Dalitz plot determination for oPs->3gamma using the J-PET detection system

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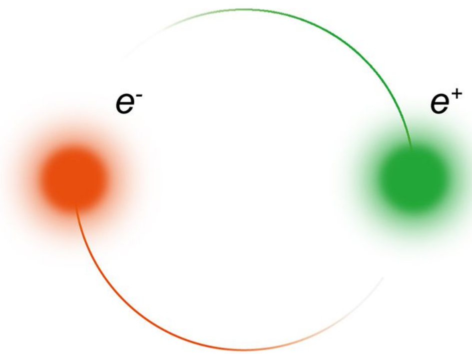
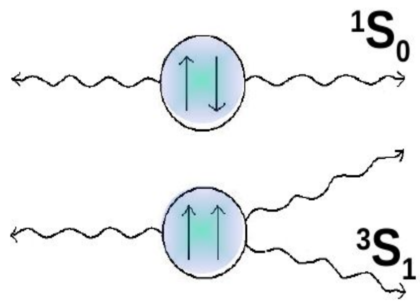
on behalf of the **J-PET** collaboration

Workshop on Fundamental Physics with
Exotic Atoms,
Frascati, 23-25.06.2025

Positronium decays

POSITRONIUM - the lightest purely leptonic object





Para–positronium (p - Ps), τ = 125ps, $^1S_0$

↓↑ -Singlet state

Ortho – positronium (o - Ps), τ = 142ns, $^3S_1$

↑↑ ↓↑ ↓↓ --Triplet state

bound by a central potential

$\Downarrow$

<u>eigenstate of the parity operator P</u>

symmetric under the exchange
of particles - anti-particles

$\Downarrow$

<u>eigenstate of the charge conjugation operator C</u>

$$C|Ps> = (-1)^{L+S}|Ps>$$

$C|\gamma\rangle = -|\gamma\rangle$ eigenvalue of n photons **(-1)^n**

Ann. Rev. Nucl. Part. Sci 30,453 (1980)

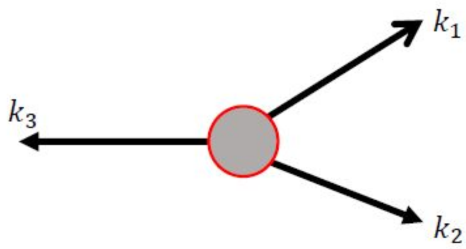
due to Charge Conjugation C

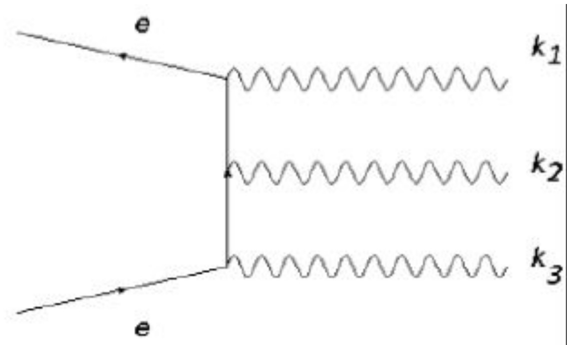
$|^1S_0\rangle \to 2\gamma, 4\gamma, \ldots$ | $|^3S_1\rangle \to 3\gamma, 5\gamma, \ldots$

even number of photons | **odd number of photons**

We can study **positronium decay to 3γ** with the **Dalitz Plot**

o-Ps decay to 3γ





Feynman diagram

non-relativistic QED

Lorentz inv. ampl. for |o-Ps|->|3γ> transition

E & p conservation

$$d\sigma_{3\gamma} = \frac{(2\pi)^4 |M|^2}{4 m_e^2 v} \delta(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\delta(E_1 + E_2 + E_3 - 2m_e)\frac{d^3k_1 d^3k_2 d^3k_3}{(2\pi)^9 2E_1 2E_2 2E_3}$$

electron positron relative velocity

electron mass

for LO

$$|M|^2 = 64(4\pi)^3\alpha^3\left[\left(\frac{m_e - E_1}{E_2E_3}\right)^2 + \left(\frac{m_e - E_2}{E_1E_3}\right)^2 + \left(\frac{m_e - E_3}{E_1E_2}\right)^2\right]$$

3 photons, each (px,py,pz,E)

12 parameters

Berestetskii, E. Lifshitz, L. Pitaevskii, Relativistic Quantum Theory,Pergamon Press 1971.

o-Ps decay to 3γ

$$|M|^2 = 64(4\pi)^3\alpha^3\left[\left(\frac{m_e - E_1}{E_2E_3}\right)^2 + \left(\frac{m_e - E_2}{E_1E_3}\right)^2 + \left(\frac{m_e - E_3}{E_1E_2}\right)^2\right]$$

3 photons,
each (px,py,pz,E)

12 parameters

3 Lorentz-vectors	12
3 Masses	-3
Energy conserv.	-1
Momentum conserv.	-3
3 Euler angles (free rotation)	-3
Remaining d.o.f	2

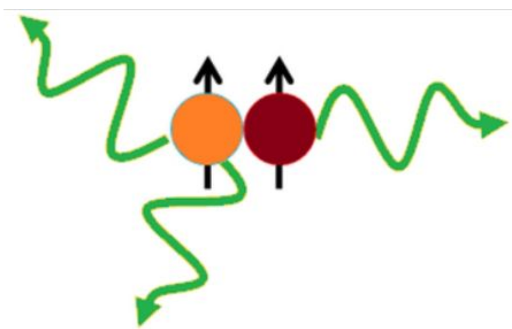
decay involves three photons

$$\boxed{d\sigma_{3\gamma} = \frac{8\alpha^3}{6m_e^2 v}|M|^2 dE_1 dE_2}$$

3! -identity of the photons

2 parameters

the complete oPs -> 3γ dynamics



presented graphically as a **Dalitz plot** - the variables on the axes represents 2 independent photon parameters, ex. angles or energies

$$E_1 + E_2 + E_3 = 2m_e$$
$$p_1 + p_2 + p_3 = 0$$

$$\theta_{12} = \cos^{-1}\left(\frac{p_3^2 - p_1^2 - p_2^2}{2p_1p_2}\right)$$
$$\theta_{23} = \cos^{-1}\left(\frac{p_1^2 - p_2^2 - p_3^2}{2p_2p_3}\right)$$
$$\theta_{31} = \cos^{-1}\left(\frac{p_2^2 - p_1^2 - p_3^2}{2p_1p_3}\right)$$

$$E_1 = -2m_e\frac{-\cos\theta_{13} + \cos\theta_{12}\cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12} - \cos\theta_{13} - \cos\theta_{23})},$$
$$E_2 = -2m_e\frac{\cos\theta_{12}\cos\theta_{13} - \cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12} - \cos\theta_{13} - \cos\theta_{23})},$$
$$E_3 = 2m_e\frac{1+\cos\theta_{12}}{1+\cos\theta_{12} - \cos\theta_{13} - \cos\theta_{23}}.$$

o-Ps decay to 3γ

$$|M|^2 = 64(4\pi)^3\alpha^3\left[\left(\frac{m_e - E_1}{E_2E_3}\right)^2 + \left(\frac{m_e - E_2}{E_1E_3}\right)^2 + \left(\frac{m_e - E_3}{E_1E_2}\right)^2\right]$$

3 photons,
each (px,py,pz,E)

12 parameters

3 Lorentz-vectors		12
3 Masses		-3
Energy conserv.		-1
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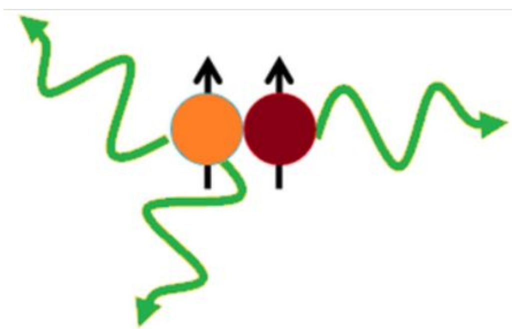
$$d\sigma_{3\gamma} = \frac{8\alpha^3}{6m_e^2 v}|M|^2 dE_1 dE_2$$

2 parameters

the complete oPs -> 3γ dynamics



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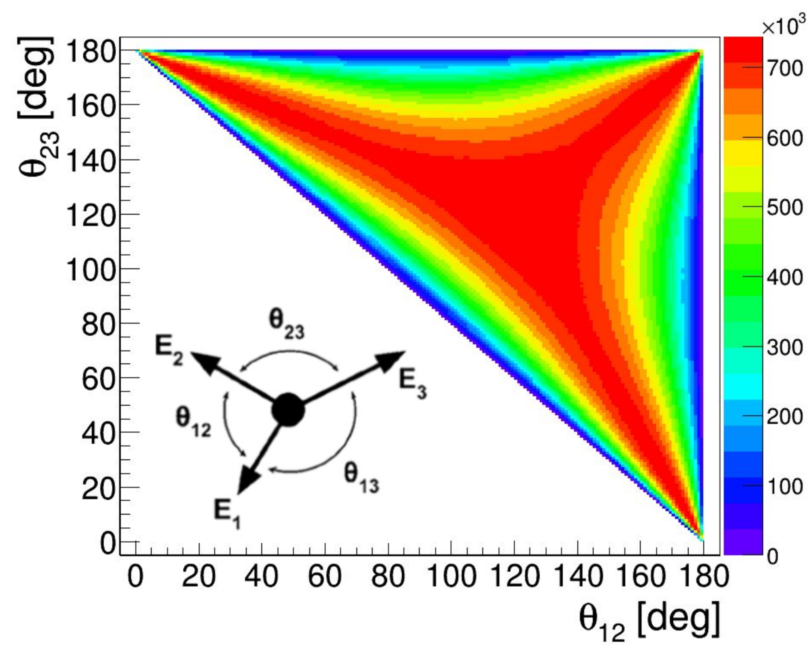
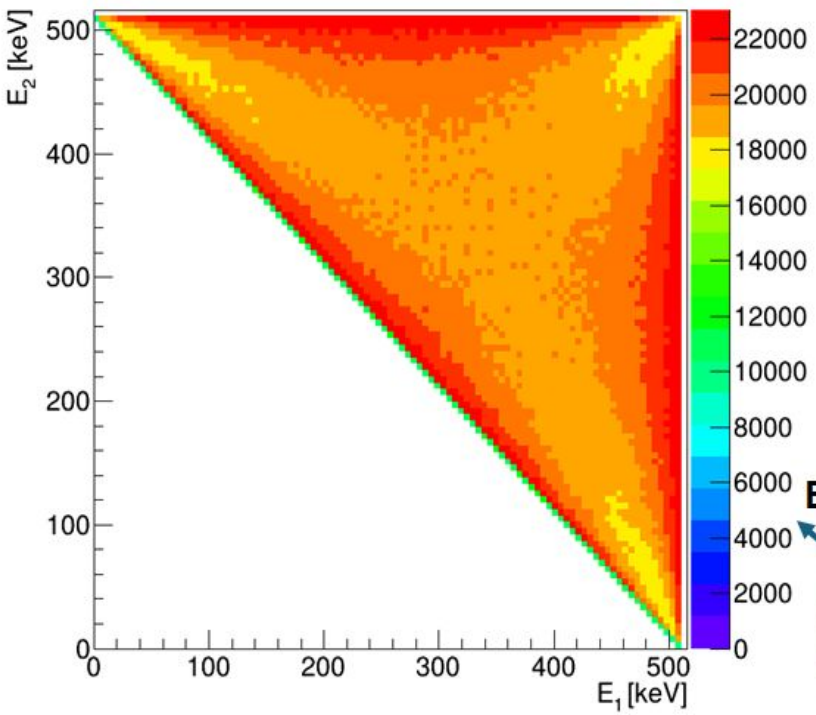


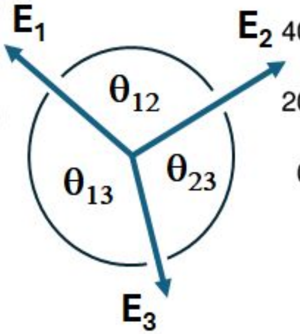
Goal:

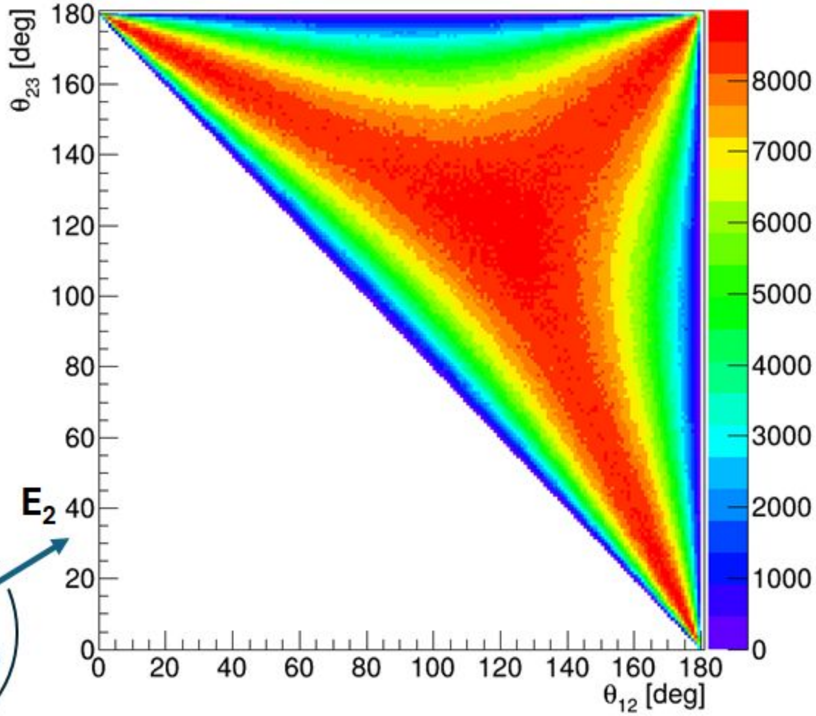
determination, for the first time ever, the experimental Dalitz plot in an angular representation for oPs -> 3γ decay

oPs -> $\gamma_1\gamma_2\gamma_3$



$E_3=M_{Ps}-E_1-E_2$





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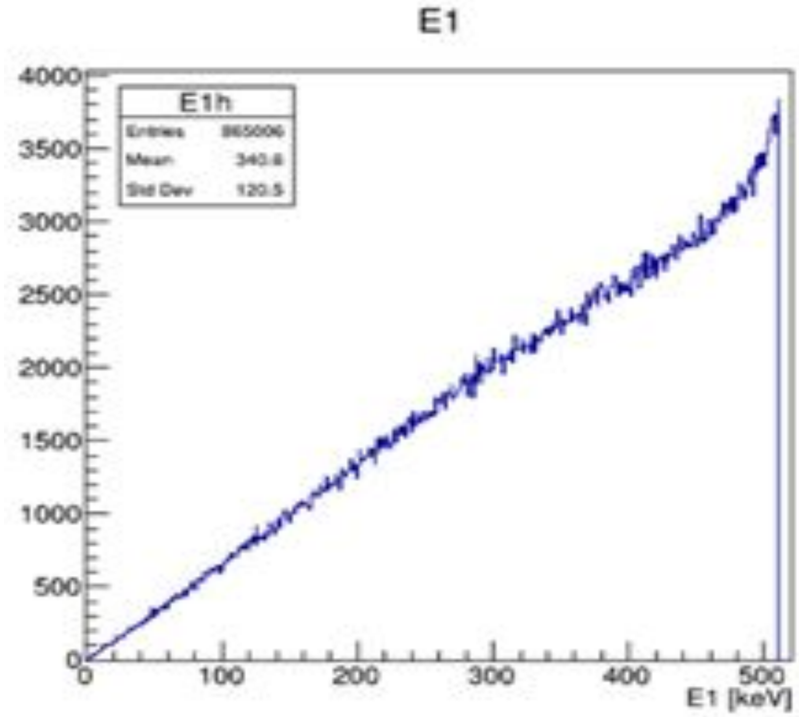

