PEP Violation Analysis with NEMO3 and Calorimeter R&D for SuperNEMO

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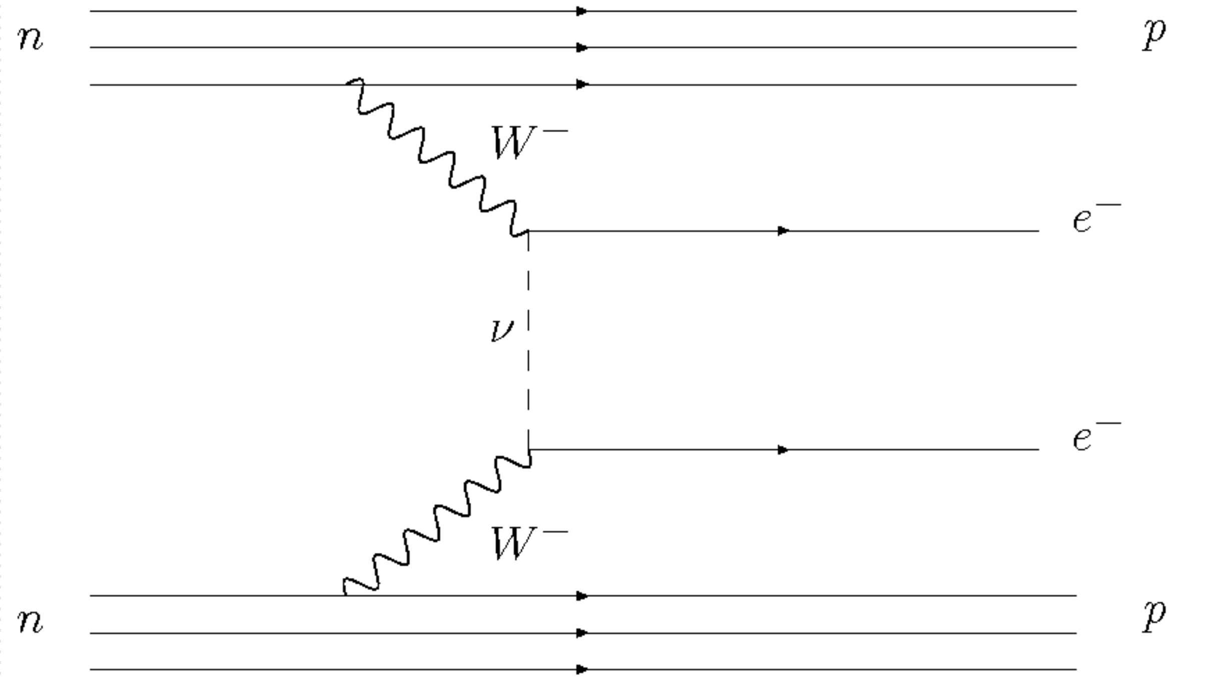
Neutrinoless Double Beta (0νββ) Decay

$$2n \rightarrow 2p + 2e^-$$



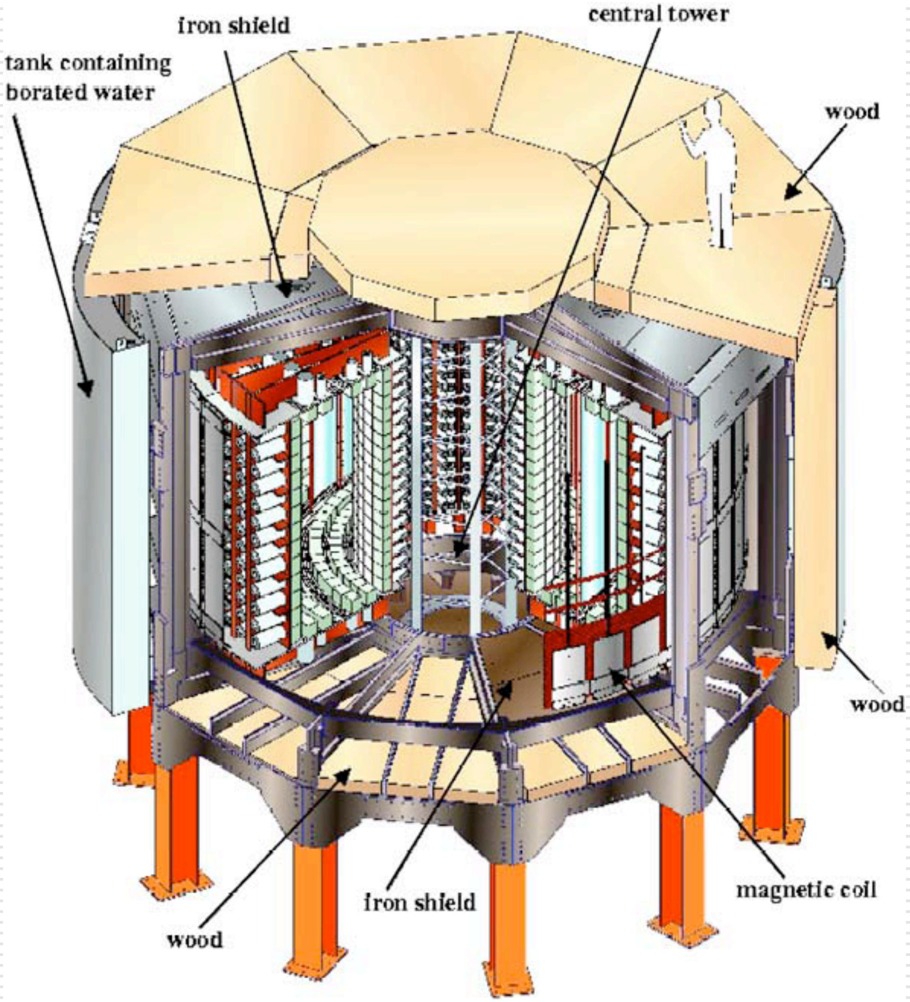
Requires:

- The neutrino to have mass
- The neutrino to be Majorana

Tells us:

- Absolute neutrino mass
- Majorana or Dirac?

The NEMO3 Detector



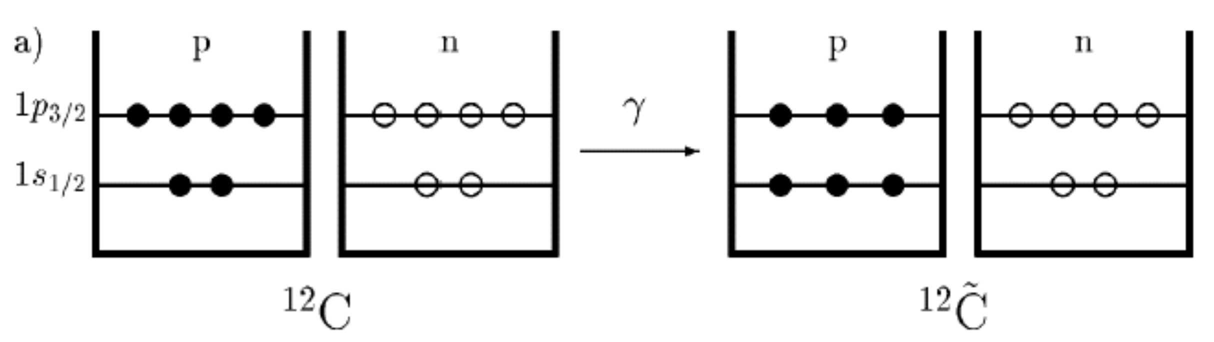
- $0\nu\beta\beta$ decay detector
- 10kg of double beta decay isotope
- Tracking wire chamber → 3D tracking of charged particles
- Calorimeter → energy and ToF measurements
- Magnetic field → positron rejection
- Projected sensitivity: $\tau_{1/2}$ > 2 x 10^{24} years

