Investigation of Nd-150 ββ decay to excited states of Sm-150 in NEMO-3.

JINR

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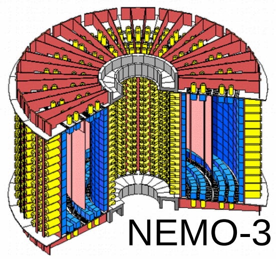
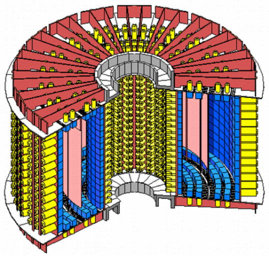
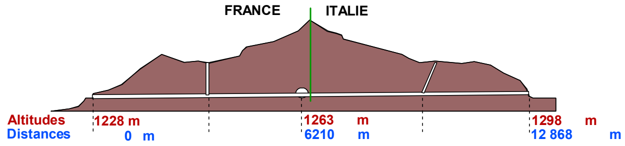
On behalf of NEMO-3 collaboration

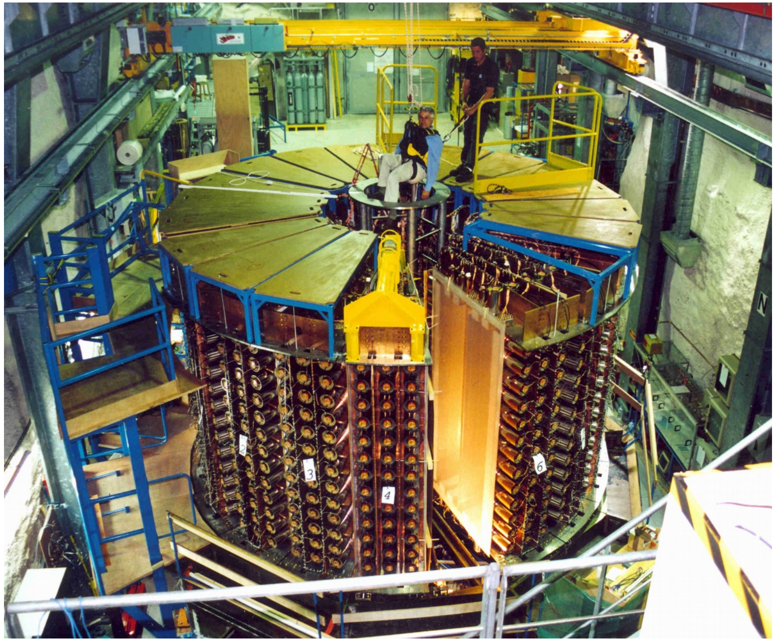


NEMO-3: The Neutrino Ettore Majorana Observatory

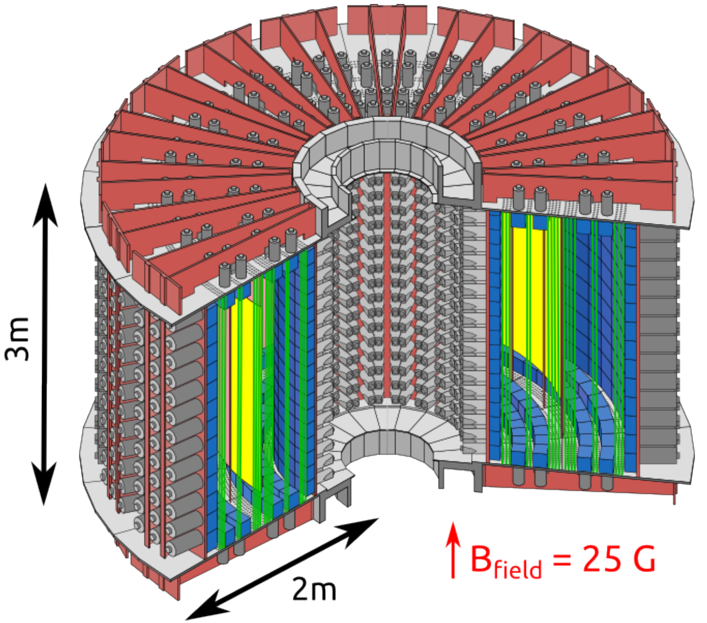


The double beta experiment NEMO-3 took data in the underground laboratory of Modane (LSM) from 2003 to 2011.





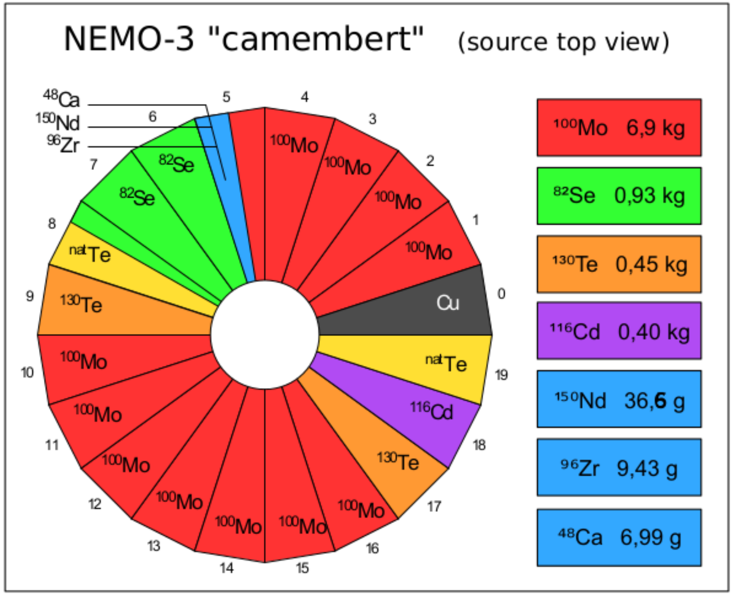
NEMO-3 detector



sources
60 mg/cm² foils
10 kg of ββ isotopes

tracker
6180 Geiger cells
vertex resolution :
σ_t = 5 mm σ_z = 1 cm

calorimeter
1940 counters :
polystyren scintillator
+ 3" and 5" PMTs
$FWHM_E$ = 15% / $\sqrt{E_{MeV}}$
σ_T = 250 ps



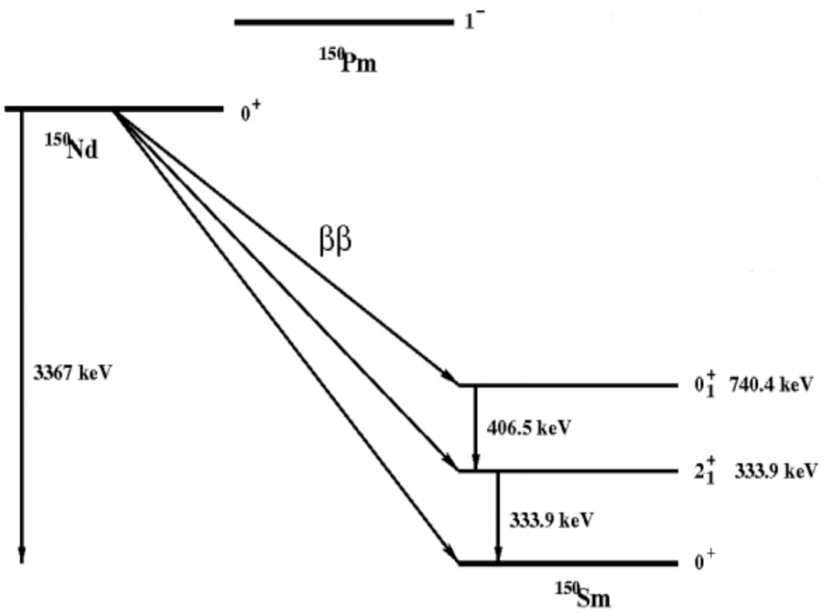
Experimental technique: calorimetry plus tracking

Particle identification: e^-, e^+, γ and α

Measurement of several final state observables:

- individual energies of electrons and gammas
- electron trajectories and vertices
- track curvature in the magnetic field
- time of flight

