Precision test with the J-PET detector

NCN grant Nr 2020/38/E/ST2/00112

Elena Perez del Rio on behalf of the J-PET Collaboration

10th International Conference on Quarks and Nuclear Physics

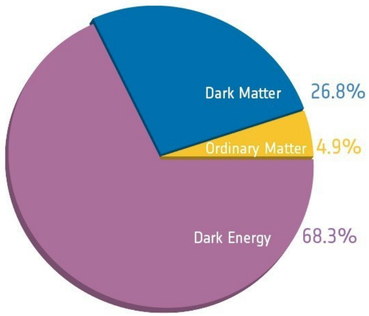
8th - 12th July 2024, Barcelona, Spain

Outline

- Dark Matter fast overview
  - Dark Photon
- Mirror Matter (MM)
  - Mirror Matter in ortho-Positronium
- J-PET (Jagiellonian PET Tomograph)
- Studies using J-PET:
  - Search of MM
  - Dark Photon
  - Rare and forbidden decays of ortho-Positronium
- Conclusions

Dark Matter

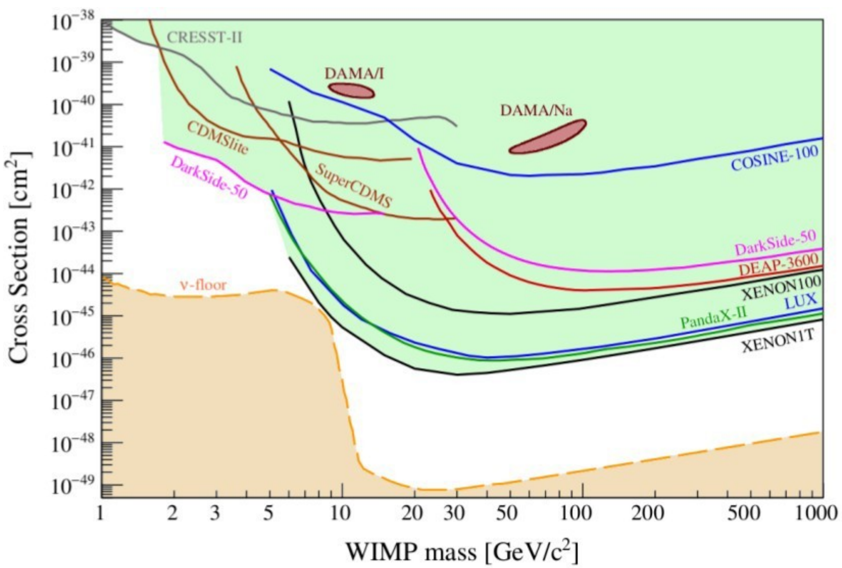
The Dark Matter Nature



- Is Dark Matter (DM) a new particle?
- Constraint on DM mass and interactions
  - should be ‘dark’ (no e.m. interaction)
  - should weakly interact with SM particles
  - should provide the correct relic abundance
  - should be compatible with CMB power spectrum

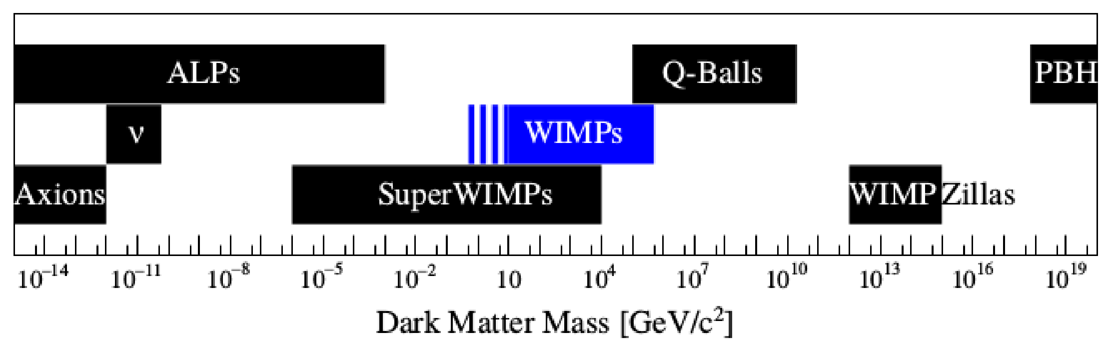
Standard Model reminder:

$SM = U(1)_{EM} \times SU(2)_{Weak} \times SU(3)_{Strong}$



arXiv:1903.03026

arXiv:1903.03026

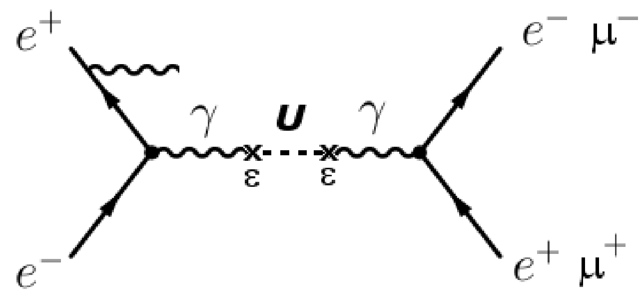


Dark Sector or Hidden Sector (DM not directly charged under SM interactions)

Dark Matter

- "Minimal case": Dark Matter couples to Standard Model (SM) particles through a kinetic mixing term → ***Dark Photon A'*** *(mixes with SM photon)*
  - Decays depending in the mass of the mediator and decaying products

$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{EM}_{\mu\nu} F^{\mu\nu}_{DM}$$



- DM is a new type of matter → The DM has two possible scenarios
  - DM interacts with the same forces as in SM
  - DM interacts through **new forces**

- Not need to introduce new interactions
  - Super-symmetric candidates: AXIONS

- **Mirror Matter**

Mirror Matter

Let's do precision physics

- Symmetry: feature of the system that is preserved or remains unchanged under some transformation.
- Symmetries in Physics are important → Invariant → Laws of Nature
- Standard Model 3-symmetries: C-, P- and T-symmetry
- Weak interactions violates parity (P).

First experimental confirmations:

C. S. Wu et al.
Phys. Rev. 105 (1956) 1413

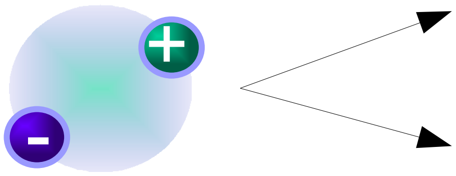
R. L. Garwin, L. Lederman and R. Weinrich
Phys. Rev. 104 (1956) 254

- Mirror Matter (or Alice Matter) was proposed as an explanation of Parity symmetry violation [T.D., Yang C. N. Phys. Rev. 1956. V. 104. P. 254.]
  - Each particle has a mirror partner with the same properties and opposite chirality (left/right - handed)
  - Mirror particles interact with normal matter mainly through gravity → **DM candidates**
  - γ − mirror γ' interaction via kinetic mixing

$$\mathcal{L}_{\gamma\gamma'} = -\epsilon F^{\mu\nu} F'_{\mu\nu}$$

Orthopositronium

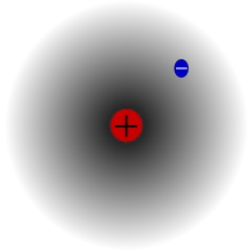
Positronium (Ps)



$^1S_0$ **Para-positronium**
τ (p-Ps) ≈ 125 ps

$^3S_1$ **Ortho-positronium**
τ (o-Ps) ≈ 142 ns

Hydrogen atom ^1H:



S. Bass Acta Phys. Pol. B 50 no7 (2019) 1319

Ps pure leptonic system:

- Clean experimental system (**no background**)
- **Lifetime accurately described** with Quantum Electrodynamics (QED) **theory**

$$\Gamma(o-Ps \to 3\gamma, 5\gamma) = \frac{2(\pi^2-9)\alpha^6 m_e}{9\pi}\left[1 + A\frac{\alpha}{\pi} + \frac{\alpha^2}{3}\ln\alpha + B\left(\frac{\alpha}{\pi}\right)^2 - \frac{3\alpha^3}{2\pi}\ln^2\alpha + C\frac{\alpha^3}{\pi}\ln\alpha + D\left(\frac{\alpha}{\pi}\right)^3 + \ldots\right]$$

Theory QED prediction

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

Experimental values

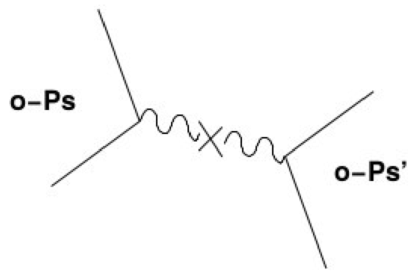
$$\Gamma = 7.0401 \pm 0.0007 \times 10^6\,\mathrm{s}^{-1}$$ Tokyo group

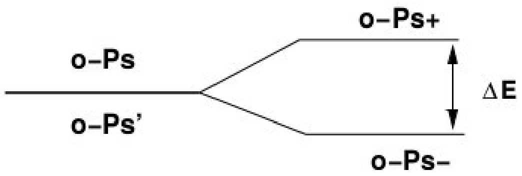
$$\Gamma = 7.0404 \pm 0.0010 \pm 0.0008 \times 10^6\,\mathrm{s}^{-1}$$ Ann Arbor group

Theory predictions 100 times more precise:
10^{-6} vs 10^{-4}

Mirror Matter in o-Ps

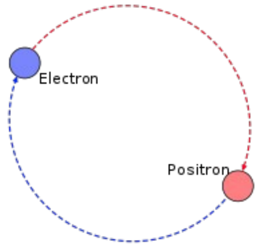
- o-Ps can be connected via one-photon annihilation to its mirror version (o-Ps’) and can be confirmed in experiments
  - o-Ps oscillates into its mirror partner o-Ps’
  - Only mimicked by very-rare decay from Standard Model Br(oPs→ $\nu\bar{\nu}$) < O(10^{-18})
  - **Precision measurements of the o-Ps decay rate and compare it to QED calculations.**
  - **NCN grant Nr 2020/38/E/ST2/00112**



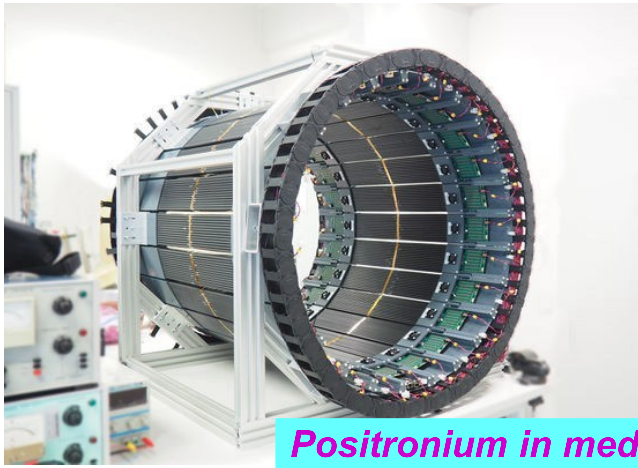


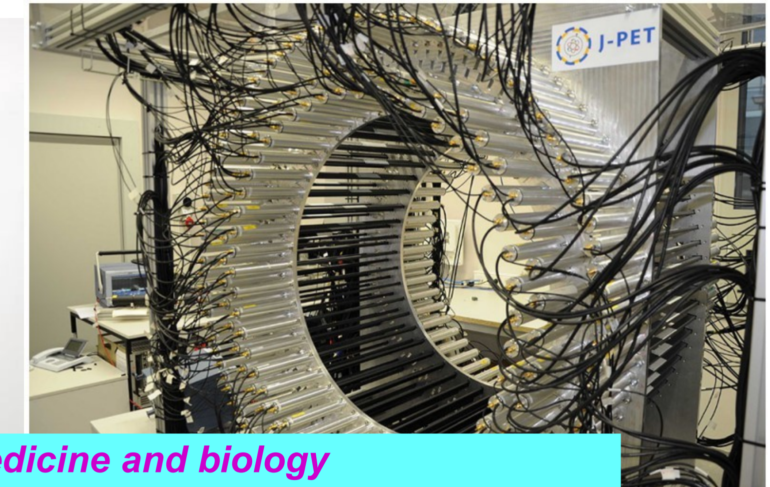
[P. Crivelli et al 2010 JINST 5 P08001]

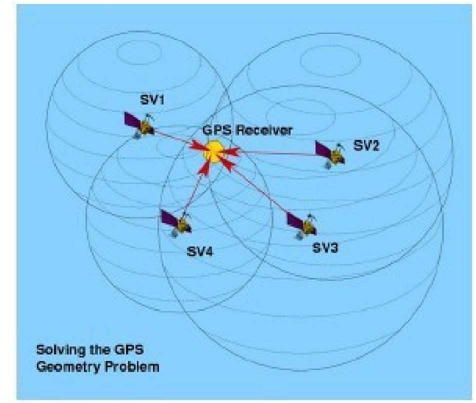
The o-Ps’ → invisible decay would manifest as an increase of the observed lifetime respect to the expected value → Precision measurement of the o-Ps lifetime



J-PET (Jagiellonian-PET TOMOGRAPHY)







Positronium in medicine and biology
Moskal, P., Jasińska, B., Stępień, E.Ł., and S. Bass.
Nature Reviews Physics 1, pages 527-529 (2019)

