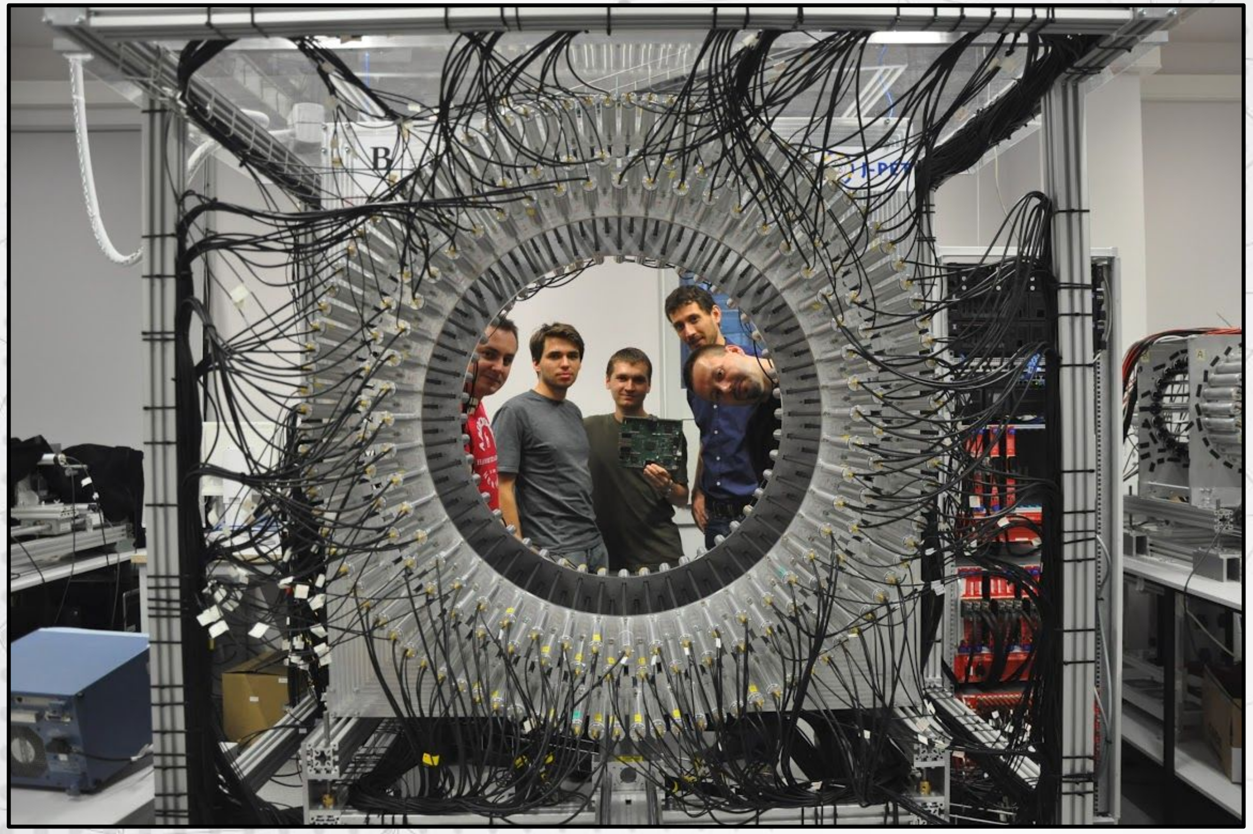
Preliminary investigation of time reversal symmetry violation using the J-PET detector

Juhi Raj
On Behalf of the J-PET Collaboration
Jagiellonian University, Krakow, Poland



“Investigating the Universe with exotic atomic and nuclear matter”, Workshop, LNF-INFN, Frascati, September 29-30, 2020

Precision tests in T-Symmetry Violation in the Leptonic Sector:

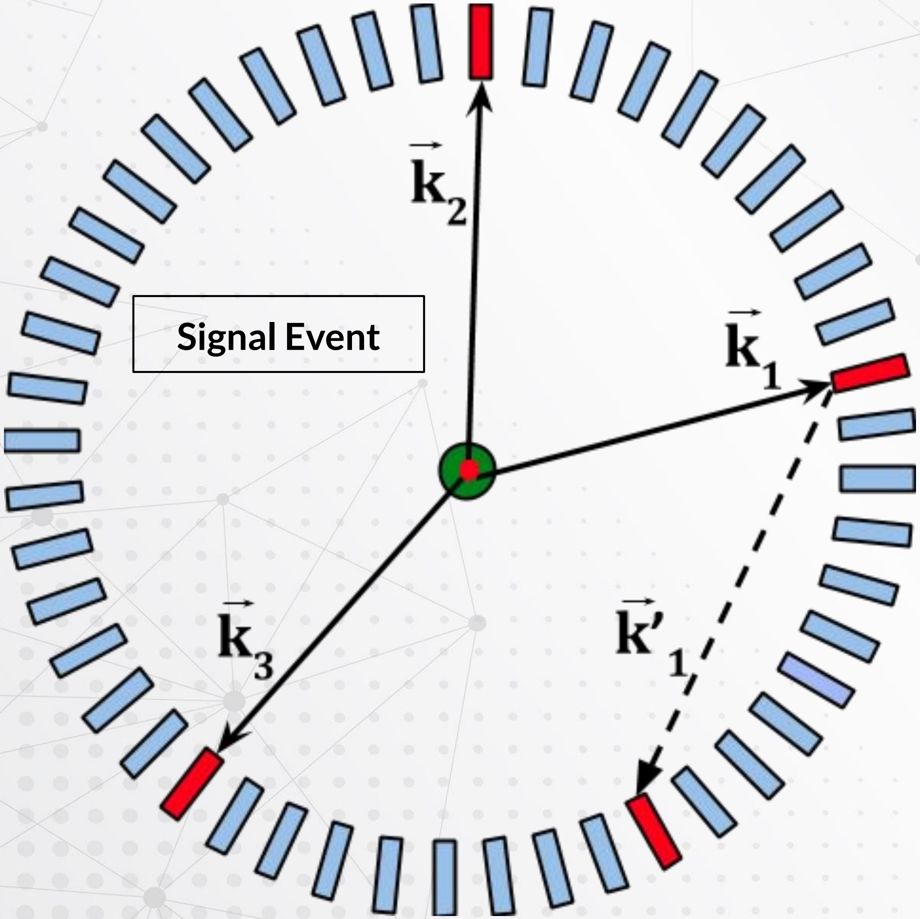


Figure 1: Schematic of the single layer of plastic scintillators in the J-PET detector as the blue ring. Measurement methods to study the operators in Table 1.

P. Moskal et al., Acta Phys. Polon. B 47, 537 (2016)

So far, No CP- violation was observed with a sensitivity of **2.2×10^{-3}**.

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

Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k_1}$	+	−	+	−	−
$\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$	+	+	−	+	−
$(\vec{S} \cdot \vec{k_1}) \cdot (\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$	+	−	−	−	+
$\vec{\epsilon_1} \cdot \vec{k_2}$	+	−	−	−	+
$\vec{S} \cdot \vec{\epsilon_1}$	+	+	−	+	−
$\vec{S} \cdot (\vec{k_2} \times \vec{\epsilon_2})$	+	−	+	−	−

Operator	C	P	T	CP	CPT
$\vec{\epsilon_1} \cdot \vec{k_2}$	+	−	−	−	+

Table 1. Discrete symmetry odd-operators using spin orientation of the o-Ps as well as polarization and momentum directions of the annihilation photons

A.Gajos et al., Adv. in HEP vol. 2018, Article ID 8271280

Energy Deposition as a function of Time Over Threshold (TOT):

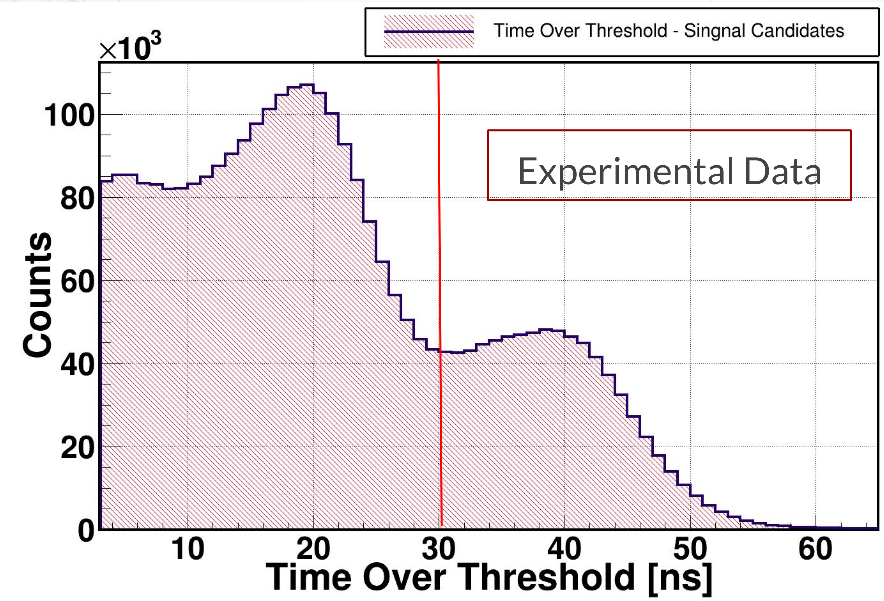


Figure (left): The de-excitation photon is identified using the time-over-threshold (TOT) measurement which is related to the energy deposited in the scintillator.

