Searching for neutrinoless double beta decay with the SuperNEMO demonstrator

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Laboratoire de l'Accélérateur Linéaire

PHENIICS Fest 2019

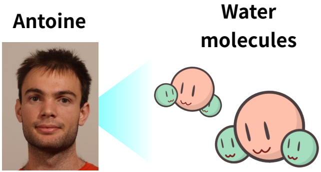
What are we composed of?

Water

What are we composed of?

Antoine

What are we composed of?



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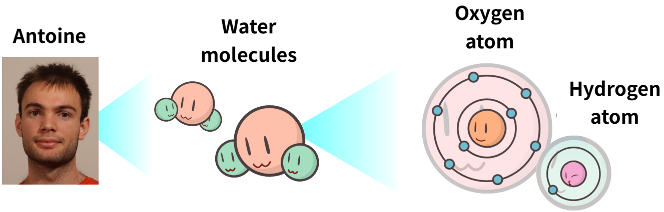

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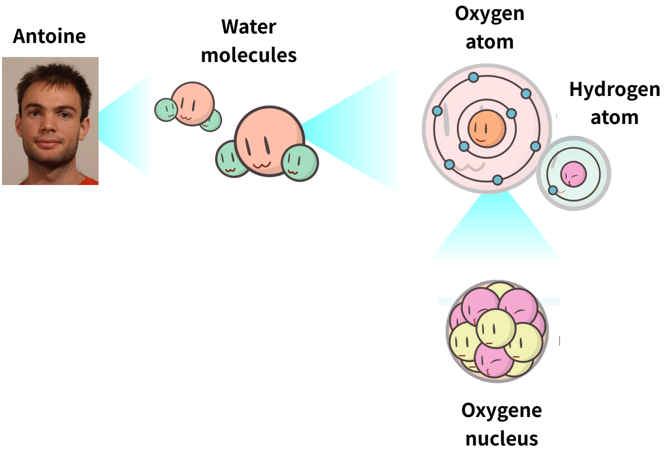

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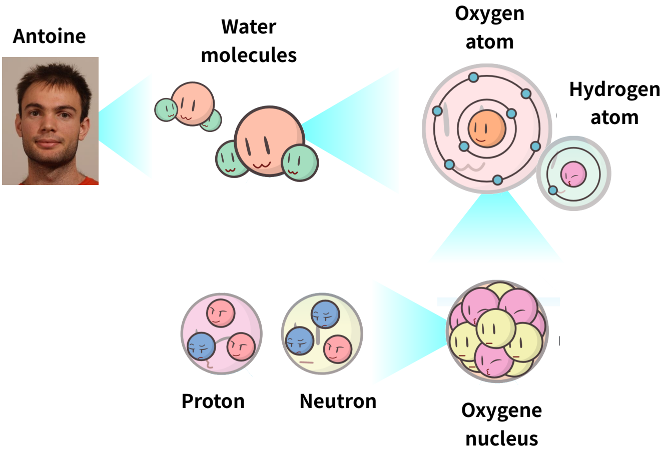

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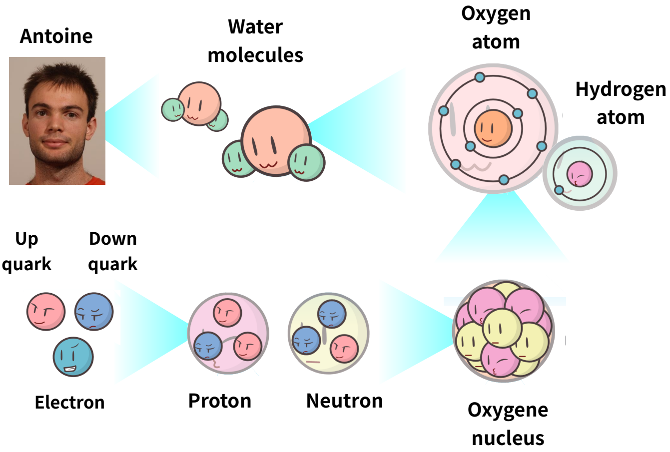
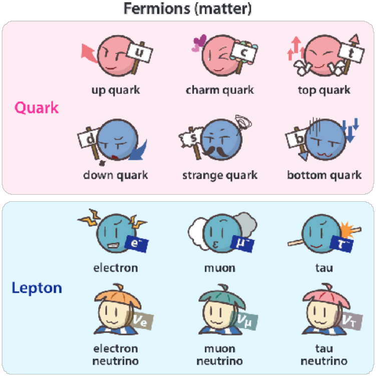
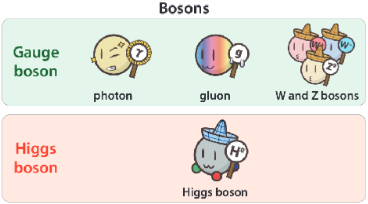
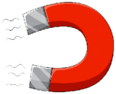
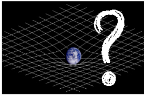


