Dark Matter and Rare Decay searches of the ortho-Positronium with the J-PET detector

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

MESON 2023

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

MESON2023

22nd - 27th June 2023, Krakow, Poland

Outline

- **Dark Matter fast overview**
  - **Beyond the Standard Model: g-2**
  - **Dark Photon**

- **Mirror Matter (MM)**
  - **Mirror Matter in ortho-Positronium**

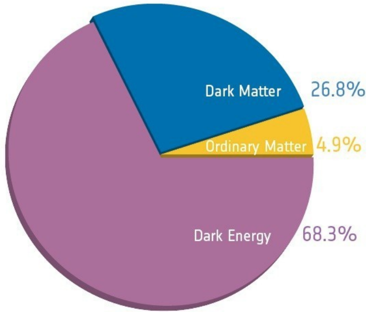
- **J-PET (Jagiellonian PET Tomograph)**

- **Studies using J-PET:**
  - **Search of MM**
  - **Dark Photon**
  - **Rare decays of ortho-Positronium**

- **Conclusions**

Dark Matter

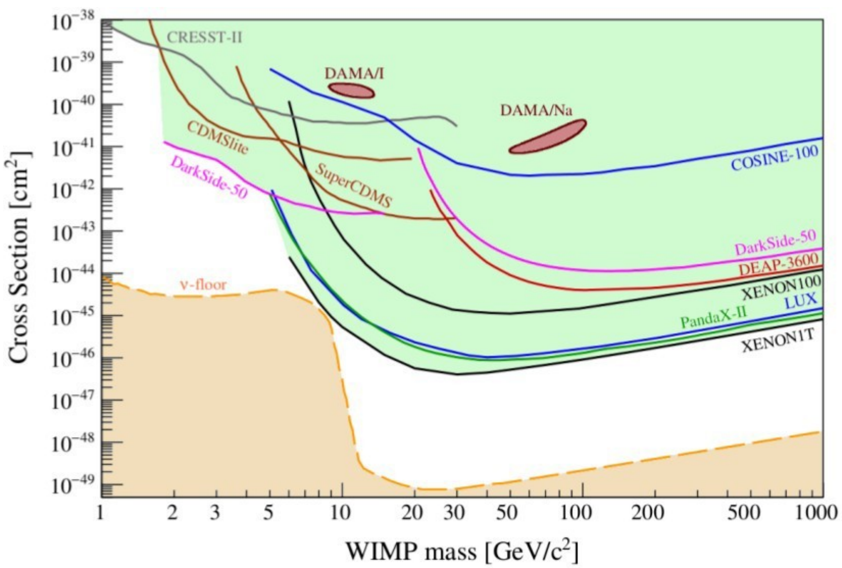
The Dark Matter Nature



- 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

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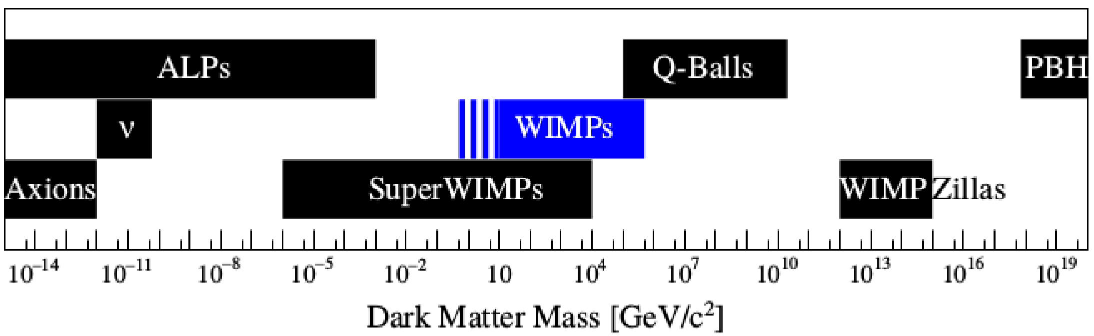
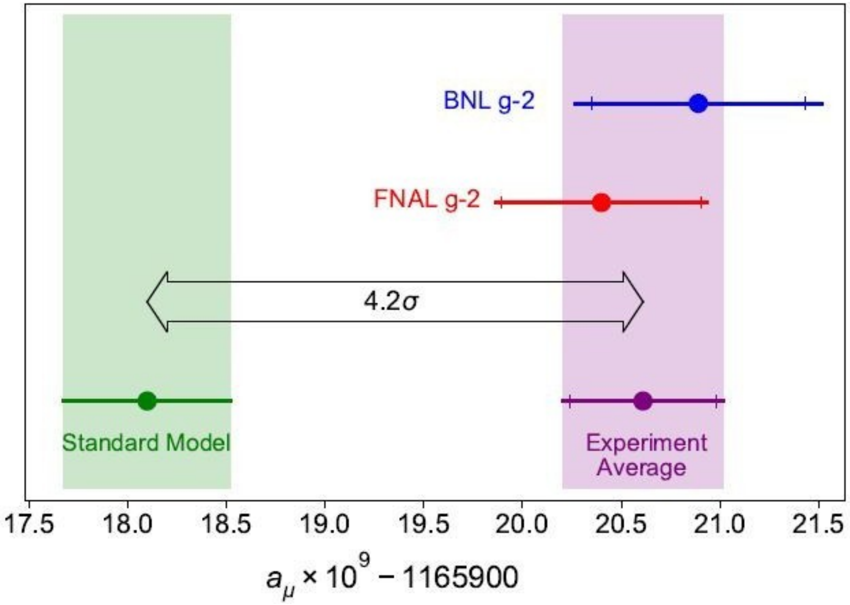
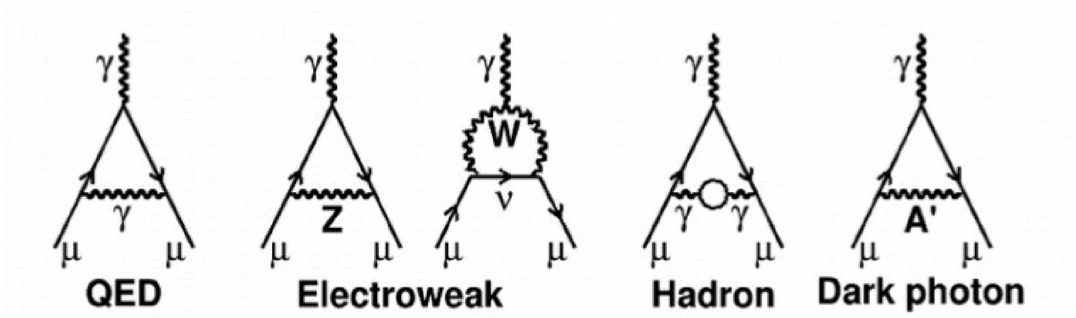


Dark Sector or Hidden Sector (DM not directly charged under SM interactions)

BSM Physics: g-2 and dark matter





- Longest standing known discrepancy between theory prediction and experiment
