Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

CENTRO FERMI
MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE ENRICO FERMI

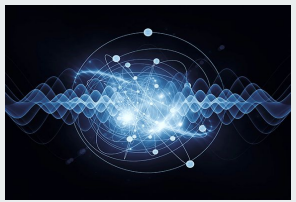
Dalitz plot analysis for the o-Ps → 3 γ decay with J-PET

Raffaele Del Grande[1,2*]

[1] INFN Laboratori Nazionali di Frascati, Frascati, Italy

[2] CENTRO FERMI - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Roma, Italy

On the behalf of the J-PET collaboration

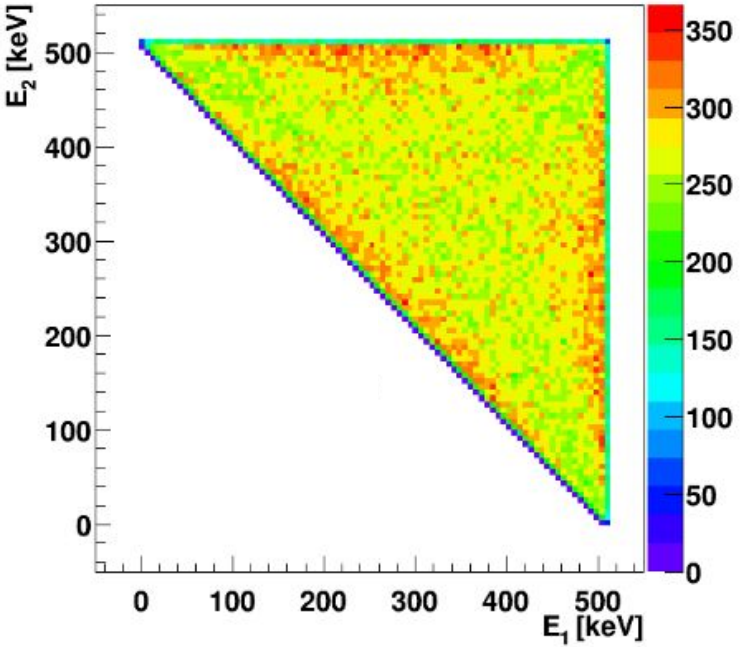


Is Quantum Theory exact? From quantum foundations to quantum applications

Frascati, 23-27 September 2019

Goal of the analysis

First experimental o-Ps Dalitz plot determination



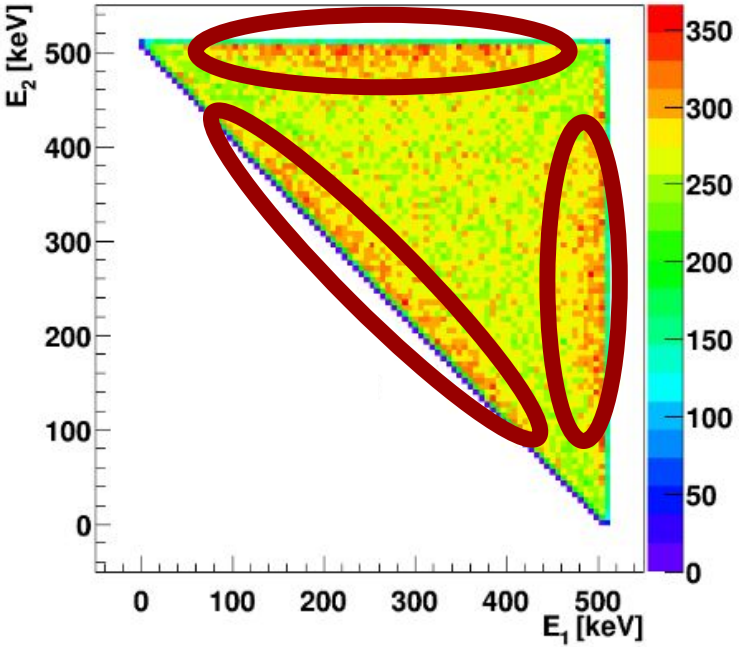
o-Ps $\rightarrow \gamma_1 \gamma_2 \gamma_3$

QED prediction:

$$\sigma_{3\gamma} = \frac{4e^6}{vm_e^2} \cdot \int_0^{m_e} \int_{m_e-\omega_1}^{m_e} \frac{(\omega_1 + \omega_2 - m_e)^2}{\omega_1^2 \omega_2^2} d\omega_1 d\omega_2$$
$$= \frac{4e^6}{vm_e^2} \cdot \frac{\pi^2 - 9}{3}$$

Goal of the analysis

First experimental o-Ps Dalitz plot determination



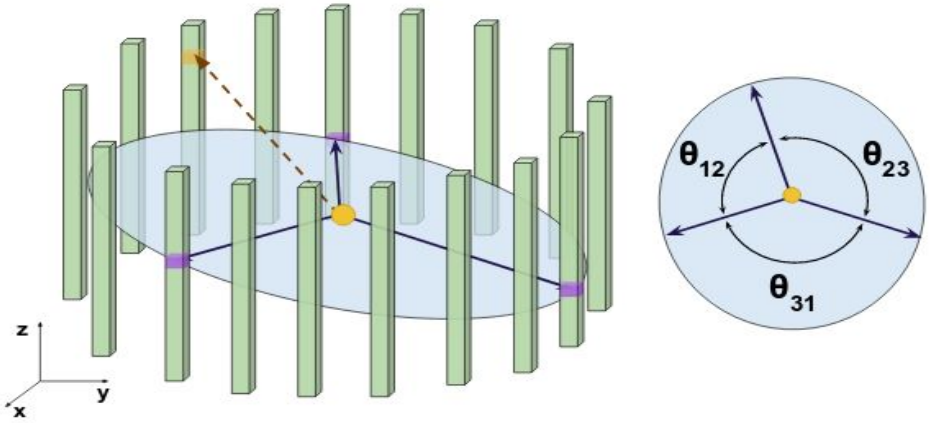
o-Ps $\rightarrow \gamma_1 \gamma_2 \gamma_3$

QED prediction:

$$\sigma_{3\gamma} = \frac{4e^6}{v m_e^2} \cdot \int_0^{m_e} \int_{m_e-\omega_1}^{m_e} \frac{(\omega_1 + \omega_2 - m_e)^2}{\omega_1^2 \omega_2^2} d\omega_1 d\omega_2$$
$$= \frac{4e^6}{v m_e^2} \cdot \frac{\pi^2 - 9}{3}$$

Peculiar shape:
accumulations at the borders

Gamma quanta energies



Using the Hits positions in the scintillators:

$\mathbf{X}_i = (x_i, y_i, z_i)$ i=1,2,3

assuming the annihilation point in the center of the detector O = (0, 0, 0)

angles are defined

$\theta_{ij} = \text{acos}(\mathbf{X}_i \cdot \mathbf{X}_j / |\mathbf{X}_i| |\mathbf{X}_j|)$

Energies can be determined using angles between momentum vectors

$E_1 + E_2 + E_3 = 2 m_e$

$p_{1x} + p_{2x} + p_{3x} = 0$

$p_{1y} + p_{2y} + p_{3y} = 0$

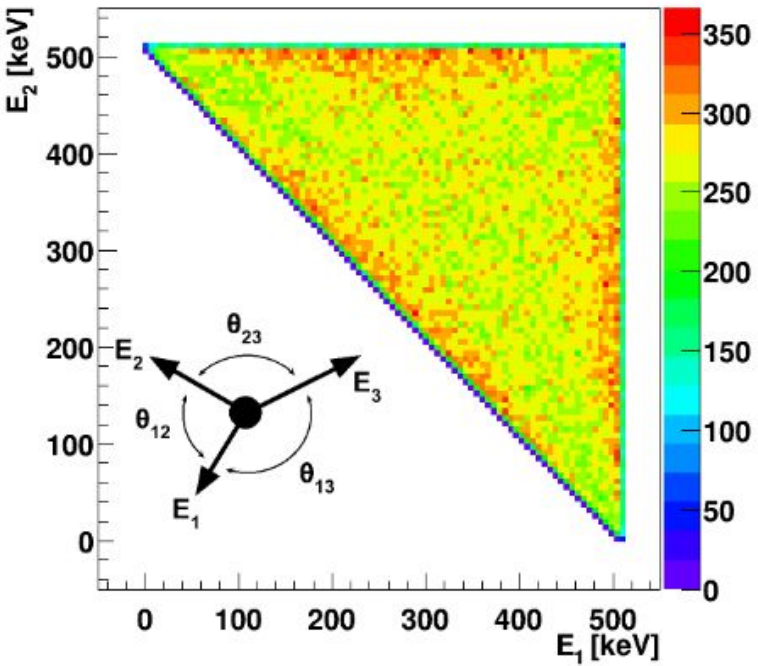
$p_{1z} + p_{2z} + p_{3z} = 0$

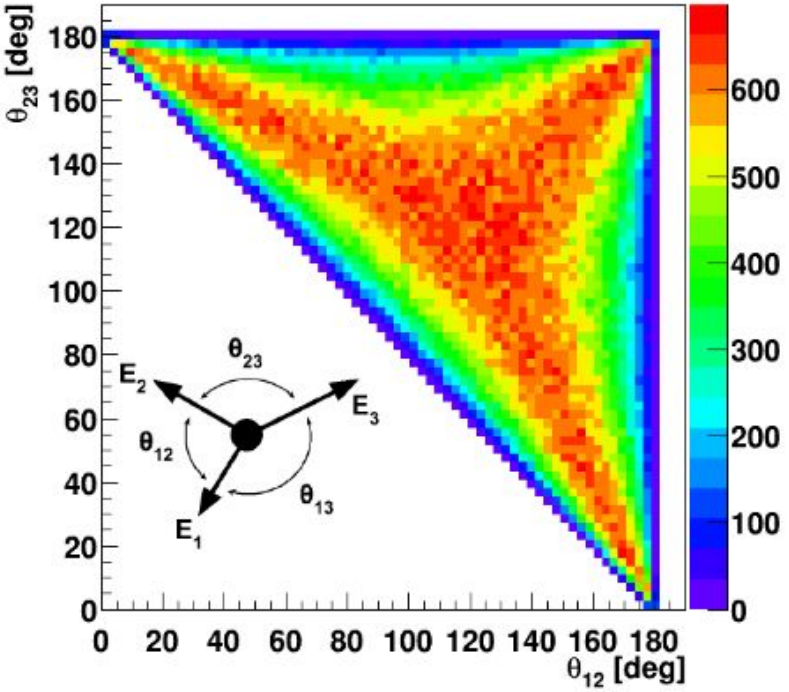
$$E_1 = -2m_e \frac{-\cos\theta_{13} + \cos\theta_{12}\cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23})},$$

$$E_2 = -2m_e \frac{\cos\theta_{12}\cos\theta_{13} - \cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23})},$$

$$E_3 = 2m_e \frac{1+\cos\theta_{12}}{1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23}}.$$

Dalitz plot for the o-Ps → 3 γ



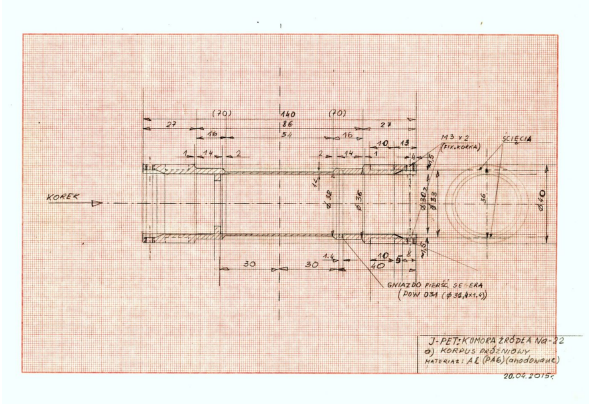


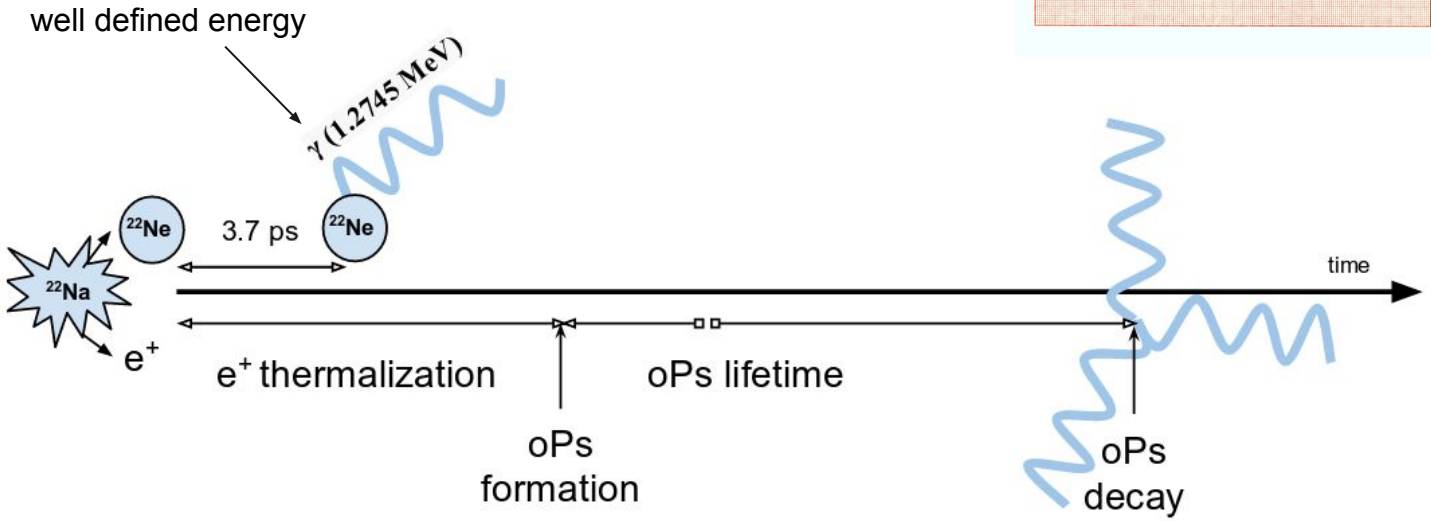
Run-5 data

Small Chamber measurements:

β⁺ source: sodium-22 ($^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$)

porous material: amberlite polymer XAD-4

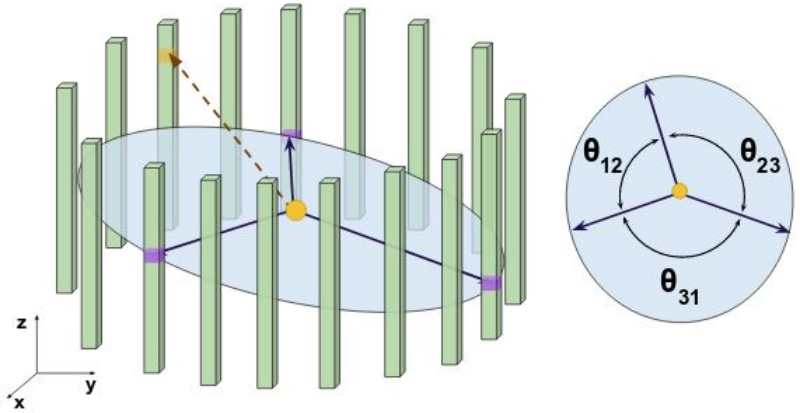


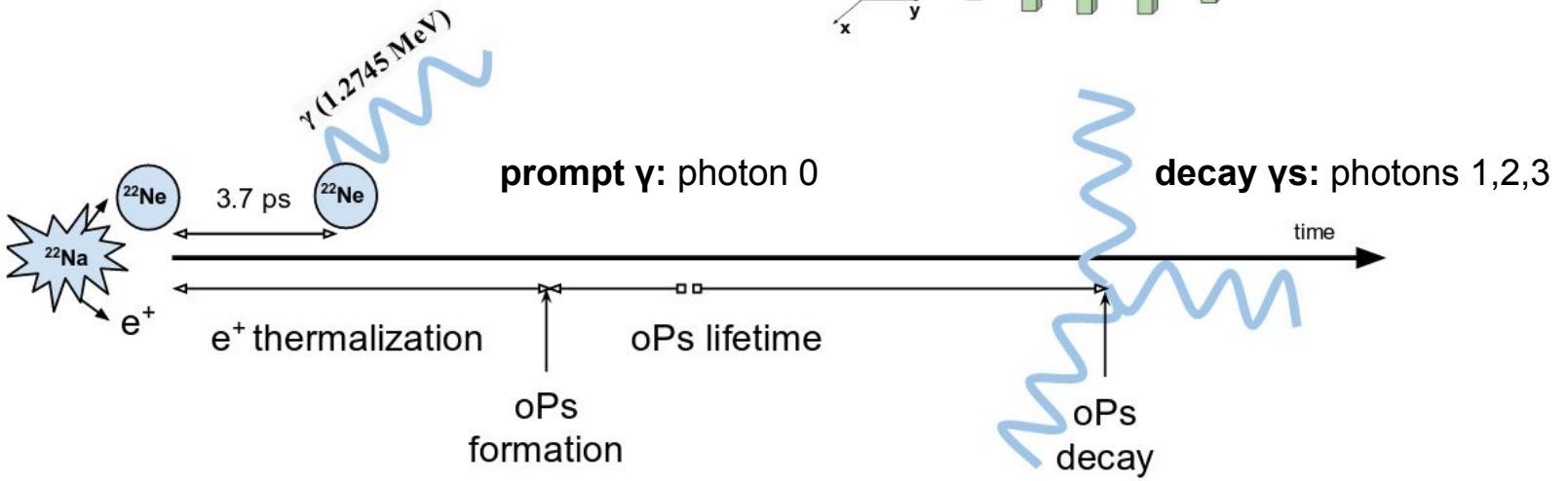


Run-5 data

Hits in the scintillators:

→ **3 hits**: 3 γ from the o-Ps decay
→ **4 hits**: 3 γ from the o-Ps + prompt γ

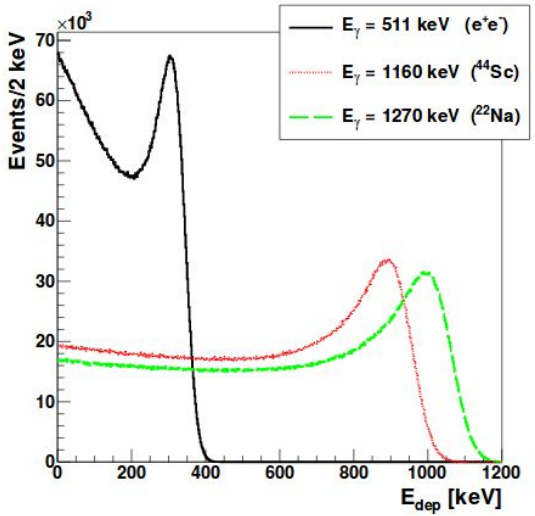




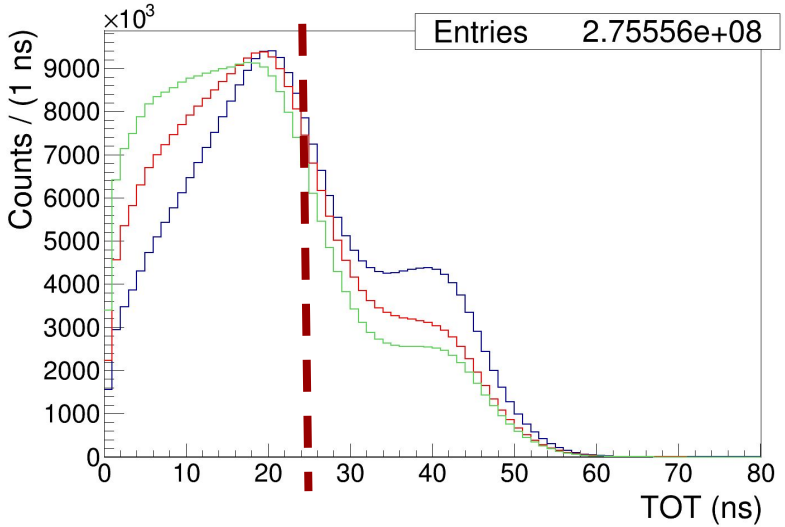
3 Hits Selection

CUT 1: selection based on the energy deposited in the scintillators (using the TOT information)

MC simulations



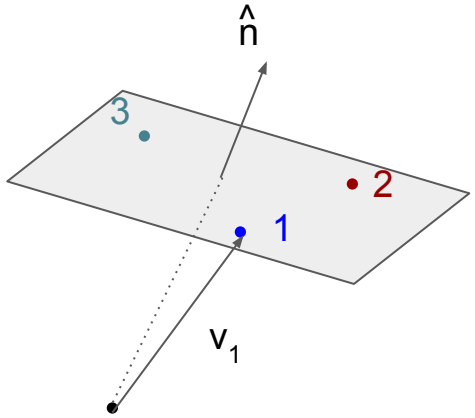
data



$TOT_1 < 25$ ns & $TOT_2 < 25$ ns & $TOT_3 < 25$ ns

3 Hits Selection

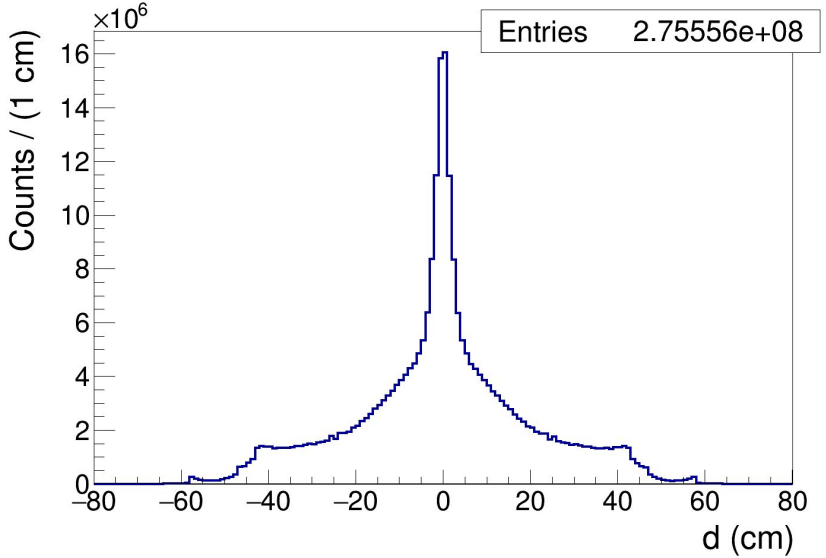
Hits: $(x^{Hit}, y^{Hit}, z^{Hit}, t^{Hit})$ → Using the coordinates of the 3 Hits the decay plane is found.



annihilation point
O = (0,0,0)

$d = \mathbf{v_1} \cdot \hat{\mathbf{n}}$

CUT2: The decay plane has to contain the annihilation point
O = (0,0,0)



|d| < 2 cm

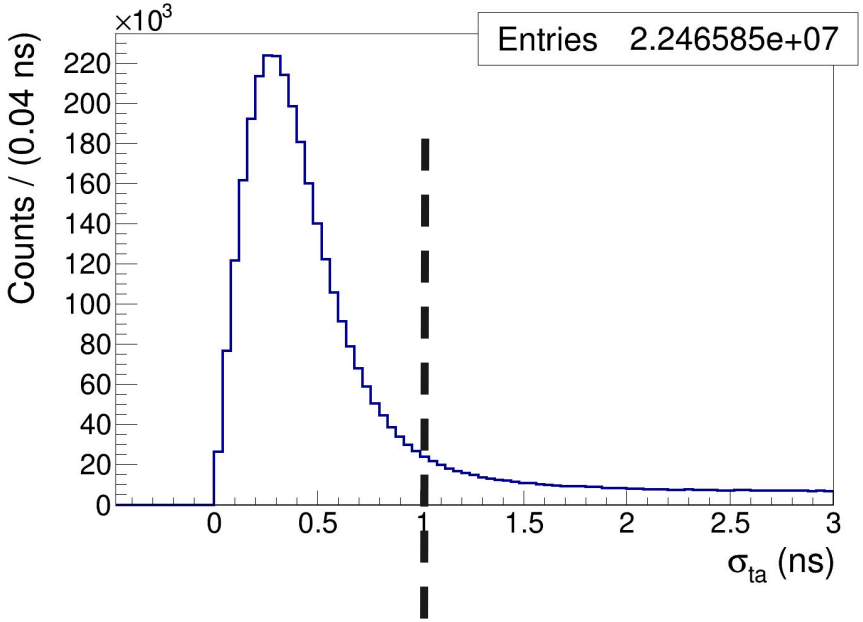
3 Hits Selection

CUT3: The three photons are emitted at the same time

- distance from the annihilation point
  $r_i = \mathrm{sqrt}(x_i^{Hit\ 2} + y_i^{Hit\ 2} + z_i^{Hit\ 2})$
- annihilation time determination for γ_i
  $t_{ai} = t_i^{Hit} - r_i / c$
- ta = ⅓ (ta1 + ta2 + ta3)

$\sigma_{ta} = \mathrm{sqrt}(⅓ [(t_{a1} - t_a)^2 + (t_{a2} - t_a)^2 + (t_{a3} - t_a)^2])$

