Development of a cryogenic veto system for CEνNS detection

in the scope of the NUCLEUS experiment

P2IO BSM-Nu workshop, May 24th, 2023

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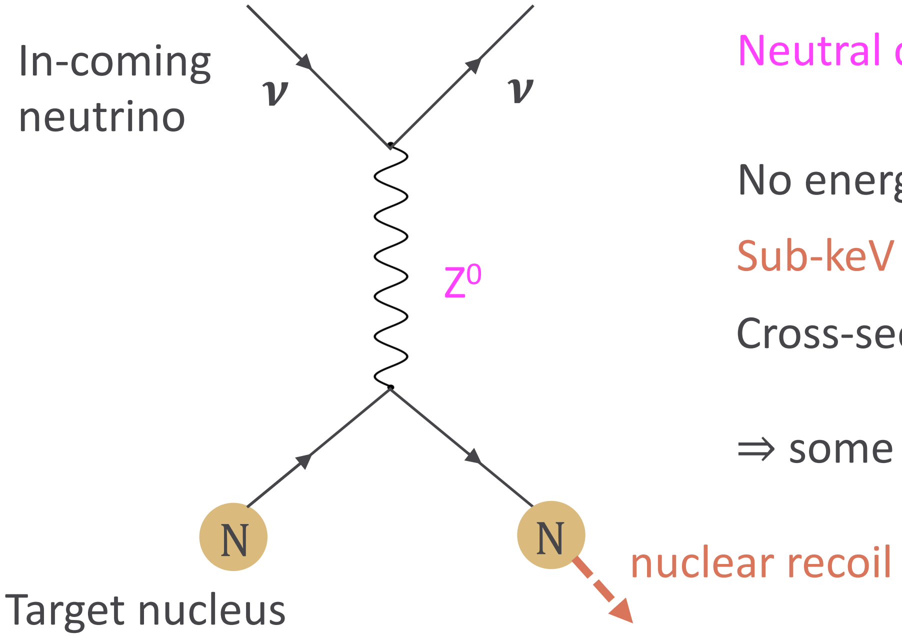
Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)



Neutral current interaction
→ flavor independent

No energy threshold

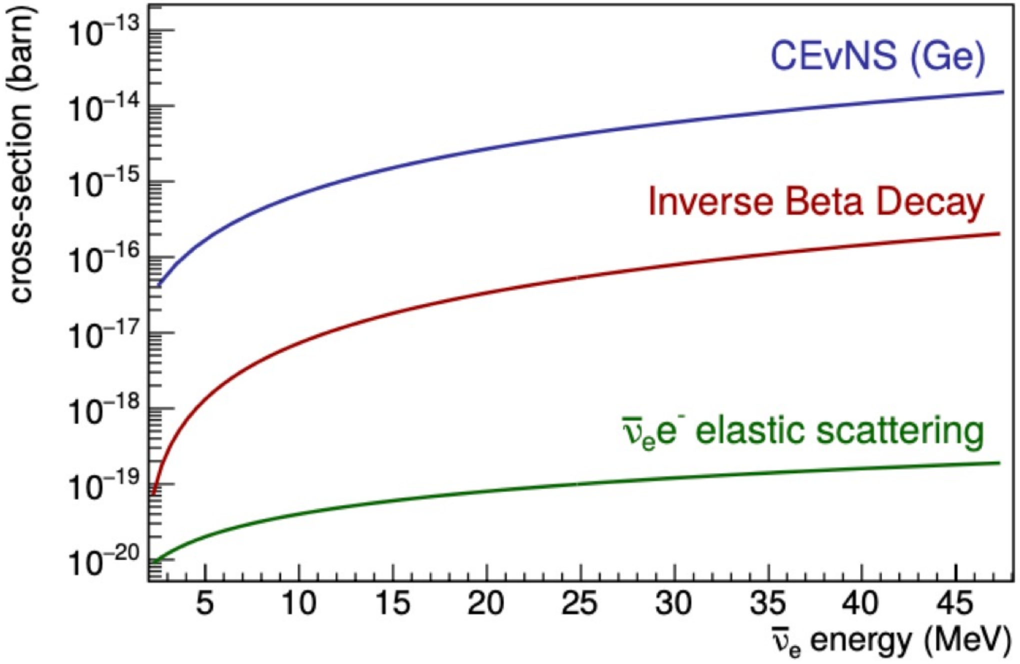
Sub-keV nuclear recoils

Cross-section proportional to N^2
→ 1000x larger than IBD

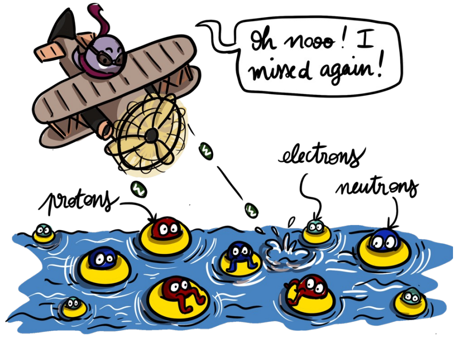
⇒ some kg/g-scale detectors

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_w^2 F^2(q^2) m(Z,N)(1 - \frac{E_r}{E_{r,max}})$$

From J. Billard - BSM-Nu workshop 2022



Elastic scattering/IBD

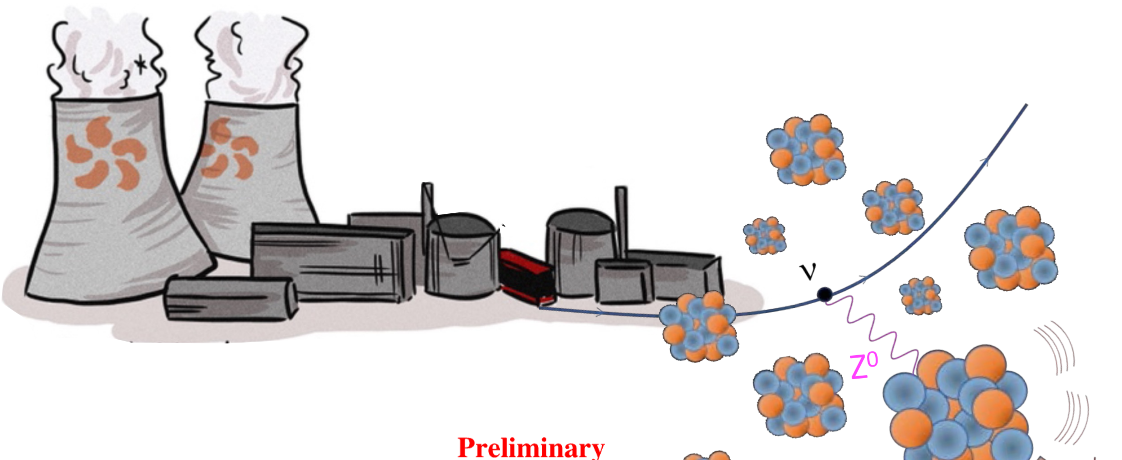


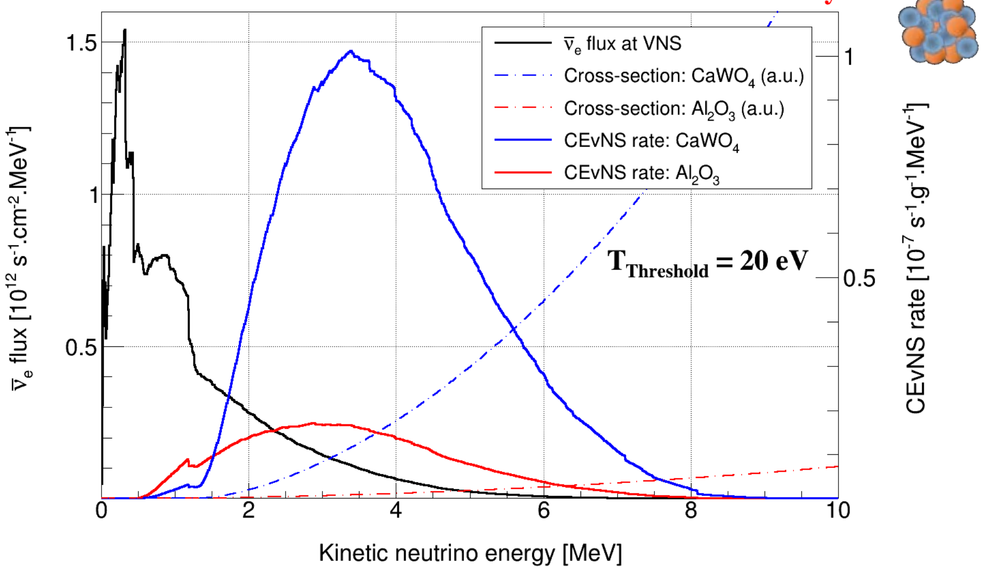
CEνNS

From Nucleus comic (nucleus-experiment.org)

Study CEνNS from reactor (anti-)neutrinos

Coherent Elastic Neutrino-Nucleus Scattering



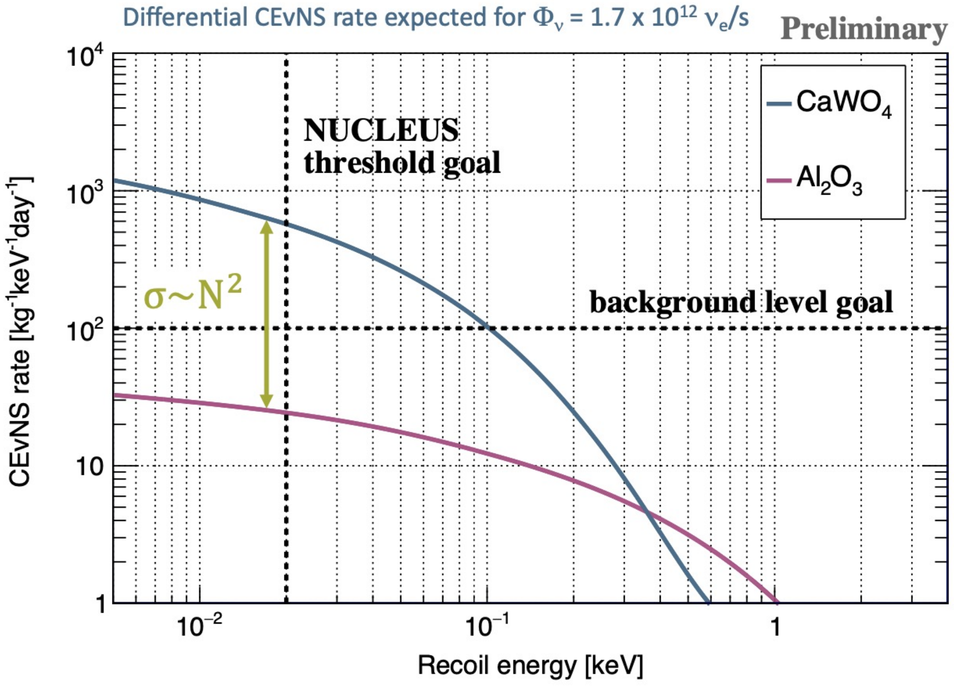


Nuclear reactors: intense sources of $\bar{\nu}_e$

E_ν < 10 MeV → fully coherent regime

⇒ Low thresholds detectors and low background counting rate required

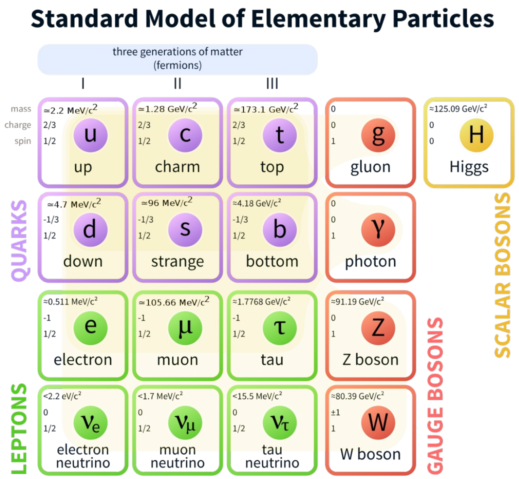
NUCLEUS @Chooz



CEνNS, what for?

1- Probe for Standard Model

CEνNS cross-section is a clean standard model prediction



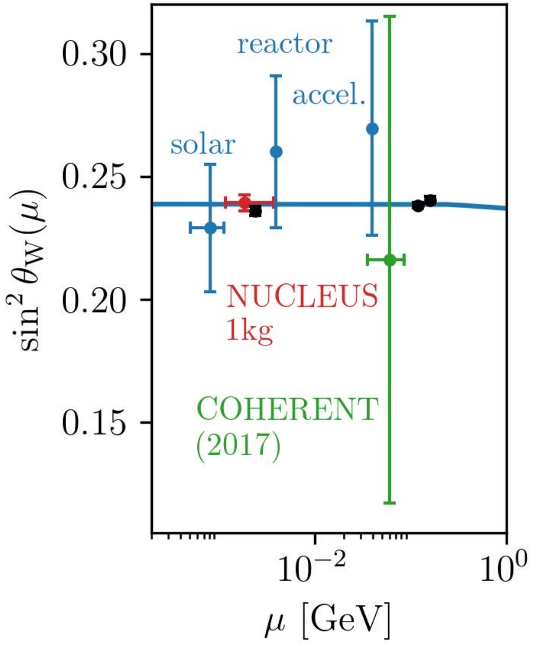
If deviations wrt SM

2- Beyond the SM

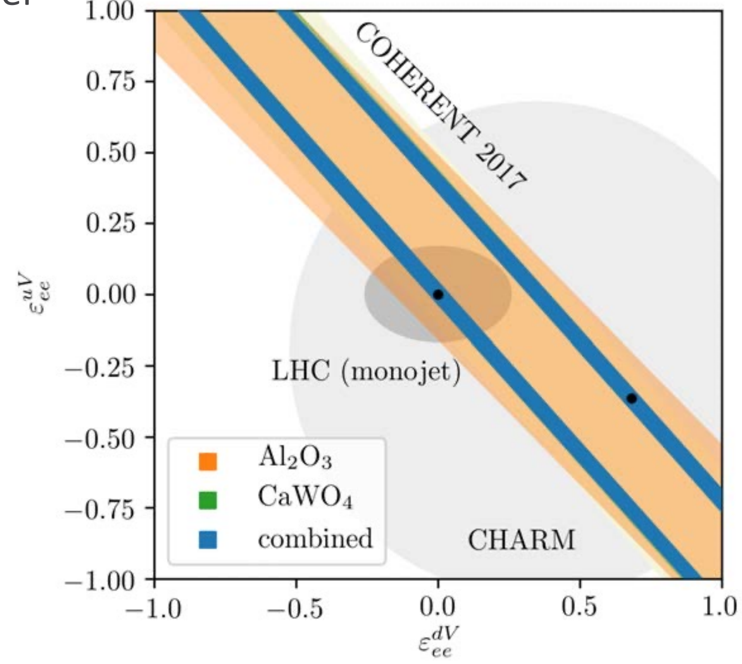
Sterile neutrino

Neutrino electro-magnetic properties (e.g. magnetic dipole moment)

Measure the Weinberg angle at low momentum transfer



Non-standard interactions



3- For Dark matter experiments:

CEνNS of solar or atmospheric neutrinos: irreducible background for experiment looking for WIMPs

⇒ “neutrino floor”

… and more!

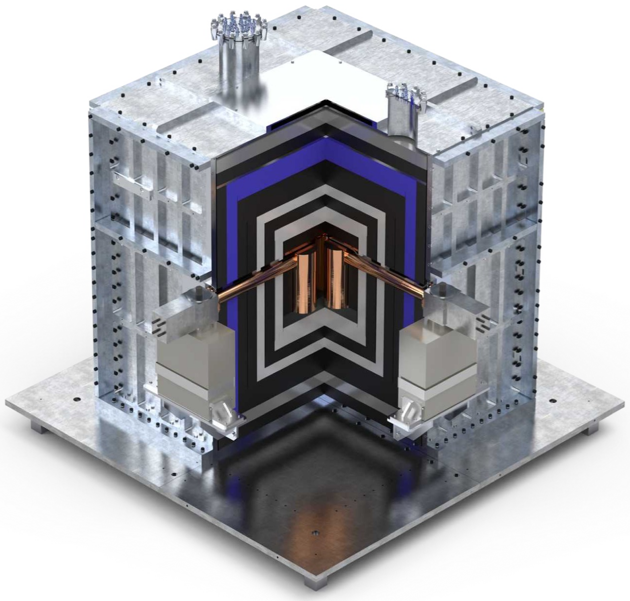
long range detection:

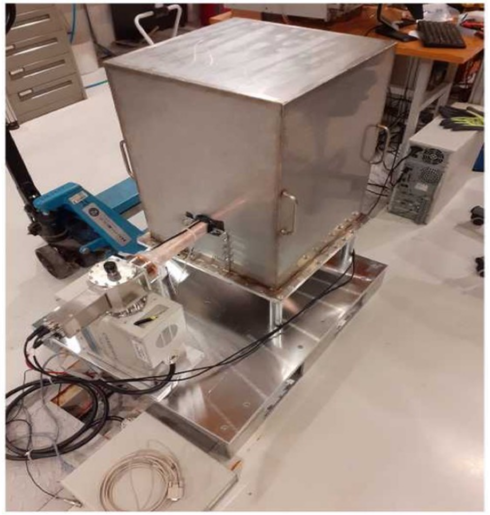
- Supernovae neutrinos
- Solar neutrinos
- Reactor monitoring

Reactor CEνNS experiments

@Brokdorf reactor (KBR) (Germany)

Significant **overburden** ≈ 24 m.w.e.





