Dalitz plot determination for the o-Ps $\rightarrow$ 3 γ decay with J-PET

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On the behalf of the J-PET collaboration

J-PET

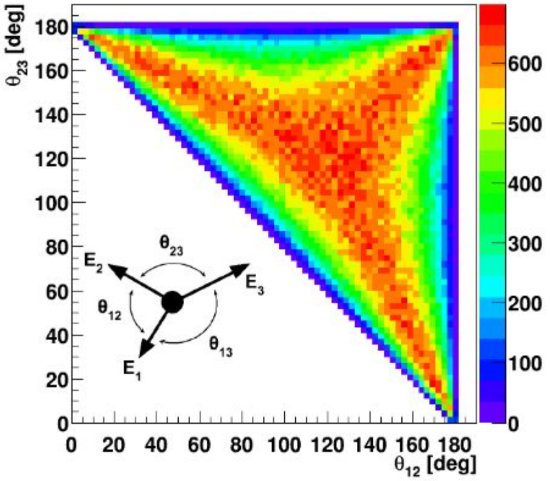
3rd Symposium on Positron Emission Tomography and 1st Symposium on Boron Neutron Capture Therapy

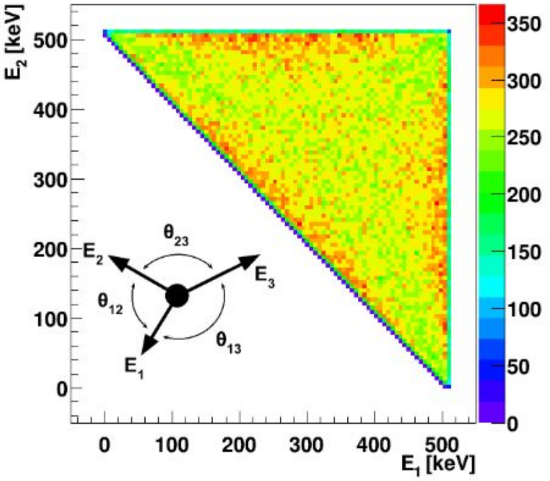
Krakòw, 10th - 15th September 2018

Goal of the analysis

First experimental o-Ps Dalitz plot determination

According to the theory →





Energies can be determined using angles between momentum vectors →

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

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

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

Outline

- **Run-5 data analysis:**

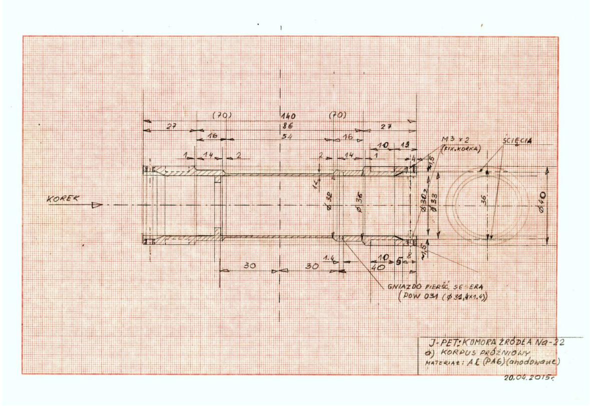
  → 3 hits and 4 hits selection

- **Monte Carlo simulations:**

  → signal (o-Ps → 3 γ)

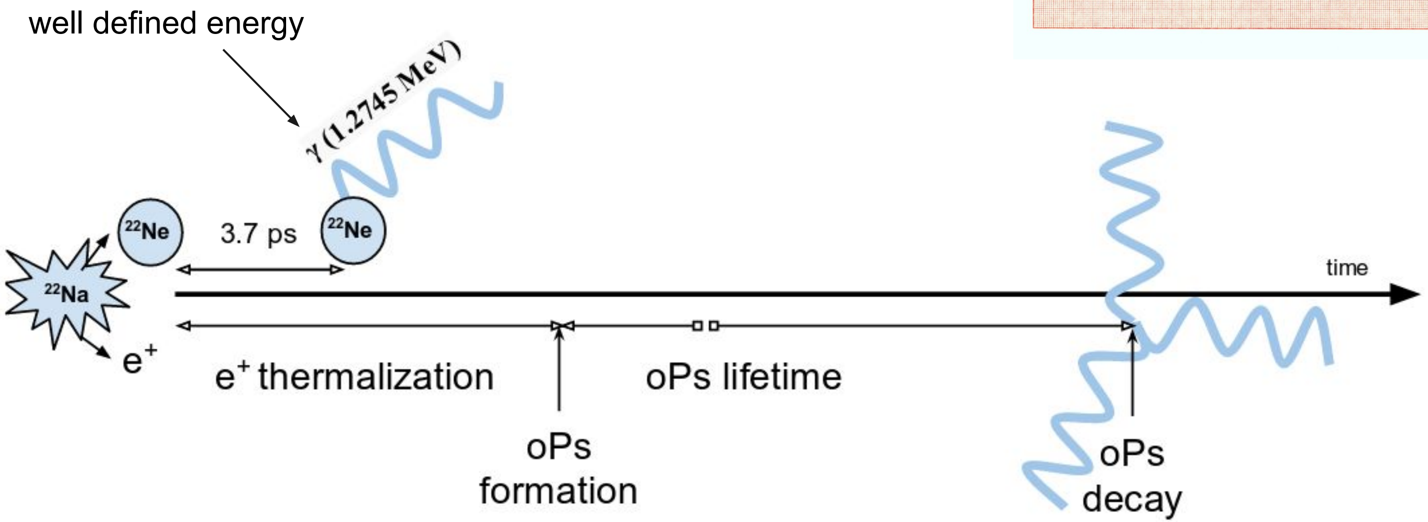
  → background (e^+e^- annihilation + scatterings)

- **Preliminary fits**



Small Chamber measurements:

β^+ source: sodium-22 ($^{22}Na \rightarrow {}^{22}Ne^* + e^+ + \nu_e$)
porous material: amberlite polymer XAD-4

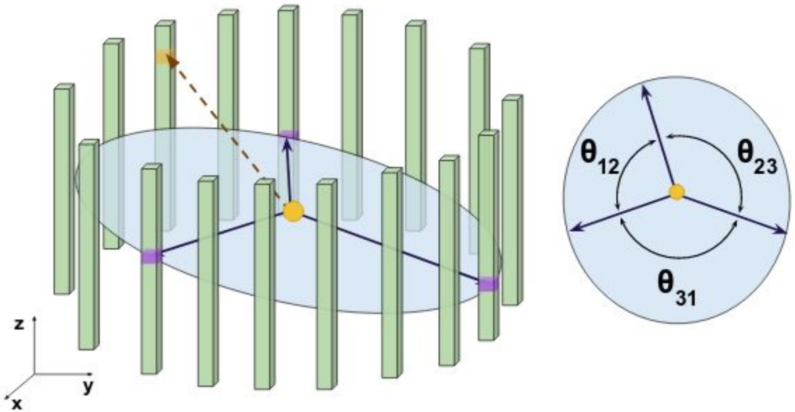


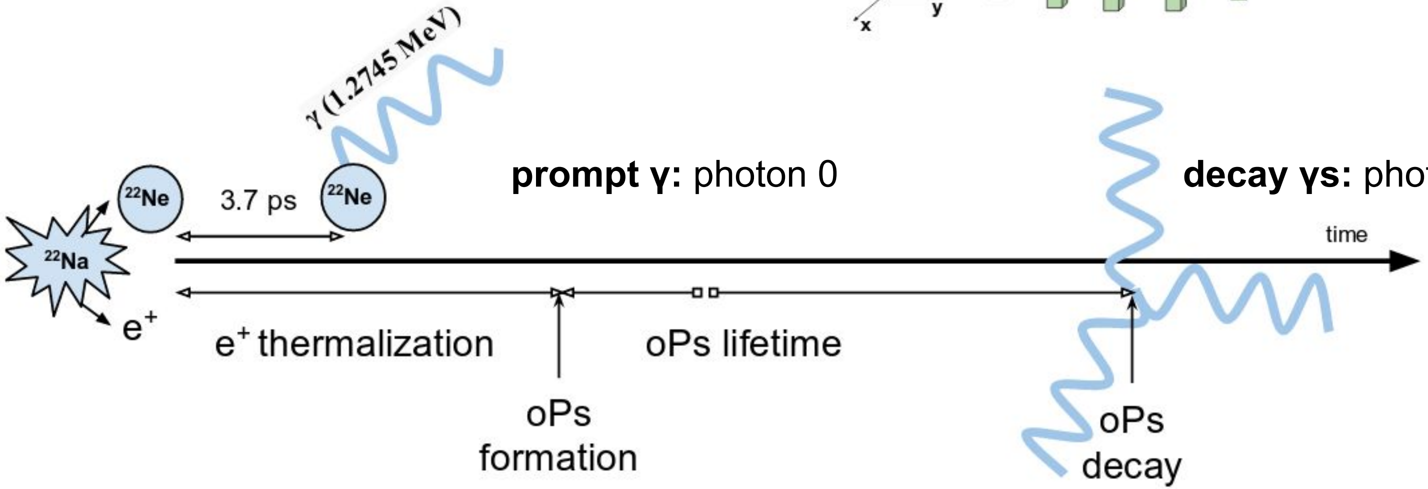
Run-5 data analysis

Hits in the scintillators:

→ **3 hits**: γs from the o-Ps decay   (signal)
→ **4 hits**: 3 γs from the o-Ps + prompt γ   (signal)

Analyzed sample: 996 data files → ~ 8 h





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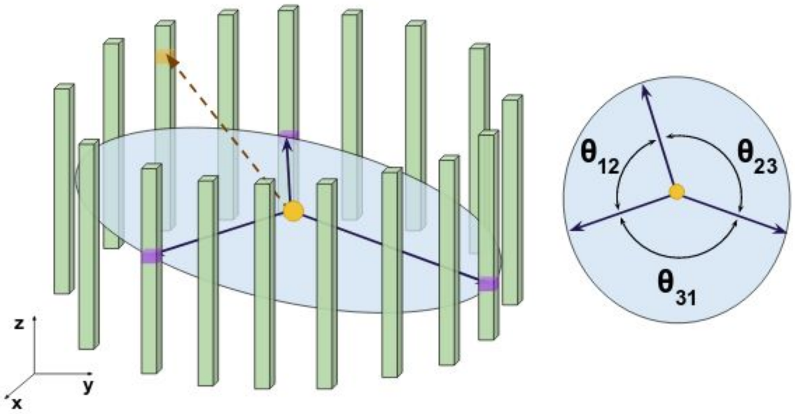
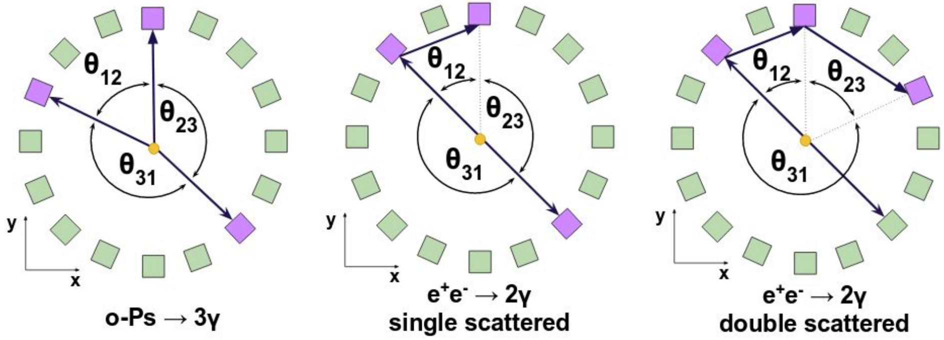


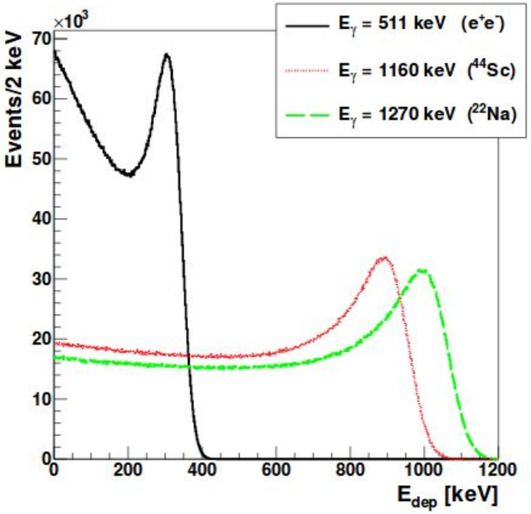
Background: scatterings in the strips



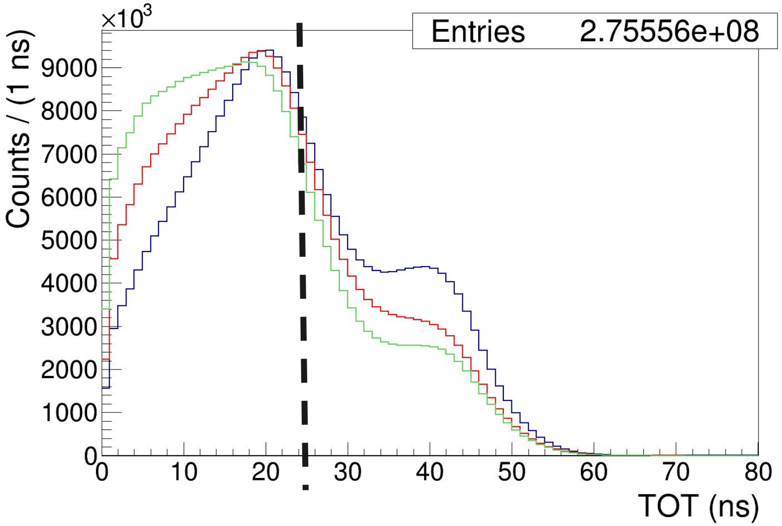
3 Hits Selection

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

MC simulations



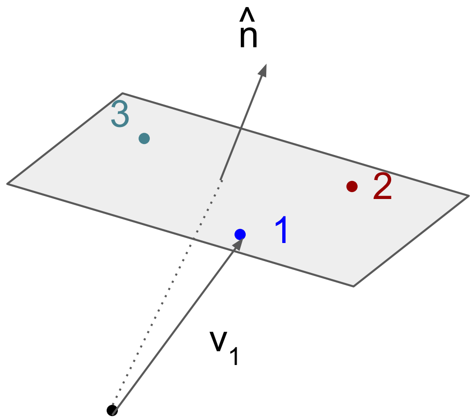
data



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

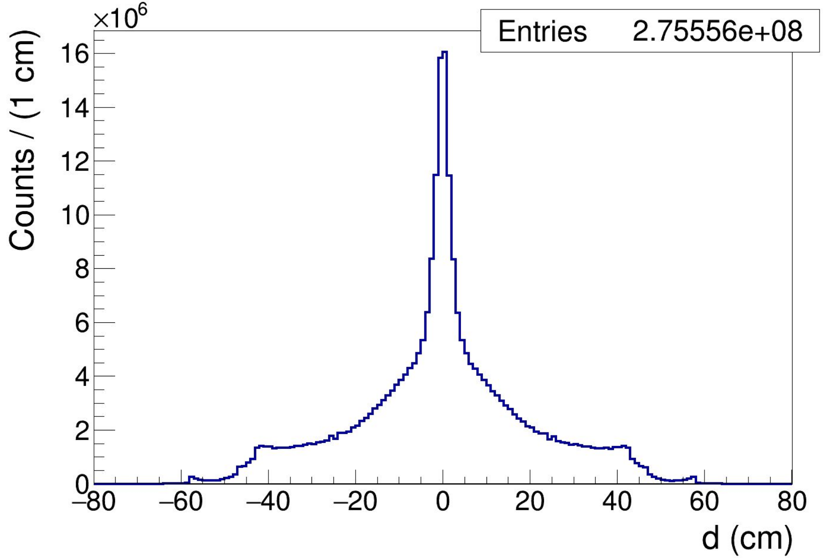
3 Hits Selection

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



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

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



|d| < 2 cm

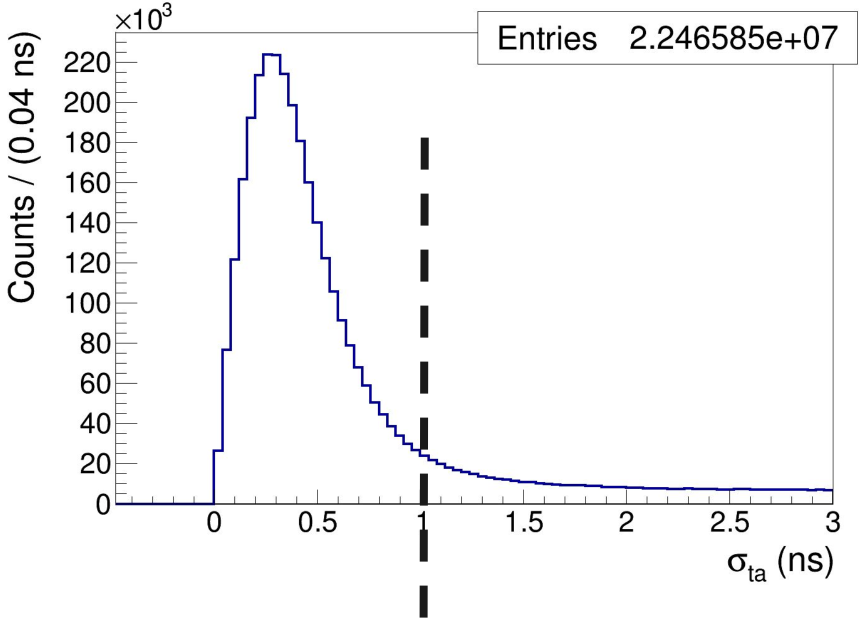
3 Hits Selection

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)

