The MAJORANA DEMONSTRATOR's Search for Double-Beta Decay of ^{76}Ge to Excited States of ^{76}Se

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On behalf of the MAJORANA Collaboration
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TAUP, Vienna, Austria

MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

Source & Detector: Array of p-type, point contact detectors

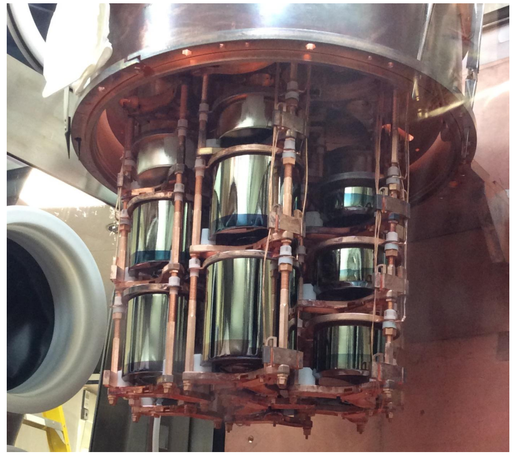
30 kg of 88% enriched ^{76}Ge crystals - 14 kg of natural Ge crystals

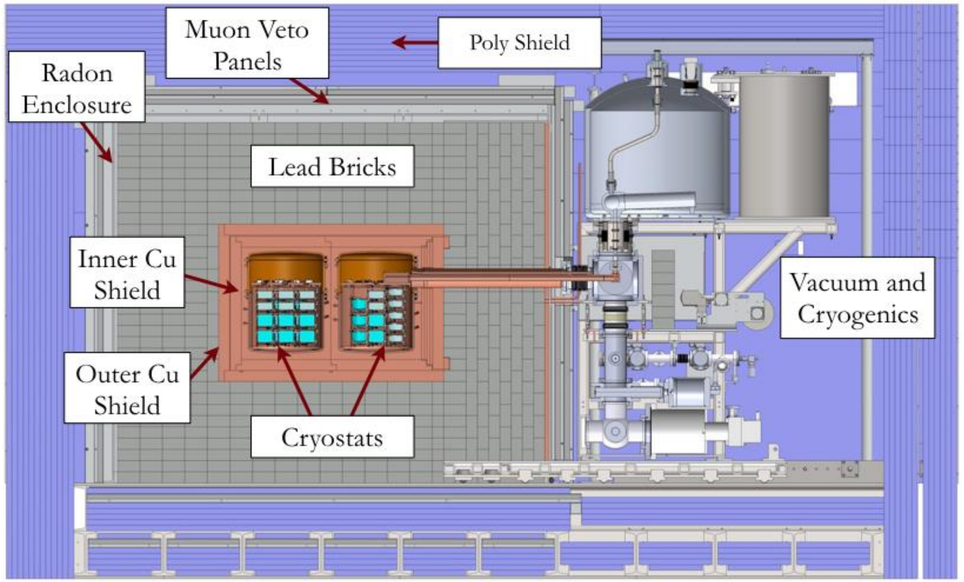
Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors in final run

Excellent Energy Resolution: 2.5 keV FWHM @ 2039 keV and **Analysis Threshold:** 1 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

Reached an exposure of ~65 kg-yr before removal of the enriched detectors for the LEGEND-200 experiment at LNGS





Continuing to operate at the Sanford Underground Research Facility with natural detectors searching for ^{180m}Ta search

See talk by R. Massarczyk

Rich and Broad Physics Programs

Tests of Fundamental Symmetries and Conservations

- Lepton number violation via neutrinoless double beta decay
- Baryon number violation
- Pauli Exclusion Principle violation

PRL **130** 062501 (2023)

PRD **99** 072004 (2019)

arXiv:2203.02033 (2022)

Standard Model Physics

BSM Physics

Standard Model Physics, particular backgrounds

- **2νββ to excited states**
- In situ cosmogenics
- (alpha, n) reactions

PRC **103** 015501 (2021)

PRC **105** 014617 (2022)

PRC **105** 064610 (2022)

MAJORANA DEMONSTRATOR

Excellent energy performance &

Low backgrounds

across broad energy regions

Low-mass dark matter signatures

- Pseudoscalar dark matter
- Vector dark matter
- Fermionic dark matter
- Sterile neutrino
- Primakoff solar axion
- 14.4-keV solar axion

PRL **118** 161801 (2017)

PRL **129** 081803 (2022)

arXiv:2206.10638 (2022)

Exotic Physics

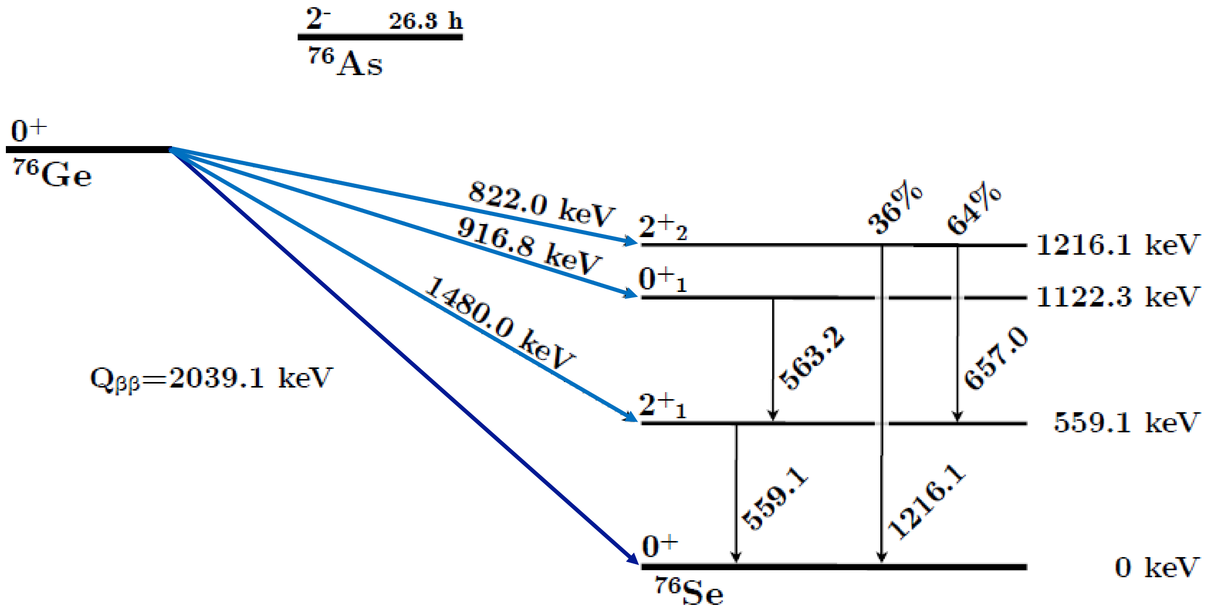
- Quantum Wavefunction collapse
- Lightly ionization particle

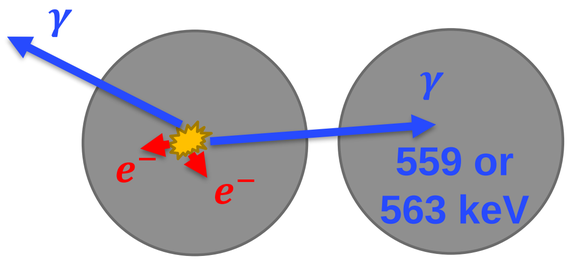
PRL **129** 080401 (2022)

