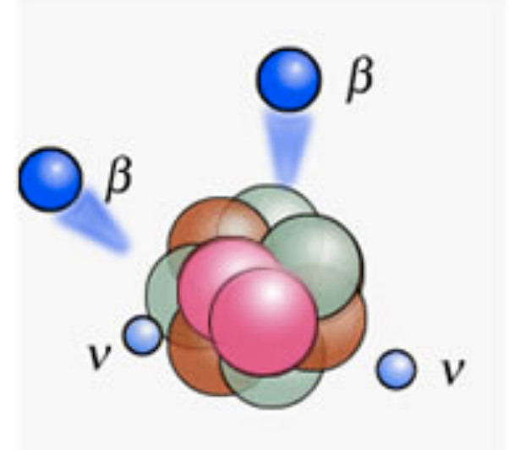
New results on the ^{76}Ge double beta decay with neutrinos and exotic decay modes from GERDA Phase II

Elisabetta Bossio (Technical University of Munich) for the GERDA collaboration

1. Two-neutrino double beta decay

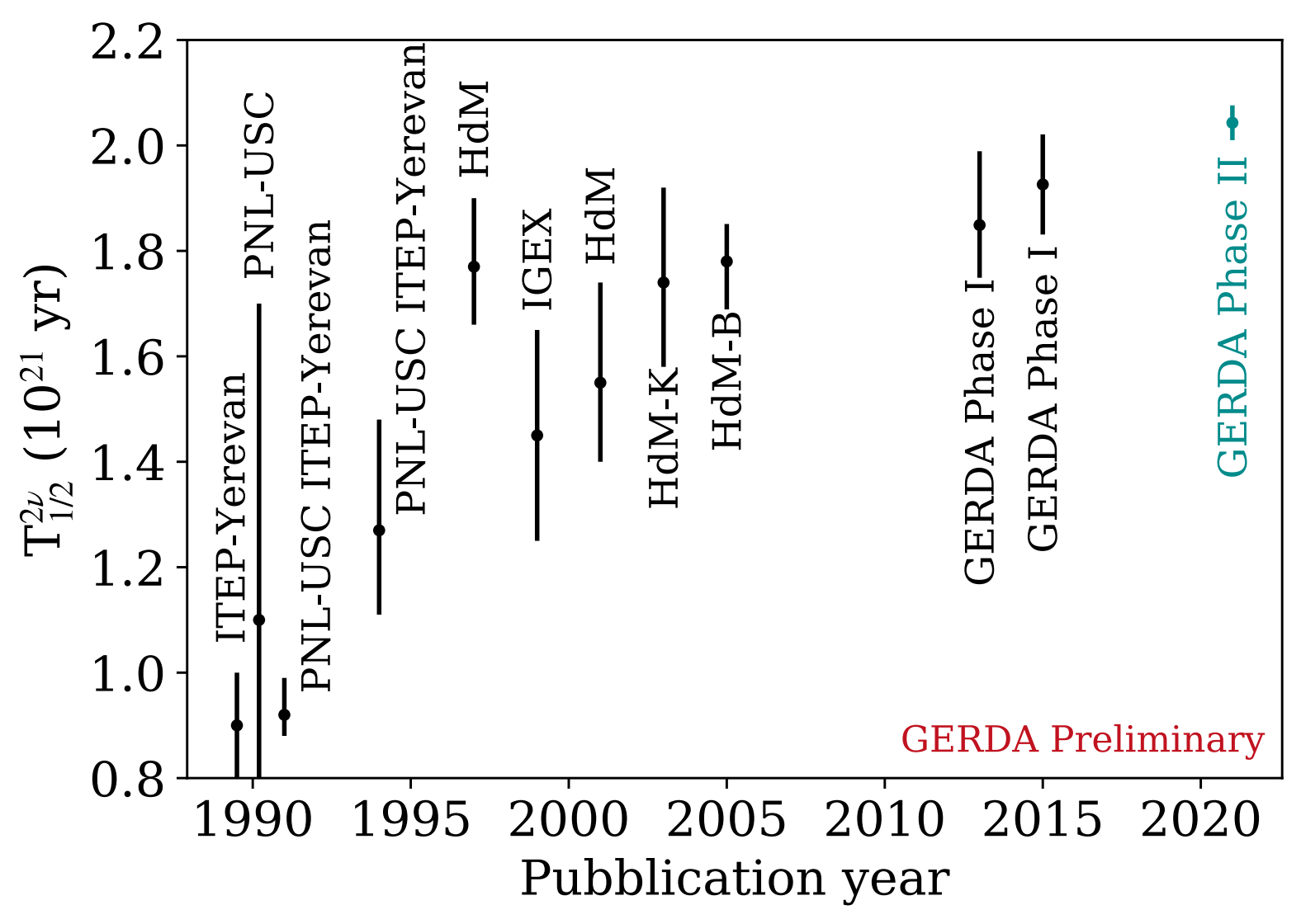


