Searching for leptonic number non-conservation with NEMO-3 and SuperNEMO

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on behalf of the NEMO-3/SuperNEMO collaboration

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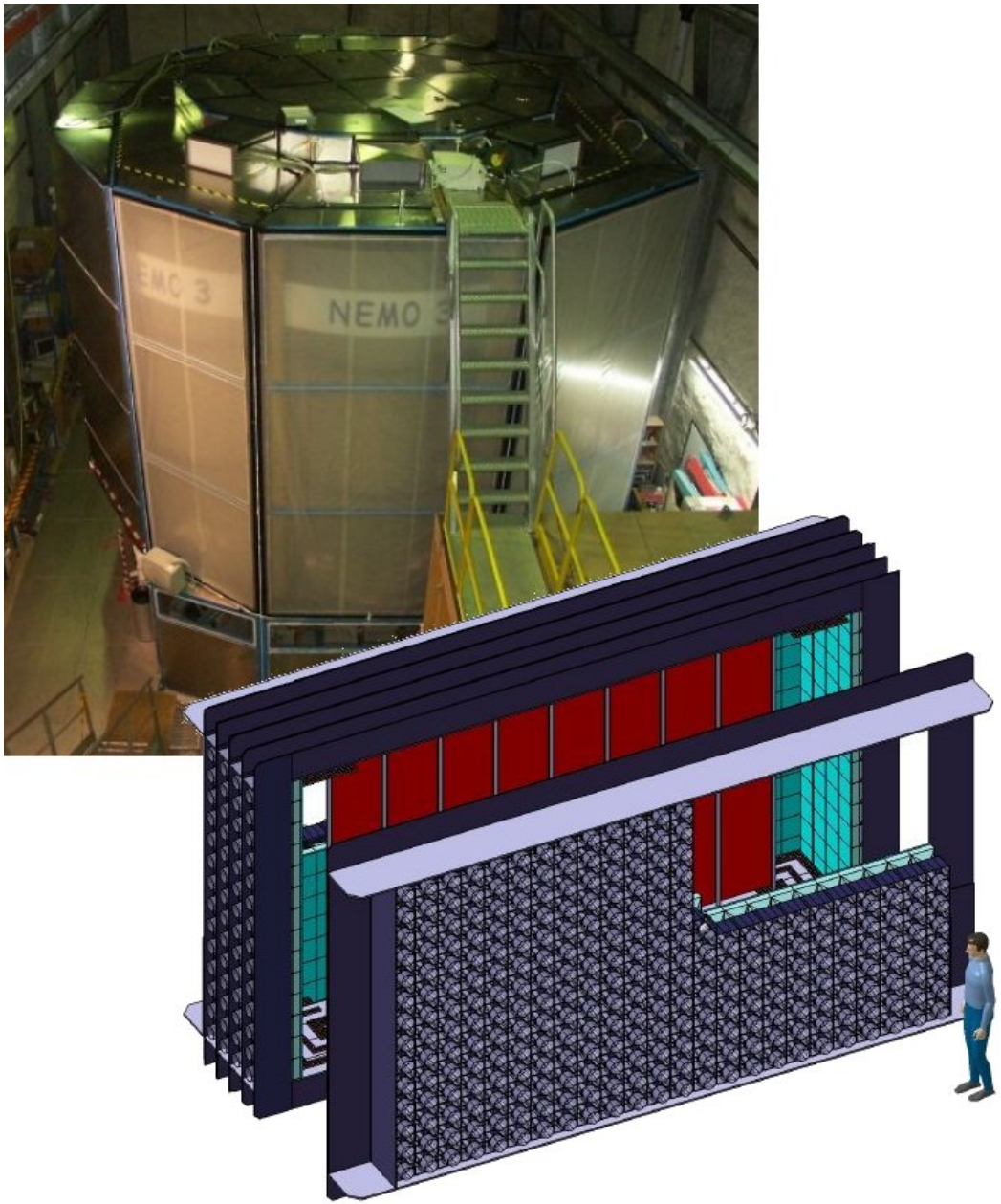
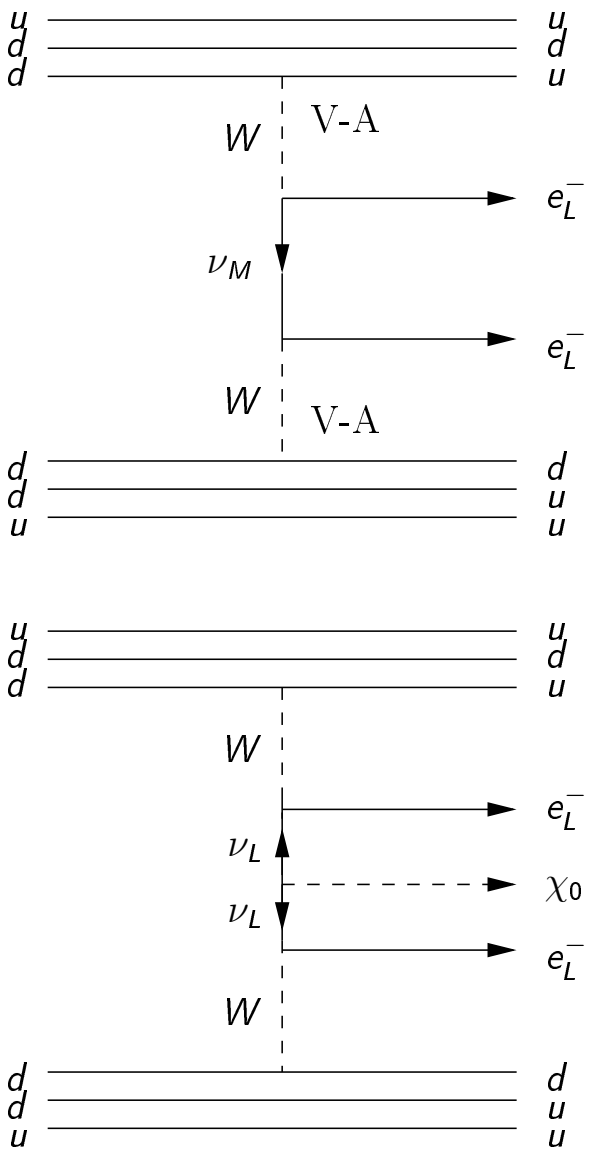
Outline

- NEMO-3:
  - technique
  - results
  - plans
- SuperNEMO:
  - new generation experiment
  - R&D status
  - plans



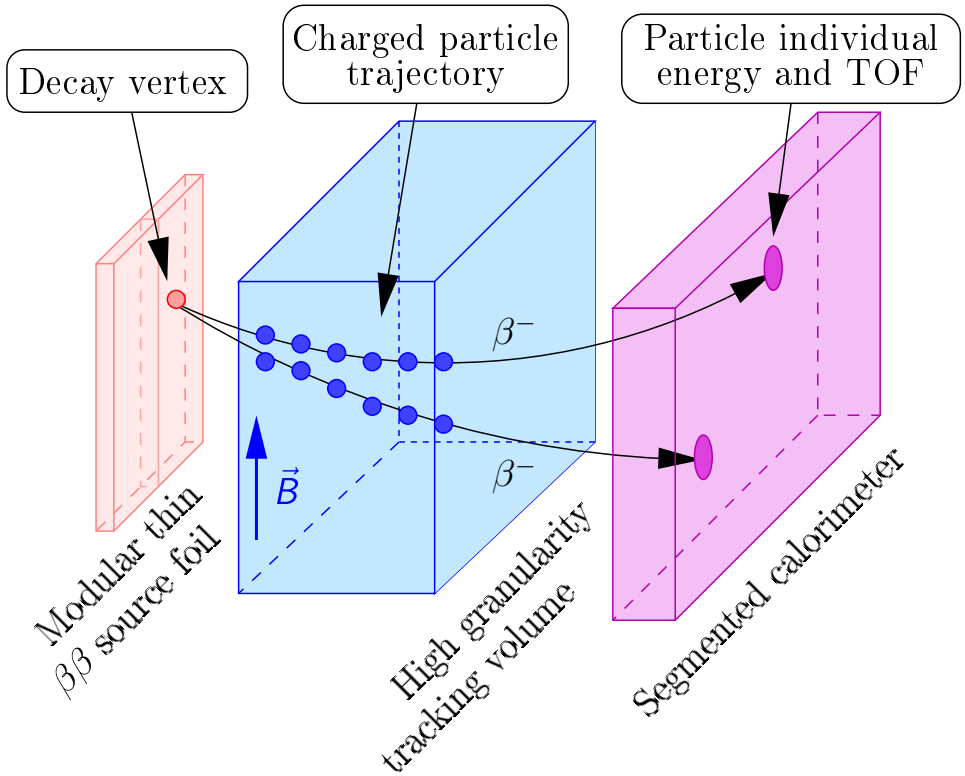
Physics goals

- Search for $0\nu\beta\beta$ decay ($\Delta L = 2$):
  $(A, Z) \rightarrow (A, Z+2) + 2\ e^-$
  sensitivity: $T_{1/2} \simeq 10^{24}$ y
  $< m_\nu > \sim$ 0.3-0.5 eV
- Search for $0\nu\beta\beta\chi_0$ (Majoron)
  $(A, Z) \rightarrow (A, Z+2) + 2\ e^- + \chi_0(\chi_0)$
  sensitivity: $T_{1/2} \simeq 10^{23}$ y
- Investigate $2\nu\beta\beta$ decay ($\Delta L = 0$):
  $(A, Z) \rightarrow (A, Z+2) + 2\ e^- + 2\bar{\nu}_e$
  $\neq$ nuclei, decays to excited states,
  SSD vs. HSD mechanisms, n.m.e.

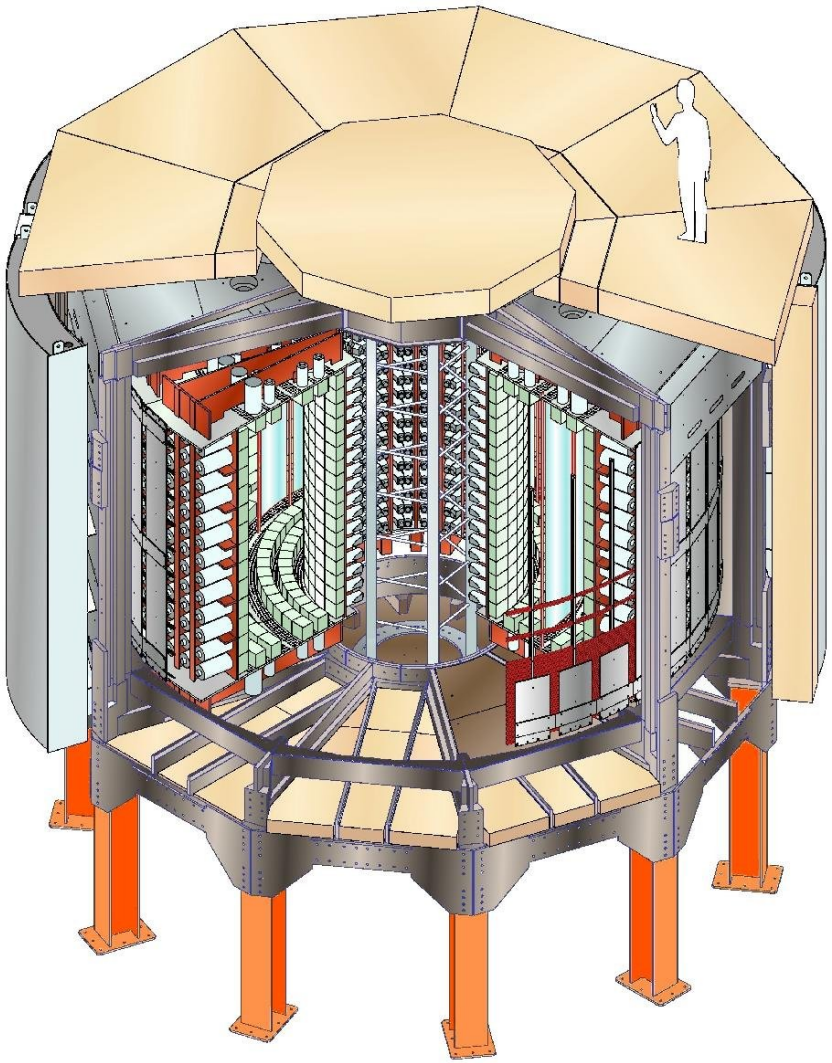


Calorimetry + Tracking

- Reconstruction of final state topology:
  - $e^{\pm}$ individual energy
  - charged particle trajectory
  - magnetic field curvature
  - vertex
  - angular distribution
  - time of flight
- Background rejection through particle identification: e^-, e^+, γ, α
- Source is separated from the detector:
  can measure several $\beta\beta$ isotopes