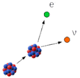




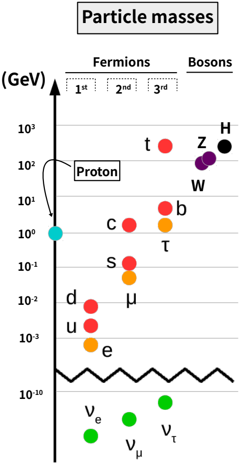
+ Antiparticles

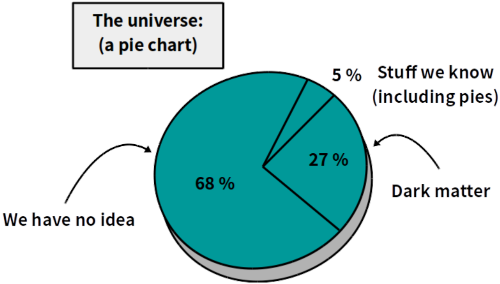






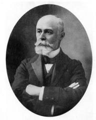
Where the Standard Model ends?





We need to go *beyond* the Standard Model

H.Becquerel (1896)

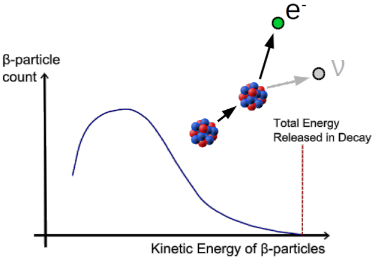


Discovery of radioactivity through β decay
Only electron observed
Non conservation of total energy

W.Pauli (1930)

Solution to conserve total energy
"Neutrino"

- Neutral
- Spin 1/2
- Small or null mass
- Small interaction probability



E.Fermi (1934)

Effective theory:
Foundation stone of weak interaction

Neutrino oscillations: neutrino masses are not described by the SM

In the Standard Model neutrinos are massless

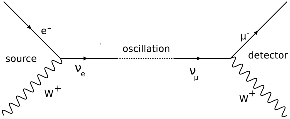
G.Pontecorvo (1957): Can neutrinos oscillate?

$$\nu_\alpha = U_{\text{PMNS}} \sum_{1,2,3} \nu_i$$

Oscillation probability (2 flavours):

$$\mathcal{P}_{e\to\mu}(t) = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{2E} L$$

Possible only if neutrinos are massive particles



SuperKamiokande experiment (1998): Observation of neutrino oscillations

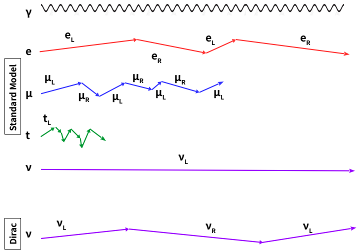
$\longrightarrow$ At least 2 massive neutrinos (considering 3 flavours)

Need to go *beyond* the Standard Model

Dirac particles: neutrino & antineutrino are distinct particles

As other fermions: Higgs mechanism

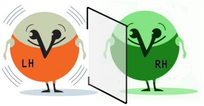
$$\mathcal{L}_\nu^{\text{Dirac}} = -\frac{v}{\sqrt{2}}\overline{\nu}_L Y^\nu \nu_R + \text{h.c.} \quad \longrightarrow \boxed{\text{Chirality}}$$



BUT weak interaction only *talk* to LH particles
AND only weak interaction for neutrinos

$\Rightarrow$ No LH neutrino described by the SM
$\Rightarrow$ Need to extend the SM

Sterile neutrino



Proof of massive neutrinos lead to extentions of SM

The mass generation mechanism depends on the neutrino nature

- $m_\nu \ll m_l$
- Neutrinos are neutral

} $\Rightarrow$ origin of neutrino masses different from those of charged fermions ?