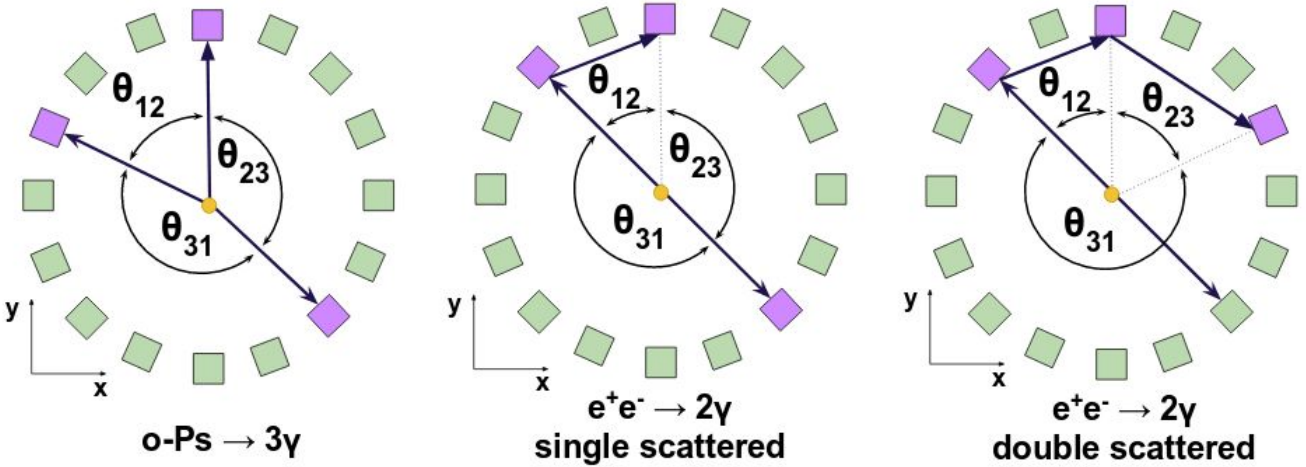
$\sigma_{ta} < 1$ ns



3 Hits Selection

CUT4: Scattering background rejection (ordering $\theta_{12} < \theta_{23} < \theta_{31}$)

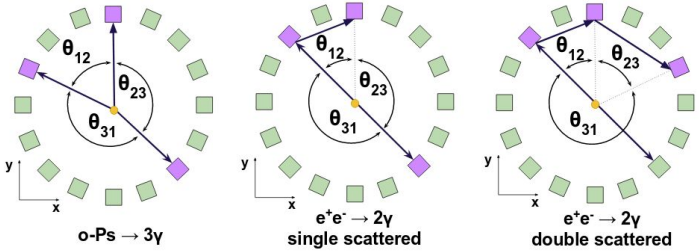
Background: scatterings in the strips

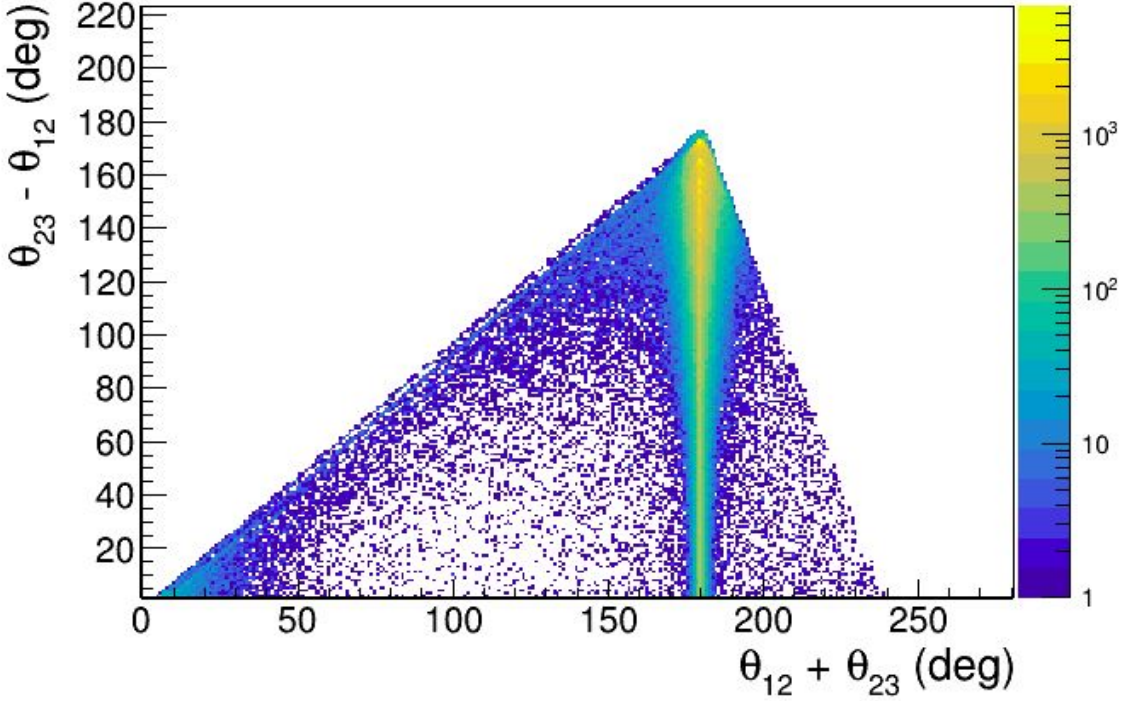


3 Hits Selection

CUT4: Momentum conservation ($\theta_{12} < \theta_{23} < \theta_{31}$)

$\theta_{12} + \theta_{23} > 180°$

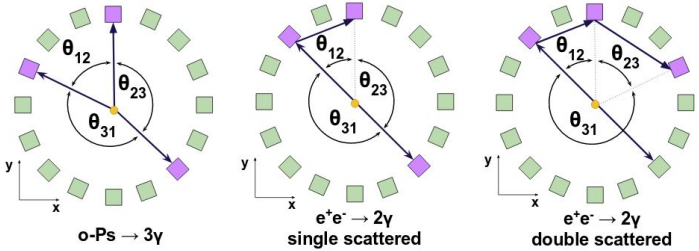


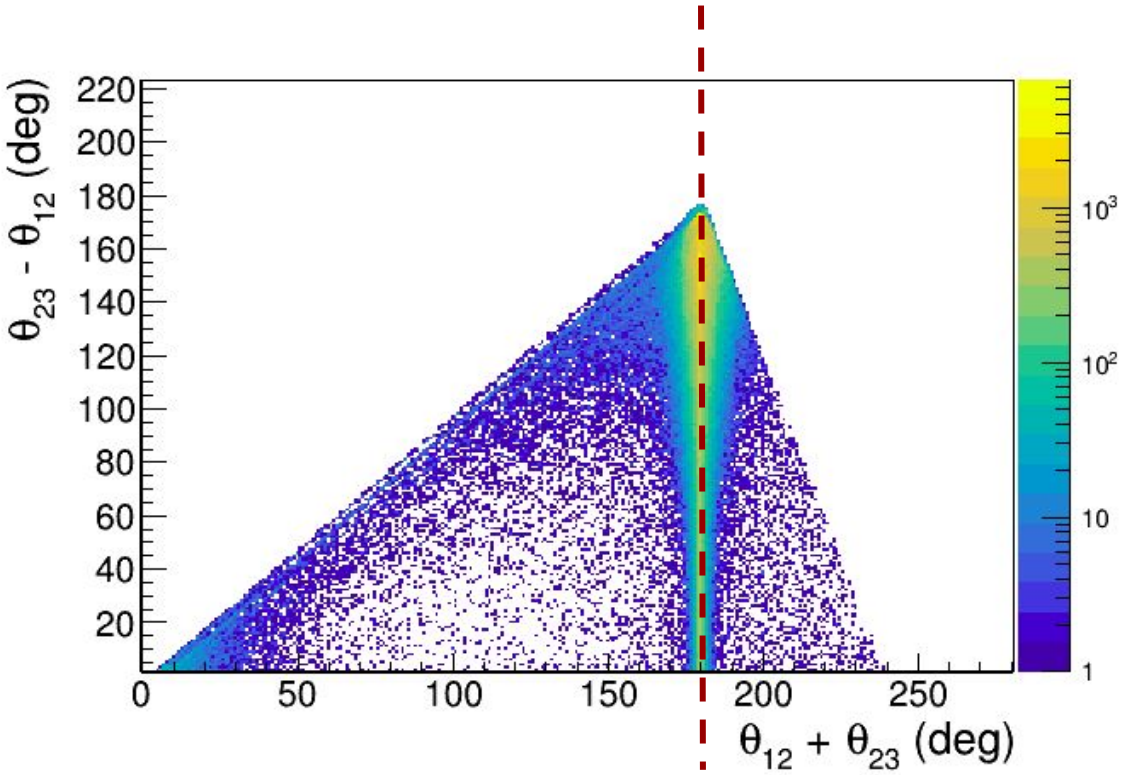


3 Hits Selection

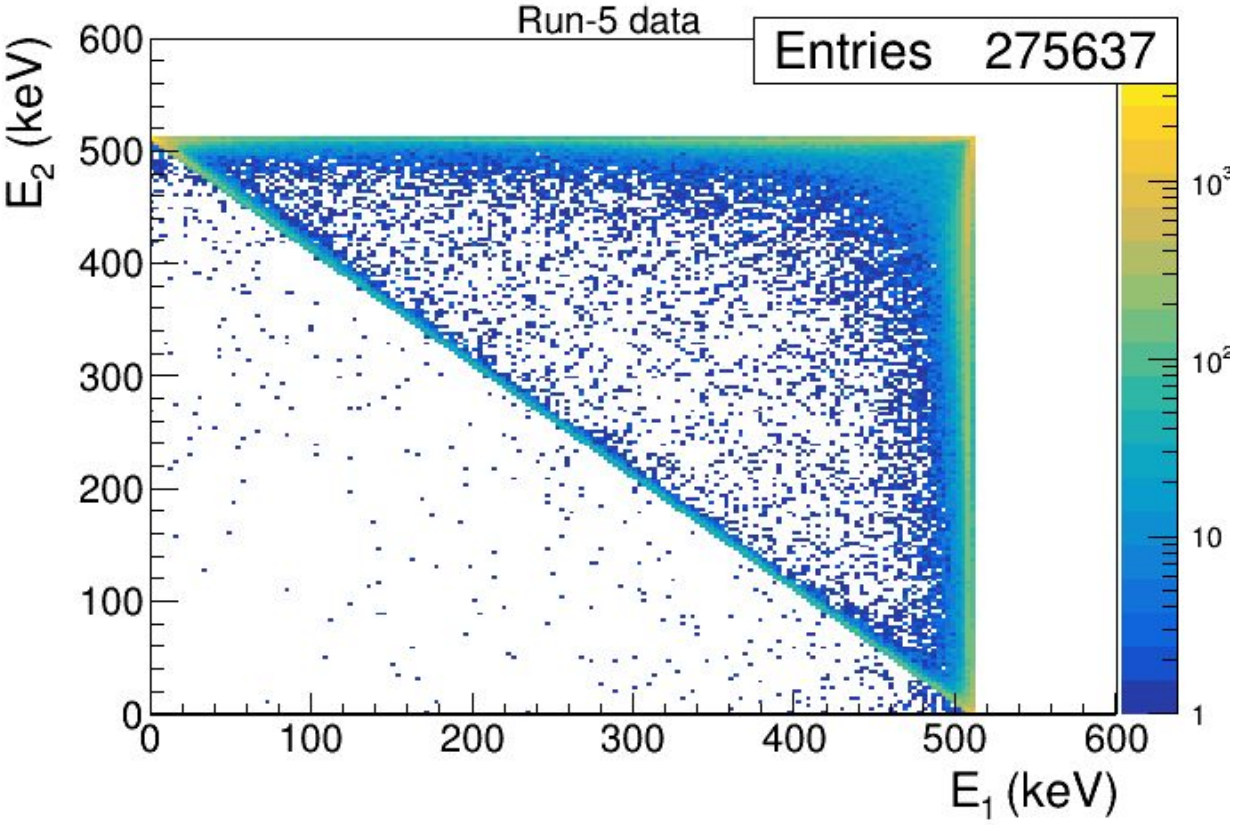
CUT4: Momentum conservation ($\theta_{12} < \theta_{23} < \theta_{31}$)