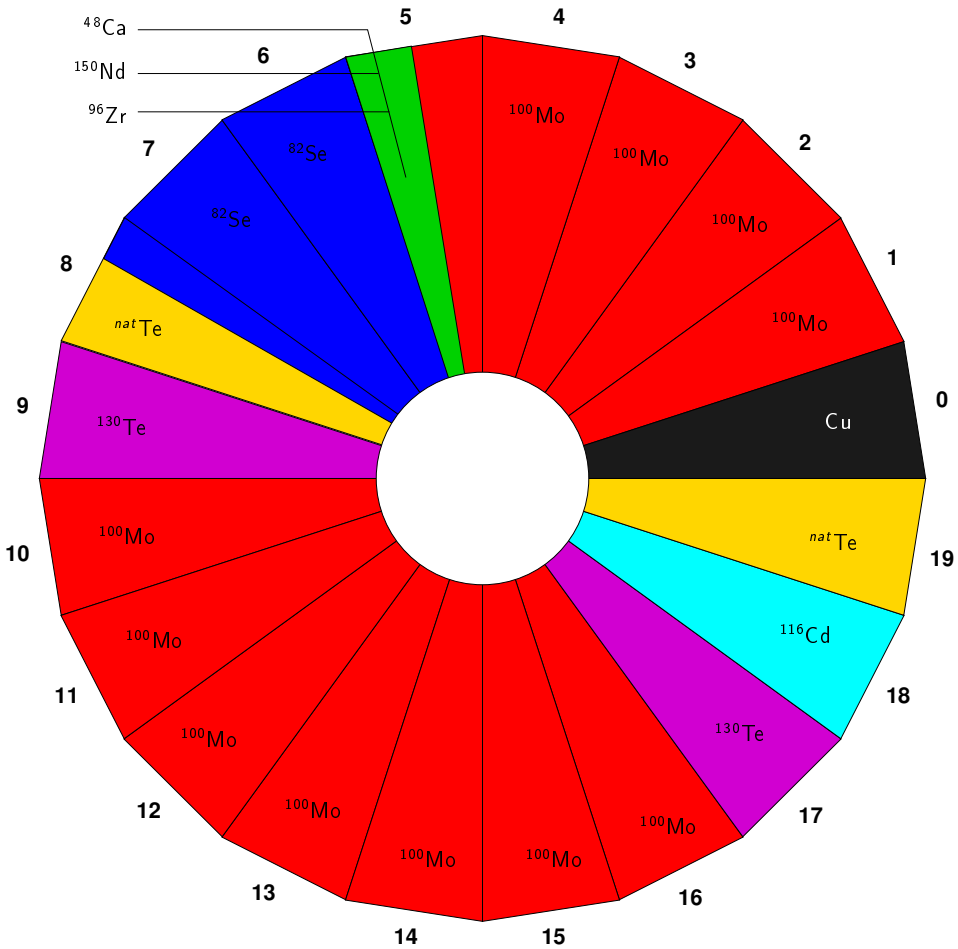
The NEMO-3 detector



Main characterisitics

- Source: 10 kg of $\beta\beta$ isotopes, S=20 m^2, $e \simeq$60 mg/cm^2
- Tracking detector: drift wire chamber operating in Geiger mode (6180 cells) gas: He+4% ethyl alcohol+1%Ar +0.1%H_2O, radon free
- Calorimeter: 1940 plastic scintillators coupled to low radioactivity PMTs
- Magnetic field: 25 gauss
- Gamma shield: pure Iron (18 cm)
- Neutron shield: borated water (30 cm, ext. wall), wood (40 cm, top+bottom)
- Rn trapping facility + tent
- Low radioactivity materials
- Fréjus Underground Laboratory (4800 m.w.e.)

The NEMO-3 detector



$\beta\beta$ decay isotopes

Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)
$0\nu\beta\beta$ search + $2\nu\beta\beta$ meas.		
^{100}Mo	6914	3034
^{82}Se	932	2995
$2\nu\beta\beta$ measurement		
^{116}Cd	405	2805
^{96}Zr	9.4	3350
^{150}Nd	37.0	3367
^{48}Ca	7.0	4272
^{130}Te	454	2529
External background measurement		
^{nat}Te	491	see ^{130}Te
Cu	621	-

Enriched isotopes produced by centrifugation in Russia

$\beta\beta$ event selection: the $(2e)_{internal}$ channel

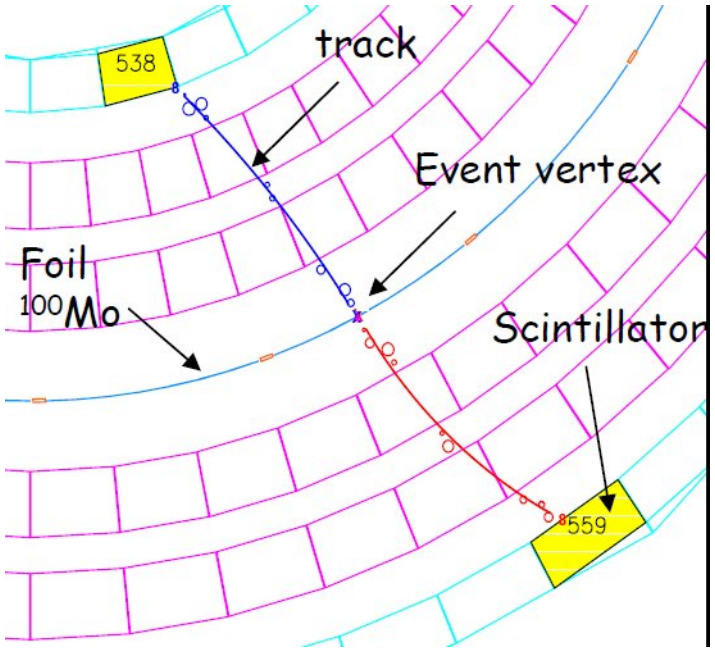
Trigger

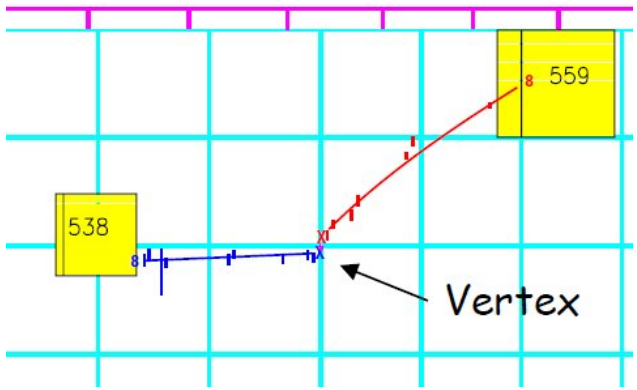
- 1 PMT $>$ 150 keV
- 3 Geiger cells (2 neighbour + 1)
- Trigger rate $\simeq$ 7 Hz

Criteria

- 2 tracks with $Q < 0$
- 2 PMTs associated with tracks
- common vertex
- internal event from the foil (TOF cut)
- No unassociated PMT (γ rejection)
- No delayed short tracks (α rejection from ^{214}Bi-^{214}Po cascade)
- $\beta\beta$ rate: 1 event / 2.5 minutes

Typical $\simeq$1 MeV $2\nu\beta\beta$ candidate event



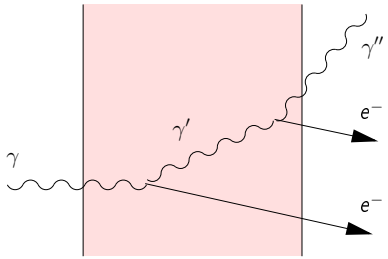


Expected backgrounds in the (2e) channel

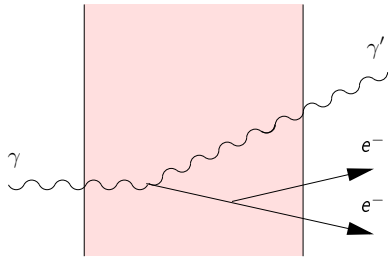
Many ways to mimic a $\beta\beta$ signal

- Natural radioactivity: U/Th chains (Rn), ^{40}K
- Cosmic μ
- Neutrons
- Artificial radioactivity

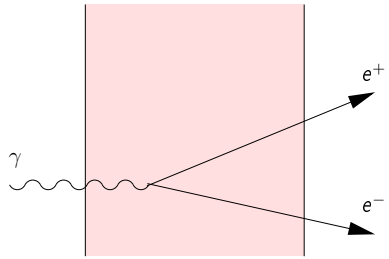
External (γ flux):



double Compton

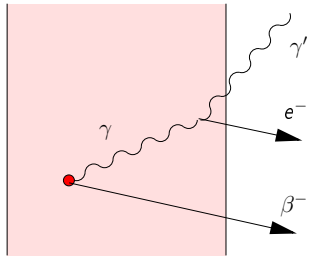


Compton+ Möller

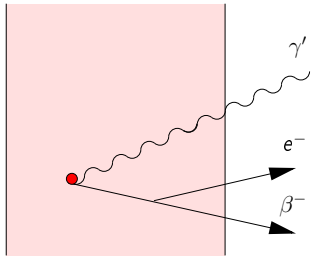


pair production

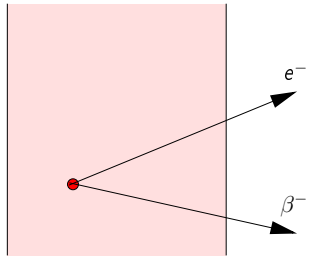
Internal (source foil contaminants):



β^-+ Compton



β^-+ Möller



β^-+ IC

Elaborate a background model

NEMO-3 is able to measure each components of its background

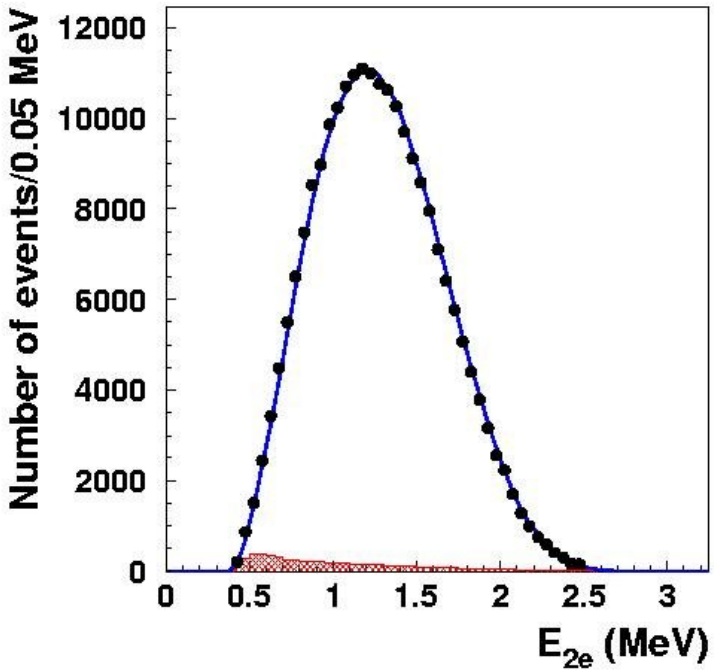
- using independant channels to identify and measure different sources of background:

Channel(s)	Background category	Radio-contaminants
$e\gamma_{external}$, $e_{crossing}$	external background	^{40}K, ^{60}Co, ^{226}Ra...
$e\gamma$, $e\gamma\gamma$, $e\gamma\gamma\gamma$	internal background from γ-emitters	^{208}Tl, ^{207}Bi...
$1e$	internal background from pure β-emitters	^{234m}Pa, ^{40}K, ^{90}Y...
$e\alpha(\gamma)$	radon daughters deposited on wires and source foils	^{214}Bi, ^{214}Po

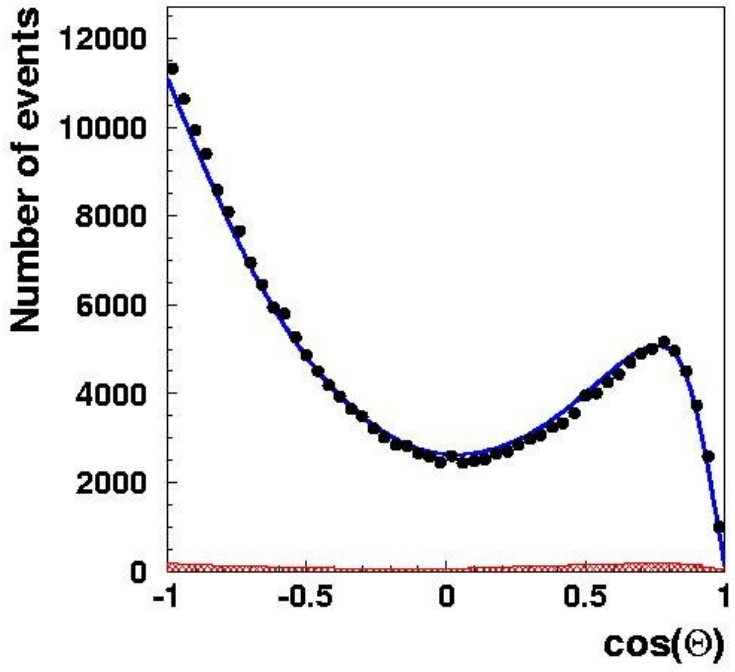
- elaborating a background model for each $\beta\beta$ isotope
- $\rightsquigarrow$ predicting background contamination in $2e$ channel, particularly at the $Q_{\beta\beta}$ end point for $0\nu\beta\beta$ search