Majorana particles: The neutrino is its own antiparticle

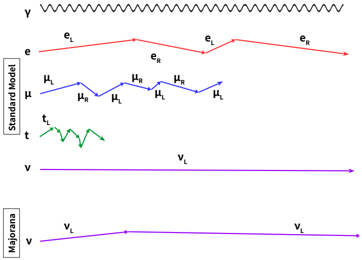
Majorana mass term in the Lagrangian

$$\mathcal{L}_\nu^{\text{Majorana}} = \frac{1}{2} m_\nu \overline{\nu}_{\text{L}}^c \nu_{\text{L}} + \text{h.c.}$$

No extra particle

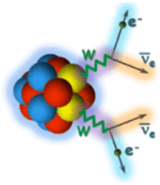
- Lepton Number Violation (LNV) with $\Delta L = 2$ (forbidden in the SM) $\rightarrow$ could explain matter/antimatter asymmetry in the universe
- Seesaw mechanisms: heavy ν_R mixes with ν_L and generates light Majorana masses for active neutrinos $\rightarrow$ could explain smallness of neurino masses

Probe: Neutrinoless double beta decay



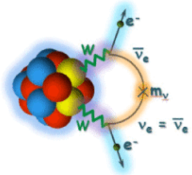
Double beta decay = 2 simultaneous neutron decays inside the nucleus

$2\nu\beta\beta$



- Allowed in SM
- Has been observed in several isotopes
- $T_{1/2}^{2\nu\beta\beta} \sim 10^{18} - 10^{21}$ years

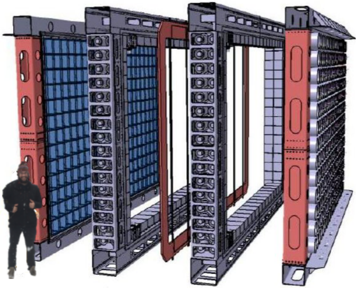
$0\nu\beta\beta$

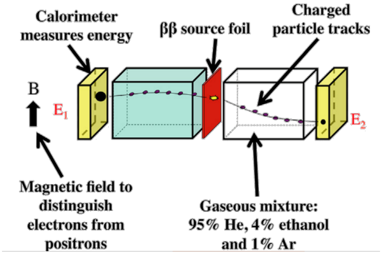


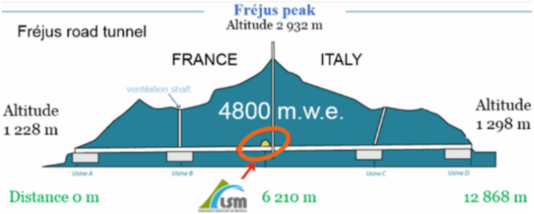
- Forbidden in SM
- Possible only if neutrinos are Majorana particles
- $T_{1/2}^{0\nu\beta\beta} > 10^{24} - 10^{26}$ years

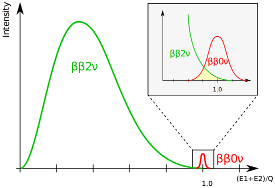
The SuperNEMO demonstrator installed @LSM

Tracko-calo experiment + ultra-low background



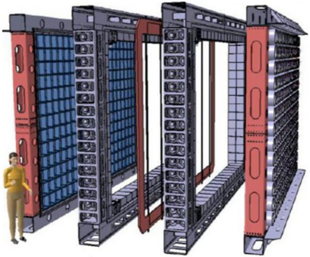


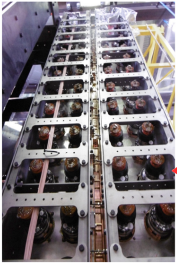


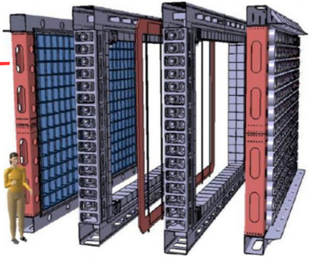


The SuperNEMO demonstrator

First commissionning datas were taken!







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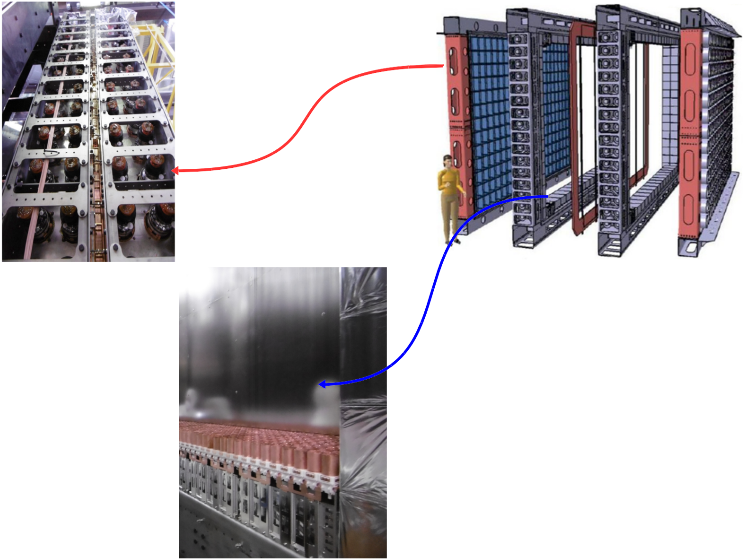

