Investigation of o-Ps Decay for Improving CP Symmetry Test Precision with the J-PET Detector

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On behalf of the J-PET collaboration

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FONDAZIONE BRUNO KESSLER

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

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J-PET GROUP

MOTIVATION

- ❑ CP is one of the discrete symmetries of nature given by the product of two components: charge conjugation (C) and parity (P).

- ✓ In 1964, Val Fitch, Jim Cronin, and collaborators observed this CP violation for the first time in the neutral kaons decay. **For this discovery Fitch and Cronin were awarded the Nobel Prize in 1980.**

- ❑ According to Standard Model prediction, QED final-state effects in the final state of photon-photon interaction can mimic CP violation at the level of $\mathbf{10^{-9}}$ and $\mathbf{10^{-14}}$ in weak interactions.

- ❑ Experiments around the world are looking for signs of charge conjugation and parity (CP) symmetry violation. We can expect some of these searches might also reveal physics beyond the standard model.

- ❑ CP symmetry test in the charged leptonic sector was conducted in the University of Tokyo in o-Ps decay, by T. Yamazaky and reaches the statistical precision of the order of 10^{-3}.

- ❑ In the year 2021, the limitations of the previous experiments were overcome by the **3-layer J-PET detector which improved the world result and reaches the statistical precision of the order of 10^{-4} for CPT and 10^{-3} CP discrete symmetry studies.**

[1] M. S. Sozzi, "Discrete Symmetries and CP Violation", Oxford (2008). [2] P. Moskal et al., Acta Phys. Polon. B 47, 509 (2016).
[3] M. Kobayashi, T. Maskawa, Prog. Theor. Phys. 49, 652 (1973). [4] T. Yamazaki, T. Namba, S. Asai, T. Kobayashi, Phys. Rev. Lett. 104, 083401 (2010). [5] P. Moskal et al., Nat. Commun. 12, 5658 (2021).

AIM

To test Charge-Parity (CP) Discrete Symmetry in the Ortho-positronium atom decay.

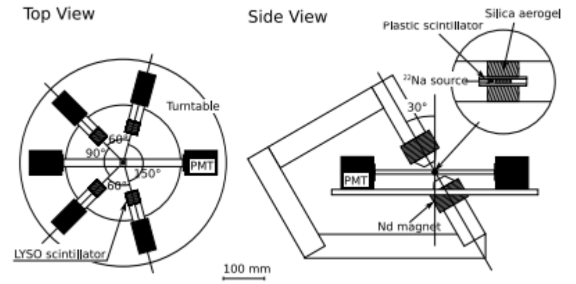
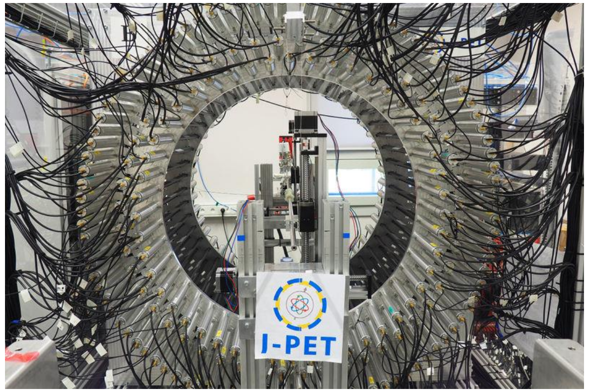
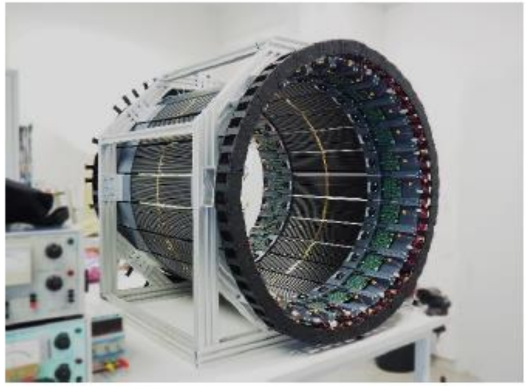


FIG. 1: Schematic diagrams of the experimental setup. The magnified view around the ^{22}Na source is shown in the circle. Left and right show the top and side view, respectively.

T. Yamazaki et. al.

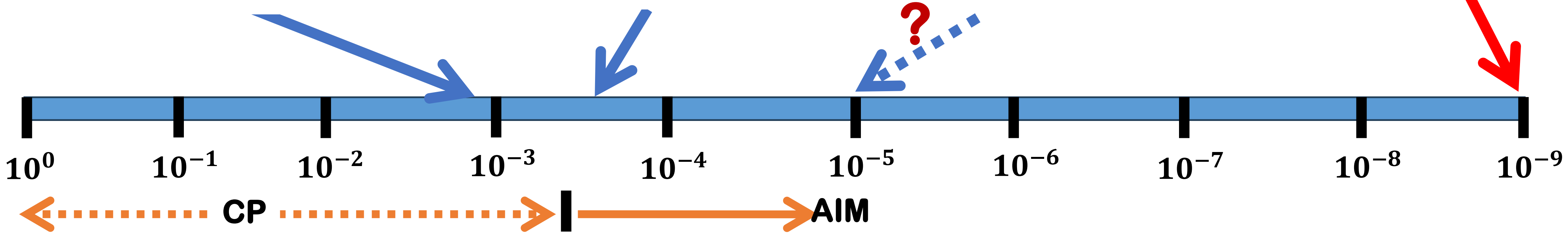


3-layer J-PET Detector



Modular J-PET Detector

Standard Model Prediction of CP-Violation



[1] P. Moskal et al., Acta Phys. Polon. B 47, 509 (2016). [2] T. Yamazaki, T. Namba, S. Asai, T. Kobayashi, Phys. Rev. Lett. 104, 083401 (2010).
[3] P. Moskal et al., Nat. Commun. 12, 5658 (2021).

Introduction

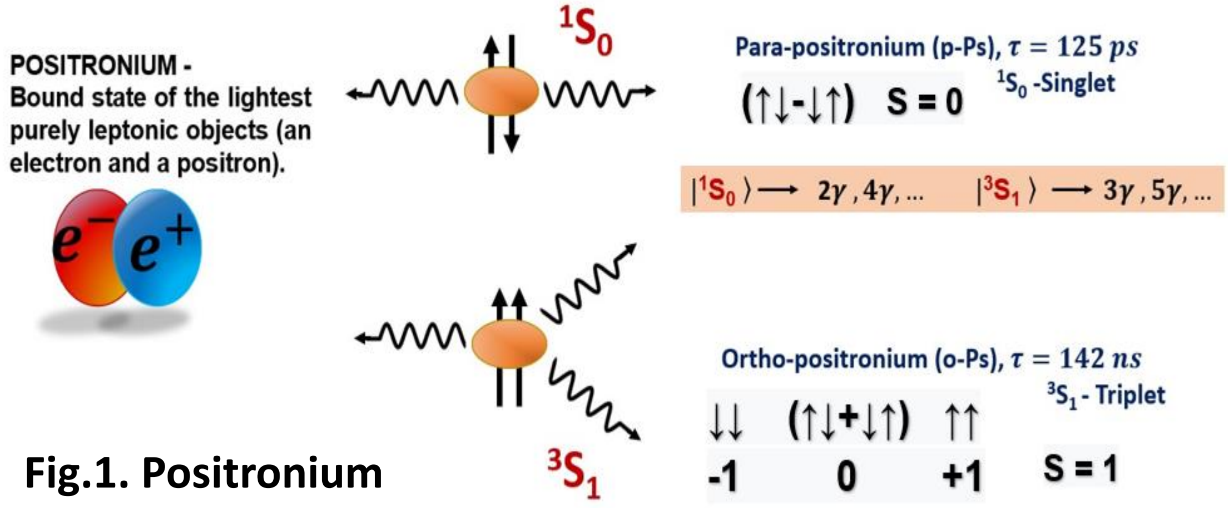


Fig.1. Positronium

Operator	C	P	T	CP	CPT
$\vec{S}.\vec{k_1}$	+	-	+	-	-
$\vec{S}.(\vec{k_1} \times \vec{k_2})$	+	+	-	+	-
$(\vec{S}.\vec{k_1}).(\vec{S}.(\vec{k_1} \times \vec{k_2}))$	+	-	-	-	+
$\vec{\varepsilon_1}.\vec{k_2}$	+	-	-	-	+
$\vec{S}.\vec{\varepsilon_1}$	+	+	-	+	-
$\vec{S}.(\vec{k_2} \times \vec{\varepsilon_2})$	+	-	+	-	-

Table.1. Discrete symmetry odd operators

- One of the unique features of the J-PET detector is its ability to measure the polarization direction of the annihilation photons without the magnetic field.

- The J-PET detector can be used to explore discrete symmetry by looking for probable non-zero expectation values of the symmetry-odd operators, constructed from spin of ortho-Positronium (o-Ps) and momentum, and polarization vectors of gamma (γ) quanta resulting from o-Ps annihilation

[1] M. S. Sozzi, "Discrete Symmetries and CP Violation", Oxford (2008).
[2] P. Moskal et al., Acta Phys. Polon. B 47, 509 (2016).

Experimental Details

❑Test Measurement with the 3-layer J-PET Detector.

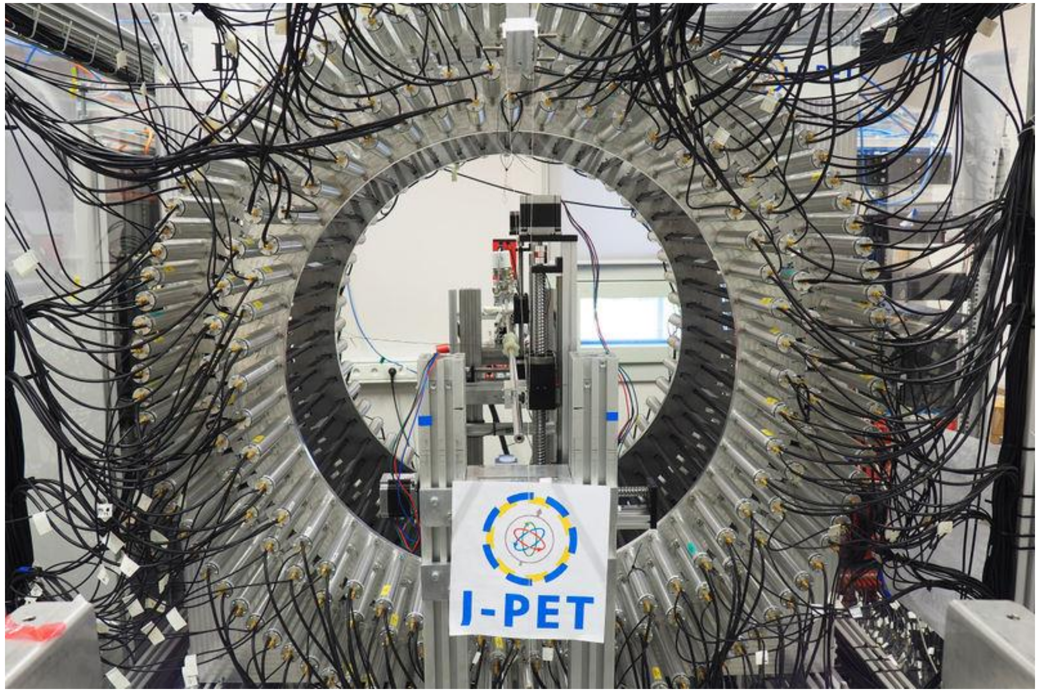
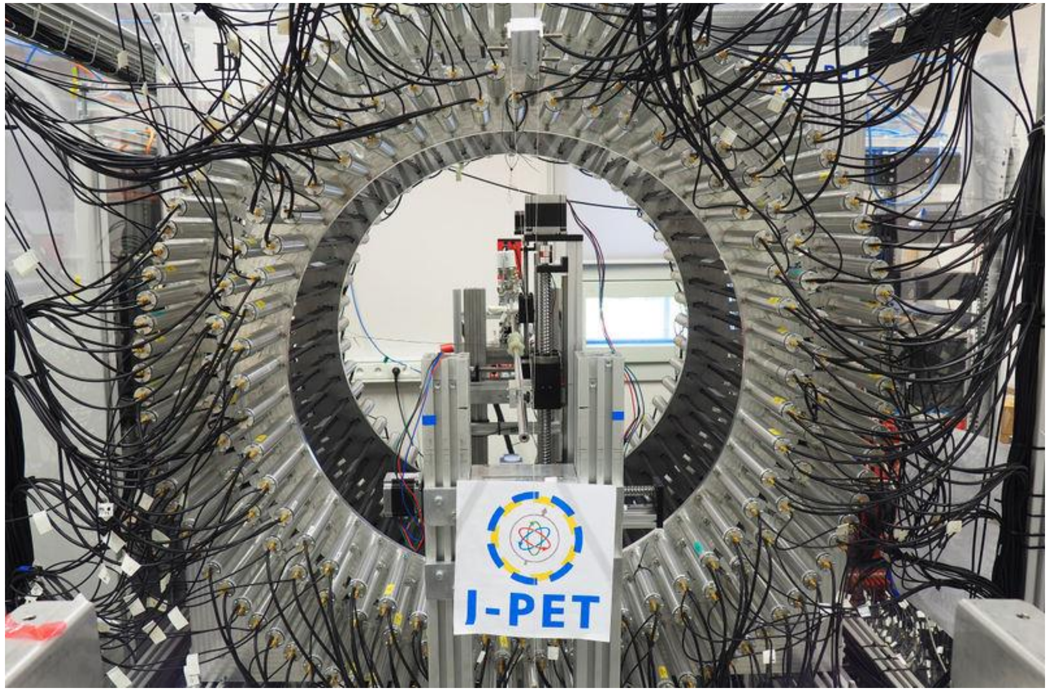