The figure shows the TOT distribution where one can clearly recognize Compton spectra from 511 keV and 1274 keV gamma photons. The de-excitation photon (1274 keV) may be rejected with the efficiency of about 66% when requiring TOT smaller than 30ns.

M. Palka et al., JINST 12 P08001, (2017)

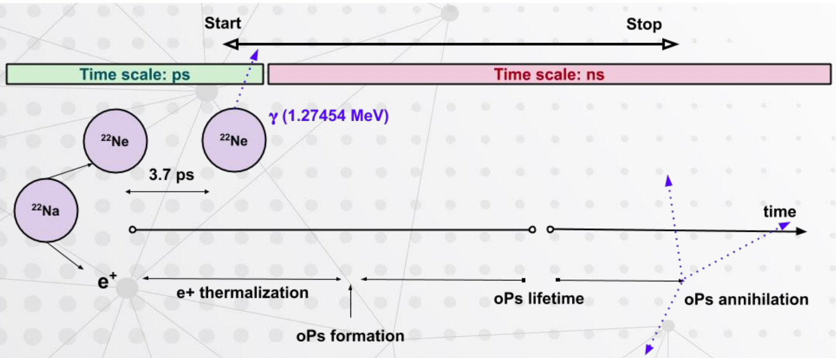
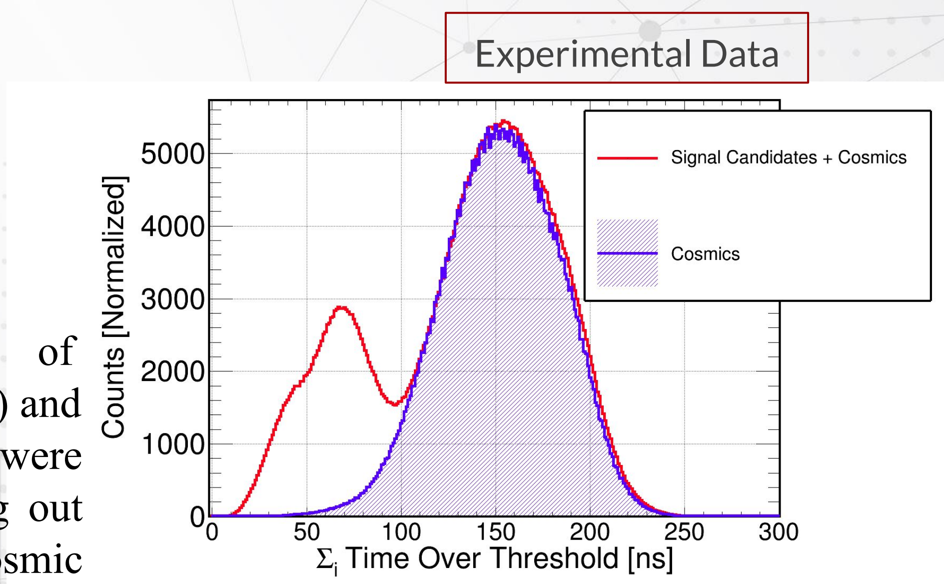


Figure (right): Experimental distribution of time-over-threshold (TOT) for measurement with (red) and without (blue) positronium source. The spectra were normalized to the same measurement time. Cutting out events above 100 ns reduces the registered cosmic radiation by 97.5%



Identification of the Scattered Photon:

Where, $\Delta_{MC} = t_M - t_C$

t_C = Calculated Time of Flight

$t_M = t_{1'} - t_1$ = Measured Time of Flight

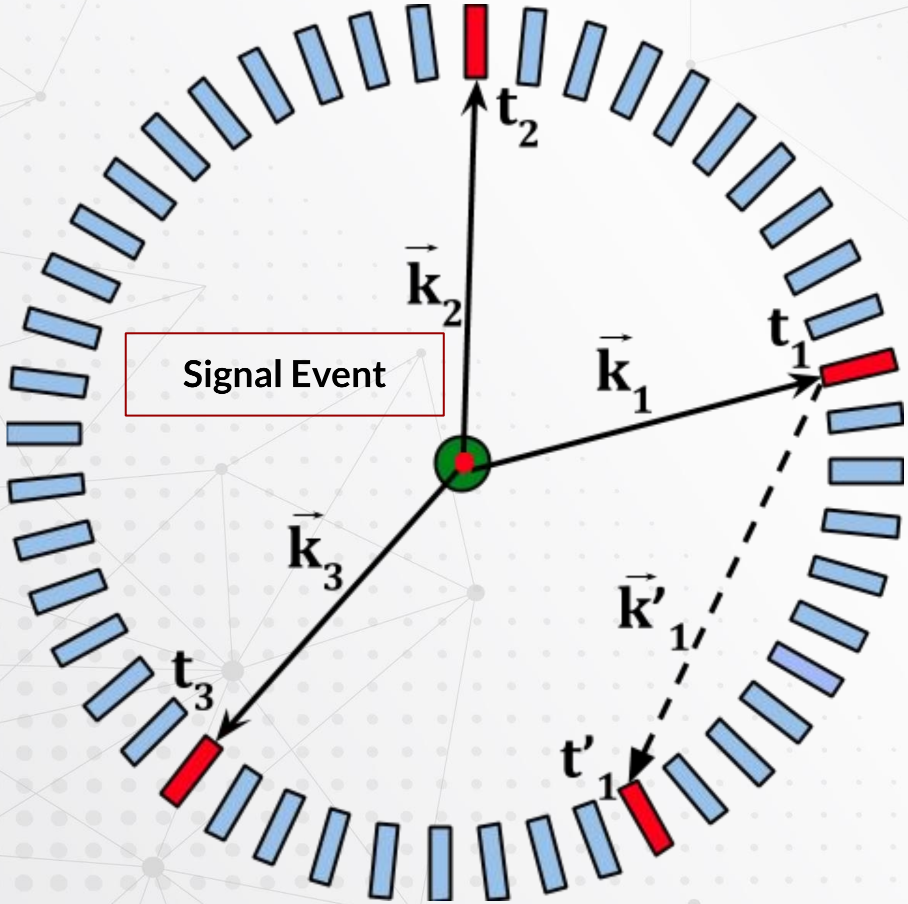


Figure 8a: Schematic of the single layer of plastic scintillators in the J-PET detector as the blue ring.
A point like positron source (red) is placed in the center, covered in XAD-4 porous polymer (green).
The superimposed arrows indicate the three gamma photons originating from the annihilation of ortho-positronium decay (k_1, k_2 and k_3), and scattered photon (k_1)

