Search for sterile neutrinos with CUPID-0

111° Congresso Nazionale SIF

Palermo, 26 Settembre 2025

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Sterile neutrinos

hypothetical right-handed neutrinos

only left-handed neutrinos undergo weak interactions

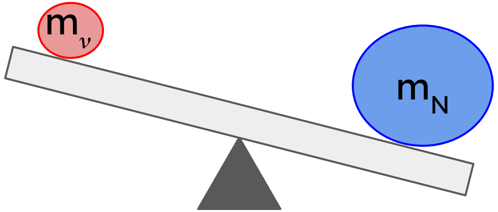
SM gauge group singlets

they effectively act as a 4th neutrino state

they can mix with SM *active* neutrinos

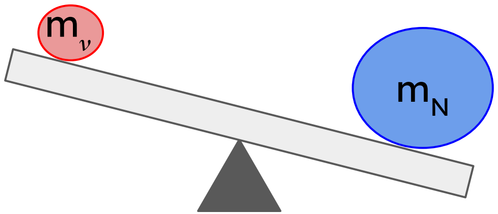
Sterile neutrinos

SEESAW
MECHANISM

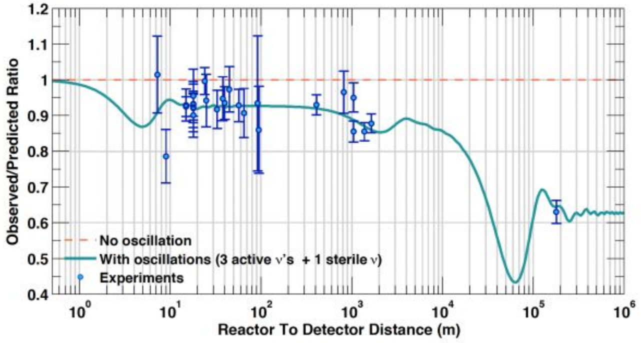


Sterile neutrinos

SEESAW MECHANISM



REACTOR ANOMALY



https://doi.org/10.1103/PhysRevD.83.073006

LSND + MiniBooNE ANOMALY

https://doi.org/10.1103/PhysRevD.64.112007
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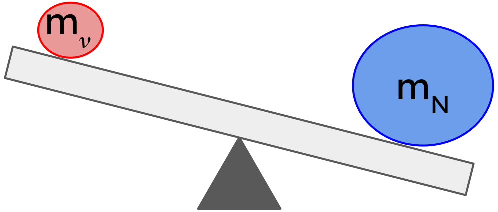
GALLIUM ANOMALY

https://www.sciencedirect.com/science/article/pii/S0146641023000637

Sterile neutrinos

SEESAW MECHANISM



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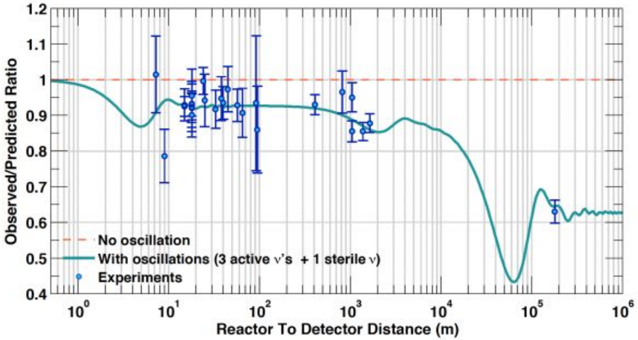

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DARK MATTER CANDIDATES

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Double beta decay with sterile neutrino

Mixing between electron neutrino and sterile neutrino N

- would happen with probability $\sin^2\theta$
- would introduce an additional double beta decay channel :

$\nu N\beta\beta$: 2n $\longrightarrow$ 2p + 2e$^-$ + $\bar{\nu}_e$ + N

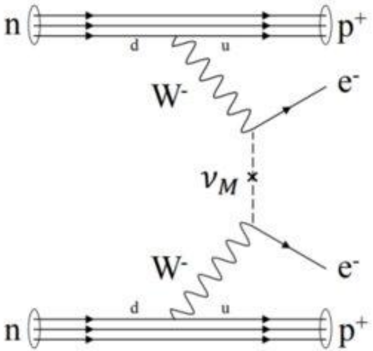
➔ continuum spectrum, distorted with respect to the $2\nu\beta\beta$ one depending on the assumed mass of N