Fig.2: 3-Layer J-PET Detector

- The Jagiellonian-Positron Emission Tomography (J-PET) is the first PET scanner designed using plastic scintillator strips.
- The 192 plastic scintillator strips (EJ230, $500 \times 19 \times 7\ mm^3$ form concentric layers of 48 modules on a radius of 425 mm, 48 modules on a radius of 467.5 mm, and 96 modules on a radius of 575 mm) make up the three layers of the 3-layer J-PET detector
- Each scintillator in the J-PET scanner is optically connected with Hamamatsu R9800 vacuum tube photomultipliers at each end, which read out the optical signals from the scintillators.
- The sides of scintillator strips are wrapped with reflective foil to reduce photon losses

Experimental Details



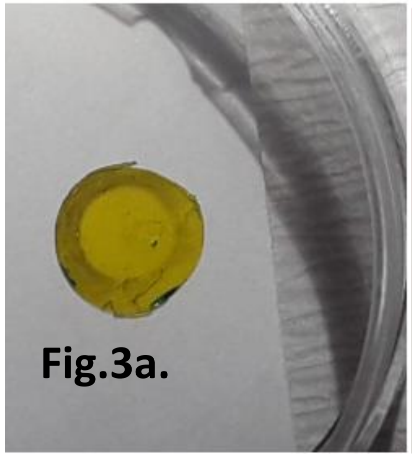


Fig.3a.

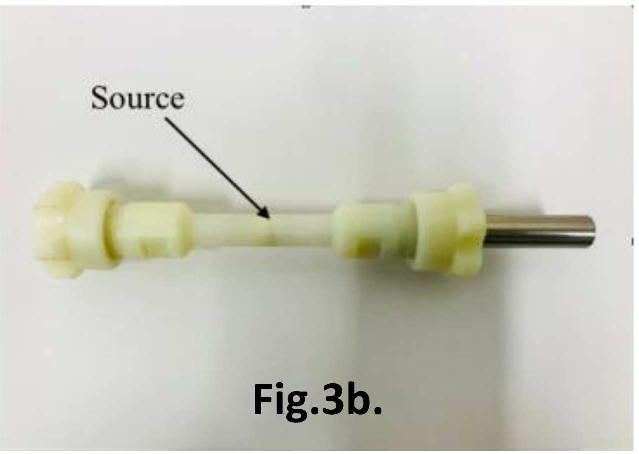


Fig.3b.

❑ Test Measurement with the 3-layer J-PET Detector.

- Measurement done for (250 days).
- A small annihilation chamber made of plastic PA6 (polyamide), with a density of 1.14 g/cm^3 is used.

- Positron Source - ^{22}Na source (Activity - 0.702 MBq).
- Source sandwiched between 3 mm thickness XAD-4 material where the o-Ps are formed and placed at the center of the annihilation chamber.

Signal Event:

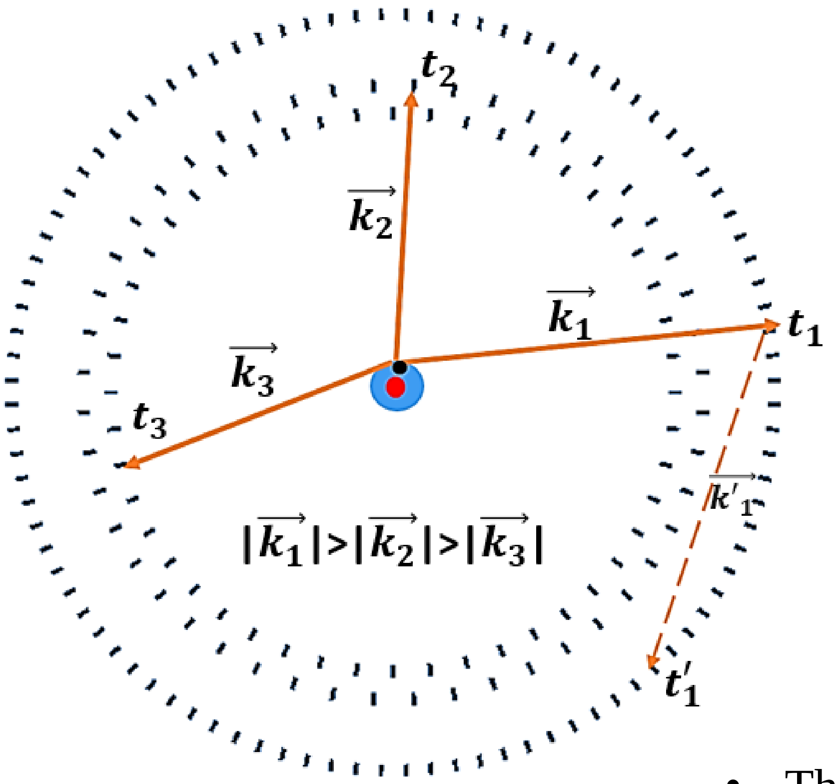


Fig.4: 4-hit Event

Operator	C	P	T	CP	CPT
$\vec{\varepsilon_1}.\vec{k_2}$	+	-	-	-	+

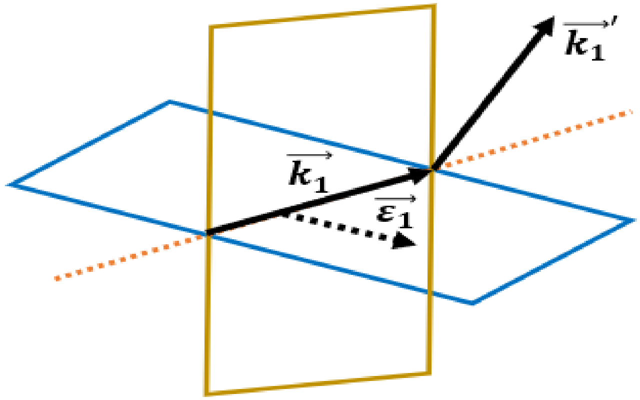
- For my study, I will be using the operator, $\vec{\varepsilon_1}.\vec{k_2}$

$\vec{\varepsilon_1}$ is the polarisation direction of the first annihillation photon.

$\vec{k_2}$ is the momentum vector direction of the second o-Ps annihillation photon.

Where, $\vec{\varepsilon_1} = \vec{k_1} \times \vec{k_1}'$

- $Cos\theta = \frac{\vec{\varepsilon_1}.\vec{k_2}}{(|\vec{\varepsilon_1}|.|\vec{k_2}|)}$



- The mean of expectation value of the operator is the measure of observed asymmetry.

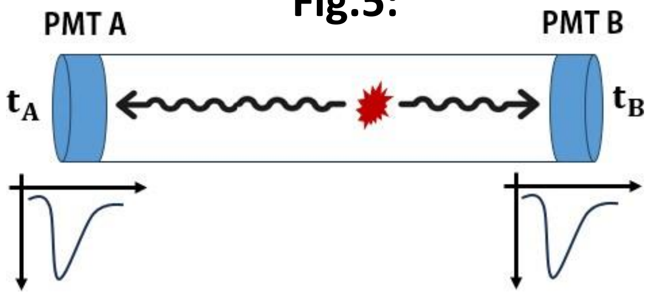
TOT Calculation: **TOT is considered as measure of energy deposited by a photon when it hits on scintillator strips.**

- TOT of the signal is approximating to the area of the rectangle. We construct a rectangle at each threshold with an area $\mathbf{A = base \cdot height = (TOT)_i \, . \, (\Delta Thr)_i}$

  where i = threshold and $(\Delta\text{Thr})_i = (\text{Thr})_i - (\text{Thr})_{i\text{-}1}$, assuming that $(\text{Thr})_0 = 0$.

- While implemented in the code there is an extra assumption. In code we make the first height of value unity, $\mathbf{(\Delta Thr)_1} = 1$, and rest of the heights are normalizing to the first threshold:

Fig.5:



- **TOT of the Signal from Side A,** $TOT_A = \text{TOT}_1 + \sum_{i=2}^{4}\left[TOT_i \, . \frac{(\Delta \text{Thr})_i}{Thr_1}\right]$

Where, TOT_i = (**Trailing edge time**)$_i$ − (**Leading edge time**)$_i$

- **TOT of a single Photon hit** = $TOT_A + TOT_B$

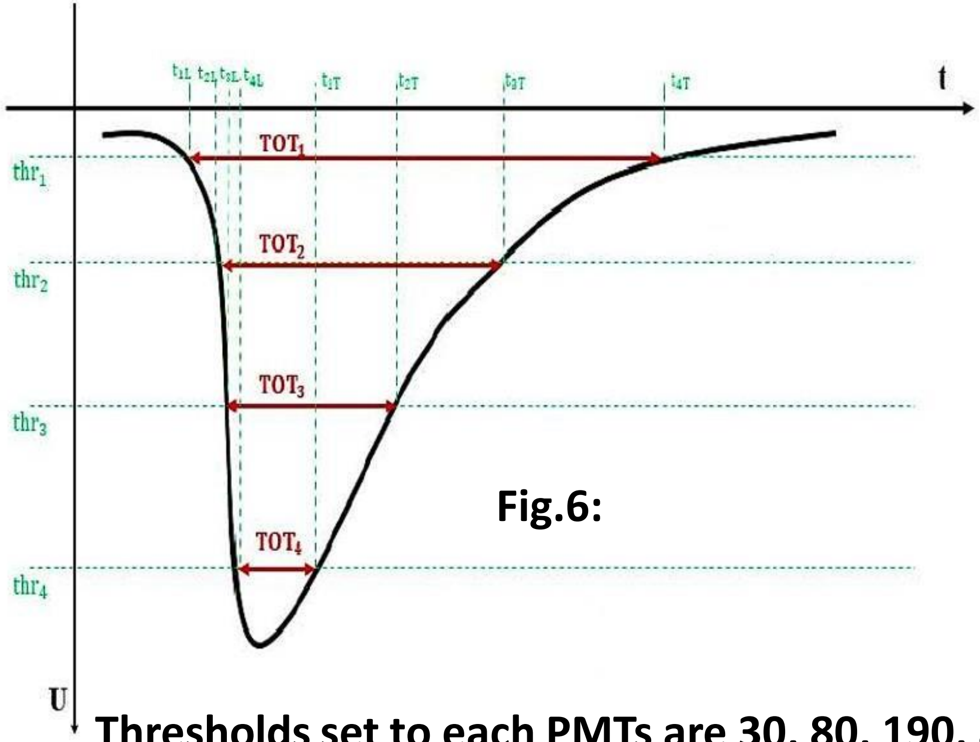


Fig.6:

Thresholds set to each PMTs are 30, 80, 190, and 300 mV.