$\theta_{12} + \theta_{23} > 180°$





3 Hits Selection



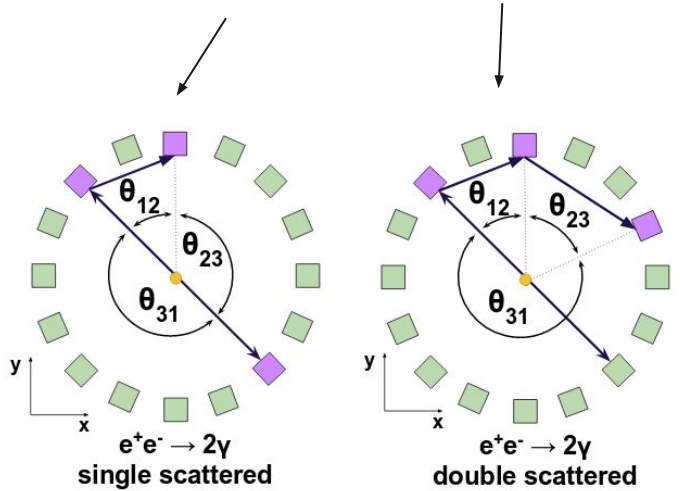
Monte Carlo simulations

1. **Signal:**

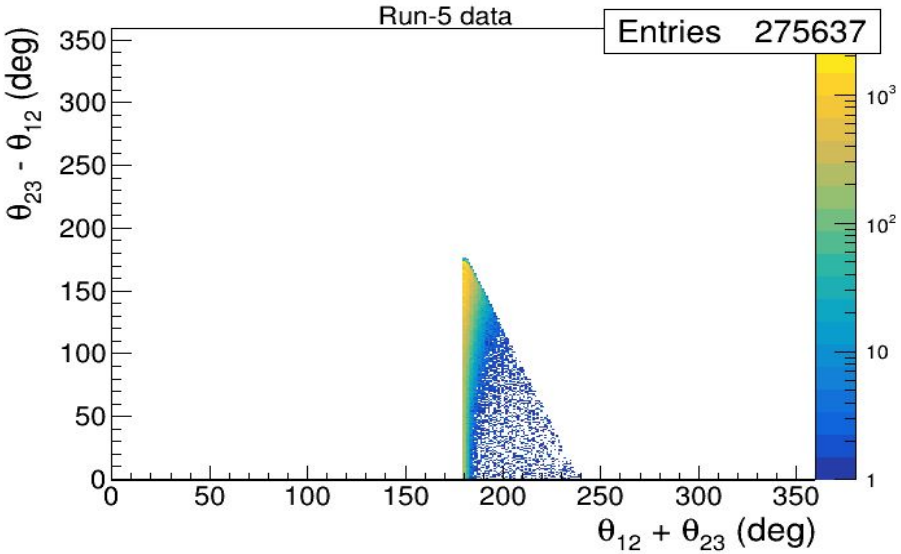
$$o\text{-}Ps \rightarrow \gamma_1 \gamma_2 \gamma_3 \qquad (Hit_1 , Hit_2 , Hit_3) = (\gamma_1 , \gamma_2 , \gamma_3)$$

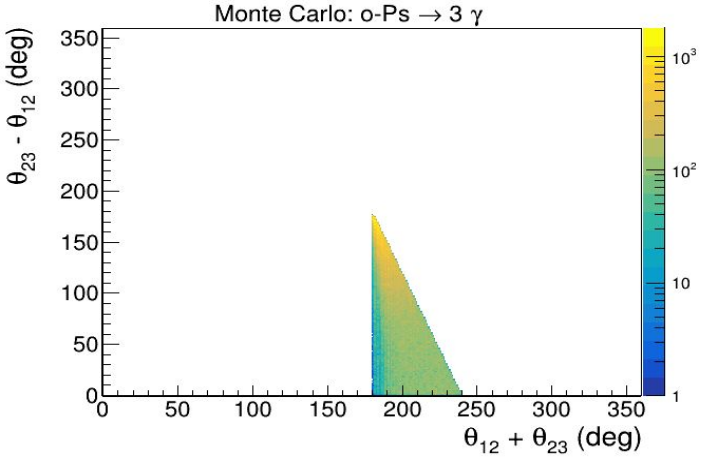
2. **Background:**

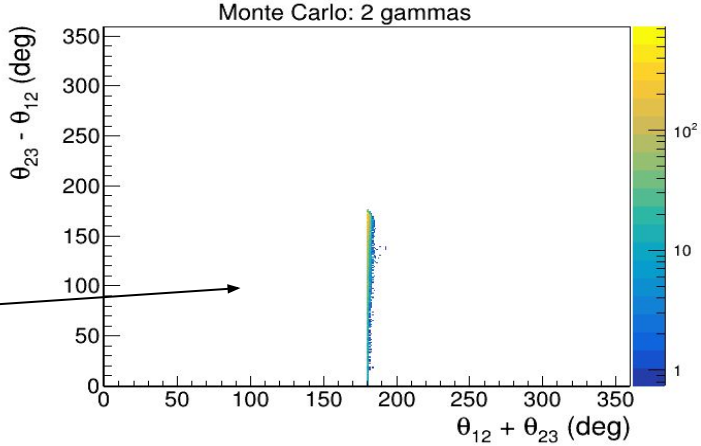
$$e^+ e^- \rightarrow \gamma_1 \gamma_2 \text{ + scattering} \qquad (Hit_1 , Hit_2 , Hit_3) = \{ (\gamma_1 , \gamma_1 , \gamma_2) , (\gamma_1 , \gamma_1 , \gamma_1) , \ldots . \}$$



Comparison MC-data

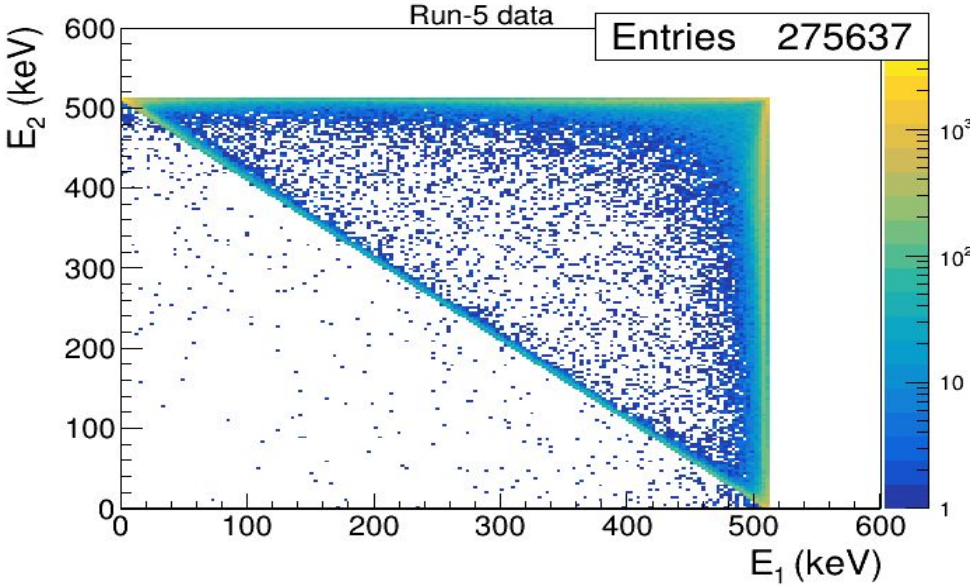


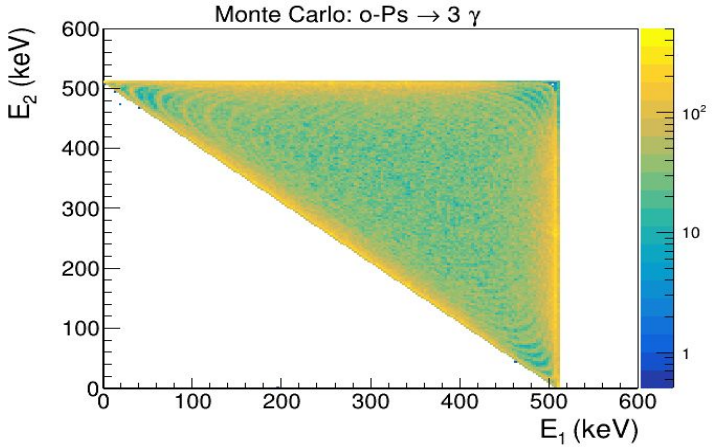


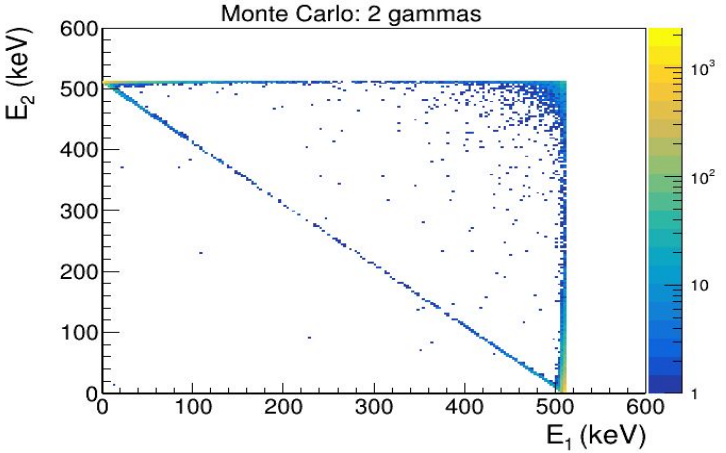


From the MC simulations we see that 2 γ events survive after the cuts are applied

Comparison MC-data

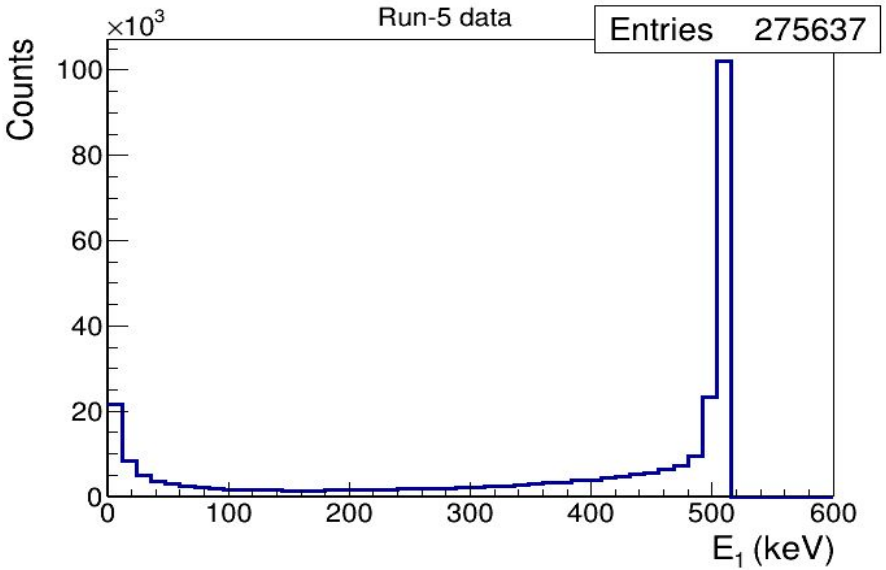


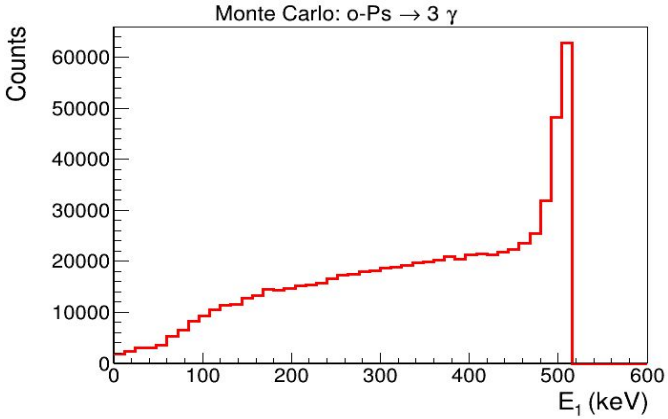


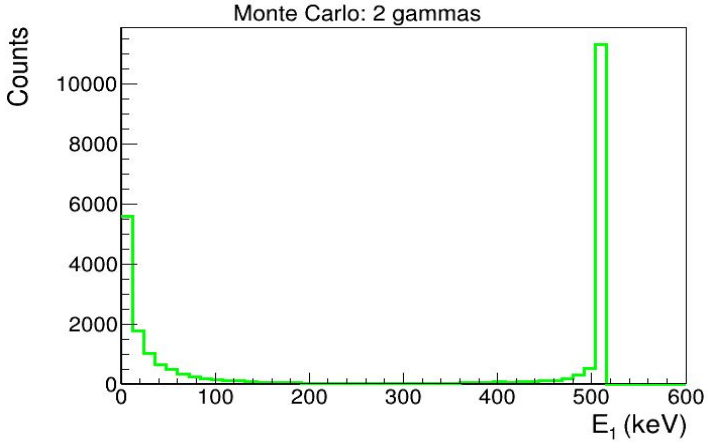


Goal: Disentangle the signal from the background using a fit of the data with MC distributions

