Background simulations for CROSS experiment

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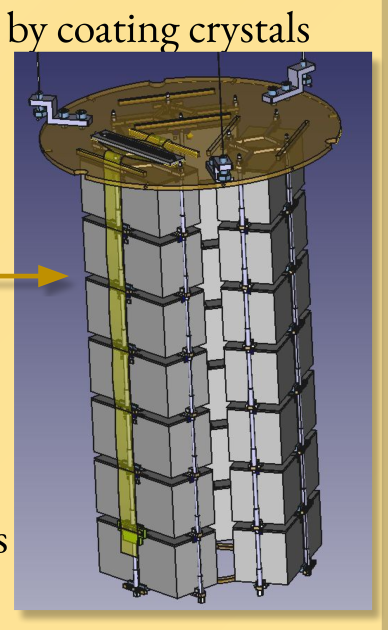
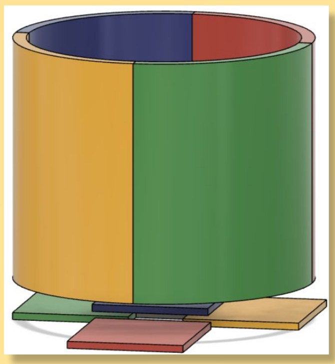
1 - The CROSS experiment

- **Cryogenic Rare-event Observatory with Surface Sensitivity**[1]
- Aimed to develop new bolometric techniques for **$0\nu\beta\beta$ decay search** in ^{100}Mo (Q_β = 3034 keV) and ^{130}Te (Q_β = 2527 keV)
  - Discrimination of background from surface interactions by coating crystals with a thin superconductive film[1,2]
- Installed in a cryogenic facility[3] at the Canfranc underground laboratory (LSC), in Spain
- Demonstrator will include 36 $Li_2{}^{100}MoO_4$ (LMO)[4] and 6 $^{130}TeO_2$ (TEO)[5] cubic (45 mm side) crystals with double read-out for particle discrimination:
  - Heat: Neutron Transmutation Doped Ge thermistors
  - Light: Neganov-Trofimov-Luke assisted light detectors (LD) made of Ge wafers with SiO_2 coating and Al electrodes



- To tag and eliminate environmental background events:
  - Lead shielding
  - Muon veto system made of plastic scintillators
    - 9 sectors (4 lateral + 4 bottom + 1 top)
    - Each sector divided in channels: 28 for lateral, 15 for bottom and 2 for top

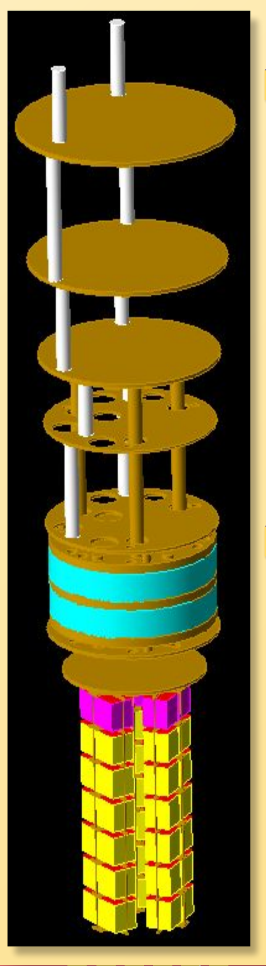


- Commissioning of the CROSS experiment on Dec. 2024

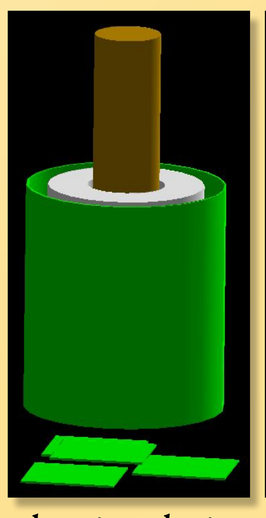
[1]JHEP 01 (2020) 018 [2]APL 118 (2021) 184105 [3]JINST 18 (2023) P12004 [4]arXiv:2405.18980 [5]arXiv:2406.01444