  - **4.2σ** discrepancy

$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)$$

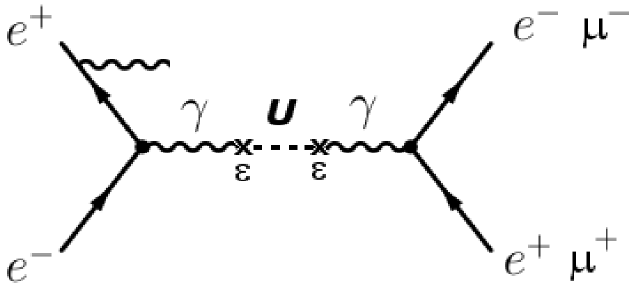
Dark matter motivated by cosmological observations could also serve as explanation to the g-2 discrepancy

$\varepsilon \sim 1\text{-}2 \cdot 10^{-3}$ and $m_V \sim$ 1-100 MeV

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

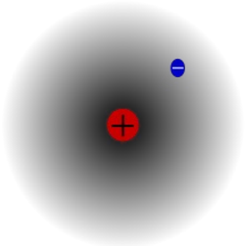
R. L. Garwin, L. Lederman and R. Weinrich
Phys. Rev. 104 (1956) 254

- 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

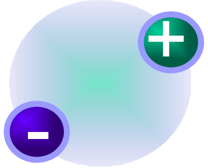
$$\mathcal{L}_{\gamma\gamma'} = -\epsilon F^{\mu\nu} F'_{\mu\nu}$$

Orthopositronium

Hydrogen atom ^{1}H:



Positronium (Ps)



$^{1}S_{0}$ **Para-positronium**
τ (p-Ps) ≈ 125 ps

$^{3}S_{1}$ **Ortho-positronium**
τ (o-Ps) ≈ 142 ns

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**

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

Theory QED prediction

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

Experimental values

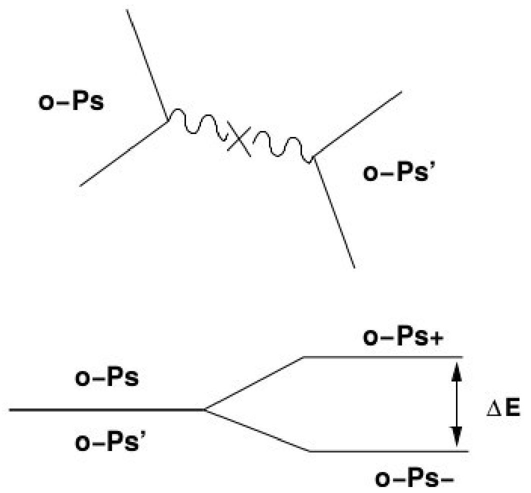
$$\Gamma = 7.0401 \pm 0.0007 \times 10^6\,\mathrm{s}^{-1}$$ Tokyo group