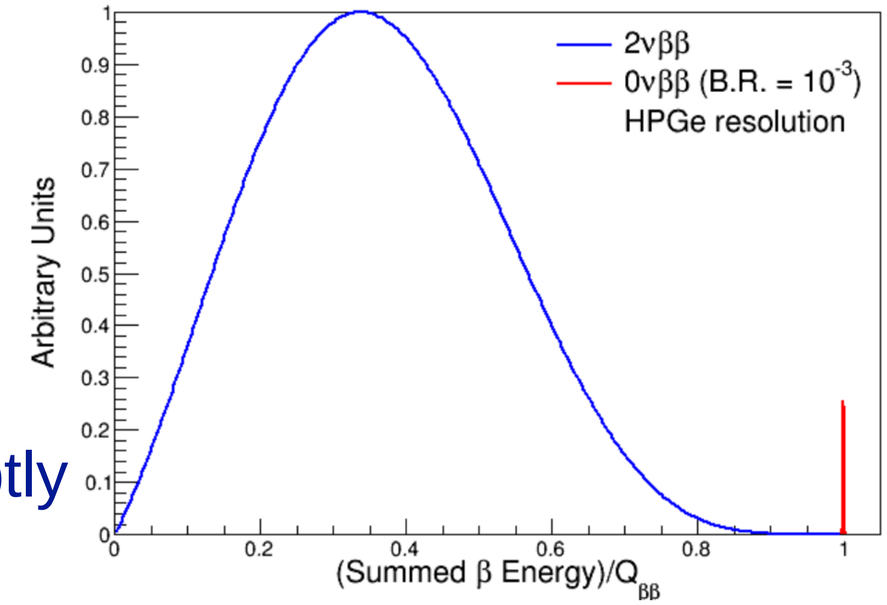
PRL **120** 211804 (2018)

Double Beta Decay to Excited States

^{76}Se has 3 excited states that ^{76}Ge can ββ-decay into







- Broad 2νββ spectrum, reduced Q-Value for decay
  - If neutrino is Majorana, could see 0νββ peak at Q-value
- One or two monoenergetic gammas emitted promptly
  - Inherently multi-site events!

Double Beta Decay to Excited States

Using data collected up to 2019, the MAJORANA DEMONSTRATOR set the most stringent limits to date for each mode of ββ to excited states of ^{76}Se. We benefited from:

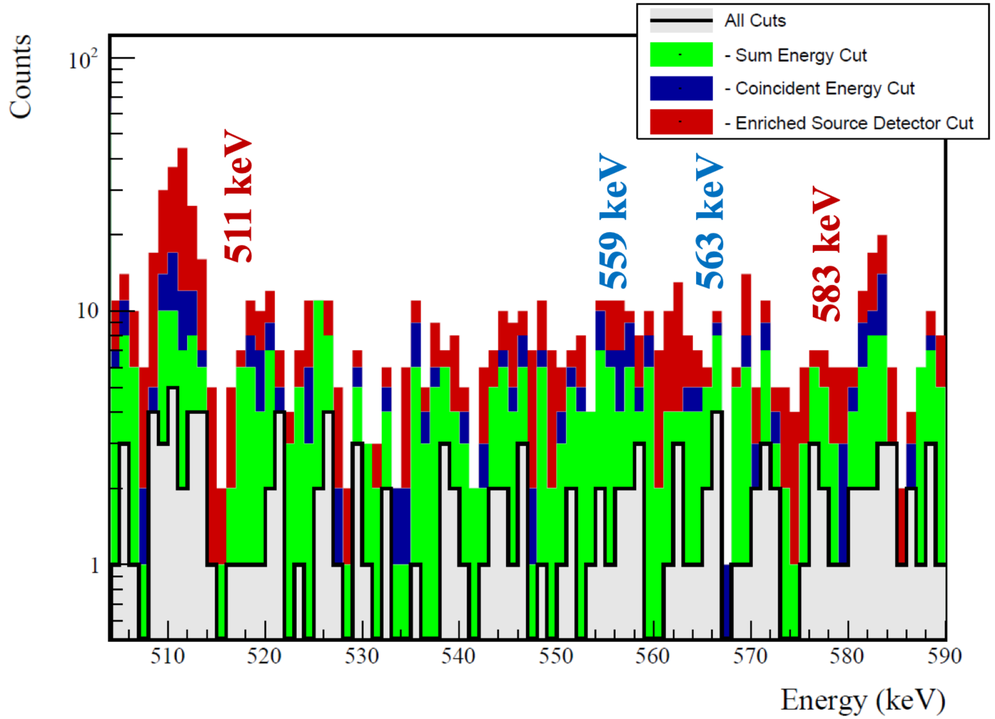
- Operating an array in vacuum: high detection efficiency
- Exquisite energy resolution for identifying peaks
- Low environmental backgrounds & analysis cuts

PRC **103** 015501 (2021)

Decay Mode	Det. efficiency (M1, M2)	$T_{1/2}$ prev. limit (90% CI)	$T_{1/2}$ new limit (90% CI)	$T_{1/2}$ sensitivity (90% CI)
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 0^+_1$	2.4%, 1.0%	$> 3.7 \cdot 10^{23} y$ [1]	$> 7.5 \cdot 10^{23} y$	$> 10.5 \cdot 10^{23} y$
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_1$	1.4%, 0.6%	$> 1.6 \cdot 10^{23} y$ [1]	$> 7.7 \cdot 10^{23} y$	$> 10.2 \cdot 10^{23} y$
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_2$	2.2%, 0.8%	$> 2.3 \cdot 10^{23} y$ [1]	$> 12.8 \cdot 10^{23} y$	$> 8.2 \cdot 10^{23} y$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 0^+_1$	3.0%, 1.2%	$> 1.3 \cdot 10^{22} y$ [2]	$> 39.9 \cdot 10^{23} y$	$> 39.9 \cdot 10^{23} y$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_1$	1.6%, 0.7%	$> 1.3 \cdot 10^{23} y$ [3]	$> 21.2 \cdot 10^{23} y$	$> 21.2 \cdot 10^{23} y$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_2$	2.3%, 1.0%	$> 1.4 \cdot 10^{21} y$ [4]	$> 9.7 \cdot 10^{23} y$	$> 18.6 \cdot 10^{23} y$

[1] M. Agostini et al. (GERDA Collaboration), J. Phys. G 43, 044001 (2015).
[2] A. Morales, et al., Nuovo Cim. A 100, 525 (2008).
[3] B. Maier (Heidelberg Moscow Collaboration), Nucl. Phys. B – Proc. Suppl. 35, 358 (1994).
[4] A. S. Barabash, A. V. Derbin, L. A. Popeko, and V. I. Umatov, Z. Phys. A 352, 231 (1995).