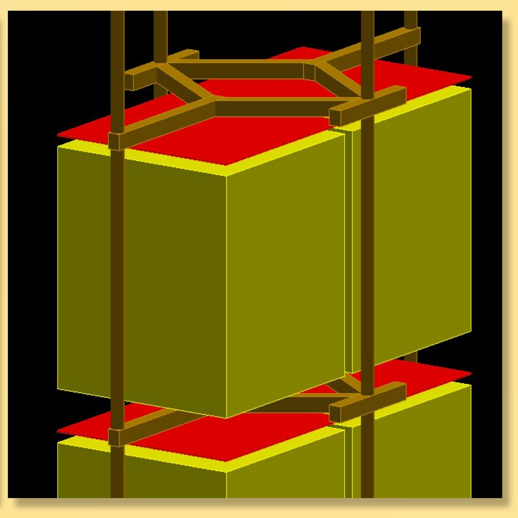
2 - MC simulation of the experiment I

- Geant4-based Monte Carlo (MC) simulations performed to:
  - Calculate the background index (BI) in the ROI considering known backgrounds (radioactive decays, muon-related events, etc) and assess the experiment's sensitivity (see poster of M. Buchynska, id. 388)
  - Reduce BI by applying event selections across different detectors



- Volumes simulated:
  - **Muon veto system**
  - **Lead shielding**
  - **Cryostat**
  - **Tower structure:**
    - **Crystals**
    - **LDs**
    - **Cu frame**





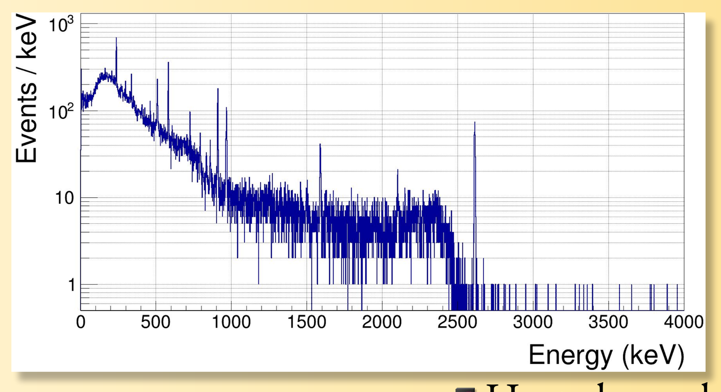
- Information provided by the simulations:
  - Energy deposited in each detector (Vetos, Crystals or LDs)
    - Scintillation light energy added to LDs using experimentally measured Light Yield (LY)
  - Δt between energy deposits
  - Multiplicity among detectors
  - Spectra convolved with an energy resolution function ($\sigma = a + b^*\sqrt{E}$)

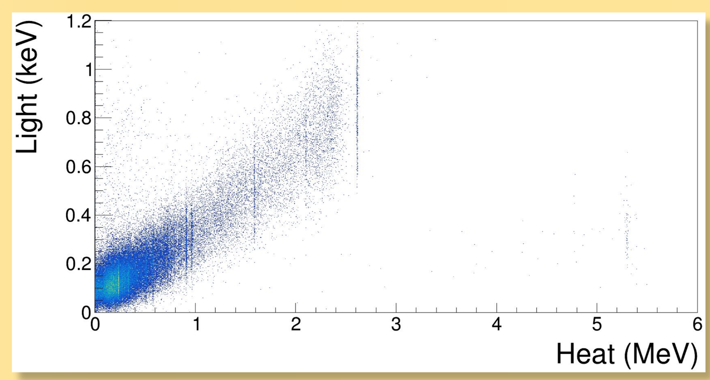
LY *	Bottom crystal	Top crystal
β/γ	300	200
α	50	30

*Units in eV(Light) / MeV(Heat)