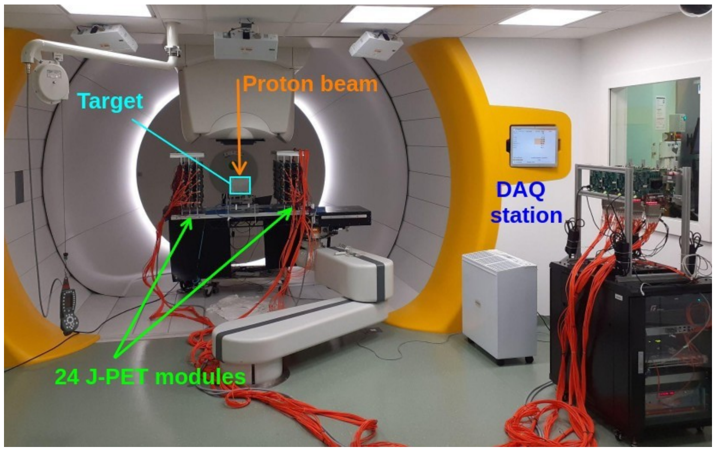
Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography
P. Moskal, A. Gajos et al
Nature Communications 12 (2021) 5658

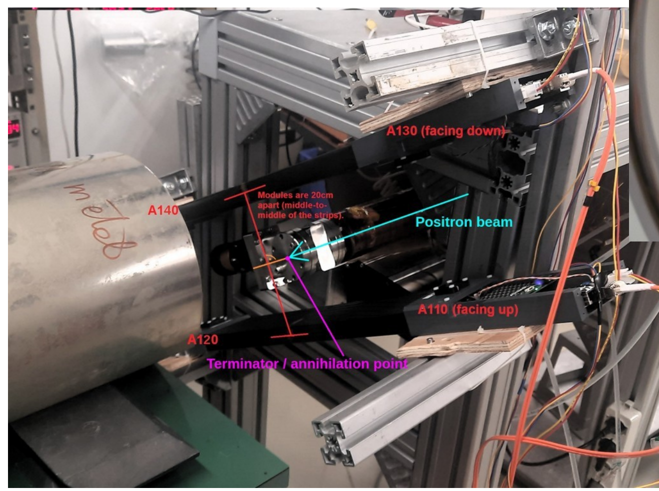
Positronium imaging with the novel multiphoton PET scanner
Moskal, P. et al.
Science Advances 7 (2021) eabh4394

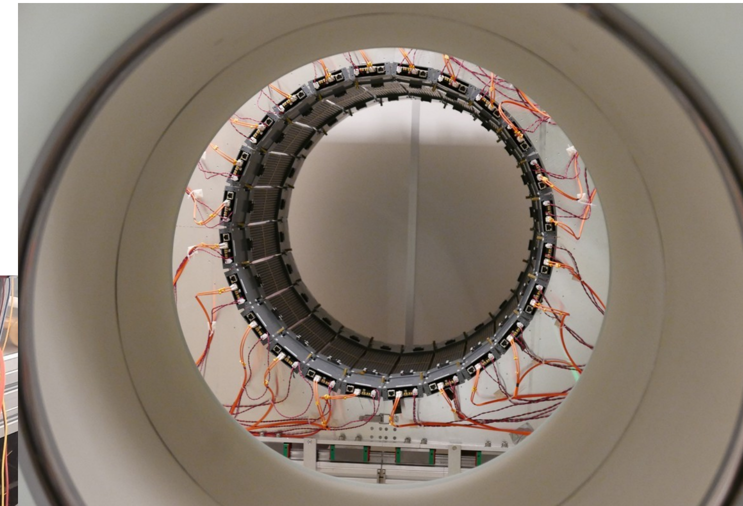
First Positron Emission Tomography scanner built from plastic scintillator

- Multidisciplinary detector
- **Portable/modular detector layer with higher detection probability High**
- **performance detector with high timing resolution**
- High acceptance
- **Trigger-less** and reconfigurable DAQ system
  - **Data has no filters: all data acquired is unfiltered**
- **GPS trilateration** reconstruction of the interaction point

J-PET (Jagiellonian-PET TOMOGRAPHY)



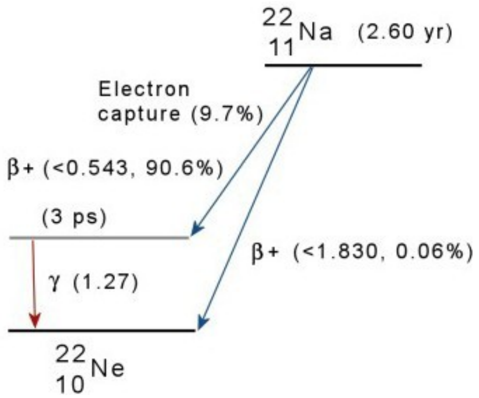




- **NCN grant Nr 2020/38/E/ST2/00112**
- **Mirror Matter search with J-PET detector and rare and forbidden decay studies**
- **New modular design of J-PET**
  - **Modular layer is portable**
  - **Re-configurable and higher efficiency**
  - **Allows future measurements with positron beam**
  - **Measurements already performed at The Cyclotron Centre Bronowice, Trento (INFN), and Warsaw University, and Cracow Hospital**

Mirror Matter in J-PET: Studies

Radioactive source Na



- Source activity 1 MBq = **10^6 e^+/s**
- o-Ps formed in vacuum chamber with probability 29%
- Number of o-Ps after 2 years

10^{13} o-Ps formed

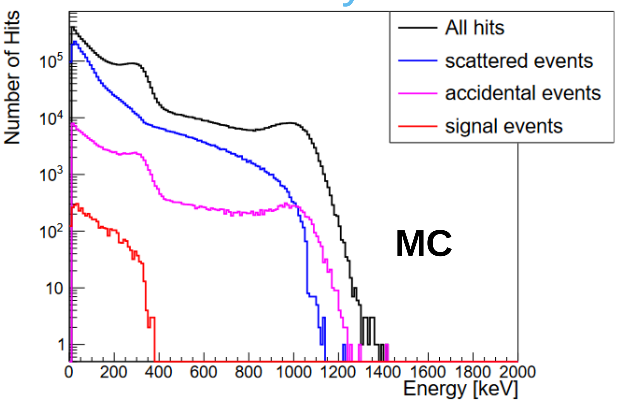
Sensitivity below O(10^{-5})

Photon mixing strength ε < O(10^{-7})

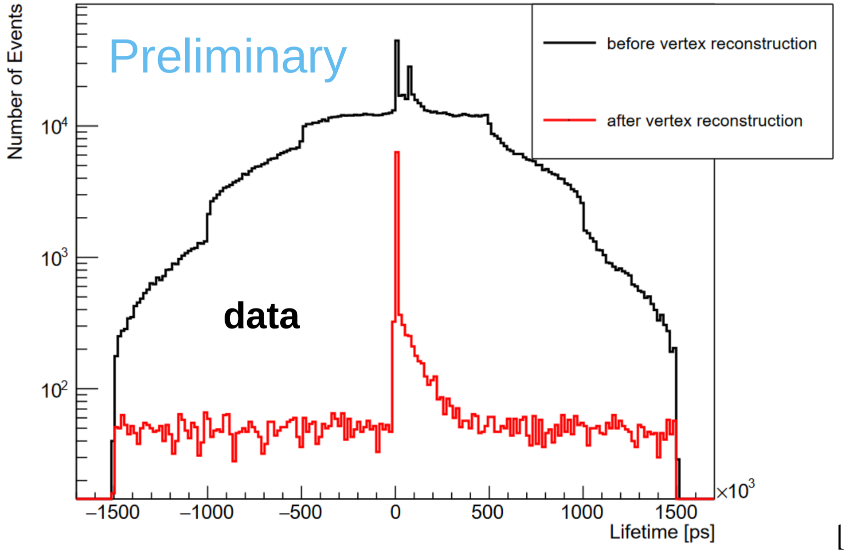
Main competitor ETH Zurich

- [Phys. Rev. D 97, 092008]
  - Slow positron beam (1.5 x $10^4 e^+$/s)

Precise measurement of the o-Ps lifetime looking for hints of new physics



- Run 11 (ongoing) + MC production
- 3 + 1 photon
- Minimum OP angles sum > 190 deg
- Reconstructed vertex inside detector



PhD thesis of **Justyna Mędrala**

Dark Photon with J-PET

- A model involving a dark photon U decaying into υυ or light DM can be explored with the JPET data
- Monte Carlo studies to set the feasibility of the analysis using the J-PET detector
- Contact with theoretitian P. Fayet

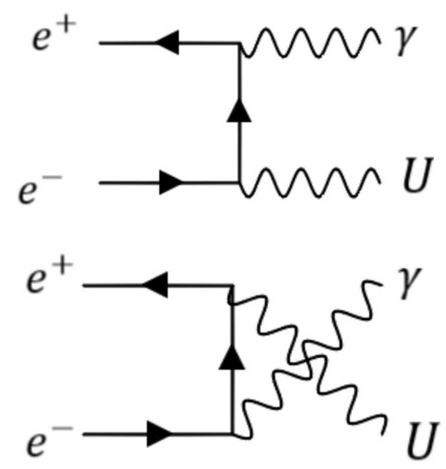
P. Fayet and M. Mezard
Phys. Lett. 104B (1981) 3

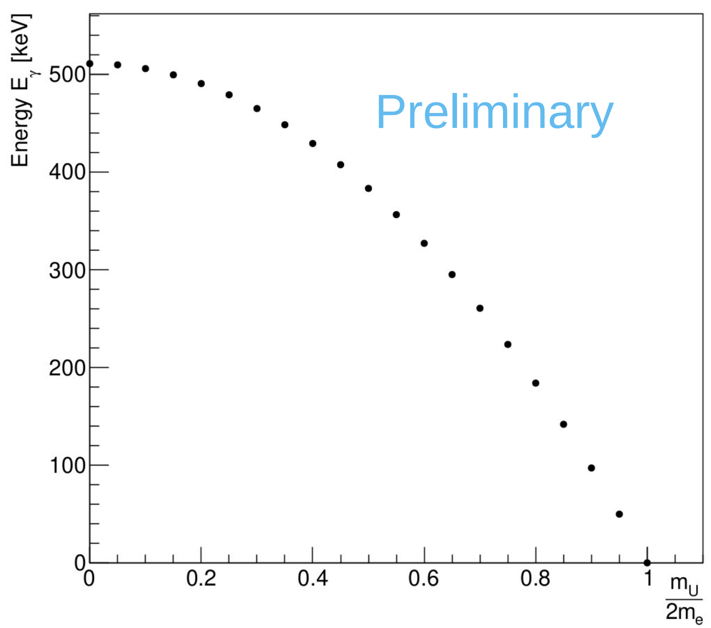
Volume 104B, number 3 PHYSICS LETTERS 27 August 1981

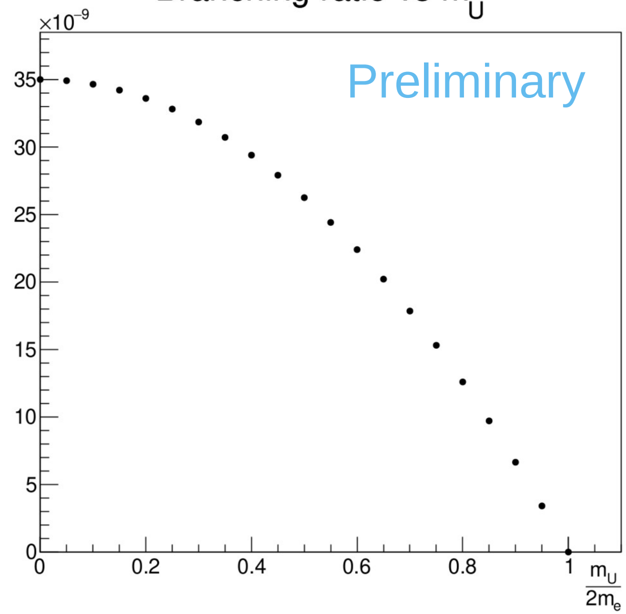
oPs→ U γ

SEARCHING FOR A NEW LIGHT GAUGE BOSON IN qt, T AND POSITRONIUM DECAYS

P. FAYET and M. MEZARD
Laboratoire de Physique Théorique de l'Ecole Normale Supérieure [1], 75231 Paris Cedex 05, France







$$\tau(1^3S_1 \to \gamma U) \simeq [4/(1-x^4)] \;\; s$$

$$x = m_U/2m_e.$$

Master thesis of **Justyna Mędrala**

Acta Phys. Pol. B Proc. Suppl. 17 (2024) 1-A5

Dark Photon with J-PET

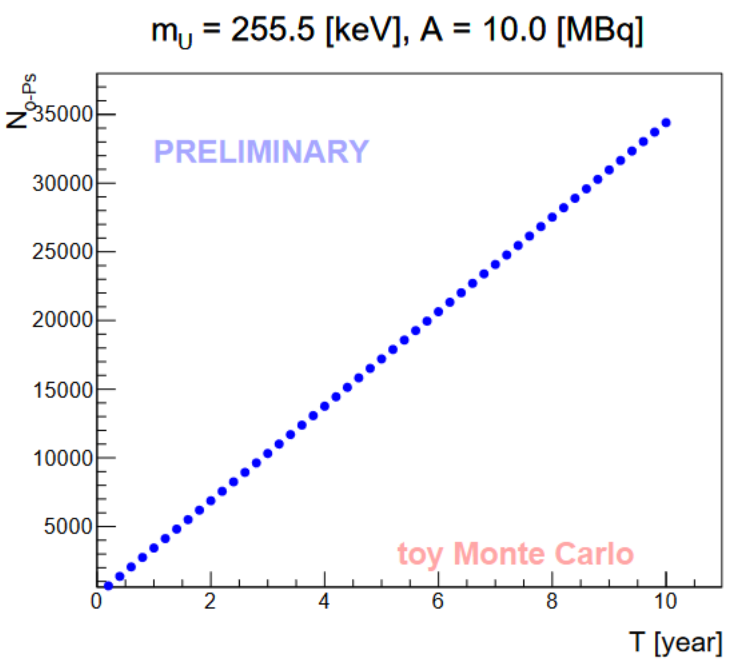
- A model involving a dark photon U decaying into υυ or light DM can be explored with the JPET data
- Monte Carlo studies to set the feasibility of the analysis using the J-PET detector