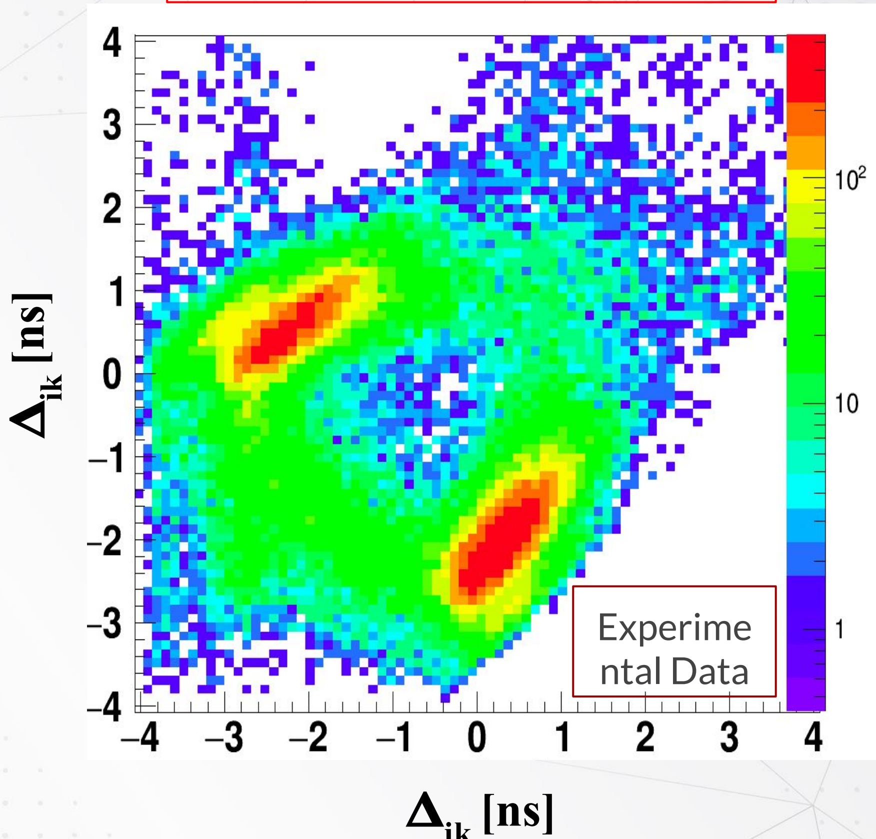


Figure 8b: To assign the scattered photon to its primary photon we introduce a parameter $\Delta_{ik} = (t_M - t_C)$, where, t_M and t_C are the measured and calculated time of flight between the i^{th} and k^{th} interaction, respectively. Therefore, Δ_{ik} should be equal to zero in case if the k^{th} signal is due to the i^{th} scattered photon

J. Raj, et al., Hyperfine Interact, 239:56 (2018)

ortho-Positronium Lifetime :

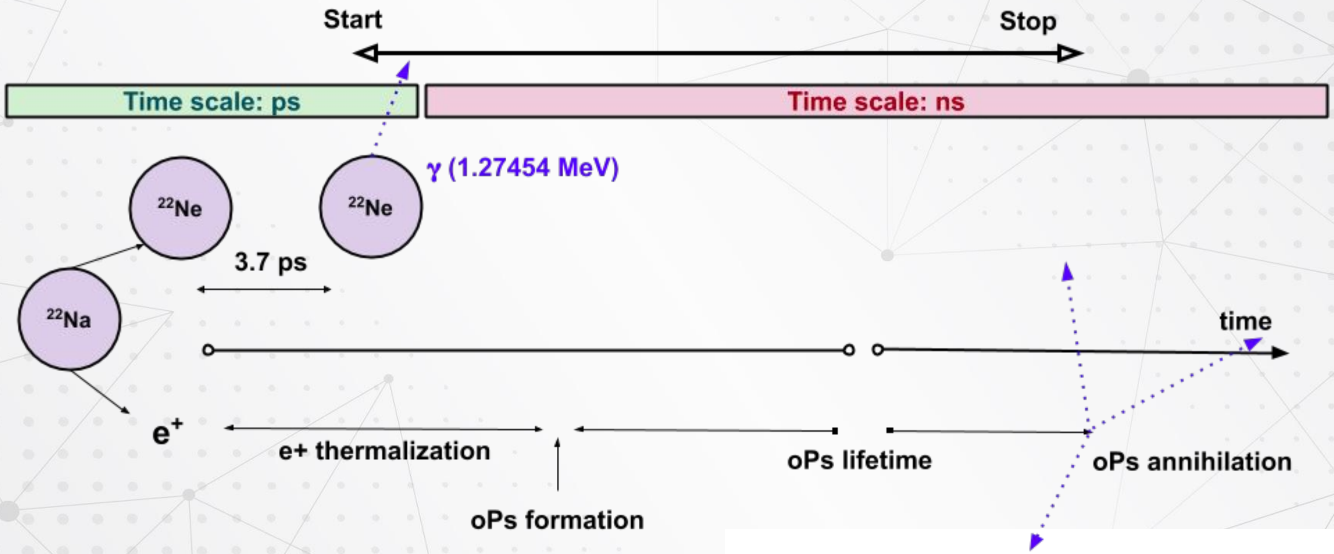


Figure 7a. Decay scheme of Sodium and formation of ortho-Positronium.

K. Dulski, et al., Hyperfine Interact, 239:40 (2018)

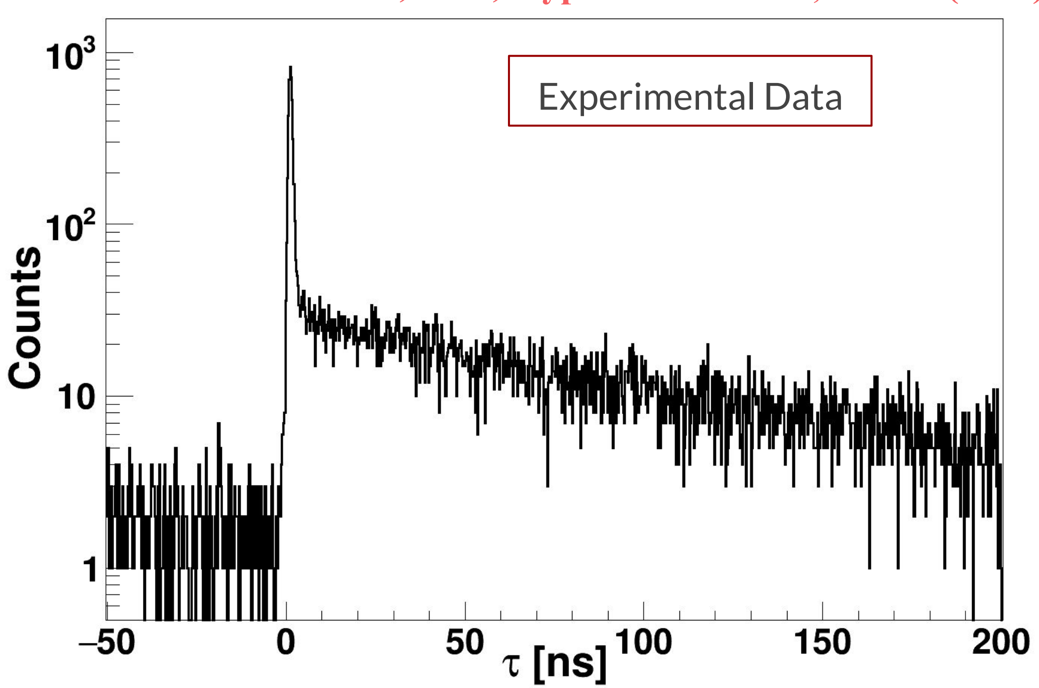
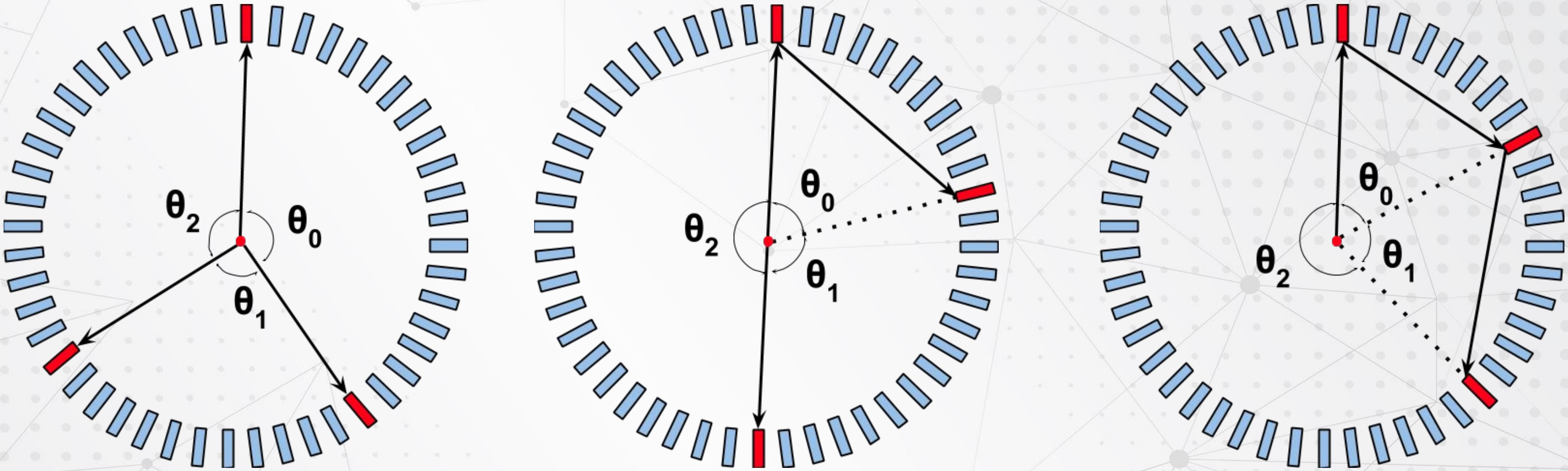