$2\nu\beta\beta$ results for ^{100}Mo

Energy sum



Angular distribution

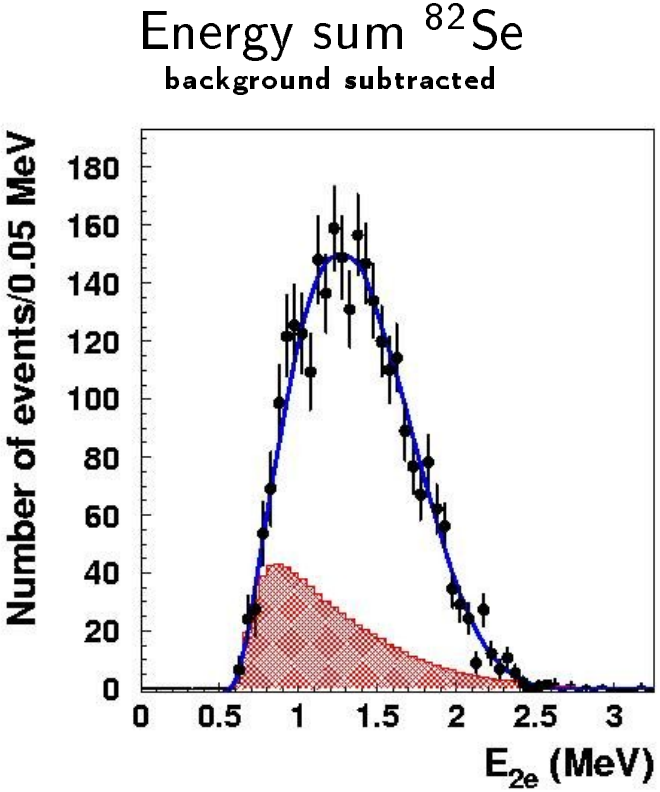


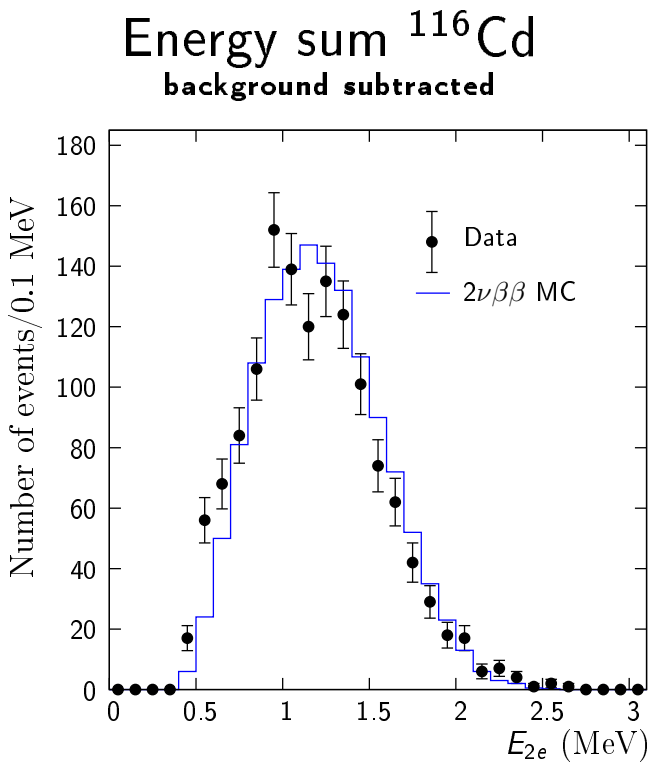
^{100}Mo

- Statistics: 219 000 events
- Exposure: 6914 g $\times$ 389 days
- S/B = 40

- data (background subtracted)
- $2\nu\beta\beta$ Monte Carlo
- background

$2\nu\beta\beta$ results for ^{82}Se and ^{116}Cd





^{82}Se

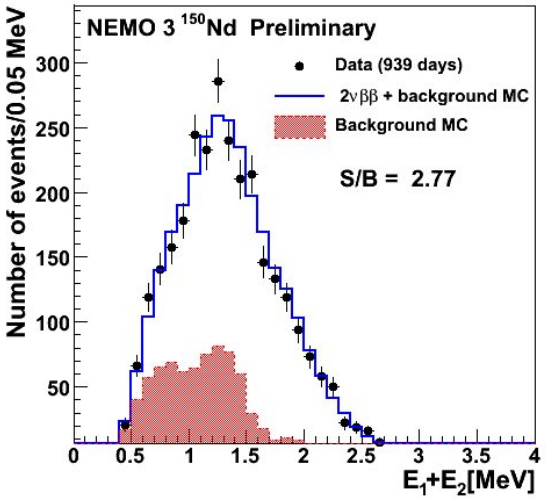
- Statistics: 2750 events
- Exposure: 932 g $\times$ 389 days
- S/B = 4

^{116}Cd

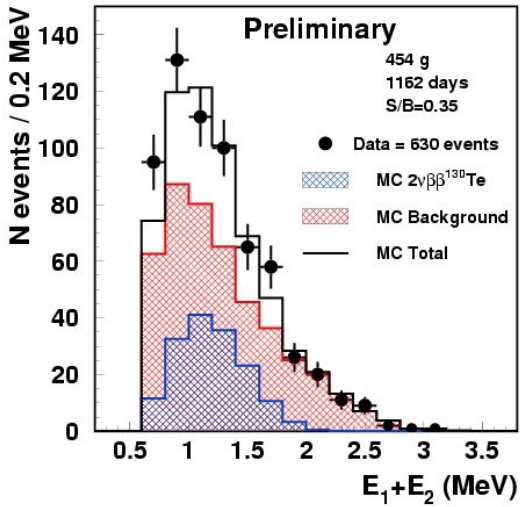
- Statistics: 1371 events
- Exposure: 405 g $\times$ 168.4 days
- S/B = 7.5

$2\nu\beta\beta$ results: ^{150}Nd, ^{130}Te, ^{48}Ca, ^{96}Zr (preliminary)

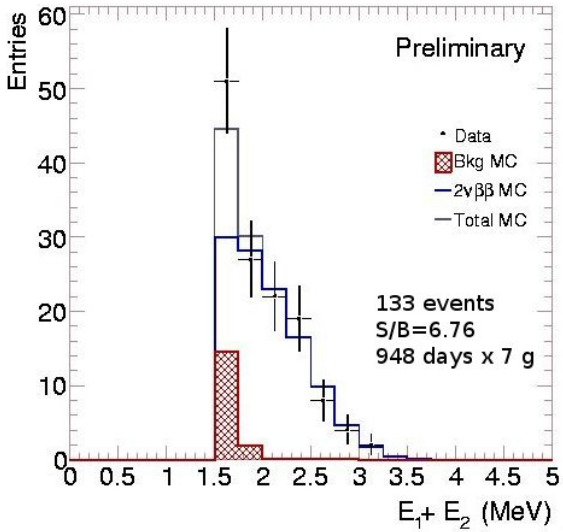
^{150}Nd



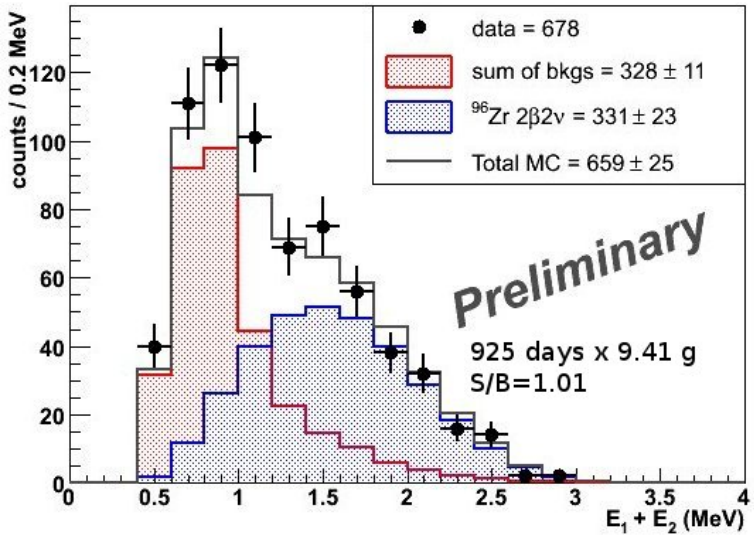
^{130}Te



^{48}Ca

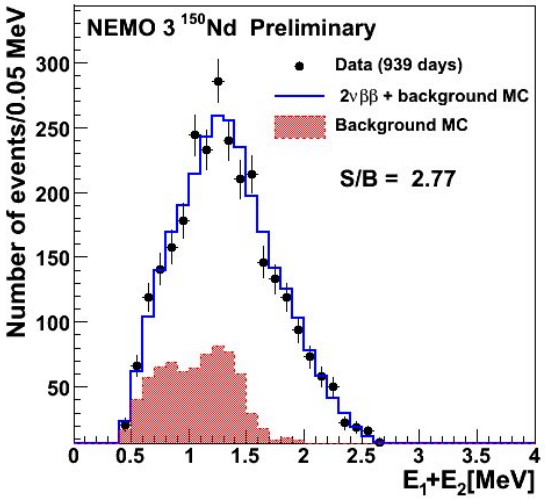


^{96}Zr

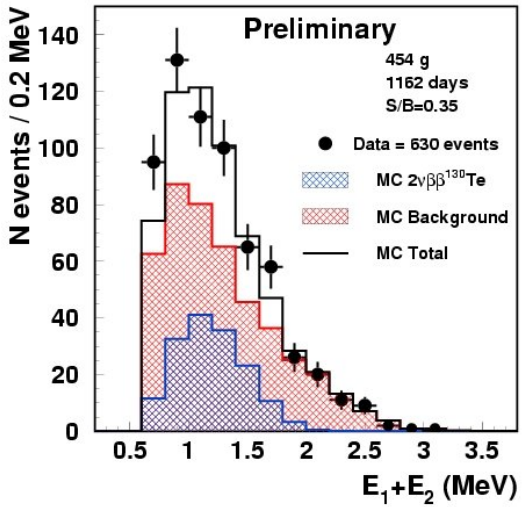


$2\nu\beta\beta$ results: ^{150}Nd, ^{130}Te, ^{48}Ca, ^{96}Zr (preliminary)

