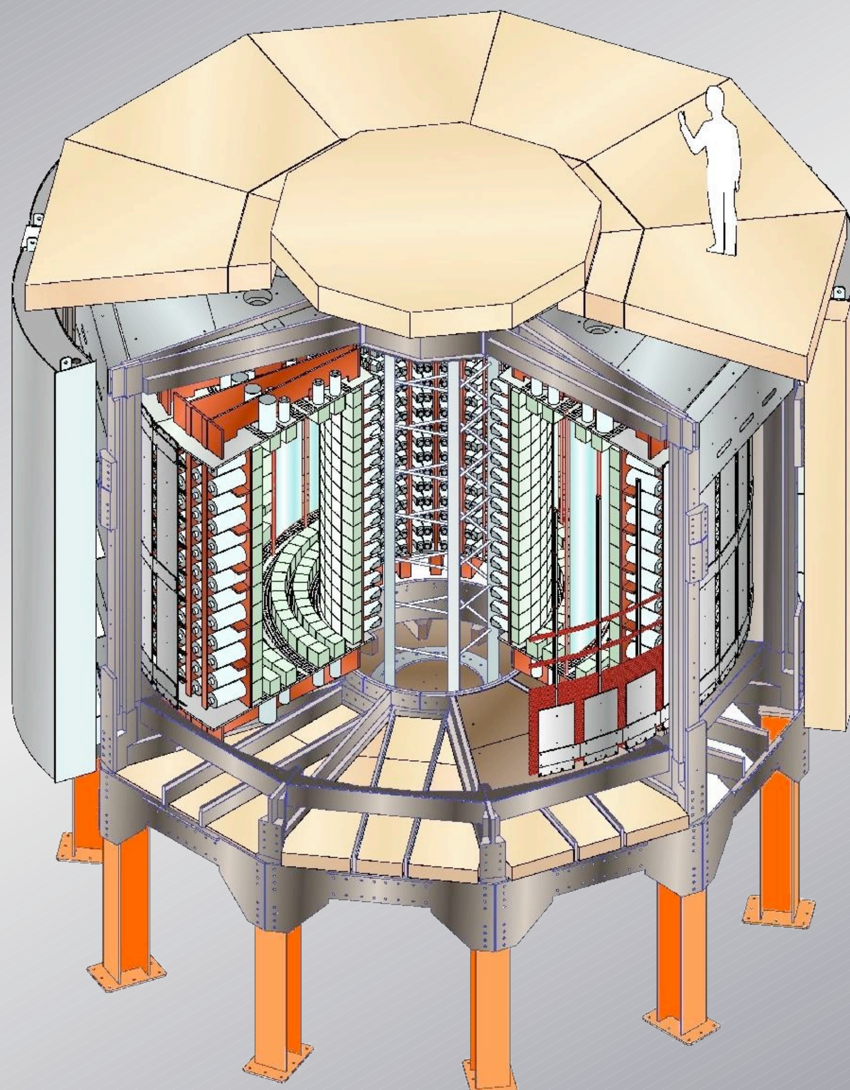
Double beta decay research in NEMO3 : an access to the nature of the neutrino



NEMO3 Collaboration

IN2P3
Institut National de Physique Nucléaire et de Physique des Particules

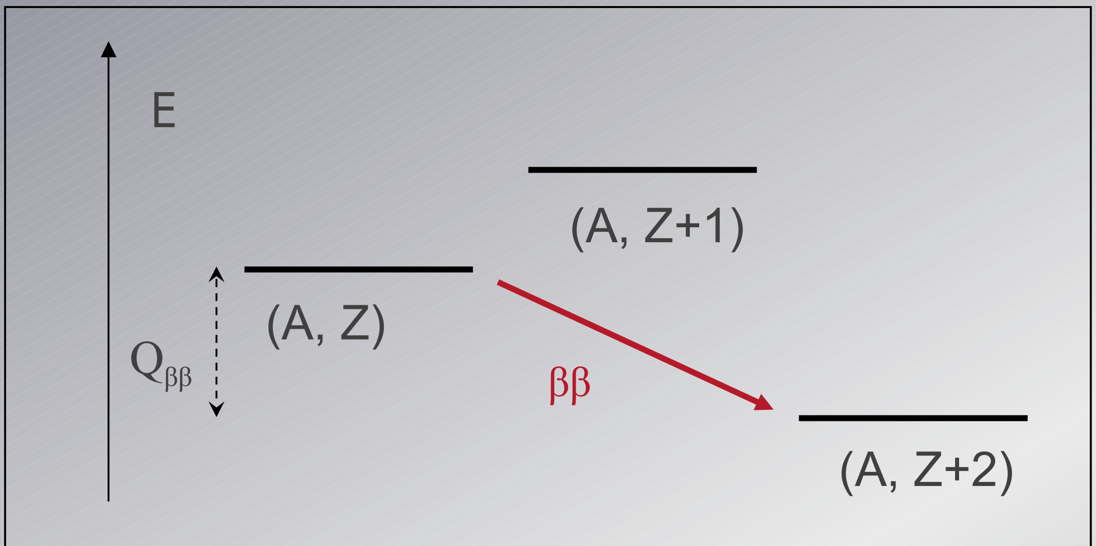
CENBG

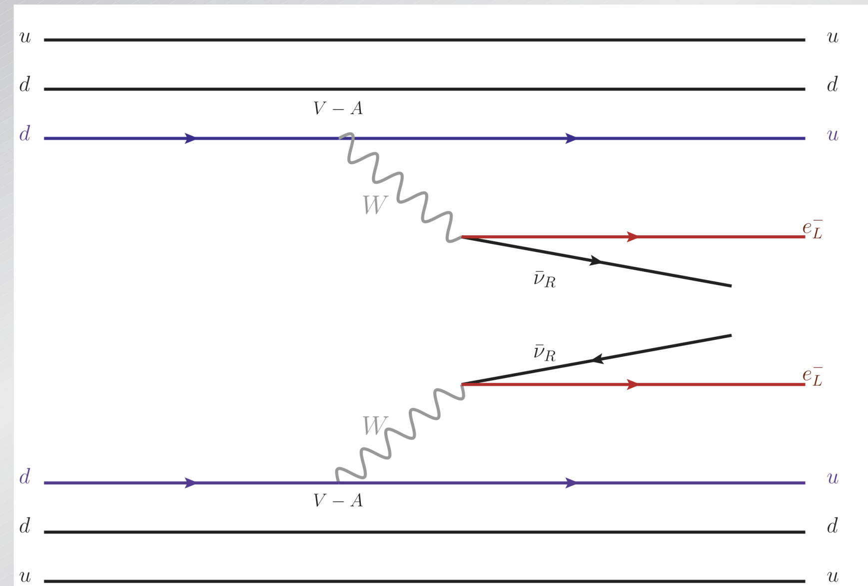
Christophe Hugon

Outline

- **The double beta decay and the Majorana model**
  - Some models beyond the Standard Model of double beta decay without neutrinos
  - The expected energy spectrum
- **NEMO3**
  - The NEMO3 Collaboration
  - Detector description
  - The 2β sources
  - Typical 2β selected event
- **Backgrounds**
- **$2\beta 2\nu$ results**
- **$2\beta 0\nu$ search**
- **Ongoing analysis and new perspectives**
- **Conclusion**

The double beta decay with neutrinos (2β2ν)





$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}$$

Allowed by the Standard Model

- Examples of nucleus which are in this favorable energetic configuration (7 used by NEMO3) :

$$^{100}\text{Mo},\ ^{82}\text{Se},\ ^{116}\text{Cd},\ ^{130}\text{Te},\ ^{150}\text{Nd},\ ^{96}\text{Zr},\ ^{48}\text{Ca},\ ^{76}\text{Ge},\ ^{136}\text{Xe}$$

Beyond the Standard Model : the Majorana model

To explain why the neutrino has a mass (oscillation) while the right handed component was never observed.

The Majorana model is a good candidate.
In this model, the neutrino becomes the two-component Weyl spinors :

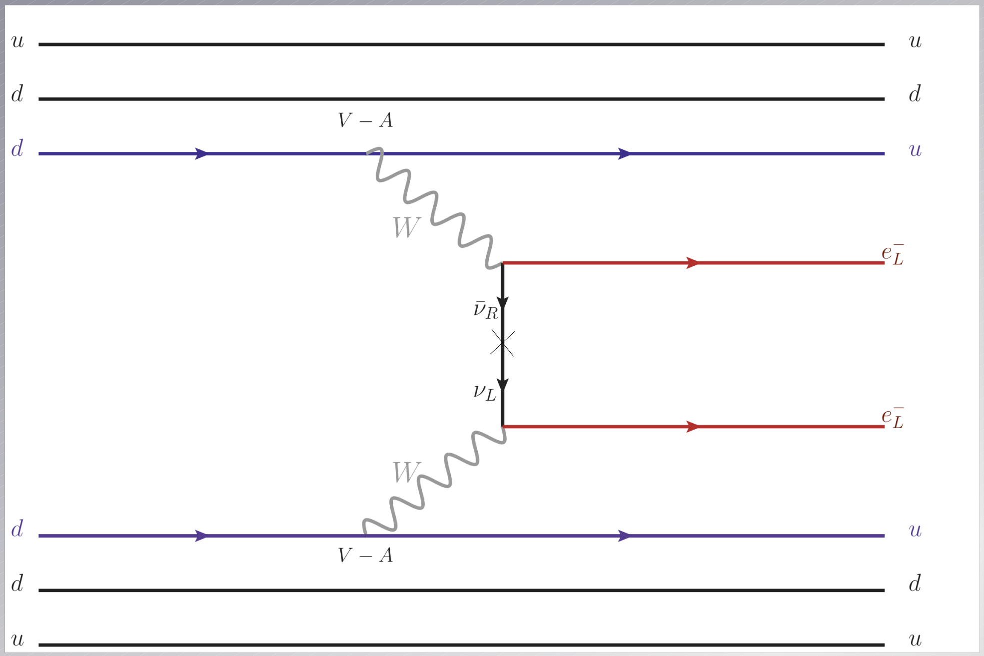
$$\nu^M = \frac{1}{\sqrt{2}}\left(\nu \pm \nu^C\right) = C\nu^M$$

Then, the lagrangian contain a mass term :

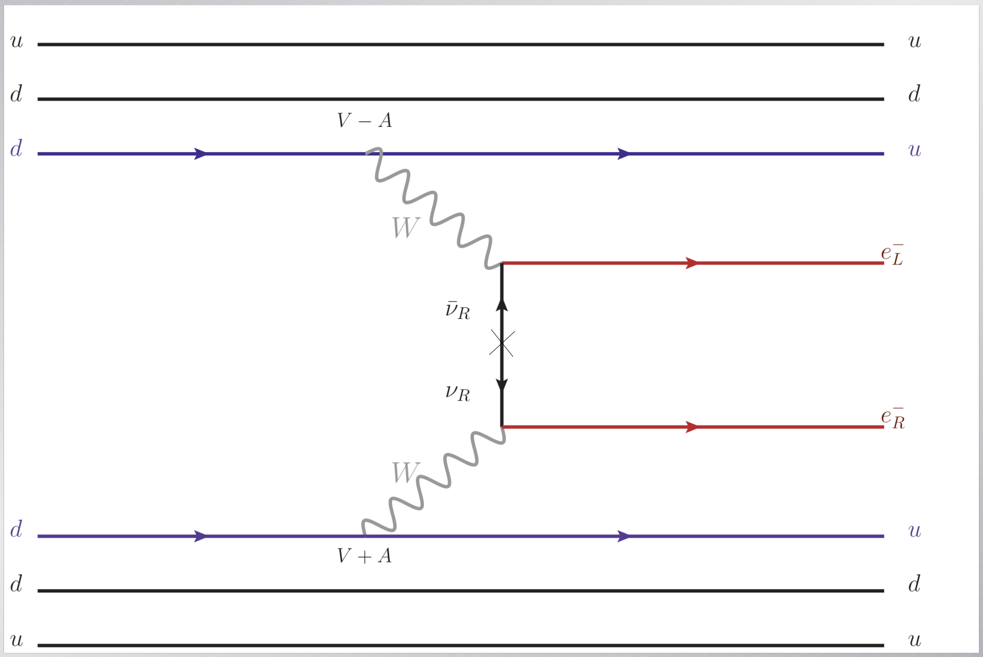
$$L_M = m_M \overline{\nu}\nu^C = \frac{1}{2} m_M \left(\overline{\nu_L}\nu_R^C + \overline{\nu_R}\nu_L^C\right)$$

Allows a double beta decay without neutrinos

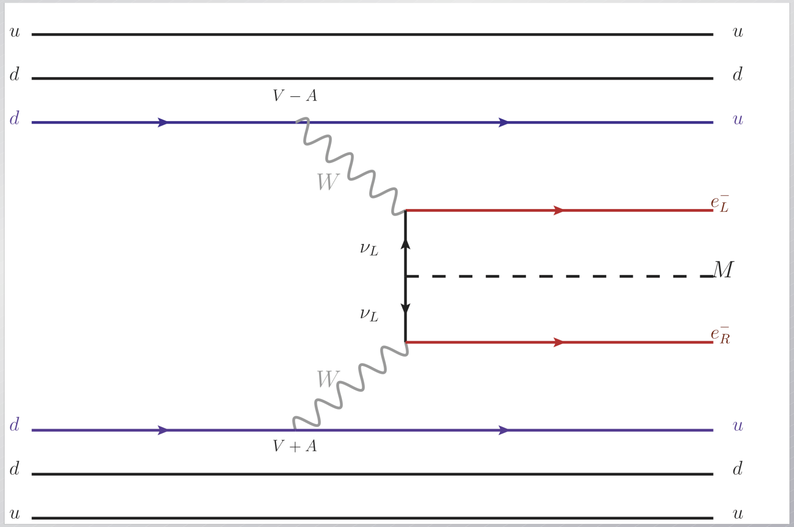
Some models of double beta decay with neutrino



