Improving the **experimental precision of ortho-positronium decay rate** in vacuum with the J-PET detector

S. Sharma, K. Dulski, P. Moskal

on behalf of the J-PET collaboration

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European Funds Smart Growth

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POSMOL 2023

XXI International Workshop on Low-Energy Positron and Positronium Physics and XXIII International Symposium on Electron-Molecule Collisions and Swarms

Outline

- **J-PET** : **J**agiellonian **P**ositron **E**mission **T**omograph

First tomograph made of plastic scintillators

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  excellent object to test bound Quantum Electrodynamics (QED)

- Positronium (Ps) decays

Fundamental Physics

- **Discrete** symmetries (C, P, T)
- **Entanglement** of photons in MeV range
- **Rare** decays
- **Positronium lifetime** - opens up several interesting aspects

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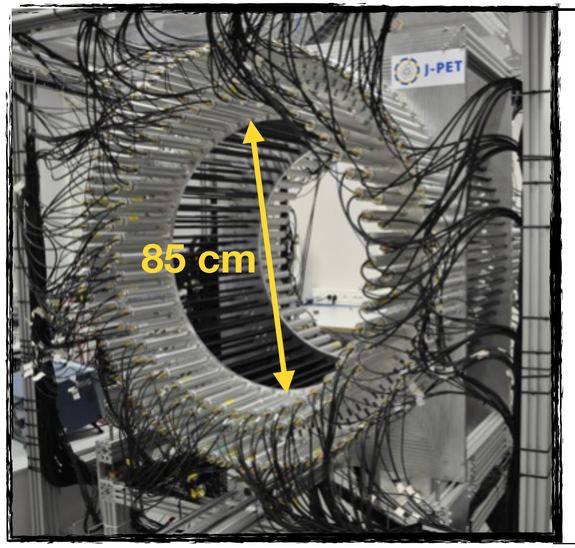
  - Ortho-positronium lifetime determination

- Summary and Outlook

Key features of J-PET

- **192** *detection modules* in 3 concentric cylinders
  (diameter of innermost is 85 cm)
- Each detection module consist of one plastic scintillator (50 x 1.9 x .7 cm^3) read-out at each end by photomultipliers
- **Trigger less** and **reconfigurable** DAQ
  G. Korcyl, IEEE Trans. Med. Imaging 37 (2018) 2526
- Good time and angular resolution



3-layers prototype

Single *detection module*

Hit-position

$= (t_i - t_j) \times Veff_{Light}/2$

Hit time

$= (t_i + t_j)/2 - L/2Veff_{Light}$

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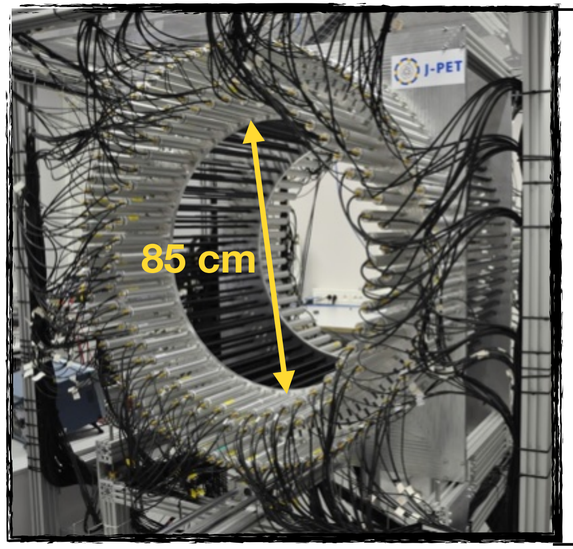

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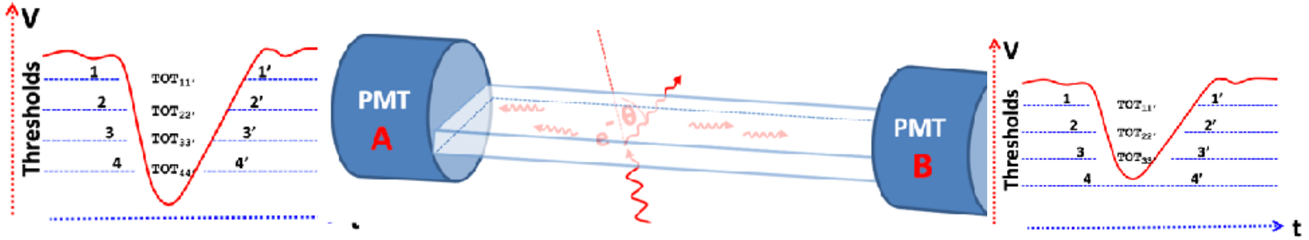
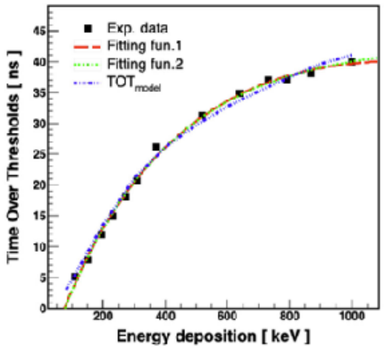
- **T**ime **O**ver **T**hreshold (**TOT**) is used, as a *<u>measure of energy deposition</u>*



$$TOT = \sum_{PMT=A,B} \sum_{Thr_{1-4}}^{TOT_{PMT,Thr}}$$

Sharma et al. EJNMMI Physics (2020) 7:39



- **A dedicated J-PET data analysis framework** : an open source software platform written in C++ , based on ROOT package

  ➡ Signal reconstruction, Calibrations, filtering procedures, event categorization

  ➡ **User-level data analysis** by **accessing** the <u>in-built function</u>

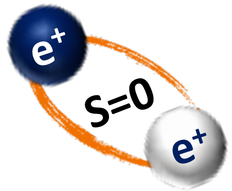
W. Krzemień et al., SoftwareX 11 (2020) 100487

- *Monte Carlo simulations package* based on Geant4-toolkit, adapted to ***simulation of Ps decays events***

Positronium decays and o-Ps lifetime determination

- Electron (e^-) and anti-electron (e^+) can form a quasi-stable bound state called Positronium atom (**Ps**)

Ps can be formed in <u>two ground state :</u>



	Charge conjugation invariance	Lifetime (τ)	Decay rate ($\lambda=1/\tau$)
para-Positronium ($^1S_0$)	$(-1)^{l+s}$ = *1* => *even no. of photons*	**0.125 ns**	**7.9852** $1/\mathrm{ns}$
ortho-Positronium ($^3S_1$)	$(-1)^{l+s}$ = *-1* => *odd no. of photons*	**142 ns**	**7.039979(11) μs^{-1}**

[2]Adkins, Fell, Sapirstein Ann. Phys. 2002

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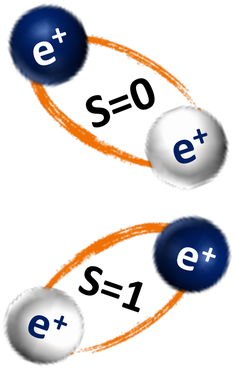