^{150}Nd decay scheme and existing results



Results of γ-spectrometry

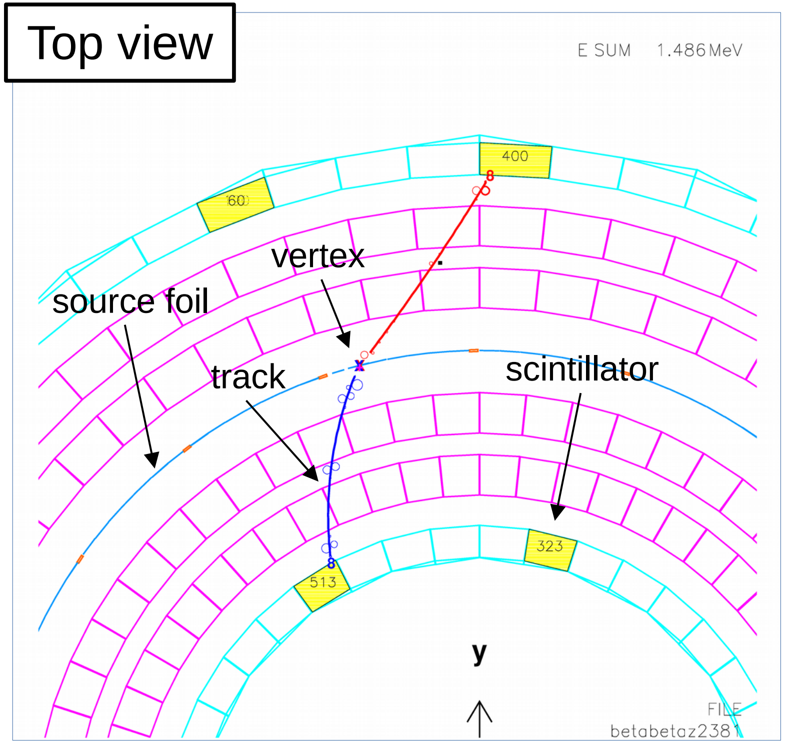
A.S.Barabash et al. *Phys.Rev. C79 (2009)054606*
0^+_1: $T_{1/2}$= (1.33+0.36-0.23(stat)+0.27-0.13(syst))·10^{20} y
S/B = 1/5, Nsignal = 177.5, S/√(S+B) = 4.75
2^+_1: $T_{1/2}$ > 2.2·10^{20} y @90% C.L. (best)

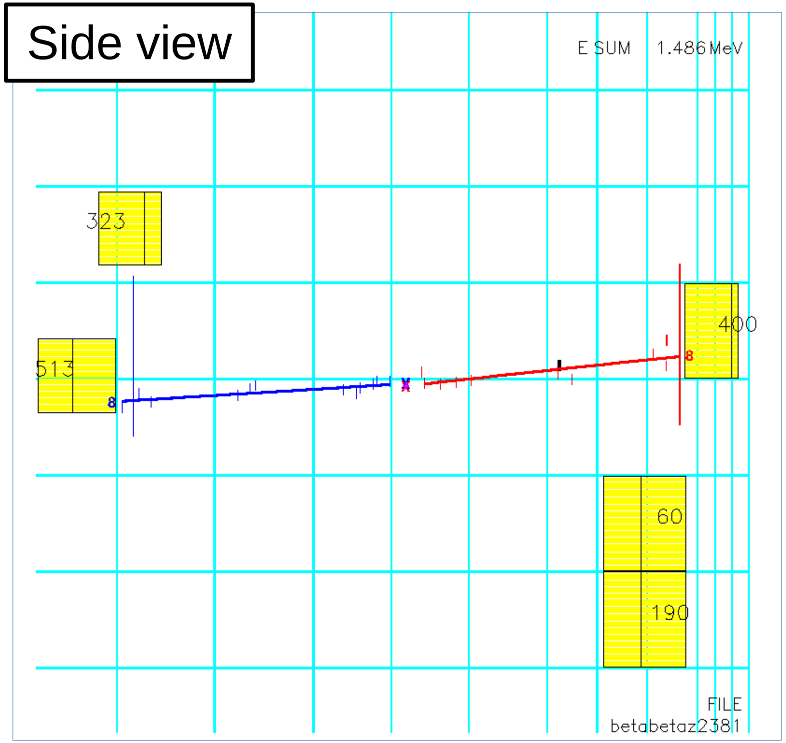
M.F.Kidd et al. *Phys.Rev. C90(2014)055501*
0^+_1: $T_{1/2}$= (1.07+0.45-0.25(stat)±0.07(syst))·10^{20} y
S/B = 1.2, Nsignal=21.6, S/√(S+B) = 3.4

O.G. Polischuk el al. *Phys.Scr.96(2021)08532*
0^+_1: $T_{1/2}$= (9.7+2.9-1.9(stat) ±1.5(syst))·10^{19} y
Nσ_stat = 4.34

NEMO-3 result for ^{150}Nd ββ decay to the ground state of ^{150}Sm R. Arnold et al. *Phys. Rev. D 94(2016)072003*
$T_{1/2}^{2\nu\beta\beta}$(g.s.) = (9.34 ±0.22 (stat) +0.62-0.60(syst))·10^{18} y $T_{1/2}^{0\nu\beta\beta}$(g.s.) > 2.0 · 10^{22} y
The same data set is used in the current analysis, 5.25 y with 36.6 g of ^{150}Nd, 0.19 kg·y exposure.

Event selection





- Two electrons $E_e > 150$ keV
- Common vertex in ^{150}Nd foil
- TOF probability $P_{int}(ee) > 5\%$

- One or two gammas $E_\gamma > 100$ keV
- TOF probability $P_{int}(ee\gamma) > 5\%$

Backgrounds

- Internal backgrounds
  - Impurities in the foil
  - e.g. Single β-decay + Møller scattering and/or Compton scattering
- External backgrounds due to high energy gamma rays
  - Reduced by 4800m water equivalent overburden and extensive passive shielding (wood, iron, borated water)
- Radon induced backgrounds
  - e.g. due to ^{214}Bi β-decay in the tracking volume close to the foil
  - Suppressed by flushing radon-free air around the detector
- 2νββ decay to the ground state
  - ββ-decay + bremsstrahlung

Use the background model described in the NEMO-3 publication
R. Arnold et al., Phys. Rev. D 94(2016)072003.

Results of event selection eeγγ, eeγ

$2\nu\beta\beta \rightarrow 0^+_1$ signal in eeγγ

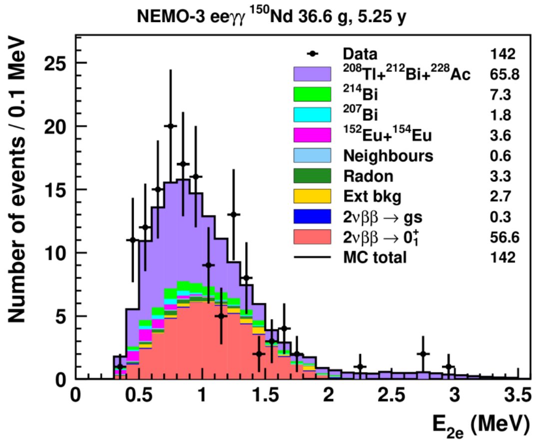
Data= 142, B=85.4, S=Data-B=56.6 , ε=0.867%
S/B=0.66, S/√(S+B)=4.75

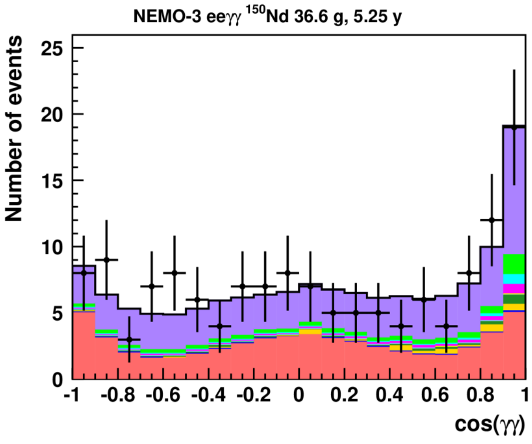
$T_{1/2}^{2\nu}(0^+_1)=[8.18^{+2.18}_{-1.42}\ (stat)\ ^{+2.03}_{-1.50}\ (syst)]\times 10^{19}$ y

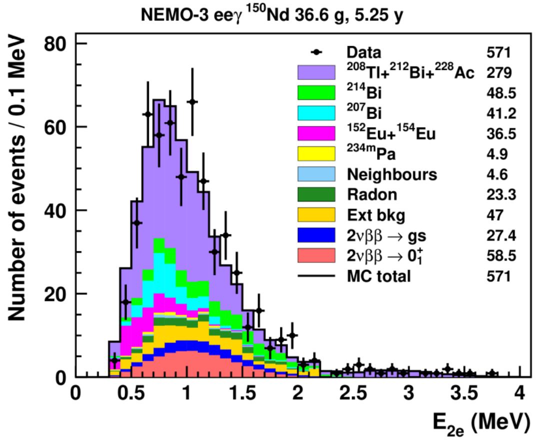
$2\nu\beta\beta \rightarrow 0^+_1$ signal in eeγ

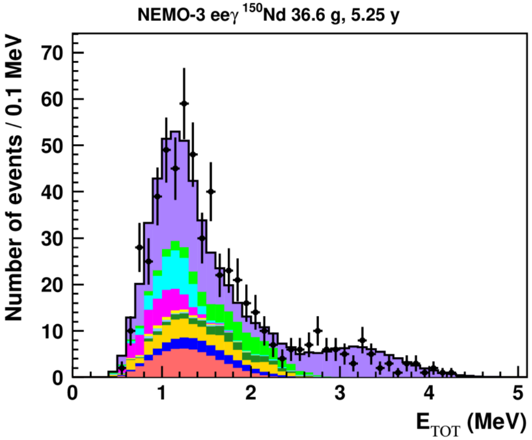
Data= 571, B=512.5, S=Data-B=58.5, ε=2.17%
S/B=0.11, S/√(S+B)=2.44

$T_{1/2}^{2\nu}(0^+_1)=[1.99^{+1.37}_{-0.58}\ (stat)\ ^{+13.35}_{-0.98}\ (syst)]\times 10^{20}$ y