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

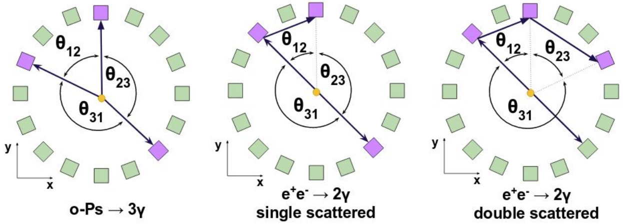
$\sigma_{ta} < 1$ ns

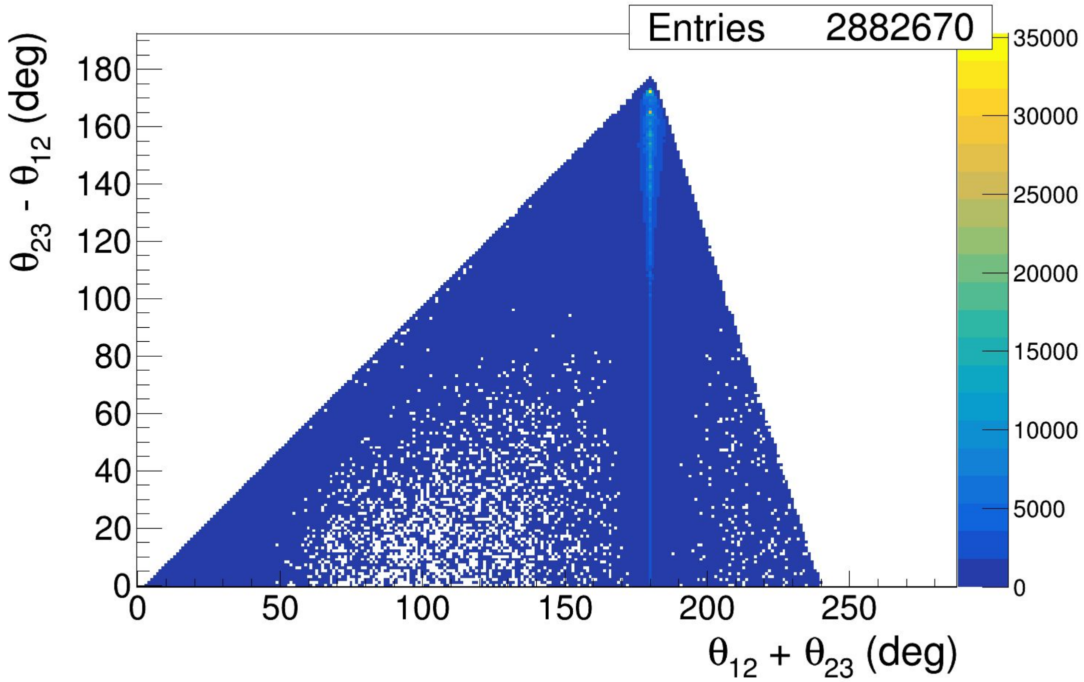


3 Hits Selection

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

$\theta_{12} + \theta_{23} > 180$

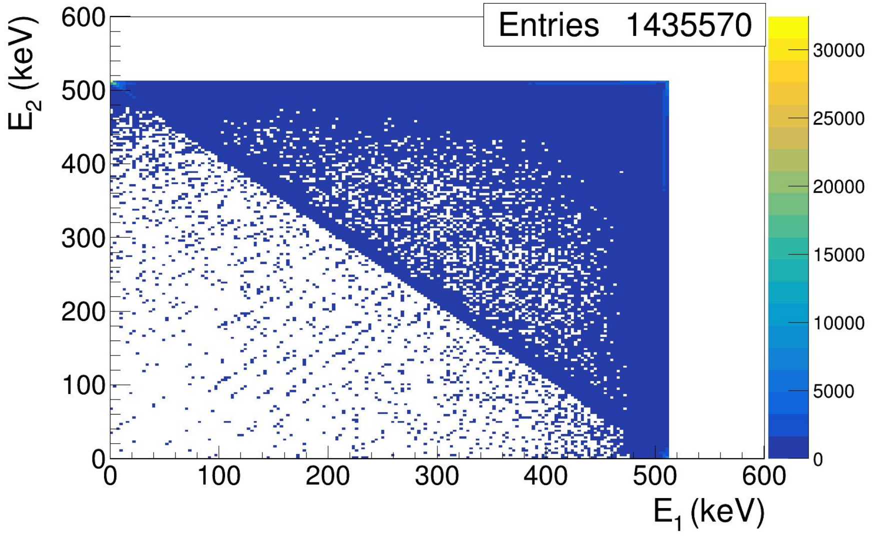


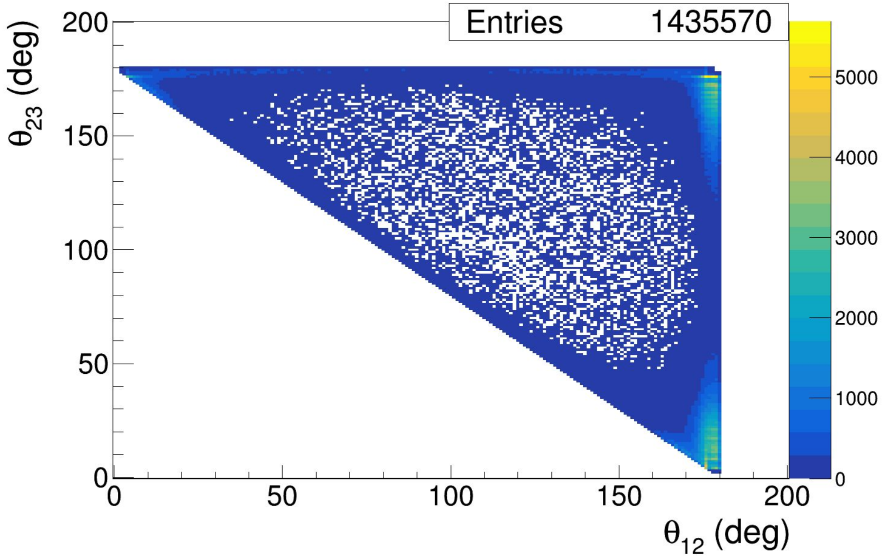


3 Hits Selection

Dalitz plot and θ_{23} vs θ_{12}

Photons are ordered by annihilation time: $t_{a1} < t_{a2} < t_{a3}$





Monte Carlo simulations

1. **Signal:**

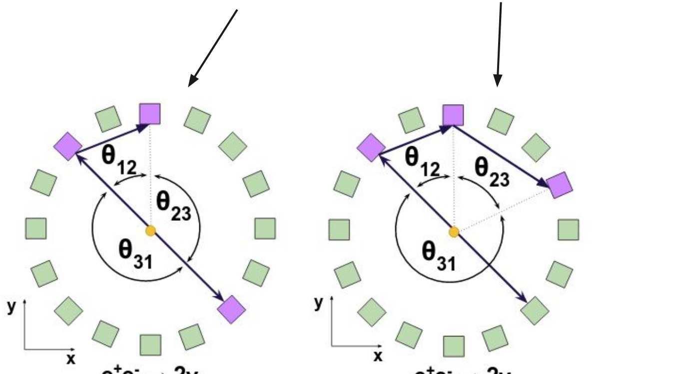
   $o\text{-}Ps \rightarrow \gamma_1\ \gamma_2\ \gamma_3$ $\qquad$ $(Hit_1\ ,\ Hit_2\ ,\ Hit_3\ ) = (\ \gamma_1\ ,\ \gamma_2\ ,\ \gamma_3\ )$