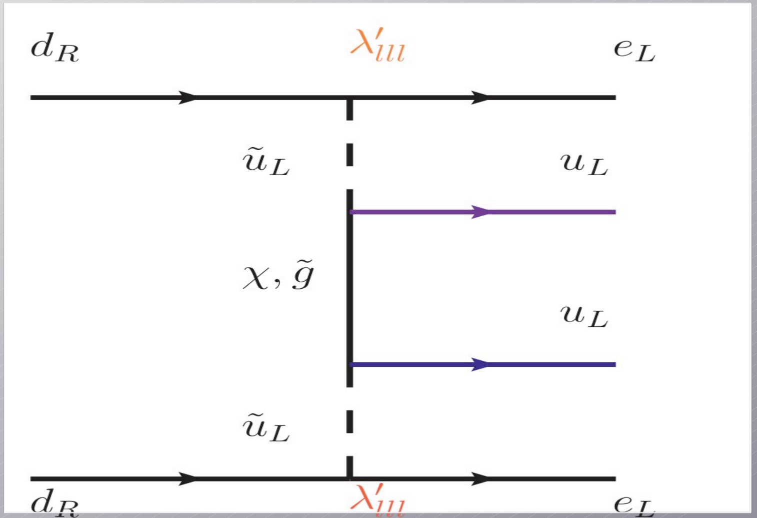
2β with Majorana neutrino



2β with Majorana neutrino and right current

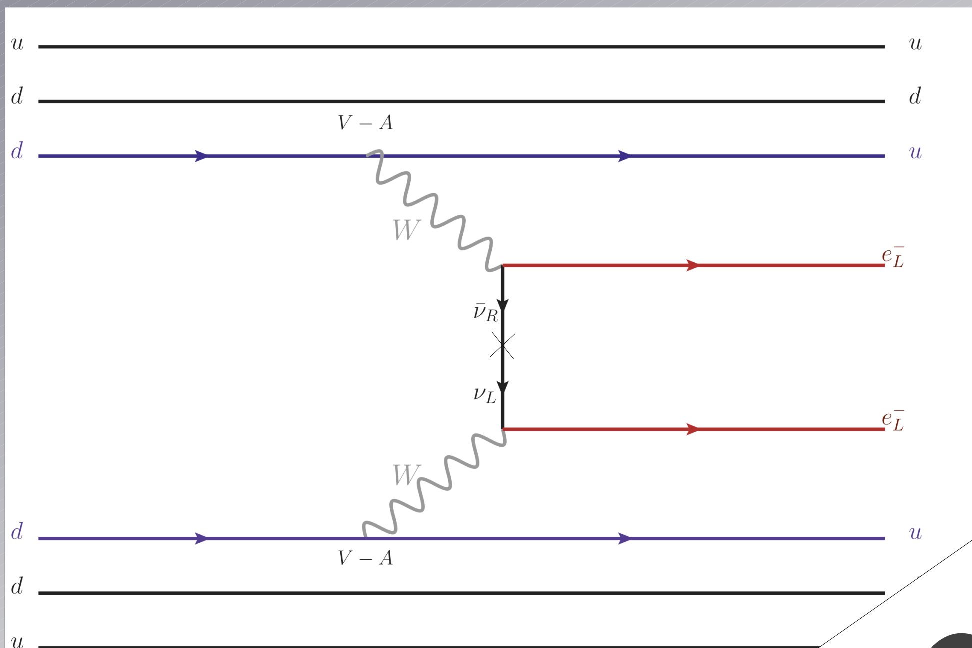


2β with Majoron emission

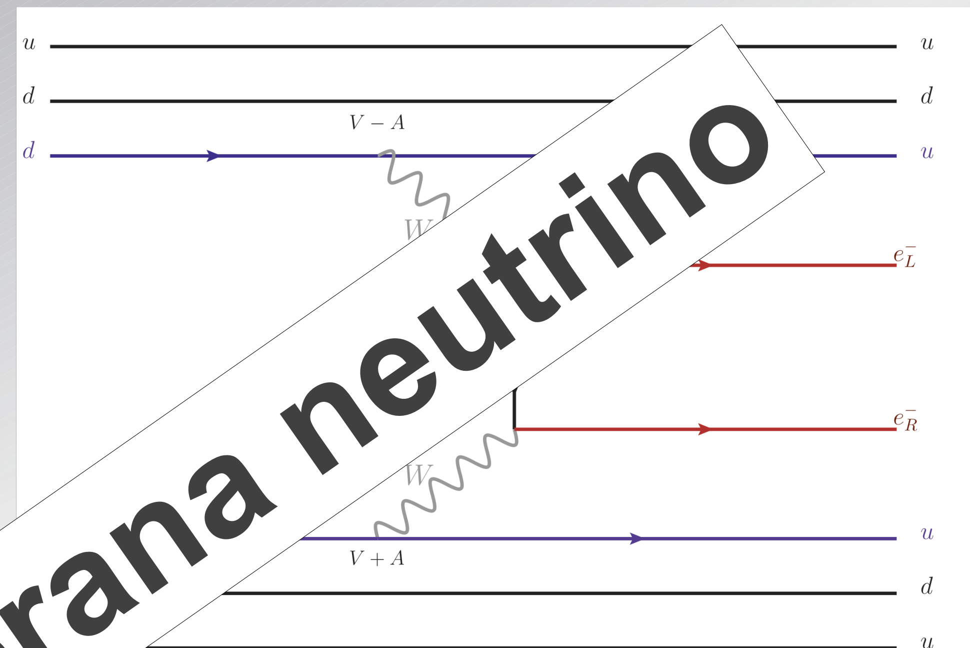


2β in SuSy

Some models of double beta decay with neutrino

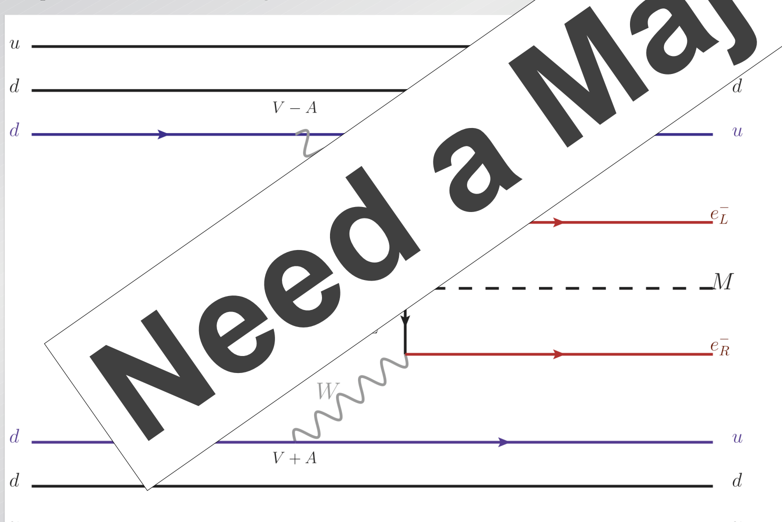


2β with Majorana neutrin

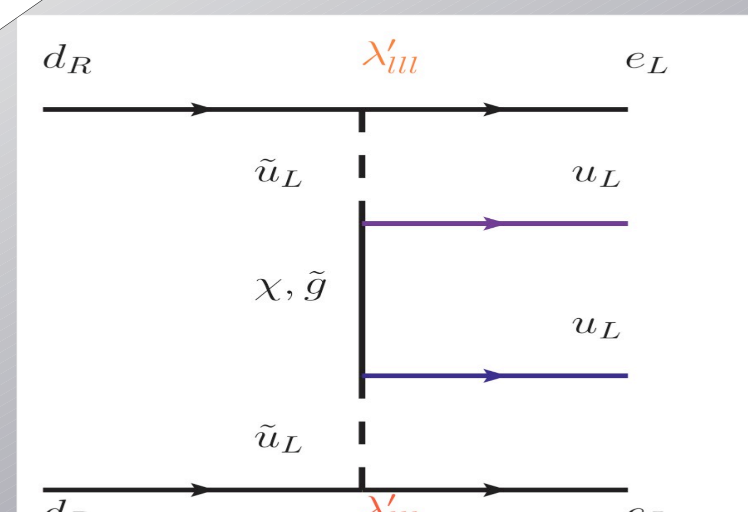


with Majorana neutrino and right current

Need a Majorana neutrino



2β with Majoron emission

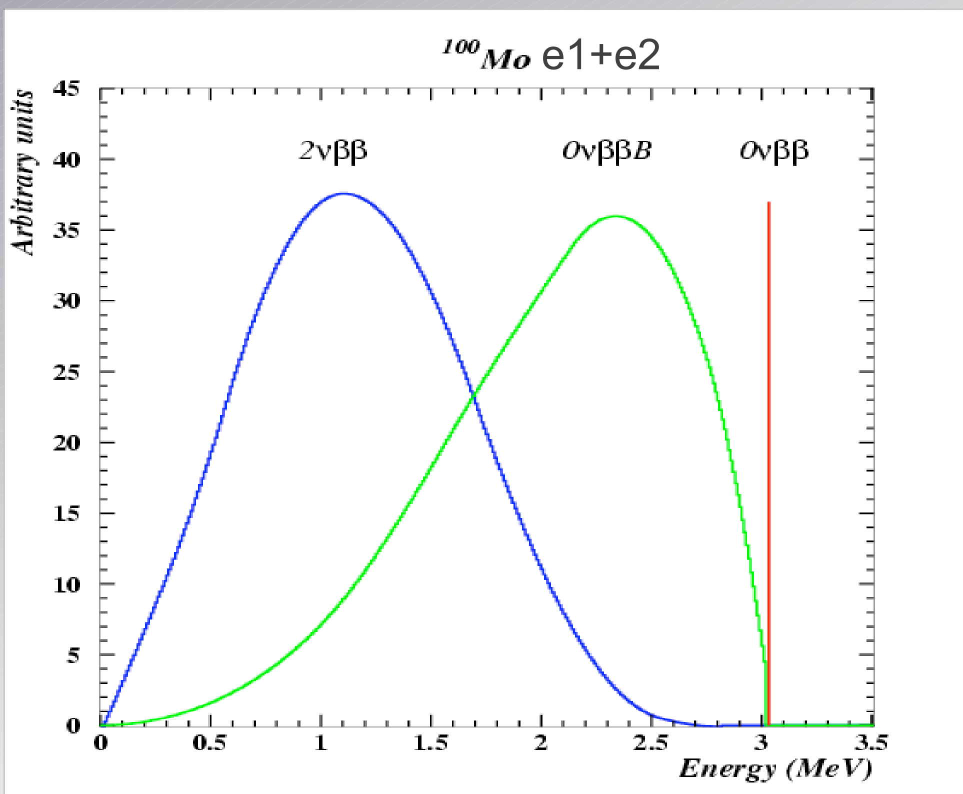


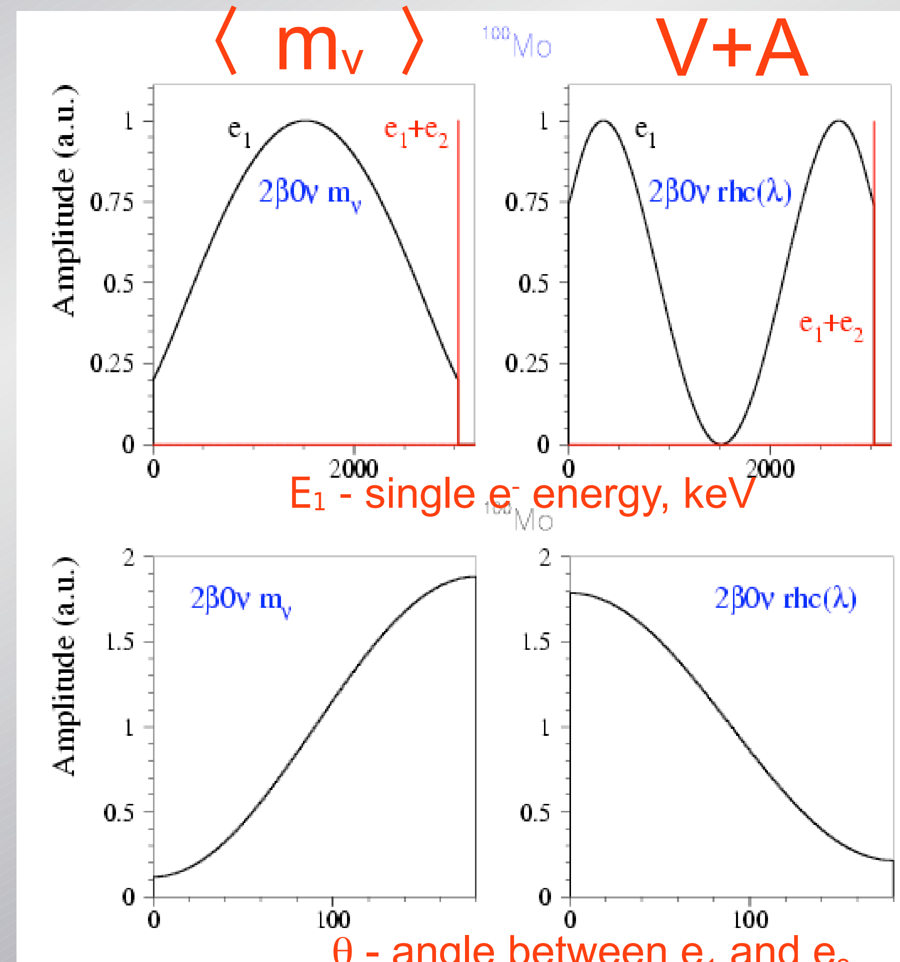
2β in SuSy

The expected spectrum

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}\left(Q_{\beta\beta}, Z\right)\left|M^{0\nu}\right|^2 \eta^2$$

η can be due to mass mechanism, V+A, majoron, SUSY, ... with different topology in the final state