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

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

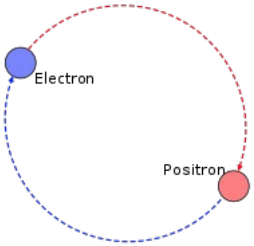
Mirror Matter in o-Ps

- 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$\rightarrow \nu\bar{\nu}$) < 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**

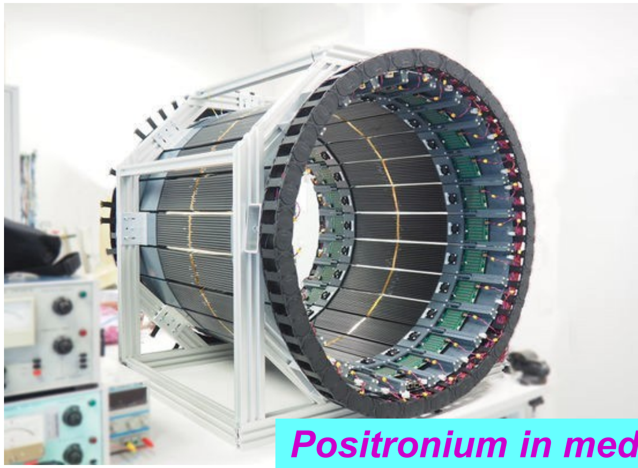


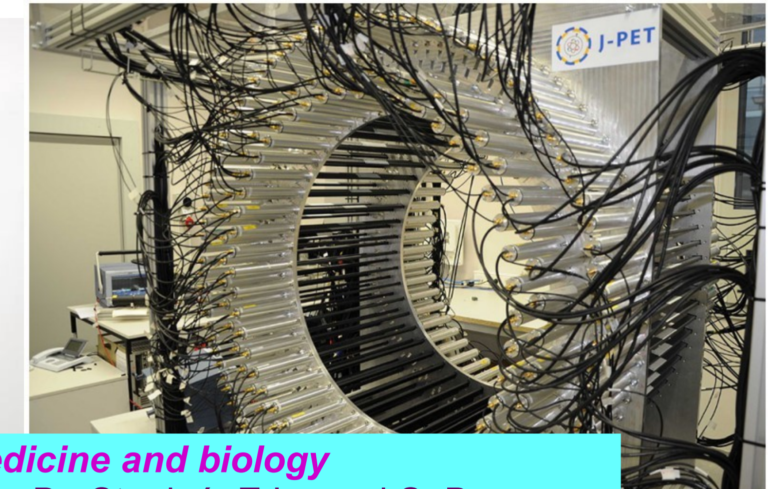
[P. Crivelli et al 2010 JINST 5 P08001]

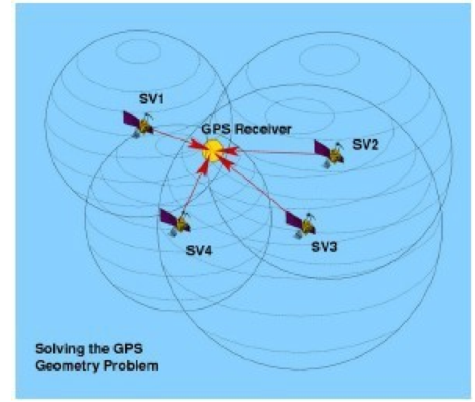
The o-Ps’ → invisible decay would manifest as an increase of the observed lifetime respect to the expected value → Precision measurement of the o-Ps lifetime



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)

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

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

First Positron Emission Tomography scanner built from plastic scintillator

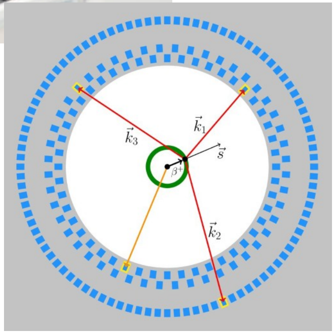
- Multidisciplinary detector
- **Portable/modular detector layer with higher detection probability High**
- **performance detector with high timing resolution**
- High acceptance
- **Trigger-less** and reconfigurable DAQ system
  - **Data has no filters: all data acquired is unfiltered**
- **GPS trilateration**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