2. **Background 1:**

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

3. **Background 2:**

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



Monte Carlo simulations

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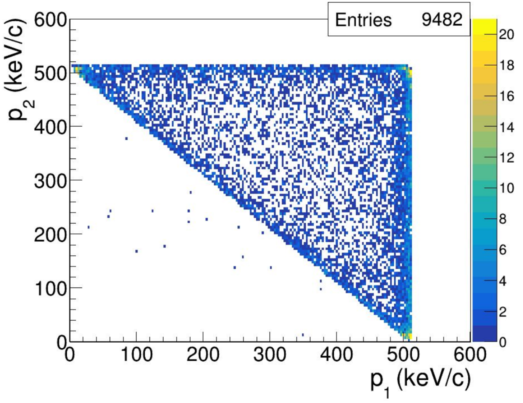
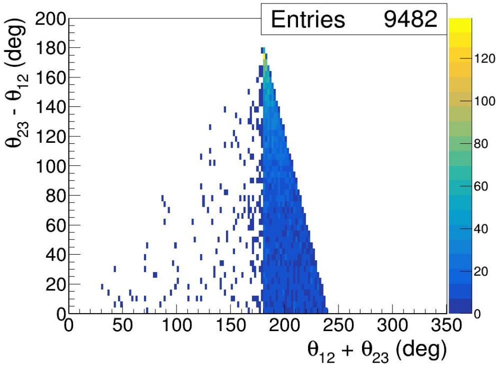
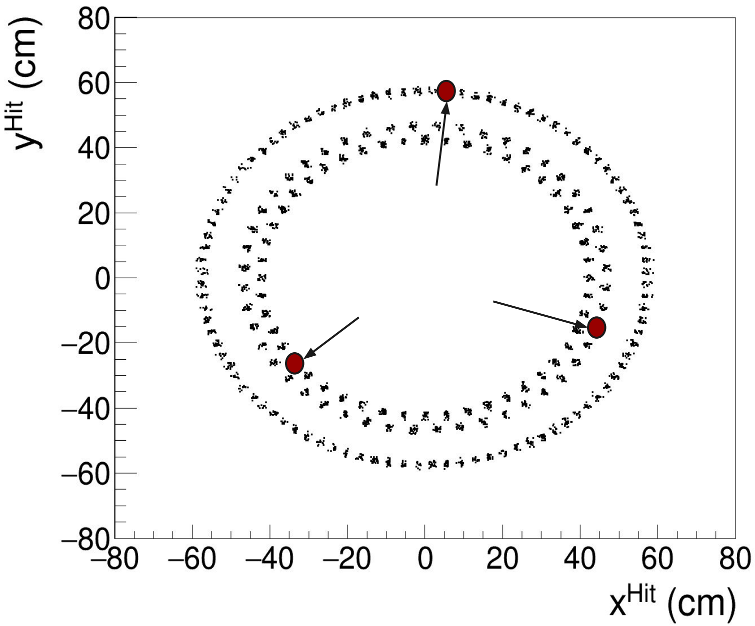
$o\text{-}Ps \to \gamma_1 \gamma_2 \gamma_3$

$(Hit_1, Hit_2, Hit_3) = (\gamma_1, \gamma_2, \gamma_3)$







Monte Carlo simulations

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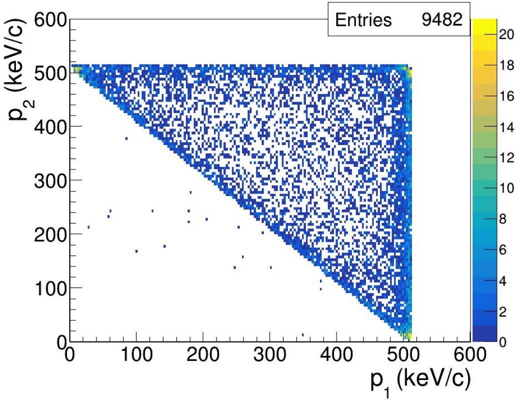
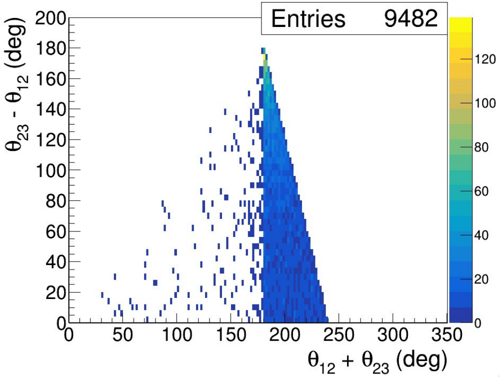
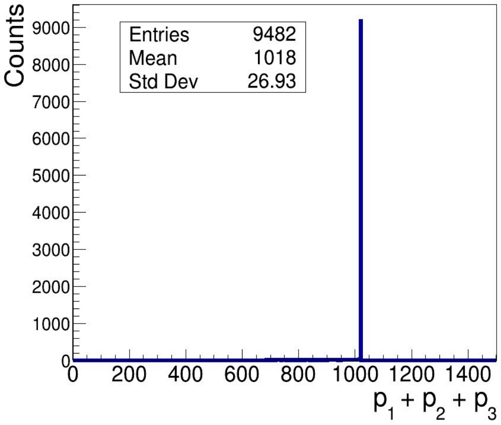
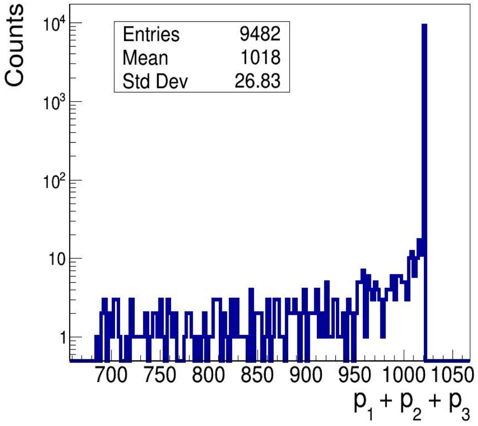




Check: energy-conservation $E_1 + E_2 + E_3 = 2m_e$



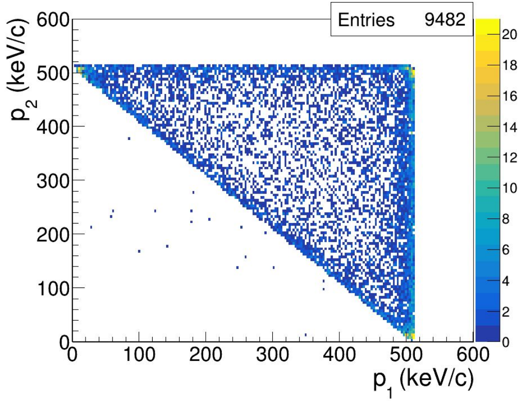


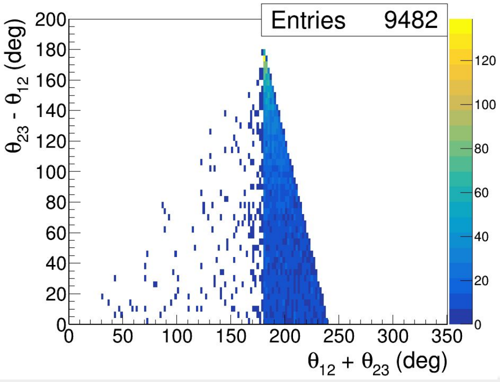
Monte Carlo simulations

1. Signal:

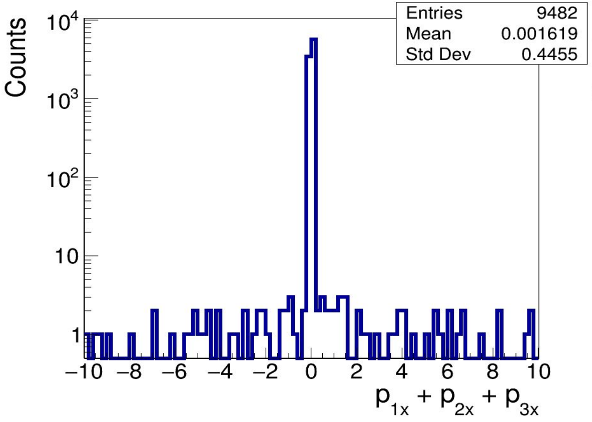
$o\text{-}Ps \rightarrow \gamma_1\ \gamma_2\ \gamma_3$

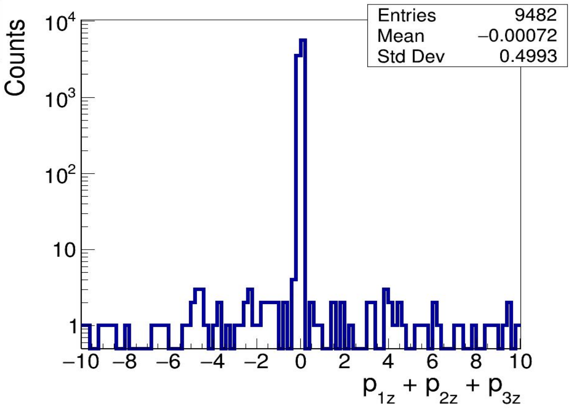
$(Hit_1\ , Hit_2\ , Hit_3\ ) = (\ \gamma_1\ , \gamma_2\ , \gamma_3\ )$





Check: momentum-conservation $\mathbf{p_1 + p_2 + p_3 = 0}$





Monte Carlo simulations

1. **Signal:**

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

Additional requirement: $E_1 + E_2 + E_3 > 1020\ \text{keV}$

Additional requirement: $|p_{1x} + p_{2x} + p_{3x}| < 0.2\ \text{keV/c}$
$|p_{1y} + p_{2y} + p_{3y}| < 0.2\ \text{keV/c}$
$|p_{1z} + p_{2z} + p_{3z}| < 0.2\ \text{keV/c}$

2. **Background 1:**

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

3. **Background 2:**

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

Monte Carlo simulations

Efficiencies:

The same cuts used for the data are applied (except for the cut on the TOT):

1. decay plane contains the annihilation point → $|d| < 2$ cm
2. same time of annihilation for the 3 γ → $\sigma_t < 1$ ns
3. momentum conservation for 3γ from o-Ps → $\theta_{12} + \theta_{23} > 180$
4. $\mathbf{E_{dep} > 50}$ **keV** (threshold)