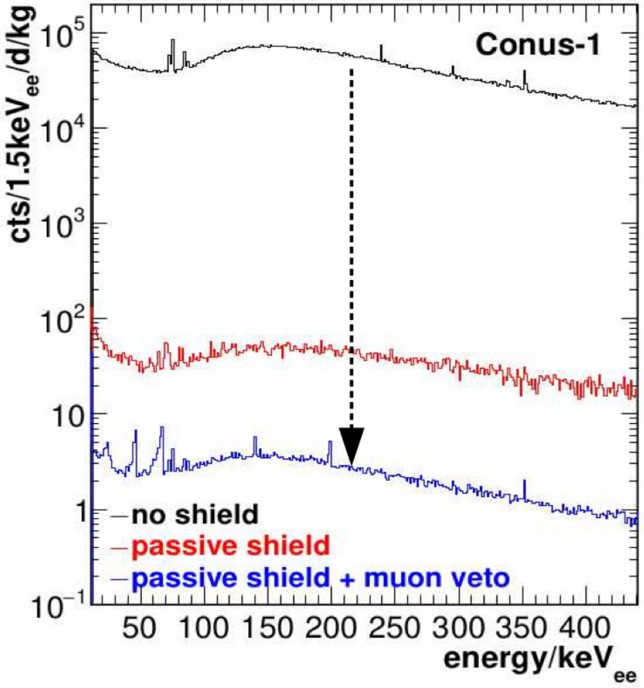
Target detectors:
Ge → ionization
(threshold: $1keV_{nr}$)

Outer Shielding

- Borated Polyethylene
- 25 cm radiopure Pb
- Muon Veto
- Stainless Steel

Background measurement

Overall background suppression
via **passive** and **active** shield



total bkg suppression (w/o PSD): $>10^4$ x
remaining bkg rate in ROI: O(10) cts/d/kg
i.e. (0.3,1.0) keV_ee

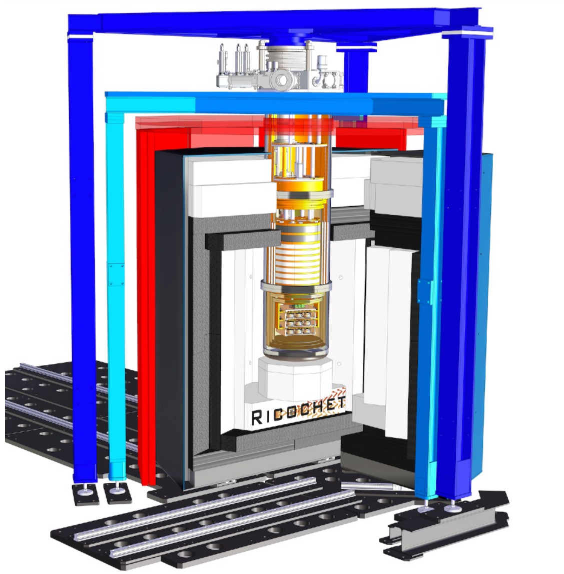
From W. Maneschg (Magnificent CEνNS, March 2023)

Reactor CEνNS experiments

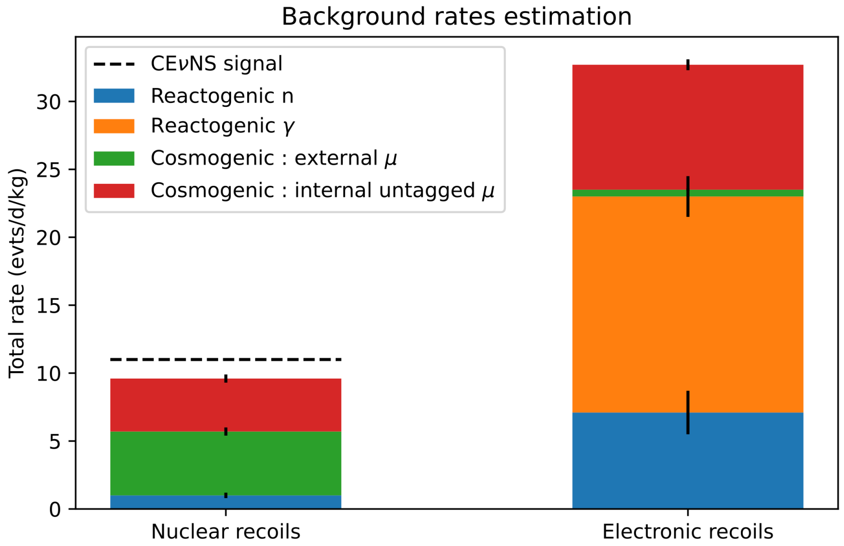
RICOCHET
A Coherent Neutrino Scattering Program

@ILL-H7 nuclear reactor site (Grenoble)

Significant **overburden** ≈ 15 m.w.e.



(known) Background prediction



Recoil type rate	Cosmogenic	Reactogenic	Total
R_{ER} (evts/d/kg)	9.5 ± 0.5	23.0 ± 1.6	32.5 ± 1.7
R_{NR} (evts/d/kg)	8.4 ± 0.4	1.0 ± 0.2	9.4 ± 0.5

From G. Chemin and J. Billard (Magnificent CEνNS, March 2023)

Target detectors:
Ge (& Si ?)
→ ionization and heat
(target RMS: 20 eV_{ee}, 10 eV_{nr})

Inner Shielding:

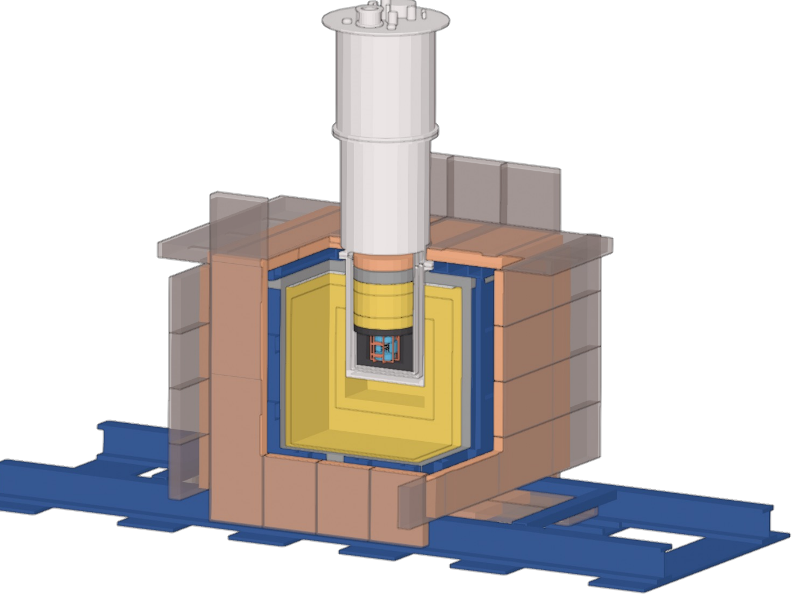
- 30 cm PE/Cu
- 15 cm Pb/Cu
- Cryogenic Muon Veto
- Mu-Metal

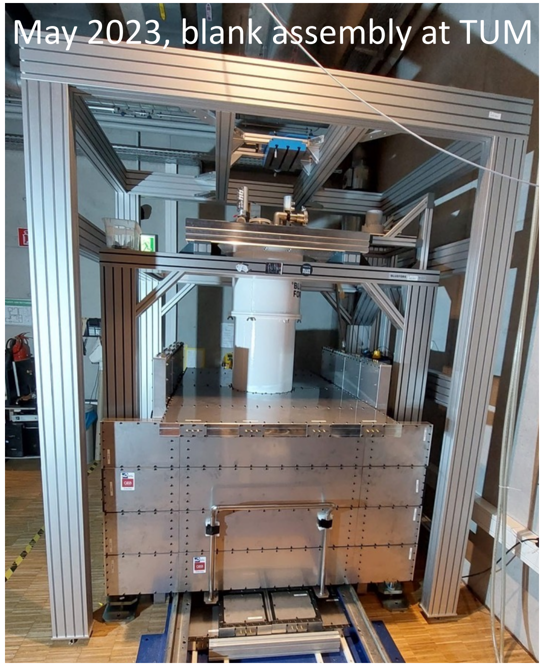
Outer Shielding

- 35 cm PE
- 20 cm Pb
- Muon Veto
- Soft Iron

Reactor CEνNS experiments

@Chooz power plant (France, Givet)




May 2023, blank assembly at TUM

Shallow overburden ≈ 3 m.w.e.
and **small foot print** required: a few m^2

(known) Background prediction

Background contribution **Rates in kg^{-1} d^{-1} *(Preliminary)***	**CaWO$_4$ array**		
	10 – 100 eV	100 eV – 1 keV	1 keV – 10 keV
Ambient gammas	$0.5^{+0.9}_{-0.3}$	$4.1^{+1.7}_{-1.4}$	92±7
Atmospheric muons	$1.2^{+0.9}_{-0.8}$	$2.7^{+1.3}_{-1.1}$	9.3±1.9
Atmospheric neutrons	≈ 9	≈ 24	≈ 90
Total	≈ 11	≈ 30	≈ 190
CEνNS signal	≈ 30	≈ 9	–

Estimated background rate in ROI (10 eV – 100 eV)
≈ 120 ev/kg/d/keV

Target detectors:
CaWO$_4$ & Al$_2$O$_3$
→ heat
(target thr ≈ 20 eV$_{nr}$)

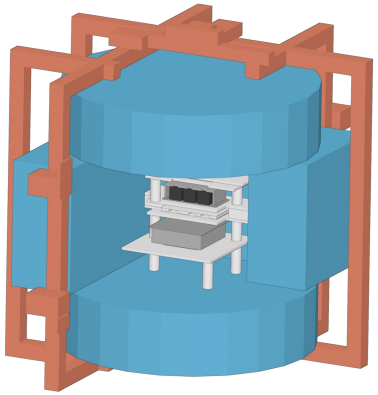
Inner Shielding:

- Inner Veto This talk
- Cryogenic Outer Veto
- 4 cm B$_4$C
- 20 cm Borated PE/Cu
- 5 cm Pb/Cu
- Cryogenic Muon Veto

Outer Shielding

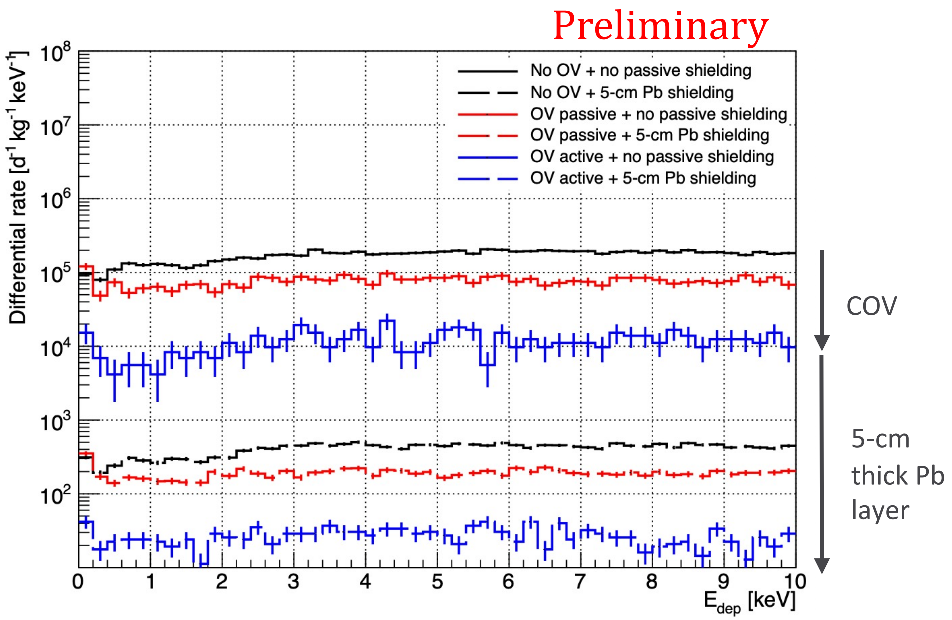
- 20 cm Borated PE
- 5 cm Pb
- Muon Veto

Development of a germanium cryogenic veto

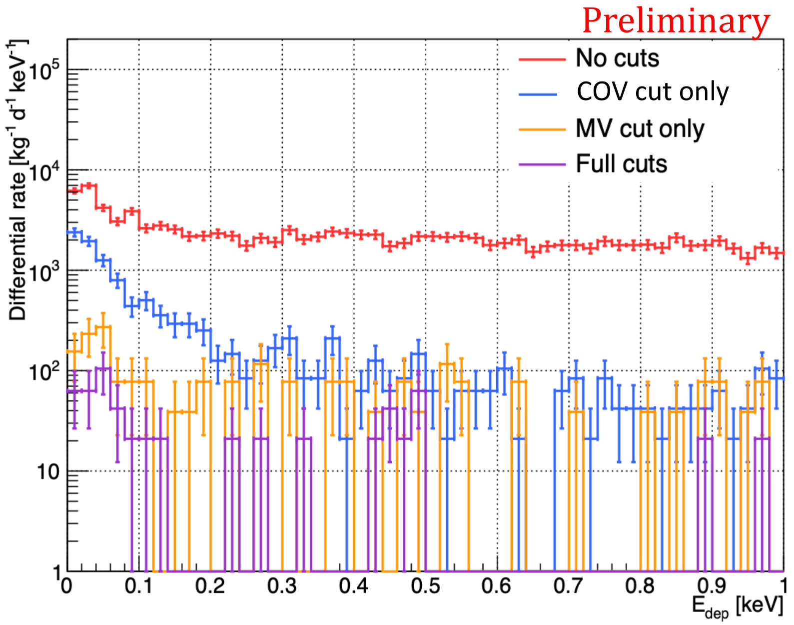


- 6 HPGe crystals
- 4π-coverage active veto
- Fast detector response
- Anti-coincidence with bolometric detectors
- O(10keV) threshold
- Compactness

⇒ Good gamma (and moderate neutron and muon) veto



Ambient gamma contribution to the residual background in $CaWO_4$ crystals with different shielding configurations

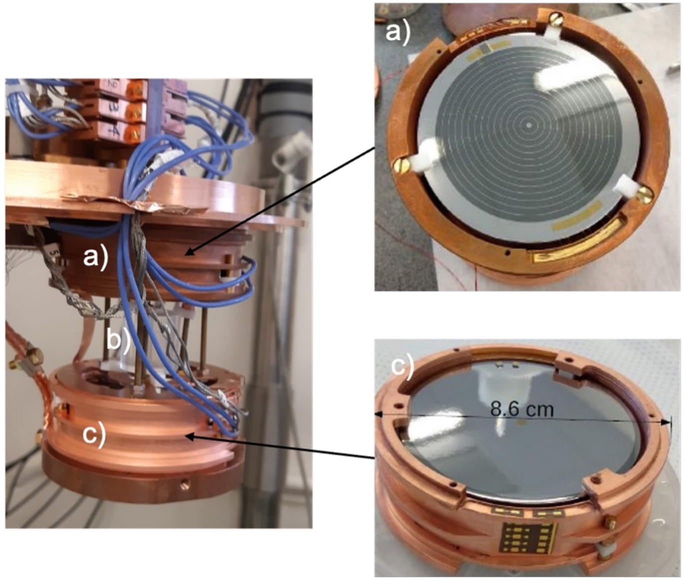


Muon-induced contribution to the residual background in $CaWO_4$ crystals with different active vetoes (simulation without the B_4C layer)

Prototyping a germanium cryogenic veto for CEνNS

Experimental setup:

2 HPGe crystals (ionization channel) → a) and c)
+ 1 Li_2WO_4 crystal in the center (heat channel (NTD), “target detector”) → b)

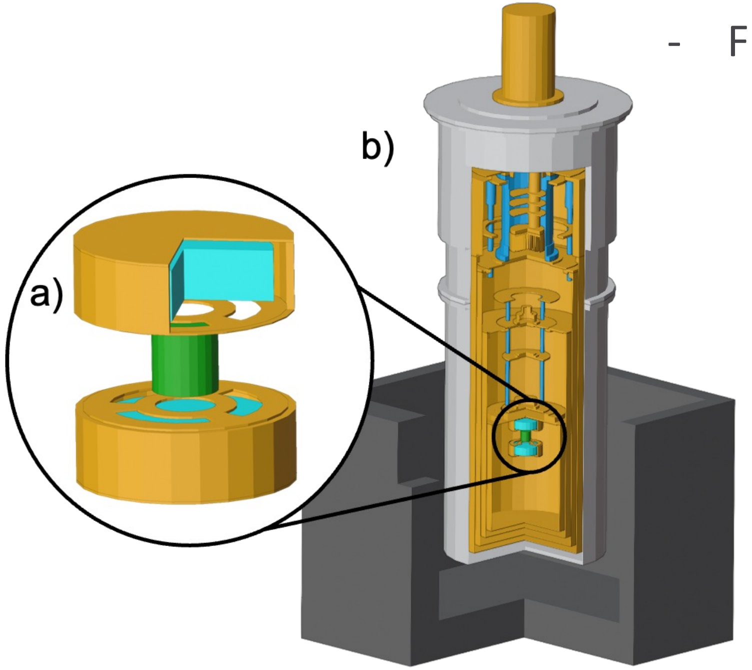


Bolometers At Sub KeV Energy Thresholds

Measurements with and without:
- 5-cm thick lead shielding,
- Neutron source (^{252}Cf)
- Gamma source (^{232}Th)

Simulation of the setup
Data described by 3 components at surface:

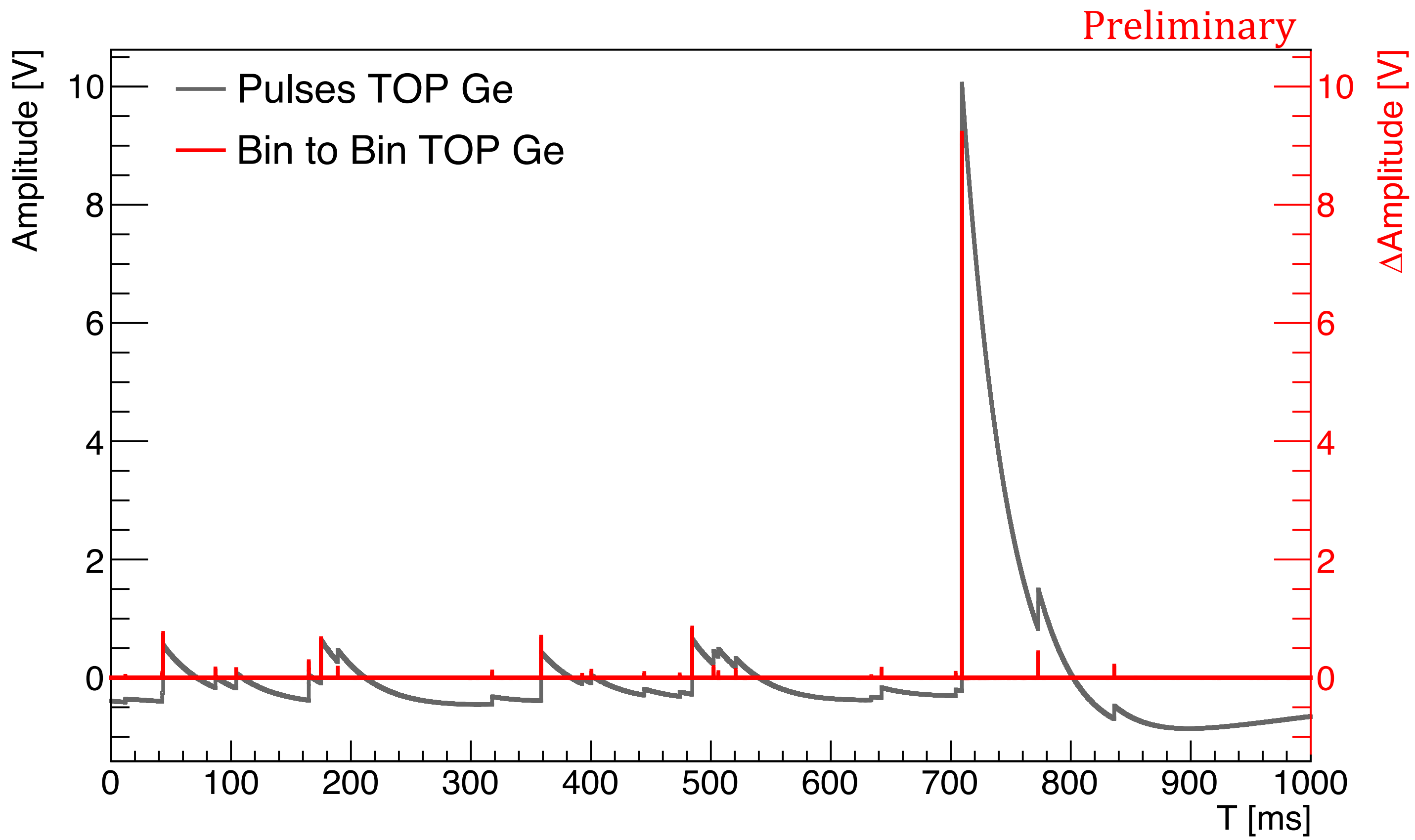
- Environmental Gammas
- From cosmic rays:
  - Neutrons
  - Muons

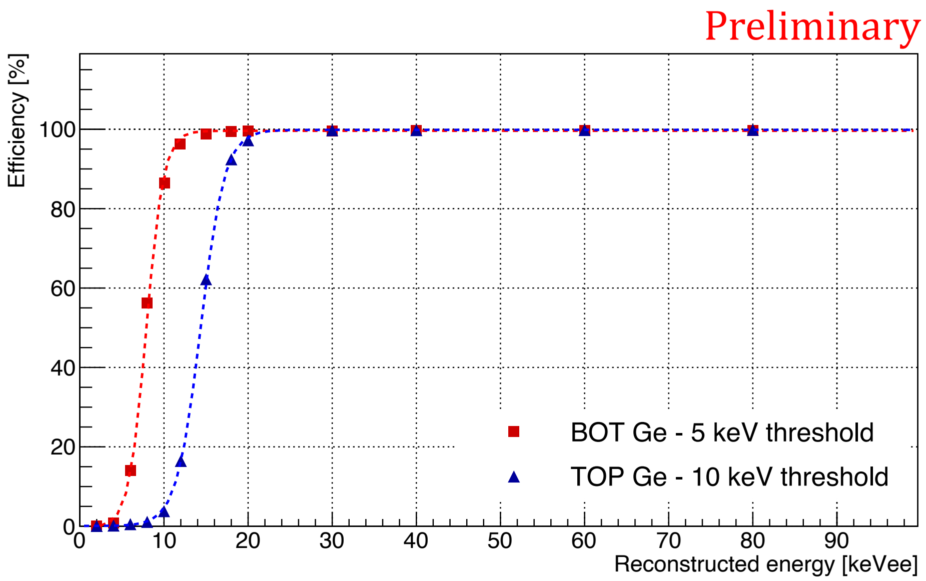


Prototyping a germanium cryogenic veto for CEνNS

Analysis method

1- Top electrode – Bot electrode = Pulses
2- Bin-to-bin differentiation
→ identify pulses rise time
+ flatten the baseline
+ deal with pile-up
3- Apply threshold
4- Calculate pulse amplitude

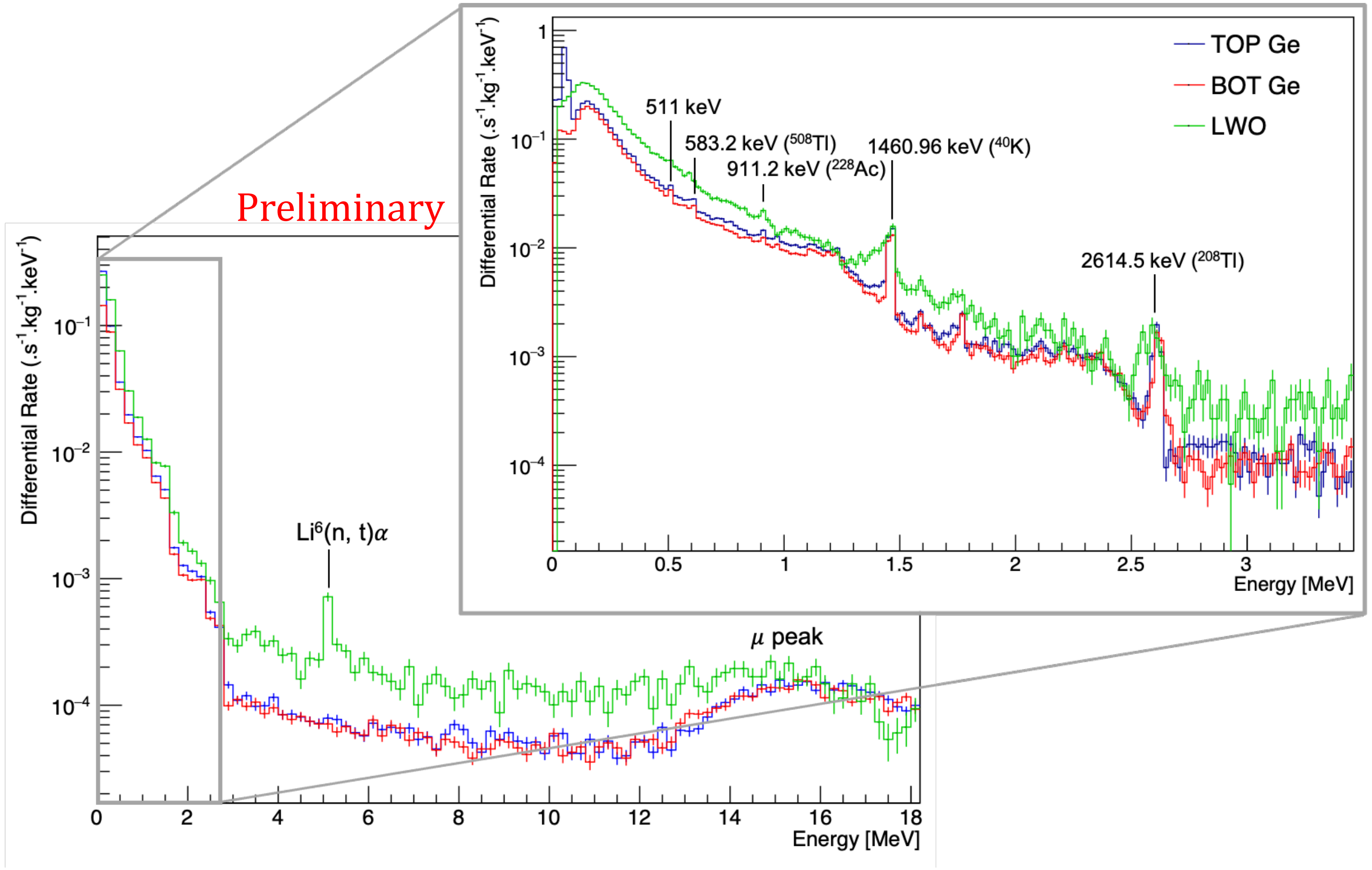




⇒ High reconstruction efficiency close to the threshold, handle the pile-up

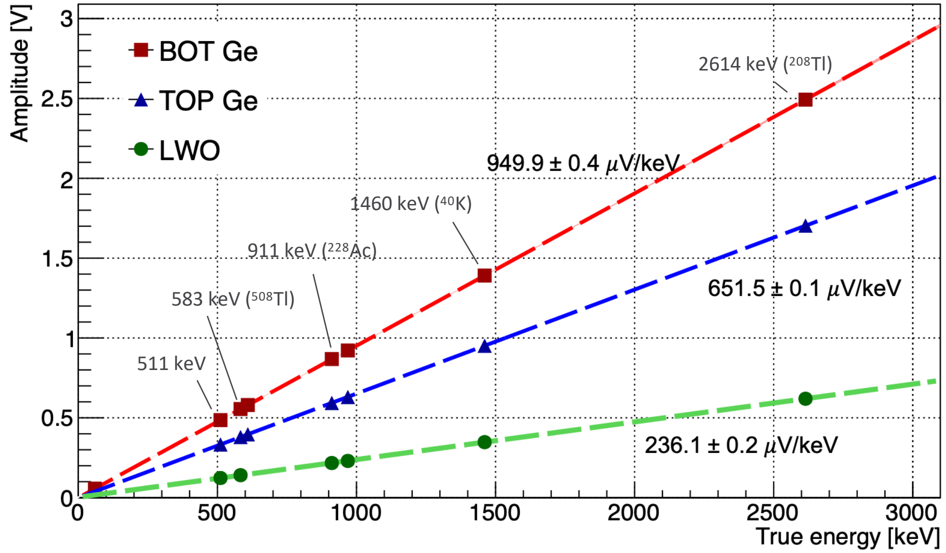
Prototyping a germanium cryogenic veto for CE$\boldsymbol{\nu}$NS

Detector response



Preliminary

Energy calibration



Preliminary

Slope linked to the sensitivity:

With a gain = 1000 on the Ge:

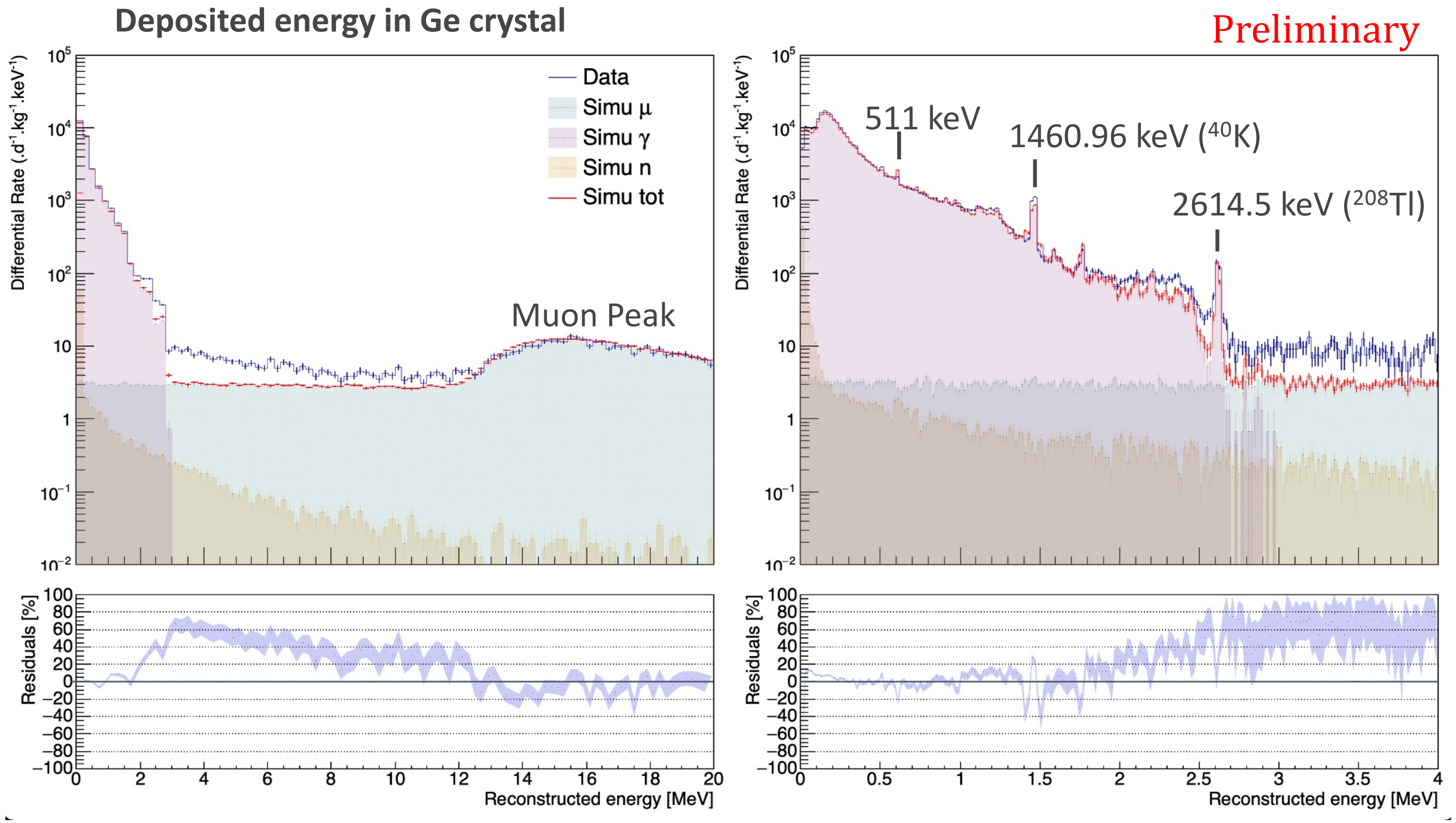
measured sensitivity = 949 nV/keV (BOT)
= 651 nV/keV (TOP)

Difference in sensitivities due to the electrode geometries (planar and ID electrodes)

Prototyping a germanium cryogenic veto for CEνNS

Fit of the signal component fluxes on the data :

- Good understanding of our data and the signal component
- Simple analysis of the germanium detectors
- Correct simulation of the expected events



Preliminary

Background contribution	Fluxes (/cm²/s)	
	This work	Reference values
Atmospheric muons	$(1.79 \pm 0.02) \times 10^{-2}$	$(1.90 \pm 0.12) \times 10^{-2}$ from [1]
Environmental gammas	3.126 ± 0.005	$3.2 \pm 0.3^{\star}$
Atmospheric neutrons	$(1.37 \pm 0.27) \times 10^{-2}$	1.34×10^{-2} from [2]

Table 1: Fitted values for the integrated fluxes of each background contribution. The errors given are fit errors calculated only from statistic errors.
* Measured value in the lab with a high purity germanium spectrometer.