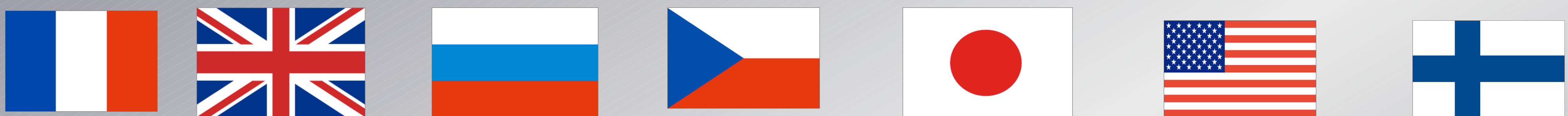


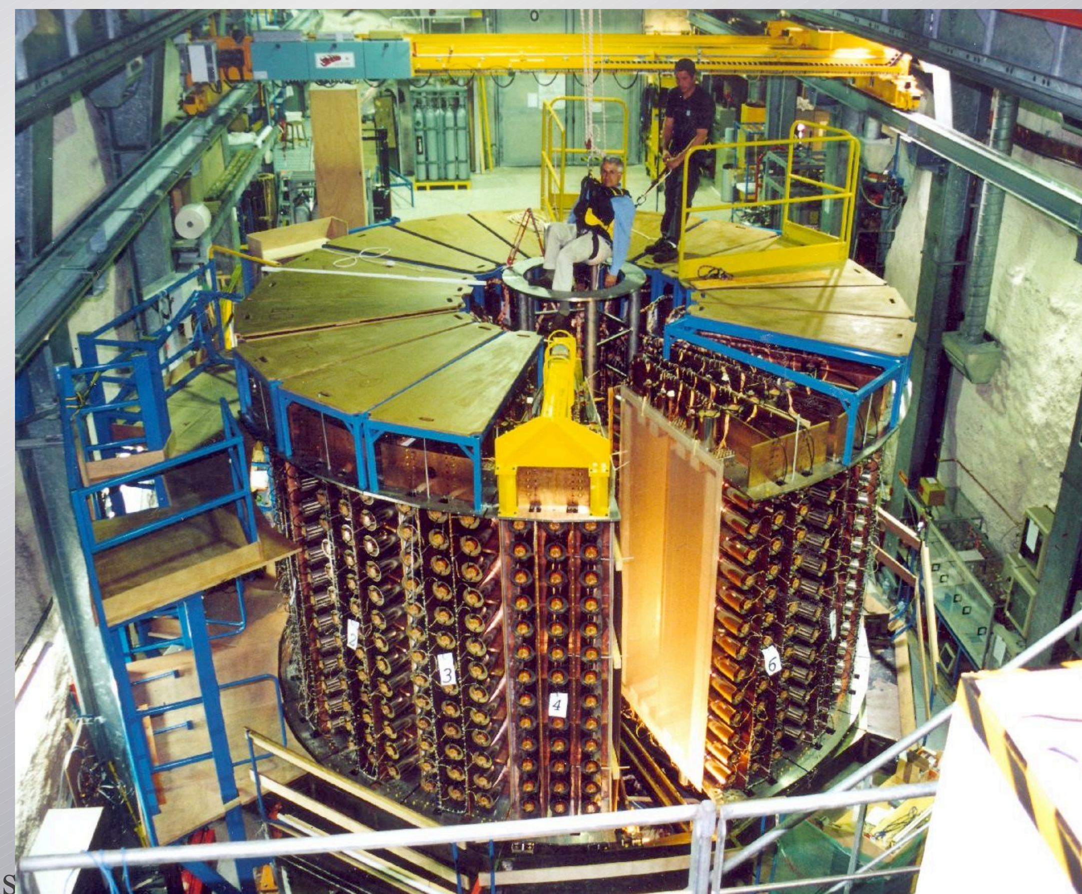


NEMO3 Collaboration

(Neutrino Ettore Majorana Observatory)

50 physicists, 17 institutions

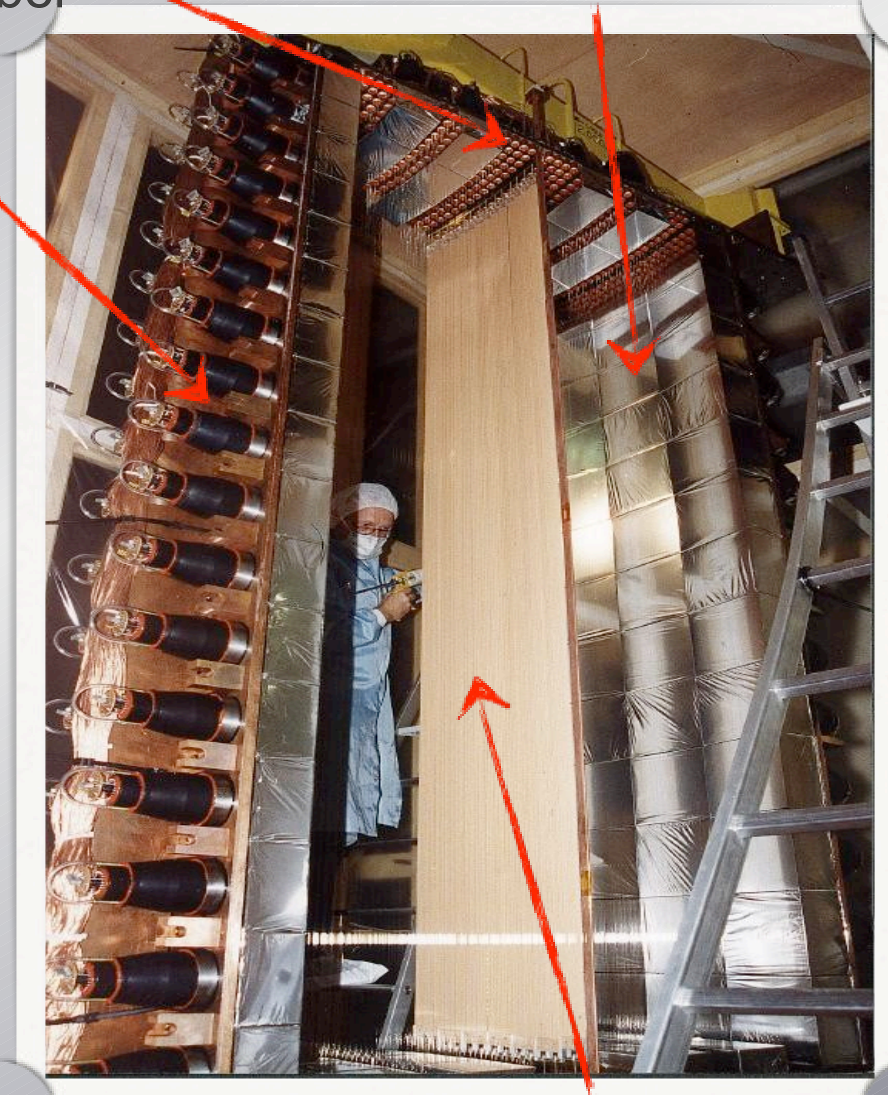




Chris

NEMO3

- A calorimeter for energy and time measurements
- A tracker for trajectory reconstruction
- 10 kg of 2β isotopes:
  - 7kg ^{100}Mo
  - 1kg ^{82}Se
  - smaller quantities of ^{116}Cd, ^{150}Nd, ^{48}Ca, ^{96}Zr, ^{130}Te
- 25 G magnetic field to identify e^-, e^+, ɣ, α
-

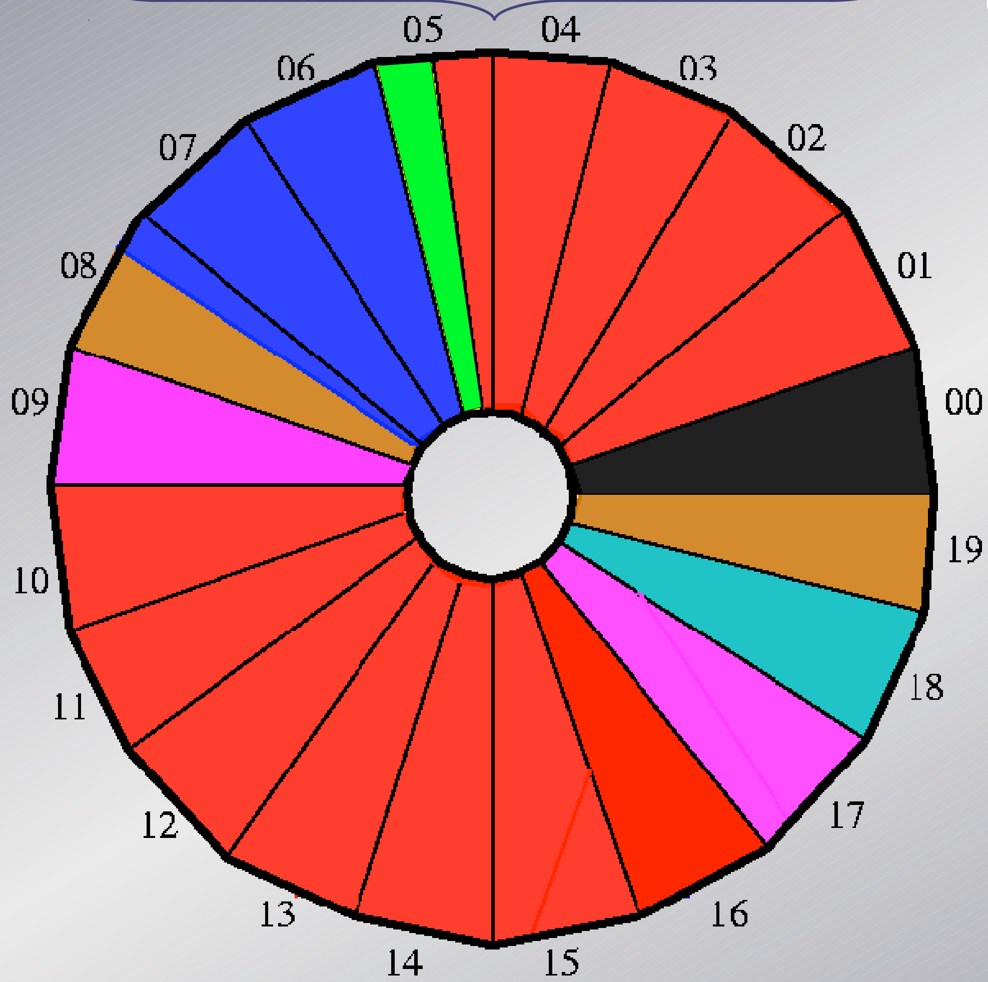


The sources

Measure 2β0ν

^{100}Mo 6,914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0,932 kg
$Q_{\beta\beta}$ = 2995 keV



Measure 2β2ν

^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9,4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37,0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7,0 g
$Q_{\beta\beta}$ = 4272 keV

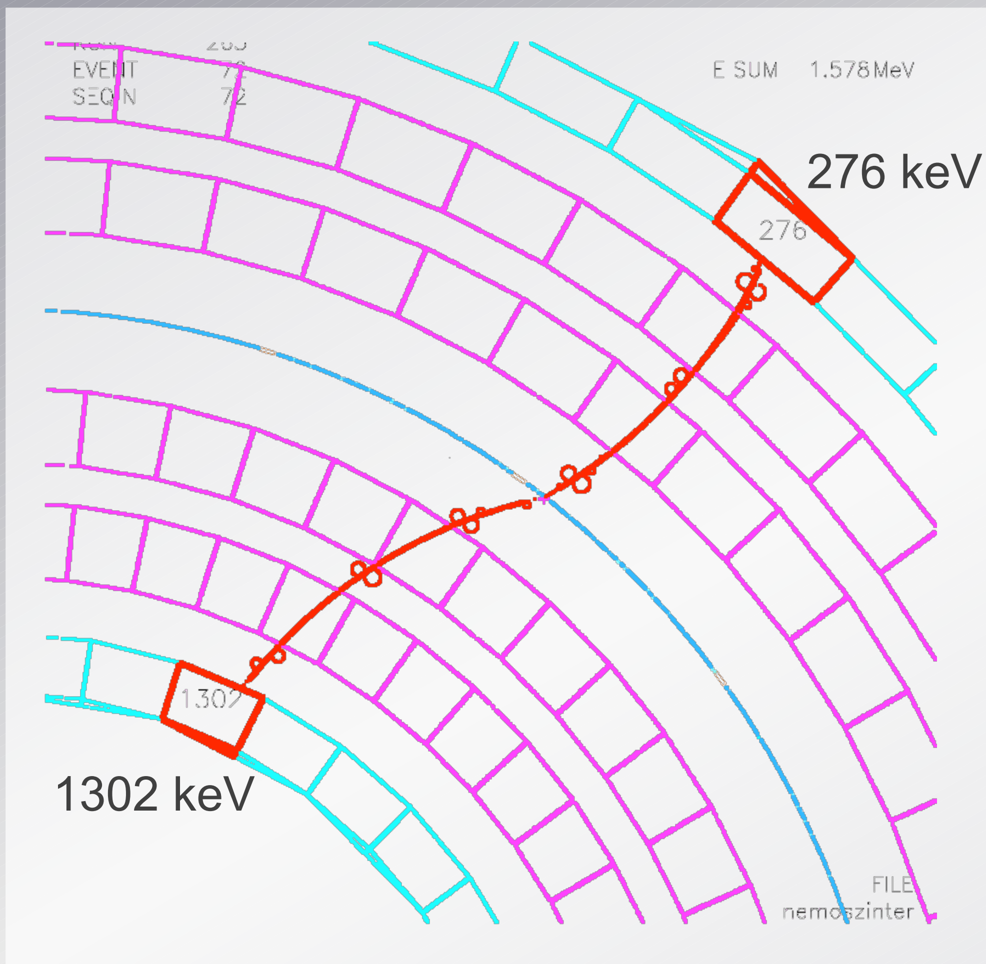
^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

