Double Beta Decay of ^{48}Ca with NEMO3
Calibration Software Development for SuperNEMO

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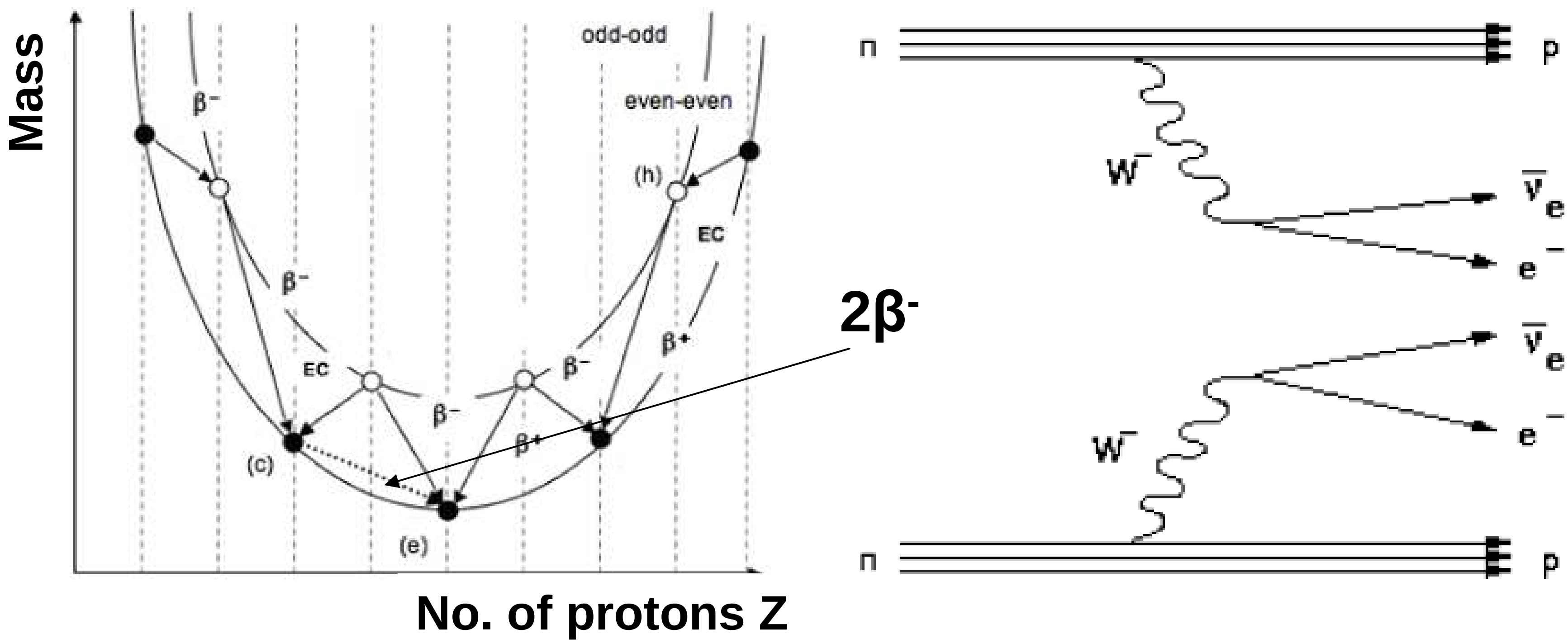
Overview

- Description of double beta decay and its implications
- NEMO3 ^{48}Ca analysis work
- SuperNEMO software developments leading to calibration studies

Double Beta Decay

For an atom with even A (mass no.) both even-even and odd-odd configurations can occur leading to the two parabolic distributions shown

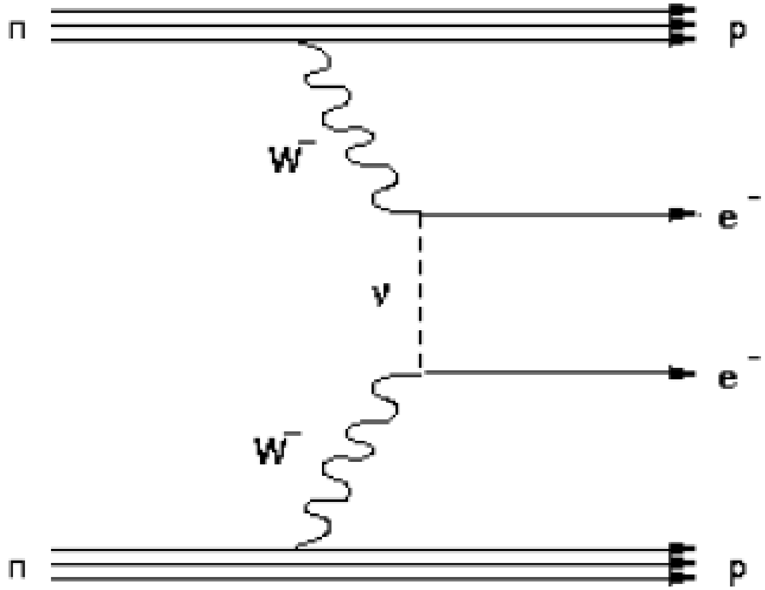


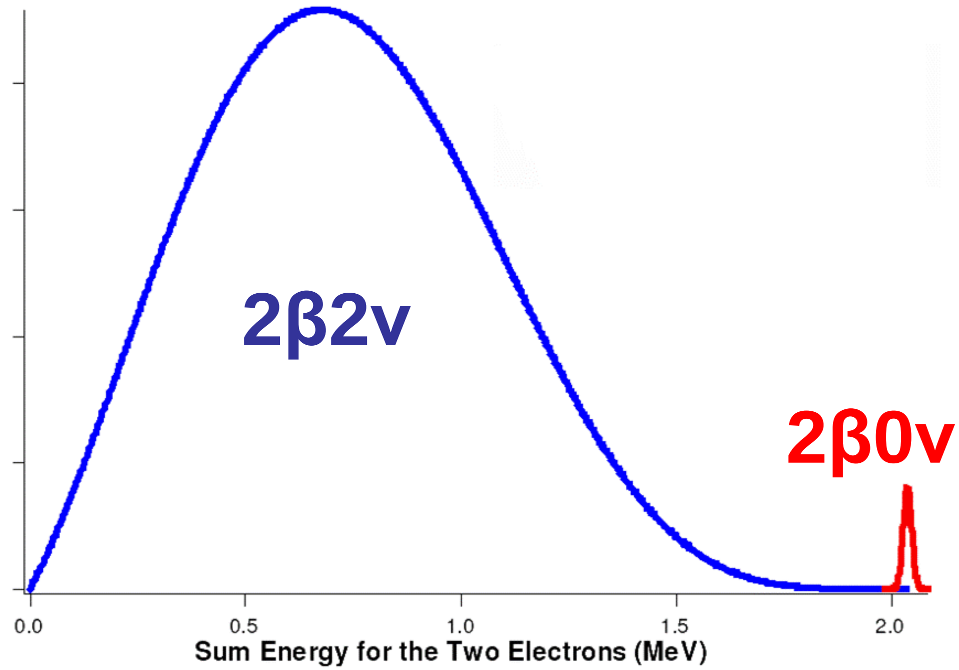
$$(A, Z) \rightarrow (A, Z+2) + e_1^- + e_2^- + \bar{\nu}_{e1} + \bar{\nu}_{e2}$$

$$(T_{1/2}^{2\nu})^{-1} = G^{2\nu} \mid M_{2\nu} \mid^2$$

Neutrinoless Double Beta Decay

$$n \rightarrow p + e^-{}_L + \nu_e{}^M{}_R$$





$$\nu_e{}^M{}_L + n \rightarrow p + e^-{}_L$$

$$(A, Z) \rightarrow (A, Z+2) + e_1^- + e_2^-$$

Mass proportional to inverse half-life

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \mid M_{0\nu} \mid^2 \langle m_\nu \rangle^2$$

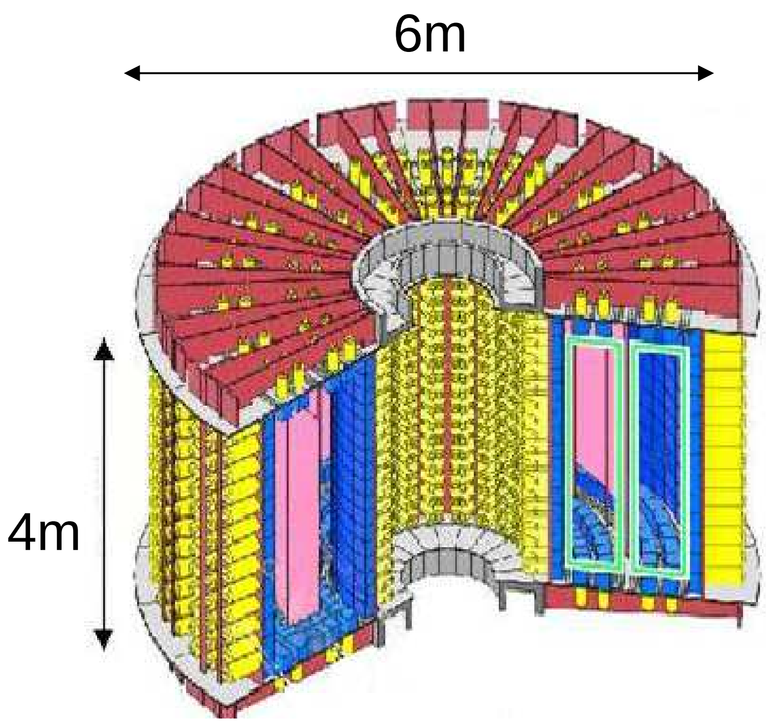
Neutrinoless ββ implications

- Lepton number violating process (new physics)
- Provides probe of absolute mass scale of neutrino
- Probes fundamental nature of neutrino (Dirac / Majorana)
- Evidence for hierarchy (normal / inverted)
- Many GUTs require Majorana nature.

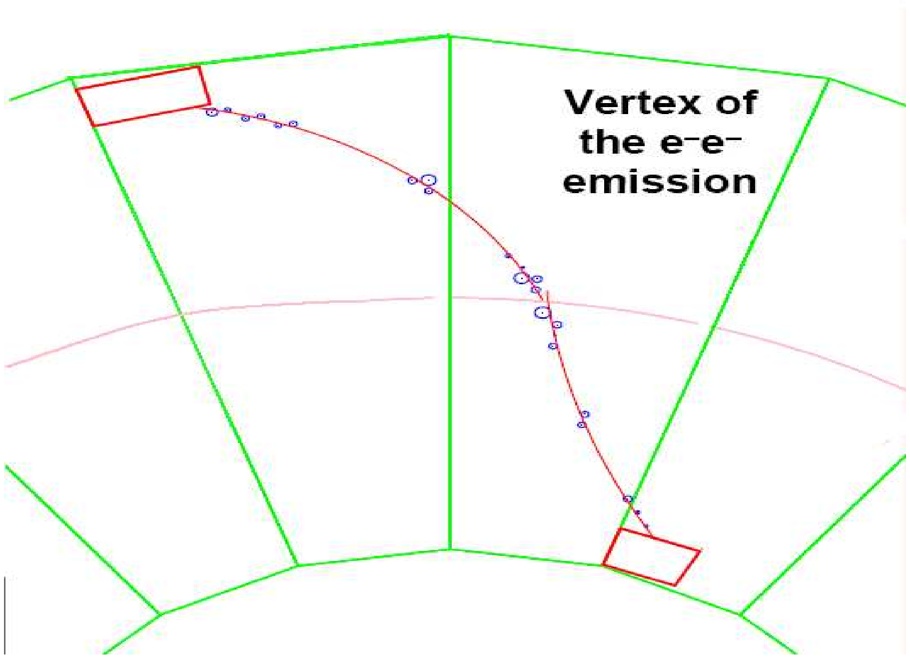
Neutrino Ettore Majorana Observatory (NEMO3)

Situated in the Fréjus Underground Laboratory (LSM) in Modane (Savoie, France)