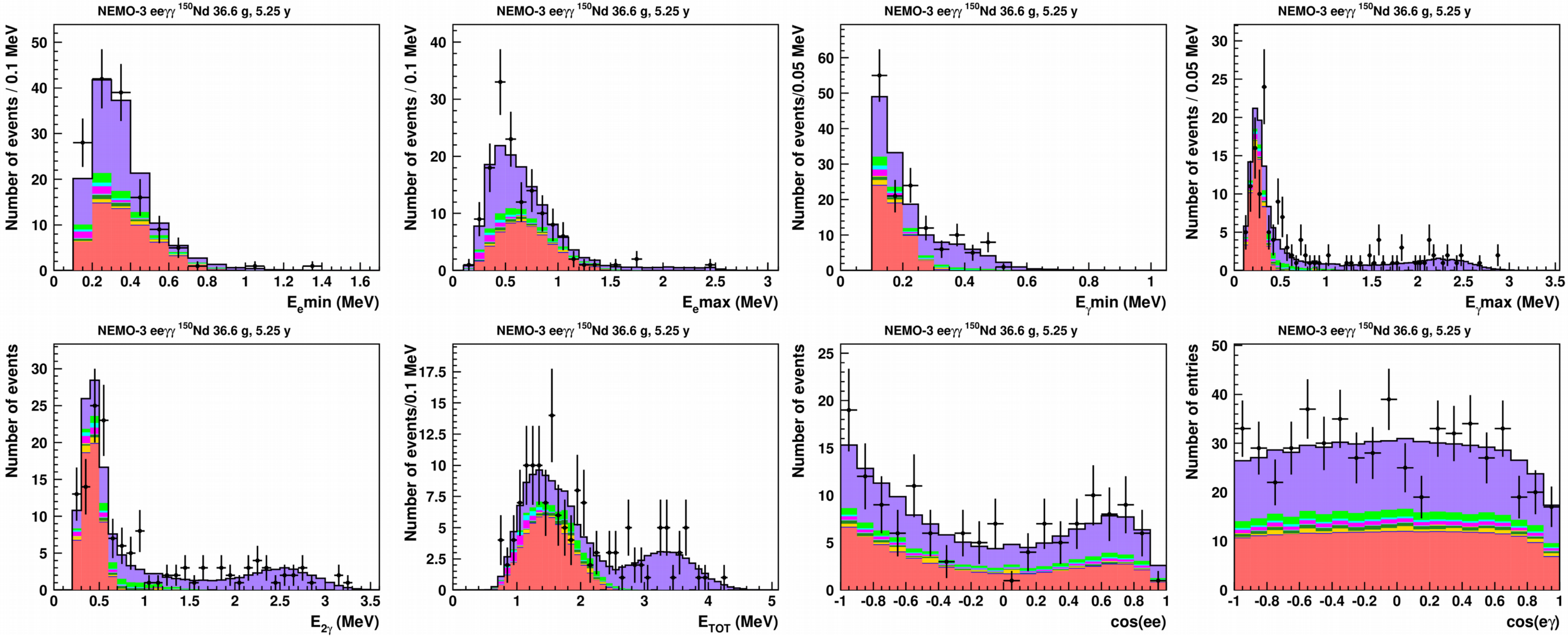




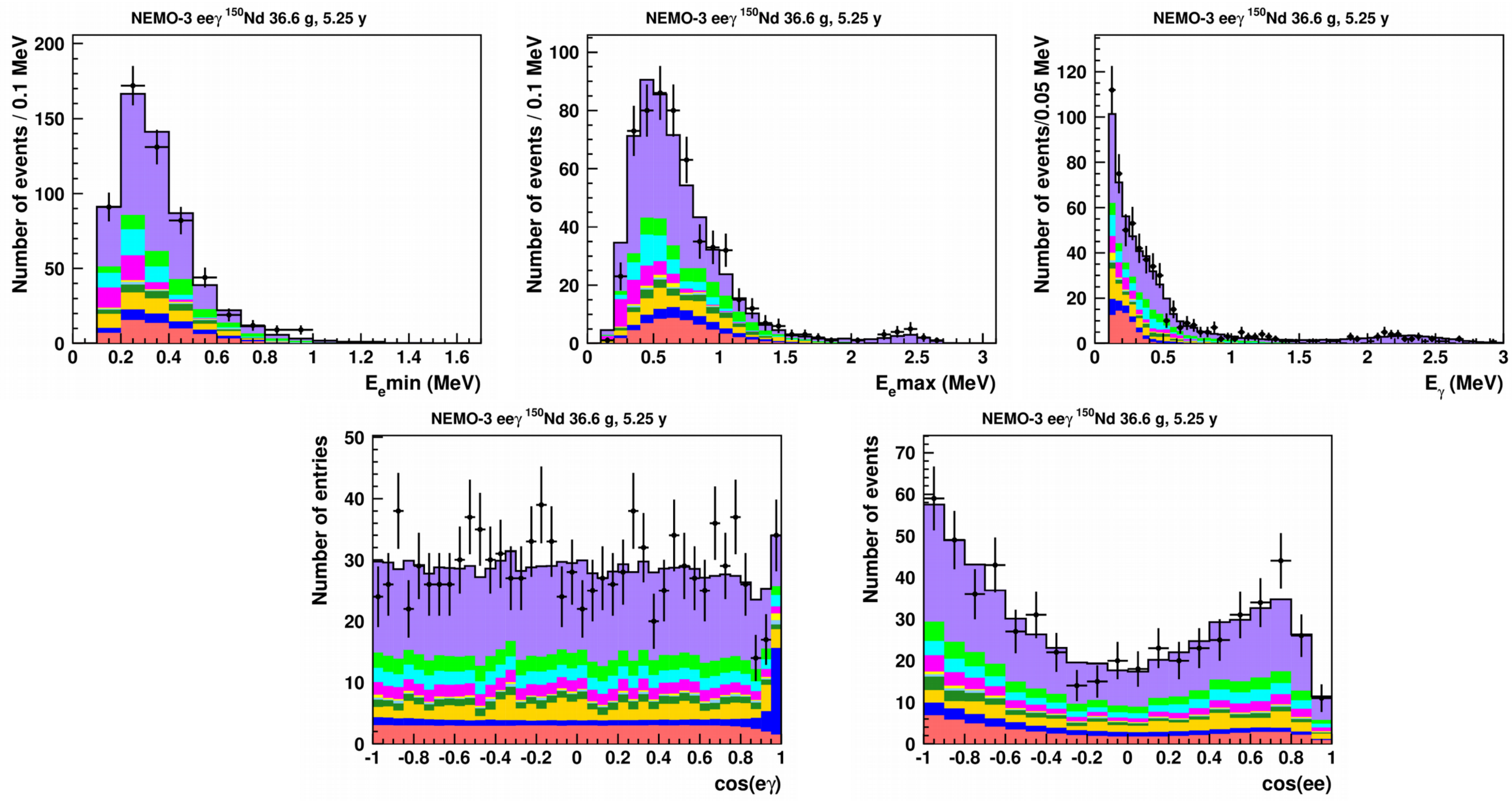




Distributions of measured quantities of selected eeγγ events



Distributions of measured quantities of selected eeγ events



Systematic uncertainties

Background contribution	Syst. uncertainty on activity,%
^{208}Tl internal	± 7
^{214}Bi internal	± 23
^{207}Bi internal	± 5.6
^{152}Eu & ^{154}Eu internal	± 14
^{234m}Pa internal	± 10
Neighbour foils	± 23
^{150}Nd bb → g.s.	± 7
Radon	± 10
Externals	+ 31 -23

Contribution	Systematic uncertainty,%
Efficiency eeγγ / eeγ	± 7.6 / ± 8.1
Energy loss in foil	± 5
Energy calibration	± 1
Bremsstrahlung modelling	± 50
Mass of ^{150}Nd	± 0.5

Method of data analysis

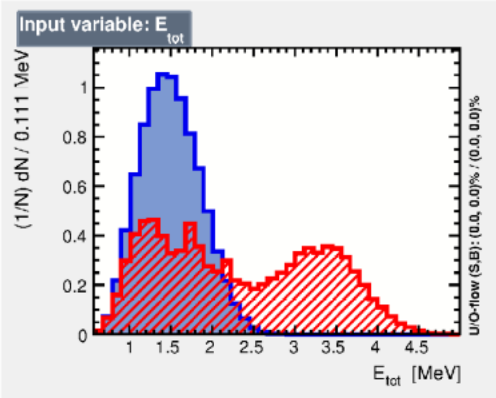
- Classify events (signal against the background) with BDT (TMVA ROOT) considering $2\nu\beta\beta \rightarrow 0^+_1$ and $0\nu\beta\beta \rightarrow 0^+_1$ in $ee\gamma\gamma$ and $ee\gamma$ channels; $2\nu\beta\beta \rightarrow 2^+_1$ and $0\nu\beta\beta \rightarrow 2^+_1$ in $ee\gamma$ channel.