41.9 kg y of isotopic exposure
(20.6 kg y of which was blinded)

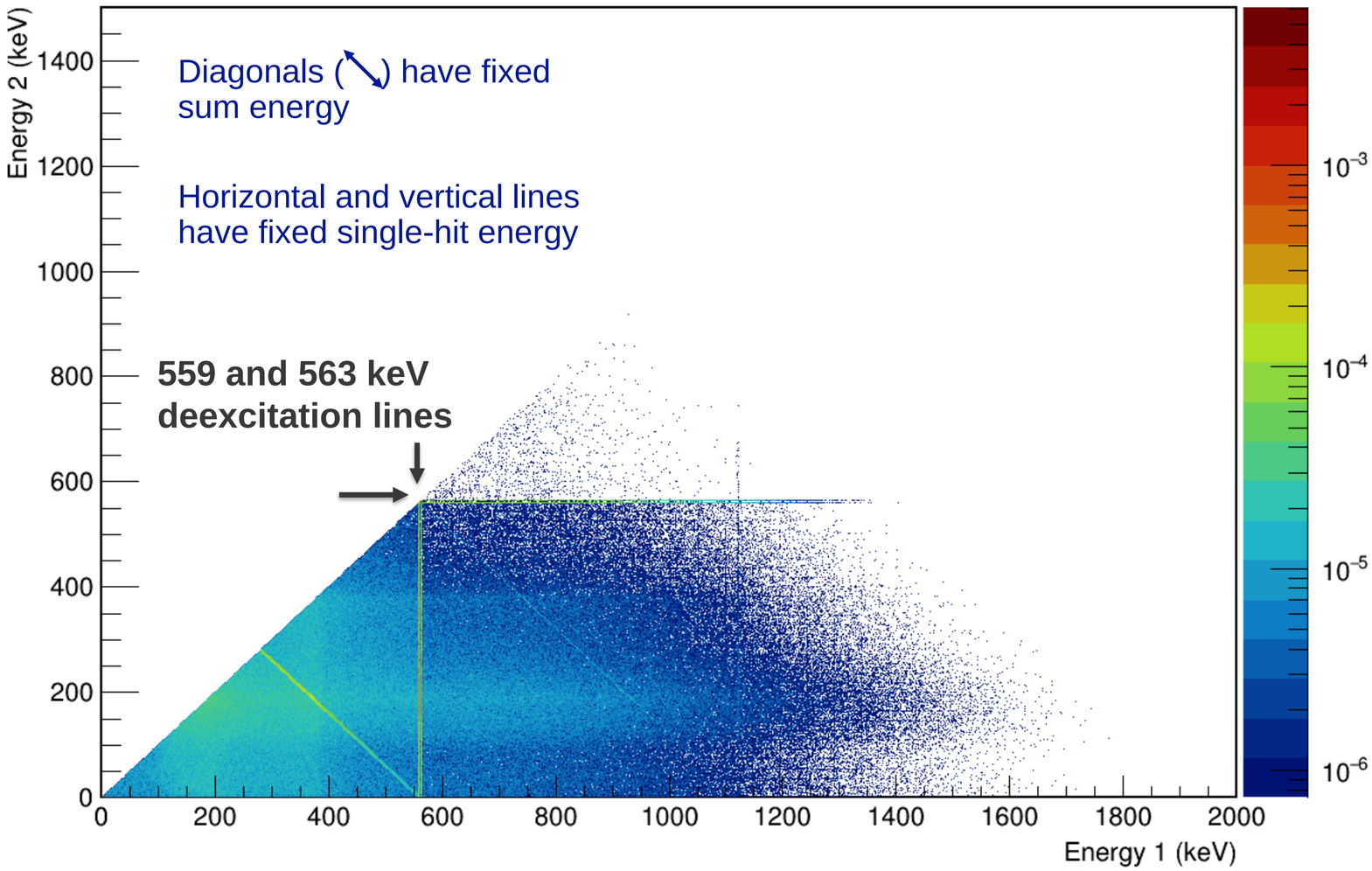


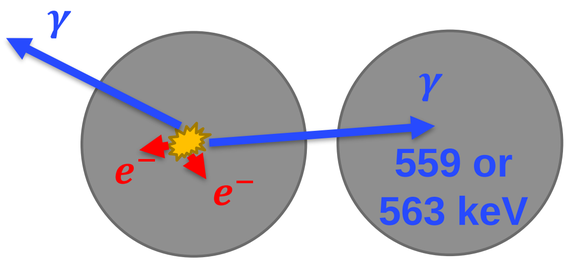
Using the full dataset of the experiment (97.4 kg-y isotopic exposure), MAJORANA will produce an improved limit

I will show upgrades to the analysis and a result for the $0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 0^+_1$ using open data (36.6 kg-y isotopic exposure)

Detection Signature

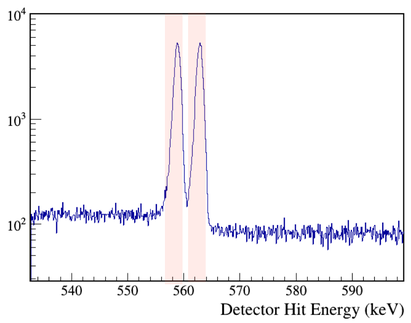
ββ to E.S. events are inherently multi-site. Look for events that hit multiple detectors, with hits at 559 or 563 keV





We are performing a peak search

Signal projected into 1D



The information from the coincident hit(s) provide powerful background rejection tools!

Multiplicity 2 events in a Geant4 simulation of $0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 0^+_1$ decay mode

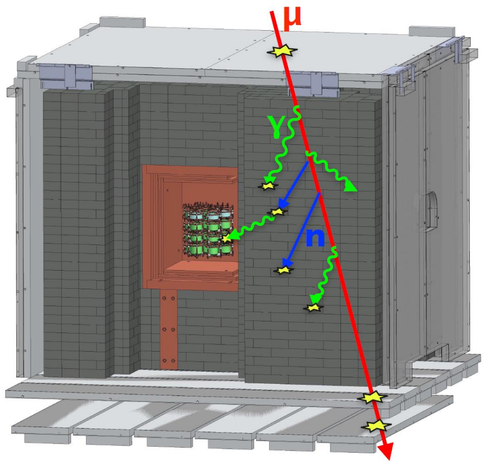
Background Rejection Cuts

Use high multiplicity events

- Combine hits within 4 μs into events
- One accidental coincidence in signal region every ~600 y!

Veto muon-associated events

- Reject events for 1 s after nearly-4π muon veto system triggers



Veto events caused by through-going muons

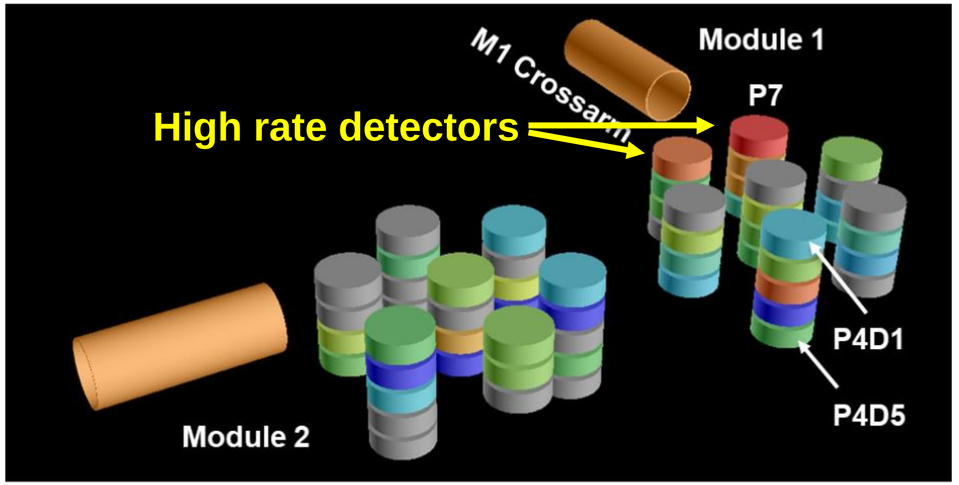
Use events originating in enriched detectors

- 95% of ^{76}Ge is found in enriched detectors

Reject events with hits in high rate detectors

- Two detectors near M1 crossarm
- See C. Haufe's talk for more details!

