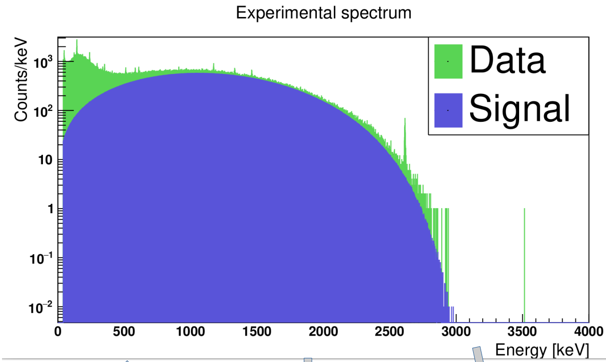
[2] PRC 105, 034312 (2022)

[3] PRC 91, 034304 (2015

[4] PRC 91, 054309 (2015

$2\nu\beta\beta$ 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



Precise 2νββ meas.

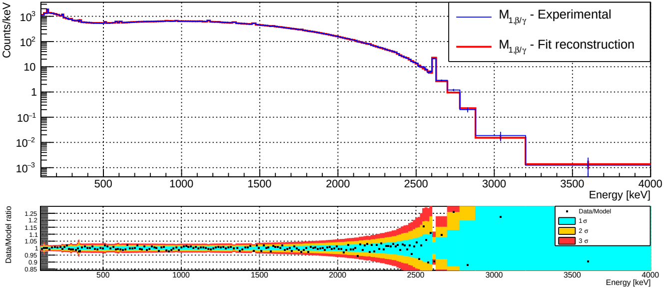
Limits on BSM processes

Studies of spectral shape

CUPID-Mo Background model

arXiv:2305.01402

- 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
- Important inputs to CUPID background budget measured



$$\boxed{b = 2.7^{+0.7}_{-0.6}\ (\text{stat.})\ ^{+1.1}_{-0.6}\ (\text{syst.}) \times 10^{-3}\ \text{cts/keV/kg/yr}}$$

$$\boxed{\mathcal{B} = 3.7^{+0.9}_{-0.8}\ (\text{stat.})\ ^{+1.5}_{-0.7}\ (\text{syst.}) \times 10^{-3}\ \text{cts/FWHM/mol}_{\text{iso}}\text{/yr}}$$

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

$2\nu\beta\beta$ decay description

- Spectral shape is proportional to products of nuclear matrix elements (NME)

$$\frac{d\Gamma}{dE} \propto \frac{1}{4}|M_{GT}^{K} + M_{L}^{GT}|^2 + \frac{1}{12}|M_{K}^{GT} - M_{L}^{GT}|^2 \tag{2}$$

$$M_{K,L}^{GT} = m_e \sum M_n \frac{E_n - (E_i - E_f)/2}{(E_n - (E_i - E_f)/2)^2 - \varepsilon_{K,L}^2} \tag{3}$$

- $\varepsilon_{K,L}$ are sums of lepton energies
- Usual approximation to factorise into NME and phase space
  - Negelct $\varepsilon_{K,L}$
  - Replace E_n with a suitably chosen average value (closure approximation)
- Two choices generally employed higher state (HSD) or Single State dominance (SSD) corresponding to different closure energy

Improved $2\nu\beta\beta$ model

PRC 97 (2018) 3, 034315

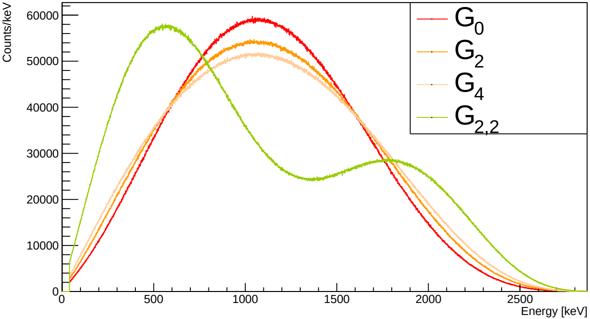
- Analysis of $2\nu\beta\beta$ decay in the framework of an *improved* $2\nu\beta\beta$ model
- Taylor expansion of the (usually neglected) lepton energy

$$\frac{d\Gamma}{dE} = g_A^{\mathrm{eff}4}|M_{GT-1}|^2\left(\frac{dG_0}{dE} + \xi_{31}\frac{dG_2}{dE} + \frac{1}{3}\xi_{31}^2\frac{dG_{22}}{dE} + \left(\frac{1}{3}\xi_{31}^2 + \xi_{51}\right)\frac{dG_4}{dE}\right) \quad (4)$$