Feb 2003 - Jan 2011



NEMO3

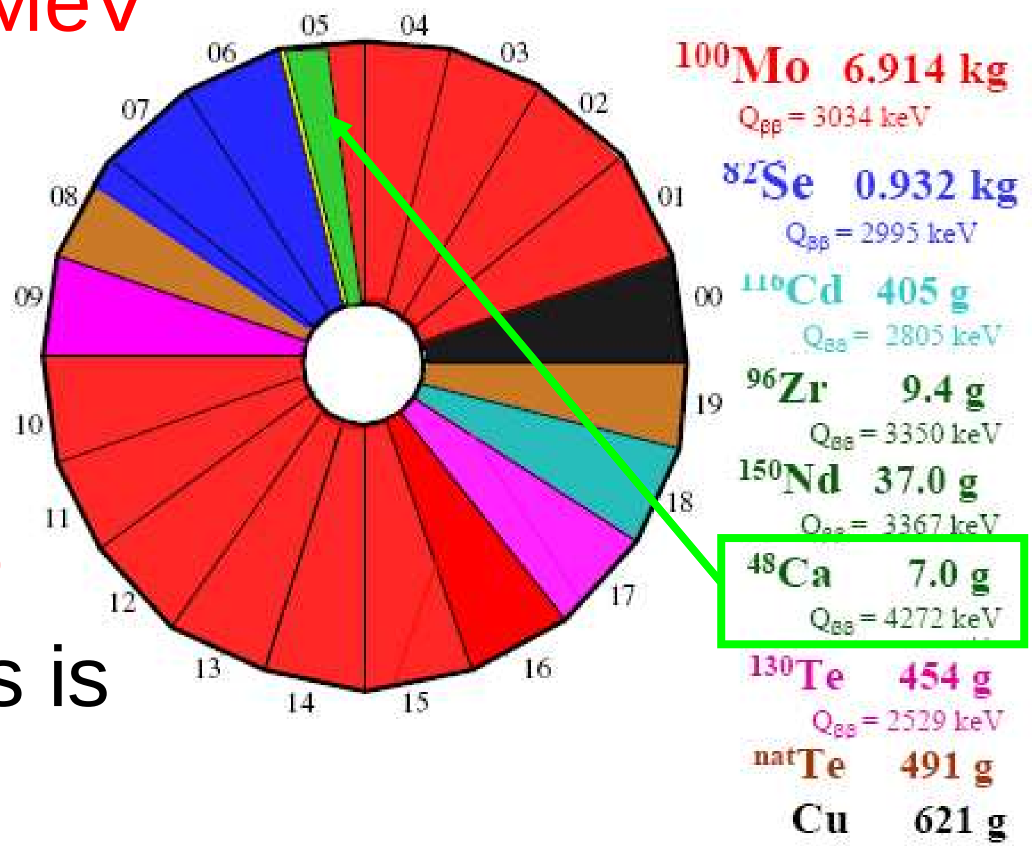


<u>NEMO3 Detector</u>

- **Geiger drift cell tracker**
- **Polystyrene calorimeter**
- **10kg of source in total**
- **7 different sources**
- **Magnetic field**
- **Passive shielding**
- **0.3 eV mass sensitivity**
- **Energy resolution ~ 14% FWHM at 1MeV**

^{48}Ca Analysis

- Highest $Q_{\beta\beta}$ = 4.27MeV
- Natural abundance 0.187%
- Enriched using electromagnetic separation ~ 39.9%
- Active isotope mass is 6.99g.



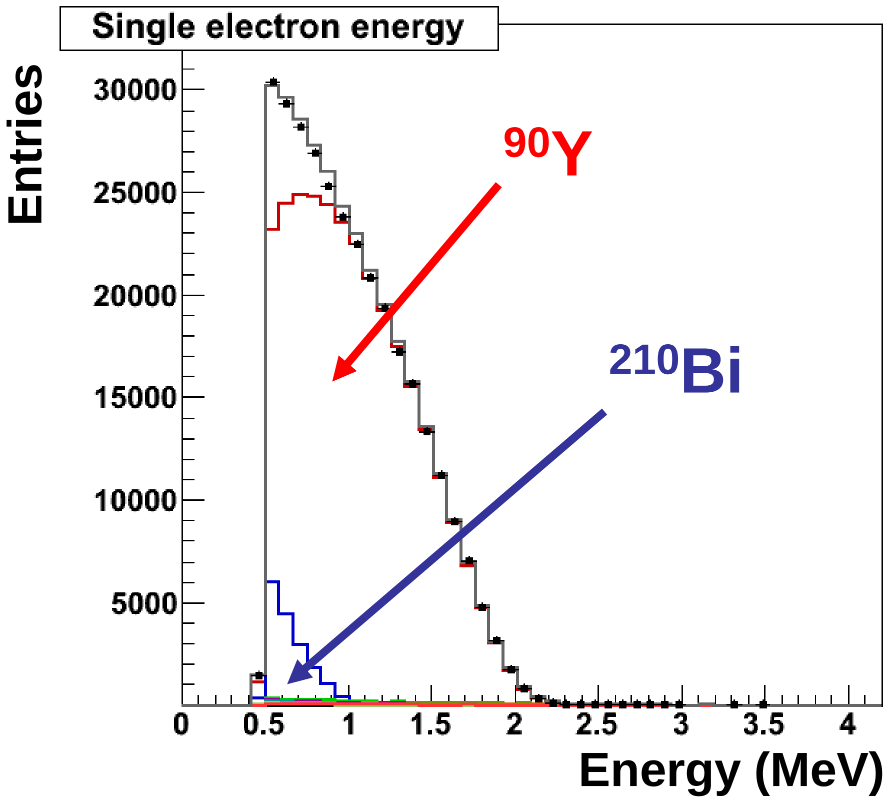
Sources of Backgrounds

- Natural impurities in PMTs and construction materials
- Internal impurities in the source foils
- Radon gas emanation leading to Bi and Pb deposits on wires and surfaces of foils

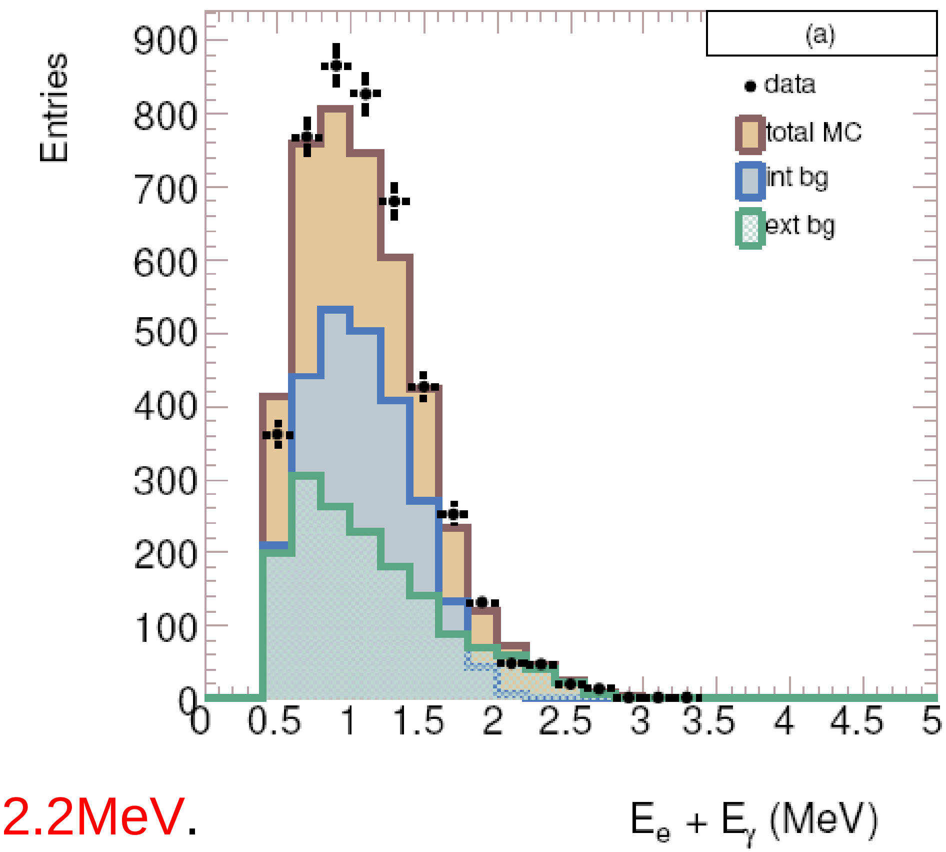
Background Component	Activity (Bq)	Efficiency to mimic 2e
^{228}Ac pmt	515	$<5.8 \times 10^{-10}$
^{208}Tl pmt	41.6	$<1 \times 10^{-8}$
^{214}Bi pmt	374	1.8×10^{-8}
^{40}K pmt	954	1×10^{-11}
^{60}Co iframe	50.7	2.5×10^{-11}
^{214}Bi swire	$(84 \pm 6) \times 10^{-3}$	$< 1 \times 10^{-6}$
^{214}Pb swire	$(84 \pm 6) \times 10^{-3}$	1.4×10^{-7}
^{208}Tl swire	2.8×10^{-3}	1.2×10^{-8}
^{210}Bi swire	5.05 ± 1	1×10^{-9}
^{214}Bi sfoil	$(8.5 \pm 1.9) \times 10^{-3}$	1.1×10^{-6}
^{214}Pb sfoil	$(8.5 \pm 1.9) \times 10^{-3}$	1.3×10^{-6}
^{210}Bi sfoil	$(17.4 \pm 5) \times 10^{-3}$	9×10^{-9}

