Detector response study of cryogenic scintillating Li_2MoO_4 detectors for next generation $0\nu\beta\beta$ search

IJCLab
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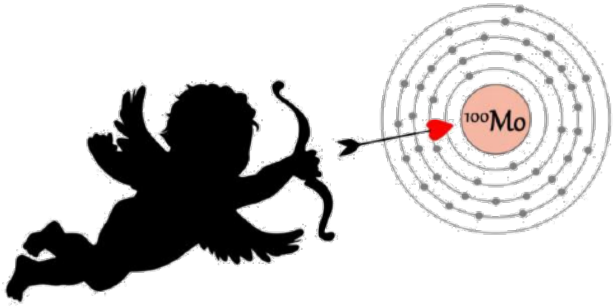
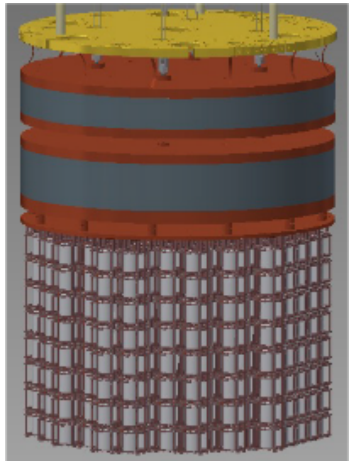
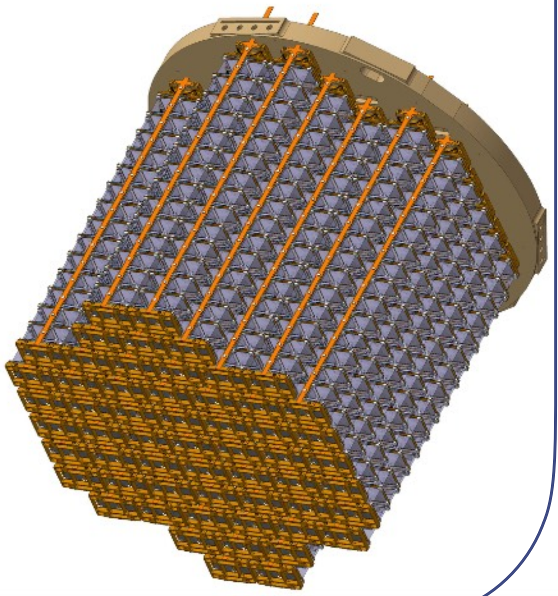


TAUP XICHANG

AMoRE-II



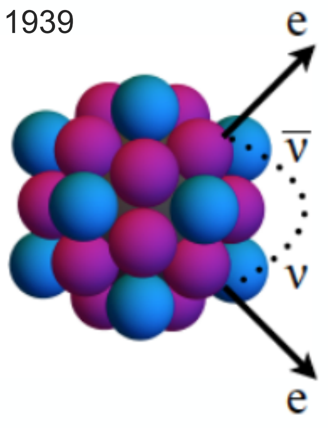
CUPID

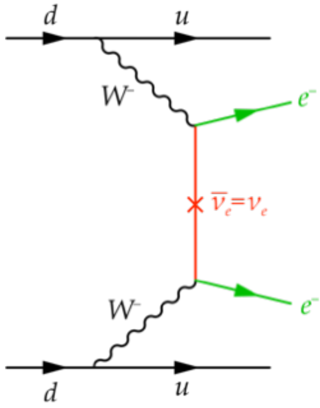


Benjamin Schmidt
for the CUPID-Mo collaboration

Neutrinoless double beta decay
Light Majorana neutrino exchange

Furry 1939





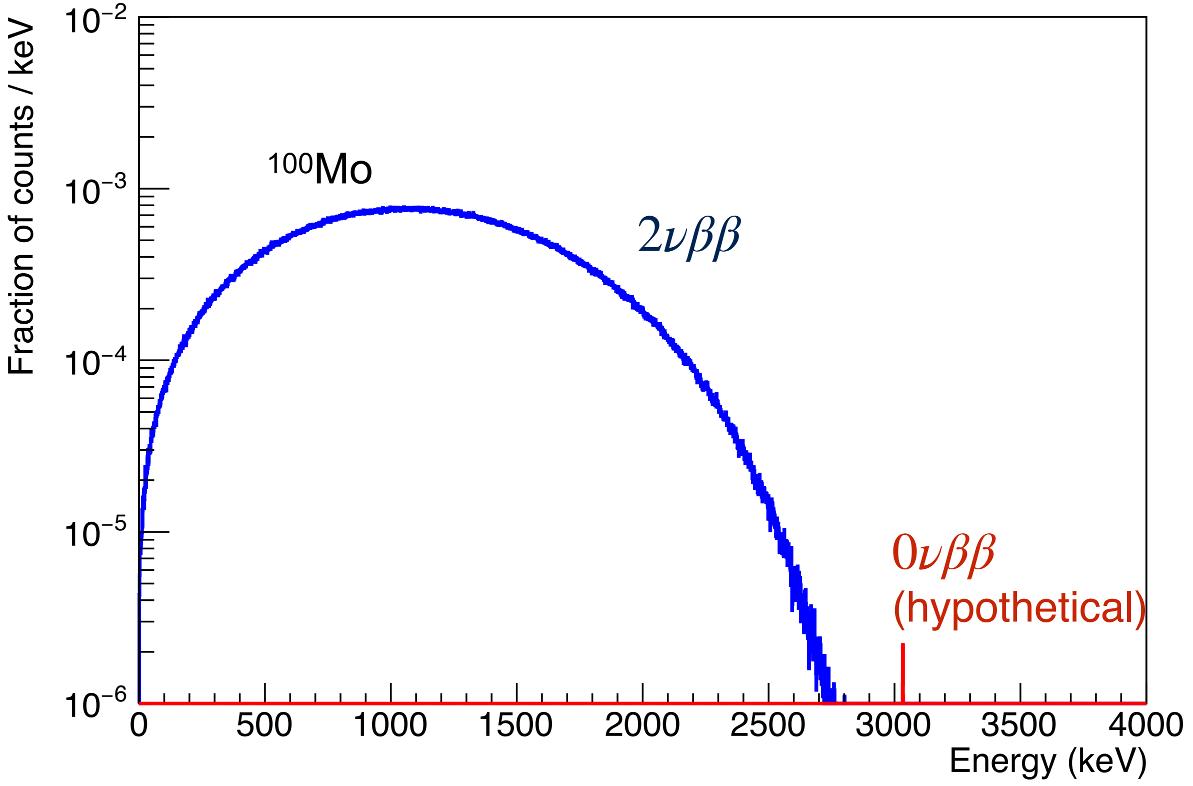
$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} \sim g_A^4 \cdot G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Effective Majorana mass:

$$\langle m_{\beta\beta} \rangle = | \sum_{i=1,2,3} U_{e,i}^2 m_i |$$

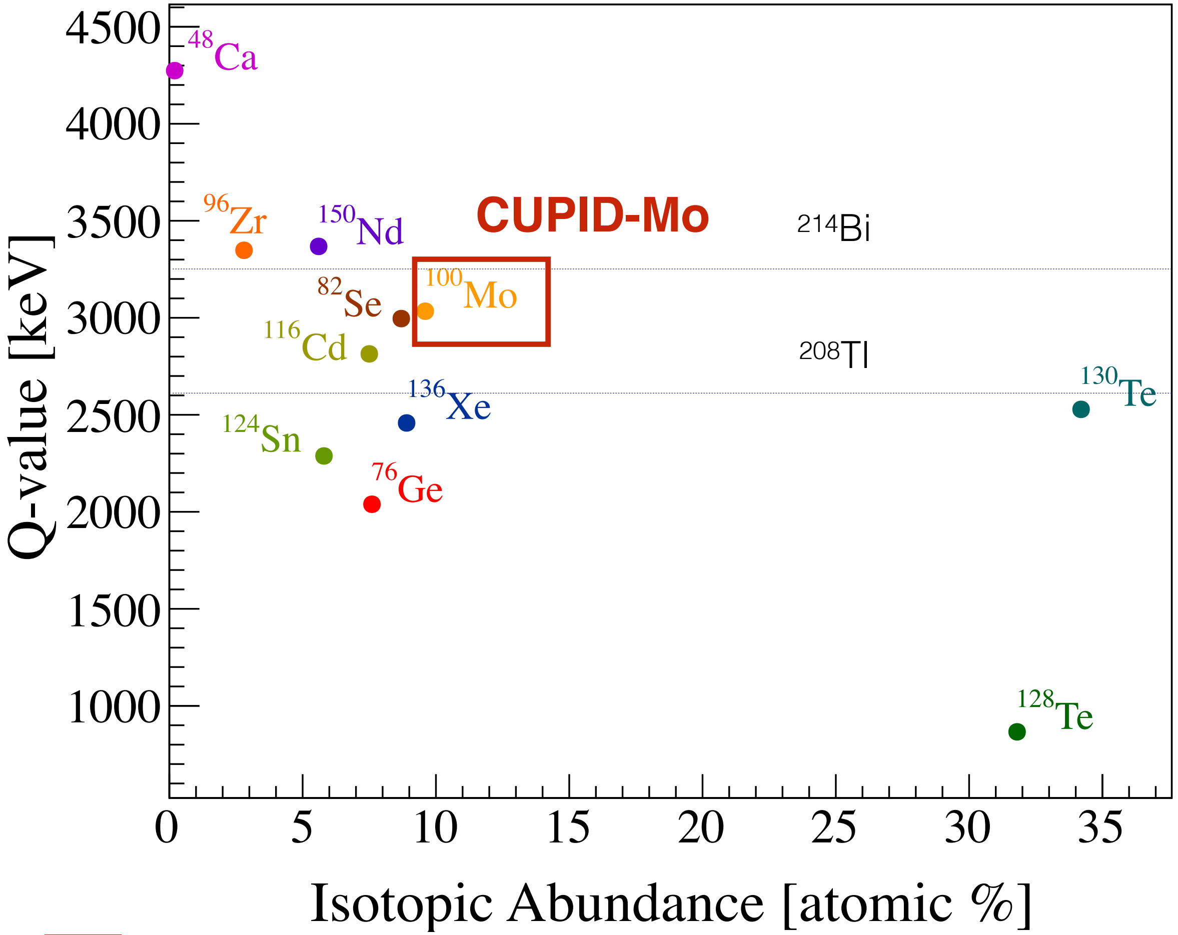
Implications:

- ΔL = 2, lepton number violation
- Majorana nature of neutrino



Experimentally considered $0\nu\beta\beta$ isotopes

11 / 35 experimentally considered candidate isotopes



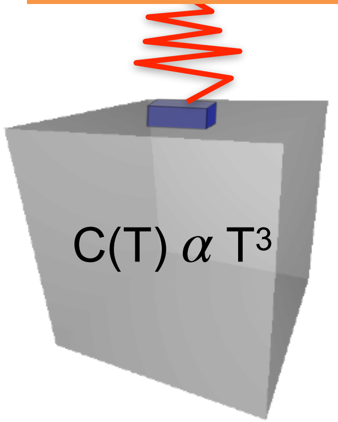
Isotope choice considerations:

high Q-value (3034 keV) -> large phase space, typically low natural radioactivity backgrounds

Backgrounds
-> improve signal/background through good energy resolution
-> dedicated Background suppression/particle ID