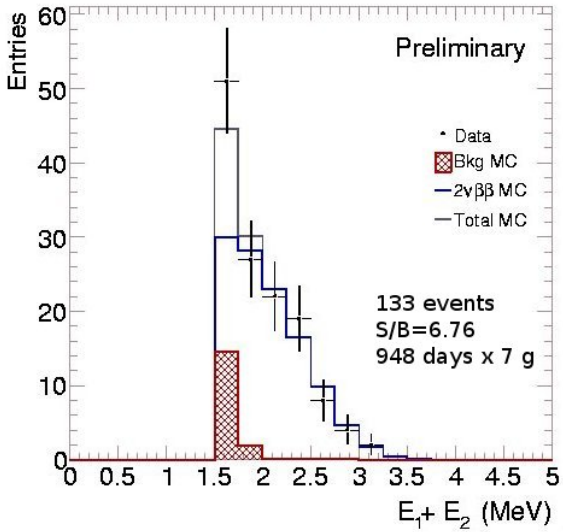
^{150}Nd



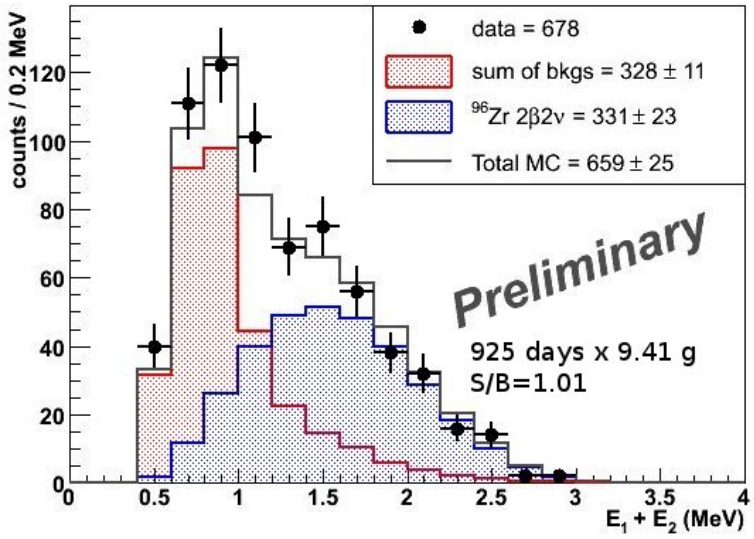
^{130}Te



^{48}Ca

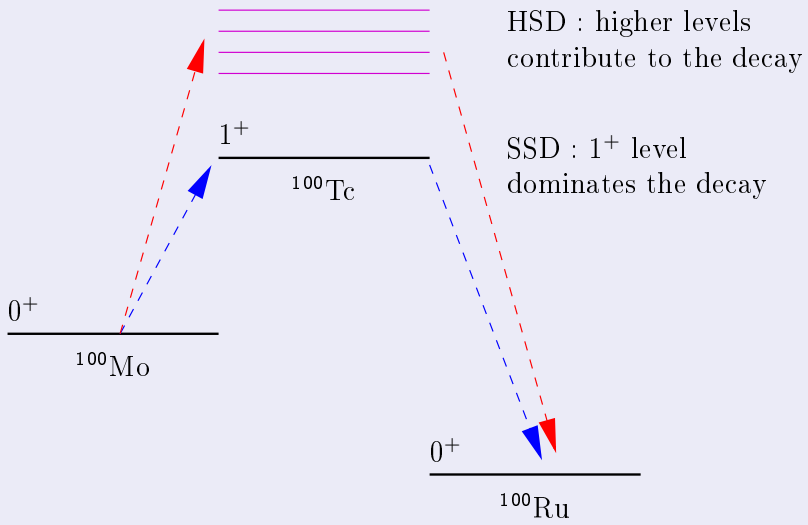


^{96}Zr

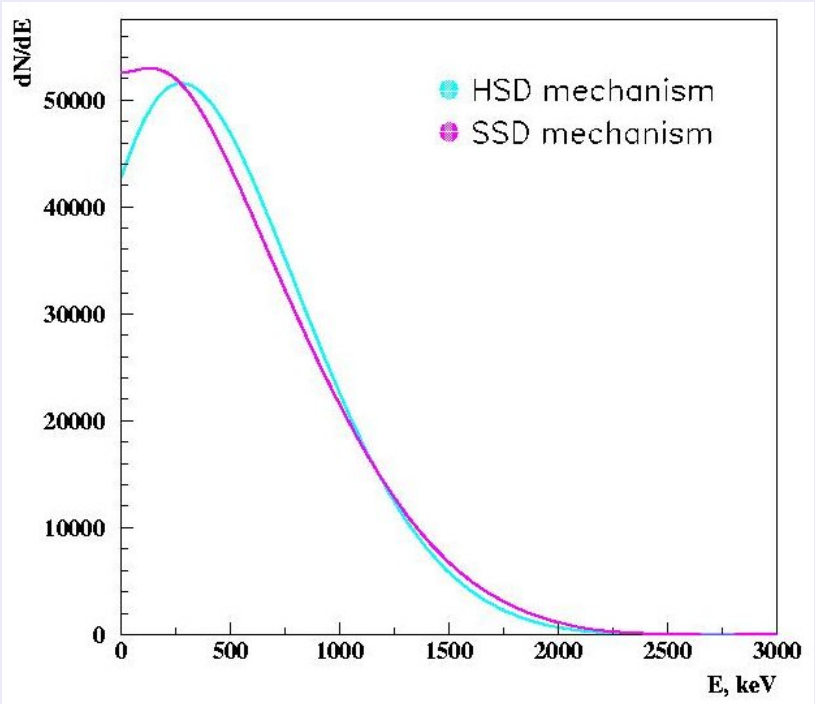


$2\nu\beta\beta$ electron energy distribution: a probe for HSD versus SSD

HSD : Higher States Dominance
SSD : Single State Dominance



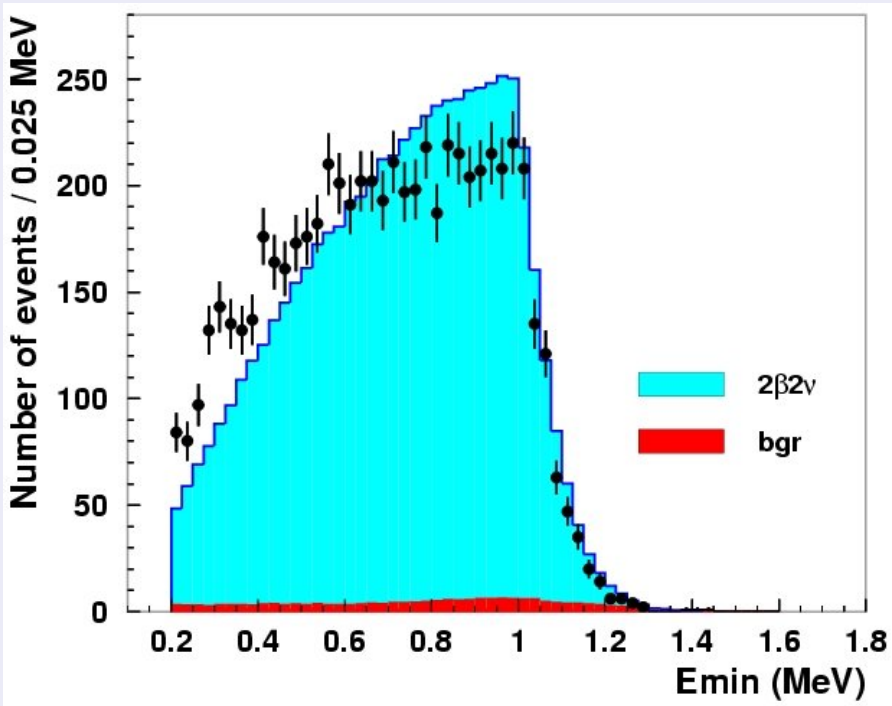
Abad et al., Ann. Fis. A 80, 9 (1984)



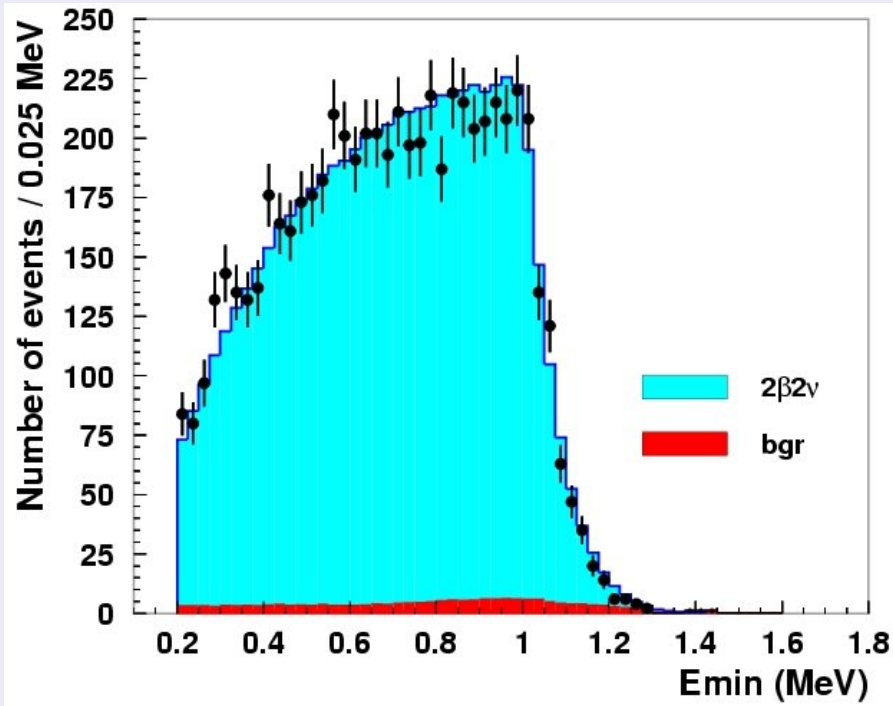
Simkovic, J. Phys. G 27, 2233 (2001)

^{100}Mo $2\nu\beta\beta$ energy distribution in favor of SSD versus HSD

HSD : χ^2/ndf = 254/42

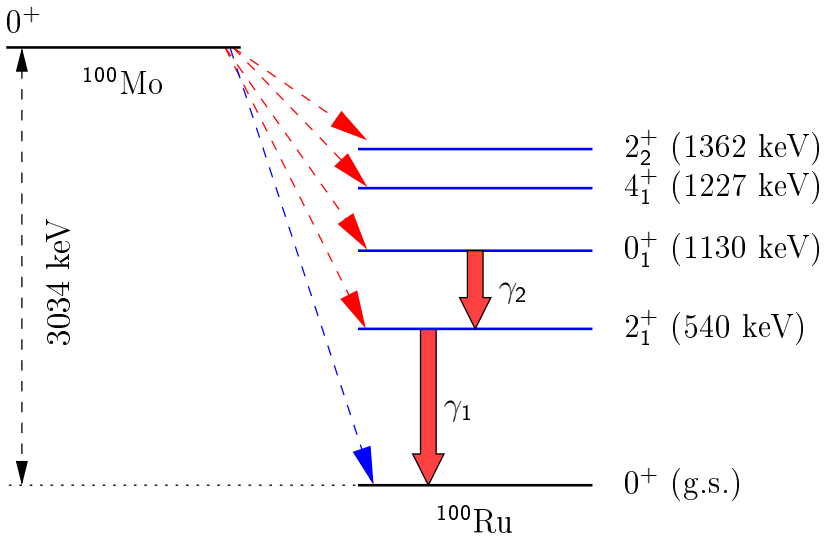


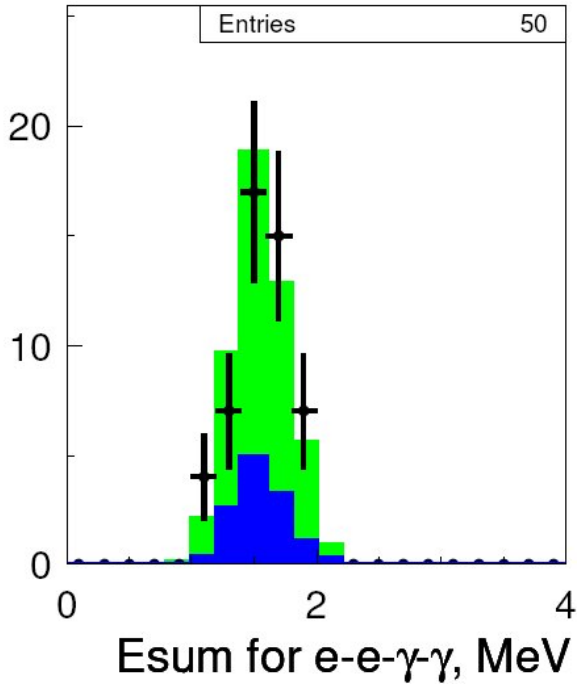
SSD : χ^2/ndf = 42.3/42



- data (5.01 kg.y, $E_1 + E_2 > 2$ MeV), background MC, $2\nu\beta\beta$ MC

^{100}Mo $2\nu\beta\beta$ decay to excited states





Event topology

0_1^+: $2e^-$+2γ with TOF and energy cuts

2_1^+: $2e^-$+1γ with TOF and energy cuts

Decay to the 0^+ excited state of ^{100}Ru

$T_{1/2} = [5.7^{+1.3}_{-0.9}\ (\text{stat}) \pm 0.8\ (\text{syst})\ ]\ 10^{20}$ y

Nucl. Phys. A781 (2006) 209-226

Summary of $2\nu\beta\beta$ results

The NEMO 3 $\beta\beta$ factory: a tool for precision tests

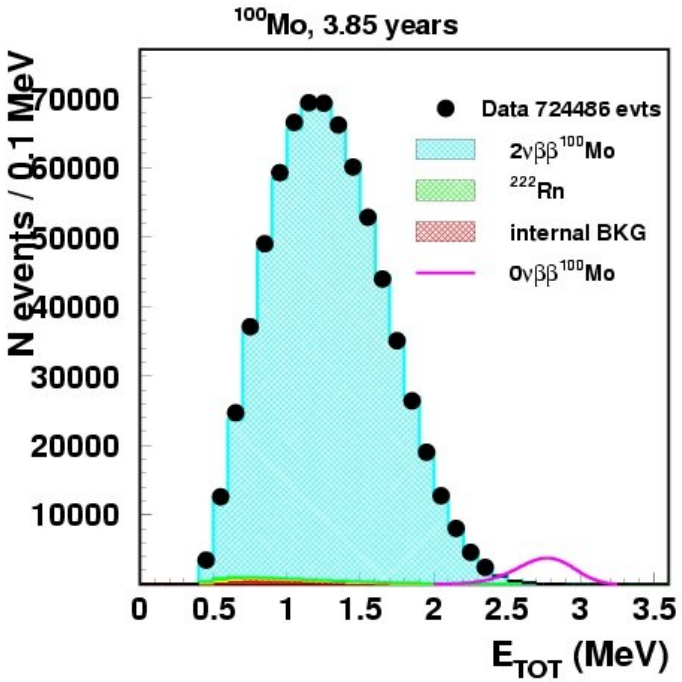
Isotope	$T_{1/2}^{2\nu\beta\beta}$ (y)
^{100}Mo	$[7.11 \pm 0.02(stat) \pm 0.54(syst)] \times 10^{18}$ * (SSD favored)
^{100}Mo(0_1^+)	$\left[5.7^{+1.3}_{-0.9}(stat) \pm 0.8(syst)\right] \times 10^{20}$ **
^{82}Se	$[9.6 \pm 0.3(stat) \pm 1.0(syst)] \times 10^{19}$ *
^{116}Cd	$[2.8 \pm 0.1(stat) \pm 0.3(syst)] \times 10^{19}$ **
^{130}Te	$[6.9 \pm 0.9(stat) \pm 1.0(syst)] \times 10^{20}$ ***
^{150}Nd	$\left[9.20^{+0.25}_{-0.22}(stat) \pm 0.73(syst)\right] \times 10^{18}$ ***
^{96}Zr	$[2.35 \pm 0.14(stat) \pm 0.19(syst)] \times 10^{19}$ ***
^{48}Ca	$\left[4.4^{+0.5}_{-0.4}(stat) \pm 0.4(syst)\right] \times 10^{19}$ ***

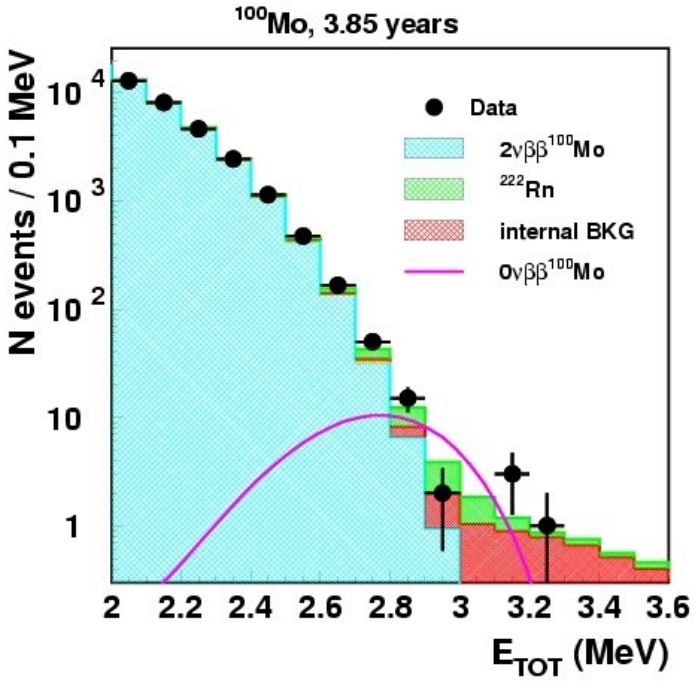
* Phase 1 (high radon data), Phys. Rev. Lett. 95 (2005) 182302
(additional statistics are being analysed, to be published soon)

