

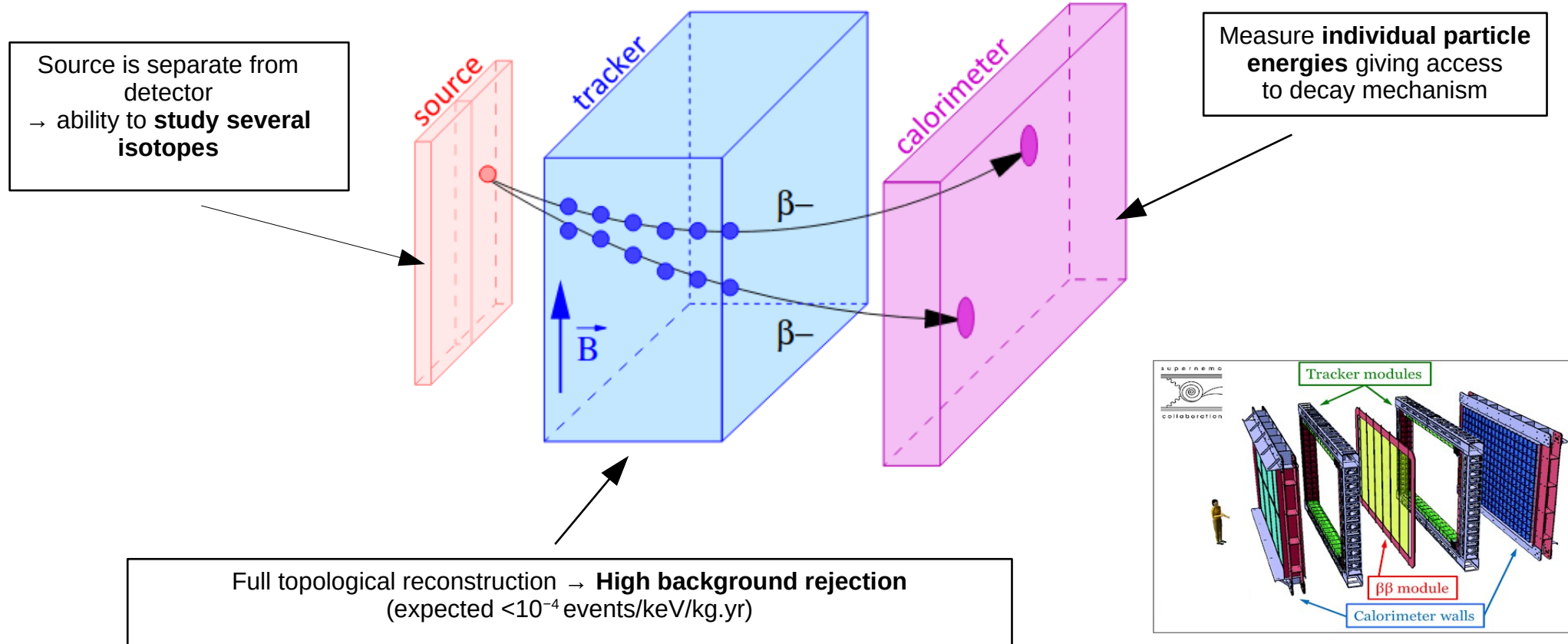
SuperNEMO

Neutrinoless Double Beta Decay Experiment

Malak HOBALLAH on behalf of the SuperNEMO Collaboration
Jun 1, 2021



SuperNEMO: Tracker-Calorimeter Detector



The SuperNEMO Demonstrator Source

6.23 kg of ^{82}Se as $\beta\beta$ source

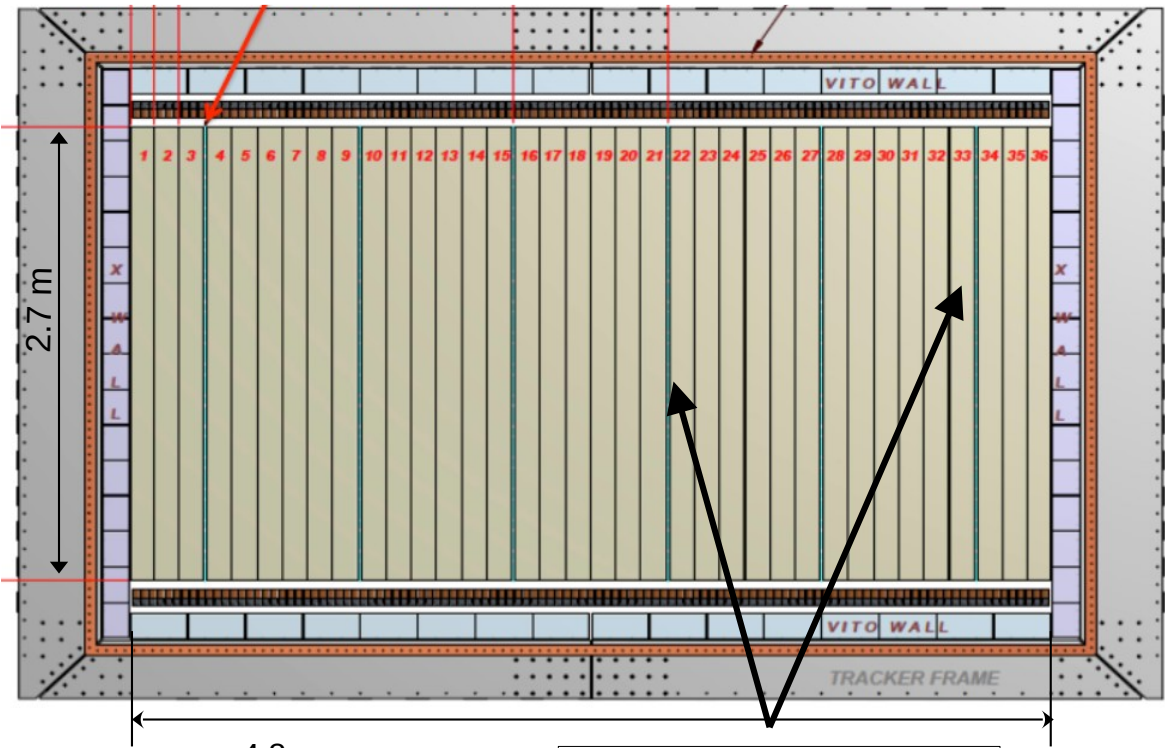
$Q_{\beta\beta} = 2.998 \text{ MeV}$
 $T_{1/2}^{2\nu} = 9.4 \times 10^{19} \text{ y}$
 (NEMO-3)

Radio-Purity of ^{82}Se foils	Specifications ($\mu\text{Bq/kg}$)	Measured values for best source using BiPo-3 detector ($\mu\text{Bq/kg}$)
^{208}Tl	< 2	$\sim 20 \pm 10$
^{214}Bi	< 10	< 290 at 90% CL

500 kg.y exposure
(100 kg, 5 years)

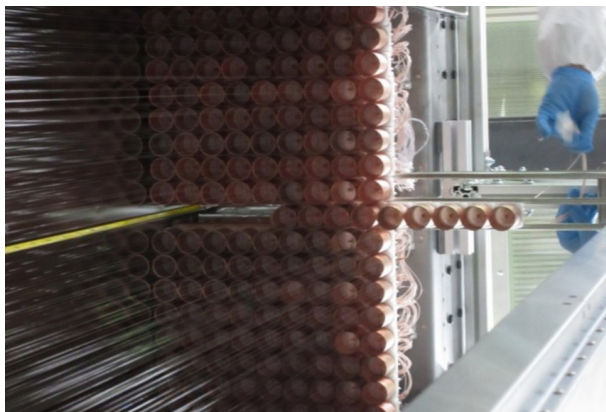
For source of demonstrator of 17.5 kg.y exposure

Selenium Source Foils Geometry



Calibration sources
 Absolute energy calibration
 ^{207}Bi

The SuperNEMO Tracker



2034 drift cells operating in Geiger mode



3D reconstruction of charged particle tracks
(μ^\pm , e^\pm , α)