➔ $$\sin^2\theta = \frac{G_{2\nu}}{2G_{\nu N}}\frac{\Gamma_{\nu N}}{\Gamma_{2\nu}}$$

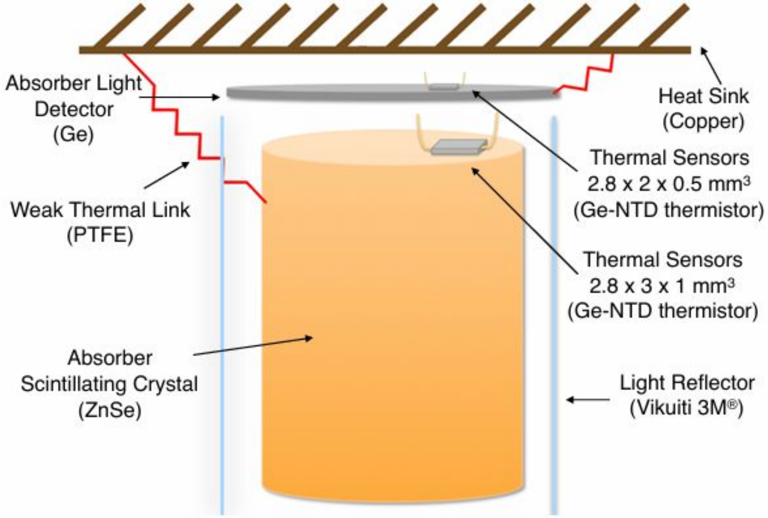
G = phase space factors

CUPID-0: scintillating bolometers for neutrinoless double beta decay search

$0\nu\beta\beta$



- ➔ *probe neutrinos nature*
- ➔ *total lepton number violation*
- ➔ *access to neutrino mass*



Heat + Scintillation

⇩

α/β particles discrimination

Search for sterile neutrinos with CUPID-0

Goal: extract the $2\nu\beta\beta$ and $\nu N\beta\beta$ decay rates to derive limits on $\sin^2\theta$

Strategy

- model the observed counts in the energy spectrum as background + signal

$$\mu_{\text{exp}}(E) = \sum_{i=1}^{N_{\text{bkg}}} a_i S_i(E) + a_{\nu N} S_{\nu N}(E, m_N)$$

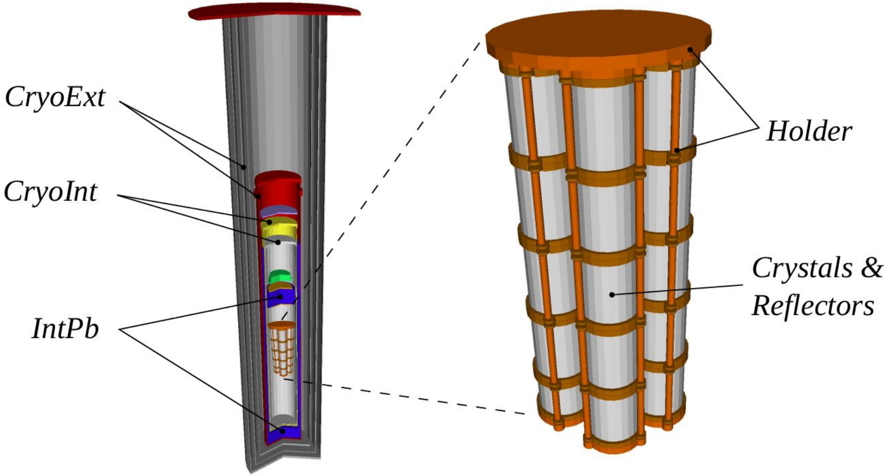
simulated spectra

- derive the scaling coefficients, proportional to the decay rates, through a Bayesian fit that constructs their *posterior* PDFs
    - the *likelihood* of observed counts given the model updates the *prior* PDFs of the coefficients

1. CUPID-0 Background Model

Background sources

1. the ^{82}Se $2\nu\beta\beta$ continuum
2. decay chains of ^{232}Th, ^{235}U, ^{238}U and ^{40}K
3. cosmogenic activation of detector's materials
4. cosmic muons, environmental γ, neutrons

