GDR-InF Annual Workshop 2024
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Cabourg

Improved Search for CP violation in ortho-Positronim Decay

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Searches for *CP* Violation at Low Energies

Two main avenues with spin controlled probes

- Searches for permanent EDMs of particles (e, μ, τ, n, …), atoms, (radioactive) nuclei, etc.

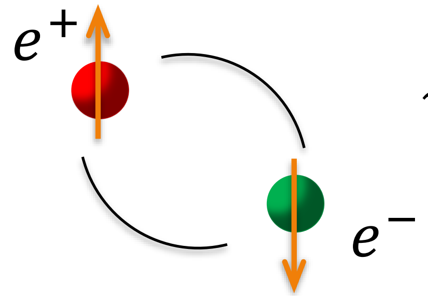
- Searches for *T*-violating correlations in decay processes involving spin observables (pure-leptontic, semi-leptonic,…)

- Here we are dealing with an em dominated process in a pure-leptonic system.

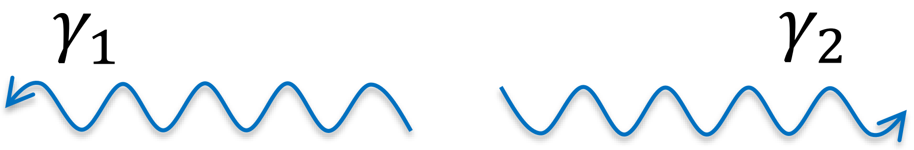
Positronium spin states and decays

$|0,0\rangle = [|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle]/\sqrt{2}$

Singlet (para)

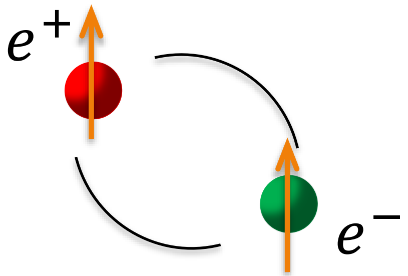


$\tau_S = 125$ ps

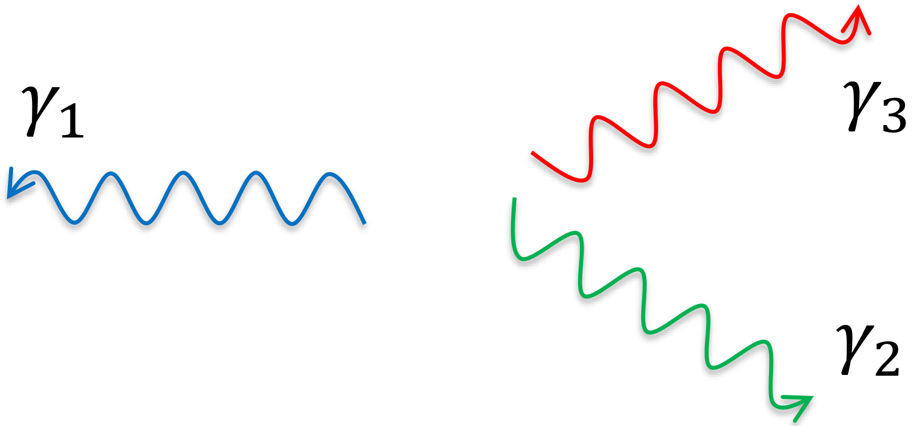


Triplet (ortho)

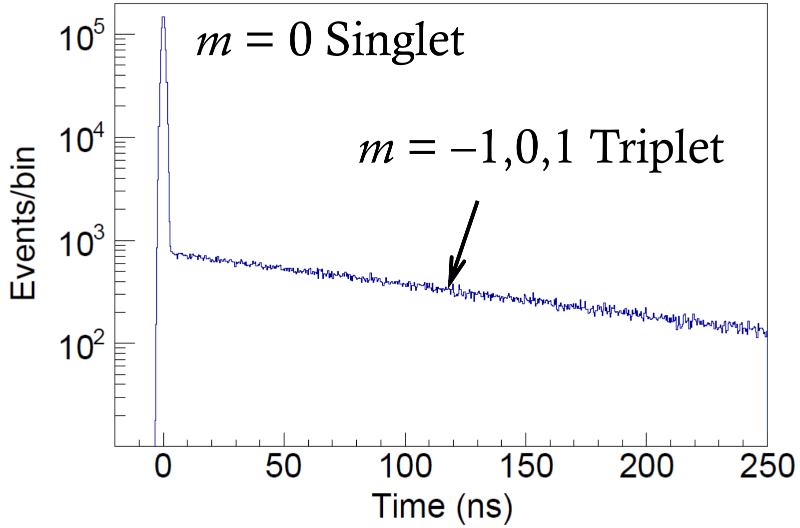
$|1,1\rangle = |\uparrow\uparrow\rangle$
$|1,0\rangle = [|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle]/\sqrt{2}$
$|1,-1\rangle = |\downarrow\downarrow\rangle$



$\tau_T = 142$ ns



Decay-time spectrum after formation of Positronium



Simulation with 40% Ps formation fraction and 1.9 ns FWHM Gaussian response

CP violation in Positronium

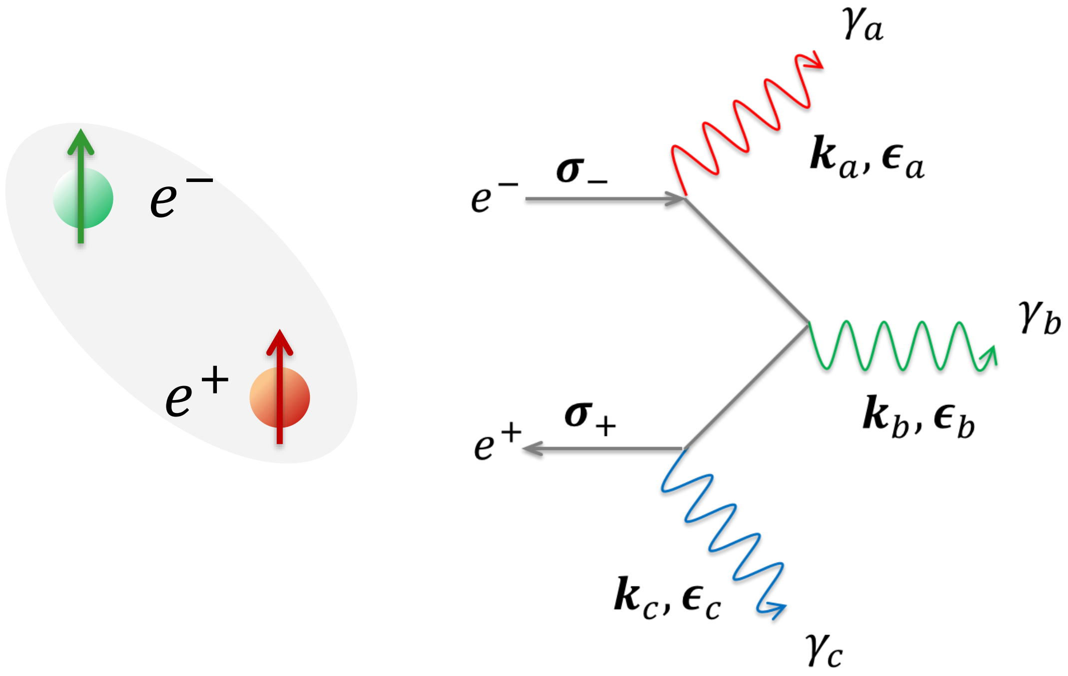
- Ps states have definite *P* and *C* quantum numbers and are hence *CP* eigen-states.

- In contrast to EDMs and weak-decay correlations, it is here possible to imagine direct *CP* violation searches such as

$$\Gamma(pPs \to 3\gamma)$$
$$\Gamma(oPs \to 2\gamma)$$

- Here we are dealing with an indirect search through the presence of a *CP*-violating form factor in the decay rate of o-Ps.