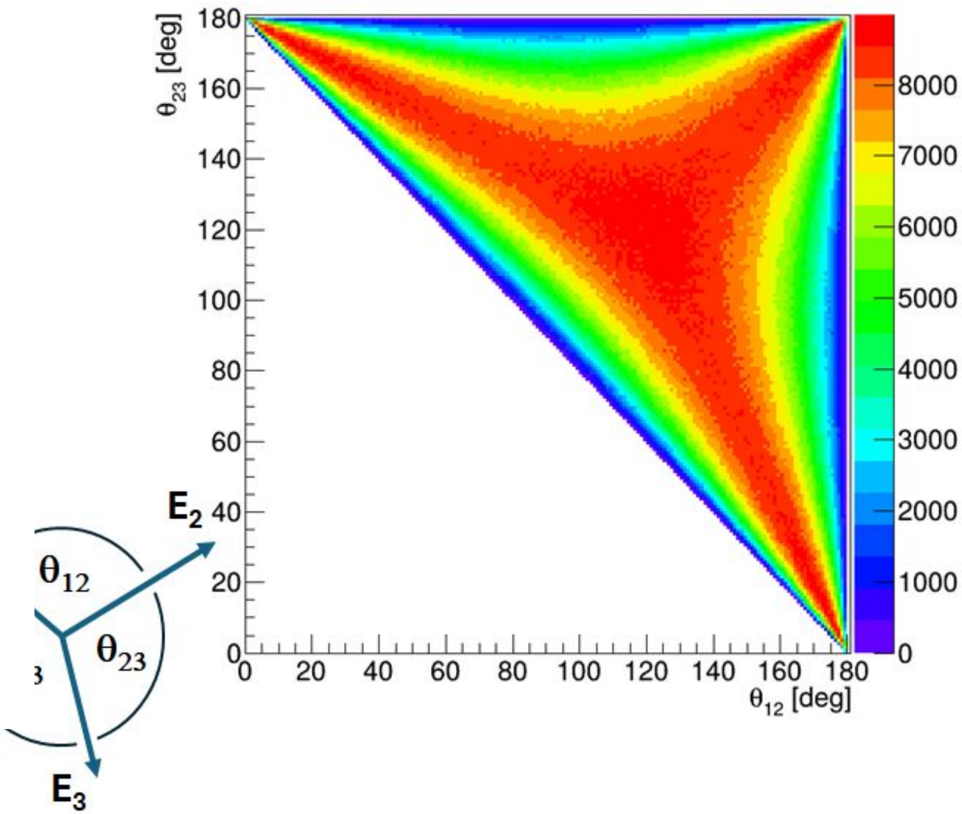

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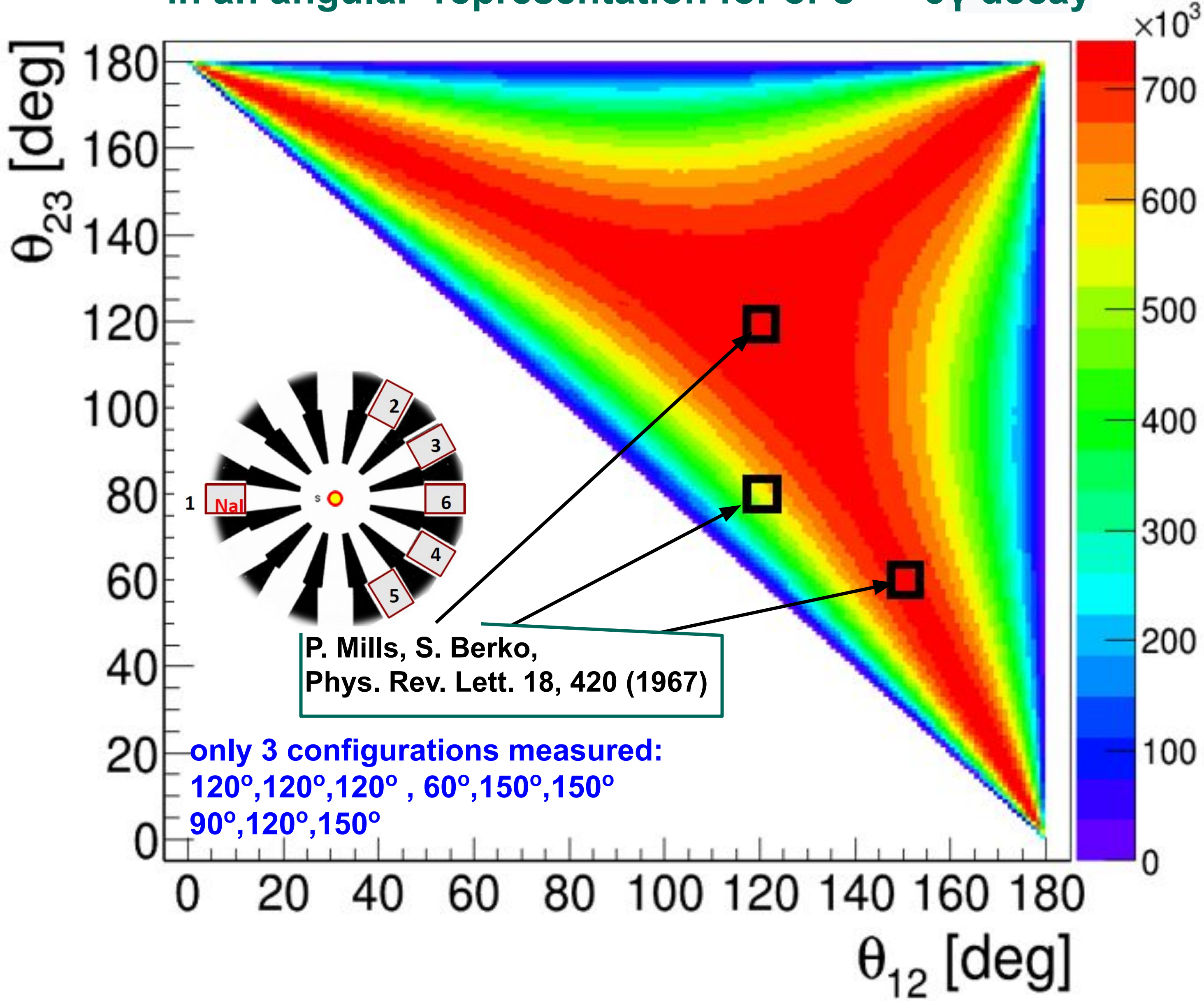
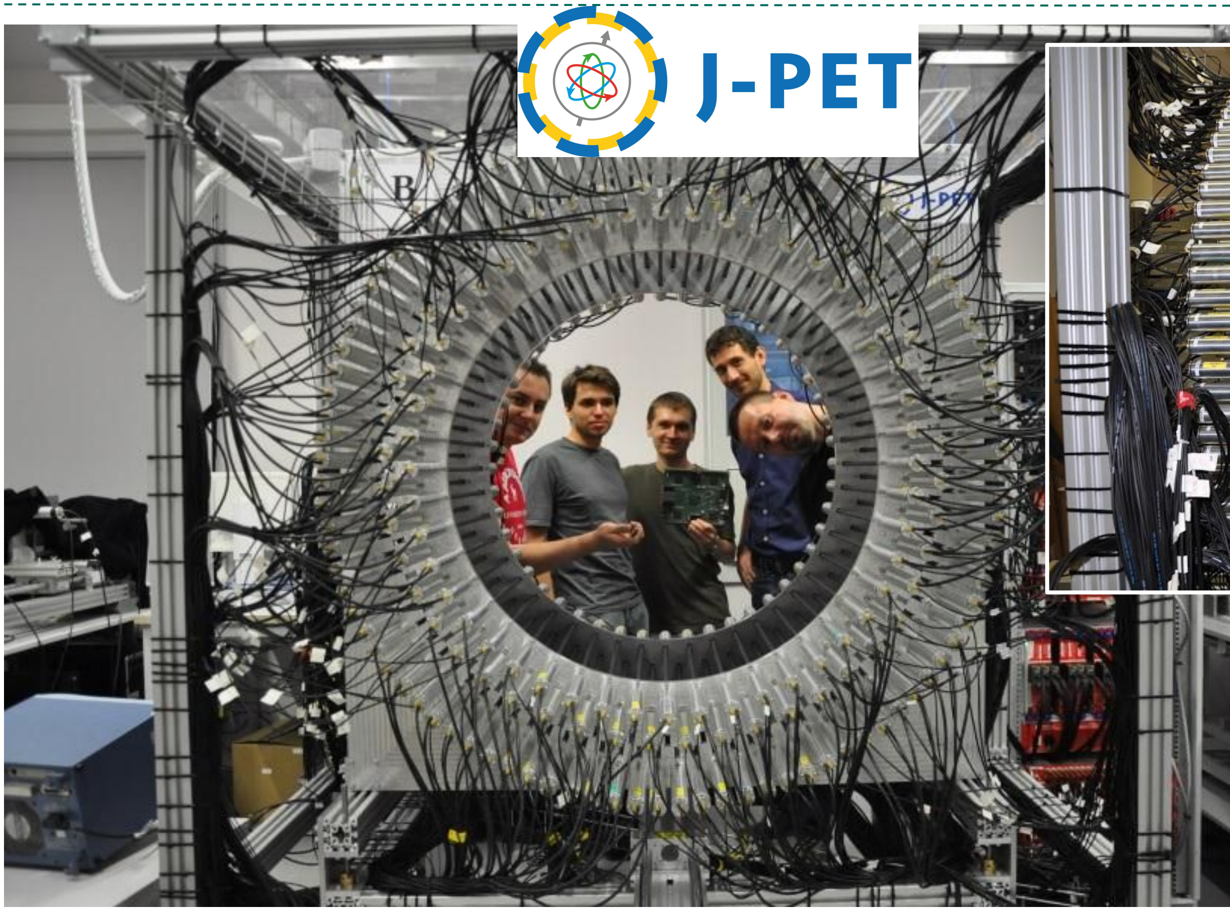
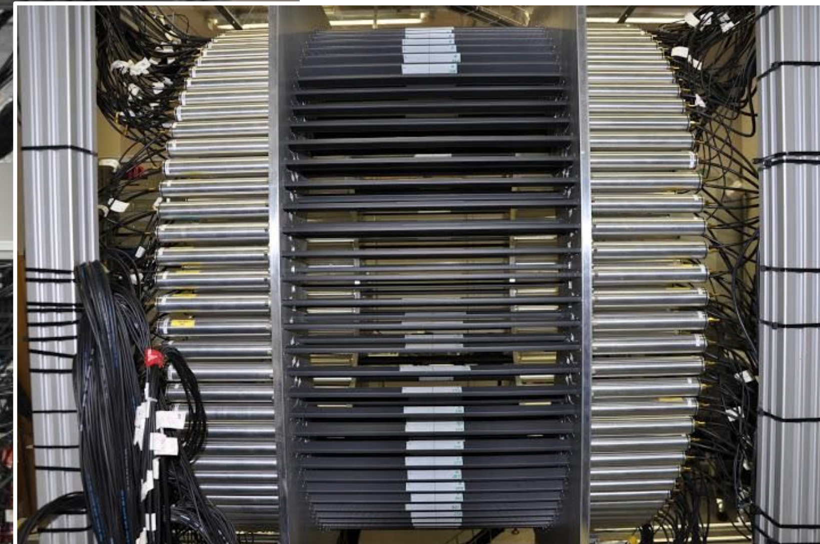
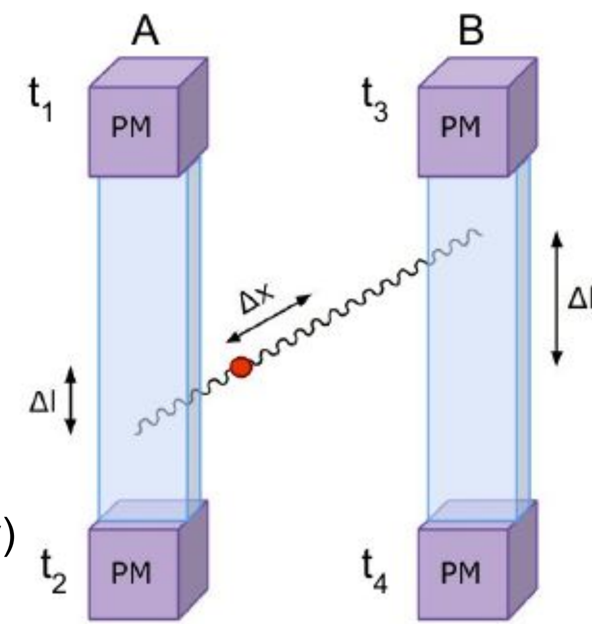


J-PET 3 layer detector at Jagiellonian University in Kraków, Poland



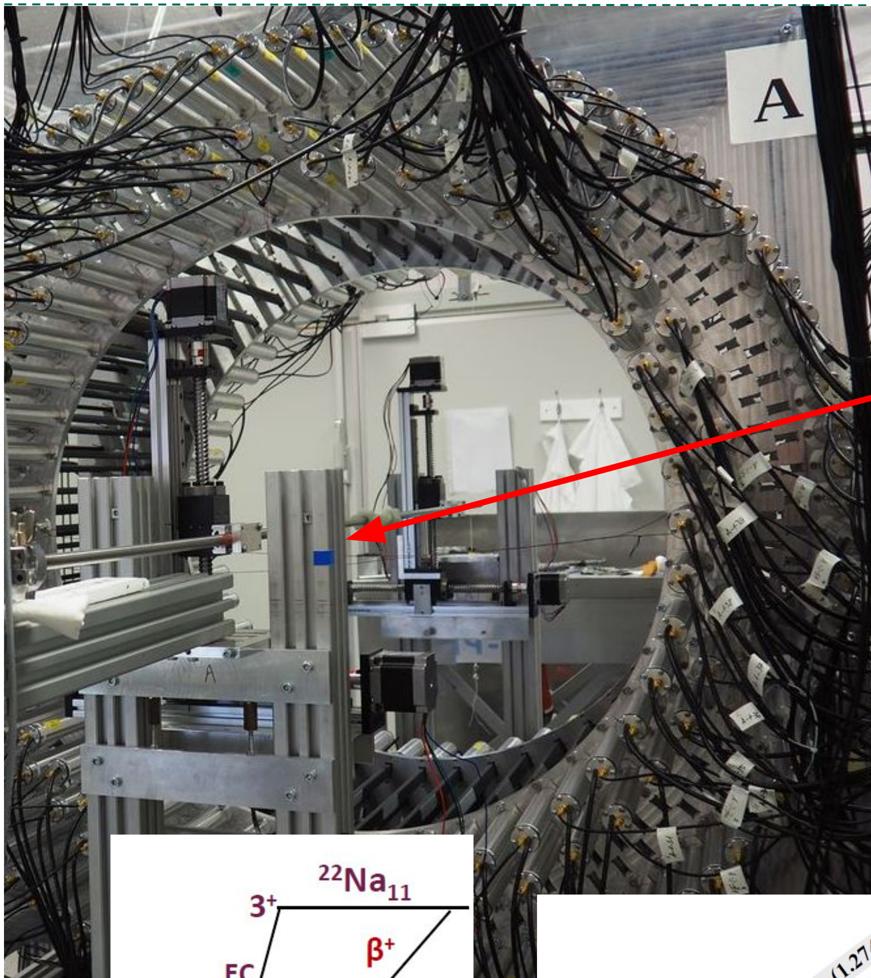




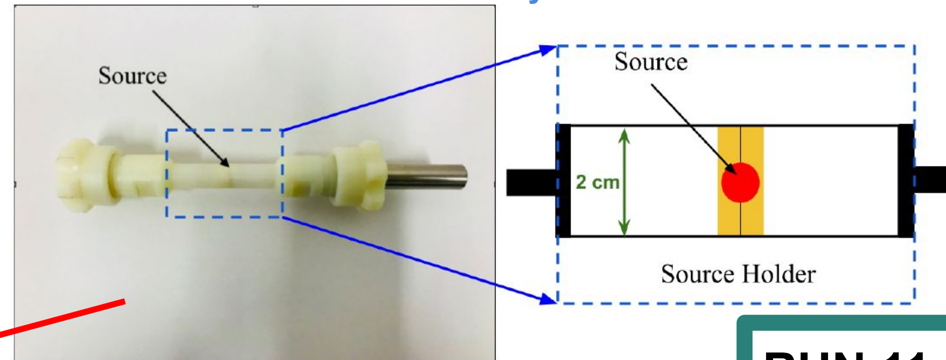
- 3 layers,192 EJ-230 scintillators: 7x19x500 mm^3
- 85 cm radius, 384 R9800 photomultipliers,1536 channels
- plastic scintillators - small light attenuation, large transparency
- dedicated multithreshold digital electronics (30ps time accuracy) and the novel trigger-less DAQ
- interaction time resolution ~250ps, angular resolution ~ 1deg

[P. Moskal et al., Acta Phys. Polon. B47 (2016) 509; G. Korcyl, et al., IEEE Trans. Med. Imag. 37, 2526 (2018)]

o-Ps production in J-PET with an annihilation chamber

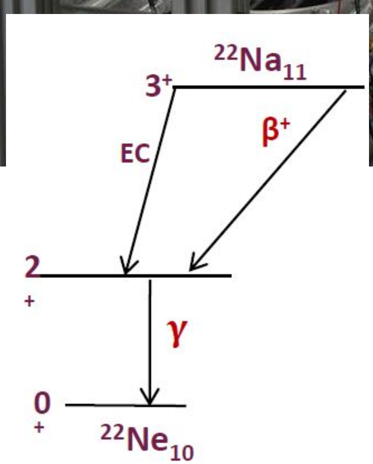


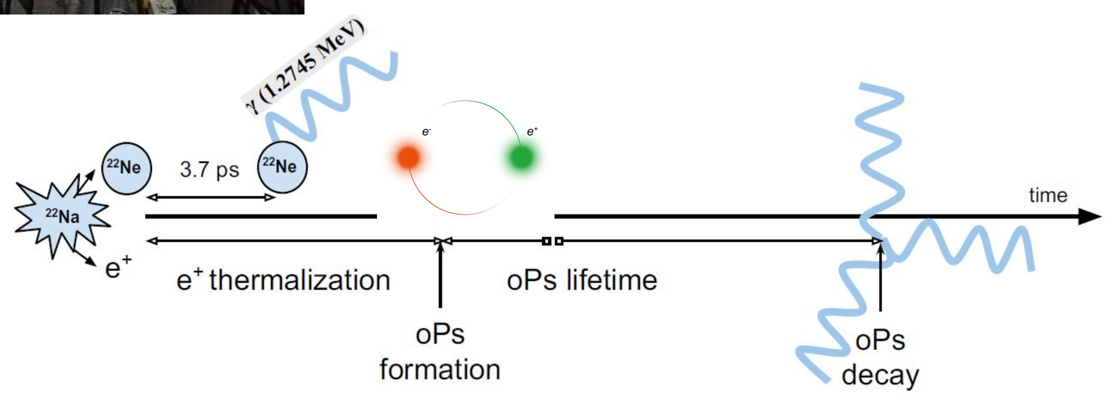
Picture from PhD Thesis J. Ray



RUN 11

- Small annihilation chamber (plastic PA6 - polyamide)
- 0.7 MBq β+ ^{22}Na source placed in the center sandwiched in XAD4 porous polymer
- data taking: 02.04.2020 - 01.03.2021 (218 d)
- thresholds: 30, 80, 190, 300 mV





[D. Kaminska, et a.l., Eur. Phys. J. C (2016) 76:445]