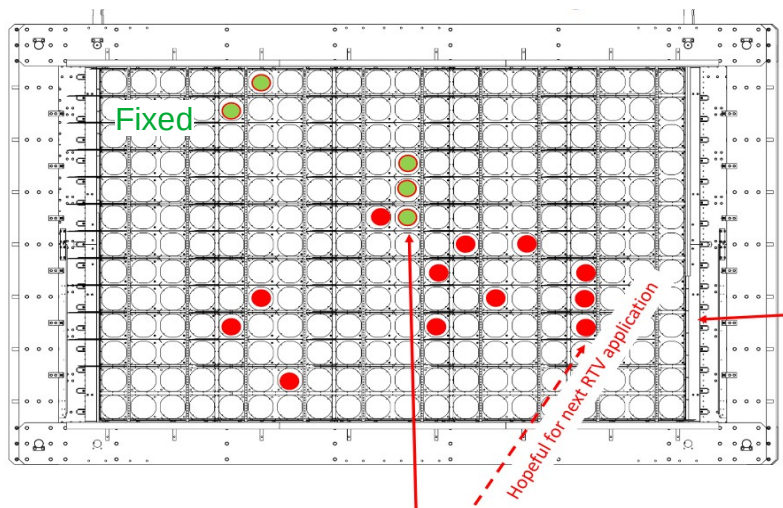
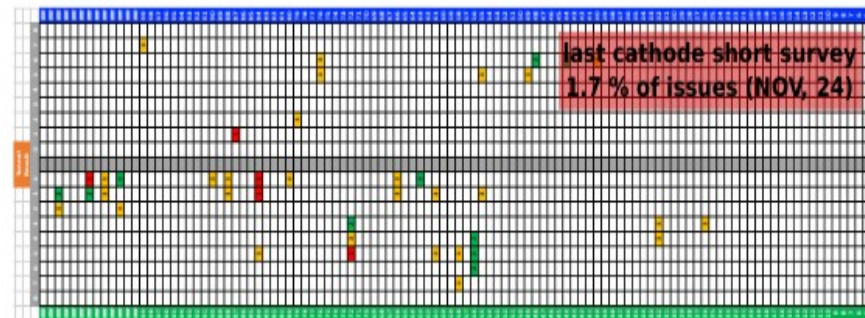
	Specifications (mBq/m ³)	Measurements extrapolated to a tracker gas flux of 2 m ³ /h (mBq/m ³)
²²² Rn emanation	0.15	0.16 ± 0.05

Tracker Deformation & Lifting: September 2020

The tracker frame was deformed → short circuit in 270 cells.

The Frame was raised ~ 4mm successfully with careful monitoring:

- Short circuit cells were reduced from approximately 20% to < 2%
- The structure is mechanically stable and is being monitored with laser gauges
- The source foils were not damaged in the process



Leaks identified in the demonstrator frame and the on site team is in a very good progress of fixing them

Tests for over pressure are planned (current measurements ~ 7 mbar with Argon → to be done with Helium)

The SuperNEMO Calorimeter



440 8" PMTs &
232 5" PMTs

712 Optical
Modules

8" PMTs




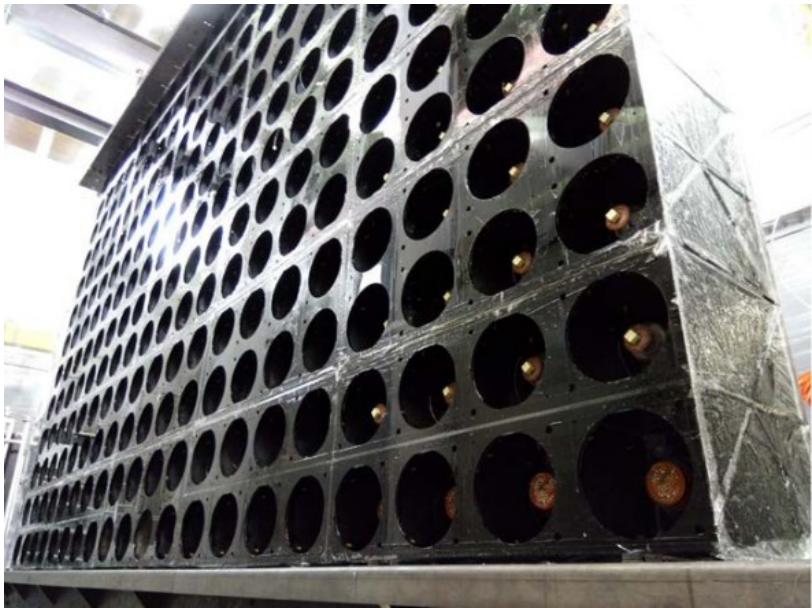
Energy resolution 8% FWHM
at 1 MeV
(14% - 17% for NEMO-3)

Time resolution < 400 ps for
electrons @ 1 MeV

Experiment	⁴⁰ K (Bq)	²²⁶ Ra (Bq)	²³² Th (Bq)
SuperNEMO Demonstrator	540	197	124
NEMO-3	832	302	49.4
Relative activity (A(SN)-A(NEMO-3))/A(NEMO-3)	-35%	-35%	+151%

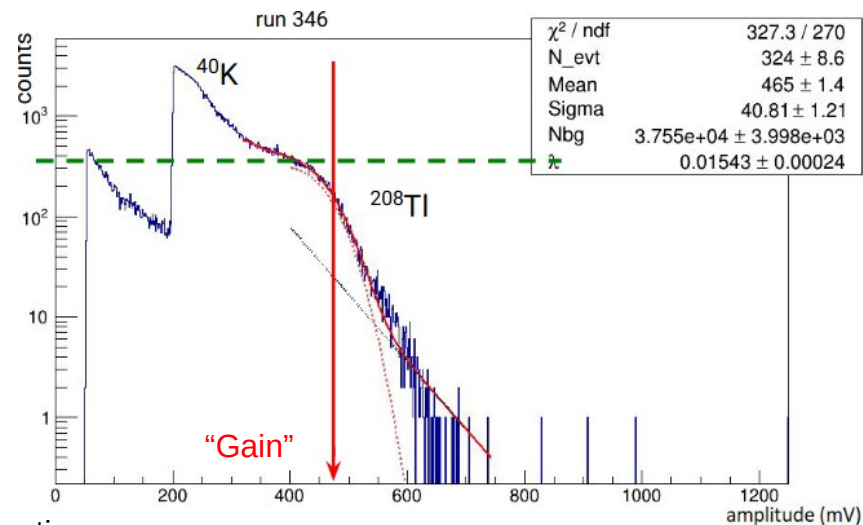
Operational and taking data since 2018!


 Not the
dominant
background for
2v and 0v
search



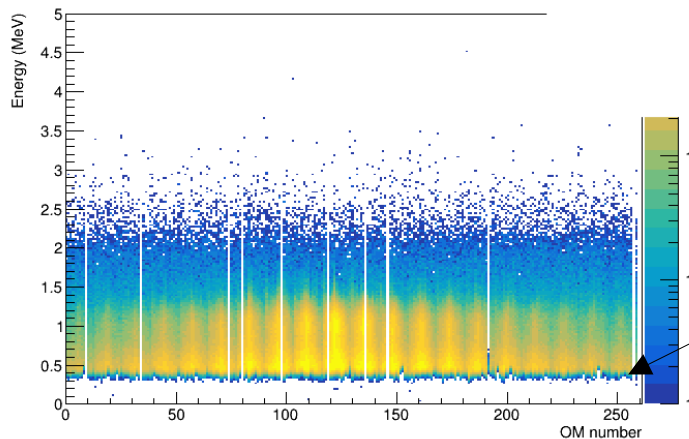
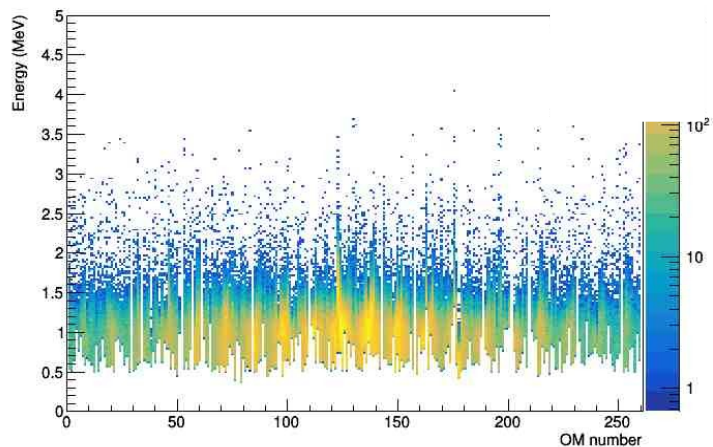
Energy Calibration of the Calorimeter

