



Improved Search for CP-Violation in Positronium Decay

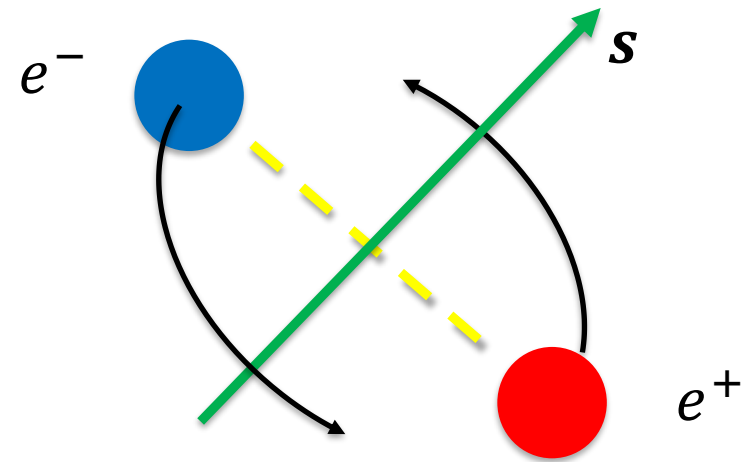
LEPP 2026

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Positronium

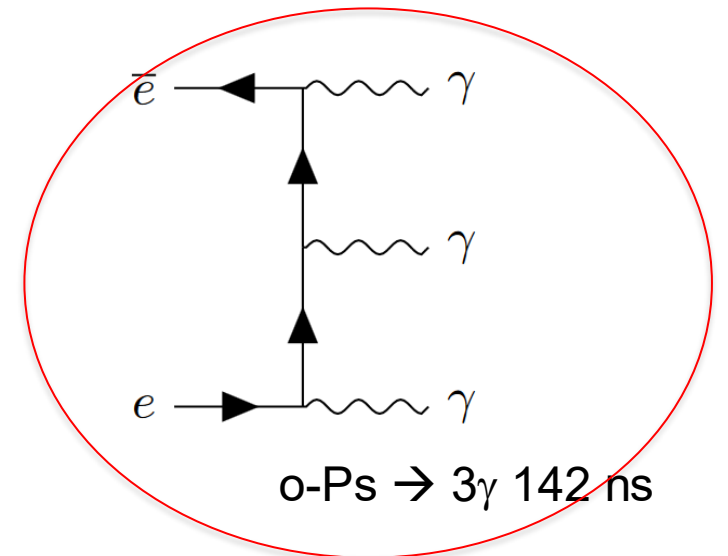
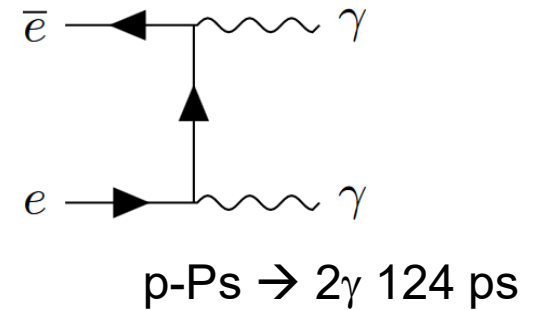
- Positronium – Hydrogen like bound state
 - Mixed matter-antimatter
 - Annihilates to photons
- Lifetime depends on relative spin orientations.
- $C = (-1)^{L+S}$
- $P = (-1)^{L+1}$
- ground state:
 - para-positronium (1^1S_0) is even under charge conjugation odd under parity
 - ortho-positronium (1^3S_1) is odd under charge conjugation odd under parity



Positronium Decay

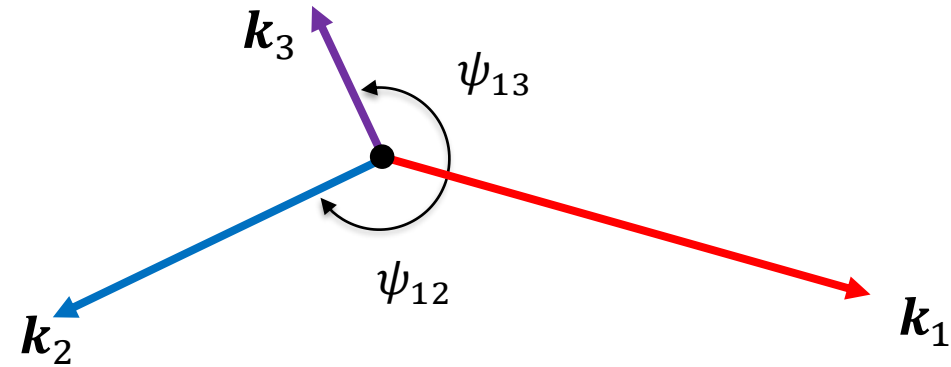
- $n\text{-}\gamma$ state has $C=(-1)^n$
- p-Ps must decay to even number of photons and o-Ps must decay to odd number
- each extra photon suppresses decay rate by α
- Leading order QED decay contribution:
 - matrix element for $e^+e^- \rightarrow n\text{-}\gamma$
 - treat wavefunction as momentum distribution of initial state
 - binding energy corrections are small
- Low momentum expansion, each higher orbital is suppressed by $1/2a \sim \alpha$

$$\begin{aligned} \langle n\gamma | \mathcal{T} | Ps, I \rangle &= \int d^3p \mathcal{M}(\mathbf{p}) \tilde{\Psi}_I(\mathbf{p}) \\ &= \mathcal{M}|_{\mathbf{p}=0} \Psi_I(\mathbf{x}=0) + (\nabla_p \mathcal{M}|_{\mathbf{p}=0}) \cdot (\nabla_x \Psi_I(\mathbf{x}=0)) + \dots \end{aligned}$$

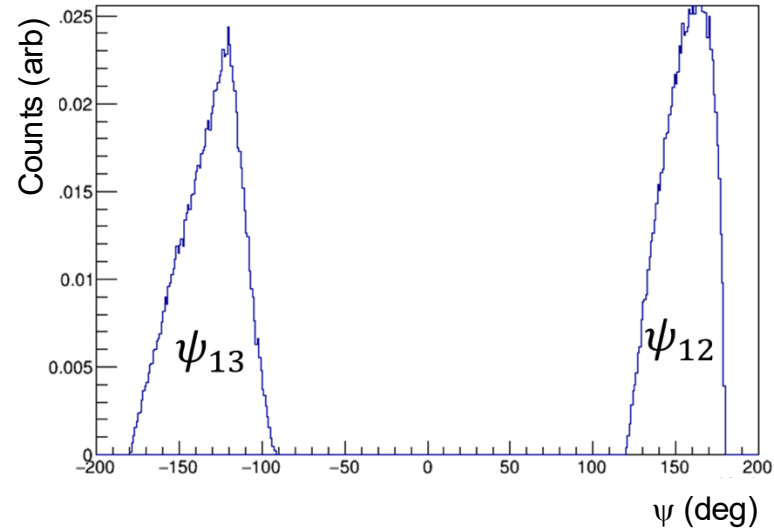
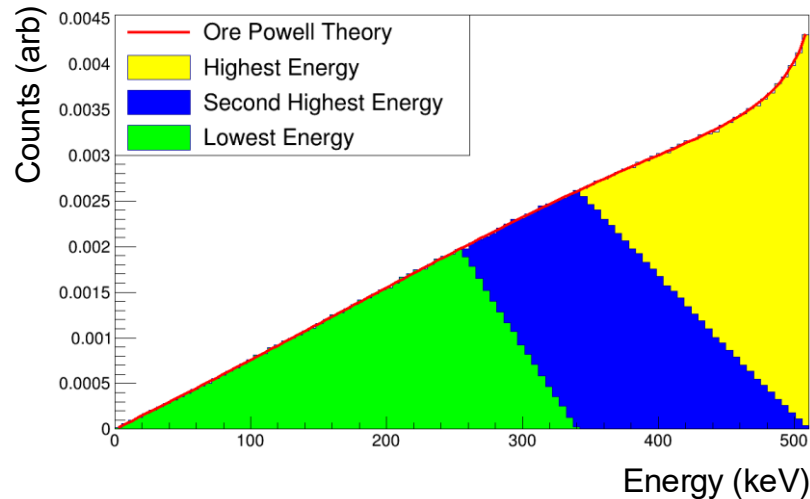


Kinematics of three photon decay

- Ore-Powell energy distribution for unpolarized o-Ps.
- Simulated angles in the plane, where the energies go as $|\mathbf{k}_1| > |\mathbf{k}_2| > |\mathbf{k}_3|$.
- Event can be fully reconstructed by only measuring two momenta.



A. Ore, J. L. Powell, Phys. Rev 75, 1696 (1949)



Three photon state

- We do not measure photon polarizations
- Event is characterized by 2 momenta and the normal to the decay plane

$$\mathbf{n} = \mathbf{k}_1 \times \mathbf{k}_2$$

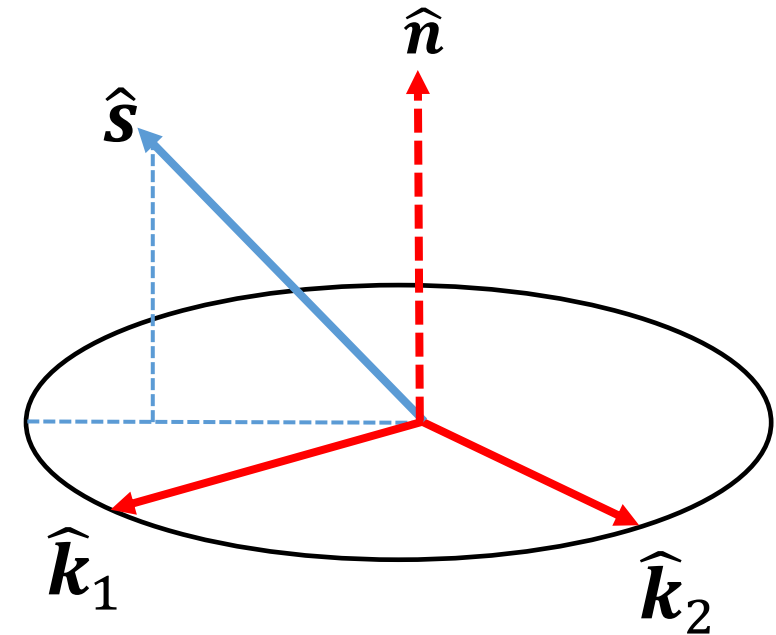
- Under parity:

$$\bullet \mathbf{s} \rightarrow \mathbf{s}, \quad \mathbf{k}_a \rightarrow -\mathbf{k}_a, \quad \mathbf{n} \rightarrow \mathbf{n}$$

- Parity odd correlation in the decay products would require combined CP violation

- CP-violation can induce a term that goes as:

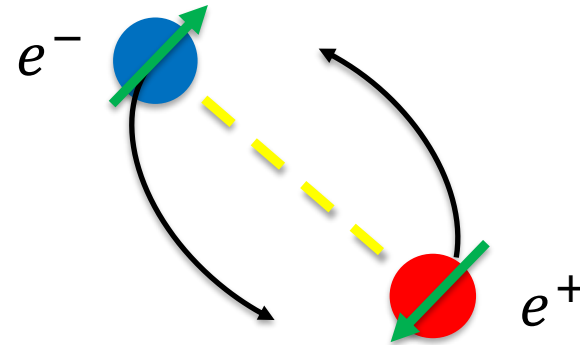
$$C_{CP}(\mathbf{s} \cdot \mathbf{k}_1)[\mathbf{s} \cdot \hat{\mathbf{n}}]$$



Positronium in a magnetic field

- Tensor polarization goes as:

- $P_{zz} = N_{+1} - 2N_0 + N_{-1} \rightarrow$ “alignment”



$$|S = 1, m = 1\rangle = |\uparrow\uparrow\rangle$$

$$|S = 1, m = 0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

$$|S = 1, m = -1\rangle = |\downarrow\downarrow\rangle$$

$$|S = 0, m = 0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

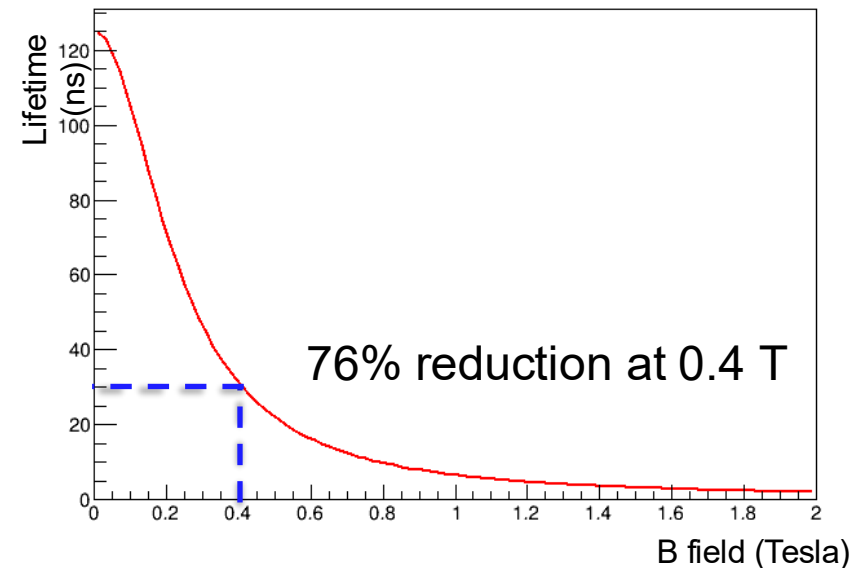
- Electron and positron have **opposite magnetic moments**

- B-field mixes:

- (s=0, m=0) – 125 **ps** lifetime

- (s=1, m=0) – 142 **ns** lifetime

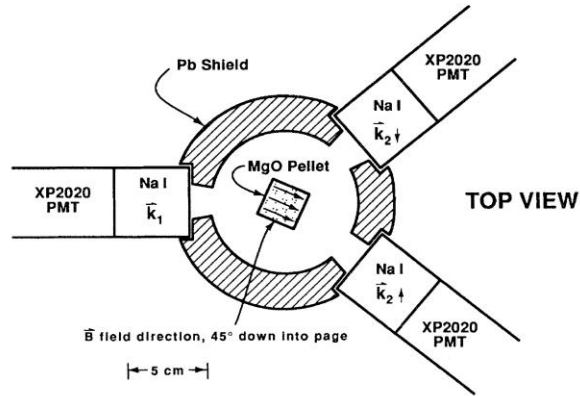
- Dramatic quenching of m=0 lifetime**



Previous measurements

University of Michigan (1991)

M. Skalsey and J. V. House, Phys. Rev. Lett. 67, 1993 (1991)



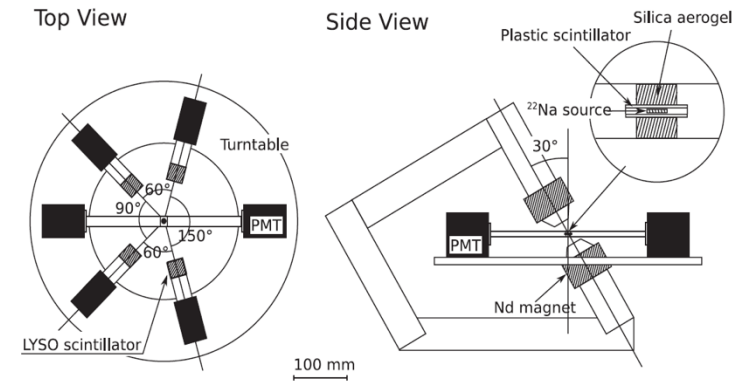
- Use permanent magnet
- Measure coincident γ ,
 - Dedicated \mathbf{k}_1 detector, two different \mathbf{k}_2 detectors
- Search for a term that goes as

$$C_{cp} \hat{\mathbf{k}}_{1z} (\hat{\mathbf{k}}_1 \times \hat{\mathbf{k}}_2)_z$$

$$C_{cp} = -0.0056 \pm 0.0154$$

University of Tokyo (2010)

T. Yamazaki, et. Al. Phys. Rev. Lett. **104**, 083401 (2010)



- Equivalent to 2 Michigan setups
- Detectors on turntable that rotates setup
- Searched for $\sin(\phi)$ dependence to counts
- Collected data for 6 months, were statistically limited

$$C_{cp} = 0.0013 \pm 0.0021 \text{ (stat)} \pm 0.0006 \text{ (syst)}$$

QED 3- γ phenomenology

■ Angular momentum 1 positronium, general state is 3x3 density matrix:

- trace = 1
- 3 vector components (s_k)
- 5 traceless symmetric tensor components (s_{ij})

Bernreuther, W., *et al.* *Z. Phys. C*, **41**, 143–158 (1988).

$$\rho_{ij} = \frac{1}{3} \delta_{ij} + \frac{1}{2i} \epsilon_{ijk} s_k - s_{ij}$$

QED 3- γ phenomenology

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$$\rho_{ij} = \frac{1}{3} \delta_{ij} + \frac{1}{2i} \epsilon_{ijk} s_k - s_{ij}$$

$$R_{ij}(\mathbf{k}_1, \mathbf{k}_2) = \delta_{ij} a^{QED}(\omega_1, \omega_2) + C_{ij}^{QED}(\mathbf{k}_1, \mathbf{k}_2)$$

- Angular momentum 1 positronium, general state is 3x3 density matrix:
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- Decay matrix is also 3x3 matrix.

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$$R_{ij}(\mathbf{k}_1, \mathbf{k}_2) = \delta_{ij} a^{QED}(\omega_1, \omega_2) + C_{ij}^{QED}(\mathbf{k}_1, \mathbf{k}_2)$$

$$C_{ij}^{QED}(\mathbf{k}_1, \mathbf{k}_2) = \left(k_{1i} k_{1j} - \frac{1}{3} \delta_{ij} \right) c_1(\omega_1, \omega_2) \\ + \left(k_{2i} k_{2j} - \frac{1}{3} \delta_{ij} \right) c_2(\omega_1, \omega_2) \\ + \left(k_{1i} k_{2j} + k_{2i} k_{1j} - \frac{2}{3} (\mathbf{k}_1 \cdot \mathbf{k}_2) \delta_{ij} \right) c_3(\omega_1, \omega_2)$$

$$N(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \text{Tr}(\rho_{ij} R_{ij}) \\ = a^{QED}(\omega_1, \omega_2) + s_{ij} C_{ij}^{QED}(\mathbf{k}_1, \mathbf{k}_2)$$

- Angular momentum 1 positronium, general state is 3x3 density matrix:
 - trace = 1
 - 3 vector components (s_k)
 - 5 traceless symmetric tensor components (s_{ij})
- Decay matrix is also 3x3 matrix.
 - Tensor decomposition gives 4 parity even terms in QED
 - $a^{QED}(\omega_1, \omega_2)$ is QED Ore-Powell distribution
 - $c_i(\omega_1, \omega_2)$ are second rank anisotropies in the angular distribution
 - angular anisotropies are driven by tensor polarization of positronium state

General 3- γ phenomenology

Bernreuther, W., et al. *Z. Phys. C*, **41**, 143–158 (1988).