Signal:

- 1×10^8 generated
- 1400 detected
- 1400 selected

Background 1:

- 1×10^8 generated
- 13347 detected
- 1356 selected

Background 2:

- 1×10^8 generated
- 24202 detected
- 9413 selected

Monte Carlo simulations

Expected number of o-Ps → 3 γ events:

$$N_{o\text{-}Ps} = A \times f_{o\text{-}Ps\rightarrow 3\gamma} \times eff \times t$$

A = annihilation rate = 10^6 for 10 MBq source and $E_{dep} > 50$ keV

$f_{o\text{-}Ps\rightarrow 3\gamma}$ = 28.6 % (in porous polymer XAD-4)

eff = 1.4×10^{-5}

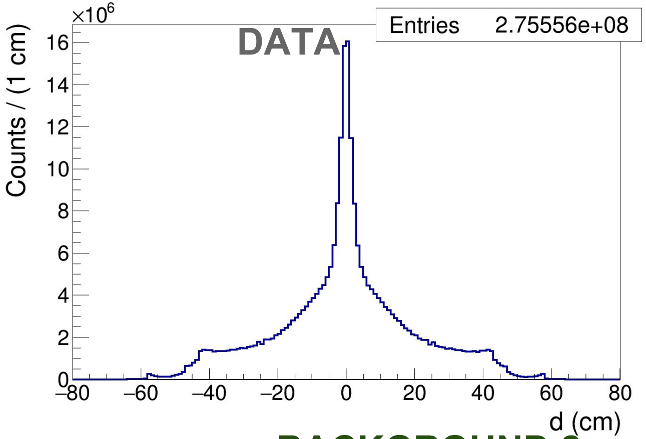
t = 29221 seconds (~ 8 hours) → 996 data files

→ $N_{o\text{-}Ps}$ = 117000 (about 8% of the events)

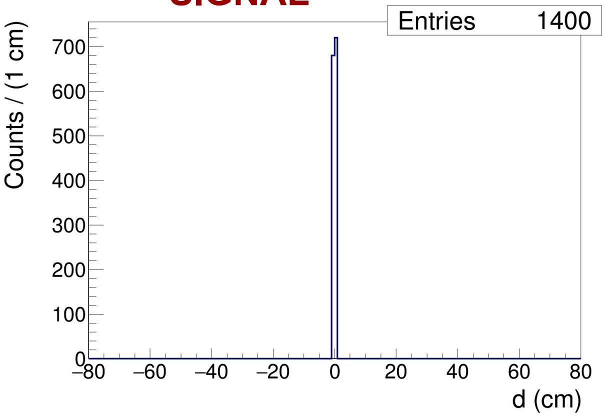
Monte Carlo simulations

CUT: |d| < 2 cm

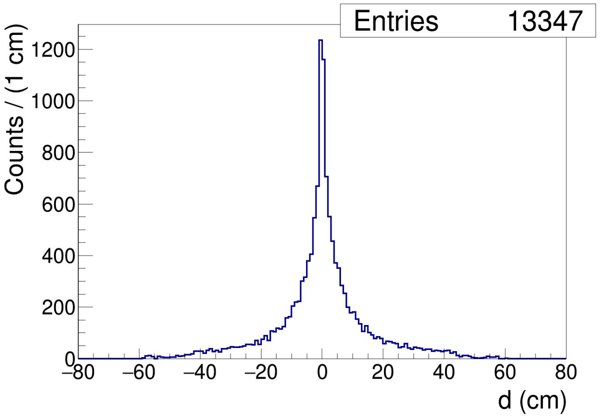
1. **Signal:** o-Ps → $\gamma_1\ \gamma_2\ \gamma_3$
2. **Background 1:** o-Ps → $\gamma_1\ \gamma_2\ \gamma_3$ + scattering
3. **Background 2:** $e^+\ e^-$ → $\gamma_1\ \gamma_2$ + scattering



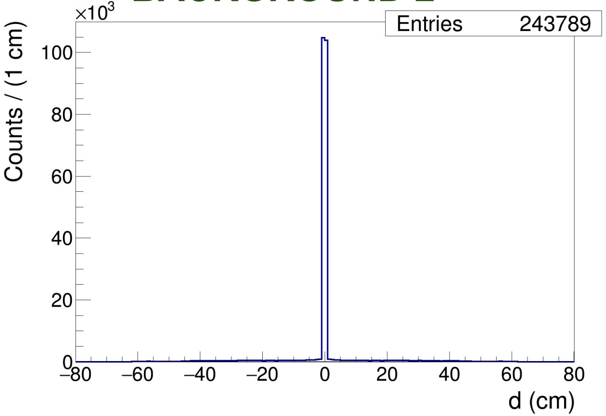
SIGNAL



BACKGROUND 1



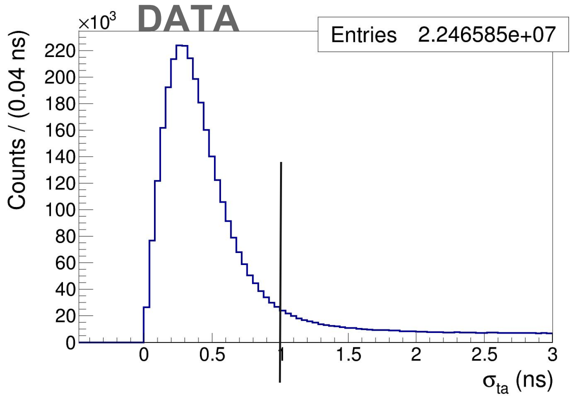
BACKGROUND 2



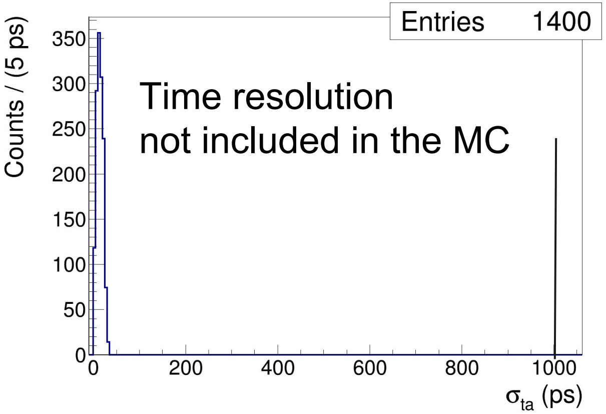
Monte Carlo simulations

CUT: σ_{ta} < 1 ns

1. **Signal:** o-Ps → $\gamma_1\ \gamma_2\ \gamma_3$
2. **Background 1:** o-Ps → $\gamma_1\ \gamma_2\ \gamma_3$ + scattering
3. **Background 2:** $e^+\ e^-$ → $\gamma_1\ \gamma_2$ + scattering



SIGNAL



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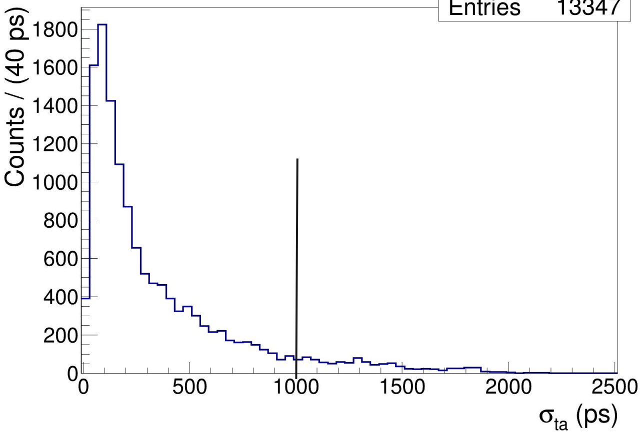
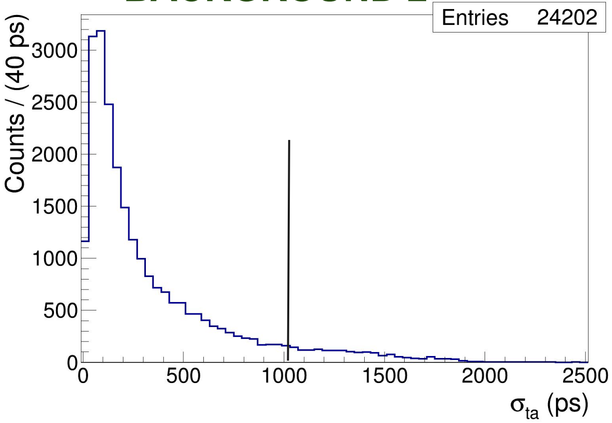