- ξ_{31}, ξ_{51} are ratios of NMEs - **novel experimental observables**

$$\xi_{i,1} = M_{GT-i}/M_{GT-1} \quad (5)$$

- G_i phase space factors

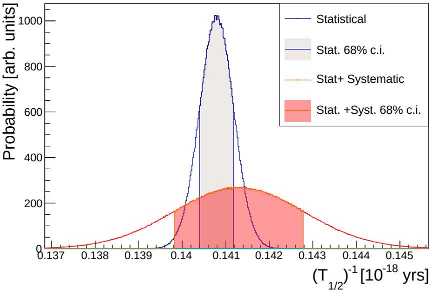


$2\nu\beta\beta$ half-life measurement

NEW!

- Fit floating 2 parameters of the spectral shape and the overall normalisation
- Systematic uncertainties related to energy reconstruction, theoretical spectral shape, binning, model choice and selection efficiencies considered
- Compatible result to a fit with single state dominance (SSD) model

$$\boxed{T_{1/2} = 7.08 \pm 0.02 \text{ (stat.)} \pm 0.11\text{(syst.)} \times 10^{18} \text{ yrs (68\% c.i.)}} \tag{6}$$

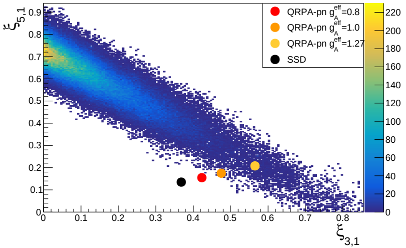


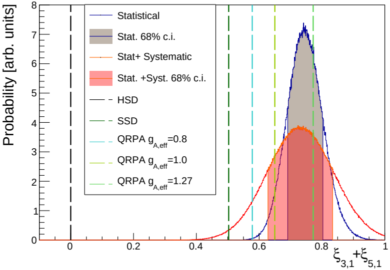
$$\boxed{\textbf{The most precise } 2\nu\beta\beta\ T_{1/2} \textbf{ measurement in any isotope}} \tag{7}$$

$2\nu\beta\beta$ spectral shape

NEW!

- Extract also the shape factor $\xi_{31} + \xi_{51}$
- Compare to QRPA theory - compatibile with moderately quenched or unquenched g_A
- Mildy incompatible with single state dominance (SSD) theory and fully incompatible with higher state (HSD) hypothesis



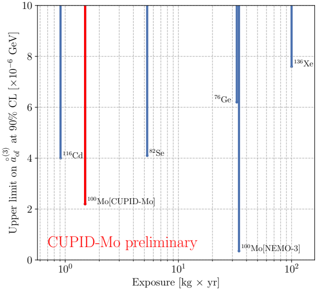


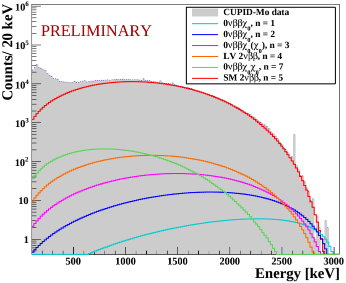
Spectral shape - Lorentz Violation and Majorons

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 $a_{of}^{(3)} = C \times \Gamma_{LV}/\Gamma_{SM}$
- Analysis uses the SSD $2\nu\beta\beta$ model

Strongest limit on LV for "source=detector" despite small exposure





Effect of $2\nu\beta\beta$ shape on BSM searches

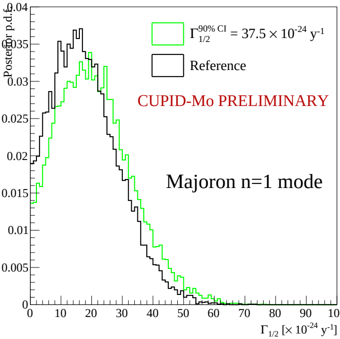
NEW!