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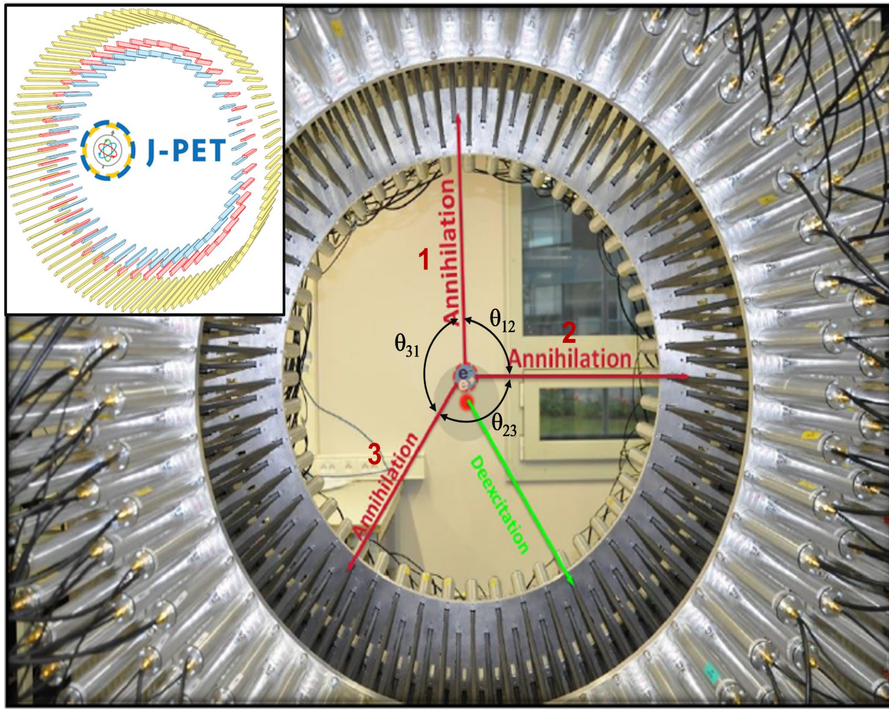

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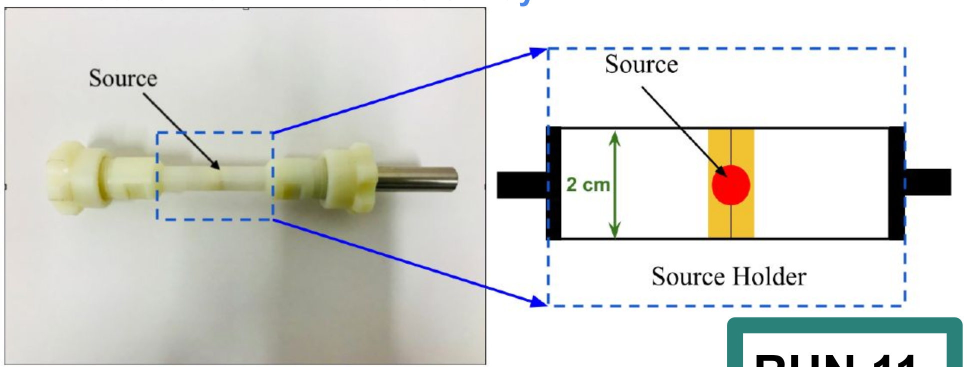

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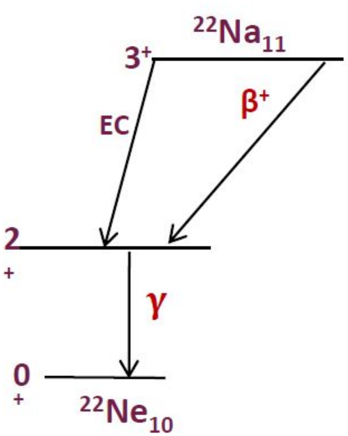

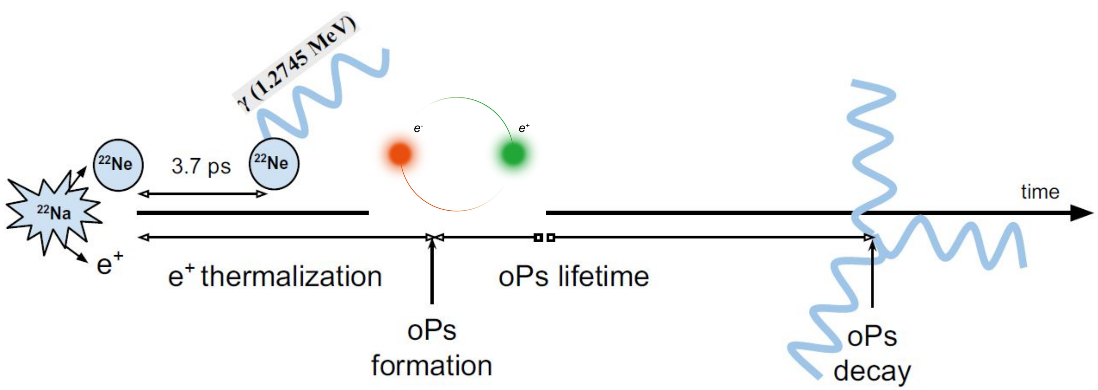

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o-Ps -> 3γ selection

MC Simulations

(J-PET Geant4)

MC oPs:

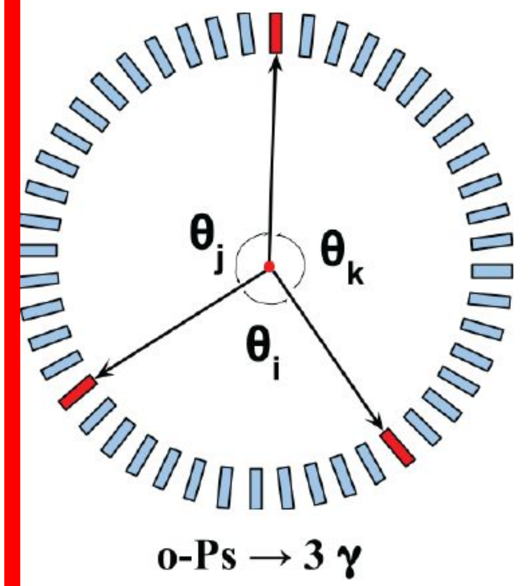
signal: 3 hits associated to oPs coming from the same vertex

MC oPs_{Mis}:

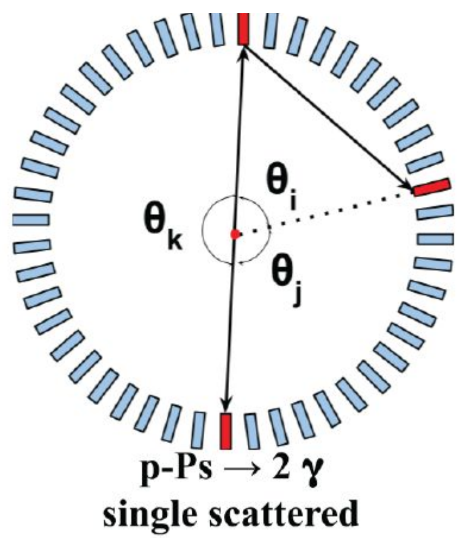
mis-reconstructed oPs: 3 hits associated to oPs, but at least one is scattered

MC background = all MC - oPs - oPs_{Mis}

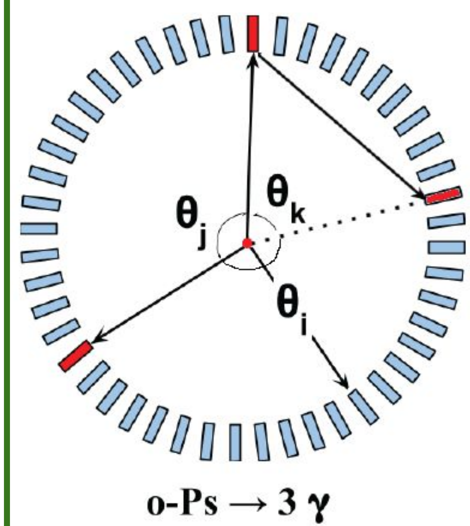
MC oPs



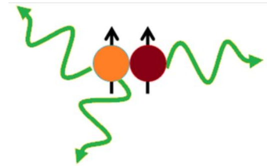
MC bcg



MC oPs_{Mis}

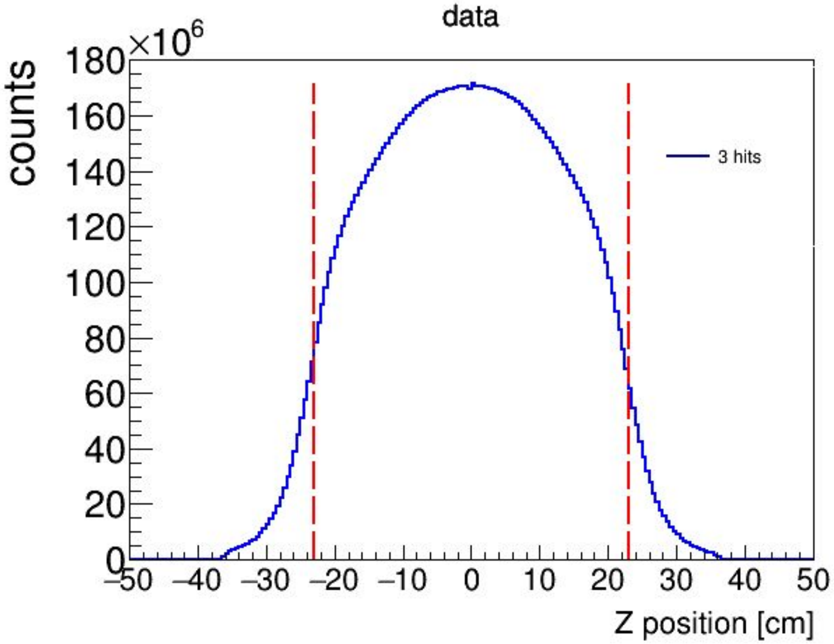


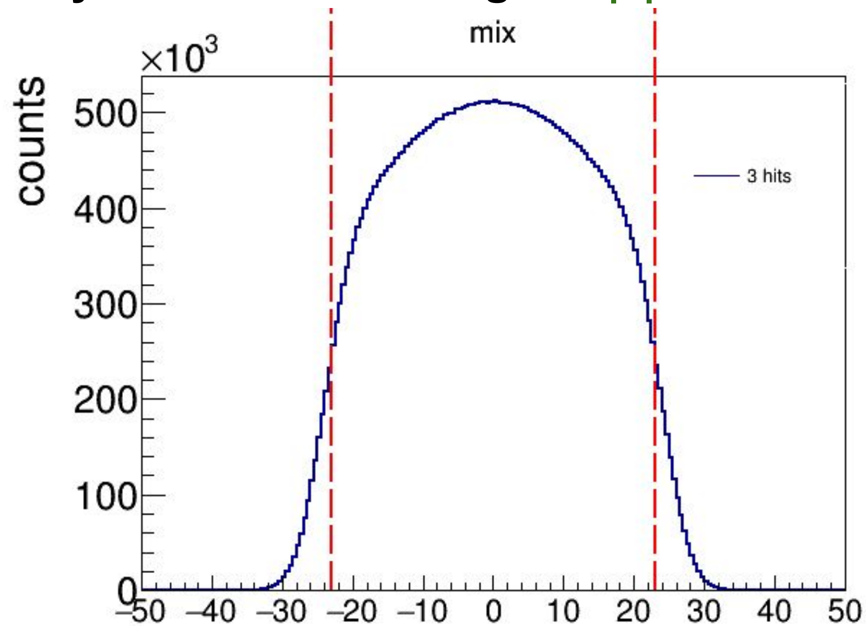
Events selection

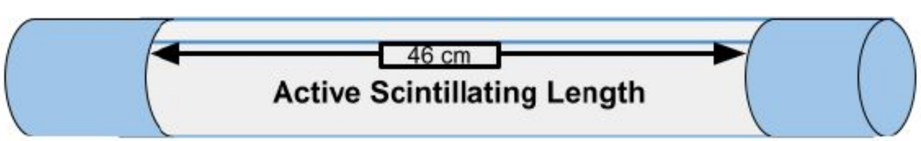


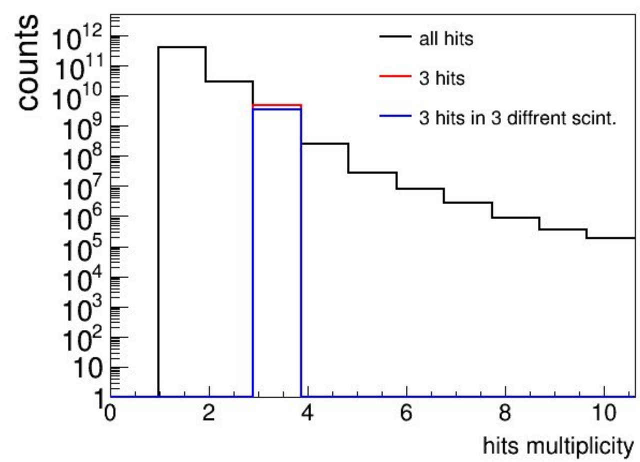
- **2.5 ns** - time window for grouping hits in one event
- **6 ns** - time window for matching Signals on the same scintillator and different sides

1) cut on Z position for the 3 hits - only active detector region: |z|<23cm



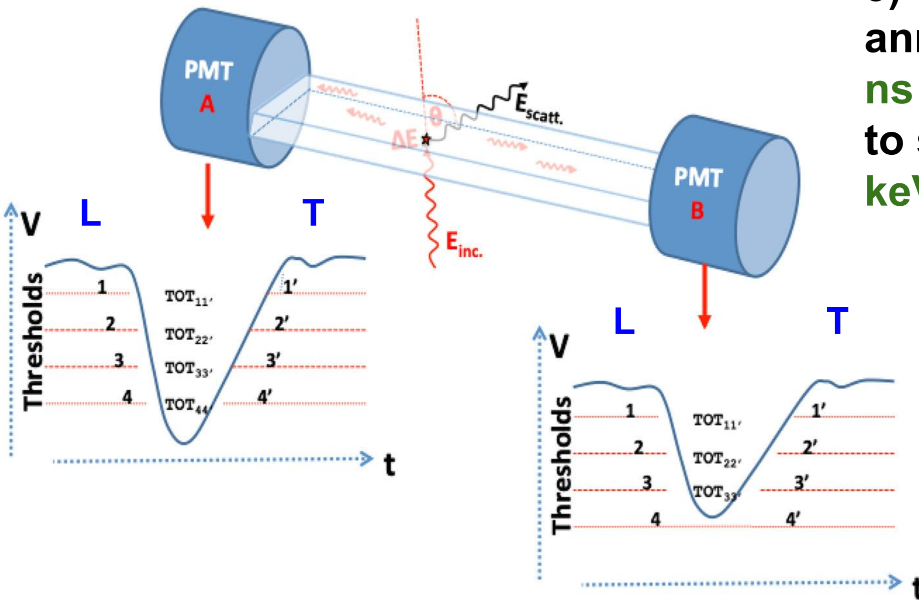




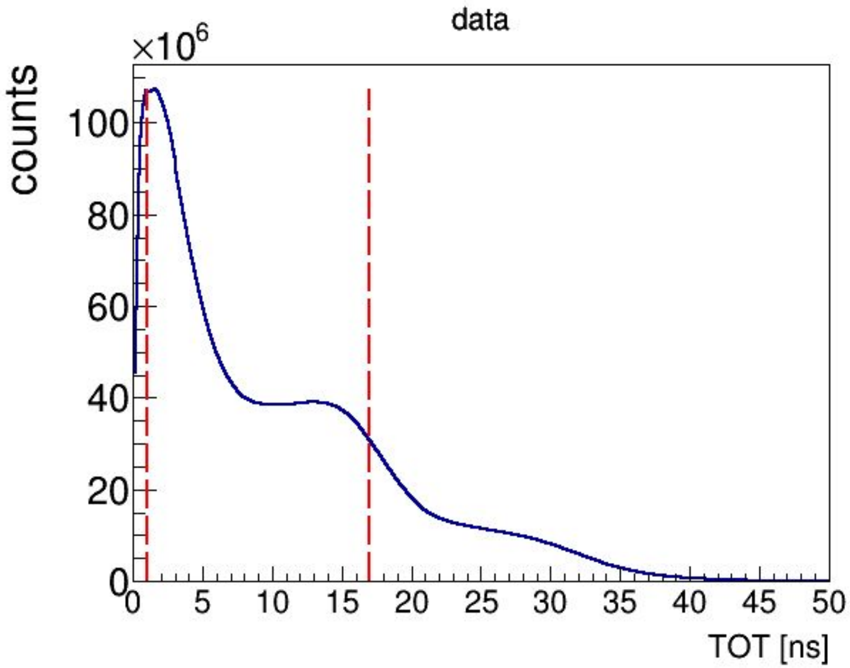


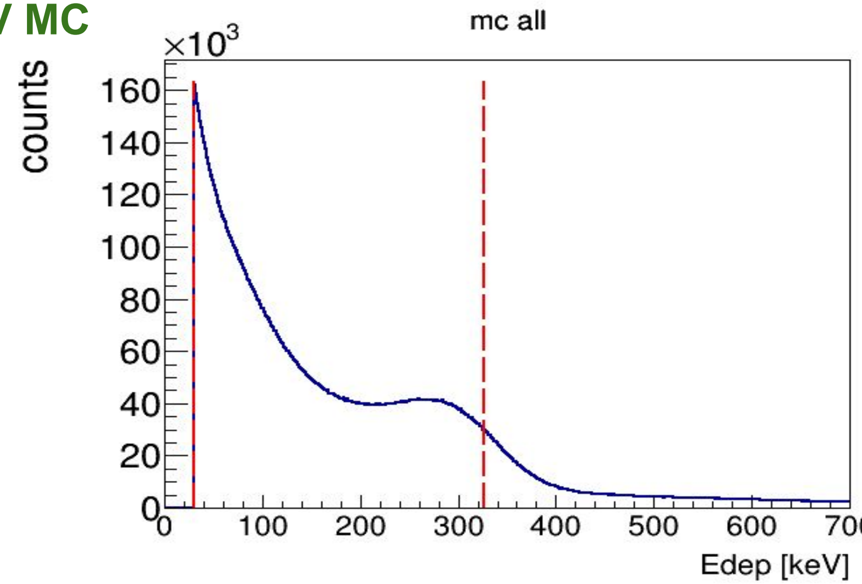
2) choose events with only 3 hits in 3 different scintillators