^{nat}Te 491 g

Cu 621 g

External background measurement

Typical 2β selected event

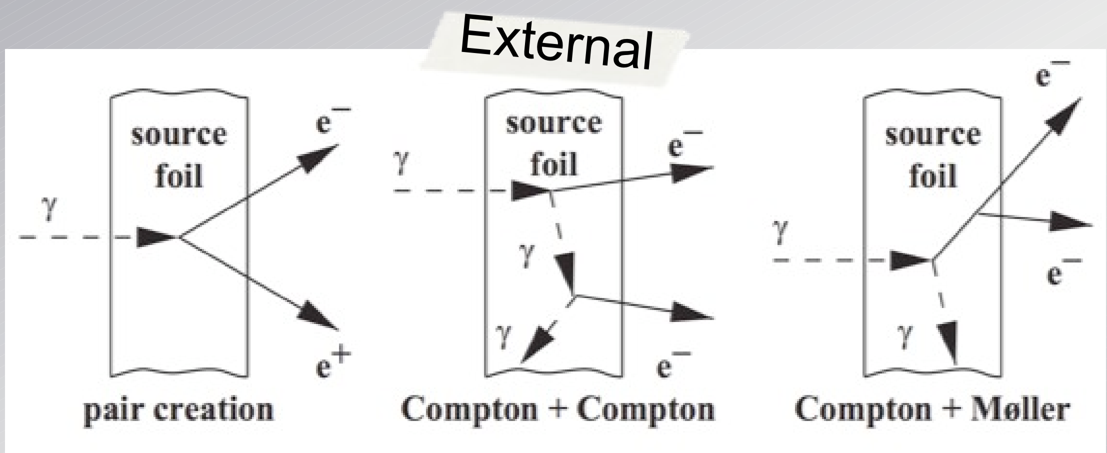


Selection criteria :

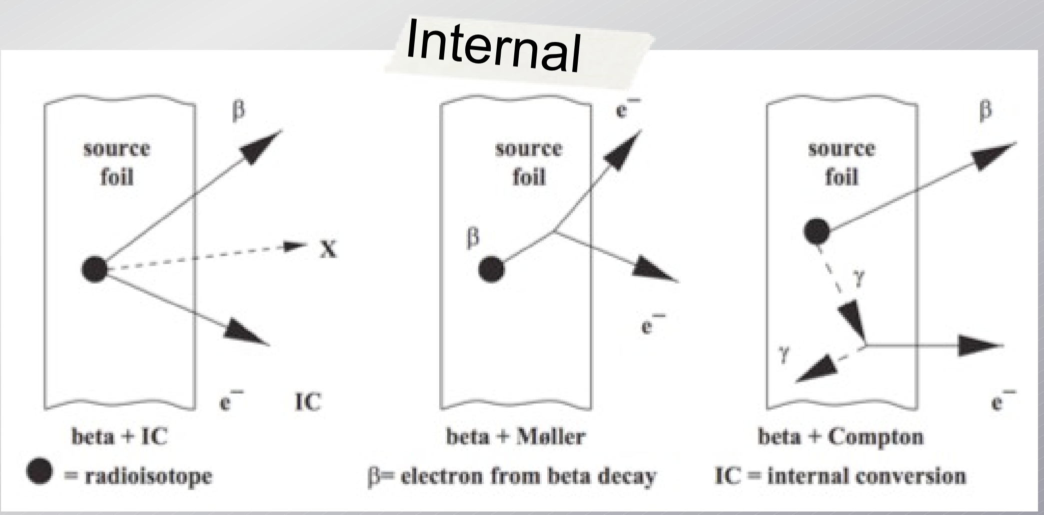
- 2 tracks with negative curvature with 2 associated PMTs with more than 200 keV
- Common vertex on foil
- Internal hypothesis based on PMTs timing
-No isolated PMT
-No delayed track

Background origins

- Cosmics
- Neutrons

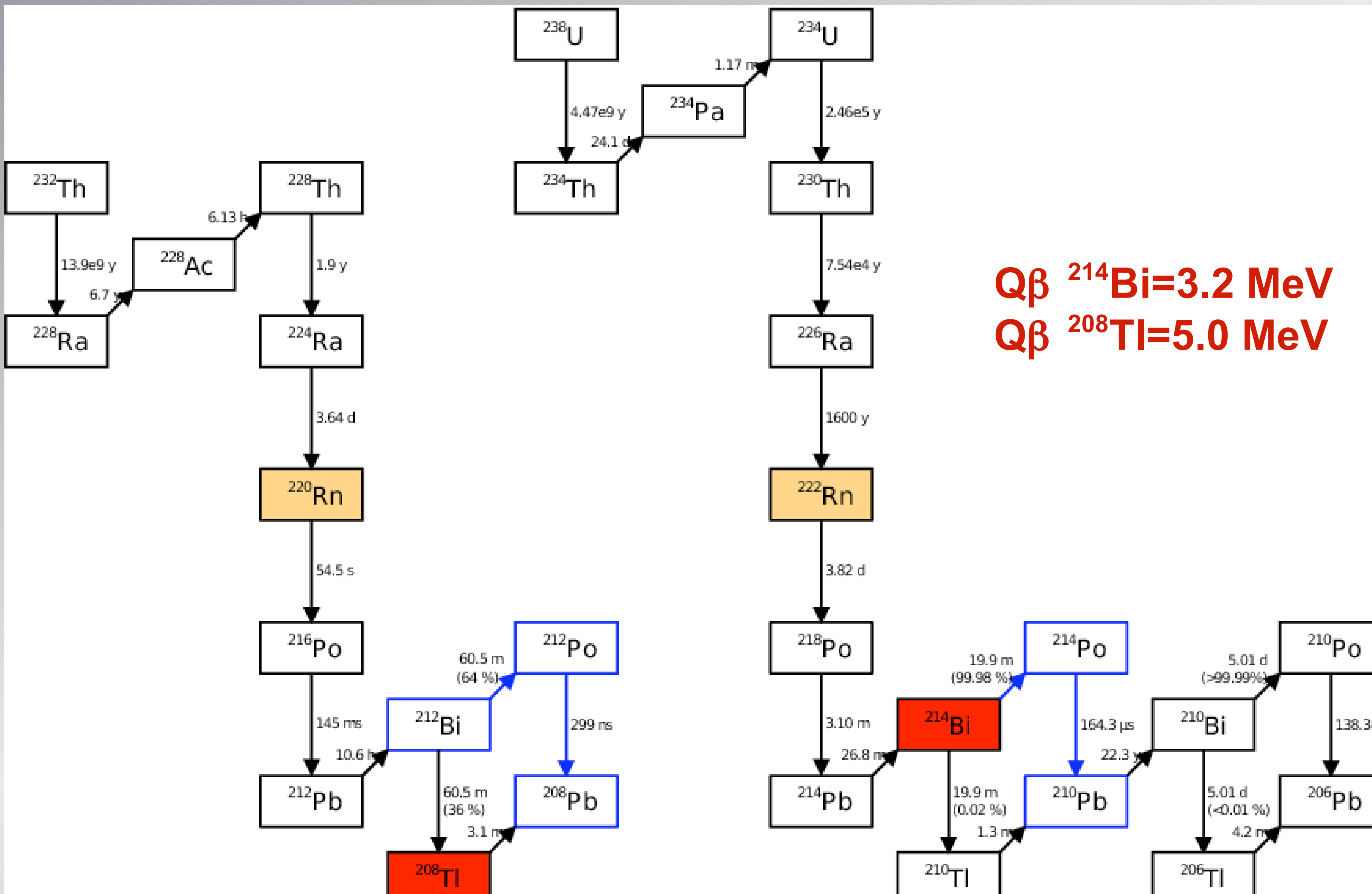


- Natural radioactivity
  ^{214}Bi, ^{208}Tl



Thanks to a good discrimination of the particles, NEMO3 can study the background with independent and hight statistic channels

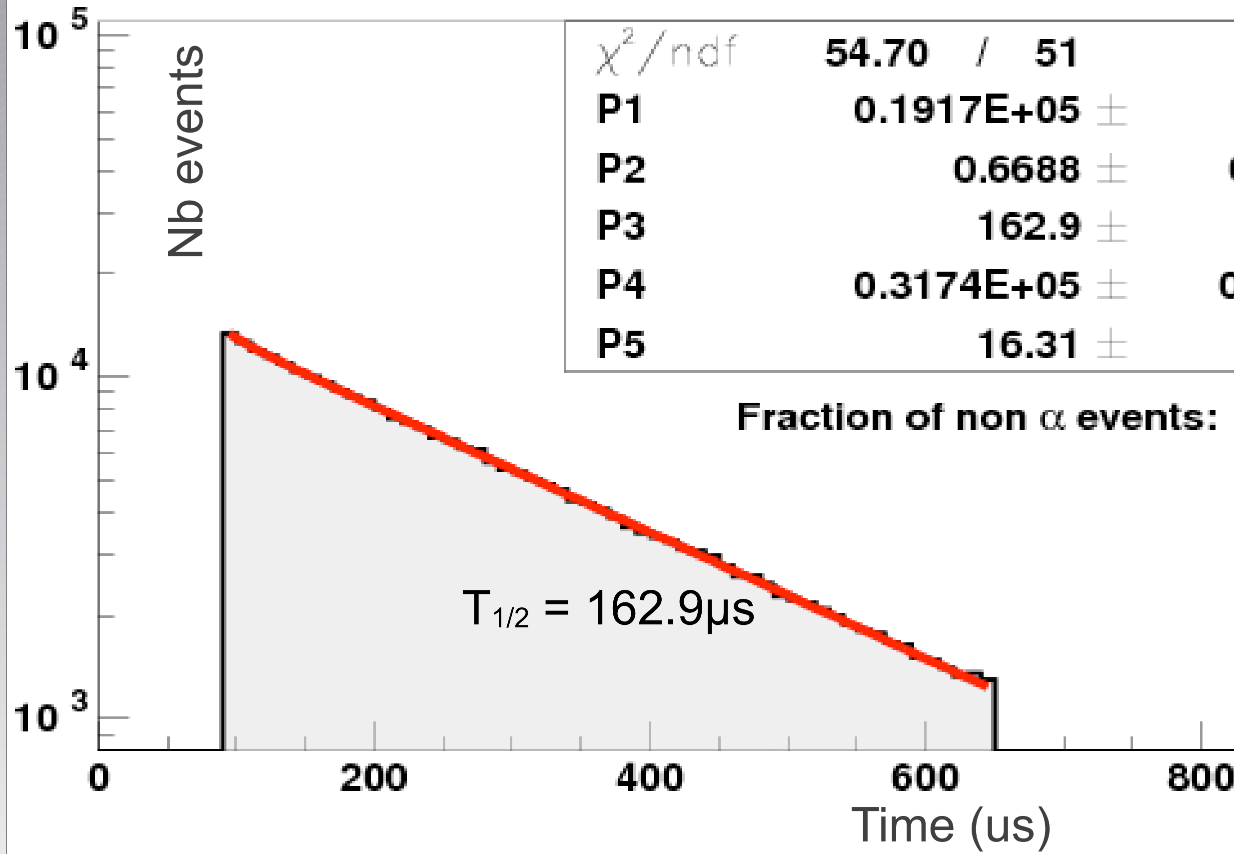
The natural radioactive chains

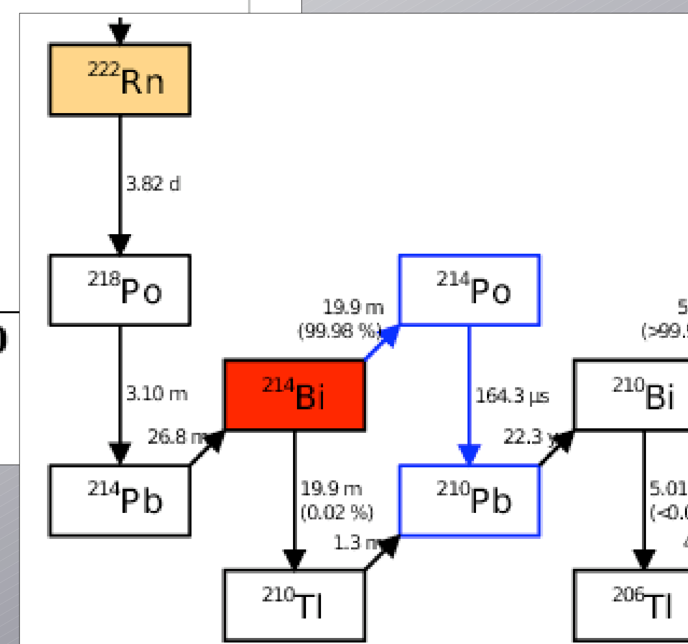


Qβ ^{214}Bi=3.2 MeV
Qβ ^{208}Tl=5.0 MeV

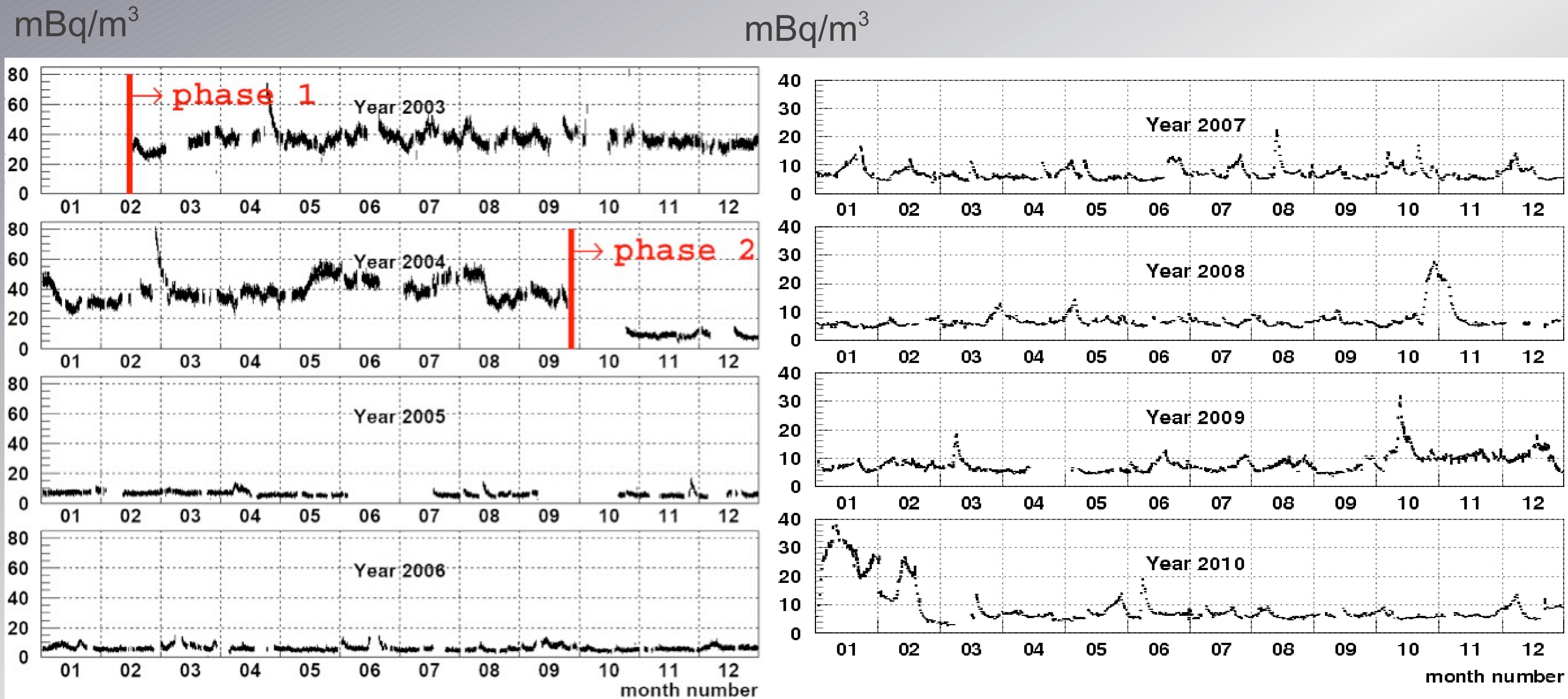
Measurement of ^{222}Rn in NEMO3

^{214}Bi to ^{214}Po decay measurement thanks to the delayed alpha emission inside NEMO3 ($1e^- + 1\alpha_{delayed}$)