CP-violating form factors in ortho-Positronium



$$c_4\,(\omega_1, \omega_2) \;\; \text{and} \;\; c_5\,(\omega_1, \omega_2)$$

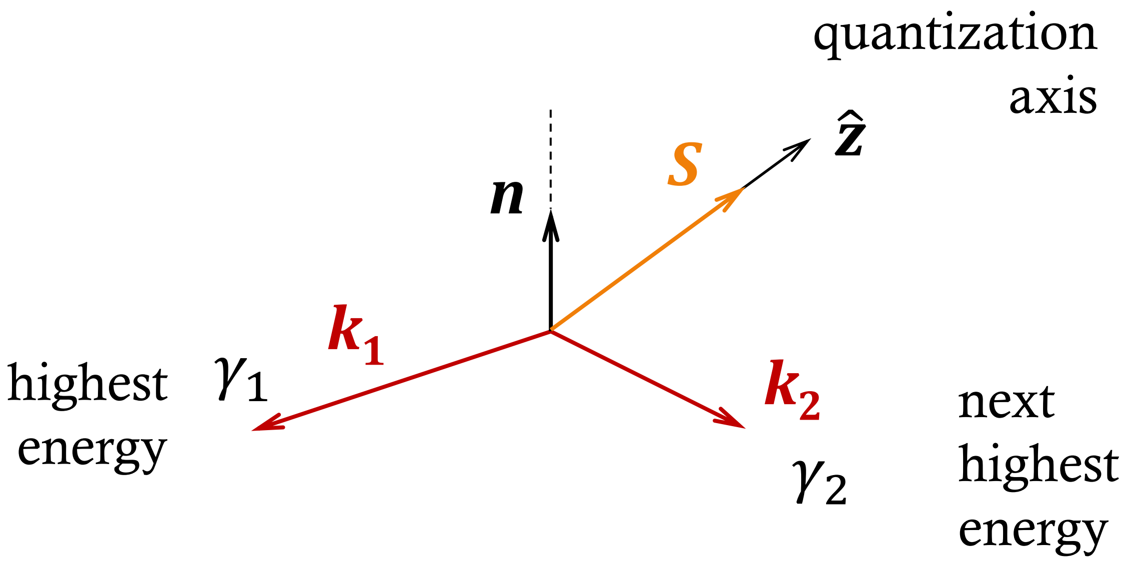
W. Bernreuther, U. Löw, J.P. Ma, O. Nachtmann Z. Phys. C **41** (1988) 143

- These signals cannot be mimicked by FSI or radiative corrections unless these also violate *CP*.

- For a system polarized along the *Oz* axis, the correlations which drive these terms are

$$S_{zz}\,\kappa_{1z} n_z \quad \text{and} \quad S_{zz}\,\kappa_{2z} n_z$$

S_{zz} is the tensor polarization of o-Ps



Vector and tensor polarizations

- For a spin-1 system (with axial symmetry) the vector and tensor polarizations can be expressed in terms of the *m*-states populations

- $|1,1\rangle \ : N_+$
- $|1,0\rangle \ : N_0$
- $|1,-1\rangle : N_-$

Vector polarization

$$P_z = \frac{N_+ - N_-}{N_+ + N_0 + N_-}$$

P_z describes the asymmetry between populations of states having opposite signs of projections along the quantization axis ($-1 < P_z < 1$).

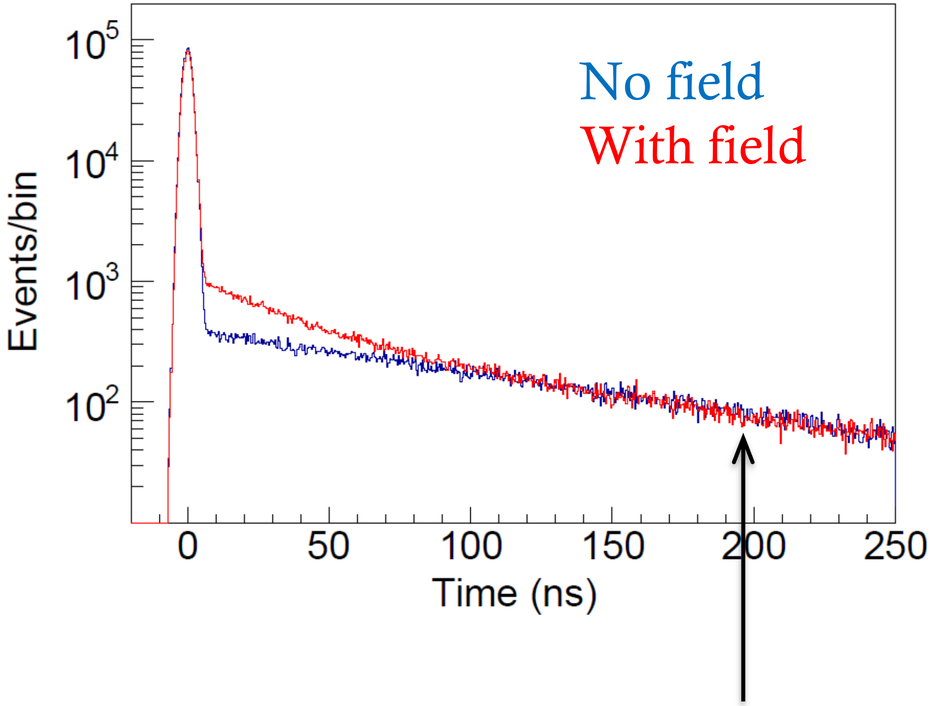
Tensor polarization

$$P_{zz} = \frac{N_+ - 2N_0 + N_-}{N_+ + N_0 + N_-}$$

P_{zz} describes the extent to which the ensemble is enriched or depleted by the m=0 state ($-2 < P_{zz} < 1$).

How to produce tensor polarization with ortho-Positronium?

- Tune the population of the m=0 sub-state



With a magnetic field, the contribution of the m=0 state is negligible at long decay times

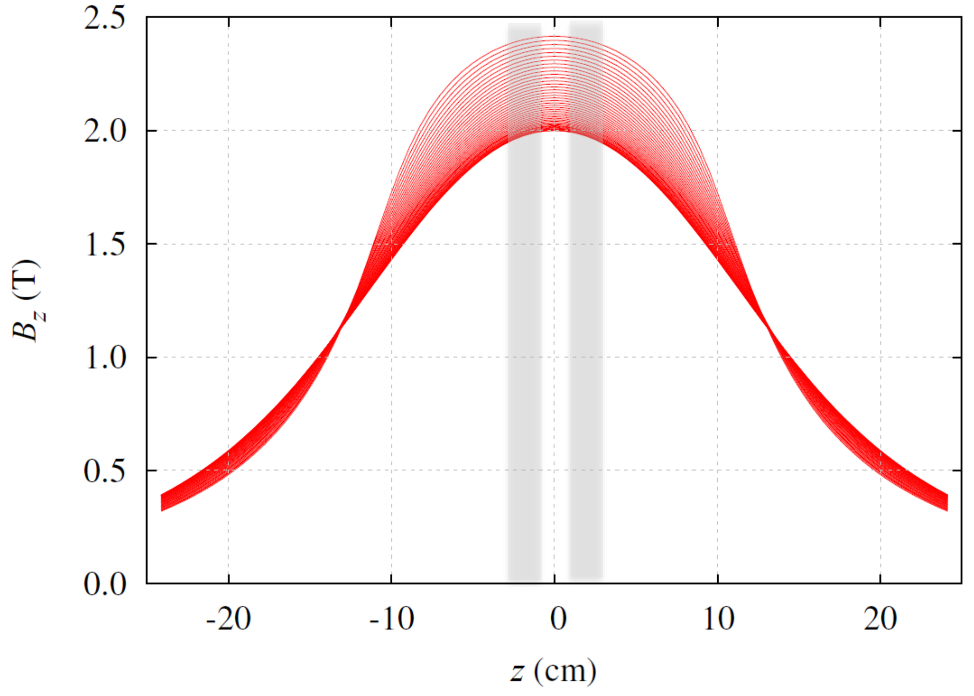
- In the absence of a magnetic field, the m=–1,0,1 sub-states of the Triplet are degenerate.