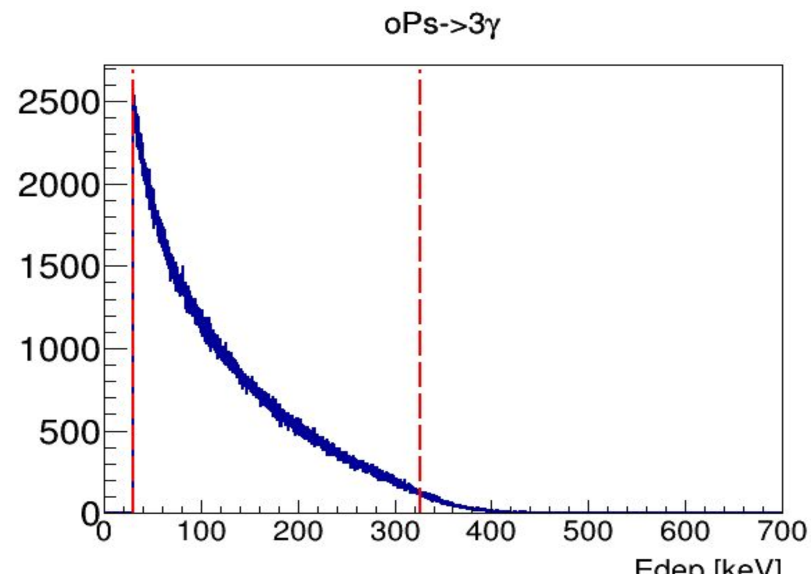
3) cut in TOT of all 3 Hits to separate the annihilation and de excitation photon: 1<TOT<17 ns DATA, cut in Energy deposition of each photon to select the annihilation candidate: 30<E<326.5 keV MC



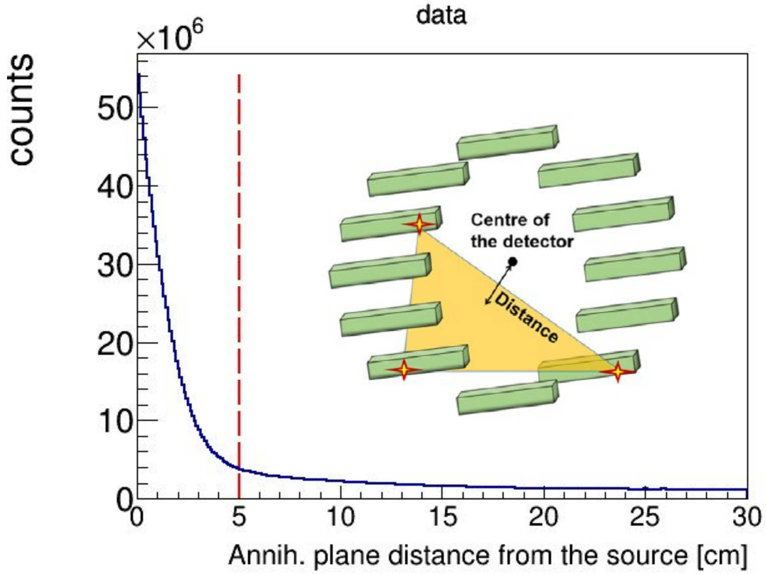
[S. Sharma, eta al., EJNMMI Phys. 7, 39 (2020)]

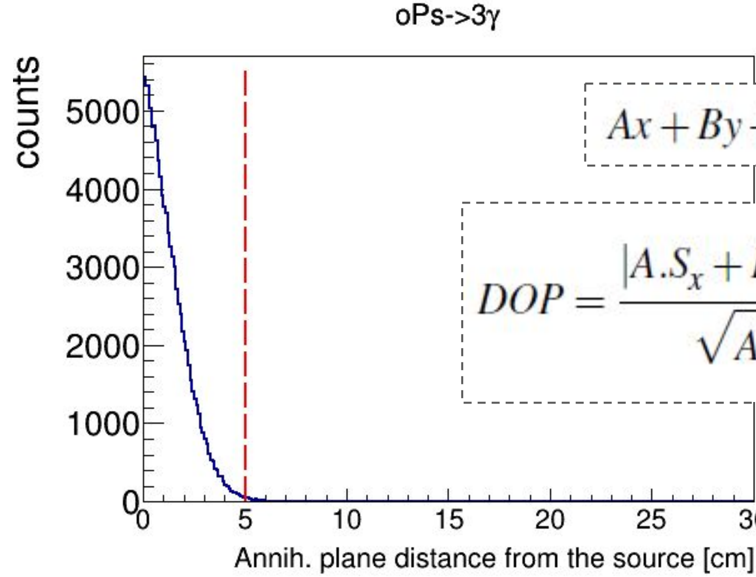






4) cut on distance between annihilation plane and the source: d<5cm

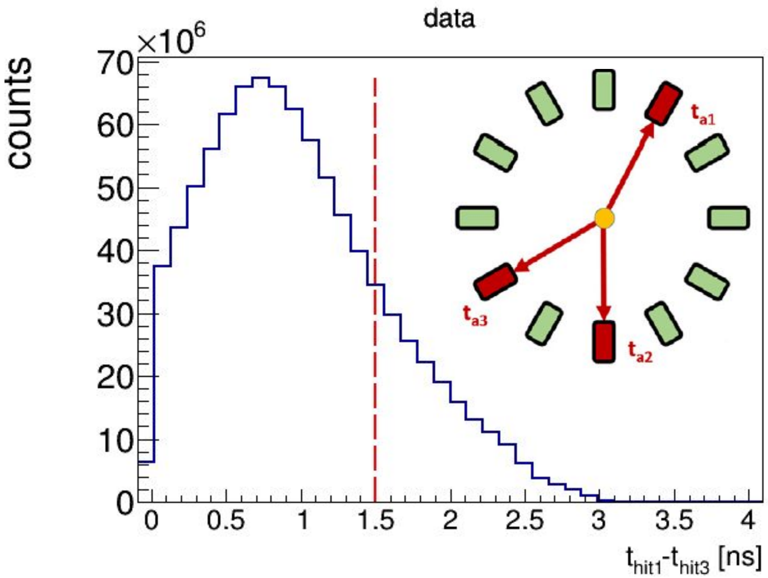


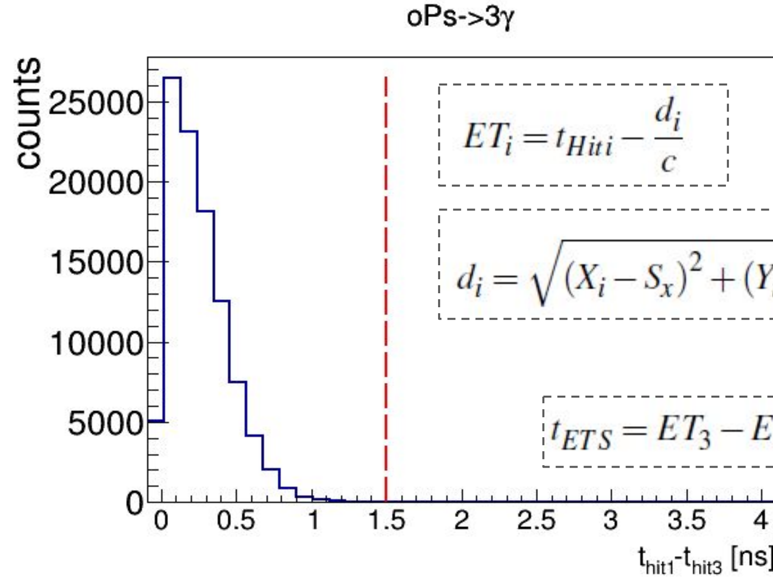


$$Ax + By + Cz + D = 0$$

$$DOP = \frac{|A.S_x + B.S_y + C.S_z + D|}{\sqrt{A^2 + B^2 + C^2}}$$

5) cut on emission time difference between the third and first hit: t<1.5ns



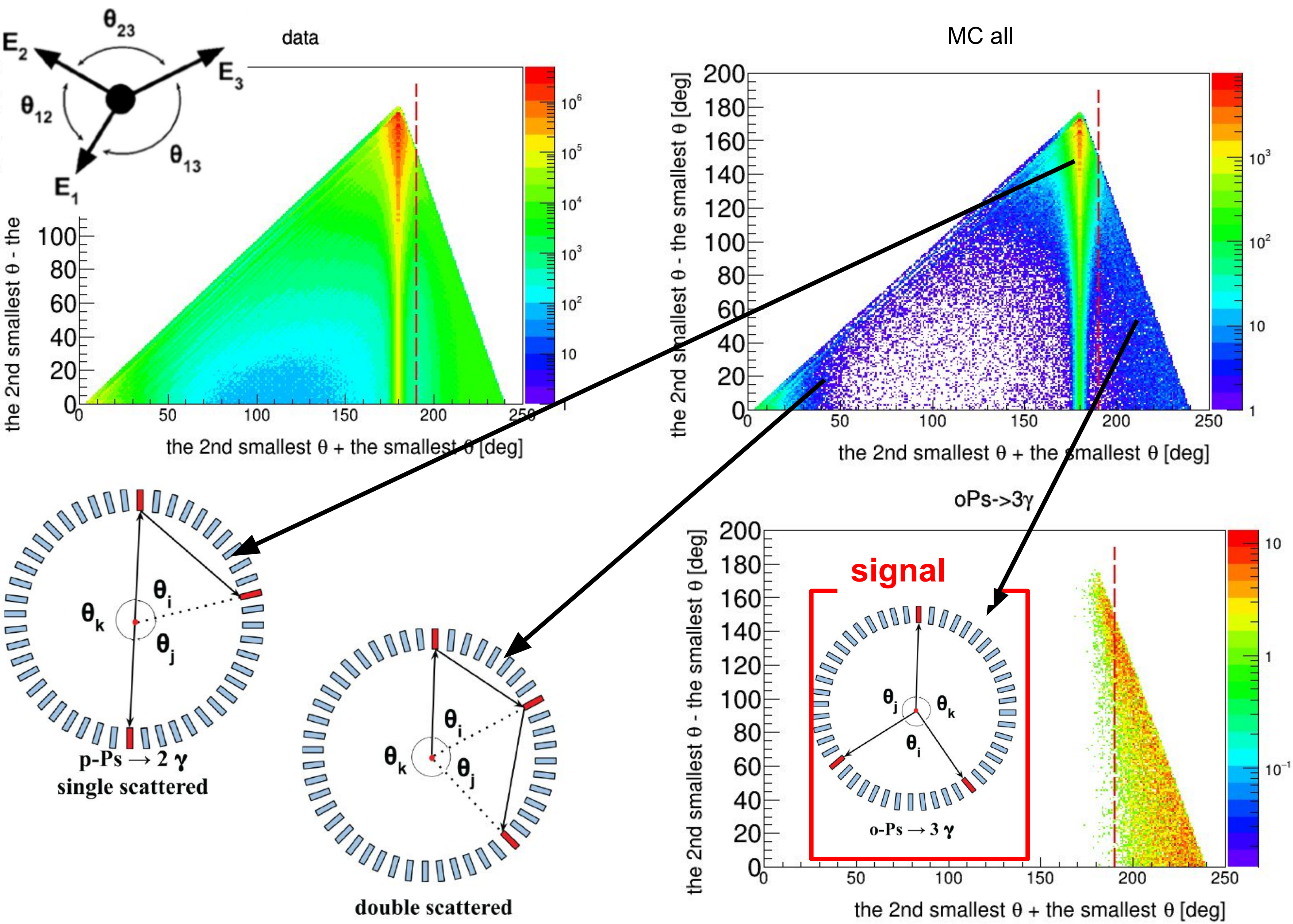


$$ET_i = t_{Hit\,i} - \frac{d_i}{c}$$

$$d_i = \sqrt{(X_i - S_x)^2 + (Y_i - S_y)^2 + (Z_i - S_z)^2}$$

$$t_{ETS} = ET_3 - ET_1$$

6) cut on the sum of two smallest angles of oPs decaying into 3γ: sum ≥ 190 deg



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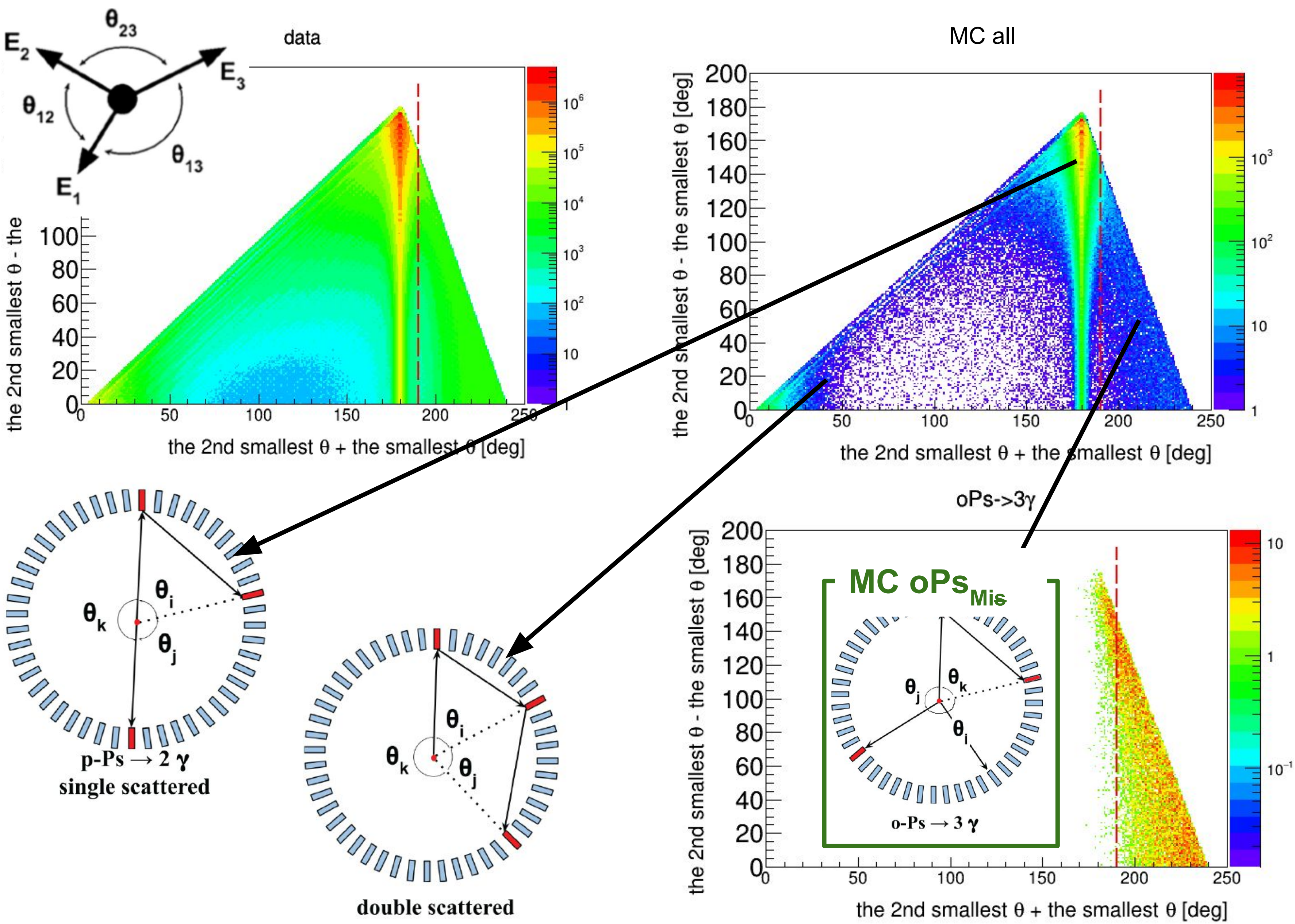
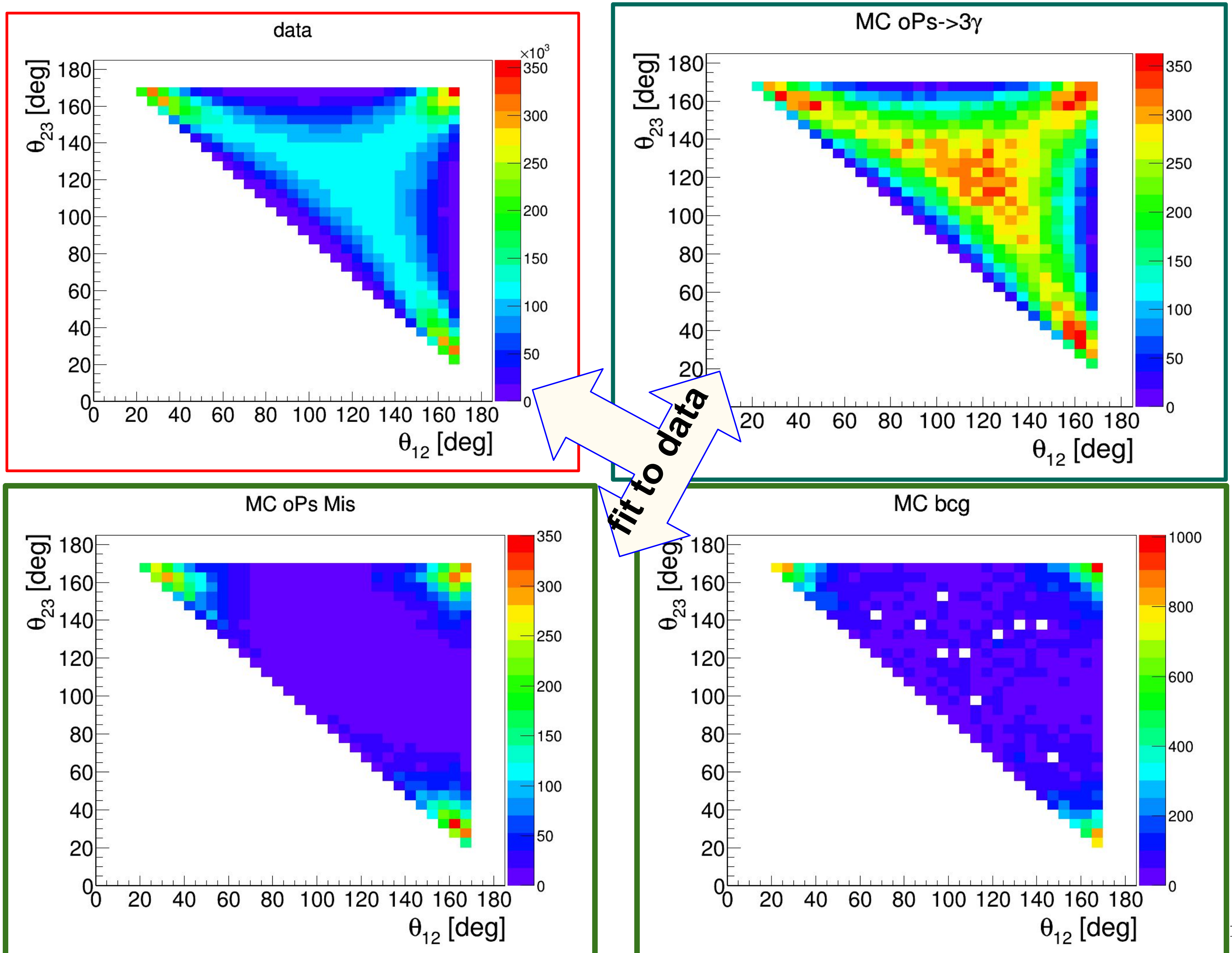
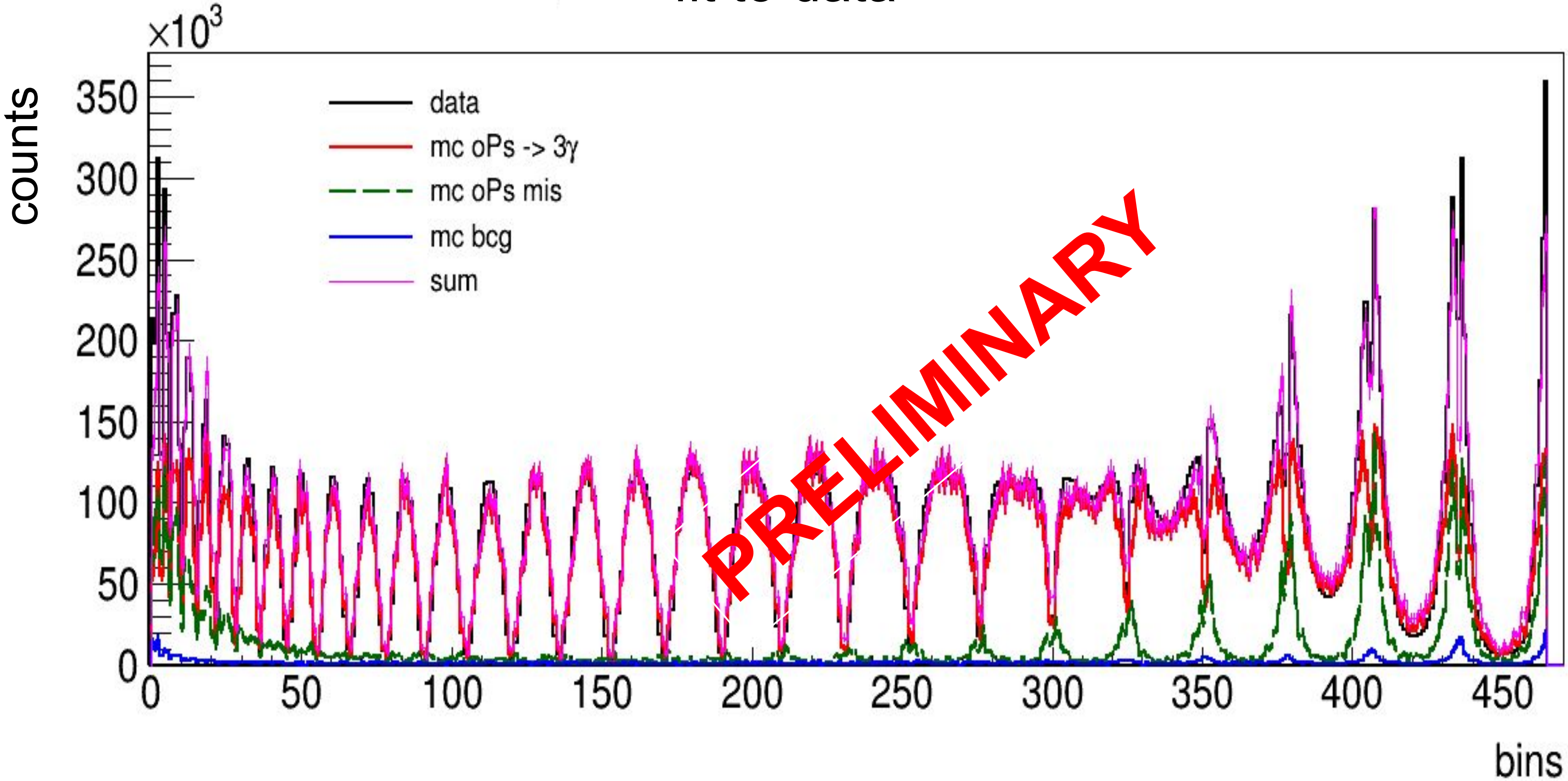