Measuring Backgrounds in ^{48}Ca

1e channel

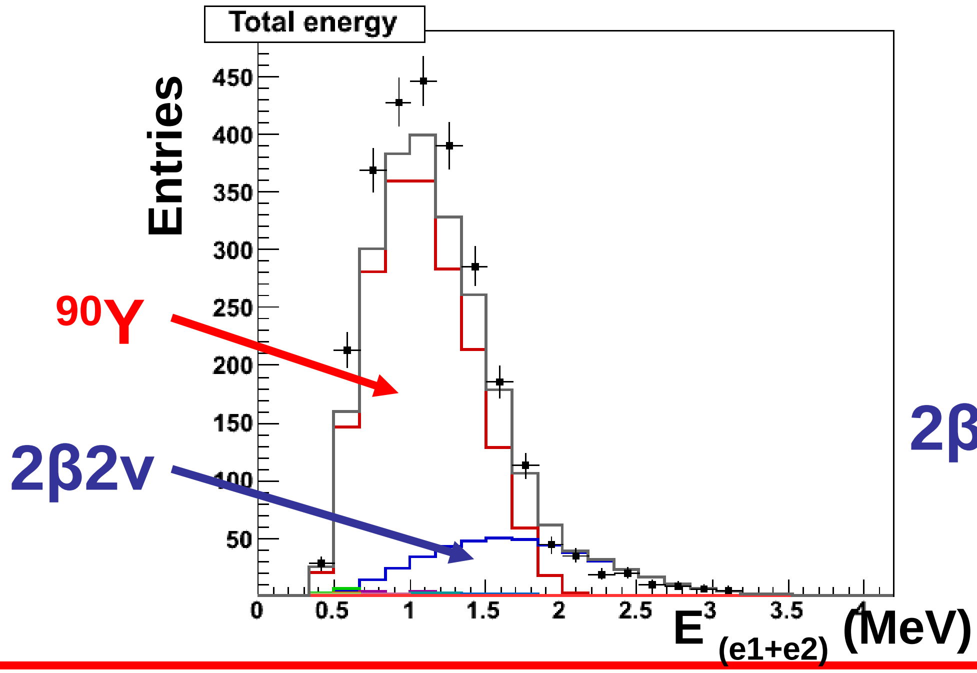


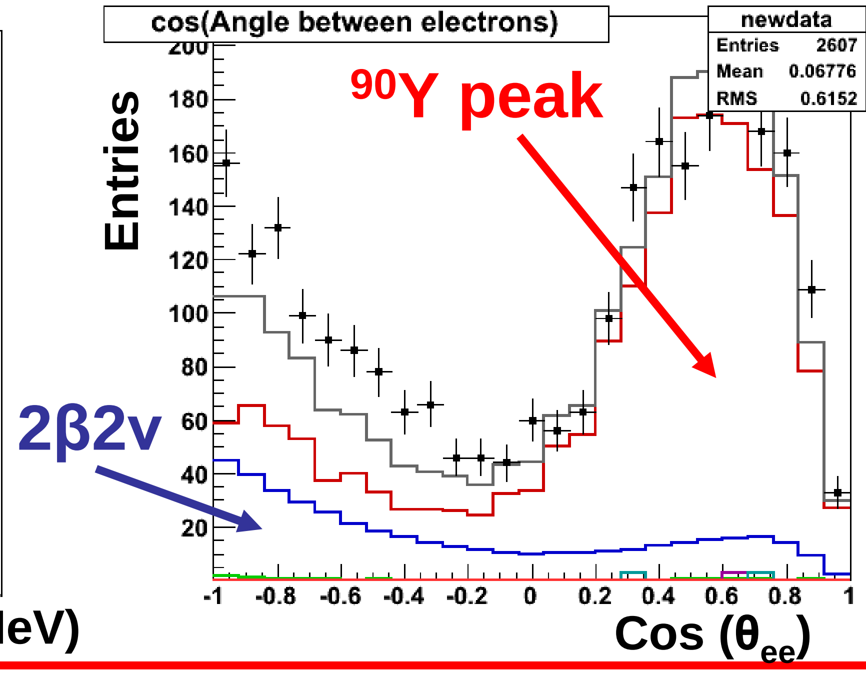
1e1γ channel

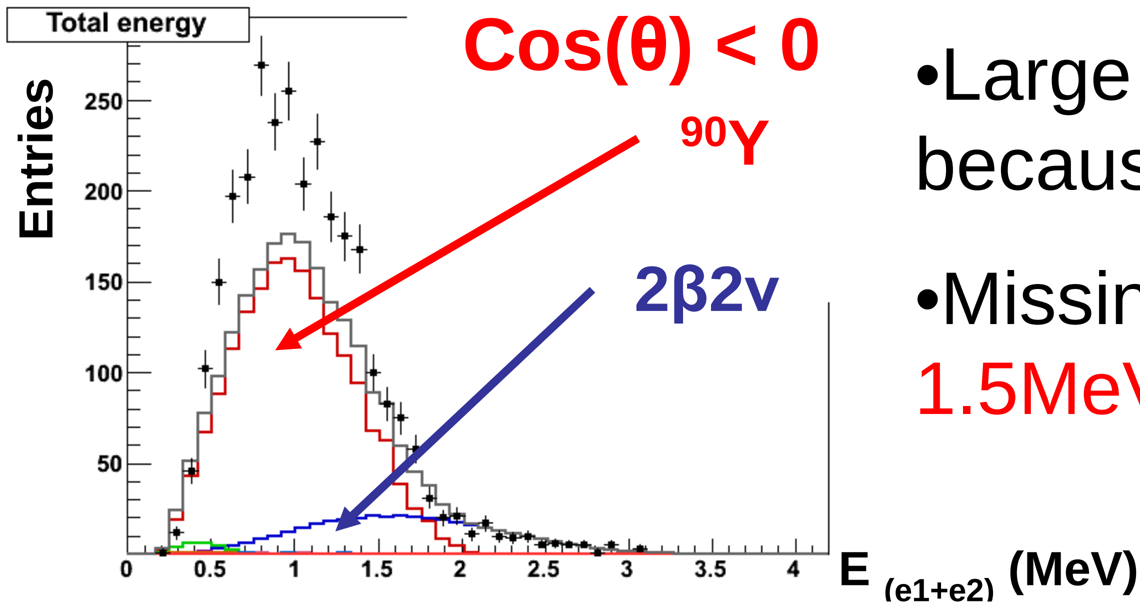


- ^{90}Y is the dominant background Q_β = 2.2MeV.
- Comes from ^{90}Sr decay half-life 28.8 years
- Evidence of a missing background in the 1e1γ channel and 2e

^{48}Ca 2e spectra

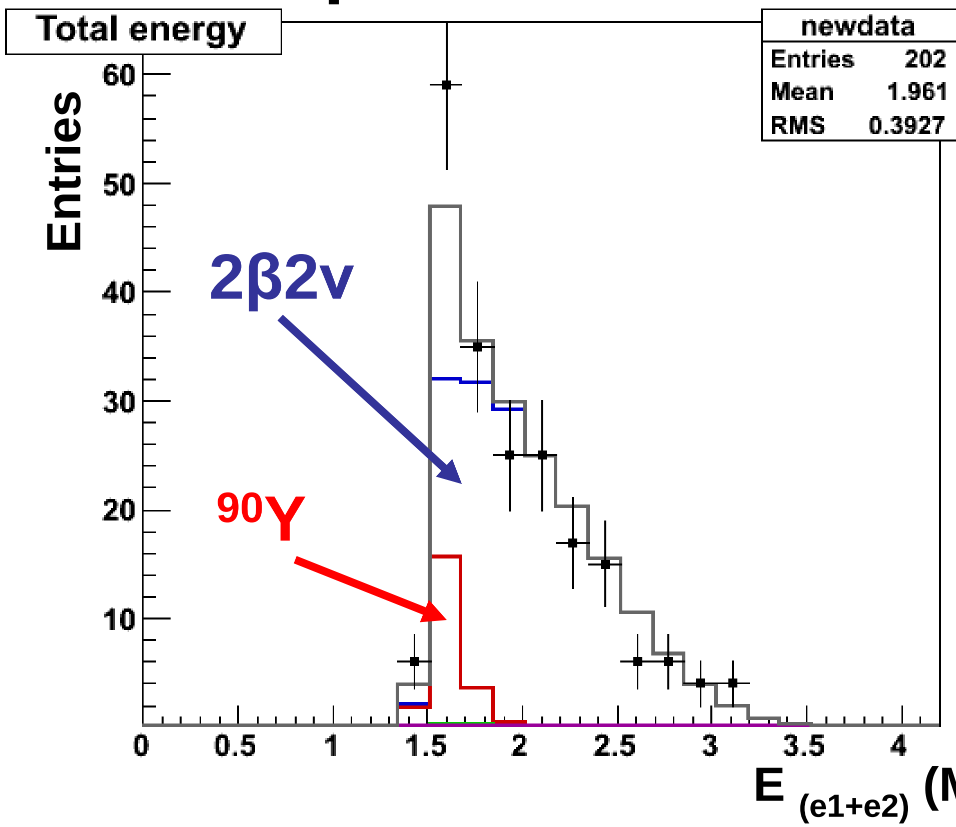






- Large peak on Cos(θ) because of ^{90}Y
- Missing background below 1.5MeV consistent with 1e1γ

2β2ν Half-life Measurement



$$T_{1/2} = \varepsilon \frac{m_i N_A}{A_r N_{dec}} ln(2)t.$$

ε = 0.03

m_i = 6.99g

N_A = 6.022x10^{23}

A_r = 48

N_{dec} = 180

t = 4.03 yr

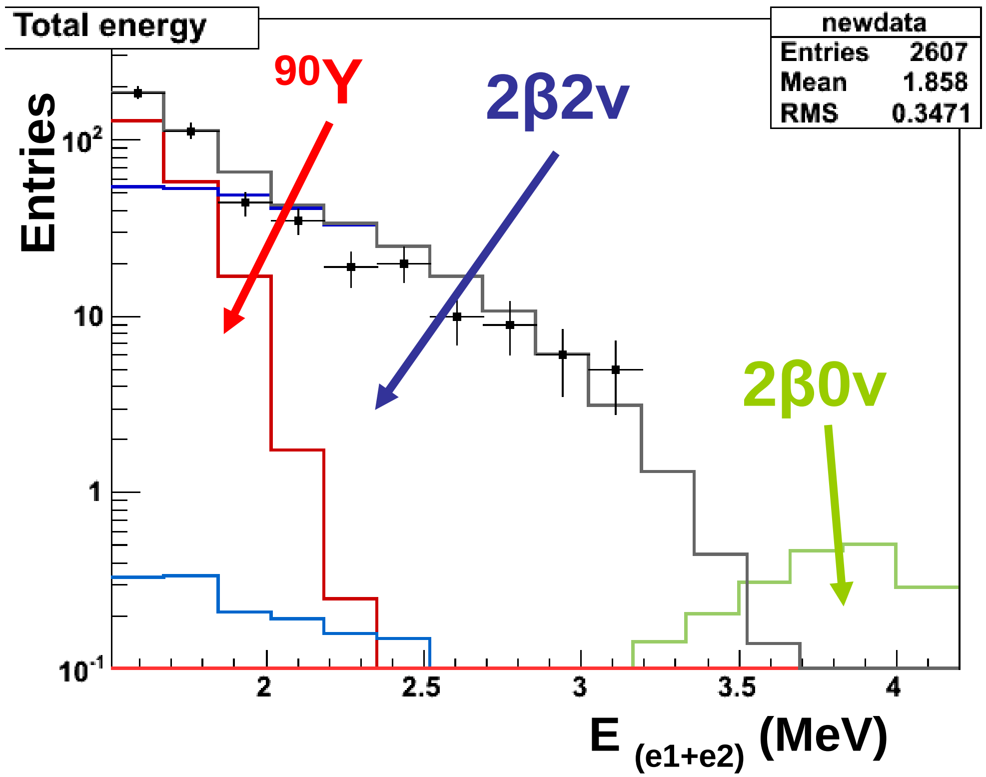
$T_{½} = 4.09^{+0.26}_{-0.24}$(stat.) ± 0.29 (syst.) x10^{19} yr

World's most precise measurement

Calculation of matrix element **$M^{2\nu}$=0.0238±0.0015**

Theoretical calculations = 0.026 & 0.028

Neutrinoless limit



$$T_{1/2} = \varepsilon \frac{m_i N_A}{A_r N_{dec}} ln(2)t.$$

ε = 0.189

m_i = 6.99g

$N_A = 6.022 \times 10^{23}$

A_r = 48

N_{dec} = 2.30

t = 4.25 yr

Energy window [3.36MeV – 4.2MeV] Chosen by optimising signal/background

$T_{1/2} > 2.12 \times 10^{22}$ yr at 90% CL

Compared to our previous result, 1.3×10^{22} yr

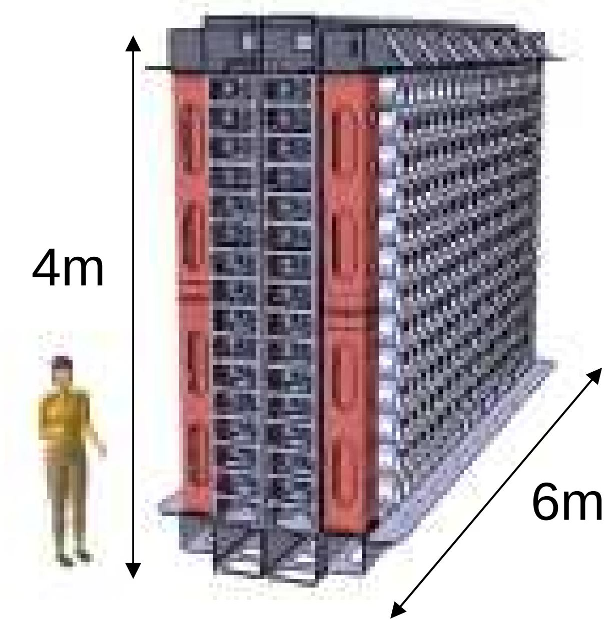
But latest ELEGANT-VI result is 5.8×10^{22} yr PRC (2008)

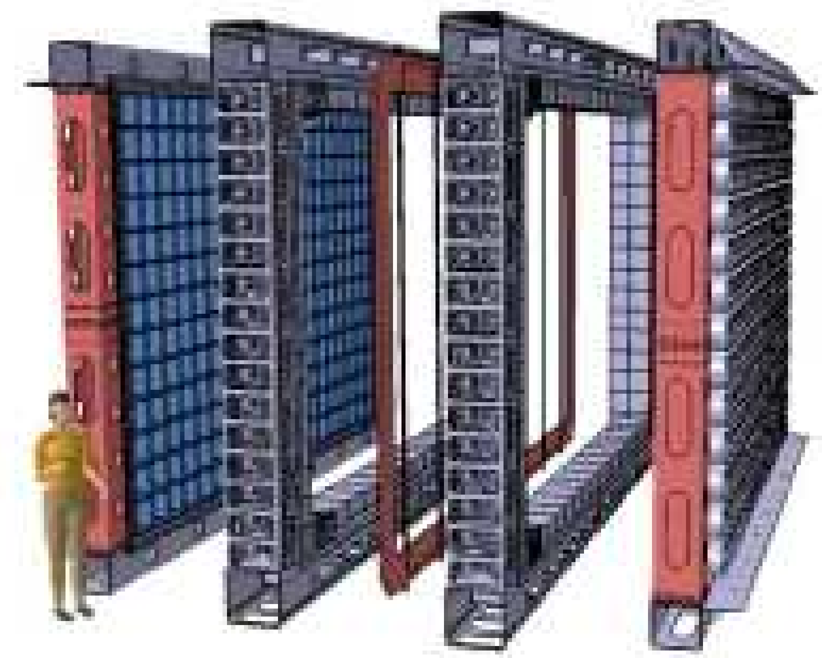
Therefore a mass limit of $m_{0\nu} < 18$ eV

Calibration Software Development for SuperNEMO

Detector description

SuperNEMO	Nemo3
• Geiger drift cell tracker (improved eff)	
• Plastic Bc404 calorimeter	polystyrene
• 100kg of ^{82}Se source	10kg (multi source)
• Modular design (~ 20 modules)	
• 50-80 meV sensitivity	0.3eV
• Energy resolution < 7% FWHM at 1Mev	14%