Scintillating cryogenic Li_2MoO_4 calorimeters

Thermal bath @ 20 mK

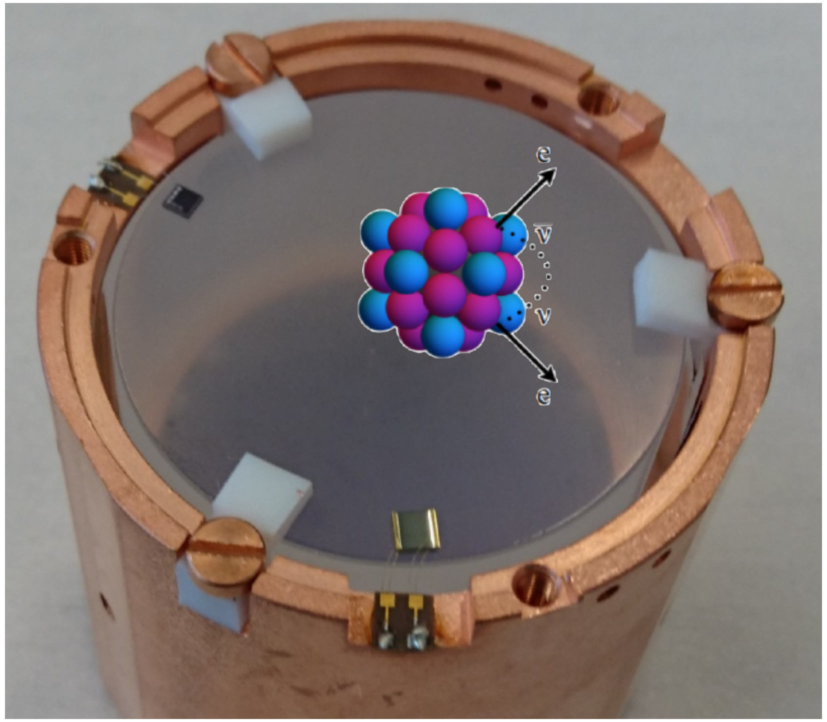


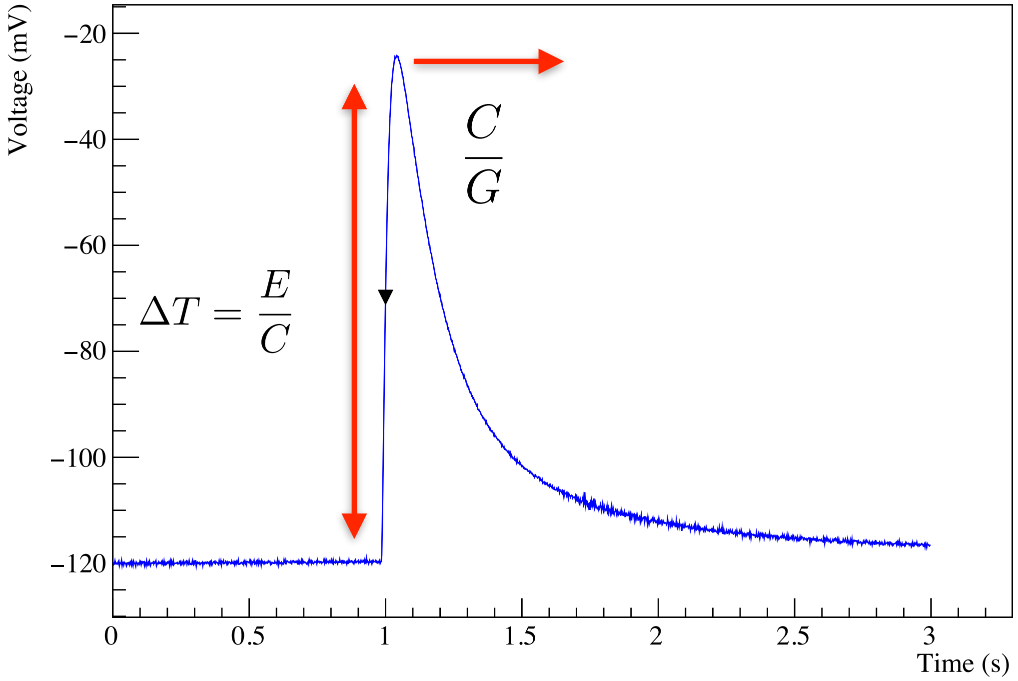
NTD-Ge thermistor
as sensor

$$R(T) = R_0 e^{\sqrt{T_0/T}}$$

Teflon & Au wire bonds: weak thermal link

Copper: Thermal Bath



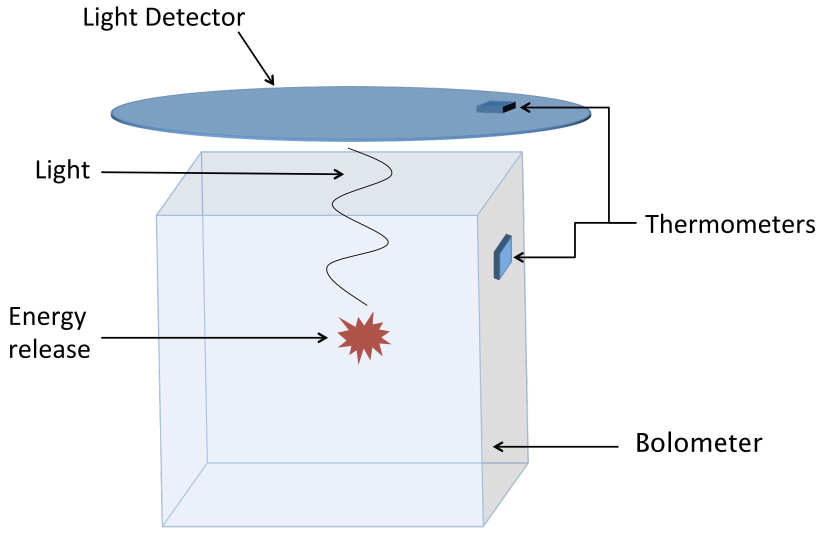


Scintillating cryogenic Li_2MoO_4 calorimeters

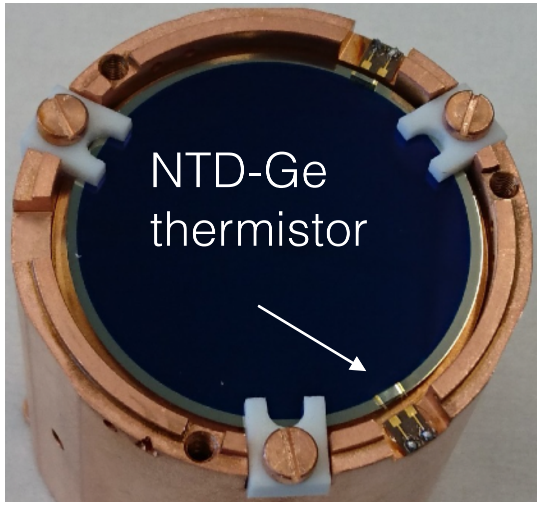
Ge semiconductor wafer as light detecter

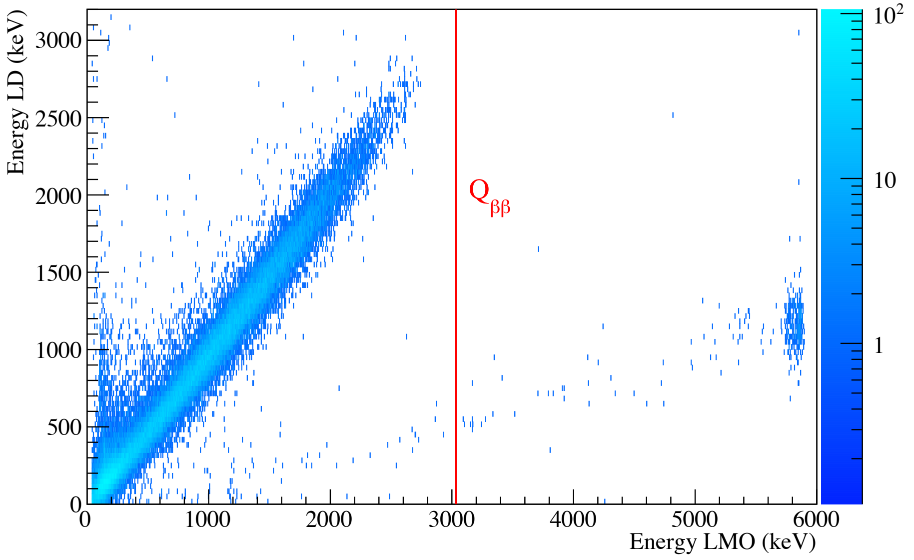
- SiO_2 anti-reflective coating to maximise light collection
- 1 x 3 mm NTD (1/3) size for improved sensitivity
- 3M reflective foils to maximise light collection

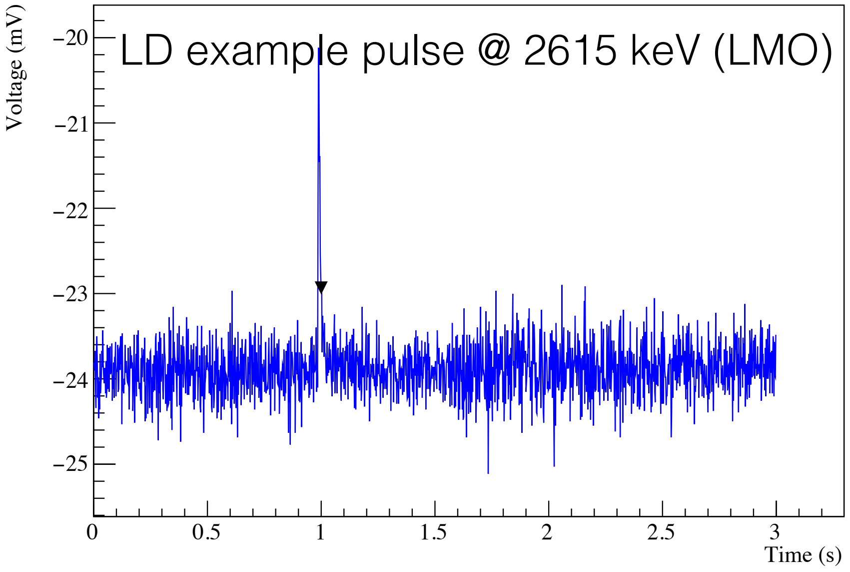
→ > 99.9% α discrimination by light yield



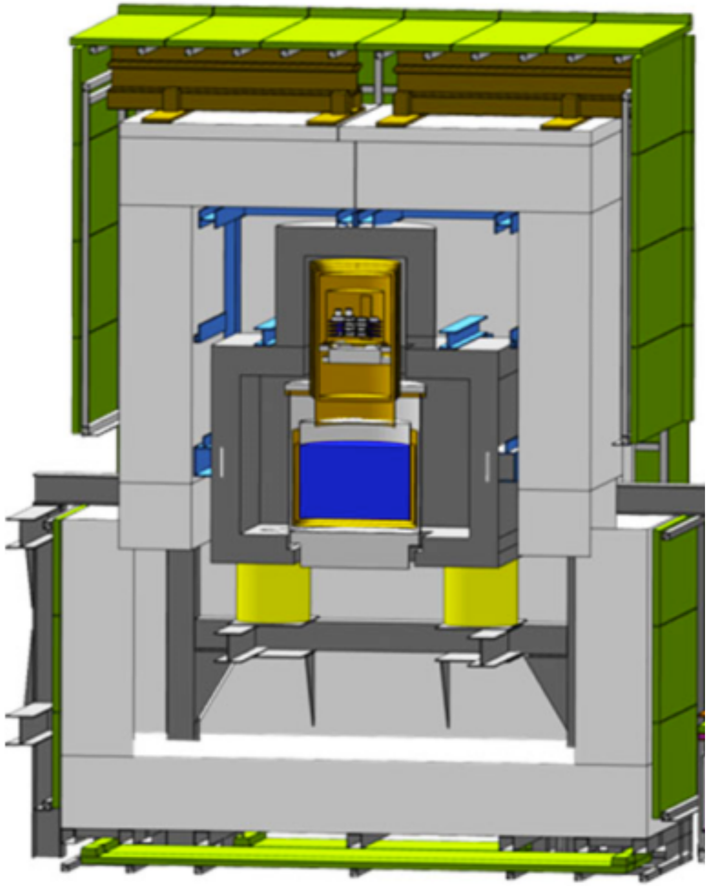
Ge light detector







CUPID-Mo at the Laboratoire Souterrain de Modane France (2018 - 2020)



Shielding:

4800 m.w.e. rock overburden

Massive Pb and PE shielding

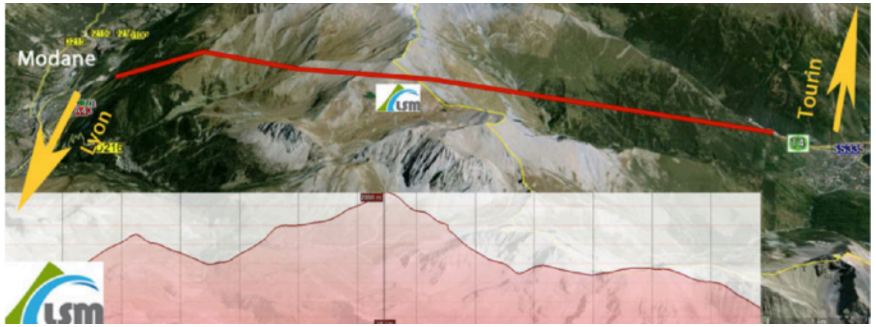
Active plastic scintillator muon-veto system