data
MC oPs->3γ
MC oPs Mis
MC bcg
fit to data
θ_{23} [deg]
θ_{12} [deg]
×10³

fit to data



$$\chi^2 = \Sigma_{i=1}^{Bins} \frac{(N_i^{DATA} - N_i^{MC})^2}{\_^2}$$

$$N_i^{MC} = A \cdot N_i^{Signal} + A \cdot N_i^{Mis-Reconstructed\ Signal} + B \cdot N_i^{Background}$$

$$\sigma^2 = (N_i^{DATA} + A^2 \cdot (N_i^{Signal} + N_i^{Mis-Reconstructed\ Signal}) + B^2 \cdot N_i^{Background})$$

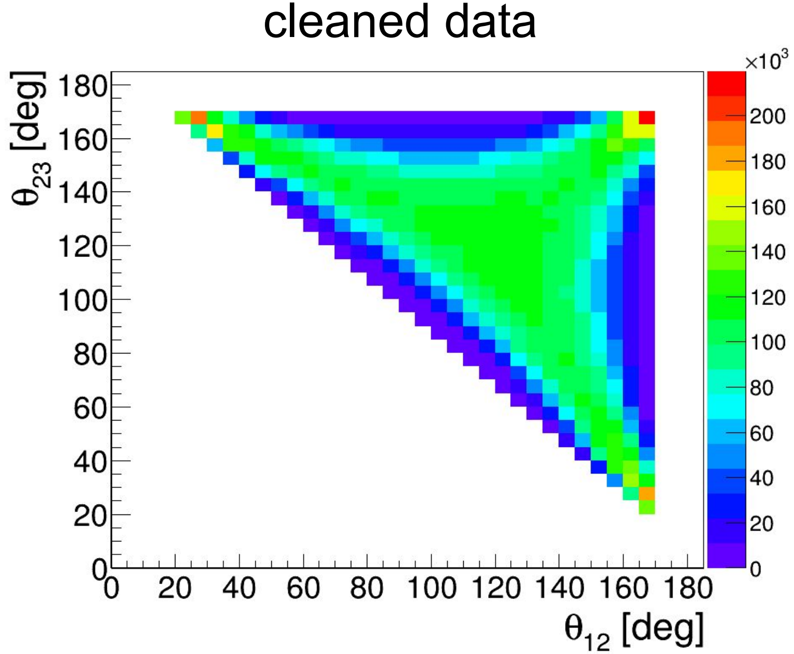
The number of o-Ps in measured sample

$\boxed{\text{N\_oPs\_data\_rec}}$ = N_data_rec - N_oPs_Mis - N_mc_bcg

number of experimental events after all selection criteria

mis-reco signal events

other bcg events



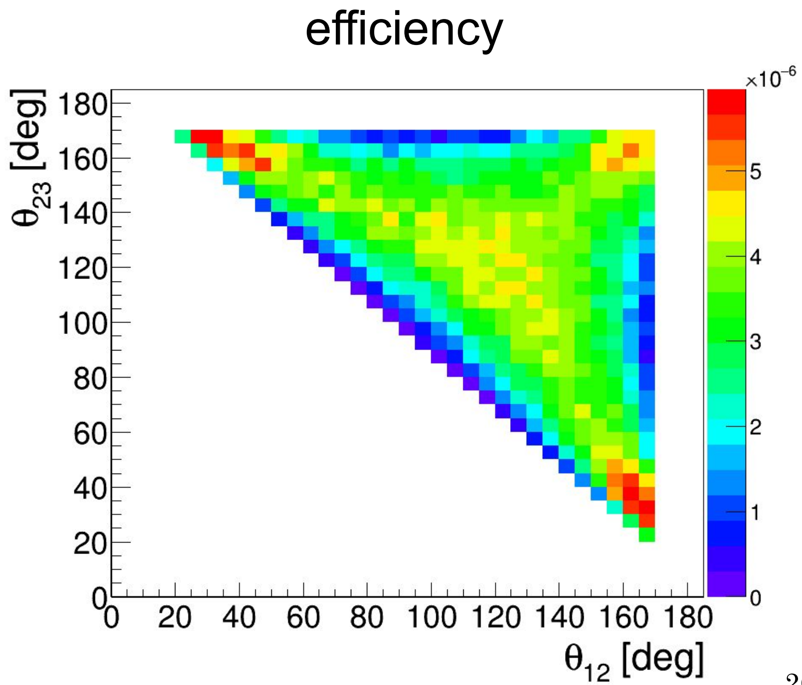
The number of o-Ps after correction (efficiency)

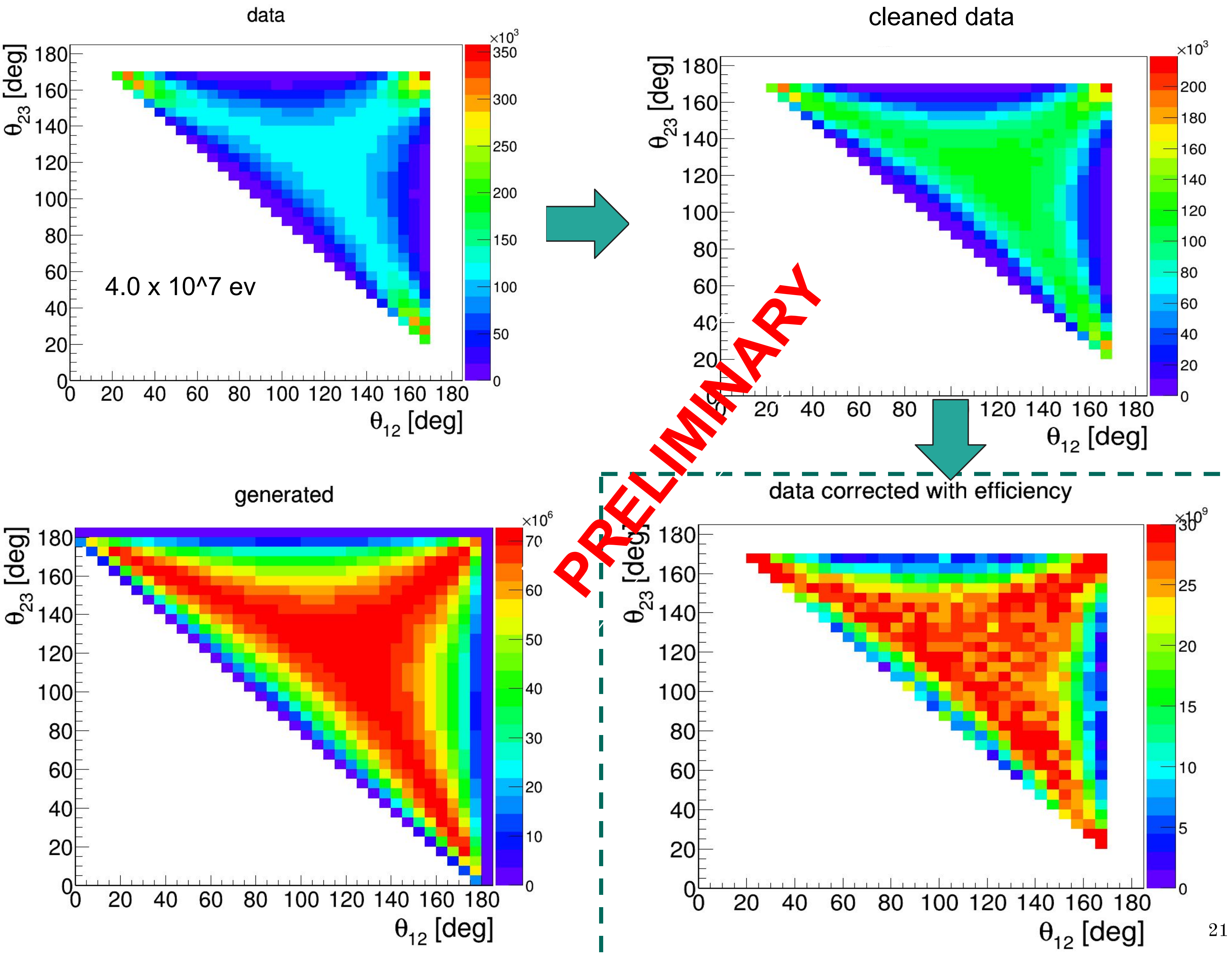
N_oPs_data = N_oPs_data_rec / ϵ

$$\epsilon = \frac{\boxed{\text{N\_mc\_oPs}}}{\boxed{N_{gen}}}$$

number of generated events

number of accepted events after all selection criteria including correction for efficiency as a function of energy deposition




data
4.0 x 10^7 ev
cleaned data
generated
data corrected with efficiency
PRELIMINARY
θ12 [deg]
θ23 [deg]
×10^3
×10^6
×10^9

Summary

- experimental Dalitz Plot determined for the first time ever for oPs -> 3γ decay with J-PET scanner

- **The precision experimental investigations of the positronium decays are crucial in particular for a sensitive probe of QED and the tests of fundamental symmetries**

- the Dalitz Plot investigation for allowed and forbidden Ps-> 3γ decays -> comment on C symmetry

Grazie per l'attenzione!

Positronium

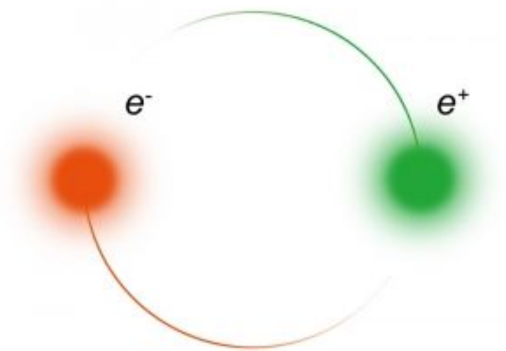
➢ **POSITRONIUM - the lightest purely leptonic object**

bound by a central potential

⇓

<u>is eigenstate of the parity operator P</u>

$$P|Ps>=(-1)^{L}|Ps>$$



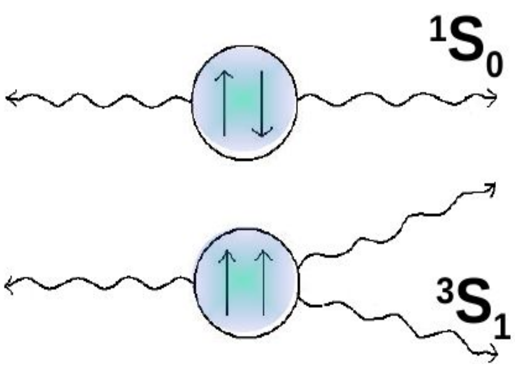
symmetric under the exchange of particles - anti-particles

⇓

<u>is eigenstate of the charge conjugation operator C</u>

$$C|Ps>=(-1)^{L+S}|Ps>$$

<u>eigenstate of the CP operator</u>



Para–positronium (p - Ps), τ = 125ps, $^1S_0$

↓↑ -Singlet state

Ortho – positronium (o - Ps), τ = 142ns, $^3S_1$

↑↑ ↓↑ ↓↓ --Triplet state

even number of photons

symm. of charge conjugation C

odd number of photons

Ps state	τ [ns]	L	S	J	J_z	P	C	CP
$^1S_0$ (para-Ps)	0.125	0	0	0	0	-	+	-
$^3S_1$(ortho-Ps)	142	0	1	1	-1,0,1	-	-	+

MC contributions

MC all: **all simulation**

MC oPs:

signal: 3 hits associated to oPs coming from the same vertex

$GenGammaMultiplicity_{i,j,k}$==3 && $vtxIndex_i$ = $vtxIndex_j$ = $vtxIndex_k$

MC oPs_{Mis}:

mis-reconstructed oPs: 3 hits associated to oPs, but at least one is scattered

$GenGammaMultiplicity_{i,j}$==3 && $GenGammaMultiplicity_k$==103 (1 scattered)
$GenGammaMultiplicity_i$==3 && $GenGammaMultiplicity_{j,k}$==103 (2 scattered)
$GenGammaMultiplicity_{i,j,k}$==103 (3 scattered)

MC background = all MC - oPs - oPs_{Mis}

o-Ps decay to 3γ

$$|M|^2 = 64(4\pi)^3\alpha^3\left[\left(\frac{m_e - E_1}{E_2E_3}\right)^2 + \left(\frac{m_e - E_2}{E_1E_3}\right)^2 + \left(\frac{m_e - E_3}{E_1E_2}\right)^2\right]$$

3 photons,
each (px,py,pz,E)