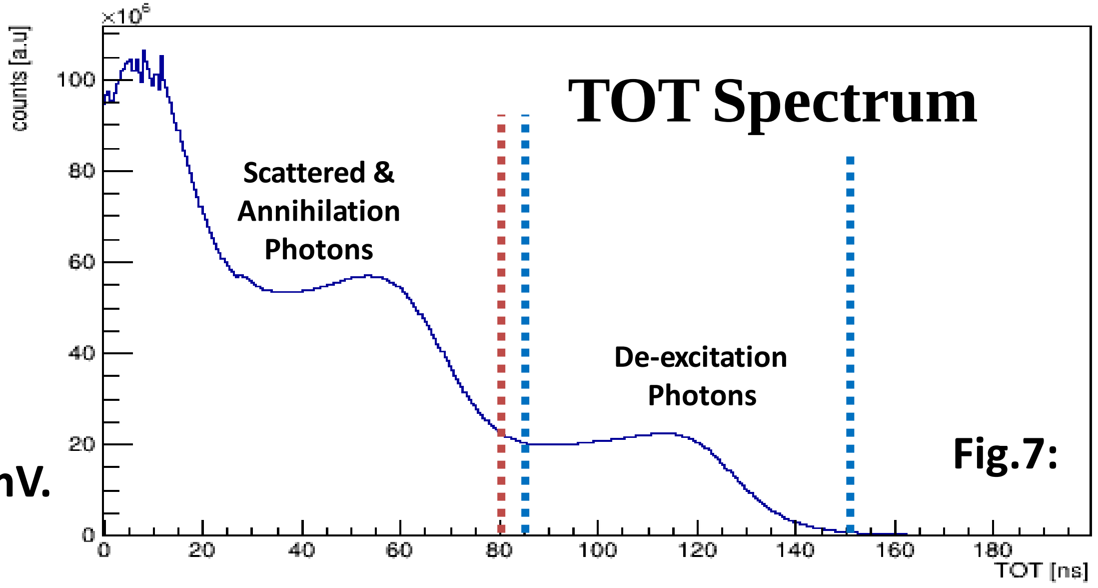


Fig.7:

Data Analysis: To Select my signal Events (o-Ps → 3γ + 1Scattered photon from primary γ)

1. Exactly 4hits per event are selected . (hit.size ==4)

2. Z cut,(-23cm< Z < 23 cm) & Make sure the assigned 4 hits are from different scintillators using ScinID information.

3. TOT region chosen for Annihilation and scattered photons,

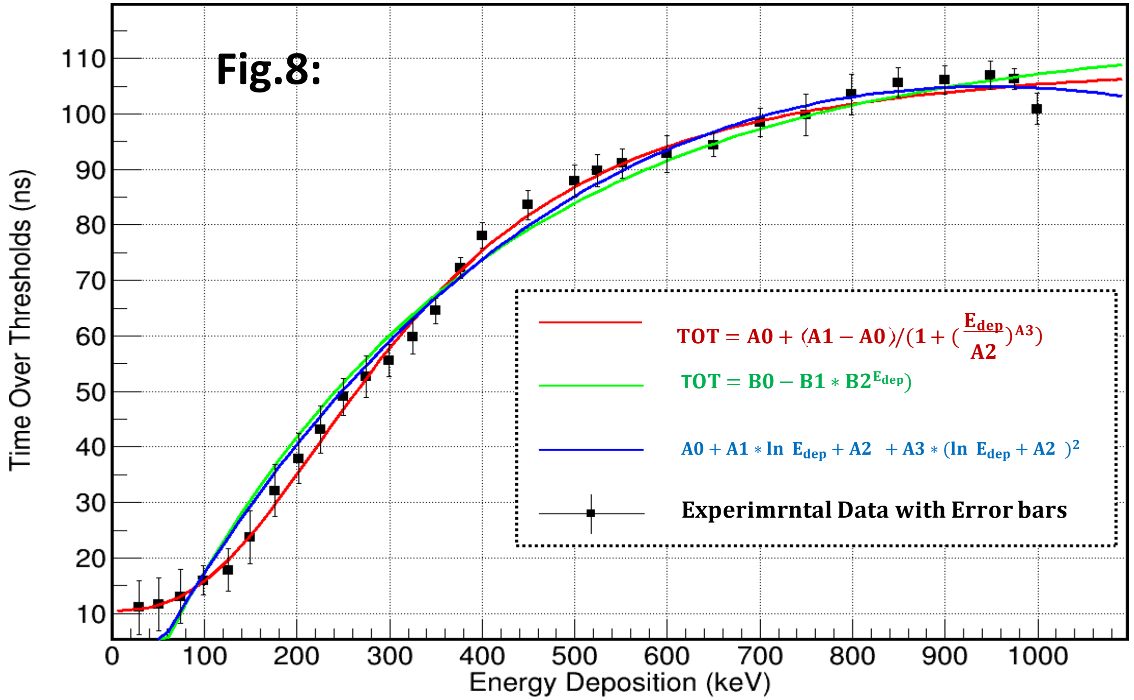


Fig.8:

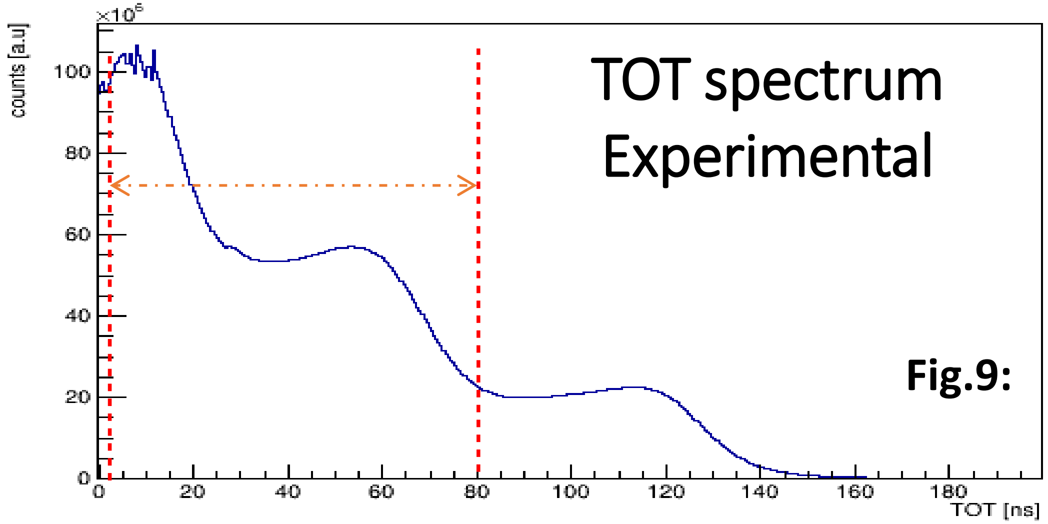


Fig.9:

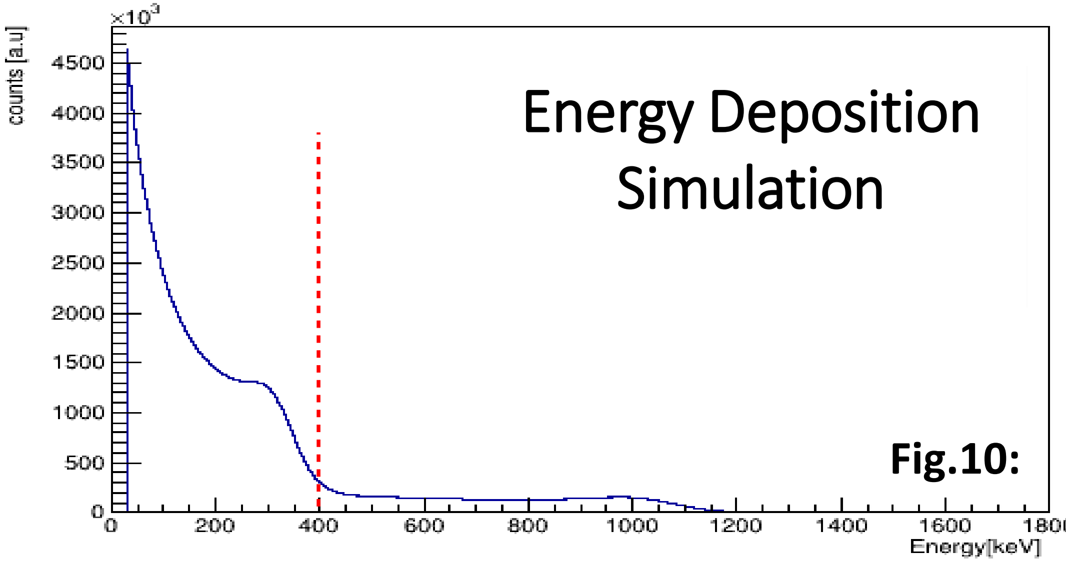
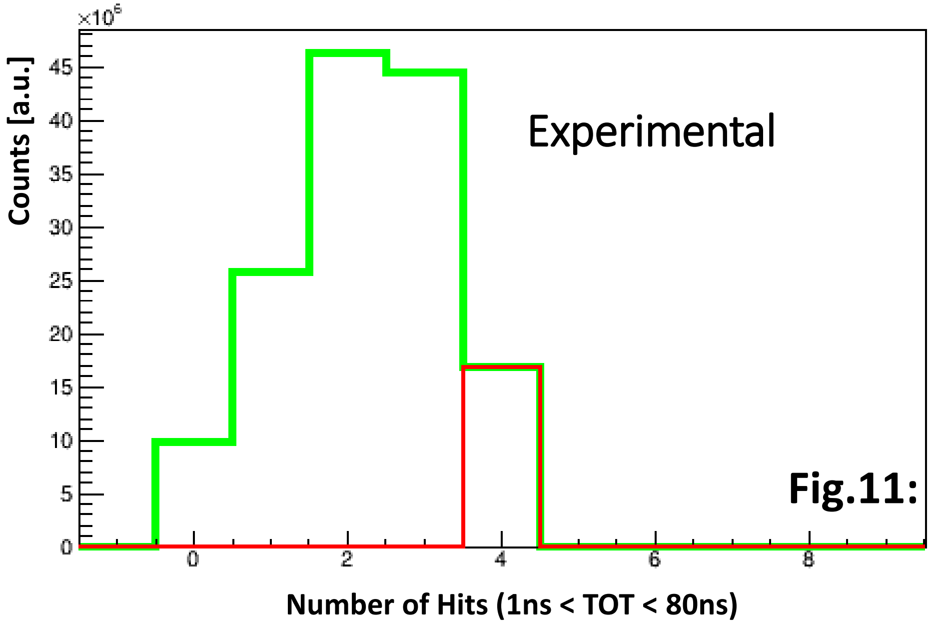
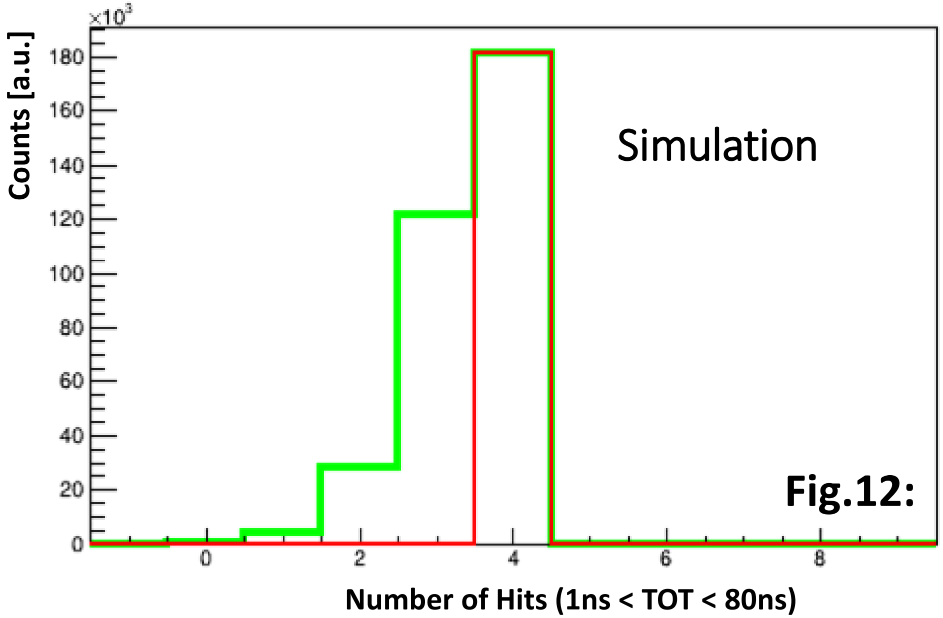