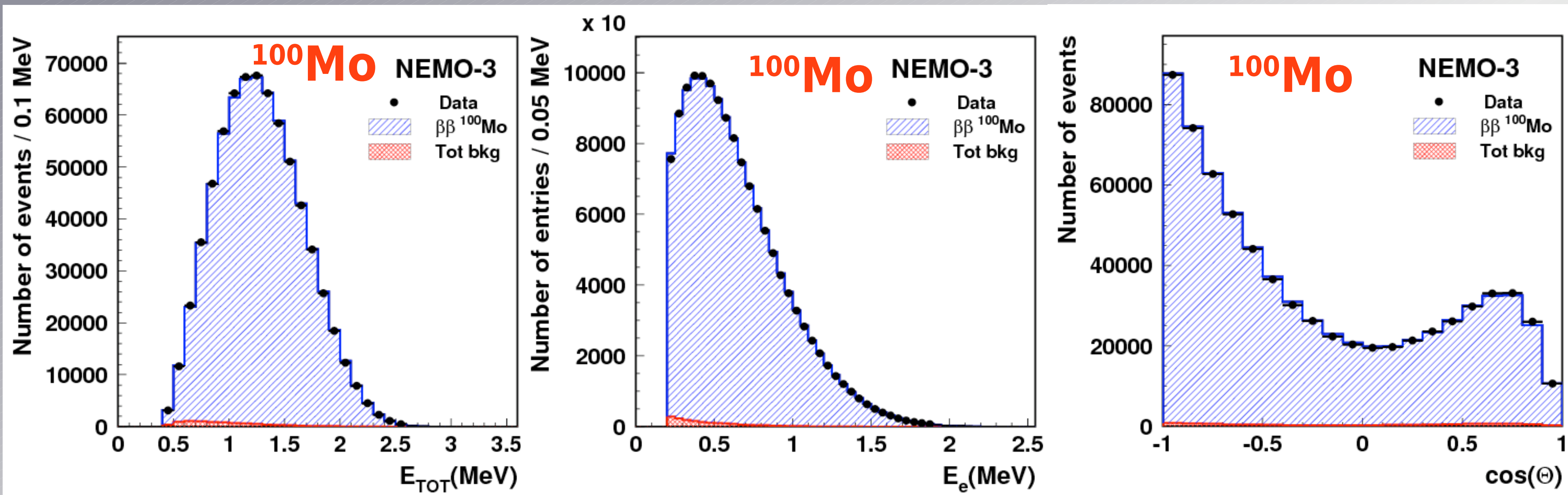
Measurements of ^{222}Rn activity in the gas of tracker



Phase 2 : Installation of the free-radon air factory and anti-radon tent around NEMO3

2β results of NEMO3

$2\beta2\nu$ ^{100}Mo Phase 2 data - 7kg x 4 years



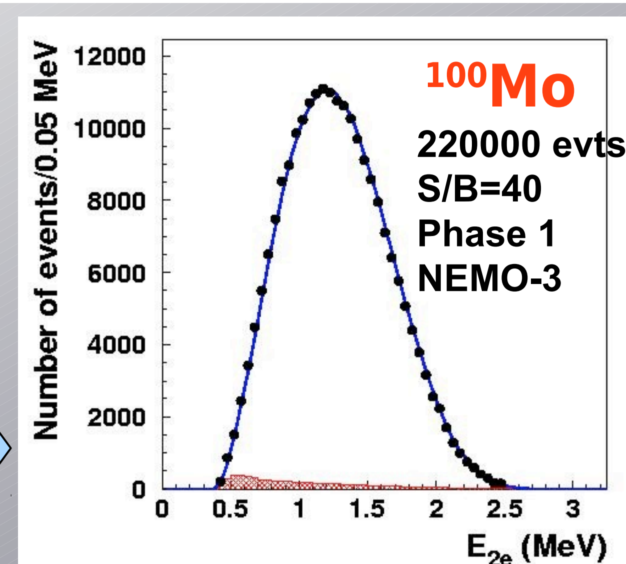
- 700,000 two-electron events from ^{100}Mo foils
- S/B = 76
- $\varepsilon(2\beta2\nu) = 0.043$

$T_{1/2}(2\beta2\nu)$ = [7.16 ± 0.01 (stat)] 10^{18} y PRELIMINARY

To be compared with the published NEMO-3 results obtained with Phase 1 data

$T_{1/2}$ = [7.11 ± 0.02(stat) ± 0.54(syst)] 10^{18} y

Phys.Rev.Lett. 95(2005)483

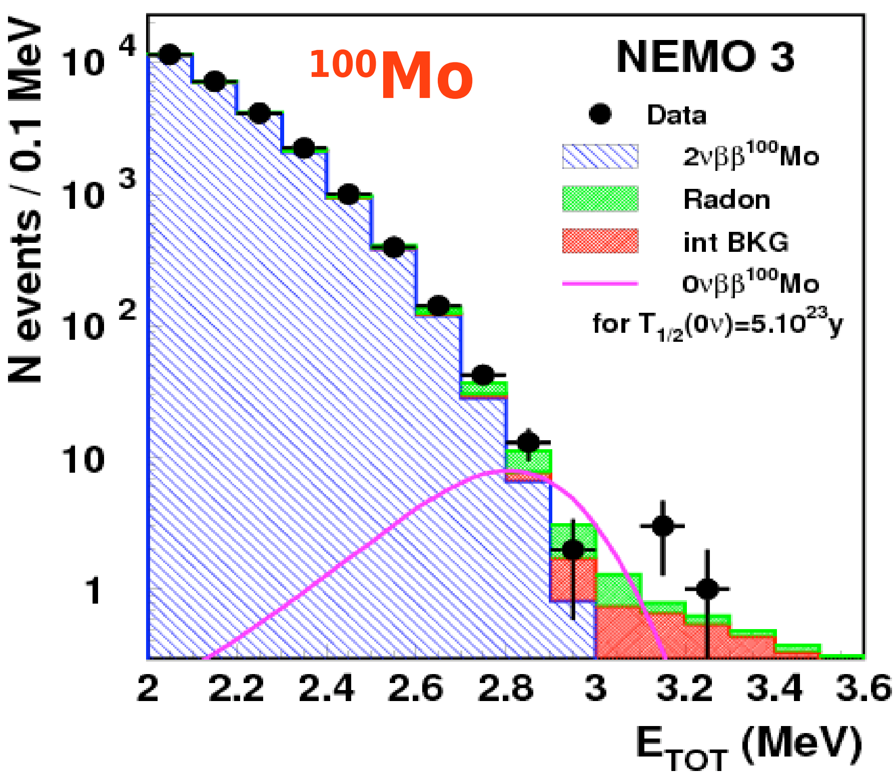


$2\beta2\nu$ Results

Isotope	Mass (g)	$Q_{\beta\beta}$(keV)	$T_{1/2}(2\nu)$ (10^{19}yrs)	S/B	Comment	Reference
^{82}Se	932	2996	9.6 ± 1.0	4	World's best!	Phys.Rev.Lett. 95(2005) 483
^{116}Cd	405	2809	2.8 ± 0.3	10	World's best!	
^{150}Nd	37	3367	0.9 ± 0.07	2.7	World's best!	Phys. Rev. C 80, 032501 (2009)
^{96}Zr	9.4	3350	2.35 ± 0.21	1	World's best!	Nucl.Phys.A 847(2010) 168
^{48}Ca	7	4271	4.4 ± 0.6	6.8 (h.e.)	World's best!	
^{100}Mo	6914	3034	0.71 ± 0.05	80	World's best!	Phys.Rev.Lett. 95(2005) 483
^{130}Te	454	2533	70 ± 14	0.5	First direct detection!!!	Phys. Rev. Lett. 107, 062504 (2011)

2β0ν search

^{100}Mo : 7kg × 4.5 years

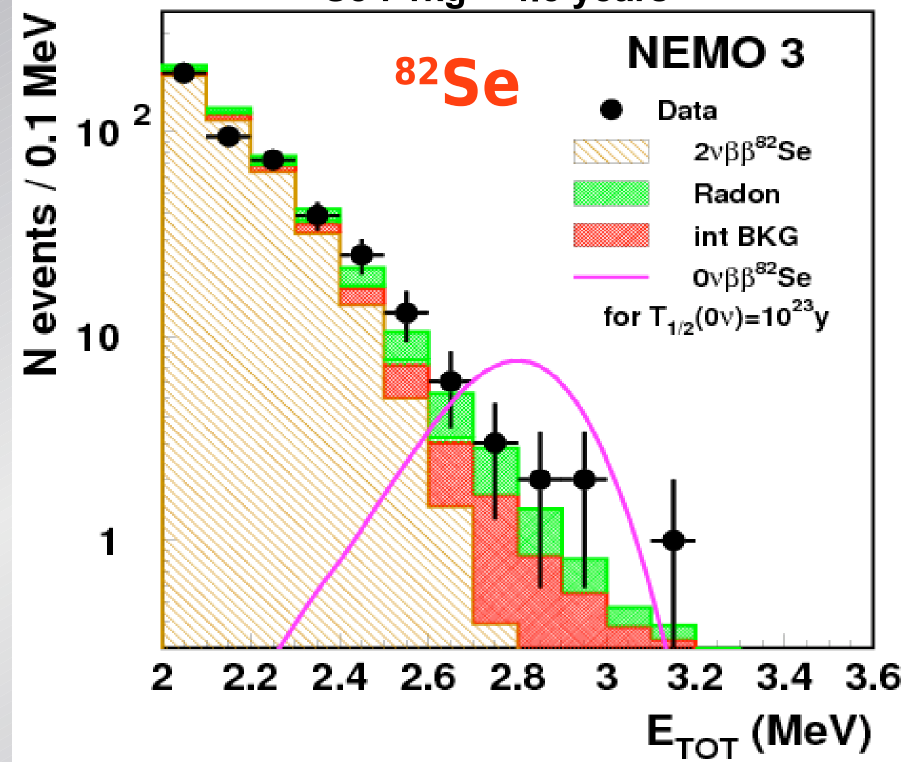


Total 0ν efficiency ε = 0.13

^{100}Mo $T_{1/2}(0\nu) > 1.0 \cdot 10^{24}$ y @90% C.L.

$\langle m_\nu \rangle$ < 0.31 – 0.96 eV NME [1-5]

^{82}Se : 1kg × 4.5 years



Total 0ν efficiency ε = 0.14

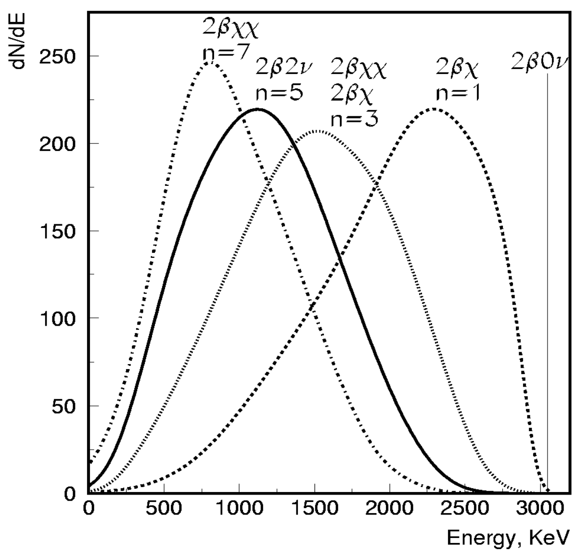
^{82}Se $T_{1/2}(0\nu) > 3.2 \cdot 10^{23}$ y @90% C.L.