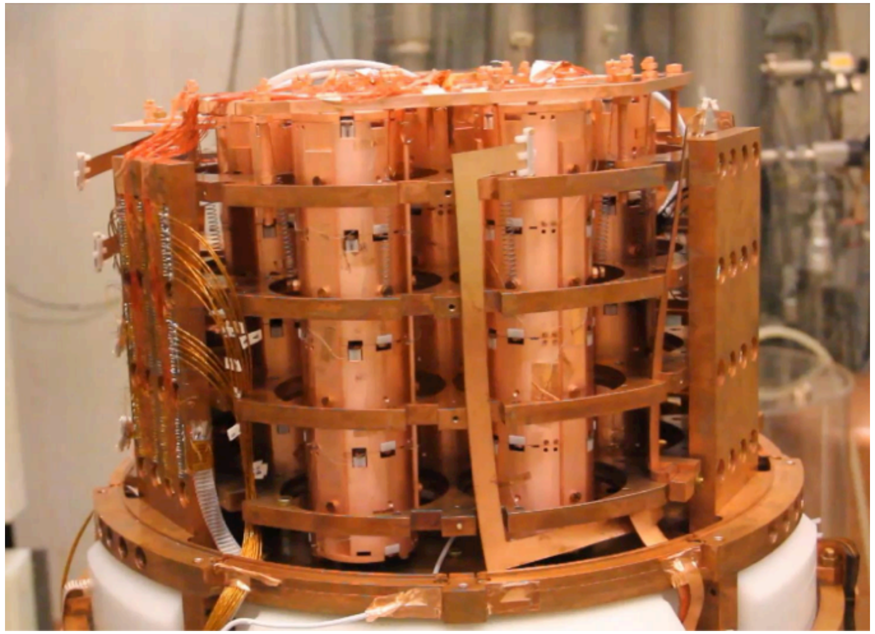
Detector operations:

EDELWEISS cryostat operated at @ 20 - 22 mK

20 $Li_2{}^{100}MoO_4$ detectors of ~210 g, ~97% enriched (2.26 kg ^{100}Mo)

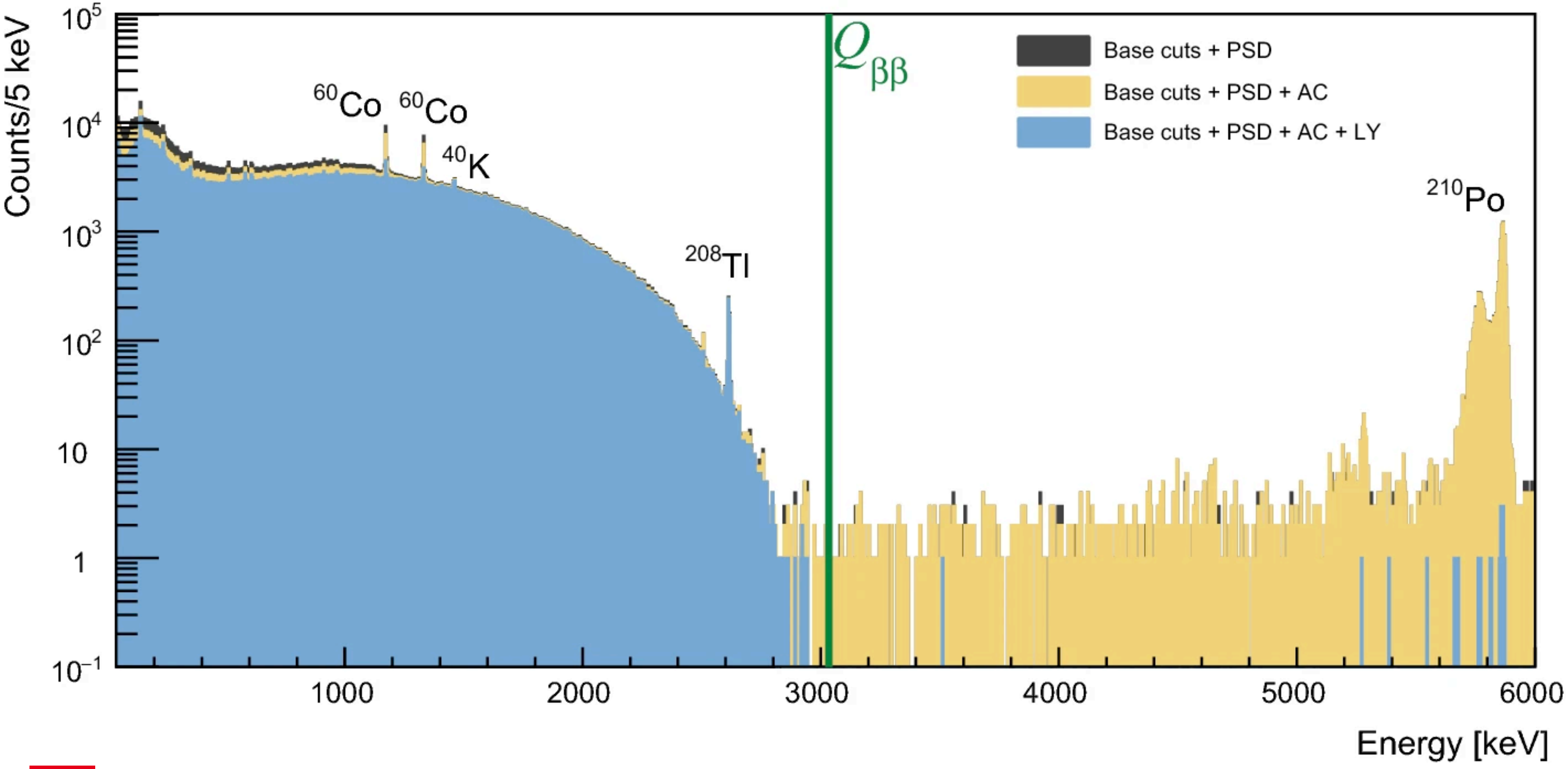
physics data taking March 2019 - June 2020





CUPID-Mo results - Recap

- 2.71 kg year of Exposure with 19 detectors of ~210 g each, 16 months total
- Spectrum dominated by $2\nu\beta\beta$ of ^{100}Mo



- Complete α discrimination with 2 LDs
- High analysis efficiency > 88%
- Lowest Bg index of a bolometric experiment within ROI:

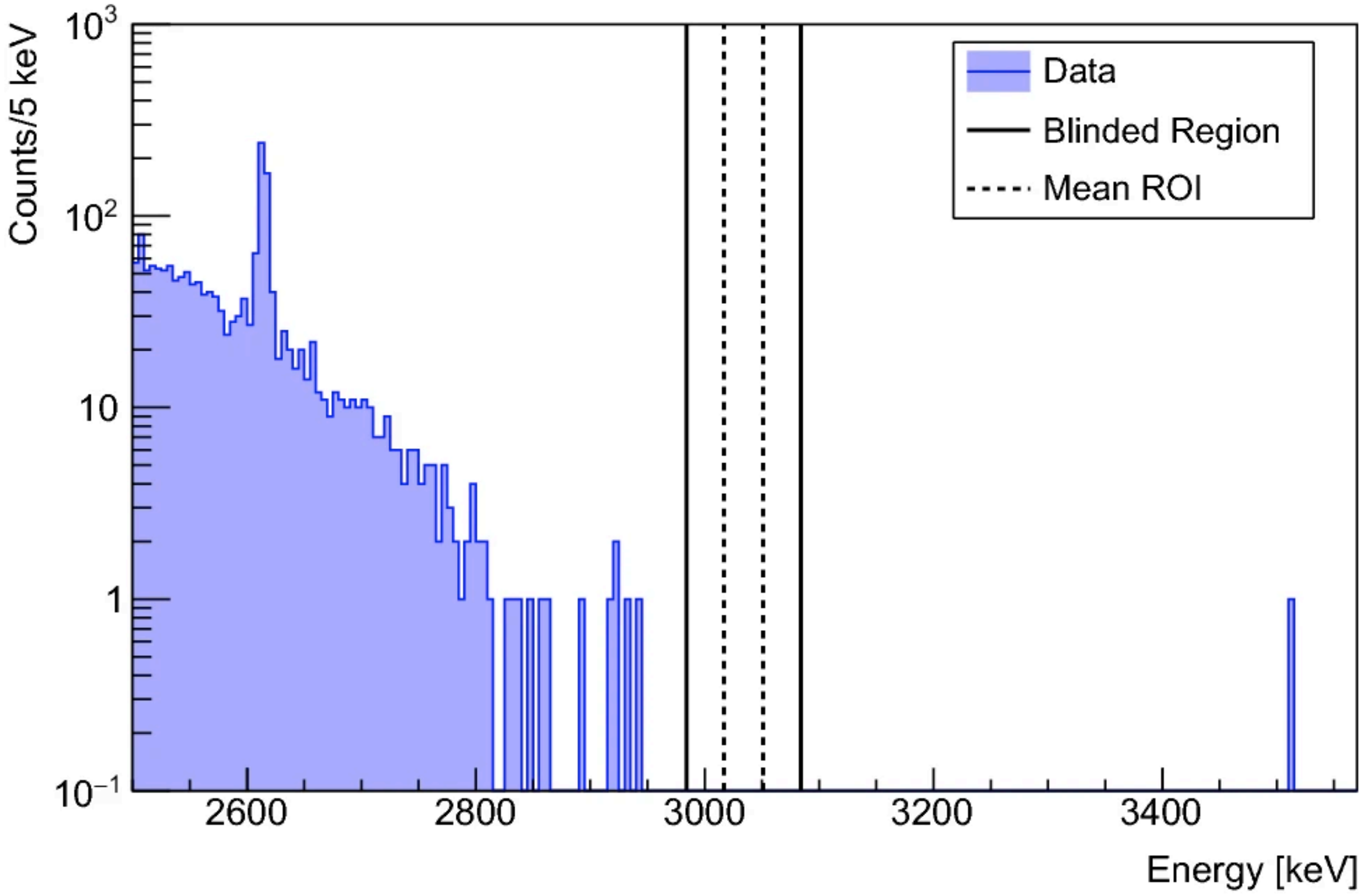
$$3.7^{+1.7}_{-1.1} \cdot 10^{-3}\ \mathrm{evts}/\Delta E_{\mathrm{FWHM}}/\mathrm{mol_{iso}}/\mathrm{yr}$$

EPJ-C 83 (7), 675, 2023

Demonstrated science potential for Mo containing bolometers for $0\nu\beta\beta$ and $2\nu\beta\beta$, PRL 131, 162501

Excited states, PRC 107, 025503, 2023
BSM physics, EPJ-C 84 (9), 925, 2024

CUPID-Mo $0\nu\beta\beta$ analysis - Recap



- 19/20 detectors with good performance
- ~7.4 keV FWHM @ $Q_{\beta\beta}$

$0\nu\beta\beta$ science results:

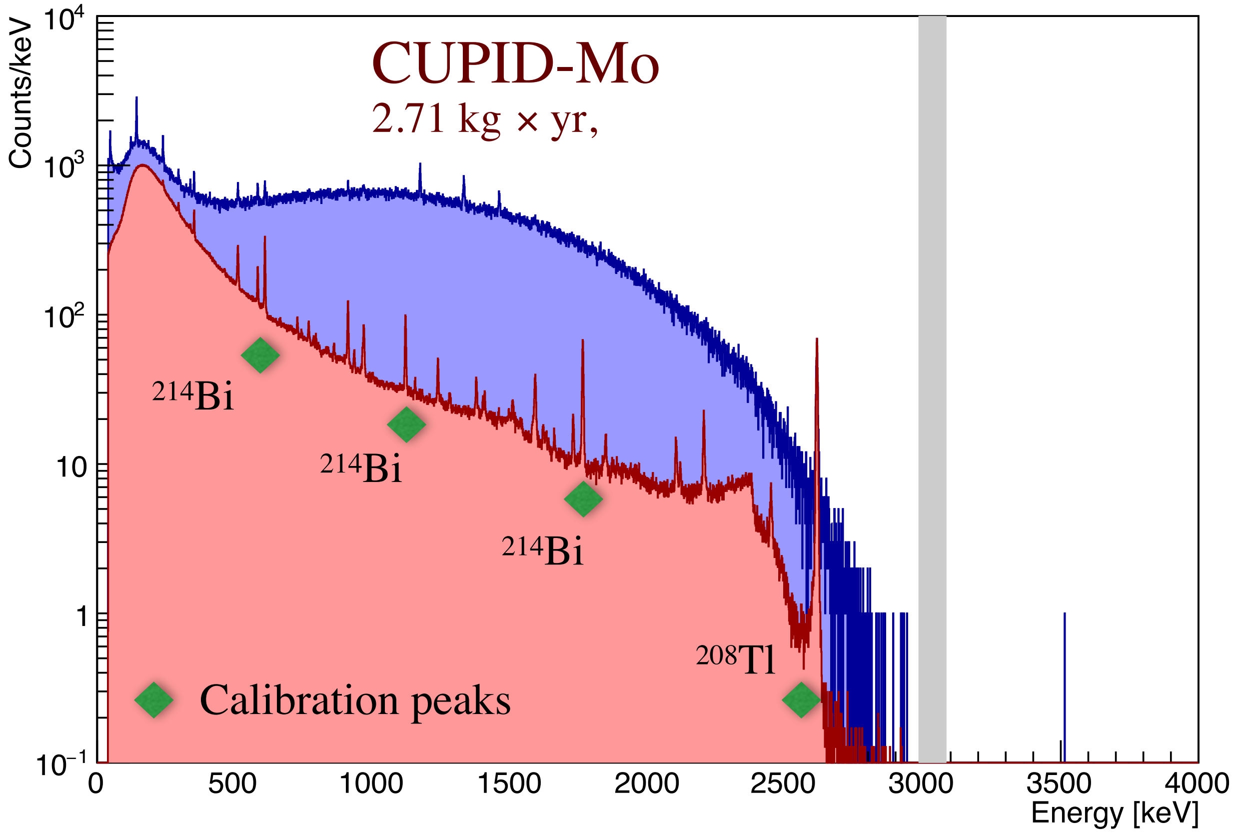
- Experiment - EPJ-C 80, 44, 2020
- 1st $0\nu\beta\beta$ result - PRL 126, 181802, 2021
- 2nd $0\nu\beta\beta$ result - EPJ-C 82, 1033, 2022

$$T^{0\nu}_{1/2} > 1.8 \times 10^{24} \text{ yr } (90\,\% \text{ C.I.})$$

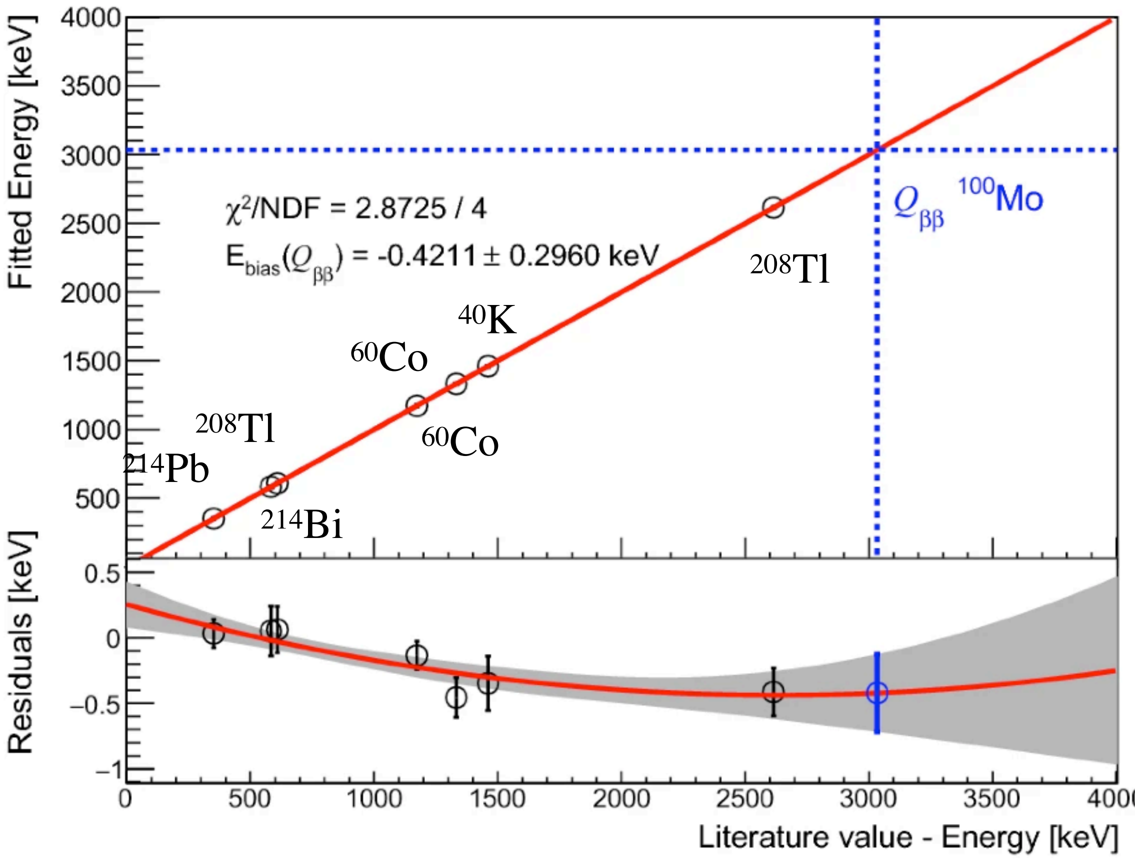
$$m_{\beta\beta} < 0.28 - 0.49 \text{ eV } (90\,\% \text{ C.I.})$$

CUPID-Mo - Energy scale

- Energy scale is set with 2nd order polynomial in calibration data (phenomenological fit to compensate for non-linearity of the NTD response)
- Tl-208 rate of calibration data normalised to low background data

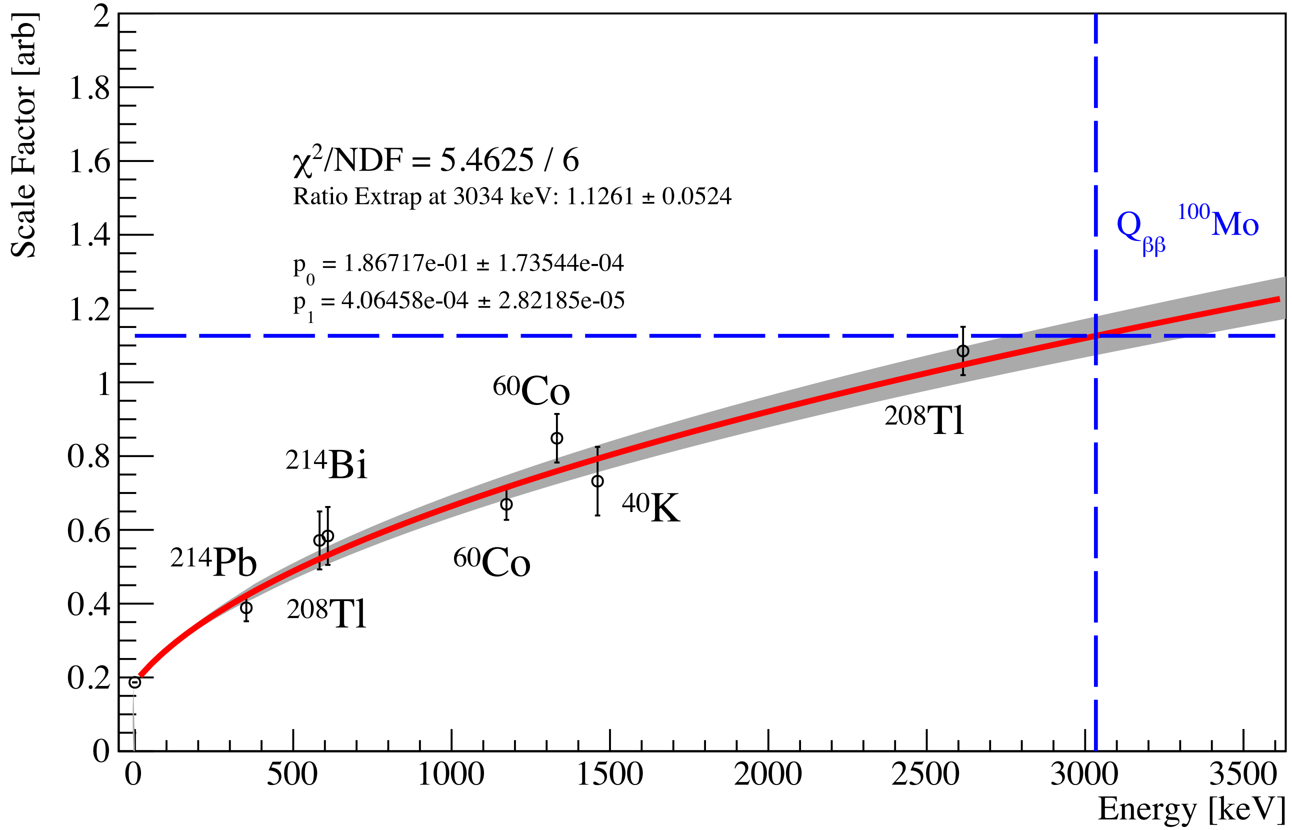


- Estimate energy bias based on physics data
  E_B = (-0.4 ± 0.3) keV



CUPID-Mo - ROI resolution scaling

- Data-driven model for resolution scaling (no general model for cryogenic calorimeters)
  - Obtain the individual detector resolution at 2615 keV
  - And a global scaling factor for the dependence
    Calibration @2615 keV <-> Low background @3034 keV



- Tested several hypothesis:
  - linear, “sqrt”, “2nd order sqrt” -> linear is ruled out by calibration data, disfavoured in background data
  - No preference between “sqrt”/ “2nd order”
- Resolution estimate at Q-value based on sqrt model

$$\Delta E = \sqrt{p_0^2 + (p_1 \cdot \sqrt{E})^2} = (7.4 \pm 0.4)\,\mathrm{keV}$$

CUPID-Mo - ^{56}Co calibration campaign

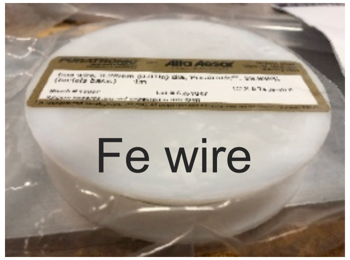
~3 weeks of ^{56}Co calibration at LSM before the final warm-up of CUPID-Mo
(Limited by operational constraints and COVID restrictions)

Fe wire irradiated at 88-inch cyclotron (LBNL)
Deployed ~120 Bq of ^{56}Co in two sources at LSM in summer 2020

Source activity tuned to provide several 100 events total at 3.2 MeV, with reasonable detector pile-up rate