** Phase 1 data

*** Phases 1 and 2, preliminary

$0\nu\beta\beta$ results for ^{100}Mo, 2003-2008 data: 3.85 years





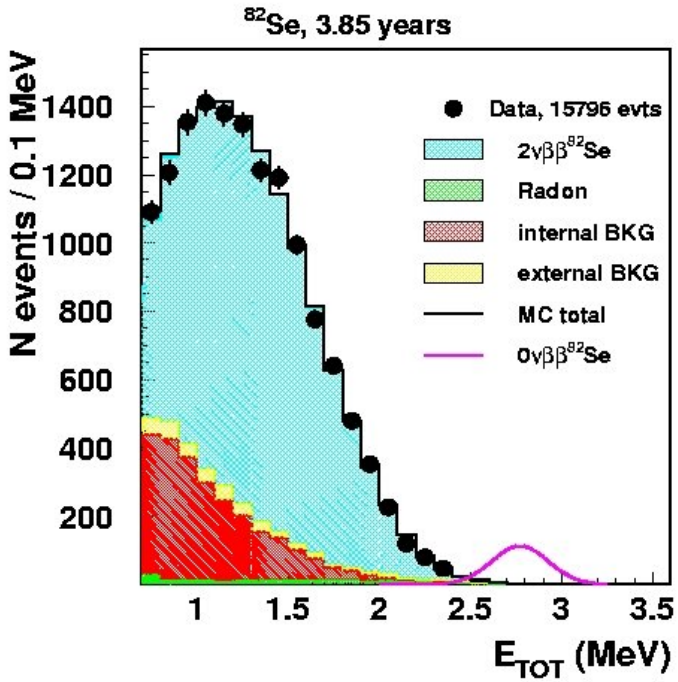
Counting [2.8 – 3.2] MeV

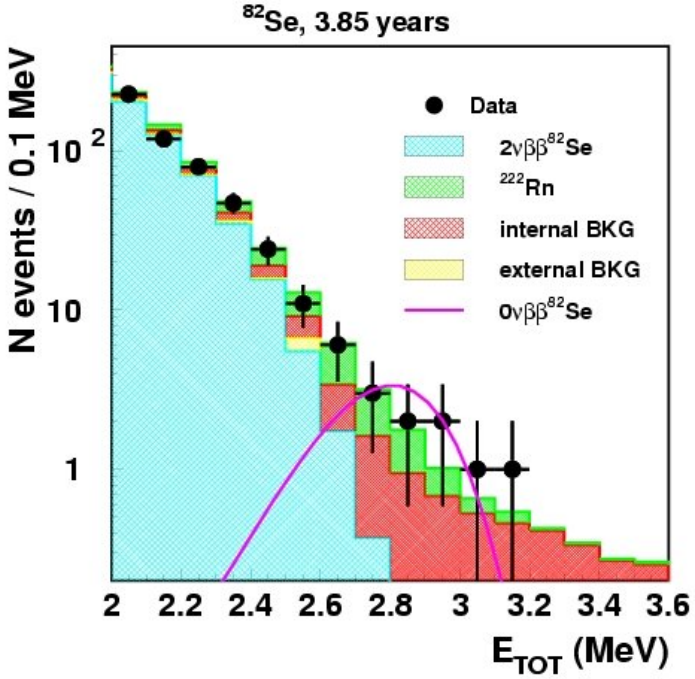
- Data: 20 events
- Expected background: 18.6 events
- Excluded 90% C.L.: 9.6 events
- Efficiency = 0.0726

Likelihood [2.0 – 3.2] MeV

- Excluded 90% C.L.: 18 events
- Efficiency = 0.174
  $T_{1/2}^{0\nu\beta\beta} > 1.1\ 10^{24}$ y @ 90 %C.L.
  $< m_\nu > < 0.45$–0.93 eV

$0\nu\beta\beta$ results for ^{82}Se, 2003-2008 data: 3.85 years





Counting [2.6 – 3.2] MeV

- Data: 15 events
- Expected background: 13.2 events
- Excluded 90% C.L.: 8.9 events
- Efficiency = 0.151

Likelihood [2.0 – 3.2] MeV

- Excluded 90% C.L.: 9.8 events
- Efficiency = 0.182
  $T_{1/2}^{0\nu\beta\beta} > 3.6\ 10^{23}$ y @ 90 %C.L.
  $< m_\nu > < 0.89$–1.61 eV

Results for ^{100}Mo and ^{82}Se

- Electron angular/energy distributions are distorted by V+A/Majoron mechanisms
- No evidence for such mechanisms
- Limits:

	V+A*	Majoron(s) emission **			
Isotope	$T_{1/2}^{0\nu\beta\beta}$ (y)	n=1	n=2	n=3	n=7
^{100}Mo	$> 5.7\ 10^{23}$ $\lambda < 1.4\ 10^{-6}$	$> 2.7\ 10^{22}$ $g_{ee} < (0.4 - 1.8)10^{-4}$	$> 1.7\ 10^{22}$	$> 1.0\ 10^{22}$	$> 7\ 10^{19}$
^{82}Se	$> 2.4\ 10^{23}$ $\lambda < 2.0\ 10^{-6}$	$> 1.5\ 10^{22}$ $g_{ee} < (0.7 - 1.9)10^{-4}$	$> 6\ 10^{21}$	$> 3.1\ 10^{21}$	$> 5\ 10^{20}$

n : spectral index

* Phase 1+Phase 2 data

** Phase 1 data, R. Arnold el al. Nucl. Phys. A765 (2006) 483

Summary of $0\nu\beta\beta$ results

No evidence for leptonic number non conservation

- Current limits on neutrinoless DBD (90% C.L.):

Isotope	Exposure (kg.y)	$T_{1/2}^{0\nu\beta\beta}$ (y)	$< m_\nu >$ (eV)	[nme ref.]
^{100}Mo	26.6	$>1.1\ 10^{24}$	<0.45-0.93	[1-3]
^{82}Se	3.6	$>3.6\ 10^{23}$	<0.9-1.6 <2.3	[1-3] [7]
^{150}Nd	0.095	$>1.8\ 10^{22}$	<1.7-2.4 <4.8-7.6	[4-5] [6]
^{130}Te	1.4	$>9.8\ 10^{22}$	<1.6-3.1	[4,5]
^{96}Zr	0.024	$>8.6\ 10^{21}$	<7.4-20.1	[2,3]
^{48}Ca	0.017	$>1.3\ 10^{22}$	<29.6	[7]

- nme: nuclear matrix element:

[1] M.Kortelainen and J.Suhonen, Phys.Rev. C 75 (2007) 051303(R)
[2] M.Kortelainen and J.Suhonen, Phys.Rev. C 76 (2007) 024315
[3] F.Simkovic, et al. Phys.Rev. C 77 (2008) 045503
[4] V.A.Rodin et al. Nucl.Phys. A 793 (2007) 213
[5] V.A. Rodin et al. Nucl.Phys. A 766(2006) 107
[6] J.H.Hirsh et al. Nucl.Phys. A 582(1995) 124
[7] E.Caurier et al. Phys.Rev.Lett 100 (2008) 052503

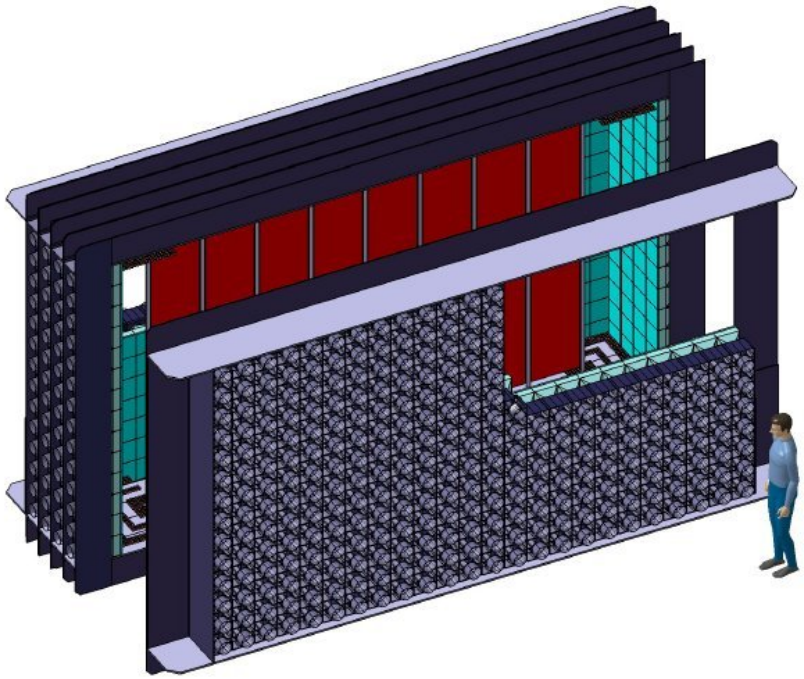
NEMO-3 conclusion

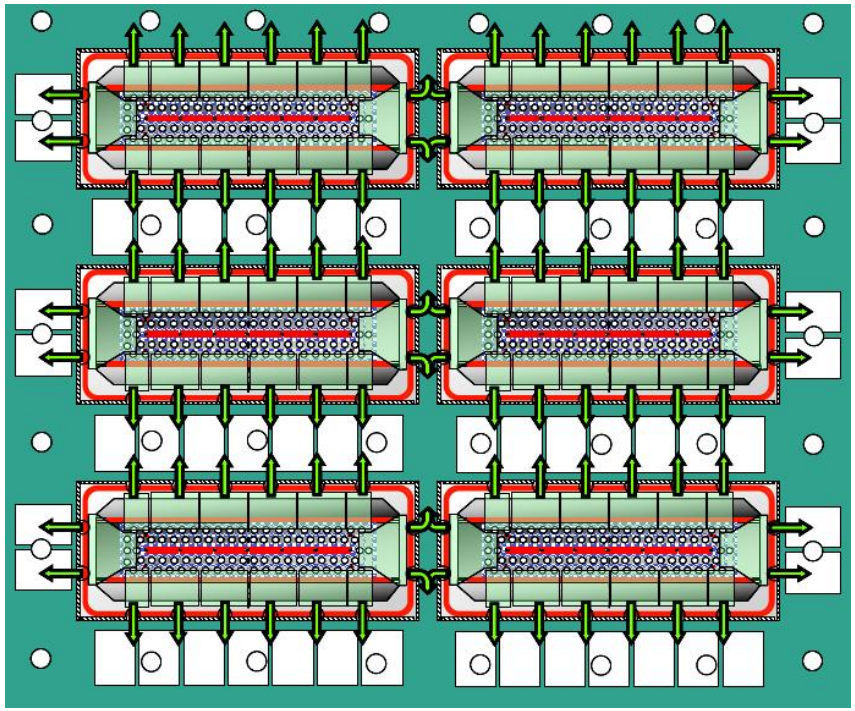
Summary

- $2\nu\beta\beta$ decay for ^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{150}Nd has been investigated $\rightsquigarrow$ accurate measurement of half-lives
- No evidence for leptonic number non conservation on $0\nu\beta\beta$ decay $\rightsquigarrow$ new limits have been obtained:
  ^{82}Se: $T_{1/2} > 3.6\ 10^{23}$ y (90% C.L.)
  ^{100}Mo: $T_{1/2} > 1.1\ 10^{24}$ y (90% C.L.)
- NEMO 3 will take data til end 2010, results will be improved:
  - higher statistics
  - improve the background model and systematics
  - improve the analysis of calorimeter survey data

Physics goals and technique

- Search for $0\nu\beta\beta$ decay at $T_{1/2} \simeq 10^{26}$ y $\rightsquigarrow < m_\nu > \simeq 50$ meV
- Extends and improves NEMO-3 technique:
  tracker+calorimeter, modular design, baseline $\simeq 100$ kg ^{82} Se
- R&D phase: 2005-2009





R&D goals

Source:

- baseline with ^{82}Se (already have 4.5 kg),
- purification techniques are available: chemical & distillation
- 40 mg/cm^2 foil production: ala NEMO-3 & new coating method
- 100 kg enrichement is possible by centrifugation in Russia

Thin source foil radiopurity:

- BiPo1 0.8 m^2 prototype detector: measure the radiopurity of thin foils in ^{214}Bi and ^{208}Tl
  $\rightsquigarrow A(^{212}\text{Bi}) \simeq 1\mu\text{Bq/m}^2$ (after 1 year)
- next step: BiPo 3.5 m^2 detector: sensitivity $A(^{208}\text{Tl}) < 3\mu$ Bq/kg (after 6 monthes)
- see S. Cebrián's poster

R&D goals

Ge and radon detectors

- radiopurity control of SuperNEMO materials
- 2×400 cm^3 HPGe detectors at LSM
  - $A(^{214}\mathrm{Bi}) > 200\mu$ Bq/kg
  - $A(^{208}\mathrm{Tl}) > 60\mu$ Bq/kg
- a new 600 cm^3 Ge detector in development
- Rn detector (emanation/diffusion at 0.1 mBq/m^3) in development
- many measurements to be done...