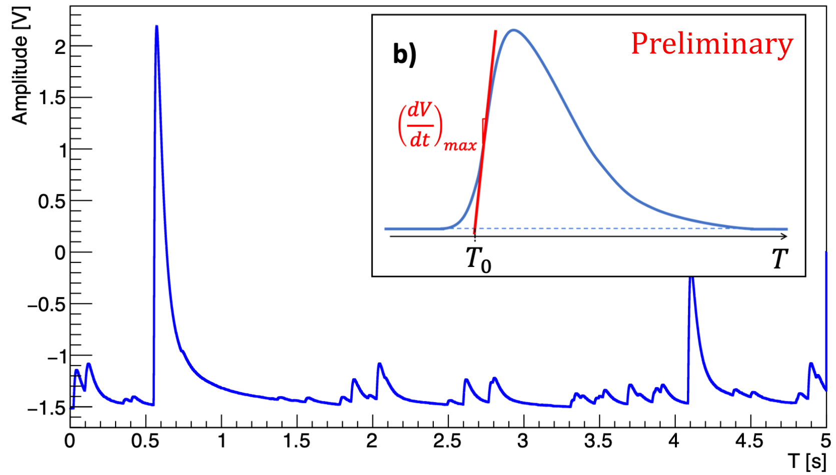
Article in preparation

[1] Tang, et al. Physical Review, 2006
[2] Gordon, et al Nuclear Science, 2005

Prototyping a germanium cryogenic veto for CEνNS

Coincidences and veto in the data

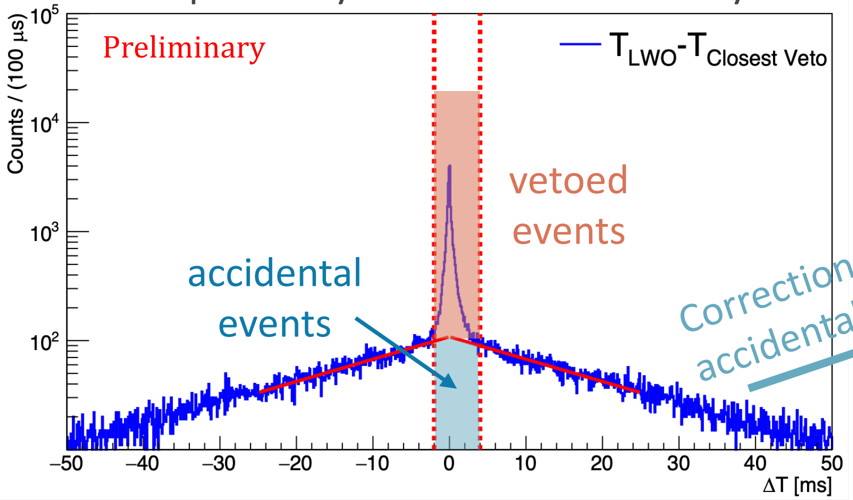
Time reconstruction of the Li_2WO_4 events



$\tau_{ioniz} \approx$ us

$\tau_{heat} \approx$ ms

Event proximity with one of the Ge crystals

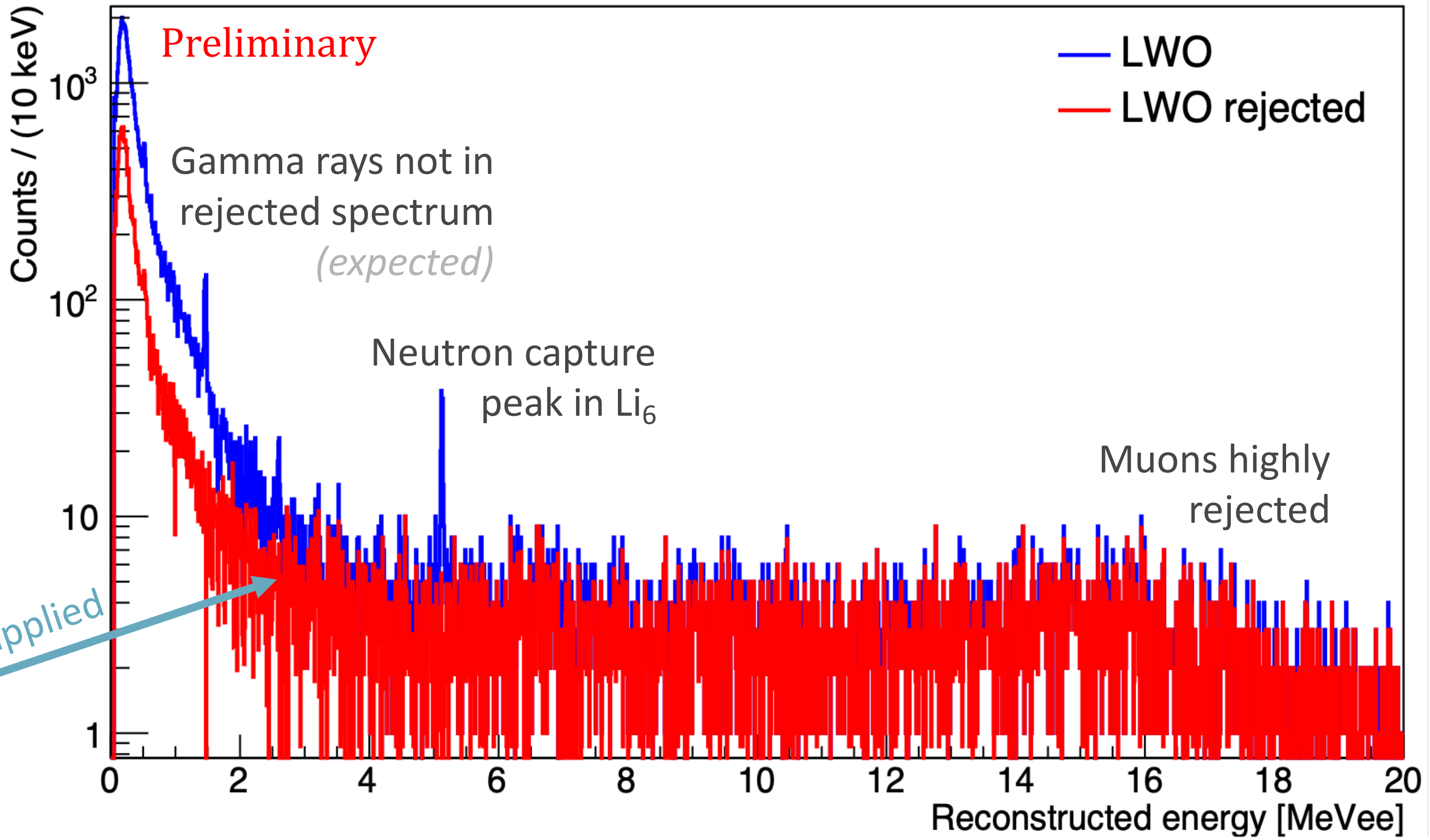


vetoed events

accidental events

Correction from accidental events applied

22% of rejected events



Gamma rays not in rejected spectrum *(expected)*

Neutron capture peak in Li_6

Muons highly rejected

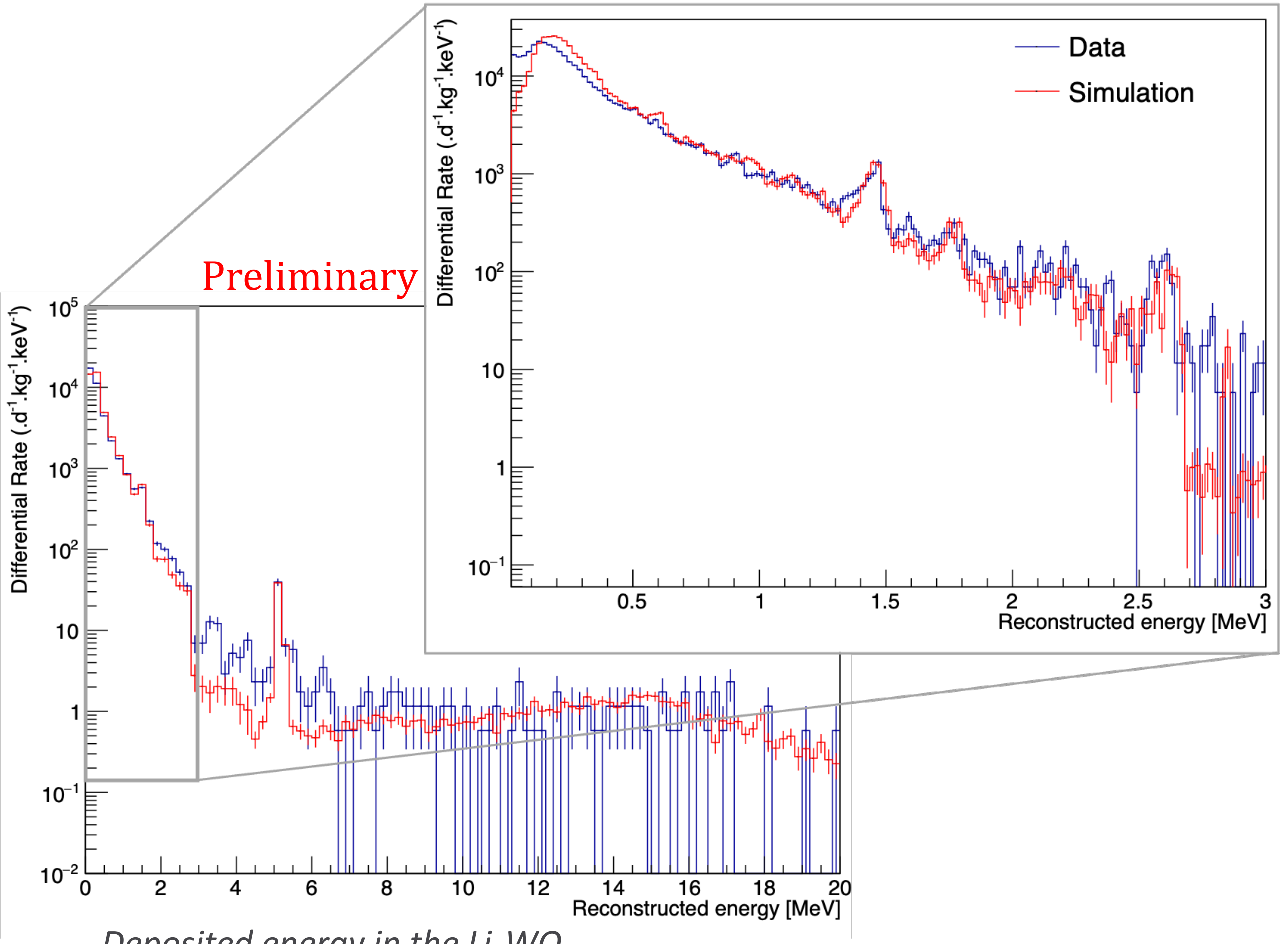
Prototyping a germanium cryogenic veto for CEνNS

Comparison with the simulation

- Really good agreement between veto rejection obtained in the data and in the simulation

Rejection power by the Ge veto in the Li_2WO_4

Preliminary	No shielding		With shielding	
Energy Range	Data	Simulation	Data	Simulation
[0.05; 20] MeV	$22.0 \pm 0.5\,\%$	$22.4 \pm 0.4\,\%$	$30.8 \pm 0.5\,\%$	$30.1 \pm 0.7\,\%$
[0.05; 3] MeV	$20.4 \pm 0.5\,\%$	$22.0 \pm 0.4\,\%$	$26.3 \pm 0.5\,\%$	$28.8 \pm 0.8\,\%$
[3; 10] MeV	$93.1 \pm 3.4\,\%$	$84.2 \pm 0.9\,\%$	$93.2 \pm 2.0\,\%$	$84.4 \pm 2.0\,\%$
[10; 20] MeV	$78.4 \pm 3.3\,\%$	$81.7 \pm 1.3\,\%$	$80.2 \pm 2.1\,\%$	$81.3 \pm 2.2\,\%$



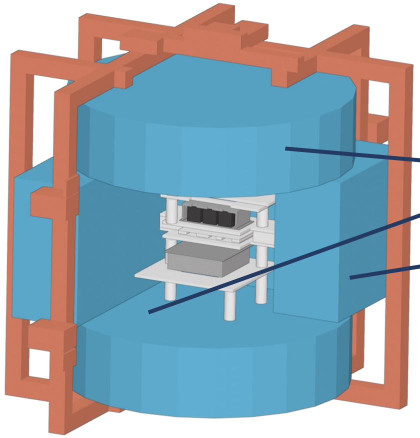
Deposited energy in the Li_2WO_4 with a veto applied

Article in preparation

Towards a 4π veto for NUCLEUS

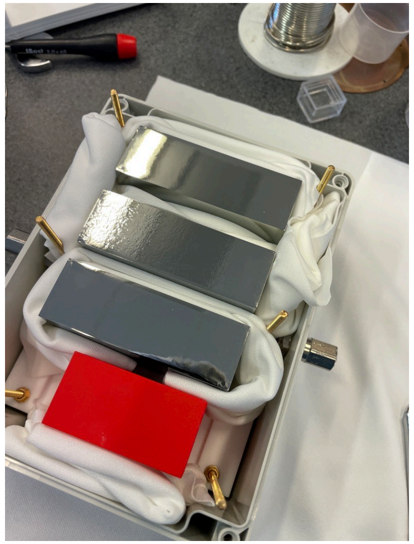
With a 4π, 2cm-thick system: rejection efficiency estimated at 95%

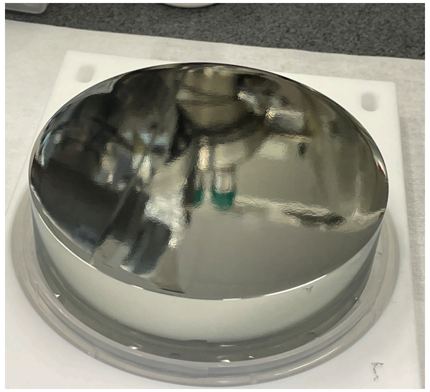
⇒ Development of this veto for NUCLEUS



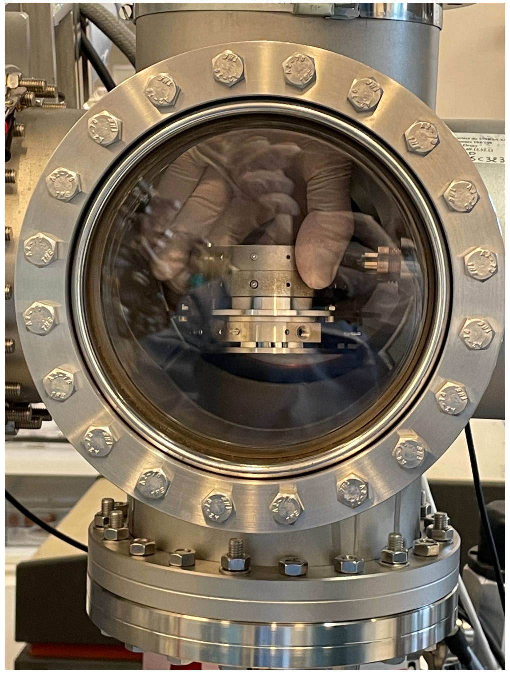
Cylindric crystal (10-cm diameter, 2.5-cm thick, 1kg)

Rectangular crystals (7 x 2.5 x 5 cm, 500g)

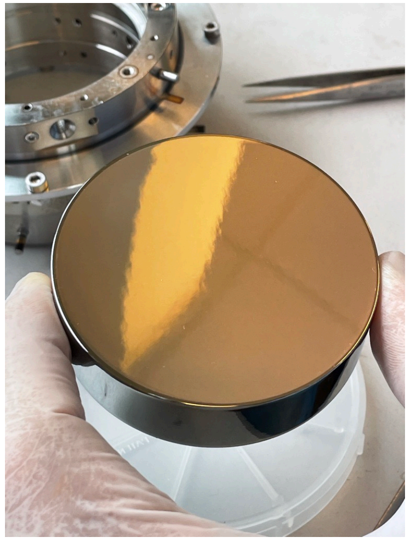


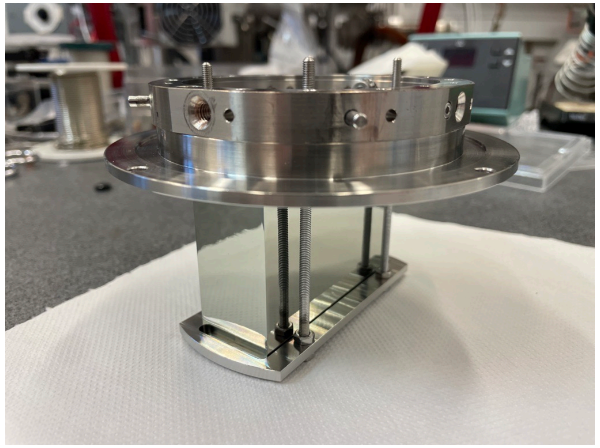


Electrode evaporation and tests @IJCLab



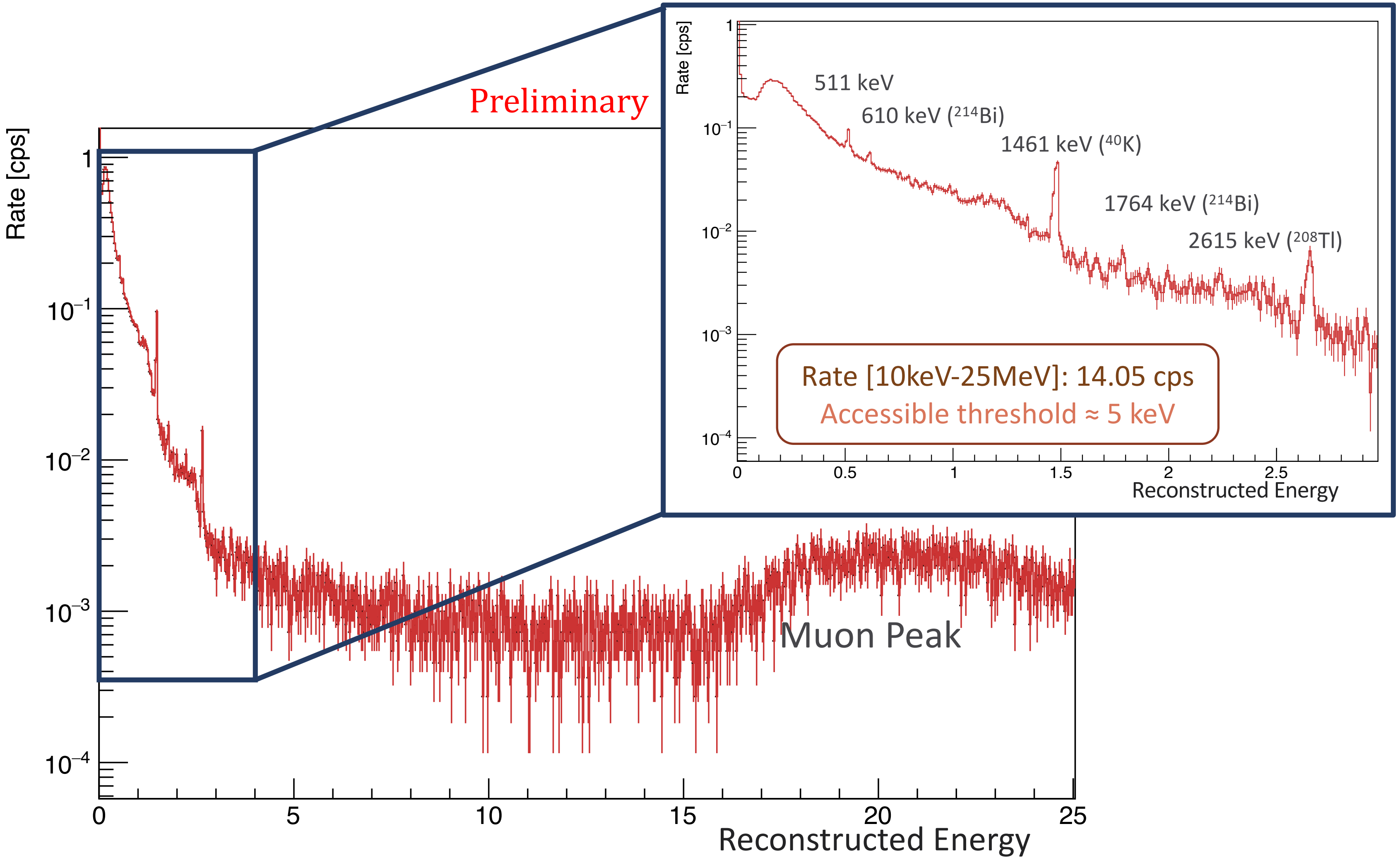
Electrode evaporation:
→ 30 nm of a-Ge:H
→ 200 nm Al electrode