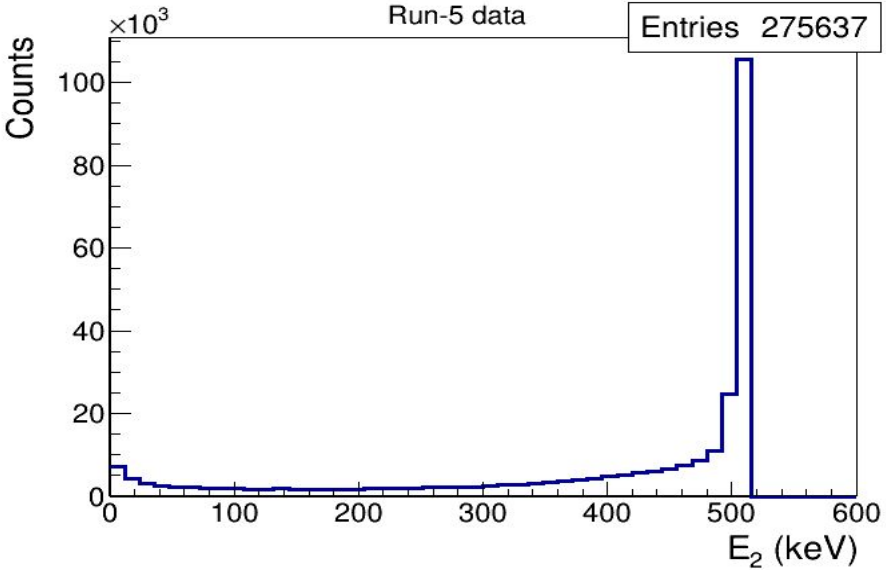
Comparison MC-data

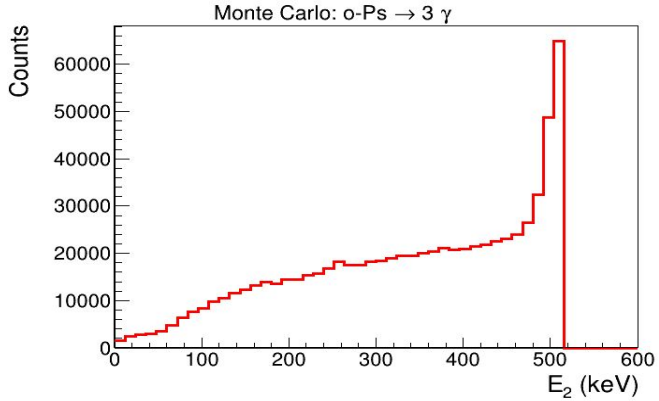


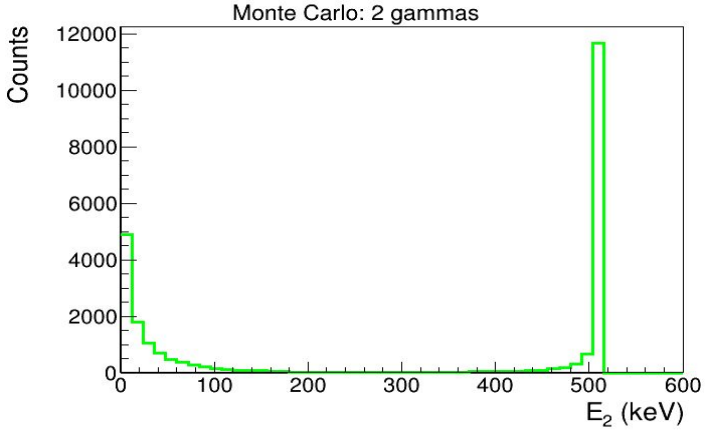




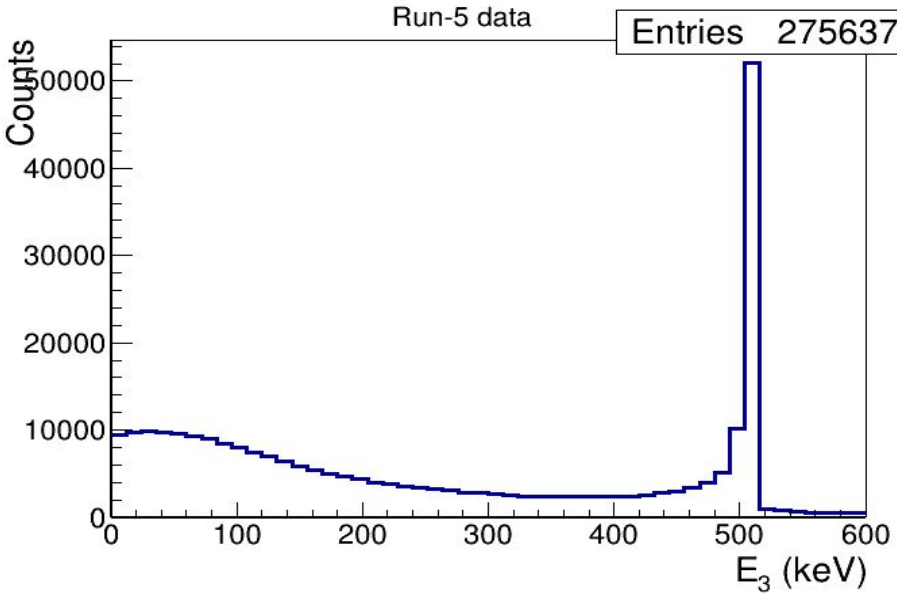
Comparison MC-data

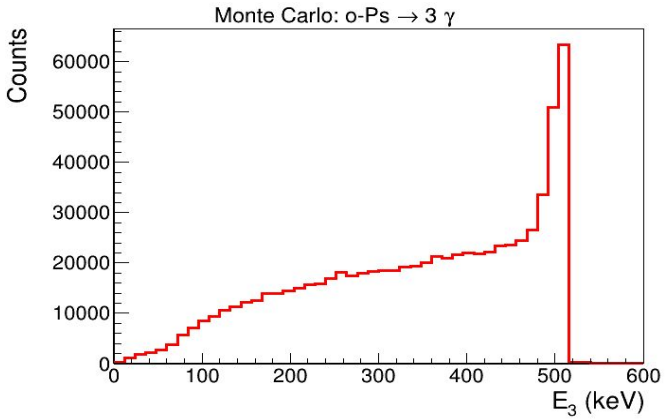


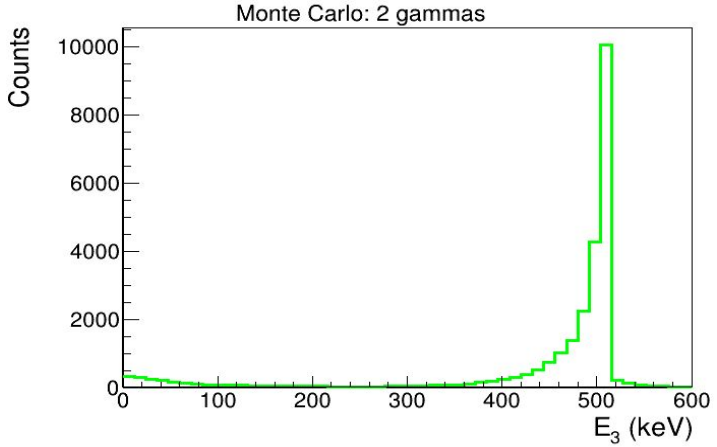




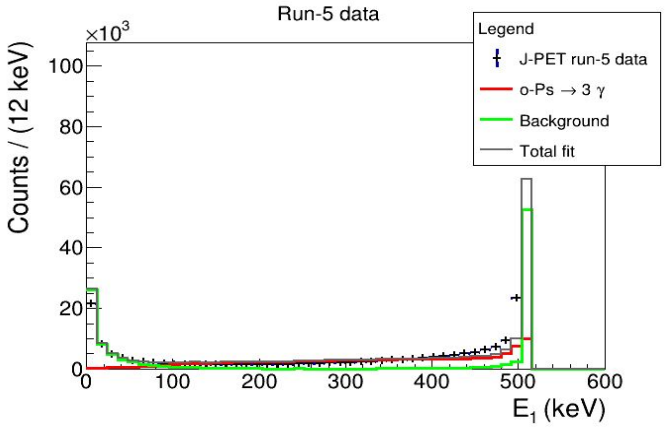
Comparison MC-data

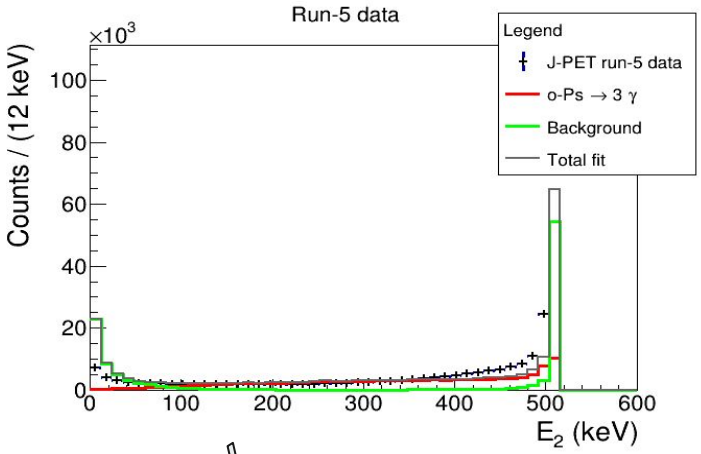


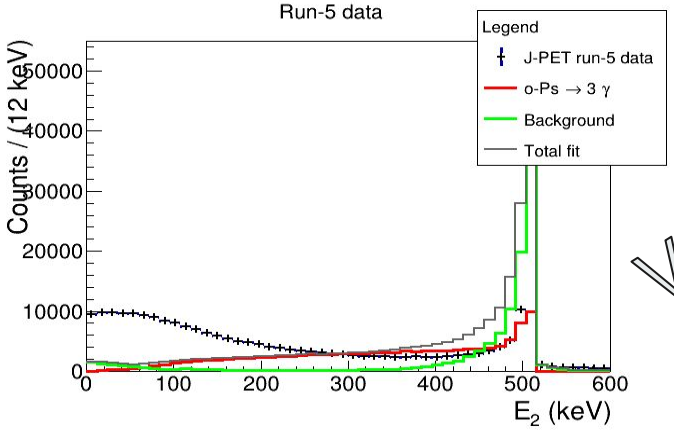




Very preliminary fit







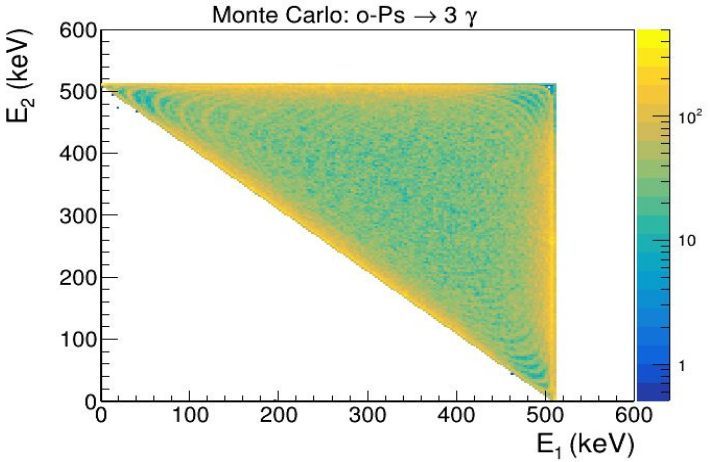
Very Preliminary

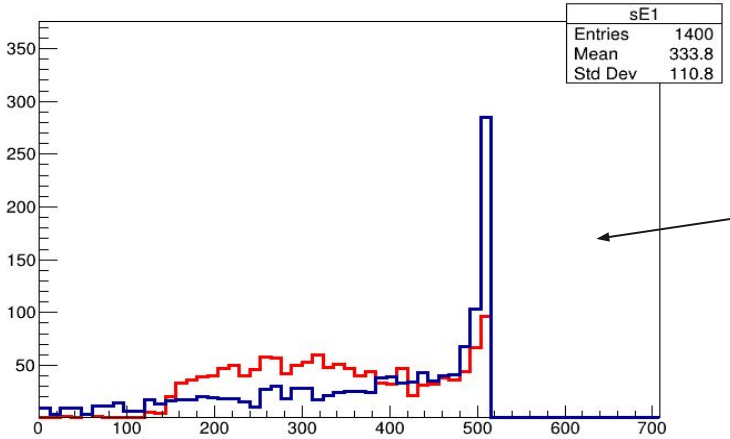
Missing component

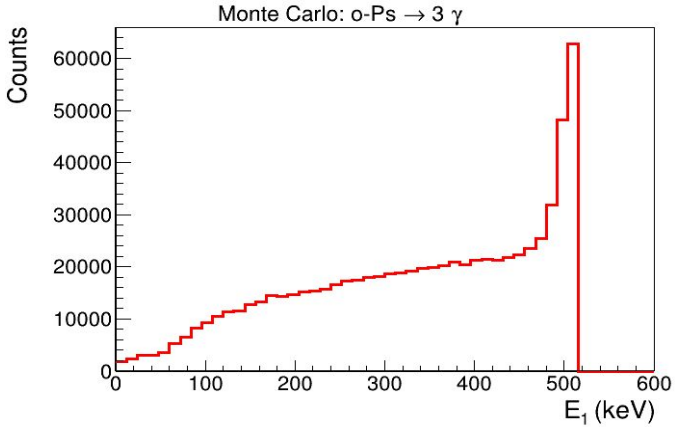
NEXT STEP:

Separated MC simulations for o-Ps → 3 γ as follows:

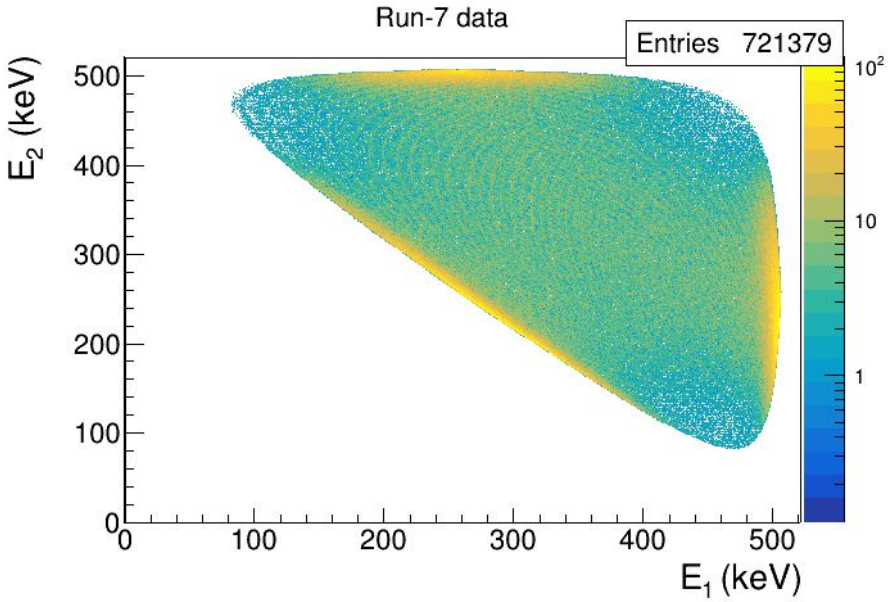
1. **3 Hits are from the o-Ps gammas**
2. **at least one hit is from scatterings**

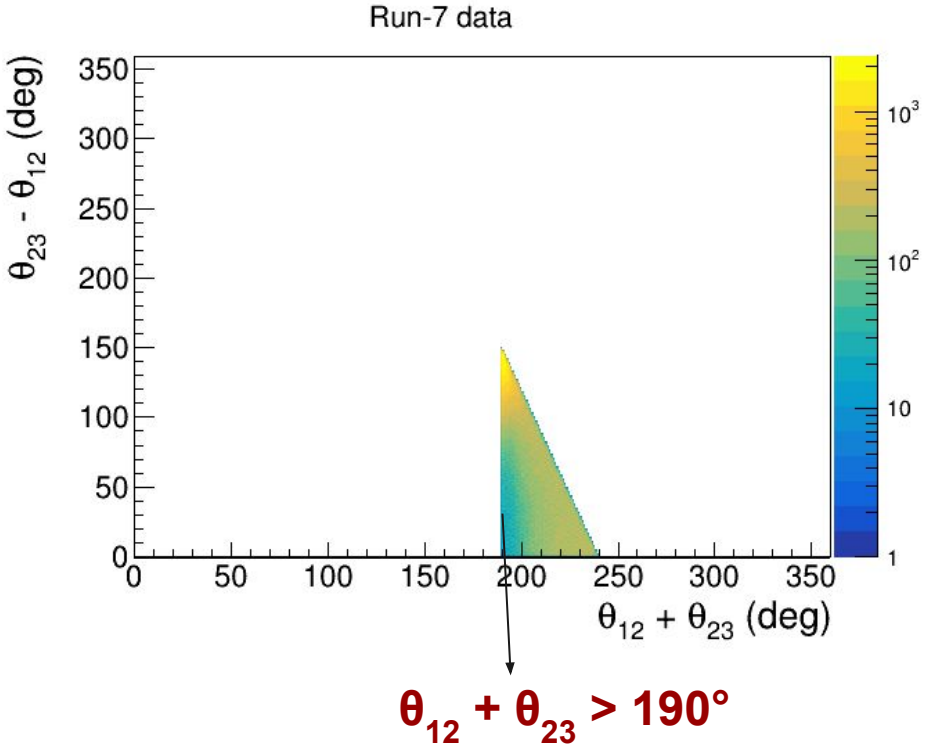






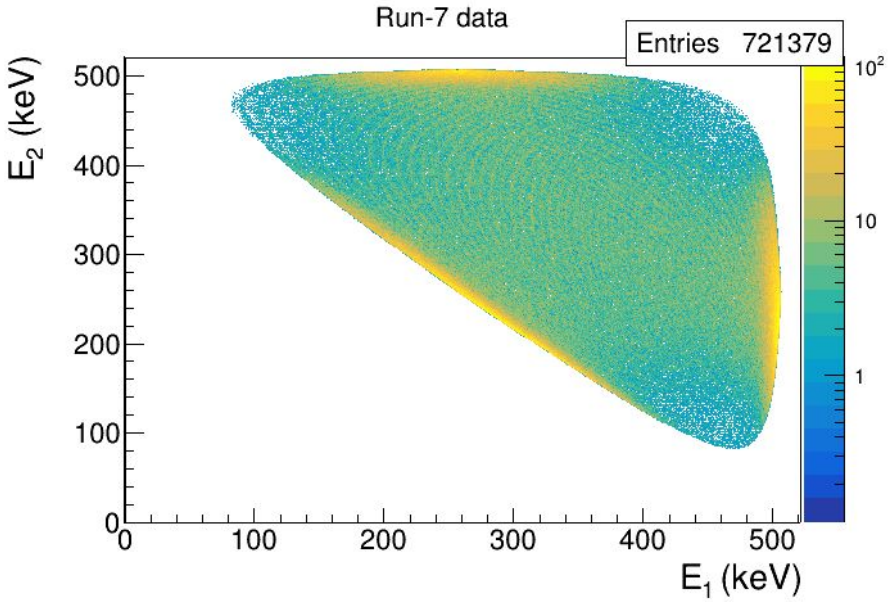
Run-7 data

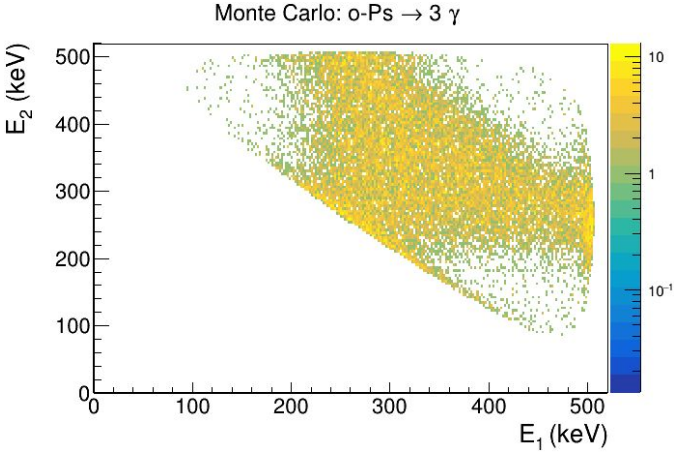


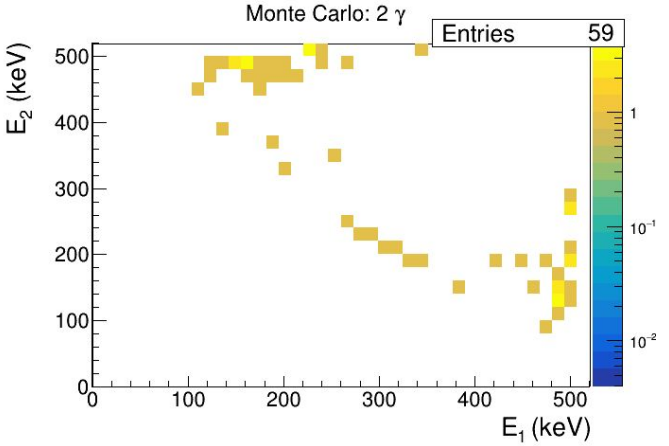


$\theta_{12} + \theta_{23} > 190°$

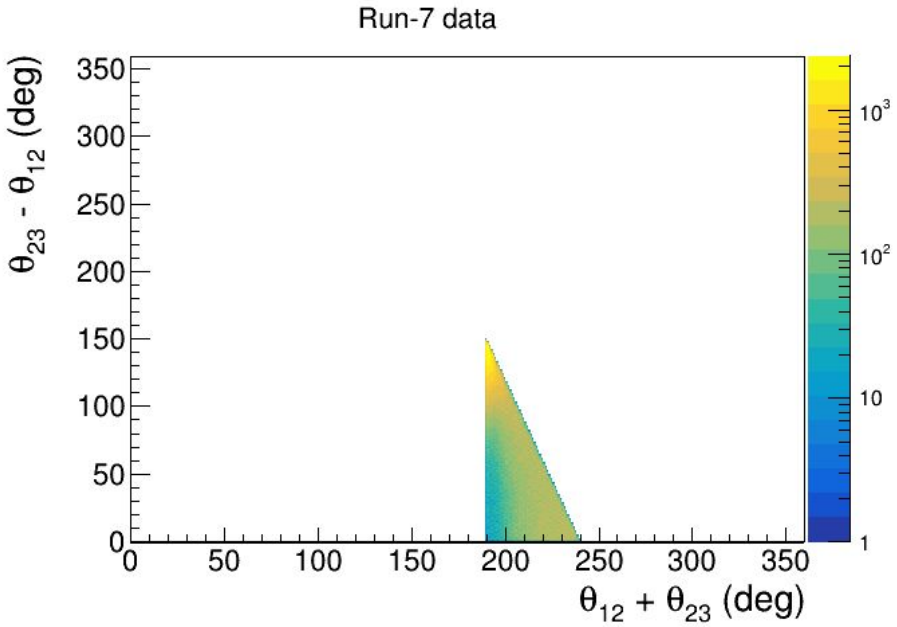
Run-7 data

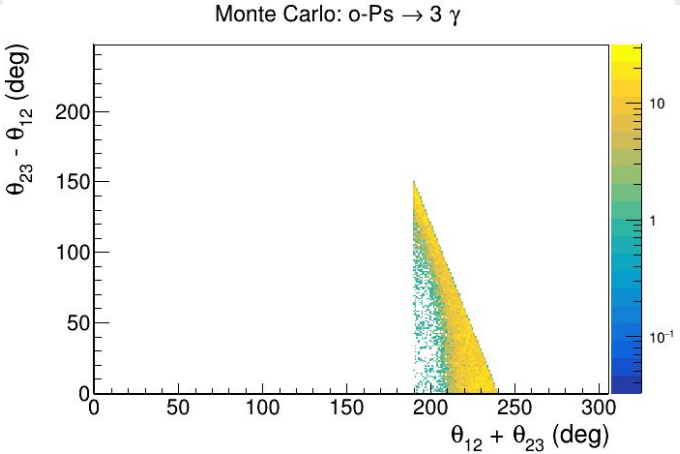

Run-7 data
Entries 721379
E_2 (keV)
E_1 (keV)
0
100
200
300
400
500
10^2
10
1

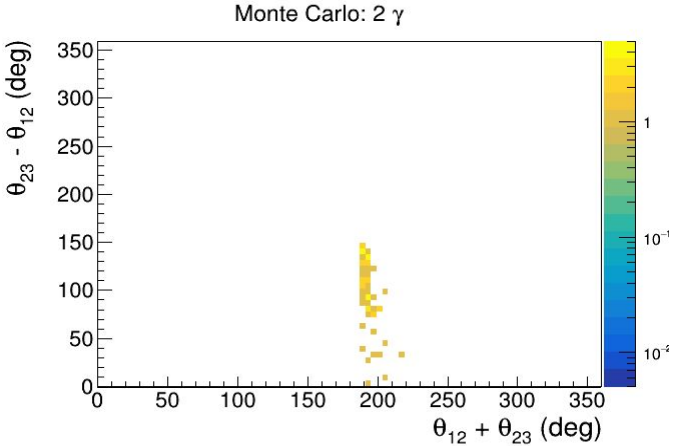

Monte Carlo: o-Ps → 3 γ
E_2 (keV)
E_1 (keV)
0
100
200
300
400
500
10
1
10^{-1}


Monte Carlo: 2 γ
Entries 59
E_2 (keV)
E_1 (keV)
0
100
200
300
400
500
1
10^{-1}
10^{-2}