BACKGROUND 2



Monte Carlo simulations

CUT: $\theta_{12} + \theta_{23} > 180$

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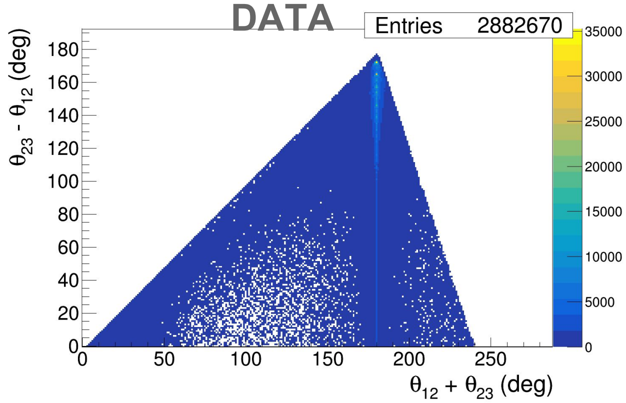
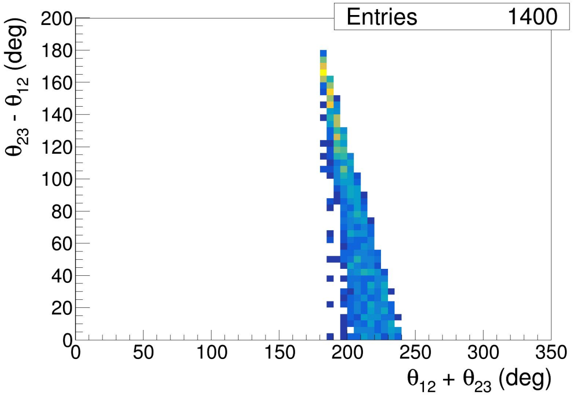


SIGNAL



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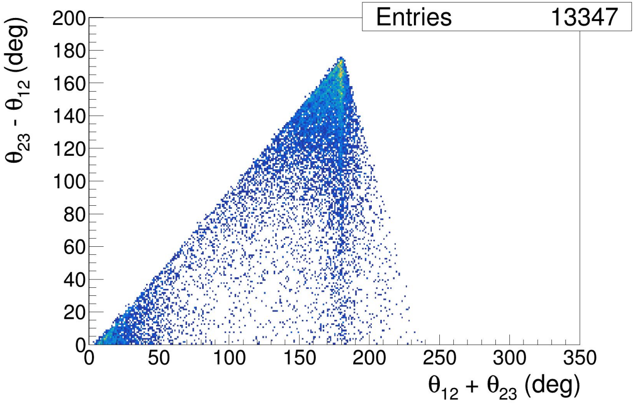
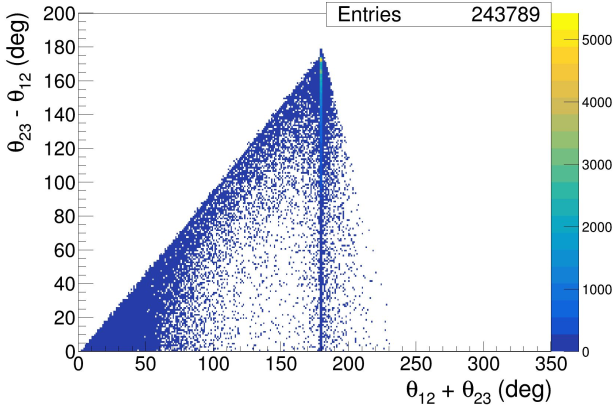


BACKGROUND 2



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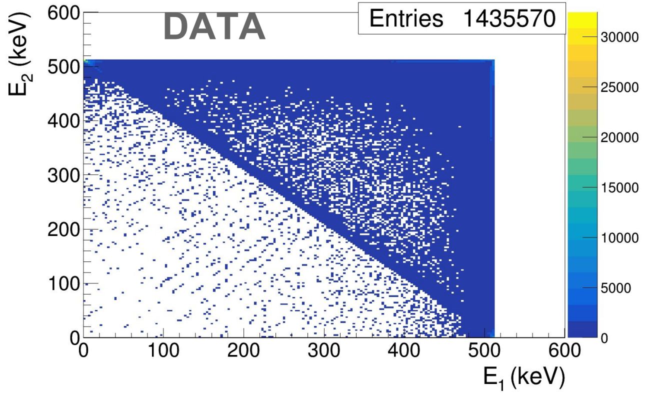

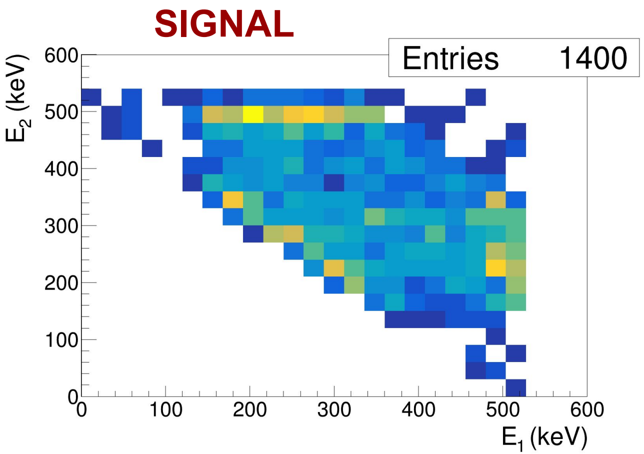

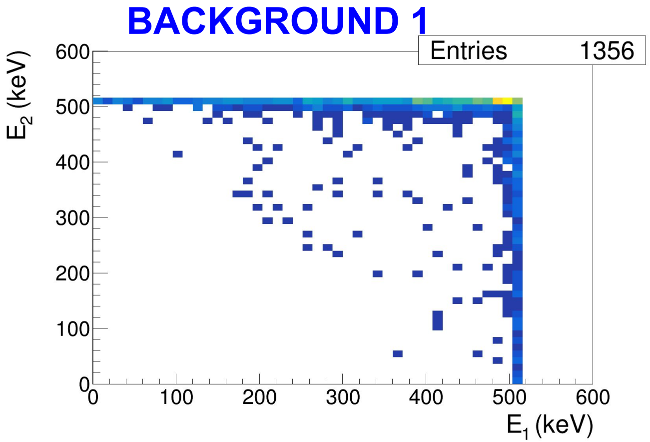

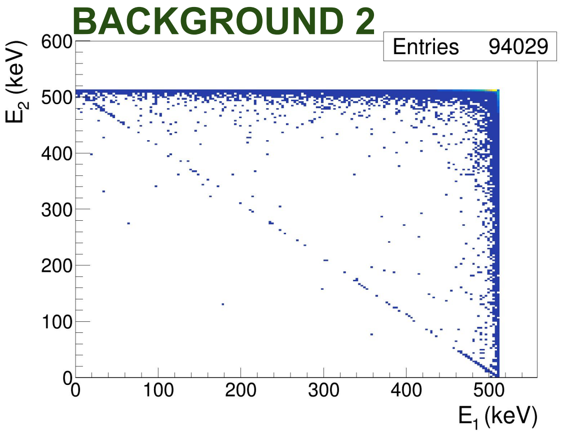

Monte Carlo simulations

1. **Signal:** o-Ps $\rightarrow \gamma_1\ \gamma_2\ \gamma_3$
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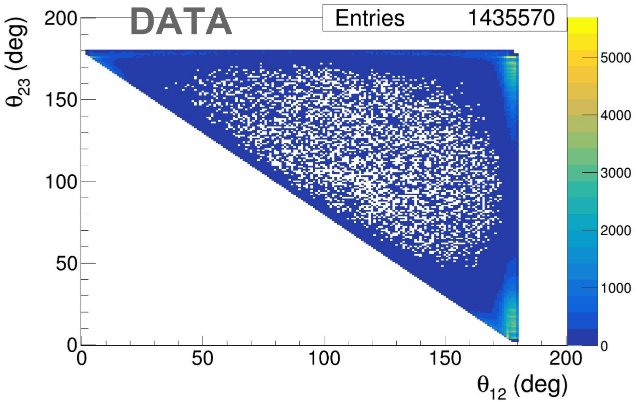
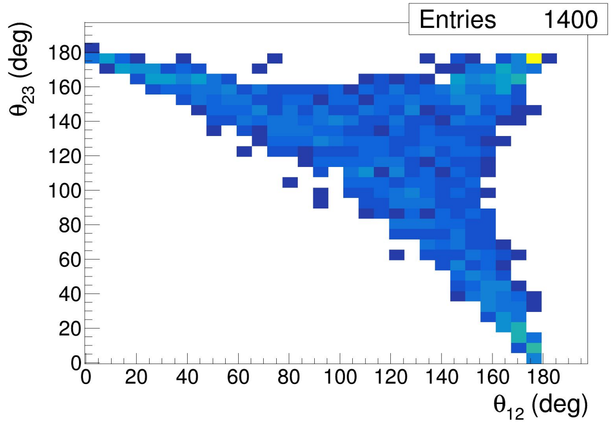