12 parameters

$$\boxed{d\sigma_{3\gamma} = \frac{8\alpha^3}{6m_e^2 v}|M|^2 dE_1 dE_2}$$

$$\boxed{d\Gamma_{3\gamma} = \frac{4}{3}d\sigma_{3\gamma}v|\psi(0)|^2}$$

$$v|\psi(0)|^2 = \frac{m^3\alpha^3}{8\pi}$$

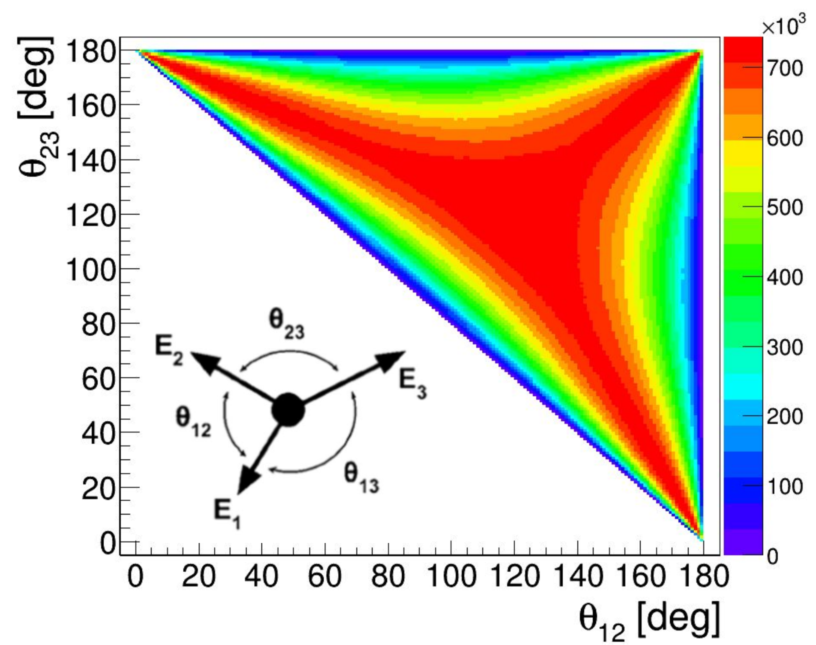
electron positron relative velocity

flux density

$$\Gamma_{\text{LO}} = \frac{2}{9\pi}(\pi^2 - 9)m\alpha^6$$

$$\Gamma_{LO} = 7.21117\ \mu s^{-1}$$

Averaging the cross-section over initial spin states three from four possible positronium spin states undergo 3γ annihilation



O(alpha) correction

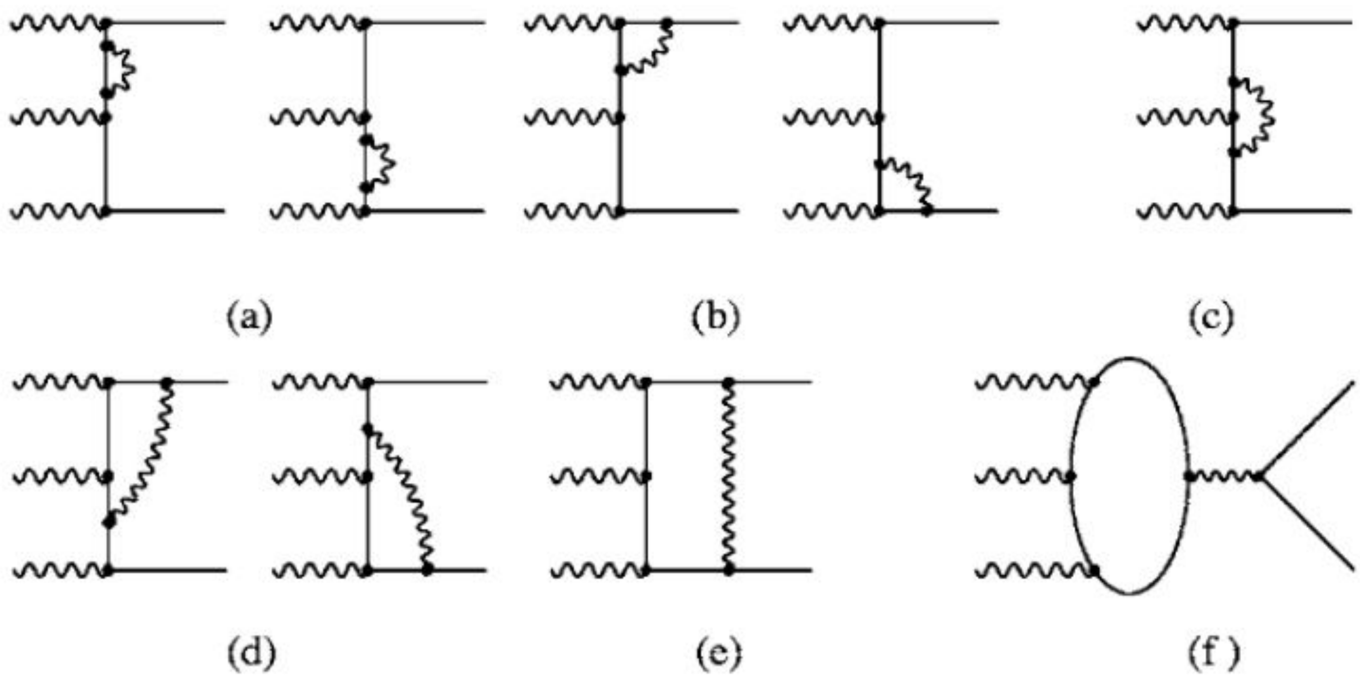


FIG. 2. Graphs contributing to the ortho-Ps decay amplitudes through order α. They are the (a) self-energy, (b) outer vertex, (c) inner vertex, (d) double vertex, (e) ladder, and (f) annihilation contributions. The wave function factors are implicit in these graphs.

$$\Gamma_1 = \frac{m\alpha^7}{36\pi^2}\int_0^1 dx_1 \int_{1-x_1}^1 dx_2 \frac{1}{x_1 x_2 x_3}\{F(x_1,x_3) + \text{permutations}\}$$

O(alpha) correction

$$F(x_1,x_3) = g_0(x_1,x_3) + \sum_{i=1}^{5} g_i(x_1,x_3)h_i(x_1) + \sum_{i=6}^{7} g_i(x_1,x_3)h_i(x_1,x_3).$$

The g functions

The g functions are given in terms of $x^{mn}=x_1^m x_3^n$ and $\bar{x}_2=x_1+x_3-1$ as

$$\begin{aligned} g_0(x_1,x_3) = \frac{1}{9x_1\bar{x}_1(1-2x_1)x_3\bar{x}_3(1-2x_3)}\{&-180+2196x^{10} \\ &-4968x^{20}+5292x^{30}-2664x^{40}+504x^{50} \\ &-5848x^{11}+22639x^{21}-20280x^{31}+8405x^{41} \\ &-1240x^{51}-24x^{61}-17551x^{22}+22982x^{32} \\ &-5857x^{42}+264x^{52}+48x^{62}-3776x^{33}-878x^{43} \\ &+400x^{53}+536x^{44}\}, \end{aligned} \tag{A5a}$$

$$\begin{aligned} g_1(x_1,x_3) = \frac{4}{x_1^2(1-2x_1)^2(x_1-x_3)x_3}\{&2x^{20}-13x^{30}+35x^{40} \\ &-36x^{50}+8x^{60}+4x^{70}+9x^{11}-59x^{21}+149x^{31} \\ &-210x^{41}+162x^{51}-51x^{61}+x^{71}-4x^{02}+3x^{12} \\ &+55x^{22}-126x^{32}+104x^{42}-39x^{52}+x^{62}+8x^{03} \\ &-26x^{13}+7x^{23}+22x^{33}+2x^{43}-2x^{53}-4x^{04} \\ &+14x^{14}-8x^{24}-8x^{34}\}, \end{aligned} \tag{A5b}$$

$$\begin{aligned} g_2(x_1,x_3) = \frac{2}{3x_1^3\bar{x}_1x_3}\{&-48x^{10}+180x^{20}-276x^{30}+228x^{40} \\ &-108x^{50}+24x^{60}+48x^{01}-48x^{11}-144x^{31} \\ &+244x^{41}-106x^{51}+2x^{61}+4x^{71}-96x^{02}+156x^{12} \\ &-108x^{22}+168x^{32}-132x^{42}+7x^{52}+6x^{62} \\ &+48x^{03}-60x^{13}-36x^{23}+42x^{33}+9x^{43}-6x^{53} \\ &+6x^{34}-4x^{44}\}, \end{aligned} \tag{A5c}$$

$$\begin{aligned} g_3(x_1,x_3) = \frac{4}{x_1^2(x_1-x_3)x_3}\{&-2x^{20}-2x^{40}-4x^{60}+5x^{11}-6x^{21} \\ &+14x^{31}-4x^{41}+18x^{51}-x^{61}-4x^{02}-2x^{12}+4x^{22} \\ &-2x^{32}-26x^{42}-x^{52}+8x^{03}-7x^{13}-2x^{23}+12x^{33} \\ &+2x^{43}-4x^{04}+4x^{14}\}, \end{aligned} \tag{A5d}$$

$$\begin{aligned} g_4(x_1,x_3) = \frac{8}{x_1^2}\{&-4+7x^{10}-7x^{20}+12x^{30}-10x^{40}+2x^{50}+8x^{01} \\ &-10x^{11}+3x^{21}-3x^{31}+2x^{41}-4x^{02}+3x^{12}+2x^{22} \\ &+x^{32}\}, \end{aligned} \tag{A5e}$$

$$\begin{aligned} g_5(x_1,x_3) = \frac{2\bar{x}_1}{x_1}\{&8-34x^{10}+29x^{20}-4x^{30}+6x^{11}+8x^{02} \\ &-4x^{12}\}, \end{aligned} \tag{A5f}$$

$$\begin{aligned} g_6(x_1,x_3) = \frac{1}{x_1\bar{x}_2x_3}\{&16-76x^{10}+136x^{20}-124x^{30}+64x^{40} \\ &-16x^{50}-60x^{01}+272x^{11}-424x^{21}+294x^{31} \\ &-104x^{41}+22x^{51}+92x^{02}-392x^{12}+484x^{22} \\ &-187x^{32}+13x^{42}+2x^{52}-76x^{03}+294x^{13}-259x^{23} \\ &+30x^{33}+3x^{43}+36x^{04}-120x^{14}+61x^{24}+3x^{34} \\ &-8x^{05}+22x^{15}+2x^{25}\}, \end{aligned} \tag{A5g}$$

$$\begin{aligned} g_7(x_1,x_3) = \frac{1}{\bar{x}_2}\{&16-48x^{10}+46x^{20}-12x^{30}-2x^{40}-48x^{01} \\ &+60x^{11}+9x^{21}-31x^{31}+10x^{41}+46x^{02}+9x^{12} \\ &-42x^{22}+11x^{32}-12x^{03}-31x^{13}+11x^{23}-2x^{04} \\ &+10x^{14}\}. \end{aligned} \tag{A5h}$$

G. S. Adkins, *Analytic evaluation of the amplitudes for orthopositronium decay to three photons to one-loop order*

$$\Gamma = 7.0401 \pm 0.0007 \times 10^6\,\mathrm{s}^{-1}$$

best published experimental result

$$\Gamma_{LO} = 7.21117\ \mu\mathrm{s}^{-1}$$

2,5% difference

$$\Gamma = 7.039979(11) \times 10^6\,\mathrm{s}^{-1}$$

QED prediction for 3gamma+5gamma decay

ANALYSIS

- determination, for the first time ever, of the experimental Dalitz plot in an angular representation for oPs -> 3γ decay

Experimental Data - Big Barrel:

RUN11

- 02.04.2020 - 01.03.2021
- small annihilation chamber (PA6 material)
- ^{22}Na source activity 0.702 MBq
- thresholds: 30, 80, 190, 300 mV

Analysed data:

- **484978** .hld files -> 950~TB.
- 40 million o-Ps -> 3g signal events identified

-> about 91% of data in RUN11

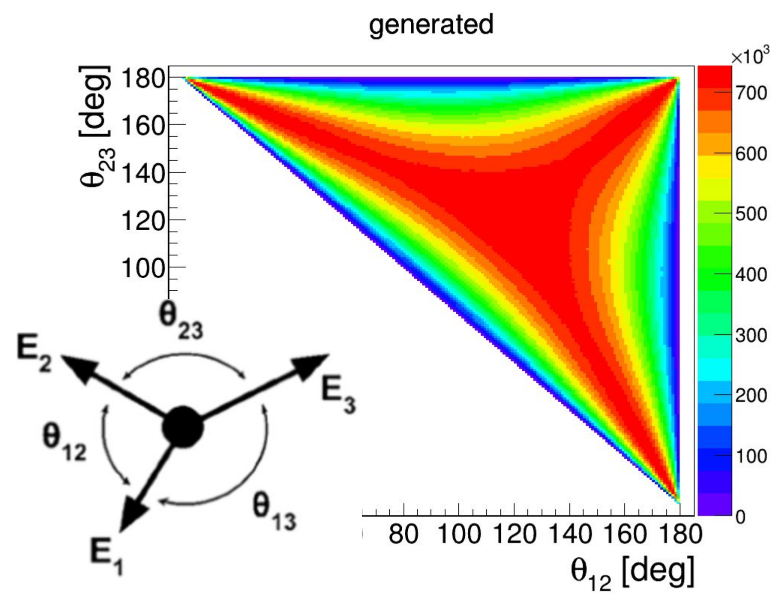
- "EventFinder_EventTime_float":2500.0 (2.5 [ns])
  time window for grouping hits in one event
- "HitFinder_ABTimeDiff_float":6000.0 (6 [ns])
  time window for matching Signals on the same scintillator and different sides

MC Simulations

- $1.564 \cdot 10^{11}$ events generated (with frame)

J-PET Report 2020 J-PET Monte Carlo simulations in Geant4 toolkit User Manual for version 4.0

P. Mills, S. Berko, Phys. Rev. Lett. 18, 420 (1967)



- “GeantParser_ZPositionSmearingParameters_std::vector<double>":[3.0] [cm]
- "GeantParser_TimeSmearingParameters_std::vector<double>":[225.0] [ps]

userParams

Data:

- preselected data
/mnt/jpet/Preselection/Run11/data

- "TimeWindowCreator_MinTime_float":-20000.0 (-20 [ns])

- "SignalFinder_EdgeMaxTime_float":3000.0 (3 [ns])
time window for matching Signal Channels on Leading Edge

- "SignalFinder_LeadTrailMaxTime_float":23000.0 (23 [ns])
time window for matching Signal Channels on the same thresholds from Leading and Trailing edge

- "HitFinder_ABTimeDiff_float":6000.0 (6 [ns])
time window for matching Signals on the same scintillator and different sides

- "EventFinder_EventTime_float":2500.0 (2.5 [ns])
time window for grouping hits in one event

MC Simulations

- “GeantParser_MinTimeWindow_double":-20000000.0 (-20 [ns])

- "EventFinder_EventTime_float":2500.0 (2.5 [ns])

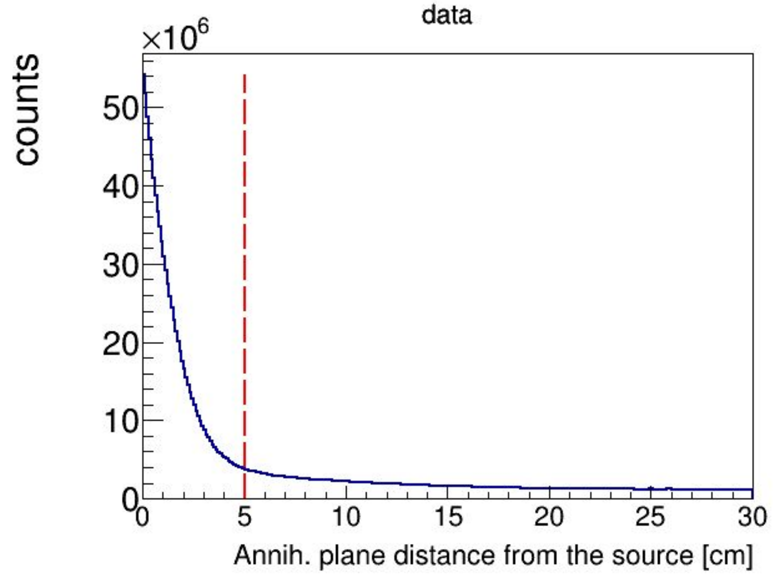
- "GeantParser_SourceActivity_double":1.1 [MBq]

- "GeantParser_EnergyThreshold_double":30.0 [keV]

- “GeantParser_ZPositionSmearingParameters_std::vector<double>":[3.0] [cm]

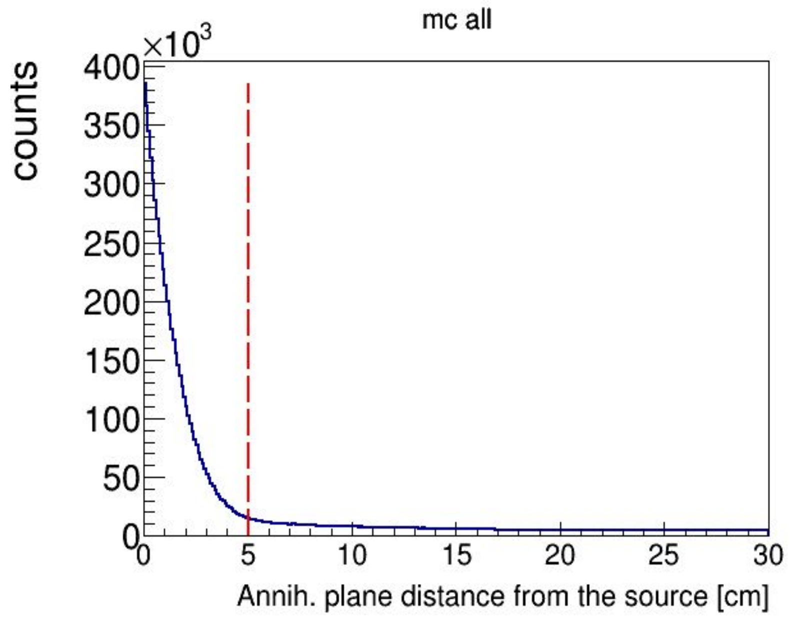
- "GeantParser_TimeSmearingParameters_std::vector<double>":[225.0] [ps]