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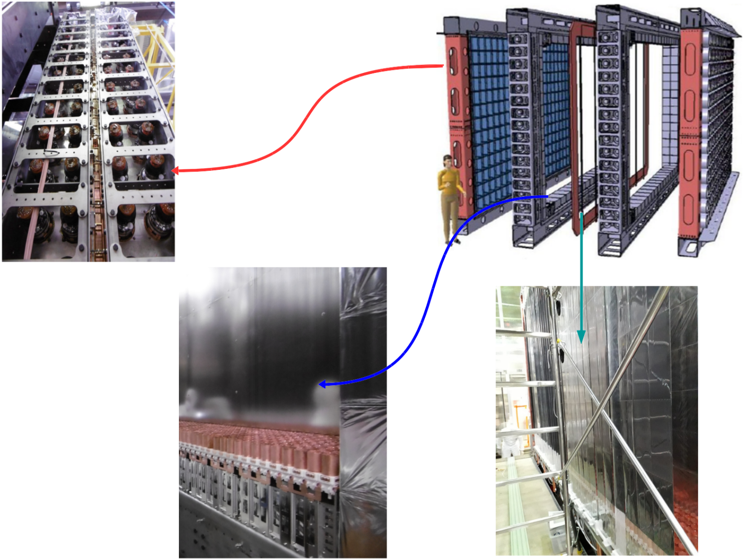

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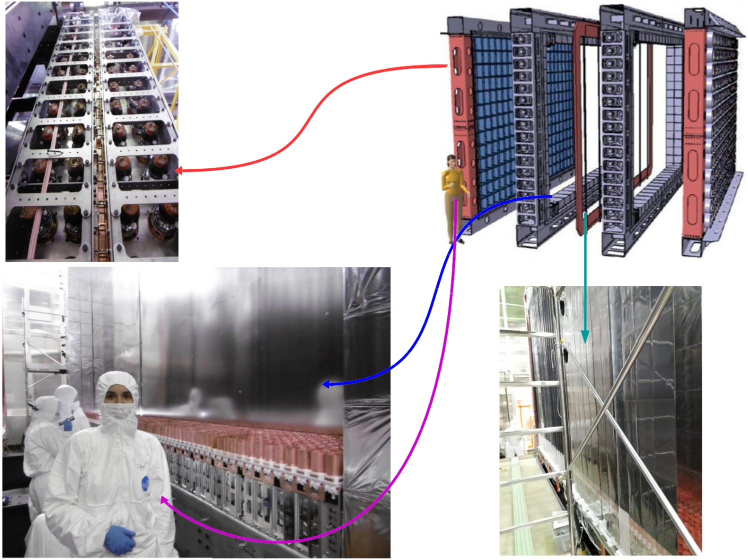

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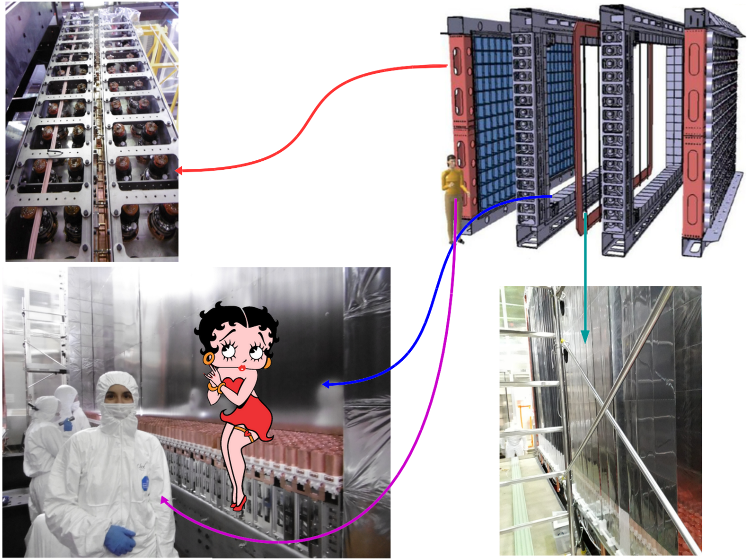
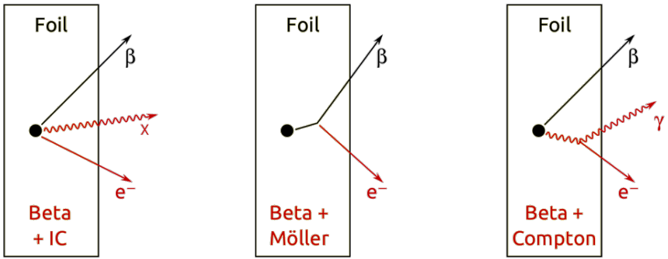