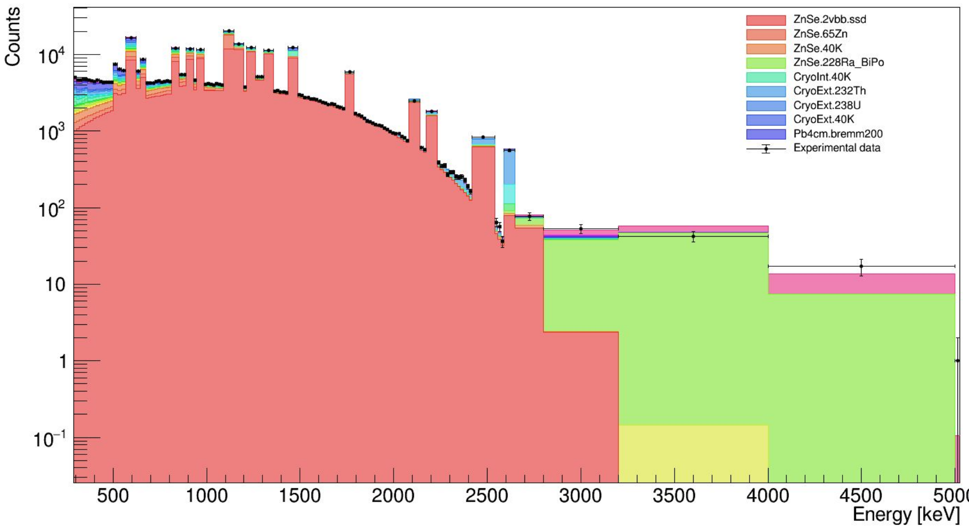


➡ the spectra of N_{bkg} = 33 sources in CUPID-0 are produced with MC simulations