- General tensor decomposition reveals 5 further terms beyond QED prediction
- 3 vector terms:
 - 2 are parity violating
 - one is parity even but odd under time reversal
- 2 tensor terms
 - odd under parity

$$R_{ij}(\mathbf{k}_1, \mathbf{k}_2) = \delta_{ij}a(\omega_1, \omega_2) + \frac{1}{2i}\epsilon_{ijk}B_k(\mathbf{k}_1, \mathbf{k}_2) + C_{ij}(\mathbf{k}_1, \mathbf{k}_2)$$

$$B_i(\mathbf{k}_1, \mathbf{k}_2) = k_{1i}b_1(\omega_1, \omega_2) + k_{2i}b_2(\omega_1, \omega_2) + n_i b_3(\omega_1, \omega_2)$$

$$\delta C_{ij}(\mathbf{k}_1, \mathbf{k}_2) = (k_{1i}n_j + k_{1j}n_i)c_4(\omega_1, \omega_2) + (k_{2i}n_j + k_{2j}n_i)c_4(\omega_1, \omega_2)$$

$$\begin{aligned} N(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) &= \text{Tr}(\rho_{ij}R_{ij}) \\ &= a^{QED}(\omega_1, \omega_2) + s_{ij}C_{ij}^{QED}(\mathbf{k}_1, \mathbf{k}_2) \\ &\quad + \mathbf{s} \cdot \mathbf{B}(\mathbf{k}_1, \mathbf{k}_2) \\ &\quad + s_{ij}\delta C_{ij}(\mathbf{k}_1, \mathbf{k}_2) \end{aligned}$$

General angular distribution

Bernreuther, W., et al. *Z. Phys. C*, **41**, 143–158 (1988).

$$N \propto A^\Omega + P_{ij} \left(C_1^\Omega \hat{\mathbf{k}}_{1i} \hat{\mathbf{k}}_{1j} + C_2^\Omega \hat{\mathbf{k}}_{2i} \hat{\mathbf{k}}_{2j} + C_3^\Omega \hat{\mathbf{k}}_{1i} \hat{\mathbf{k}}_{2j} \right) \\ + \mathbf{s} \cdot \left(B_1^\Omega \hat{\mathbf{k}}_1 + B_2^\Omega \hat{\mathbf{k}}_2 + B_3^\Omega \hat{\mathbf{n}} \right) \\ + P_{ij} \left(C_4^\Omega \hat{\mathbf{k}}_{1i} \hat{\mathbf{n}}_j + C_5^\Omega \hat{\mathbf{k}}_{2i} \hat{\mathbf{n}}_j \right)$$

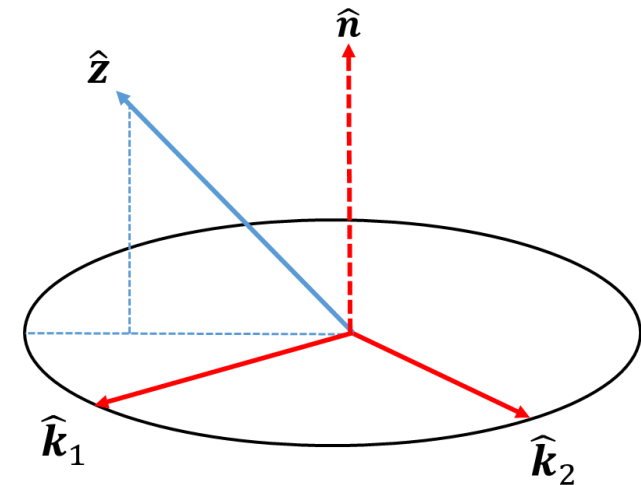
■ Summarizing:

- 3 P-even QED anisotropies
- 4 P-odd BSM anisotropies
- 1 "T-odd" BSM anisotropy
- All isotropies are characterized by form factors integrated over detector acceptances

■ We intend to measure $C_4^\Omega \hat{\mathbf{k}}_{1i} \hat{\mathbf{n}}_j + C_5^\Omega \hat{\mathbf{k}}_{2i} \hat{\mathbf{n}}_j$

- There are two terms that contribute
- Without a model exact comparisons between experiments cannot be performed

■ Previous experiments have searched for C_4^Ω and B_3^Ω , B_1^Ω and B_2^Ω have never been searched for.

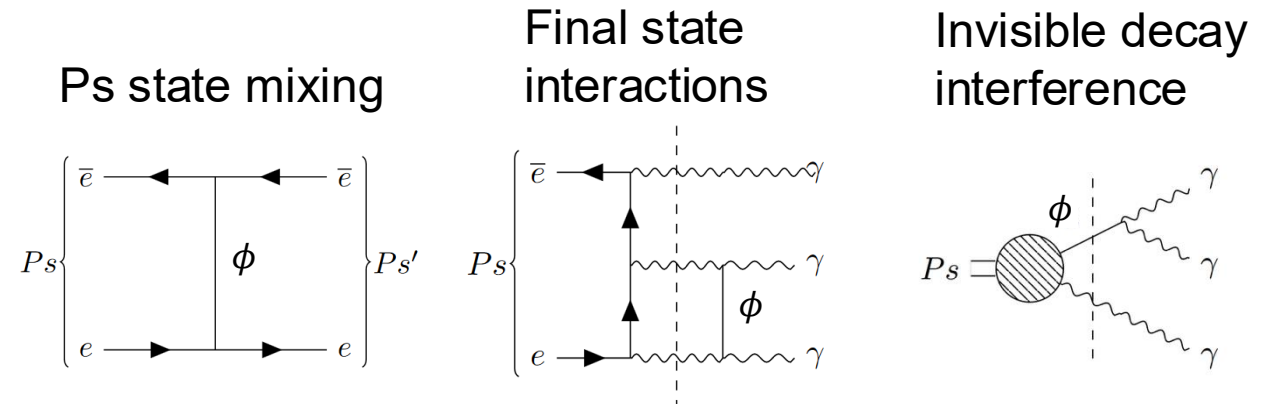


Clean CP-violation

Bernreuther, W., et al. *Z. Phys. C*, **41**, 143–158 (1988).

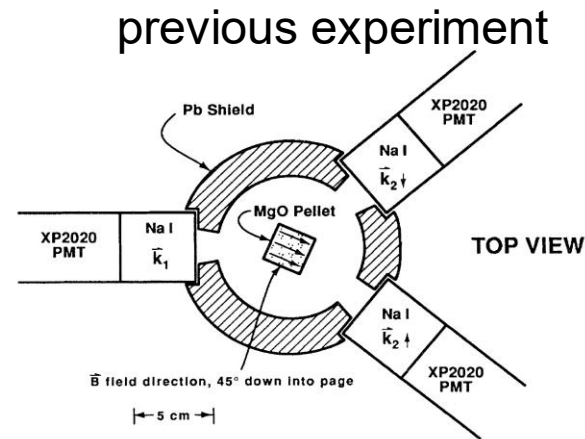
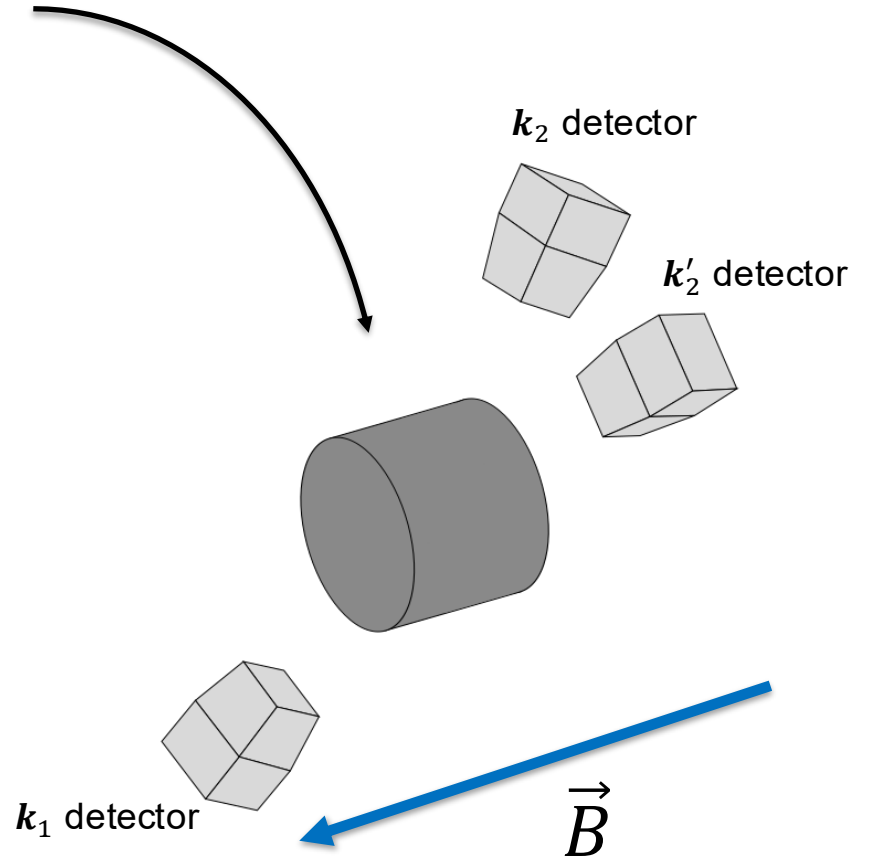
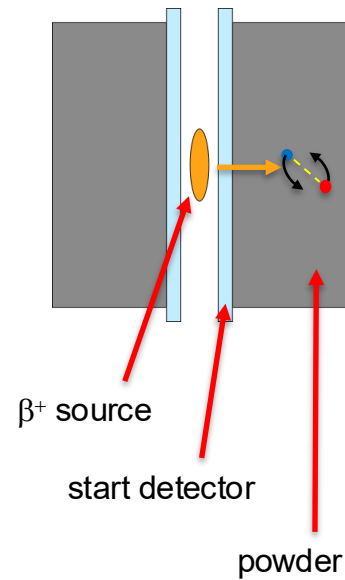
$$\begin{aligned}
 N \propto & A^\Omega + P_{ij} \left(C_1^\Omega \hat{\mathbf{k}}_{1i} \hat{\mathbf{k}}_{1j} + C_2^\Omega \hat{\mathbf{k}}_{2i} \hat{\mathbf{k}}_{2j} + C_3^\Omega \hat{\mathbf{k}}_{1i} \hat{\mathbf{k}}_{2j} \right) \\
 & + \mathbf{s} \cdot \left(B_1^\Omega \hat{\mathbf{k}}_1 + B_2^\Omega \hat{\mathbf{k}}_2 + B_3^\Omega \hat{\mathbf{n}} \right) \\
 & + P_{ij} \left(C_4^\Omega \hat{\mathbf{k}}_{1i} \hat{\mathbf{n}}_j + C_5^\Omega \hat{\mathbf{k}}_{2i} \hat{\mathbf{n}}_j \right)
 \end{aligned}$$

- CP-violation searches usually entail searching for T-odd correlations.
 - Equated with CP-violation through CPT
 - T-odd signatures can be mimicked by final state interactions
- CP-violation in o-Ps decay is **"clean"**
 - it cannot be mimicked by final state interactions or radiative corrections
- B_3^Ω has been interpreted as "CPT-violating" but it can be mimicked.
 - nonzero signal does not inherently indicate CPT violation as CPT-violation is not required to generate signal



Experiment outline

1. Form Positronium
2. Induce Tensor Polarization
 - Use FRIB Positron Polarimeter magnet
3. Measure decay event
4. CP-violation manifests as difference in coincidences:
 - Between pairs $(\mathbf{k}_1, \mathbf{k}_2)$ and $(\mathbf{k}_1, \mathbf{k}'_2)$

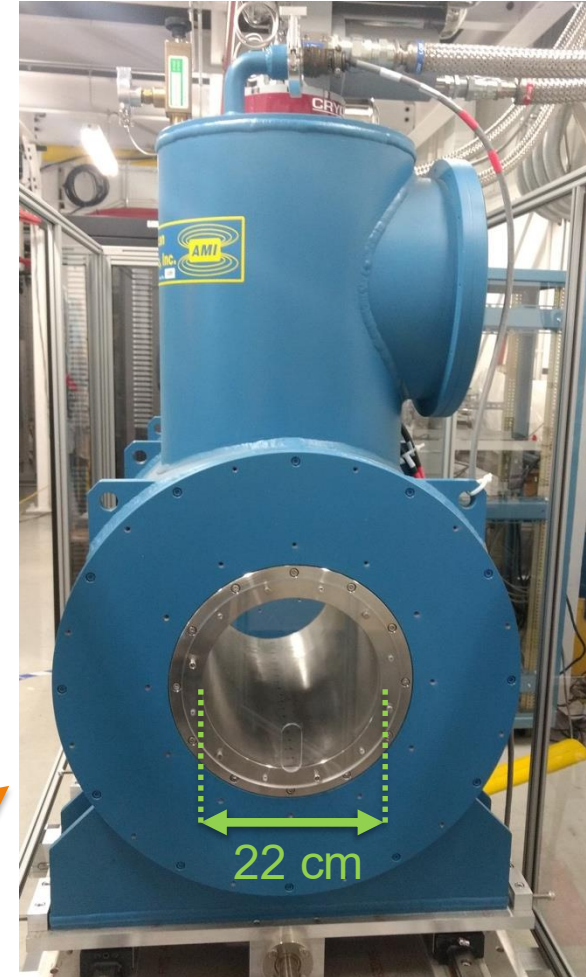
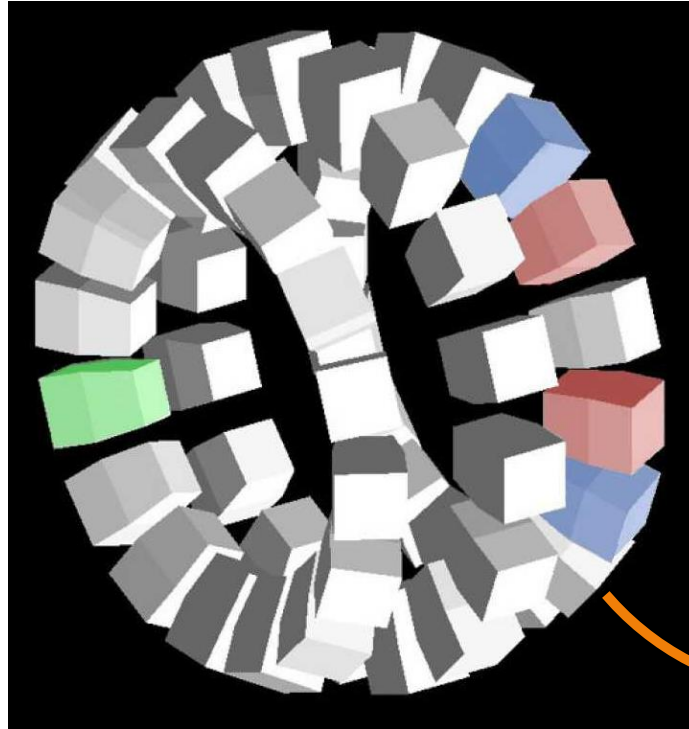


M. Skalsey and J. V. House, Phys. Rev. Lett. 67, 1993 (1991)

Experiment outline

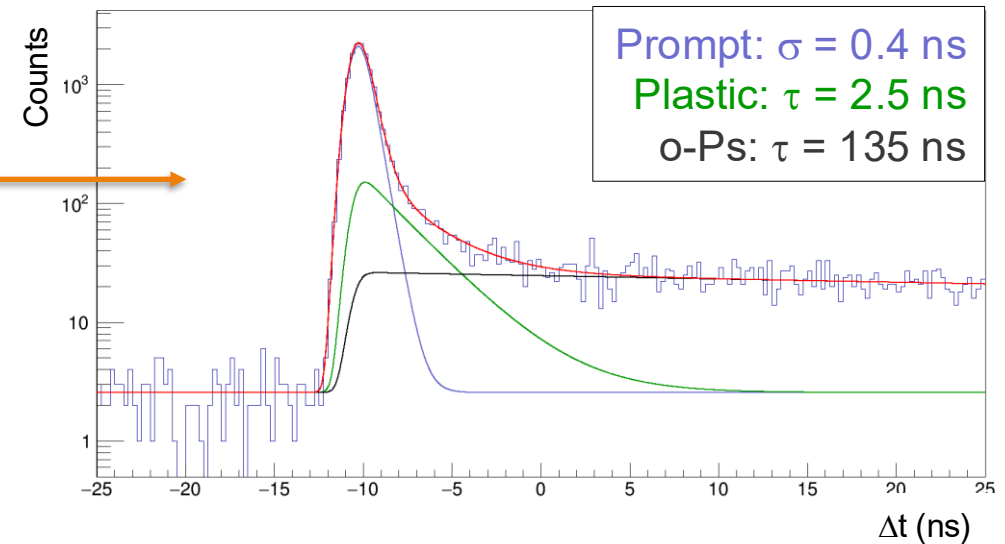
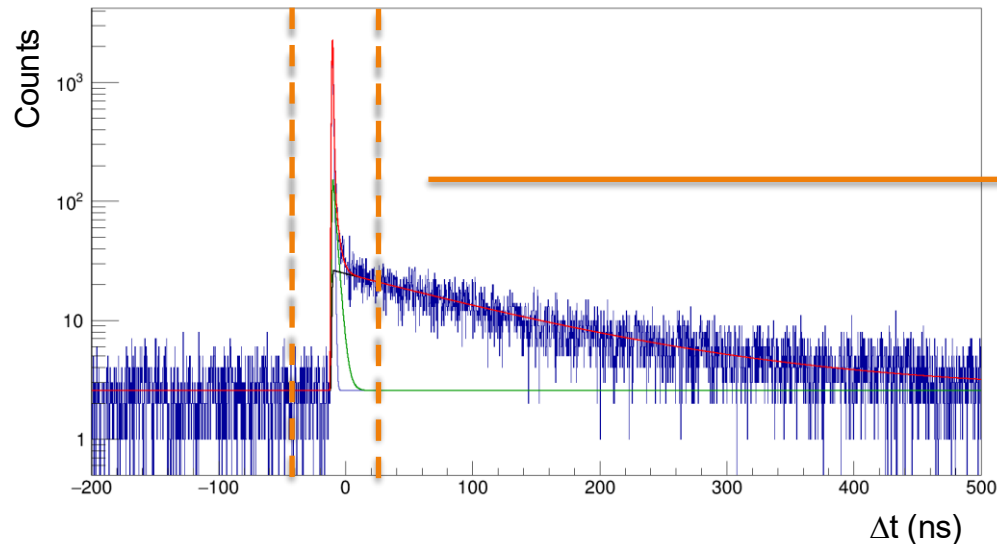
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Increase number of detectors in array to reach higher statistics



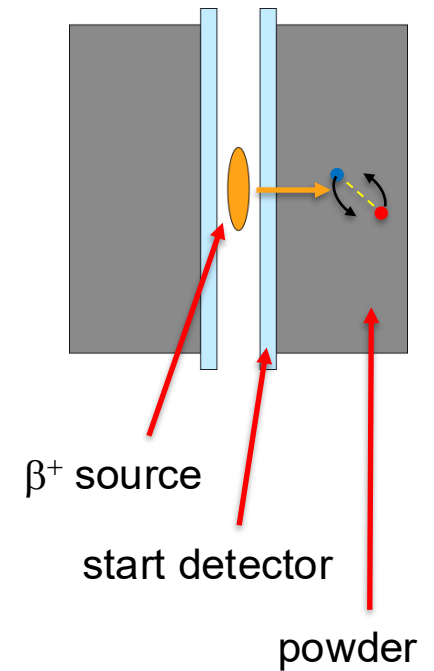
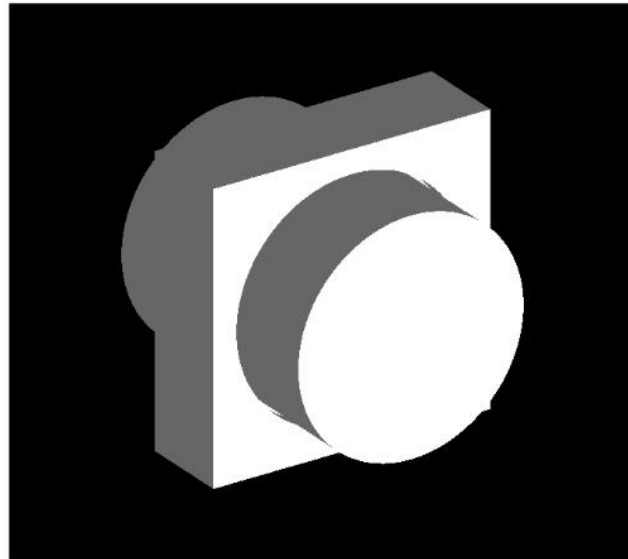
Positronium formation test-stand