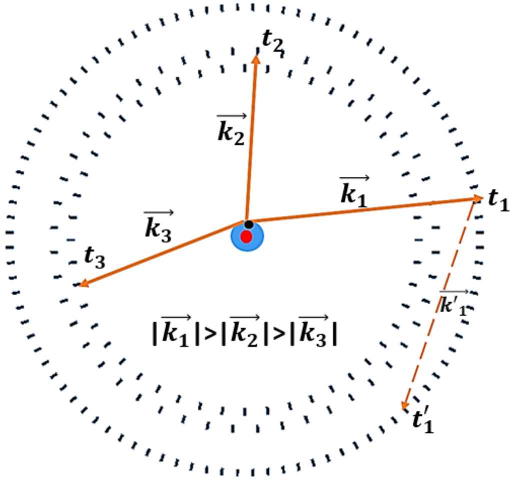
Fig.10:

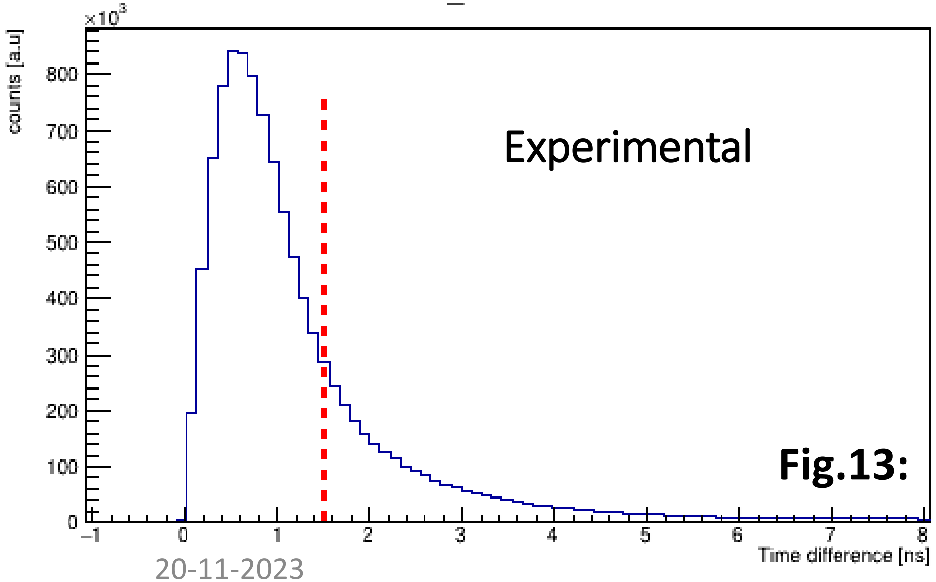
Data Analysis: To Select my signal Events (o-Ps → 3γ + 1Scattered photon from primary γ)

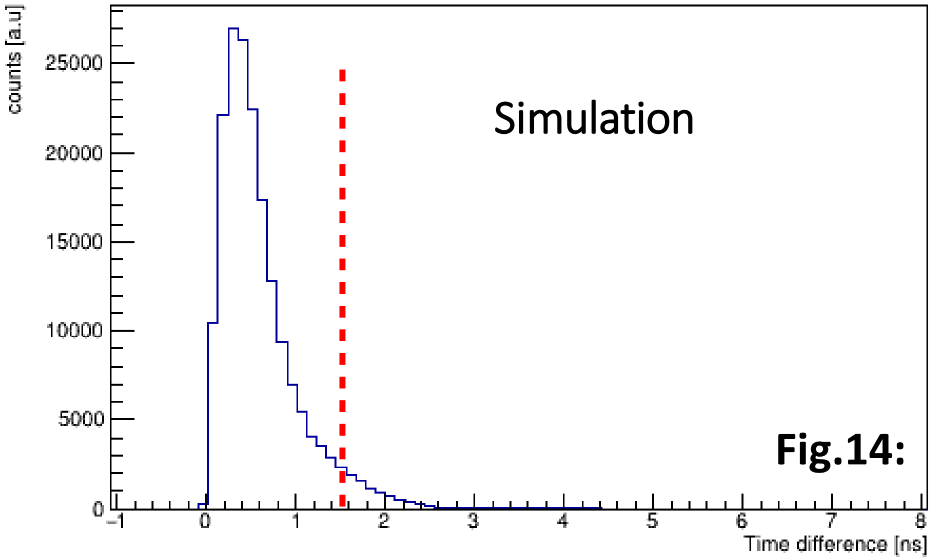




Need to make sure exactly 4 hits are in the region (1ns < TOT < 80ns).





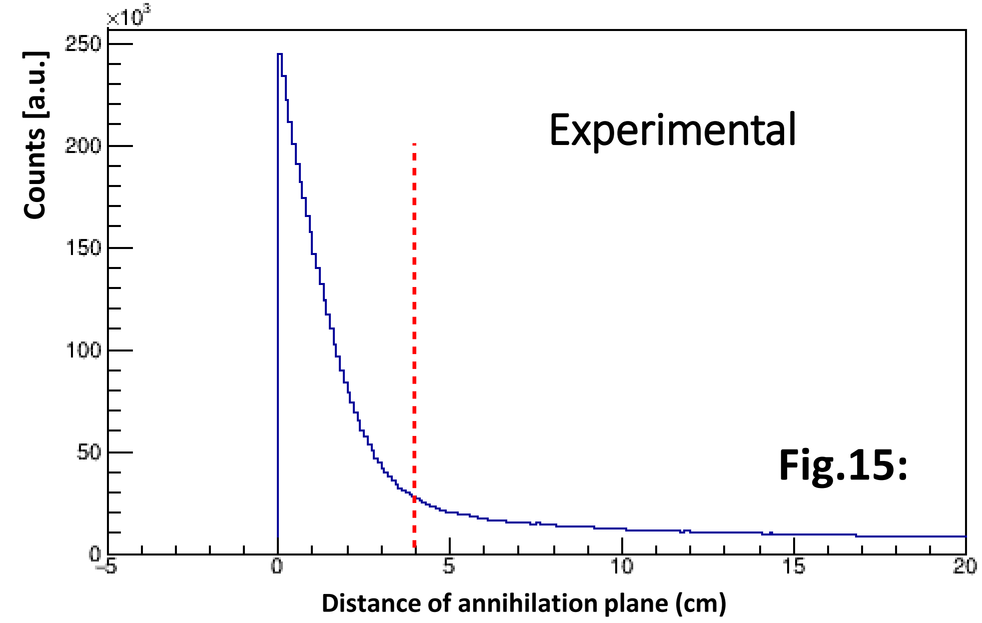


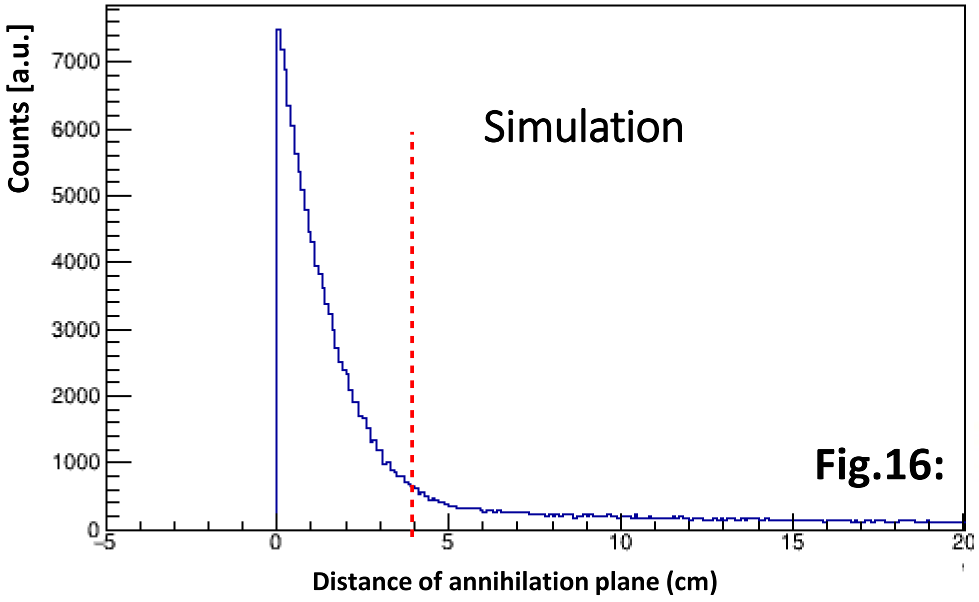
$ET_1 < ET_2 < ET_3 < ET_4$

Emission time = $t_{hit} - d_{hit}/c$

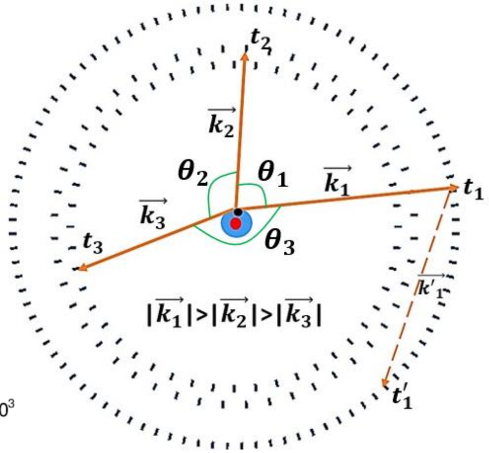
Emission time difference between hit-3 and hit-1 annihilation hits <1.5ns

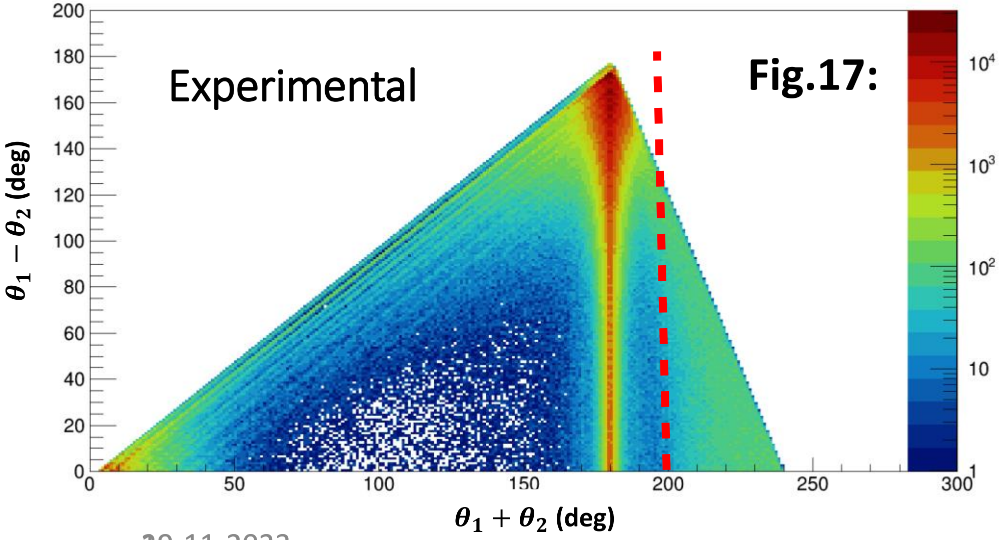
Data Analysis: To Select my signal Events (o-Ps → 3γ + 1Scattered photon from primary γ)