PMT Gain equalization done with a dedicated method
using ^{208}Tl Compton edge



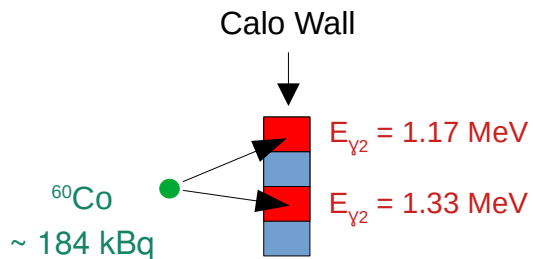
Before correction

After correction

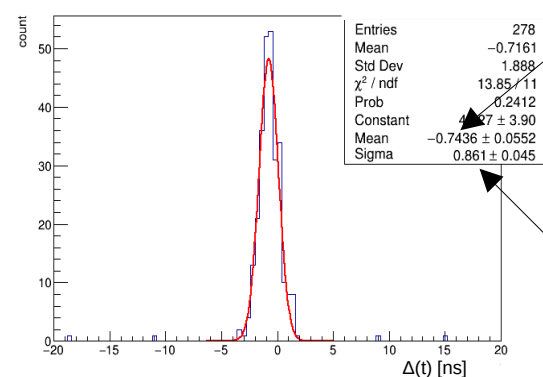


Gain equalization is very good in order to perform
energy cuts to reject
backgrounds

Time Calibration and Time Resolution of Calorimeter Walls: ^{60}Co Source Runs



$$\Delta(t) (ns) = t_{\gamma_1} - t_{\gamma_2}$$



Mean: Used to determine the time offset per OM (time calibration)

Sigma: Used to determine the time resolution per OM

Offer a good calculation of the:

- Time offset per OM, it takes into account: cable length + total delays inside (electronics, scintillation time, ...)
- Time resolution of Calorimeter for γ s @ 1 MeV

Time Calibration: Final Offset Values per OM for a Calorimeter Wall

Combining all Runs

ITALY TUNNEL		Q0.1.15	Q0.1.14	Q0.1.13	Q0.1.12	Q0.1.11	Q0.1.10	Q0.1.9	Q0.1.8	Q0.1.7	Q0.1.6	Q0.1.5	Q0.1.4	Q0.1.3	Q0.1.2	Q0.1.1	Q0.1.0	MOUNTAIN	
row	column	X0.1.15	X0.1.14	X0.1.13	X0.1.12	X0.1.11	X0.1.10	X0.1.9	X0.1.8	X0.1.7	X0.1.6	X0.1.5	X0.1.4	X0.1.3	X0.1.2	X0.1.1	X0.1.0	X0.0.1.15	X0.0.1.14
X0.1.15	X0.1.15	M0.18.18	M0.18.17	M0.17.17	M0.16.17	M0.15.17	M0.14.17	M0.13.17	M0.12.17	M0.11.17	M0.10.17	M0.9.17	M0.8.17	M0.7.17	M0.6.17	M0.5.17	M0.4.17	M0.3.17	M0.2.17
X0.1.14	X0.1.14	28.38	21.77	22.44	23.21	19.07	16.70	17.53	14.33	14.33	11.22	12.81	11.66	11.75	10.10	7.97	6.05	9.29	4.27
X0.1.13	X0.1.13	M0.18.11	M0.18.11	M0.17.11	M0.16.11	M0.15.11	M0.14.11	M0.13.11	M0.12.11	M0.11.11	M0.10.11	M0.9.11	M0.8.11	M0.7.11	M0.6.11	M0.5.11	M0.4.11	M0.3.11	M0.2.11
X0.1.12	X0.1.12	17.60	16.71	13.80	11.53	15.26	13.35	12.27	12.08	8.85	9.65	6.41	4.10	3.89	4.79	1.32	-2.80	0.21	-1.18
X0.1.11	X0.1.11	M0.18.10	M0.18.10	M0.17.10	M0.16.10	M0.15.10	M0.14.10	M0.13.10	M0.12.10	M0.11.10	M0.10.10	M0.9.10	M0.8.10	M0.7.10	M0.6.10	M0.5.10	M0.4.10	M0.3.10	M0.2.10
X0.1.10	X0.1.10	18.90	19.14	18.41	15.64	14.16		13.00	13.01	13.76	11.11	9.80	7.03	8.88	5.66	4.38	0.56	2.86	-1.08
X0.1.9	X0.1.9	M0.18.9	M0.18.9	M0.17.9	M0.16.9	M0.15.9	M0.14.9	M0.13.9	M0.12.9	M0.11.9	M0.10.9	M0.9.9	M0.8.9	M0.7.9	M0.6.9	M0.5.9	M0.4.9	M0.3.9	M0.2.9
X0.1.8	X0.1.8	17.27	16.76	15.76	14.77	10.83	11.75	10.16	10.82	8.14	8.40	6.71	6.32	4.15	2.33	-1.14	-2.30	-4.21	-3.48
X0.1.7	X0.1.7	M0.18.8	M0.18.8	M0.17.8	M0.16.8	M0.15.8	M0.14.8	M0.13.8	M0.12.8	M0.11.8	M0.10.8	M0.9.8	M0.8.8	M0.7.8	M0.6.8	M0.5.8	M0.4.8	M0.3.8	M0.2.8
X0.1.6	X0.1.6	18.70	15.22	17.00	13.42	8.05	13.62	9.31	9.27	6.68	6.46	4.25	3.09	2.02	-0.12	1.24	5.03	-2.78	-5.14
X0.1.5	X0.1.5	M0.18.7	M0.18.7	M0.17.7	M0.16.7	M0.15.7	M0.14.7	M0.13.7	M0.12.7	M0.11.7	M0.10.7	M0.9.7	M0.8.7	M0.7.7	M0.6.7	M0.5.7	M0.4.7	M0.3.7	M0.2.7
X0.1.4	X0.1.4	14.56	13.02	12.28	12.10	11.81	9.31	8.00	5.97	4.92	3.89	1.72	0.49		-2.62	-1.64	-4.33	-7.69	-4.35
X0.1.3	X0.1.3	M0.18.6	M0.18.6	M0.17.6	M0.16.6	M0.15.6	M0.14.6	M0.13.6	M0.12.6	M0.11.6	M0.10.6	M0.9.6	M0.8.6	M0.7.6	M0.6.6	M0.5.6	M0.4.6	M0.3.6	M0.2.6
X0.1.2	X0.1.2	17.21	12.27	12.89	12.30	8.58	10.14	9.56	8.12	5.48		0.98	1.86	-0.30	-0.68	-3.68	-4.75	-2.31	-2.73
X0.1.1	X0.1.1	M0.18.5	M0.18.5	M0.17.5	M0.16.5	M0.15.5	M0.14.5	M0.13.5	M0.12.5	M0.11.5	M0.10.5	M0.9.5	M0.8.5	M0.7.5	M0.6.5	M0.5.5	M0.4.5	M0.3.5	M0.2.5
X0.0.1.15	X0.0.1.15	11.67	9.77	7.88	6.46	6.21	5.54	5.96	3.12	4.56	4.32		-0.95	-2.29	-1.25	-3.41	-2.53	-9.38	-7.02
X0.0.1.14	X0.0.1.14	M0.18.4	M0.18.4	M0.17.4	M0.16.4	M0.15.4	M0.14.4	M0.13.4	M0.12.4	M0.11.4	M0.10.4	M0.9.4	M0.8.4	M0.7.4	M0.6.4	M0.5.4	M0.4.4	M0.3.4	M0.2.4
X0.0.1.13	X0.0.1.13	11.84	9.91	8.00	8.60	7.15	6.21	5.49	5.99	3.13	3.76	-2.16	0.24	2.21	-2.14	-3.88	-2.36	-7.13	-8.86
X0.0.1.12	X0.0.1.12	M0.18.3	M0.18.3	M0.17.3	M0.16.3	M0.15.3	M0.14.3	M0.13.3	M0.12.3	M0.11.3	M0.10.3	M0.9.3	M0.8.3	M0.7.3	M0.6.3	M0.5.3	M0.4.3	M0.3.3	M0.2.3
X0.0.1.11	X0.0.1.11	11.91	7.50	6.39	5.22	3.26	3.99	3.91	1.77		-2.35	-3.67	-3.19	-2.83	-5.96	-8.43	-6.22	-8.12	-13.09
X0.0.1.10	X0.0.1.10	M0.18.2	M0.18.2	M0.17.2	M0.16.2	M0.15.2	M0.14.2	M0.13.2	M0.12.2	M0.11.2	M0.10.2	M0.9.2	M0.8.2	M0.7.2	M0.6.2	M0.5.2	M0.4.2	M0.3.2	M0.2.2
X0.0.1.9	X0.0.1.9	9.58	6.11	7.85	4.48	6.23	4.06	1.16	4.26	2.09	-0.26		-2.08	-3.58	-6.83	-6.43	-6.88	-9.85	-8.94
X0.0.1.8	X0.0.1.8	M0.18.1	M0.18.1	M0.17.1	M0.16.1	M0.15.1	M0.14.1	M0.13.1	M0.12.1	M0.11.1	M0.10.1	M0.9.1	M0.8.1	M0.7.1	M0.6.1	M0.5.1	M0.4.1	M0.3.1	M0.2.1
X0.0.1.7	X0.0.1.7	3.66	6.47	3.65	3.08	3.76	0.98	1.71	-0.57	-0.74	-0.88	-3.39	-4.15	-3.62	-7.83	-6.27	-8.43	-9.98	-12.74
X0.0.1.6	X0.0.1.6	M0.18.0	M0.18.0	M0.17.0	M0.16.0	M0.15.0	M0.14.0	M0.13.0	M0.12.0	M0.11.0	M0.10.0	M0.9.0	M0.8.0	M0.7.0	M0.6.0	M0.5.0	M0.4.0	M0.3.0	M0.2.0
X0.0.1.5	X0.0.1.5	9.44	8.20	7.36	10.81	6.02	4.24	3.16	3.64	2.10	-0.46	0.08		-3.28	9.52	-4.03	-0.92	-7.21	-7.05
X0.0.1.4	X0.0.1.4																		
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X0.0.0.0.0.1.9	X0.0.0.0.0.1.9																		
X0.0.0.0.0.1.8	X0.0.0.0.0.1.8																		
X0.0.0.0.0.1.7	X0.0.0.0.0.1.7																		
X0.0.0.0.0.1.6	X0.0.0.0.0.1.6																		
X0.0.0.0.0.1.5	X0.0.0.0.0.1.5																		
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X0.0.0.0.0.1.0	X0.0.0.0.0.1.0																		
X0.0.0.0.0.0.1.15	X0.0.0.0.0.0.1.15																		
X0.0.0.0.0.0.1.14	X0.0.0.0.0.0.1.14																		
X0.0.0.0.0.0.1.13	X0.0.0.0.0.0.1.13																		
X0.0.0.0.0.0.1.12	X0.0.0.0.0.0.1.12																		
X0.0.0.0.0.0.1.11	X0.0.0.0.0.0.1.11																		
X0.0.0.0.0.0.1.10	X0.0.0.0.0.0.1.10																		
X0.0.0.0.0.0.1.9	X0.0.0.0.0.0.1.9																		
X0.0.0.0.0.0.1.8	X0.0.0.0.0.0.1.8																		