- LaBr_3 start and stop detectors
- ^{22}Na source
 - 1275 keV γ for start signal
- In silica powder (~ 100 μm) we see:
 - **formation fraction of 40%**
 - **lifetime 135 ns** – when pumped with roughing pump



Start detector

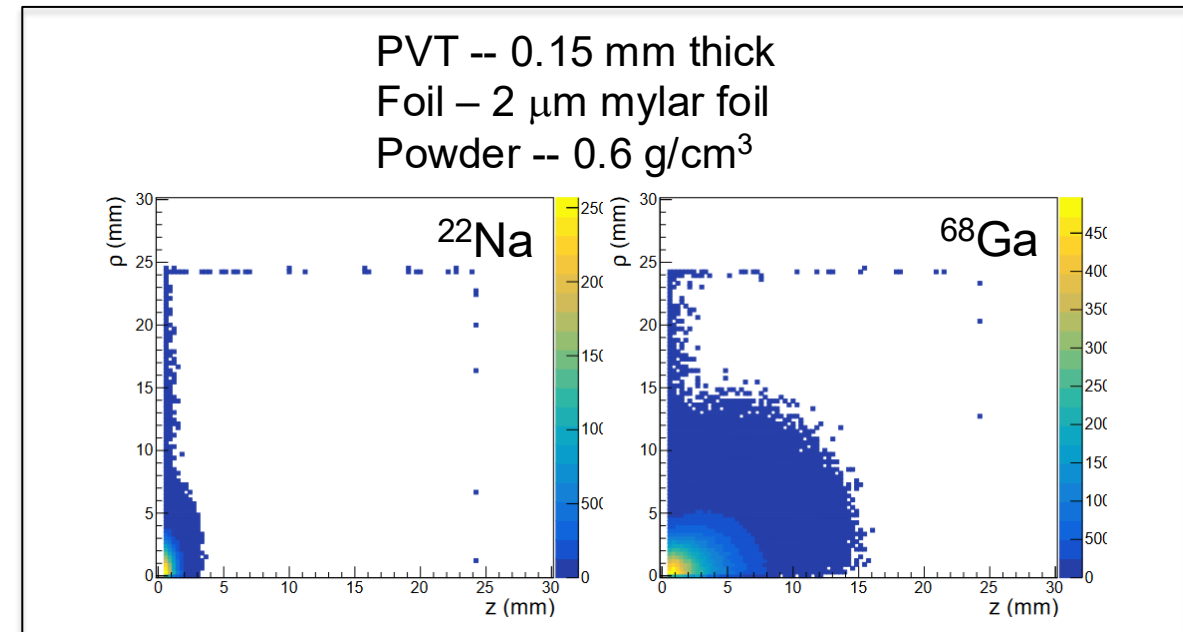
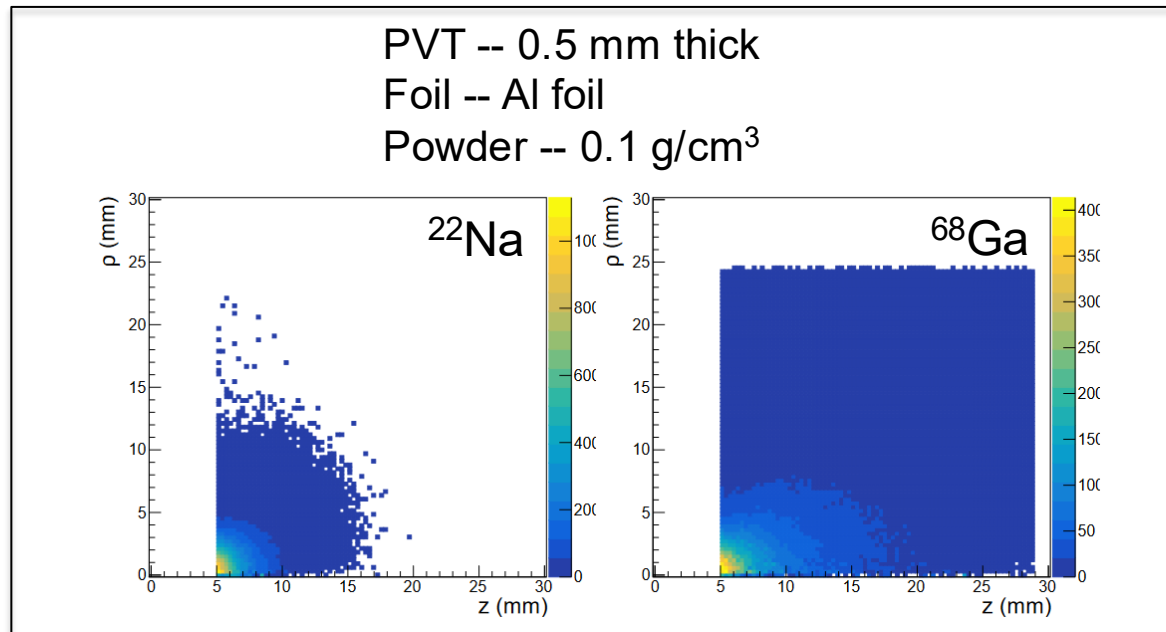
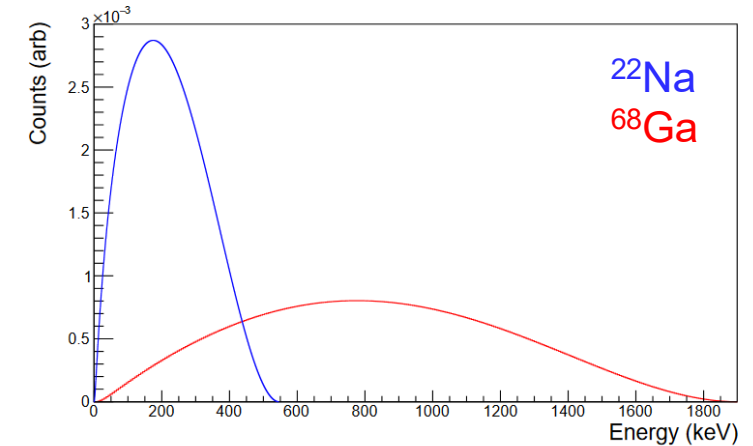
- Test stand start detector:
 - 0.5 mm thick plastic (PVT) scintillator with foil covering both sides
 - Plexiglass lightguide to connect to SiPM
- All β that reach powder must traverse start detector



Positron stop distribution

Stopping position depends on:

- Energy of source
- Thickness of start detector
- Density of powder
- Size of β source

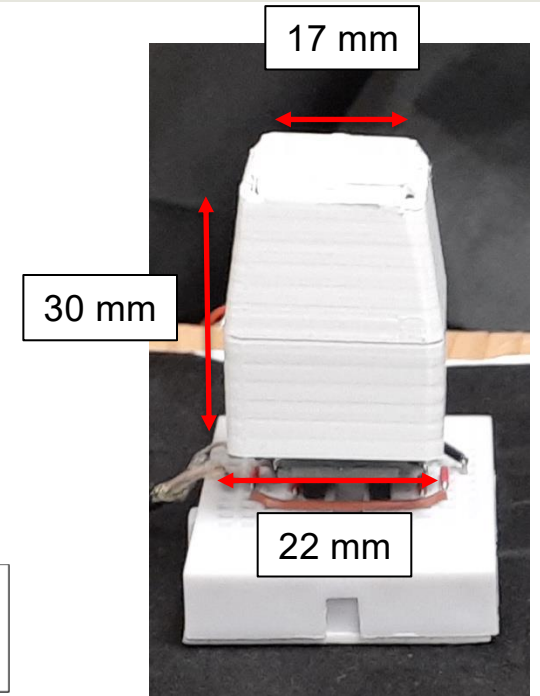
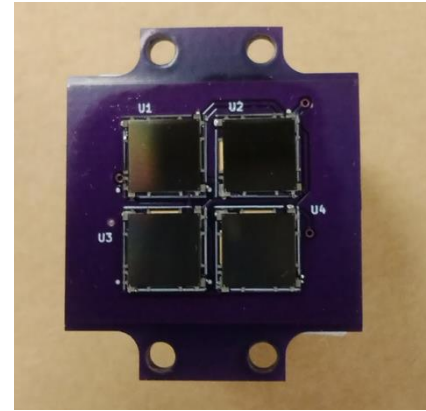


David-Michael Peterson (MSU)

Scintillation Detectors

LYSO crystals

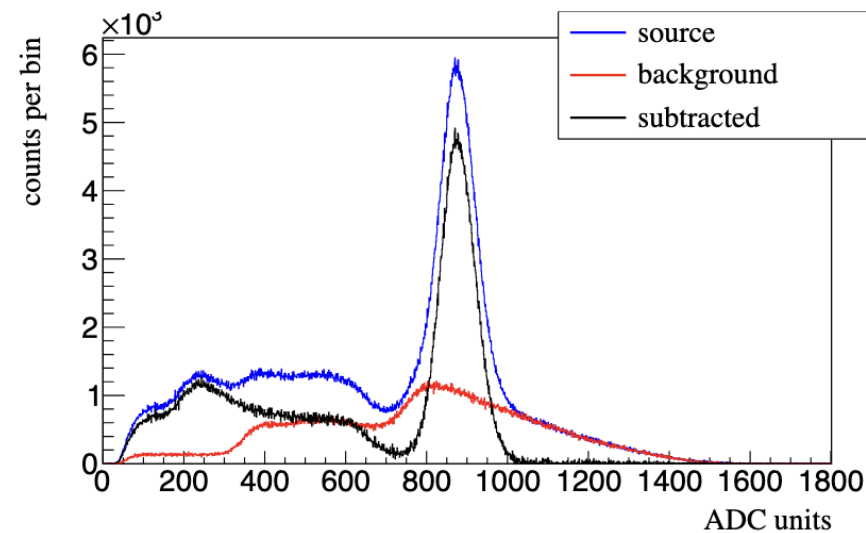
- Cerium doped – light emitters
- 45 ns decay time
- 10% FWHM at 662 keV
- radioactive within our energy range



Silicon Photomultiplier (SiPM)

- Small compared to photomultiplier tube (PMT)
- Run at much lower voltage, ~ 27 V
- Impervious to magnetic field

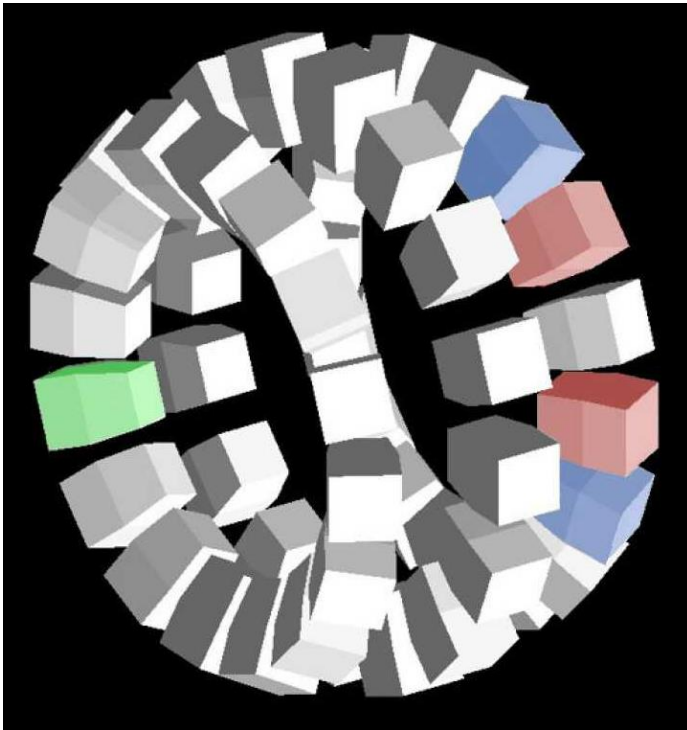
We can place many of these small detectors directly in our electromagnet



Gamma array and Monte Carlo simulations

■ Design:

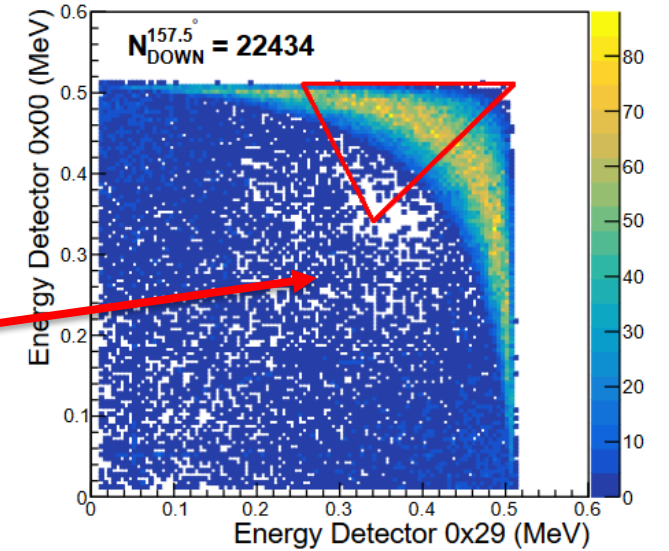
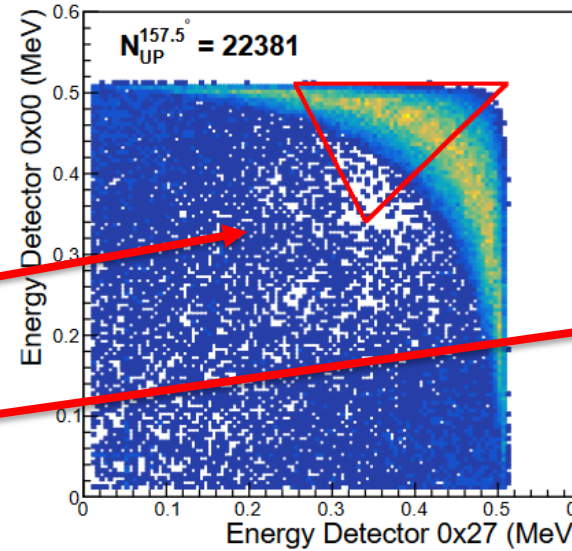
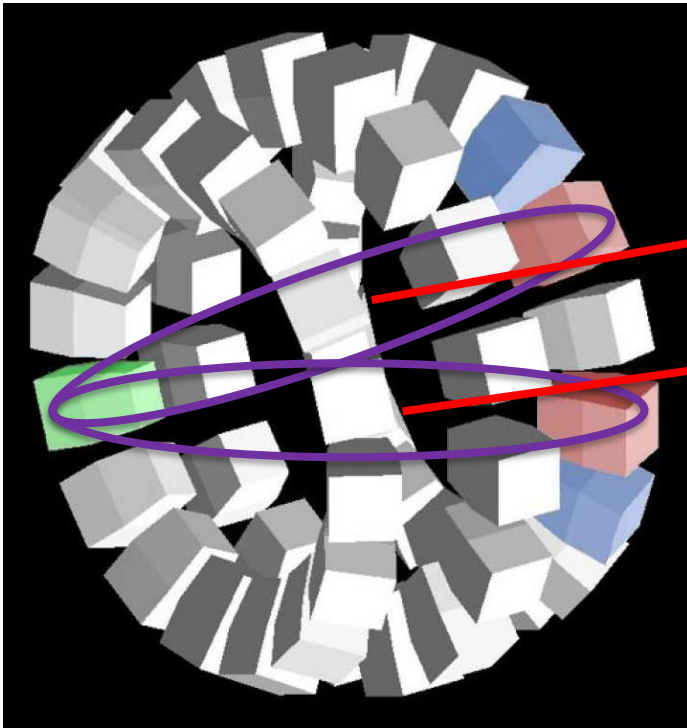
- Full array must fit within warm bore of magnet
- Three rings of 16 detectors each
- Form combinations between rings



Gamma array and Monte Carlo simulations

■ Design:

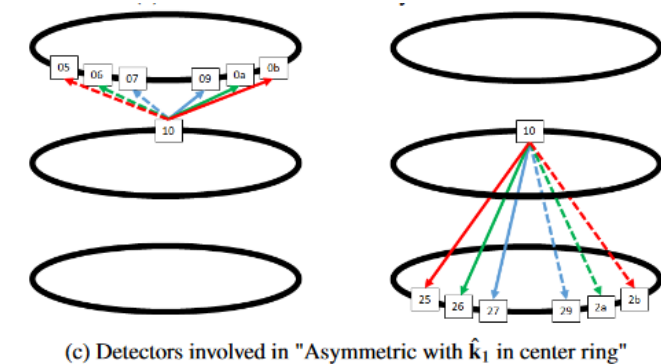
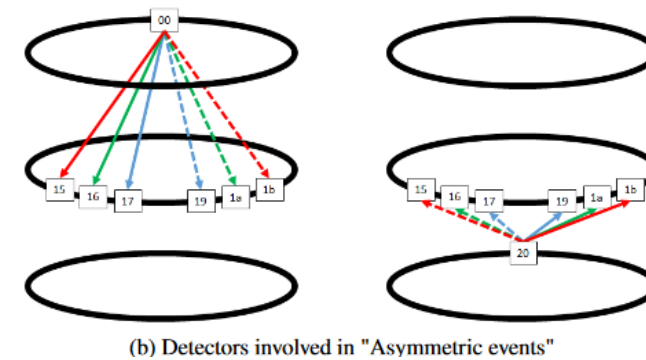
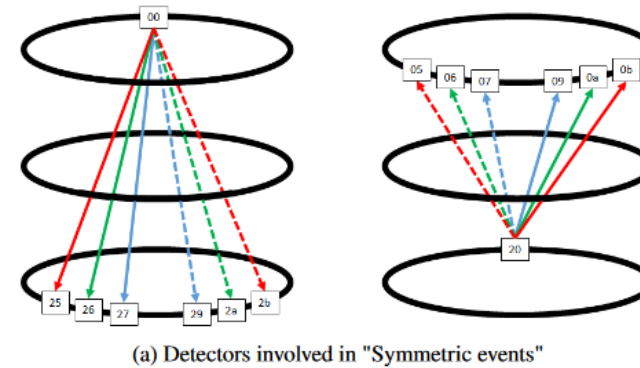
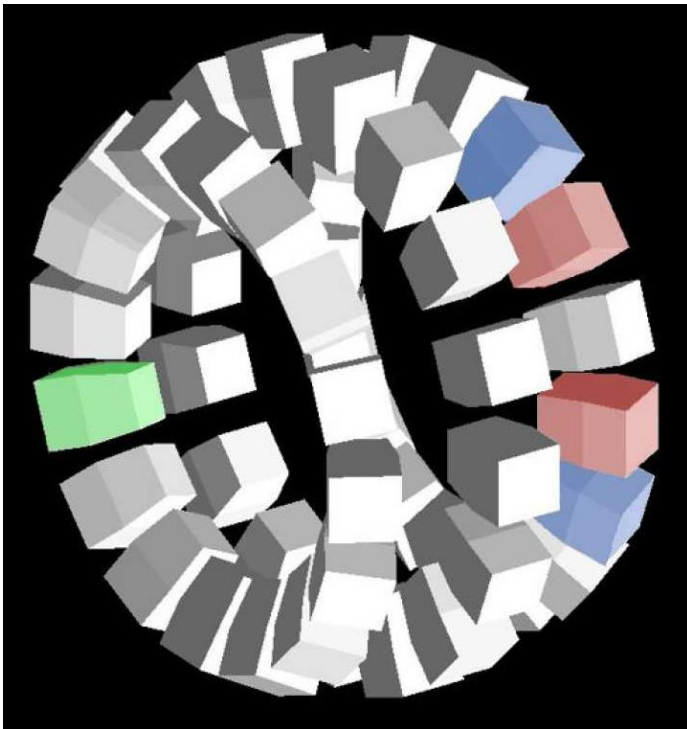
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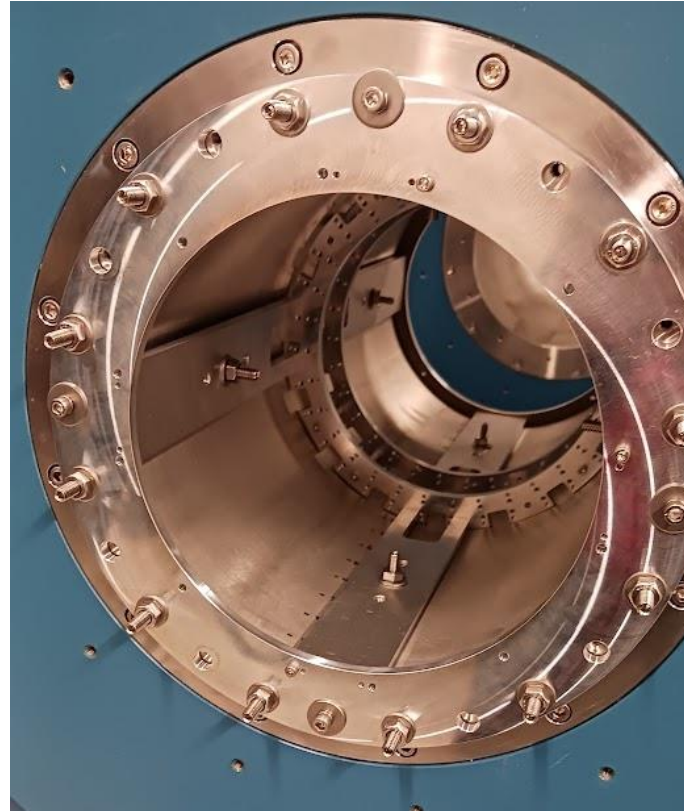
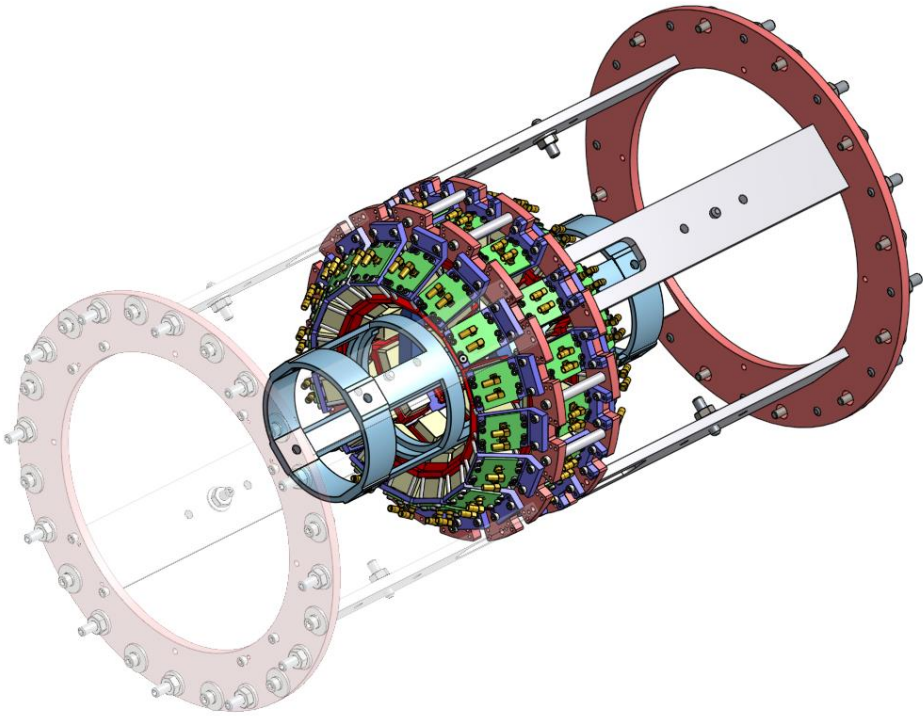
■ Design:

- Full array must fit within warm bore of magnet
- Three rings of 16 detectors each
- Form combinations between rings
- About 30% solid angle coverage



Full array design and construction

- FRIB engineers designed and manufactured support structure
- Holds detector array within warm bore of magnet



Craig Snow (FRIB), David-Michael Peterson, Vimbainashe Chado (MSU)

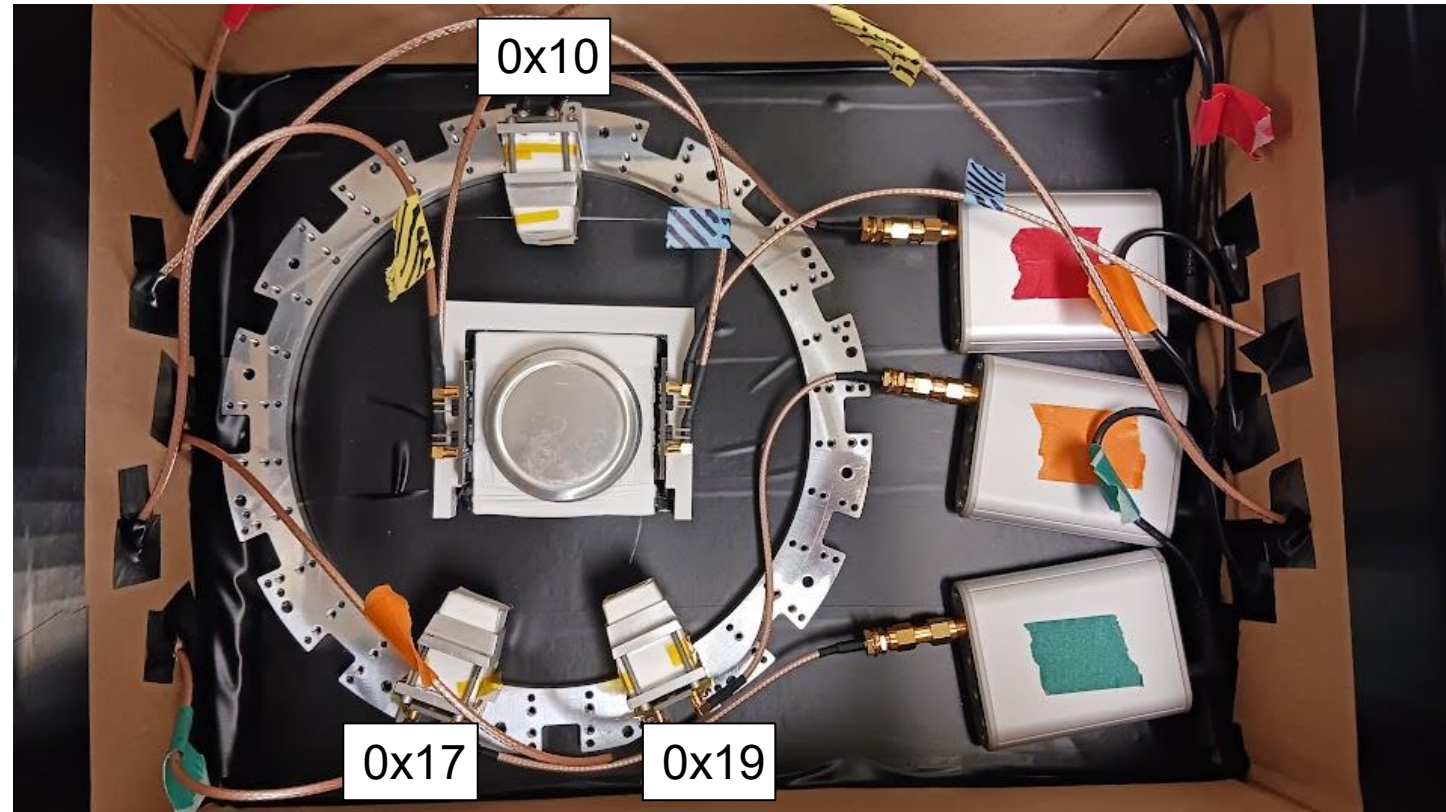
Single ring prototype

■ Constructed 3-crystal demonstrator:

- Two pairs of symmetrically placed detectors
- Start detector + powder for Ps formation

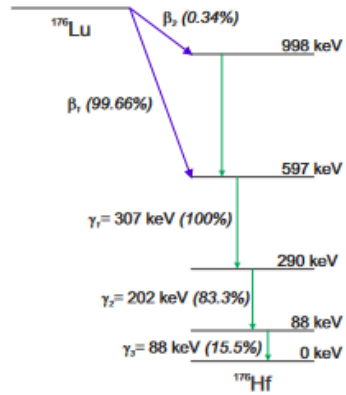
■ We can now study different coincidences:

- 2 hits in LYSO crystals
- 1 hit in LYSO, 1 hit in start
- 2 hits in LYSO, 1 hit in start

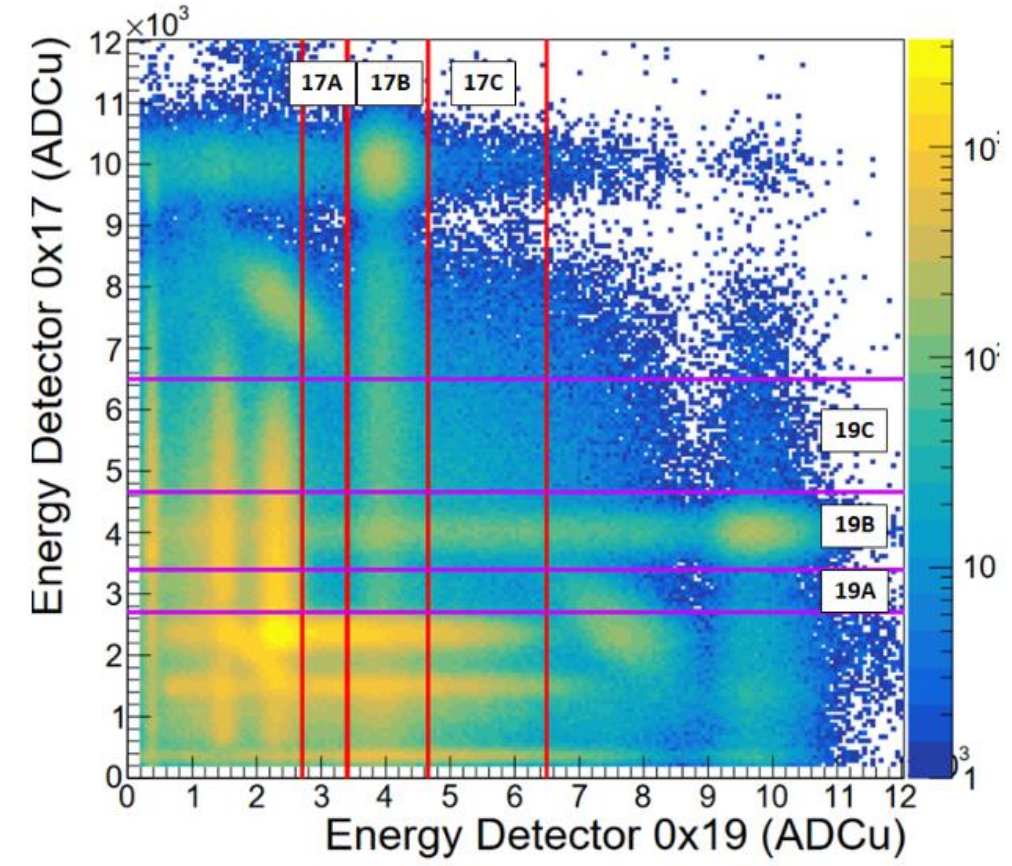
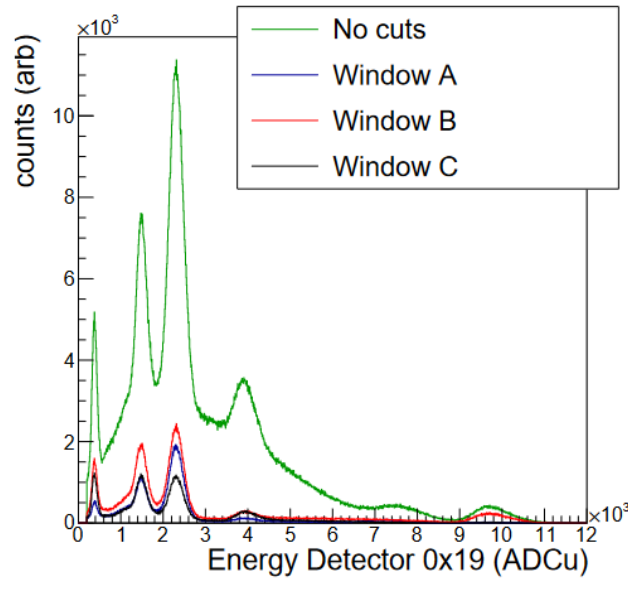
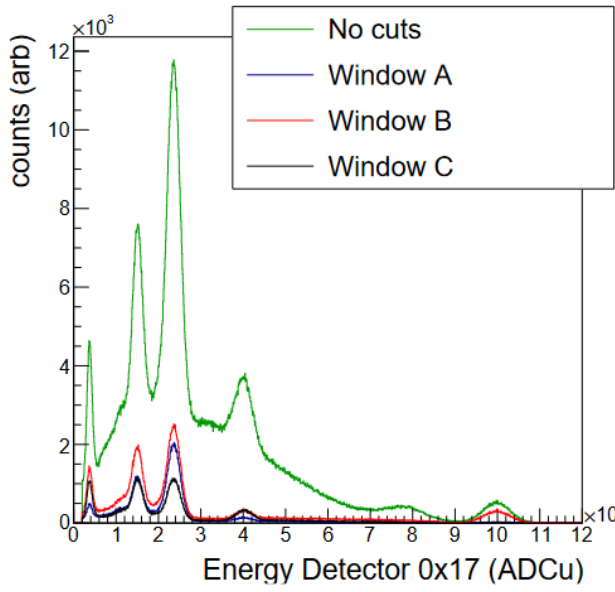


Internal coincidences

Alva-Sánchez, *et al. Sci Rep* 8, 17310 (2018).



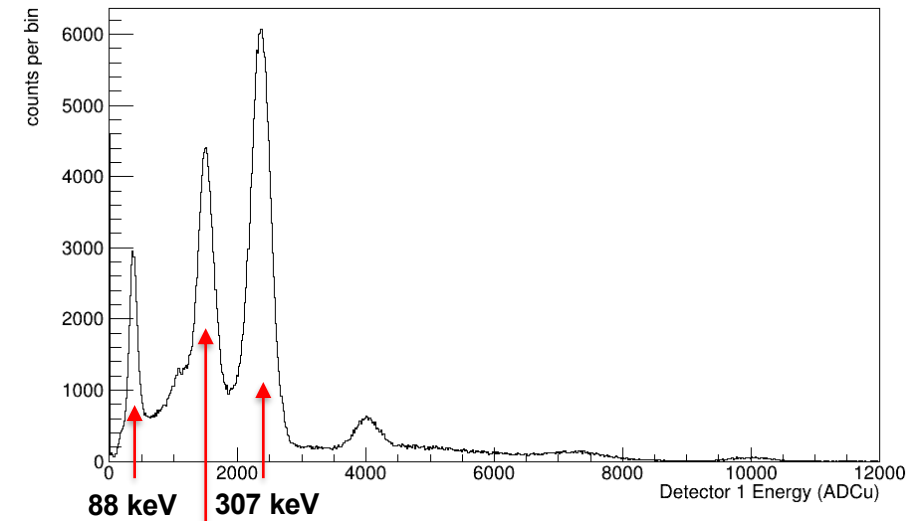
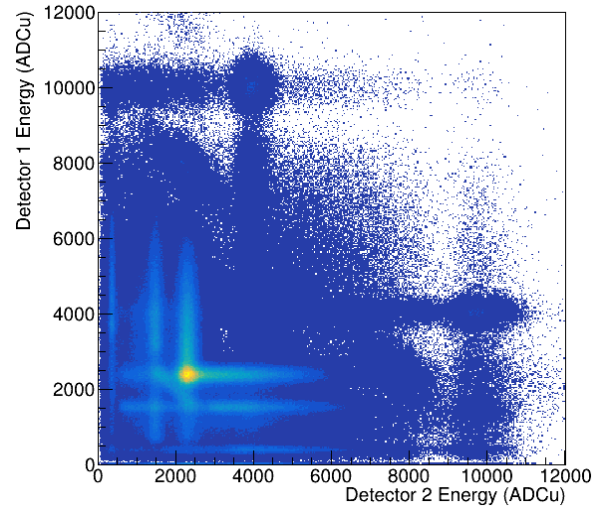
- Require only 2 hits
- LYSO-LYSO spectrum shows clear structure
- 511 keV – 1275 keV from ^{22}Na
- 88, 202, 307 keV from internal radioactivity



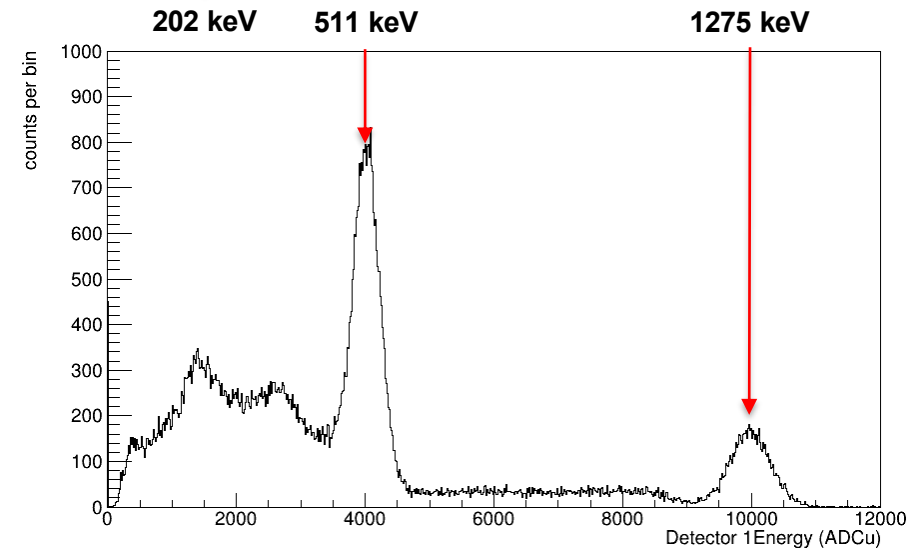
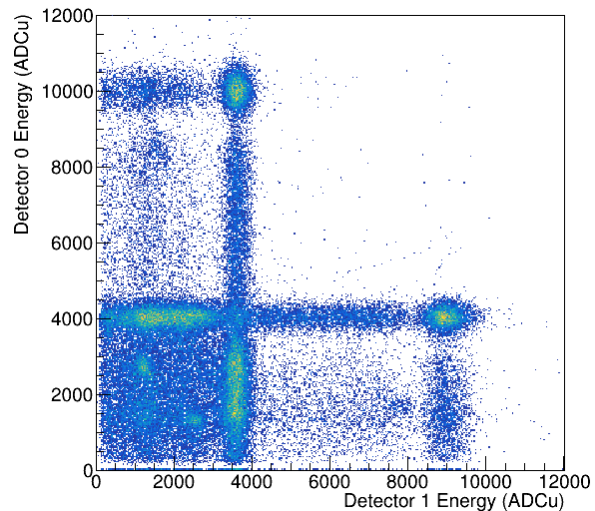
Single ring prototype

- Requiring coincidence with start detector removes internal coincidence
- Routinely monitor the gain and thresholds using the internal radioactivity
- 1275 keV peak is for the ^{22}Na source specifically