$\langle m_{\nu e} \rangle = 0.3 - 0.9$ eV

Pauli Exlusion Principle (PEP) and NEMO3

- No two identical fermions can occupy the same state at the same time

- Use NEMO3 to search for PEP Violation:
  - ^{12}C (stable) in plastic scintillators of Nemo3
  - Search for evidence of non-Paulian transition of a nucleon from the p shell to the fully occupied s shell



  - Accompanied by γ emission: energy is difference between the p and s levels (~20 MeV)

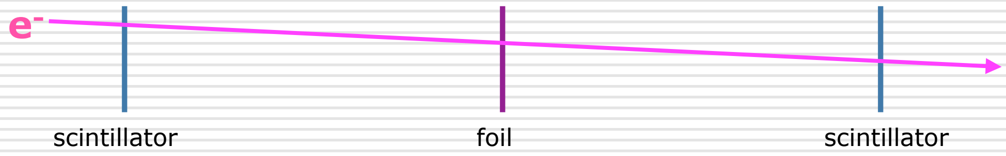
- Obtain half-life limit on PEP violation

γ Emission by Nucleon: Event Selection

- γ from non-Paulian transition crosses the tracking volume interacting with the source foil → e^+e^- pair

- Require:
  - 2 tracks (originating in same vertex near the foil)
    - of any curvature (due to high energies)
    - sum of energies > 4 MeV
  - and a fired scintillator associated with each track

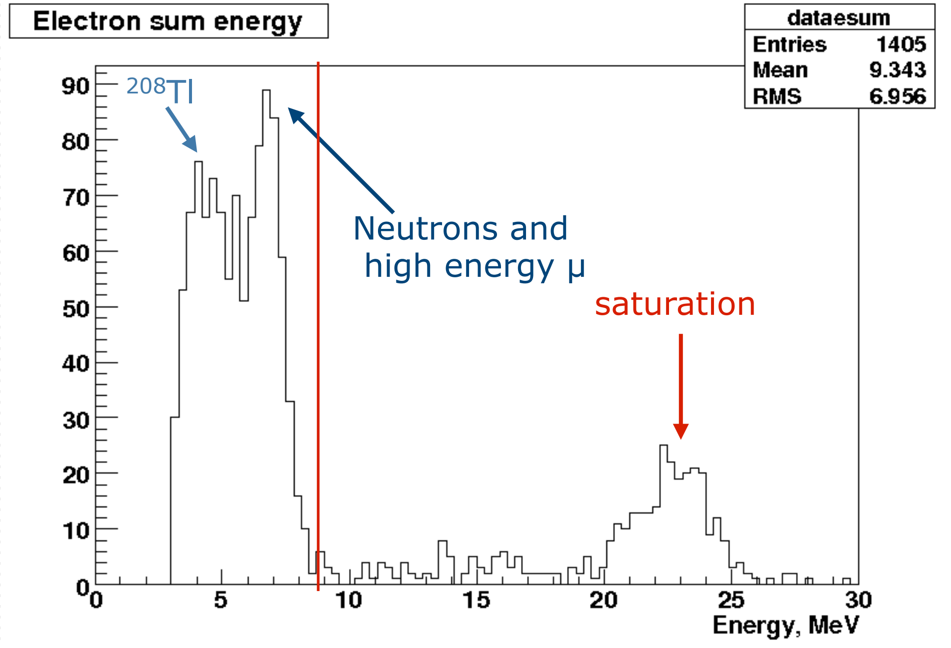
- Crossing electron background:
  - Cannot rely on ToF at high energies (different for MC and data) → no internal/external probability cuts



- MC: 10 million 20 MeV γ events generated uniformly in scintillator walls and petals for all available data so far

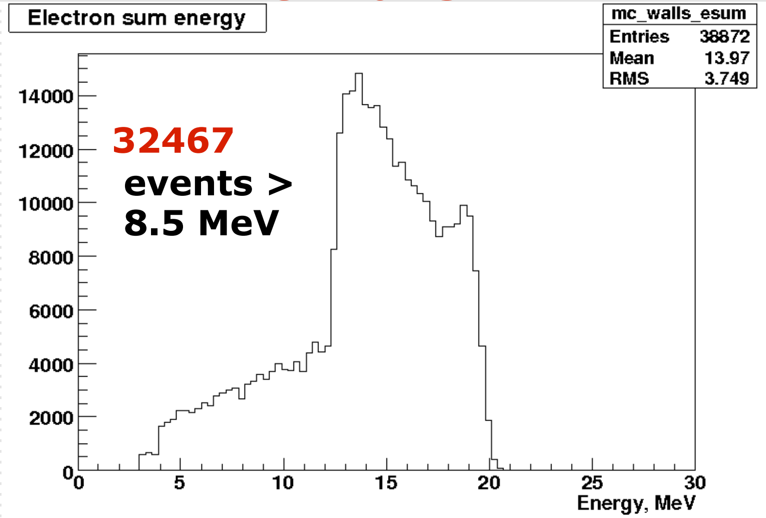
2 Track Sum Energy Plots

Data:

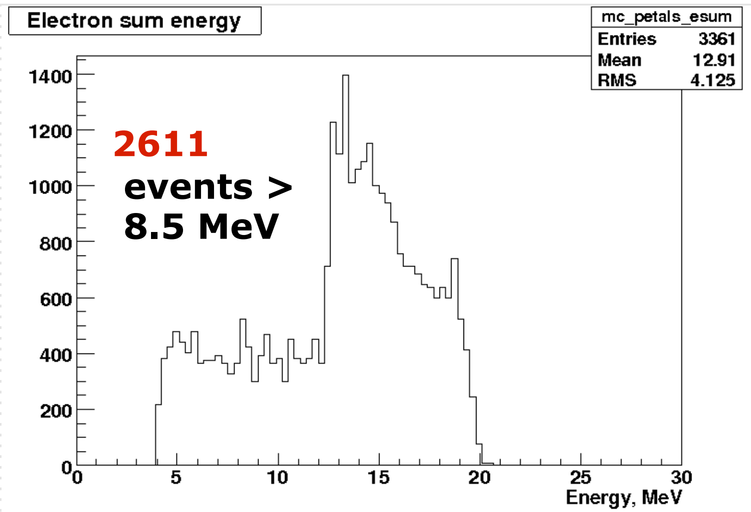


104 events > 8.5 MeV

MC Walls:



MC Petals:



Results

N_0 = 2.96 x 10^{29} ^{12}C atoms	η = 2.78 x 10^{-3} = 0.28%
N_{decay} = 117 at 90% CL	t = 2.28 years

$$\tau_{1/2} > \frac{N_0}{N_{decay}^{90\%CL}} \eta \ln 2t$$

- $\tau_{1/2} > 1.1 \times 10^{25}$ years

- Limit on PEP violating transitions of nucleons from the *p*-shell to the fully occupied $1s_{1/2}$-shell in ^{12}C at 90% C.L. is:

$\tau_{1/2} > 8.9 \times 10^{25}$ years

(cf 4.2 x 10^{24} years for Nemo2)

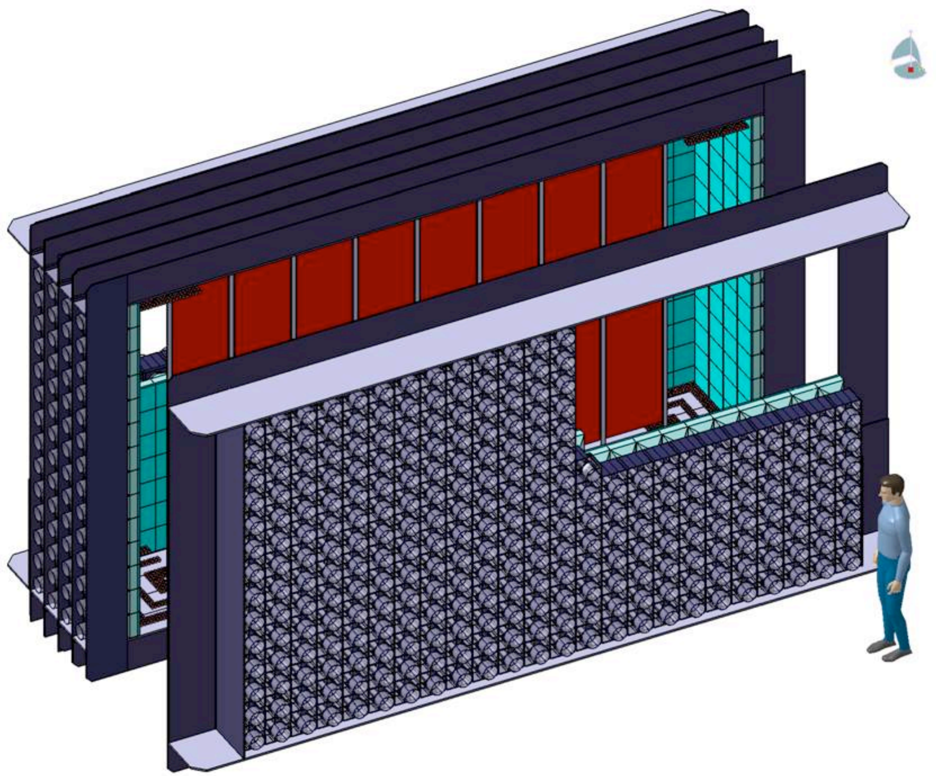
- Borexino CTF Result: 2.1 x 10^{27} years (2005)
  - Better efficiency (4.3 x 10^{-2}) and less background than Nemo3
  - Nemo3 has larger scintillator mass: 6.4 tonnes (cf 4.2 tonnes)

Improve backgrounds and efficiency to improve result!

PEP Future Plans

- Apply high energy corrections to ToF information
- Improve efficiency to obtain best possible limit by finding optimal cuts
- Analyse other PEP violating channel in ^{12}C (β decay)
- Publish!
- Extend $\gamma \rightarrow e^+e^-$ analysis for all e^+e^- events in NEMO3 and extrapolate to SuperNEMO
  - Will SuperNEMO require a magnetic field?

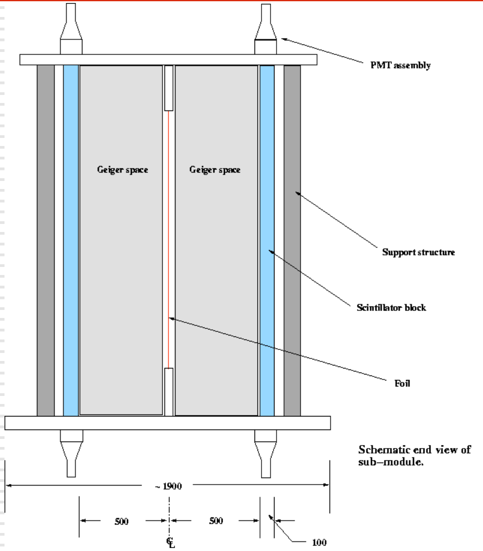
SuperNEMO

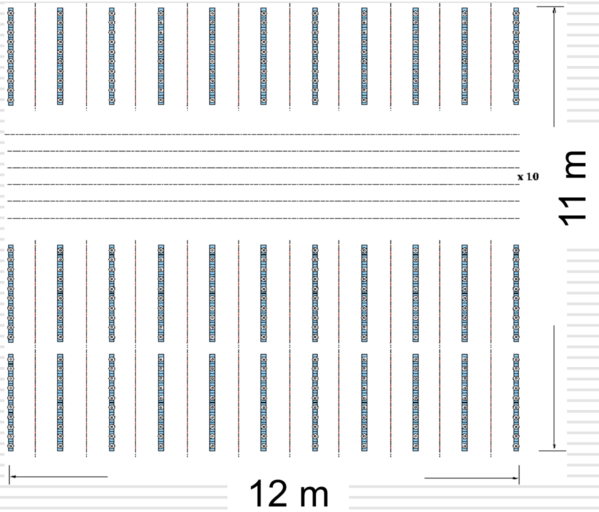


- Next generation $0\nu\beta\beta$ decay detector
- 100kg of either ^{82}Se and/or ^{150}Nd
- Modular baseline design
- Design sensitivity: $\tau_{1/2} > 10^{26}$ years