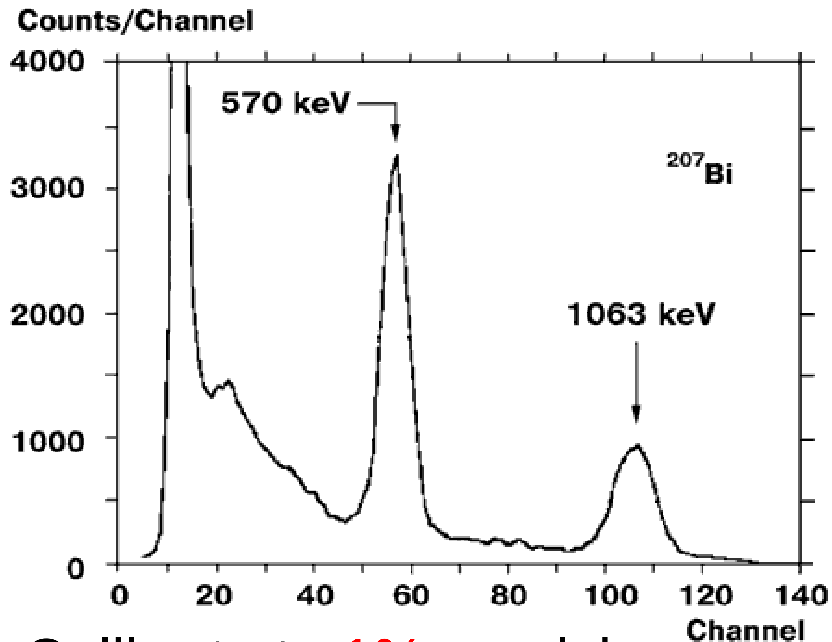


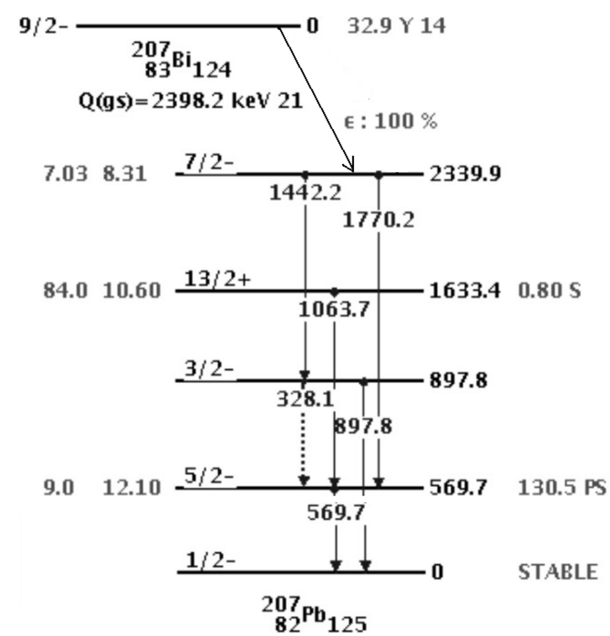


Energy Calibration Constraints

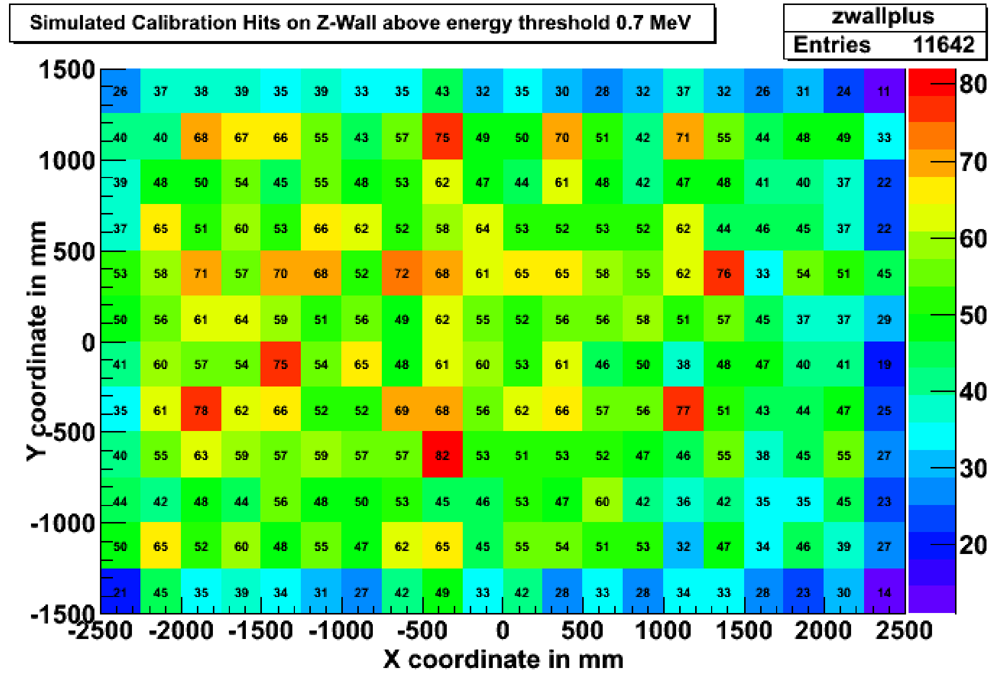
Calibration of ADC with energy scale needed periodically

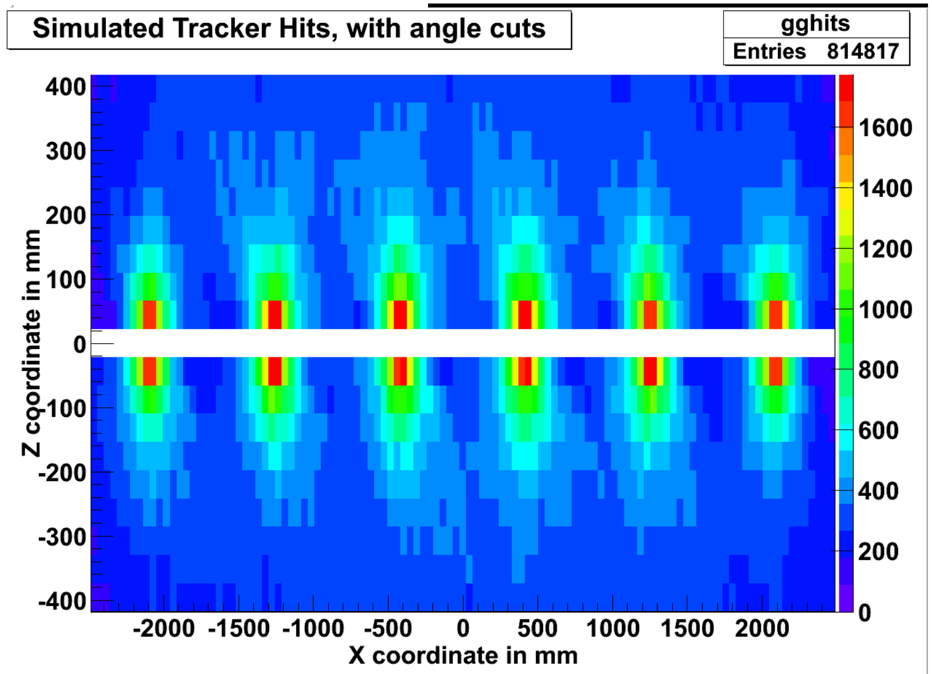
^{207}Bi used as a conversion electron source of ~ 1MeV electrons

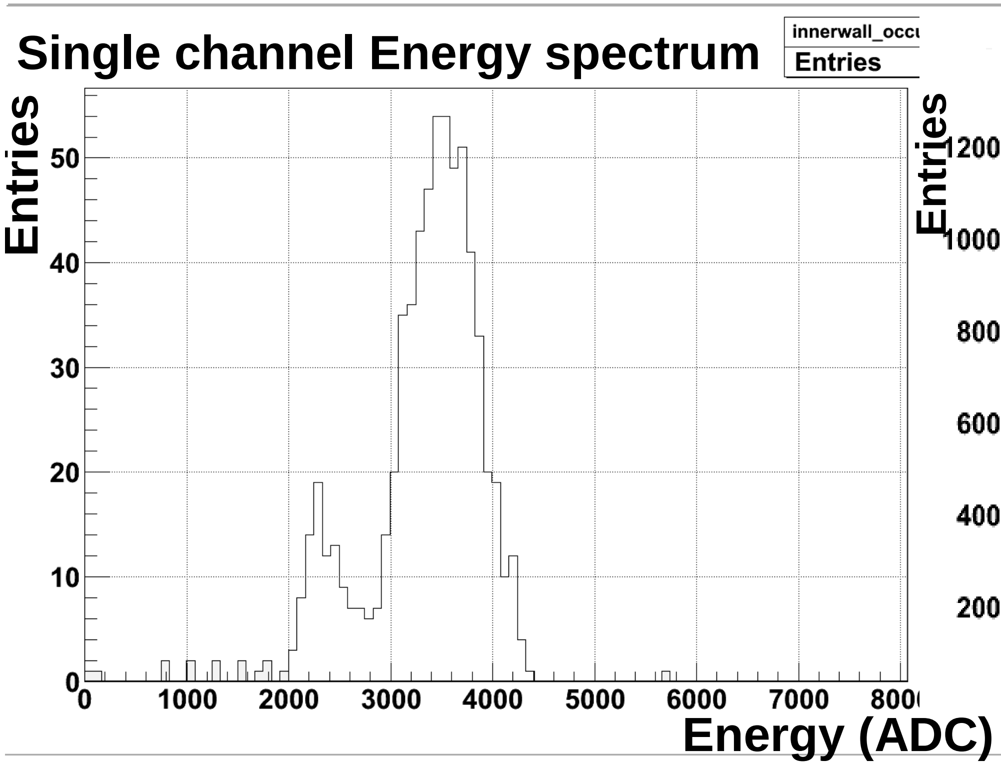


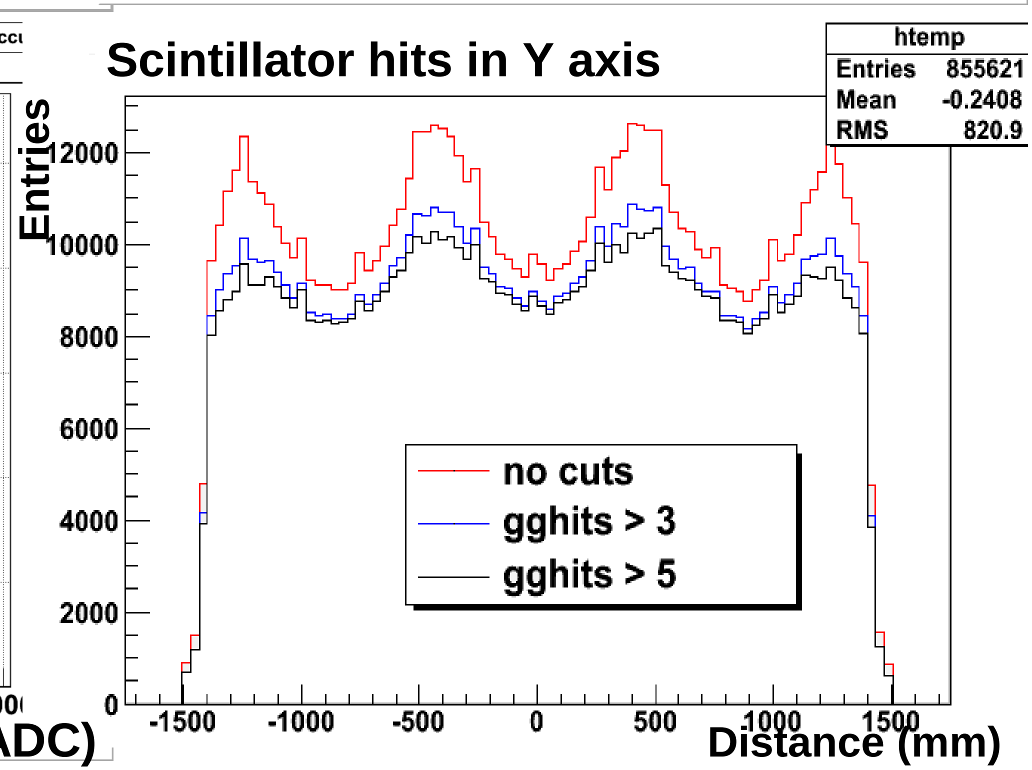


- Calibrate to 1% precision
- Enough hits in each channel to reconstruct 1MeV peak
- Smallest area possible
- Little downtime as possible
- Without going over maximum Geiger rate