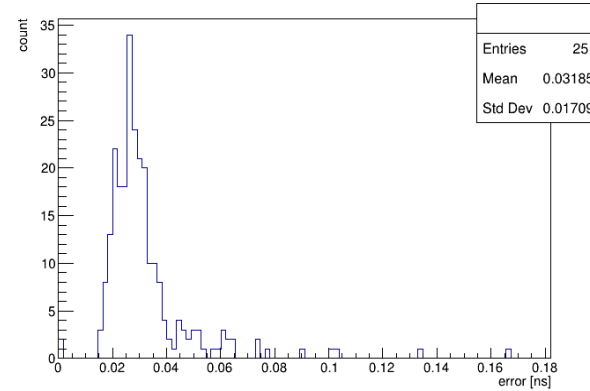
NOTATIONS:
wall:module.side.col:row
wall:module.col:row

Color scale:
Final offset
values / OM
[ns]

Dead OMs

Reference OM

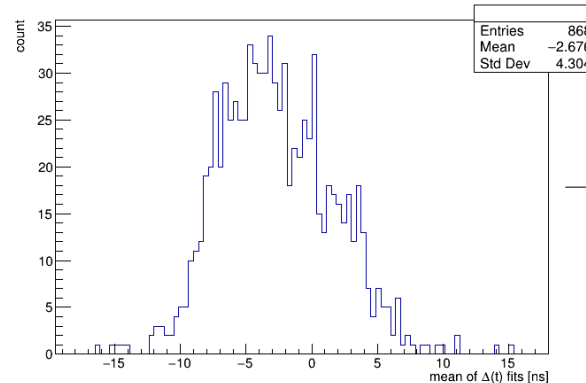
Error on final offset values



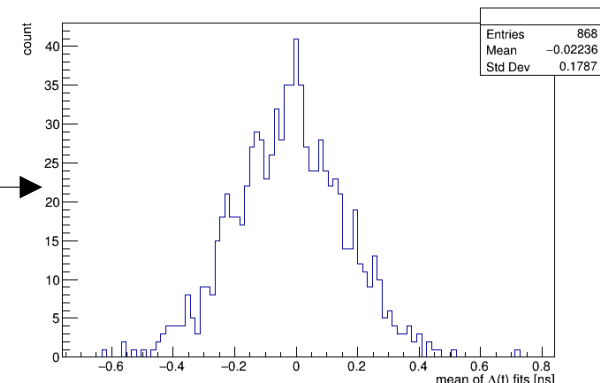
These maps are produced for
the full calorimeter walls

The time calibration performed achieved **1 [ns]**
precision on timing after applying the
calibration. Perfect for rejecting background
using time of flight measurements.

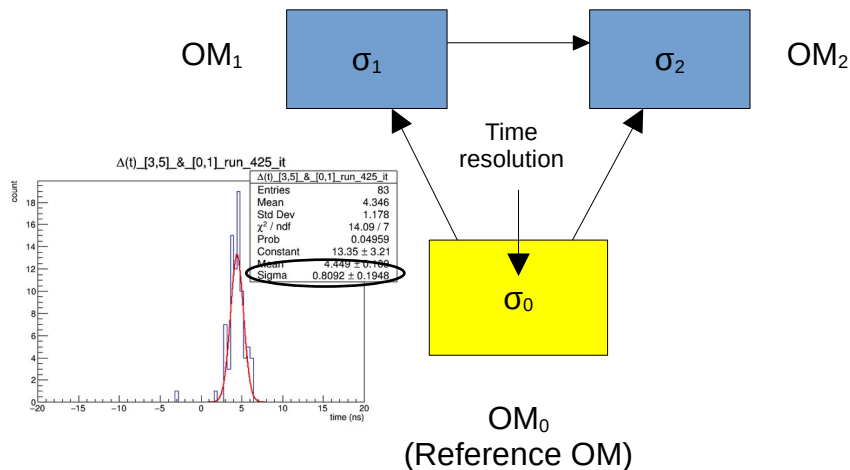
$\Delta(t)$ distribution before correction



$\Delta(t)$ distribution after correction



Time Resolution: Method to Determine the Time Resolution Per OM



Using parameters from the 3 coincidences we can retrieve the time resolutions σ_0 , σ_1 and σ_2

For a given OM, several independent measurements of time resolutions (σ_0) for γ s @ 1 MeV are combined.