- Also perform a new study of the effect of the spectral shape uncertainity (improved model) on the BSM limits
- Analysis of different Majoron models

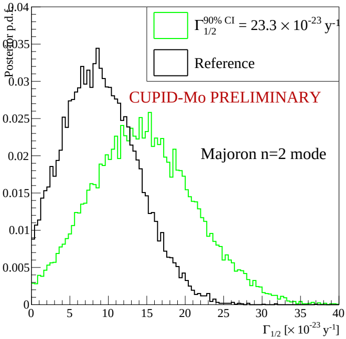
Process	Reference (SSD) [10^{21} yrs]	*improved* [10^{21} yr]
$\beta\beta\chi_0$ (n=1)	2.1	1.8
$\beta\beta\chi_0$ (n=2)	4.5	3.0
$\beta\beta\chi_0(\chi_0)$ (n=3)	1.4	0.6
$\beta\beta\chi_0\chi_0$ (n=7)	0.5	0.2

1. **The $2\nu\beta\beta$ model is an important systematic for BSM search**
2. **Previously not considered by any experiment**

Improved



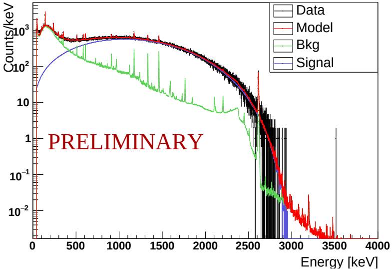
Improved



Measurement of $Q_{\beta\beta}$

NEW!

- Could be a systematic shift due to difference between γ events used for calibration and $\beta\beta$ signal
- Or some energy loss due to atomic physics as proposed in [5]
- Bayesian fit to the spectrum floating $Q_{\beta\beta}$
- In-situ measurement useful to rule out systematics shifts
- Result compatible with expected $Q_{\beta\beta}$ position (3034.4(4) keV)



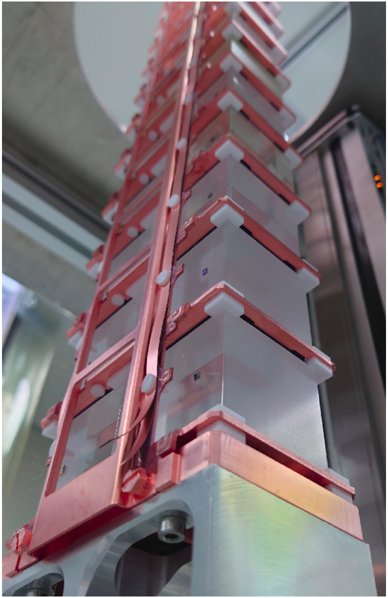
$$\boxed{Q_{\beta\beta} = 3038.4 \pm 1.5(\text{stat.}) \pm 7(\text{syst.})\ \text{keV}}$$

---

[5] Nucl. Phys. A 1032 (2023) 122623

Prospects: CUPID

- **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



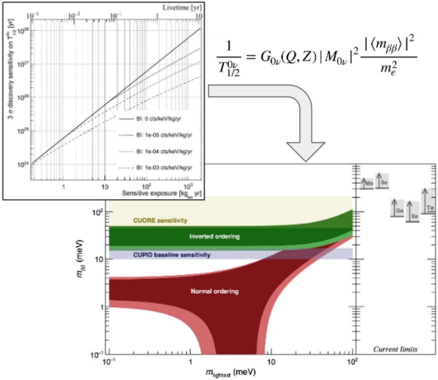
Conclusion

1. CUPID-Mo 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. Results of novel analysis of the $2\nu\beta\beta$ spectrum shape
5. Limits on other BSM processes

Thanks for your attention!