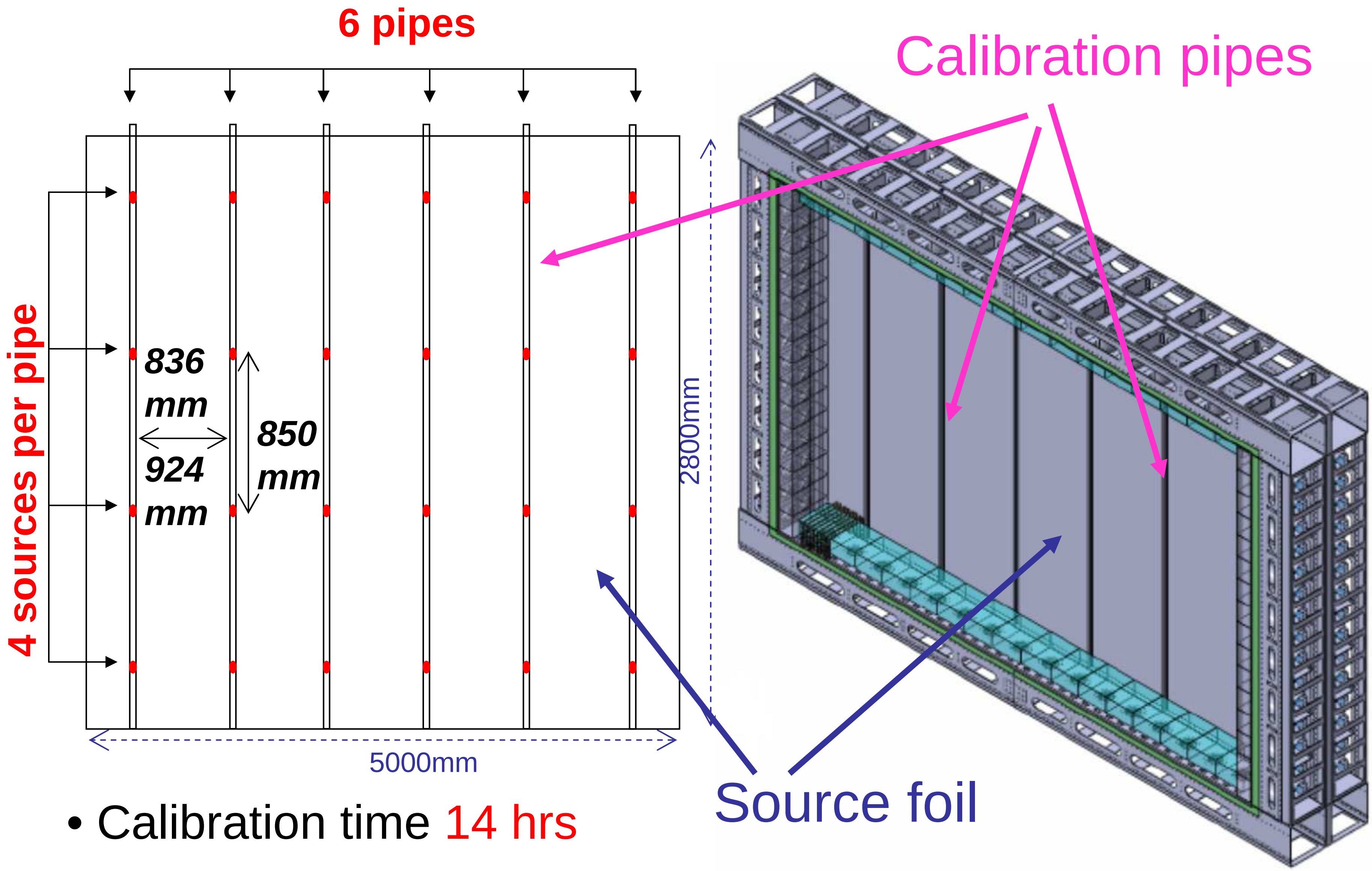

Simulated Calibration Hits on Z-Wall above energy threshold 0.7 MeV
zwallplus
Entries 11642
26 37 38 39 35 39 33 35 43 32 35 30 28 32 37 32 26 31 24 11
40 40 68 67 66 55 43 57 75 49 50 70 51 42 71 55 44 48 49 33
39 48 50 54 45 55 48 53 62 47 44 61 48 42 47 48 41 40 37 22
37 65 51 60 53 66 62 52 58 64 53 52 53 52 62 44 46 45 37 22
53 58 71 57 70 68 52 72 68 61 65 65 58 55 62 76 33 54 51 45
50 56 61 64 59 51 56 49 62 55 52 56 56 58 51 57 45 37 37 29
41 60 57 54 75 54 65 48 61 60 53 61 46 50 38 48 47 40 41 19
35 61 78 62 66 52 52 69 68 56 62 66 57 56 77 51 43 44 47 25
40 55 63 59 57 59 57 57 82 53 51 53 52 47 46 55 38 45 55 27
44 42 48 44 56 48 50 53 45 46 53 47 60 42 36 42 35 35 45 23
50 65 52 60 48 55 47 62 65 45 55 54 51 53 32 47 34 46 39 27
21 45 35 39 34 31 27 42 49 33 42 28 33 28 34 33 28 23 30 14
1500
1000
500
0
-500
-1000
-1500
-2500 -2000 -1500 -1000 -500 0 500 1000 1500 2000 2500
Y coordinate in mm
X coordinate in mm
80
70
60
50
40
30
20


Simulated Tracker Hits, with angle cuts
gghits
Entries 814817
400
300
200
100
0
-100
-200
-300
-400
-2000 -1500 -1000 -500 0 500 1000 1500 2000
Z coordinate in mm
X coordinate in mm
1600
1400
1200
1000
800
600
400
200
0


Single channel Energy spectrum
innerwall_occu
Entries
Entries
50
40
30
20
10
0
0 1000 2000 3000 4000 5000 6000 7000 8000
Energy (ADC)


Scintillator hits in Y axis
htemp
Entries 855621
Mean -0.2408
RMS 820.9
Entries
12000
10000
8000
6000
4000
2000
0
-1500 -1000 -500 0 500 1000 1500
Distance (mm)
no cuts
gghits > 3
gghits > 5

Physical Model



- Calibration time 14 hrs
- Geiger Rate < 9 Hz
- 6 x 4 configuration

Future Work

^{48}Ca Analysis:

- Disentangle low energy background
- Consolidate all data for better precision 2β2v result (factor of 2)
- Improve on 2β0v limit

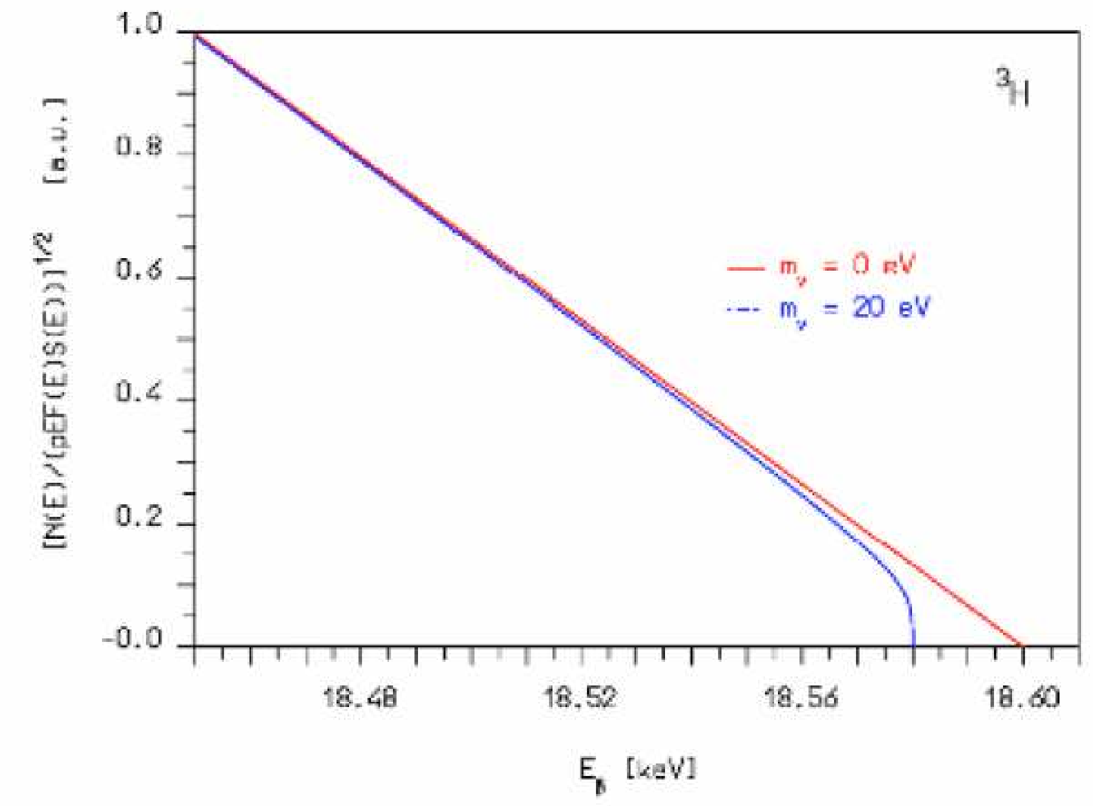
Software Development & Calibration:

- Extend simulation for ^{90}Sr (third calib point at 2.2MeV) and ^{60}Co (coincident gammas 1.1MeV for timing)
- Core software development
- Commissioning the tracker module

Extra Slides

Tritium β Decay

$$^3H \rightarrow ^3He^+ + e^- + \bar{\nu}_e$$



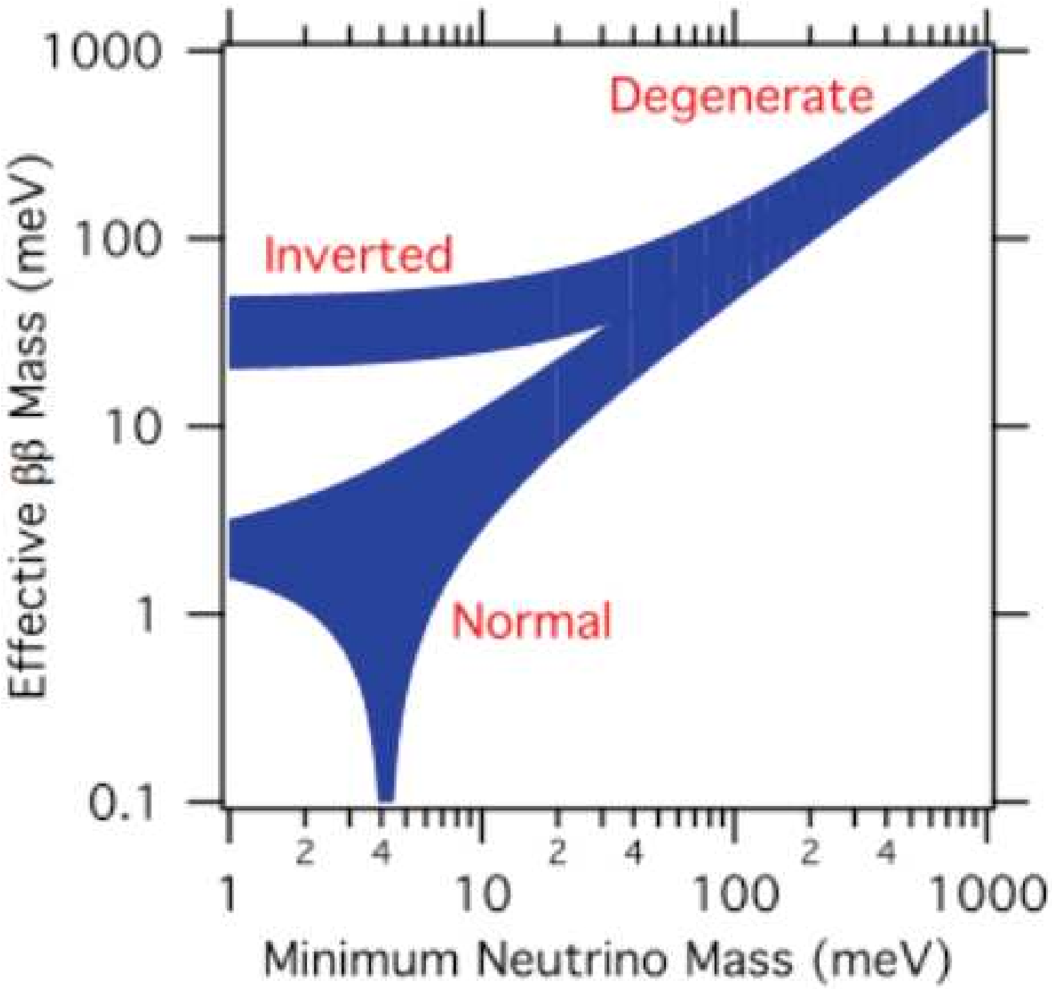
$$m_{\bar{\nu}_e} < 2.2\,\mathrm{eV}$$

At 2σ

Super allowed so the matrix element does not affect the shape of the spectrum

$$K(E) = \sqrt{\frac{N(E)}{Fp_eE}} \propto (E_0 - E)\left[1 - \left(\frac{m_{\bar{\nu}_e}c^2}{E_0 - E}\right)^2\right]^{1/4}$$