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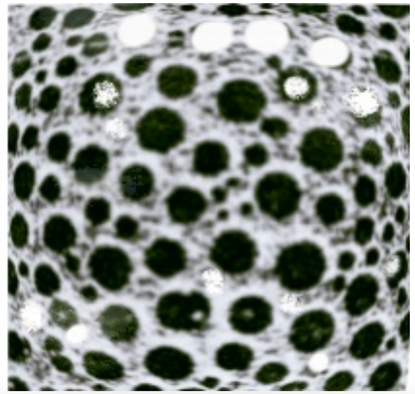
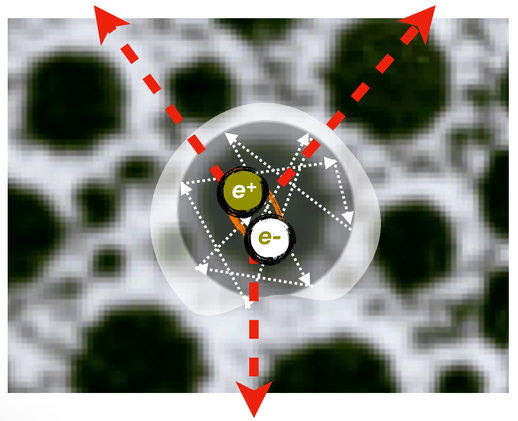
Ortho-positronium lifetime in porous material :

In matter, o-Ps lifetime can be shortened due to the interaction of the positron with electrons from the material (pick-off process) or para-magnetic molecule (conversion).

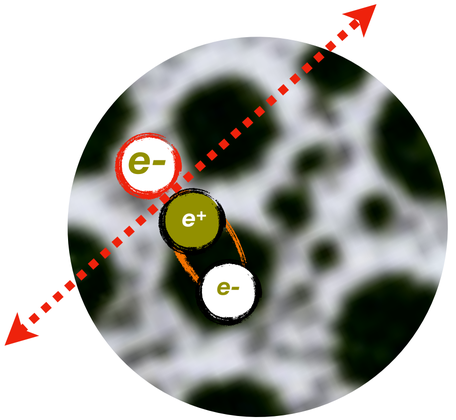
$$\lambda_{exp}(t) = \lambda_{o-Ps} + \lambda_{pick-off}(t)$$



Porous material



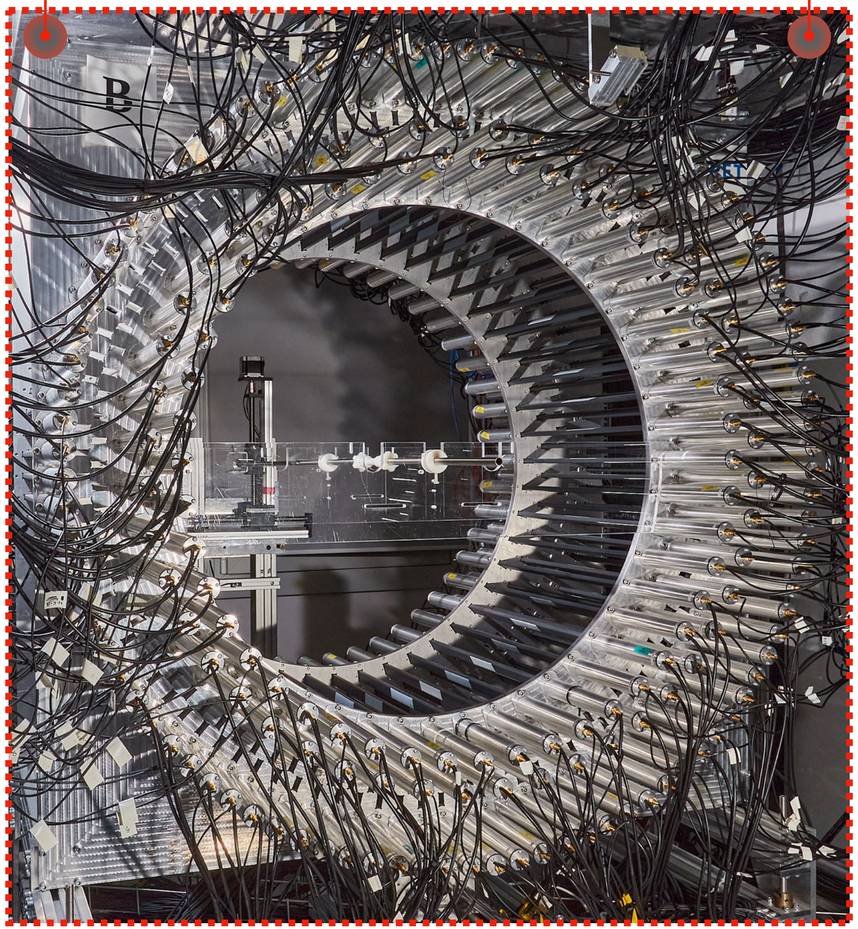
o-Ps decay



Pick-up process

Ortho-positronium decay rate determination with J-PET

Jagiellonian Positron Emission Tomography



J-PET as multi-photon detector

J-PET: P. Moskal et al., Nature Communications 12 (2021) 5658

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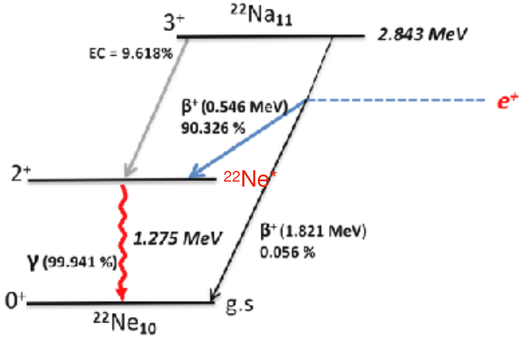
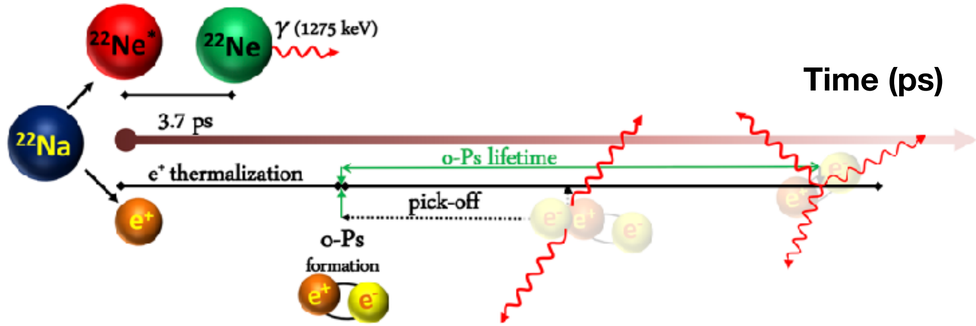
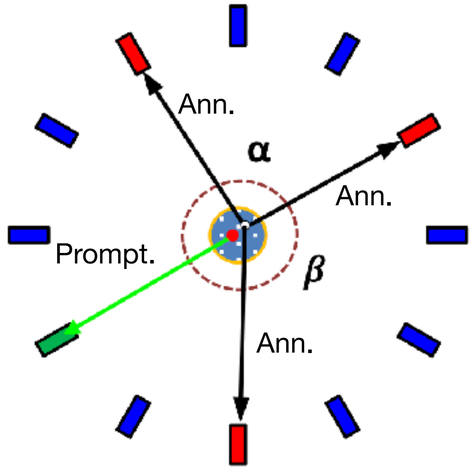
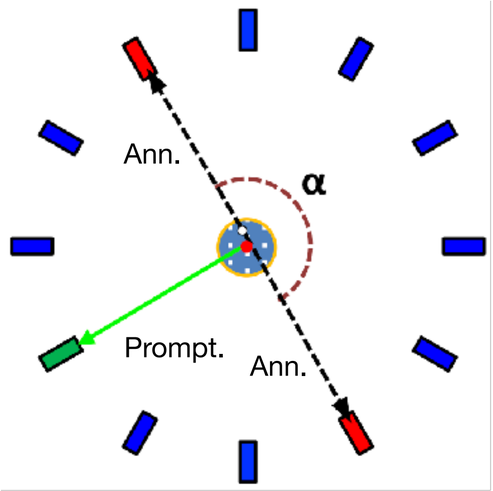
^{22}Na source is placed inside the plastic chamber sandwiched between **XAD4 porous** material