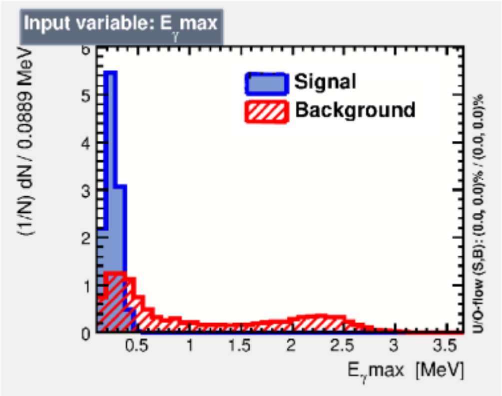
- In order to measure $2\nu\beta\beta \rightarrow 0^+_1$ transition apply BDT cut to maximize the signal significance.

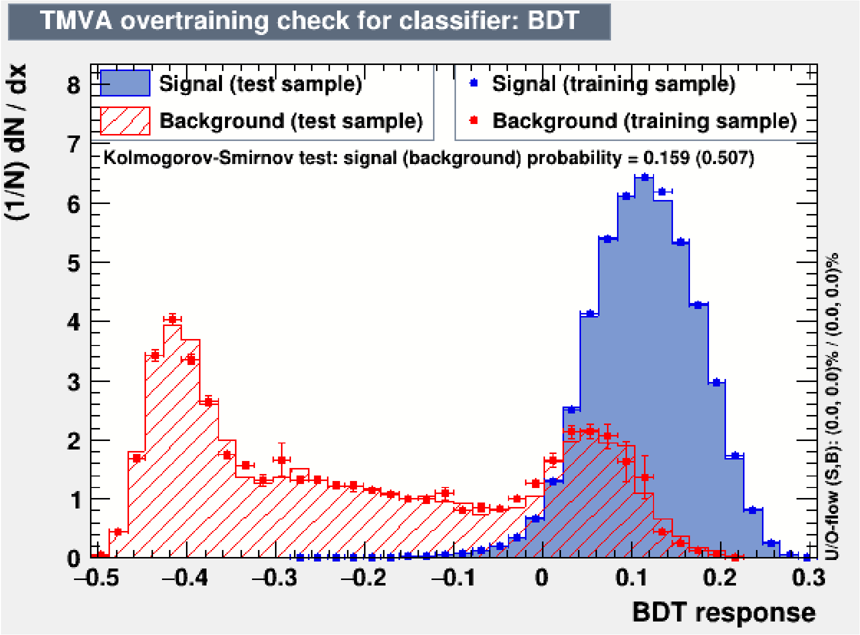
- For other decay modes, when a signal presence is not evident, evaluate the 90% C.L. limit from the BDT score distribution with Collie program (FNAL DØ experment) using Modified frequentist method taking into account the systematic uncertainties.

^{150}Nd 2$\nu\beta\beta$ --> 0^+_1 BTD training, ee$\gamma\gamma$ channel

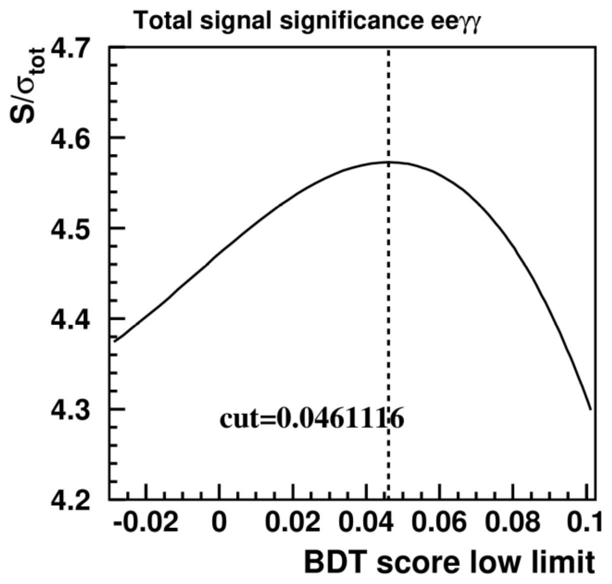
	Variable	Importance
1	E_{TOT}	1.195e-01
2	$E_\gamma max$	1.108e-01
3	$cos(\gamma\gamma)$	8.812e-02
4	$cos(\gamma_{max} e_{min})$	8.464e-02
5	$cos(\gamma_{max} e_{max})$	8.083e-02
6	$cos(\gamma_{min} e_{min})$	7.790e-02
7	$cos(ee)$	7.771e-02
8	$cos(\gamma_{min} e_{max})$	7.676e-02
9	$E_e min$	6.575e-02
10	$E_\gamma min$	6.297e-02
11	$E_e max$	5.857e-02
12	E_{2e}	5.421e-02
13	$Sign_{max}$	2.377e-02
14	$Sign_{min}$	1.849e-02

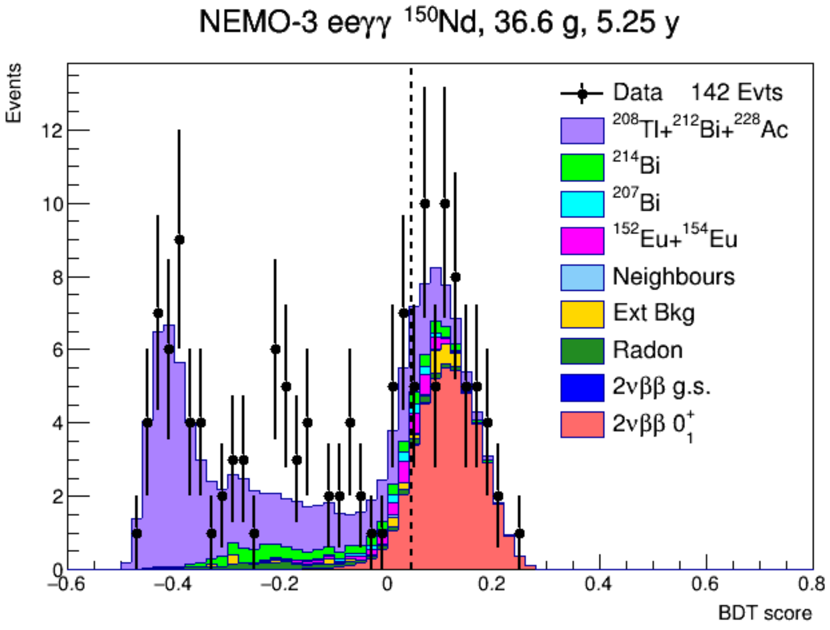






^{150}Nd $2\nu\beta\beta$ --> 0^+_1 masurement in $ee\gamma\gamma$ channel



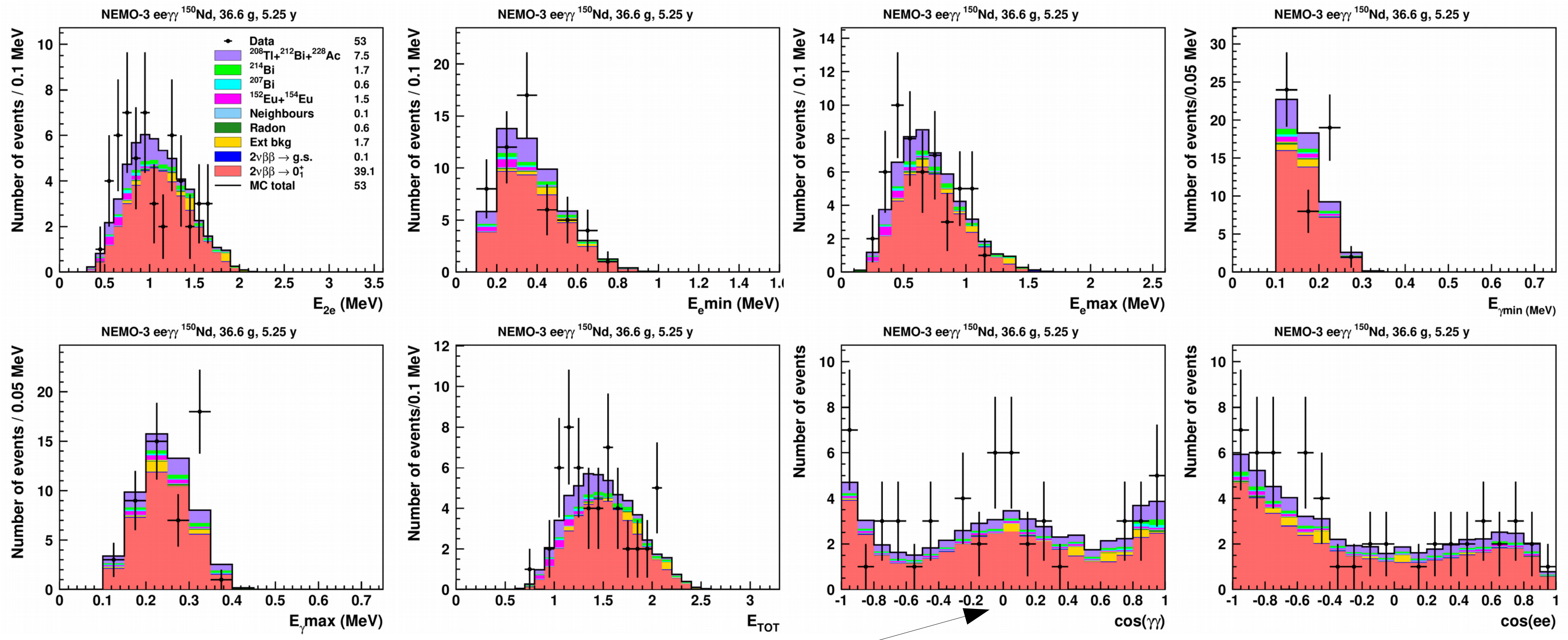


Cut out events with low BDT score values to maximize the signal significance

Data= 53, B=13.9, ε=0.761%, S=Data-B=39.1
S/B=2.82, $S/\sqrt{(S+B)}=5.37$,

$T_{1/2}^{2\nu}(0^+_1)=[1.04\,^{+0.24}_{-0.16}(\text{stat})\,^{+0.12}_{-0.11}(\text{syst})]\times10^{20}$ y