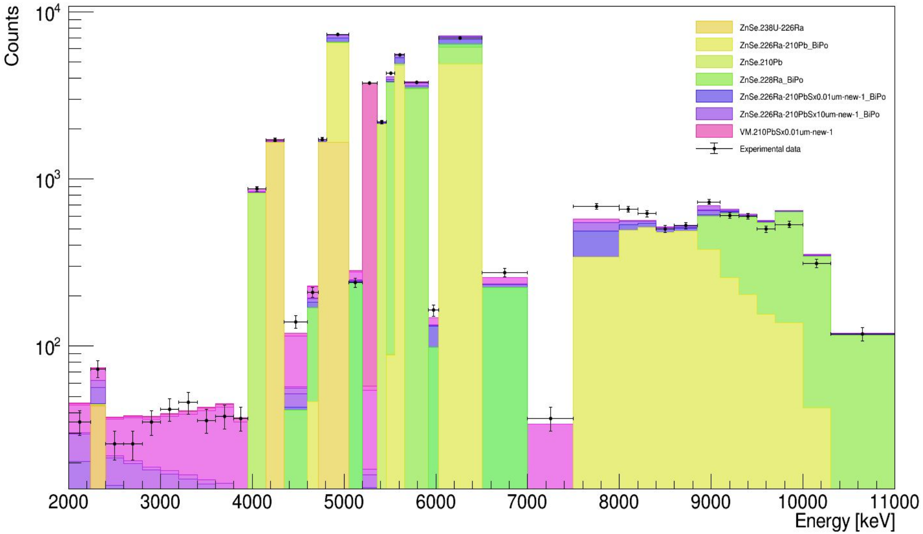
1. CUPID-0 Background Model

$$\mu_{\exp}(E) = \sum_{i=1}^{N_{\text{bkg}}} a_i S_i(E)$$

β/γ spectrum

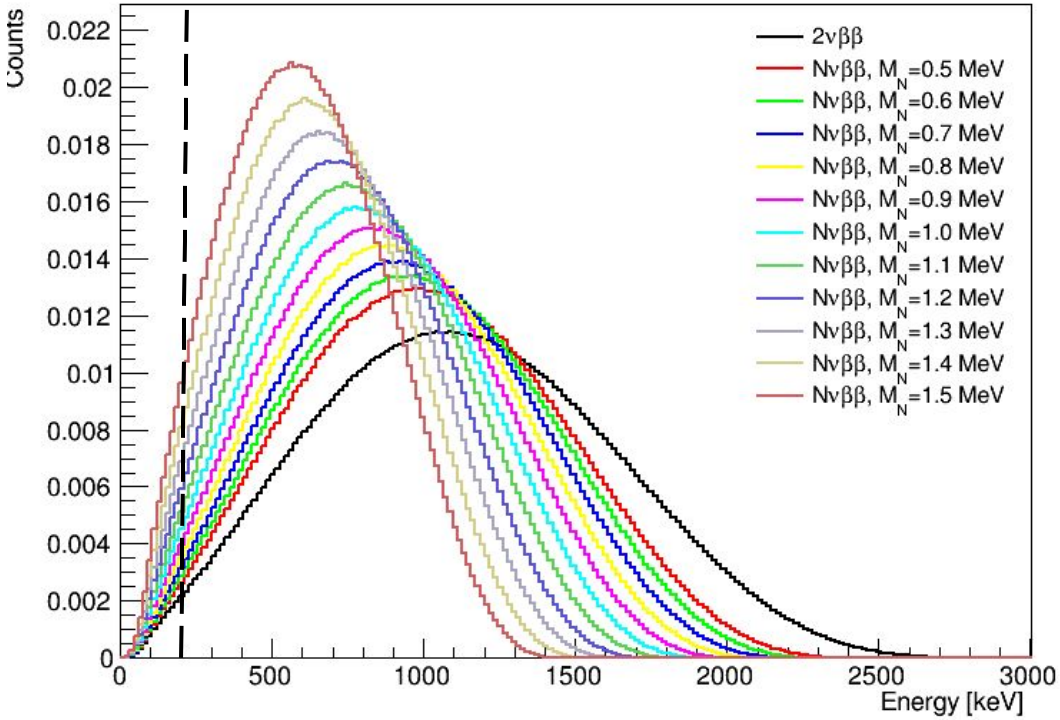


α spectrum



2. νNββ analysis

MC spectra | $0.5\ \mathrm{MeV} \leq m_N \leq 1.5\ \mathrm{MeV}$

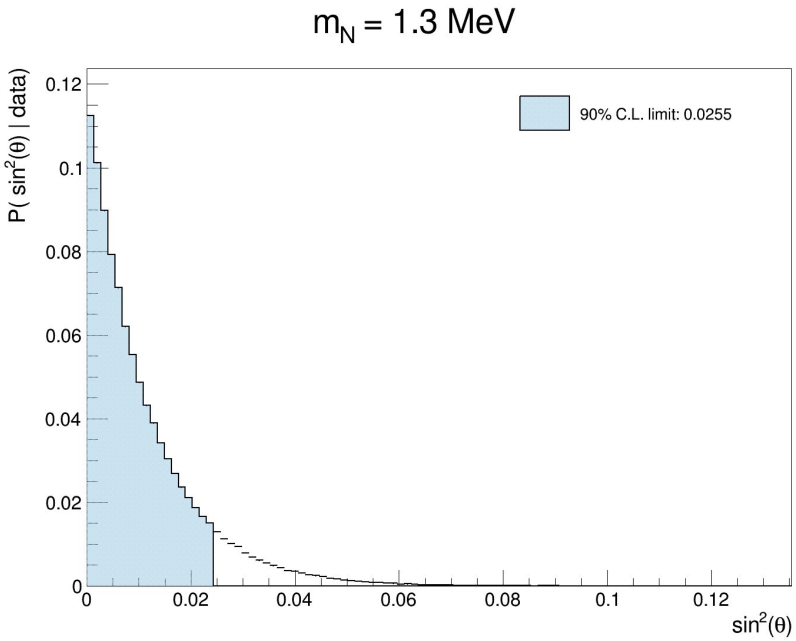


The sterile components for different masses are individually incorporated in the model and the fit is repeated

2. $\nu N\beta\beta$ analysis

In all cases the posterior distributions are compatible with the background-only hypothesis