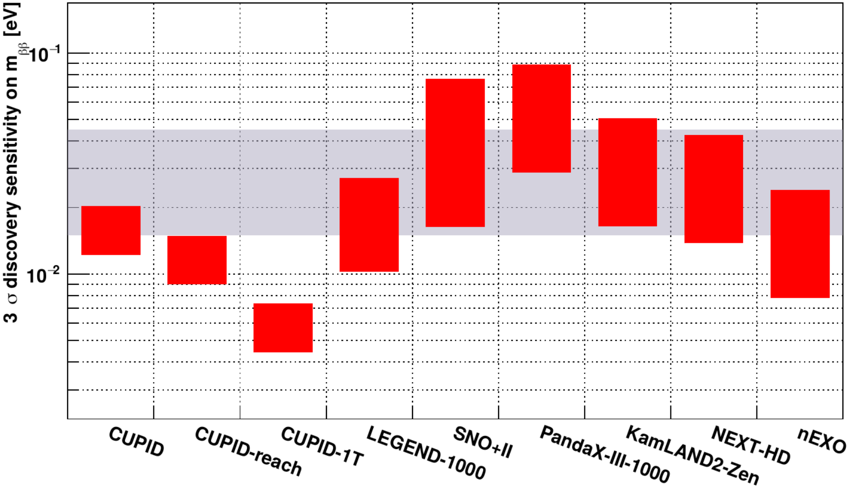
CUPID sensitivity

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



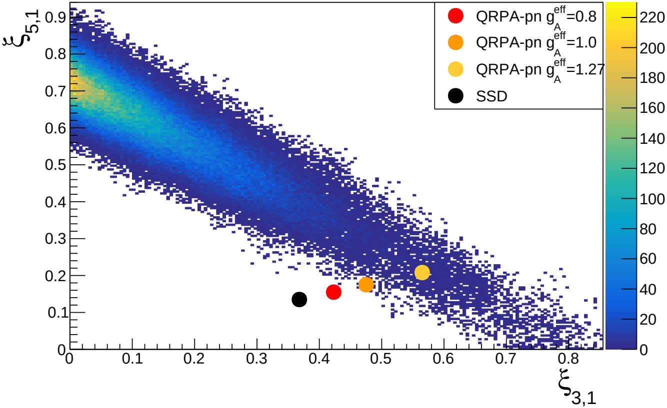
$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

CUPID sensitivity-2



Improved model fit

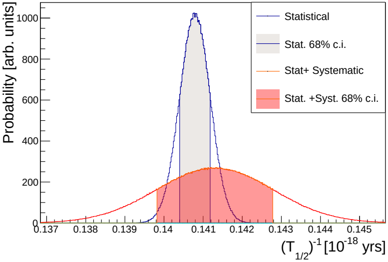
- Next look at extracted value of ξ_{31}, ξ_{51}
- We draw 3 main conclusions:
  1. A large higher order contribution is needed to fit the data
  2. It is not well constrained whether this should be G_4 or G_2
  3. The data is mildly incompatible with SSD and QRPA theory



Systematics

- Systematics focus on:
- **Background model**
  1. Vary the source location (±0.79%)
  2. Remove a contribution of pure β (^{90}SrY) (+1.14%)
  3. Vary model parameters (±0.21%)
- **Energy reconstruction**
  - Shift MC energies (energy bias) (0.17%)
  - Vary the binning (0.36 %)
- $2\nu\beta\beta$ **shape + MC accuracy**
  - MC statistics (0.09%)
  - Vary Geant4 cross sections (Bremstrallhung) (0.26%)
- **Isotope abundance (0.20%) and selection efficiency (1.2%)**
- Each is assigned a posterior distribution (Gaussian for all but SrY which is uniform)

- Sample from all to convolve systematics into posterior



$$\boxed{T_{1/2} = 7.08 \pm 0.02 \text{ (stat.)} \pm 0.11\text{(syst.)} \times 10^{18} \text{ yrs (68\% c.i.)}} \quad (8)$$