P. Fayet and M. Mezard
Phys. Lett. 104B (1981) 3

Acta Phys. Pol. B Proc. Suppl. 17 (2024) 1-A5

PRELIMINARY

	m_U [keV]	0.0	255.5	511.0	715.4
efficiency %	geometric	70.71			
	detection	17.47	17.90	19.41	22.12
	contribution from deposited energy	74.52	72.00	61.18	0.75
	contribution from the time window (t_{shitf} = 200 ns, t_{acc} = 50 ms)	1.24			
	total efficiency %	0.114	0.113	0.104	0.001



- Background simulation and rejection can be refined
- Full detector response to be incorporated

Master thesis of **Justyna Mędrala**

Rare decays of the oPs

- JPET **trigger-less acquisition** ensures all data taken is unfiltered
- These decays are practically **background free**
- Selection of the events is similar to the case of 3 gamma events
  - Reduction of systematic uncertainties normalizing to 3 gamma decay

•**NCN grant Nr 2020/38/E/ST2/00112**

Ph.D. thesis of **Pooja Tanty**

C-symmetry test

(o-Ps -> 4γ)/(o-Ps -> 3γ) < 3.7 x 10^{-6} (90% C.L.)
[S. J. Freedman P. A. Vetter. Phys. Rev. A 66 (2002) 052505]

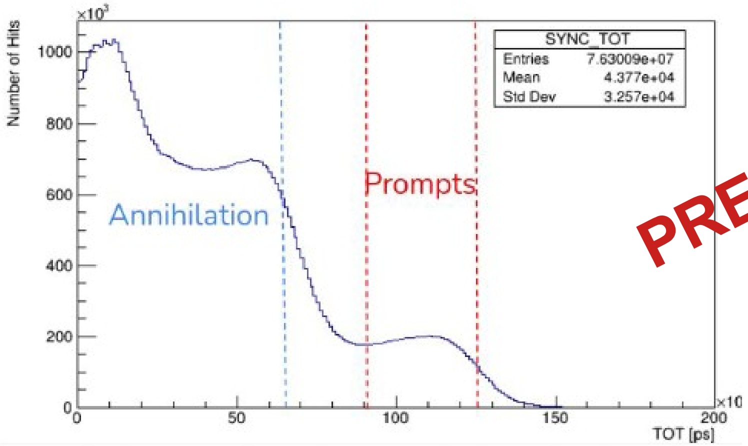
Previous limit (1996) < 2.6 x 10^{-6} (90% C.L.)
[Yang et al., Phys. Rev. A 54, 1952 (1996)]

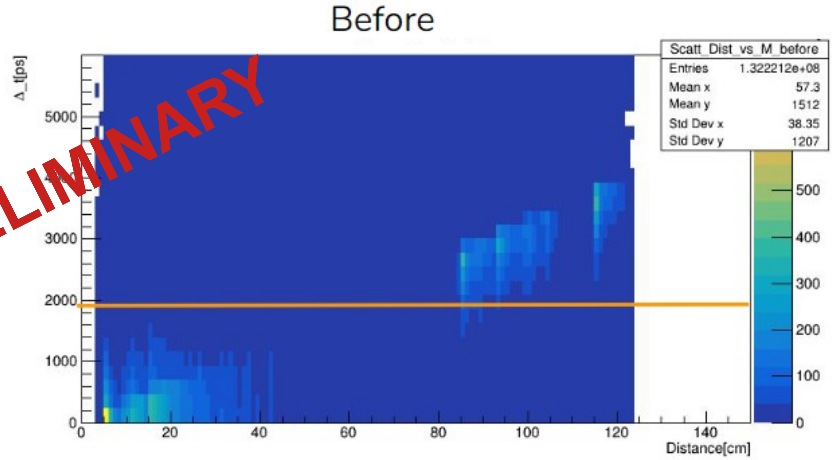
QED test

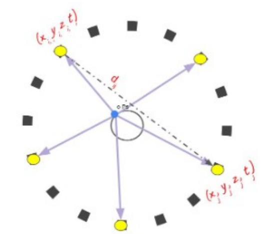
(O-Ps -> 5g)/(O-Ps -> 3g) = 1.67(99)(37) x 10^{-6}
[S. J. Freedman P. A. Vetter. Phys. Rev. A 66 (2002) 052505]

QED value(tree) = 0.9591 x 10^{-6}

Previous (1 event, '95) = 2.2(2.2) x 10^{-6}
[Matsumoto et al., Phys. Rev. A 54, 1947(1996)]







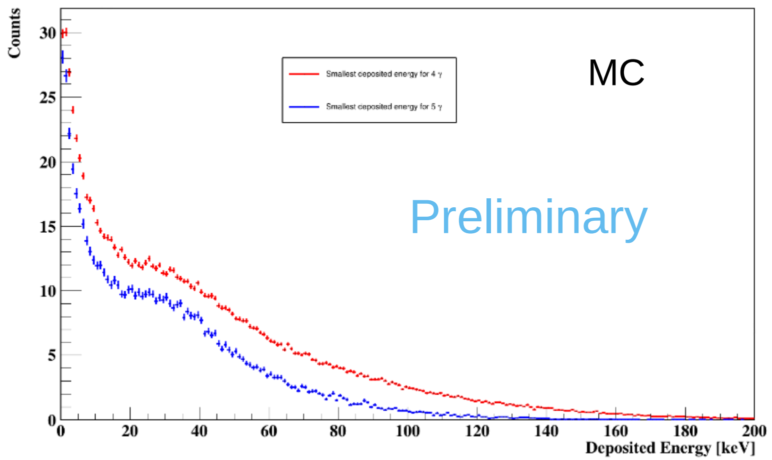
Distance $d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}$

Run11 data

Rare decays of the oPs

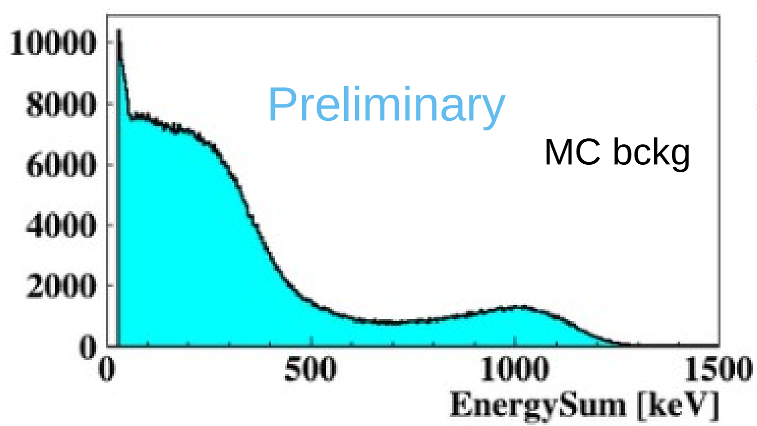
- **simplified Monte Carlo simulations for 4- and 5-gamma decay**
  - **5-gamma decay GEANT4 J-PET MC ongoing**
- Data analysis on-going
- Efficiencies studies
- Background characterization for Machine Learning algorithms separation

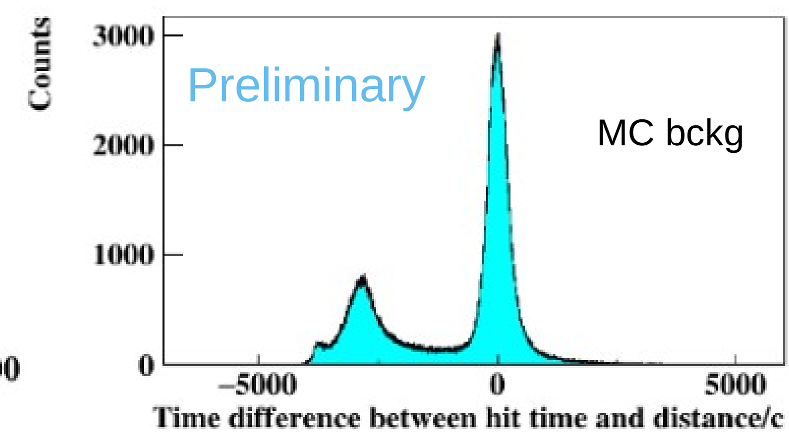
Ph.D. thesis of **Pooja Tanty**



Acta Phys. Pol. B Proc. Suppl. 17 (2024) 1-A9

Relative eff. (in %)	$4\ \gamma$	$5\ \gamma$
ϵ_{geo}	11.75	5.9
ϵ_{det}	0.34	0.15
ϵ_{reg}	31.8	17.39
Total Eff. (in frac.)	$4\ \gamma$	$5\ \gamma$
$\epsilon_{reg}{}^*\epsilon_{det}{}^*\epsilon_{geo}$	1.3×10^{-4}	1.6×10^{-5}

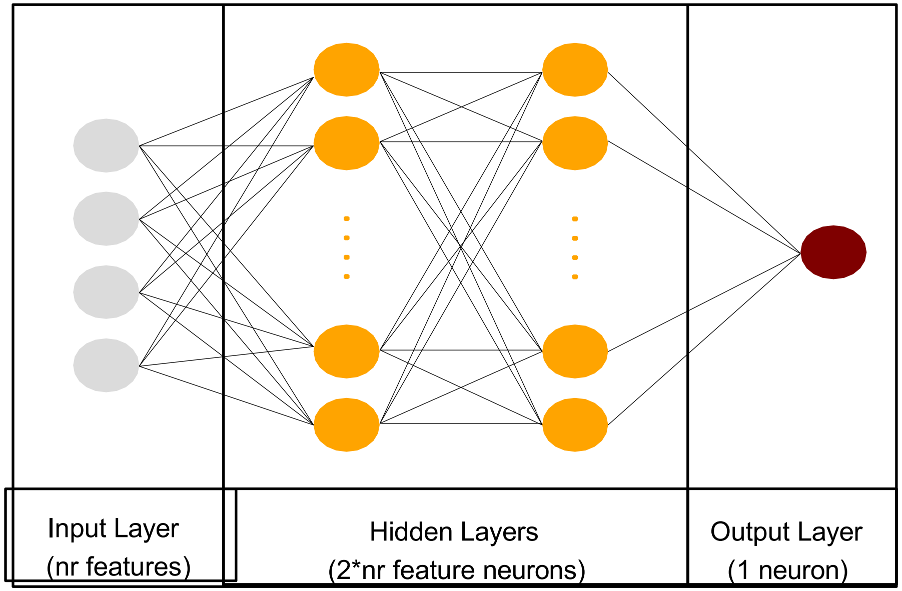




Background suppression using Machine Learning (ML)

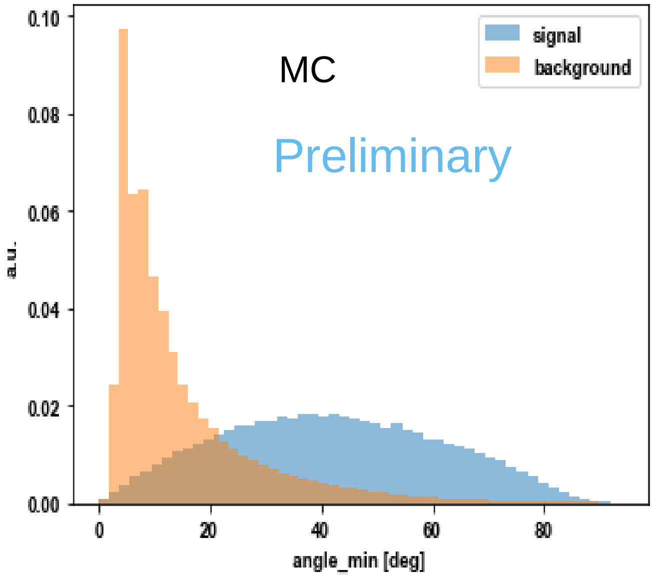
Multiphoton decays background dominated by 2-gamma and 3-gamma events w/w.o prompt and/or w/w.o. scattered photons plus the random coincidences/
S/B enhancement searched.
Features = observables to discriminate