90% C.I. limits are extracted

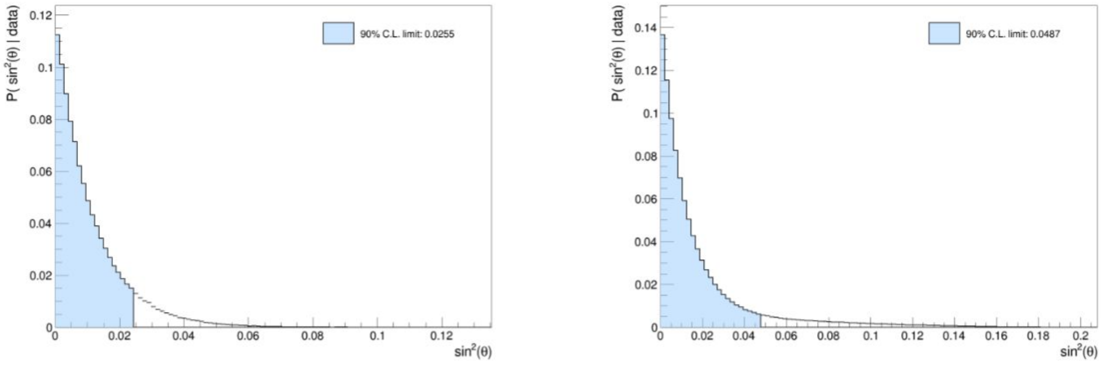


3. Systematic effects

Different fit choices
Binning
Low threshold
Energy calibration

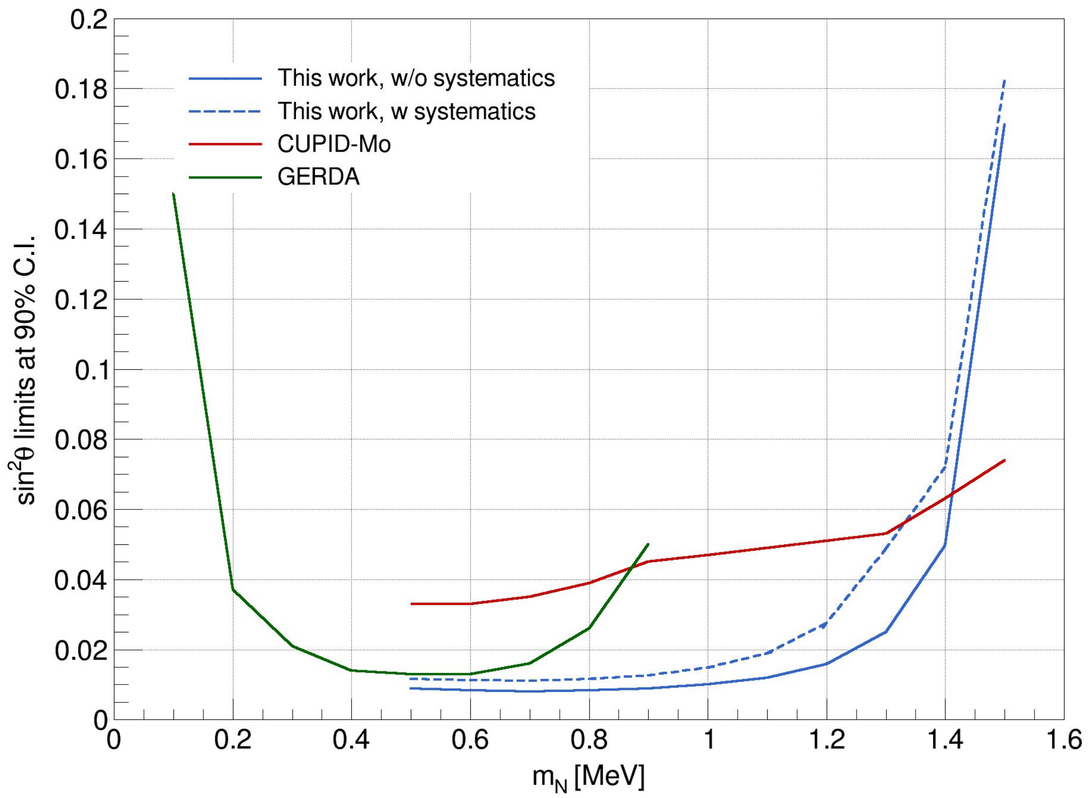
Different modeling
Contaminants placement
Reduced list of background sources
Contribution of fission product ^{90}Sr

combined treating each configuration as an alternative model and forming the final posterior with equal prior weight



(a) Reference (b) Reference + Systematics

Results



- the most stringent bound is $\sin^2\theta < 8 \times 10^{-3}$ at m_N = 0.7 MeV
- the systematics slightly increase the limits
- these results improve those of previous $0\nu\beta\beta$ experiments such as CUPID-Mo and GERDA

Thank you for the attention!