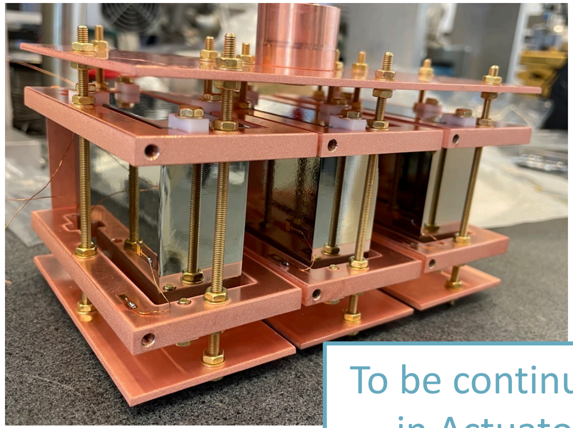
Towards a 4π veto for NUCLEUS

Test of the cylindric crystals @IJCLab



Rate [10keV-25MeV]: 14.05 cps
Accessible threshold ≈ 5 keV

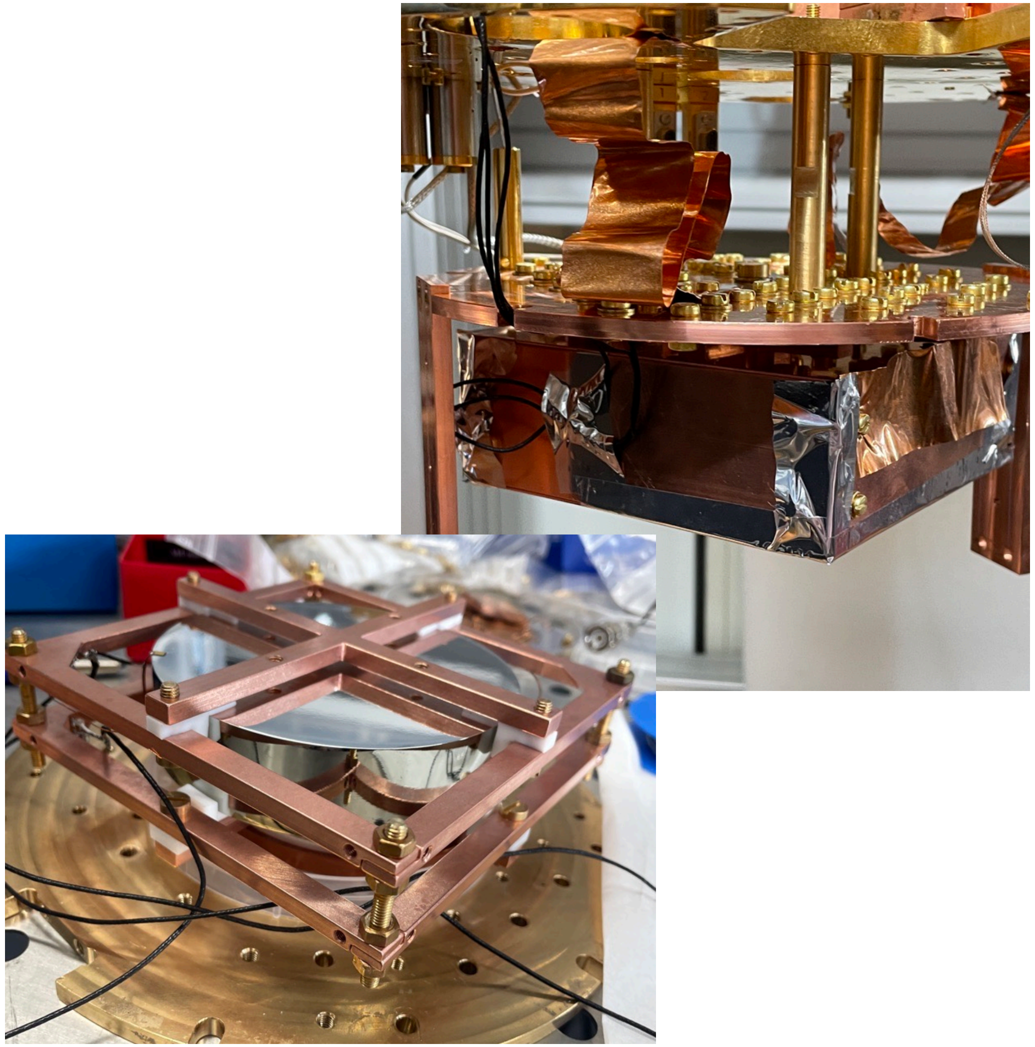
Test of the rectangular crystals…



To be continued at IJCLab
in Actuator Cryostat

Towards a 4π veto for NUCLEUS

In the NUCLEUS cryostat for the commissioning:



- First light in March 2023
- Base temperature (7mK) achieved

Next steps:

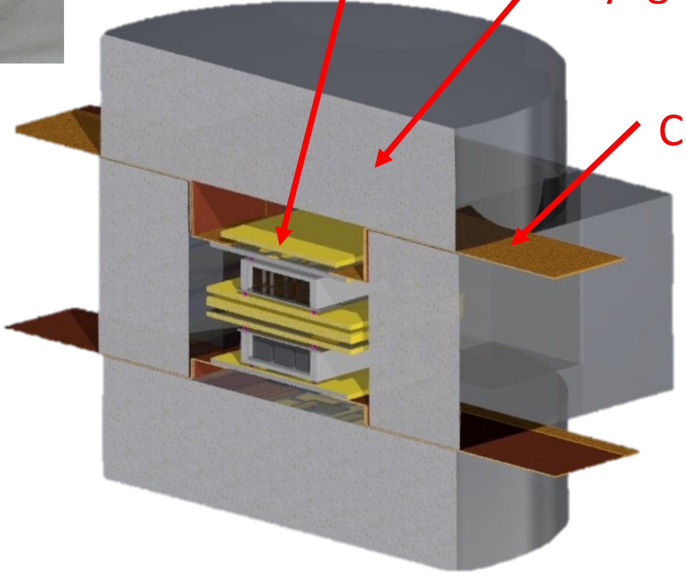
- Long time measurement
- Background spectrum
- Final acquisition scheme
- Run in anti-coincidence with the NUCLEUS target detectors

Towards a 4π veto for NUCLEUS

Scaling up and role in the future commissioning plan

Copper cage

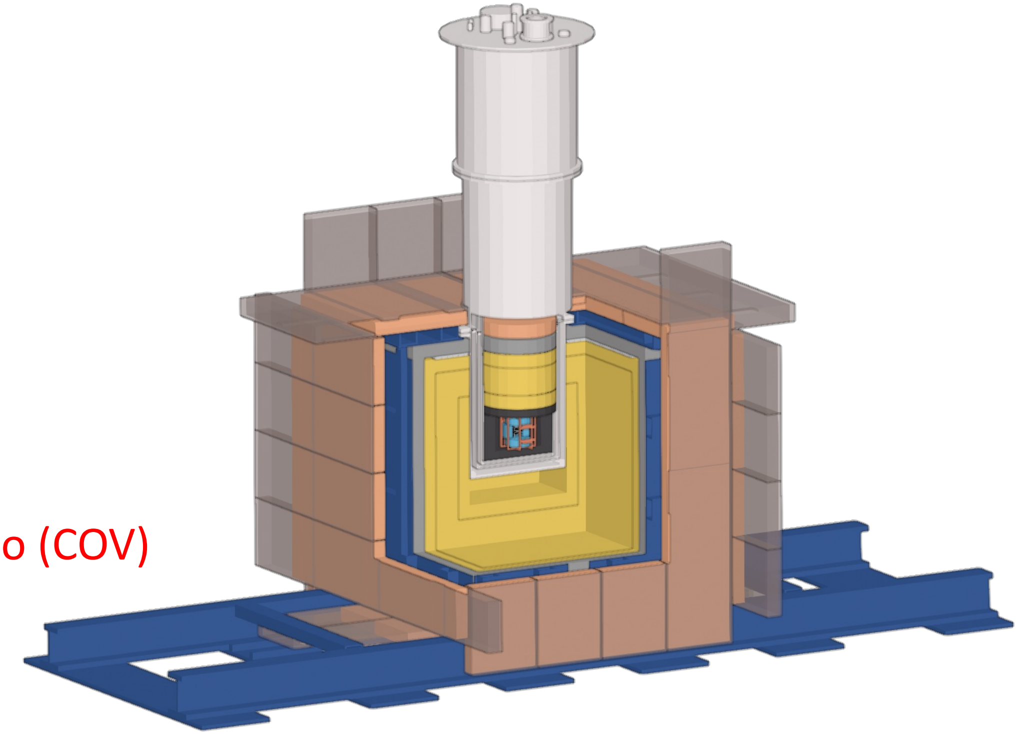
(Additional Cu shielding)



Cryogenic detectors

Cryogenic Outer Veto (COV)

Cables



Role in the coming commissioning

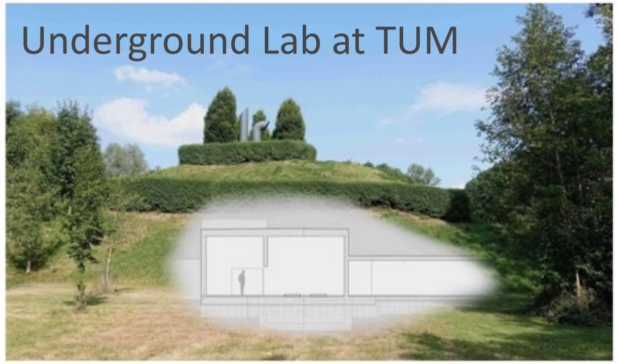
- Target detector for the Muon Veto efficiency measurement
- Shielding efficiency measurement
- First operation in anti-coincidence with the target detectors

From blank assembly towards on-site installation

May 2023

Beginning 2024

Blank Assembly & commissioning



→ Mechanical integration tests

→ Calibrations at keV energies and below:
  - LED
  - XRF
  - Neutrons with CRAB

    (*JINST* **16** P07032 (2021))

→ Detector performances

→ Background studies at sub-keV (EXCESS)

On-site installation

Full COV installation

→ Background measurement in the UGL

→ Shielding efficiency characterization

2024

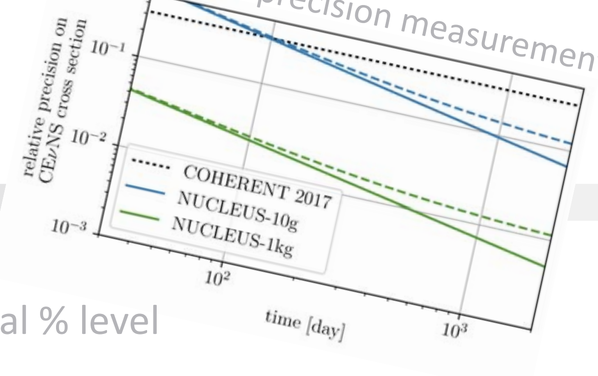
NUCLEUS-10g physics run

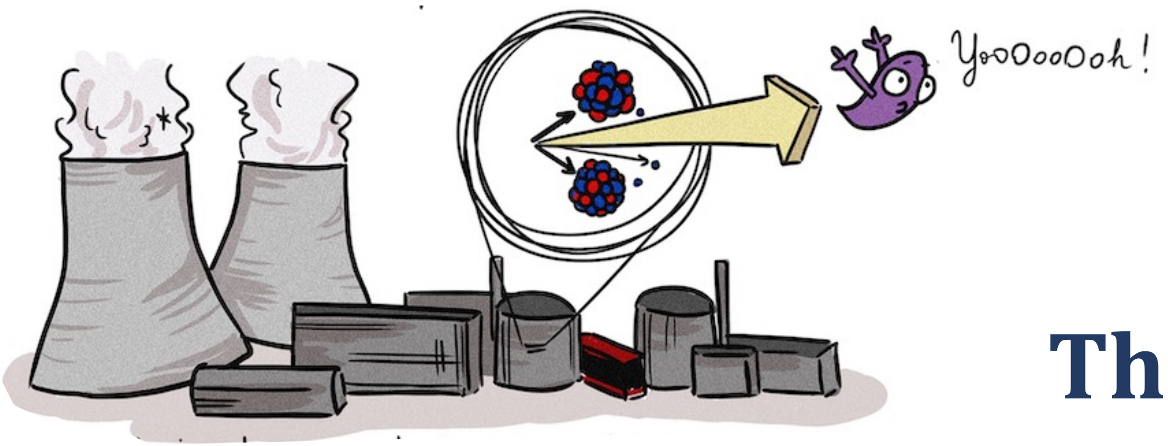
Phase 1: observe CE𝜈NS

Towards NUCLEUS-1kg

Phase 2: measure CE𝜈NS at the several % level

CE𝜈NS precision measurement?





Thanks for your attention

nucleus EXPERIMENT

https://nucleus-experiment.org

ββ
BSM
solar
reactor
accelerator
atmospheric
coherent scattering
P2IO

Development of a cryogenic veto system for CEνNS detection

in the scope of the NUCLEUS experiment

Back-up slides

CE$\boldsymbol{\nu}$NS, what for?

Differential cross section

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_w^2 F^2(q^2) m(Z,N)\left(1 - \frac{E_r}{E_{r,max}}\right)$$

G_F: Fermi constant

$Q_w = N - Z(1 - 4sin^2\theta_W) \sim N$: Nuclear weak charge

F: Nuclear form factor, depends on q^2

q: Momentum transfer

$m(Z,N)$: Total mass of the nucleus

E_r: nuclear recoil energy

$E_{r,max} = 2E_v^2/(m(Z,N) + 2E_v)$: maximal recoil energy

Non-standard interactions

$$\sigma \sim \left[Z\left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right) + N\left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right)\right]^2$$

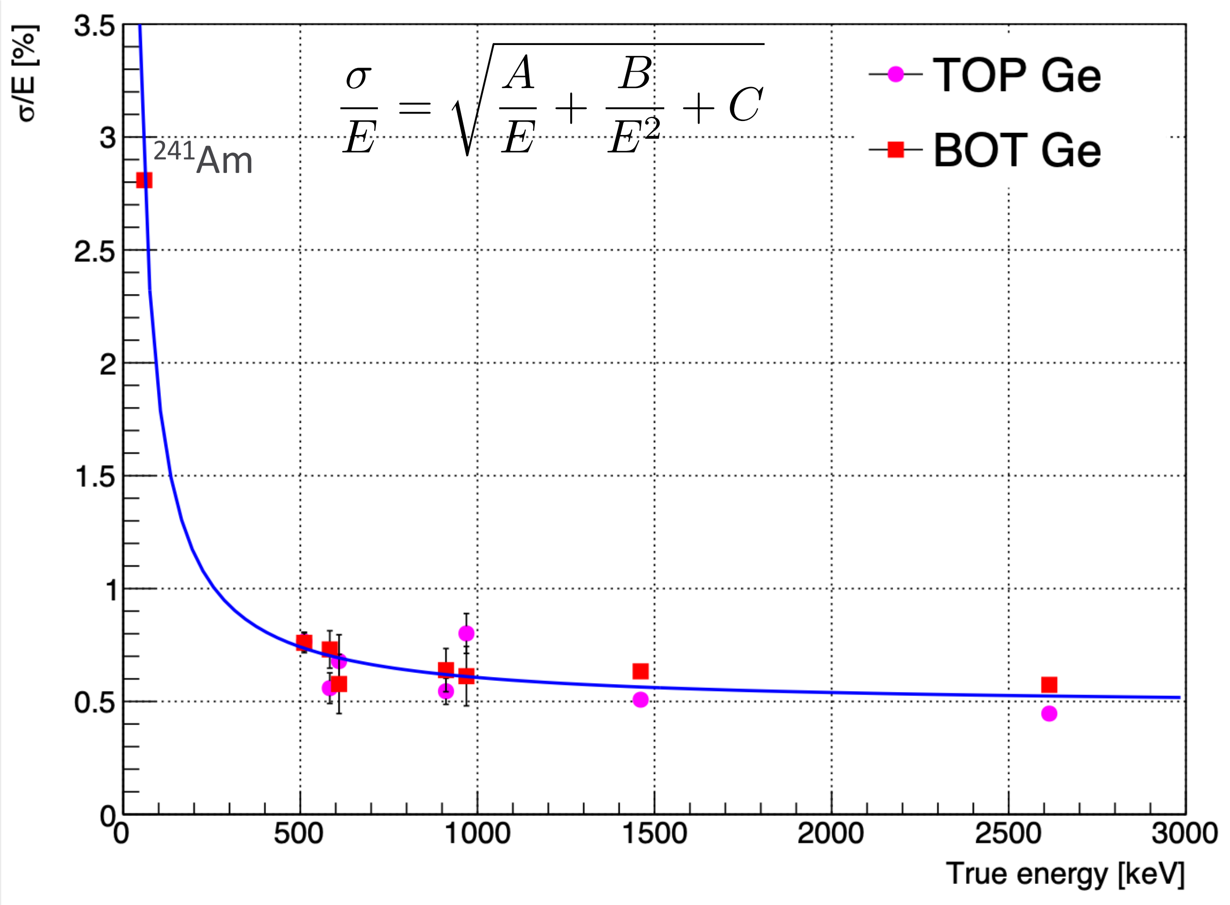
$$g_V^p = +\frac{1}{2} - 2\sin^2\theta_W$$