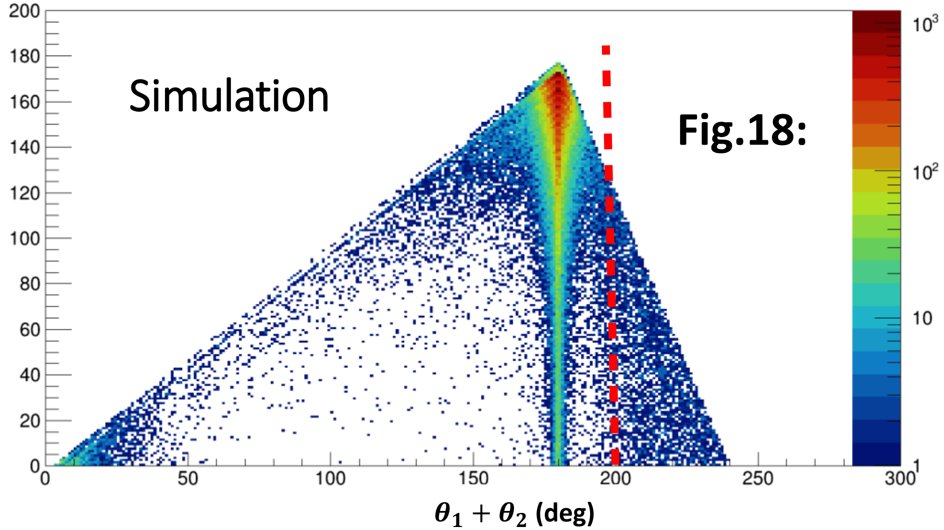




Annihilation plane for hit1 hit2 and hit3 <4cm





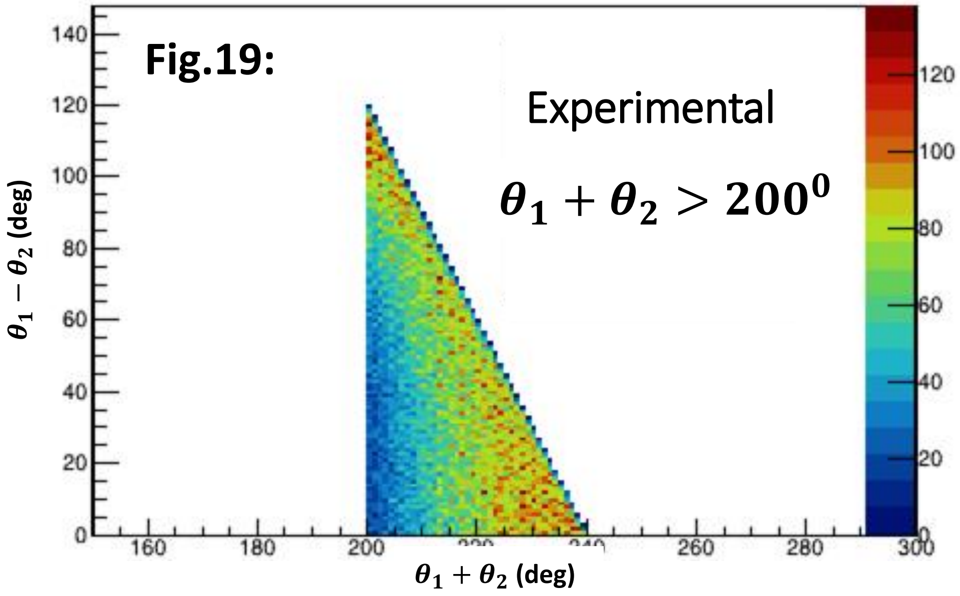


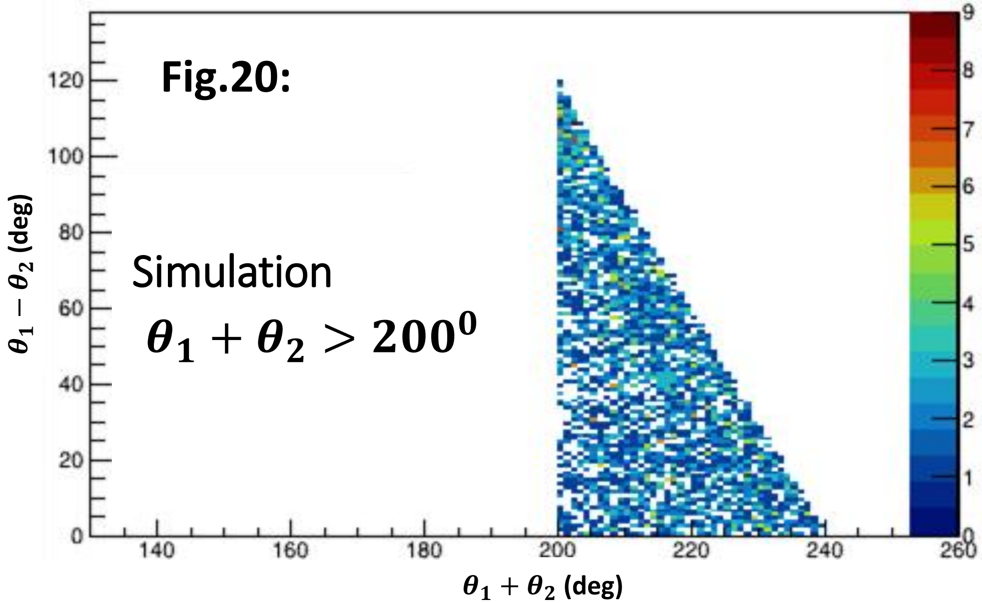
Angles between the annihilation hits are calculated and ordered from smallest to largest.

$$\theta_1 < \theta_2 < \theta_3$$

$$\theta_1 + \theta_2 > 200^0$$

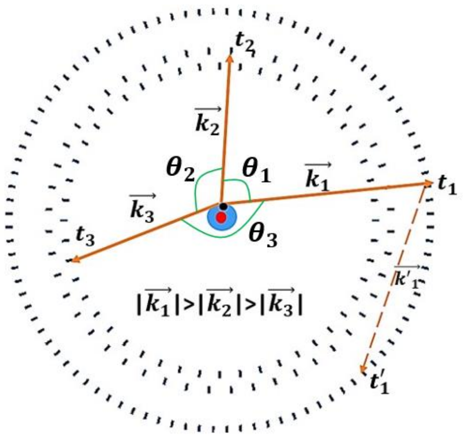
Data Analysis: To Select my signal Events (o-Ps $\rightarrow 3\gamma$ + 1Scattered photon from primary γ)

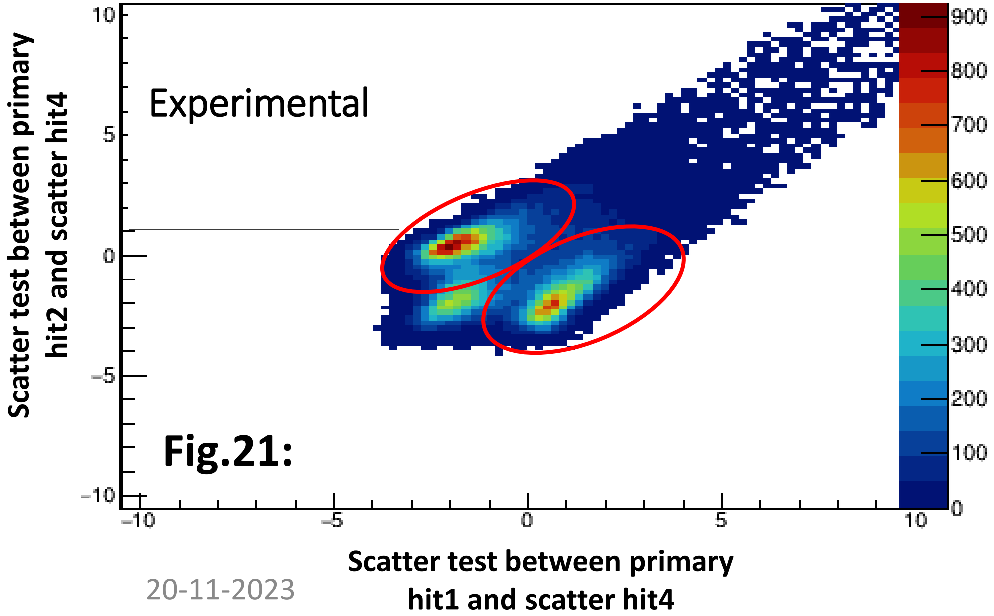


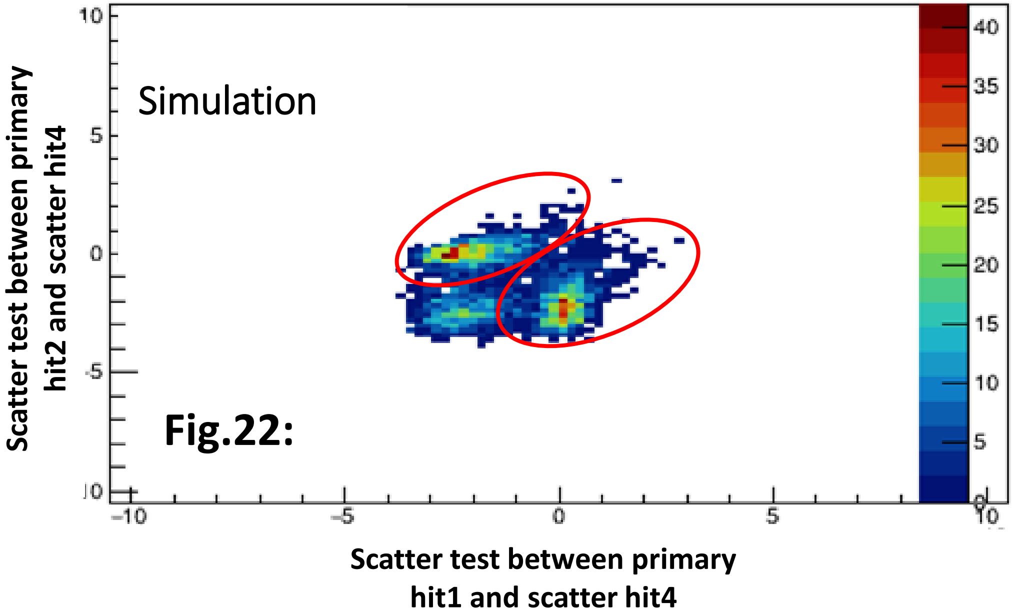


Angles between the annihilation hits are calculated and ordered from smallest to largest.

$\theta_1 < \theta_2 < \theta_3$





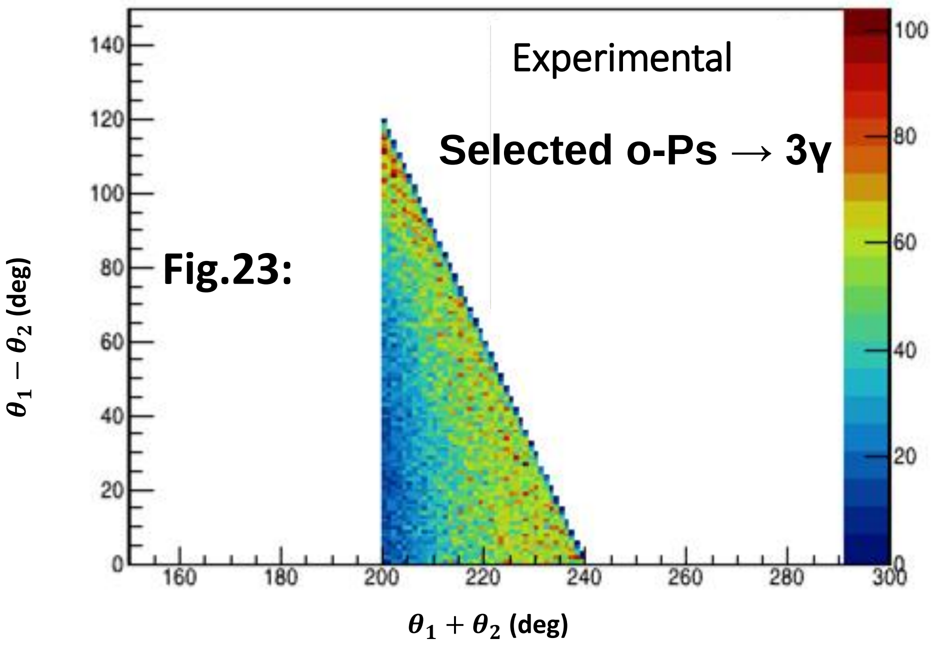


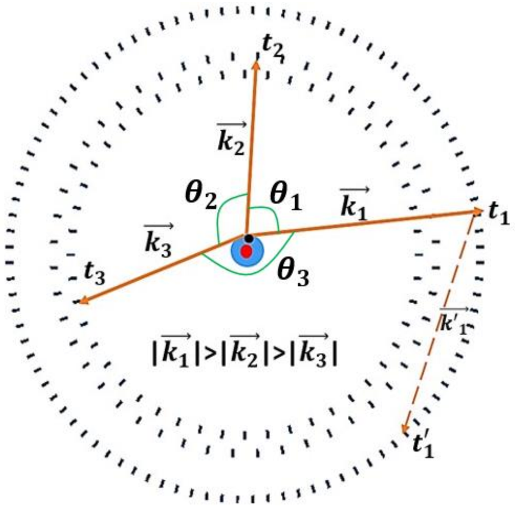
Scatter test = $\Delta t - \Delta d/c$

Δt – hit time difference between primary hit and scatter hit.