Figure 7b. Positron lifetime distribution in the XAD4, obtained from measurement with the J-PET detector.

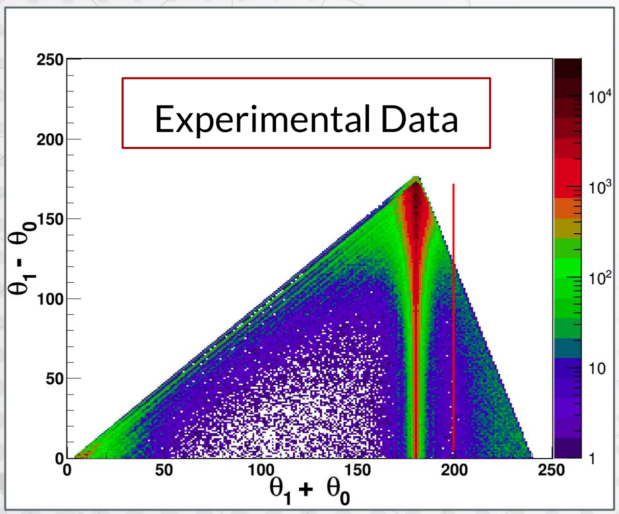
Measurement was conducted by placing a ^{22}Na source covered in XAD4 polymer in the center of the geometry.

The lifetime spectra was obtained by identifying the prompt photon and the three annihilated photons from the decay of o-Ps

Relative azimuthal angles of the interacting photons in an event:



o-Ps -> 3g   p-Ps -> 2g + g'   1 g + 2g'



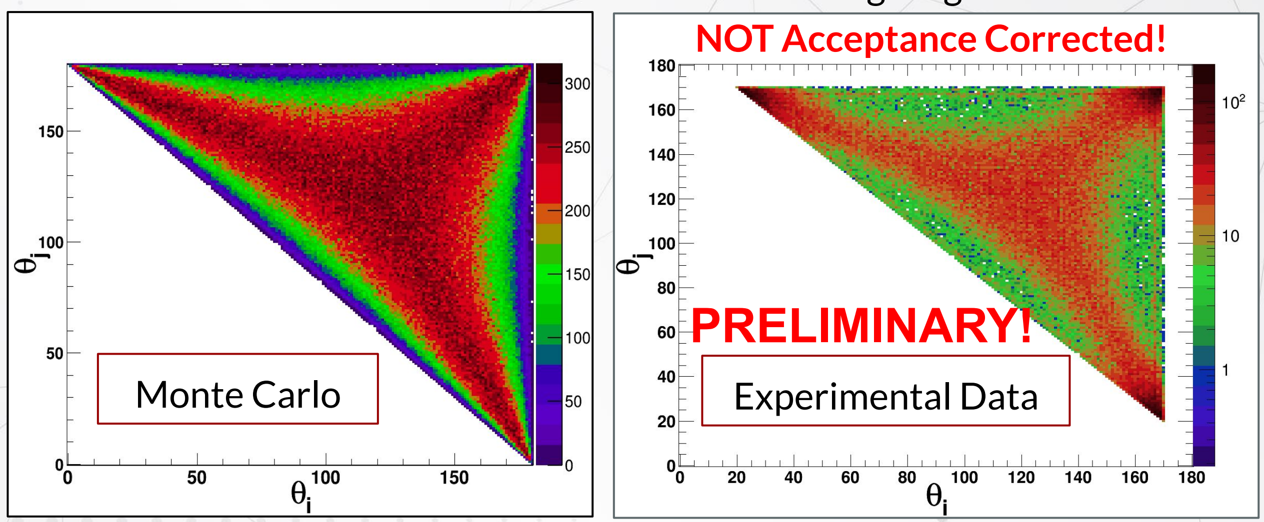


Figure 6 a: Represents the distribution of the sum ($\theta_1 + \theta_0$) and difference ($\theta_1 - \theta_0$) of the two smallest azimuthal angles between the 3γ of o-Ps decay.

Figure 6 b: Represents the distribution of the relative azimuthal angles between the decay of o-Ps into 3γ. (Left) Generated Monte Carlo and (Right) Measured Experimental Data.

Analysis Optimization:

There are six analysis cuts that we use in the analysis chain:

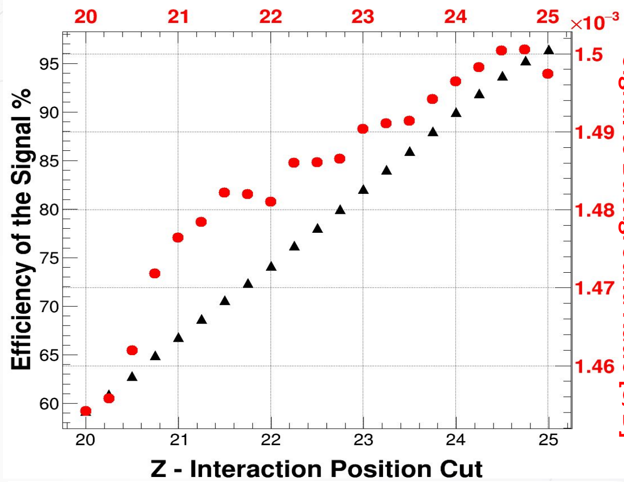
- |Scatter Test Least| <= 0.4 ns
- Angle 3D Sum >= 189.75 degrees
- Emission Time <= 0.35 ns
- Time Over Threshold <= 21.75 ns
- |Z - Interaction Position| <= 22.0 cm
- Distance of the Annihilation plane <= 1.35 cm

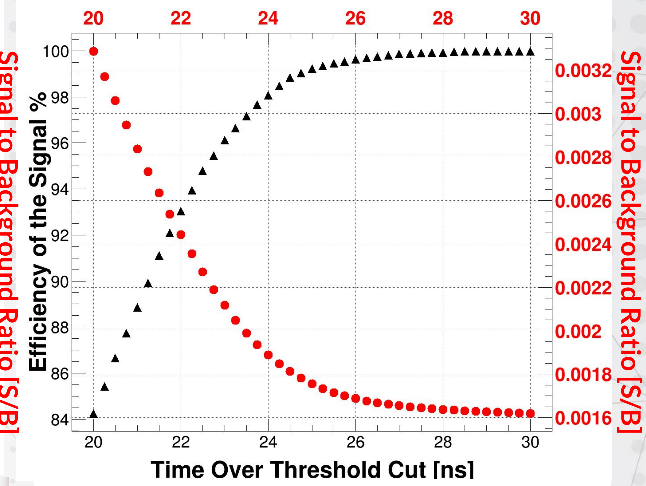
The cuts are optimized using the following quantities:

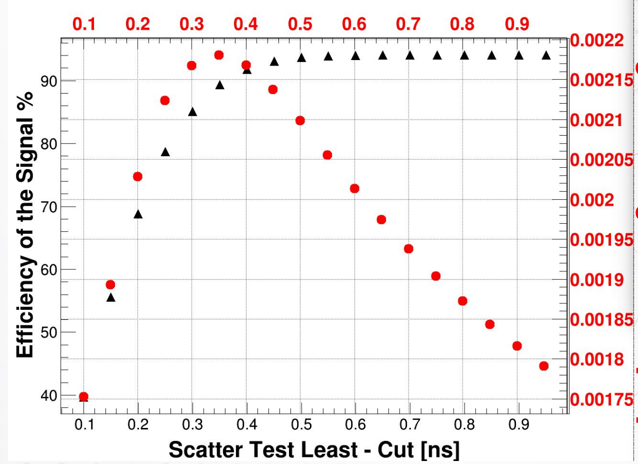
Efficiency of Signal % = (no. events before_cut/ no. events after_cut)x100
S/B = no. Signal Events / no. Background Events

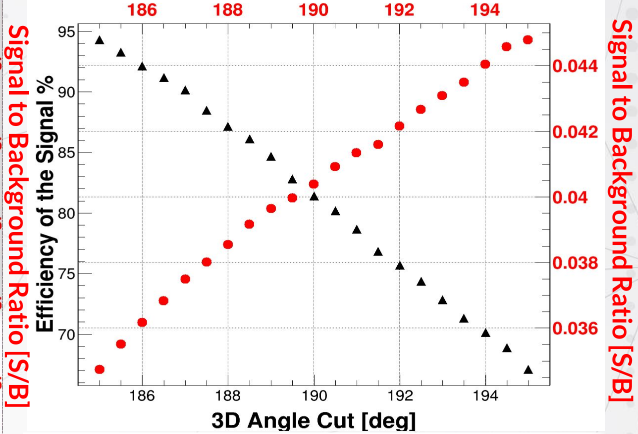
Purity of the Data Sample =**~76.64%**
Efficiency of the Signal Events =**~45.13%**

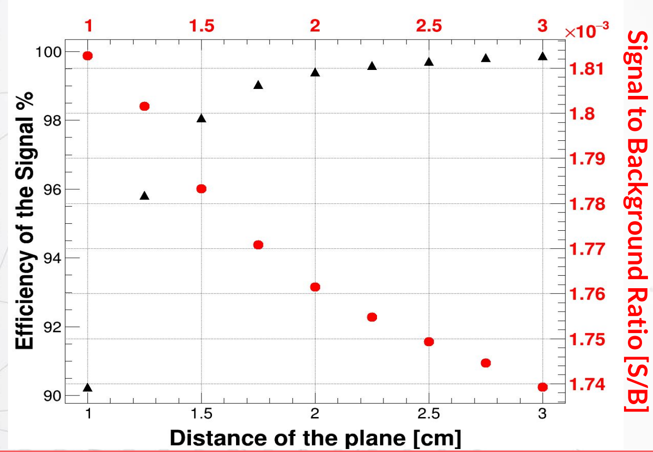
Note: All of the above information is obtained from the default monte-carlo production.

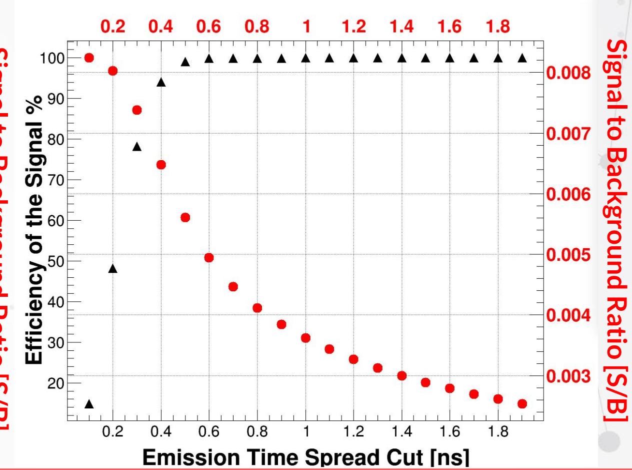




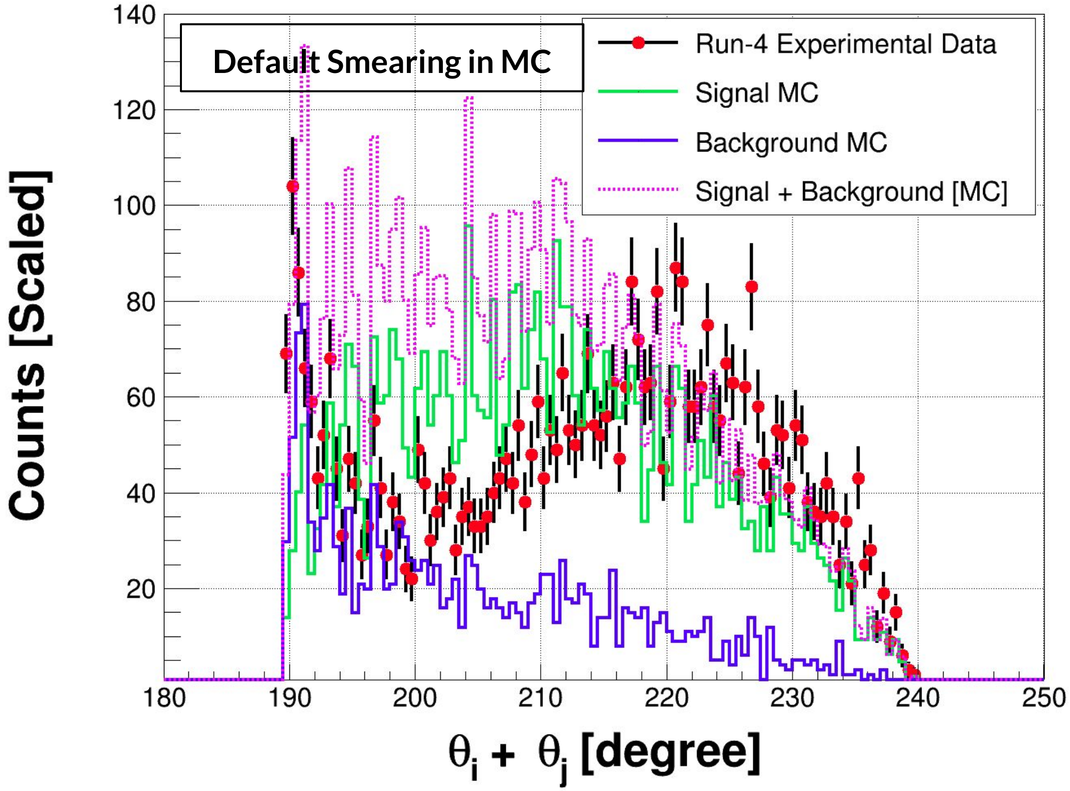


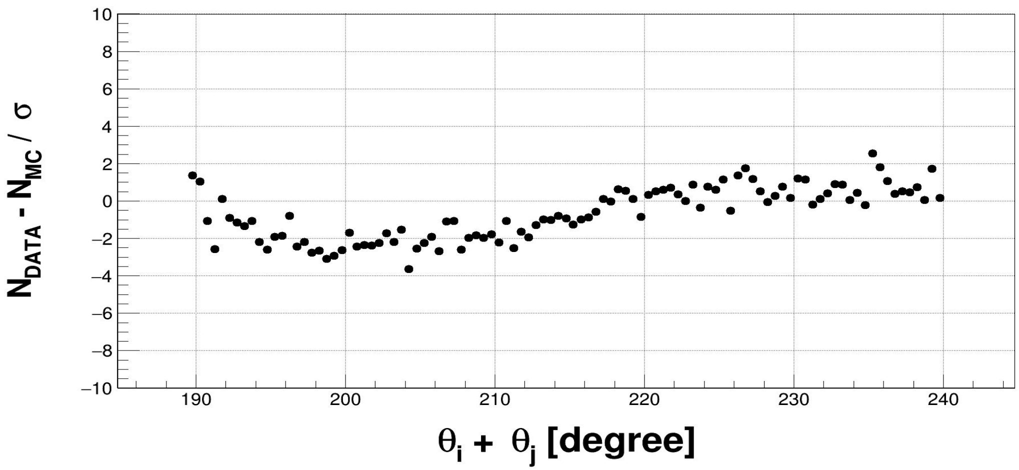






Minimization for maximum likelihood between MC and Experimental Data:





$$\chi^2 = \frac{(N_{Di} - N_{MCi})^2}{Error^2}$$

$$N_{MCi} = A \times N_{Sigi} + B \times N_{Bcgi}$$

$$Error = Error(N_{Di}) + Error(N_{MCi})$$

$$Error = Error(N_{Di}) + Error(N_{MCi})$$

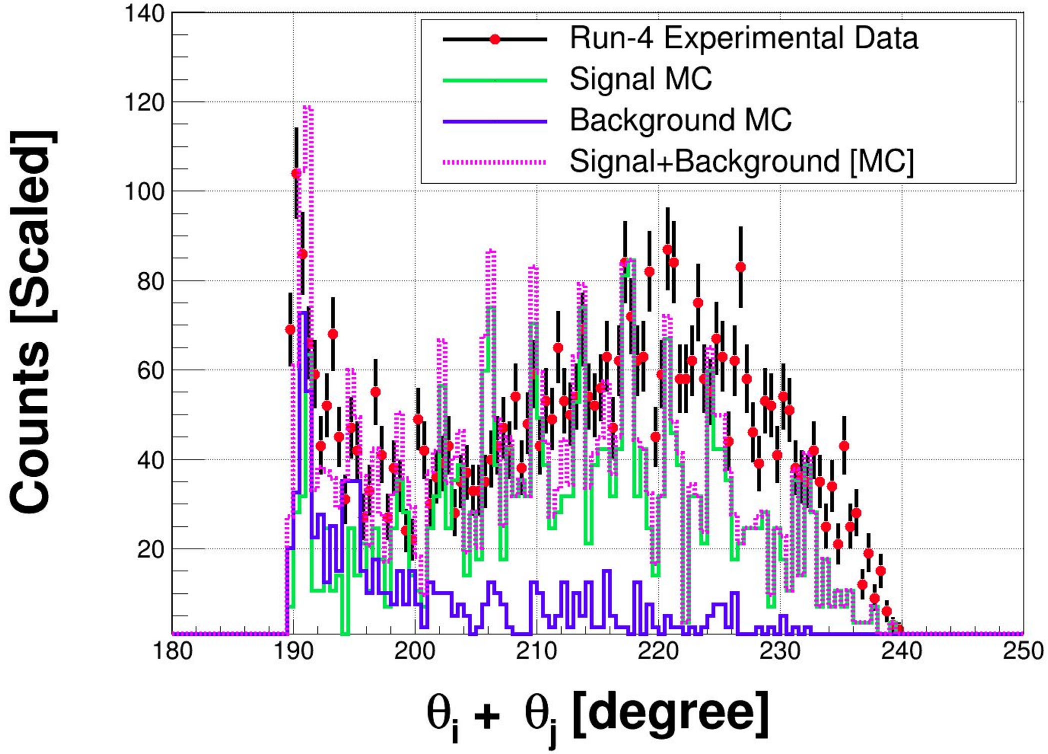
$$Error(N_{Di}) = \sqrt{(N_{Di})}$$

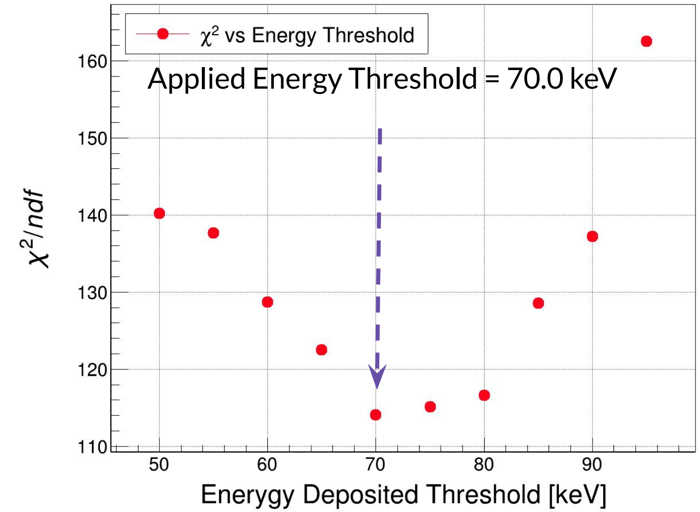
$$Error(N_{MCi}) = A \times \sqrt{(N_{Sigi})} + B \times \sqrt{(N_{Bcgi})}$$

- The results on the left panel show the maximum likelihood between the Monte Carlo (default settings) and Experimental Data.
- The spectra on the lower left panel shows the residual between the Monte Carlo and Experimental Data.
- The Scaling Parameter for Signal Monte Carlo events is A = 15.427 +/- 0.027
- The Scaling Parameter for Background Monte Carlo is B = 9.916 +/- 0.042

*MC - Monte Carlo

Minimization for maximum likelihood between MC and Experimental Data:



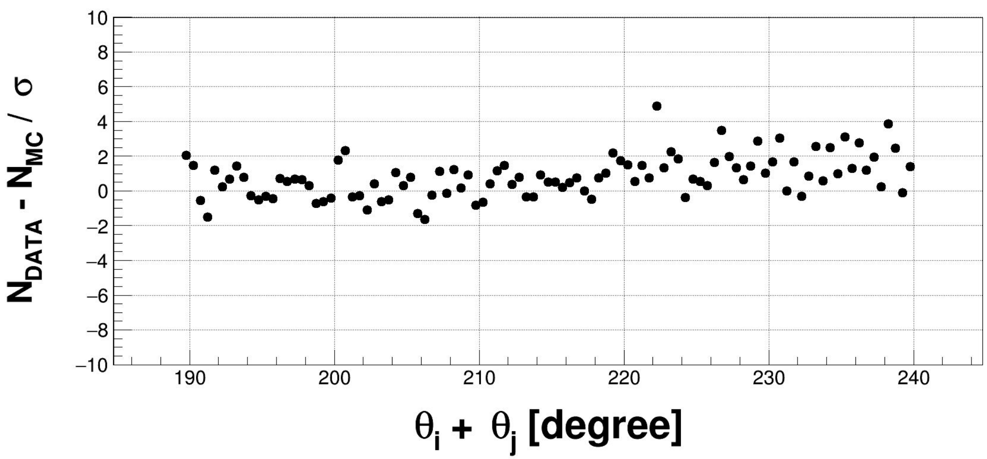


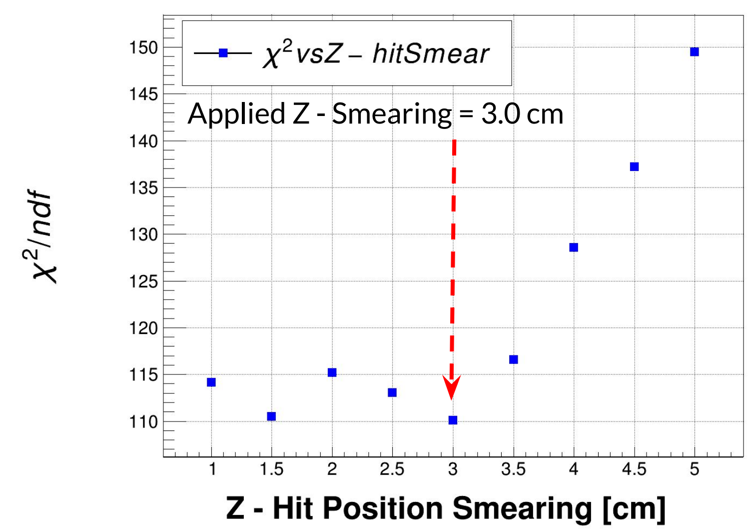
$$\chi^2 = \frac{(N_{Di} - N_{MCi})^2}{Error^2}$$

The X^2 minimization is used to find the scaling factors for the signal and background. The X^2 is estimated as shown in the formula on the left and Slide #8.