BERKELEY LAB

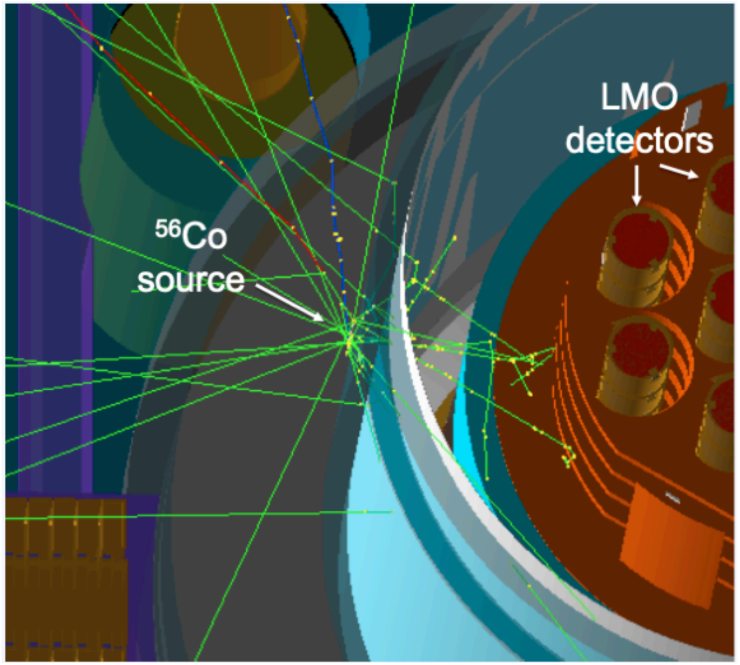
88-Inch Cyclotron

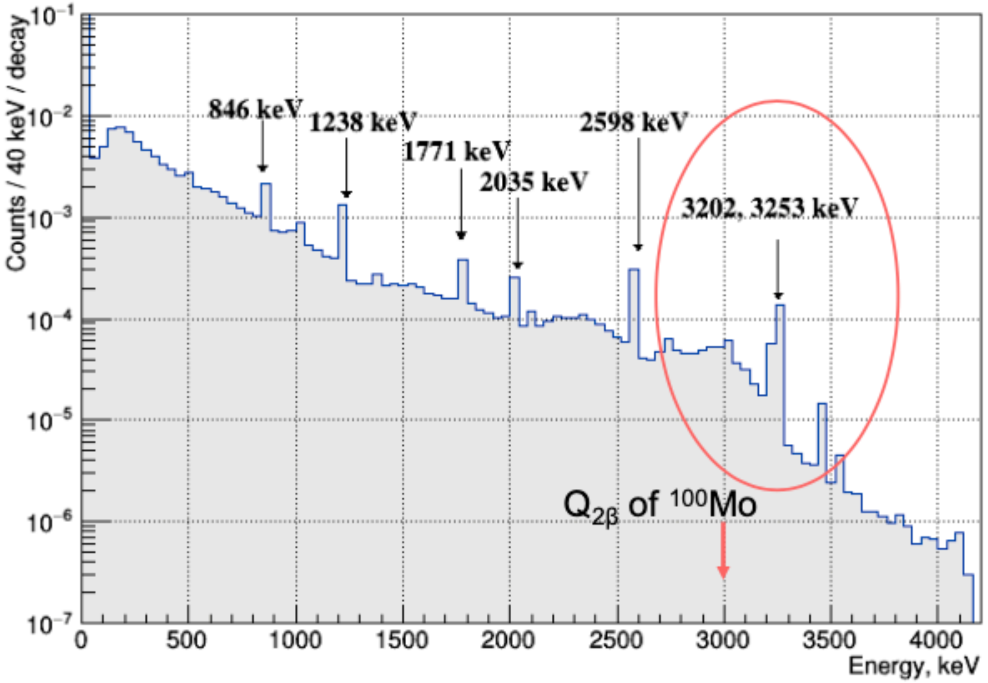


88-Inch Cyclotron

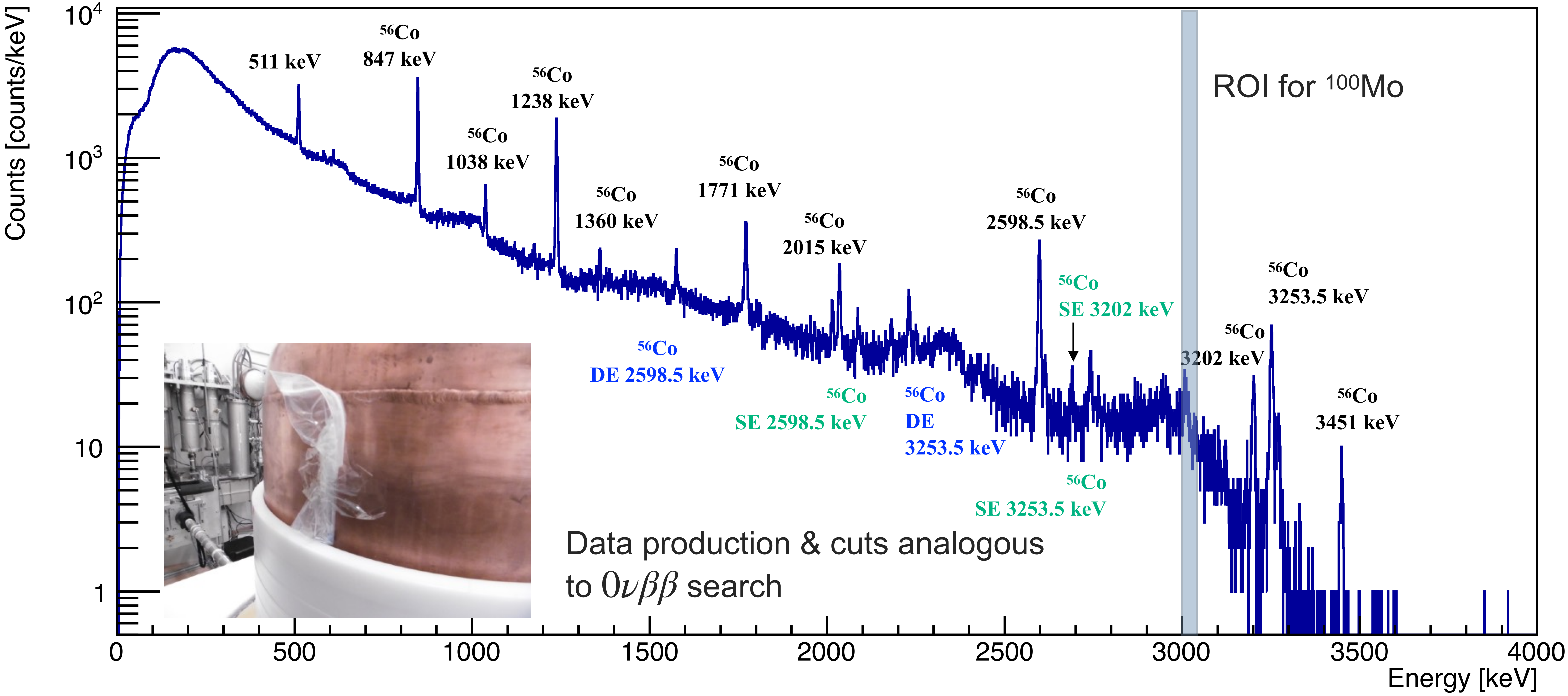
20 MeV protons

^{56}Fe (p, n) ^{56}Co

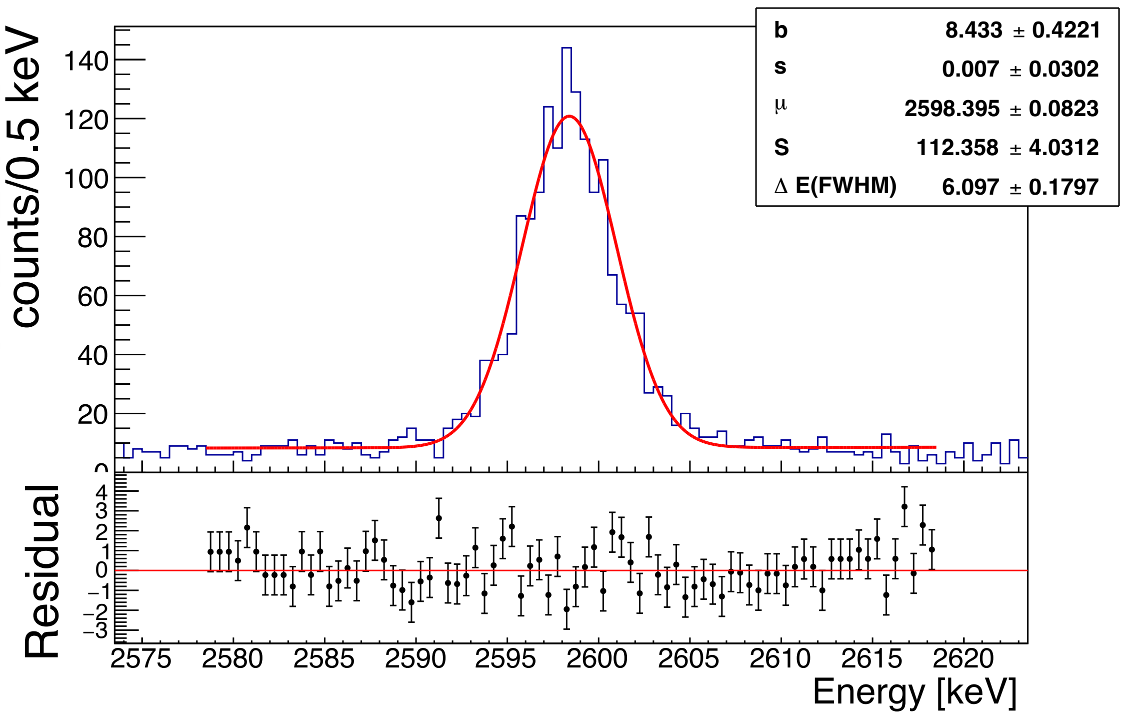


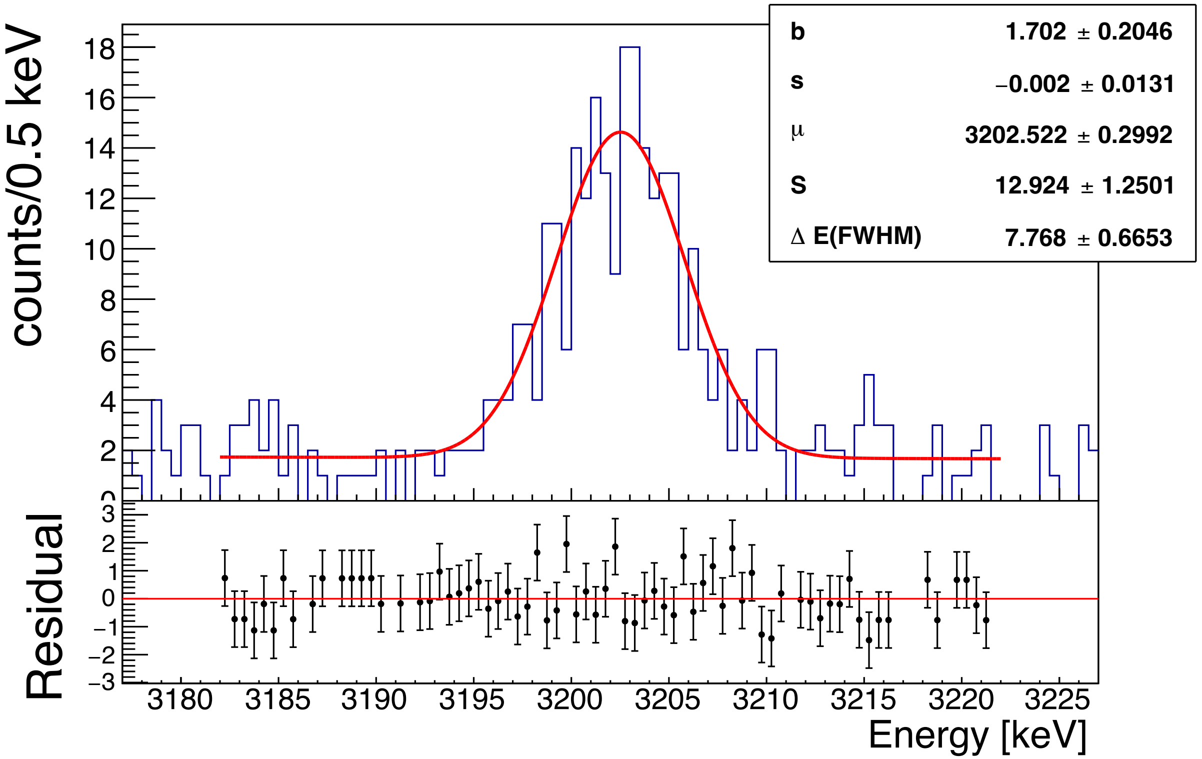


CUPID-Mo - ^{56}Co calibration campaign