Two-neutrino double beta ($2\nu\beta\beta$) decay is among the rarest radioactive processes ever detected (half-life ranging between 10^{18}-10^{24} yr).

Precise measurements of the half-life ($T^{2\nu}_{1/2}$) provide a test-stand to validate complex nuclear matrix element calculations.

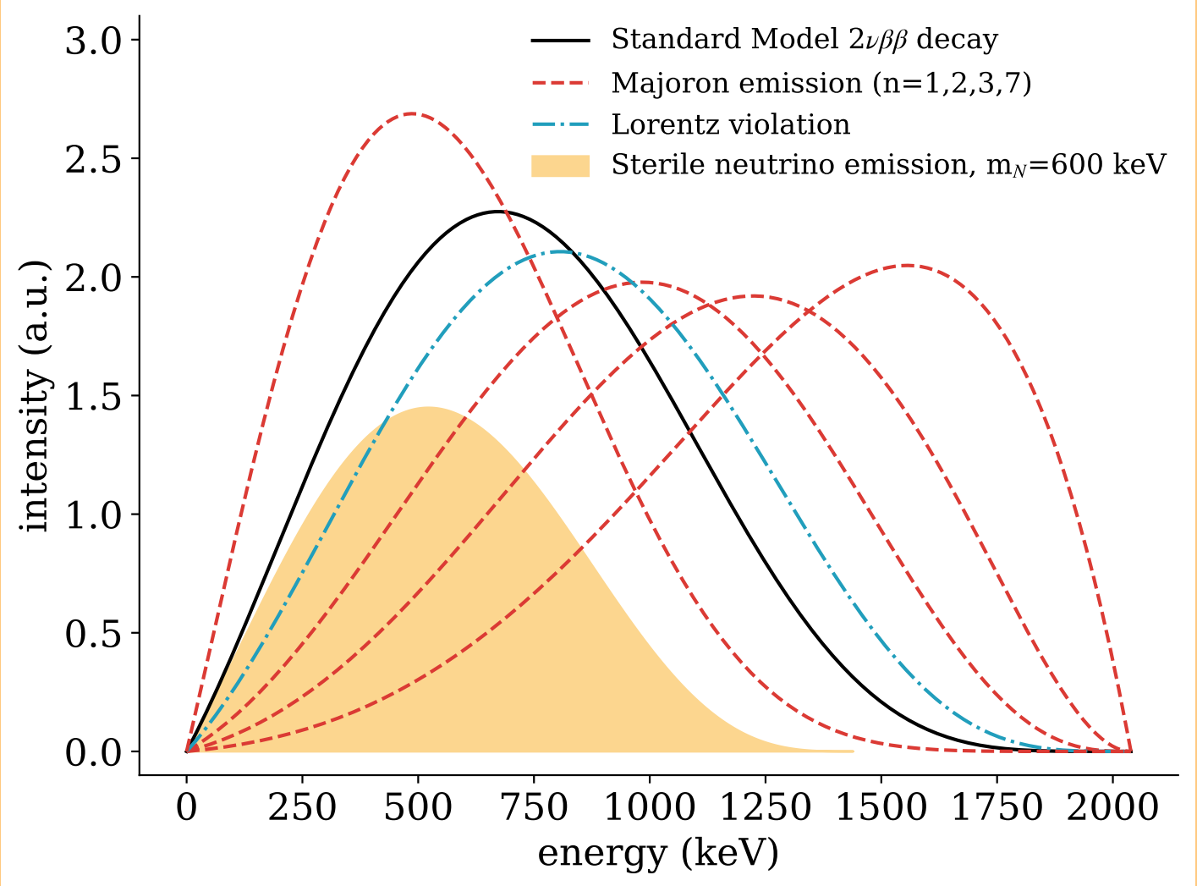
Measuring the $2\nu\beta\beta$ decay half-life of ^{76}Ge