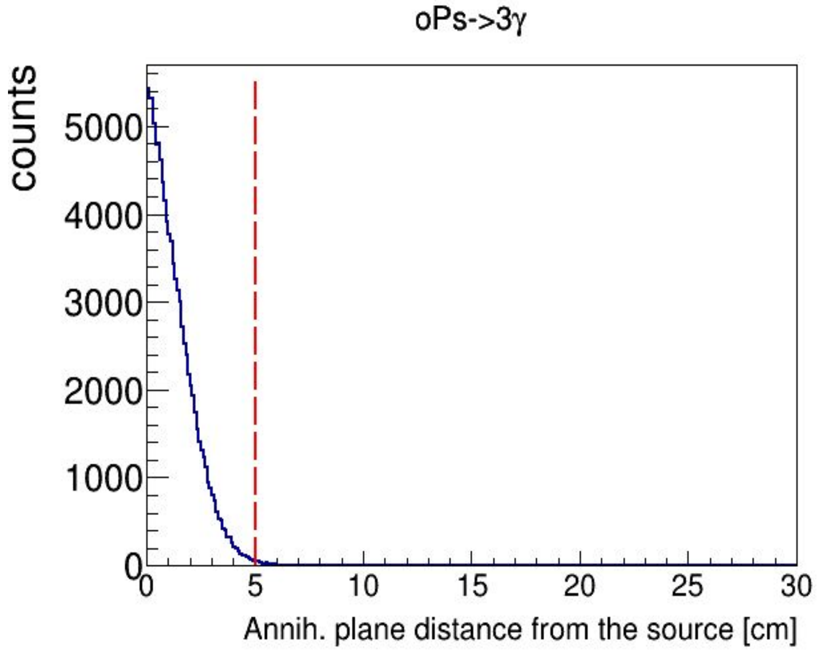
4) cut on distance between annihilation plane and the source: d<5cm



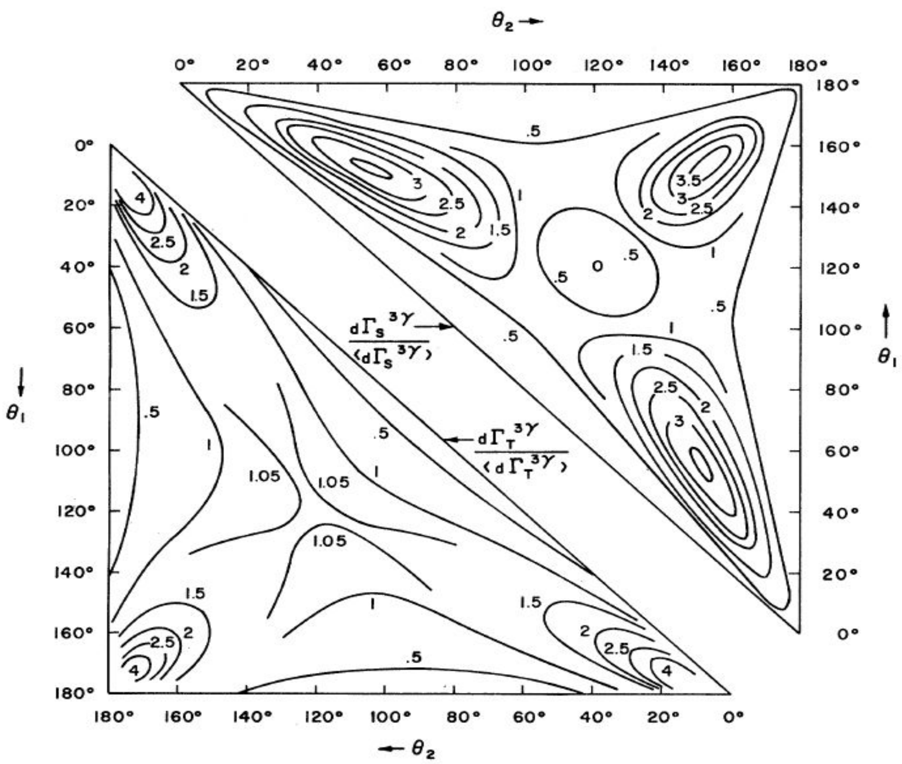
$$Ax + By + Cz + D = 0$$

$$DOP = \frac{|A.S_x + B.S_y + C.S_z + D|}{\sqrt{A^2 + B^2 + C^2}}$$





Goal of the analysis

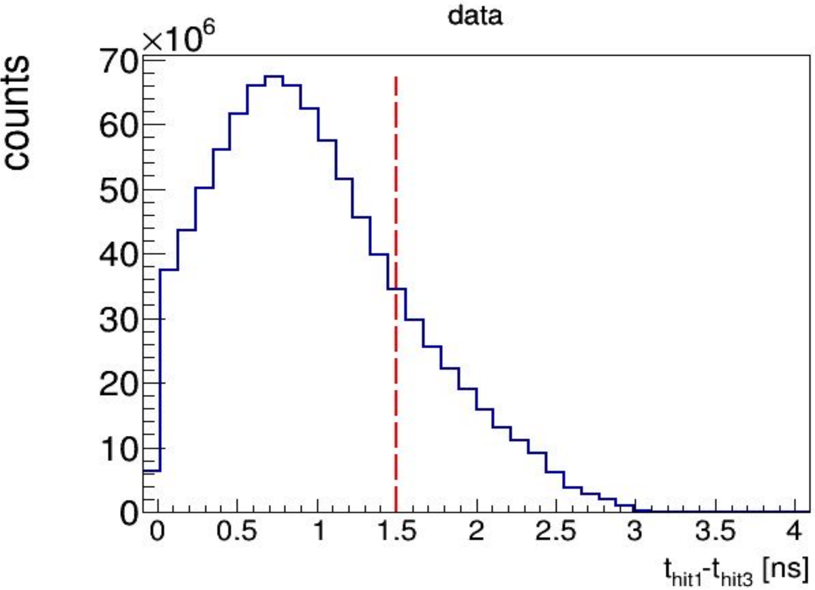


$$d\Gamma_T^{3\gamma} = \frac{8\alpha\Gamma_s^{2\gamma}}{3\alpha^2\,(2\pi)^4}\,(\omega_1\omega_2\omega_3)^{-1}\sum_{1\to2\to3}\omega_i^2\left(\frac{1}{2}-\omega_i\right)^2 d\theta_{12}d\theta_{13}d\Omega_1 d\varphi_1,$$

$$\Gamma_T^{3\gamma} = \frac{4\alpha\Gamma_s^{2\gamma}}{3\pi^2}\int_0^{1/2} d\omega \int_{1/2-\omega_1}^{1/2}\sum_{1\to2\to3}\left(\frac{1}{2}-\omega_1\right)^2 / \left(\omega_2\omega_3\right)^2 d\omega_2 \approx 0.898\cdot 10^{-3} g^2\Gamma_s^{2\gamma}$$

Events selection

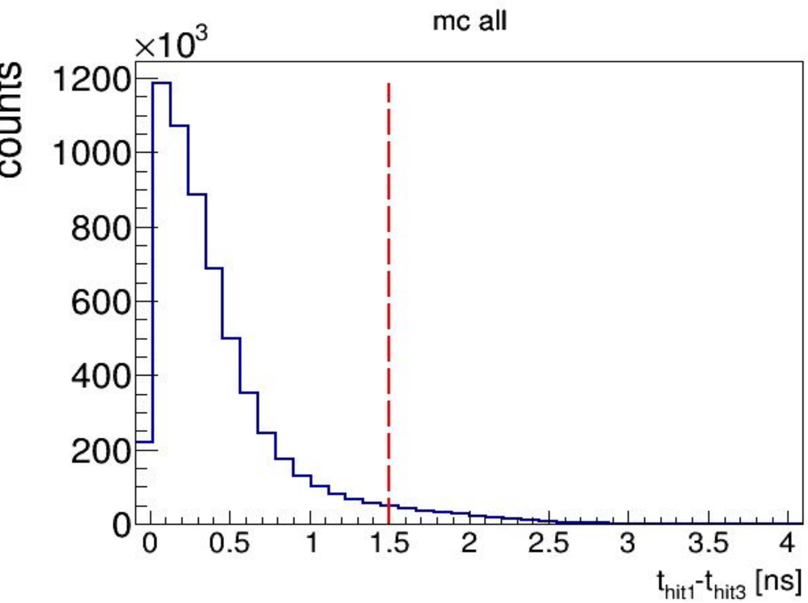
5) cut on emission time difference between the third and first hit: t<1.5ns

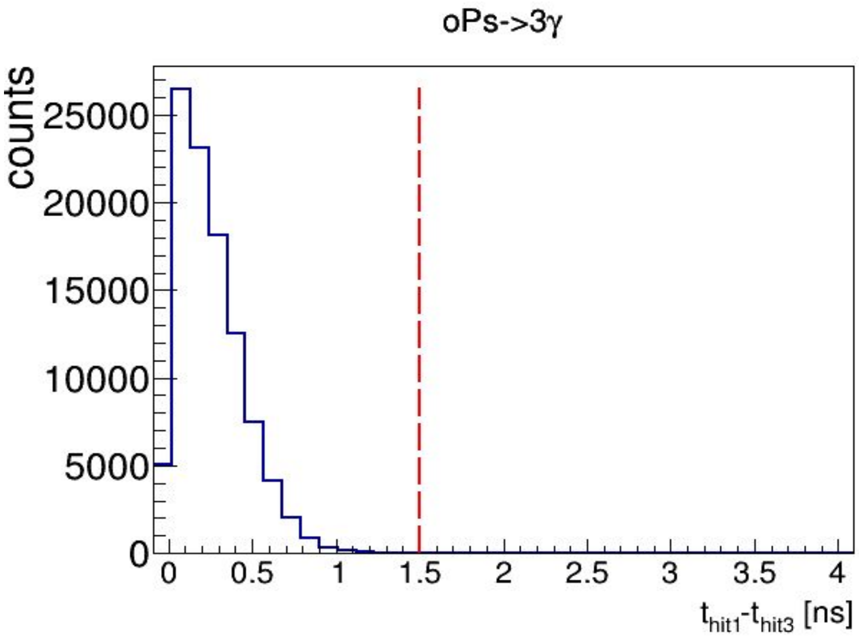


$$ET_i = t_{Hit\,i} - \frac{d_i}{c}$$

$$d_i = \sqrt{(X_i - S_x)^2 + (Y_i - S_y)^2 + (Z_i - S_z)^2}$$

$$t_{ETS} = ET_3 - ET_1$$





ANALYSIS

Experimental Data:

RUN11

- 02.04.2020 - 01.03.2021
- small annihilation chamber (PA6 material)
- ^{22}Na source activity 0.702 MBq
- thresholds: 30, 80, 190, 300 mV

Analysed data:

- tapes 186-200, 239 - 127057 .hld files

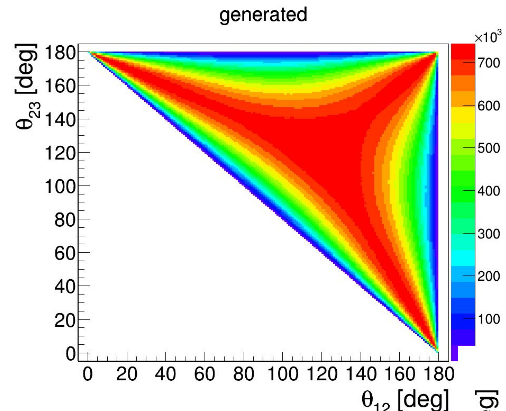
-> about 20% of data in RUN11 (616708 files), 42 days

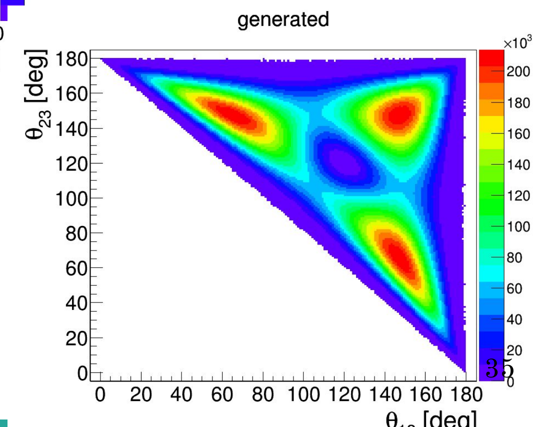
MC Simulations

- oPs -> 3γ $8.49*10^9$ events generated
- pPs -> 3γ 10^9 events generated

J-PET Report 2020 J-PET Monte Carlo simulations in Geant4 toolkit User Manual for version 4.0

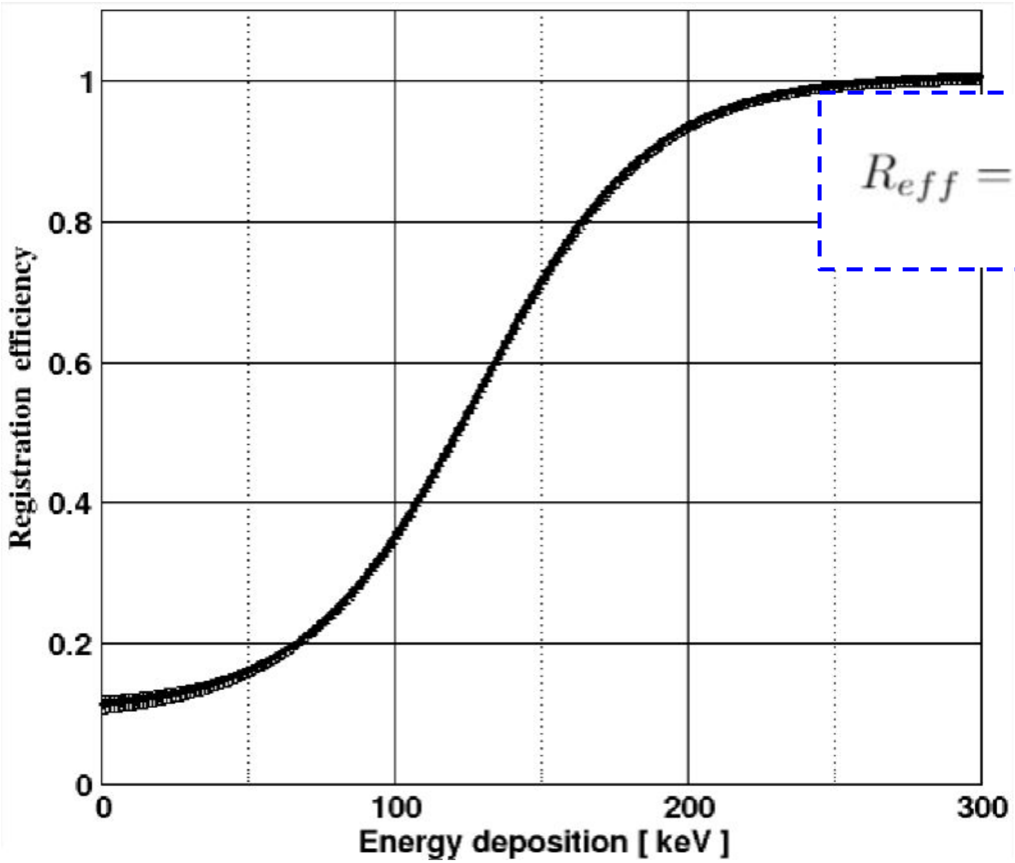
P. Mills, S. Berko, Phys. Rev. Lett. 18, 420 (1967)





correcting MC with Edep efficiency

RUN 11



Boltzmann Sigmoid Function

$$R_{eff} = 0.94 \cdot \left(1.069 + \frac{0.1088 - 1.069}{1 + e^{(E_{dep} - 128.5)/29.23}}\right)$$

In order to apply the RE function, the 3 step procedure was performed for each hit.

1. For an estimated value of energy deposition (direct Edep in a hit or via TOT to Edep conversion), Function (RE) is calculated.
2. A random number (Rndm) is generated in a Uniform interval [0,1].
3. Decision on the fate of event:

    if(RE (Edep) > Rndm) Accept

    else Reject

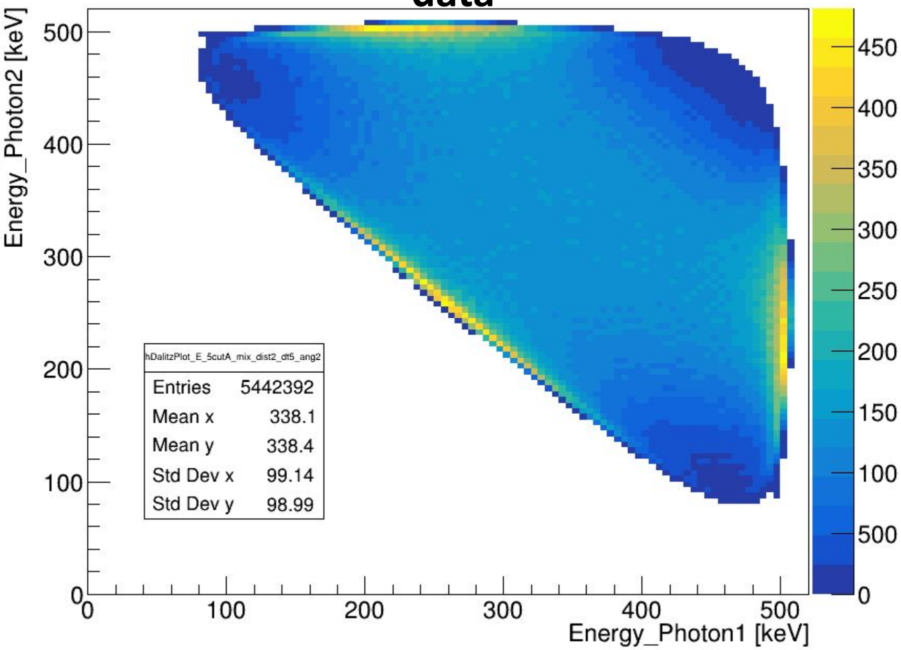
As in Simulation, we have information of the energy deposition by scattering photon: We followed the steps (1-3) in deciding the fate of the event.

determined by **Sushil Sharma**, more details in:

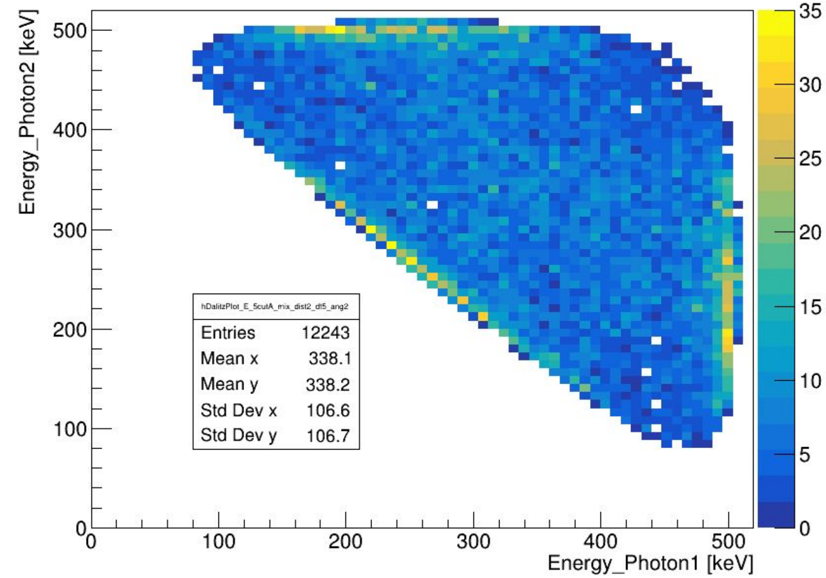
https://koza.if.uj.edu.pl/petwiki/images/b/b5/AnalysisStatus_210120201.pdf
https://koza.if.uj.edu.pl/petwiki/images/5/52/EfficiencyOfJPet.pdf

Dalitz Plots Energy

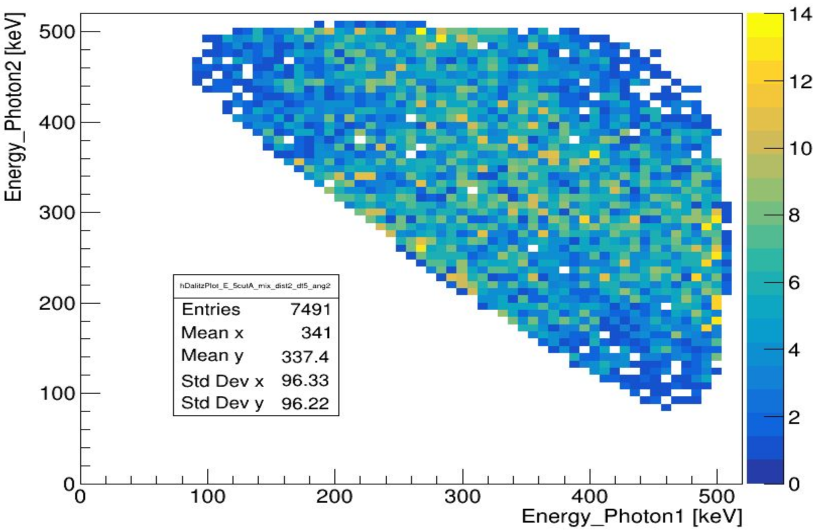
data



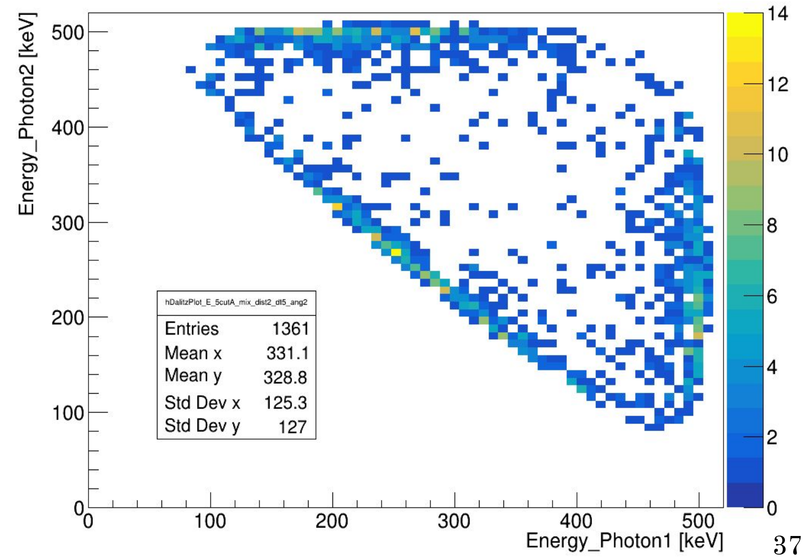
all

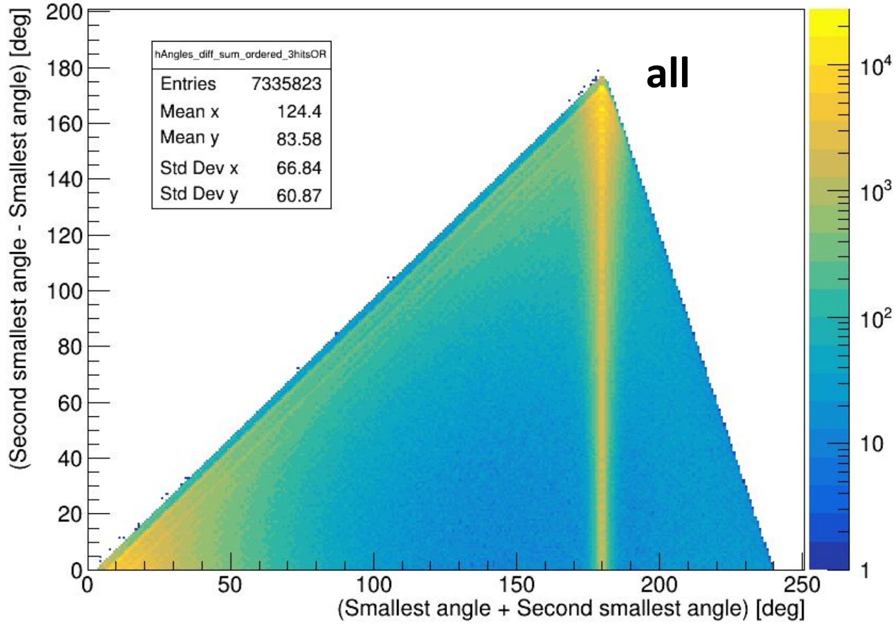


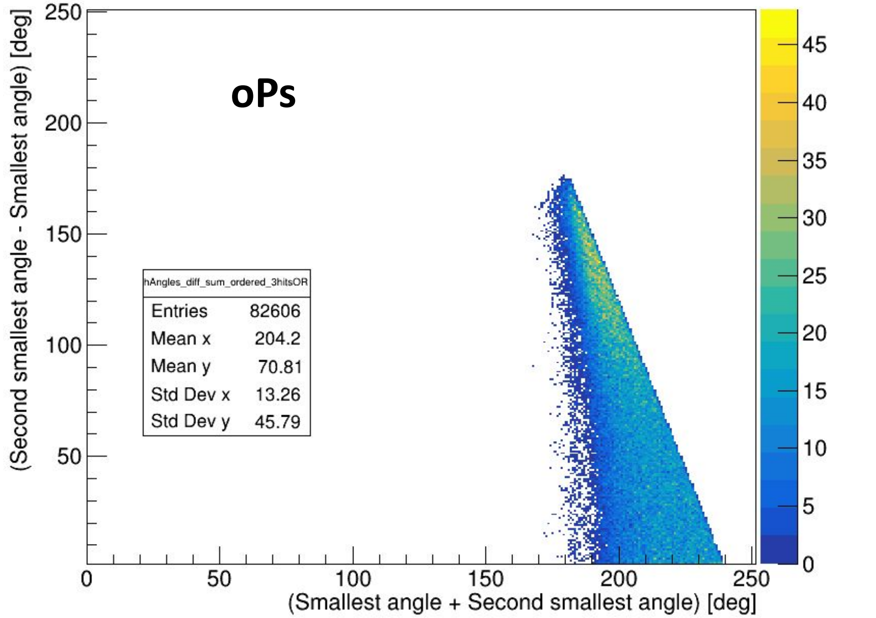
oPs

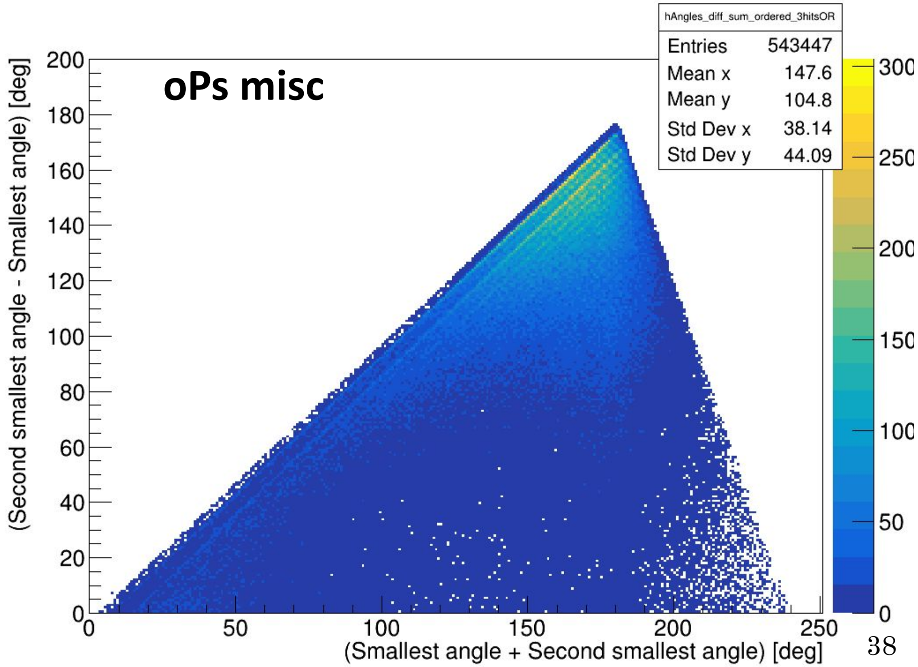


oPs mis




all
hAngles_diff_sum_ordered_3hitsOR
Entries 7335823
Mean x 124.4
Mean y 83.58
Std Dev x 66.84
Std Dev y 60.87
(Second smallest angle - Smallest angle) [deg]
(Smallest angle + Second smallest angle) [deg]


oPs
hAngles_diff_sum_ordered_3hitsOR
Entries 82606
Mean x 204.2
Mean y 70.81
Std Dev x 13.26
Std Dev y 45.79
(Second smallest angle - Smallest angle) [deg]
(Smallest angle + Second smallest angle) [deg]


oPs misc
hAngles_diff_sum_ordered_3hitsOR
Entries 543447
Mean x 147.6
Mean y 104.8
Std Dev x 38.14
Std Dev y 44.09
(Second smallest angle - Smallest angle) [deg]
(Smallest angle + Second smallest angle) [deg]

Charge Conjugation Symmetry Test

- experimental tests of C-symmetry in Ps decays

$$\mathrm{BR}(\text{o-Ps} \to 4\gamma/\text{o-Ps} \to 3\gamma) < 2.6 \times 10^{-6} \quad \text{at} \quad 90\% \text{ C.L.}$$

[1] J. Yang eta al., Phys. Rev. A 54, 1952 (1996)

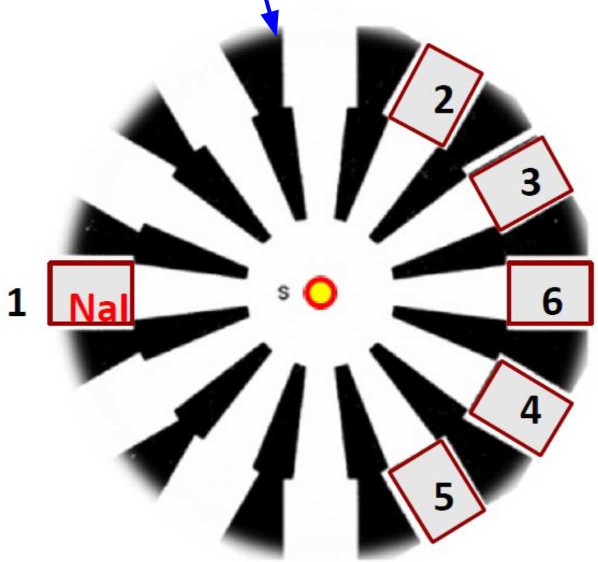
*the best limit for **p-Ps -> 3γ***

$$\boxed{\mathrm{BR}(\text{p-Ps} \to 3\gamma/\text{p-Ps} \to 2\gamma) < 2.8 \times 10^{-6} \quad \text{at} \quad 68\% \text{ C.L.}}$$

[2] **P. Mills, S. Berko, Phys. Rev. Lett. 18, 420 (1967)**

$$\mathrm{BR}(\text{p-Ps} \to 5\gamma/\text{p-Ps} \to 2\gamma) < 2.7 \times 10^{-7} \quad \text{at} \quad 90\% \text{ C.L.}$$

[3] P. Vetter, S. Freedman, Phys. Rev. A 66, 052505 (2002)



- Cu^{64} source (in gas chamber)
- 6 NaI(Tl) scintillators, multiple coinc. electronics
- NO quenching to suppress o-Ps-3γ

- the C forbidden p-Ps->3γ decay separated from the allowed o-Ps->3γ decay by studying angular distribution of 3 photons:
  - symmetric configuration (120°,120°,120°)
  - 60°,150°,150°
  - 90°,120°,150°

due to Bose statistic assumption
C-nonconserving p-Ps->3γ must vanish

o-Ps decay to 3γ

$$E_1 = -2m_ec^2 \frac{-cos\theta_{13} + cos\theta_{12}cos\theta_{23}}{(-1 + cos\theta_{12})(1 + cos\theta_{12} - cos\theta_{13} - cos\theta_{23})} = \omega_1$$

$$E_2 = -2m_ec^2 \frac{cos\theta_{12}cos\theta_{13} - cos\theta_{23}}{(-1 + cos\theta_{12})(1 + cos\theta_{12} - cos\theta_{13} - cos\theta_{23})} = \omega_2$$

$$E_3 = 2m_ec^2 \frac{1 + cos\theta_{12}}{(1 + cos\theta_{12} - cos\theta_{13} - cos\theta_{23})} = \omega_3$$

Solution of equation can be presented as:

In the **CM frame**, E of gamma quanta from PS annihilation can be expressed as a function of angles between momentum vectors $\theta_{12}, \theta_{23}, \theta_{13}$

Momentum-energy conservation

relation between Theta's and energy calculated

$$w_1 + w_2 + w_3 = 2m$$

$$m = 511\ keV$$

$$0 \leq \theta_{12}, \theta_{23}, \theta_{13} \leq 180°$$

$$\theta_{12} = cos^{-1}\left(\frac{p_3^2 - p_1^2 - p_2^2}{2p_1p_2}\right)$$

$$\theta_{23} = cos^{-1}\left(\frac{p_1^2 - p_2^2 - p_3^2}{2p_2p_3}\right)$$

$$\theta_{31} = cos^{-1}\left(\frac{p_2^2 - p_1^2 - p_3^2}{2p_1p_3}\right)$$

o-Ps decay to 3γ

$$d\sigma_{3\gamma} = \frac{(2\pi)^2 |M_{fi}|^2}{4I} \delta(k_1 + k_2 + k_3)\, \delta(\omega_1 + \omega_2 + \omega_3 - 2m) \frac{d^3k_1 d^3k_2 d^3k_3}{(2\pi)^9\, 2\omega_1 2\omega_2 2\omega_3}$$

amplitude can be calculated as:

$$\sum_{polarisation} |M_{fi}| = 64\,(4\pi)^3 e^6 \left[\left(\frac{m-\omega_1}{\omega_2\omega_3} \right)^2 + \left(\frac{m-\omega_2}{\omega_1\omega_3} \right)^2 + \left(\frac{m-\omega_3}{\omega_1\omega_2} \right)^2 \right]$$

the resulting differential cross-section for annihilation of photons having specified energies

$$d\sigma_{3\gamma} = \frac{1}{6} \frac{8e^6}{vm^2} \left[\left(\frac{m-\omega_1}{\omega_2\omega_3} \right)^2 + \left(\frac{m-\omega_2}{\omega_1\omega_3} \right)^2 + \left(\frac{m-\omega_3}{\omega_1\omega_2} \right)^2 \right] d\omega_1 d\omega_2$$

$$\sigma_{3\gamma} = \frac{8e^6}{6vm^2} \cdot 3 \int_0^m \int_{m-\omega_1}^m \sum_{1\to2\to3} \left(\frac{m-\omega_1}{\omega_2\omega_3} \right)^2 d\omega_1 d\omega_2$$

J-PET Report 2020 *J-PET Monte Carlo simulations in Geant4 toolkit User Manual for version 4.0*

o-Ps decay to 3γ

amplitude can be calculated as:

$$\boxed{\sum_{polarisation} |M_{fi}| = 64\,(4\pi)^3\,e^6\left[\left(\frac{m-\omega_1}{\omega_2\omega_3}\right)^2+\left(\frac{m-\omega_2}{\omega_1\omega_3}\right)^2+\left(\frac{m-\omega_3}{\omega_1\omega_2}\right)^2\right]}$$

angle between k_1, k_2

to ged rid of δ(k) - integrate over d^3k_3

$$d^3k_1 d^3k_2 \to 4\pi\omega_1^2 d\omega_1 \cdot 2\pi\omega_2^2 \boxed{d\left(\cos\theta_{12}\right)} d\omega_2$$

differentiating

$$d\left(\cos\theta_{12}\right) = \frac{\omega_3}{\omega_1\omega_2} d\omega_3 \leftarrow \omega_3 = \sqrt{\omega_1^2+\omega_2^2+2\omega_1\omega_2\cos\theta_{12}}$$

to ged rid of δ(ω) - integrate over $d^3\omega_3$

the resulting differential cross-section for annihilation of photons having specified energies

$$\boxed{d\sigma_{3\gamma} = \frac{1}{6}\frac{8e^6}{vm^2}\left[\left(\frac{m-\omega_1}{\omega_2\omega_3}\right)^2+\left(\frac{m-\omega_2}{\omega_1\omega_3}\right)^2+\left(\frac{m-\omega_3}{\omega_1\omega_2}\right)^2\right] d\omega_1 d\omega_2}$$