Events defintion :





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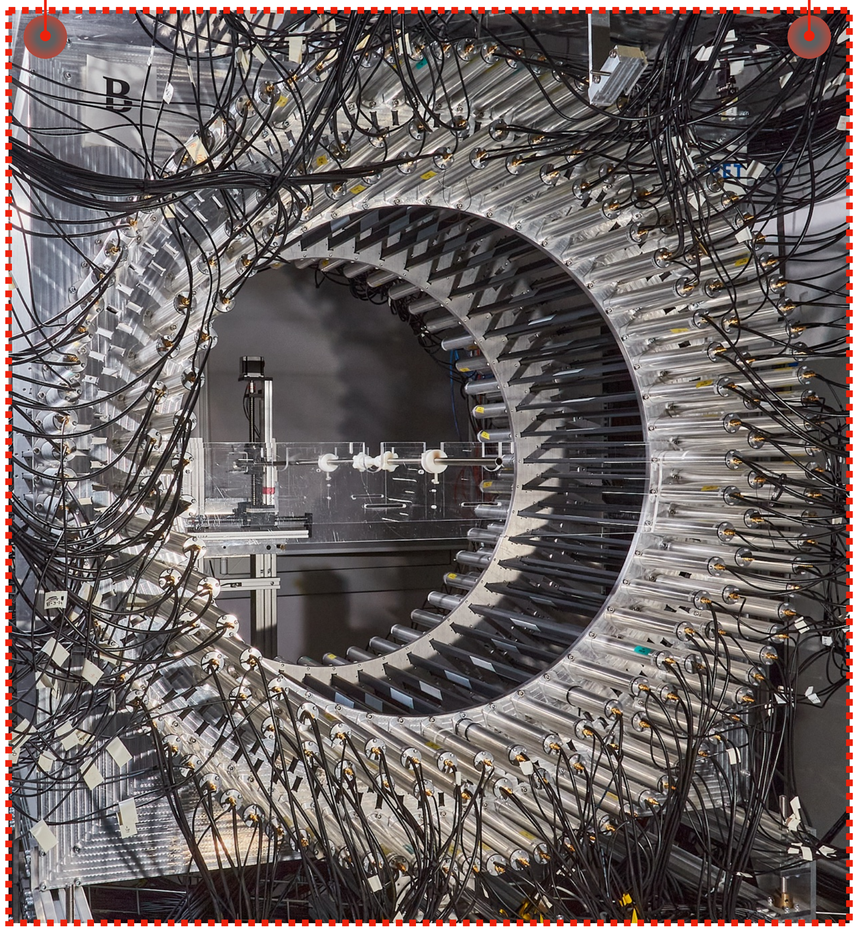

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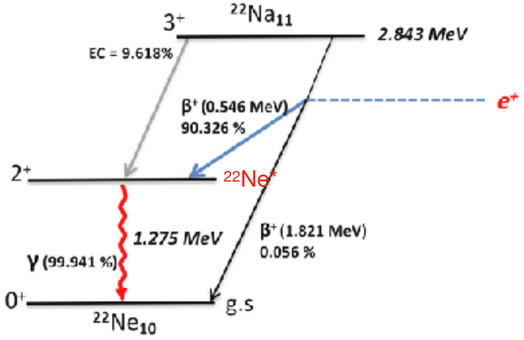

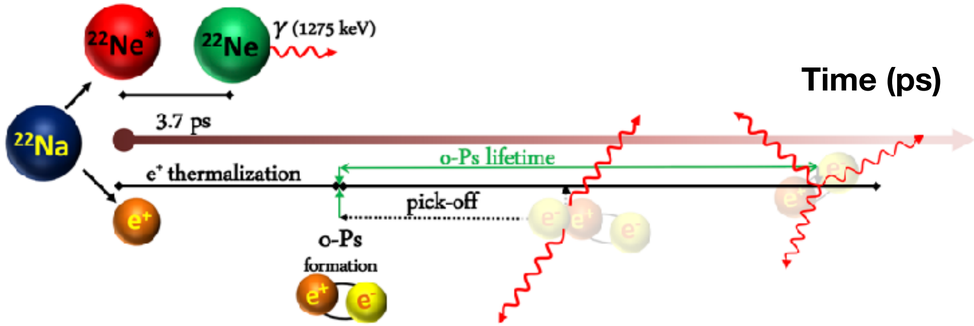

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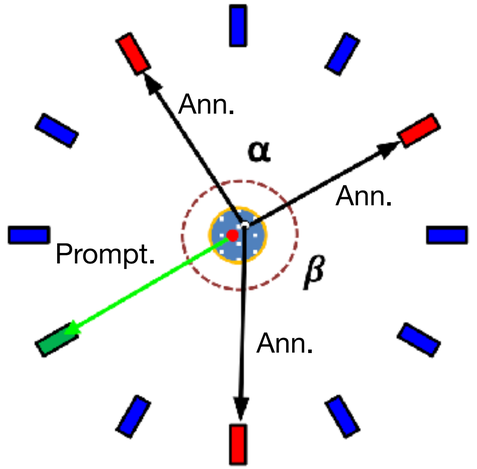
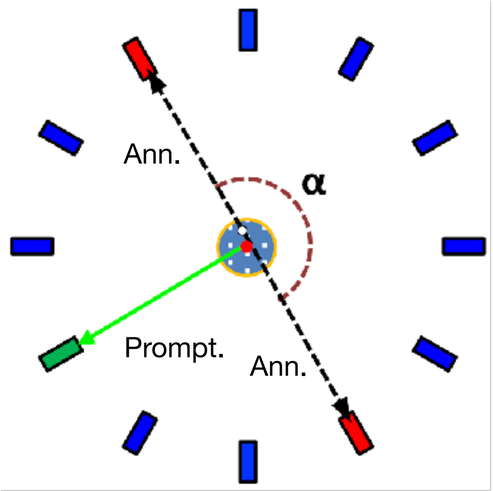


4-hit events
1 Prompt + 3 annihilations (o-Ps)