Pioneering measurements already in the nineties. Past measurements not fully compatible and with large uncertainties. The increasing of the central value over the years can be attributed to systematic underestimation of the background, that decreases as the experiments keep on reducing the background level. References for the plot in [1].



Probing new physics with double beta decay

Extensions of the Standard Model that predict the emission of exotic particles (Majorons, sterile neutrinos, ...), as well as violation of Lorentz symmetry, can be tested searching for deformation of the continuous $2\nu\beta\beta$ decay spectrum [2-4].



2. The GERDA experiment

The Germanium Detector Array searched for $0\nu\beta\beta$ decay of ^{76}Ge with enriched high purity germanium detectors in liquid argon (LAr) at Laboratori Nazionali del Gran Sasso (LNGS) in Italy.

The $64 m^3$ LAr cryostat was instrumented with wave-length-shifting fibers connected to silicon photomultipliers and low-activity photomultiplier tubes, allowing the detection of scintillation light due to events depositing energy in the LAr volume surrounding the detectors.

The Phase II data taking lasted from December 2015 to December 2019, corresponding to more than 100 kg·yr of exposure. Key technologies, such as pulse shape discrimination (PSD) and the detection of coincident scintillation light from the LAr, allowed a background-free search of $0\nu\beta\beta$ decay [5].

Watch C. Wiesinger's recorded talk for more details and final GERDA $0\nu\beta\beta$ decay results!