Prototyping a germanium veto

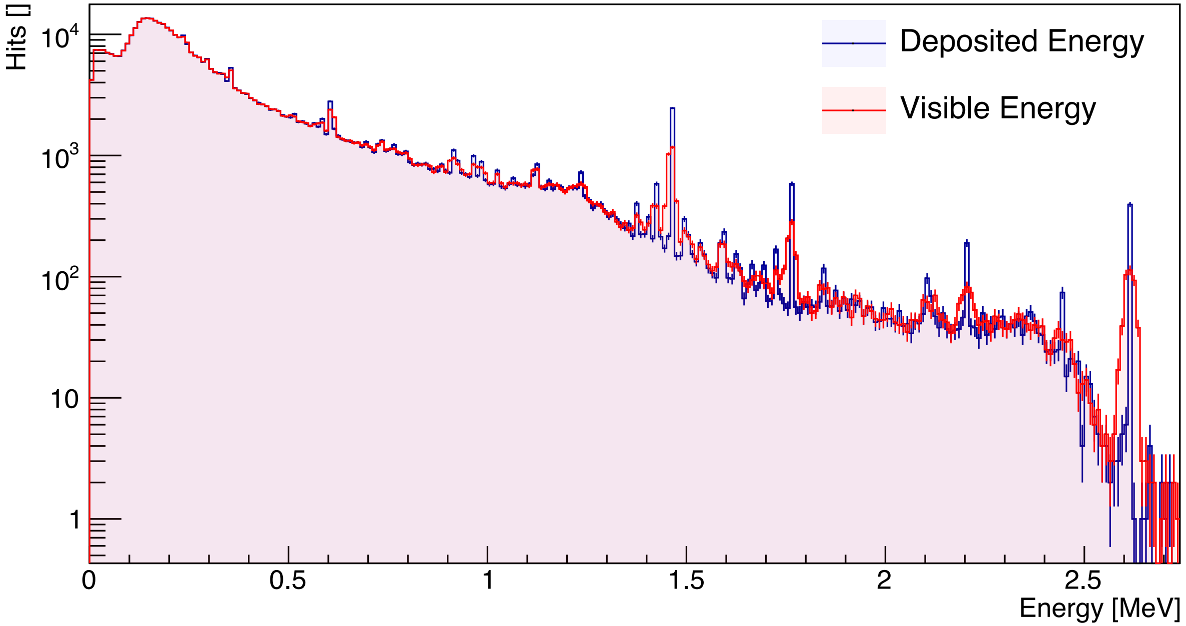
Analysis details

Energy resolution

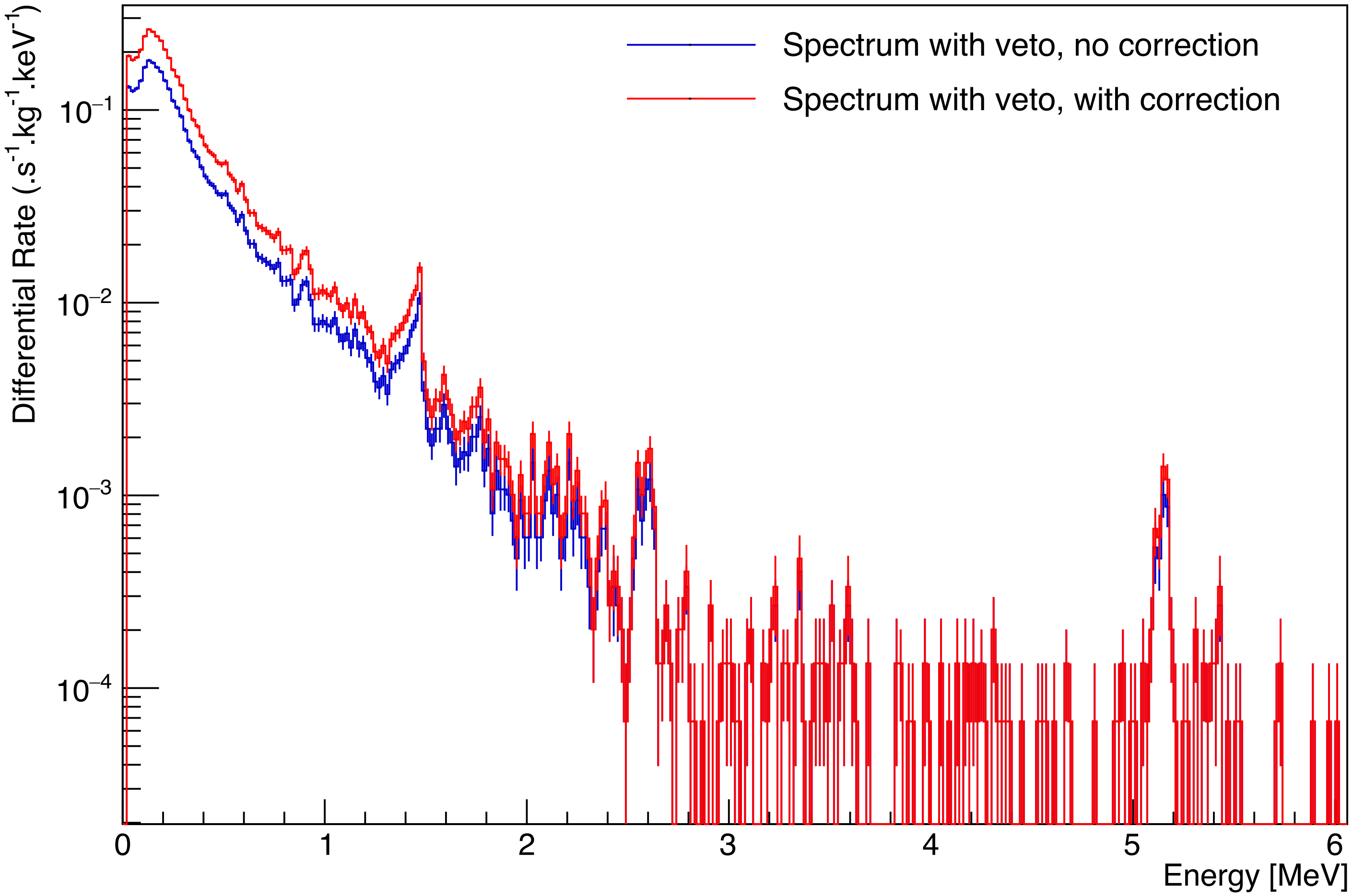
Energy resolution



Energy resolution in the simulation



Accidental events in veto



Higher rejection if no accidental correction is applied ⇒ Not the true coincidence rate.

- correction important in the gamma range
- less important at higher energy (> 5 MeV)

COV prototype simulation

Multi-steps fitting procedure

Multi-steps fitting procedure

Principle

Data = reconstructed energy spectra

Model = scaled simulations

$$\text{Minimize} \quad \chi^2 = \sum_{det.} \frac{(\ D_{det}\ -\ M_{det}\ )^2}{\sigma^2_{D_{det}} + \sigma^2_{M_{det}}}$$

Sum over three detectors

Stat. errors only

$$\begin{aligned} M_{det} = {} & \phi_\mu \times S_{\mu,det} \\ & + \phi_n \times S_{n,det} \\ & + \phi_\gamma \times S_{\gamma,det} \end{aligned}$$

From MC simulations (fixed)

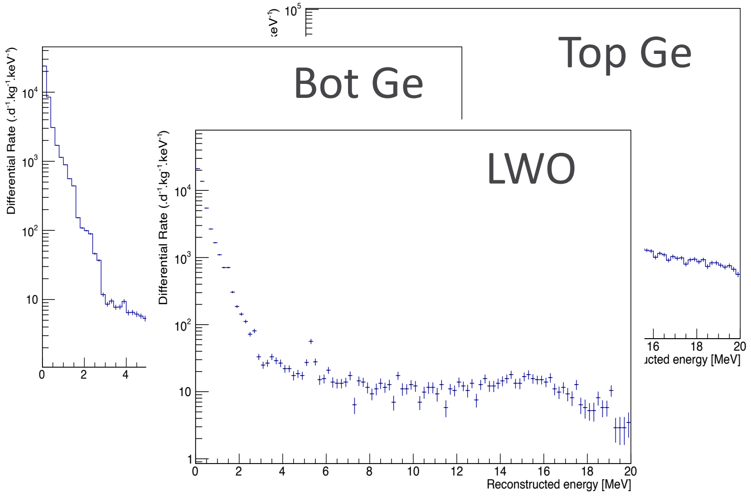
Fitted parameters

Multi-steps fitting procedure

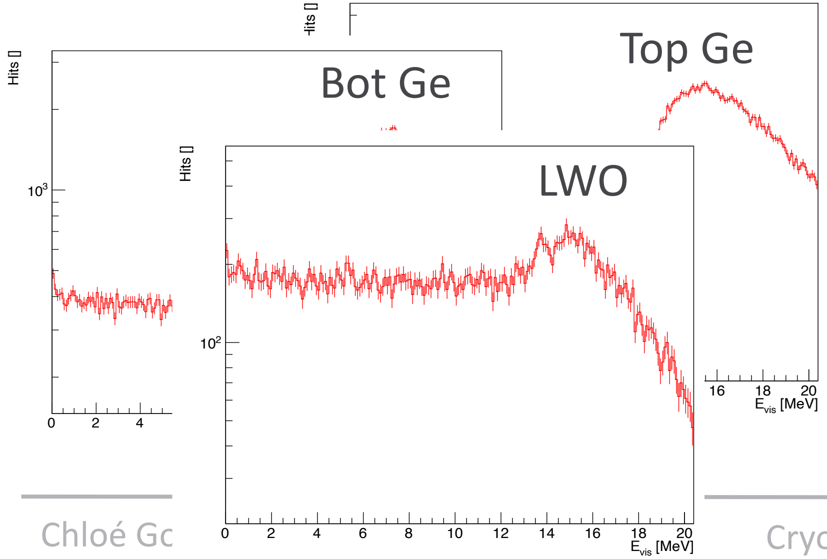
Step 1 : Muons

ϕ_μ

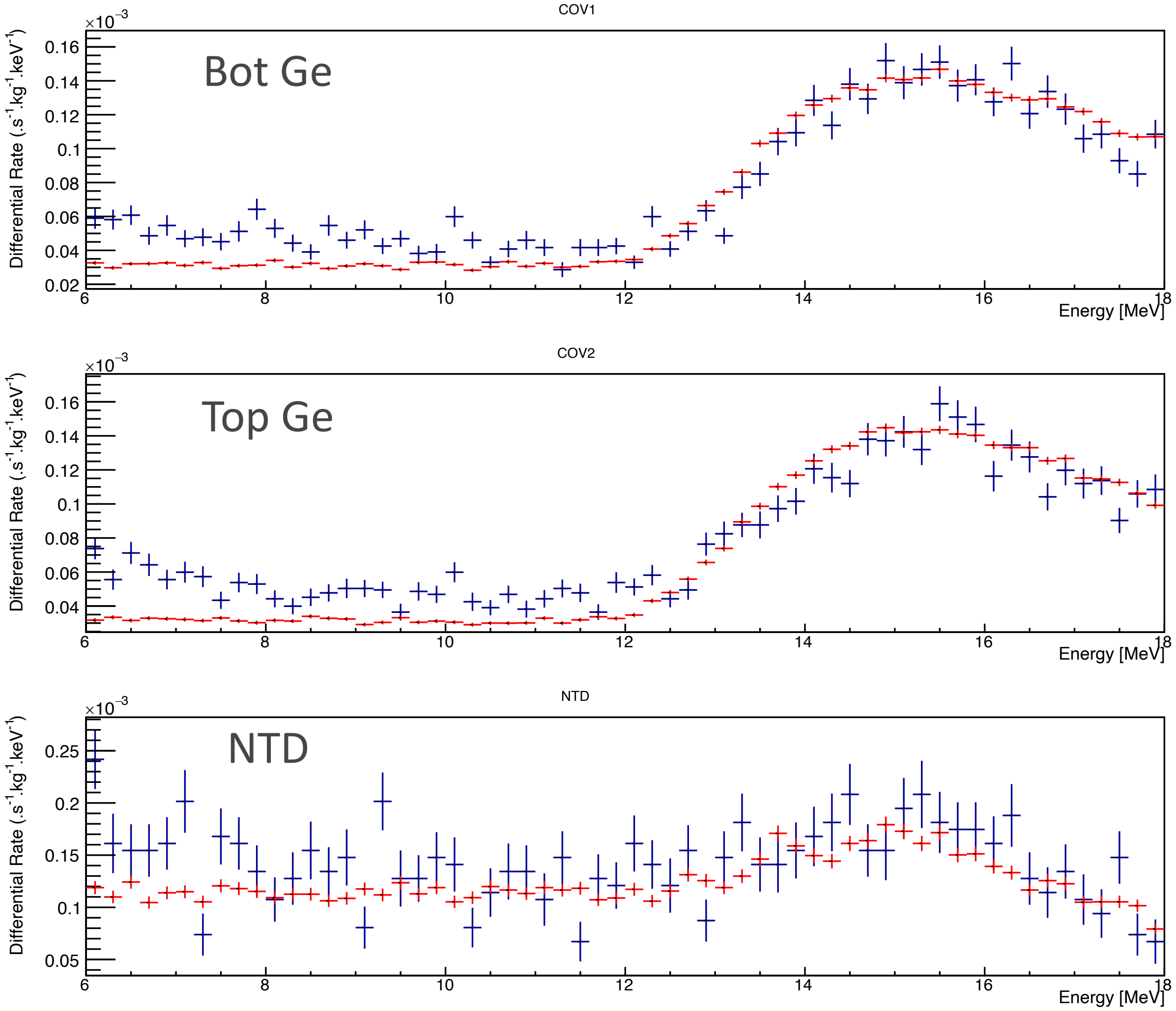
Calibrated and time normalized data



Simulation muons



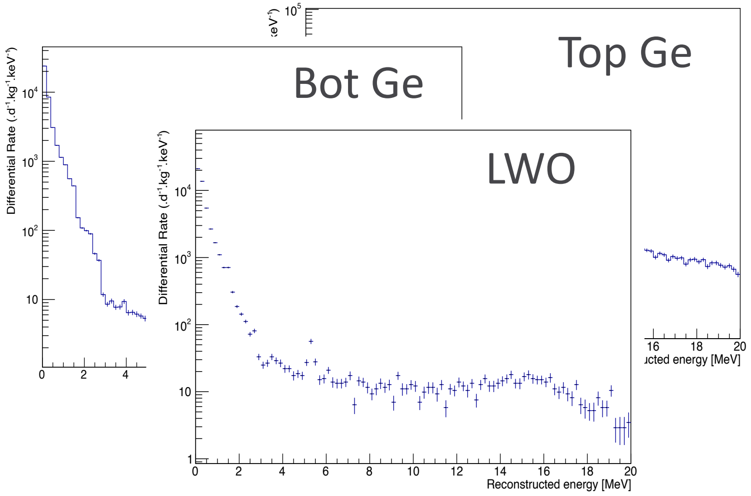
Fit Muon – 6-18MeV



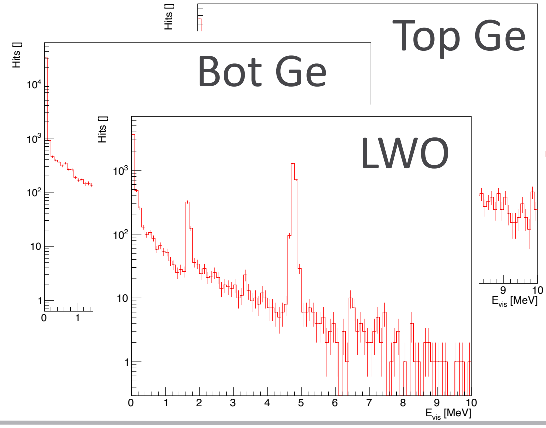
Multi-steps fitting procedure

Step 2 : Neutron from Li capture peak

Calibrated and time normalized data



Simulation neutron (shifted)