Scaling Parameter for Signal **(A)** = 22.939 +/- 0.756

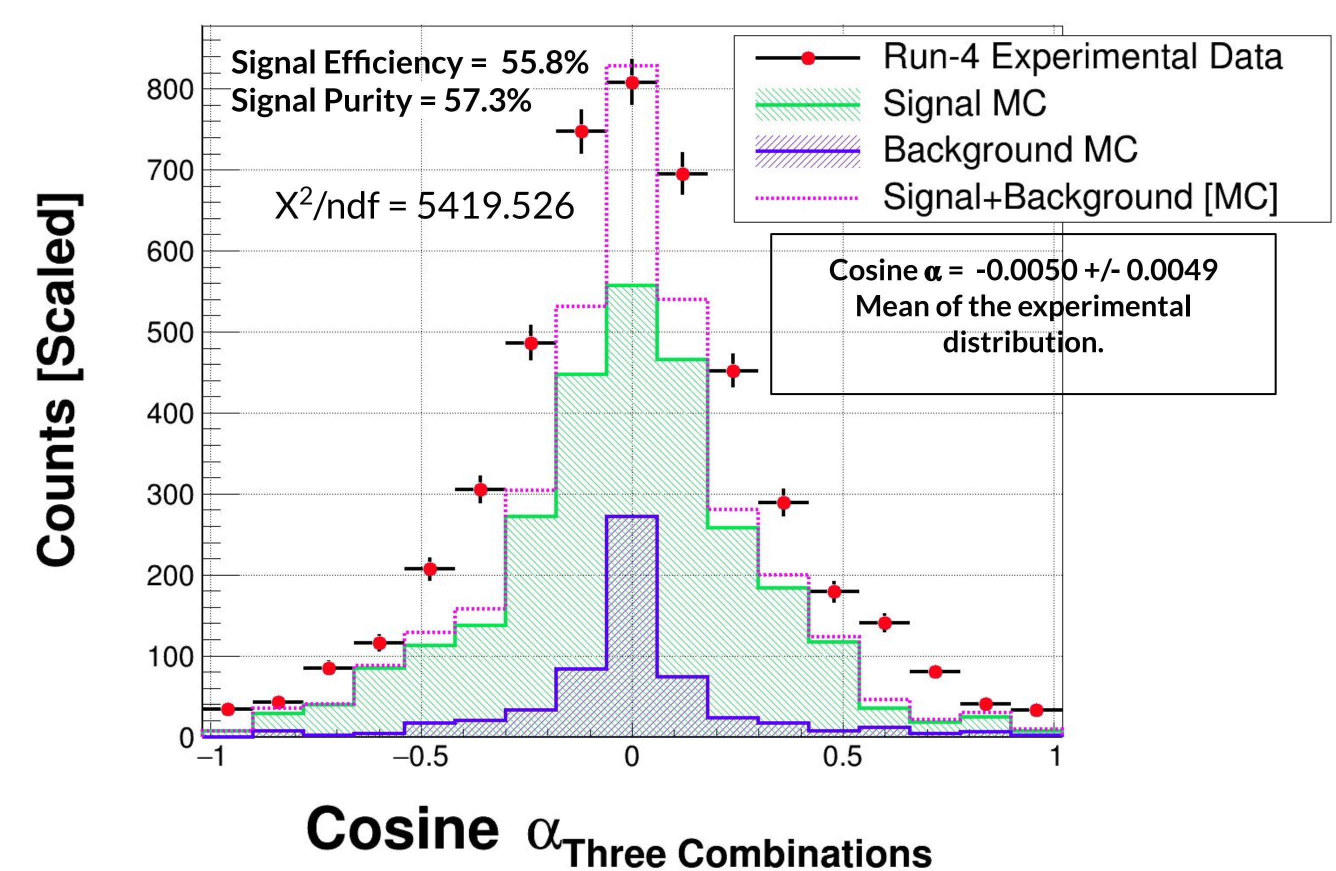
Scaling Parameter for Background **(B)** = 7.698 +/- 0.123





Minimizer for maximum likelihood between MC and Experimental Data:

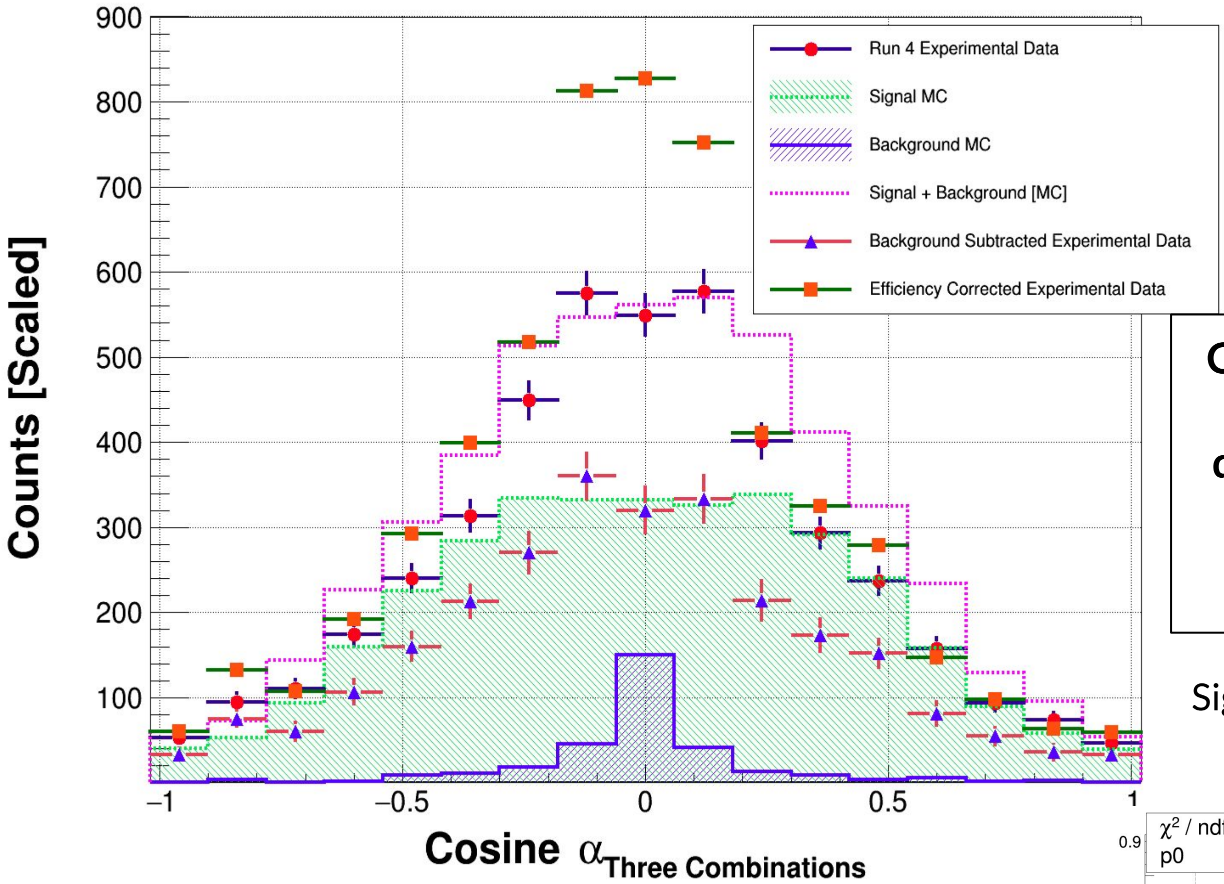
- Scaling Parameters for the Signal and Background is obtained using the Minimization on the sum of the two smallest angles spectra as shown in Slide #9.
- The obtained scaling parameters are used on the below given distribution for maximum likelihood between the MC and experimental data.
- The Purity of the Signal sample after the analysis is ~ 57.3 %
- Signal efficiency of the analysis is ~ 55.8 %



$$Cosine(\alpha) = \frac{\vec{\epsilon_i} \cdot \vec{k_j}}{|\vec{\epsilon_i}||\vec{k_j}|}$$

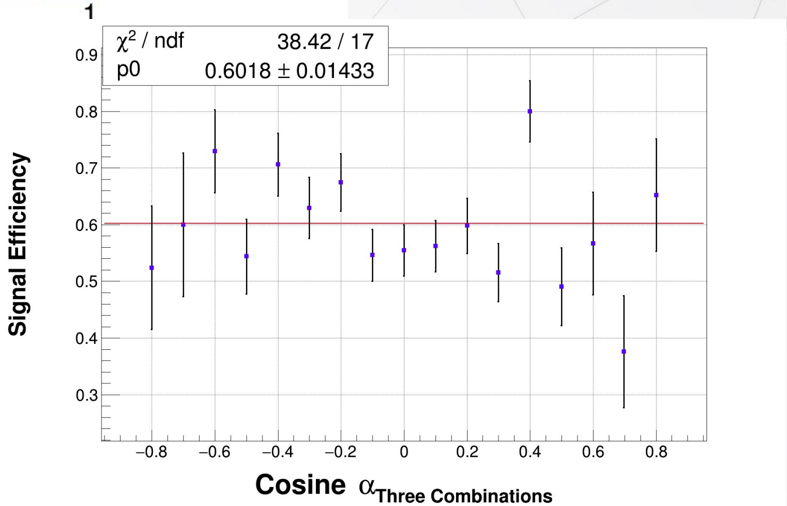
- The Distribution on the left panel is the spread of the expectation value i.e., the angle between the two vectors in the symmetry-odd operator.
- The background monte-carlo and signal monte-carlo is scaled using the parameters from the minimization used in the previous.