https://www.mpi-hd.mpg.de/

3. Analysis methods and determination of the half-life

$2\nu\beta\beta$ decay signal: localised energy deposition in one detector

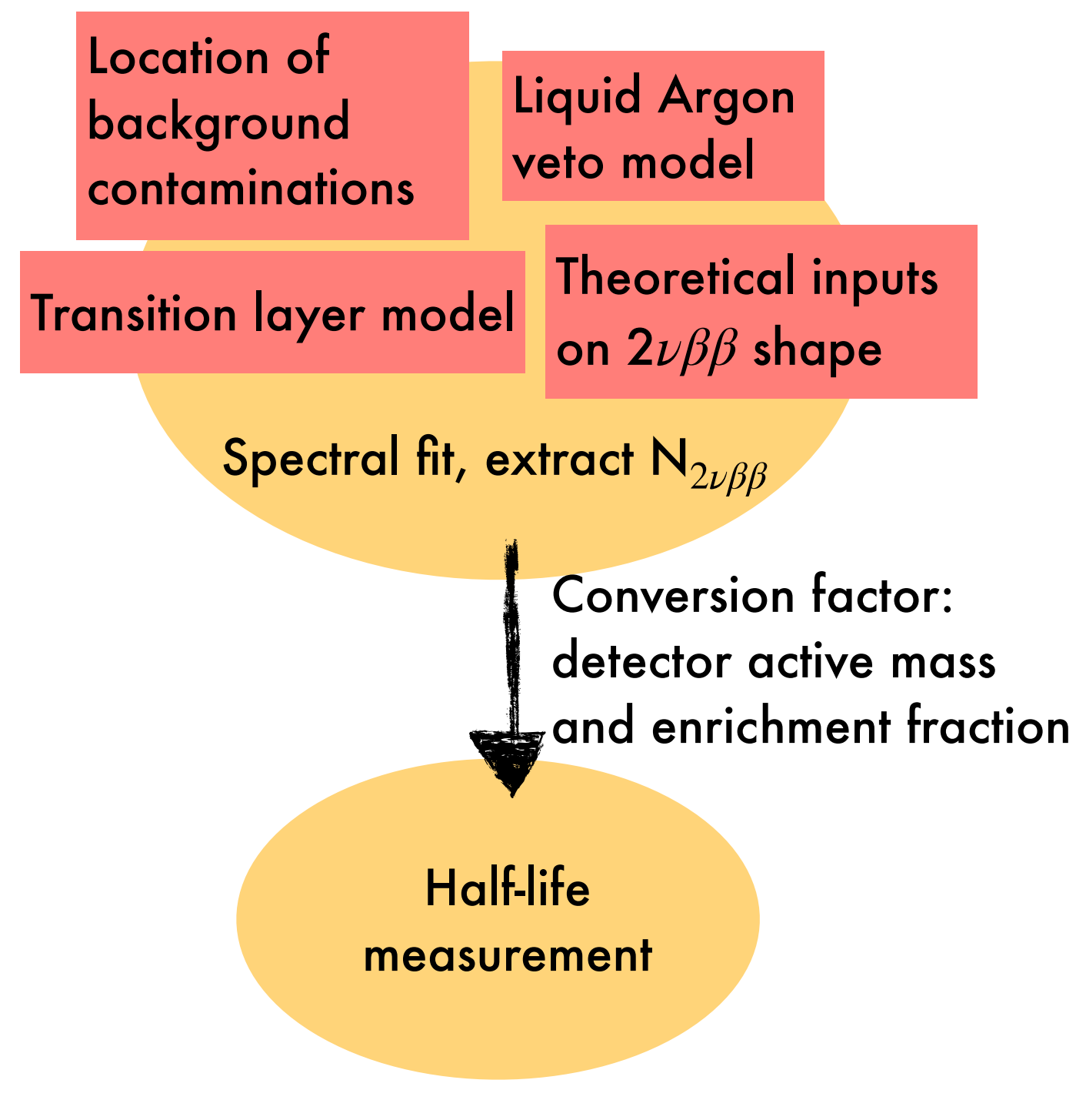
Background: coincident energy deposition in more detectors (detector anti-coincidence cut) and/or coincident energy deposition in the Liquid Argon volume (LAr veto cut)

Background model. The event rate of GERDA is dominated by the $2\nu\beta\beta$ decay of ^{76}Ge in the energy range between 560keV and 2000keV. Minor contribution from ^{228}Ac, ^{228}Th, ^{214}Bi, ^{60}Co, ^{40}K decays in the structural materials, ^{42}Ar decay in the liquid argon and α decays on the detector surface are also expected in this energy region. Below the 560keV threshold, ^{39}Ar, a cosmogenic isotope of argon, becomes dominant. Differences from the background model in [6] are expected in this analysis due to the application of LAr veto cut.

Exposure. Data collected between December 2015 and May 2018 with the BEGe detectors are used, corresponding to an exposure of 32.8 kg·yr. Better knowledge of the detector active mass and response. The analysis is not limited by the statistical uncertainty.

Statistical analysis. A maximum binned likelihood fit is performed to estimate the number of $2\nu\beta\beta$ decay events. The parameters of the fit are the scaling factors of the signal and background distributions, all unconstrained. The statistical inference is based on a profile likelihood ratio test statistic, whose probability distribution is evaluated with Monte Carlo techniques.

Systematic uncertainties that affect the energy distributions, and in turn the estimation of $N_{2\nu\beta\beta}$, are folded into the analysis during the computation of the test statistic distribution. Systematic uncertainties that affect the conversion between the number of events and $T^{2\nu}_{1/2}$ are simply summed in quadrature (see scheme on the right).