3 - MC simulation of the experiment II

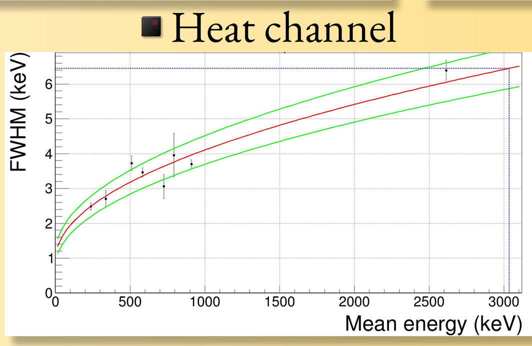
- Experimental data (calibration with a ^{232}Th source) for inputs to MC:

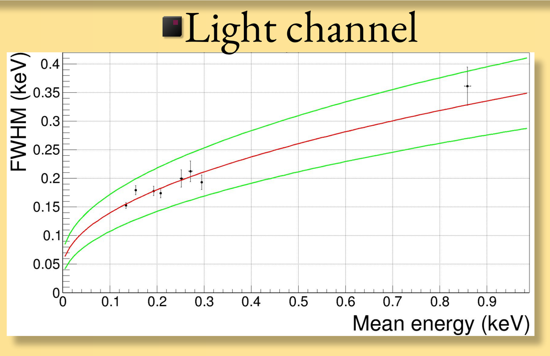




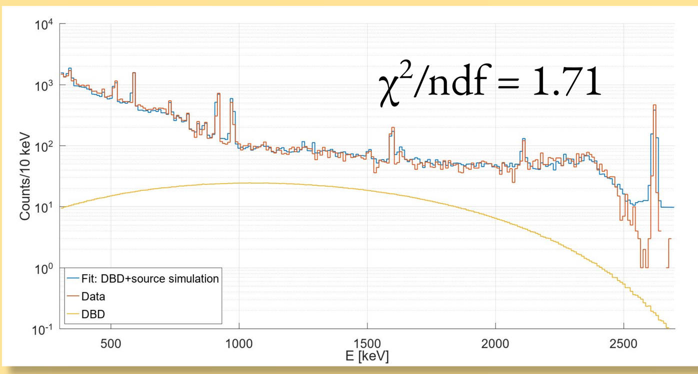
Heat channel Light channel

- Energy dependence of detectors' energy resolution:





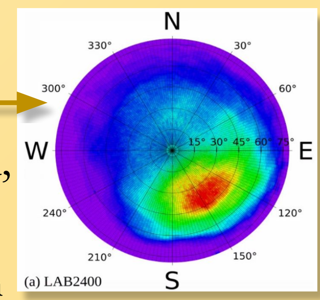
- MC spectrum fitted to experimental data for the ^{232}Th calibration
  - $2\nu\beta\beta$ of ^{100}Mo simulated and included in the fit, as it is the main background contribution
  - Good agreement between spectra indicates **accurate simulation of geometry** and **detector response**



4 - Muons and radioactive decays

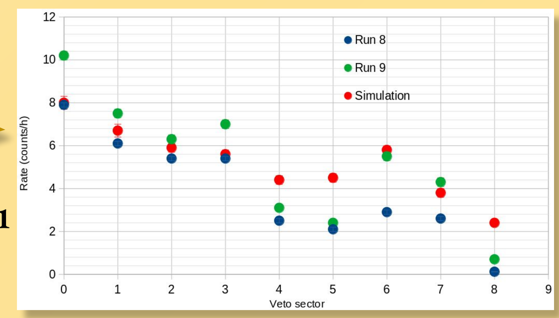
Muons:

- Initial conditions obtained randomly:
  - **Momentum:** From angle distribution measured at LSC[1]
  - **Energy:** From an approach for E_μ > 100 GeV aboveground, then calculated underground with the rock depth[2]



- Activity normalized with flux measured at LSC[1]: 18.9 ± 0.8 $\mu/m^2/h$
- Validation with the experimentally measured rates:
  - In each veto sector in coincidence with other sector(s) (for two different cryogenic runs)
  - In bolometers for events with E > 10 MeV

Exp: 1.44 ± 0.22 day^{-1} Sim: 1.49 ± 0.05 day^{-1}



Radioactive decays:

- **Chains of ^{226}Ra (down to ^{210}Pb) and ^{228}Th** in volumes surrounding crystals
  - Activities measured with HPGe or in CUPID-Mo exp.[3]

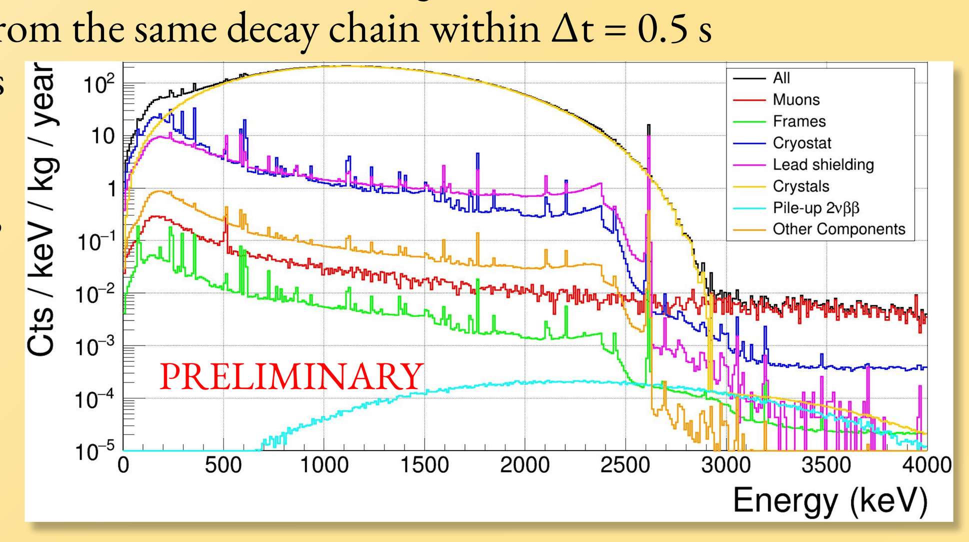
Material	^{226}Ra (μBq/kg)	^{228}Th (μBq/kg)
Cryostat screens	600 ± 100	300 ± 100
Electronic pins	$(1325 \pm 36) \cdot 10^3$	$(2386 \pm 26) \cdot 10^3$
Crystals (bulk)[3]	0.39 ± 0.06	0.57 ± 0.07
Copper frame[3]	25 ± 15	33 ± 16
Lead shielding	< 120	< 460
Fiberglass bars	3400 ± 400	1410 ± 50

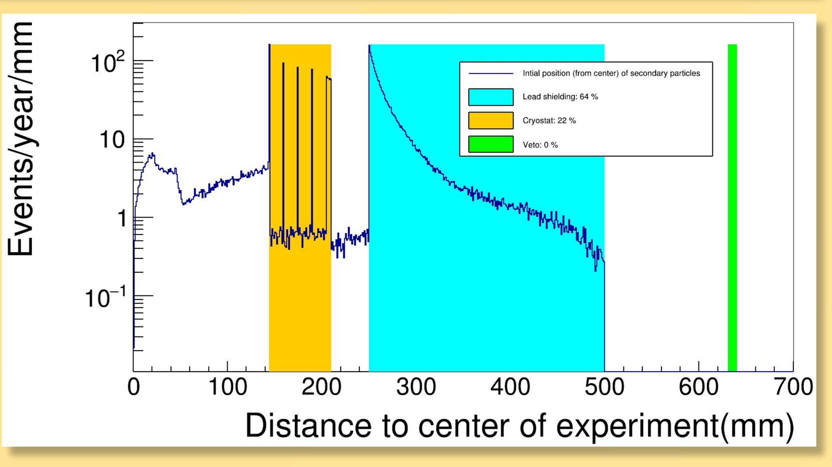
- **$2\nu\beta\beta$ of ^{100}Mo** considering the most accurate decay rate measurement[4]
  - Activity: 10.5 ± 0.2 mBq/kg
- **Pile-up of $2\nu\beta\beta$ of ^{100}Mo**[5]
  - Rejection efficiency simulated as a step function (0 if Δt < 1 ms, 1 otherwise)