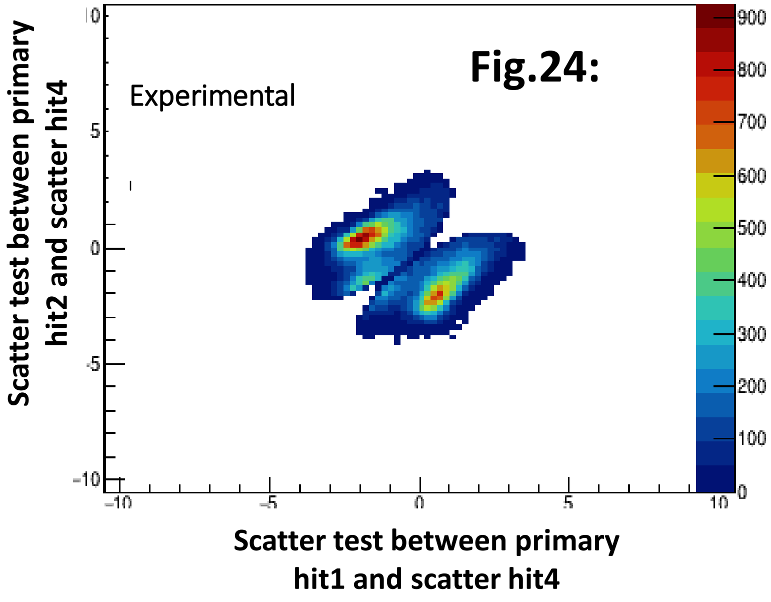
Δd – distance between the primary hit and scatter hit.

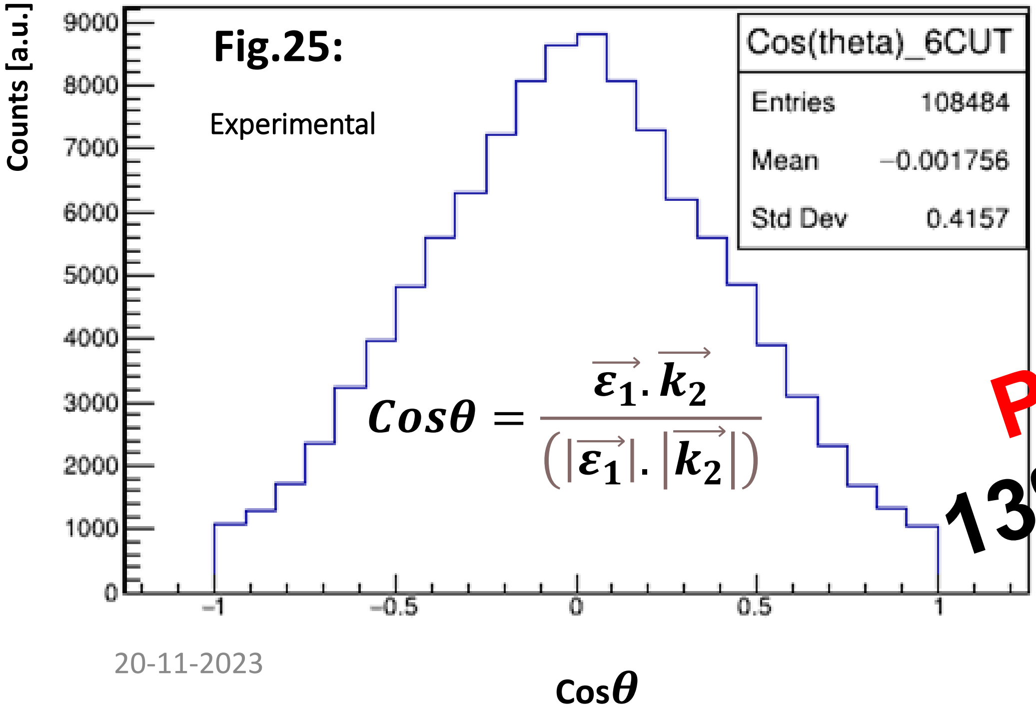
c – Velocity of light





Scatter hit4 assigned to primary annihilation hit1 and hit2





PRELIMINARY RESULTS

13% of RUN11 Data analysed

Simulation Studies to background events

Fig.29:

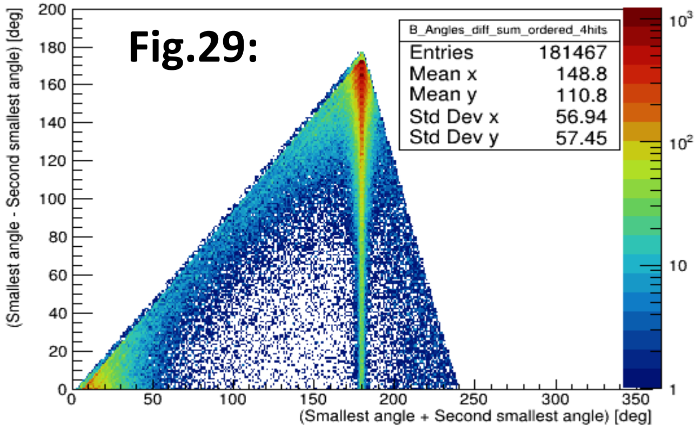
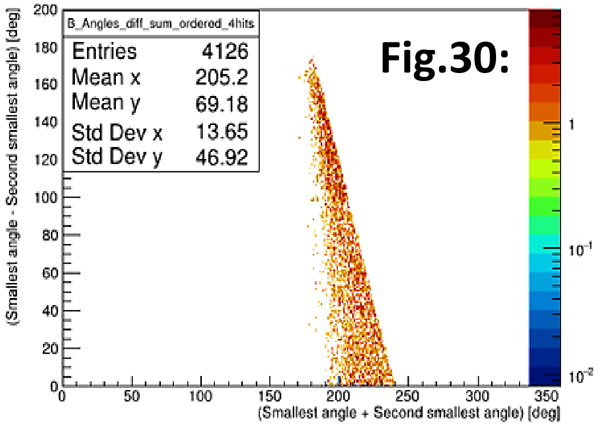
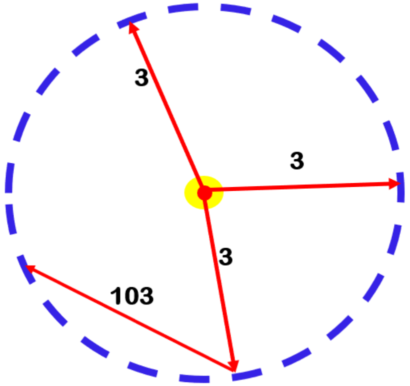


Fig.30:





Signal Event:
o-Ps → 3γ + 1Scattered photon from primary γ

Gamma Multiplicity (M) is the numbering scheme condition given during Monte-Carlo photon generation.

For **prompt photons (M=1), p-Ps -> 2γ (M=2), o-Ps -> 3γ (M=3), and +100 were added for each scattering** in the sensitive part of the detector (scintillators).

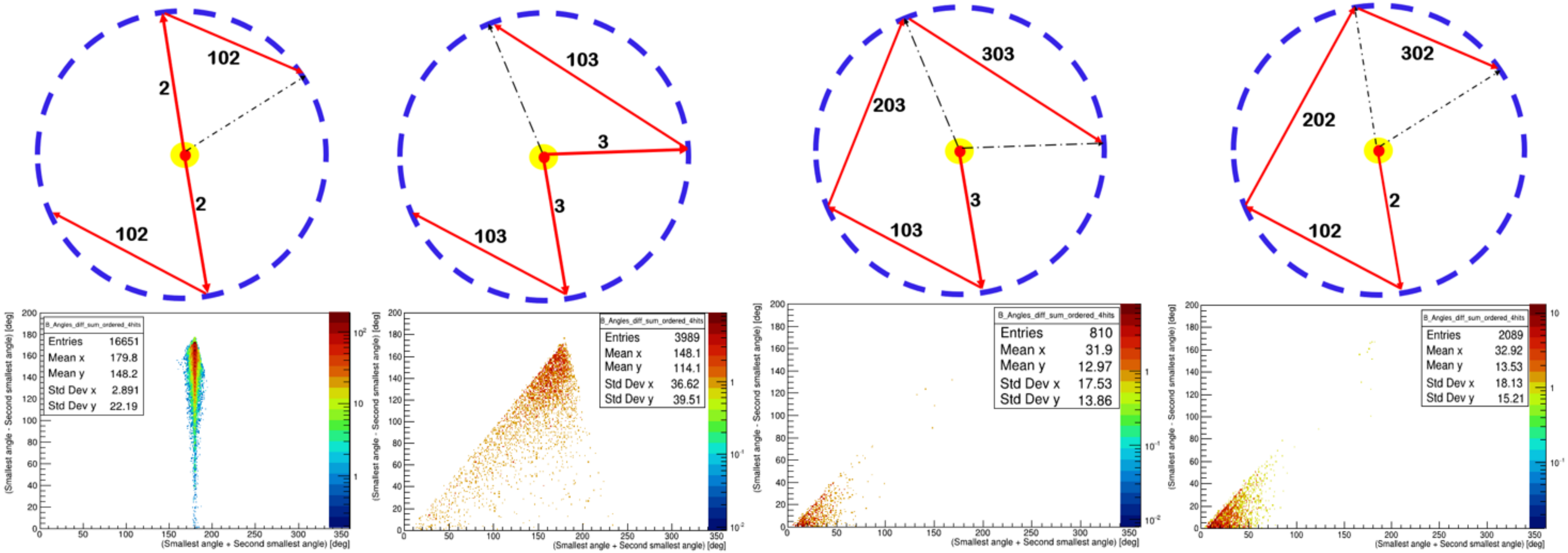


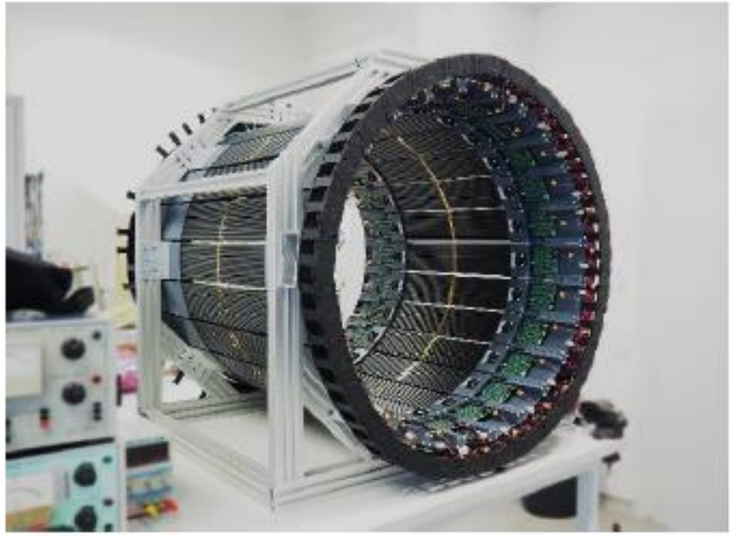
Fig.31:

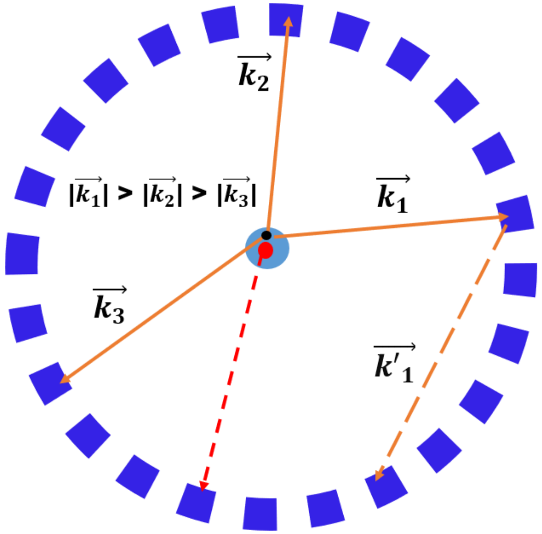
Future Plan:

- ❑ Optimisation of analysis algorithm using simulation (ongoing)

- ❑ Experiment with the Modular J-PET detector with a small annihilation chamber and ^{22}Na radioactive source with an activity of 5 MBq to test CP discrete symmetry (planned in the beginning of 2024).