Location of background contaminations

Liquid Argon veto model

Transition layer model

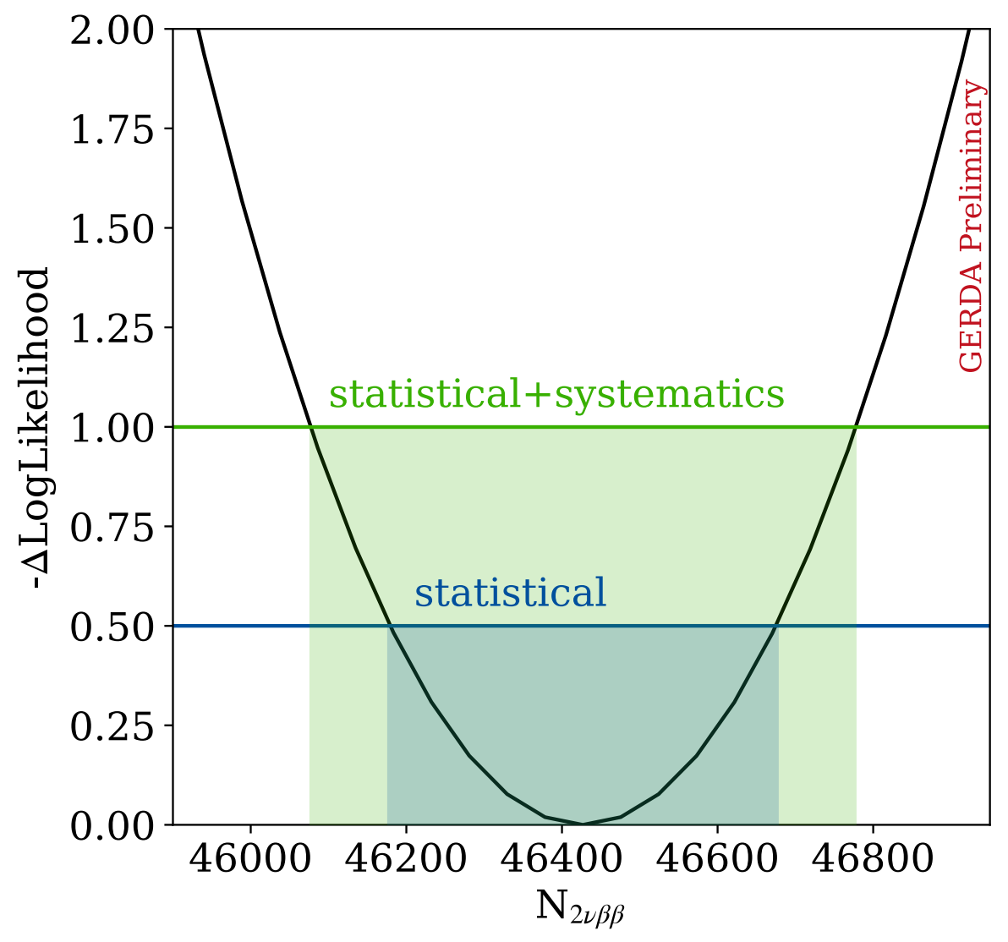
Theoretical inputs on $2\nu\beta\beta$ shape