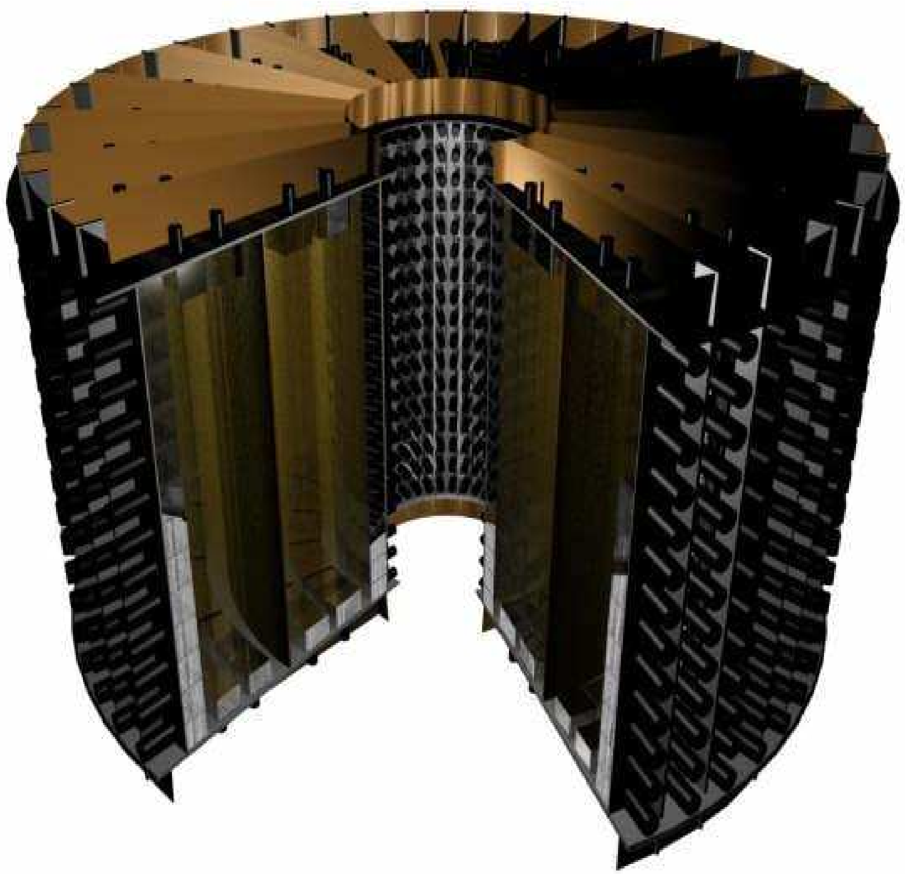
Evidence for hierarchy



$$m_{ee} \equiv \sum_i U_{ei}^2 m_i \equiv m_1 |U_{e1}|^2 e^{i\alpha_1} + m_2 |U_{e2}|^2 e^{i\alpha_2} + m_3 |U_{e3}|^2 e^{-2i\delta}$$

NEMO3 Detector

- **Tracker + Calorimeter**
- **10Kg of source**
- **Magnetic field**
- **Passive shielding**
- **4800 MWE**
- **0.3 eV sensitivity**
- **Energy resolution ~ 14% FWHM at 1Mev**

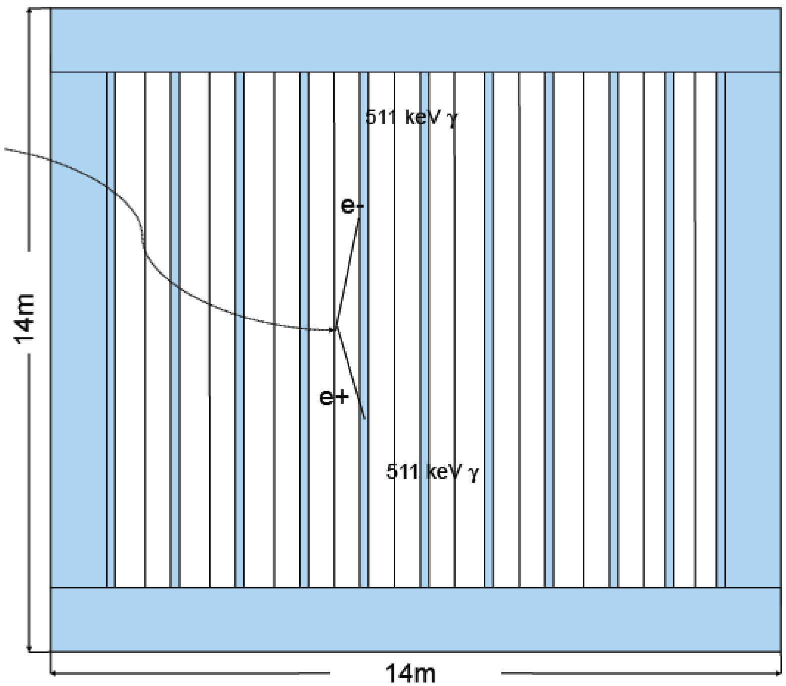


- Divided into 20 individual segments
- Source foils 3.1m in diameter, 2.5m high, 30-60mg= cm2 thick and of different isotopes
- Either side of the foil are concentric tracking volumes composed of 6180 drift cells
- The drift cells are 270 cm long and contain an ethyl alcohol and helium gas mixture
- Surrounding this is the calorimeter made up of 1940 polystyrene scintilator blocks of 10cm
- A magnetic field parallel to the foil access of 25G is generated by an external solenoid.
- There is an external shield of 20cm iron that reduces gamma rays and thermal neutrons
- Outside this there is a borated water shield thermalize fast neutrons and capture thermal neutrons

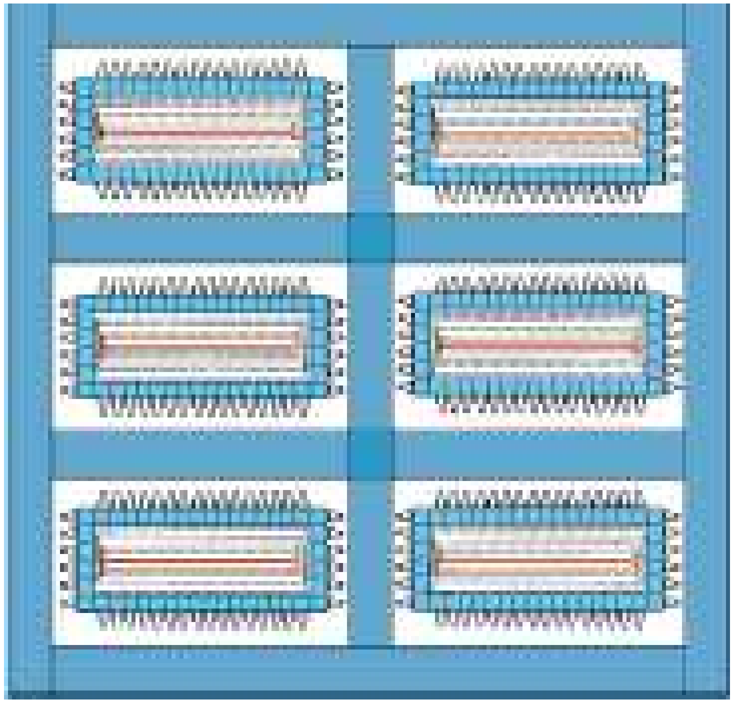
SuperNEMO

- Tracker + Calorimeter
- 100Kg of source
- modular design (~ 20 modules)
- 4800 MWE
- 50-80 meV sensitivity
- Energy resolution < 7% FWHM at 1Mev

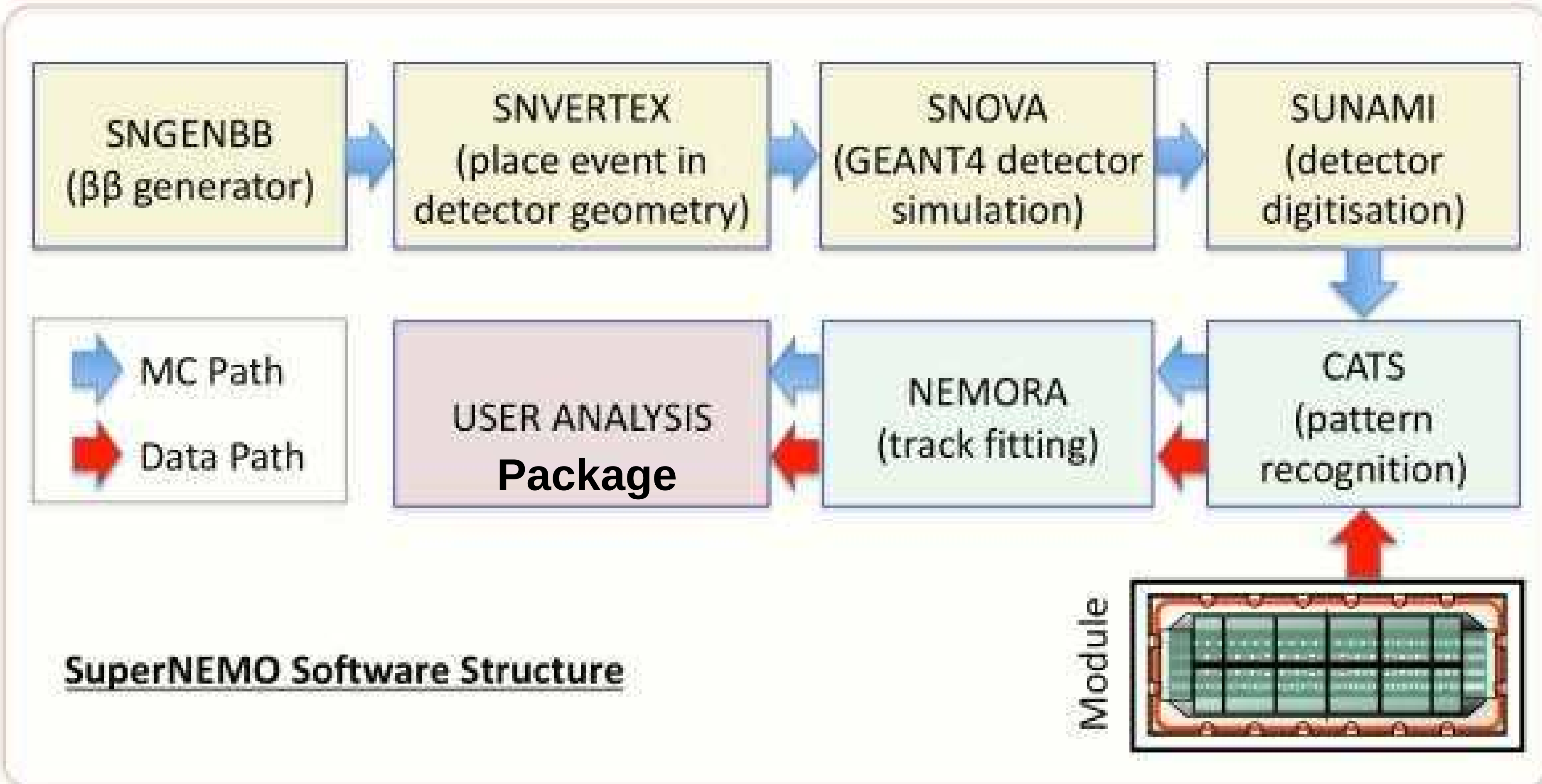
Bar design



Block design



Software description



Analysis Package

Provides:

- Full and easy access to both reconstructed, true and raw data
- Easy to use inbuilt data structure and root io
- Framework for applying cuts, event selection and plots
- Inbuilt analysis debugging
- Tools and functions for analysis

Simulation Results

n_T	n_S	x_T (mm)	y_T (mm)	No of events simulated	C_{min} (E> 0.7 MeV)	T_{max}	Cal time (hrs)	Tracker max hit rate (Hz)*	Possible ββ Foil Sheet width (mm)
5	4	1012	850	10^6	5	2200	27.8	8.8	
6	4	748	850	10^6	5	1921	23.1	9.2	
6	**4**	**836**	**850**	**9.5×10^5**	**8**	**1771**	**13.7**	**8.9**	**200**
6	**4**	**924**	**850**	**10^6**	**8**	**1840**	**14.5**	**8.8**	**180**
6	4	924	900	10^6	6	1897	19.3	9.1	