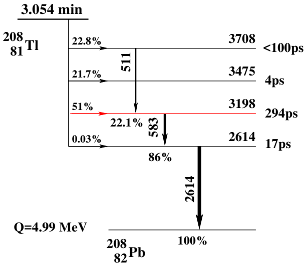
Main backgrounds:

- External γ from natural radioactivity | Background events for $2\nu\beta\beta$
  - Origin: detector PMs, laboratory
  - $E_\gamma < 2.6$ MeV
- Internal contamination of Radon in the tracker | Background events for $0\nu\beta\beta$
- **Internal contamination in the source foils** | Background events for $0\nu\beta\beta$
  - **^{208}Tl from ^{232}Th decay chain**
  - **^{214}Bi from ^{238}U decay chain**



Analysis to reject ^{208}Tl background events

Use the electron of internal conversion of ^{208}Tl:

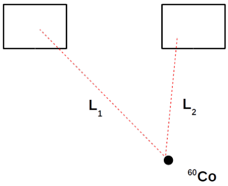


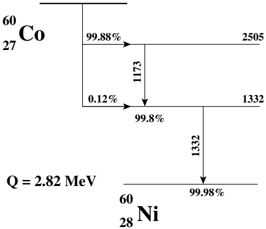
2e topologies in [2.7,3.2] MeV:
75% of ^{208}Tl decays are β decay + internal conversion of the 2.615 MeV-γ

Delayed electron

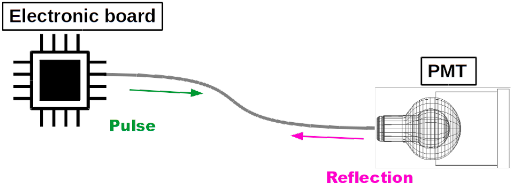
$\Rightarrow$ Possible rejection of ^{208}Tl background events

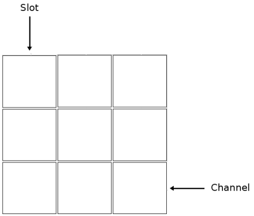
^{60}Co source to determine σ_t in optical modules:



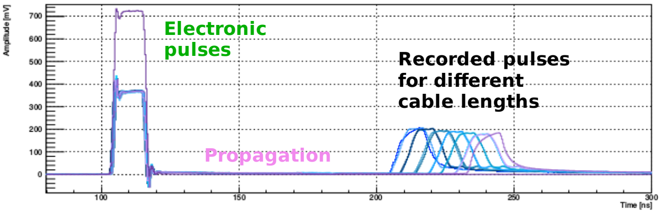


Electronic pulses generated at boards

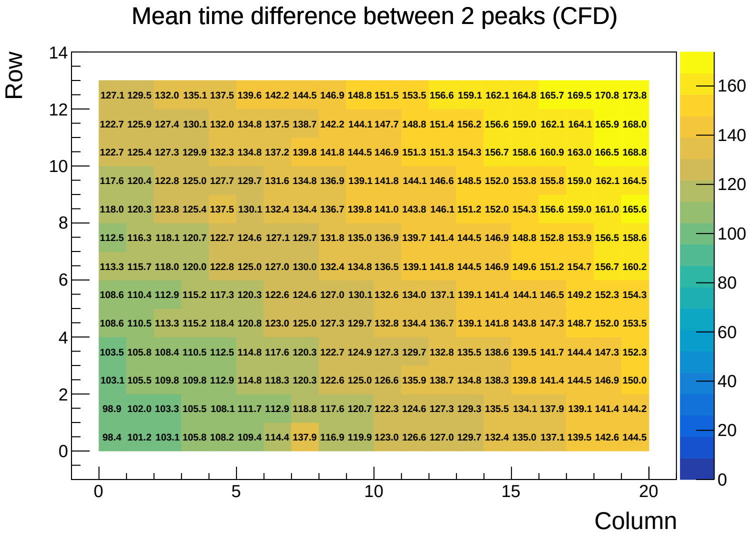




Multiple pulses for each PMT (13 channels - 20 slots)