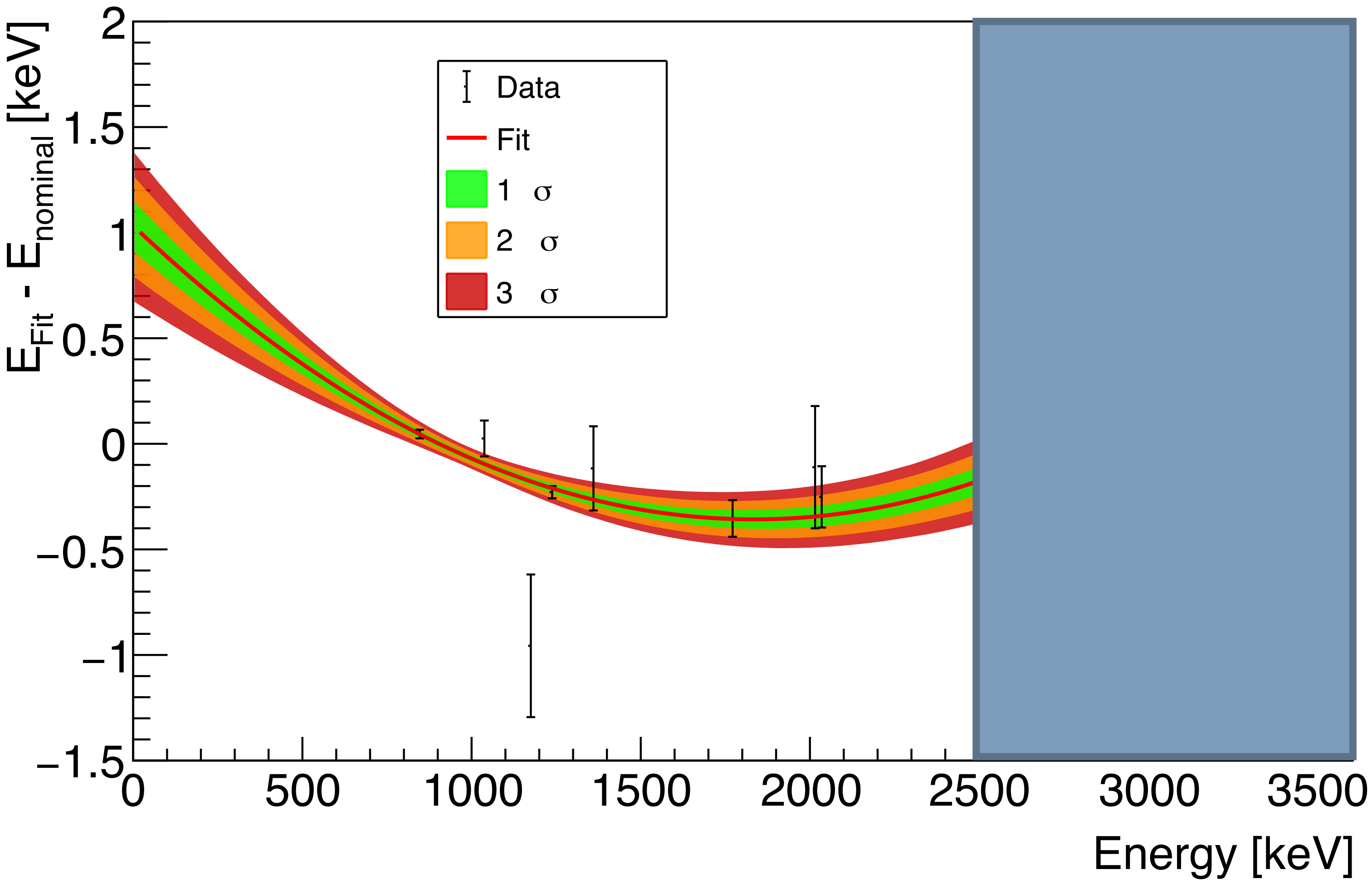
CUPID-Mo - ^{56}Co Fit example



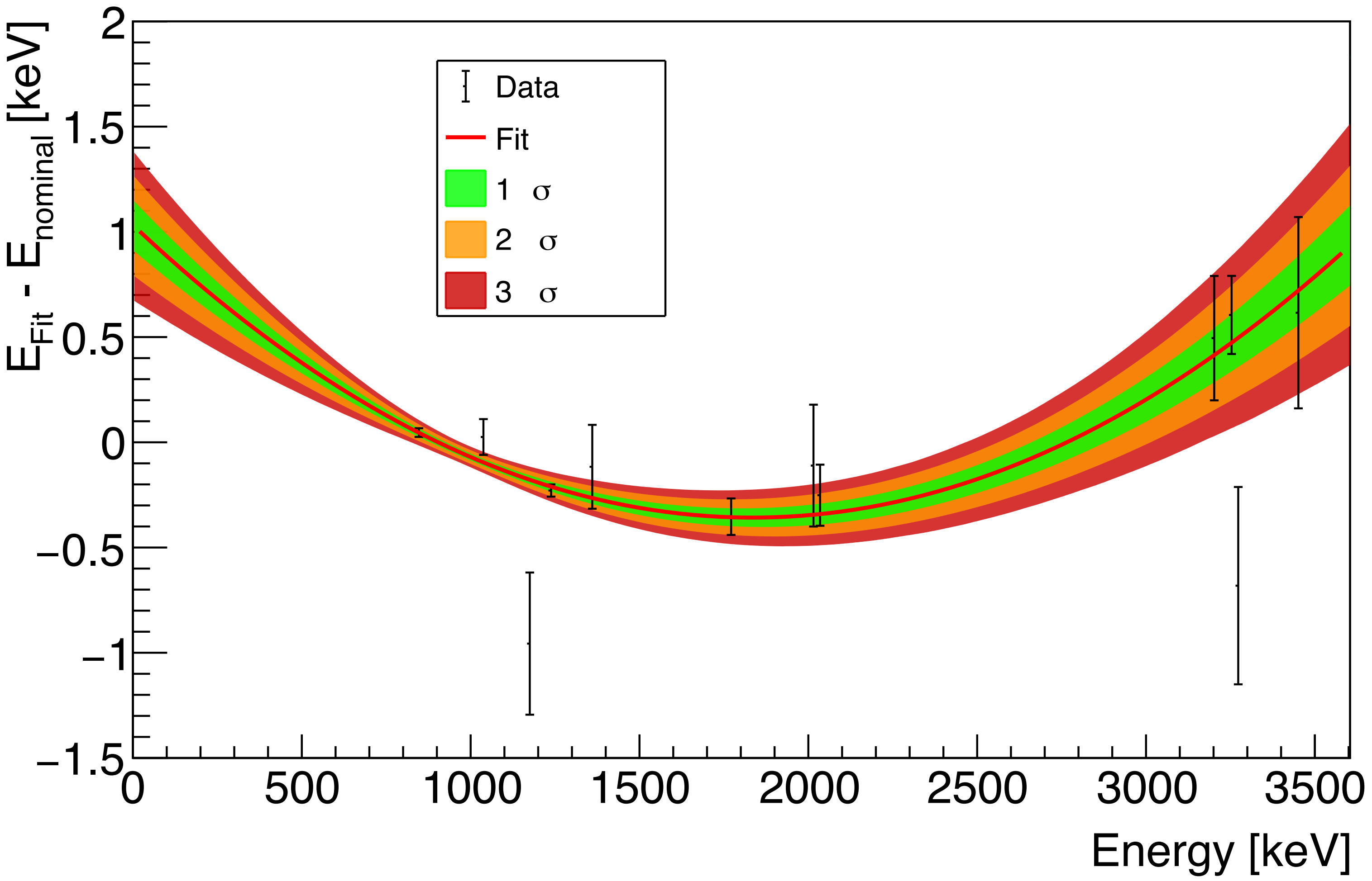


- Bayesian analysis based on fitting of Co-56 peaks over background
- All fits performed as binned likelihood fits with MCMC sampling in BAT
- Due to limited statistics fits of the summed 19 detector spectrum (Multiplicity 1 and 2)