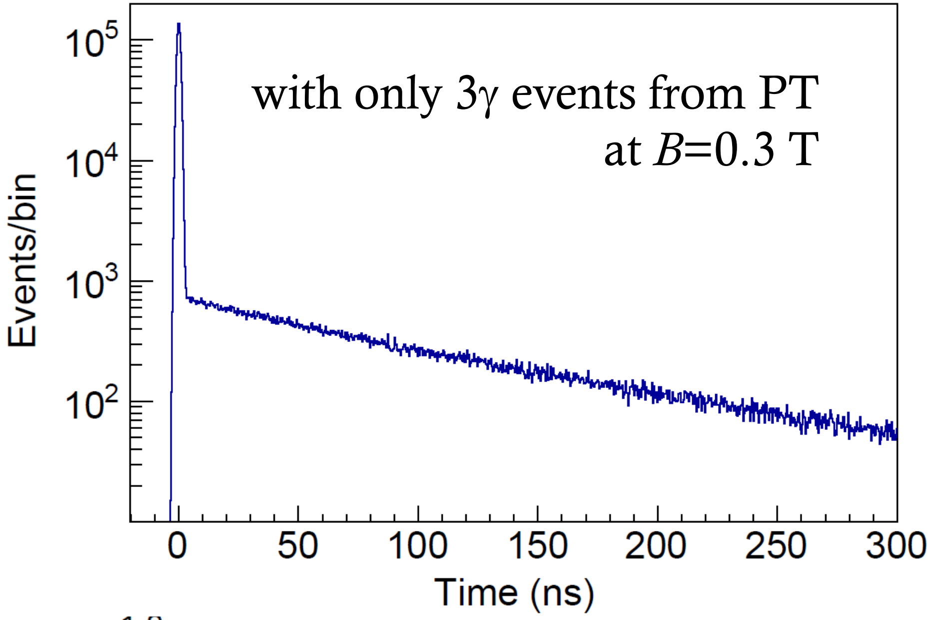
- In the presence of a magnetic field, the $|00\rangle$ and $|10\rangle$ states mix.
- Due to this mixing, the two new m=0 states get very different lifetimes than the $m=\pm 1$ states.

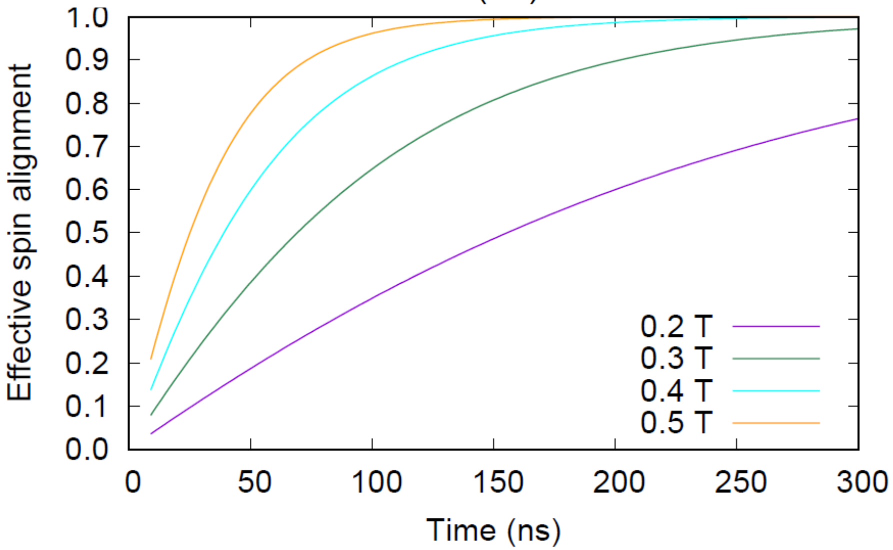
- The "Pseudo-triplet" state lifetime depends on the field intensity.

Main control of systematics: the tensor polarization

Magnetic field map

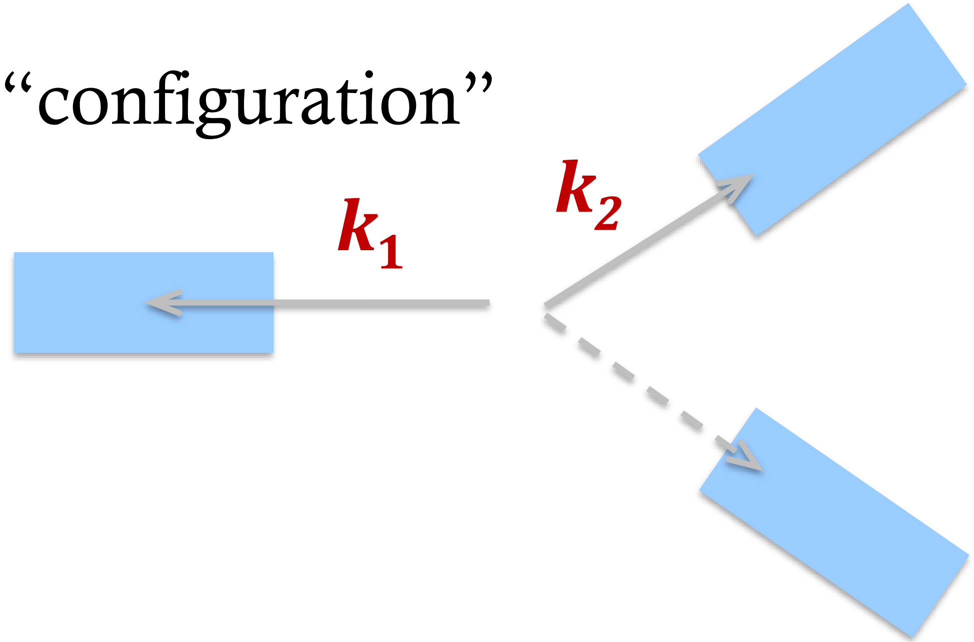


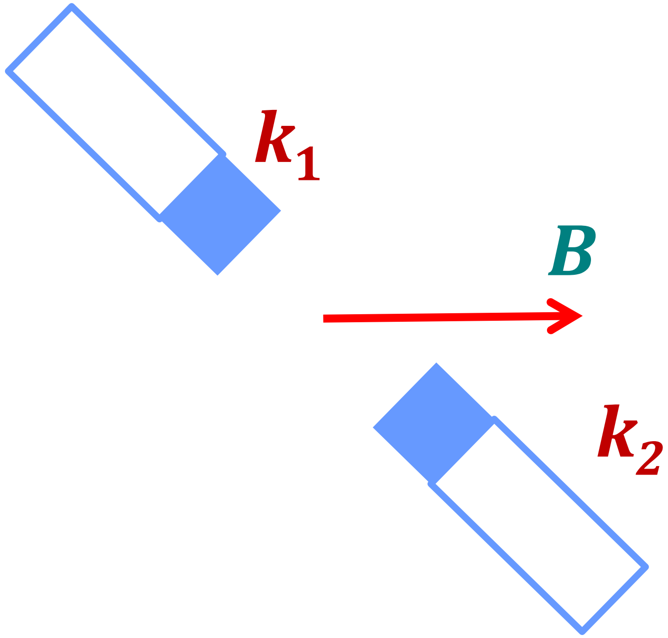




General Principle, Previous Measurements, Sensitivity Goal

A “configuration”