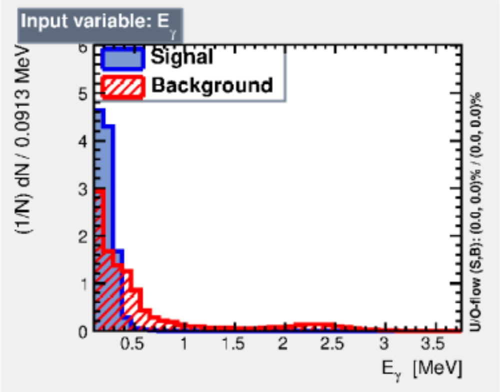
Distributions eeγγ events after BDT cut

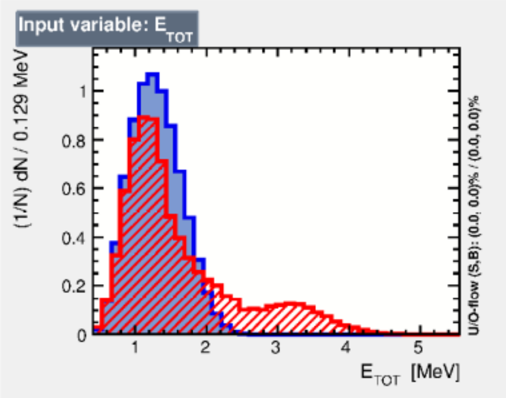


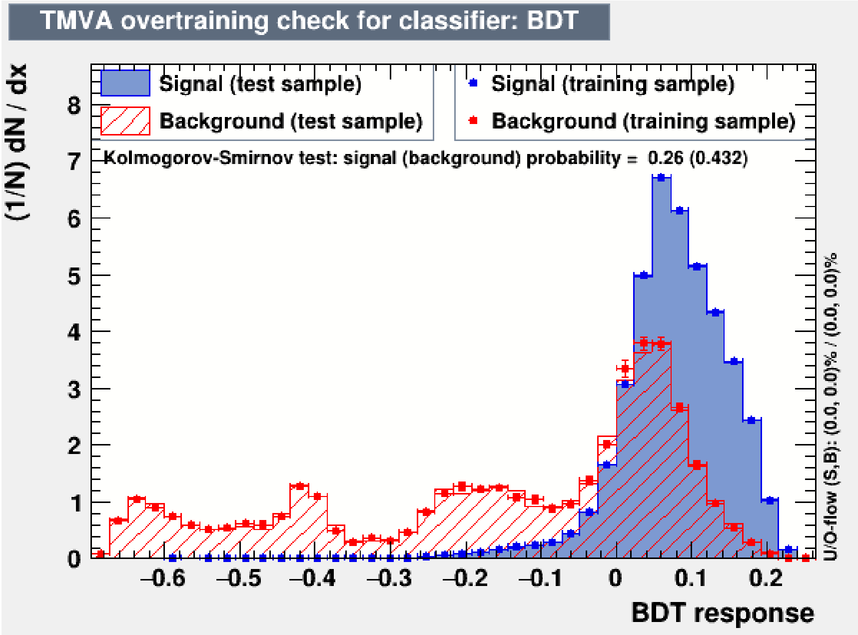
Angular correlation γγ for $0^+_1 \rightarrow 2^+_1 \rightarrow 0^+_{g.s.}$: $W(\Theta) = 1\text{-}3\cos^2(\Theta)+4\cos^4(\Theta)$

^{150}Nd $2\nu\beta\beta$ --> 0^+_1 BTD training, $ee\gamma$ channel

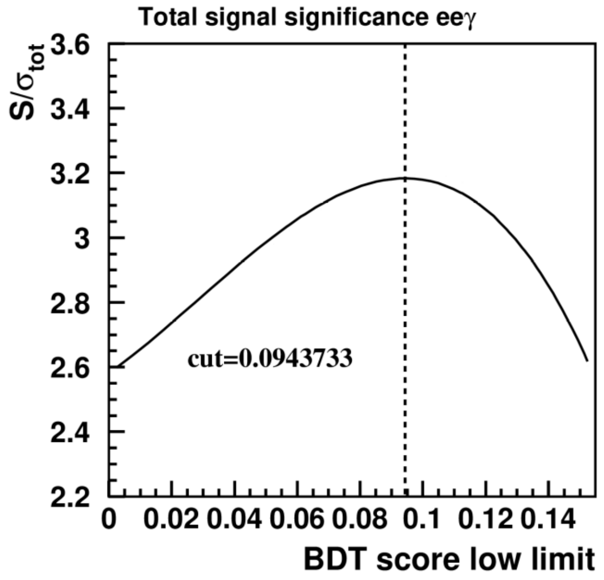
	Variable	Importance
1	E_γ	2.116e-01
2	E_{TOT}	1.255e-01
3	$\cos(\gamma\ e_{min})$	9.169e-02
4	$(E_e max-E_e min)/E_{2e}$	8.998e-02
5	cos(ee)	8.917e-02
6	$\cos(\gamma\ e_{max})$	8.768e-02
7	$E_e min$	8.471e-02
8	E_{2e}	7.729e-02
9	$E_e max$	6.869e-02
10	$Sign_{max}$	3.761e-02
11	$Sign_{min}$	3.608e-02