CUPID-Mo - ^{56}Co energy bias



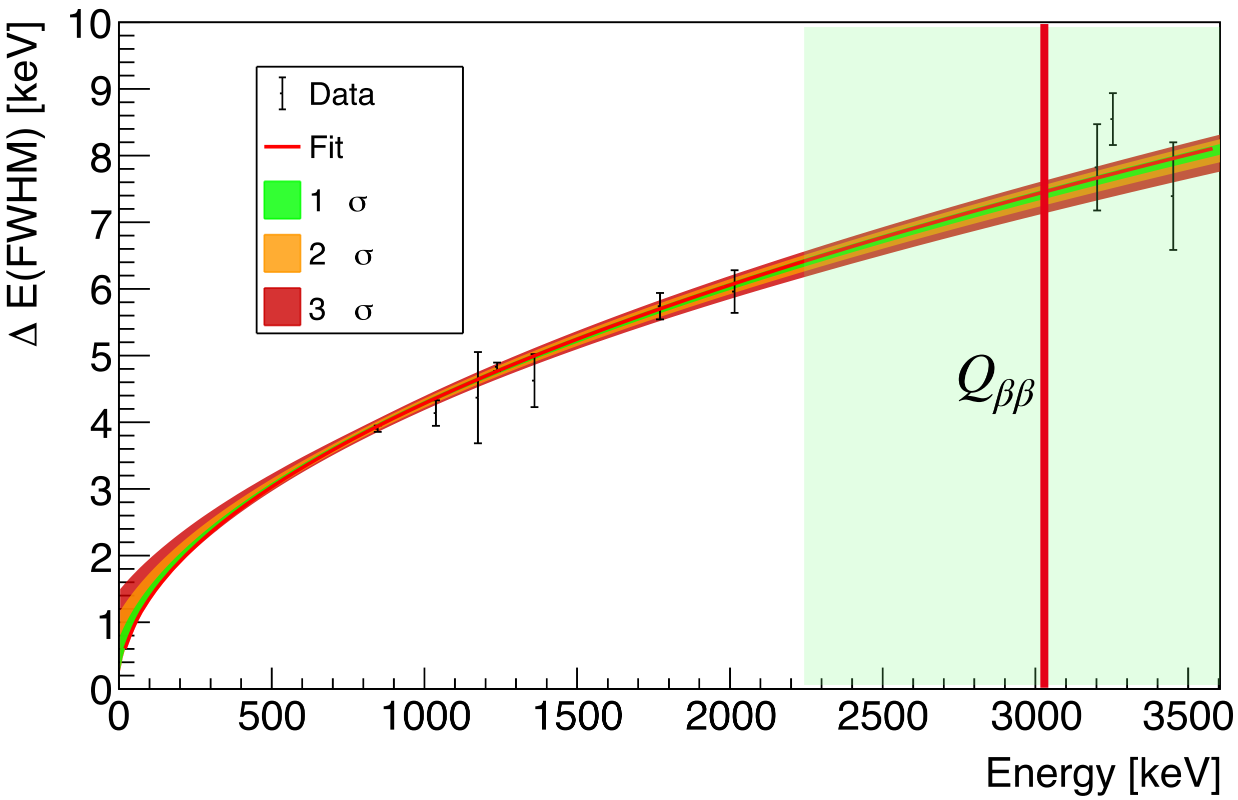
CUPID-Mo - ^{56}Co energy bias

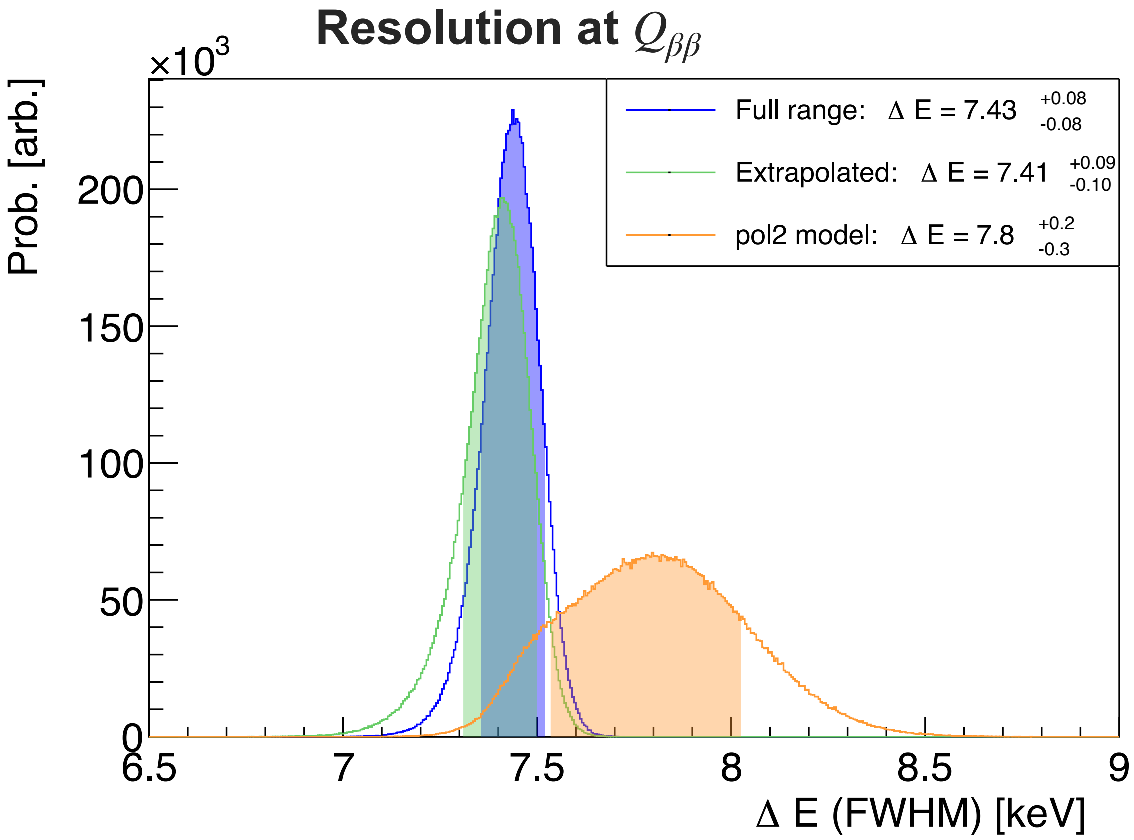


3 MeV region is well behaved and follows pol2 model

It can be well extrapolated from [0,2.6] MeV fit as with U/Th calibration

CUPID-Mo - ^{56}Co resolution scaling

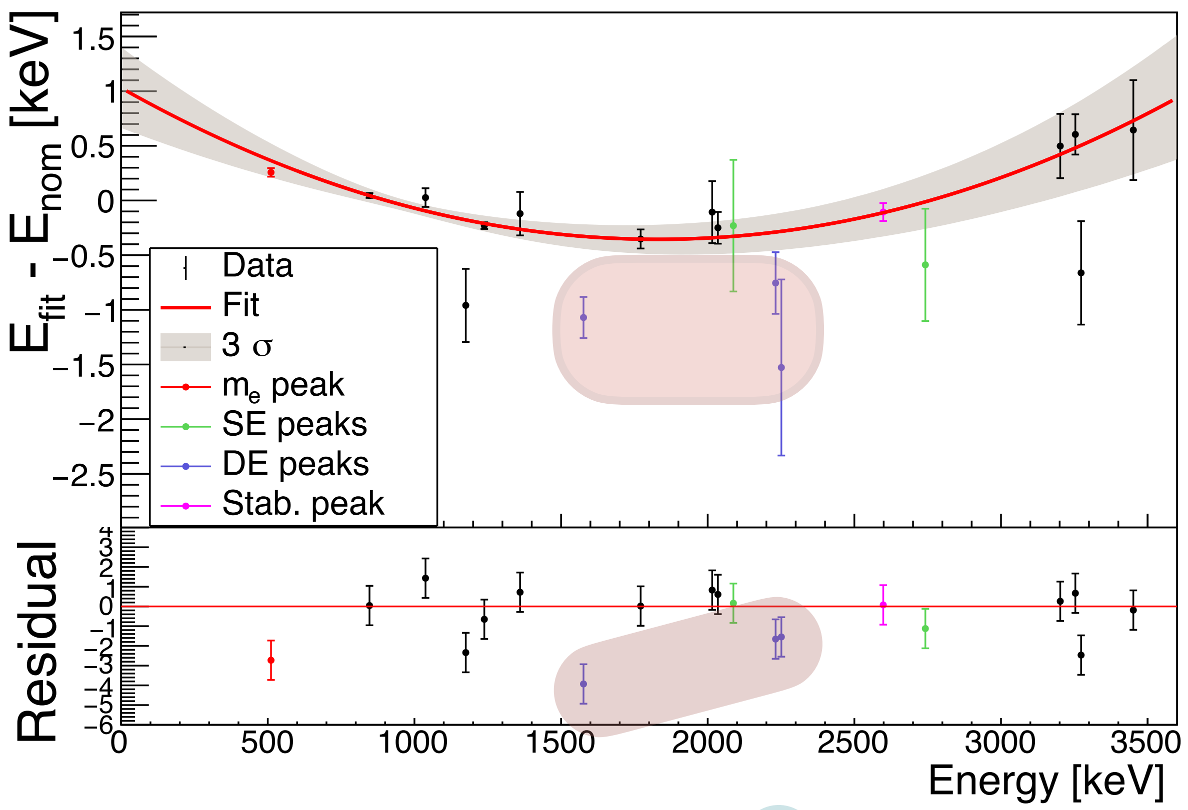


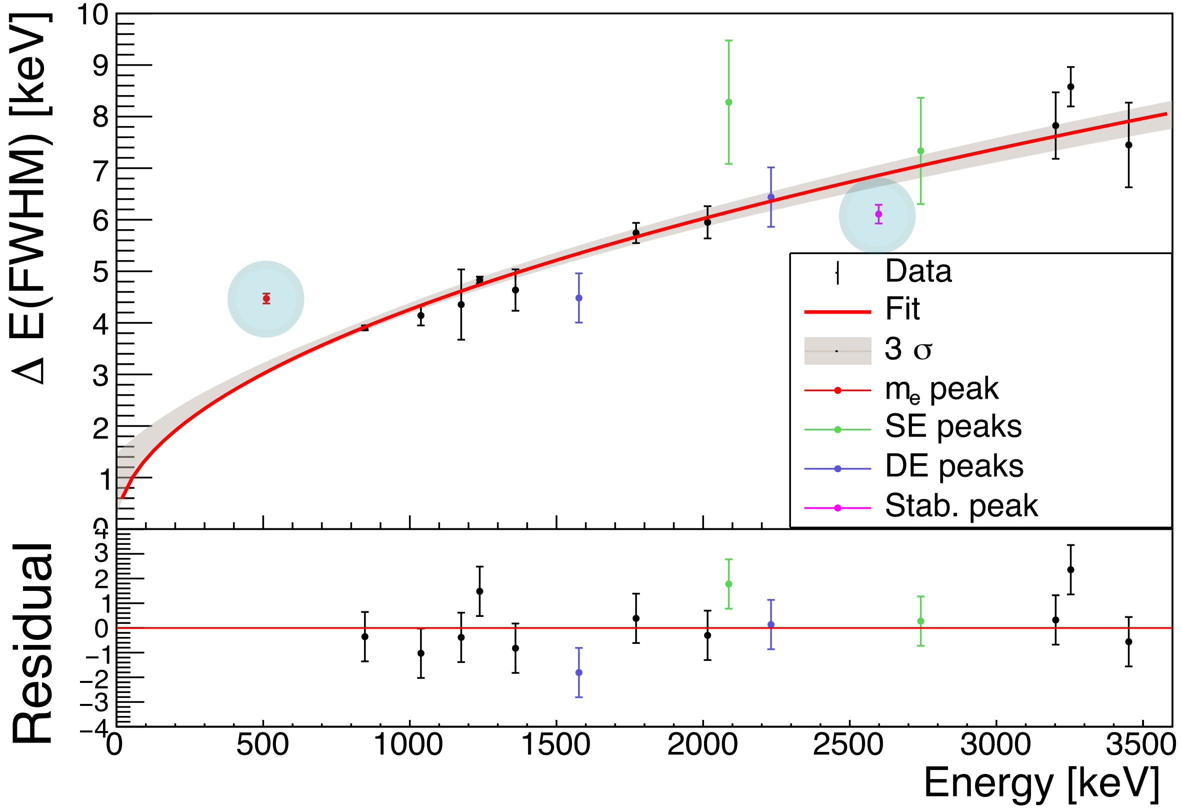


Extrapolation of $\Delta E = \sqrt{p_0^2 + (p_1 \cdot \sqrt{E})^2}$ from [0, 2.6] MeV to $Q_{\beta\beta}$ **consistent with [0, 3.6] MeV fit**

Limited statistics does not allow to draw conclusions on additional terms in resolution scaling

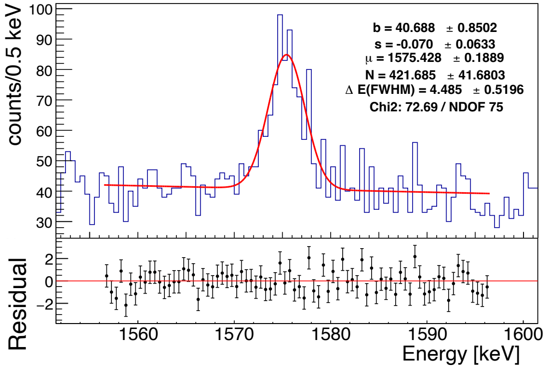
CUPID-Mo - ^{56}Co Event topology

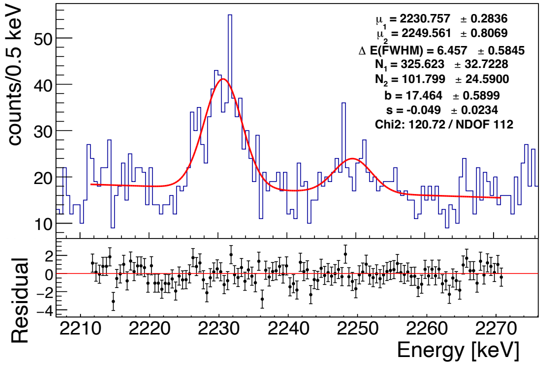


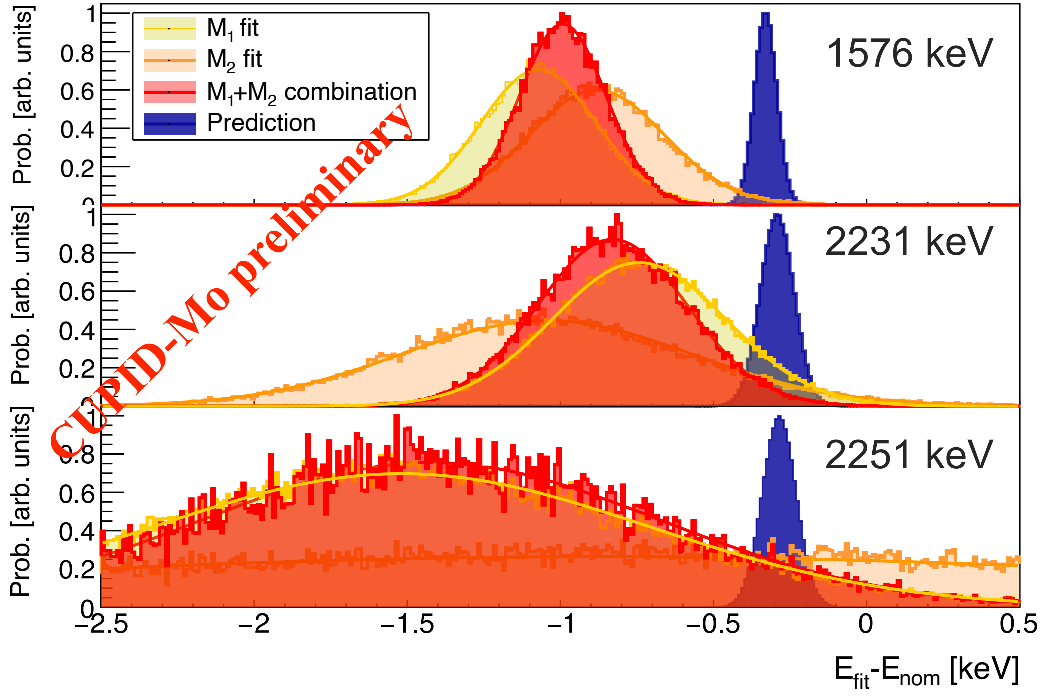


- Some expected features:
  Annihilation peak reconstructs high in resolution / Thermal Gain Stabilisation peak reconstructs low in resolution
  Low statistics on single escapes SE hides any deviations
- Note: All double escape DE peak reconstruct low in energy (E_{fit} - E_{nom})