Mirror Matter in J-PET: Studies

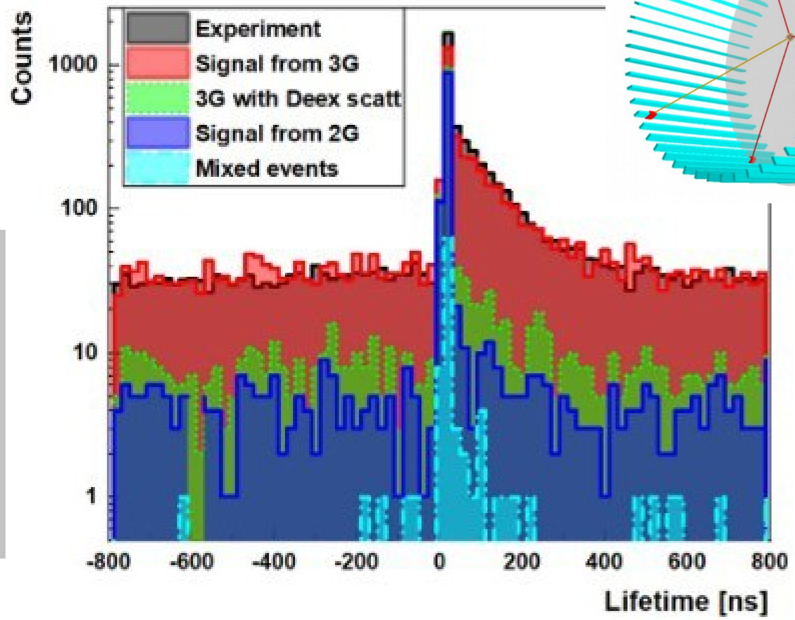
Radioactive source Na

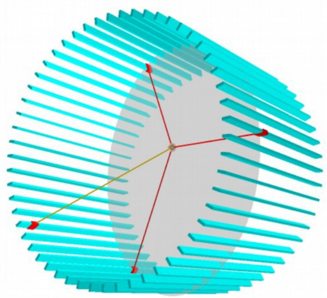
Precise measurement of the o-Ps lifetime looking for hints of new physics

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



[Nucl. Instr. Meth. A 1008 (2021) 165452]





10^{13} o-Ps formed

Sensitivity below O(10^{-5})

Photon mixing strength ε < O(10^{-7})

Already available statistics

- **E.g. 7.3 × 10^6 event candidates in a continuous 26-day measurement using a 10 MBq ^{22}Na positron source. [*Nature Communications 12 (2021) 5658*]**