SIGNAL



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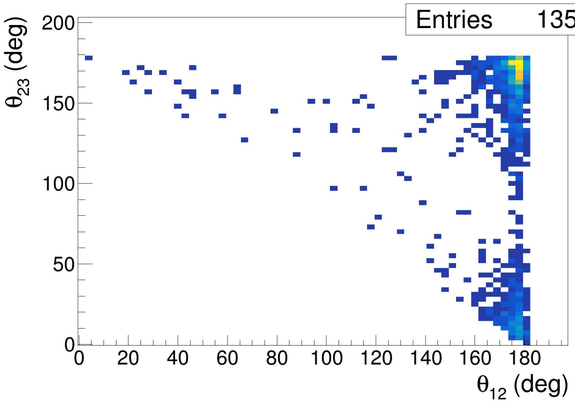
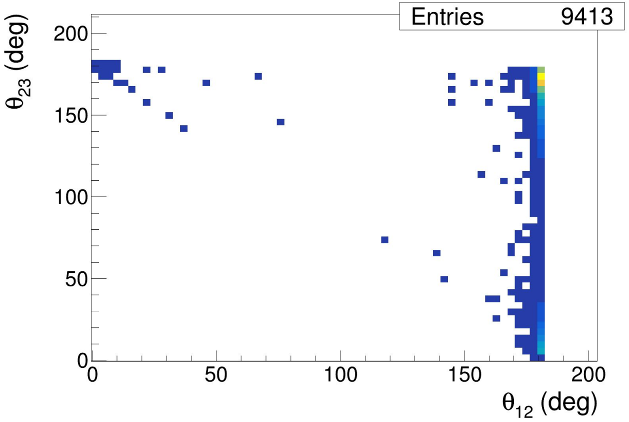
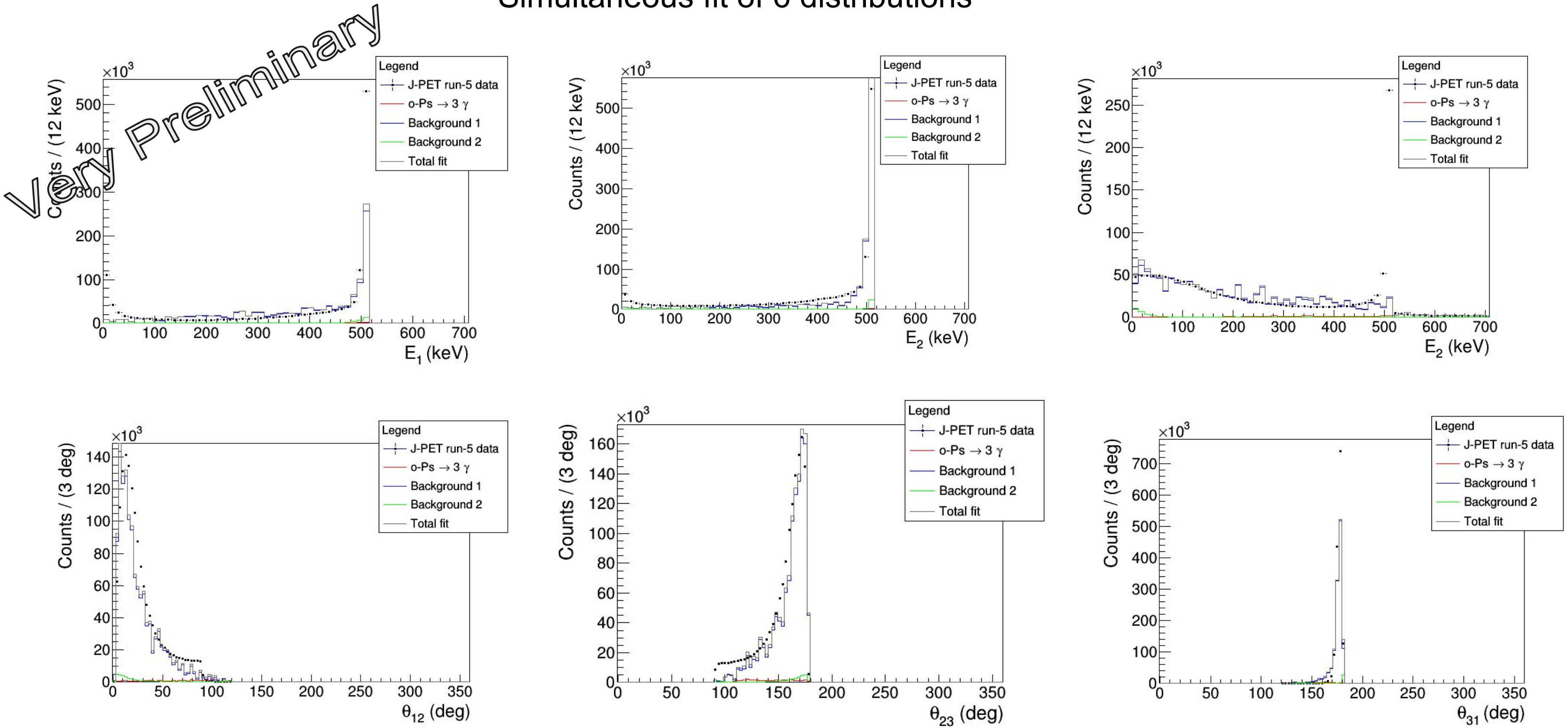


BACKGROUND 2



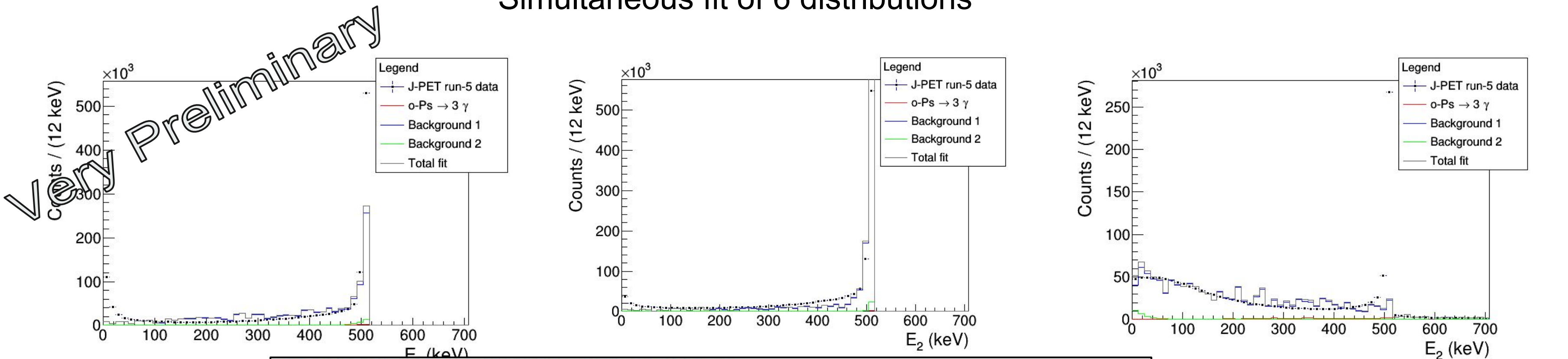
Fit of the data

Simultaneous fit of 6 distributions



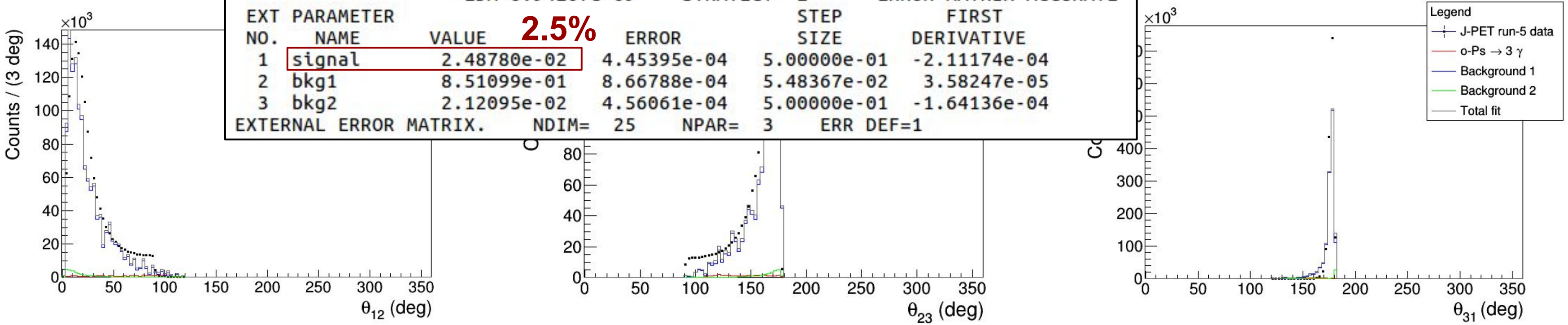
Fit of the data

Simultaneous fit of 6 distributions




```
COVARIANCE MATRIX CALCULATED SUCCESSFULLY
FCN=1.1528e+06 FROM MIGRAD    STATUS=CONVERGED      73 CALLS         496 TOTAL
                     EDM=6.94207e-09    STRATEGY= 2      ERROR MATRIX ACCURATE
 EXT PARAMETER                                STEP         FIRST
 NO.   NAME        VALUE            ERROR          SIZE      DERIVATIVE
  1  signal        2.48780e-02   4.45395e-04   5.00000e-01  -2.11174e-04
  2  bkg1          8.51099e-01   8.66788e-04   5.48367e-02   3.58247e-05
  3  bkg2          2.12095e-02   4.56061e-04   5.00000e-01  -1.64136e-04
EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  3    ERR DEF=1
```