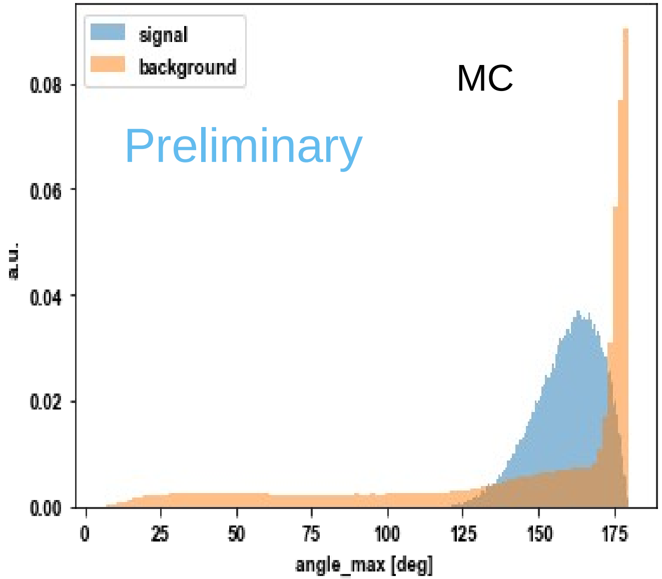
In collaboration with **W. Krzemien**

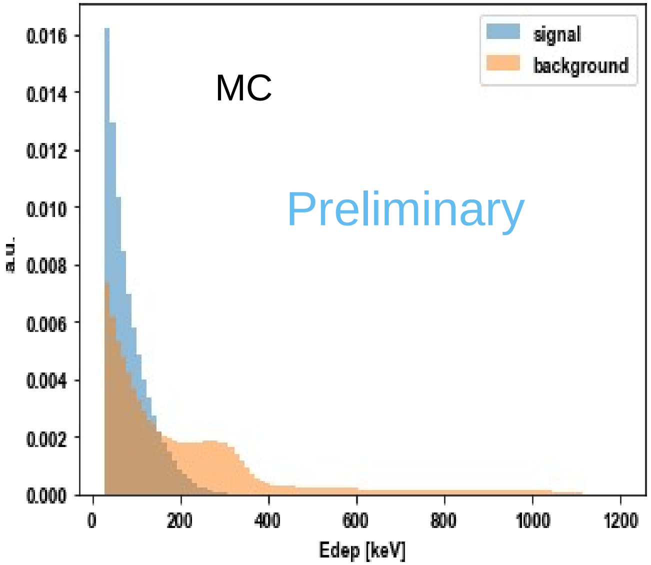


4-gamma decay oPs simplified MC

Features (4-gamma):
- 5 x energy-based
- 4 x angular-based
- 19 distance and time-based
- 4 x vertex reco-based



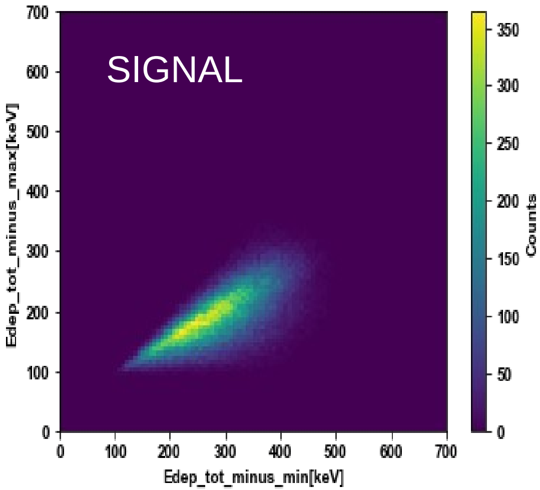


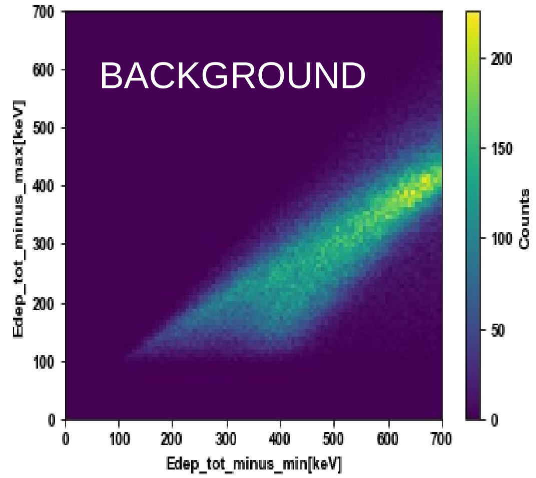


Background suppression using Machine Learning (ML)

In collaboration with **W. Krzemien**

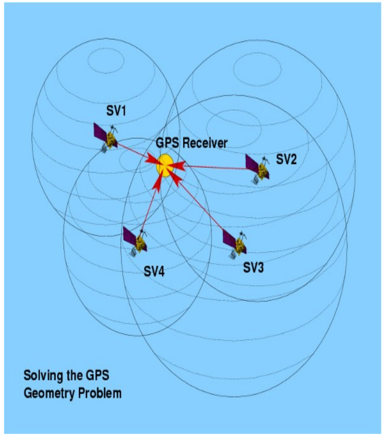
MC - features Preliminary





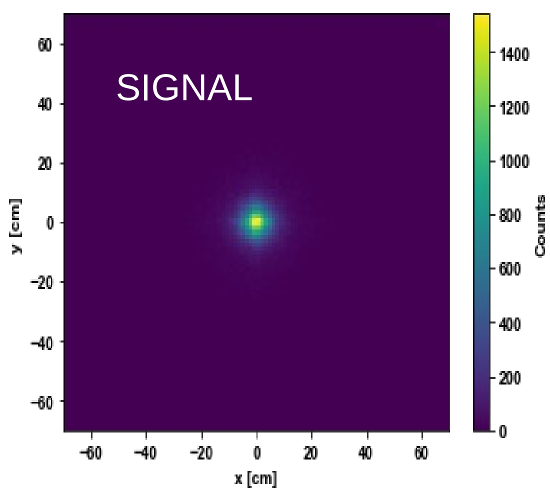
Vertex reconstruction:

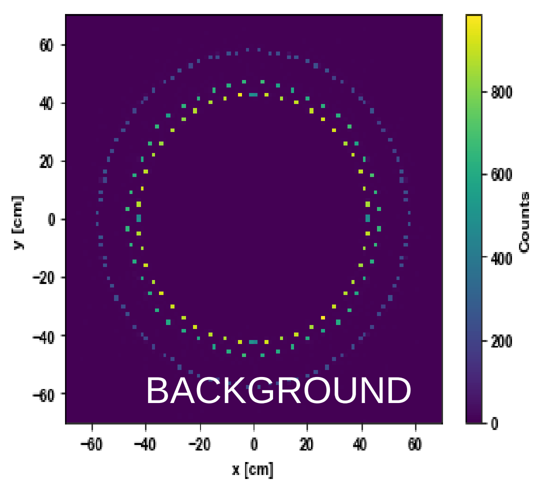
- Trilateration-like method
- Nelder-Mead algorithm
- Loss function can be regularized with energy-momentum constraints



4-gama decay of oPs reconstruction

Preliminary





Work on ML application

- Boosted Decision Trees (XGBoost)
- Deep Neural Networks (PyTorch)

Conclusions

Project:

Search for Mirror Matter as DM candidate. New type of matter.
Precision test of QED theory.
Measurement of rare decays of ortho-Positronium.
DM mediator, U boson in ortho-Positronium.

Method:

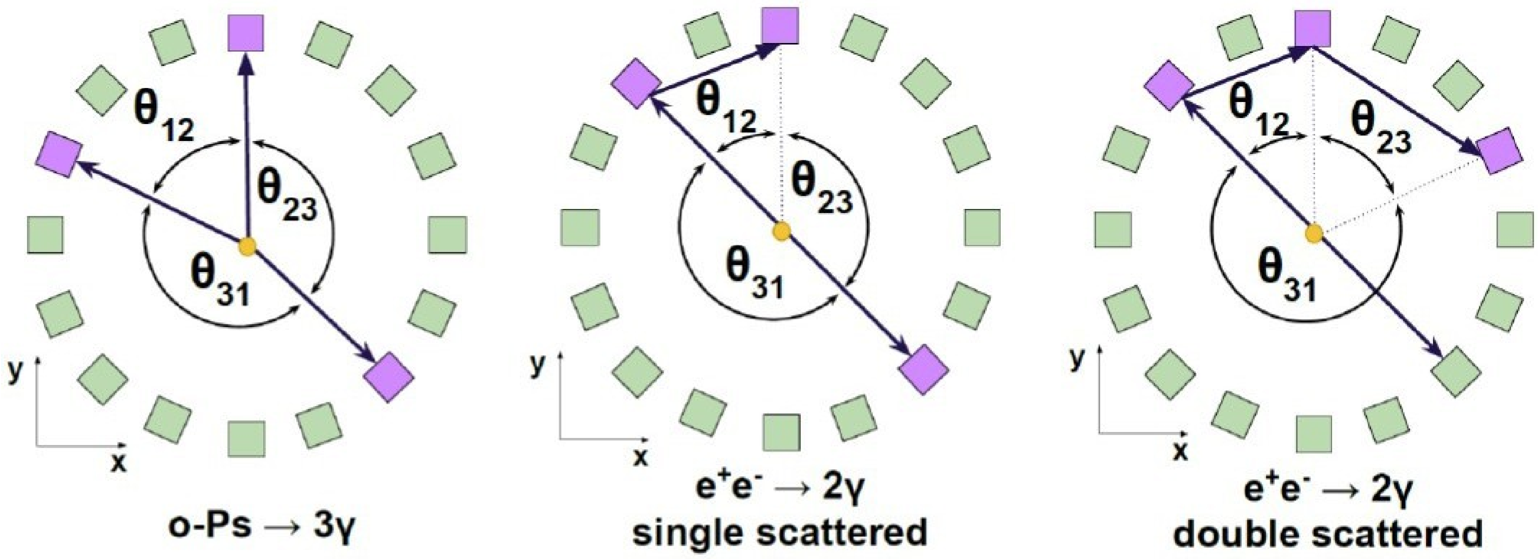
Precise determination of the lifetime of the Positronium to compare to the QED theory expectation.
Machine learning techniques to reduce the background sources and to be later on implemented in medical imaging.
Monte Carlo dedicated modeling of DM mediator and rare decays.

Facility:

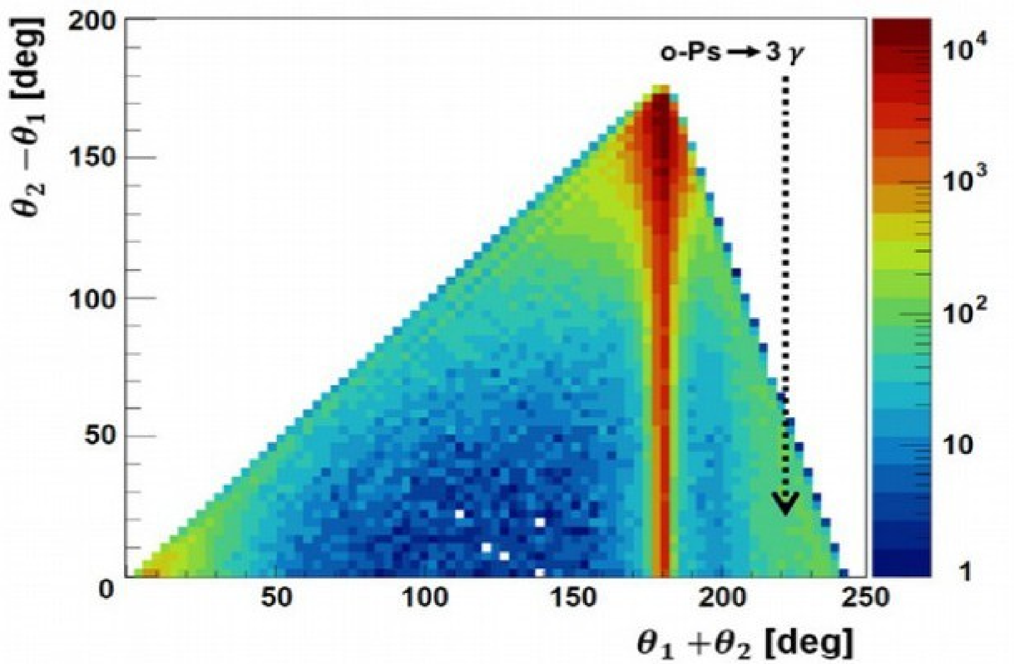
J-PET tomograph at Jagiellionan University
High performance and timing resolution with trigger-less acquisition system.
Modular/portable configuration.