3-hit events
1 Prompt + 2 annihilations (B2B)

Scheme for analysis procedure

1. Selection of **prompt** and **annihilation** candidates based on Time Over Threshold (**TOT**) values.

TOT *is the measure of energy deposition**

*J-PET: EJNMMI Phys. 7, 39 (2020)

2. Distance of reconstructed annihilation **plane (3g)** / **point (2g)** from the center

3. **Time difference** between the registered annihilation photons

4. Angular correlation of the registered annihilation photons

Lifetime measurement

"Results presented are from ***25% of the total data measured*** using small chamber "

Positronium decay rate - analysis cuts

4-hit events

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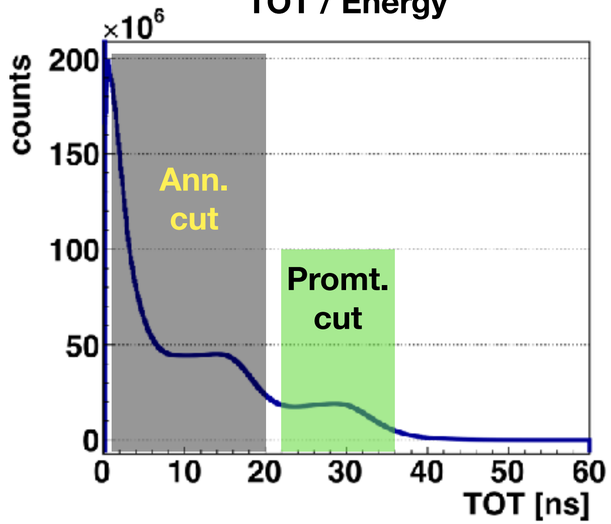
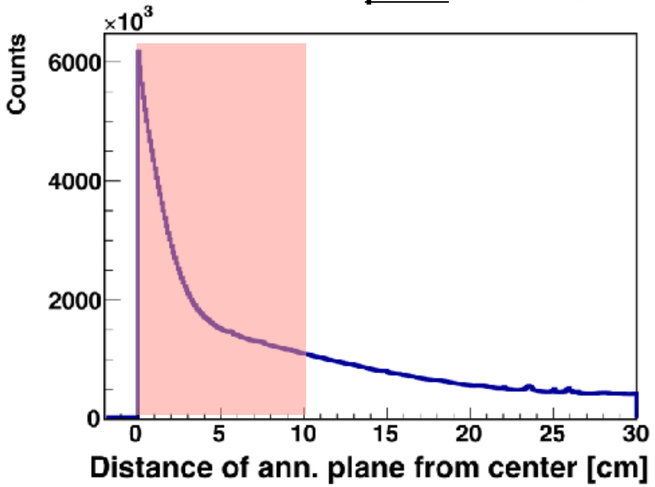
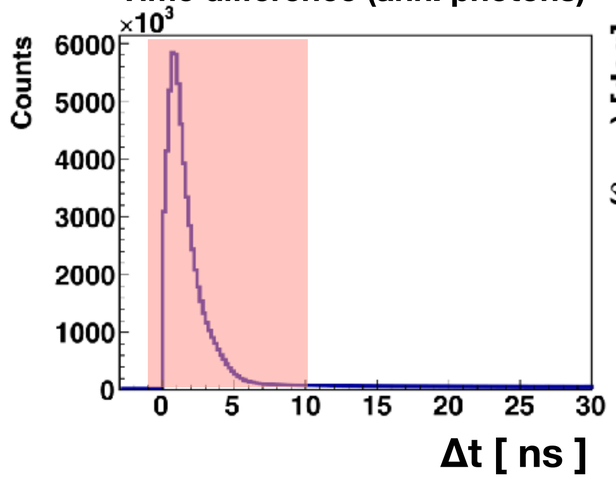
TOT / Energy



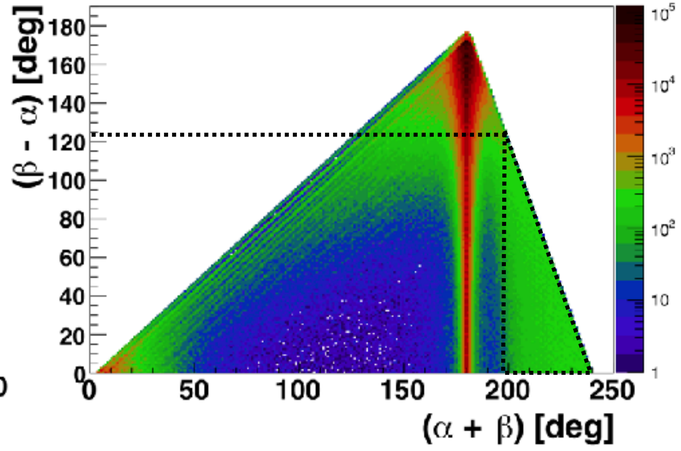
Annihilation plane distance



Time difference (ann. photons)



Sum of two smallest angles vs diff.



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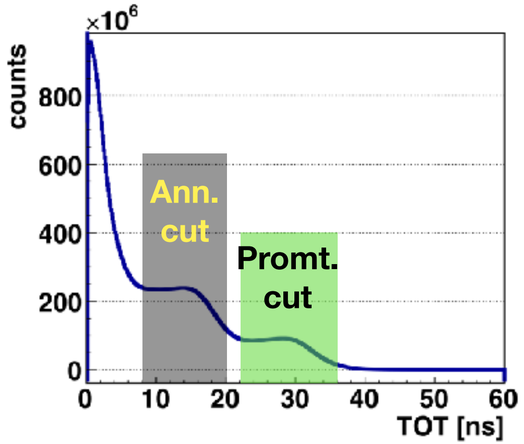
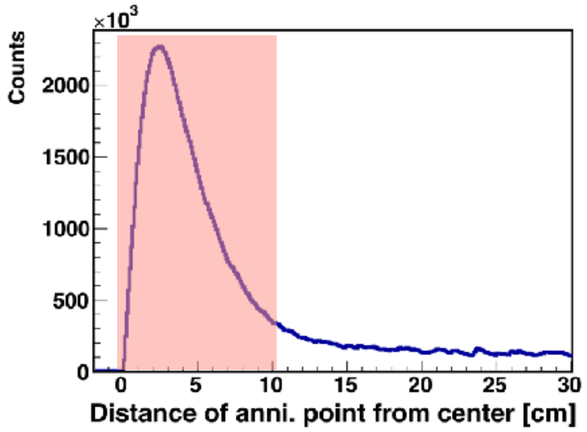


Annihilation point distance



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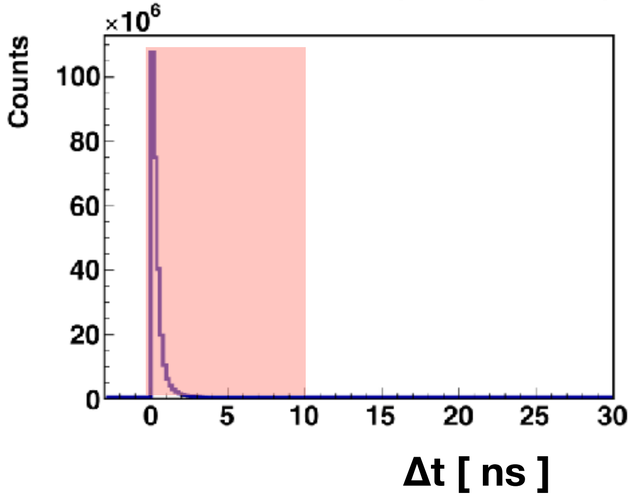