Require 2 hits

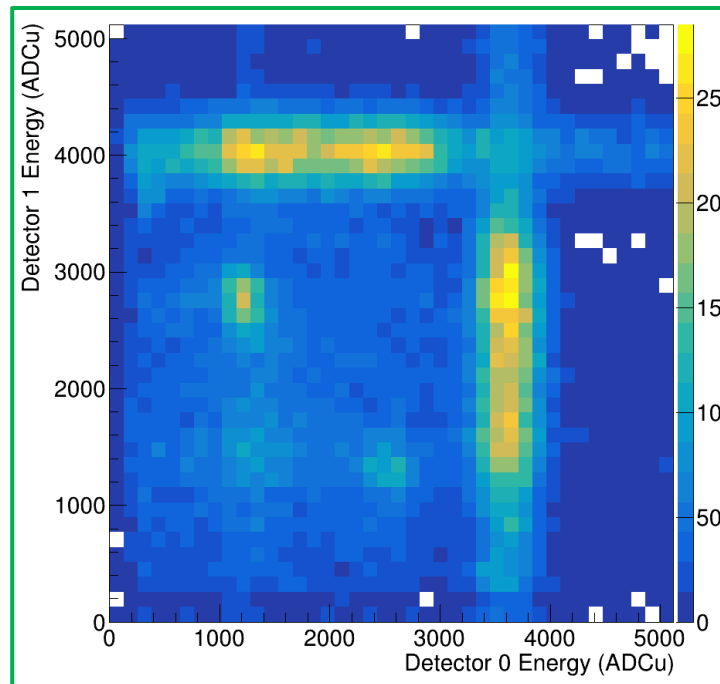
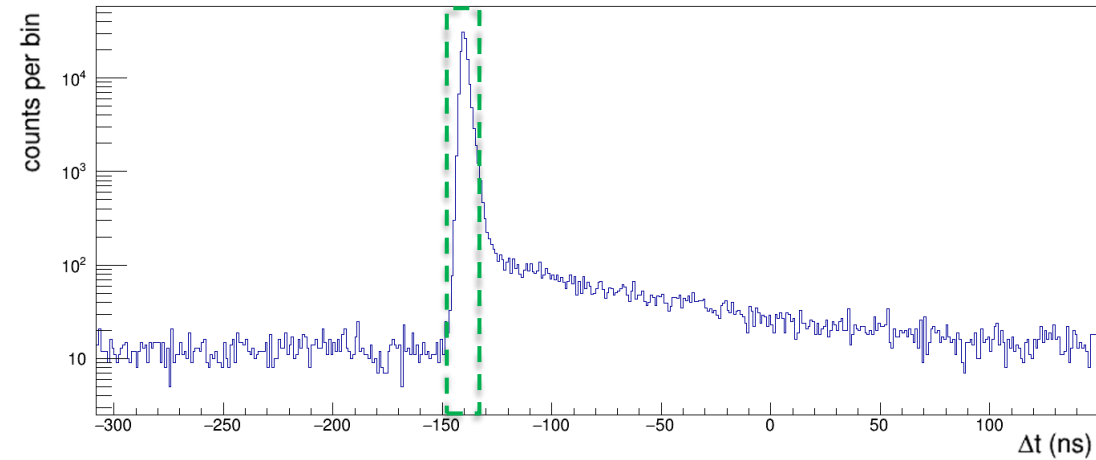


Require 3 hits (one in plastic)



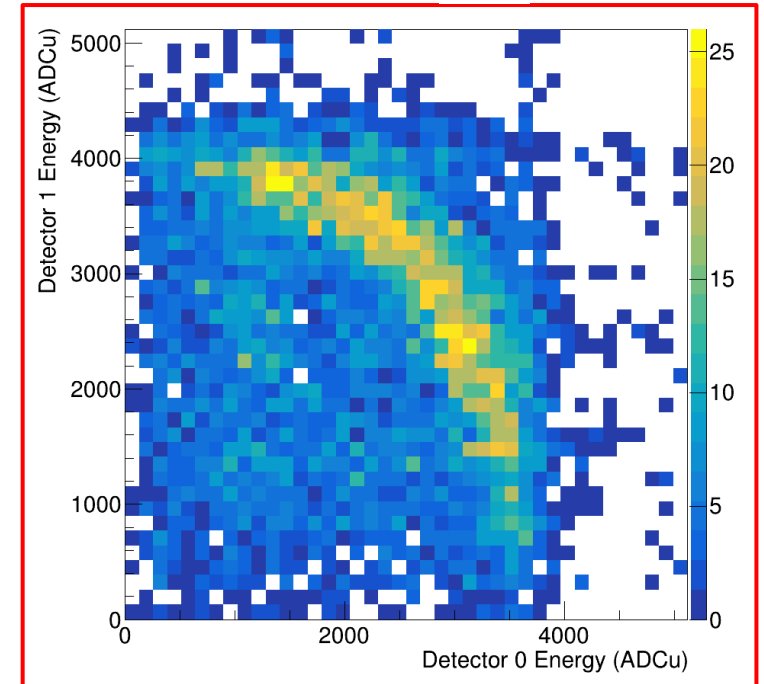
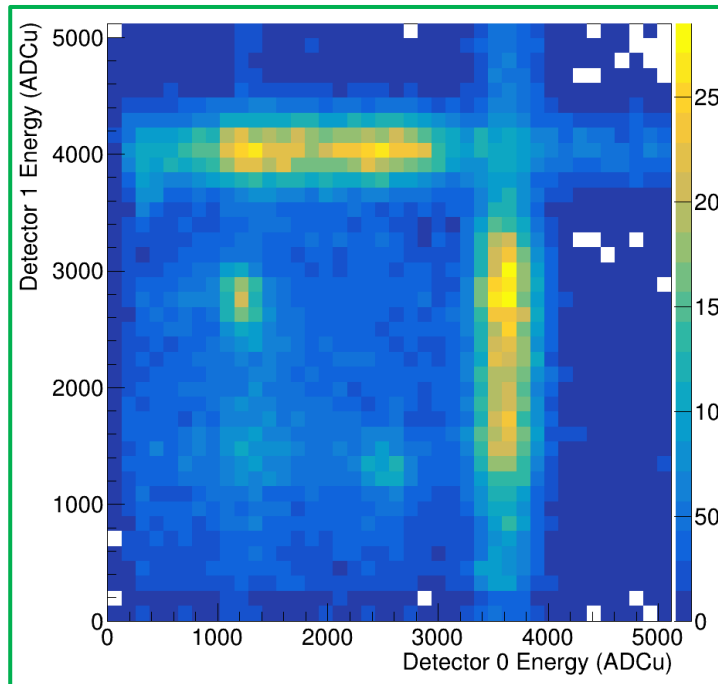
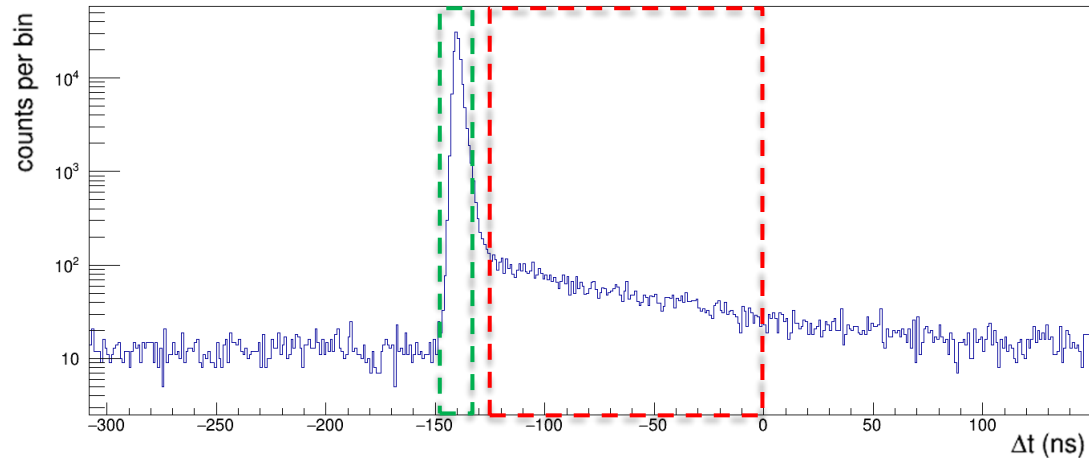
Measured 3- γ distribution

- We can build a clean time spectrum with plastic + LYSO detectors
- Energy distribution can be cleanly separated with timing cuts
 - Peak events are mostly 1275 keV + 511 keV γ -coincidences



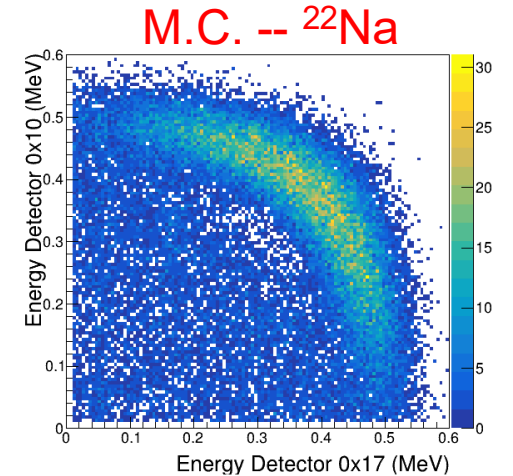
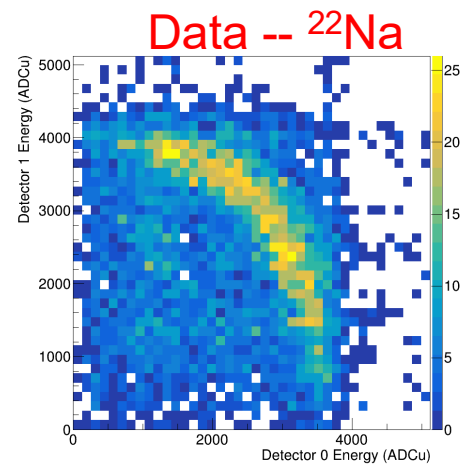
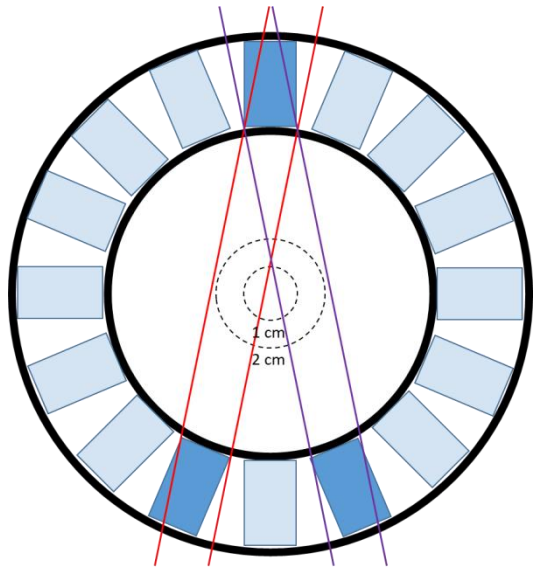
Measured 3- γ distribution

- We can build a clean time spectrum with plastic + LYSO detectors
- Energy distribution can be cleanly separated with timing cuts
 - Peak events are mostly 1275 keV + 511 keV γ -coincidences
 - **Long lifetime events are dominated by 3- γ decay**

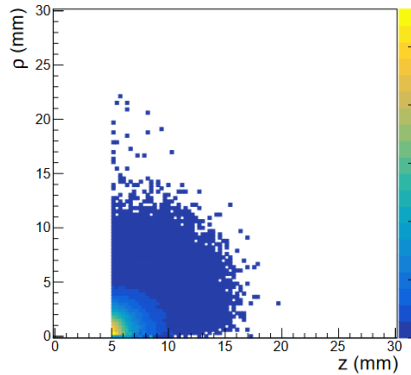


Data versus Monte-Carlo

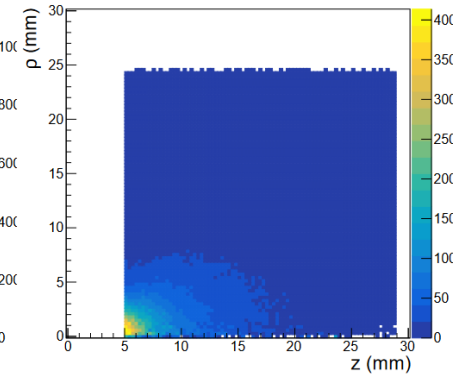
- Simulation can reproduce the main qualitative features of the distribution
- Little to no 2γ events for ^{22}Na , lots of ^{68}Ga



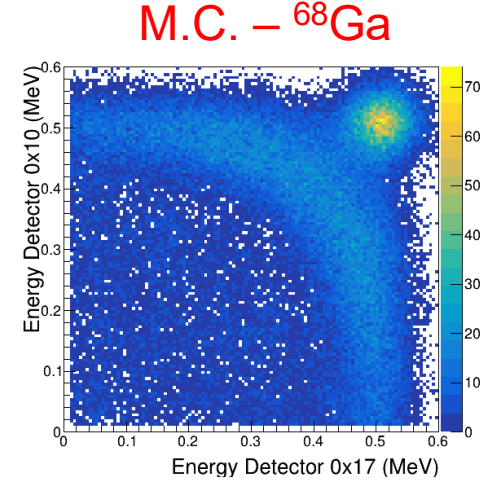
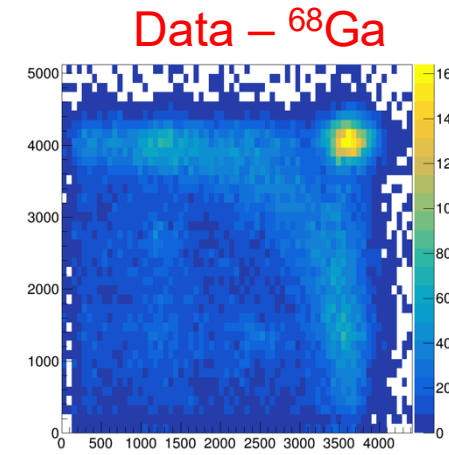
M.C. -- Stopping position



(a) ^{22}Na



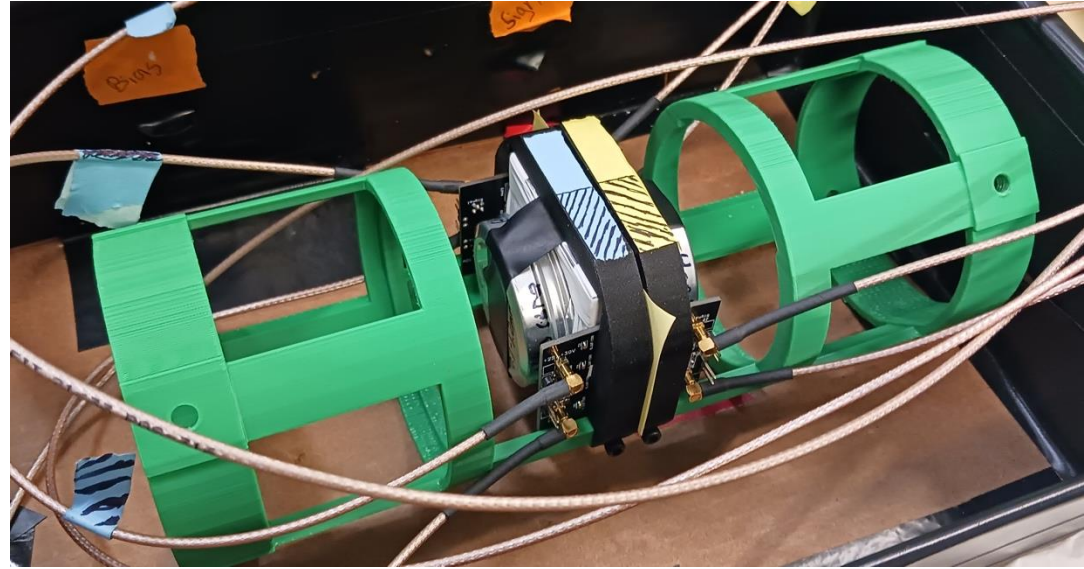
(b) ^{68}Ga



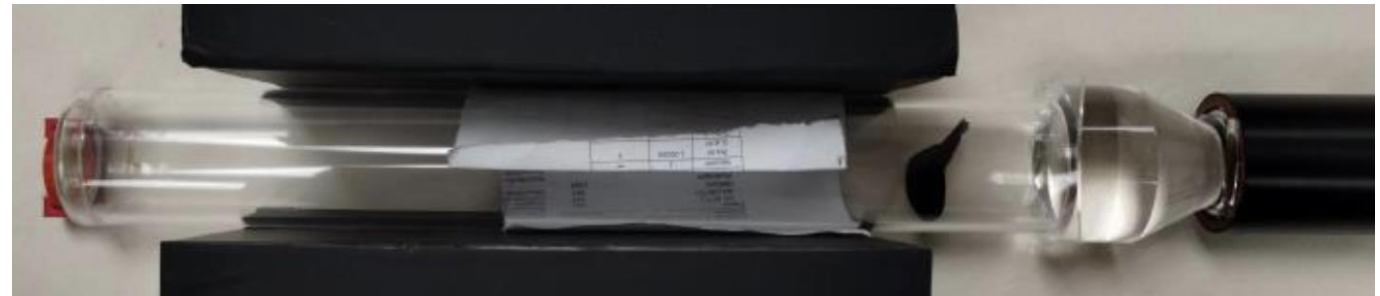
Start detector

- Prototype start detector for commissioning featuring 3D printed support structure
- Work underway on final start module
 - 0.15 mm thick PVT
 - Aluminized mylar coating
 - lightguide to collect light from scintillator
 - PMTs outside of magnetic field
- Final design will have:
 - higher survival fraction for positrons
 - faster readout
 - less material in center of array
 - cylindrically symmetric