Thank you

Mirror Matter in J-PET: Studies



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

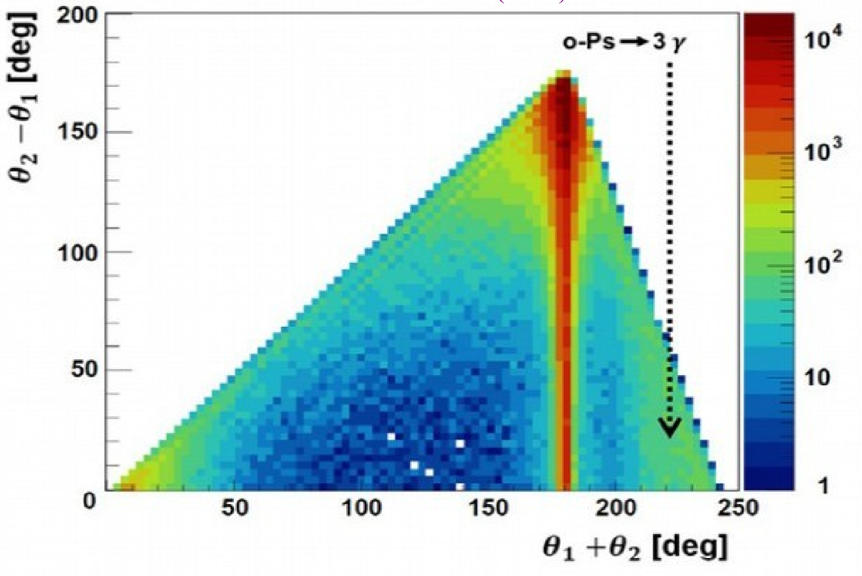


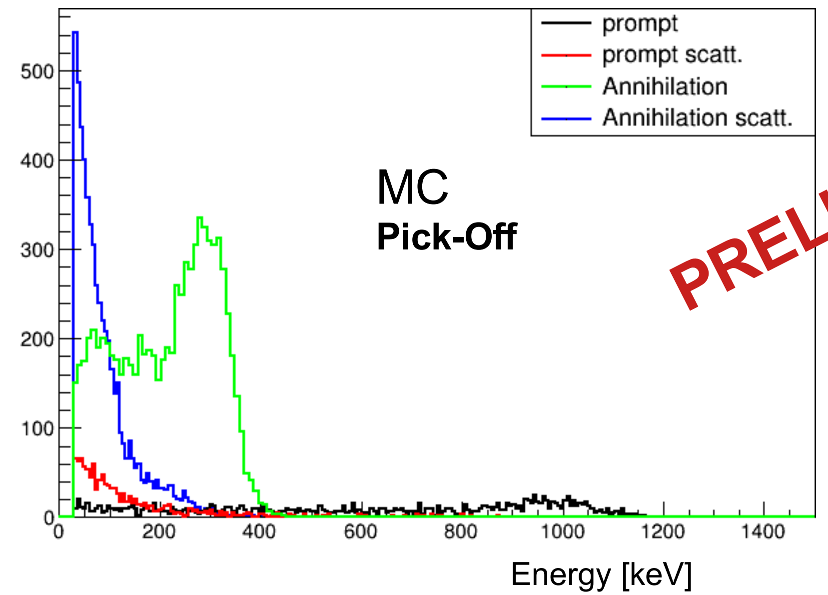
K. Dulski et al. NIM A 1008 (2021) 165452

Analysis o-Ps lifetime

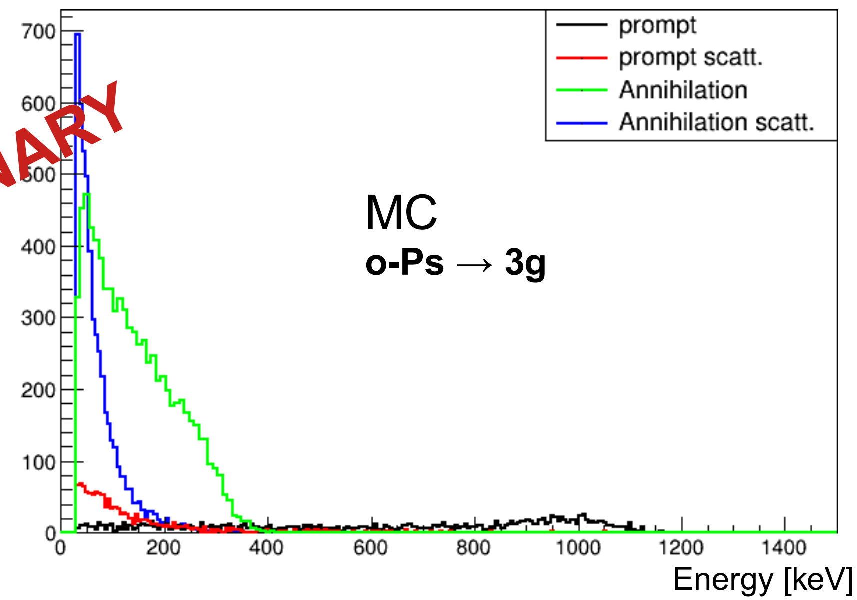
- **Machine Learning(ML) models tested for background identification and discrimination**
  - Number of features, different architectures, strategies, correlations, etc … studies on-going
  - Impemented in Keras + TensorFlow
  - Training, validation and test performed in GEANT4 Monte Carlo (MC) simulations with J-PET detector response
  - Work in collaboration with Dr. Krzemien & B. Kłósek
  - Comparison with baseline model corresponding to standard selection criteria
  - Main preliminary focus studies efficient **signal oPs/pick-off discrimination**
- **Preliminary results**

K. Dulski et al. NIM A 1008 (2021) 165452



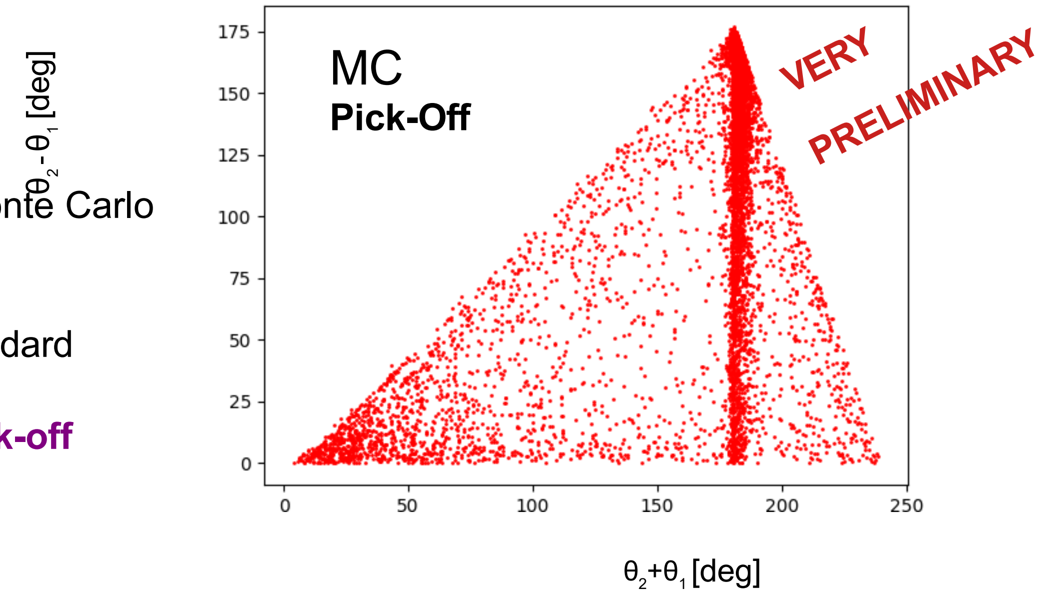


PRELIMINARY

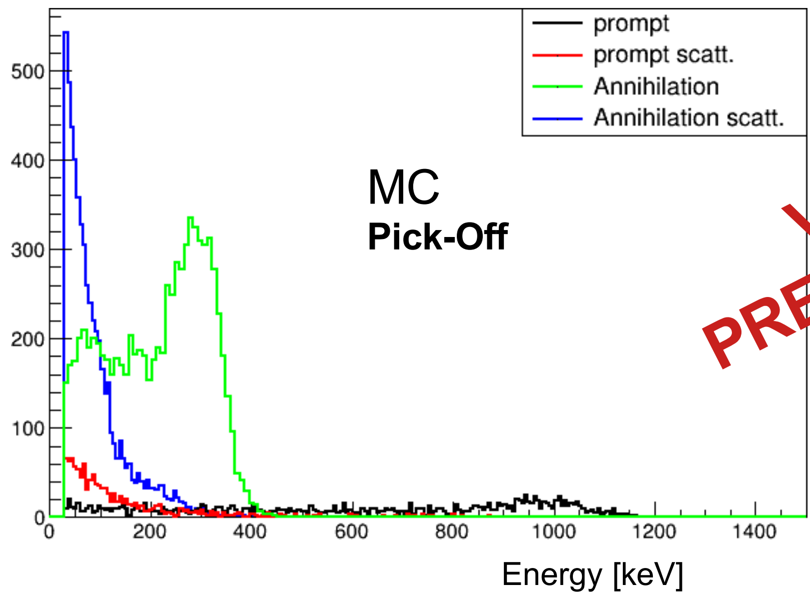


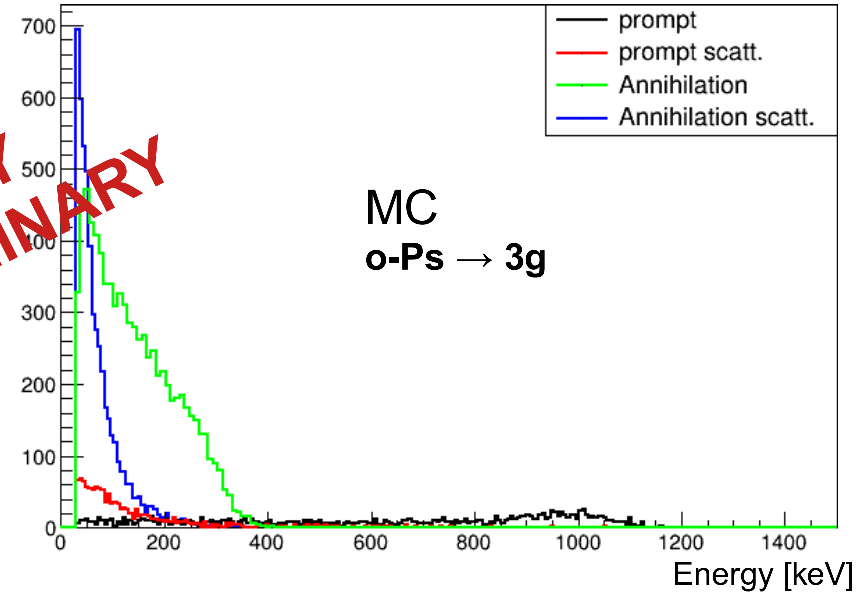
Analysis o-Ps lifetime

- **Machine Learning(ML) models tested for background identification and discrimination**
  - Number of features, different architectures, strategies, correlations, etc … studies on-going
  - Impemented in Keras + TensorFlow
  - Training, validation and test performed in GEANT4 Monte Carlo (MC) simulations with J-PET detector response
  - Work in collaboration with Dr. Krzemien & B. Kłósek
  - Comparison with baseline model corresponding to standard selection criteria
  - Main preliminary focus studies efficient **signal oPs/pick-off discrimination**



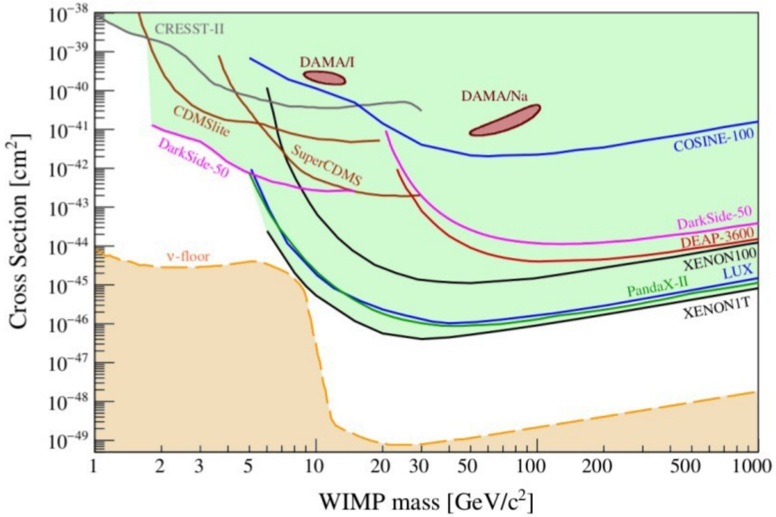
- **Preliminary results**





Dark Matter: WIMPs

- WIMPs (Weakly Interacting Massive Particles)



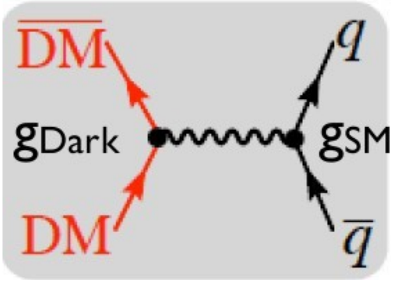
arXiv:1903.03026

- Massive DM with massive mediator
- For ~100 GeV DM mass, weak-scale mediators provide reasonable annihilation rate
  and range of DM-scattering rates

- No signal of DM in direct detection
- Experiments don't have sensitivity (almost) to light DM (< 1 GeV)

Dark Matter: mass and interaction

- Based on the direct searches outcome a first idea comes: the DM interaction is in the range of the weak force (WIMPs) but the DM particles mass in the TeV range



Light Dark Matter (< TeV)