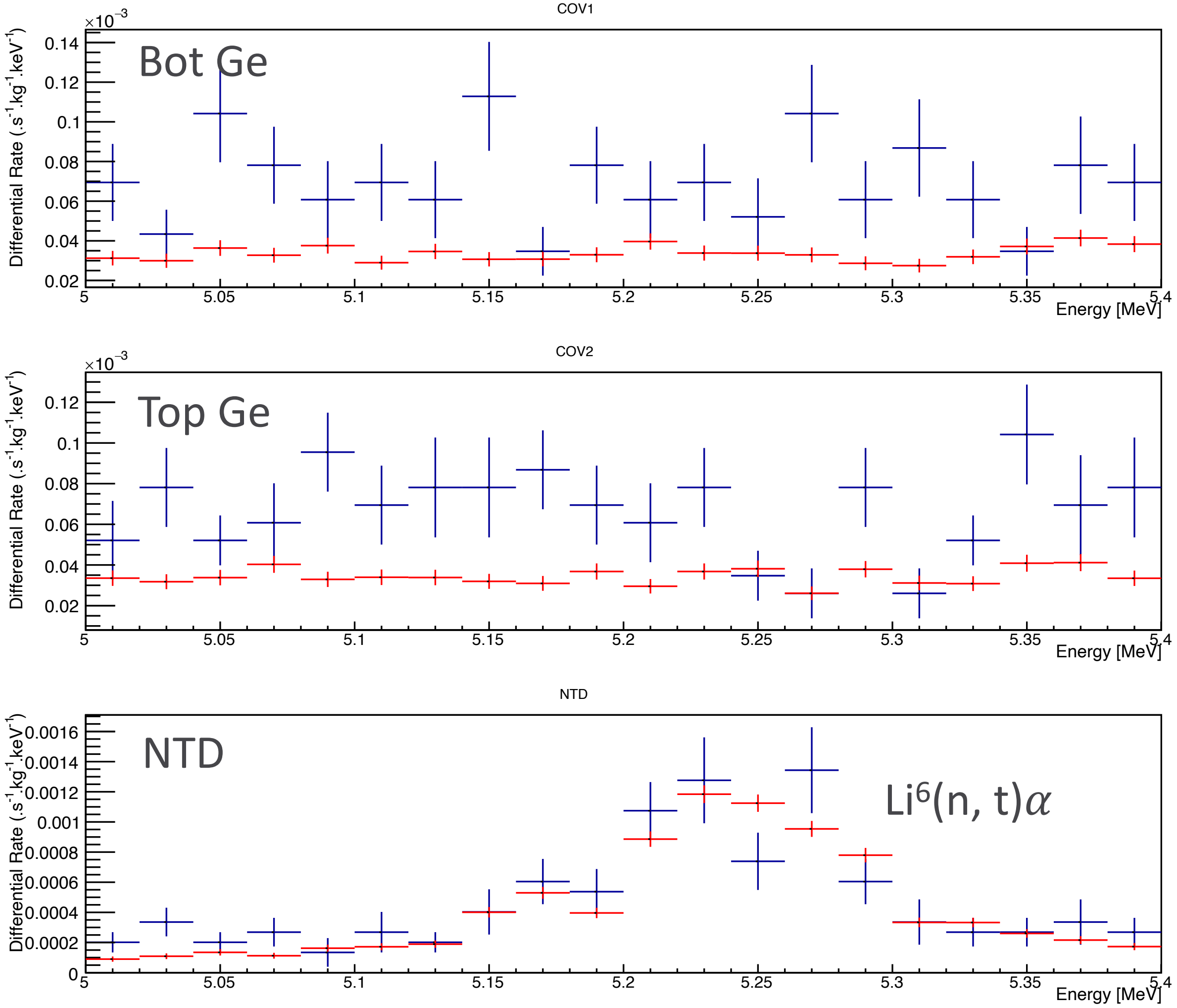
ϕ_μ

Simulation muons scaled with ϕ_μ

+

ϕ_n

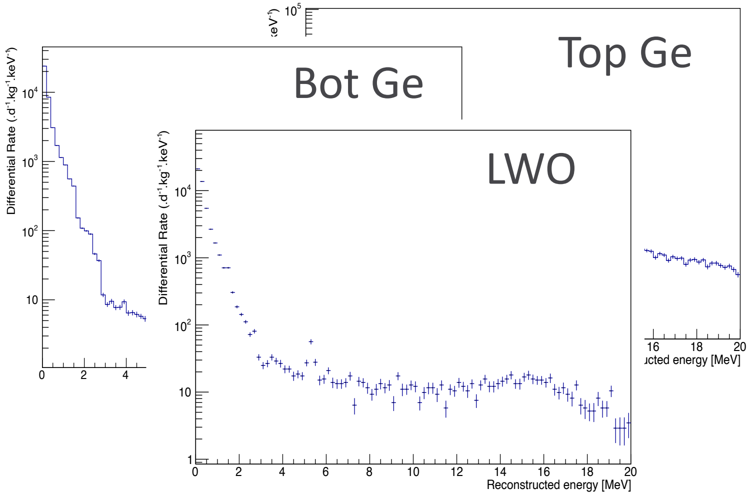
Fit Neutrons – 5-5.4MeV



Multi-steps fitting procedure

Step 3 : Gammas

Calibrated and time normalized data

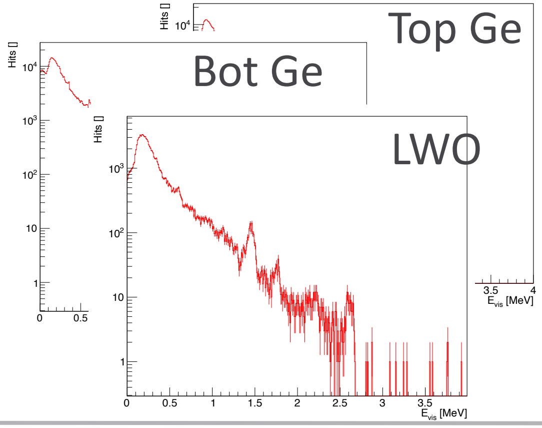


Simulation Gammas

ϕ_μ Simulation muons scaled with ϕ_μ

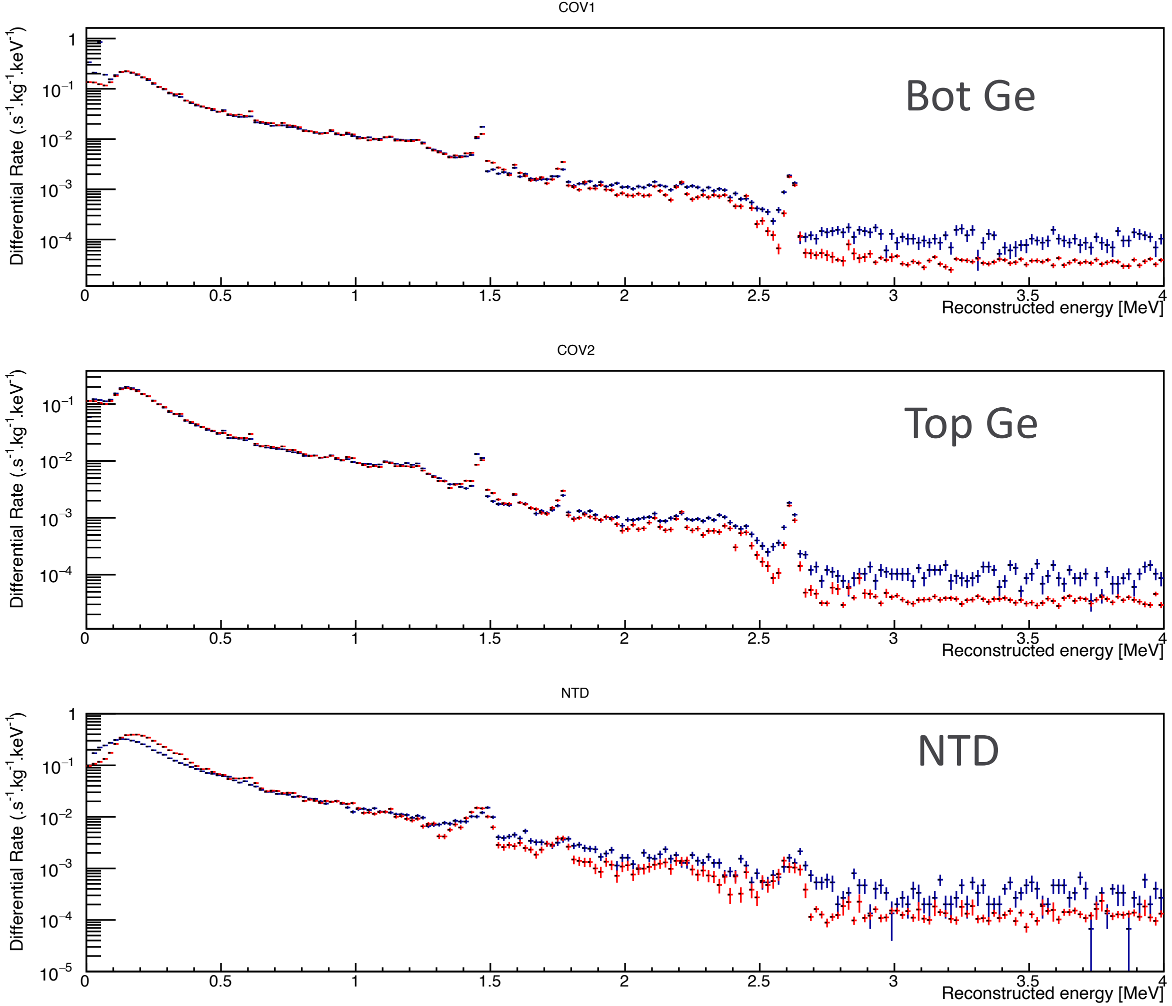
+

ϕ_n Simulation neutrons scaled with ϕ_n



ϕ_γ

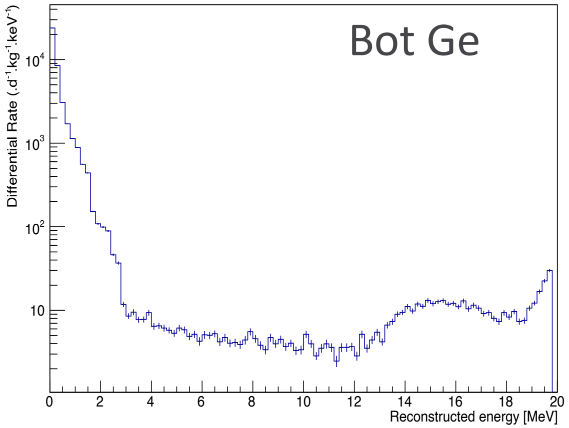
Fit Gammas – 0.1-4MeV



Multi-steps fitting procedure

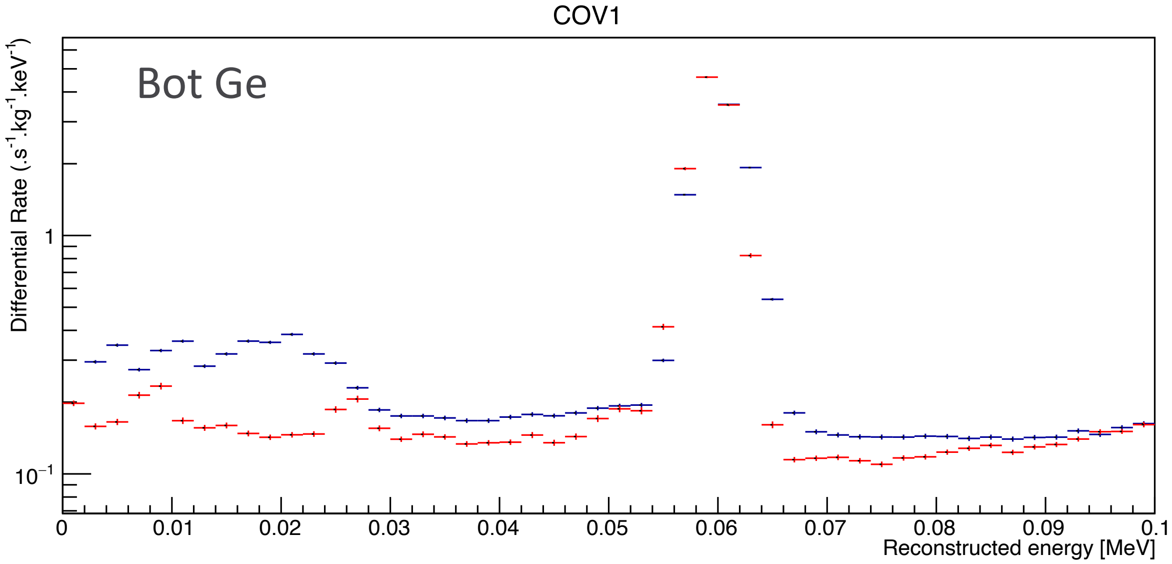
Step 4 : Am241

Calibrated and time normalized data



Fit Am241 – 0-0.1MeV

ϕ_{Am} ↑