Signal Efficiency Correction using the most optimum Monte Carlo:



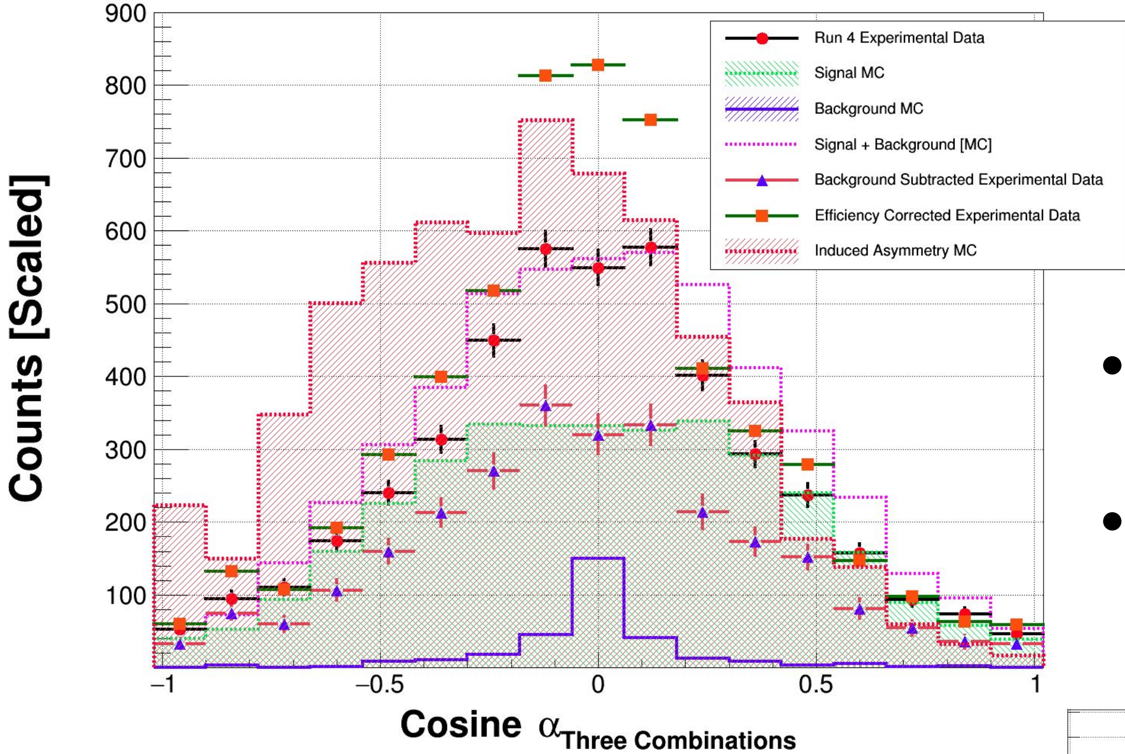
Cosine $\boldsymbol{\alpha}$ = -0.0039 +/- 0.0010 Mean of the experimental distribution with background subtraction and efficiency correction.

Signal Efficiency Map for the Cosine($\boldsymbol{\alpha}$) distribution using Monte-Carlo.



- The efficiency map is obtained from the generated and reconstructed Monte-Carlo.
- The errors of the efficiency is obtained using the binomial method.
- The Scaled background is subtracted from the experimental data.
- Then the efficiency calculated (right panel) is applied to the experimental data in order to obtain the true spread of the operator.

Inducing the Asymmetry in the generated Monte Carlo to obtain the best fit result:



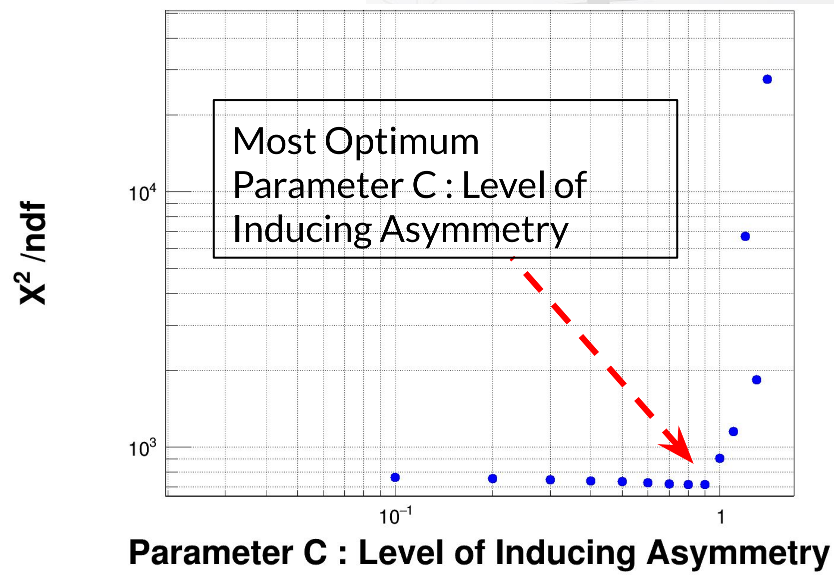
$$\chi^2 = \Sigma_i [\frac{Data_i - D.(1 - CX_i).Sig_i}{\sigma}]^2$$

Where,

$$\sigma^2 = (\sqrt{Sig_i})^2 + (D.(1 - CX_i)\sqrt{Data_i})^2$$

- Parameter D: Scaling factor for the MC - Signal Events.
- Parameter C: Induced Asymmetry.

- The Monte-Carlo simulations are produced without any asymmetry i.e., completely symmetric.
- So we use a function to produce a set of scaling parameters for maximum likelihood of the Monte-Carlo to the experimental data.



Systematic Error Estimations:

Systematic Contribution from the Experimental Analysis			
Type of Data Used	Name of the Analysis Cut:	**σ** (Resolution)	Systematic Error (**σ**)
Monte - Carlo (Signal)	X Position Source	0.06 mm	+/- 0.00006
	Y Position Source	0.06 mm	+/- 0.00006
	Z Position Source	0.2 mm	+/- 0.00003
Experimental Data	Time Over Threshold	0.5 ns	+/- 0.00071
	3D Angle Sum	0.03 degree	+/- 0.000008
	Emission Time Spread	0.0002 ns	+/- 0.000348
	Z Position Interaction	0.0005 cm	+/- 0.001305
	Distance of the Plane	0.0018 cm	+/- 0.00444

- In order to estimate the contributions to the systematic uncertainty of the result, the full analysis chain is repeated varying all the analysis cut values of selection variables by +/- an amount comparable to their experimental resolution.
- The full analysis chain is repeated varying all the analysis cut values of selection variables by +/- an amount comparable to their experimental resolution.

Cosine ***α*** = **-0.905 +/- 0.0055 ($\sigma_{\text{statistical}}$) +/- 0.0047 ($\sigma_{\text{systematical}}$)**

Note: The above mentioned checks are the basic contributions to the analysis. There are some more checks to be made for the future.

Things to do:

- Re-order the estimations for the final investigation of the asymmetry.
- Optimization of the remaining monte-carlo smearing parameters.
- Make the X^2 estimations for the monte-carlo more granular.
- Fit a continuous function on the X^2 estimations for the smearing parameters.
- Time - Smearing adjustment.
- Redo everything for all the respective Experimental Runs.
- Systematic contribution.

Acknowledgments:

- This work is funded by the DSC grant no. 2019-N17/MNS/ 000036 and Opus-11 2019-N17/MNS/000017.
- The pre-selection of data was greatly supported by the computational resources provided by CIS-Swierk and Jagiellonian University.
- The experimental data-campaign was conducted in Jagiellonian University.