↓

New mediators

↓

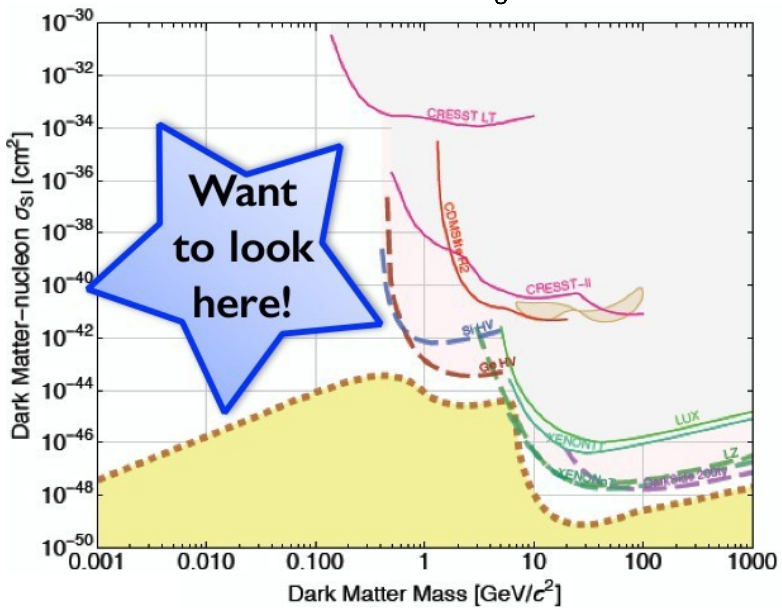
New Force

$$\sigma_V \sim g^2_{DM} g^2_{SM} \frac{M^2_{DM}}{M^4_{mediator}} \sim \epsilon^2 \alpha_{DM} \frac{M^2_{DM}}{M^4_{mediator}}$$

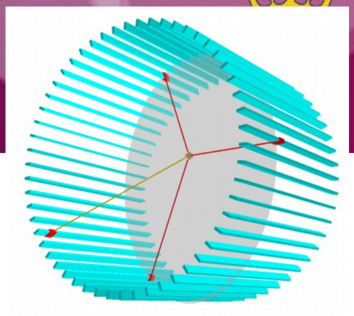
Light Dark Matter

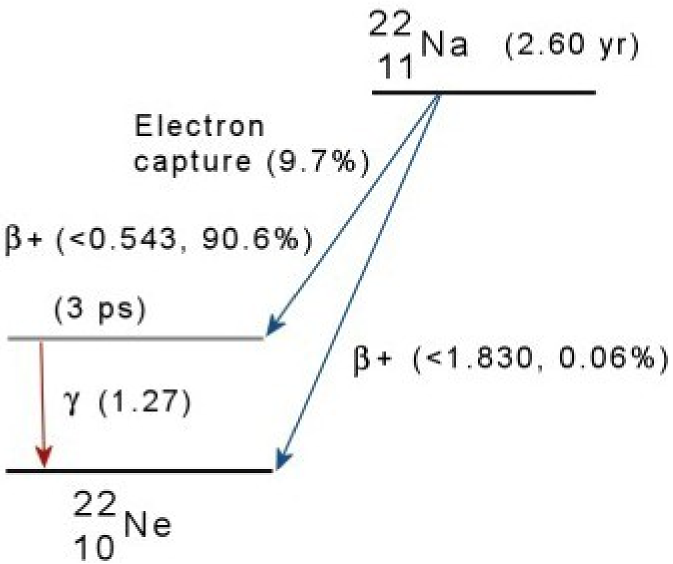
- **Dark Matter with a weak interaction (new force!)**
- Direct Detection is (almost) impossible
  - Low energies would require a complete new technology
- **Lab-based DM search**
  - covers an unexplored mass region
  - We do it in our labs/colliders/accelerators

M.Battaglieri talk



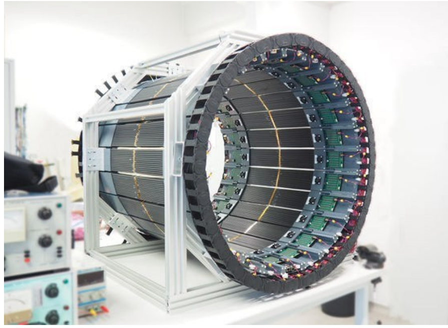
Dark Sector or Hidden Sector (DM not directly charged under SM interactions)





- Source activity 1 MBq = **10^6 e⁺/s**
- o-Ps formed in vacuum chamber with probability 29%
- o-Ps formation triggered by emission e⁺ and de-excitation gamma quanta
- Number of o-Ps after 2 years

10^{13} o-Ps formed



Main competitor

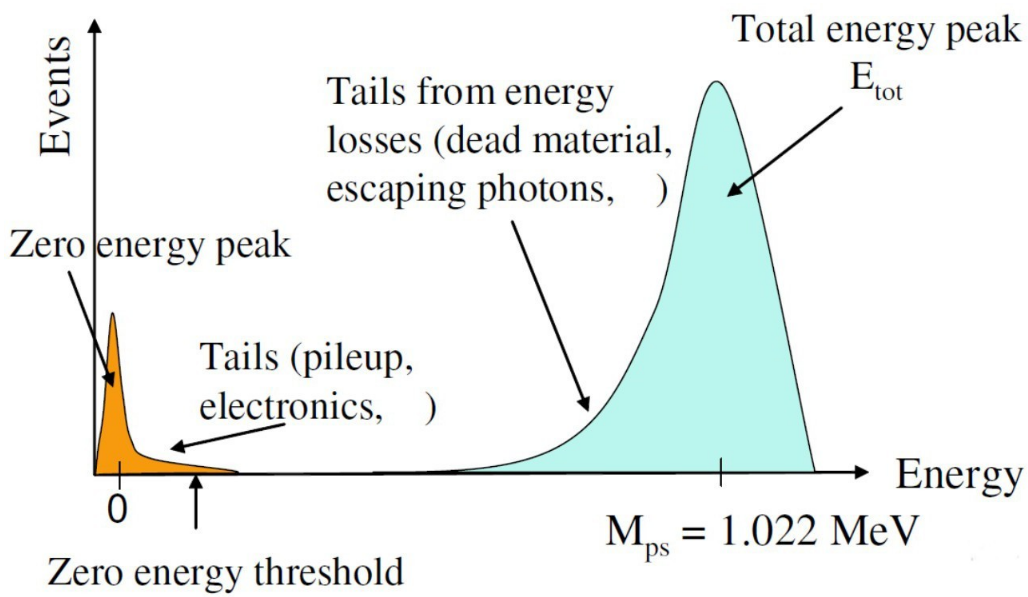
- *Searches in vacuum* [Phys. Rev. D 97, 09200]
  - Slow positron beam (15000 e⁺/s)
  - BR < 5.9 × 10^{-4} (90% C.L.)
  - Photon mixing strength
    ε < 3.1 × 10^{-7} (90% C.L.)

- Probability registering the gamma quanta in J-PET (energy dependent)
  - De-excitation quanta 20%
  - 3 gamma decay 2%
- After 2 year data taking we will have **registered ~ 10^{13} o-Ps**
- **Sensitivity O(10^{-5})**
- **Photon mixing strength ε < O(10^{-7})**

“zero-signal” experiment

“zero-signal” experiment performed at ETH in Zurich with common characteristics:

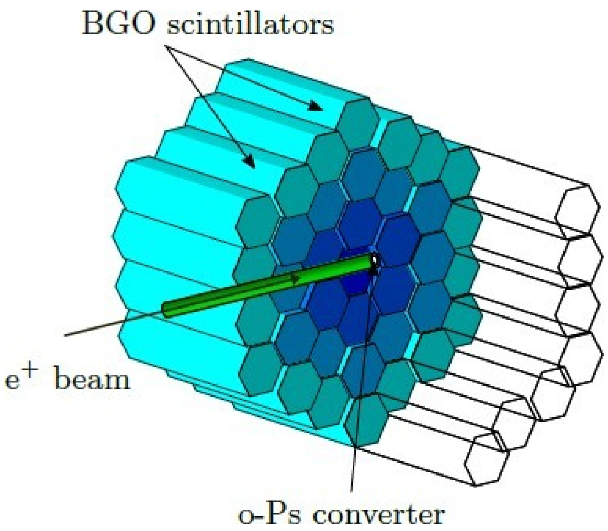
- Time measurement: time start by triggering on positron, time stop when detecting any of the annihilation photons
- Use of a calorimeter (BGO crystals) to measure the energy of γ from ortho positronium decay products and calculate $E_{tot} = \sum E_i$.
- Search for excess events (peak) in the spectrum below the noise level threshold
- The shape of the background (noise) below noise threshold based on MC simulations.



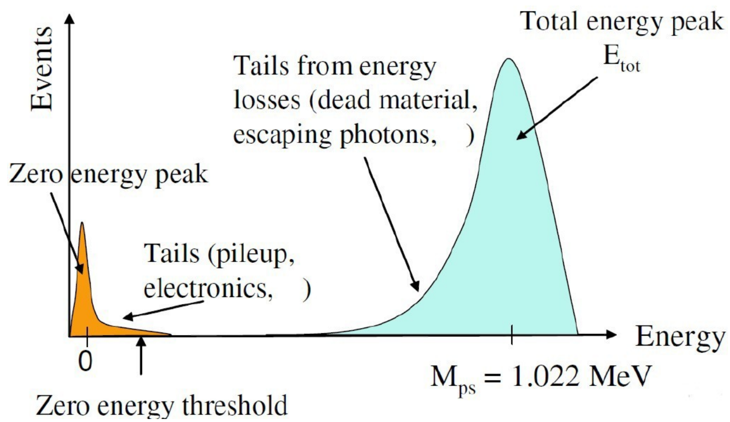
Decay not observed
UL calculated for BR

- *Searches in vacuum* [Phys. Rev. D 97, 092008]
  - BR < 5.9 × 10^{-4} (90% C.L.)
  - Photon mixing strength
    ε < 3.1 × 10^{-7} (90% C.L.)

Searching for „zero-signal” events



C. Vigo et al . Phys.Rev.D 97 (2018) 092008

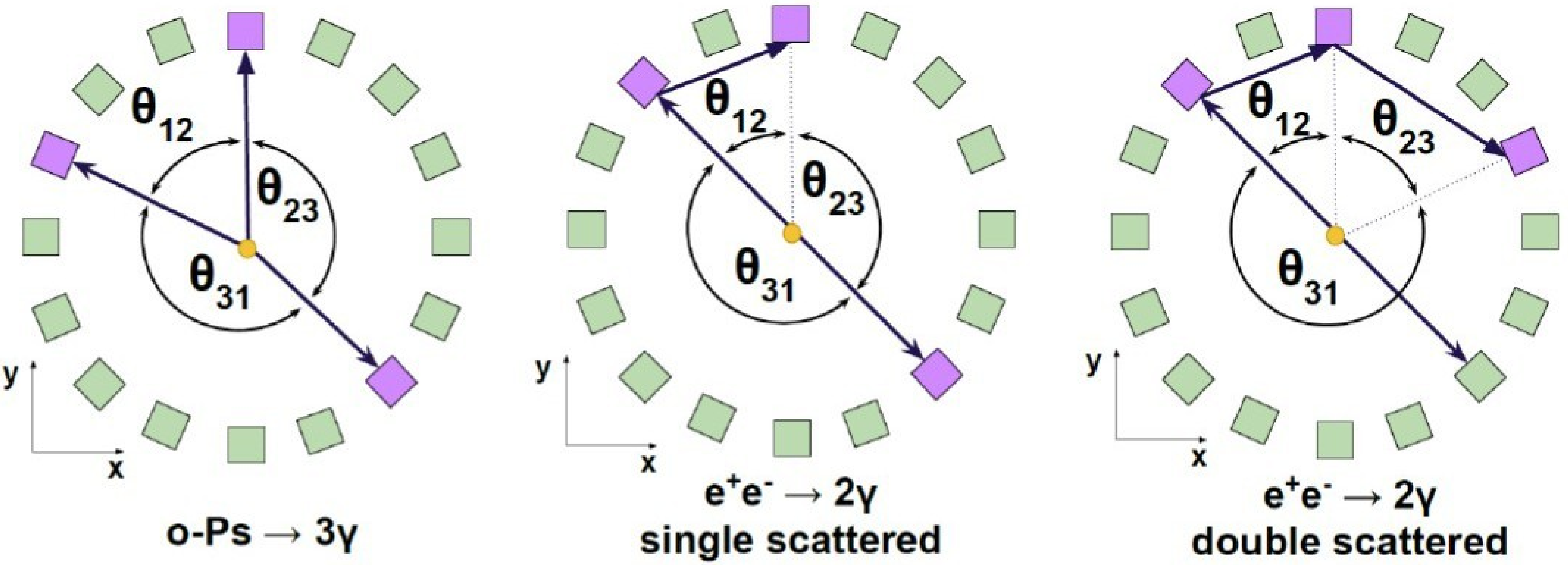


P. Crivelli Phd Thesis, ETHZ (2006)

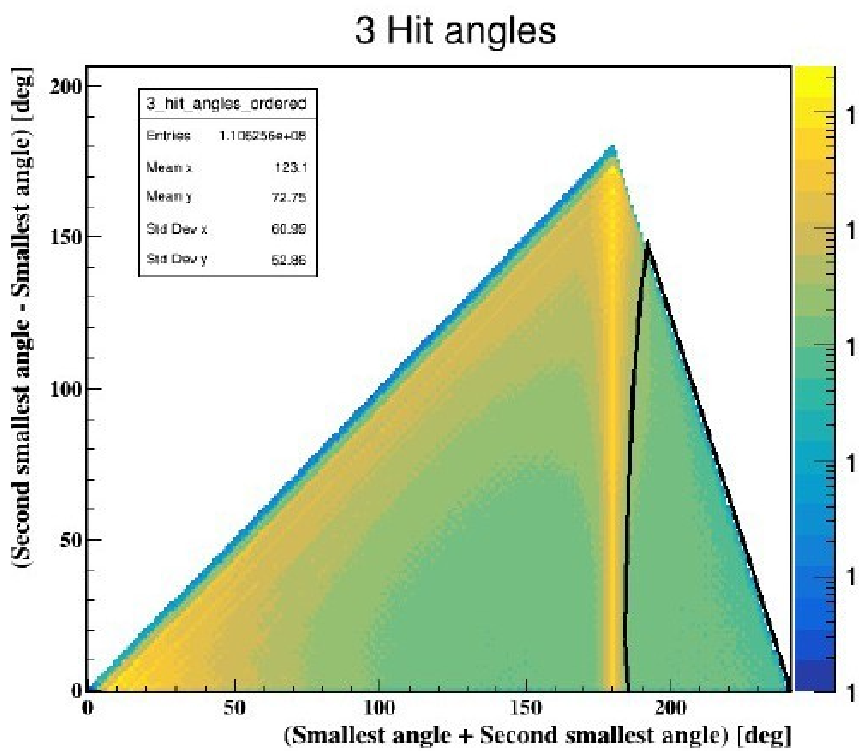
- Several measurements by ETHZ group
- Use of slow positron beam (~15000 e^+/s) on thin silica films (~ 30% prob. of o-Ps)
- Micro-Channel Plate detector to tag positron (Start signal)
- Highly hermetic BGO calorimeter (total signal efficiency ~92%)
- Decay of o-Ps in a vacuum cavity