[1]EPJC 79, 721 (2019) [2]PDG, Cosmic Rays (2021) [3]EPJC 83, 675 (2023) [4]PRL 131, 162501 (2023) [5]EPJC 83, 373 (2023)

5 - Preliminary results

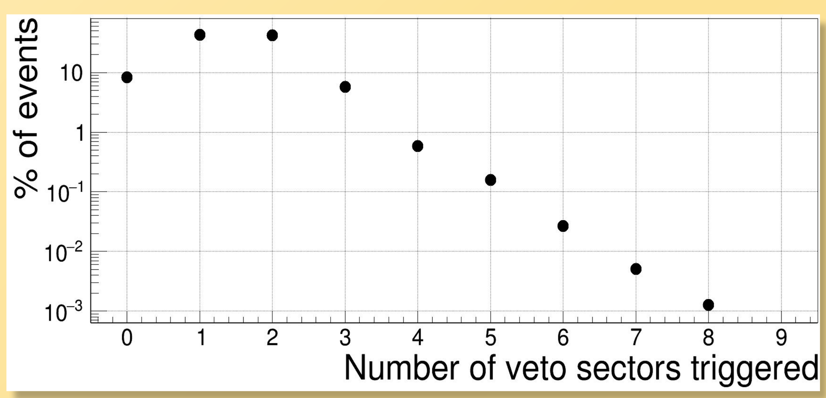
- Event selections to minimize BI and maximize acceptance of $0\nu\beta\beta$:
  - Crystal multiplicity = 1
  - No coincidence in veto sectors within Δt = 2 ms
  - Event in the β/γ band: LY $\in$ [150,450] eV(Light)/MeV(Heat)
  - No energy deposits from the same decay chain within Δt = 0.5 s
- MC-simulated backgrounds
  - "Crystals" includes $2\nu\beta\beta$ of ^{100}Mo
  - "Other components" includes electronic pins and fiberglass bars
  - **Main contribution (80 %) from muon induced events**
    - Secondary particles (mainly γs) produced around crystals after muon interactions
    - Mostly produced in the lead shielding; Cu screens provide insufficient protection, being the "source" too



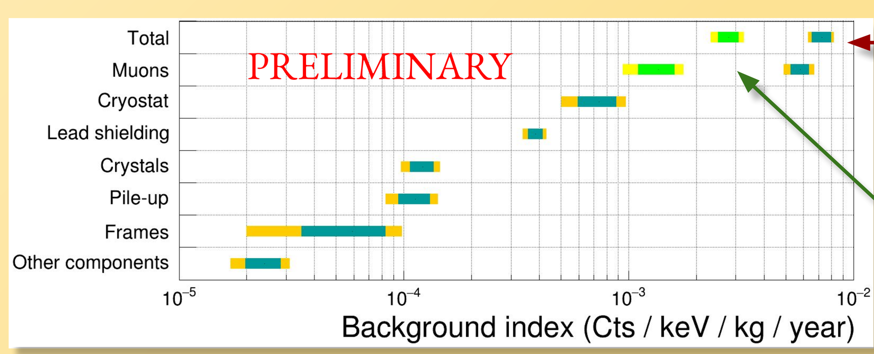


6 - Strategy to reduce the BI

- Event selection optimization to reduce muon-induced background:
  - Current muon event trigger is based on coincidences of two veto modules, but 43 % of events trigger only a single veto sector (1 MeV threshold)
  - Rejecting coincidences between crystals and a single veto sector can reduce the BI by a factor of 2.7



- Preliminary BI calculated in the ROI for ^{100}Mo (3034 keV):



Current event selection:
BI = $(7.2 \pm 0.9) \cdot 10^{-3}$ ckky

Rejecting coincidences between crystals and single veto:
BI = $(2.8 \pm 0.5) \cdot 10^{-3}$ ckky

- We are designing an acquisition strategy to:
  - Ensure the same energy threshold in all veto channels
  - Avoid high trigger rate in each channel to limit dead time