Improvement to analysis!



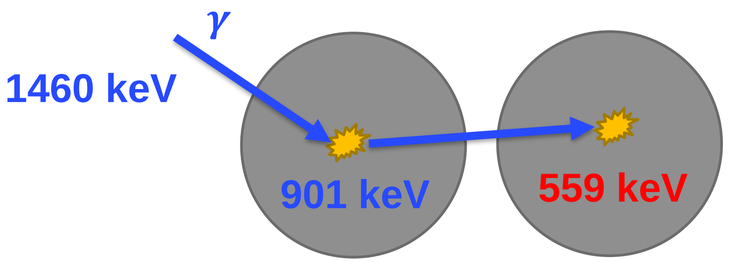
2615 keV rate in datasets prior to upgrade*

*Excluding high background commissioning data

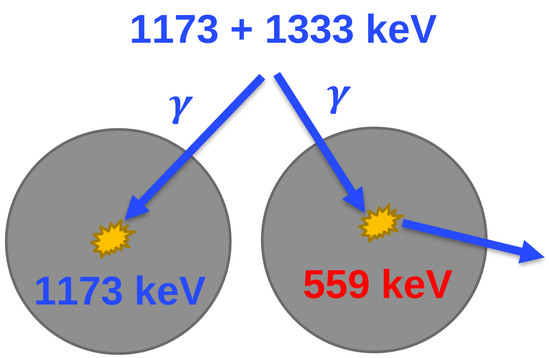
Background Rejection Cuts

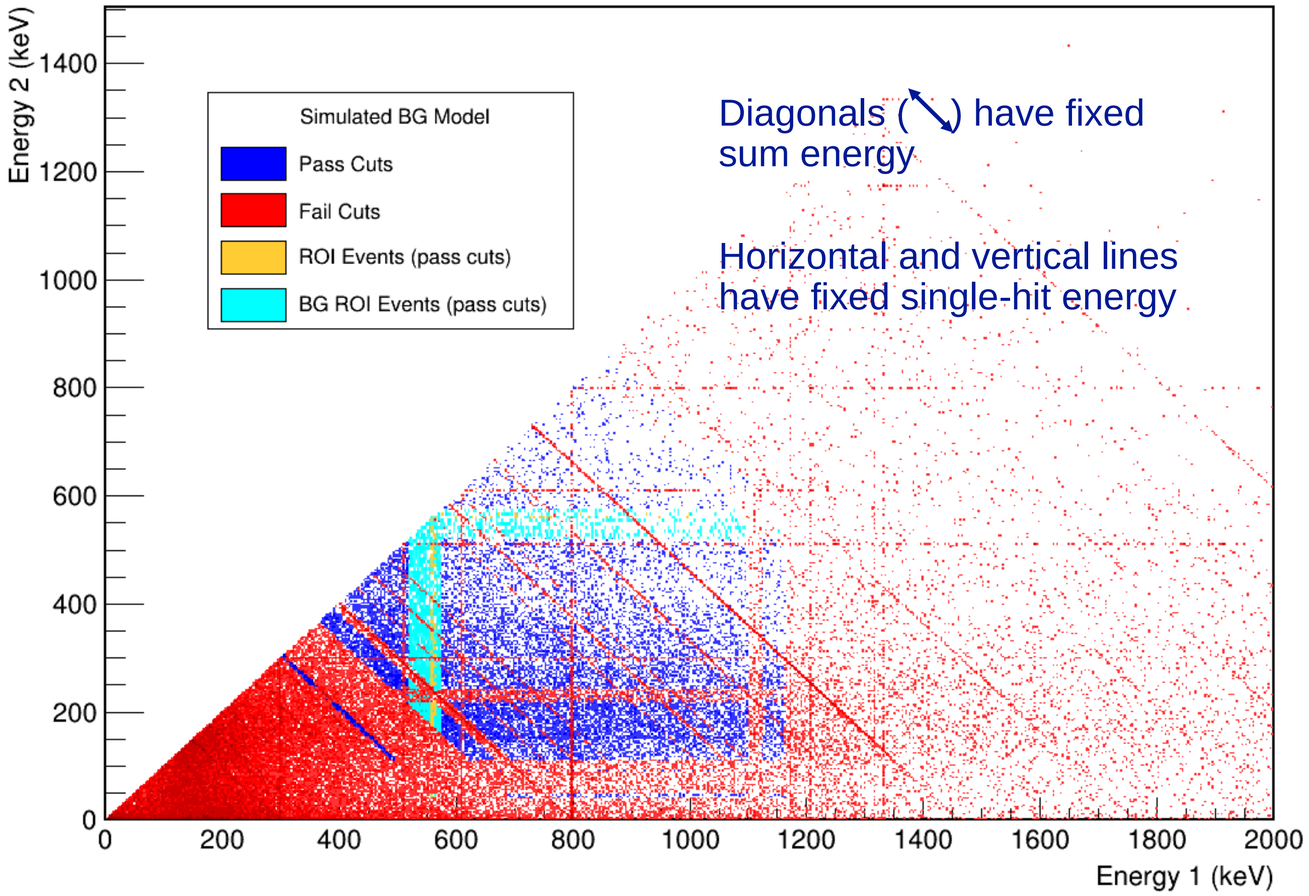
Reject Compton scattered γ-rays and γ-ray cascades using the sum energy of events and the hit energy in coincidence with our candidate events

Example: sum energy of ^{40}K decay



Example: coincident energy from ^{60}Co decay





Use an optimization algorithm to choose energy ranges to cut events based on sum E and coincident E