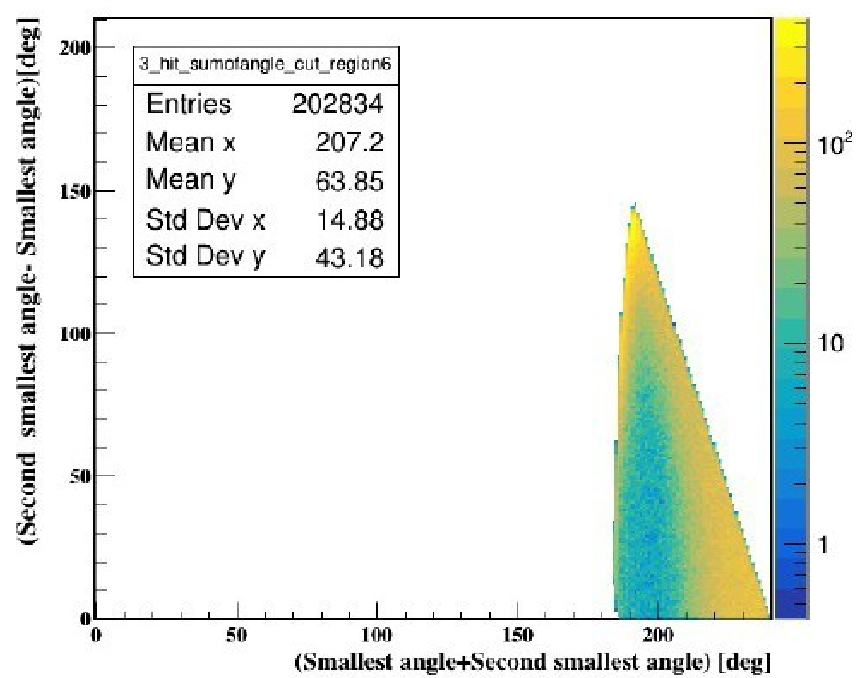
$$\mathrm{BR}(\text{o-Ps} \to \text{invisible}) < 5.9 \times 10^{-4}, \qquad 90\%\ \mathrm{C.L.}$$

$$\varepsilon < 3.1 \times 10^{-7} \ (90\%\ \mathrm{C.\ L.})$$

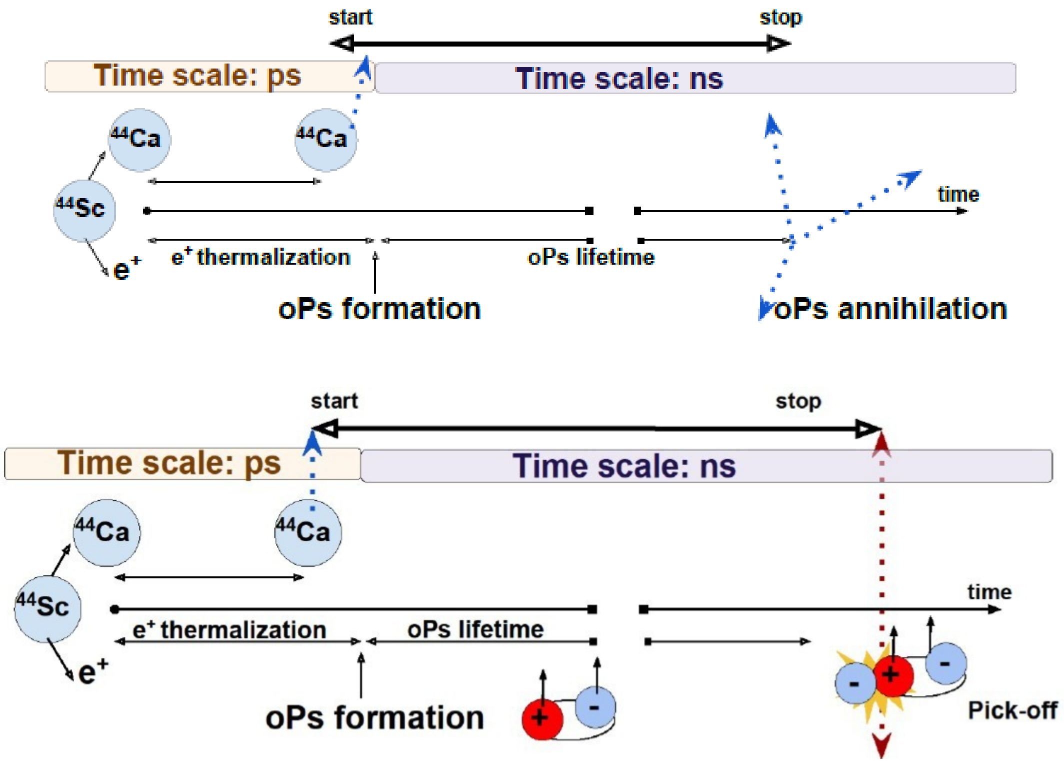


$\theta_{23} + \theta_{12} > 180$ $\theta_{23} + \theta_{12} = 180$ $\theta_{23} + \theta_{12} < 180$





The main experimental challenge: pick-off effect



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

$$\lambda_{\text{pick}}(t) = n\sigma_{\text{a}}v(t)$$

velocity of o-Ps

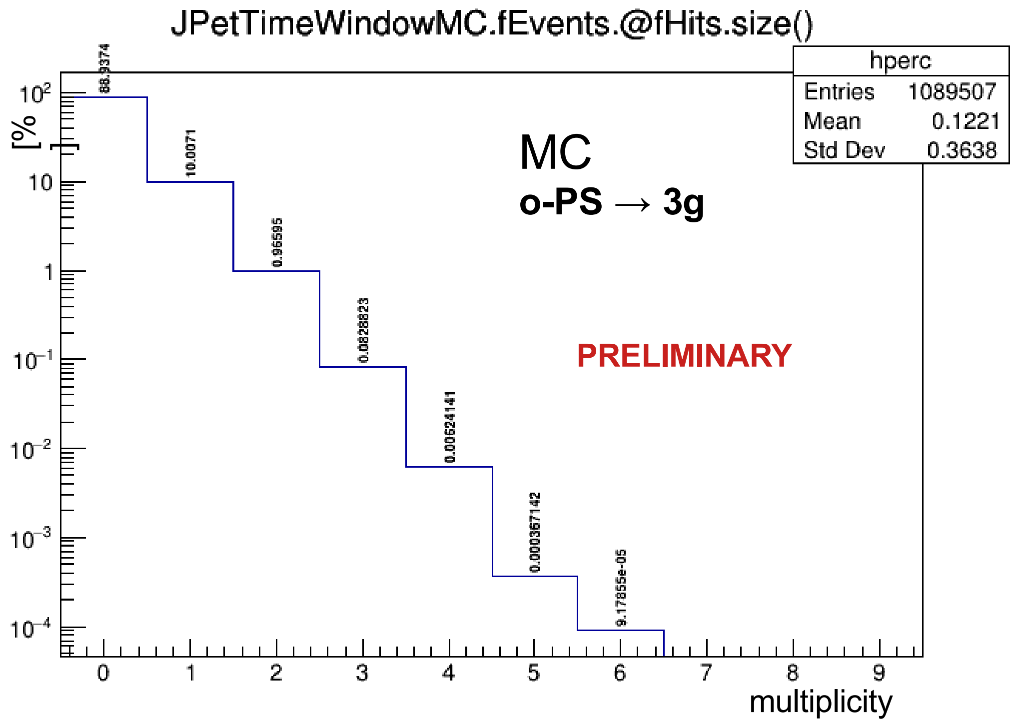
target density

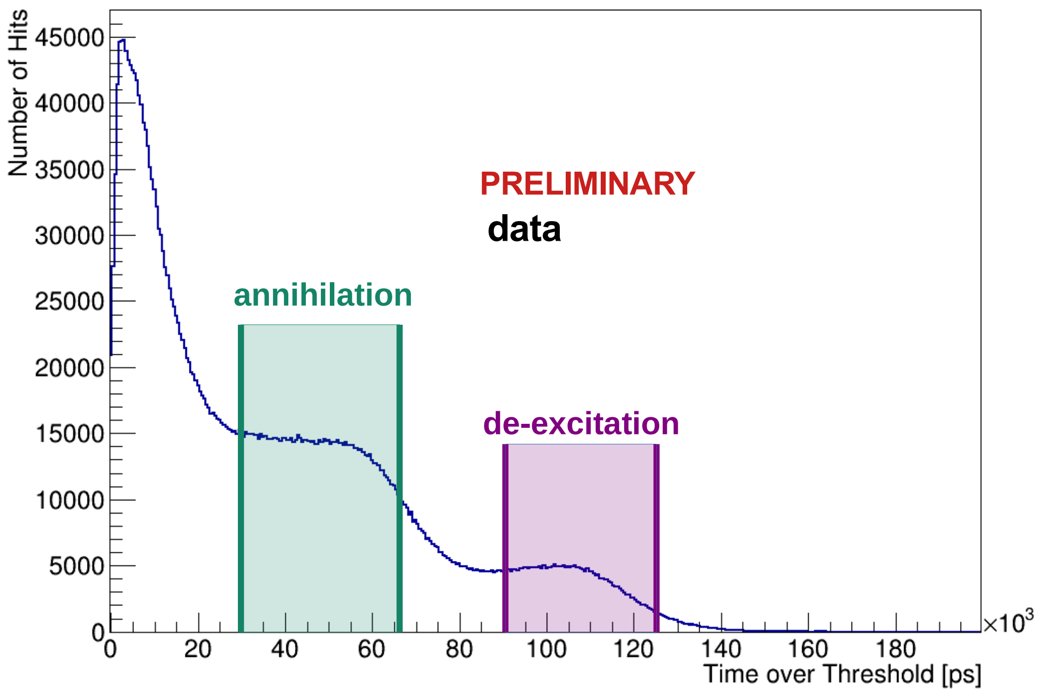
annihilation cross-section

Mirror Matter in J-PET: Studies

- **4-gamma events** to reconstruct the life-time
- Accurate measurement/**Precision Frontier**
  - High purity/high statistics

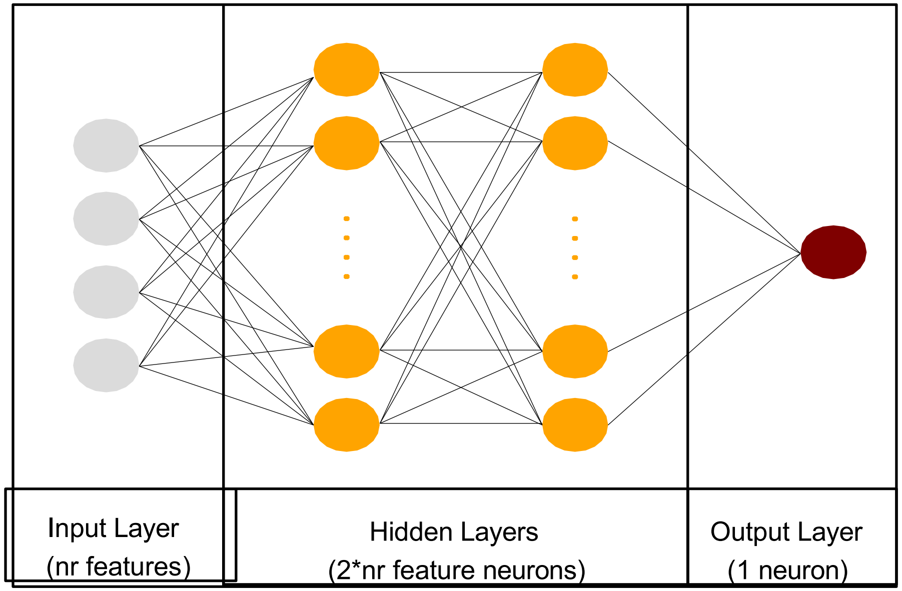
- Event pre-selection/identification:
  - 4 hit multiplicity
  - 3 annihilation gamma + de-excitation
    - Time-Over-Threshold (TOT) selection → Compton edges
  - Ortho-Ps angular identification
  - Other decay features