current inner module for testing

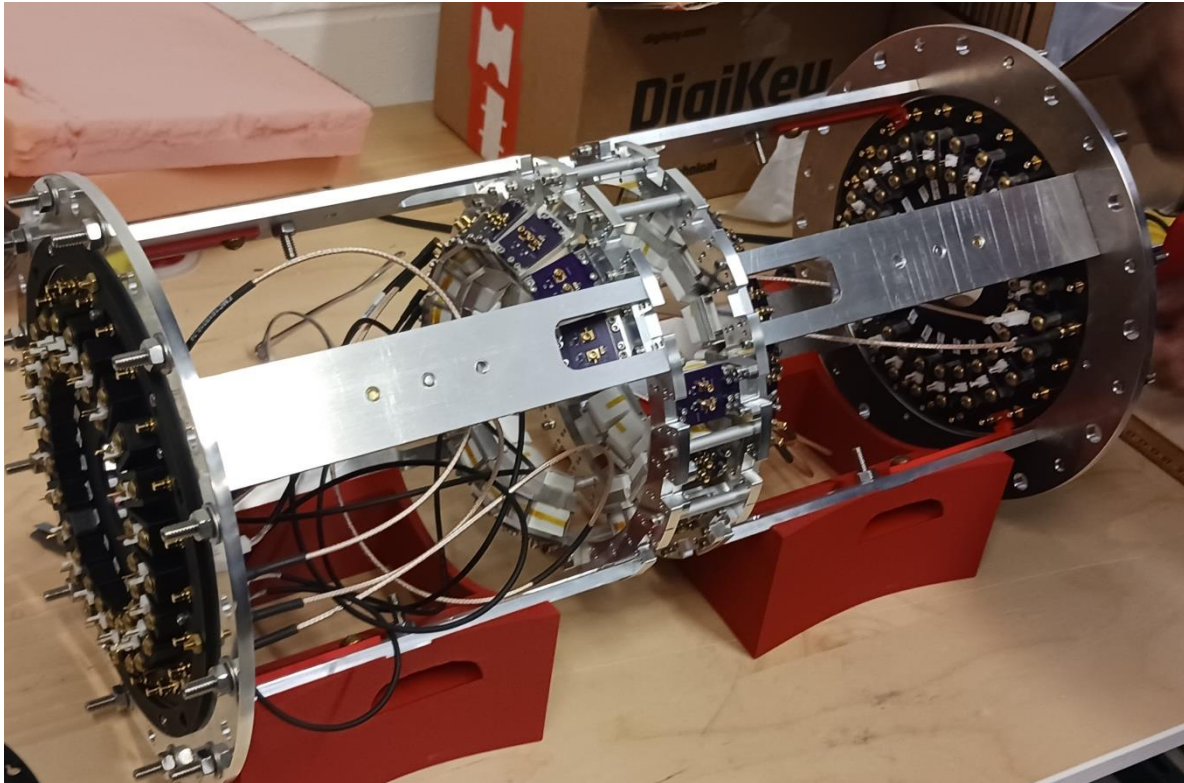


Prototype of final start detector design

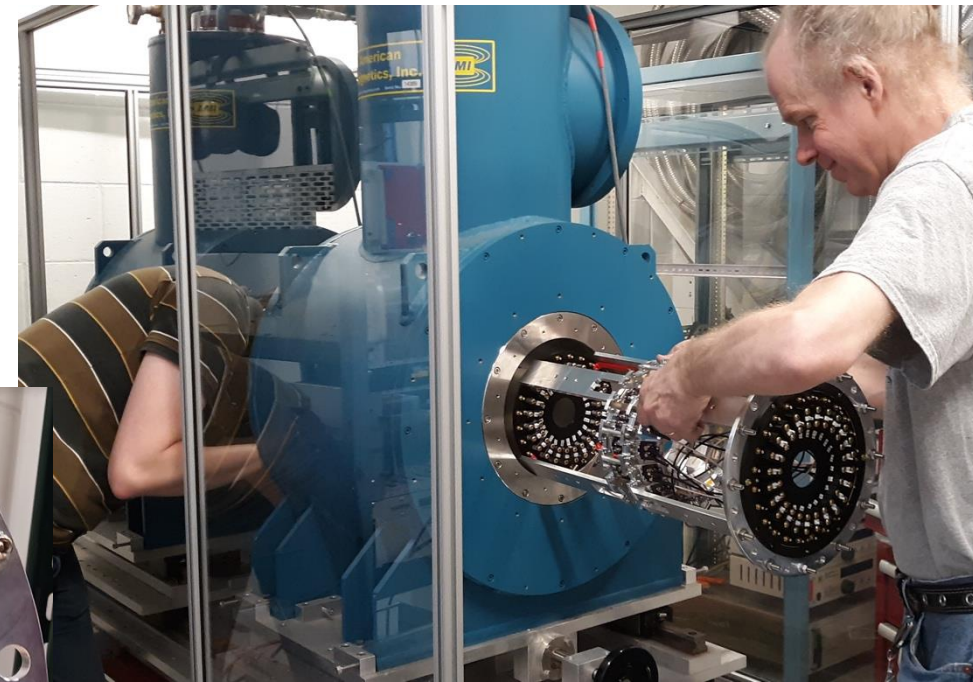
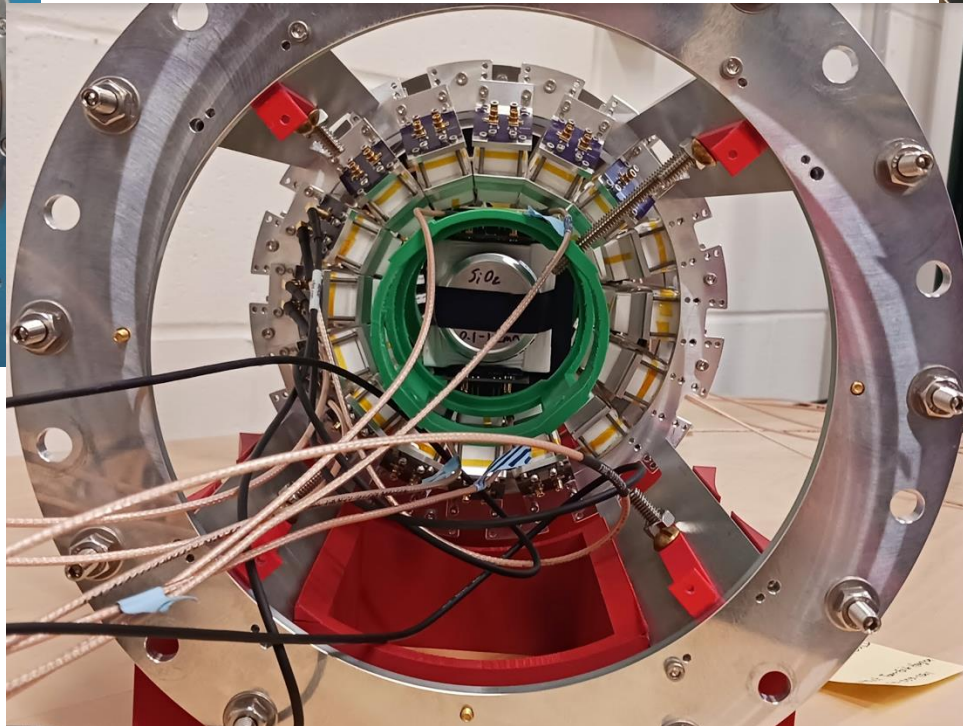


Installation

- All 48 detectors are completed and cabled
- Pictures are of partially assembled array



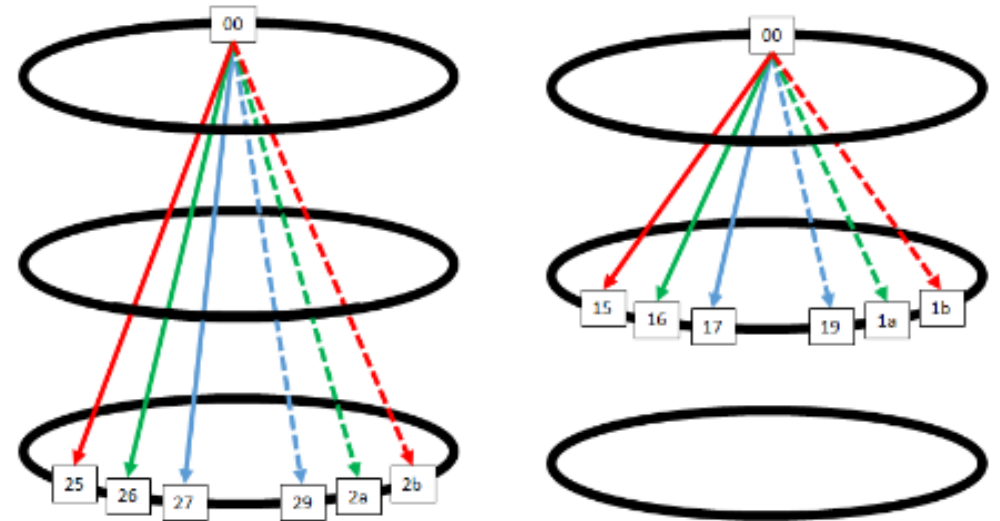
Installation



Sensitivity estimate

- Source rate: 1.85 MBq
- 50% survival rate for start detector
- 40% Ps formation
- ½ go into +/- 1 o- Ps
- Using initial time of 20 ns, 85% of +/- 1 o- Ps decay within time window
- Rate of good decays – 1.5×10^5 1/s
- Combining geometric analyzing powers we can reach sensitivity of $C_{CP} \sim 10^{-4}$ with 35 days of runtime
 - Factor of 10 improvement over previous experiments

Configuration	Counts	G_{an}	FoM
S157.5	22381	0.125	19.92
S135	10050	0.242	24.83
S112.5	1753	0.294	12.93
A157.5	12651	0.144	17.25
A135	3552	0.258	15.87
A125.5	34	0.240	1.67



Model dependence

- Analogues to CP-violation in meson physics there can be direct and indirect
 - CP-violation in decay amplitude or in Ps mass matrix
- Direct CP-violation would be dominated by permanent electric dipole moment of electron
- Indirect CP-violation would be mixing between 2^1P_1 - n^3S_1 states
- 1^3S_1 decays to parity odd 3-gamma state, 2^1P_1 decays to parity even 3-gamma state
 - Interference between two amplitudes generates the angular distribution
 - Suppressed by $\frac{\alpha}{2\sqrt{8}} \sim \frac{1}{775}$ from 2^1P_1 decay

$$\begin{aligned}
 N \propto & A^\Omega + P_{ij} (C_1^\Omega \hat{\mathbf{k}}_{1i} \hat{\mathbf{k}}_{1j} + C_2^\Omega \hat{\mathbf{k}}_{2i} \hat{\mathbf{k}}_{2j} + C_3^\Omega \hat{\mathbf{k}}_{1i} \hat{\mathbf{k}}_{2j}) \\
 & + \mathbf{s} \cdot (B_1^\Omega \hat{\mathbf{k}}_1 + B_2^\Omega \hat{\mathbf{k}}_2) \\
 & + P_{ij} (C_4^\Omega \hat{\mathbf{k}}_{1i} \hat{\mathbf{n}}_j + C_5^\Omega \hat{\mathbf{k}}_{2i} \hat{\mathbf{n}}_j)
 \end{aligned}$$

$$C_4^\Omega, C_5^\Omega \propto \frac{\alpha}{2\sqrt{8}} \text{Re}(\delta)$$

$$B_1^\Omega, B_1^\Omega \propto \frac{\alpha}{2\sqrt{8}} \text{Im}(\delta)$$

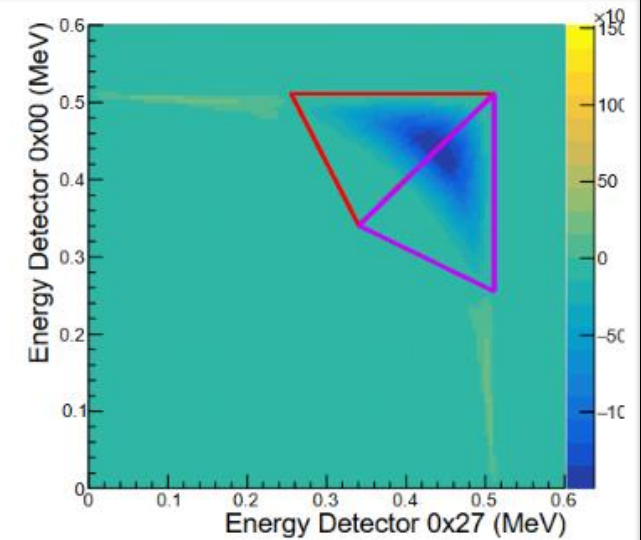
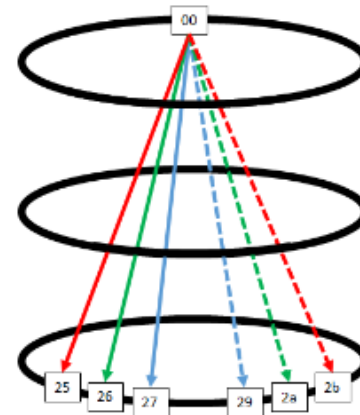
Model dependence

- Now with a concrete model, the form factors can be put into an event generator, and a full analysis can be performed
- Full detector acceptance/energy cut dependence can now be removed.

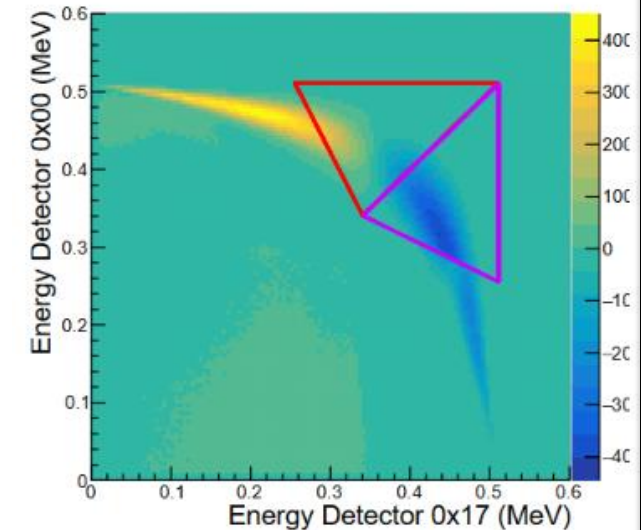
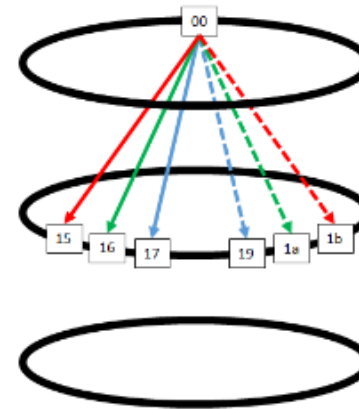
Statistical sensitivity for 35 days of data collection

configuration	hit order	S_{an}	N_a	$\sigma_{\text{Re}(\delta_1)}$
Sym 157.5°	(0,2)	-1.14×10^{-4}	1.08×10^9	0.19
Sym 135°	(0,2)	-7.72×10^{-5}	4.89×10^8	0.41
Sym 112.5°	(0,2)	-3.26×10^{-5}	8.39×10^7	2.37
Asym 157.5°	(0,1)	5.61×10^{-6}	6.85×10^8	4.82
Asym 135°	(0,1)	6.50×10^{-6}	1.83×10^8	8.03
Asym 157.5°	(1,0)	-5.14×10^{-5}	6.51×10^8	0.54
Asym 135°	(1,0)	-4.54×10^{-5}	1.79×10^6	1.34
Combined	–	–	–	0.10

Symmetric configuration



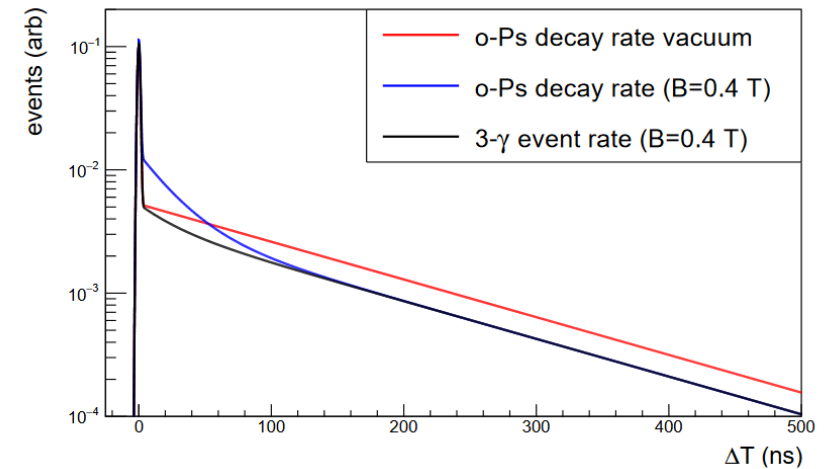
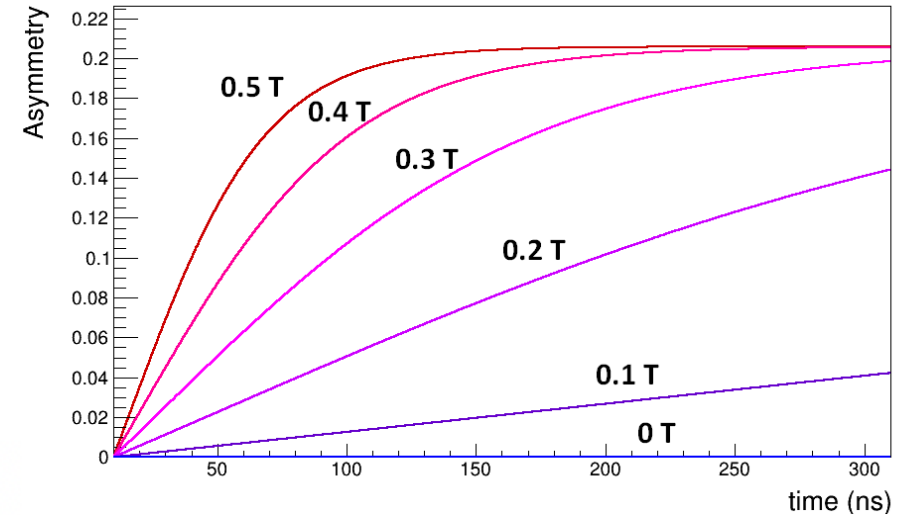
Asymmetric configuration



Full treatment of time dependence

- Addition of B-field breaks rotational invariance, full time dependence of all tensor moments is complicated
- $m=0$ state becomes quenched, but a portion of the polarization along B-axis is carried into the state populations as well

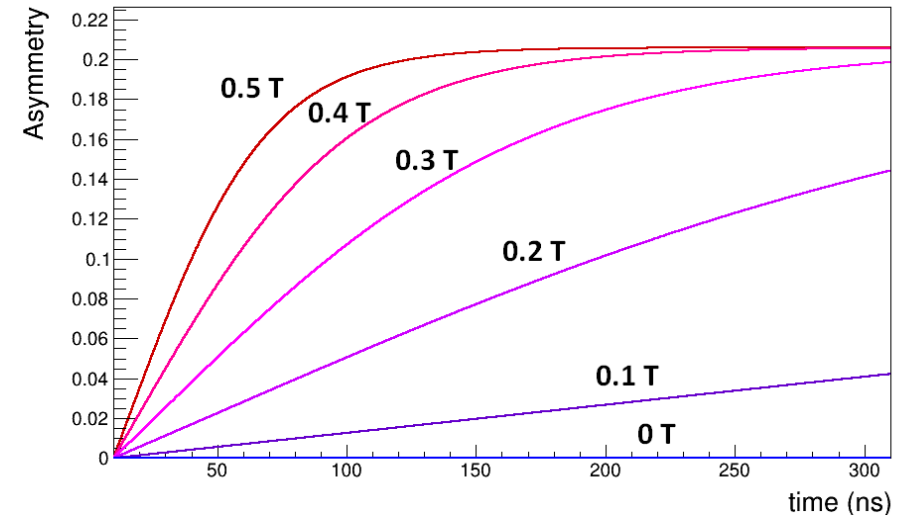
$$\dot{N}_{3\gamma}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \Gamma_{3\gamma} \left\{ \frac{1}{4} A (2e^{-t\Gamma_T} + c^2 (1 - 4scs_z) e^{-t\Gamma_{pT}}) \right. \\ \left. + \frac{1}{4} C_{zz} (e^{-t\Gamma_T} + c^2 (1 - 4scs_z) e^{-t\Gamma_{pT}}) \right\}$$



Full treatment of time dependence

- Addition of B-field breaks rotational invariance, full time dependence of all tensor moments is complicated
- $m=0$ state becomes quenched, but a portion of the polarization along B-axis is carried into the state populations as well

$$\begin{aligned} \dot{N}_{3\gamma}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = & \Gamma_{3\gamma} \left\{ \frac{1}{4} A (2e^{-t\Gamma_T} + c^2 (1 - 4s c s_z) e^{-t\Gamma_{PT}}) \right. \\ & + \frac{1}{4} C_{zz} (e^{-t\Gamma_T} + c^2 (1 - 4s c s_z) e^{-t\Gamma_{PT}}) \\ & + B_x c^2 s_x \cos(\omega_3 t) e^{-t\Gamma_3} + B_y s c s_x \sin(\omega_3 t) e^{-t\Gamma_3} + B_z s_z e^{-t\Gamma_T} \\ & \left. + C_{xz} s c s_x \cos(\omega_3 t) e^{-t\Gamma_3} + C_{yz} c^2 s_x \sin(\omega_3 t) e^{-t\Gamma_3} \right\} \end{aligned}$$



Using polarized betas the various tensor moments develop a "pulsing" time dependence