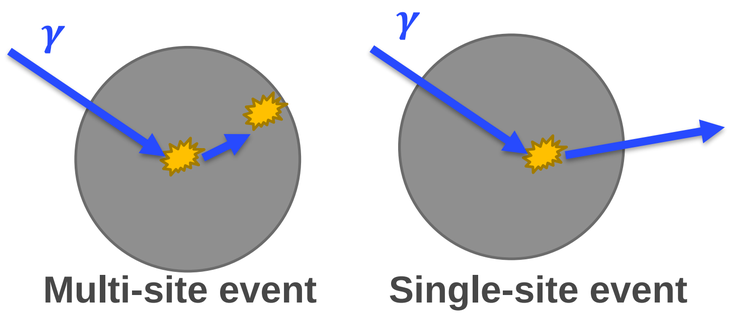
Background Rejection Cuts

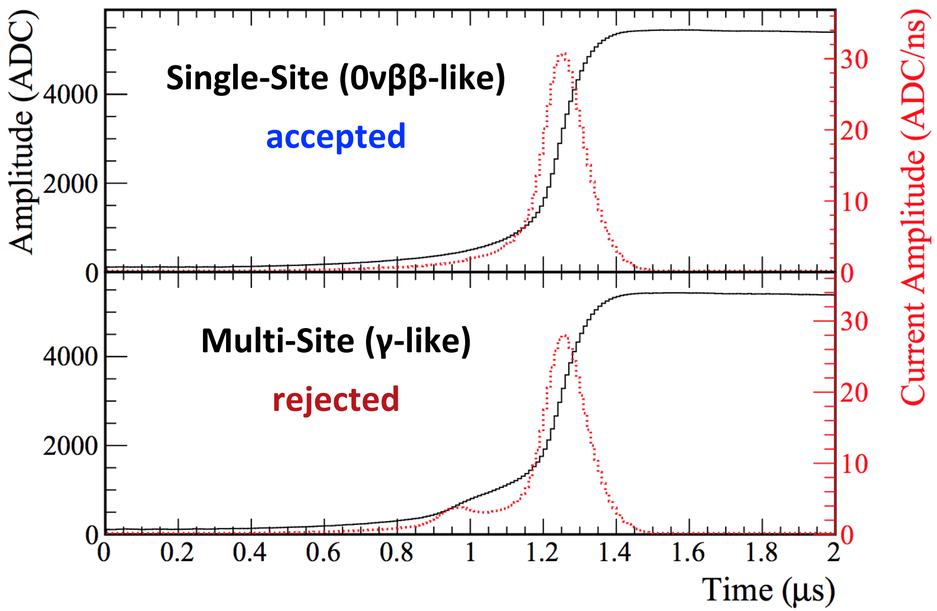
Use pulse-shape discrimination to reject single-site events

Full energy peaks (FEPs) of γ-rays are 80-90% multi-site

Backgrounds are ~50% multi-site

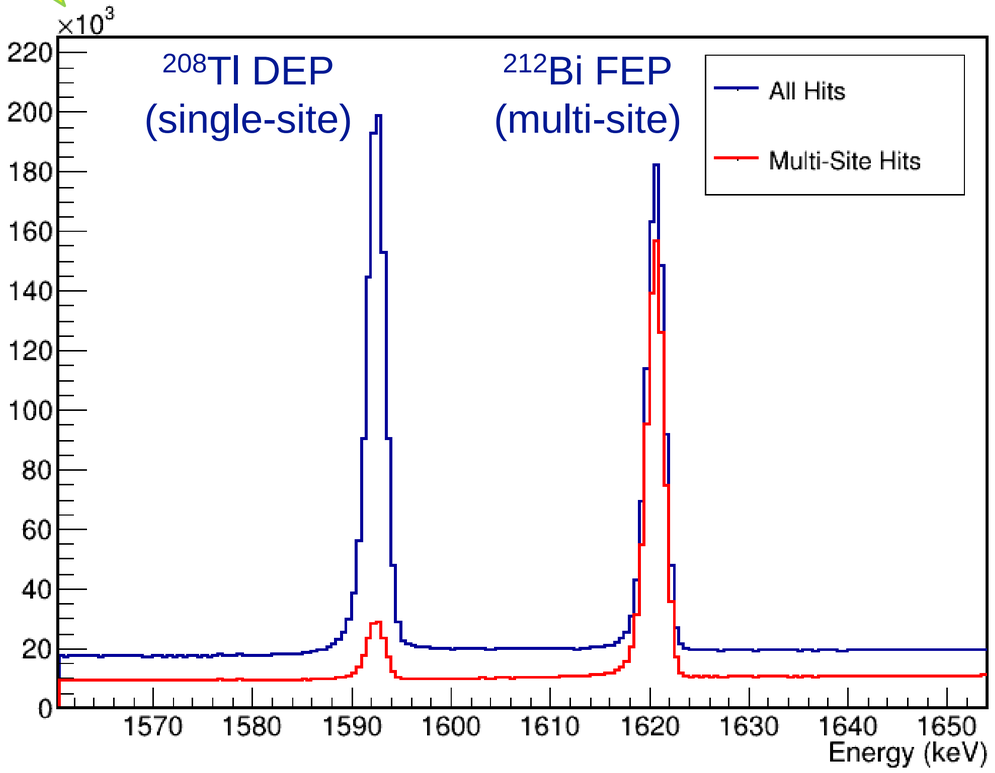
Improvement to analysis!





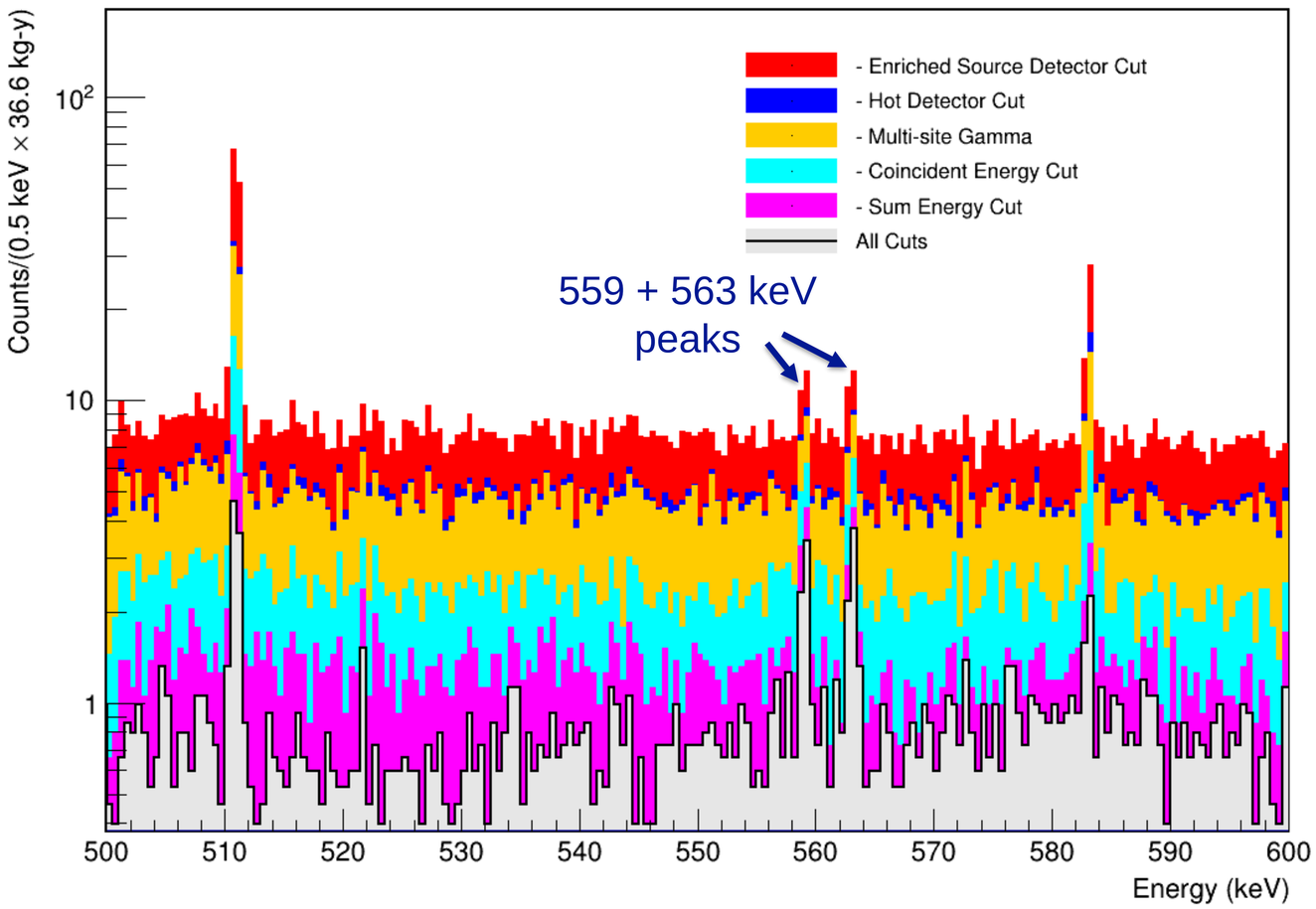
Use AvsE discriminator to select for multi-site events