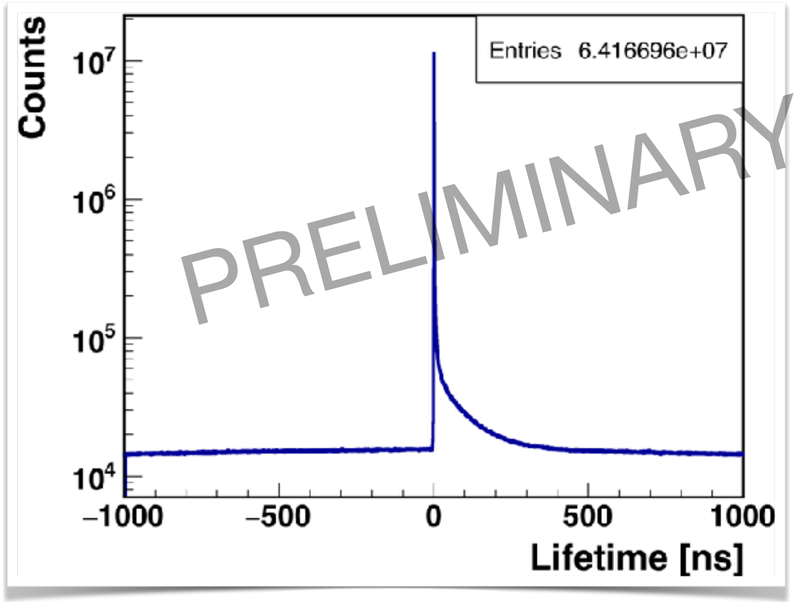
LifeTime spectra

Experimental

3-hit events

1 Prompt + 2 annihilations (B2B)

LT (2g)



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1 Prompt + 3 annihilations (o-Ps)

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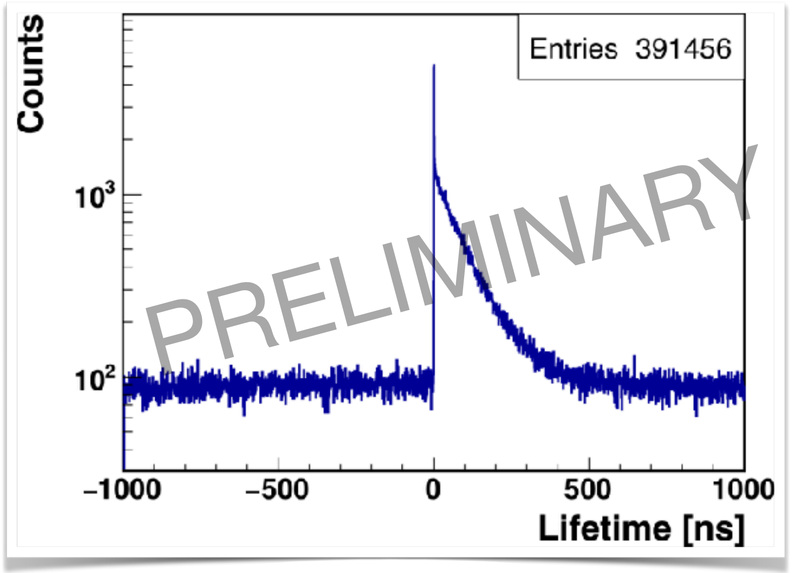

LifeTime spectra

Experimental

Simulated

using J-PET geant4 package*

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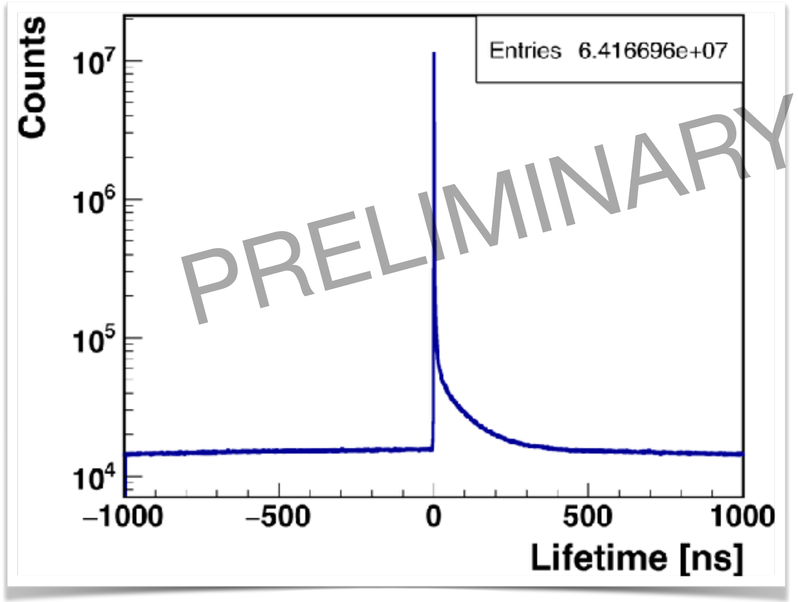