2.5%



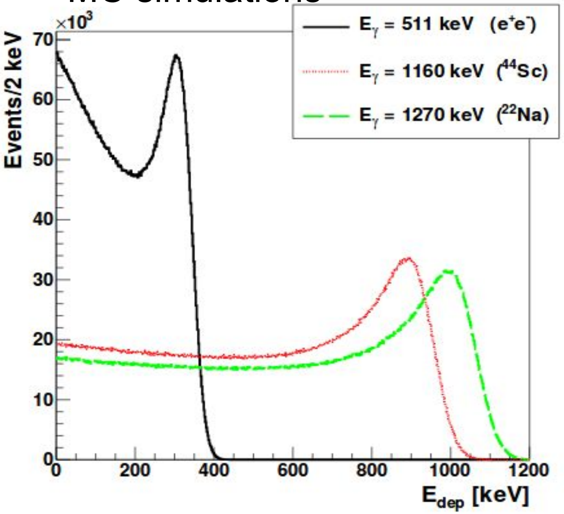
4 Hits Selection

Same cuts as before but:

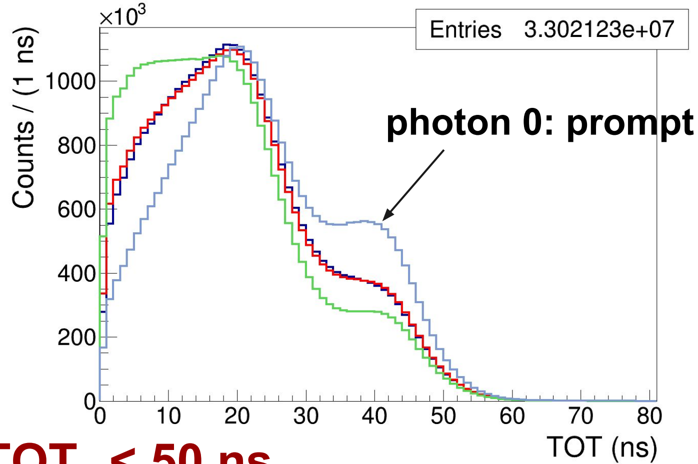
CUT 1: selection based on the energy deposited in the scintillators (using the TOT information) also for the prompt γ

Photons are ordered by annihilation time: $t_{a0} < t_{a1} < t_{a2} < t_{a3}$

MC simulations



data



30 ns < TOT_0 < 50 ns

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

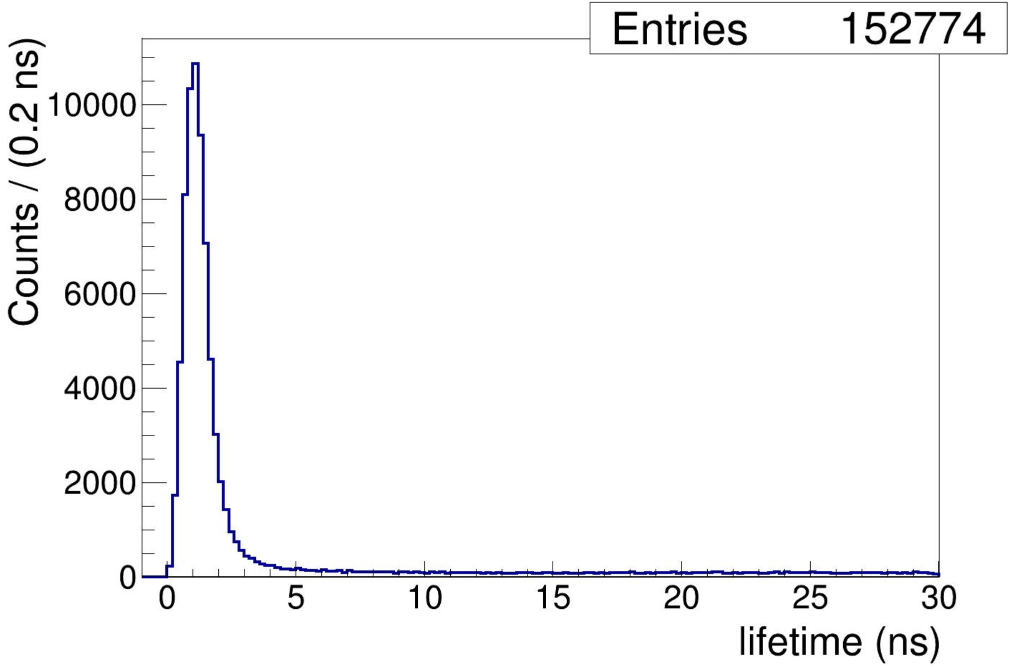
4 Hits Selection

Additional Cut → Selection based on the o-Ps lifetime

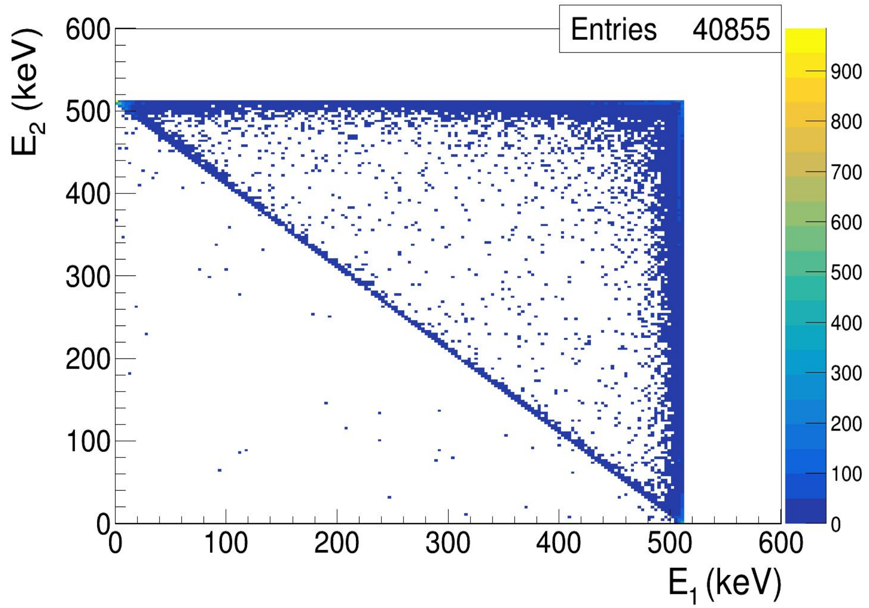
<u>In vacuum:</u>

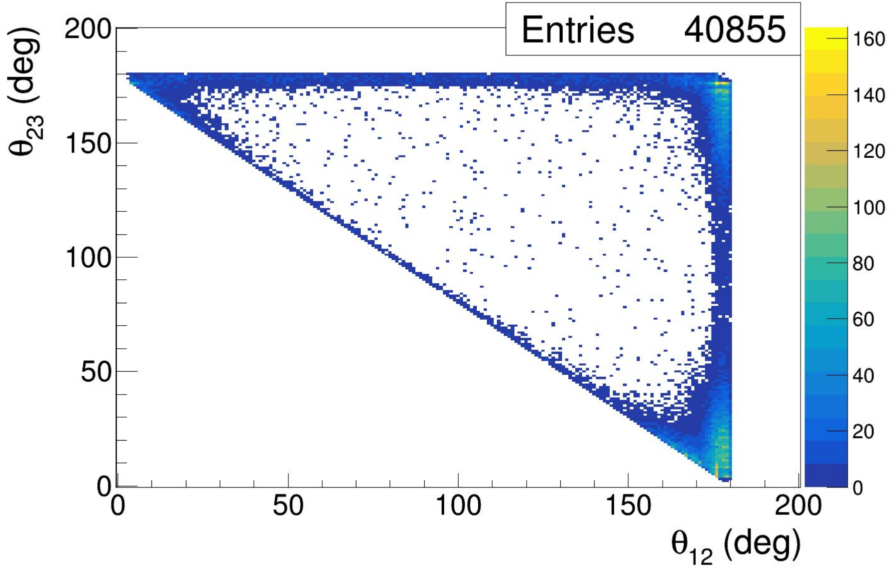
- direct e+e- annihilation ~ 400 ps
- para-positronium lifetime ~ 125 ps
- ortho-positronium lifetime ~ 142 ns

lifetime = $t_a - t_{a0}$ > 10 ns



4 Hits Selection





Next steps

- Monte Carlo simulations for the scatterings in the small chamber
- Include the detector time and energy resolutions
- Same procedure for 4 hits events