PRC **99** 065501 (2019)



Effect of Background Rejection Cuts

Simulation of signal+background for $0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 0^+_1$ with a half-life of 10^{24} y

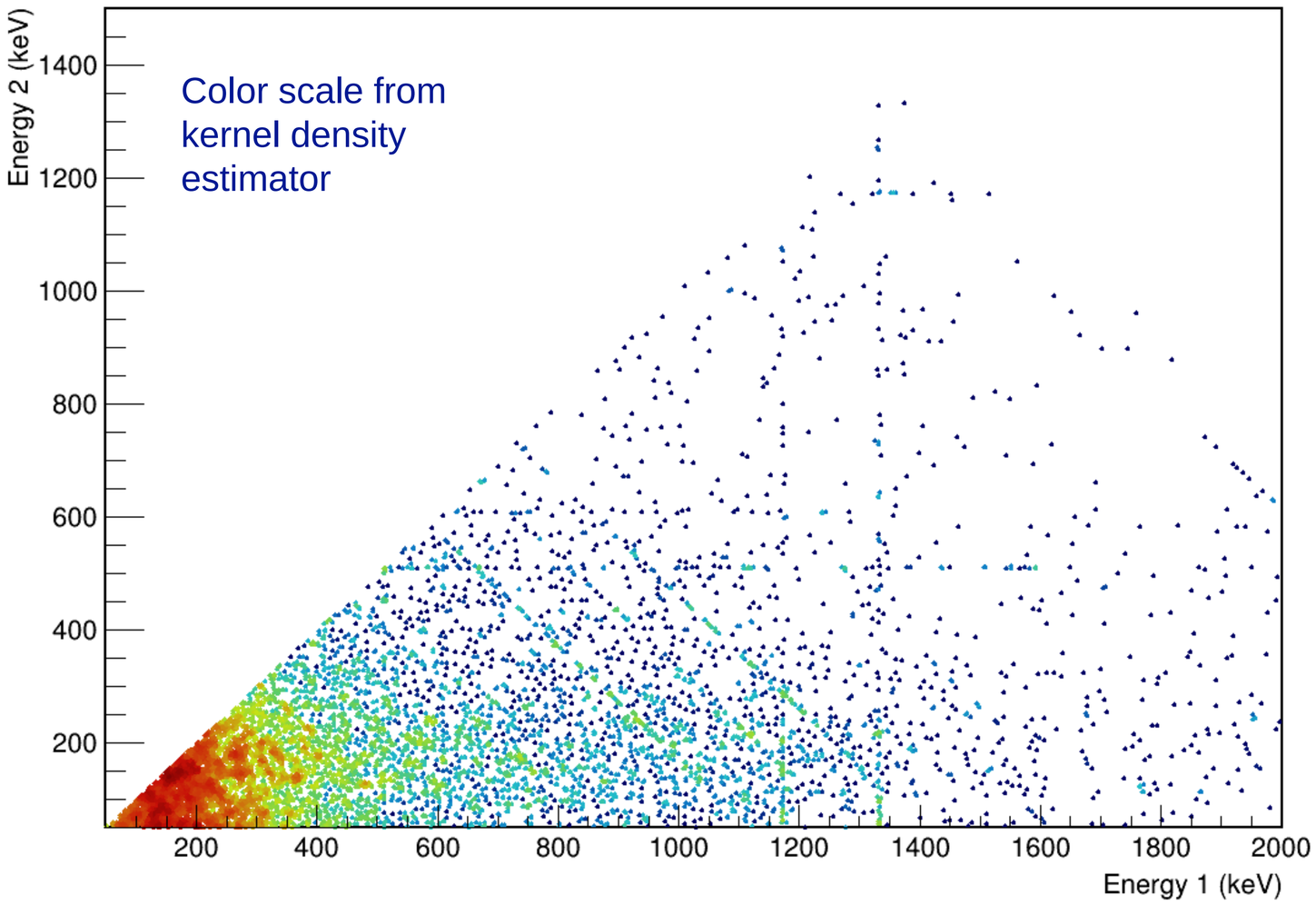


Background rejection cuts:

- Remove 30% of signal events based on simulations
- Remove 90% of backgrounds from data
- Improve sensitivity by 80% relative to no cuts applied