$\langle m_\nu \rangle$ < 0.94 – 1.71 eV NME [1-4]

$\langle m_\nu \rangle$ < 2.6 eV NME [6]

[1] QRPA M.Kortelainen and J.Suhonen, Phys.Rev. C 75 (2007) 051303(R)
[2] QRPA M.Kortelainen and J.Suhonen, Phys.Rev. C 76 (2007) 024315
[3] QRPA F.Simkovic, et al. Phys.Rev. C 77 (2008) 045503
[4] IBM2 J.Barrea and F.Iachello Phys.Rev.C 79(2009)044301
PHFB [5] P.K. Rath et al., Phys. Rev. C 82 (2010) 064310
SM [6] E.Caurrier et al. Phys.Rev.Lett 100 (2008) 052503

$2\beta2\nu$ with Majoron, V+A and excited states



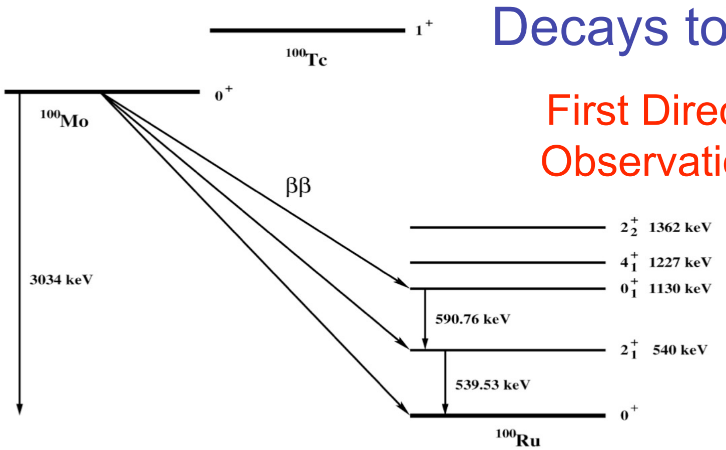
Majoron emission would distort the shape of the energy sum spectrum

	V+A*	n=1**	n=2**	n=3**	n=7**
Mo	$>5.7\cdot10^{23}$ $\lambda<1.4\cdot10^{-6}$	$>2.7\cdot10^{22}$ $G_{ee}<(0.4-1.8)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1.0\cdot10^{22}$	$>7\cdot10^{19}$
Se	$>2.4\cdot10^{23}$ $\lambda<2.0\cdot10^{-6}$	$>1.5\cdot10^{22}$ $G_{ee}<(0.7-1.9)\cdot10^{-4}$	$>6\cdot10^{21}$	$>3.1\cdot10^{21}$	$>5\cdot10^{20}$

n: spectral index, limits on half-life in years

* Phase I+Phase II data (including 2008)

** Phase I data, ***R.Arnold et al. Nucl. Phys. A765 (2006) 483***



Decays to excited states have several photons in final state

First Direct Observation

$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9}$ (stat) $\pm$ 0.8 (syst) $\times 10^{20}$ y

$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22}$ y @ 90% C.L.

$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21}$ y @90% C.L.

$T_{1/2}^{0\nu}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23}$ y @ 90% C.L.

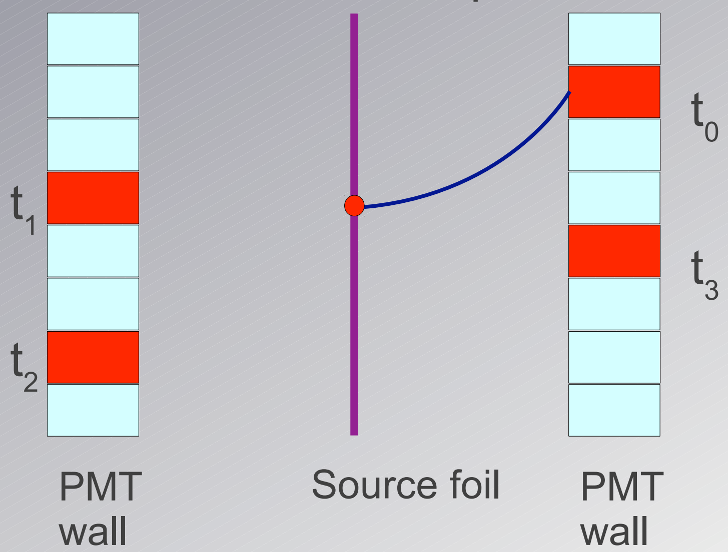
Nuclear Physics A781 (2006) 209-226.

Perspectives

- Ongoing calibration
  - Laser run analysis
  - Calibration run analysis
- Ongoing analysis
  - Other sources and channels
  - Last calibrated run analysis
- Analysis development
  - Collaboration analysis software development
  - New analysis algorithms like Gamma Tracking

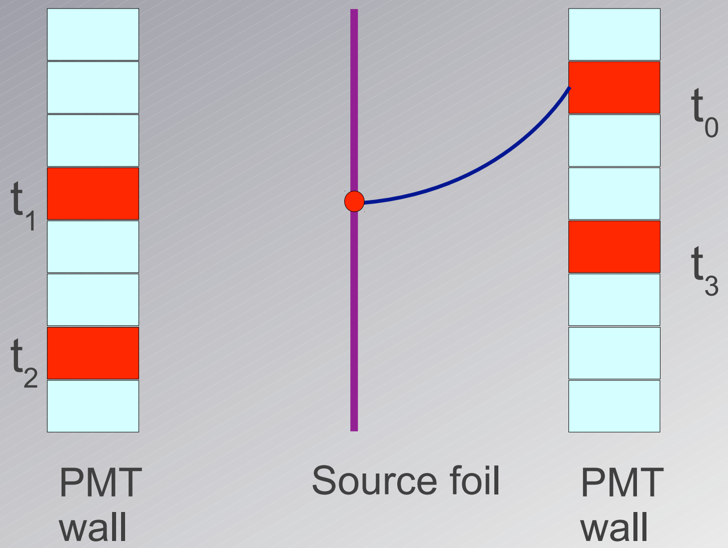
Ongoing analysis : new perspective with the gamma tracking

An event example

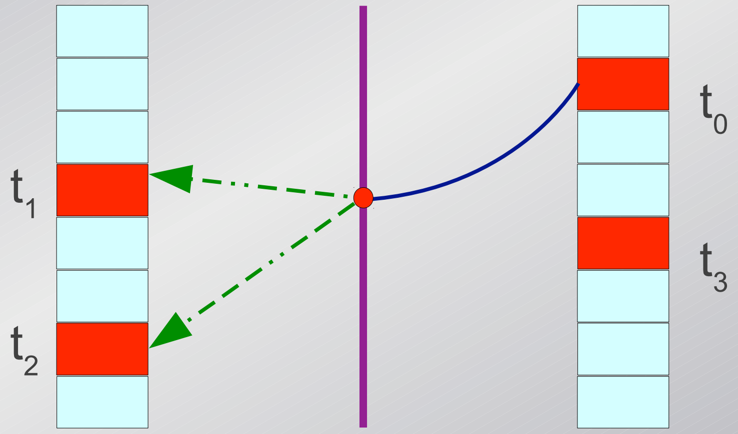


Ongoing analysis new perspective with the gamma tracking

An event example



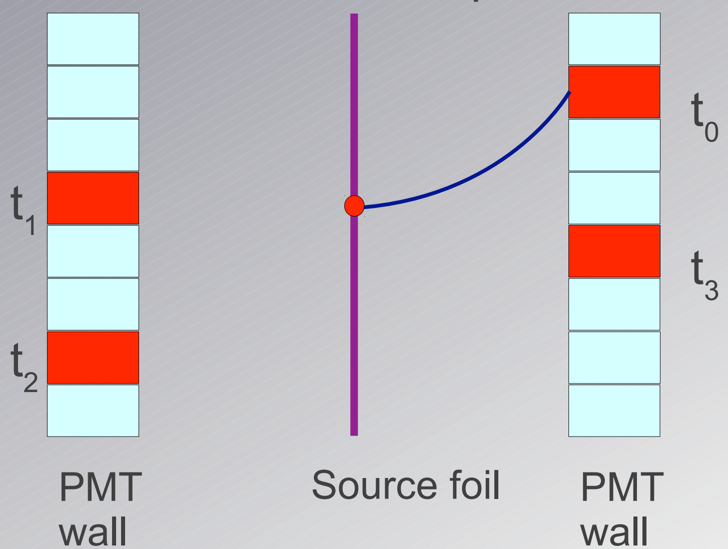
Internal gamma measurement



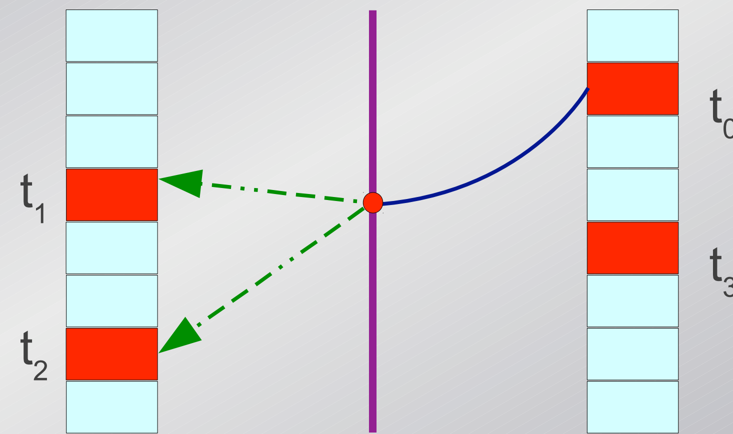
Old method stops analysis at this step

Ongoing analysis new perspective with the gamma tracking

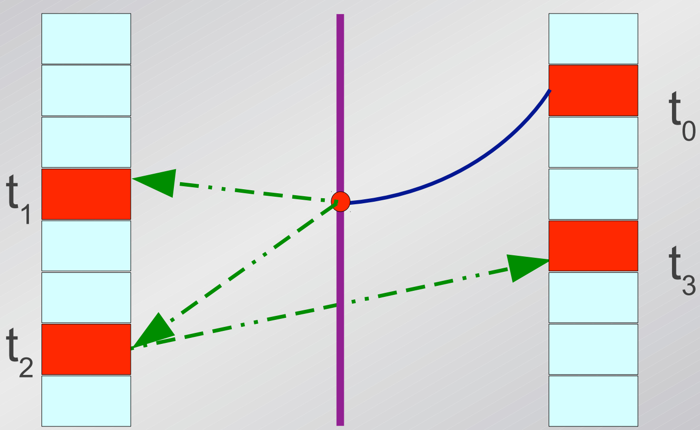
An event example



Internal gamma measurement



Old method stops analysis at this step



Gamma tracked event

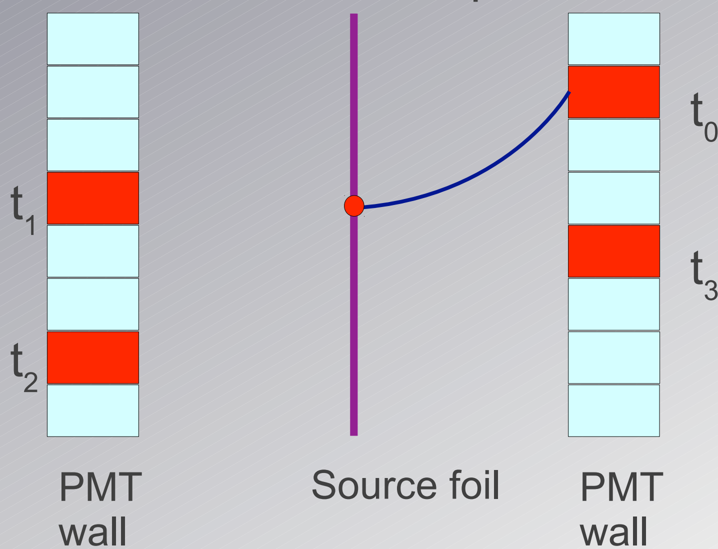
The gamma tracking is the reconstruction of the gamma trajectories in the detector

Developed to study :
-The gamma background channels
-The 2β excited states channels

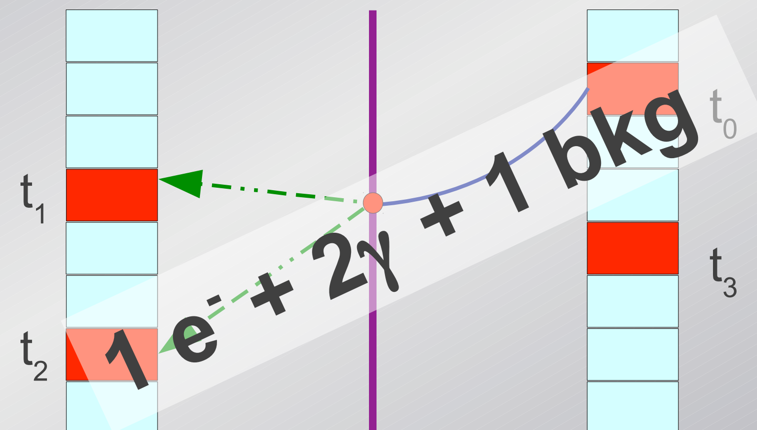
Main difficulty :
-The gamma time resolution

Ongoing analysis new perspective with the gamma tracking

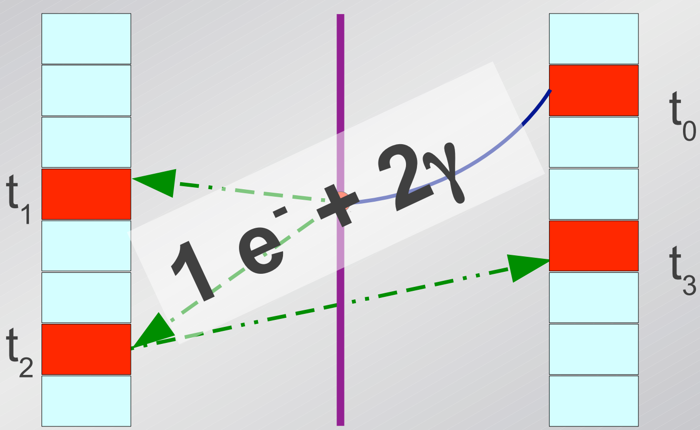
An event example



Internal gamma measurement



Old method stops analysis at this step



Gamma tracking method

The gamma tracking is the reconstruction of the gamma trajectories in the detector

Developed to study :
-The gamma background channels
-The 2β excited states channels