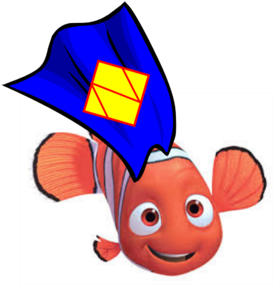
Reflectometry tests on signal cables for one board (slot)



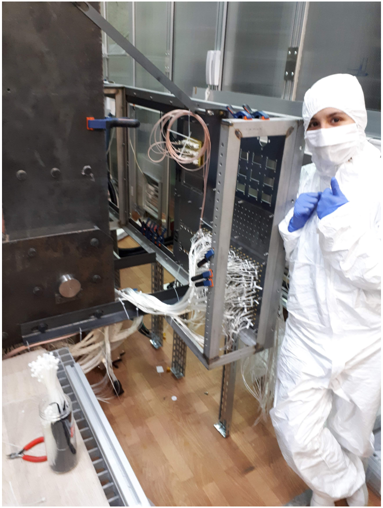
Conclusion

- Neutrinoless double beta decay is the best known process to probe LNV
- SuperNEMO is a tracko-calorimeter detector searching for $0\nu\beta\beta$
- In installation @Modane underground laboratory
- First commissionning data analysis in progress

Pandas & Cartoon fishes



Thank you



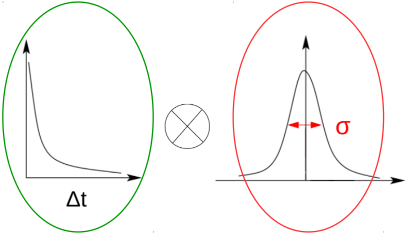
Back up

Exponentially modified gaussian

Convolution of an exponential and a gaussian function:

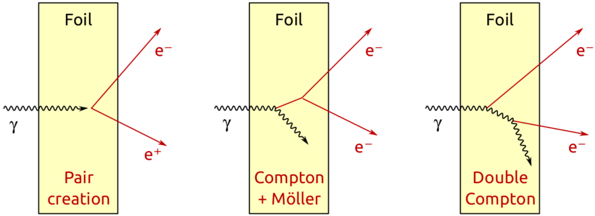
$$f(x,\mu,\sigma) = \frac{\lambda}{2} \exp^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)} \operatorname{erfc}\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right)$$

with $\mu = 0, \sigma = \sqrt{\sigma_t^2 + \sigma^2_{(\frac{L}{\beta c})} + \sigma_T^2}$ and $\tau = 294$ps

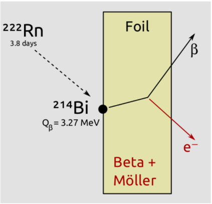


Background scheme for external gammas and Radon

External gamma background:

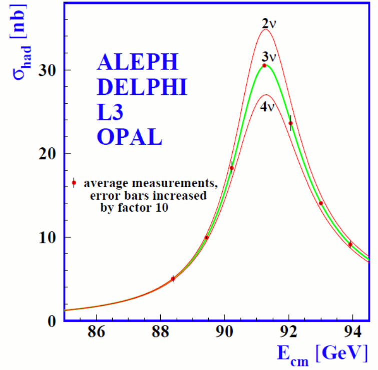


Internal Radon background:



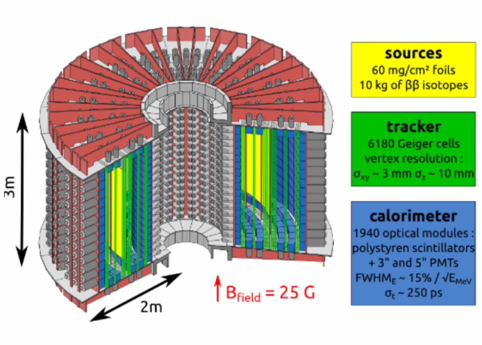
Active light neutrino number with the total Z width

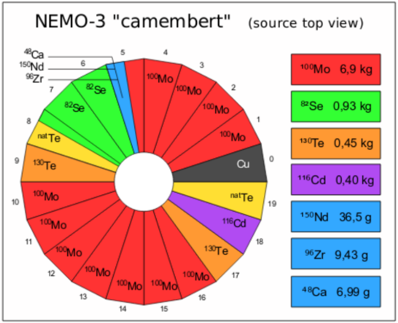
The most precise measurements of the number of light neutrino types come from studies of Z production in e^+e^- collisioners.