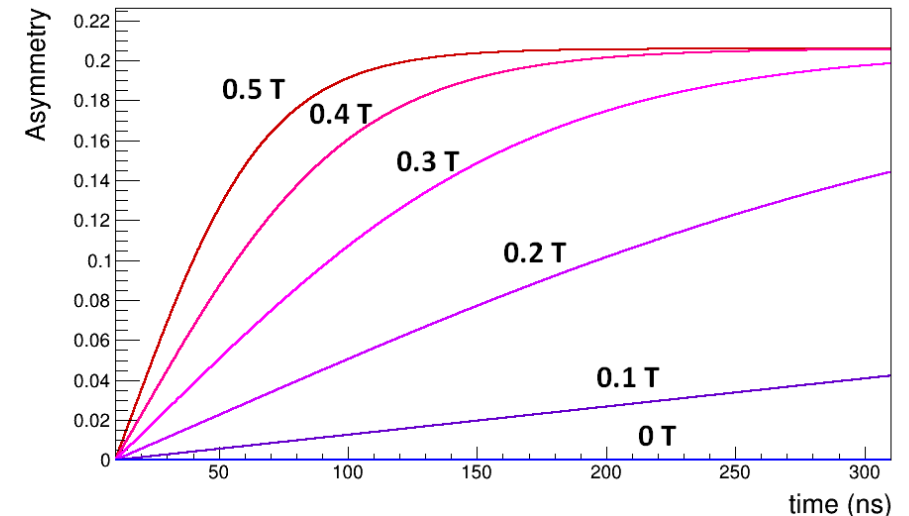
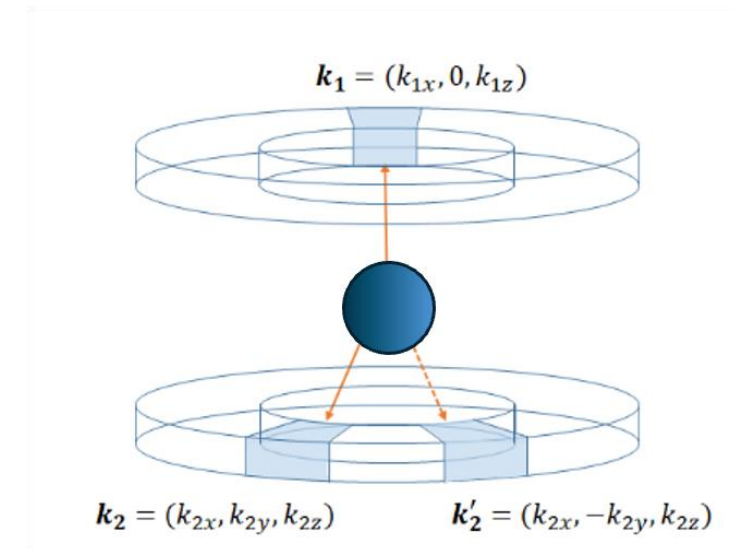
The BSM vector moments also precess in a field

This term has been measured ("quantum beating"): Phys. Lett. A, 136(7):428–432, 1989

Has been used for measuring HFS as well: Phys. Lett. B, 697(2):121–126, 2011

Systematics

- The signal has no phi dependence
- Time independent (phi dependent):
 - Varying detector efficiencies, thresholds, etc.
 - Geometric asymmetries, offset of source, asymmetric source distribution, powder inhomogeneity
- Time dependent (phi dependent):
 - Misalignment of magnetic field w.r.t. detector array
- Cylindrical symmetry of array gives strong control over systematics.
- We can run with the field off without changing any mechanical configuration, giving further control.



Summary and next steps

- We have demonstrated:
 - Efficient positronium formation
 - Time and energy resolution for sufficient background separation
 - Preliminary agreement between data and simulation
- Completed commissioning of 48 gamma detectors
- Finalizing inner module design
- We will be able to reach a 10-fold improvement in sensitivity with 1 month of continuous run time.

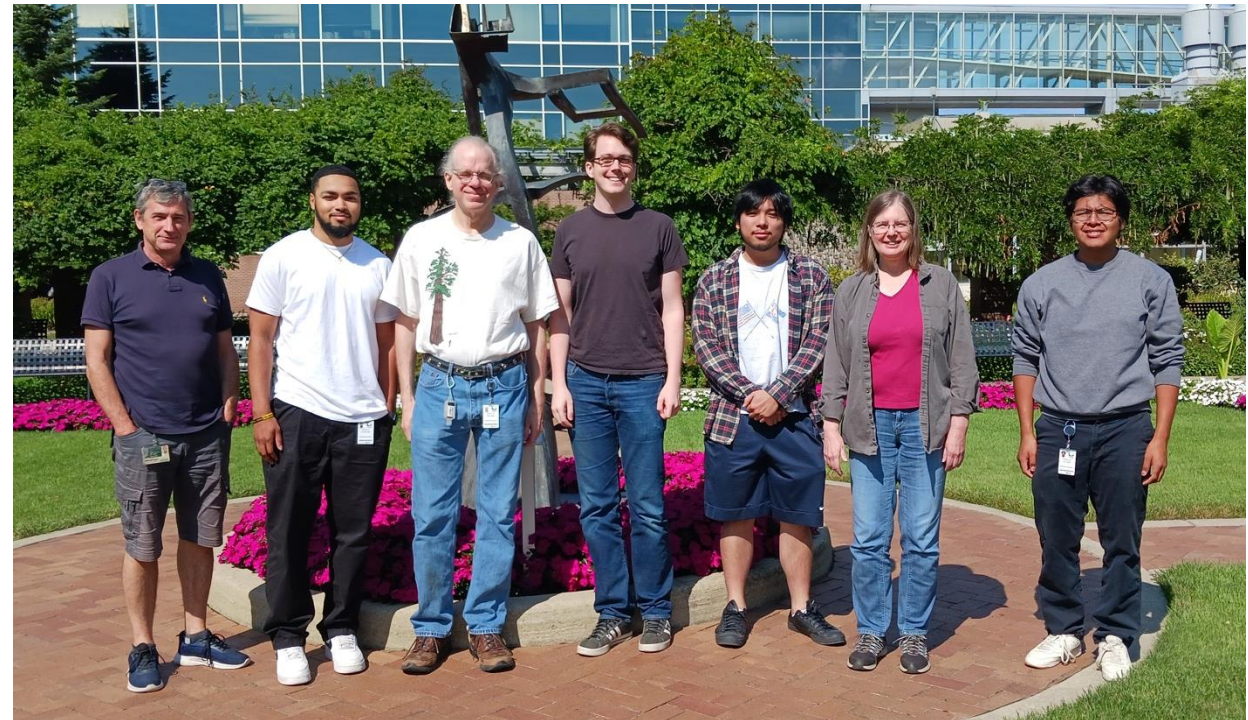
Thank you

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Model for Ps Formation

■ The counts in each component should go as:

- N_β : How many decays
- f^P : fraction that stop in plastic
- f_{Ps}^P : formation fraction in the plastic
- f_{Ps}^{MgO} : formation fraction in MgO

■ Ran dedicated tests to determine plastic formation, and stopping fraction in source.

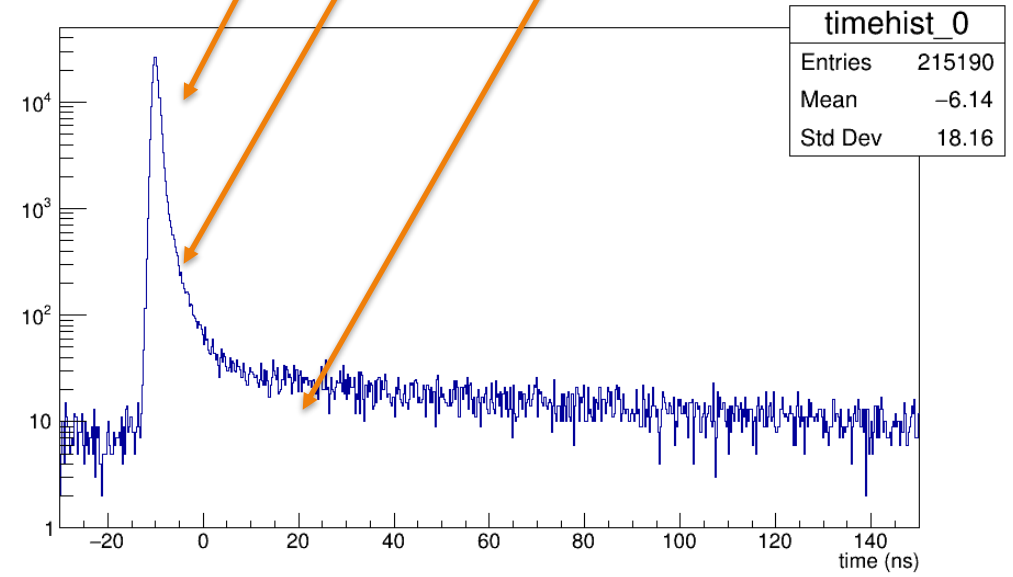
- Measured formation fraction for plastic matched existing literature.

■ Dedicated (simple) Geant4 simulation of setup to estimate relative detection efficiencies.

$$N_\beta \left(f^P \left(1 - \frac{3}{4} f_{Ps}^P \right) + (1 - f^P) \left(1 - \frac{3}{4} f_{Ps}^{MgO} \right) + (1 - f^P) \right) \epsilon_{2\gamma}$$

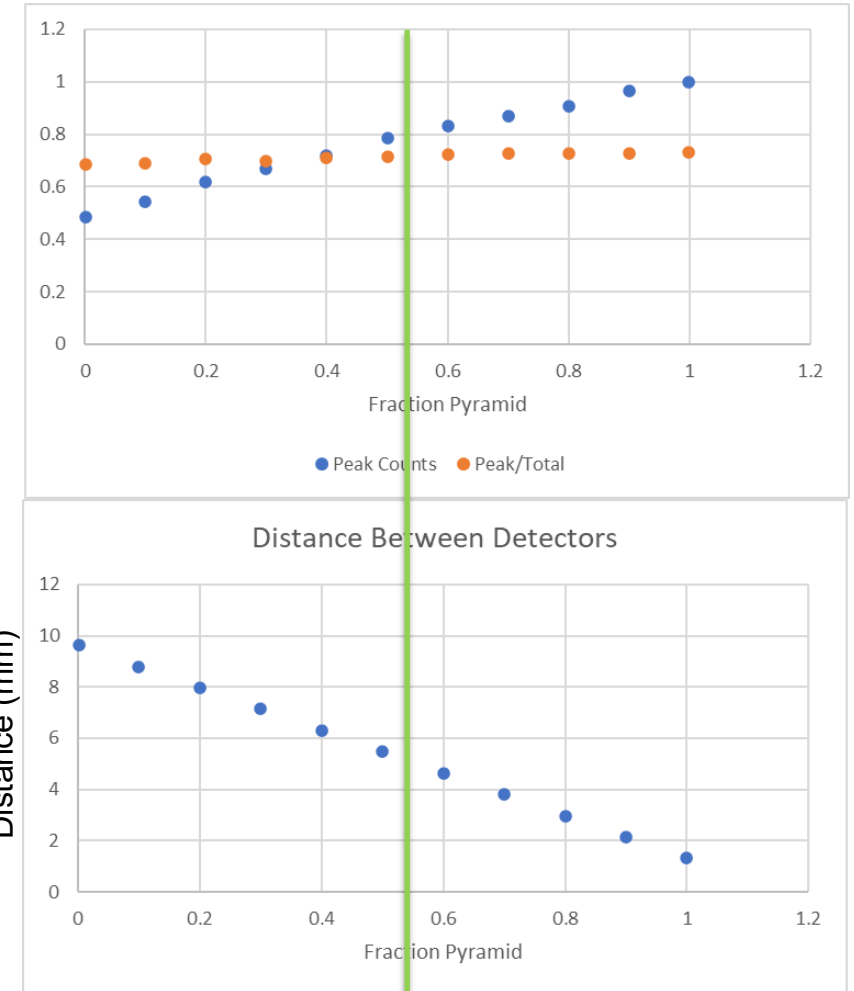
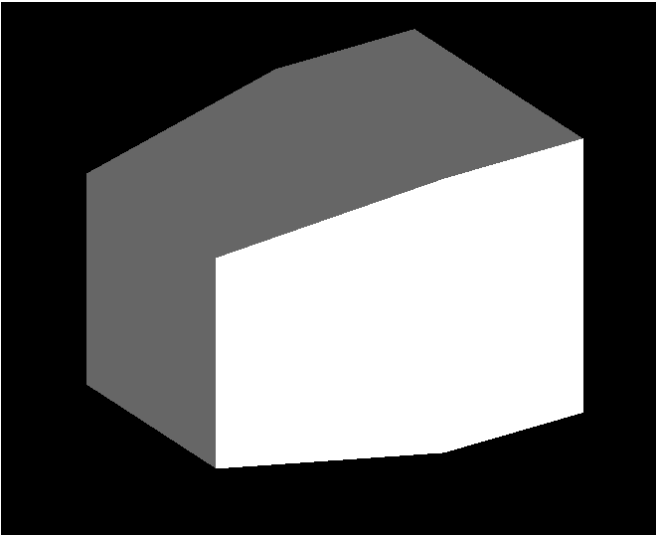
$$N_\beta \frac{3}{4} f^P f_{Ps}^P \epsilon_{2\gamma}$$

$$N_\beta (1 - f^P) \frac{3}{4} f_{Ps}^{MgO} \epsilon_{3\gamma}$$



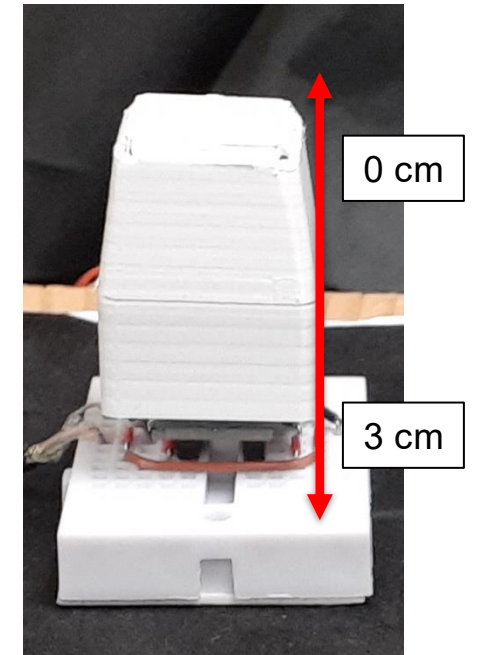
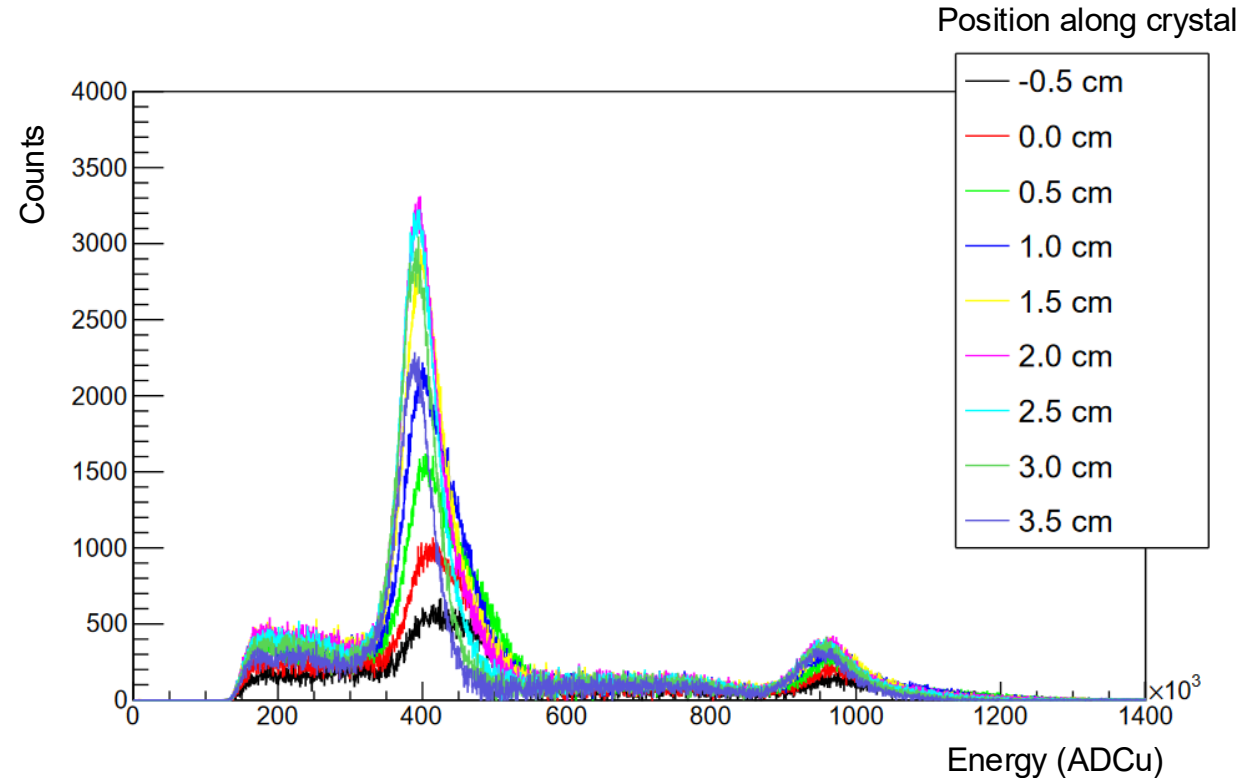
Size and Shape

- Tapered design greatly increases detection efficiency for the same solid angle
- Partial taper allows for more space to mount crystal onto ring.