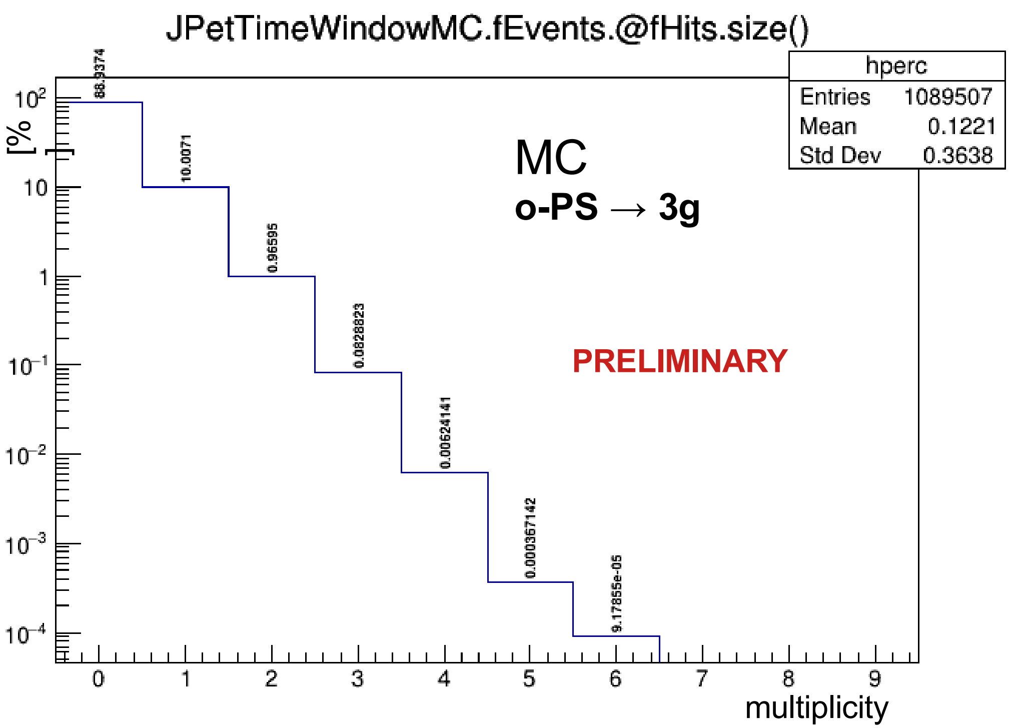
Main competitor ETH Zurich

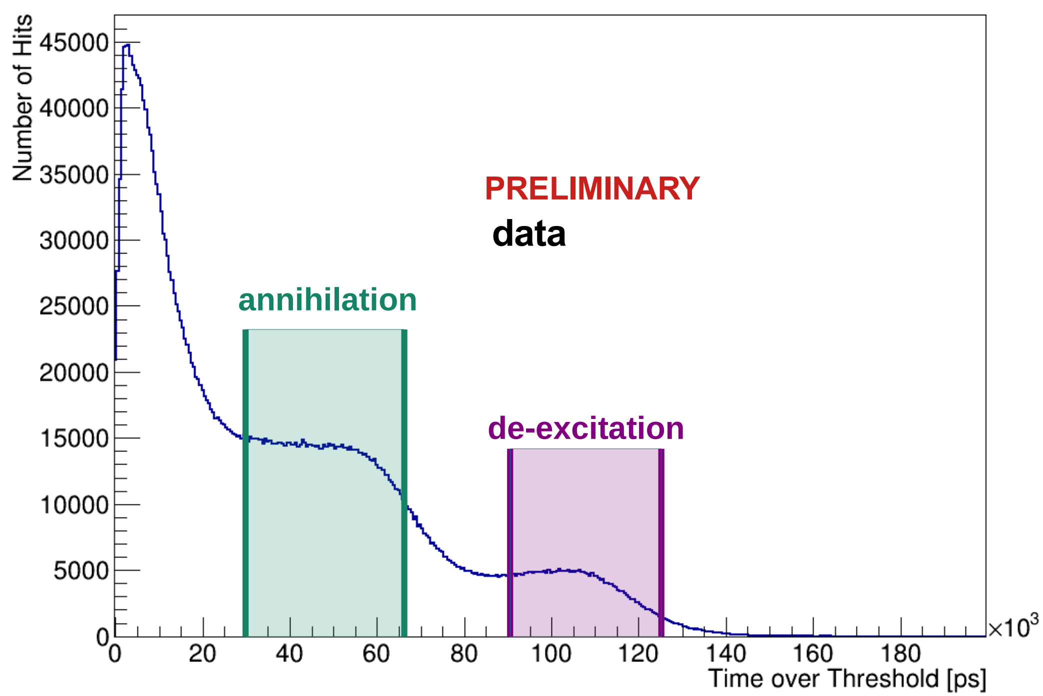
- [Phys. Rev. D 97, 092008]
  - Slow positron beam (1.5 x 10^4 e^+/s)

Mirror Matter in J-PET: Studies

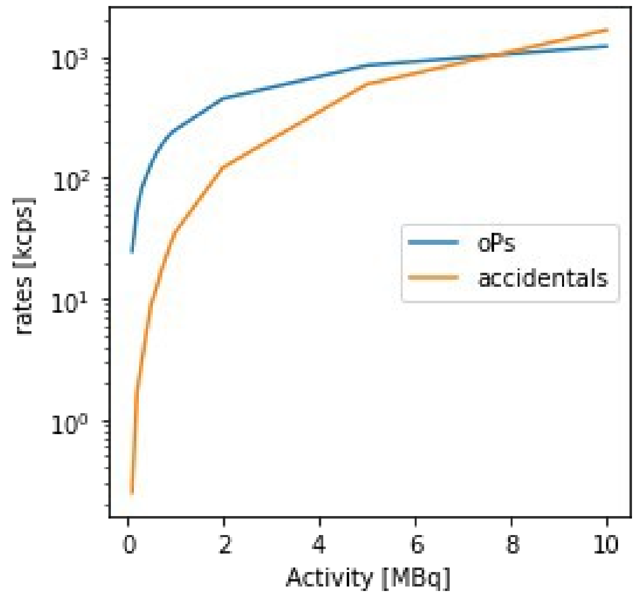
- **4-gamma events** to reconstruct the life-time
- Accurate measurement/**Precision Frontier**
  - High purity/high statistics