  $<m_{\nu e}> = 0.04 – 0.11$ eV
- Required resolution: 7-8% FWHM at 1 MeV

Scintillator Bar Calorimeter Design

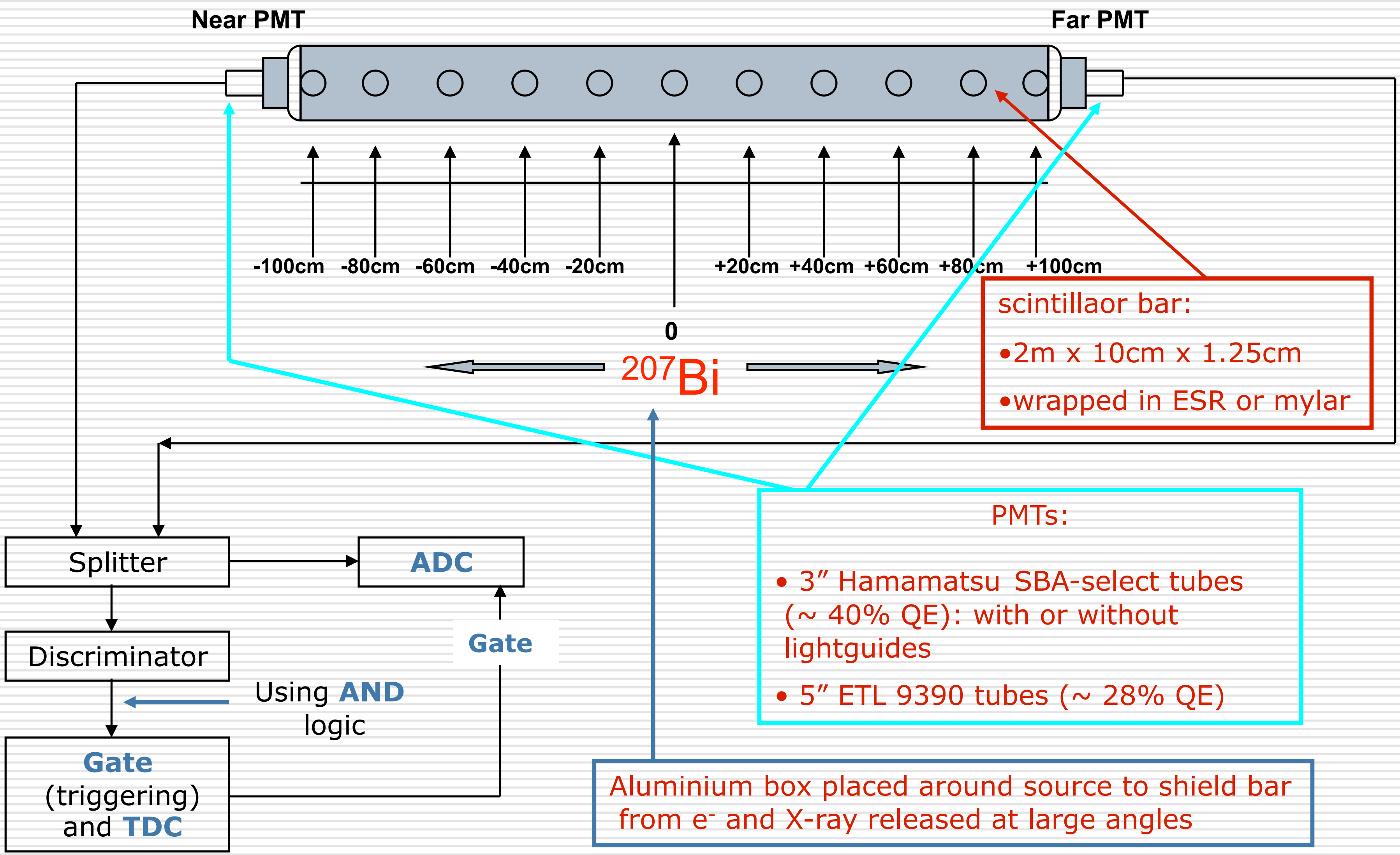




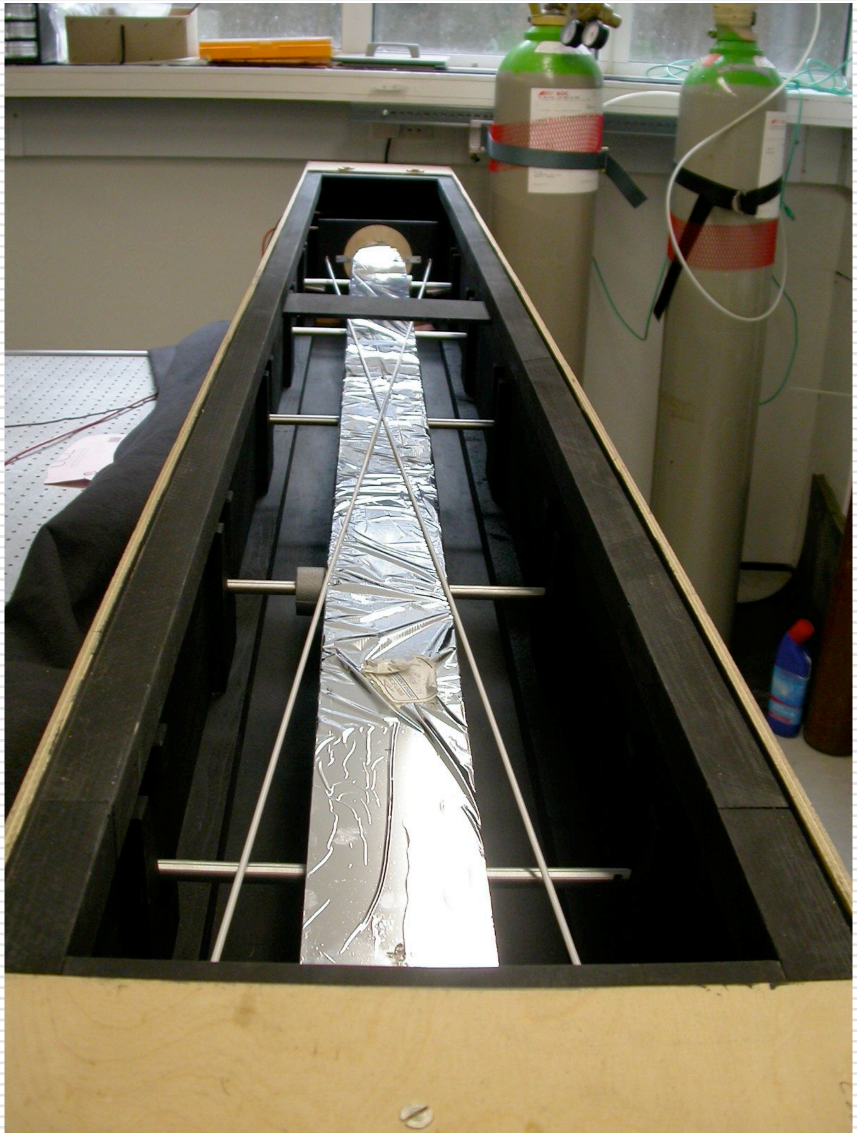
- Bar dimensions: 2m x 10cm x 2.5cm
- Much more compact:
  - 11×12 m^2 floor area will accommodate ~100 kg of isotope (40 mg/cm^2)
- External walls as active shielding by anti -coincidences
- Huge savings on ***number of PMTs***: only ~2900 "cheap" 3" or 5" PMTs (flat) instead of 12,000 8" in baseline
  - 6M€ - baseline
  - 0.5M€ - bars (if 3")
- Lower radioactivity due to PMTs
- More options for background suppression, ToF can be relaxed (possibly). Hence may try smaller scintillator-foil gap ⇒ higher efficiency

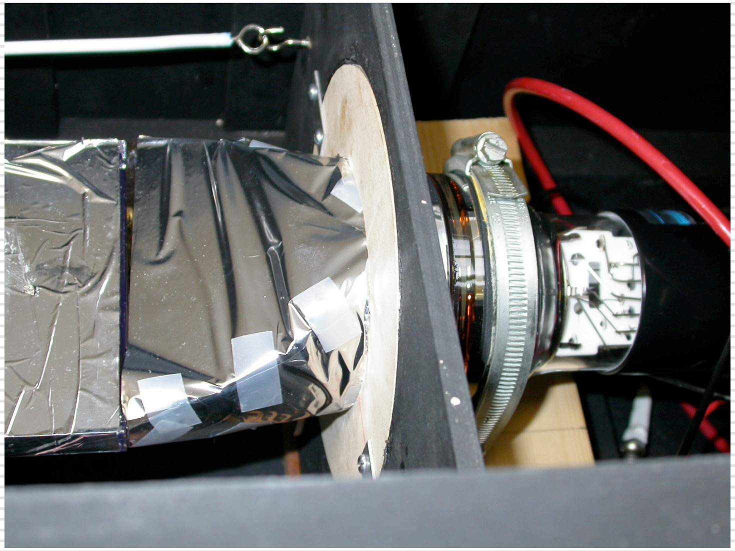
Perhaps energy resolution requirement can be relaxed in this configuration? 10-11% @1 MeV may be enough (physics simulations needed).