Use weighted average to get
final resolution/OM

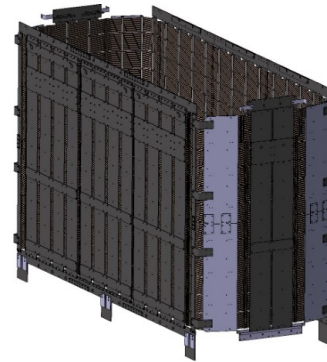
& full wall resolution

Time resolution for γ s @ 1MeV (for 8" OMs) : 0.614 ± 0.002 (stat) + 0.064 (sys) – 0.000 (sys) [ns]
 Time resolution for γ s @ 1MeV (for 5" OMs) : 0.814 ± 0.006 (stat) + 0.073 (sys) – 0.000 (sys) [ns]

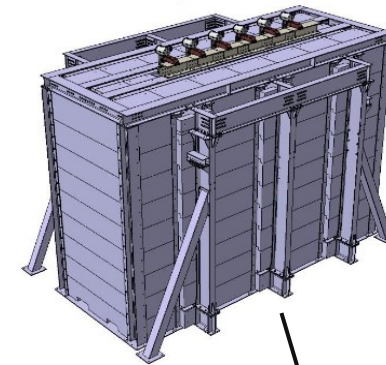
SuperNEMO: Hardware Status

Remaining Tasks:

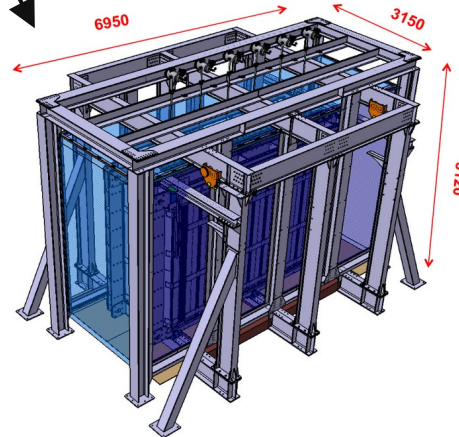
- Tracker Commissioning
- Magnetic field
- Shielding



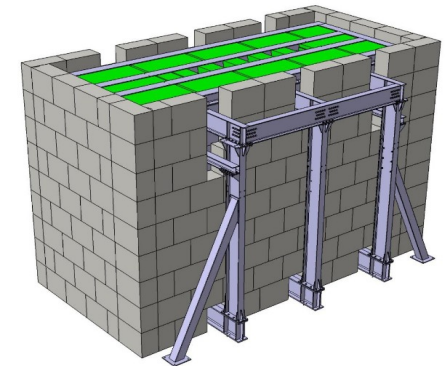
Magnetic field coils
25G



Iron shielding
20 cm



Anti-Radon tent



polyethylene water tanks
and boron polyethylene
plates

SuperNEMO: The Physics

Demonstrator :

- Expected sensitivity: 17.5 kg.y exposure of ^{82}Se



$$T_{1/2}^{0\nu} > 4 * 10^{24} \text{ y}$$

$$\langle m_{\nu} \rangle < (260 - 500) \text{ meV (90\% CL)}$$

- Measure background contamination

More physics :

$0\nu\beta\beta$ Search :

- Different double beta decay mechanisms (Light Majorana neutrino, right handed currents, ...) using the full kinematics (single electron energy and angular distribution)

$2\nu\beta\beta$ Study:

- Quenching of axial-vector coupling constant (g_A)
- Higher State Dominance (HSD) and Single State Dominance (SSD)
- Exotic Decays (Majoron ($n = 2, 3, 7$), Lorentz violation and Bosonic neutrino)

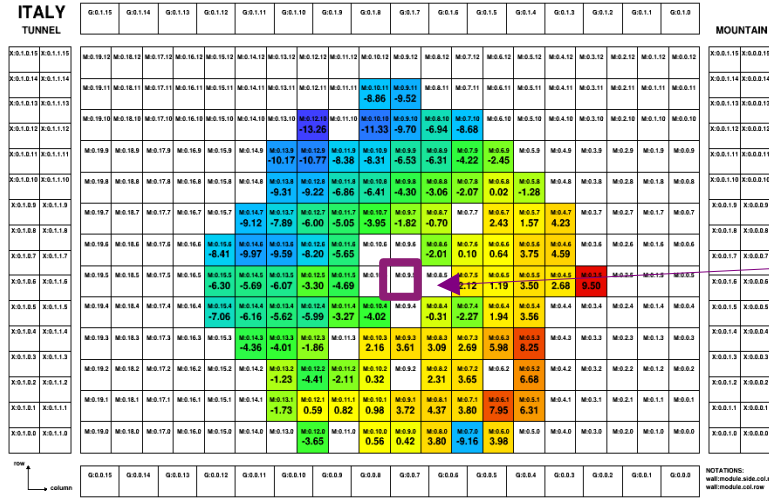
- The calorimeter is commissioned, working and taking data since 2018.
- A time and energy calibration of the calorimeter walls is done.
- Preliminary time resolution is extracted for γ s @ 1 MeV.
- The tracker has been lifted and the shorts in the tracker cells have been reduced to $< 2\%$.
- The tracker chamber tightness is in a very good progress, over pressure achieved.
- Final checks are being made for the very soon commissioning of the tracker.