NME comparison

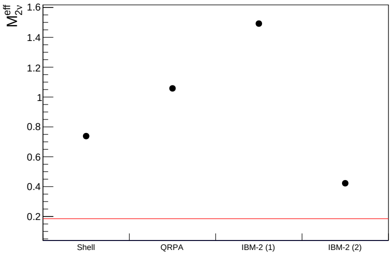
- Compute the effective NME

$$\frac{1}{T_{1/2}} = |M_{2\nu}^{\text{eff}}|^2 \times G \qquad (9)$$

$$M_{2\nu}^{\text{eff}} = \sqrt{\frac{1}{T_{1/2} G}} \qquad (10)$$

- Consider $g_A^{\text{eff}} = 1.27$
- Complication: For $2\nu\beta\beta$ decay G also depends on the model
- Use SSD value 4.134×10^{-18} yr^{-1}
- Decay rate quenched significantly compared to theoretical expectation [6][7][8]

$$\boxed{M_{2\nu}^{\text{eff}} = 0.1851 \pm 0.0014} \qquad (11)$$



---

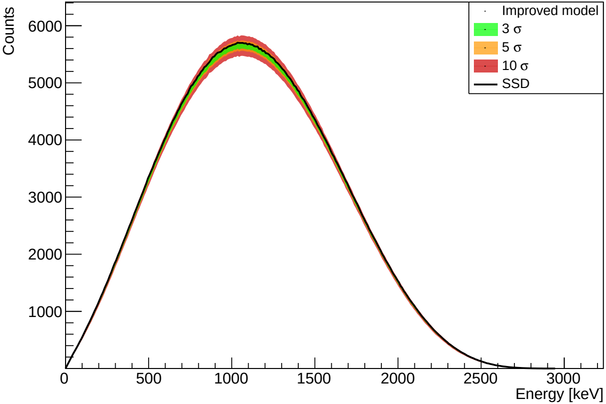
[6] Shell model from Phys. Rev. C 105, 034312 (2022)

[7] QRPA from Phys. Rev. C 91, 054309 (2015)

[8] IBM-2 from , Phys. Rev. C 91, 034304 (2015) and Phys. Rev. C 105, 044301 (2022)

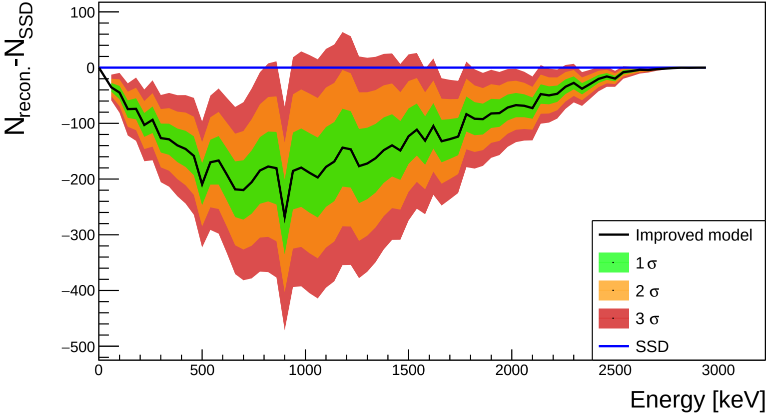
Reconstructed spectral shape

- Reconstruct the spectral shape and a confidence band
- Errors are very small
- The two models reconstruct a slighly ($\sim 3\sigma$) incompatible shape
- Improved model gives a flater spectrum
- This can be considered as a *measurment* of the spectrum shape