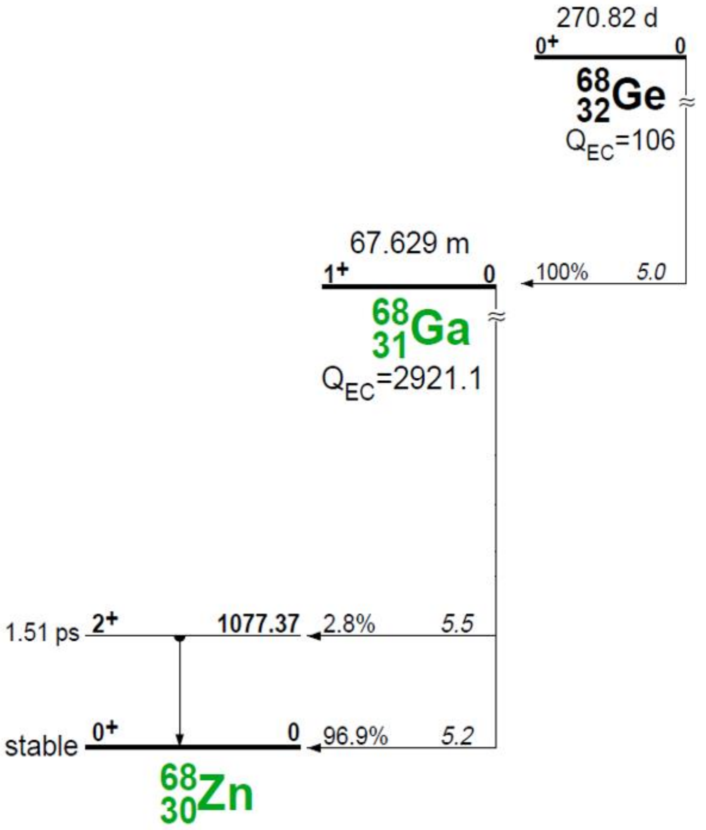
Configs.	B Field	Measuring scheme	Sensitivity	Duration	Ref.
1	Fixed	Sequential	1.5×10^{-2}	?	PRL **67** (1991) 1993
2	Fixed	Sequential	$(21_{stat} \pm 6_{syst})10^{-4}$	6 months	PRL **104** (2010) 083401
256	Tunable	Simultaneous	2×10^{-4}	1 month	This work

Ignore P. Moskal et al. Nature Comm. **15** (2024) 78; because of arXiv:2406.16228

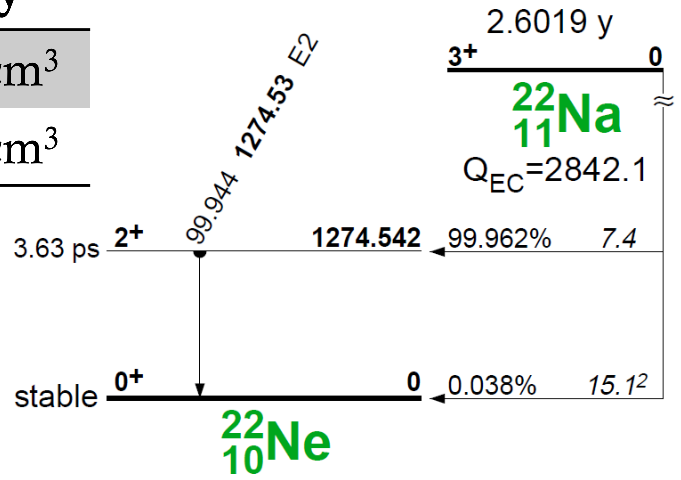
Goals and driving scheme

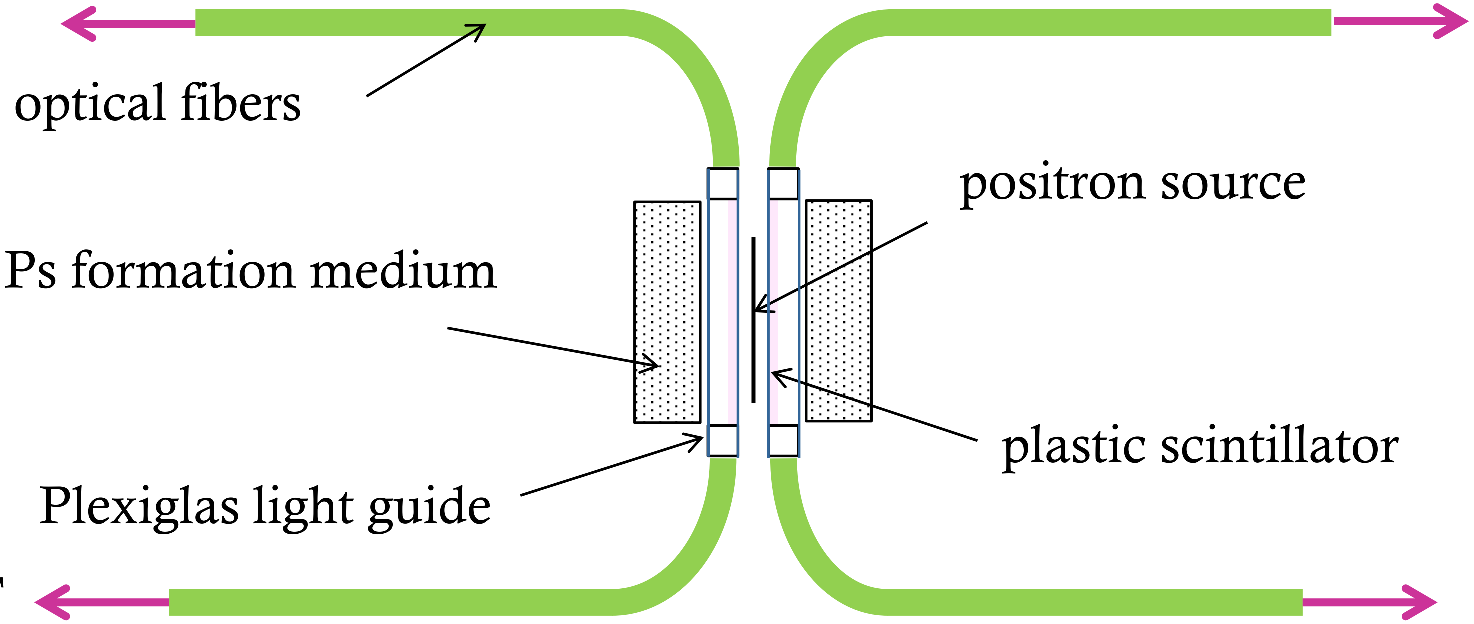
- Improve the statistical sensitivity by an order of magnitude within a reasonable measuring time (~one month).
- Reduce systematic uncertainty by at least a factor 3.
- Measure several configurations (asymmetries) simultaneously.
- Use a tunable magnetic field in an open bore to produce tensor polarization (no permanent magnets and yokes).
- Build a highly symmetric setup for further control systematics.

Beta trigger module with ^{68}Ga and ^{22}Na sources



Source	PVT thickness	Ps medium	Density
^{22}Na	0.15 mm	SiO_2	0.1 g/cm^3
^{68}Ga	0.50 mm	MgO	0.6 g/cm^3