END

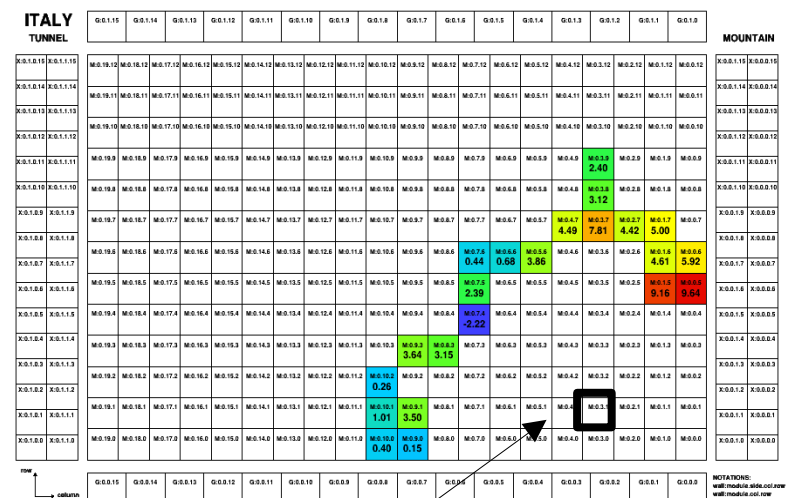
Backup

Time Calibration: Steps to Calculate the Time Offset per OM One Run Example

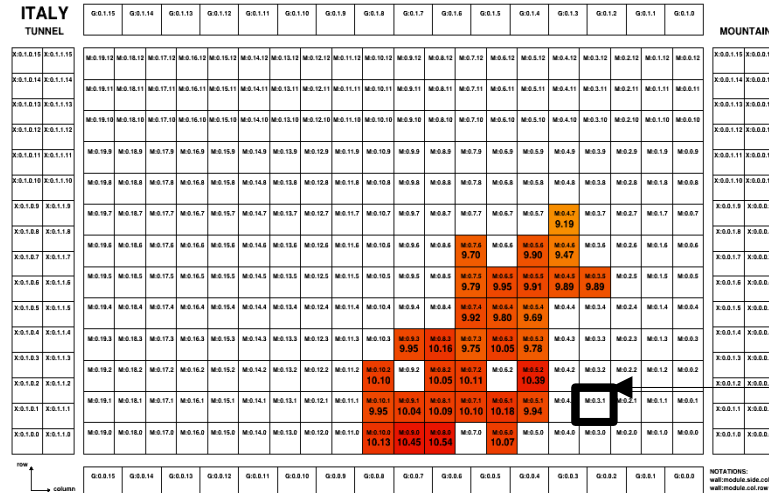
Step 1



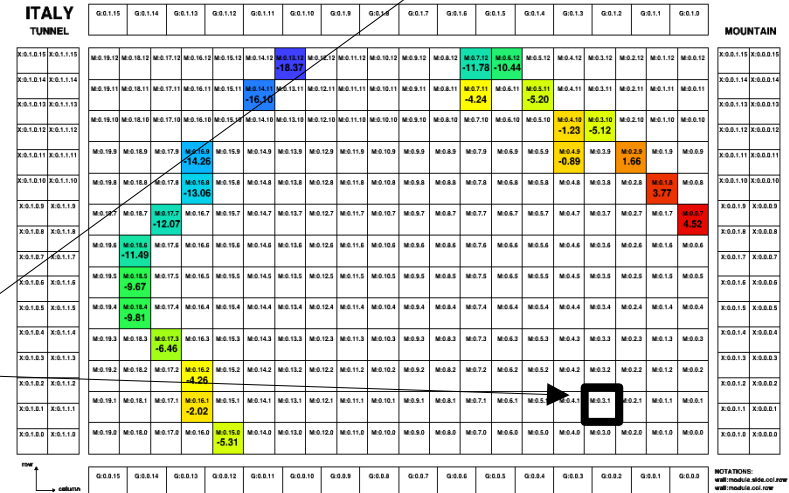
Step 3



Step 2

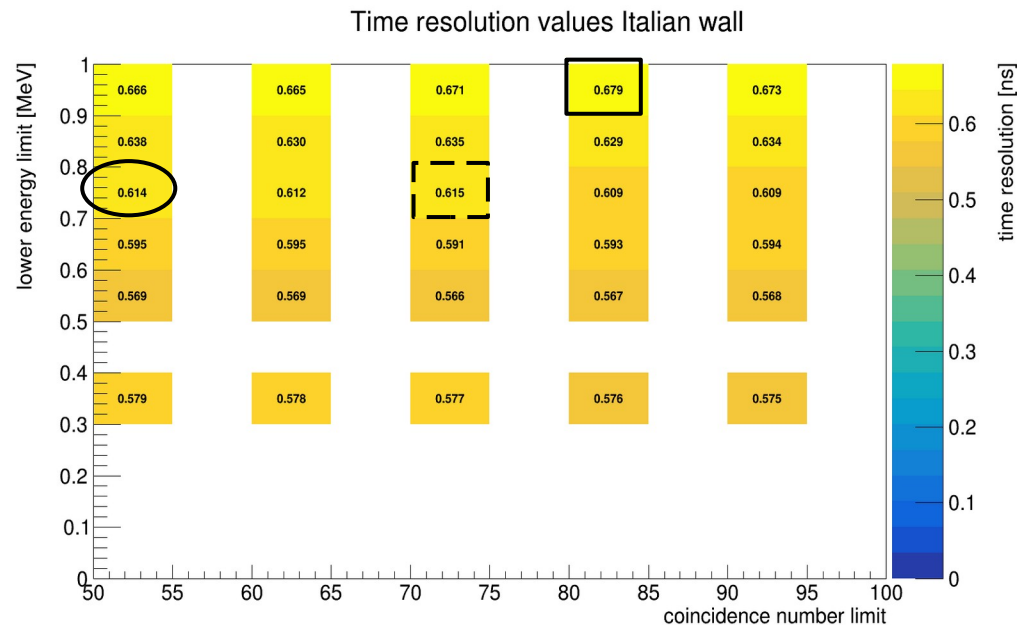


Step 4
Extra
extrapolation



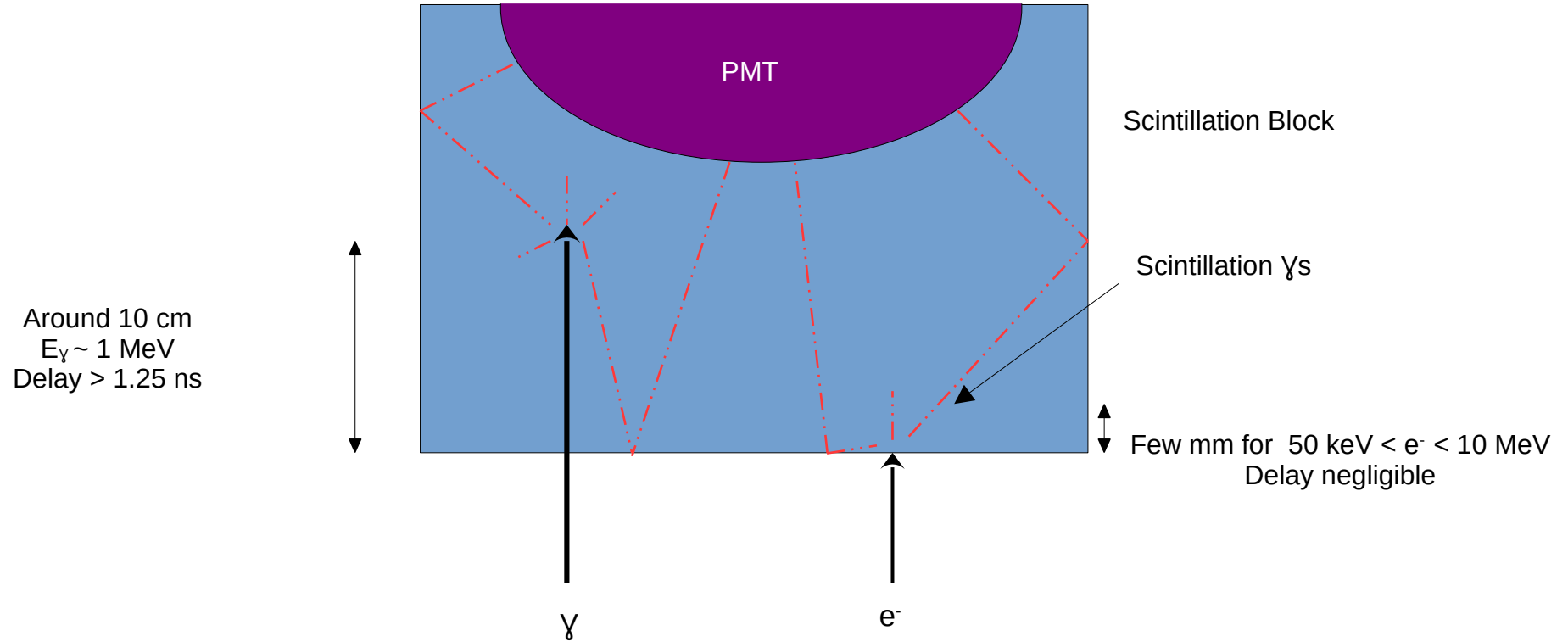
Time Resolution & Systematic Errors, Italian Wall 8" OMs

- Reference value at 0.7 MeV and > 50 coincidences
- Maximum difference from reference value
- Minimal difference from reference value

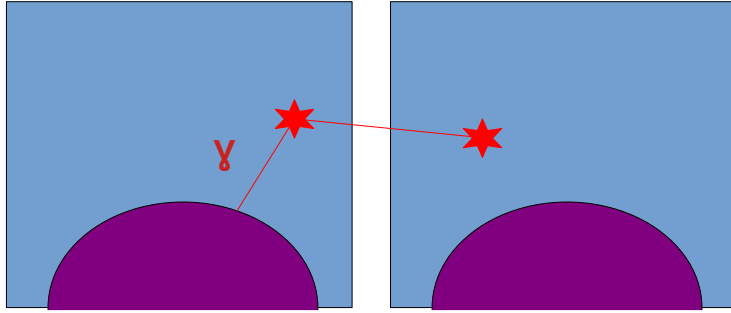


Time resolution 8" = 0.614 ± 0.002 (stat) + 0.064 (sys) – 0.000 (sys) ns

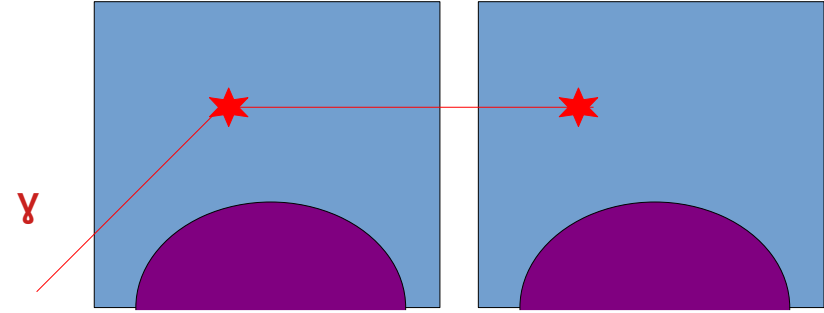
Interaction of γ s and e^- s Inside the Scintillation Block