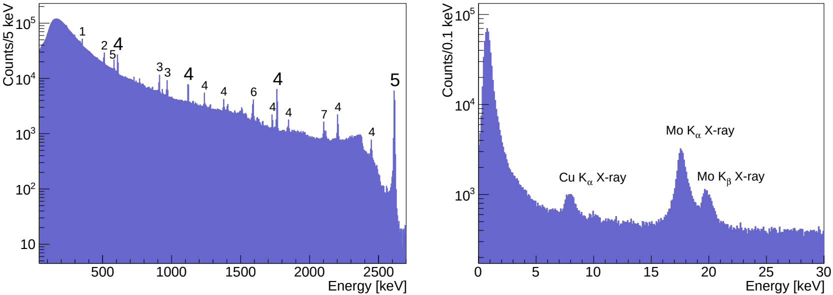
Reconstructed spectrum (2)

- To see more clearly look at the difference in improved-SSD counts
- SSD reconstructs slightly more counts - also a sharper spectrum?



Data processing: Calibration / stabilisation

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

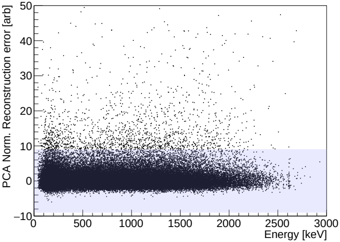


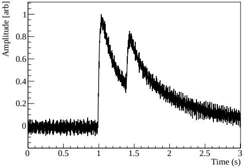
Data processing: PSD

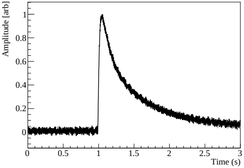
- Remove pileups and other superious events (eg noise spikes)
- Principle components trained on $2\nu\beta\beta$ events
- Reconstruct each pulse using first 6 components
- Define a reconstruction error:

$$R = \sqrt{\sum_i (x_i - \sum_k q_i w_{k,i})^2} \tag{12}$$

- Normalise by the observed Median and MAD



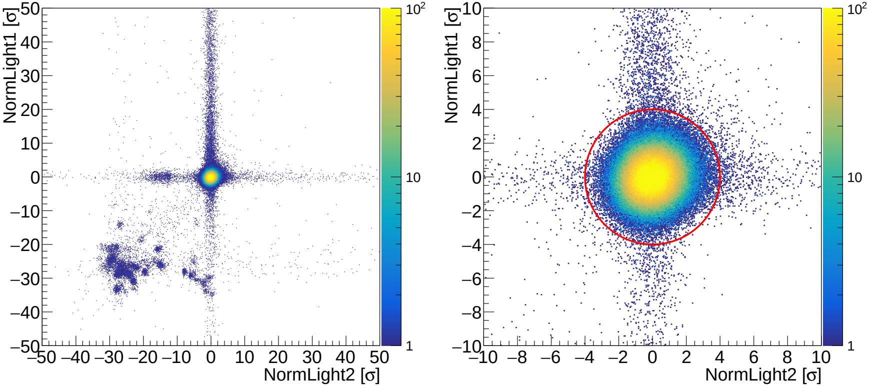




Data processing: LD cuts

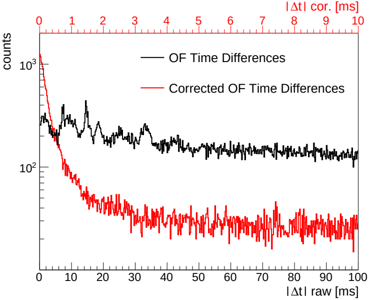
- Each detectors sees two LDs
- Combine the two pieces of information for a 2D cut
- LD energy centered and normalised based on energy resolution

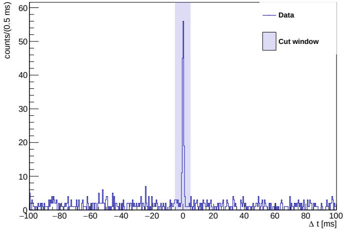
$$n_i = \frac{E_{i,\mathrm{LD}} - E_{i\mathrm{LD,exp}}}{\sigma_i(E)}$$