First tapered prototype

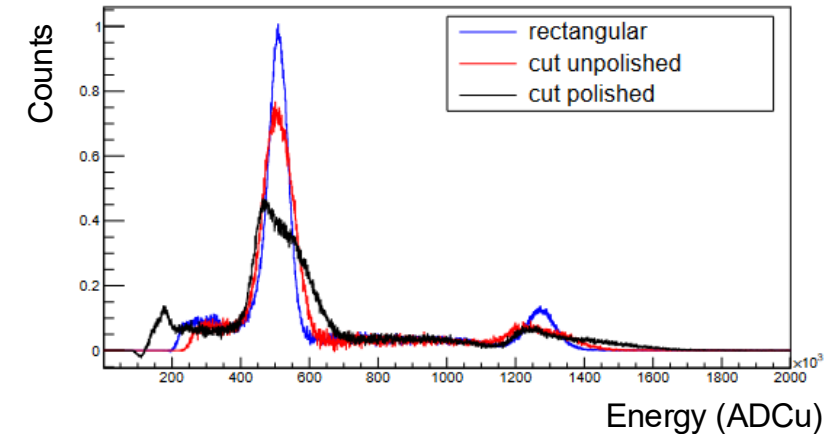
- First tapered crystal showed poor results
 - Position dependent response
 - Could be geometric, or poor doping uniformity
- Scans alone could not distinguish between these effects



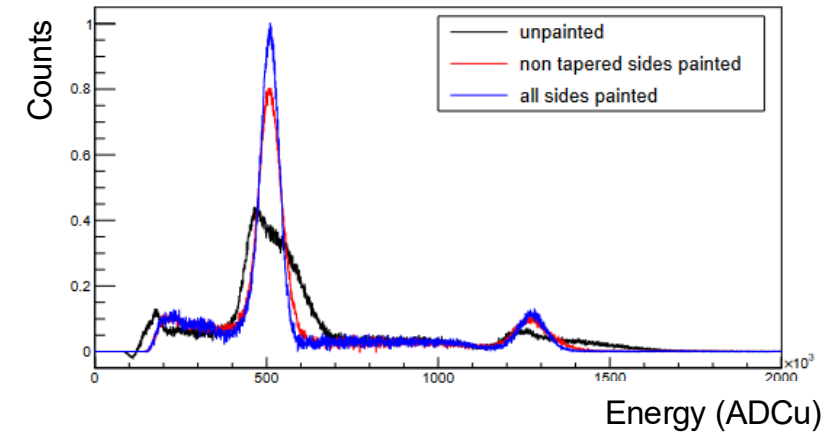
Light collection distortion

- Our tapered crystals showed large distortion to signal.
 - Could be geometric, or poor doping uniformity
- Taper adds geometric focusing effect
 - Reflection causes favorable angle for emission of light to PMT
 - Painting with TiO_2 paint removes total internal reflection

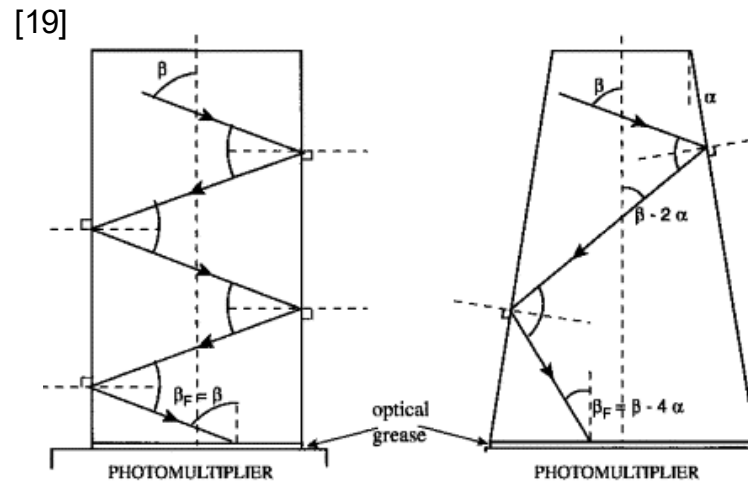
Geometric distortion to light collection



(a) Response after cutting, and after polishing



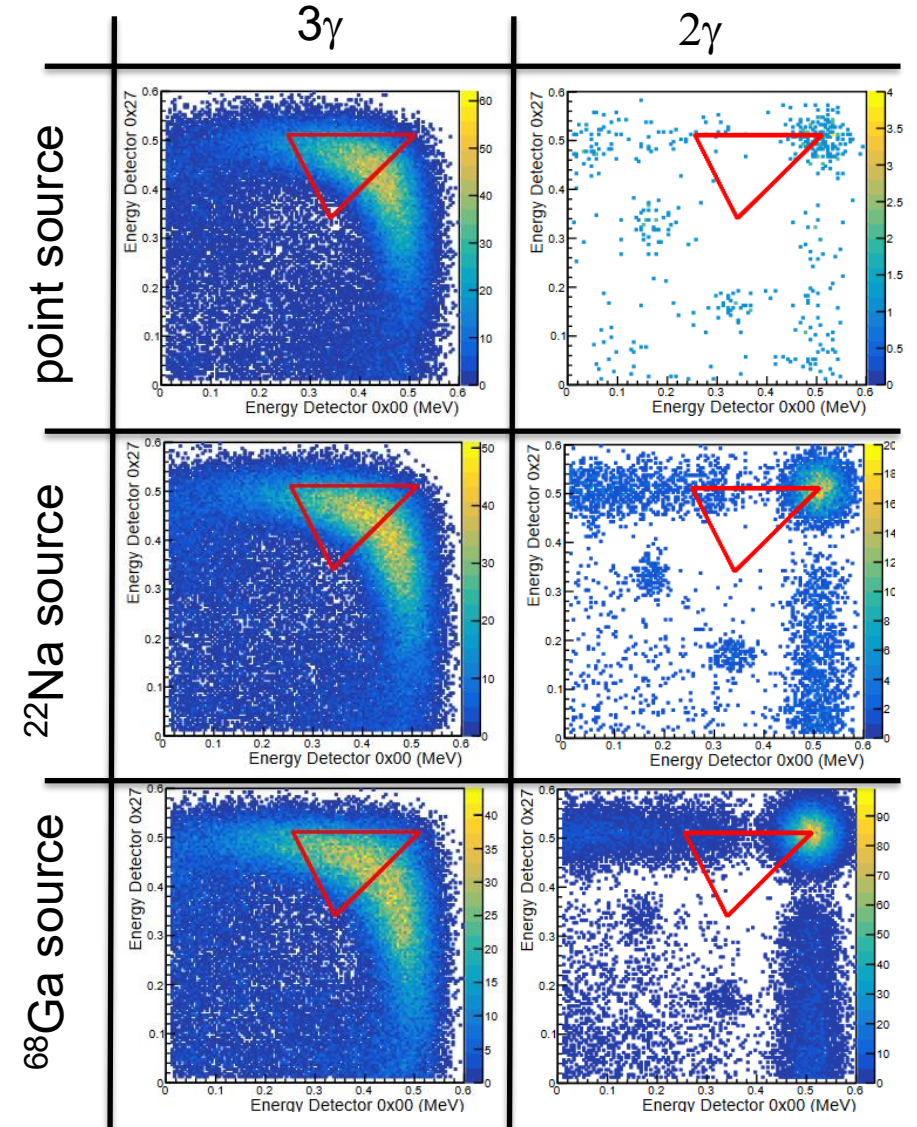
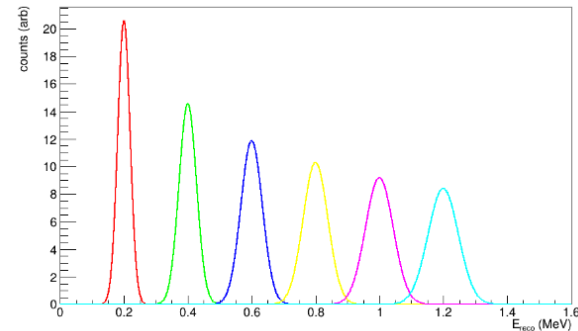
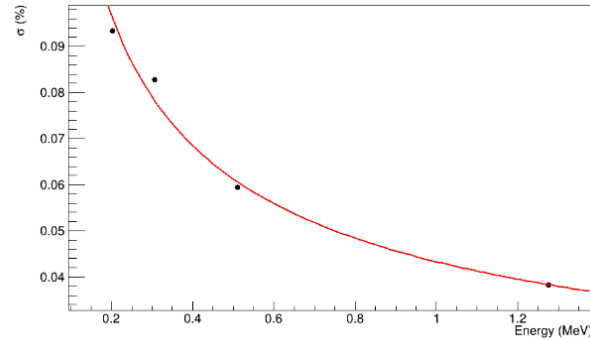
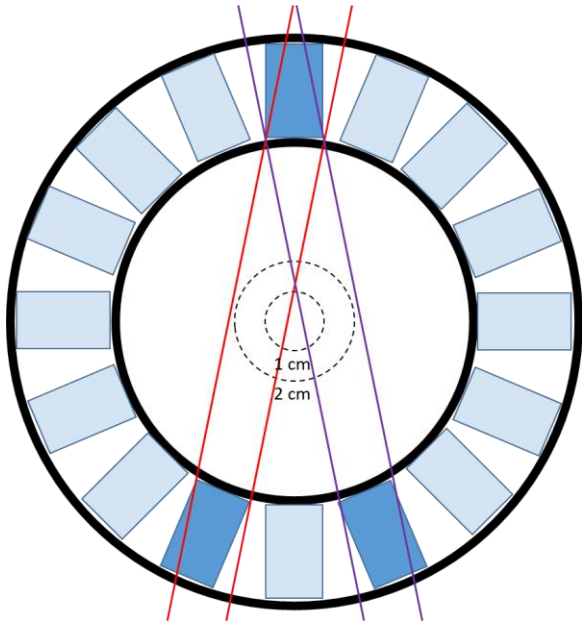
(b) Response after partial painting, and full painting.



[19] E. Auffray, F. Cavallari, M. Lebeau, P. Lecoq, M. Schneegans, and P. Sempere-Roldan. Nucl. Instrum. Meth. A, 486:22–34, 2002

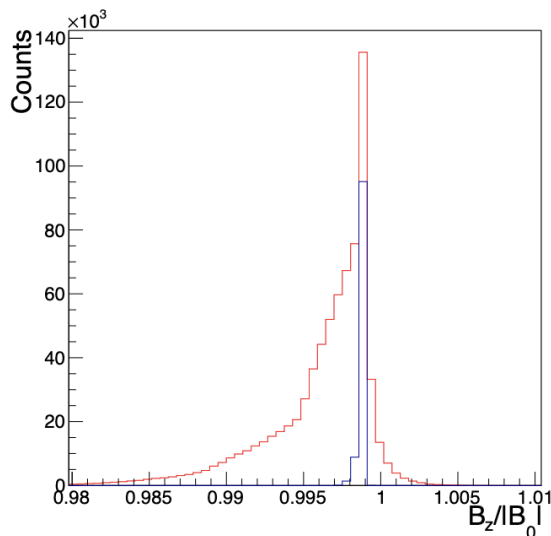
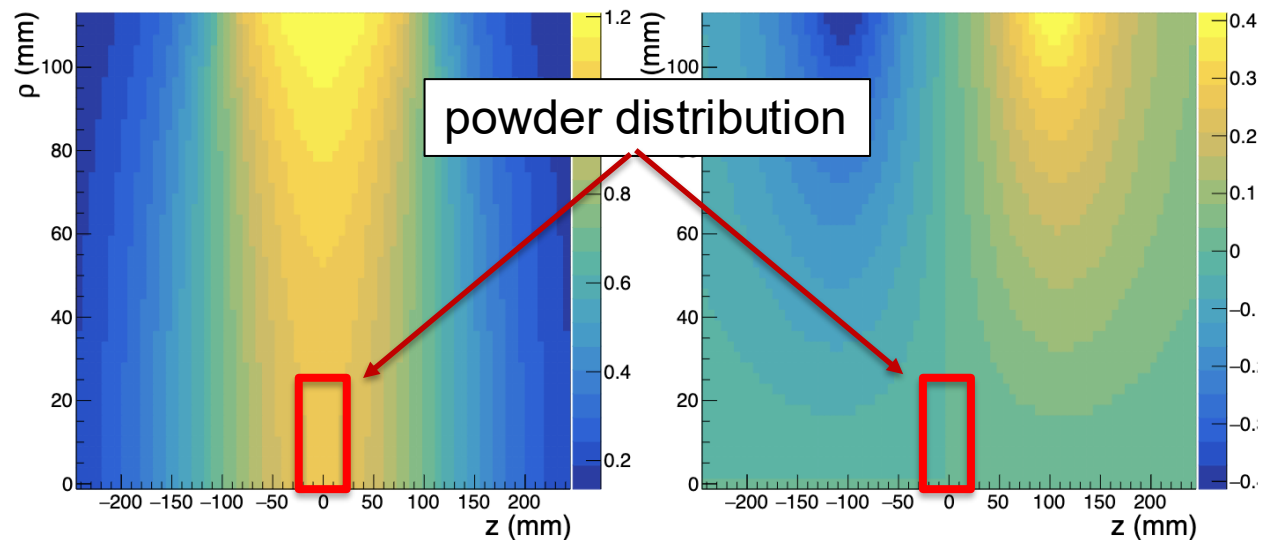
Source spreading and finite resolution

- Spreading of source means we become sensitive to 511's
- Finite energy resolution impedes our ability to fully separate these events.
- Directly sample Ps annihilation position from earlier β stopping simulations

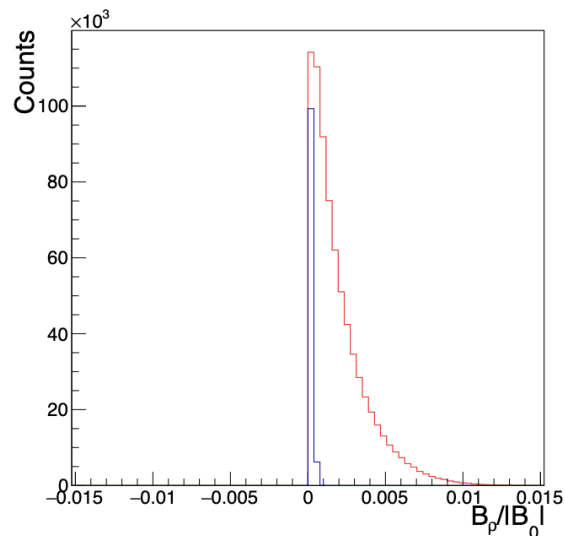


Field inhomogeneity over powder

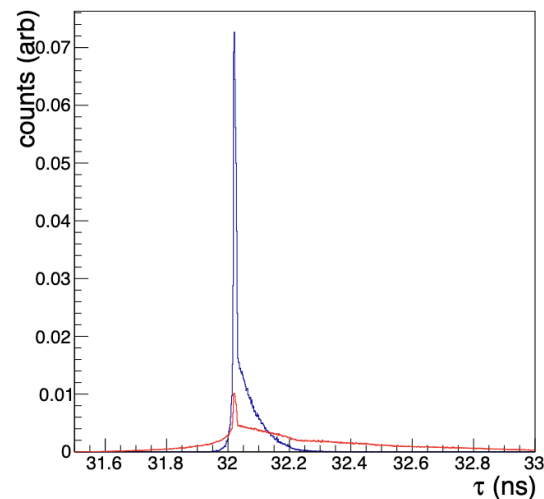
- Magnetic field is very uniform over powder distribution
- Primary effect is giving distribution of lifetimes
- Results for ^{22}Na (^{68}Ga) shown in blue (red)



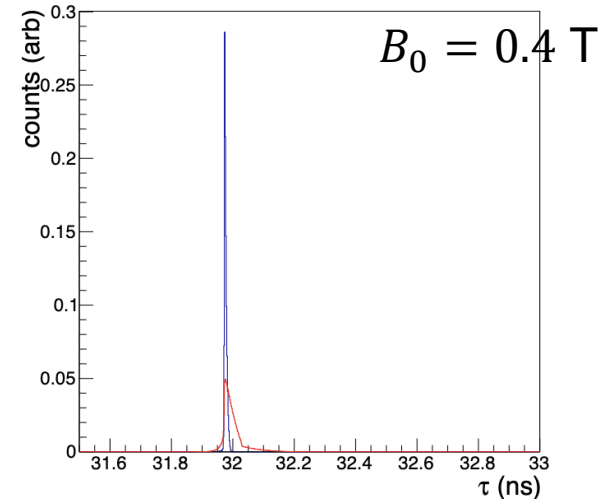
(a) B_z for forward β^+



(b) B_ρ for forwards β^+



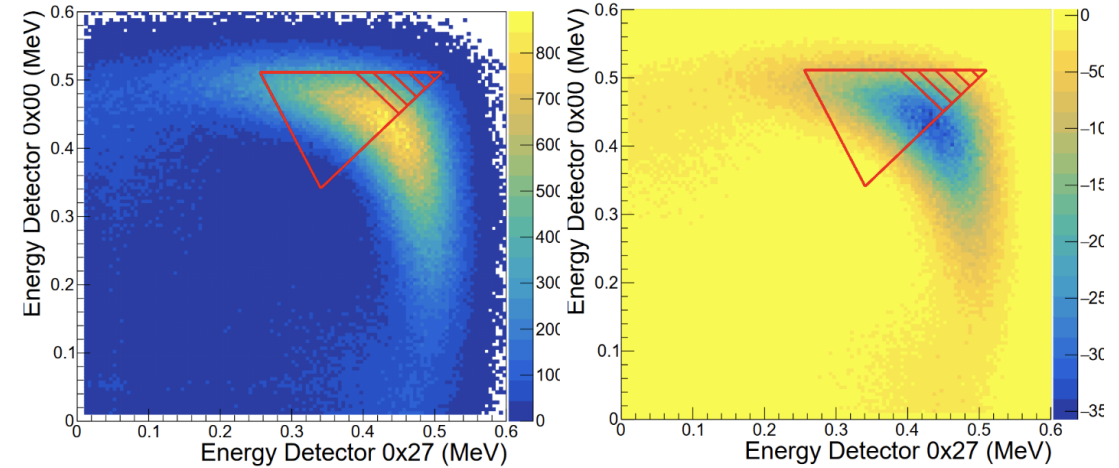
(a) Current start detector, SiO_2 at 0.1 g/cm^3



(b) Optimized start detector, MgO at 0.6 g/cm^3

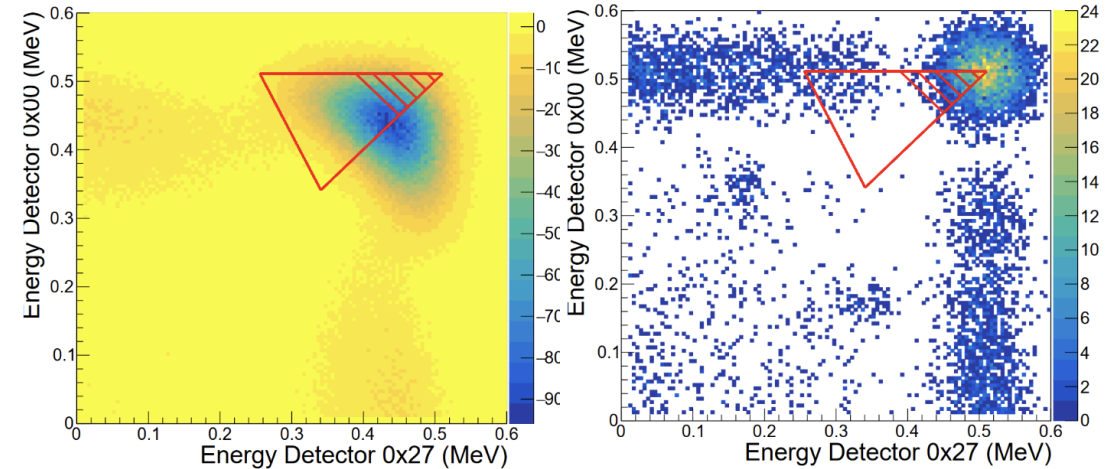
Source spreading and finite resolution

- Removing 2- γ background requires coincident energy cut
- Signal is peaked in high energy part of phase space
- non-trivial interplay between energy cut and form factor contributions
- With o-Ps lifetime of 135 ns, only 5% of positronium in time window decays to 2 photons



(a) Isotropic distribution

(b) QED anisotropy



(c) CP -violating signal

(d) 2- γ events

Comparison with Theory (1988)

- Current limits (EDM) indicate it is difficult to develop a scenario with CP-violation sensitive in Ps. However direct comparison of observables is not possible in a model dependent way, and more particles/couplings can be added and fine tuned to avoid current limits:
 - “Thus any relation of CP-violating effects in Ps decay to other observables remains model-dependent and strictly speaking we get *new information from Ps experiments*”
- Possible sources for this signal:
 - Effective 4-fermion interaction from massive intermediate particle
 - » For \sqrt{s} greater than PETRA and PEP, we can get limit from scattering data of $|\delta_1| < 10^{-19}$
 - » For \sqrt{s} less than PETRA but higher than m_e^2 , low energy electron scattering data gives $|\delta_1| < 10^{-11}$
 - EDM for electron gives $|\delta_1| \propto \frac{(d_e m_e)^2}{e^2} < 10^{-26}$
 - Neutrino mixing induced CP-violation (Dirac or Majorana)
 - » No signal to fourth order in g
 - Massive neutral spin-0 bosons with indefinite parity (for example several doublets of Higgs fields)
 - » Assume a single new particle, no FCNC couplings, two Yukawa couplings, parity even and odd.
 - » This simple model generates an EDM. Translating EDM limit into limit on couplings (and mass) sets limit on state mixing
 $|\delta_1| < 10^{-16}$ for $m_\phi \approx 30m_e$ and lower for higher mass boson

Bernreuther, W., Löw, U., Ma, J.P. et al. Z. Phys. C - Particles and Fields 41, 143–158 (1988).