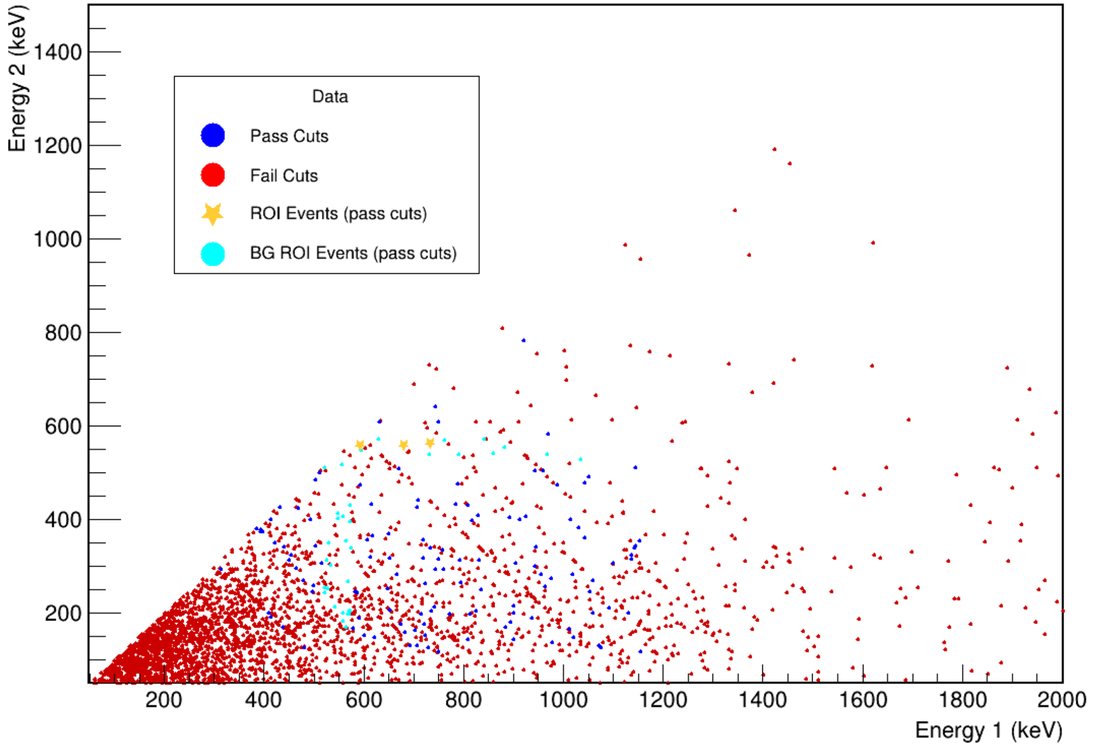
A Look at Open Data

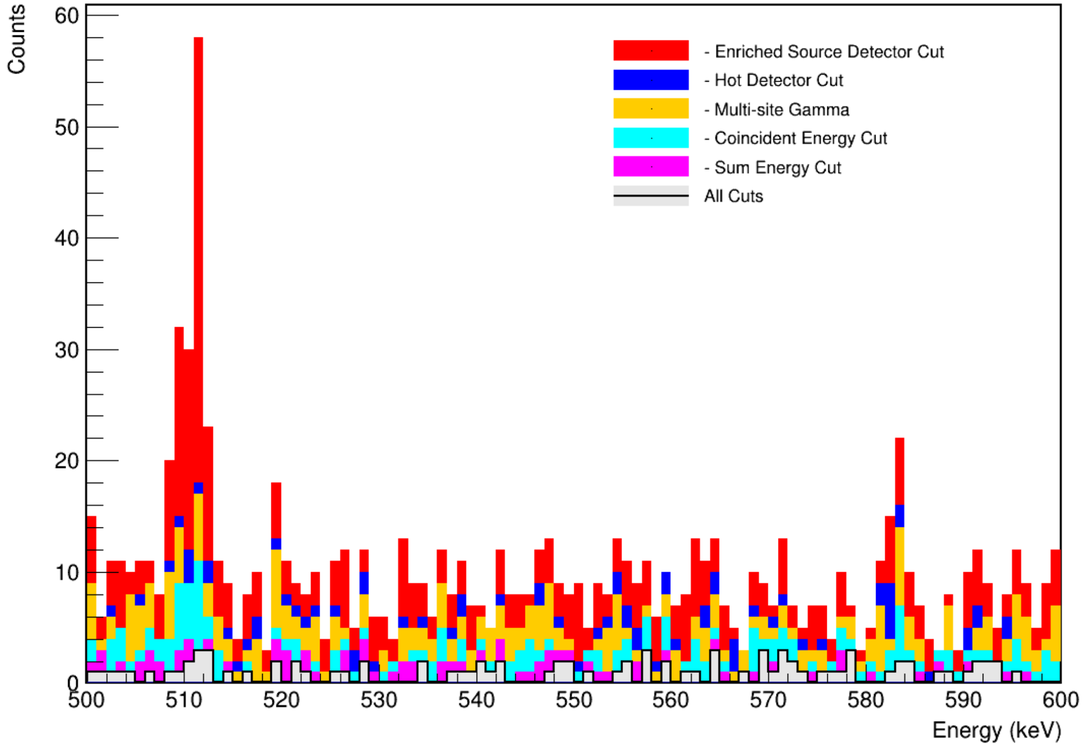
Scatter plot of multiplicity ≥ 2 events in 36.6 kg-y of open data from the full MAJORANA DEMONSTRATOR enriched dataset



A Look at Open Data

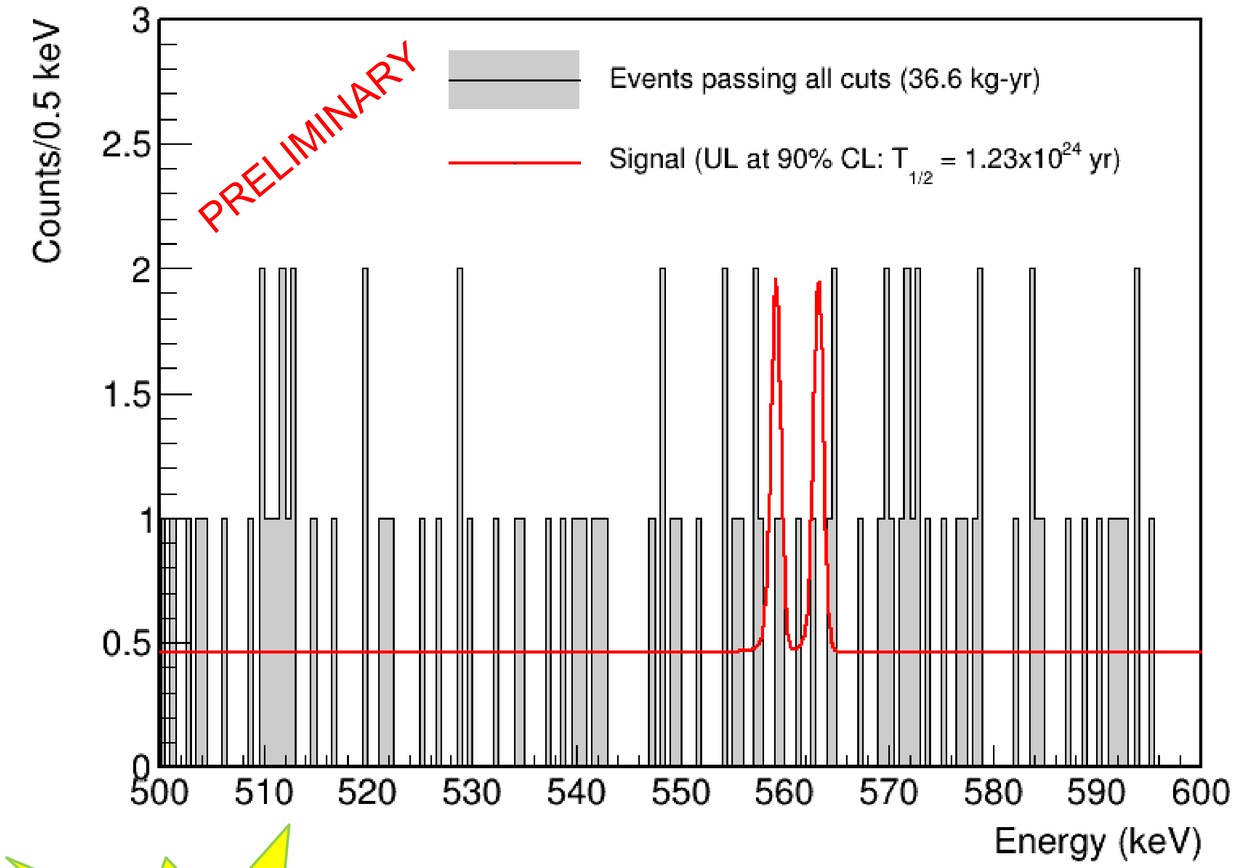
Effect of cuts on multiplicity ≥ 2 events in 36.6 kg-y of open data
from the full MAJORANA DEMONSTRATOR enriched dataset





New Best Limit using 36.6 kg-y of Open Data

Background after cuts with signal at 90% CL upper limit



Preliminary result for 2νββ of ^{76}Ge to 0_1^+ excited state of ^{76}Se

Isotopic Exposure: **36.6 kg-y**

Detection Efficiency: **2.7% (M1), 1.4% (M2)**

Background Index (after cuts): **0.025 cts/keV-kg-y**

Compared to previous analysis, upgrades have improved detection efficiency, with similar background reduction

Improvement to analysis!