Main difficulty :
-The gamma time resolution

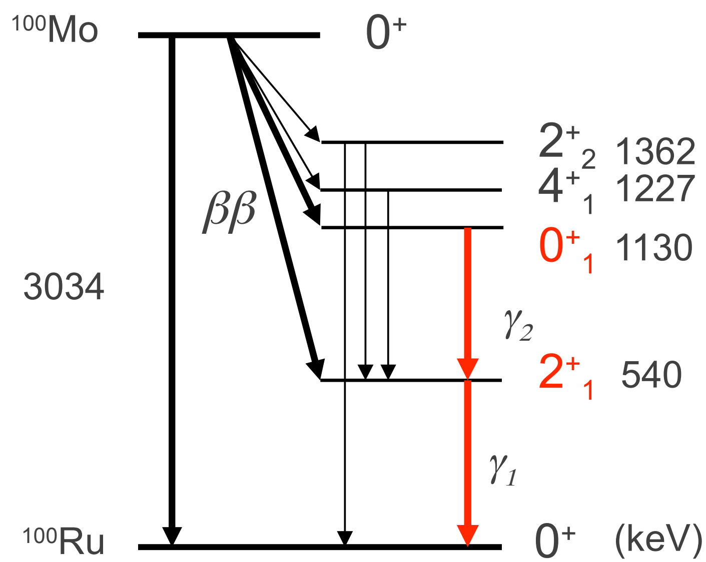
Conclusion

- NEMO3 has stopped the 12^{th} January 2011
- No evidence of $2\beta0\nu$ and lepton violation
- $2\beta2\nu$ process of 7 isotopes has been measured (ground and excited states)
- The systematics are still ongoing, and are useful for SuperNemo
- The analysis is still ongoing with new perspectives like the gamma tracking

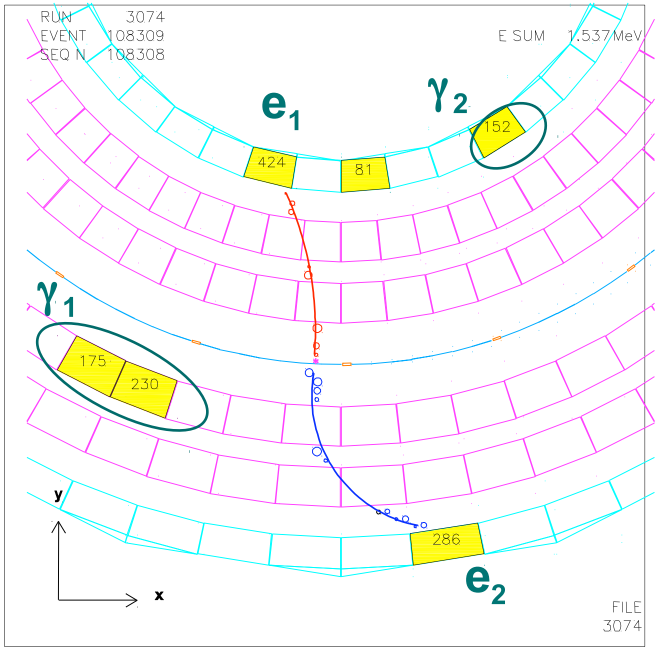
Backup

^{100}Mo ββ to the excited states of ^{100}Ru

Scheme of DBD of ^{100}Mo



TOP view (0+1 event)

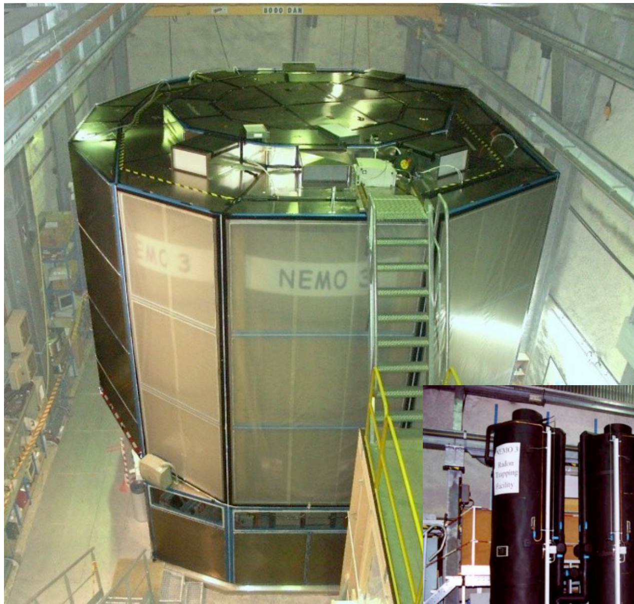


Event topology

2^+_1 : 2e+1("internal")γ+ [X<7 "not internal" γ]

0^+_1 : 2e+2("internal")γ+ [X <6 "not internal" γ]

Radon-free air system



A(^{222}Rn) LSM ~ **20 Bq/m³**
In NEMO 3 ~ **20 mBq/m³**
(measured with NEMO 3 and radon detectors developed by the collaboration sensitive to 1mBq/m³)

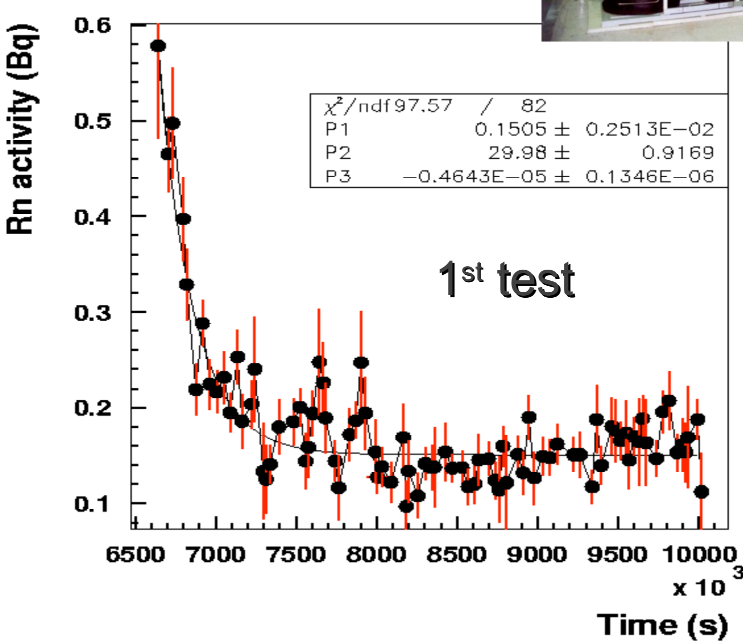
⇓

May 2004 : **Tent around the detector**

⇓

October 2004 : **Free-radon air factory**
(≡ SuperKamiokande free-Rn factory)
2×500 kg active charcoal @ -50°C

⇓



December 2004
A(^{222}Rn) ~ **0,2 Bq/m³** in the tent
reduction ~100

In NEMO 3 ~ **2 mBq/m³**

Reduction of Radon BKG ~ 10

NEMO3 background levels

Backgrounds

✓ **External :** **negligeable**

✓ **Internal :** **^{208}Tl :** 60 μBq/kg for ^{100}Mo
300 μBq/kg for ^{82}Se
^{214}Bi : < 300 μBq/kg
~ 0,2 evt kg^{-1} y^{-1} with $2{,}8 < E_1 + E_2 < 3{,}2$ MeV

✓ **ββ2ν ^{100}Mo** $T_{1/2} = 7.11\ 10^{18}$ y
~ 0,3 evt kg^{-1} y^{-1} with $2{,}8 < E_1 + E_2 < 3{,}2$ MeV

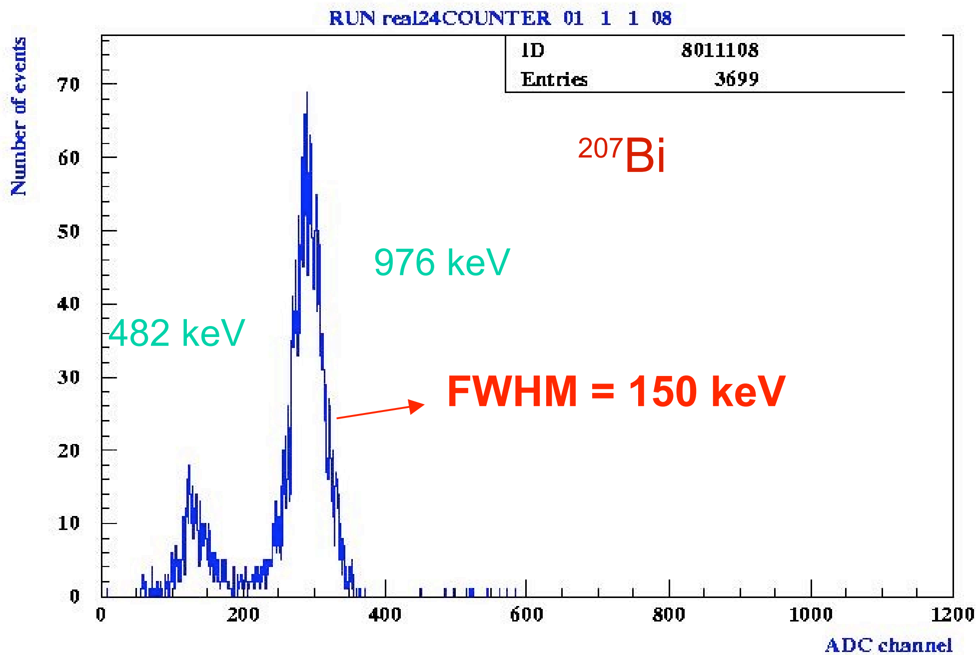
SuperNEMO and others...

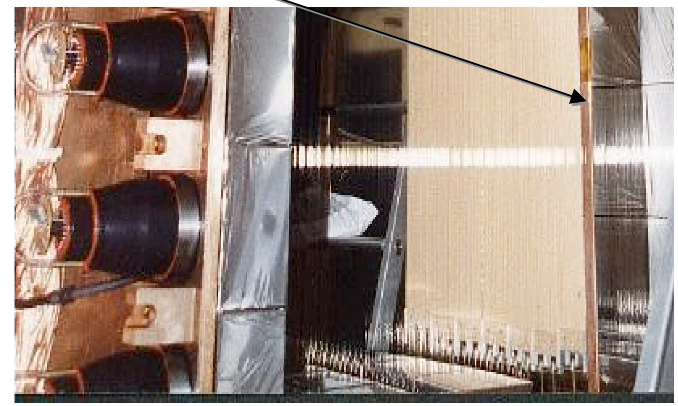
Experiment	Nucleus	Mass (kg)	FWHM at $Q_{\beta\beta}$ (keV)	Background counts/FWHM.kg.y	$T_{1/2}(0\nu)$ limit (years)	$<m_\nu>$ limit (meV)
NEMO 3	^{100}Mo	7	350	~ 0.5	$2.\ 10^{24}$	300 – 1300
	^{82}Se	1	350	~ 0.1	$8.\ 10^{23}$	600 – 1700
CUORICINO	^{130}Te	10	7	~ 0.2	$4.\ 10^{24}$	250 – 850
MOON	^{100}Mo	1000	350	~ 0.2	$2.\ 10^{27}$	30 – 80
EXO	^{136}Xe	160	50	0.95	$3.\ 10^{25}$	90 – 550
GERDA Phase 1	^{76}Ge	15	4	0.04	$3.\ 10^{25}$	250 – 780
GERDA Phase 2	^{76}Ge	100	4	0.004	$2.\ 10^{26}$	100 – 290
GERDA Phase 3	^{76}Ge	300	4	0.004	$6.\ 10^{27}$	25 – 80
MAJORANA I	^{76}Ge	180	4	0.003	$3.\ 10^{26}$	90 – 250
MAJORANA II	^{76}Ge	540	4	0.003	$4.\ 10^{27}$	20 – 65
SuperNEMO	^{82}Se	100	210	0.01	$2.\ 10^{26}$	35 – 105
CUORE	^{130}Te	203	5	0.05	$2.\ 10^{26}$	35 – 120
			5	0.005	$6.6\ 10^{26}$	20 – 65

Features and expected sensitivities of the neutrinoless double beta decay running experiments (CUORICINO and NEMO 3) and projects for the next 10 years.

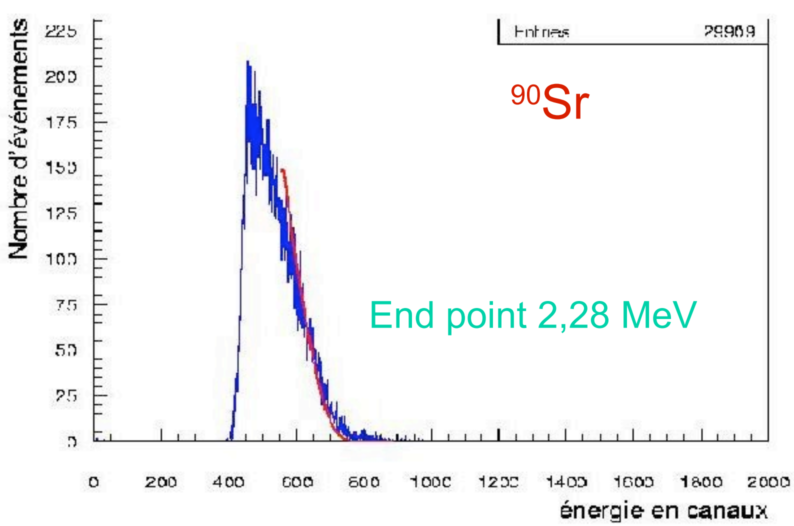
Energy calibrations

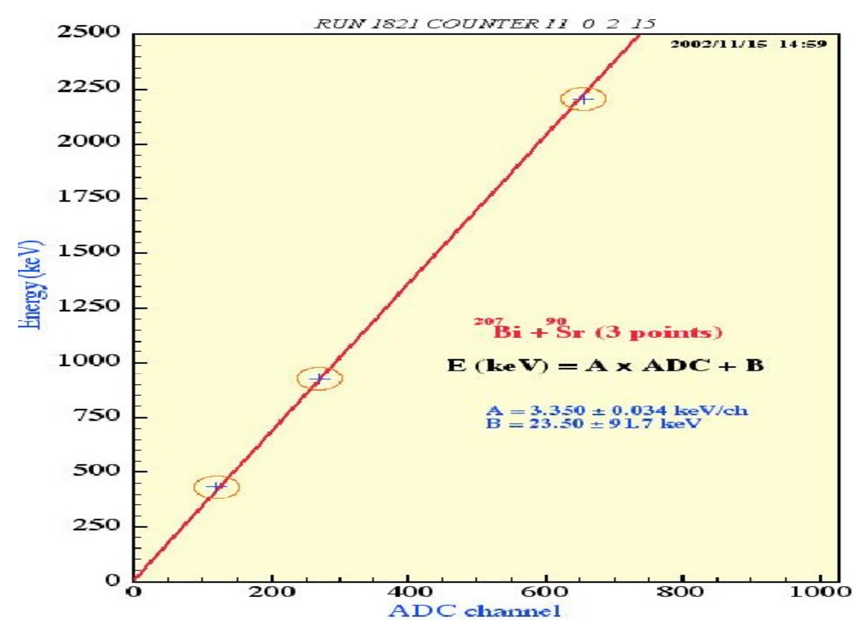
Calibration sources are introduced in tube in each sector (3 positions/sector)
3 electron energies : 486 keV and 976 keV with **^{207}Bi**, and 2.28 MeV with **^{90}Sr**