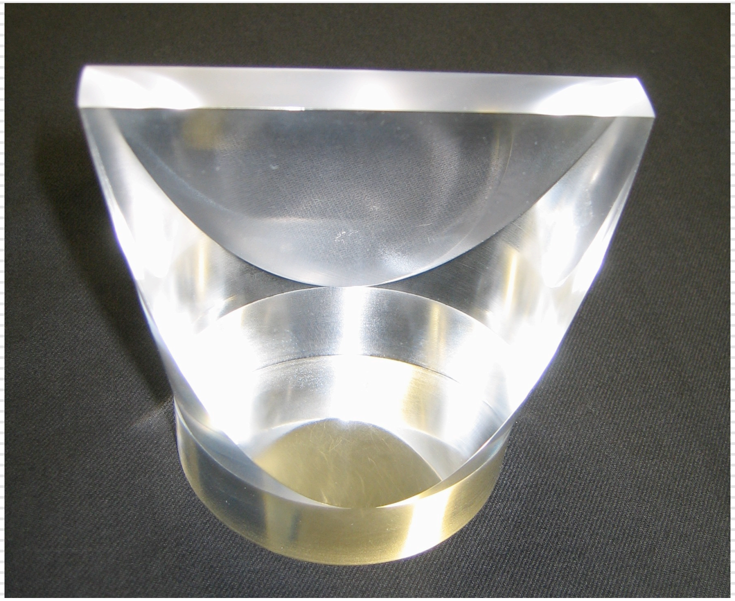
Setup and Testing Procedure



Setup



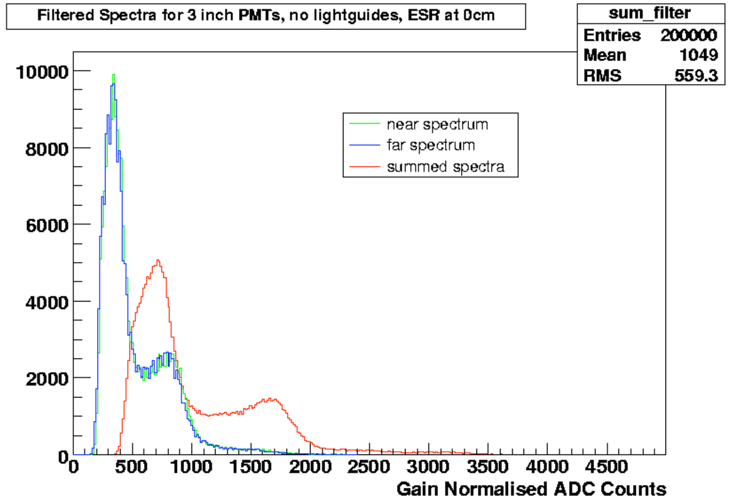


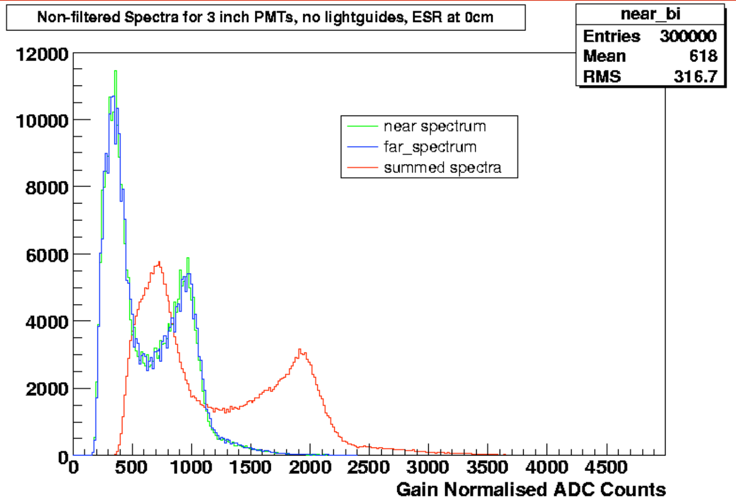


Measurements

PMTs Used:	Light Guides?	Aluminium Box?	Wrapped in:	Voltage:
3″ SBA-Select (Hamamatsu)	Yes	No	Mylar	1450 V
3″ SBA-Select (Hamamatsu)	No	Yes	Mylar	1450 V
3″ SBA-Select (Hamamatsu)	No	Yes	ESR	1450 V
5″ ETL 9390	No	Yes	ESR	1300-1400 V

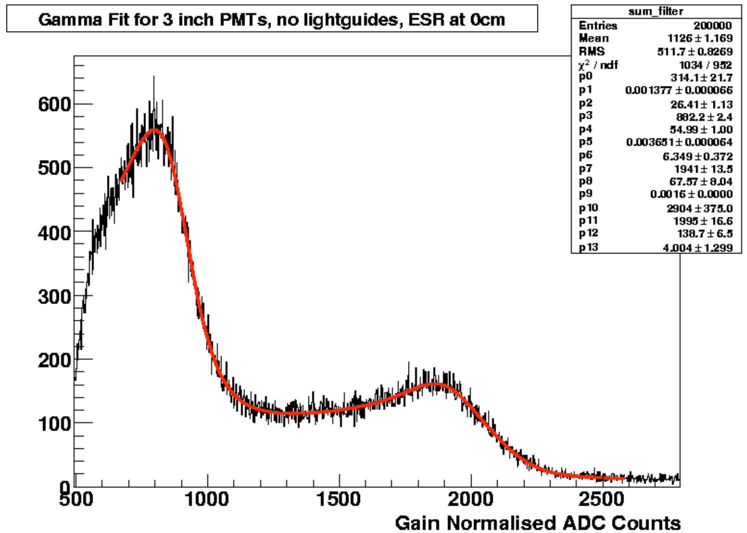
Measurements: 3” PMT, no lightguides, ESR at 0cm