R&D goals

Tracker:

- 90 cells prototype shows good tracking performances (efficiency and resolution)
- wiring robot is under development (full detector is $\simeq$500000 wires)

Calorimeter:

- main goal is r=7% FWHM @ 1 MeV (scintillator block + 8" PMT)
- accurate calibration and control quality of mass production
- r=6.7 % and 7.8 % have been reached resp. with Photonis and Hamamatsu high QE PMTs + 10 cm thick plastic scintillator block.
- Calorimeter design to be choosen between:
  - blocks (15000 channels @ r=7%)
  - or bars (7500 ch. @ r=10%)

SuperNEMO demonstrator (1st module)

- Demonstrate the feasibility of a large scale detector with required perfomances: efficiency, energy resolution, radiopurity...
- Measure the radon background
- Finalize the detector design
- Produce competitive physics measurements:
  $T_{1/2}^{0\nu\beta\beta} > 6.5\ 10^{24}$ y
  $< m_\nu > < 210 - 570$ meV
  with 7 kg of ^{82}Se after 2 y of data taking
- Schedule:
  - construction: 2010-2011 (+BiPo 3.5 m^2)
  - running: 2012-2013
- Location: possibly @ LSM (in place of NEMO 3)

SuperNEMO full detector

- Baseline: $\simeq$ 20 modules with 5 kg of ^{82}Se
- Other candidate isotopes: ^{48}Ca and ^{150}Nd
- Expected sensitivity with 500 kg.y of ^{82}Se (preliminary):
  $T_{1/2}^{0\nu\beta\beta} > 1\ 10^{26}$ y $\rightsquigarrow < m_\nu > < 53 - 145$ meV
- Schedule:
  - construction: 2012+
  - running: 2013+
- Location: new 60000 m^3 extension at LSM (2012)

Conclusion

- The NEMO/SuperNEMO collaboration (80 physicists, 29 labs, 11 countries) is searching for leptonic number violating physics:
  - investigating $0\nu\beta\beta$ decay
  - through NEMO technique (calorimeter+tracking)
- NEMO-3 (2003-2008) provides:
  - results for both particles and nuclear physics (nme calculation)
  - no evidence of $\Delta L \neq 0$ so far
  - $0\nu\beta\beta$ sensitivity: $T_{1/2}$ @ 10^{24} y (^{100}Mo)
  - improvements are expected (end 2010)...
- SuperNEMO is the new generation experiment:
  - R&D shows that 500 kg.y with NEMO experimental approach is possible
  - next step: demonstrator module (2012+) $T_{1/2}$ @ 6 10^{24} y (15 kg.y with ^{82}Se)

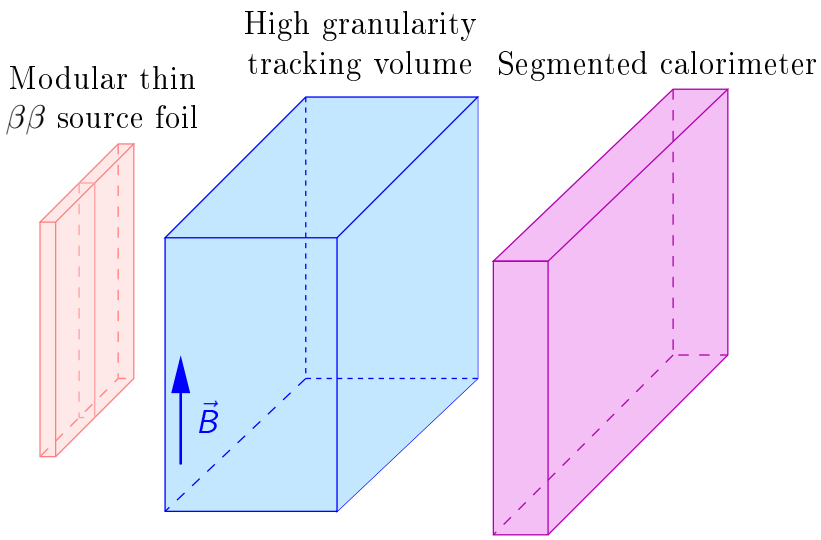
thanks to Viktor Tretyak and Emmanuel Chauveau (MEDEX 09, Praha, http://medex09.utef.cvut.cz/papers.php),
also see the BiPo poster by Susana Cebrián...

http://nemo.in2p3.fr/

Backup slides

Calorimetry + Tracking

- Reconstruction of final state topology and kinematics for double beta decays, and nuclear decays from natural radioactivity:
  - $e^{\pm}$ individual energy (100 keV-10MeV),
  - charged particle trajectory ($e^{\pm}$, α, μ)
  - angular distribution, vertex, magnetic field curvature
  - time of flight,
- Background rejection through particle identification: e^{-}, e^{+}, γ, α
- Source is separated from the detector: can measure several $\beta\beta$ isotopes



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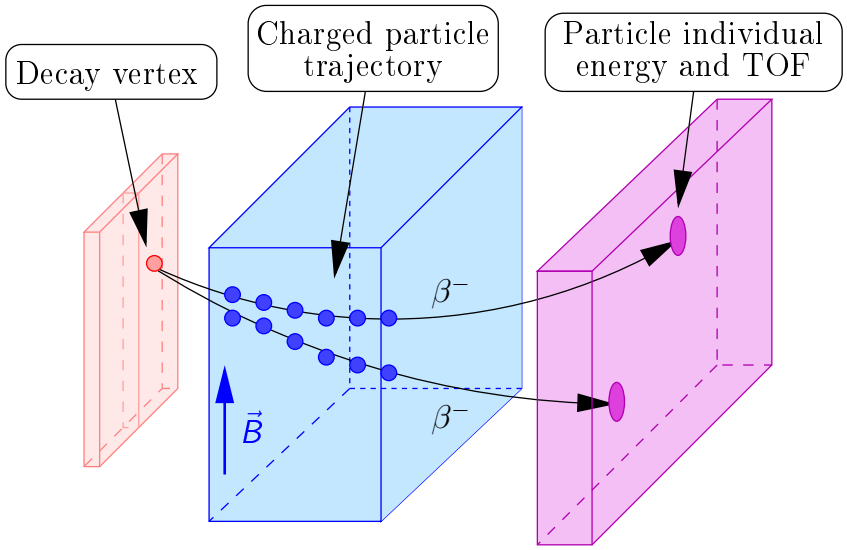

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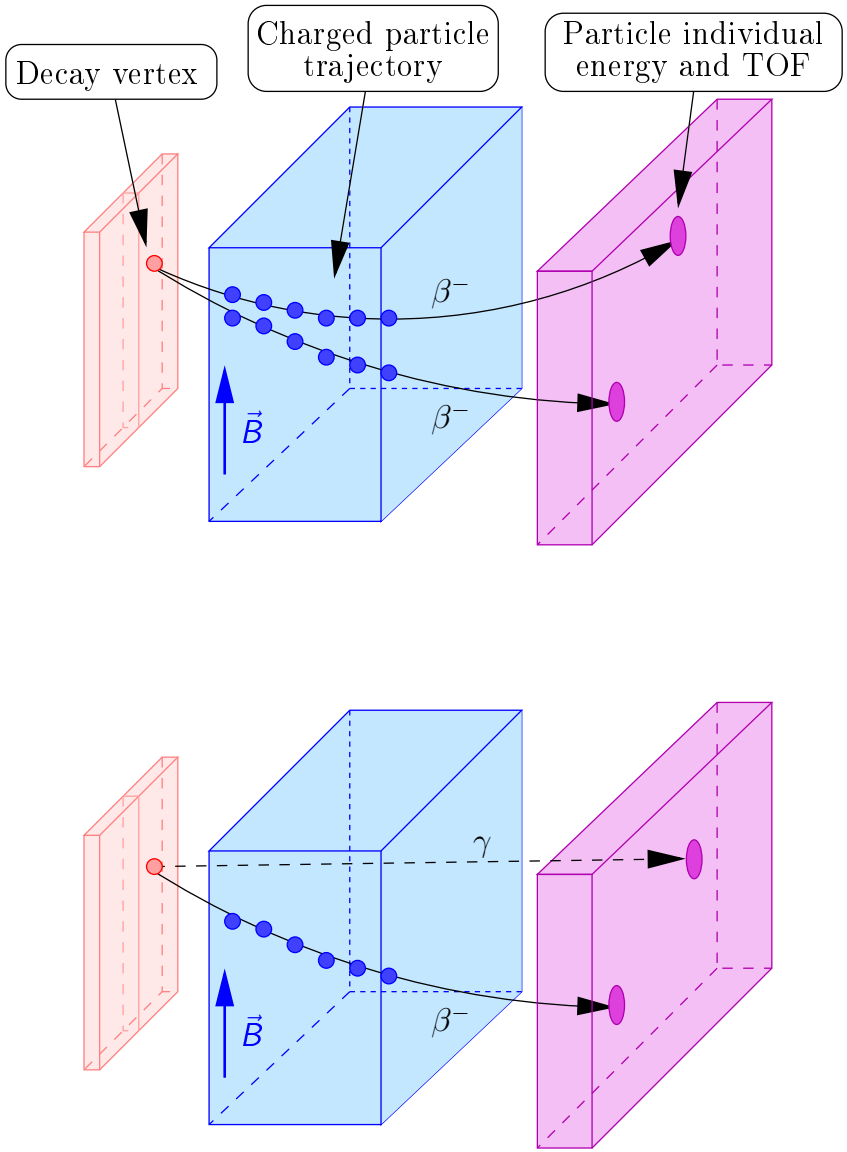

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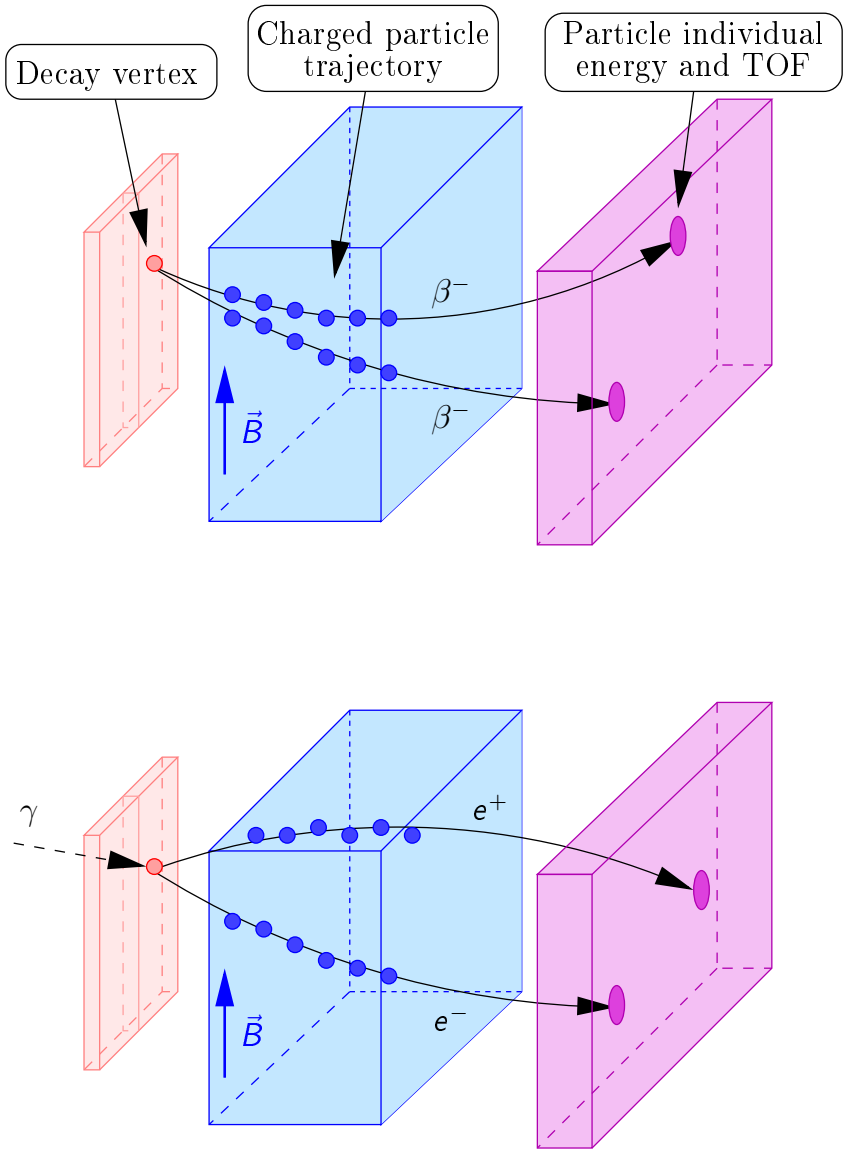

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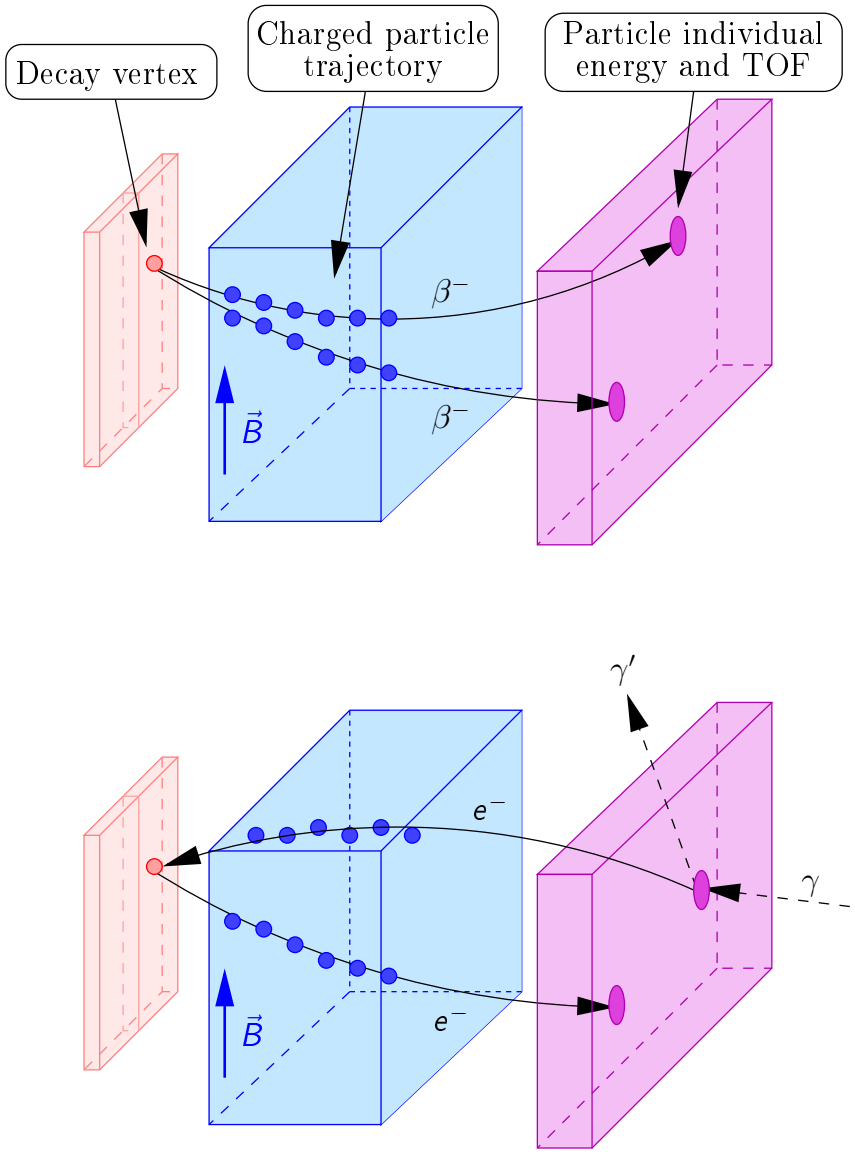