CUPID-Mo - DE peak topology

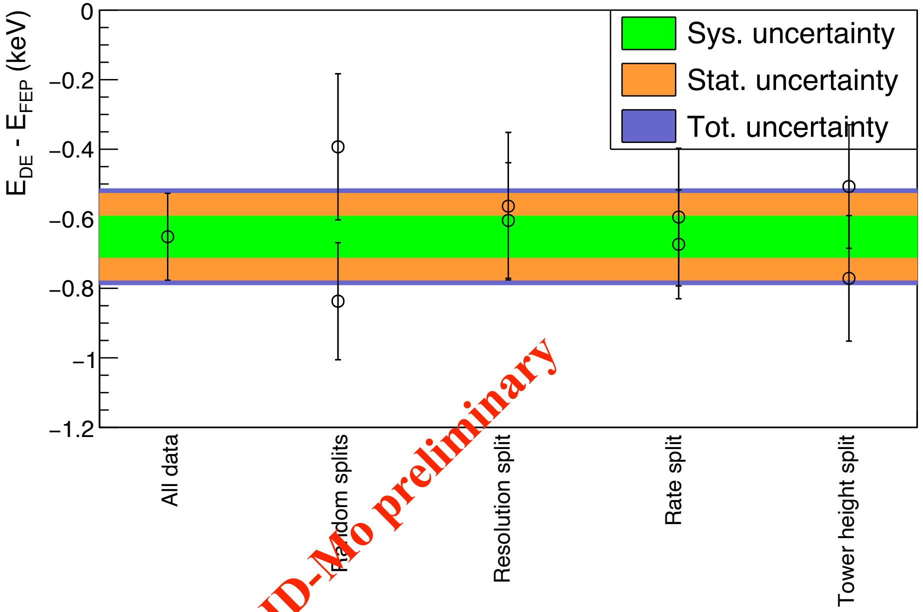


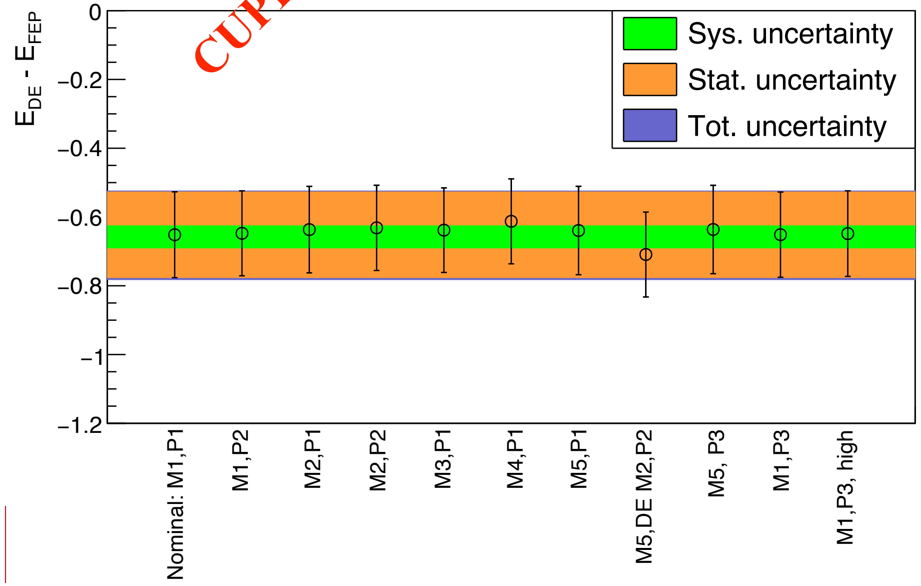




- Check fit quality
- Further verify fitting procedure and coverage through toy studies
  No bias observed
- Repeat analysis of DE peak bias in M2
  All M2 peaks reconstruct low
- Combine evidence for DE peak bias assuming a constant reconstruction offset for all peaks
- Study systematics:
  - Repeat fits on 1/2 of the channels
  - Study Binning/Fit range/Background model/Prior dependence

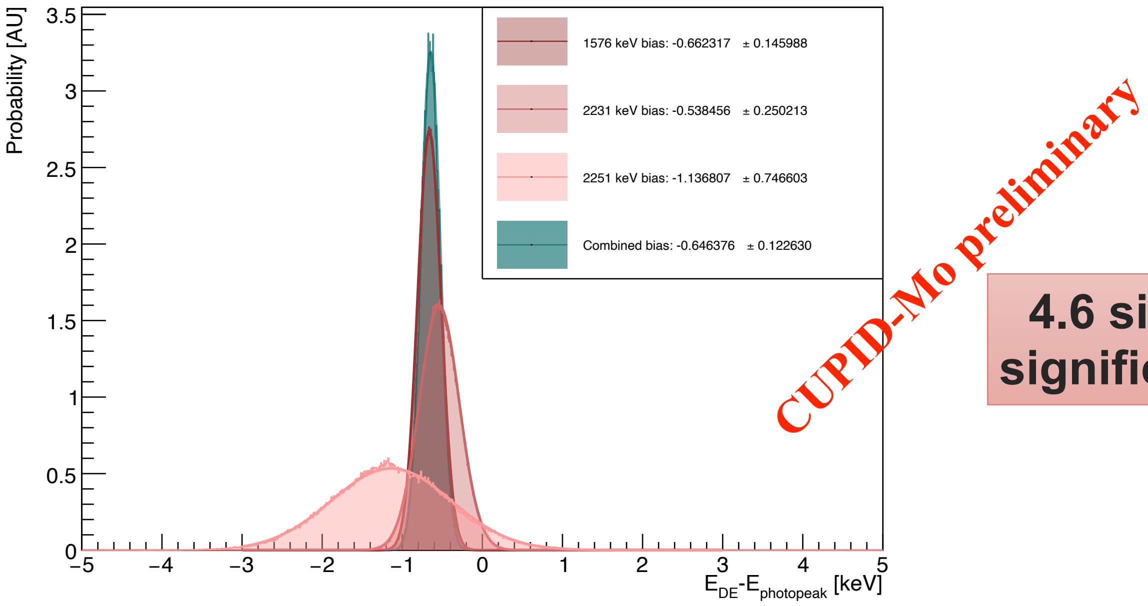
CUPID-Mo - DE peak topology: Systematics





- Repeat fits on 1/2 of the channels
  All 8 data splits reconstruct low
- Study Binning/Fit range/Fit model/Prior dependence

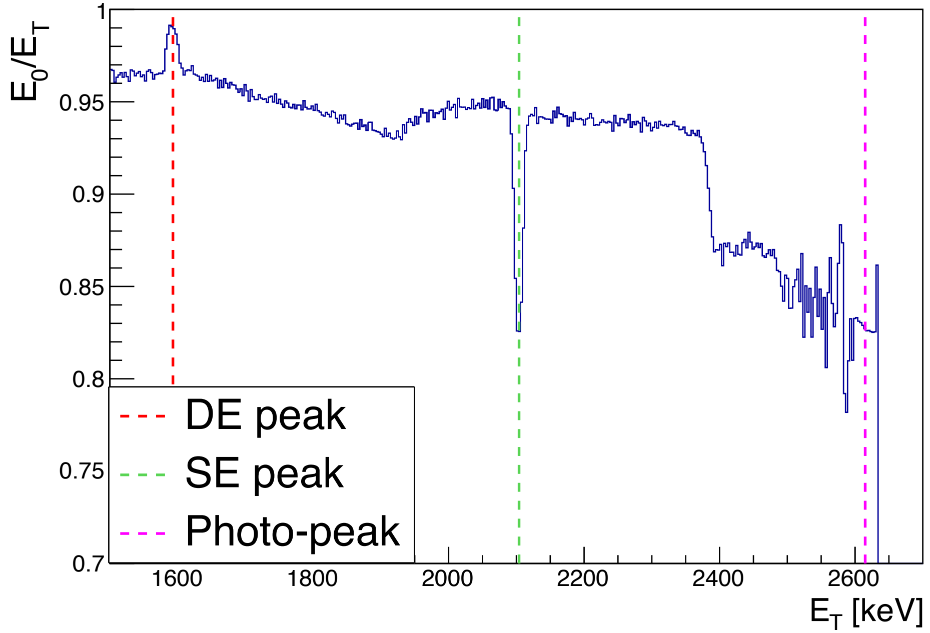
$$E_{DE} - E_{FEP} = \left(-0.65 \pm 0.13\,(stat)\ \pm\ 0.07\,(sys)\right)\ \text{keV}$$

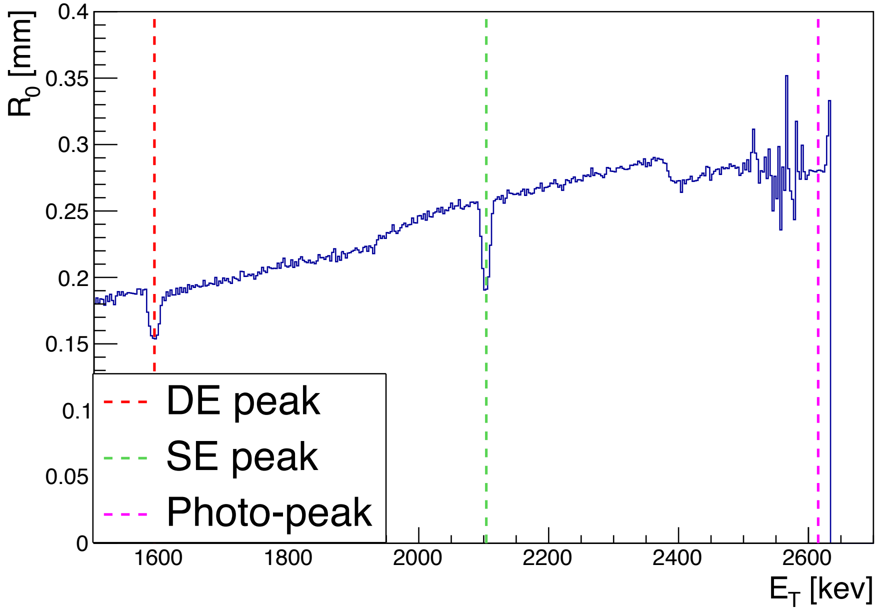


4.6 sigma significance

CUPID-Mo - DE peak topology: Possible origin

- **Origin of detector response difference of DE peaks unknown!**
  More detailed investigations to follow
- DE peak events are expected to show several peculiarities in terms of
  - Preferential position close to surfaces for 511 keV γ to escape
  - Preferential single site-topology - vs preferential multi-site for γ calibration lines (few MeV region)
    —> "Charge density" difference of primary interaction site (E_0, R_0)





Conclusions - Next steps

- **CUPID-Mo bias and resolution extrapolation methods validated**
  - Statistical uncertainty on resolution scaling in CUPID-Mo $0\nu\beta\beta$ analysis > systematics for most extreme model tests in Co-56 campaign

- **Identified a seemingly significant bias in energy reconstruction of DE peak events in Li_2MoO_4 cryogenic calorimeters**

4.6 sigma significance

CUPID-Mo preliminary

- **Follow up plans:**
  - Study of DE peak events / ^{56}Co calibration with higher statistics in single/multiple Li_2MoO_4 detectors -> *CUPID*
  - Study of DE peak events / ^{56}Co calibration measurement with high statistic in TeO_2 -> *CUORE*
  - Potential investigation of other crystals
  - Investigation of effects related to position dependence with dedicated experimental set-ups

CUPID-Mo collaboration

Related talks/posters - $0\nu\beta\beta$ search with ^{100}Mo

Talks and posters CUORE/CUPID/BINGO/CROSS/AMoRE
Talks:

The CUPID neutrinoless double-beta decay experiment, I. Nutini, 25/08/2025 - North Hall #1
Toward a background-free ton-scale $0\nu\beta\beta$ bolometric experiment: status and prospects of BINGO, C. Nones, 25/08/2025 - North Hall #1
AMoRE-II construction status, S. Kim, 25/08/2025 - North Hall #1
Sensitivity of the CUPID experiment to $0\nu\beta\beta$ decay of ^{100}Mo, P. Loaiza, 26/08/2025 - North Hall #1
CUPID-CJPL: a cryogenic bolometer testbed, H. Chen, 26/08/2025 - North Hall #1
The CROSS demonstrator: structure, performance and physics reach, A. Giuliani - 27/08/2025 - North Hall #2
Updated background simulation and detector design for AMoRE-II, E. Jean - 27/08/2025 - North Hall #2
Validation of LMO crystals for the CUPID Experiment, M. Girola - 27/08/2025 - North Hall #3

Posters:
CERES: Cryogenic Experiment to Reconstruct Energy Systematics in TeO2 bolometers, Tong Zhu - 27/08/2025
Neganov-Trofimov-Luke light detectors in $0\nu\beta\beta$ experiments, H. Khalife - 27/08/2025
Progress on CUPID prototype towers - Vertical Slice Test Tower, I. Nutini - 27/08/2025
Background modelling of AMoRE-1, E.J. Jean - 27/08/2025
Muon-induced backgrounds in the AMoRE-II underground detector, J. Seo - 27/08/2025