$N_\nu = 2,984 \pm 0,012$ light neutrinos

(Pour Laurent : je voudrais mettre ici un tableau comparatif NEMO3/SuperNEMO, est-ce que tu aurais a quelque part en stock ?)





$0\nu\beta\beta$ sensitivity

Neutrinoless double beta decay sensitivity:

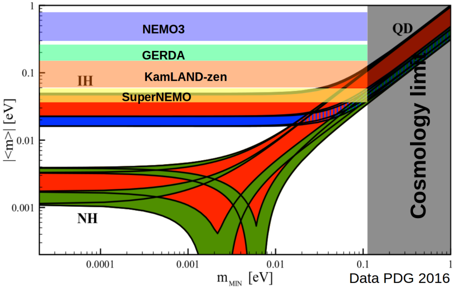
$$\tau_{1/2}^{0\nu\beta\beta} \propto \frac{a\epsilon}{m_{\text{mol}}} \sqrt{\frac{M \times t}{N_{bkg} \times \Delta E}}$$

a - abundance of isotope
ϵ - efficiency of the detector
$M \times t$ - exposure
N_{bkg} - the background rate (counts.keV^{-1}.kg^{-1}.y^{-1})
ΔE - energy resolution

To have a better sensitivity:

- High detection efficiency
- Long period data taking
- Big quantity of isotope
- Low background level

Double beta decay and mass hierarchy

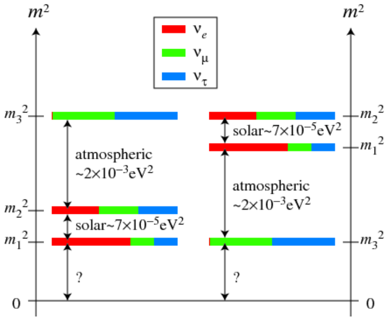


SuperNEMO gas composition

Gas proportions chosen to have the wire chamber functioning at optimal performances

- 95% He: low atomic number $\Rightarrow$ low energy losses for incoming particles (1 MeV electron: 50 keV energy loss)
- 4% ethanol: absorption of UV photons generated by Geiger plasma
- 1% Ar: ionisable $\Rightarrow$ ease the Geiger plasma propagation

Neutrino mass ordering

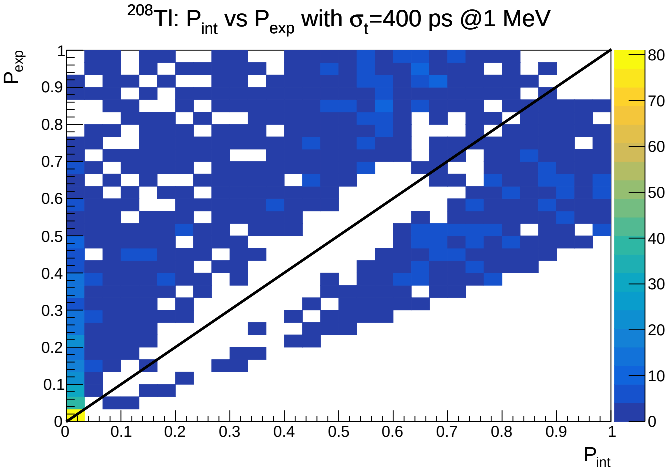


- High $Q_{\beta\beta}$ to reduce natural radioactivity background
  $Q_{\beta\beta} > 2.615$ MeV
- $(T^{0\nu}_{1/2})^{-1} = g_A^4 G^{0\nu} |M_{0\nu}|^2 |\frac{m_{\beta\beta}}{m_e}|^2$
  High phase space factor $G^{0\nu}$ and matrix elements $M^{0\nu}$ to minimise $0\nu\beta\beta$ half life
- Isotopic abundance
- Highest $T^{2\nu}_{1/2}$ to reduce the $2\nu\beta\beta$ background contribution

  ...