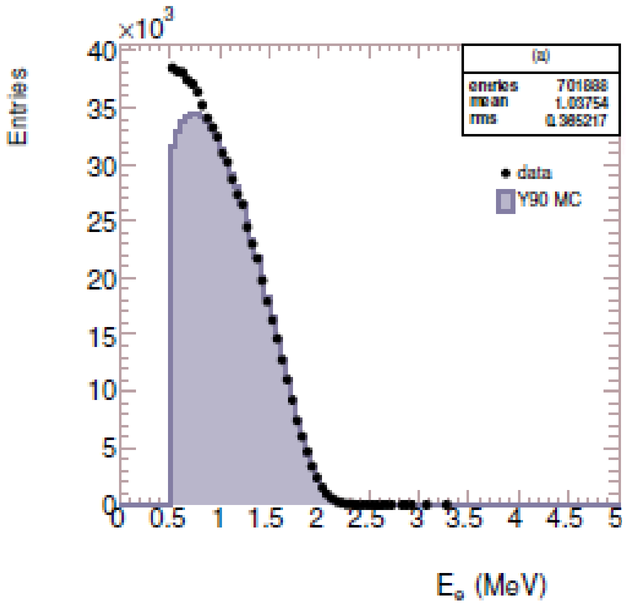
Backgrounds

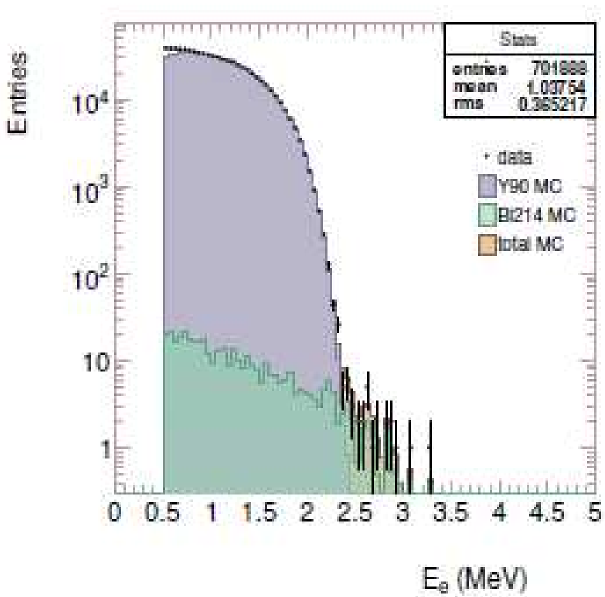
- For time being using existing Internal background measurements
- Sources :
- HPGE measurements
- Nemo3 1e and 1e1γ measurements

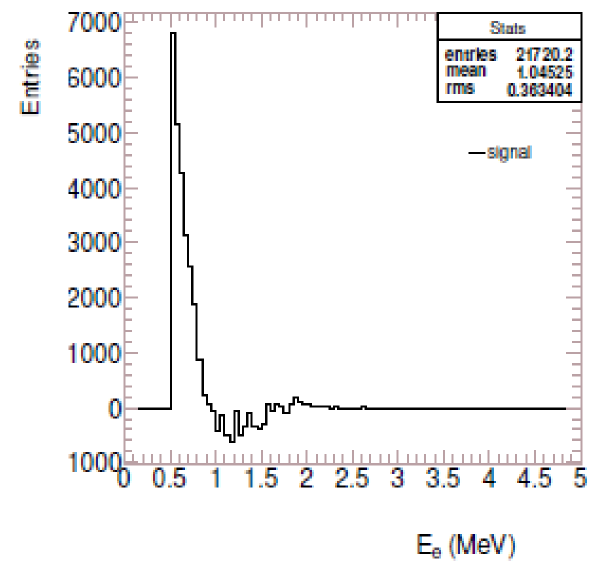
Background	Activity (Bq)
^{228}Ac	1.46×10^{-5}
^{212}Bi	1.46×10^{-5}
^{214}Bi	4.45×10^{-6}
^{137}Cs*	4.95×10^{-5}
^{152}Eu*	5.25×10^{-4}
^{40}K	8.00×10^{-4}
^{214}Pb	4.60×10^{-6}
^{208}Tl	5.25×10^{-6}
^{90}Y	0.03

The Y90 background

- The Y90 background component dominates
- It was measured using the 1e spectrum



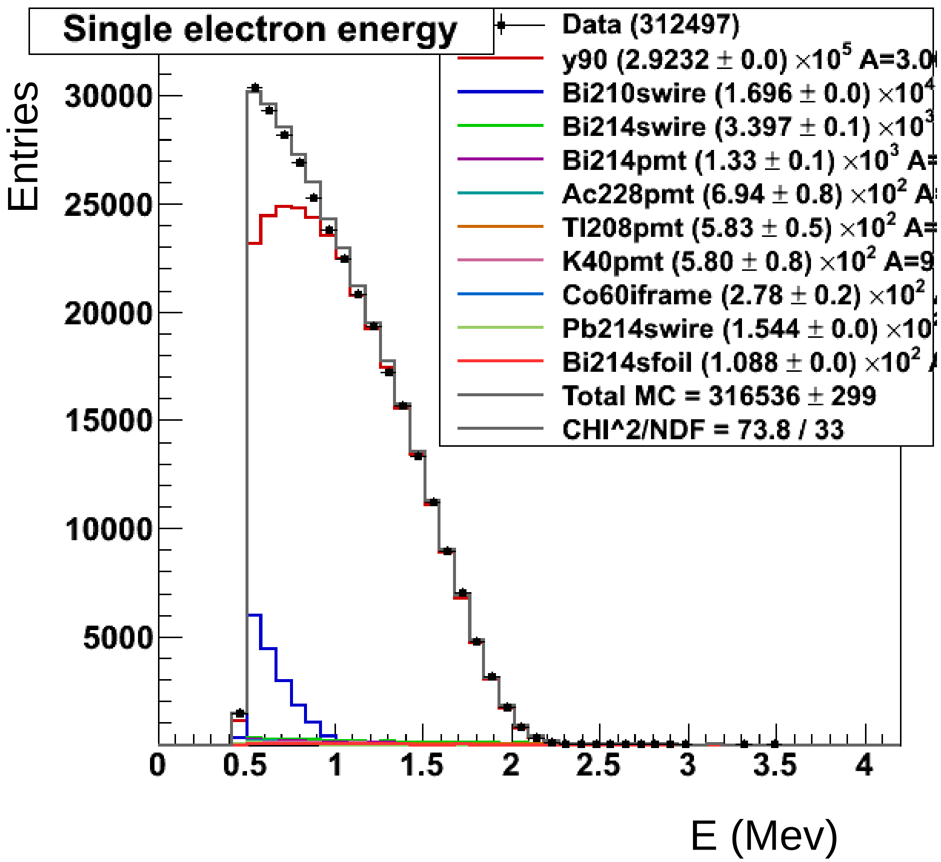




- High energy deficit was fit by Bi214 Swire & Sfoil
- Low energy deficit not determined

Y90 Background

- Bi210 is a good fit for the low energy
- With an activity of 5.05Bq
- Can be out of equilibrium with Bi214 due to Pb210



Cuts and Efficiencies

Cuts used

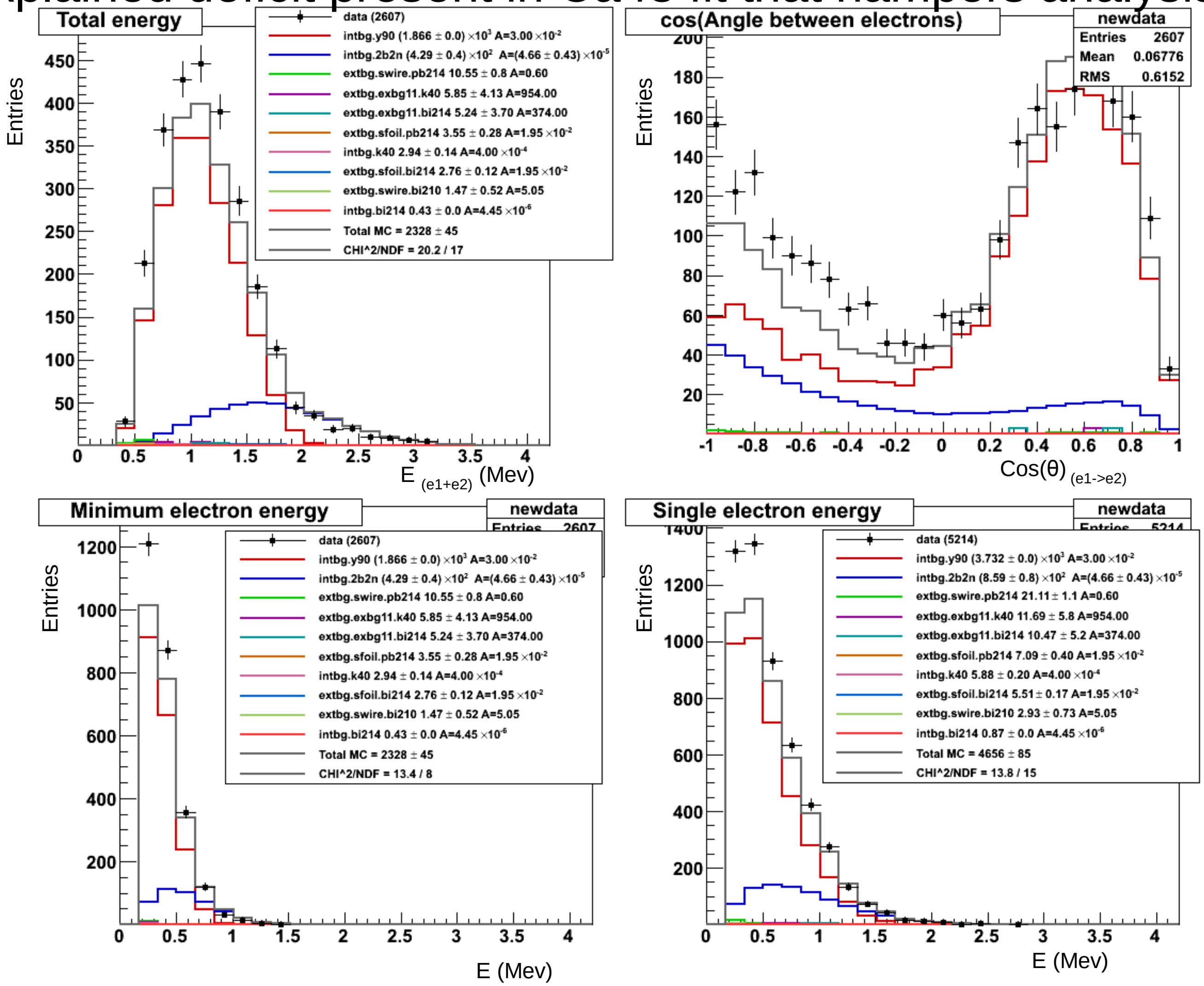
- Scintillator hits = 2
- Tracks = 2
- Associated tracks
- Track Charge < 0
- Reconstructed correctly
- ΔXY < 2cm
- ΔZ < 7cm
- Reconstructed to vertex on Ca foil
- Triggered blocks below threshold
- Scintillator hits > 200kev
- Track hits in first 2 layers near foil
- Track hits in last 2 layers near blocks
- Track length >60 cm
- TOF 0.04<pint<1
- TOF 0<pext<0.01
- Isolated scintillator hits
- Delayed alpha single hit > 70μs
- Delayed alpha grouped hit > 20 μs
- Cut on no associated fast hits
- Only one gamma > 200kev
- No gammas 150kev < E < 200kev

Largest background efficiencies

Background	**Efficiency**
Bi214 sfoil	1.08E-006
Pb214 sfoil	1.34E-006
Bi210 swire	1.15E-009
Bi214 swire	1.00E-006
Pb214 swire	1.41E-007
Co60 in petal iron	2.48E-010
Ac228 intbgr	1.98E-004
Bi214 intbgr	7.57E-004
Eu152 intbgr	1.08E-005
Tl208 intbgr	3.92E-004
Y90 intbgr	4.79E-004