- ❑ Introduce o-Ps life time condition to confirm selected signal events are exactly the o-Ps to 3 gamma decay signals events.





CONCLUSION

So far reached statistical precision for CP discrete symmetry studies in the order of 10^{-3}. The main aim of this Ph.D. study is to improve the sensitivity level at least by one order for CP discrete symmetry studies in the o-Ps atom decay with the help of modular J-PET detector.

Thank you for listening!!

BACK – UP SLIDES

Energy Deposition vs TOT

- ✓ Selected the incident photons of different energies (511 keV and 1275 keV)
- ✓ Their scattering angles are estimated based on the hit characteristics.
- ✓ With information of incident energy of photon and its scattering angle, the energy transfer to the electrons inside the scintillator can be calculated using the formula:

Energy Deposition = gamma * (1 - (1 / (1 + ((gamma / 511) * (1 - cos(scatterAngle * Pi/ 180))))))

For Run11 preselected data

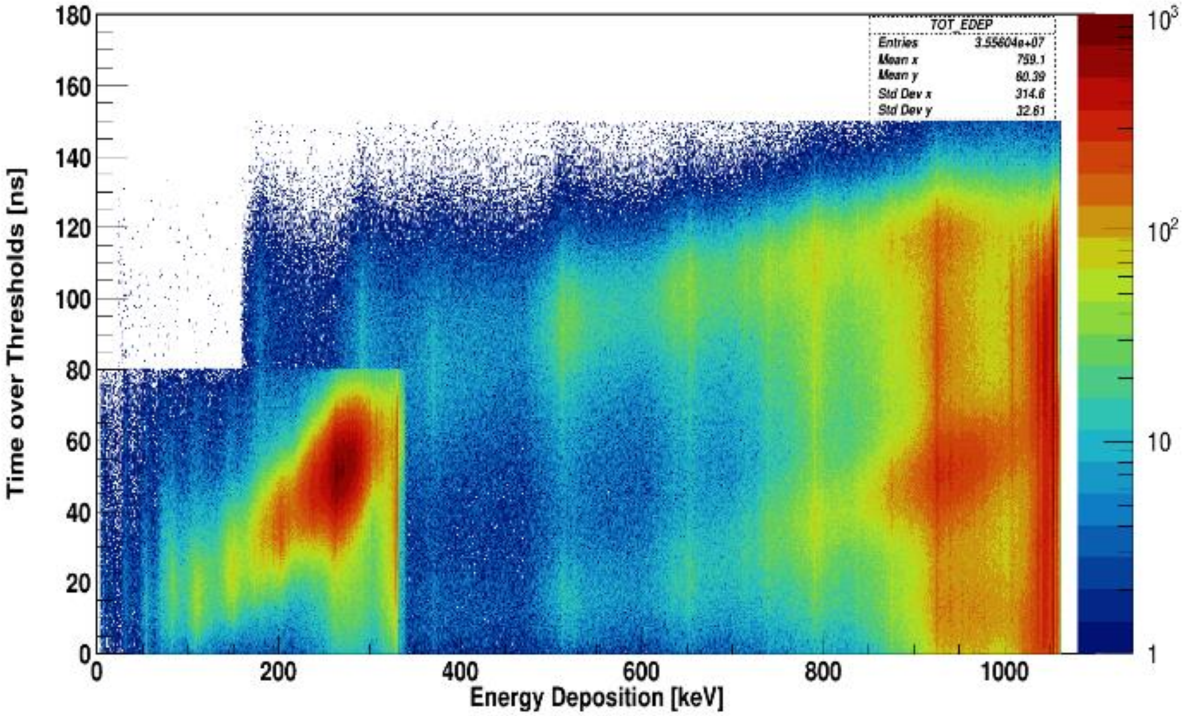


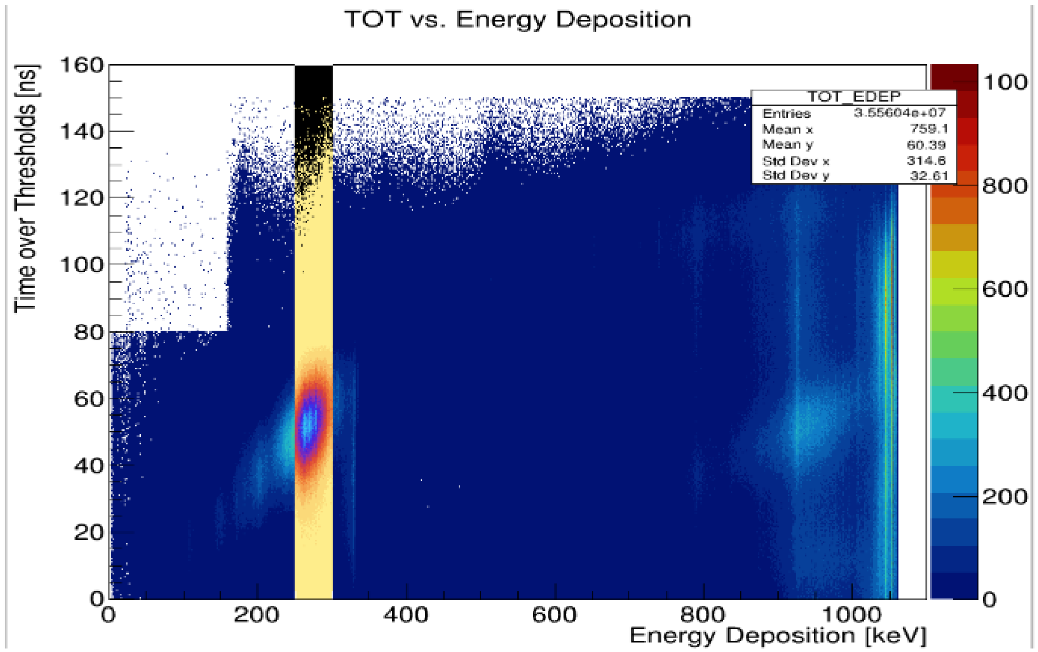
Fig: Relationship between measured TOT values and the estimated energy deposition for all selected hits,

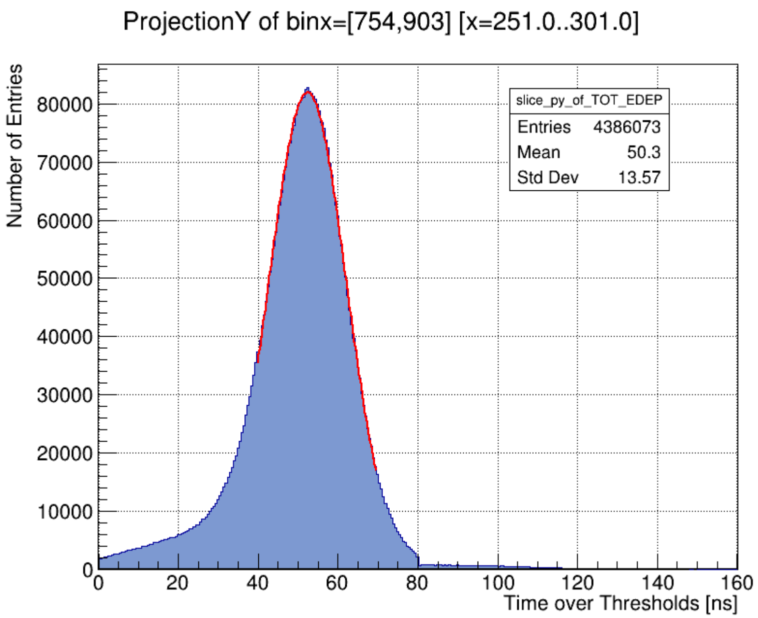
An enhancement in TOT values is observed with increasing energy depositions.

Some contributions are visible with large energy deposition but with smaller TOT values this is interpreted as wrongly tagged photons due to accidental coincidences,
i.e., instead of 1275 keV photon, photons with lower incident energies (511keV) were used to estimate the energy deposition for the scattering angles.

- For the final relationship, the most populated energy bins are selected by taking y projection for small intervals of Energy deposition values.