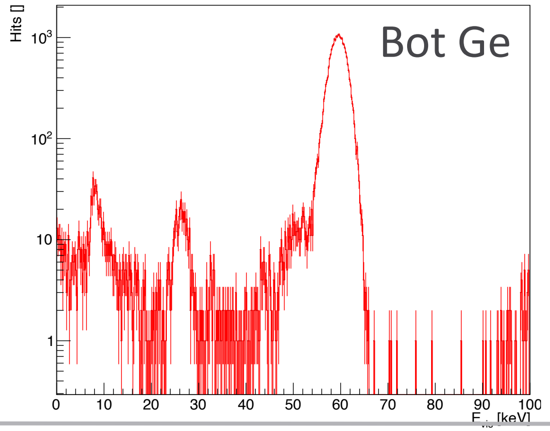
ϕ_μ → Simulation muons scaled with ϕ_μ

ϕ_n → Simulation neutrons scaled with ϕ_n

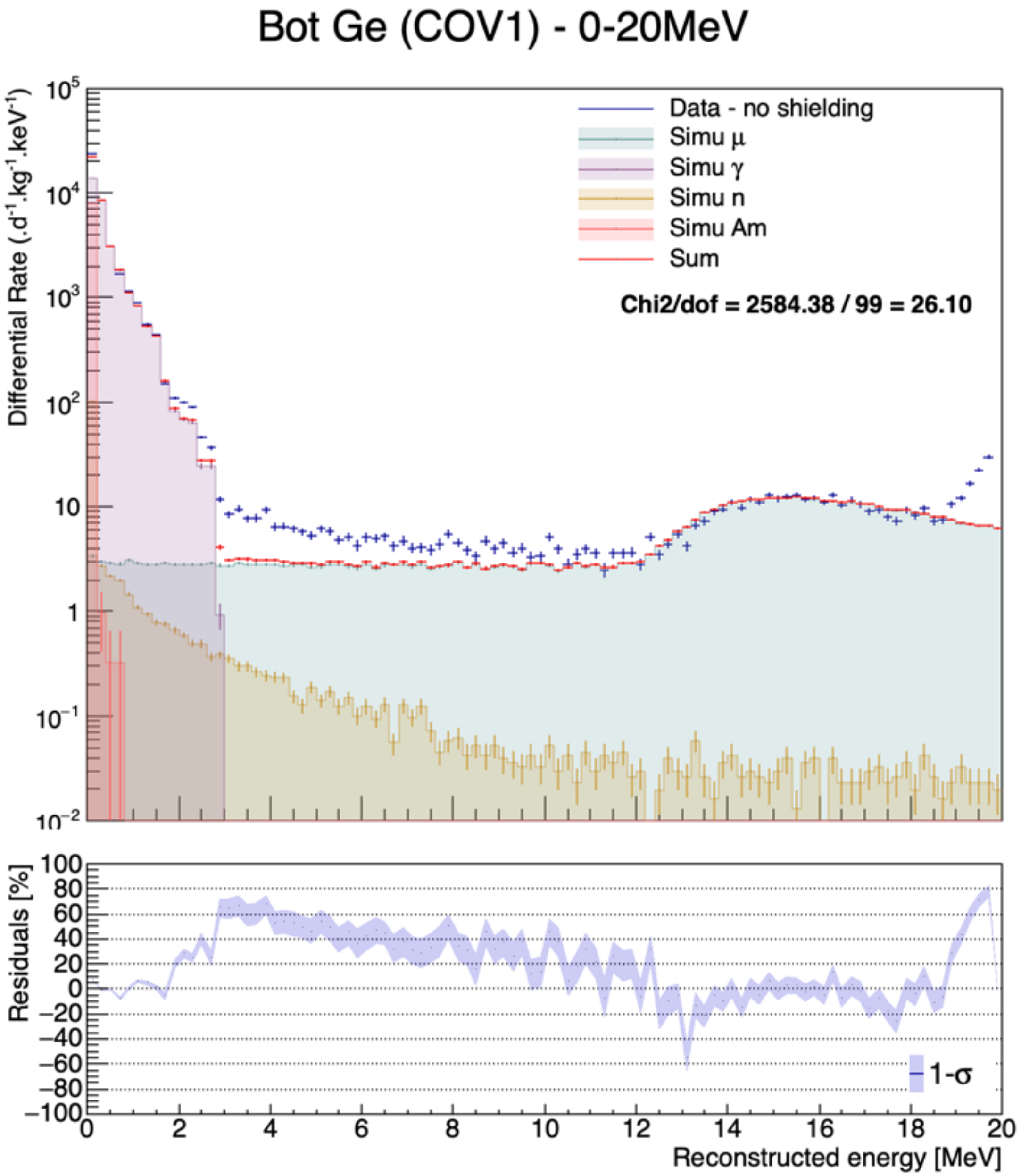
ϕ_γ → Simulation gammas scaled with ϕ_γ

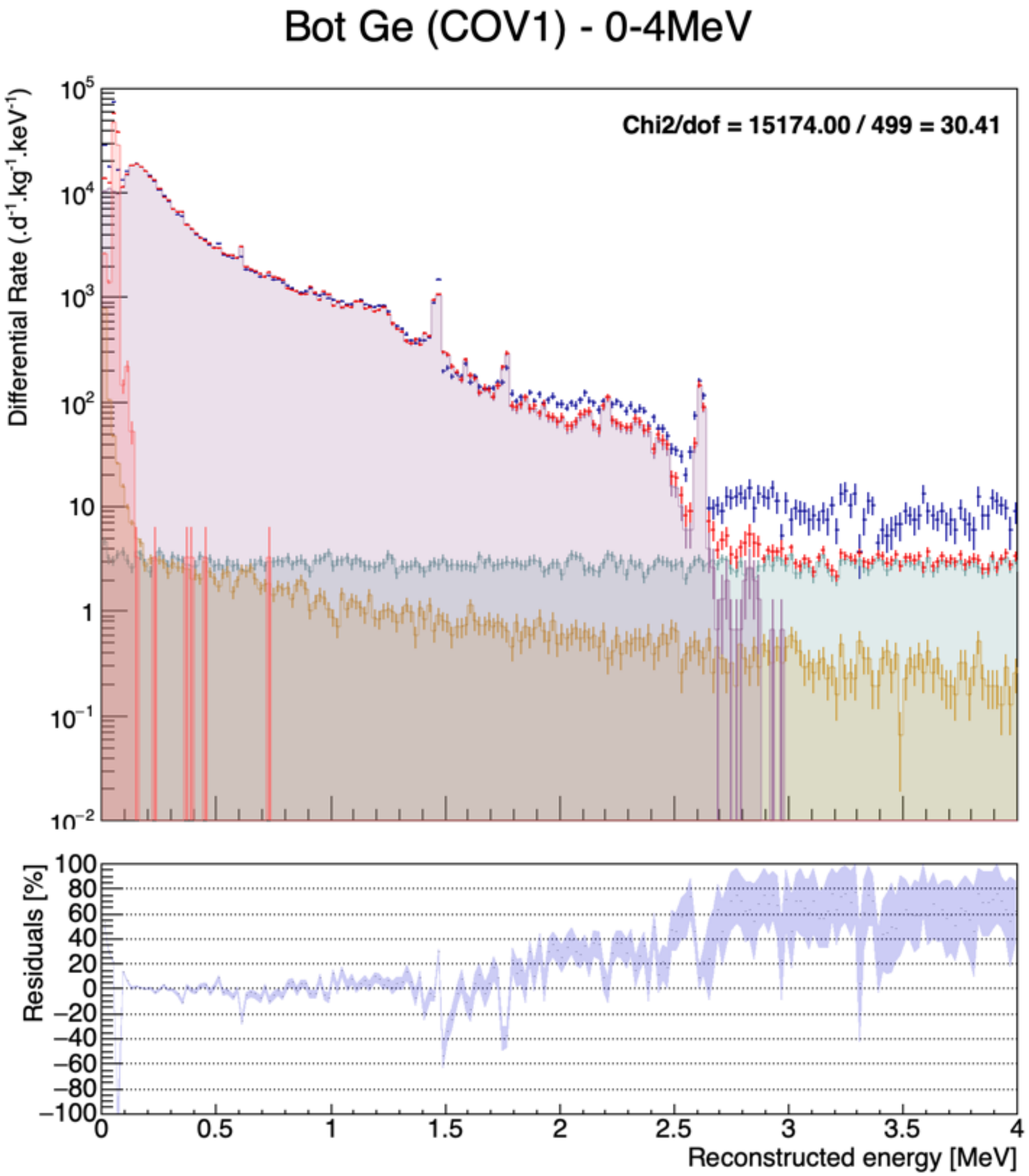
+

Simulation Am241



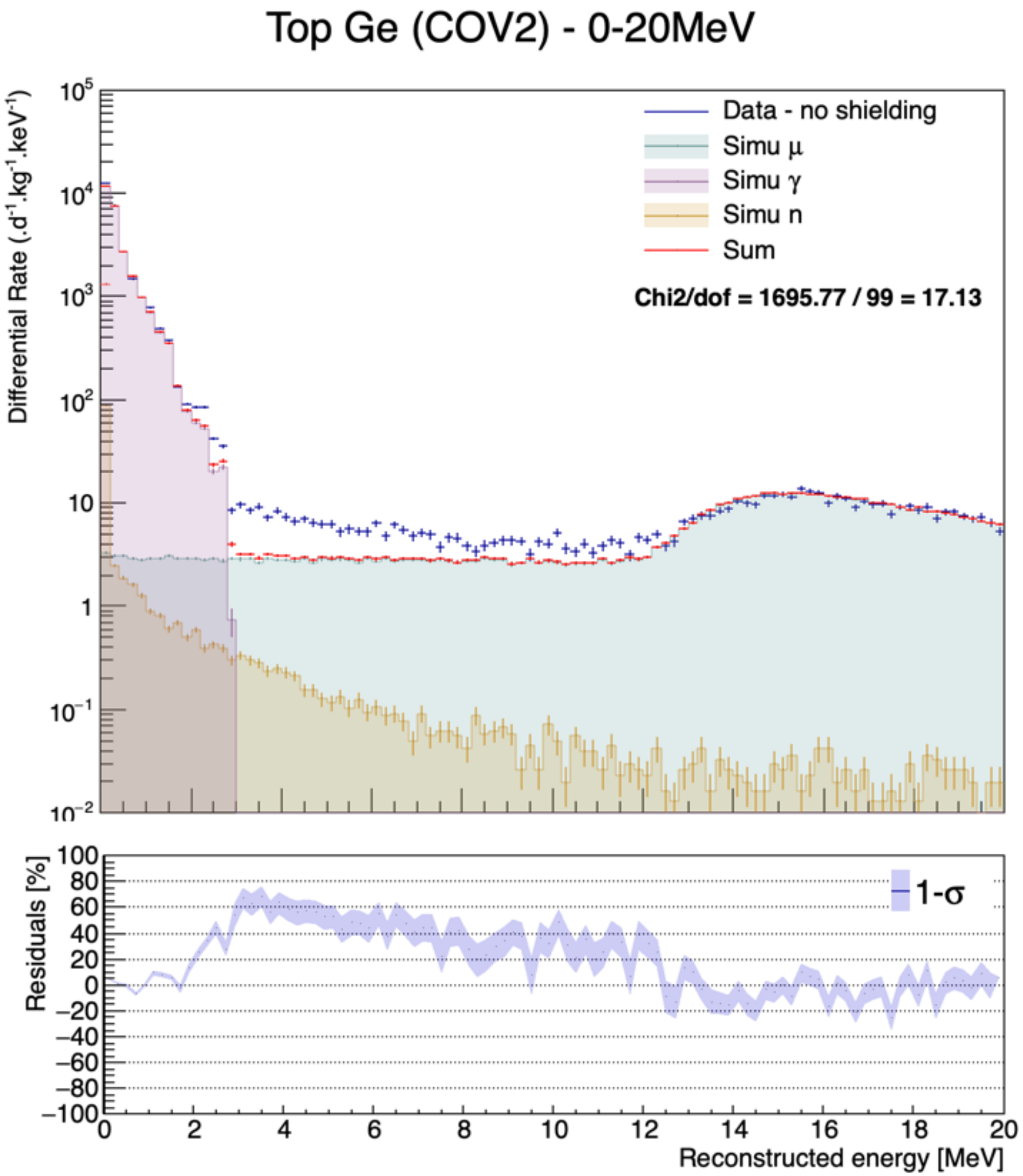
Fit results – Bot Ge

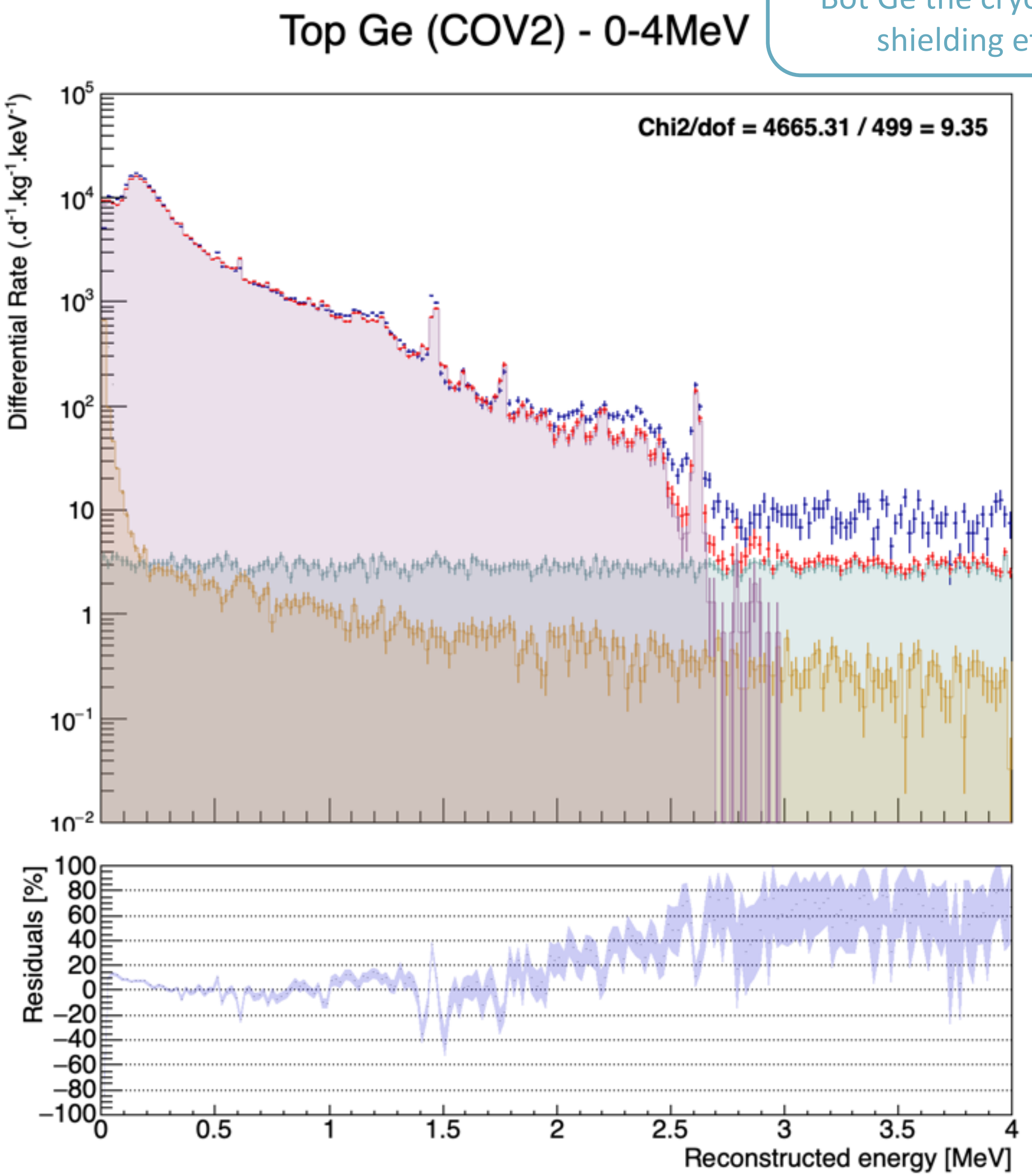




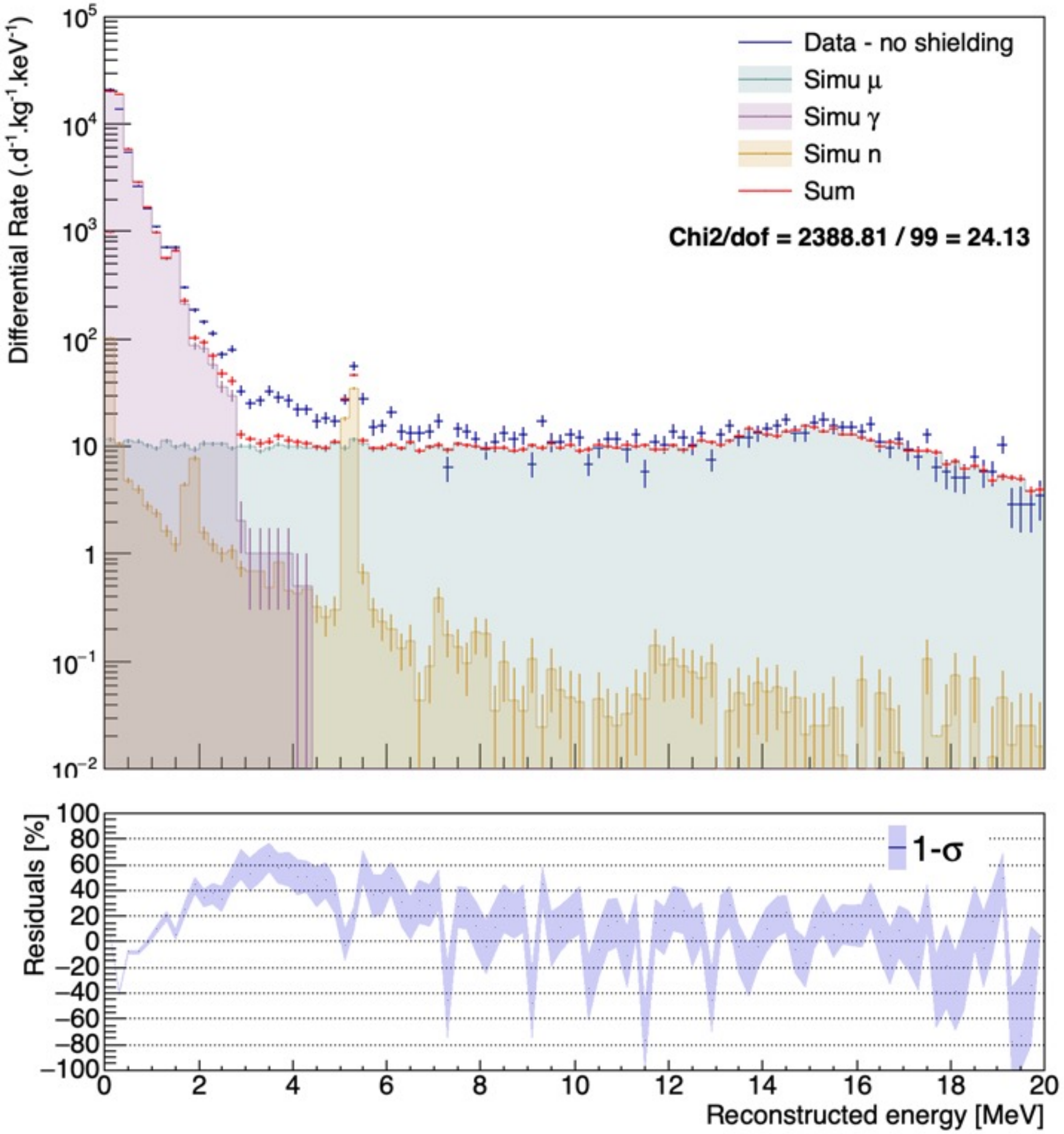
Fit results – Top Ge

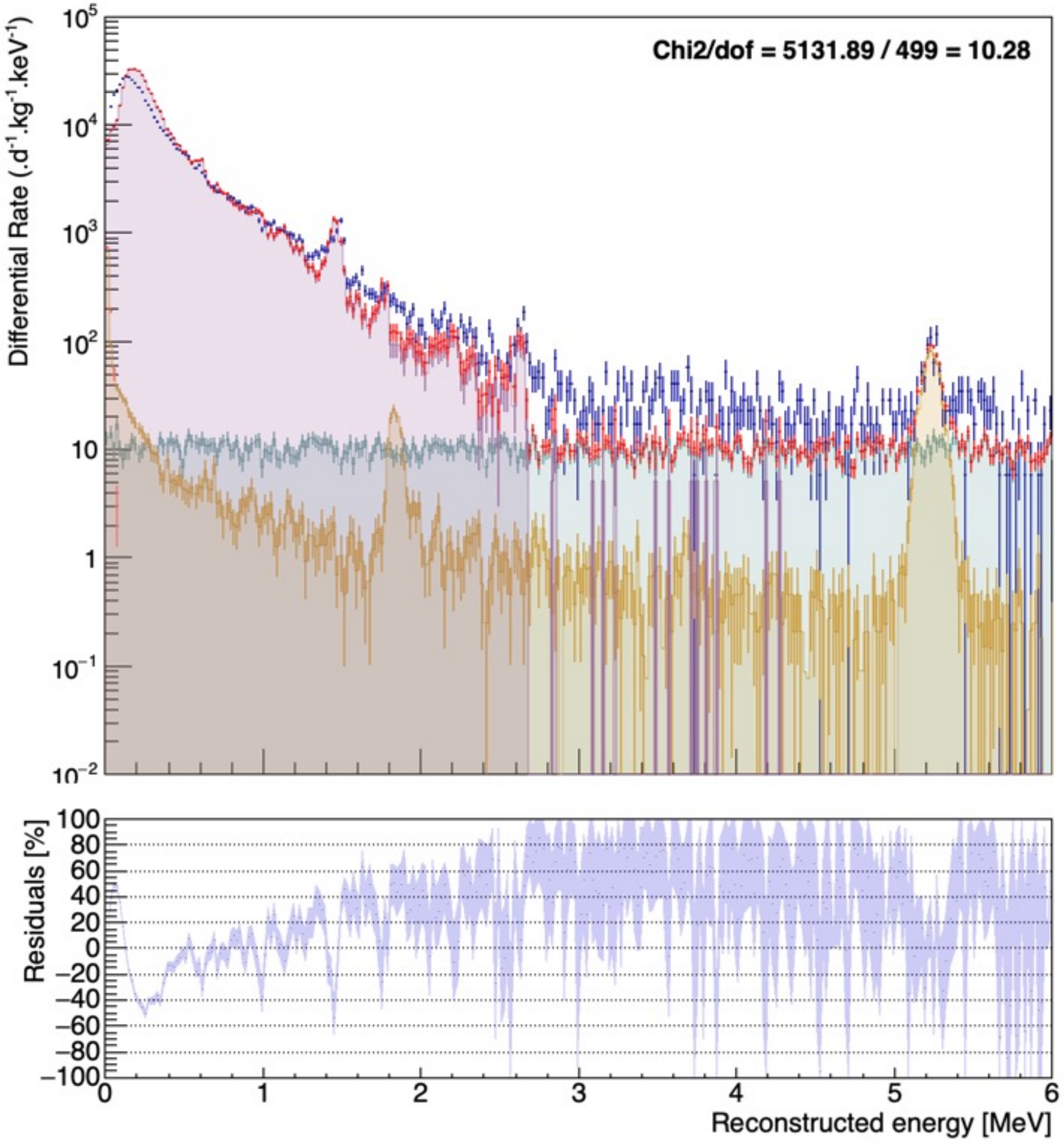
Remark:
Rate lower in Top Ge than in Bot Ge the cryostat has a shielding effect*.


Top Ge (COV2) - 0-20MeV


Top Ge (COV2) - 0-4MeV

Fit results - LWO


Mid LWO (NTD) - 0-20MeV


Mid LWO (NTD) - 0-6MeV