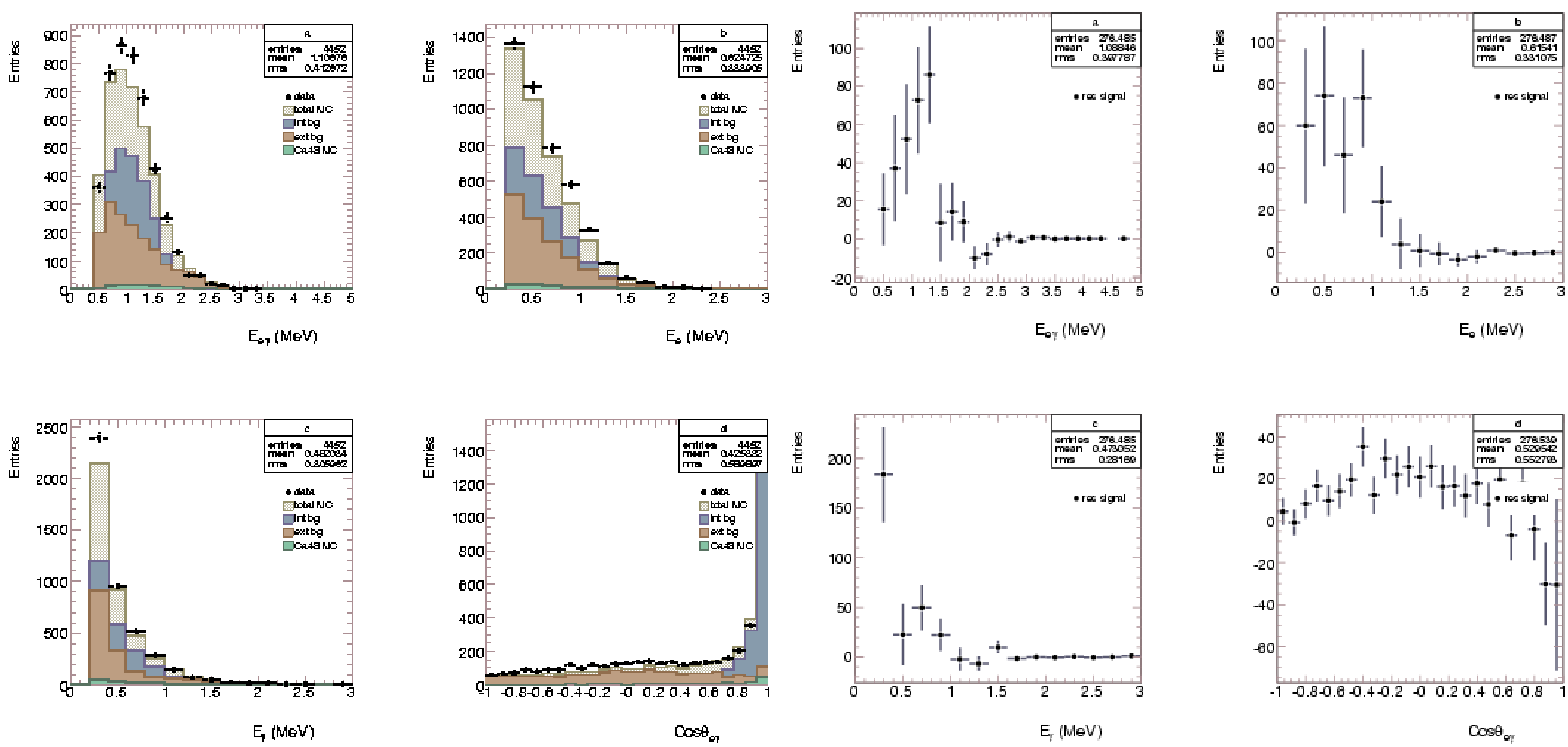
Issues with the Ca48 spectra

- The dominant background is of Y90. However, there is an apparent unexplained deficit present in Ca48 fit that hampers analysis.

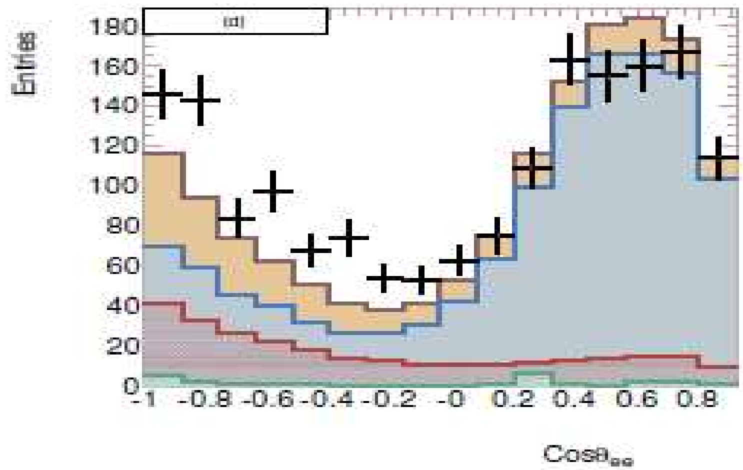


Issues with the Ca48 spectra

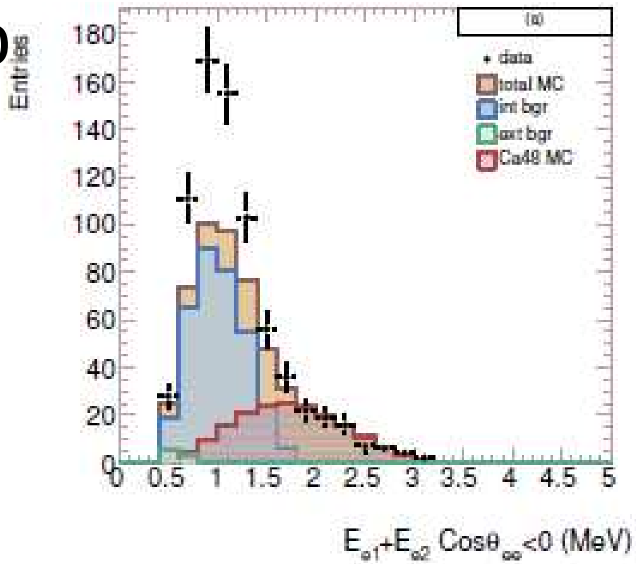
- Deficit also present in the 1e1γ spectra
- Backgrounds are well understood for $E_{(e1+e2)}$ > 1.5Mev

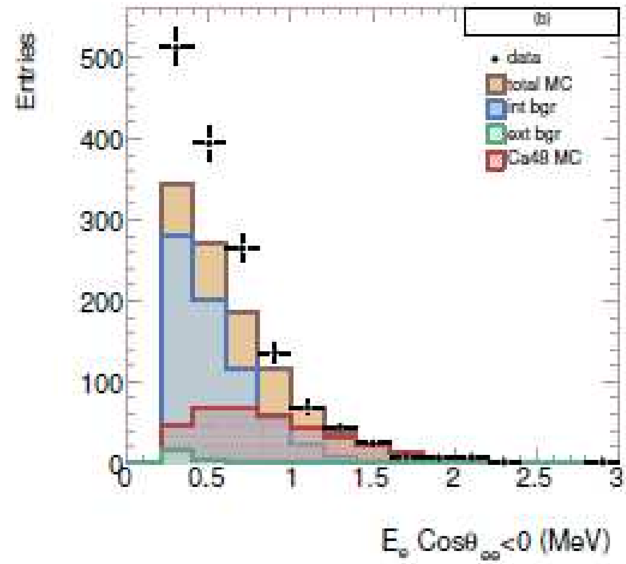


Issues with the Ca48 spectra

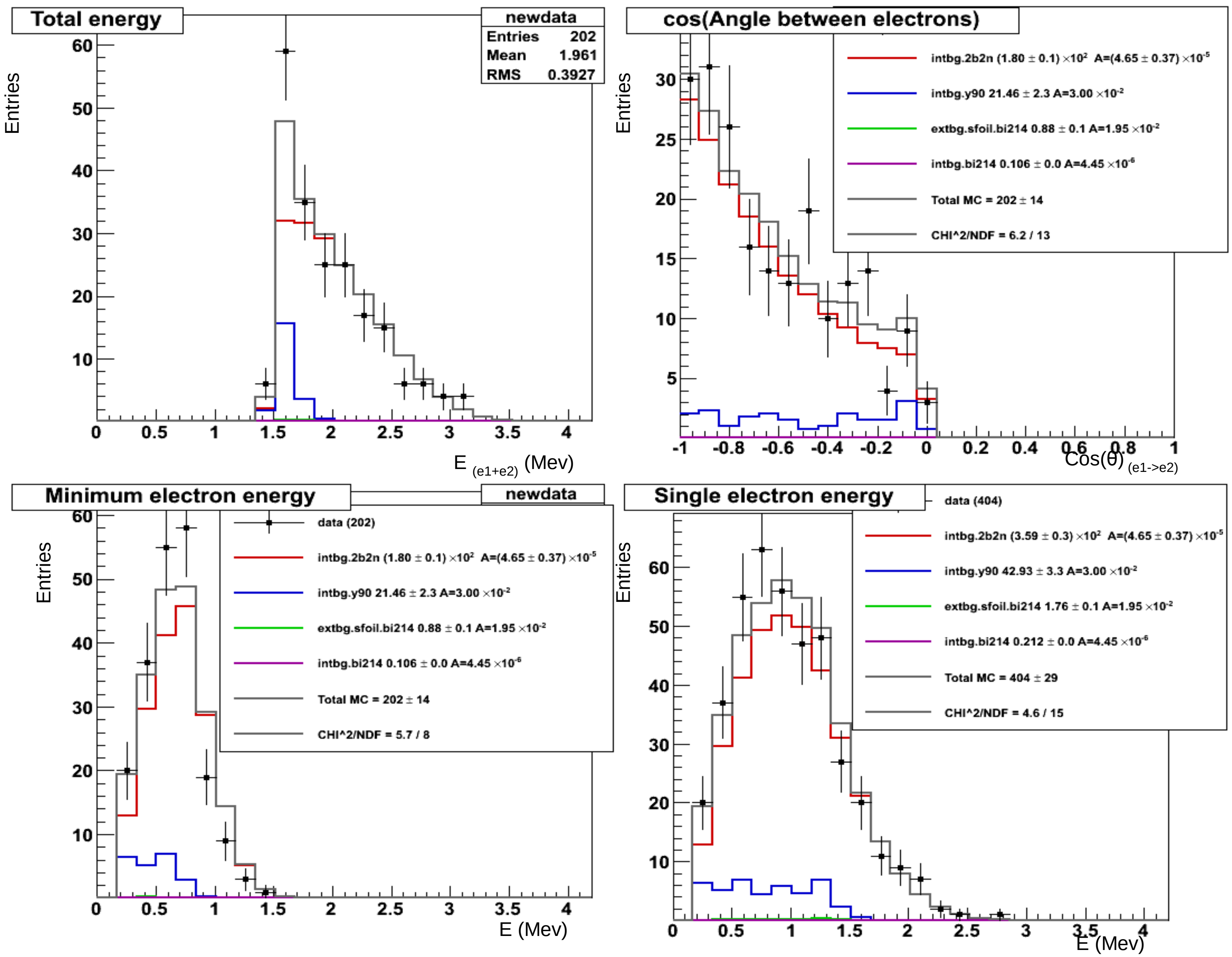


- Cut cos(θ) > 0 to increase signal to background ratio





Results


Total energy
newdata
Entries 202
Mean 1.961
RMS 0.3927
Entries
E (e1+e2) (Mev)
cos(Angle between electrons)
intbg.2b2n (1.80 ± 0.1) ×10² A=(4.65 ± 0.37) ×10⁻⁵
intbg.y90 21.46 ± 2.3 A=3.00 ×10⁻²
extbg.sfoil.bi214 0.88 ± 0.1 A=1.95 ×10⁻²
intbg.bi214 0.106 ± 0.0 A=4.45 ×10⁻⁶
Total MC = 202 ± 14
CHI^2/NDF = 6.2 / 13
Cos(θ) (e1->e2)
Minimum electron energy
newdata
data (202)
intbg.2b2n (1.80 ± 0.1) ×10² A=(4.65 ± 0.37) ×10⁻⁵
intbg.y90 21.46 ± 2.3 A=3.00 ×10⁻²
extbg.sfoil.bi214 0.88 ± 0.1 A=1.95 ×10⁻²
intbg.bi214 0.106 ± 0.0 A=4.45 ×10⁻⁶
Total MC = 202 ± 14
CHI^2/NDF = 5.7 / 8
E (Mev)
Single electron energy
data (404)
intbg.2b2n (3.59 ± 0.3) ×10² A=(4.65 ± 0.37) ×10⁻⁵
intbg.y90 42.93 ± 3.3 A=3.00 ×10⁻²
extbg.sfoil.bi214 1.76 ± 0.1 A=1.95 ×10⁻²
intbg.bi214 0.212 ± 0.0 A=4.45 ×10⁻⁶
Total MC = 404 ± 29
CHI^2/NDF = 4.6 / 15
E (Mev)