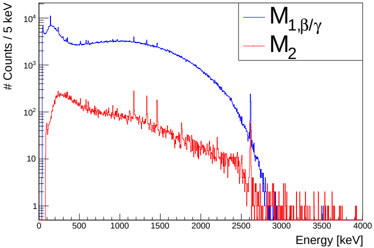


Data processing: Coincidences

- 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

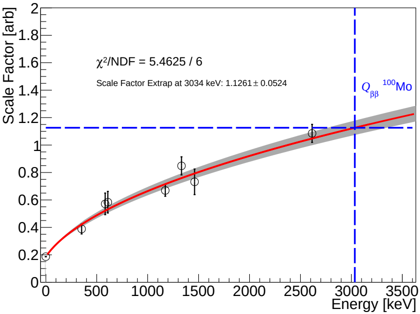
$$^{212}\mathrm{Bi} \xrightarrow[\alpha(6207\ \ \mathrm{keV})]{60.6\ \ \mathrm{min},\ \ \ 35.9\%\ \ \mathrm{BR}} {}^{208}\mathrm{Tl} \xrightarrow[\beta^-(4999\ \ \mathrm{keV})]{3.1\ \ \mathrm{min},\ \ \ 100\%\ \ \mathrm{BR}} {}^{208}\mathrm{Pb}.$$

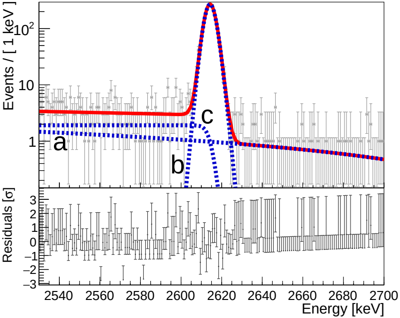
- Low CUPID-Mo radioactivity allows a novel cut on ^{214}Bi with a long dead time

$$\begin{aligned}
&^{222}\mathrm{Rn} \xrightarrow[\alpha(5590\ \ \mathrm{keV})]{3.8\ \ \mathrm{day},\ \ \ 100\%\ \ \mathrm{BR}} {}^{218}\mathrm{Po} \xrightarrow[\alpha(6115\ \ \mathrm{keV})]{3.1\ \ \mathrm{min},\ \ \ 99.98\%\ \ \mathrm{BR}} {}^{214}\mathrm{Pb} \\
&^{214}\mathrm{Pb} \xrightarrow[\beta^-(1018\ \ \mathrm{keV})]{27.1\ \ \mathrm{min},\ \ \ 100\%\ \ \mathrm{BR}} {}^{214}\mathrm{Bi} \xrightarrow[\beta^-(3269\ \ \mathrm{keV})]{19.7\ \ \mathrm{min},\ \ \ 99.98\%\ \ \mathrm{BR}} {}^{214}\mathrm{Po} \\
&^{214}\mathrm{Po} \xrightarrow[\alpha(7834\ \ \mathrm{keV})]{163.4\ \ \mu\mathrm{s},\ \ \ 100\%\ \ \mathrm{BR}} {}^{210}\mathrm{Pb}
\end{aligned} \tag{12}$$

Energy resolution

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

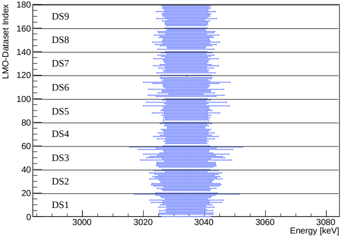


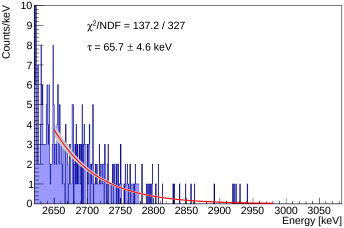


Bayesian counting analysis

- 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

$$\lambda_i = \sum_{c=1}^{19}\sum_{d=1}^{9}(Mt)_{c,d}/Mt \cdot \Bigg(\varepsilon_i(c,d)\cdot\Gamma^{0\nu}\frac{N_A\cdot\cdot\eta}{W} + \int_{E_{a,i}(c,d)}^{E_{b,i}(c,d)} f(E)dE\Bigg). \tag{13}$$





$2\nu\beta\beta$ 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%]