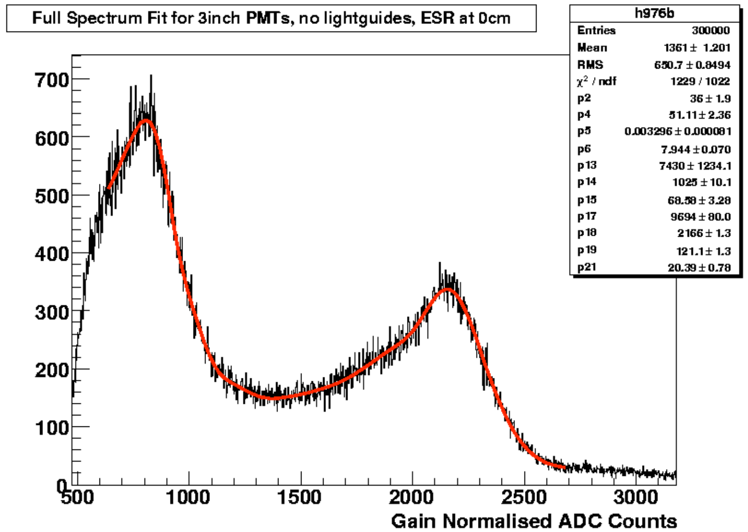




1) Fit to gamma spectrum

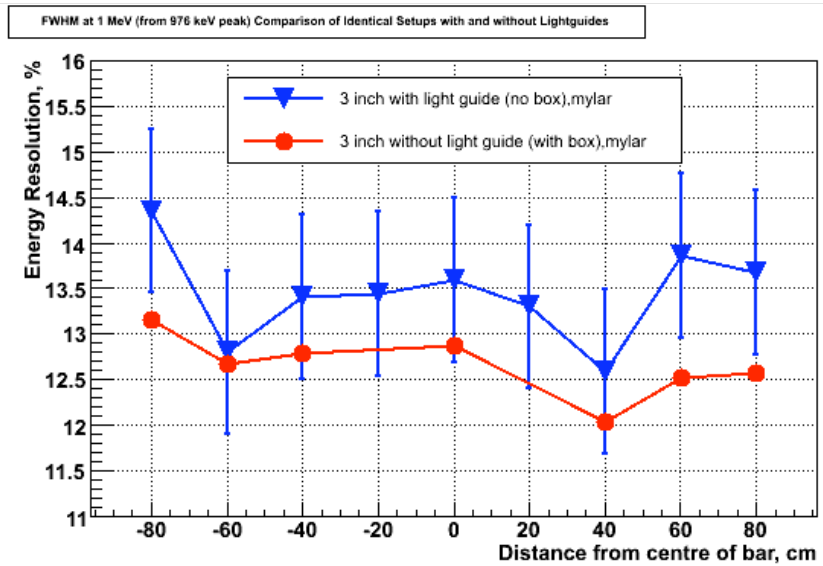
2) Fit to ^{207}Bi spectrum

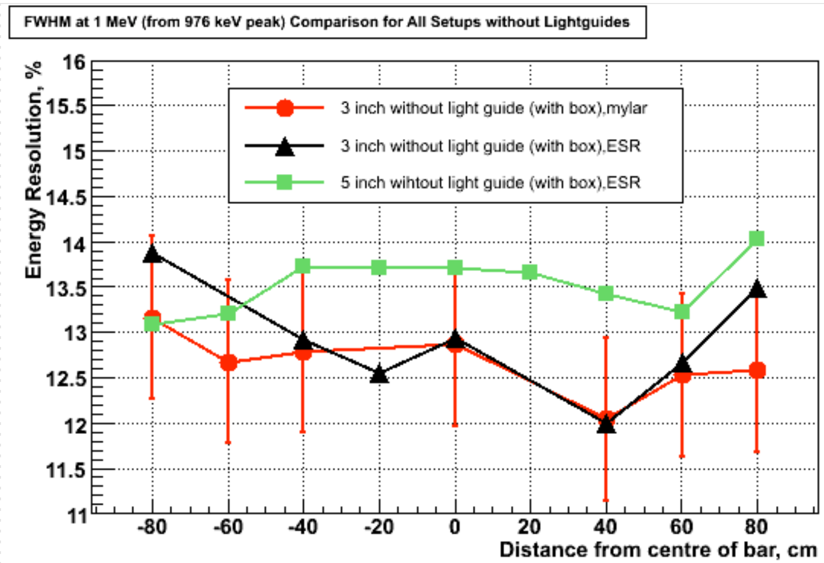


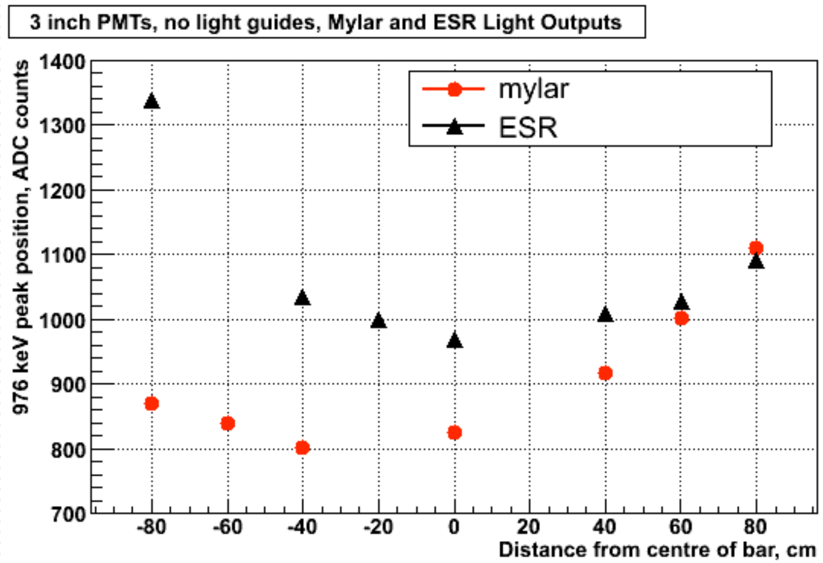


X^2/ndf = 1229/1022, FWHM at 1 MeV: **12.93%**

Results



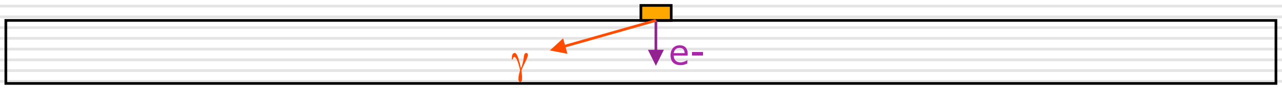




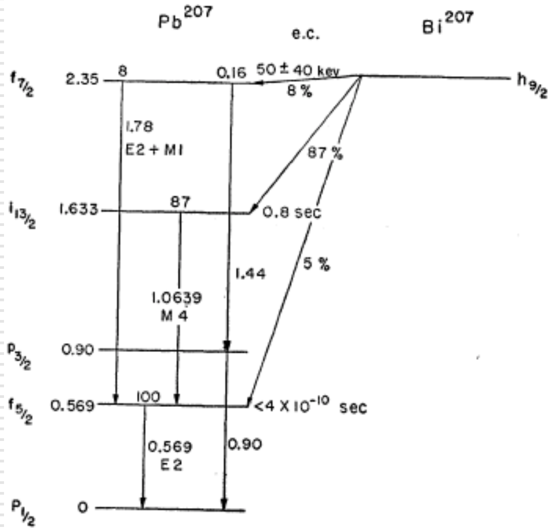
- Systematic errors obtained from fit to generated MC
- All setups give similar results → resolutions vary between 12% and 14.3%
- Improvement in light output when using ESR rather than mylar BUT no improvement in resolution
- Limiting factor?