BACKUP

Bayesian spectral fit

- **Data.** Observed counts in bin i of spectrum type δ: $C^{\text{exp}}_{i,\delta}$
- **Model**. Expected counts in bin i of spectrum type δ

$$\mu^{\text{exp}}_{i,\delta} = \sum_{j=1}^{33} a_j \, C^{\text{MC}}_{ij,\delta} \quad \text{with } \delta \in \{\mathcal{M}_{1\beta/\gamma}, \mathcal{M}_{1\alpha}, \mathcal{M}_2, \Sigma_2\}$$

- **Likelihood.** Poisson pdf of the observed counts as a function of the model parameters

$$\mathcal{L}(\{C^{\text{exp}}\}|\{a_j\}) = \prod_{i,\delta} \frac{e^{-\mu_{i,\delta}} \, \mu_{i,\delta}^{C^{\text{exp}}_{i,\delta}}}{C^{\text{exp}}_{i,\delta}!}$$

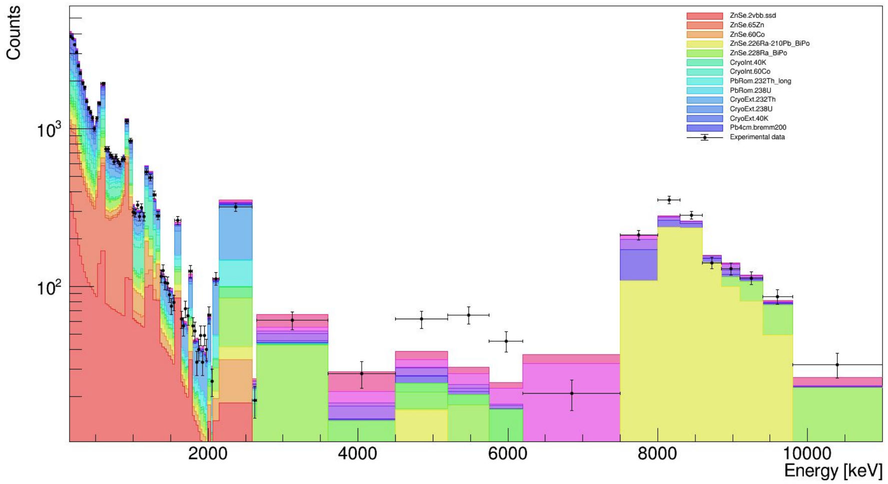
- **Parameters posterior pdf.** The Bayes theorem links the posteriors to the priors through the likelihood

$$P(\{a_j\}|\{C^{\text{exp}}\}) \propto \mathcal{L}(\{C^{\text{exp}}\}|\{a_j\}) \, \pi(\{a_j\})$$

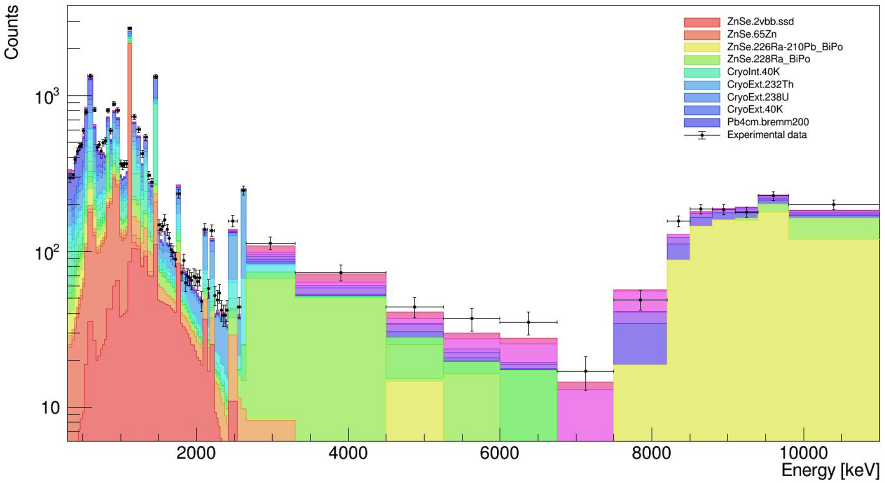
Some more details on the background model