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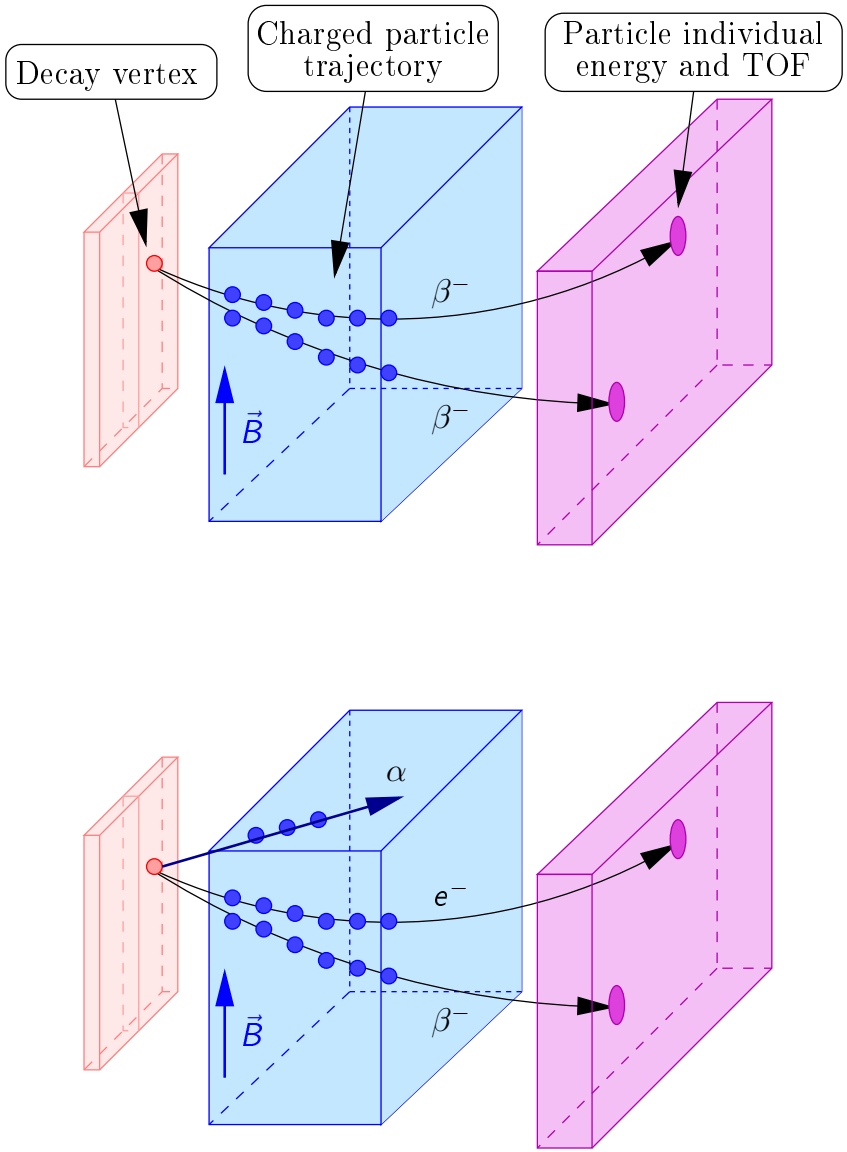

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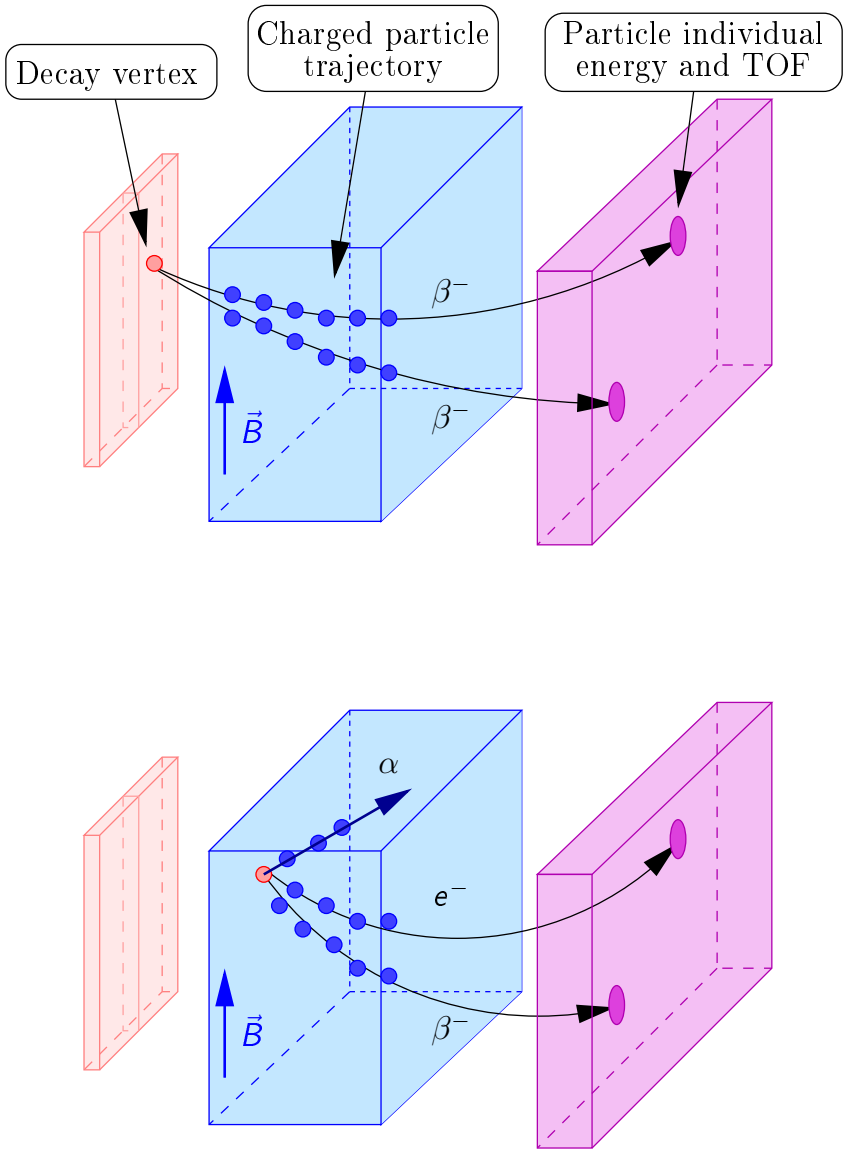

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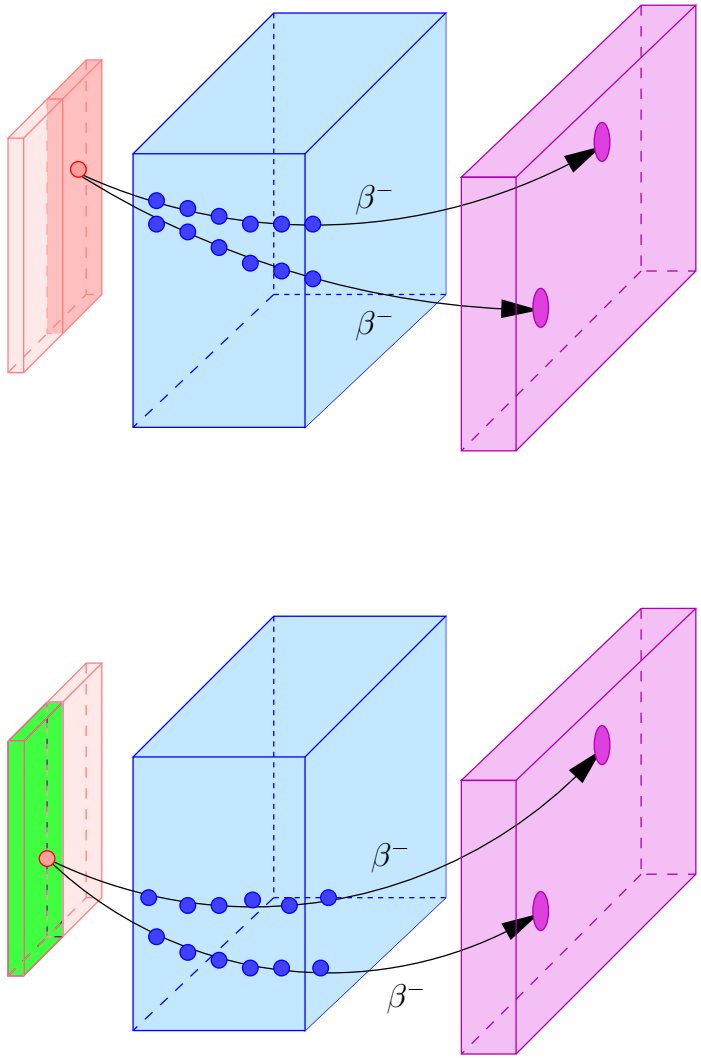


The NEMO-3 detector

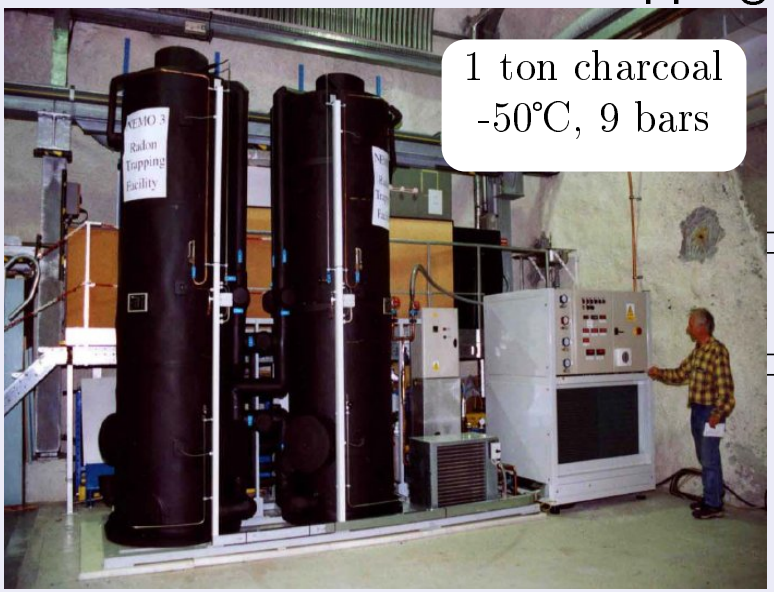
Sector interior view

- Calibration tubes:
  - ^{207}Bi : IC lines $\simeq$ 500 & 1000 keV
  - ^{90}Sr: β^- end point
  - ^{60}Co: 2 γ coincidence (timing)
- Daily calorimeter survey: Laser reference light through fibers for each scintillator block

Radon in the tracking volume

Radon trapping facility

- Phase 1: february 2003 – september 2004 (high radon data)
  $\rightsquigarrow$ 1 $0\nu\beta\beta$-like event/y/kg with $2.8 < E_1 + E_2 < 3.2$ MeV
- Installation of the radon trapping facility



Laboratory

Input: $A(^{222}\mathrm{Rn}) \simeq 15$ Bq/m^3

$\phi = 150$ m^3/h

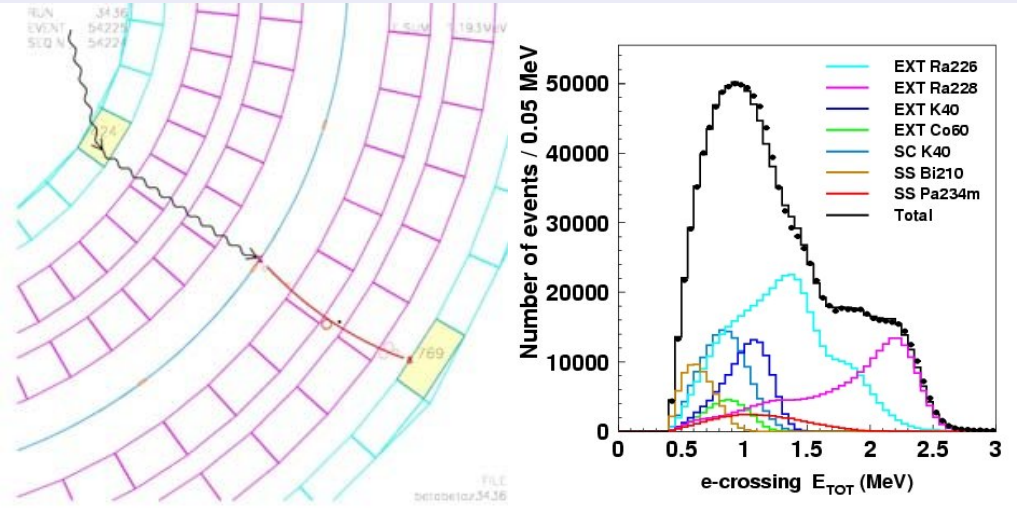
Output: $A(^{222}\mathrm{Rn}) < 15$ mBq/m^3