- 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



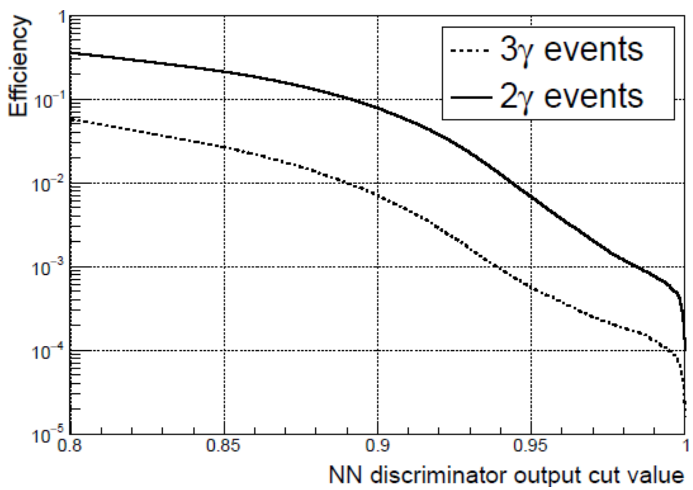


Mirror Matter in J-PET: Studies



- **Accidental events**: events in coincidence but not correlated
  - Can be controlled with source activity
  - Evaluation performed in 2020 article

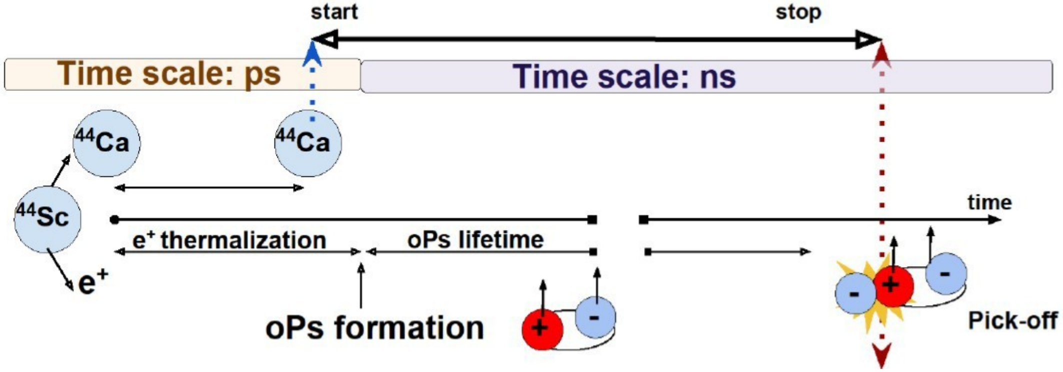
Acta Phys.Polon. B51 (2020) 165



C. Vigo et al. (2019) [805.06384v]

J. of Phys.: Conf. Series, Vol. 1138, conf 1

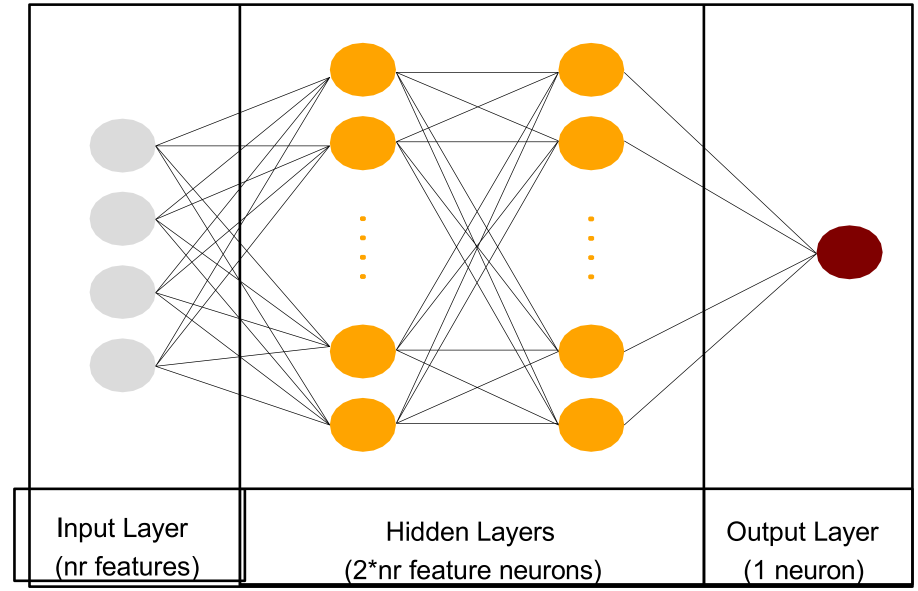
- **oPs interacting with the material (Pick-Off)**:
  - Can be directly evaluated from data
  - Can be used to train Machine Learning algorithms to reject the events (below 12 ppm level)