Isotope	$Q_{\beta\beta}$ (MeV)	$G_{0\nu}$ (10^{-15} y^{-1})	$T^{2\nu}_{1/2}$ (y)	η (%)
^{48}Ca	4.273	24.81	6.37×10^{19}	0.187
^{76}Ge	2.039	2.363	1.926×10^{21}	7.8
^{82}Se	2.995	10.16	9.6×10^{19}	9.2
^{96}Zr	3.350	20.58	2.35×10^{19}	2.8
^{100}Mo	3.035	15.92	6.93×10^{18}	9.6
^{116}Cd	2.809	16.70	2.8×10^{19}	7.6
^{130}Te	2.530	14.22	6.9×10^{20}	34.5
^{136}Xe	2.458	14.58	2.165×10^{21}	8.9
^{150}Nd	3.367	63.03	9.11×10^{18}	5.6

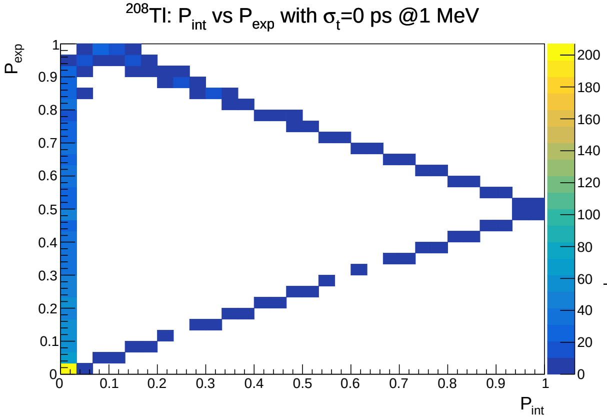
Applying cut $P_{int} > P_{exp}$ to reject ^{208}Tl background events

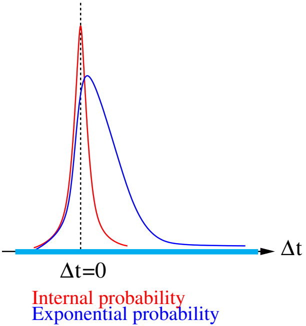


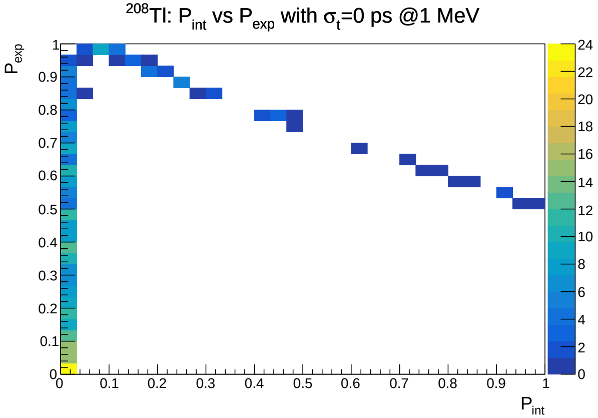
$P_{int} > P_{exp}$ allow to reject 70% of ^{208}Tl events ($[2.7, 3.2]$ MeV and 2e topologies)

Internal and exponential probabilities

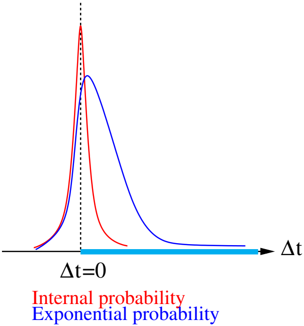
Specific case where $\sigma_t = 0$







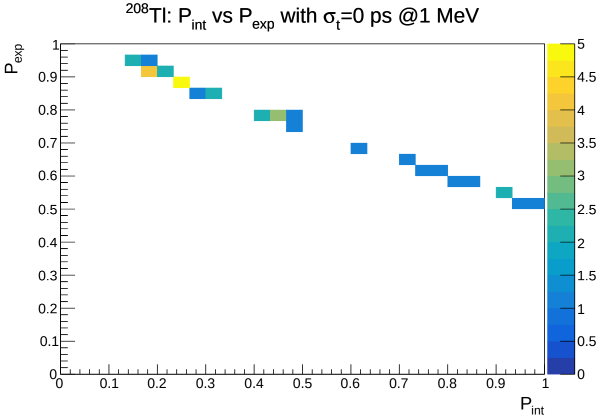
^{208}Tl: P_{int} vs P_{exp} with σ_t=0 ps @1 MeV
P_{exp}
P_{int}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
12
14
16
18
20
22
24

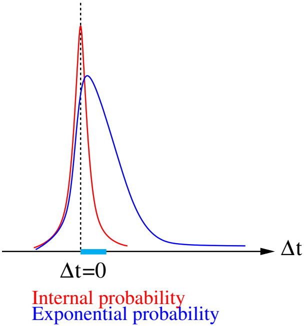


Δt
Δt=0
Internal probability
Exponential probability

Internal and exponential probabilities

$\Delta t \in [0, x_{max}^{exp}]$





Internal and exponential probabilities

$\Delta t < 0$