Y – Projection and Gaussian fitting



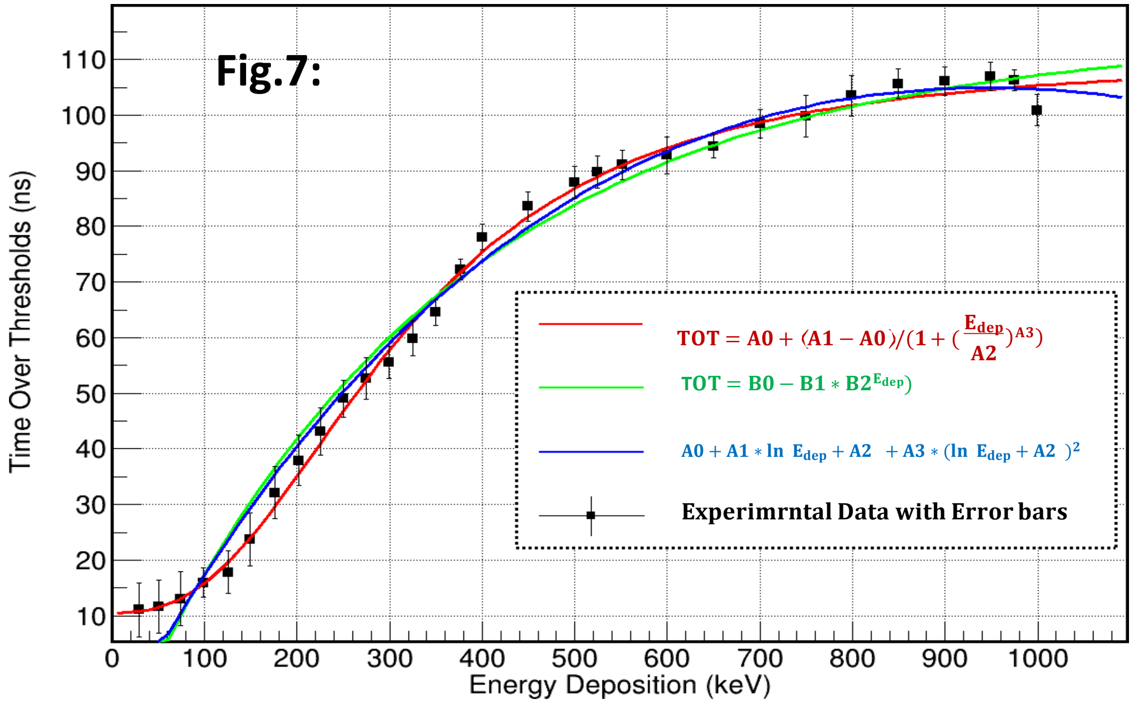


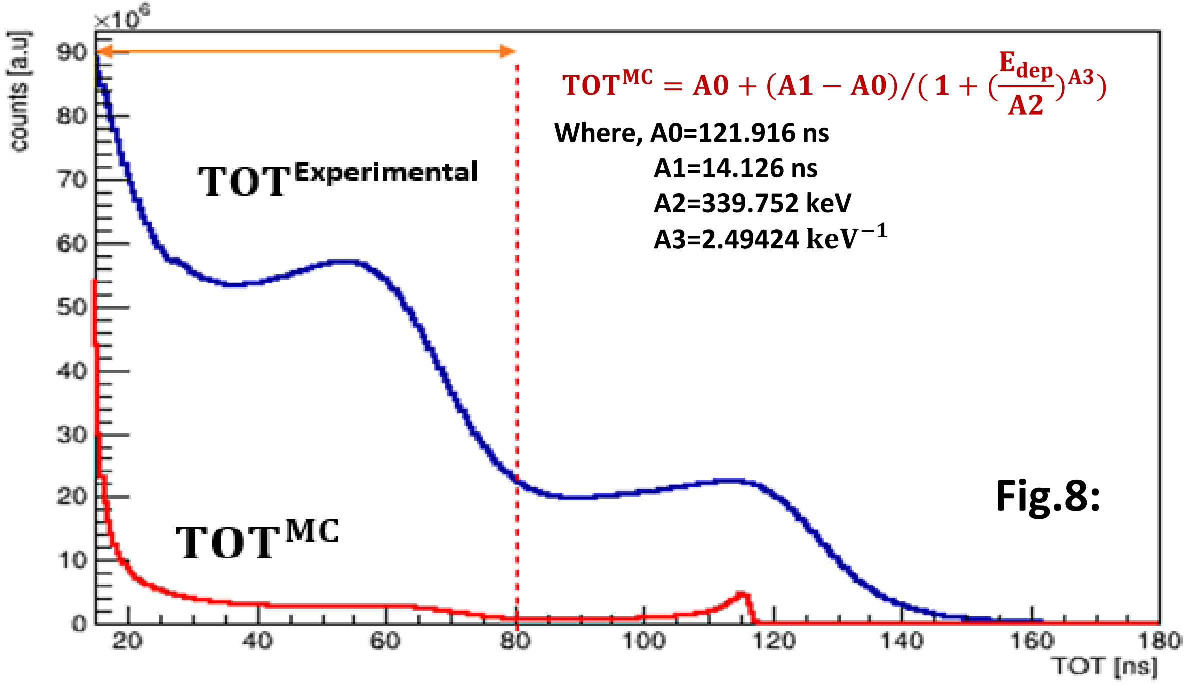
- The most populated energy bins are selected by taking y projection
- The center value of the energy interval is taken as the x value in the final TOT vs Edep plot.
- Corresponding mean values of the TOT in the selected interval are taken as the y value in the final TOT vs Edep plot.
- And the standard deviation value is taken as the experimental error.

EXT NO.	PARAMETER NAME	VALUE	ERROR	STEP SIZE	FIRST DERIVATIVE
1	Constant	8.19903e+04	5.95729e+01	-3.93619e-02	1.16703e-06
2	Mean	5.23555e+01	7.44932e-03	5.96828e-06	-2.45669e-05
3	Sigma	9.66722e+00	8.57181e-03	-9.81143e-07	3.18085e-01

The TOT spectra for selected energy intervals fitted for a fixed range around the maximum distribution such that the standard deviation is very small which considered as the experimental error.

Relationship between TOT and energy loss by photons interacting inside the plastic scintillators used in the J-PET scanner.





- To apply this method effectively, it is essential to precisely describe the non-linear relationship between the energy deposition of an initial photon and the measured TOT values.
- Results presented here is based on the identification of photons of two different energies 511 keV and 1275 keV photons obtained using the ^{22}Na source, their scattering angles which is used for the estimation of energy depositions in an event-wise manner.

Ref.1:Sharma et al. EJNMMI Physics, 7:39https://doi.org/10.1186/s40658-020-00306-x

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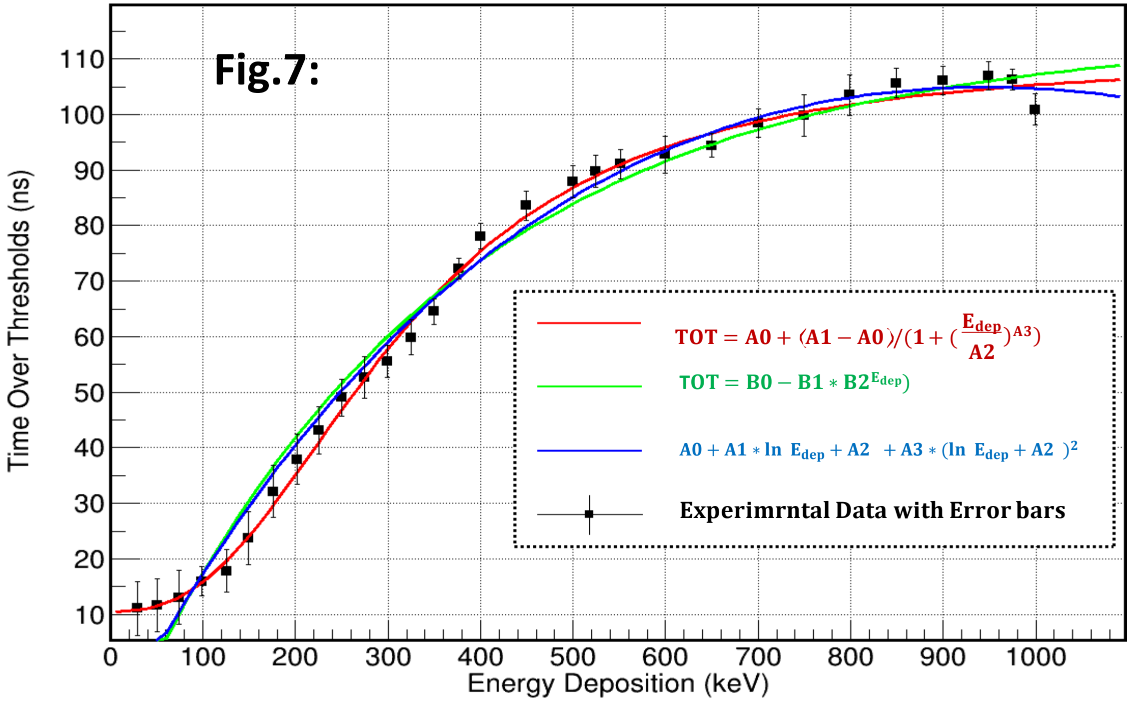

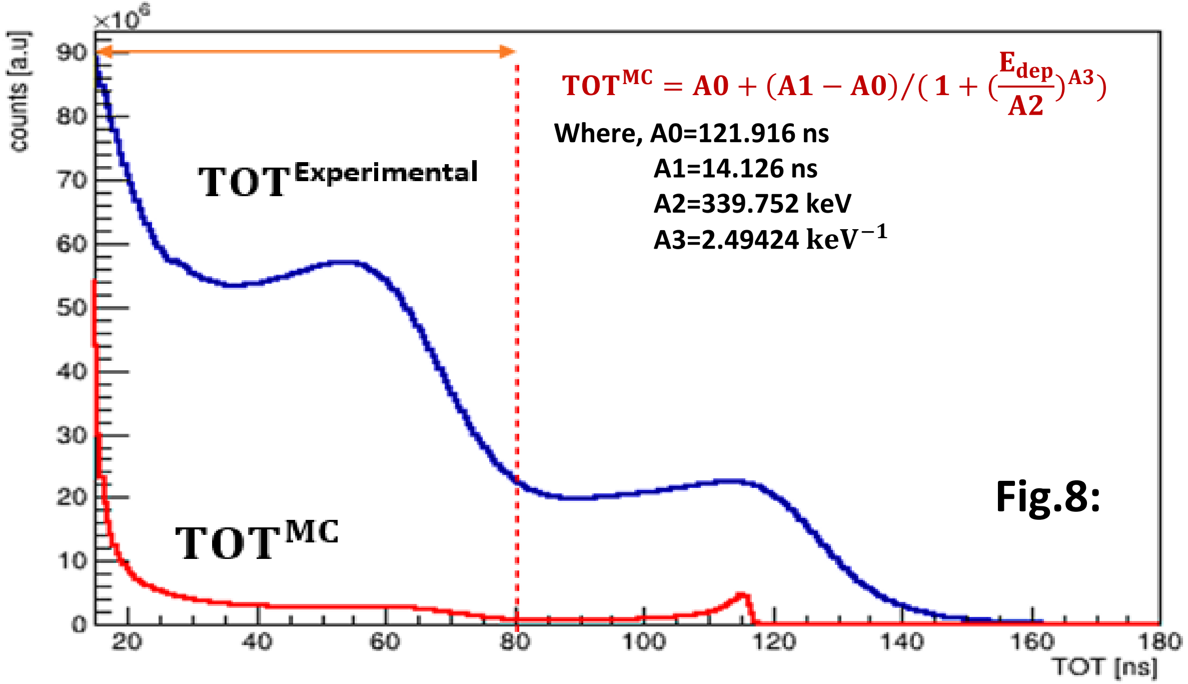

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➔ Results presented here is based on the identification of photons of two different energies 511 and 1275 keV photons obtained using the ^{22}Na source, their scattering angles which is used for the estimation of energy depositions in an event-wise manner.

● Using scattered angle, calculate theoretical value of energy deposition can be obtained by the formula:

Energy Deposition = gamma * (1 - (1 / (1 + ((gamma / 511) * (1 - cos(scatterAngle * Pi/ 180)))))) , where, Scatter Angle = $\cos^{-1}$(scatterVec.primary1Vec)

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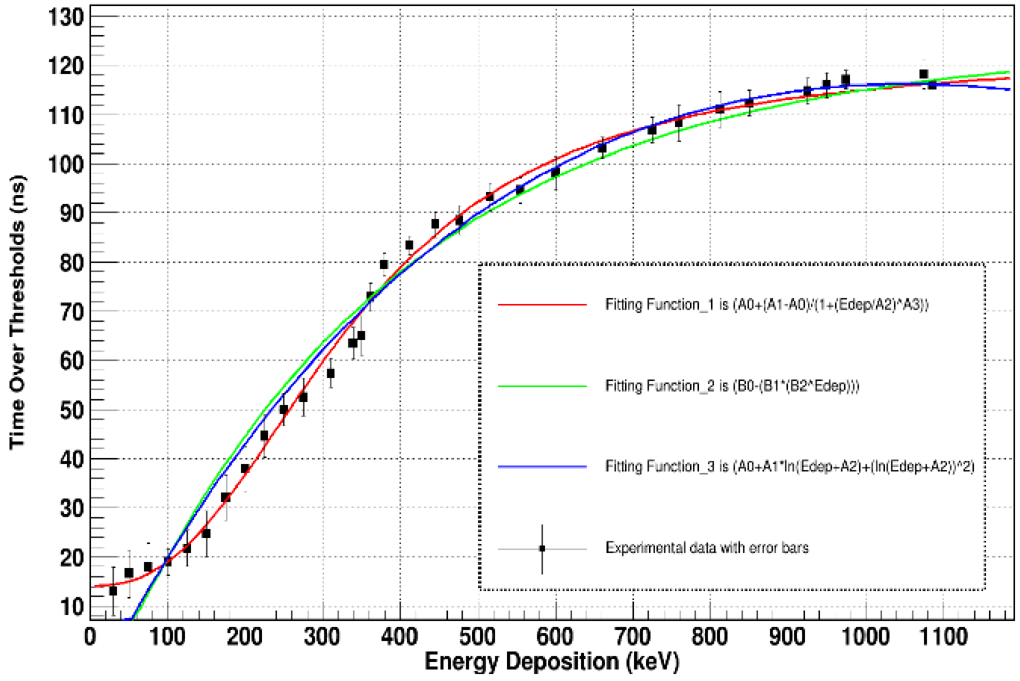
Conclusion: Energy Deposition vs TOT for Run11 preselected data



$$\mathbf{TOT = A0 + A1 * \ln(E_{dep} + A2) + A3 * (\ln(E_{dep} + A2))^2}$$

where, A0=-29087.9
A1=7421.57
A2=1565.55
A3= - 471.506

$$\mathbf{TOT = B0 - B1 * B2^{E_{dep}})}$$

Where, B0=124.082
B1=136.803
B2=0.99786

$$\mathbf{TOT = A0 + (A1 - A0)/(1 + (\frac{E_{dep}}{A2})^{A3})}$$

Where, A0=121.916
A1=14.126
A2=339.752
A3=2.49424

Using a ^{22}Na source emitting 1275 keV prompt and 511 keV annihilation photons, the TOT versus energy loss relationship up to about 1000 keV was established. The proposed functions fits the Run-11 experimental data as well.

- This precisely describe the non-linear relationship between the energy deposition of an initial photon and the measured TOT values.