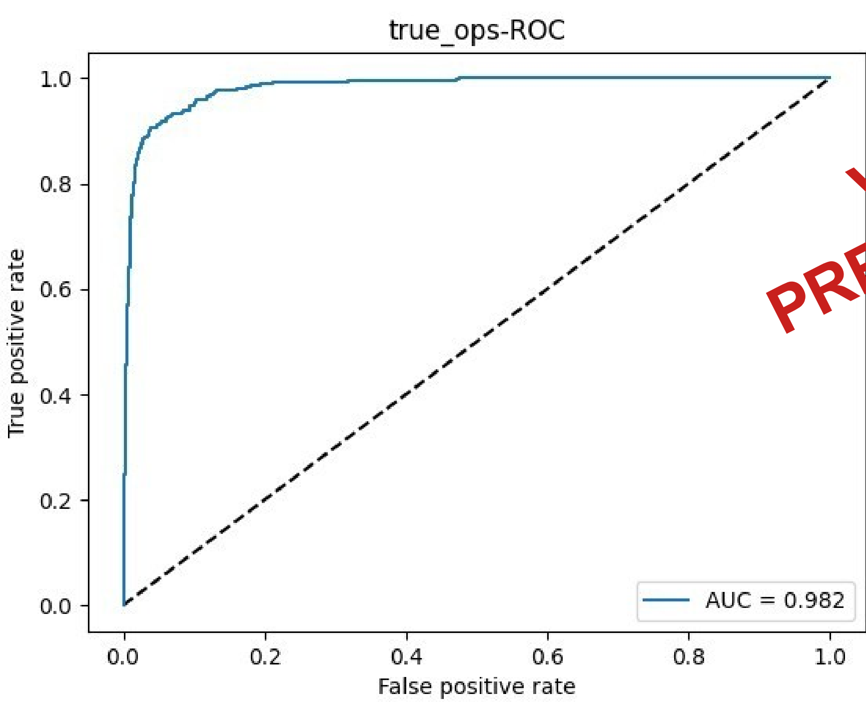


Mirror Matter in J-PET: Studies

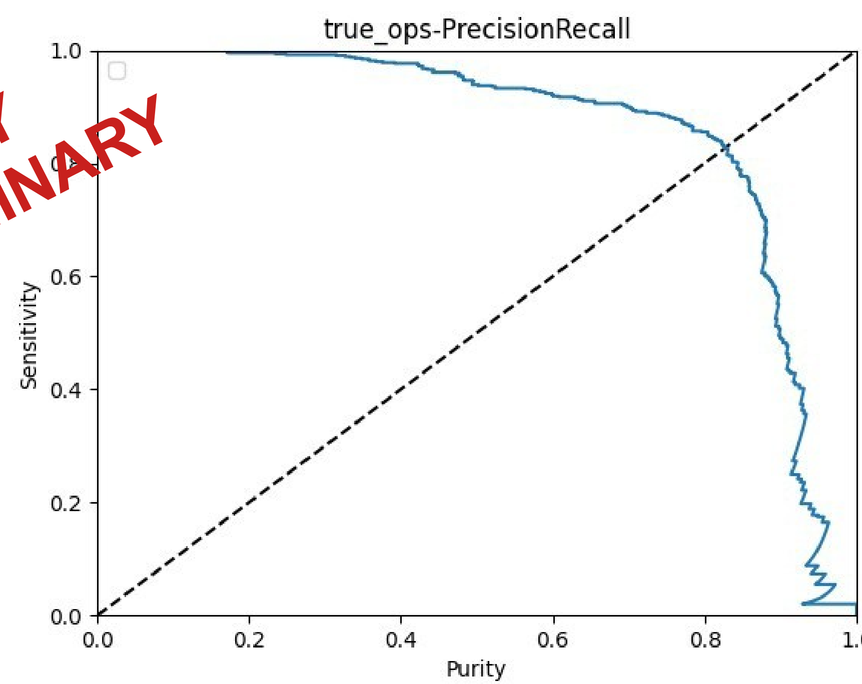
- Machine Learning studies with MC simulations
  - **Deep Neural Network**
  - Challenge: Imbalanced dataset (oPs/Pick-off ratio very small)
  - **Different strategies tested-ongoing:** under-sampling,over-sampling(bootstrap), NN re-weighting

  - Goal classification model robust to the variation in the oPs/Pick-off ratio
  - In collaboration with Dr. Krzemien & B. Kłósek





VERY PRELIMINARY



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

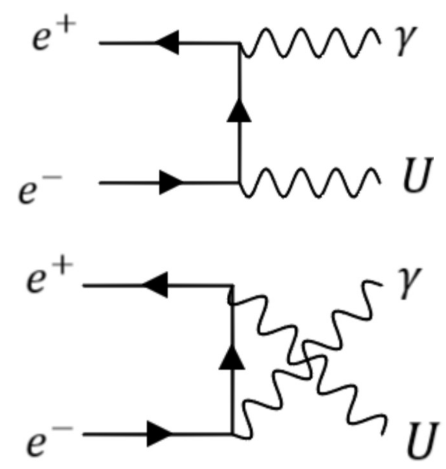
P. Fayet and M. Mezard
Phys. Lett. 104B (1981) 3