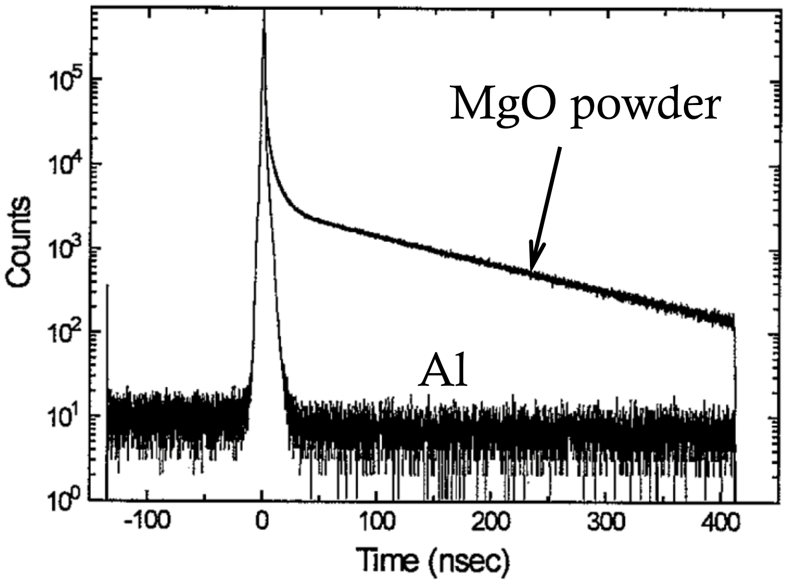




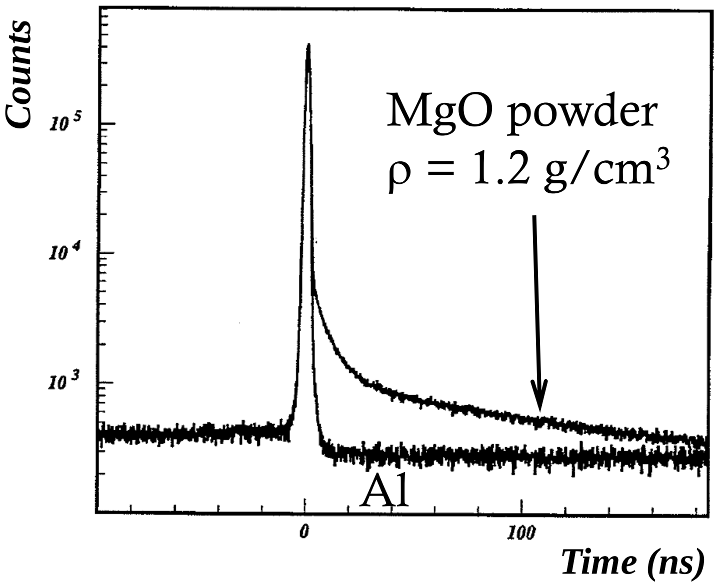
Examples: Ps formation in MgO and decay in a magnetic field

^{107}In decay

J. Camps, PhD Thesis, K.U. Leuven 1997



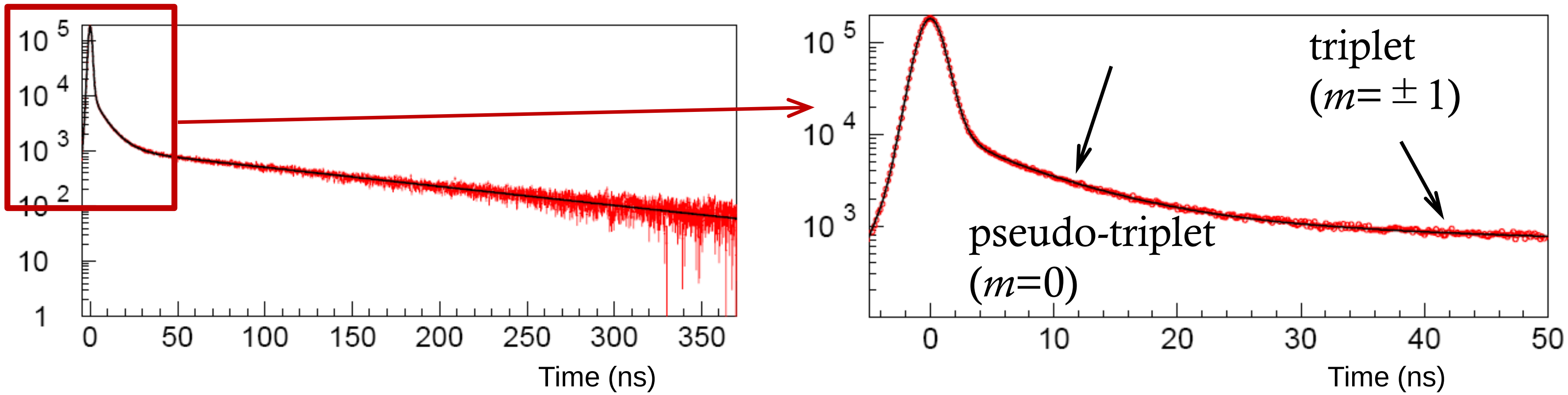
M. Allet. PhD Thesis, ETH Zurich 1994



^{12}N decay

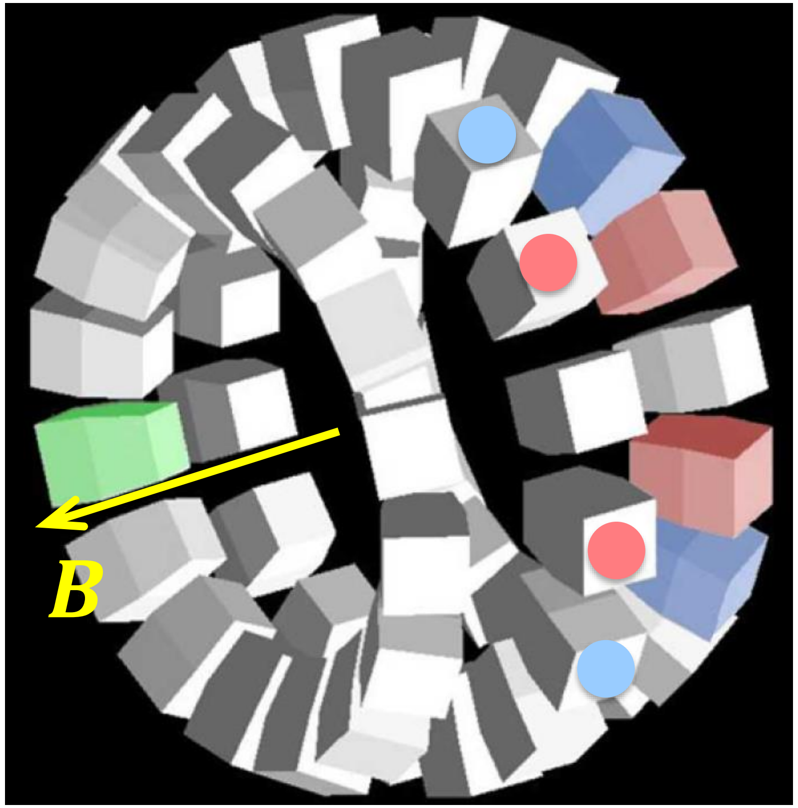
E. Thomas *et al.*, Nucl. Phys. **694** (2001) 559 and PhD Thesis, U.C. Louvain 1999

MgO powder
$\rho = 0.6$ g/cm^3



^{12}N decay

Improving the angular coverage



- 48 LYSO detectors distributed in three rings of 16.
- 32 asymmetries from “outer-red” pairs + 32 asymmetries from “outer-blue” pairs.
- 32 asymmetries from “central-red” pairs + 32 asymmetries from “central-blue” pair; (central events have a smaller analyzing power).
- 128 sets sensitive to one of the *CP*-violation correlations
- 254 sets sensitive to both correlations