Spectral fit, extract $N_{2\nu\beta\beta}$

Conversion factor: detector active mass and enrichment fraction

Half-life measurement

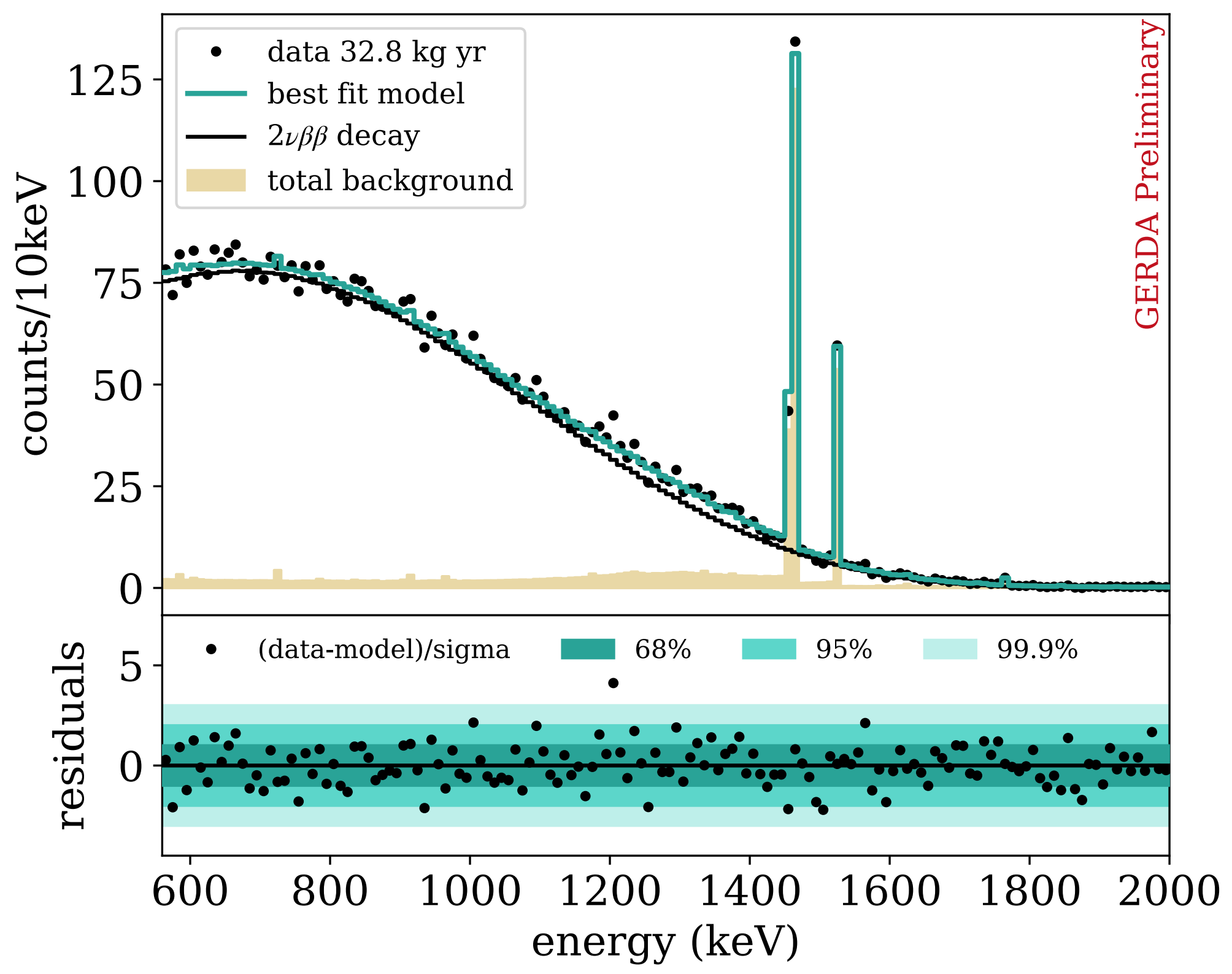
Results



The experimental data and the best fit model are shown in the plot below. Highest signal-to-background ratio of 22:1 in the $2\nu\beta\beta$ decay dominated region obtained with germanium detectors thanks to the LAr veto cut (only 2:1 before).

The 68% probability interval on $N_{2\nu\beta\beta}$ is extracted from the profile-likelihood as shown in the plot on the right. $N_{2\nu\beta\beta} = (46427 \pm 250(\text{stat}) \pm 245(\text{sys}))$ counts

Converting into $T^{2\nu}_{1/2}$ we obtain: $T^{2\nu}_{1/2} = (2.043 \pm 0.011(\text{stat}) \pm 0.031(\text{sys})) \cdot 10^{21}$ yr



The total uncertainty of 1.6% is dominated by the systematic uncertainty on the active volume.

Systematic uncertainties	
Active volume ± 1.37 %	LAr veto model ± 0.26 %
Background model ± 0.42 %	Transition layer < 0.01 %
Enrichment fraction ± 0.30 %	Theoretical inputs < 0.01%
Total 1.50 %	

This is the most precise measurement of the $2\nu\beta\beta$ decay half-life of ^{76}Ge, but also the most precise half-life determination of a $2\nu\beta\beta$ decay.