Tent

- Phase 2: since october 2004 (low radon data)
  - Inside the NEMO-3 tent: reduction factor by $\simeq$ 100-300
  - Inside the NEMO-3 tracking chamber: reduction factor by $\simeq$ 6

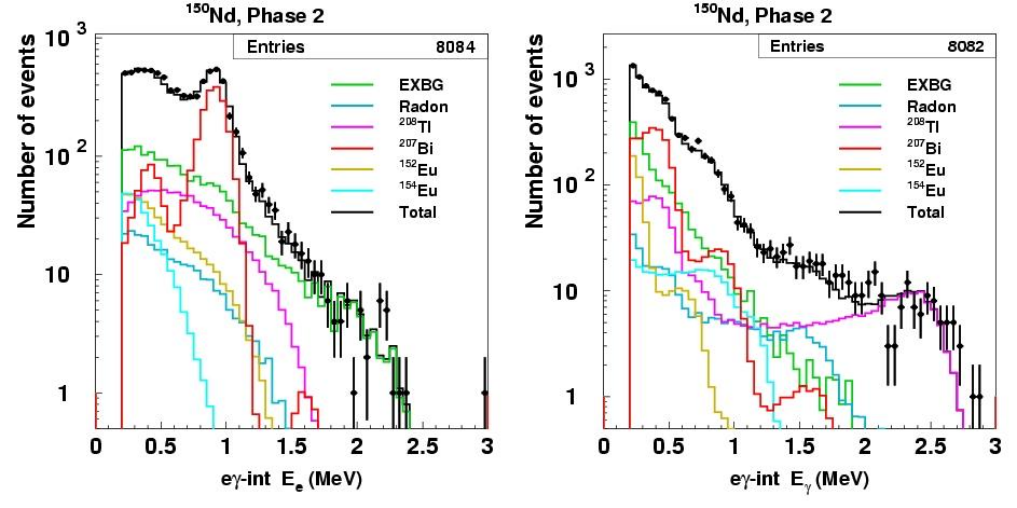
Measuring each components of the background

$e\gamma$ – *external* and *e*-crossing: external background



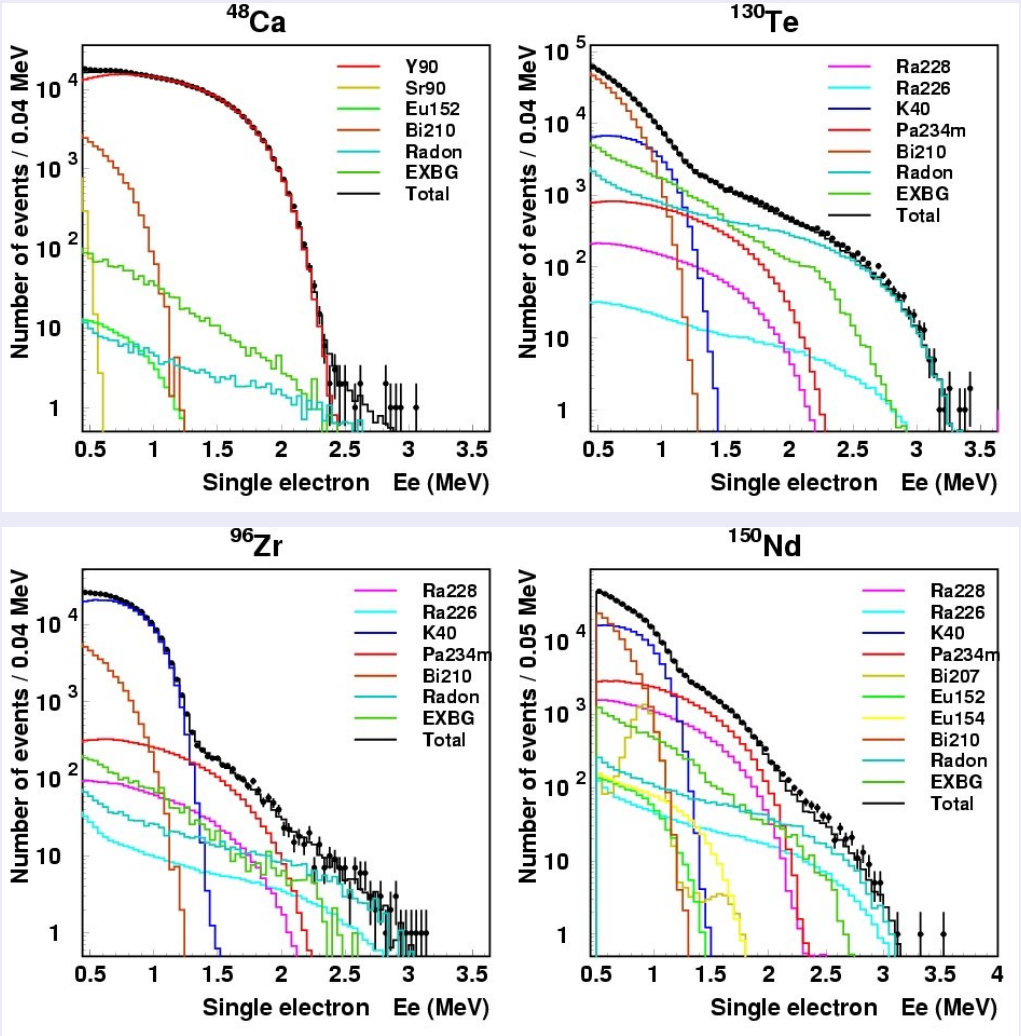
Measuring each components of the background

$e\gamma$, $e\gamma\gamma$, $e\gamma\gamma\gamma$: internal background from γ-emitters (^{208}Tl, ^{207}Bi...)



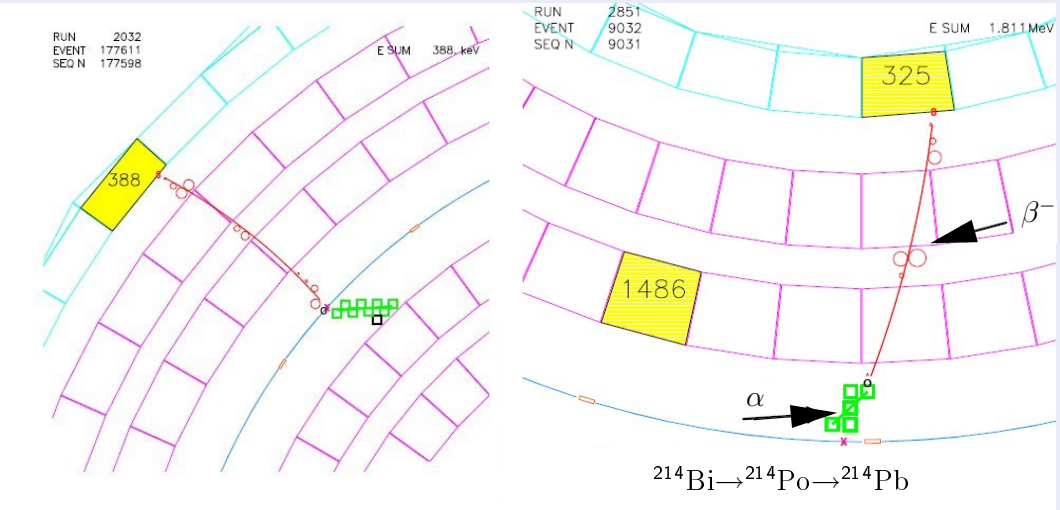
Measuring each components of the background

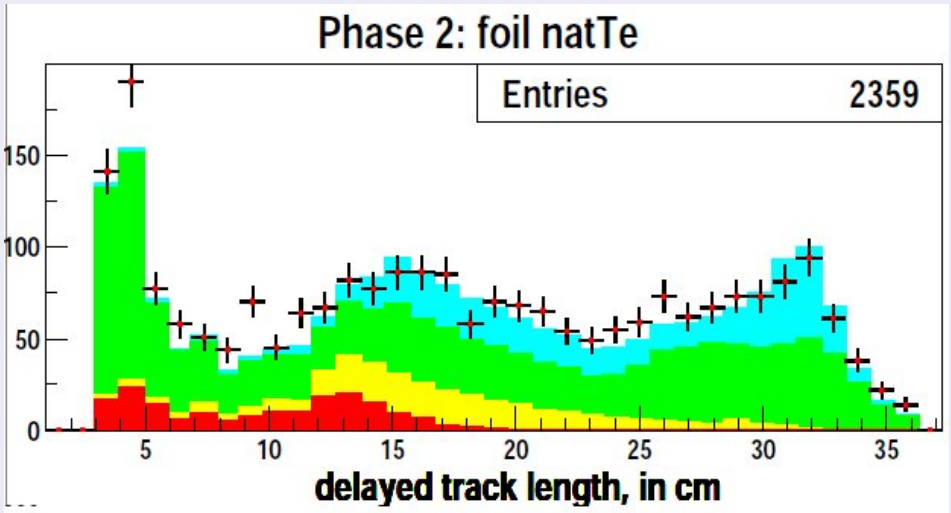
1e: internal background from pure β-emitters (^{234m}Pa, ^{40}K, ^{90}Y...)



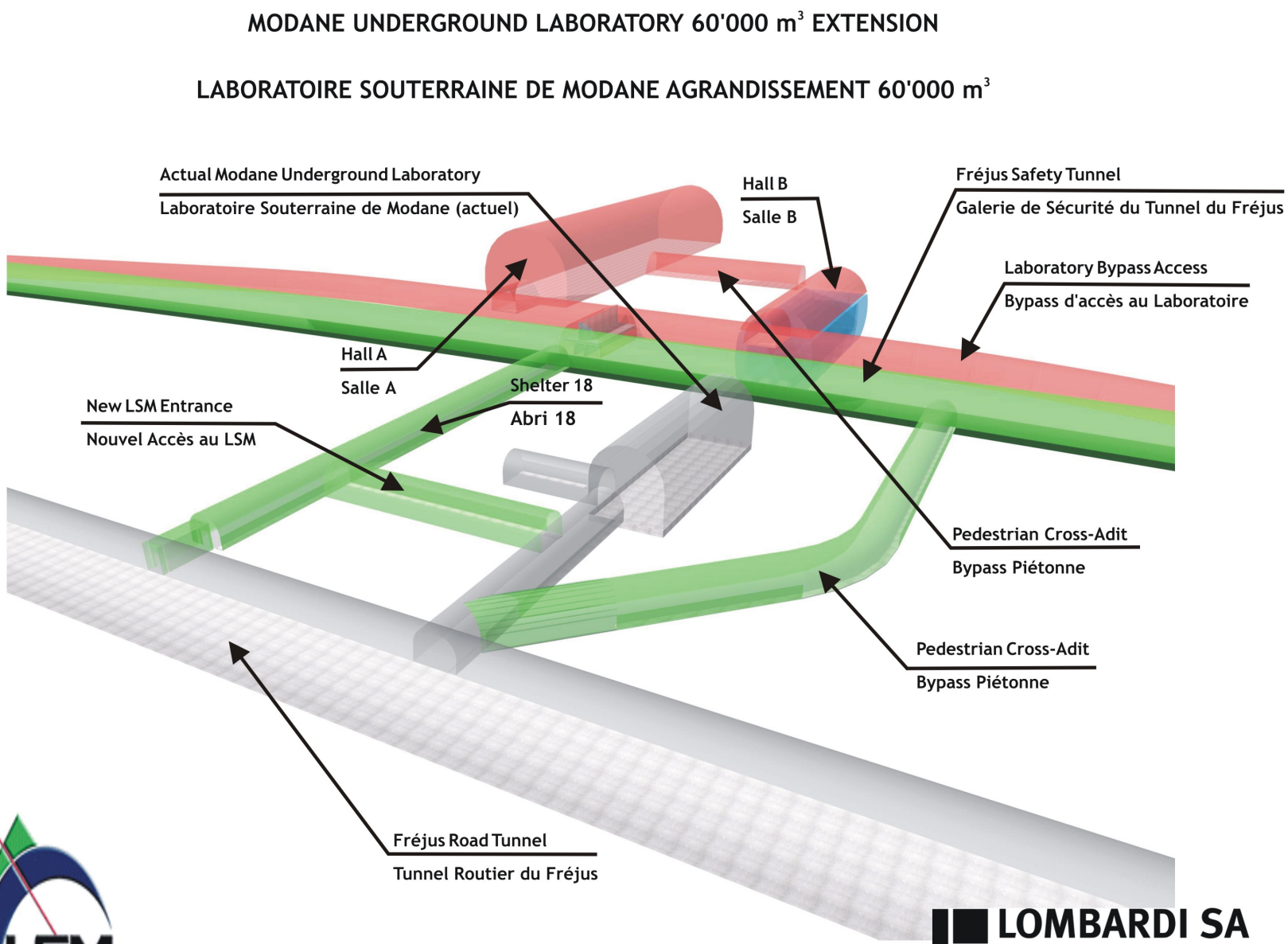
Measuring each components of the background

$e\alpha(\gamma)$: ^{214}Bi due to radon and from source foils





LSM future extension (from 2012)



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