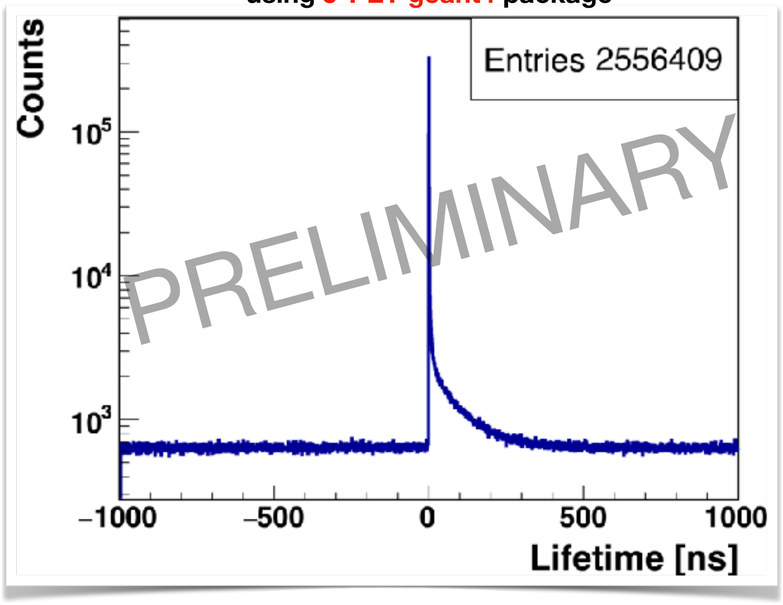

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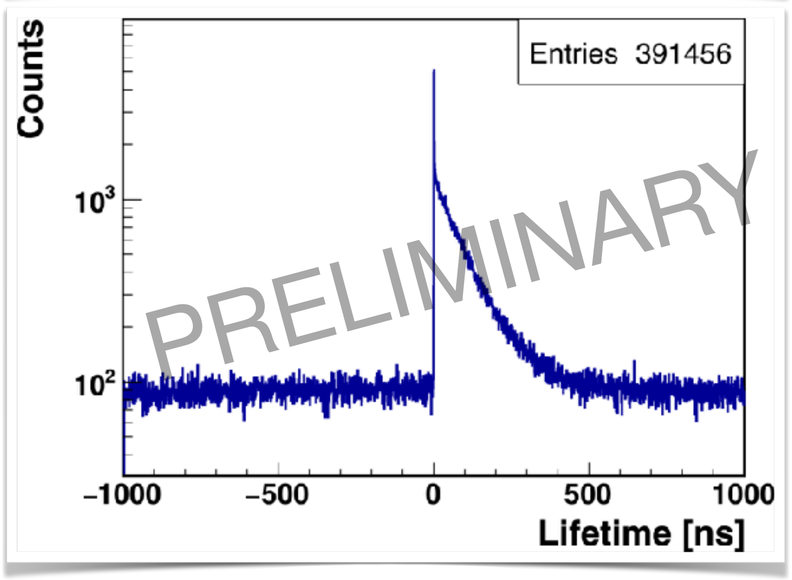
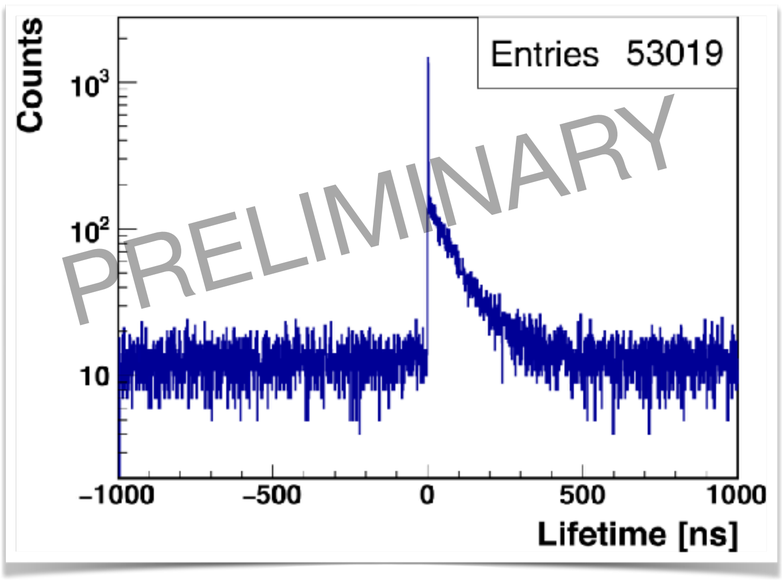
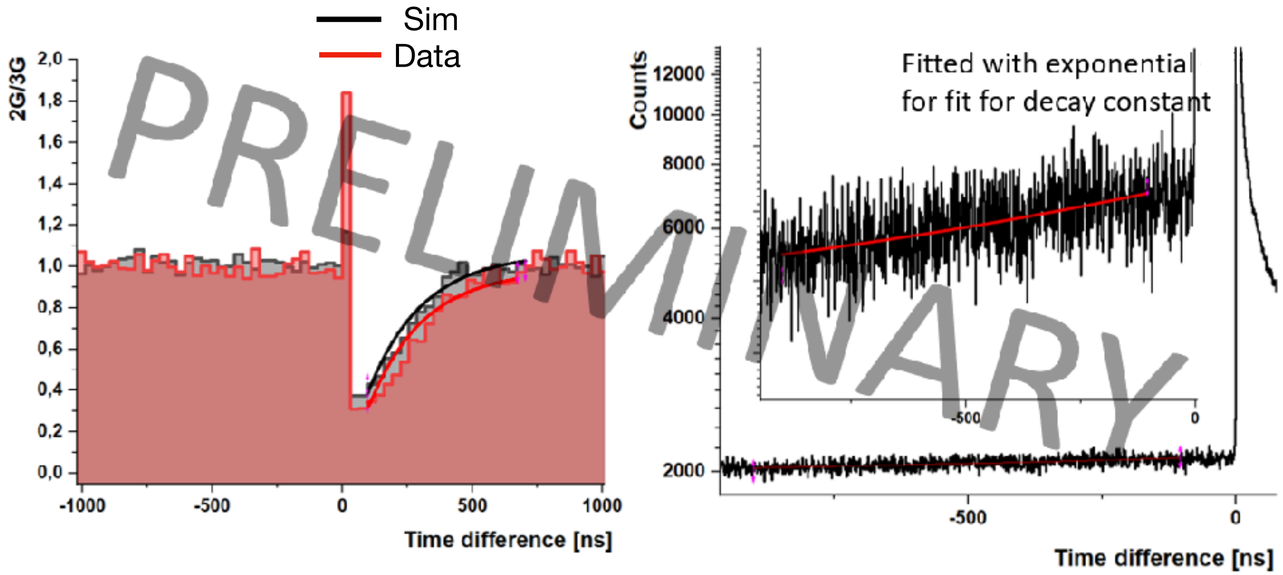




o-Ps lifetime determination using J-PET : preliminary results



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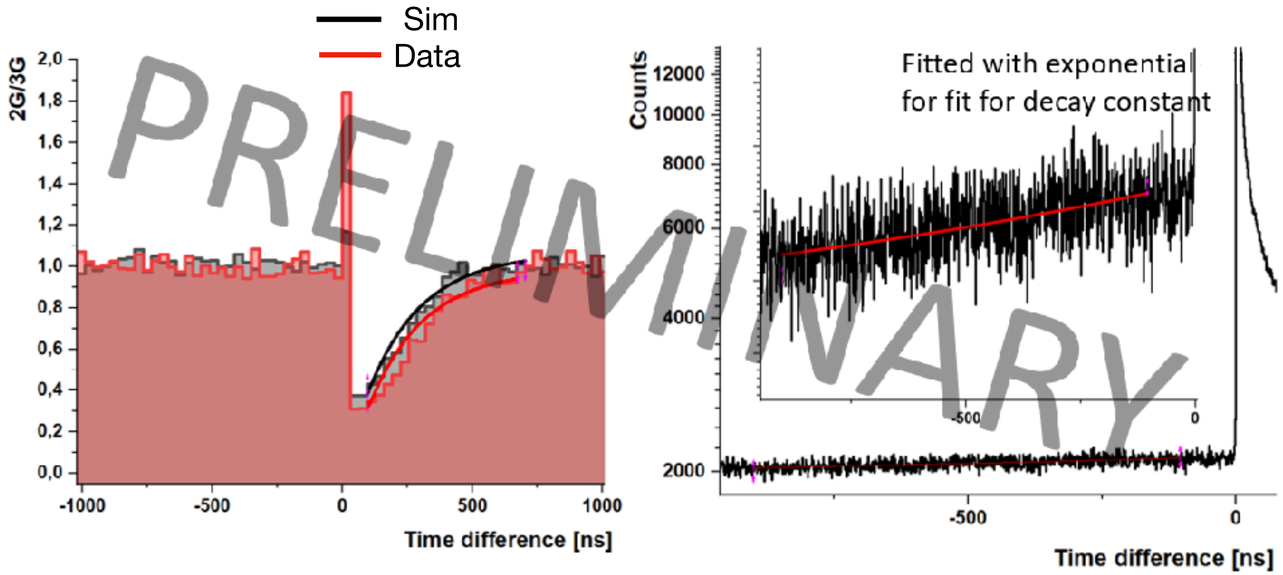