Pile Up

- Pile up: 976 keV e^- “always” accompanied by 570 keV γ + X-rays



In this geometry (due to solid angle) we are much more likely to pick up γ-s



- Run simulations to see how big of an effect this is
  - Take this effect into consideration when doing energy resolution calculation
- Only affects calorimeter R&D, NOT actual SuperNEMO

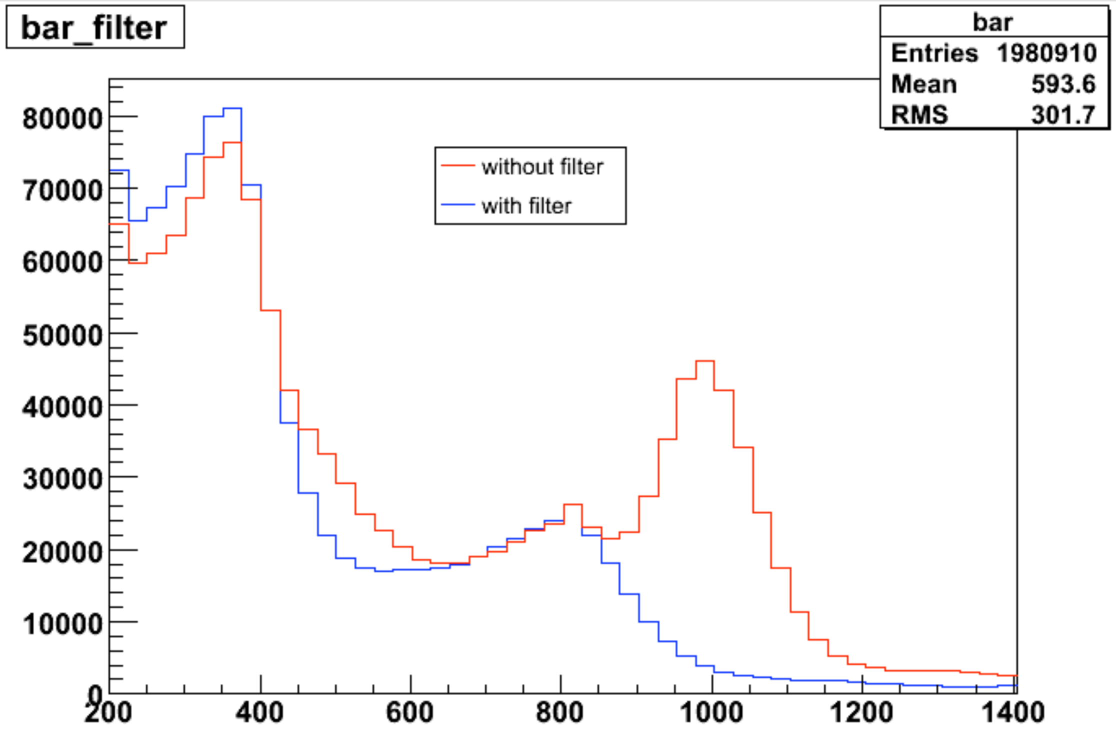
Pile Up Simulations

- Give simulation number of photo electrons (PE) corresponding to wanted resolution

fractional resolution → $\delta = \frac{\sigma}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$ ← number of photo electrons

$$FWHM\, at\, 1\, MeV = 2.35\delta$$

- Fluctuate PE according to Poisson statistics and smear resolution



400 PE Output:

- MC truth: 11.61% FWHM at 1 MeV
- Resolution from bar simulation: 12.48% FWHM at 1 MeV

→ 0.87% away from MC truth

Scintillator Bar Future Plans

- Analyse obtained TDC data

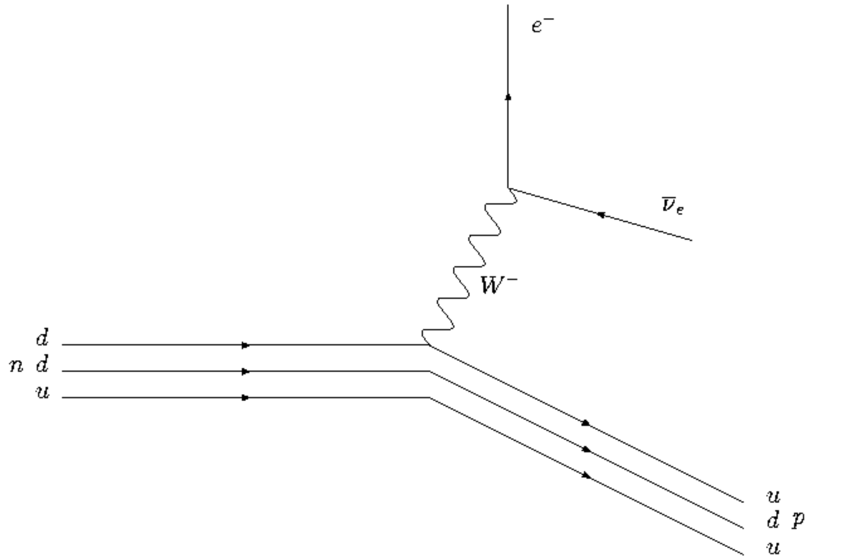
- Test more setups:
  - with uniform wrapping
  - with “tapered” bar to fit 3” PMT
  - with bar of smaller width to fit 3” PMT

- Generate MC for 0.1% resolution intervals with high statistics to simulate pile up
  - Fit data to MC for more accurate fitting

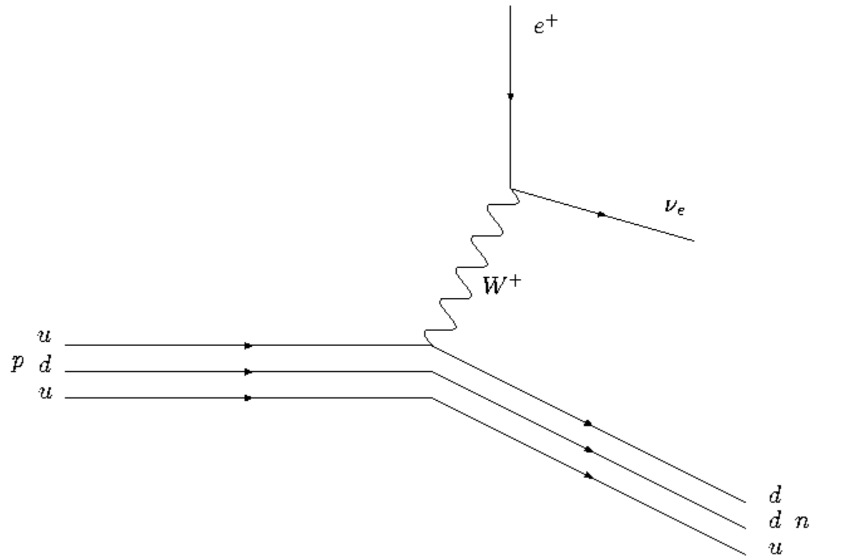
Back Up Slides

Single β⁻ and β⁺ Decay

β⁻ decay:

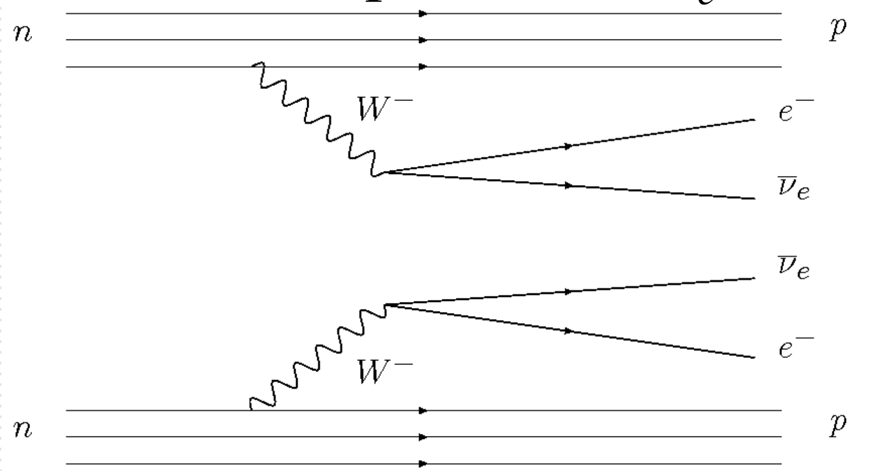


β⁺ decay:



Double Beta Decay (2νββ)

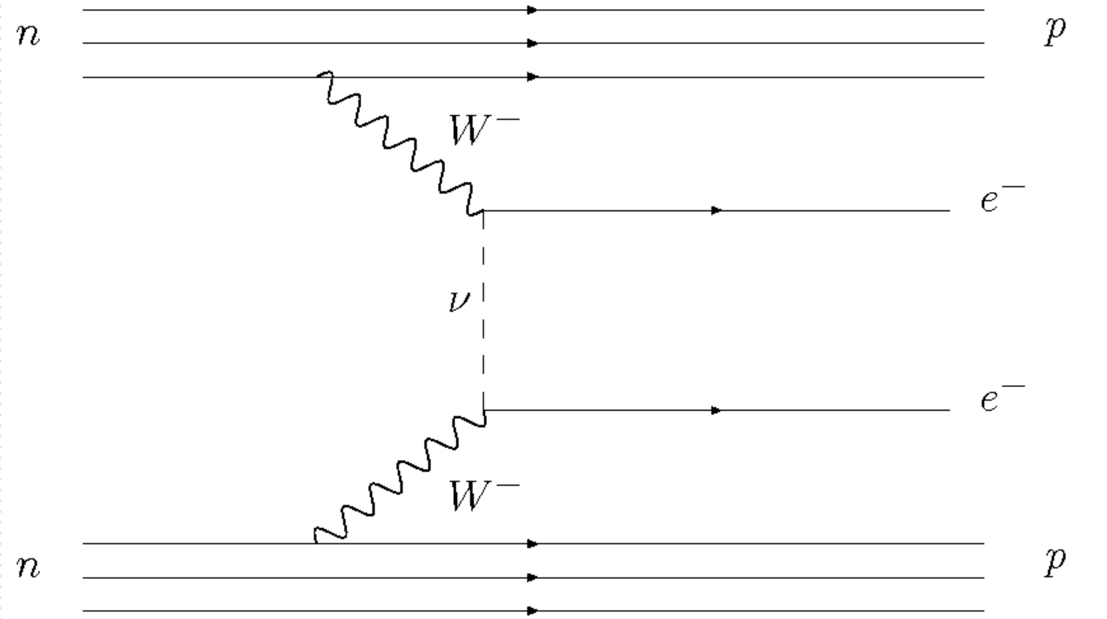
$$2n \rightarrow 2p + 2e^{-} + 2\overline{\nu}_e$$



- Occurs when simple beta decay is not energetically favourable
- For even-A (mass number) nuclei:
  - Two stability curves due to non-zero pairing term of SEMF
  - Even-even (even A and even Z (atomic number)) nuclei lie on lower energy curve
  - Odd-odd nuclei lie on the higher energy curve
  - For nearest even-even nuclei the nearest odd-odd nucleus will almost always have a higher mass → single β decay is not possible
  - Odd-odd nuclei always have nearby even-even nuclei to decay to → 2νββ

0νββ Decay

$$2n \rightarrow 2p + 2e^-$$



Consider two stages of process:

$$1)\ n \rightarrow p + e^- + '\overline{\nu}_R'$$

$$2)\ '\nu_L' + n \rightarrow p + e^-$$

PEP Results

$$\tau_{1/2} > \frac{N_0}{N_{decay}^{90\%CL}} \eta \ln 2t$$

where:

- N_o = initial number of atoms of ^{12}C in scintillators = 2.96 x 10^{29} atoms (mass of wall and petal scintillators = 6.4 tonnes)
- N_{decay} = number of PEP violating events from data = 117 at 90% CL
- η = efficiency:

η_{walls} = 3.25 x 10^{-3} → 0.33% η_{petals} = 2.61 x 10^{-4} → 0.03%

$$\eta_{combined} = (x_{walls}\,\eta_{walls} + x_{petals}\,\eta_{petals})$$

mass fraction in walls = 5.4/6.4

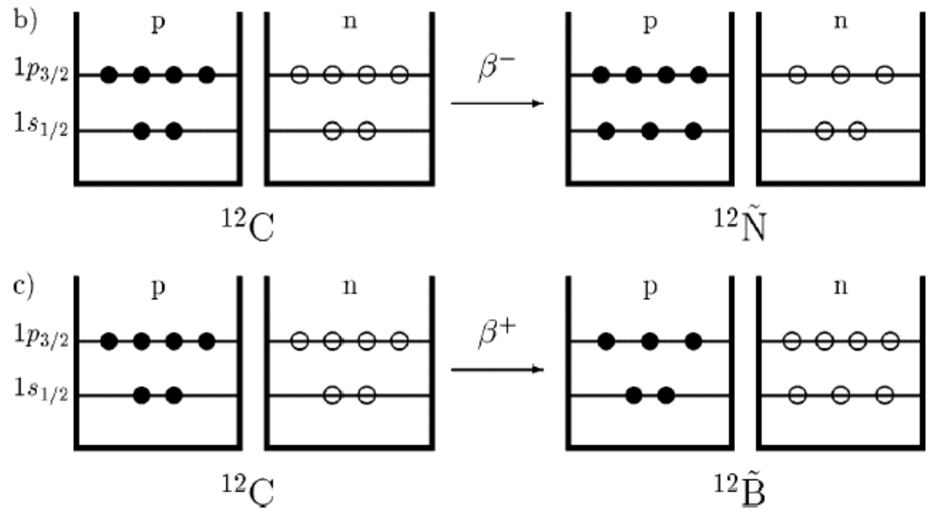
mass fraction in petals = 1/6.4

$\eta_{combined}$ = 2.78 x 10^{-3} → 0.28%

- t = length of measurement = 2.28 years

PEP Beta Decay Channel

- Nucleon from p shell falls to the fully occupied s shell via β decay



β^- decay:

$$n \to p + e^- + \bar{\nu}_e$$

β^+ decay:

$$p \to n + e^+ + \nu_e$$

- The emitted e^+/e^- are distributed as ordinary β-decay spectra with $Q_{\beta\beta}$ value = 20 MeV