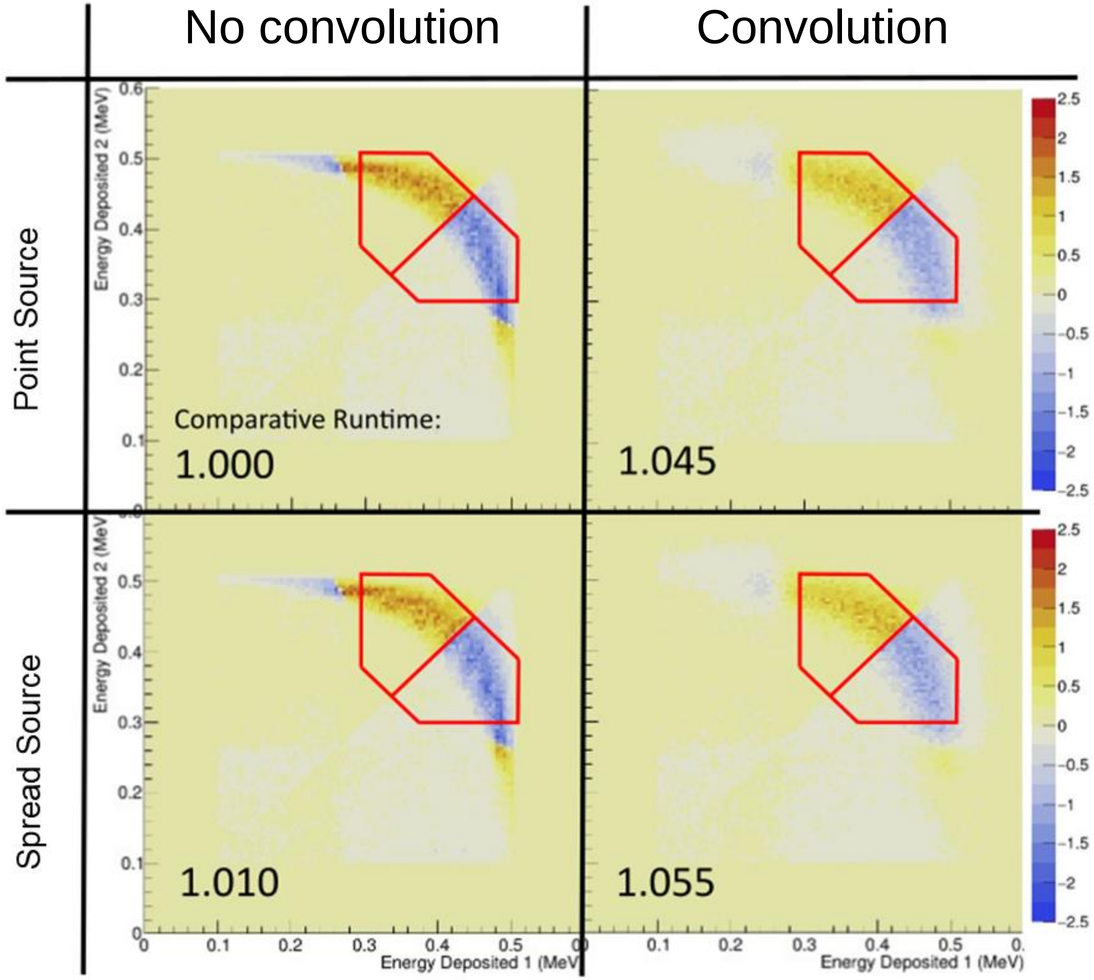
- The central ring almost doubles the statistics but, most important, it provides a check of systematics: when both photons are emitted perpendicular to the spin, the analyzing power is zero.

Monte-Carlo simulations (MSU and WU)

T.E. Haugen, MSU

Instrumental effects included so far

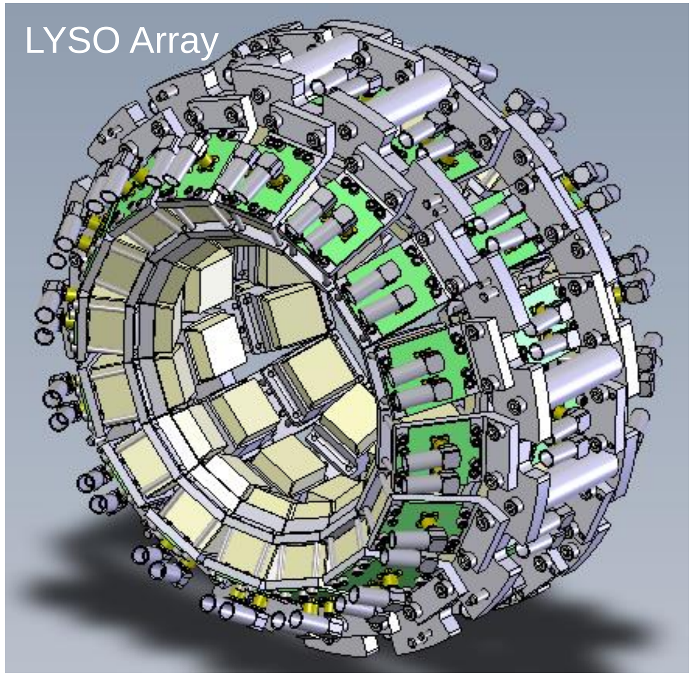
- Scattering of photons from the Ps formation medium
- (Dis)advantage of adding shield between rings
- Contribution of real 2γ events
- Effect of magnetic field on source distribution
- Orientation of crystals in outer rings relative to the vertical plane
- Truncation and shapes of LYSO crystals
- Energy resolution
- Accidental coincidences from 511 keV events, LYSO intrinsic radioactivity and 1.27 MeV photon from ^{22}Na decay

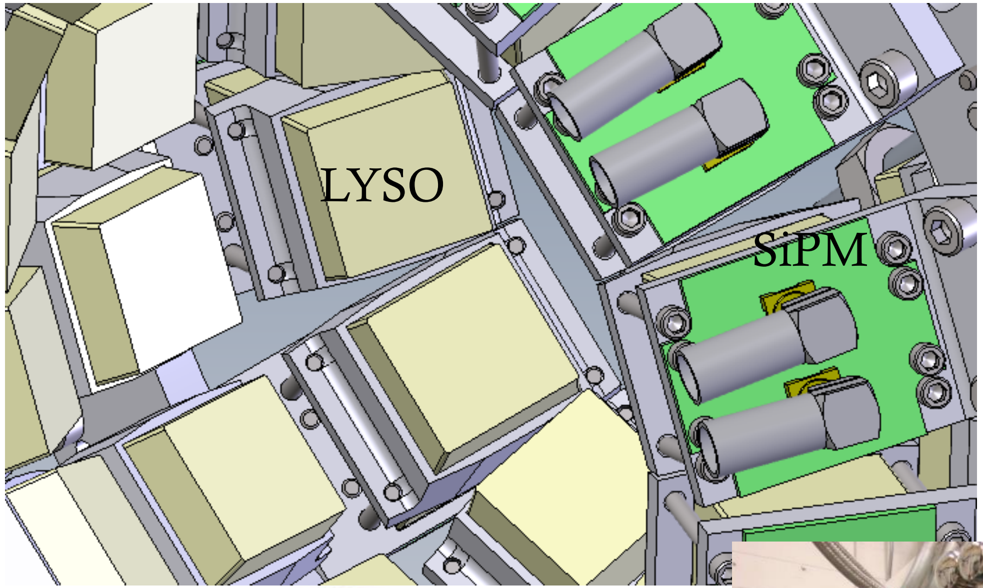


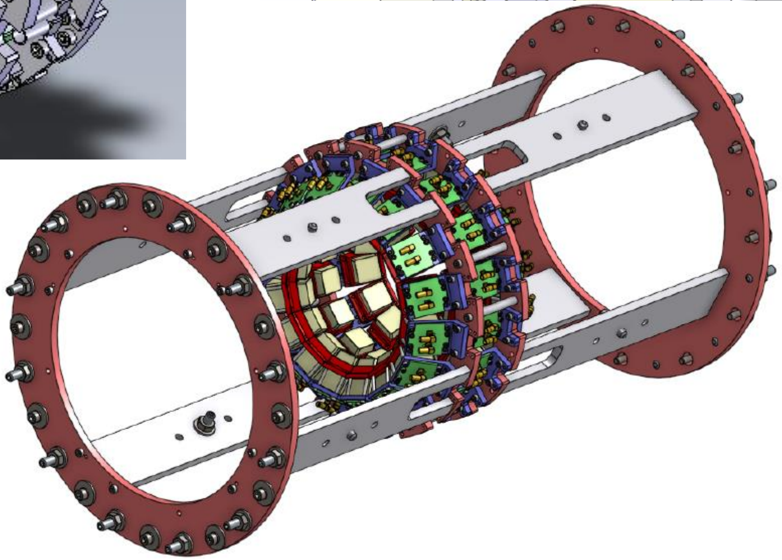
No show stopper so far to reach an order of magnitude improvement