- events of multiplicity = 2 (energy released in 2 crystals)

1 crystal energy spectrum

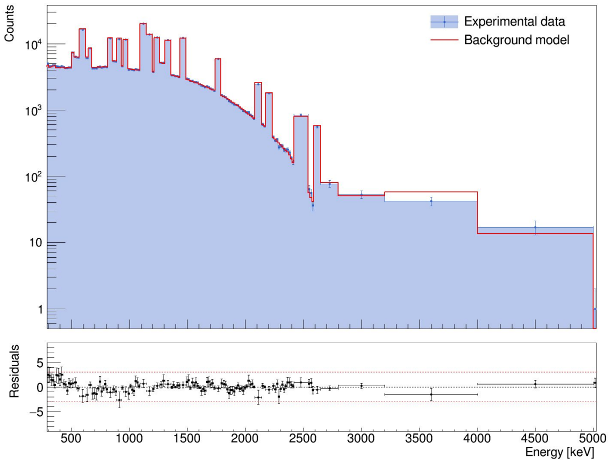


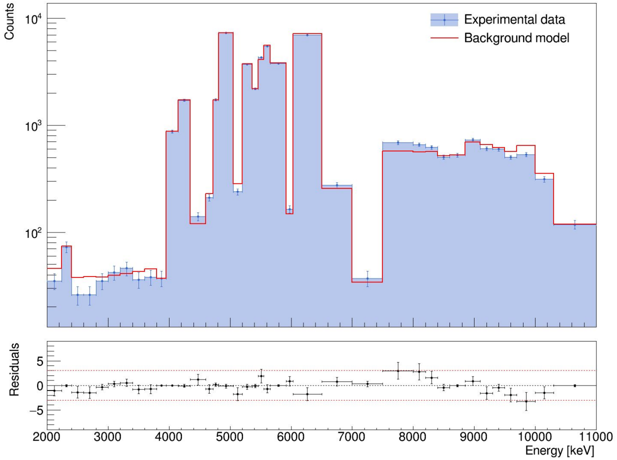
total energy spectrum

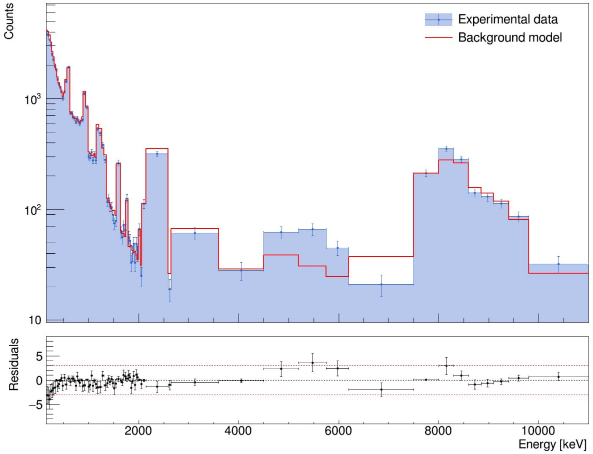


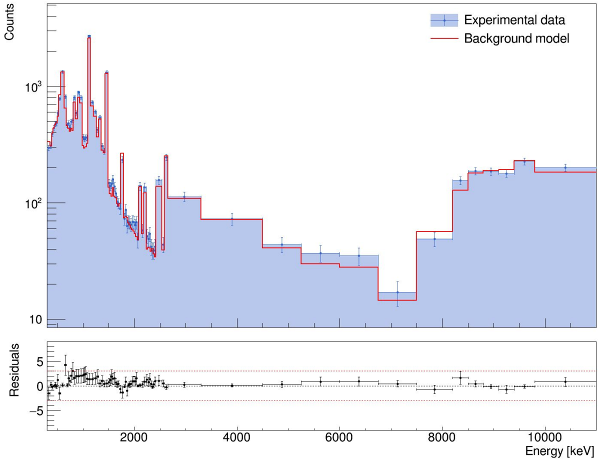
- non uniform binning to compact α peaks and γ-ray lines in single bins and to avoid low statistics