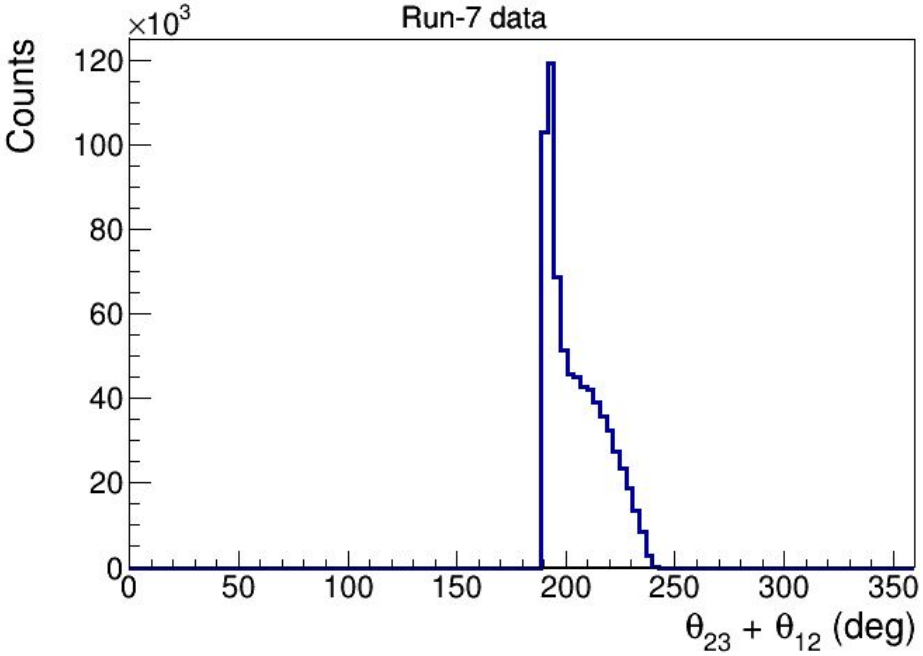
Comparison MC-data

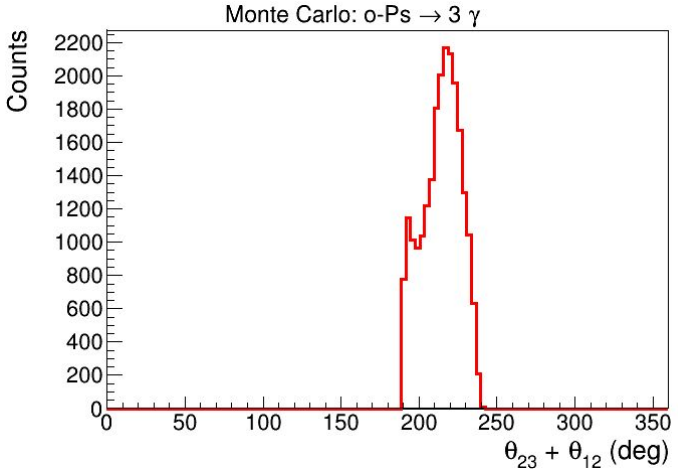


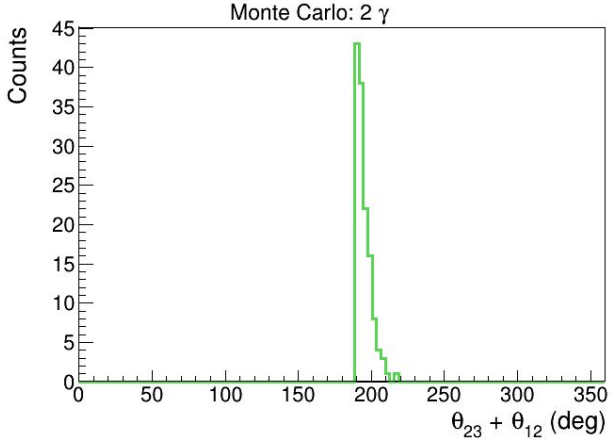




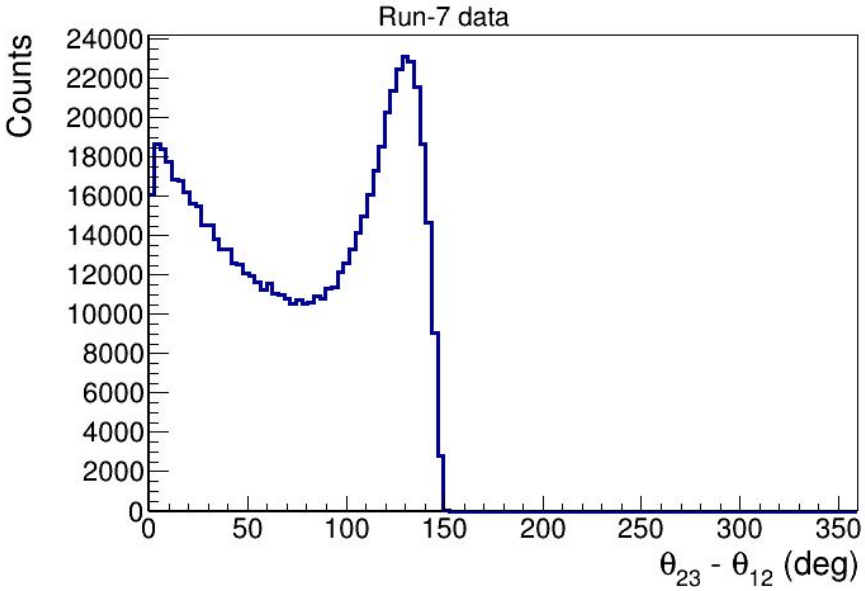
Comparison MC-data

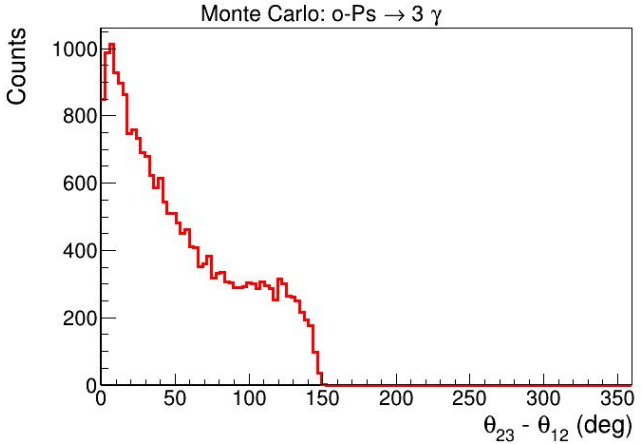


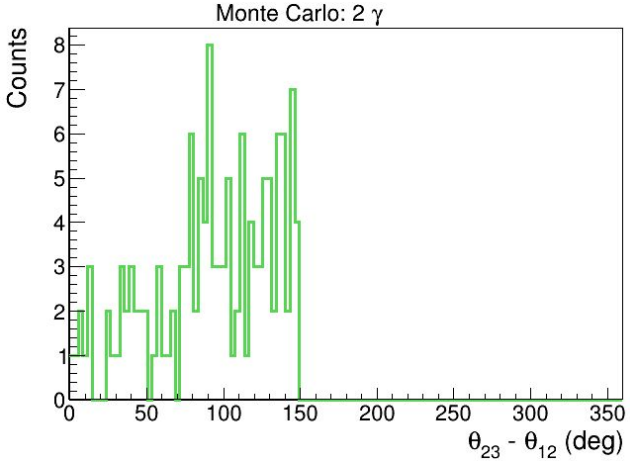




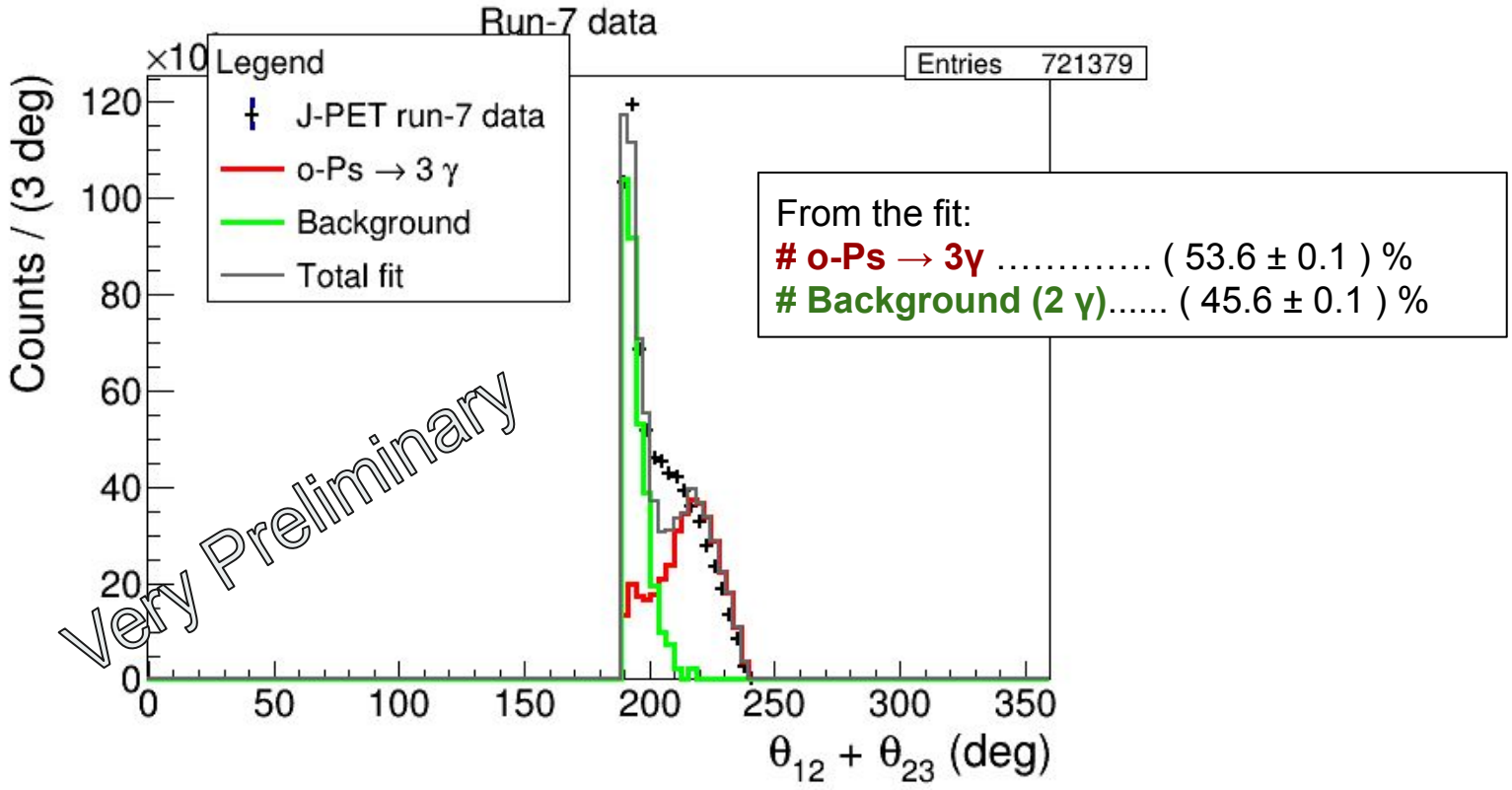
Comparison MC-data







Fit of the Run-7 data

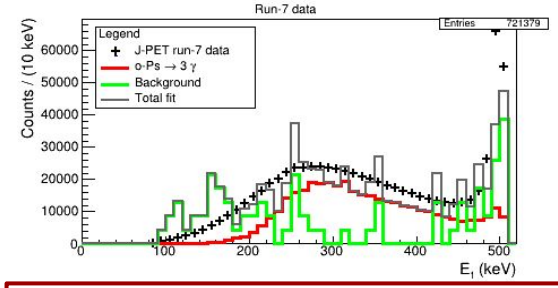


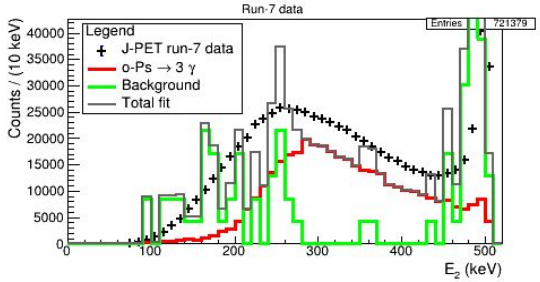
From the fit:

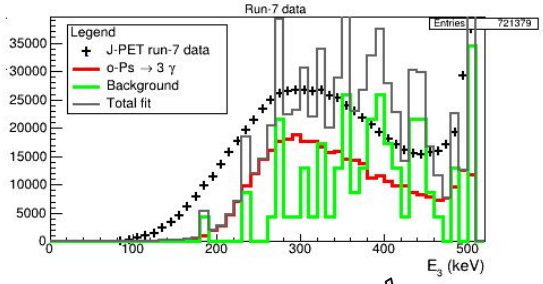
 # o-Ps → 3γ ..... (53.6 ± 0.1) %

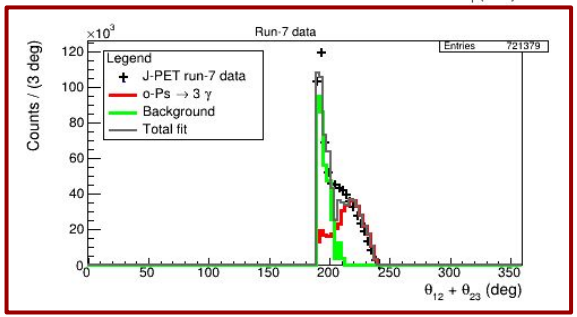
 # Background (2 γ)..... (45.6 ± 0.1) %

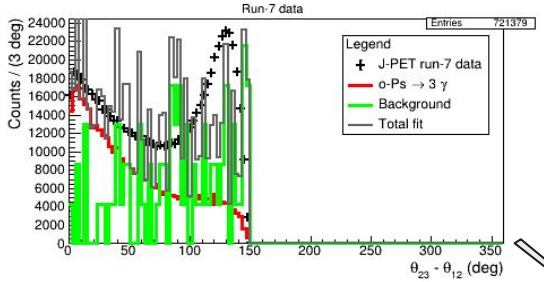
Fit of the Run-7 data



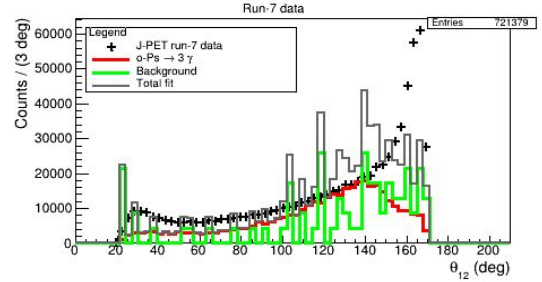


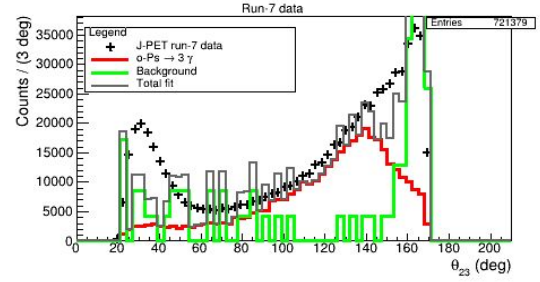


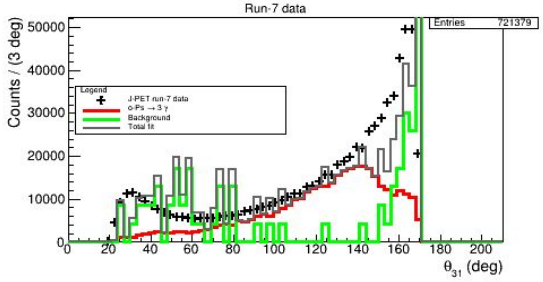




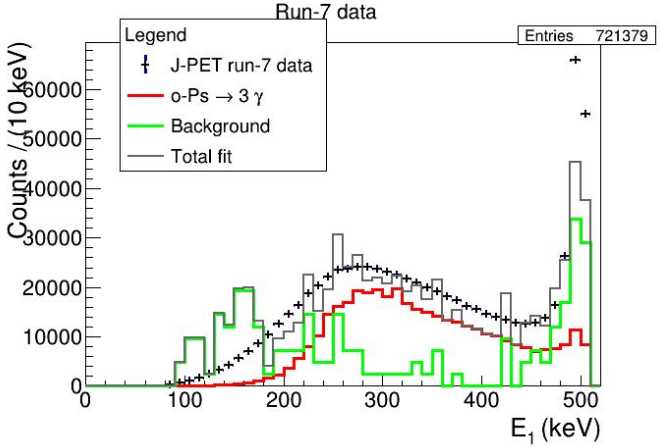
Very Preliminary

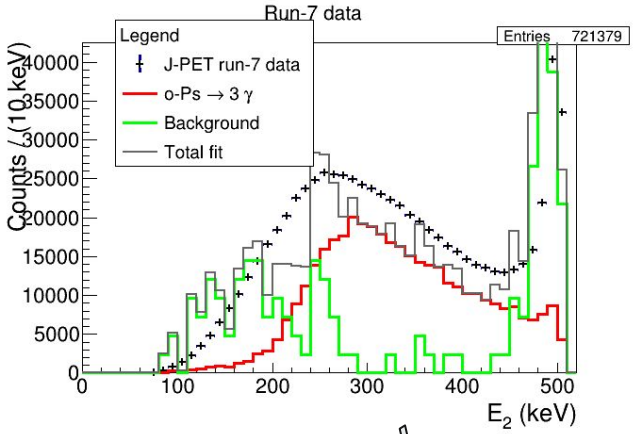


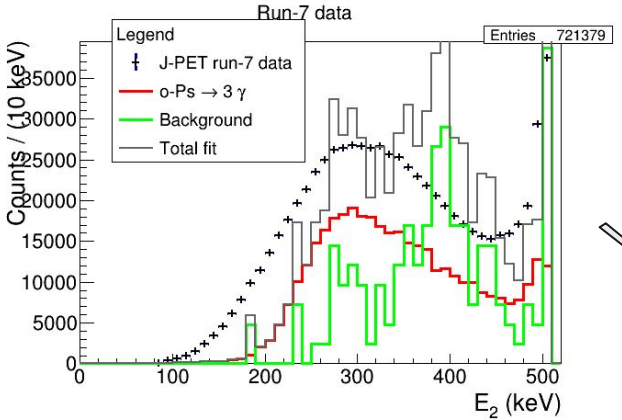




Fit of the Run-7 data

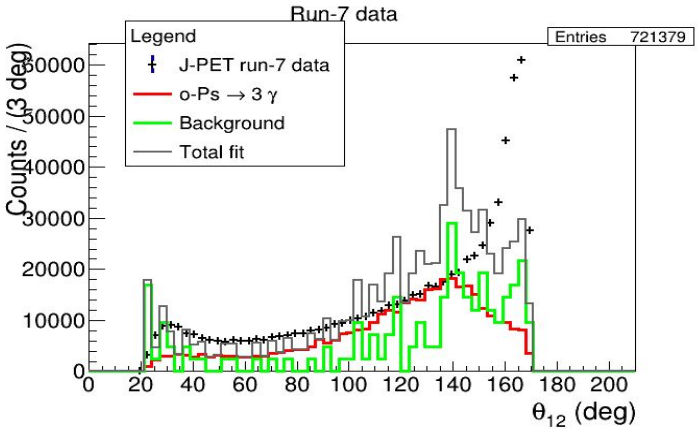


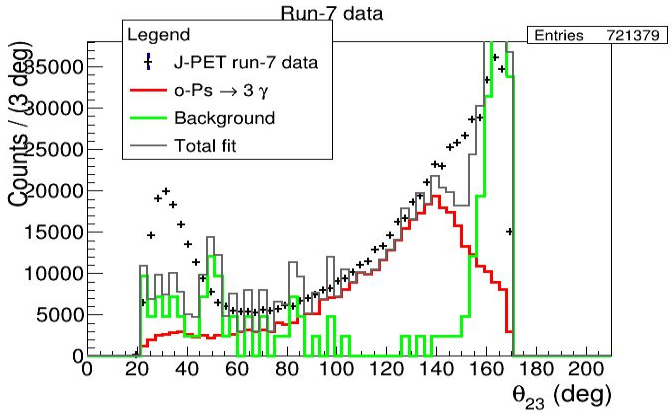


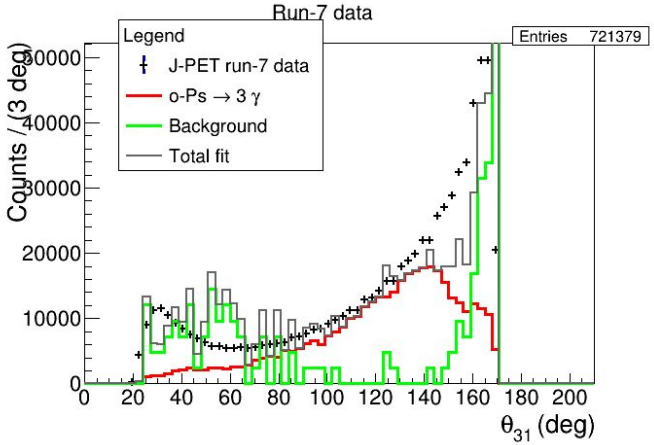


Very Preliminary

Fit of the Run-7 data

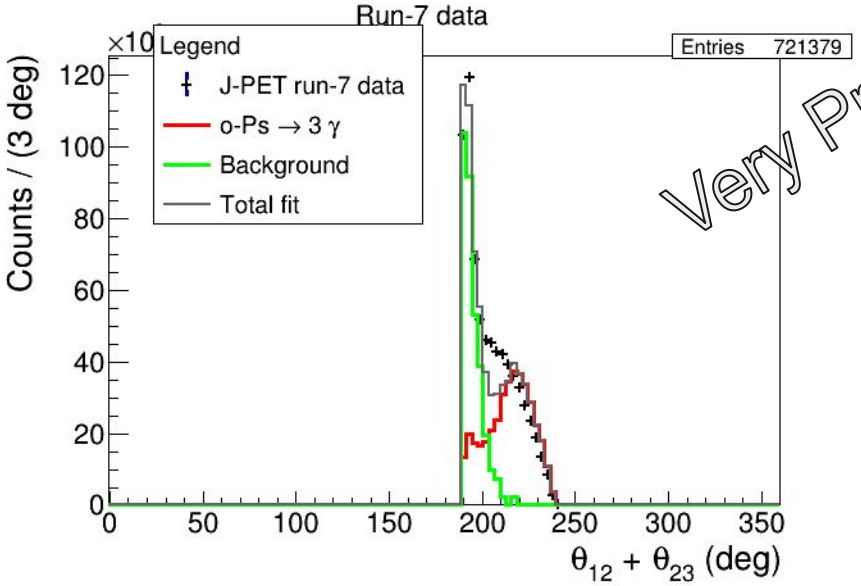


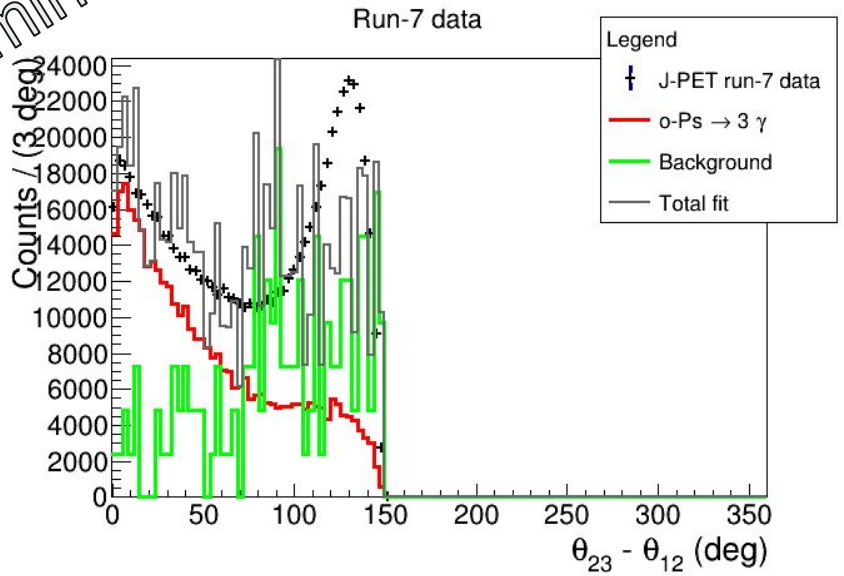




Very Preliminary

Fit of the Run-7 data





Very Preliminary

Conclusions

- **FIRST experimental Dalitz plot** for the o-Ps → 3 γ decay will be produced with the J-PET detector;
- Monte Carlo simulations are fundamental for the determination of new events selection criteria;
- Run-7 data are promising → a considerable amount of o-Ps events can be selected (simultaneous fit of the spectra)

Thank you for your attention