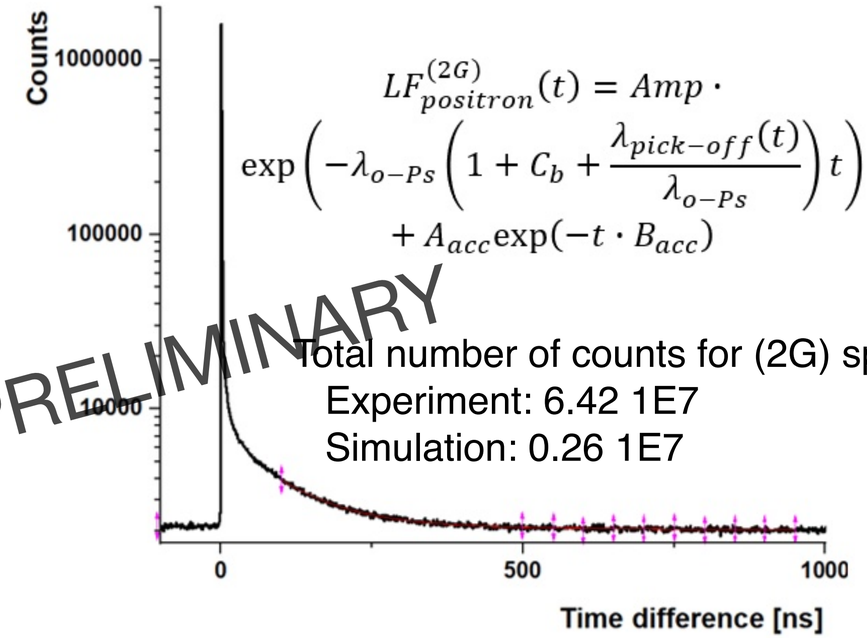

$$LF^{(2G)}_{positron}(t) = Amp \cdot \exp\left(-\lambda_{o-Ps}\left(1 + C_b + \frac{\lambda_{pick-off}(t)}{\lambda_{o-Ps}}\right)t\right) + A_{acc}\exp(-t \cdot B_{acc})$$

Total number of counts for (2G) spectrum
Experiment: 6.42 1E7
Simulation: 0.26 1E7

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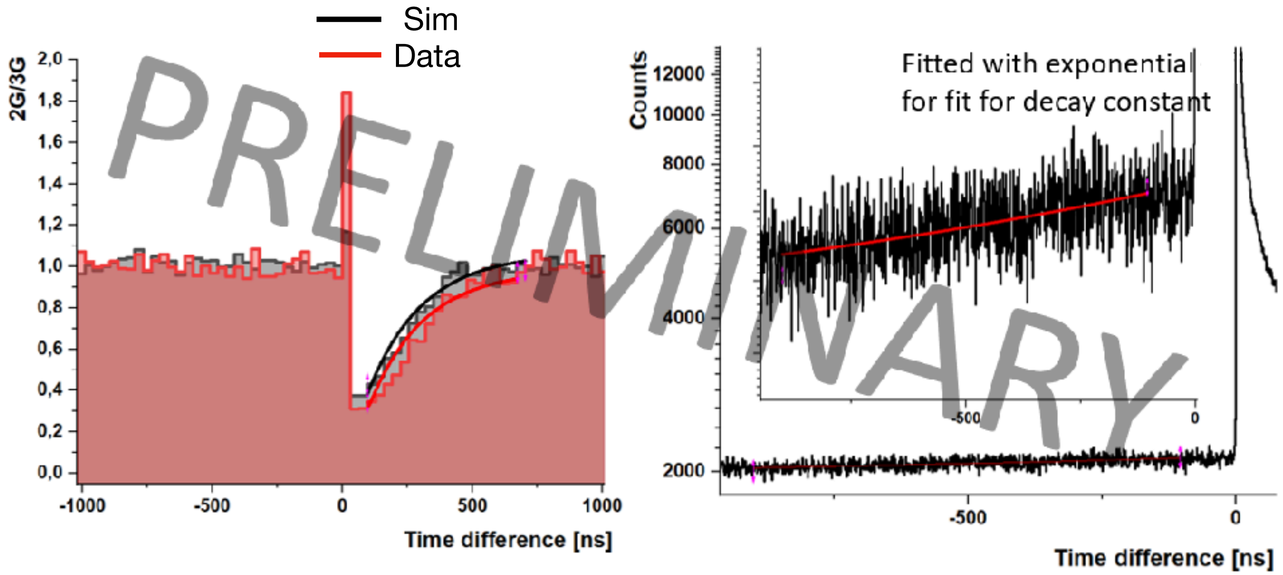