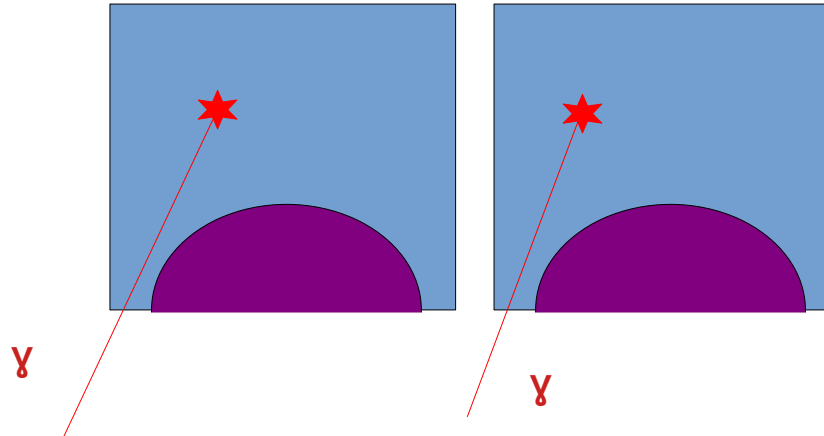
Cobalt Source Background



PMT glass contamination



Gamma from source or lab undergoing double Compton



Random coincidences

Axial-Vector Coupling Constant (g_A) Studies

Following the paper *F.Šimkovic et al. Phys. Rev. C 97, 034315 (2018)* the $2\nu\beta\beta$ decay rate may be expressed as:

(ignoring higher order terms)

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \simeq (g_A^{\text{eff}})^4 |M_{GT-3}^{2\nu}|^2 \frac{1}{|\xi_{31}^{2\nu}|^2} (G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu})$$

where

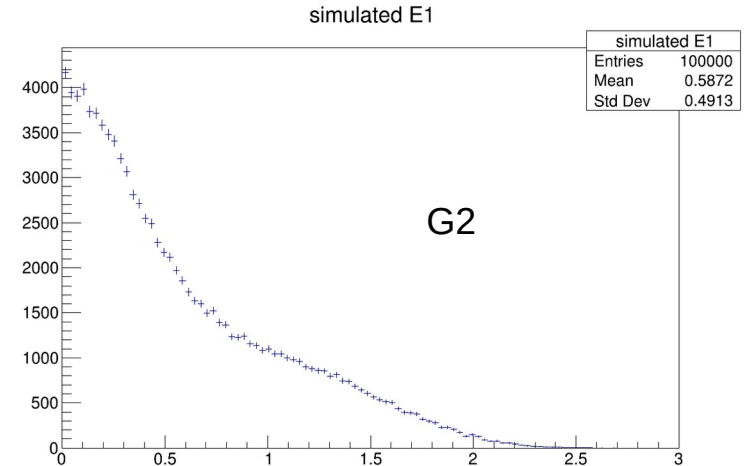
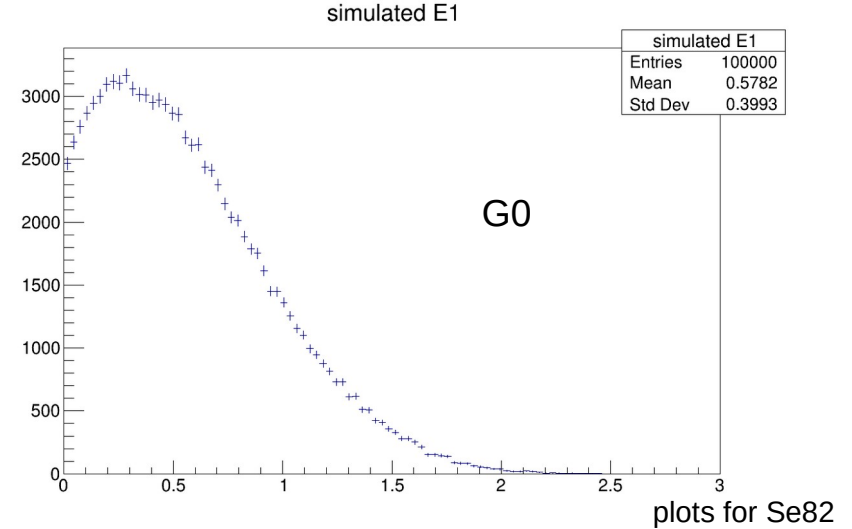
$$\xi_{31}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}},$$

The “ g_A ” processes

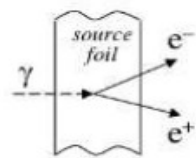
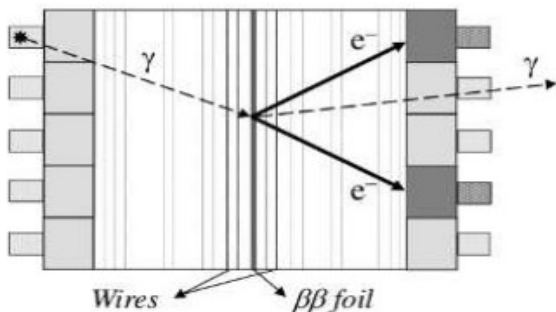
Fit single and total energy spectra to get a value for ξ_{31}

Gamow–Teller matrix element from Shell Model calculation

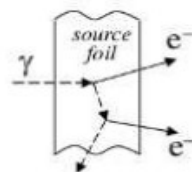
Finally obtain g_A value for $2\nu\beta\beta$



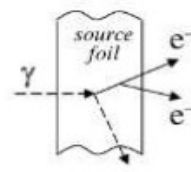
SuperNEMO: Background Identification



Pair creation



Double Compton

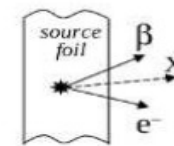
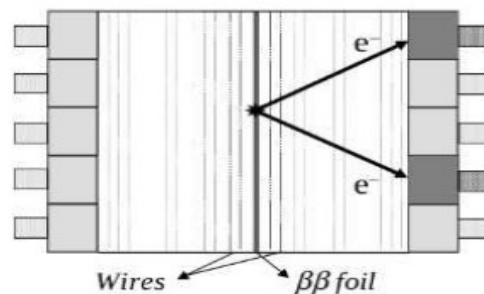


Compton + Möller

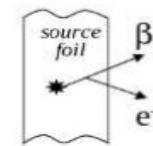
2 e^- produced by an external γ ,

Detected through (γ, e) external channel

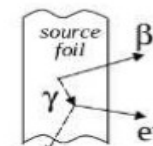
2 e^- produced by ^{214}Bi and ^{208}Tl
contamination inside the $\beta\beta$ foils



β -decay +
internal conversion

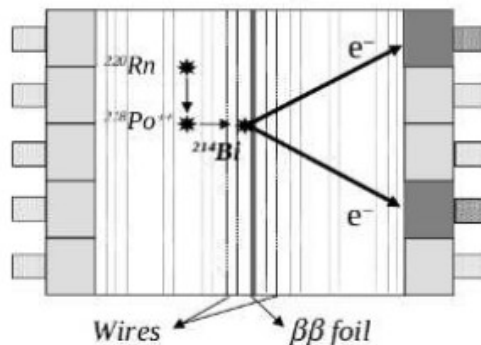


β -decay +
Möller



β -decay +
Compton

Detection Channels:
(1e, 2 γ) for ^{208}Tl
(1e, 1 α) for ^{214}Bi
(γ, e) for external backgrounds



Radon background, ^{222}Rn can emanate from the
detector materials, or the rocks of the laboratory then
diffuse towards the tracker.