Some more details on the background model









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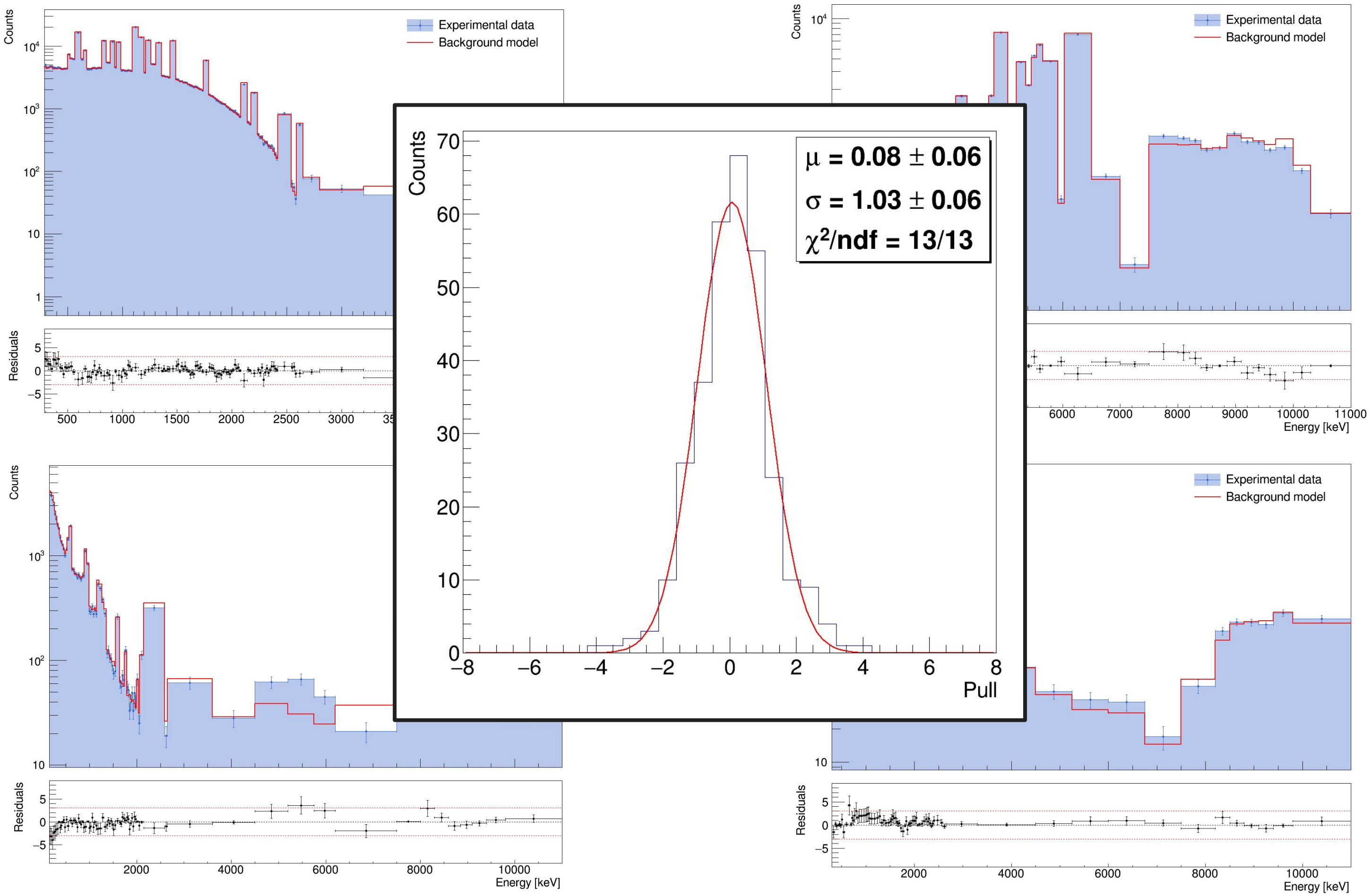

Future prospects: CUPID

$$\sigma_{\sin^2\theta} \xrightarrow{\sin^2\theta\sim 0} \mathcal{G}_{2\nu}/\mathcal{G}_{\nu N} \cdot \sqrt{\frac{(R_{2\nu}+R_{others})}{R^2_{2\nu}\cdot\mathcal{E}}}$$

- total background rate will be 10 times smaller
- ^{100}Mo $2\nu\beta\beta$ rate is 10 times higher than the ^{82}Se one
- exposure will be 10^3 times higher

→ 10^{-3} times better constraints