Simultaneous extended unbinned likelihood fit used to extract limit

90% Sensitivity:

$T_{1/2} > 1.1 \times 10^{24}$ yr

90% Limit

$T_{1/2} > 1.2 \times 10^{24}$ yr

Looking Ahead

The MAJORANA DEMONSTRATOR has set a new upper limit on 2νββ of ^{76}Ge to 0_1^+ excited state of ^{76}Se using 36.6 kg-y of open data from the full dataset

- An unblinded analysis with 97.4 kg-y of data will have a projected half-life sensitivity of 2.2×10^{24} y
- Analysis of all decay modes will be performed

LEGEND will continue the search

- Larger ICPC detectors and shielding from liquid Argon → reduced signal efficiency with this technique
- Backgrounds from ^{42}K expected to dominate
- LEGEND will require creative improvements to event reconstruction to get large gains in sensitivity!

Thanks for listening!

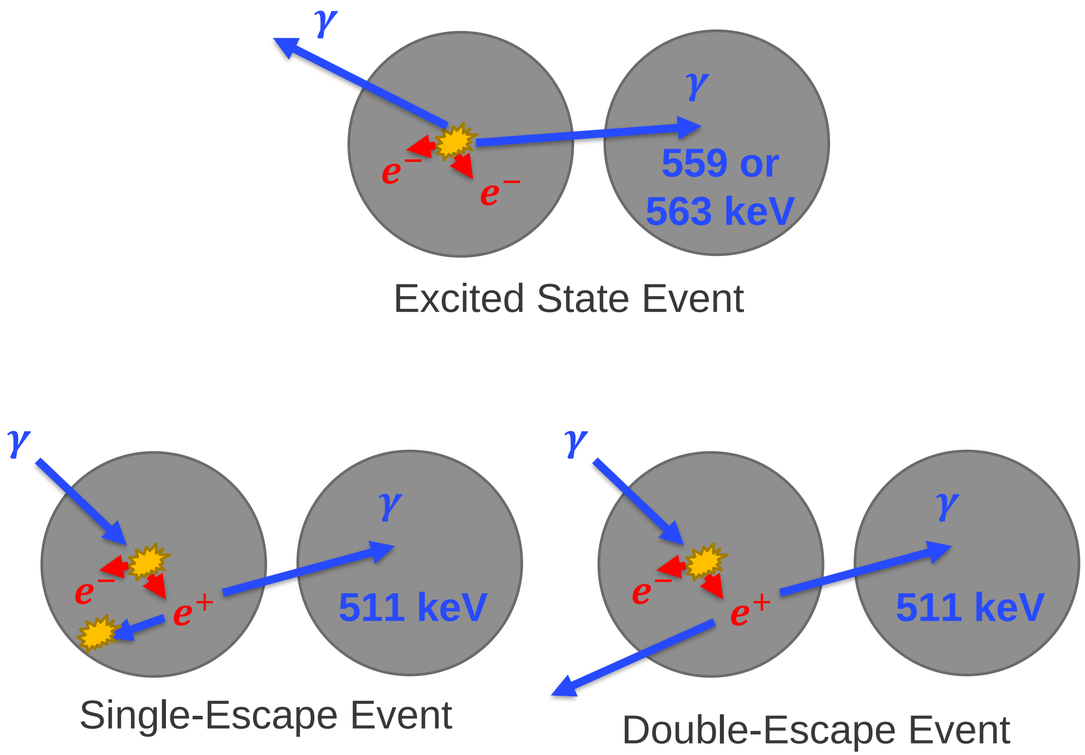
This material is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, the Particle Astrophysics and Nuclear Physics Programs of the National Science Foundation, and the Sanford Underground Research Facility.

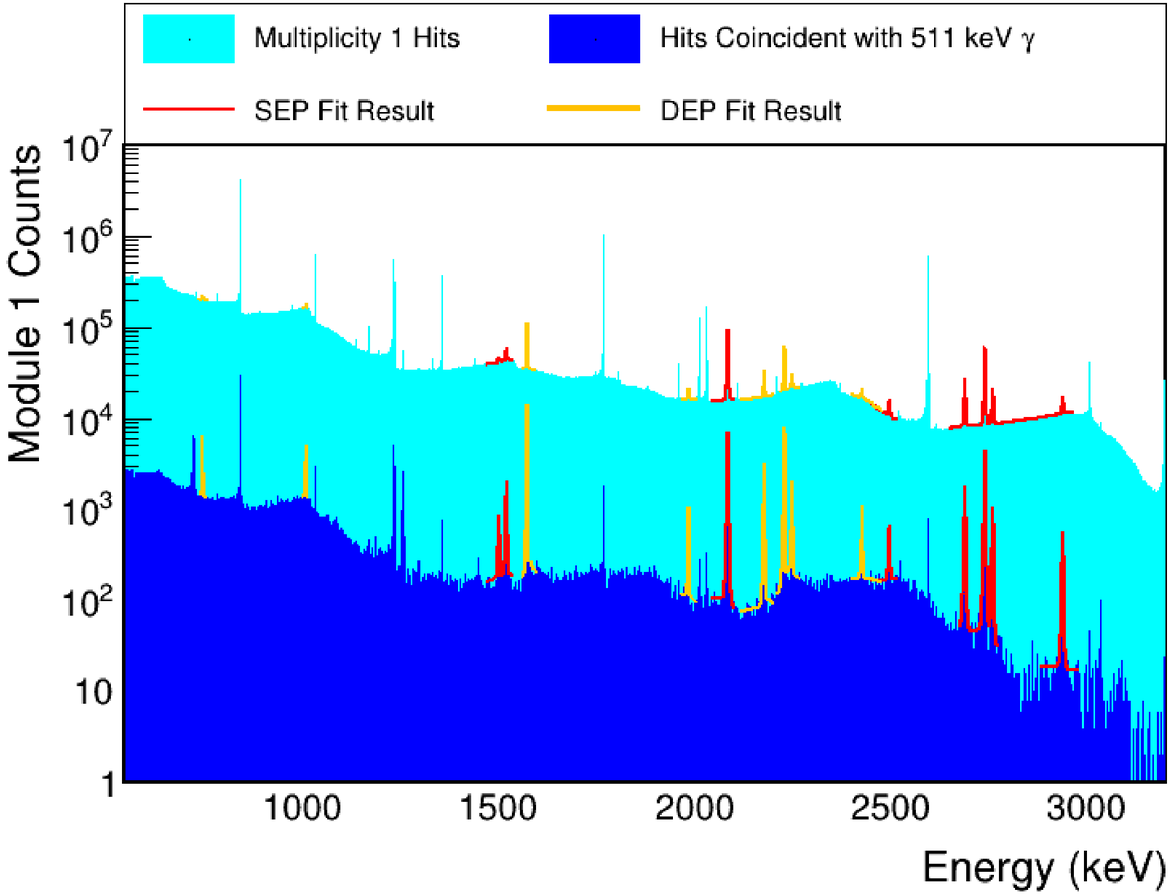
Backup Slides

Validating Simulations

Using single- and double-escape events from pair-production events in ^{56}Co calibration data as a proxy for our ES decay signature, we can validate our simulated detection efficiency

Use ratio of multi-detector events involving the full absoprion of the 511 keV gamma, to single-detector events in double- and single-escape peaks (DEPs and SEPs)





Validating Simulations

Use ratio of DEP/SEP amplitudes in multi-detector events with a 511 keV hit to single-detector events as a proxy for the signal-efficiency of ββ-decays to excited states

- Extract a systematic uncertainty term from the measured differences in ^{56}Co data and simulation
- Improved simulation of source geometry resulted in reduced systematic term
- Data+simulation consistent for SEPs, but have a small difference for DEPs