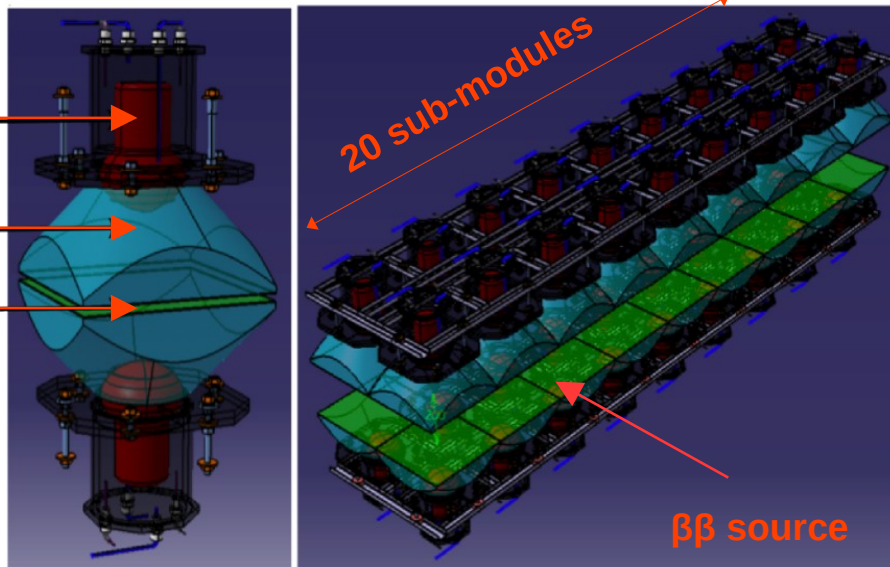
Also, the entrance gas of the tracker can be
contaminated

BiPo-3 Detector: Successfully running since 2012

5" photomultiplier

Light guide

Scintillator

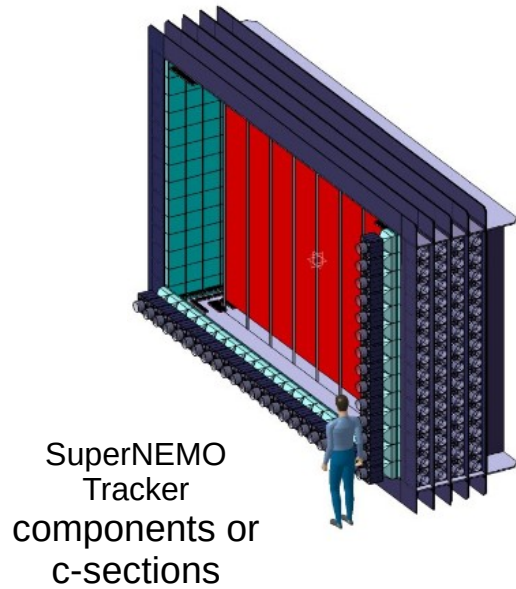


Scheme of two optical sub-modules (on the left) and of the whole detector (on the right)

The ^{212}Bi (^{208}Tl) and ^{214}Bi contaminants inside the foil are identified by the detection of a β decay followed by delayed α particles emitted in the opposite direction.

Surface covered with 200 nm of evaporated ultrapure aluminium in order to optically isolate each scintillator and to improve the light collection efficiency

Can also identify random coincidences, radiopurity of the scintillators and Radon and Thoron presence in the gas between the foil and the scintillators.



RnCL

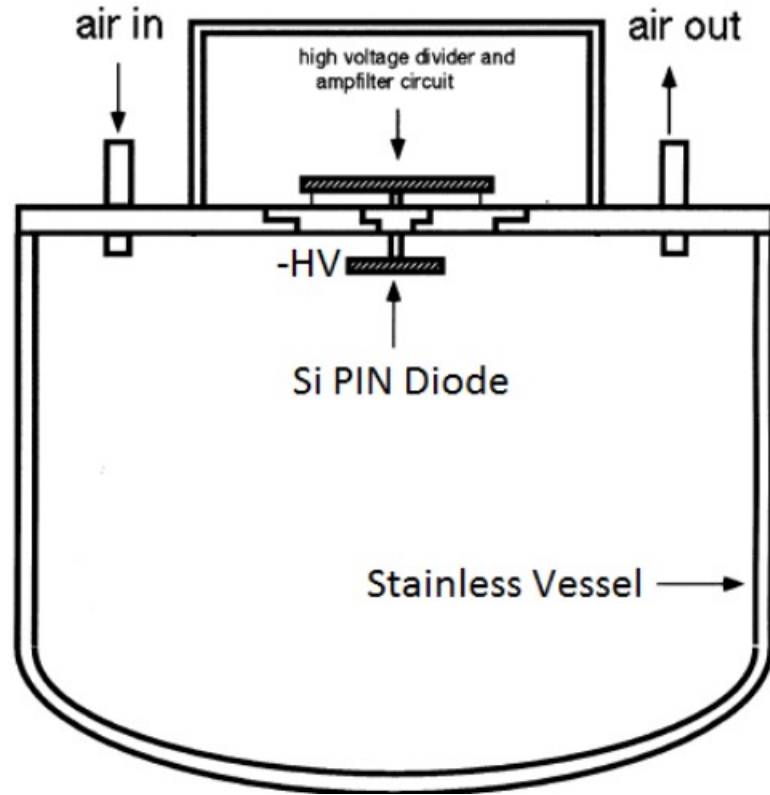


Electrostatic
Detector

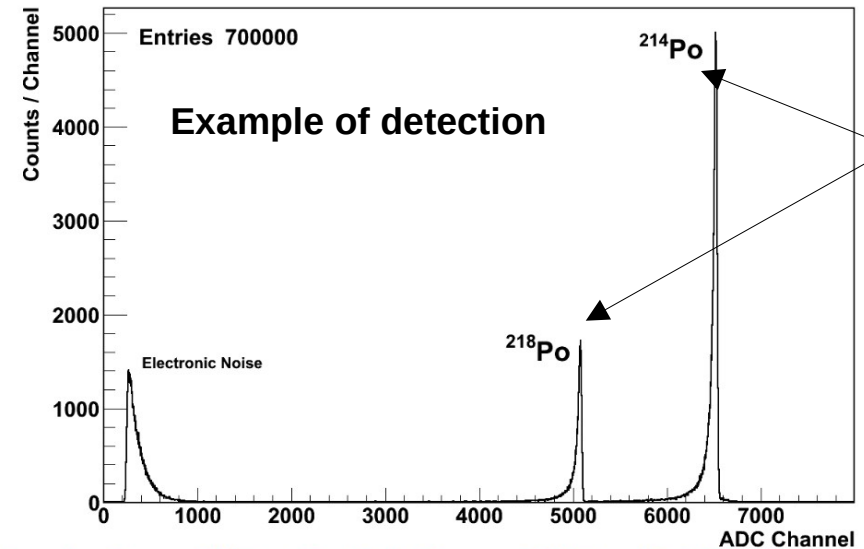


measures activities as low as $0.1 \mu\text{Bq}/\text{m}^3$ for large volumes

- Gas from the tracker components inside emanation chambers is pumped through a cooled ultra-pure carbon trap and the ^{222}Rn in the gas is adsorbed
- The concentrated sample is then heated and transferred to an electrostatic detector via helium purge.



- ^{222}Rn is pumped into the vessel where it decays.
- Daughters of ^{222}Rn decay are mostly positive ions \rightarrow these ions are collected on the PIN diode due to the applied negative HV.
- Once on the photodiode, they decay and their α particles can be identified by the energy deposited.



Daughters
of ^{222}Rn