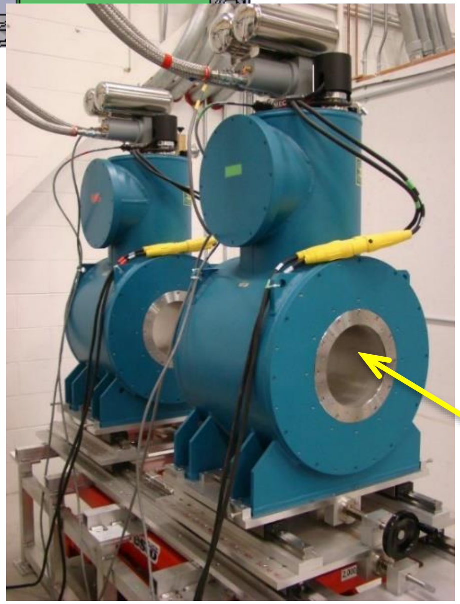
LYSO Array Design

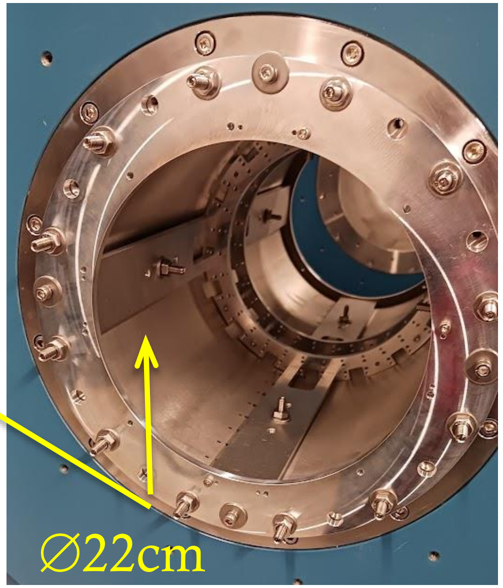
- LYSO: cost effective choice





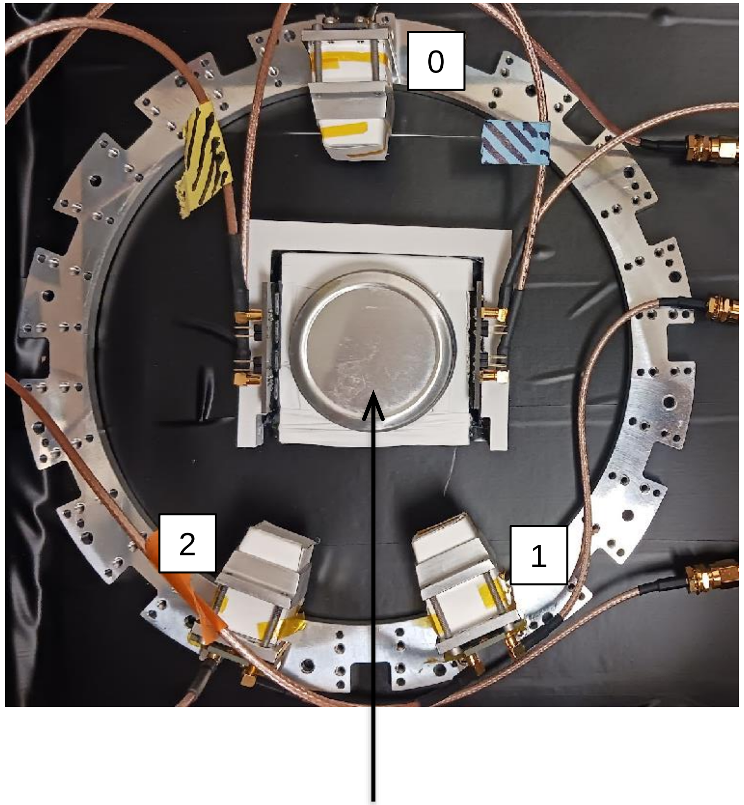




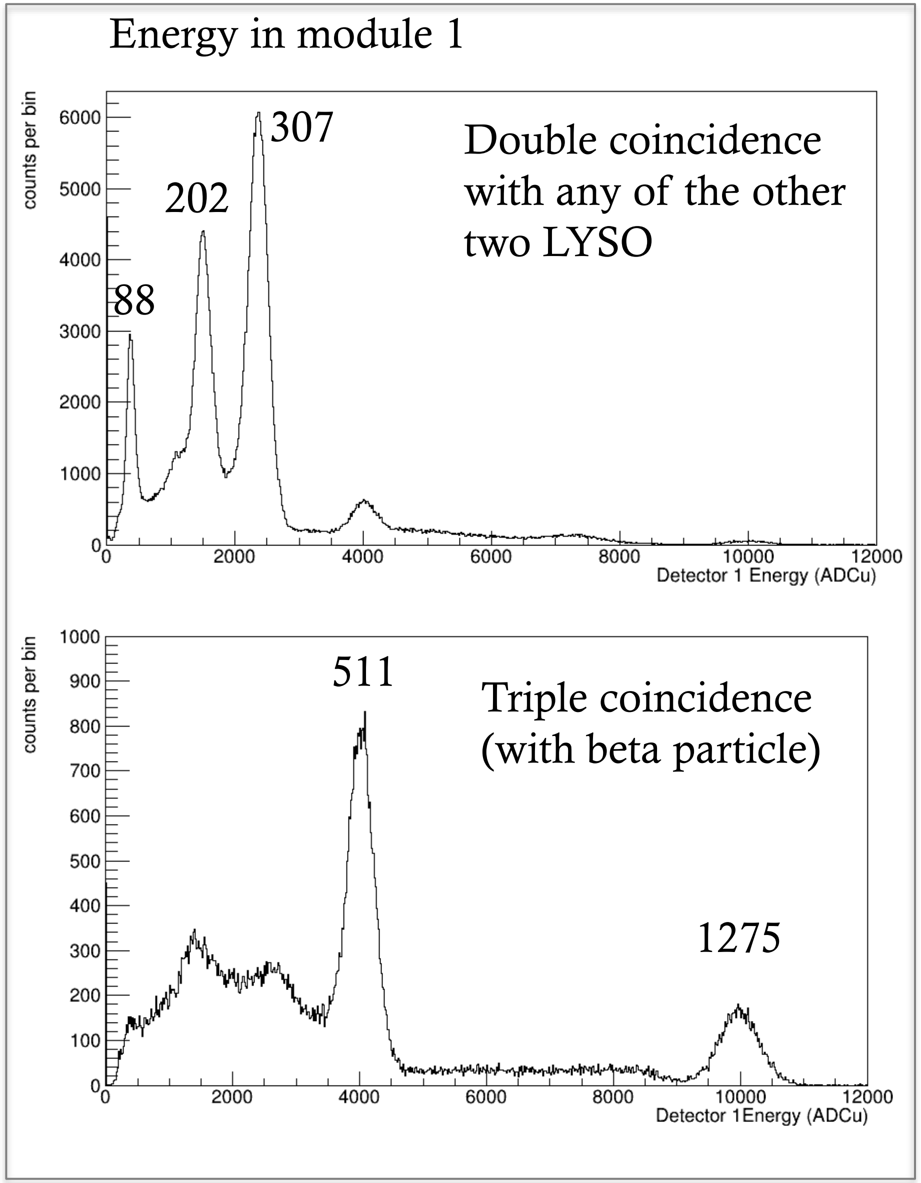


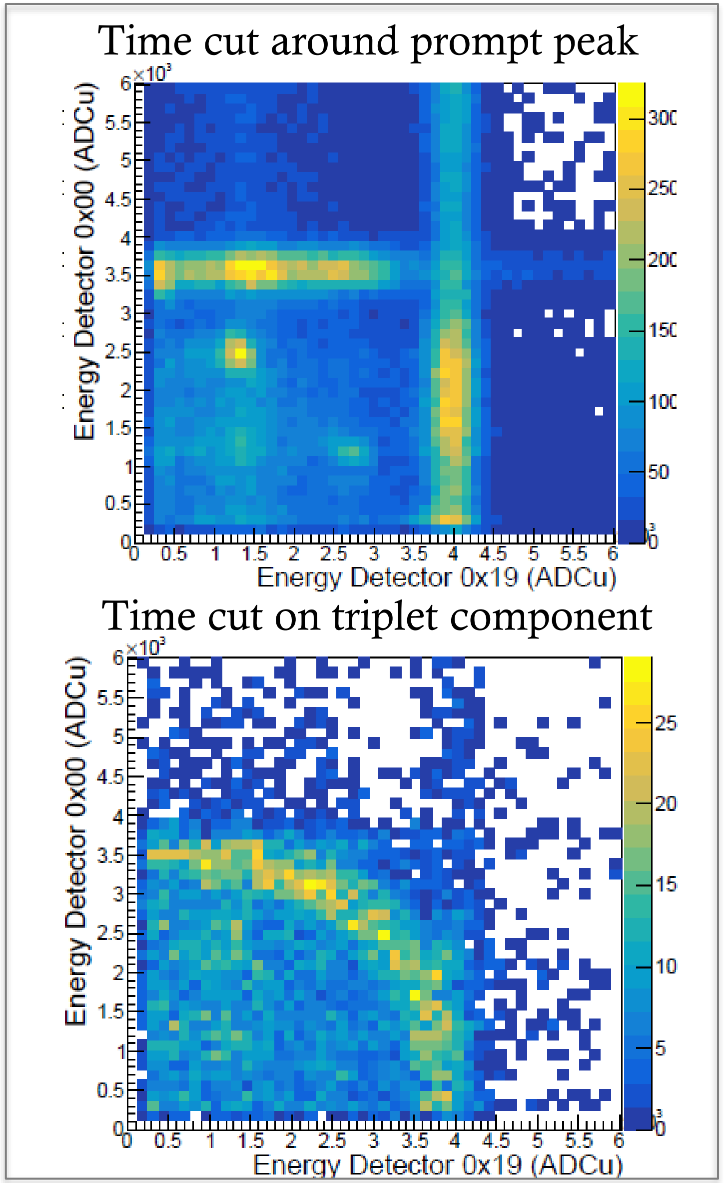
Triple LYSO prototype

T.E. Haugen, FRIB-MSU, 2024



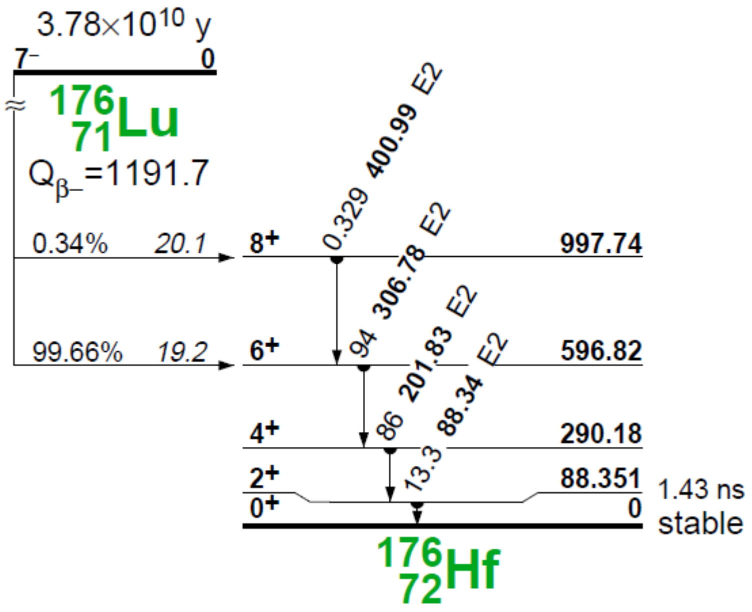
- ^{22}Na source and silica aerogel
- PVT start detector readout with SiPMs



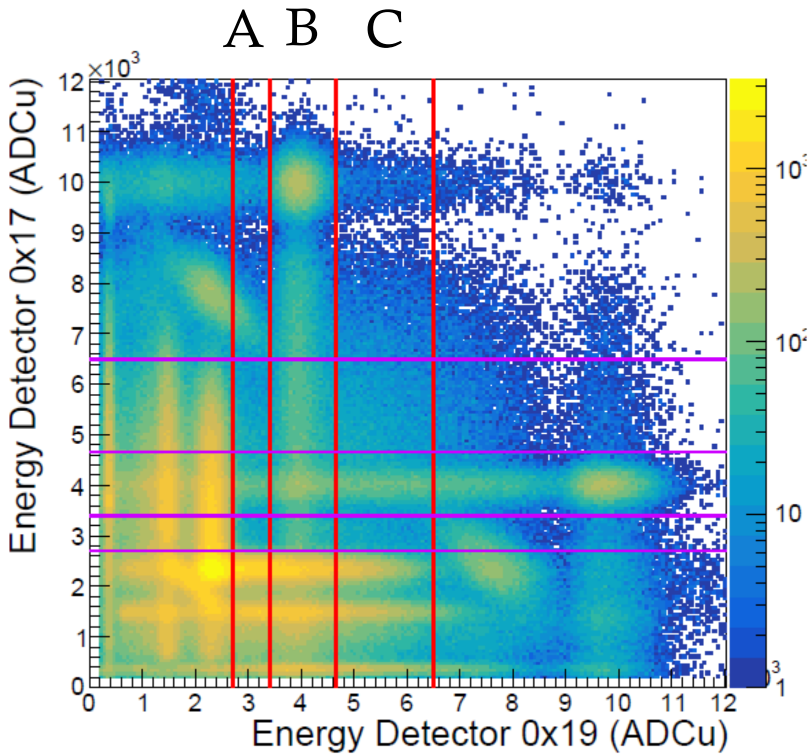


LYSO intrinsic background

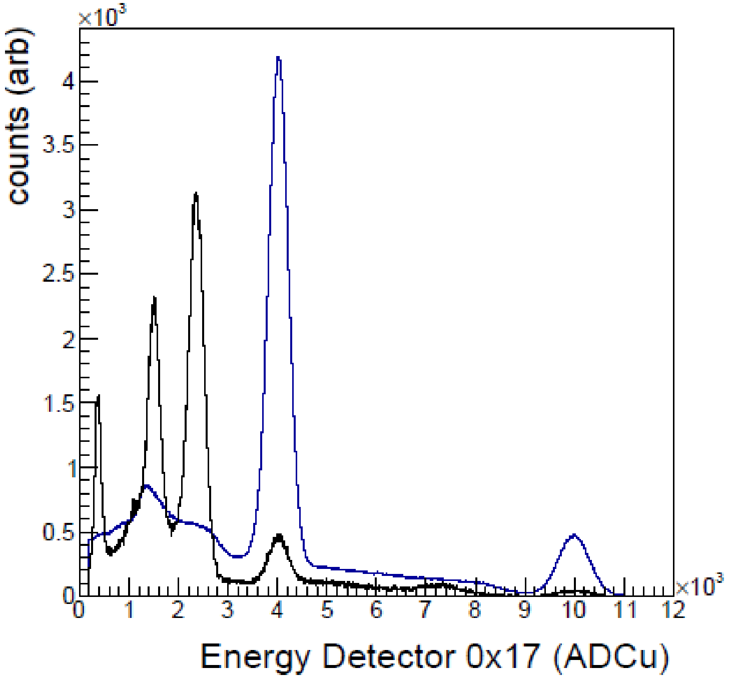
T.E. Haugen, FRIB-MSU, 2024



$E_{\beta max}$ = 595 keV



Blue: in coincidence with start
Black: projection from windows A and C



LYSO background will be used to routinely monitor the gain stability and position of energy thresholds

Summary and Timeline

- We have designed a setup that will enable an order of magnitude improvement in sensitivity to search for *CP* violation in ortho-Positronium decay.
- The measuring scheme uses a tunable magnetic field to enhance or cancel the *CP*-violating signal.
- The setup is planned to be completed and commissioned in the spring-summer 2025.
- First run is expected to take place in 2025…stay tuned!

People & Institutions

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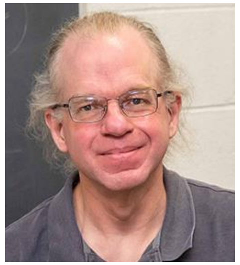

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