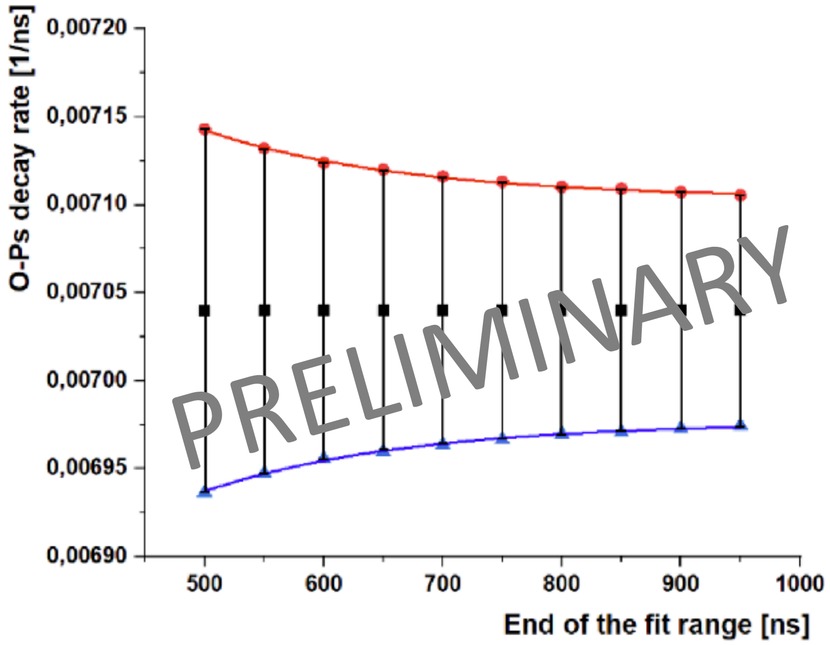

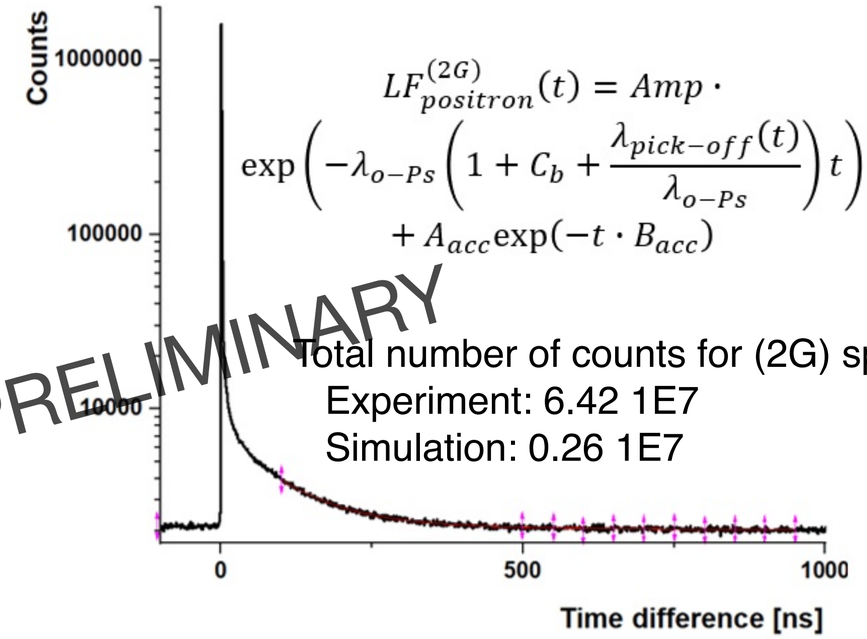

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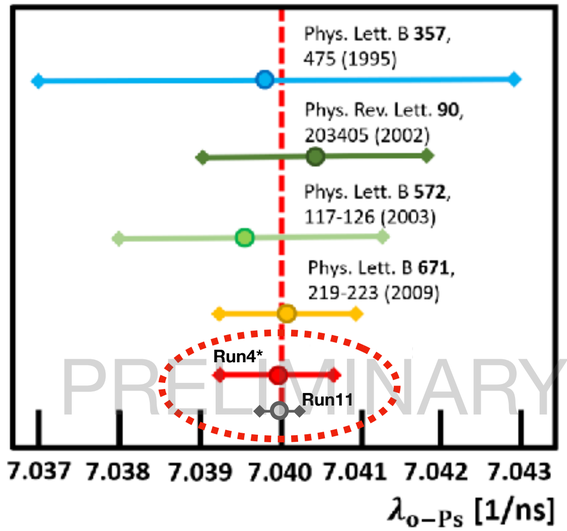
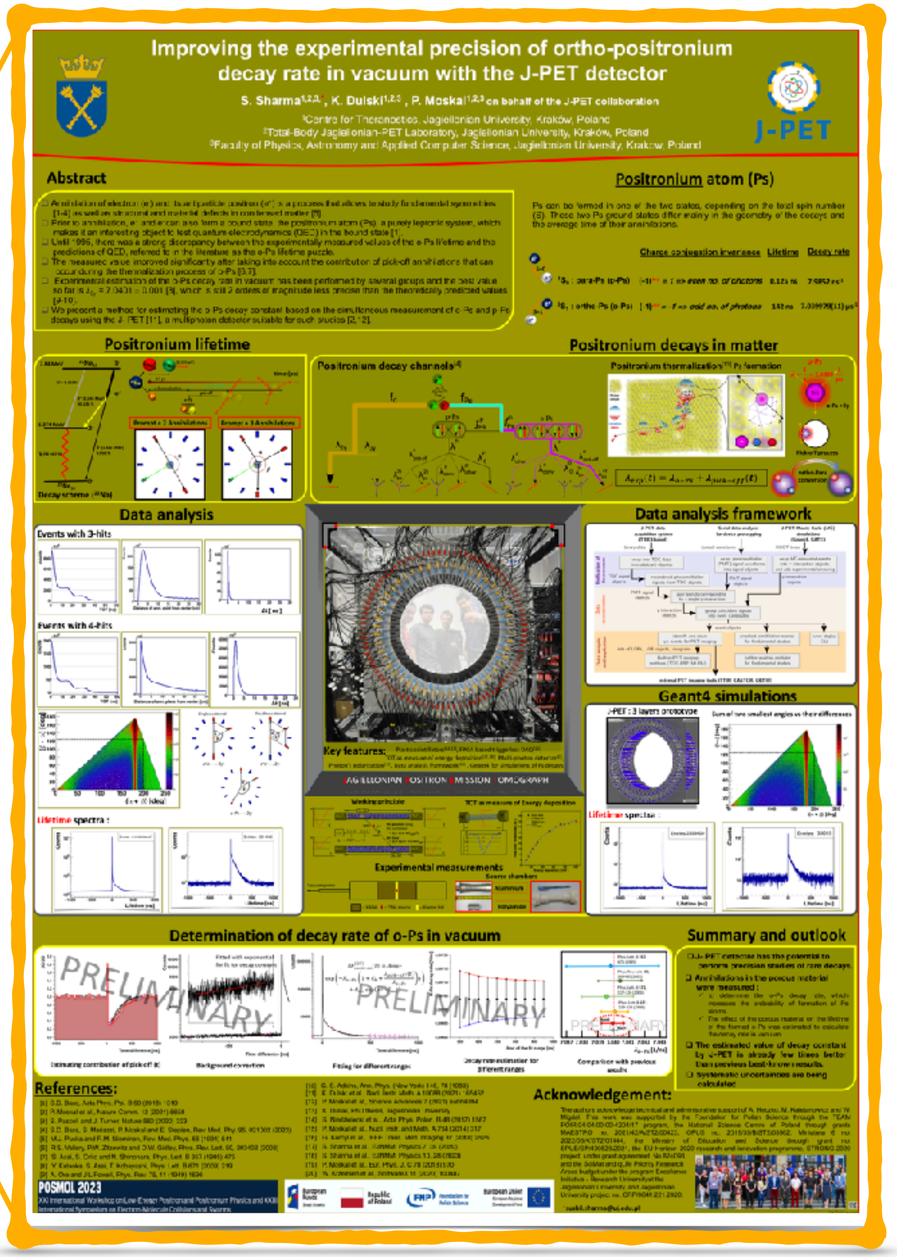


*J-PET, K. Dulski (PhD thesis)

o-Ps lifetime determination using J-PET : preliminary results

Poster 42



Thank you on behalf of the J-PET collaboration

http://koza.if.uj.edu.pl/

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universität wien

Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
ŚWIERK
JRC collaboration partner

The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences

Summary and conclusions

- The J- PET detector, with its ability to simultaneously register multiphoton events, has the potential to perform precision studies of rare decays.

  S. D. Bass, S. Mariazzi, P. Moskal, E. Stępień, Rev. Mod. Phys. 95 (2023) 021002

- Annihilations in the porous material were measured
  - ✓ to determine the o-Ps decay rate, which increases the probability of formation of Ps atoms.
  - ✓ The effect of the porous material on the lifetime of the formed o-Ps was estimated to calculate the decay rate in vacuum.

- The estimated value of decay constant by J-PET is already few times better than previous best known results by Kataoka et al.

  "With analysis of full measured data, and increasing the simulation statistics, the results will be further improved".

- Estimation of systematic uncertainty is being calculated.