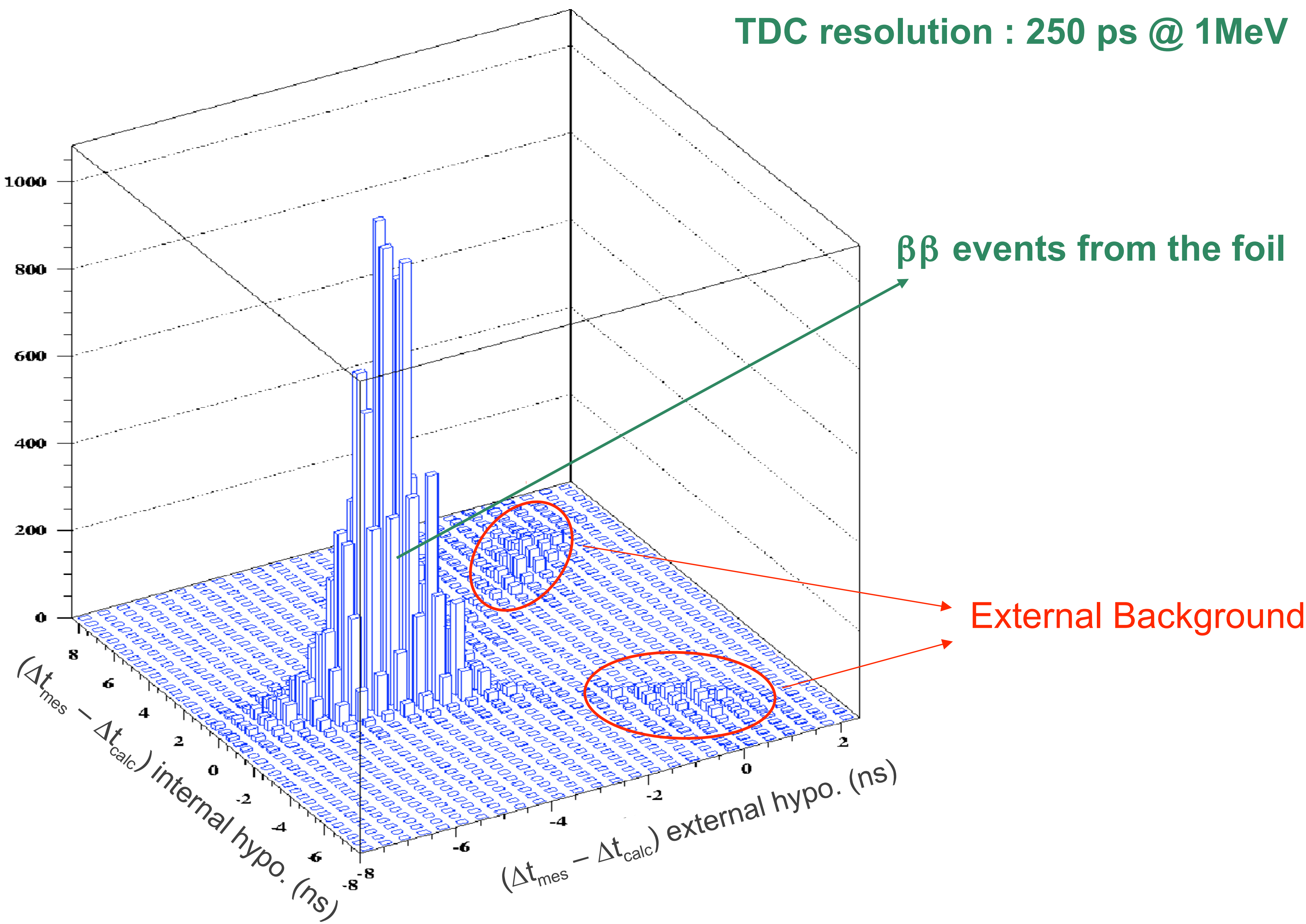


- **FWHM~ 8% @ 3MeV (σ_E/E = 3%)**
- **Daily survey of the gain with a laser system**





Time of flight rejection



Systematic uncertainties for ^{100}Mo $\beta\beta$ to excited states

- **2 e- detection efficiency** error due to GEANT simulation and tracking : ~**5%**
- **2γ efficiency** calculation error due to GEANT simulation : ~**8%**
- uncertainty of **energy calibration** : ~ **2%**
- **low energy threshold** cut : ~**3%**
- composite/metallic **thin foil simulation** (or foil position in detector) : ~ **4%**
- uncertainty of the **Rn level measurement** (≈20%) : ~ **6%** for MC bkg method

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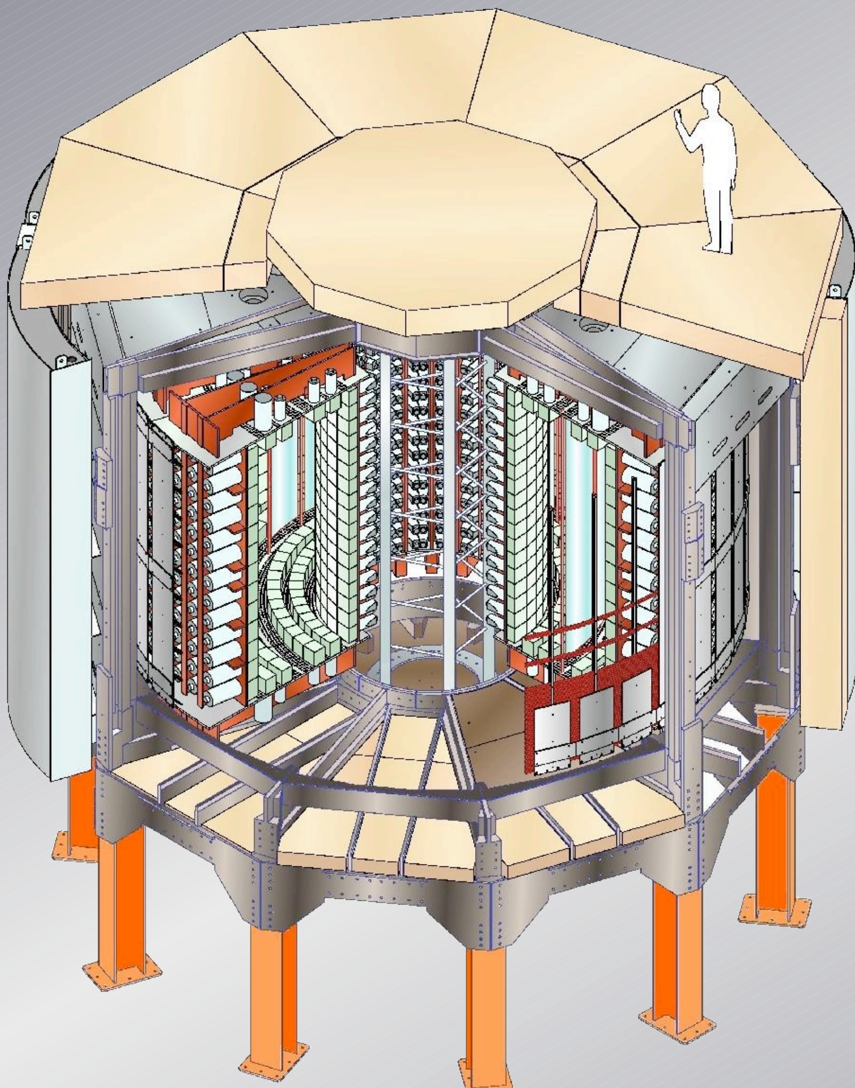
Total systematic error is ~ 12.5% for MC bkg method
~ 11.0% for bkg calculation with other sectors

$2\beta0\nu$ research : the NEMO3 experiment



- source distributed on cylindrical surface
- drift wire chamber operated in geiger mode (6180 cells)
  - He + 4% ethyl alcohol + 1% Ar + 0.1%H_2O
- calorimeter made of 1940 plastic scintillators coupled to low radioactivity PMTs
- Magnetic field: 25 Gauss
- Gamma shield: iron
- Neutron shield:
  - 30cm borated water (external wall)
  - 40cm wood (top and bottom)

Able to identify e^-, e^+, γ et α

Time of flight calculation

$$t_i = \frac{l_i}{\beta_i c}$$ Avec $$\beta_i = \frac{\sqrt{E_i (E_i + 2 m_0 c^2)}}{E_i + m_0 c^2}$$

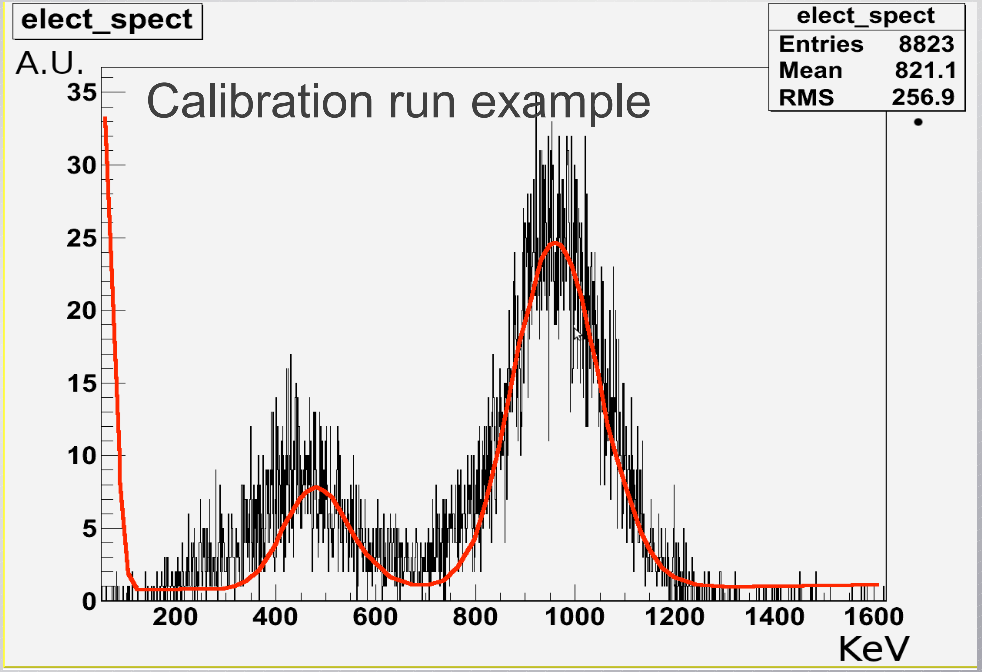
$$\chi_i^2 = \frac{\delta t_{mes} - \delta t_{th,i}}{\sigma_{mes}^2 + \sigma_{th,i}^2}$$ with i=internal, external

The probability tha an hypothesis is true is :

$$P_i(\chi) = \int_{\chi_i^2}^{\infty} dN d\chi_i^2$$ Avec i=interne, externe

Calibration

- Two calibrations
  - Absolute with ^{207}Bi
  - Relative, with a laser of 380 nm



The Standard Model, Dirac equation

$$\bar{\psi}(i\gamma_{\mu}\delta^{\mu} - m)\psi = 0$$

Dirac Lagrangian :
Momentum component
Mass component

Au repos

$$L_m = m_D(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$$

The right handed neutrino and left handed neutrino have never been observed. The bispinor cannot be null, so the mass is null

Consequencies :
-The neutrino mass should be null in the Standard Model
-There is no referencial where it rest, then it has the speed of light

Preliminary results gt

Cut's description

- **Cut 1 : 2β topology**
  - Old style
    - 2 tracks with associated scins
    - 2 unassociated scins
    - No positive tracks
    - At least a negative track
    - No delayed track
  - Gamma tracking style (general 2β topology cut)
    - 2 tracks with associated scins
    - 0 <= unassociated scins
    - No positive tracks
    - At least a negative track
    - No delayed track

Cut's description

- **Cut 2 : the Time of Flight**
  - Old style
    - exclusive 2e2γ
    - Internal γe > 1%
    - external γe < 1%
    - Internal ee > 1%
    - External ee < 0.1%
  - Gamma tracking style
    - Inclusive 2e2γ_t+nγ
    - Internal γ_te > 1%
    - external γ_te < 1%
    - Internal ee > 1%
    - External ee < 0.1%

/!\ No cluster /!

γ_t means tracked gamma

Cut's impact on the simulated data

	generated	Trigged	Cut 1	Cut 2	Cut 3	
^{214}Bi in chamber	1 1	0.58 0.58	1.2e-3 1.4e-2	1.0e-3 1.6e-3	… ...	Old style GT stlye
^{208}Tl in chamber	1 1	0.62 0.62	2.6e-3 1.8e-2	3.3e-4 9.8e-4	… ...	Old style GT stlye
^{214}Bi in foil	1 1	0.58 0.58	2.7e-3 2.4e-2	8.5e-4 2.5e-3	... ...	Old style GT stlye
^{208}Tl in foil	1 1	0.65 0.65	4.5e-3 3.1e-2	1.4e-3 4.5e-3	… ...	Old style GT stlye
$2\beta2\nu$ ^{100}Mo	1 1	0.76 0.76	6.0e-4 1.3e-1	2.2e-4 3.8e-3	… ...	Old style GT stlye
$2\beta2\nu$->0+ ^{100}Mo	1 1	0.68 0.68	1.4e-2 5.0e-2	4.3e-3 1.5e-2	… ...	Old style GT stlye
$2\beta0\nu$->0+ ^{100}Mo	1 1	0.98 0.98	6.5e-1 2.3e-1	3.4e-2 9.0e-2	… ...	Old style GT stlye

At the cut 2

~050% more ^{214}Bi in chamber
~300% more signal

Comparaison avec autre

- Efficacité laurent
- Questions
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