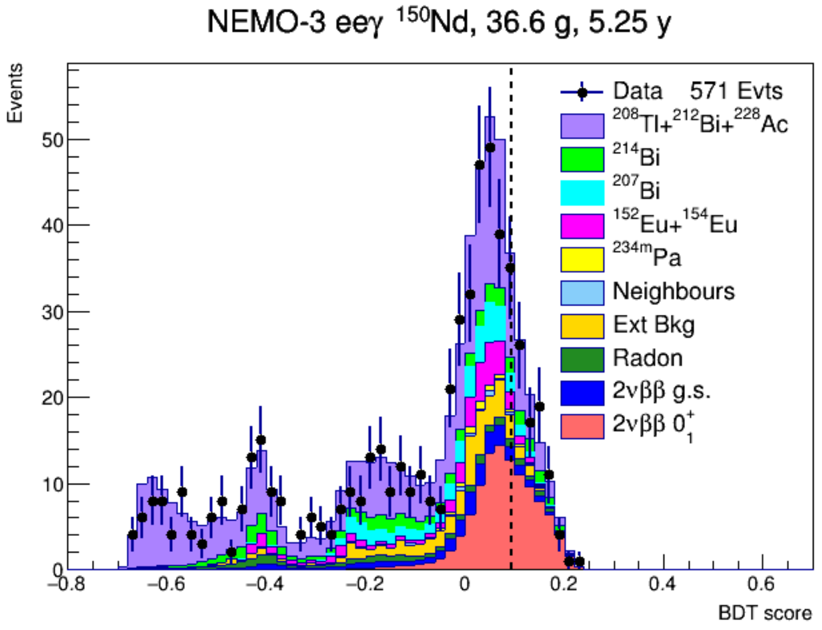






^{150}Nd $2\nu\beta\beta$ --> 0^+_1 measurement in $ee\gamma$ channel



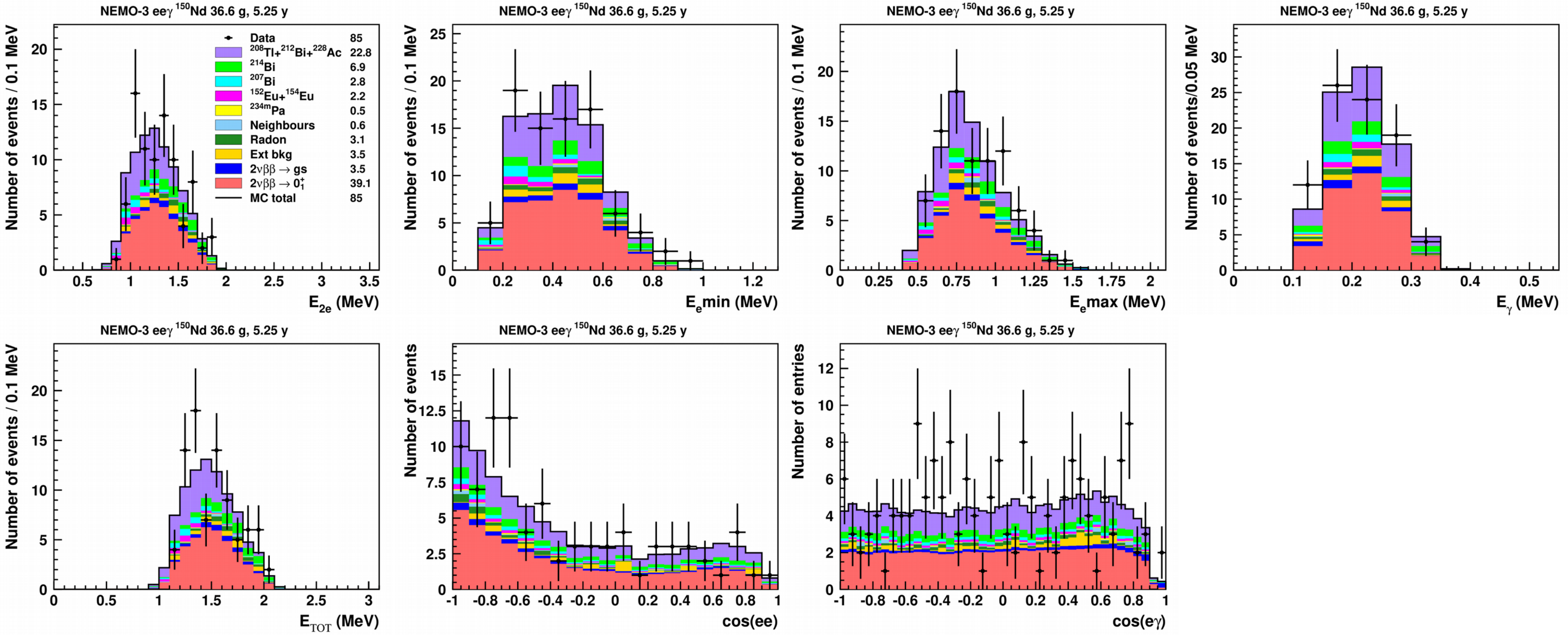


Cut out events with low BDT score values to maximize the signal significance

Data= 85, B=45.9, ε=0.882%, S=Data-B=31.9
S/B=0.85, $S/\sqrt{(S+B)}=4.24$

$$T_{1/2}^{2\nu}(0^+_1)=[1.21\,^{+0.37}_{-0.23}(\text{stat})\,^{+0.26}_{-0.20}(\text{syst})]\times10^{20}\text{ y}$$

Distributions eeγ events after BDT cut



^{150}Nd $2\nu\beta\beta$ --> 0^+_1 , $ee\gamma\gamma$, $ee\gamma$ and mean value

$T_{1/2}^{2\nu}(0^+_1)=[1.04\,^{+0.24}_{-0.16}(\text{stat})\,^{+0.12}_{-0.11}(\text{syst})]\times 10^{20}$ y eeγγ

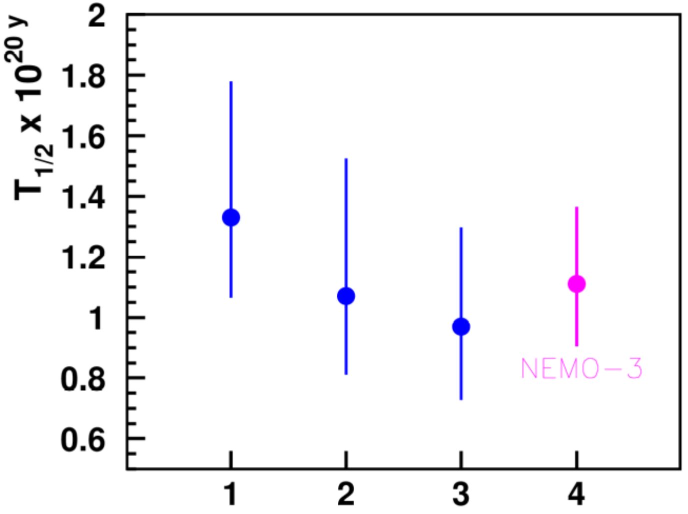
$T_{1/2}^{2\nu}(0^+_1)=[1.21\,^{+0.37}_{-0.23}(\text{stat})\,^{+0.26}_{-0.20}(\text{syst})]\times 10^{20}$ y eeγ

$T_{1/2}^{2\nu}(0^+_1)=[1.11\,^{+0.19}_{-0.14}(\text{stat})\,^{+0.17}_{-0.15}(\text{syst})]\times 10^{20}$ y mean

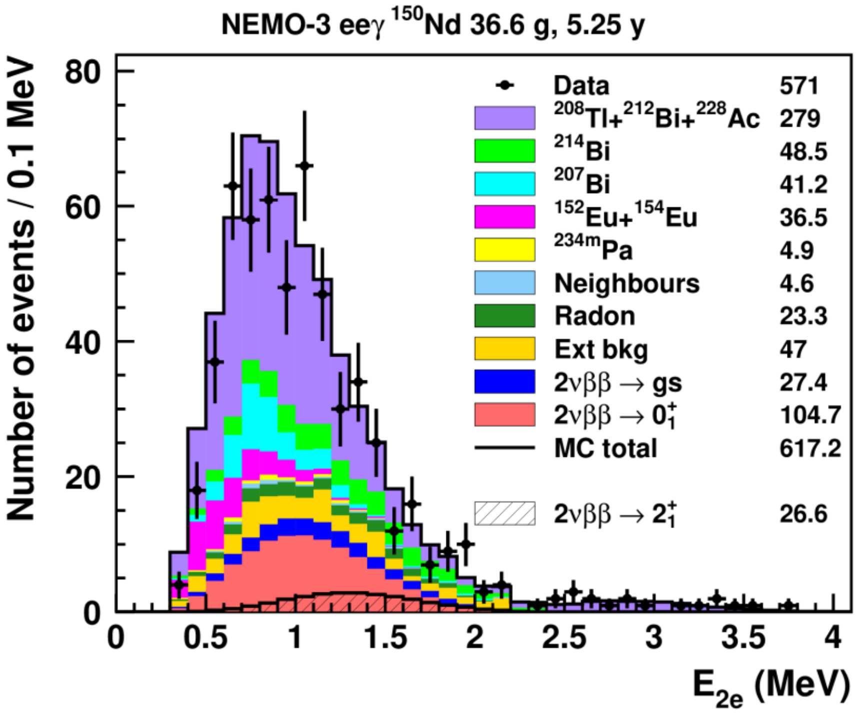
Nσ_tot	Nσ_stat	S/B	Eff, %	Channel
4.73	5.37	2.82	0.761	eeγγ
3.39	4.24	0.85	0.882	eeγ
5.07	6.83	1.31	1.643	eeγγ+eeγ

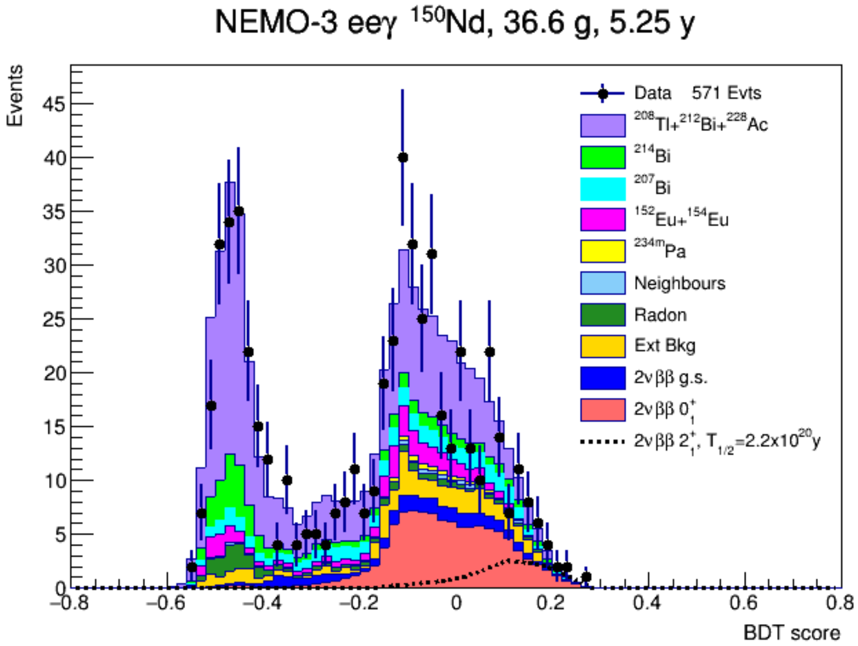
Compared to HPGe results

[1] *A.S.Barabash et al,Phys.Rev. C79 (2009)054606*
[2] *M.F.Kidd et al.,Phys.Rev. C90(2014)055501*
[3] *O.G.Polischuk et al,Phys.Scr.96(2021)08532*