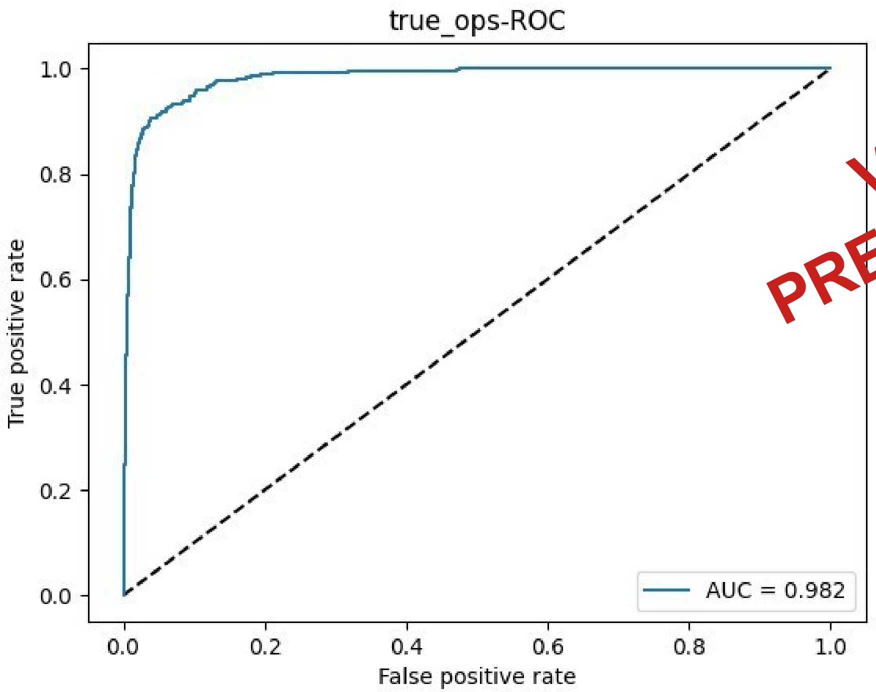




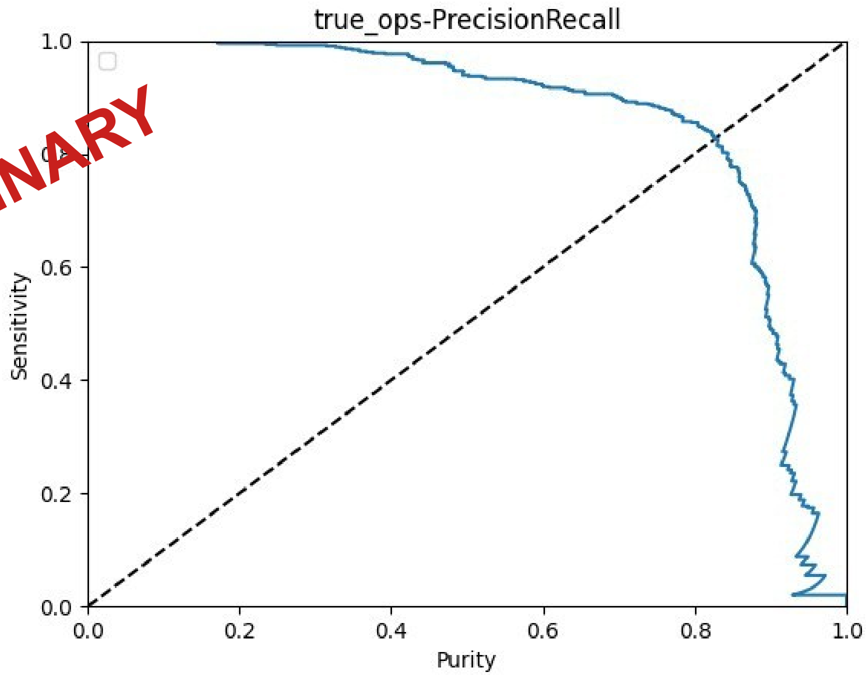
Mirror Matter in J-PET: Studies

- Machine Learning studies with MC simulations
  - **Deep Neural Network**
  - Challenge: Imbalanced dataset (oPs/Pick-off ratio very small)
  - **Different strategies tested-ongoing:** under-sampling,over-sampling(bootstrap), NN re-weighting
  - Goal classification model robust to the variation in the oPs/Pick-off ratio
  - In collaboration with Dr. Krzemien & B. Kłósek





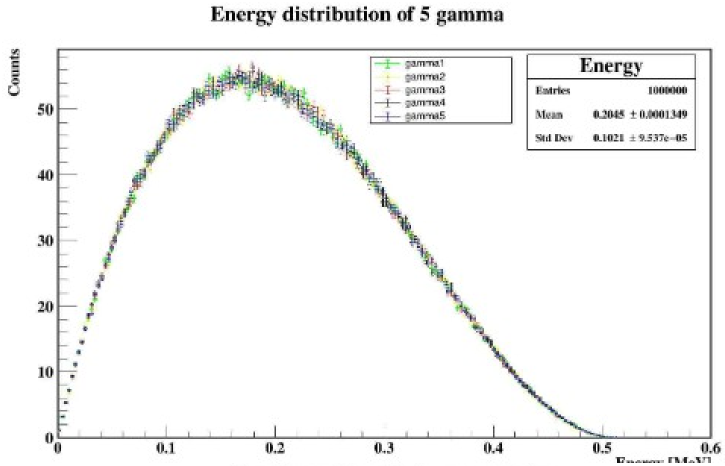
VERY PRELIMINARY



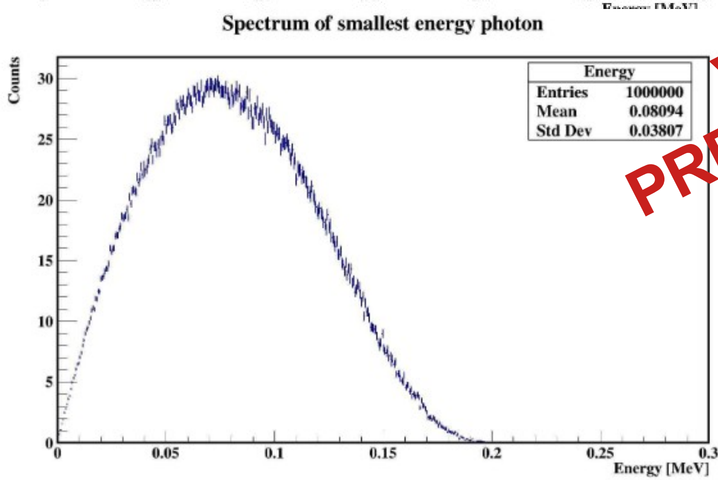
Rare decays of the oPs

- **Monte Carlo simulations for 4- and 5-gamma decay** in preparation
- Data analysis on-going
- Efficiencies studies in evaluation

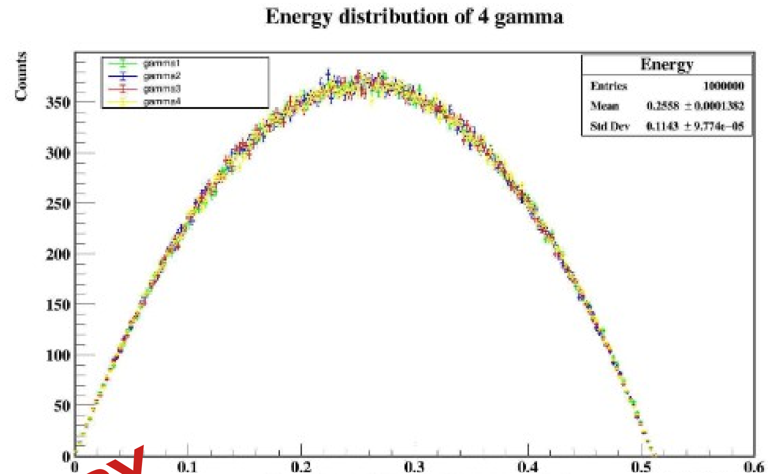
5-gamma

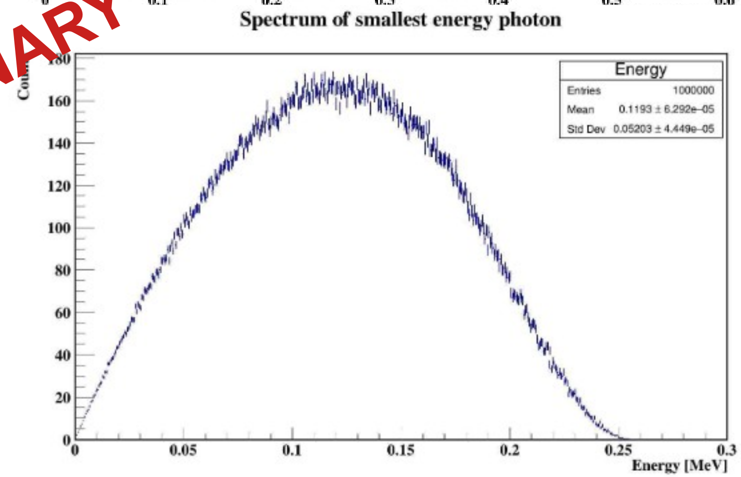


Generated true Monte Carlo



4-gamma

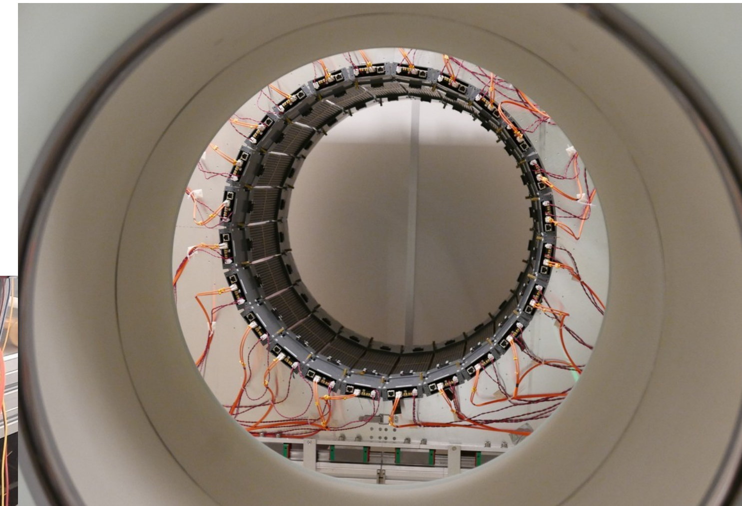


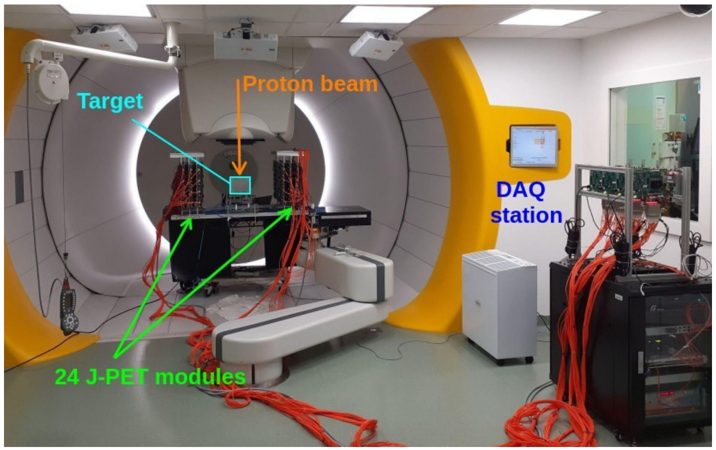


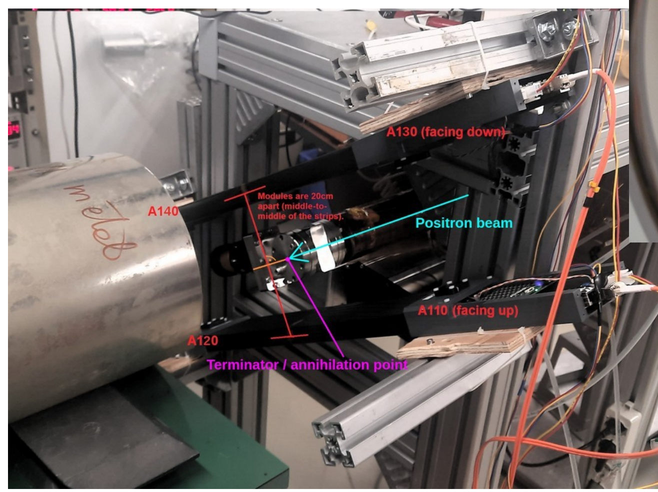
VERY PRELIMINARY

Ph.D. thesis of Pooja Tanty
In collaboration with W. Krzemien

Mirror Matter in J-PET







- **NCN grant Nr 2020/38/E/ST2/00112**
- **Mirror Matter search with J-PET detector**
- **Development of a tagger system**
  - **Positron tagger implementation to trigger the start of the reaction**
  - **Reduction of background**
  - **Additional start measurement**
  - **Extra measurement to trigger the formation of positronium**
- **Use of modular layer J-PET for a higher efficiency**
  - **Modular layer is portable**
  - **Allows future measurements with positron beam**
    - **Measurements already performed at The Cyclotron Centre Bronowice, Trento (INFN), and Warsaw University**