4. Search for new physics

The same analysis method used for the determination of the $2\nu\beta\beta$ decay half-life have been used to search for Lorentz violation and $0\nu\beta\beta$ with emission of Majorons (χ). No deviations from the Standard Model $2\nu\beta\beta$ decay are observed: no indications of Lorentz violation or Majorons emission are found.

90% C.L. lower limits on the half-life of $0\nu\beta\beta\chi(\chi)$ decay for 4 different theoretical models (spectral index n=1,2,3,7) and a two-side limit on the Lorentz violating parameter ($a^{(3)}_{of}$) have been set. The limits include all the systematic uncertainties (impact 10-35%).

	Limit on half-life	Sensitivity on half-life	Limit on coupling
$0\nu\beta\beta\chi$ n=1	6.3 10^{23} yr	3.5 10^{23} yr	1.8 10^{-5}
$0\nu\beta\beta\chi$ n=2	2.9 10^{23} yr	2.5 10^{23} yr	-
$0\nu\beta\beta\chi(\chi)$ n=3	1.2 10^{23} yr	1.3 10^{23} yr	1.7 10^{-2} / 1.2
$0\nu\beta\beta\chi\chi$ n=7	1.0 10^{23} yr	5.8 10^{22} yr	1.1
Limit on Lorentz violation		Sensitivity	
($-2.7 < a^{(3)}_{of} < 6.2$) 10^{-6} GeV		($-3.8 < a^{(3)}_{of} < 4.9$) 10^{-6} GeV	

GERDA Preliminary

Limits on the coupling neutrino-Majorons are obtained using phase spaces and nuclear matrix elements in [7-8]. The limits on the Lorentz violation use the phase space in [9].

5. Discussion and conclusions

Despite the long half-life of ^{76}Ge compare to other isotopes, we reached an unprecedented precision, reducing the 5% uncertainty of GERDA Phase I to only 1.6%.

$$T^{2\nu}_{1/2} = (2.043 \pm 0.033) \cdot 10^{21}\, yr$$

GERDA Preliminary

This result is compatible with the past Phase I result, but confirms the slightly increasing $T^{2\nu}_{1/2}$ central value, as the background is drastically reduced with the detection of the scintillation light in liquid argon.

With this measurement of the half-life, the effective nuclear matrix elements can be extracted, $[T^{2\nu}_{1/2}]^{-1} = G_{2\nu} |\mathscr{M}^{2\nu}_{eff}|^2$, $\mathscr{M}^{2\nu}_{eff} = 0.1008 \pm 0.0008$, with a precision better than 1%. This is a valuable input for nuclear structure calculations that benefit the interpretation of $0\nu\beta\beta$ decay results.

The uncertainty is limited by systematics. In the future, an improvement of this result will not require a larger exposure but a further reduction of the systematic uncertainties. The LEGEND experiment will face the challenge of improving the accuracy of the active volume determination.

We improved the limits on $0\nu\beta\beta$ with emission of Majorons with respect to Phase I, and set the first limit on Lorentz violation with ^{76}Ge $2\nu\beta\beta$. These limits are competitive with the results of other double beta decay experiments. Improvements will be obtained in LEGEND with more statistic if also the systematic uncertainties are reduced. This would also allow the search for more exotic physics (e.g. sterile neutrinos) as pointed out in [4].

References

[1] Front. in Phys. 7, 6 (2019)
[2] Phys. Rev. D 89 (2014)
[3] Phys. Lett. B 372, 8 (1996)
[4] Phys. Lett. B 815, 136127 (2021)
[5] Phys. Rev. Lett. 125, 252502 (2020)
[6] J. High Energ. Phys. 2020, 139
[7] Phys. Rev.C 92, 2, 029903(2015)
[8] Phys. Rev. C 103, 044302 (2021)
[9] J. Phys. G, vol. 47, 5, 055112, 2020

The 28th International Workshops on Weak Interactions and Neutrinos (WIN2021), University of Minnesota, June 7-11 2021