^{150}Nd $2\nu\beta\beta$ --> 2^+_1 , eeγ channel





$eff^{2\nu}(2^+_1)$=1.10 %

Data-MC= -46.2 events

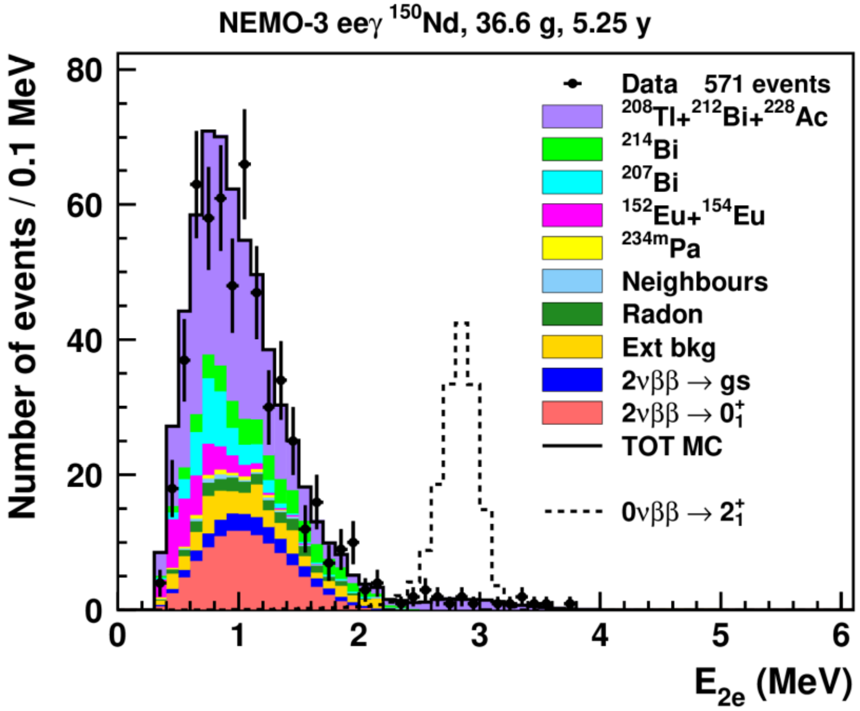
No room for 2^+_1

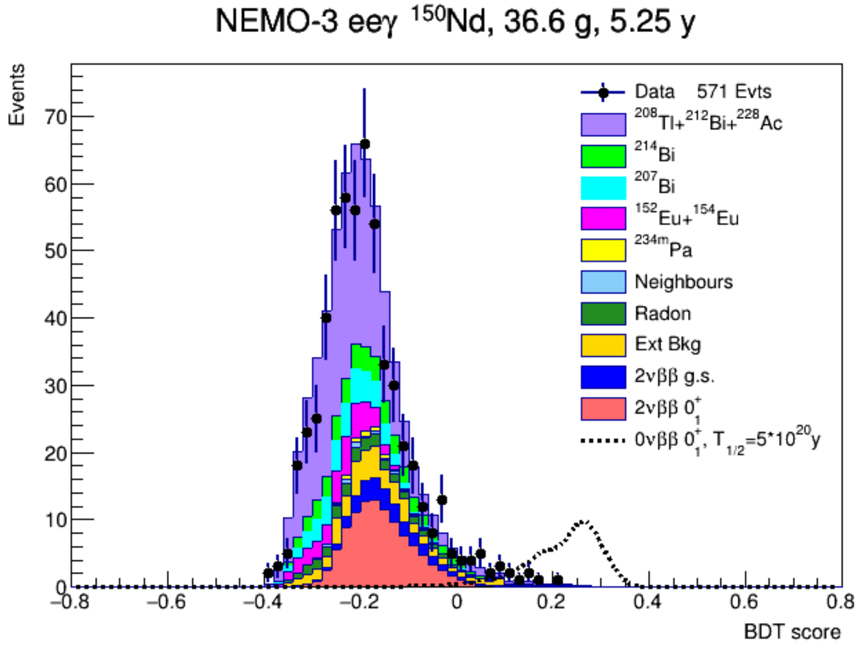
$1-CL_b$ = 1-0.3996 = 0.6004

Expected $T_{1/2} > 2.21 \times 10^{20}$ y

Observed $T_{1/2} > 2.42 \times 10^{20}$ y

^{150}Nd 0νββ --> 2^+_1 , eeγ channel





$eff^{0\nu}(2^+_1)$ = 6.89%

2.4 MeV < E_{2e} < 3.2 MeV

Data = 12 events

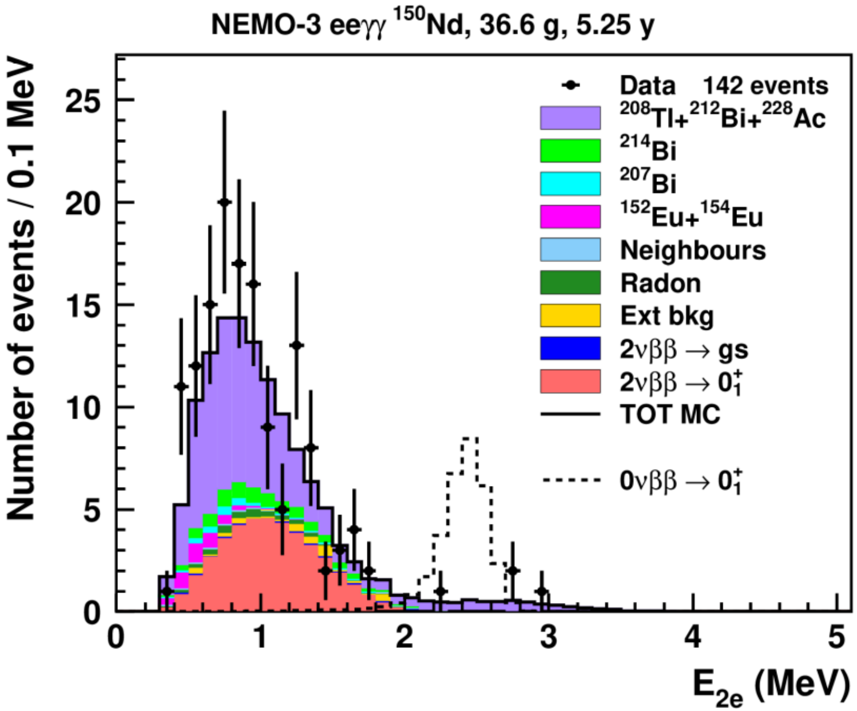
MC = 11.6 events

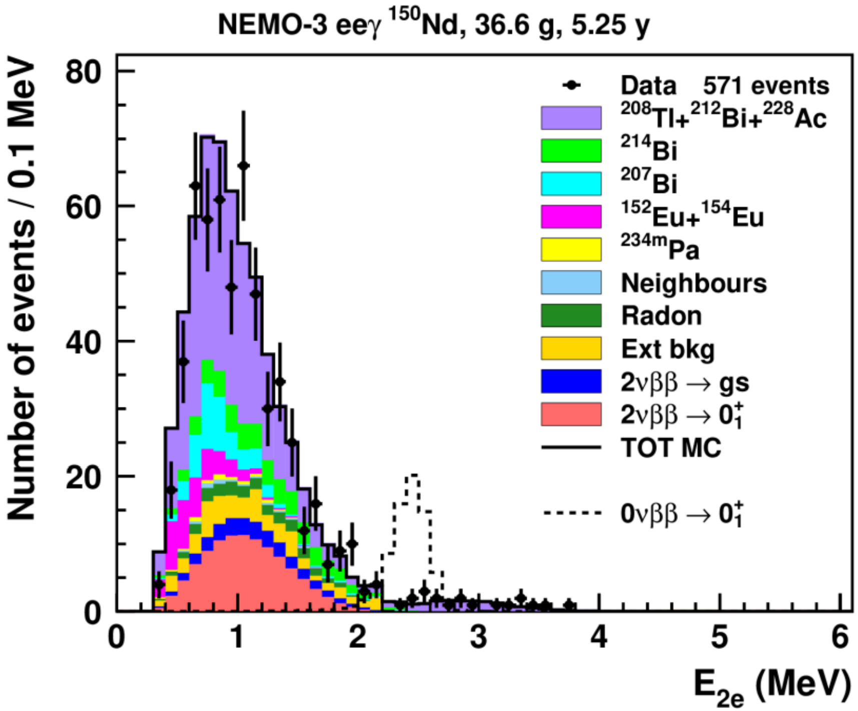
1-CL_b = 1-0.3640 = 0.636

Expected $T_{1/2}$ > 1.01 x 10^{22} y

Observed $T_{1/2}$ > 1.26 x 10^{22} y

Search for ^{150}Nd 0νββ --> 0^+_1 eeγγ, eeγ





eeγγ $eff^{0\nu}(0^+_1) = 4.89\%$

2 MeV < E_{2e} < 2.8 MeV

Data = 3 events

MC = 4.2 events

eeγ $eff^{0\nu}(0^+_1) = 7.02\%$

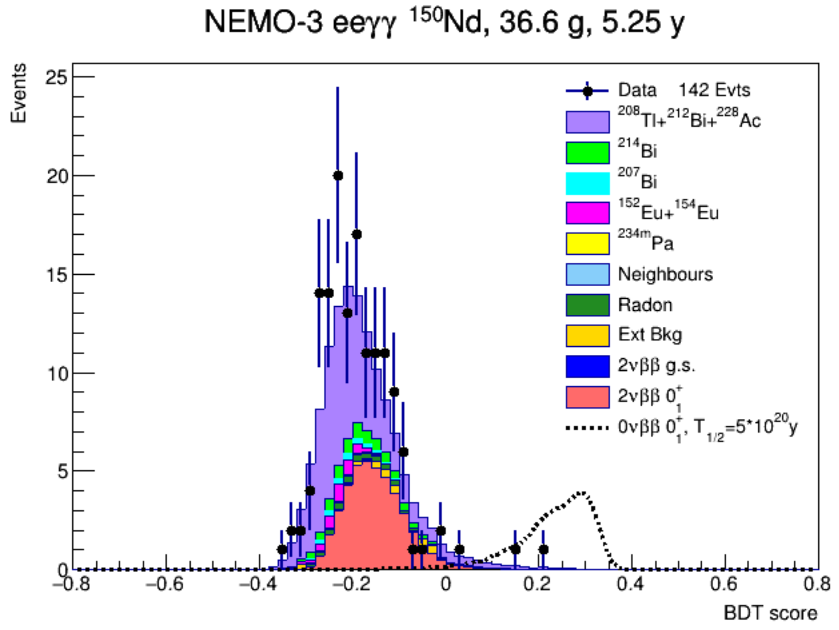
2 MeV < E_{2e} < 2.8 MeV

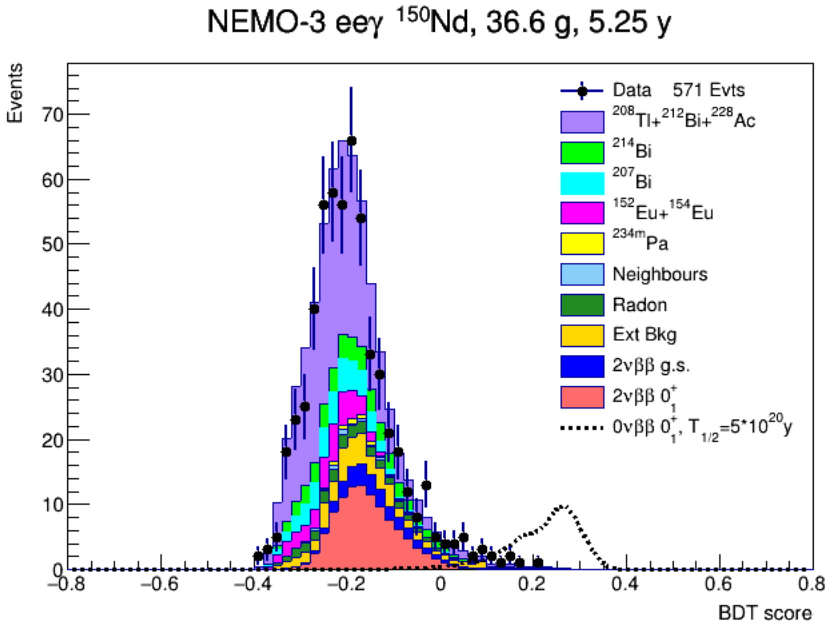
Data = 16 events

MC = 16.1 events

No any data excess in the region of interest for the 0ν signal

90% C.L. limit on ^{150}Nd $0\nu\beta\beta$ --> 0^+_1, $ee\gamma\gamma$, $ee\gamma$





eeγγ

$1\text{-}CL_b$ = 1-0.6256 = 0.3744

Expected $T_{1/2} > 6.0 \times 10^{21}$ y

Observed $T_{1/2} > 5.2 \times 10^{21}$ y

eeγ

$1\text{-}CL_b$ = 1-0.6421 = 0.3575

Expected $T_{1/2} > 9.21 \times 10^{21}$ y

Observed $T_{1/2} > 9.97 \times 10^{21}$ y

eeγγ+eeγ

$1\text{-}CL_b$ = 1-0.6550 = 0.345

Expected $T_{1/2} > 1.31 \times 10^{22}$ y

Observed $T_{1/2} > 1.36 \times 10^{22}$ y

Summary

- For the first time the ββ decay of ^{150}Nd to the 0^+_1 excited state of ^{150}Sm has been detected with the signal significance exceeding 5σ. Most accurate for the date measurement of the decay half life has been produced:

$$T_{1/2}^{2\nu}(0^+_1)=[1.11\ ^{+0.19}_{-0.14}\ (stat)\ ^{+0.17}_{-0.15}\ (syst)]\times 10^{20}\ y$$

- The limit on 2νββ decay to the 2^+_1 excited state is slightly improved:

$$T_{1/2}^{2\nu}(2^+_1) > 2.42 \times 10^{20}\ y \quad @\ 90\%\ C.L.$$

- No evidence has been found for the neutrinoless ββ decay:

$$T_{1/2}^{0\nu}(0^+_1) > 1.36 \times 10^{22}\ y \quad @\ 90\%\ C.L.$$

$$T_{1/2}^{0\nu}(2^+_1) > 1.26 \times 10^{22}\ y \quad @\ 90\%\ C.L.$$

Backup slides

90% C.L. limit on ^{150}Nd $0\nu\beta\beta \rightarrow 0^+_1$

The obtained low half limit $T_{1/2}^{0\nu}(0^+_1) > 1.36 \times 10^{22}$ y corresponds to the upper limit on the effective Majorana neutrino mass

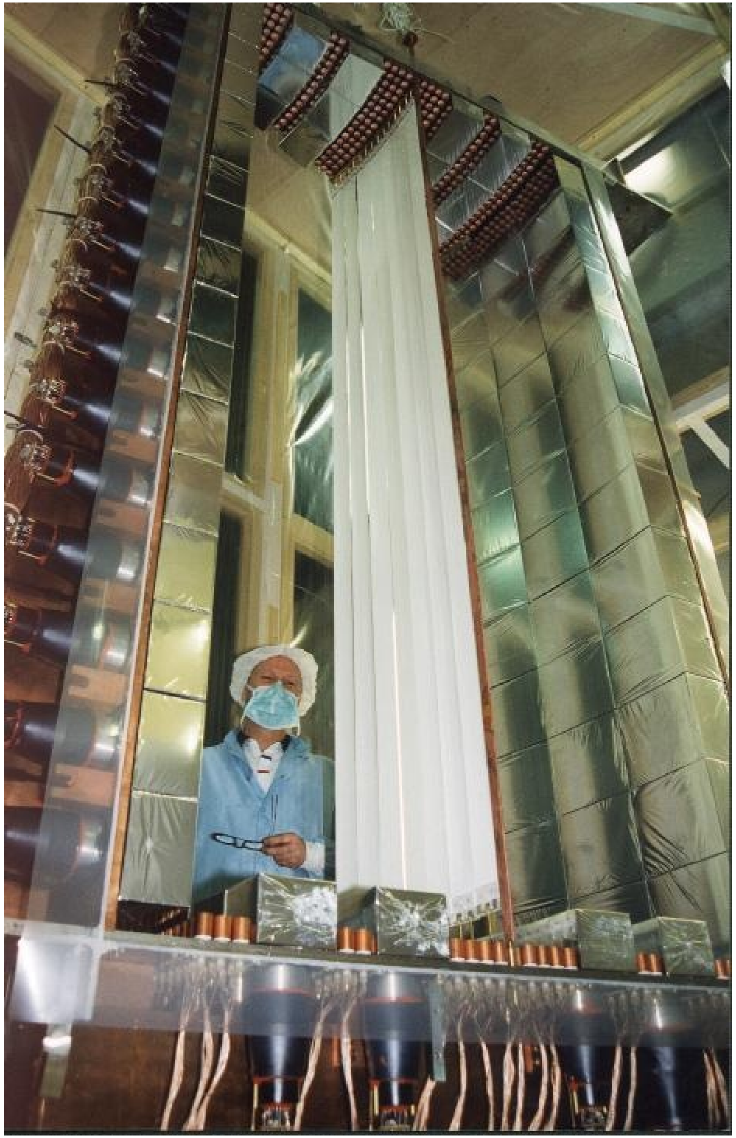
$$\langle m_\nu \rangle < 6 - 43 \text{ eV}$$

According to the NME calculations:

J. M. Yao and J. Engel, Phys. Rev. C 94(2016)014306
L.S. Song et al.,Phys. Rev. C 90 (2014) 054309
J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C 87(2013)014315
J. Beller et al., Phys.Rev. Lett. 111(2013)172501.

That is less stringent compared to our results for the ground state transition

$T_{1/2}^{0\nu}(\text{g.s.}) > 2.0 \times 10^{22}$ y, $\langle m_\nu \rangle < 1.6 – 5.3$ eV *R. Arnold et al., Phys. Rev. D 94(2016)072003*



NEMO-3 detector

Source foils of Sector 5

46.64 g of Nd_2O_3 powder mixed with 8% of PVA glue were uniformly distributed between two layers of mylar to produce the composit foil with the total mass of 57.15 g. The size of foil was 2484 mm in length, 65 mm in width.
The ^{150}Nd composite strip was located in the NEMO-3 sector 5 at the position of foil 6 between the composite ^{100}Mo (foil 5) and the foil containing ^{96}Zr and ^{48}Ca (foil 7).
The enrichment factor in ^{150}Nd is 91 ± 0.5 %, ^{150}Nd mass = 36.6 ± 0.2 g