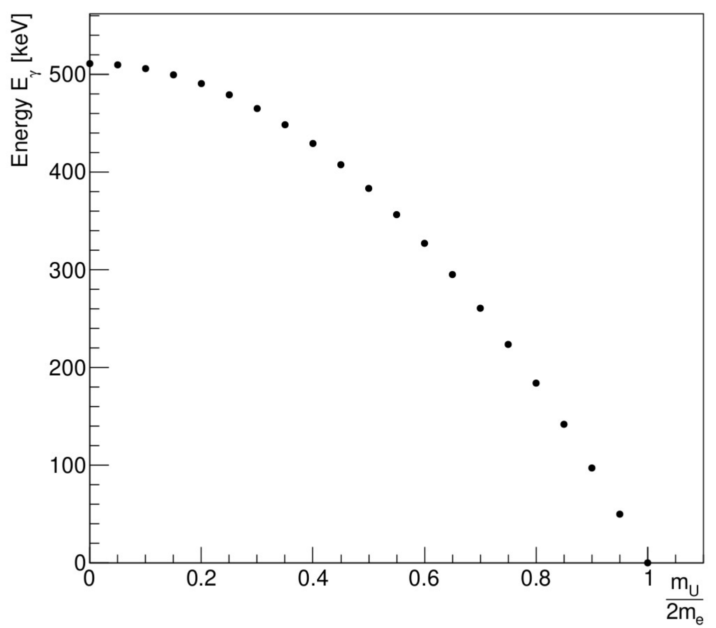
Volume 104B, number 3 PHYSICS LETTERS 27 August 1981

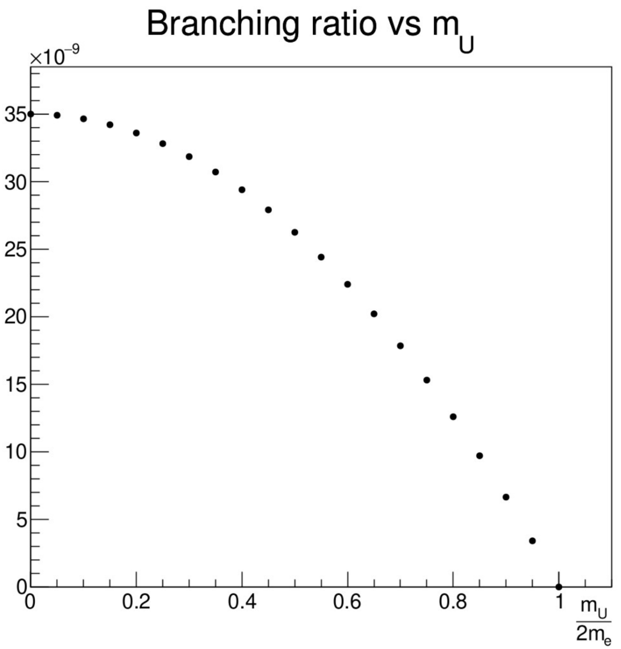
oPs→ U γ

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







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

$$x = m_U/2m_e.$$

Master thesis of Justyna Mędrala
In collaboration with W. Krzemien

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**

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]

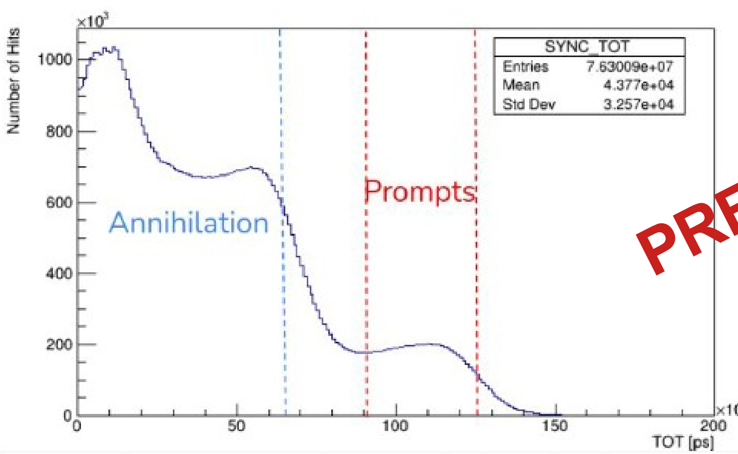
Previous limit (1996) < 2.6 x 10^{-6} (90% C.L.)
[Yang et al., Phys. Rev. A 54, 1952 (1996)]

QED test

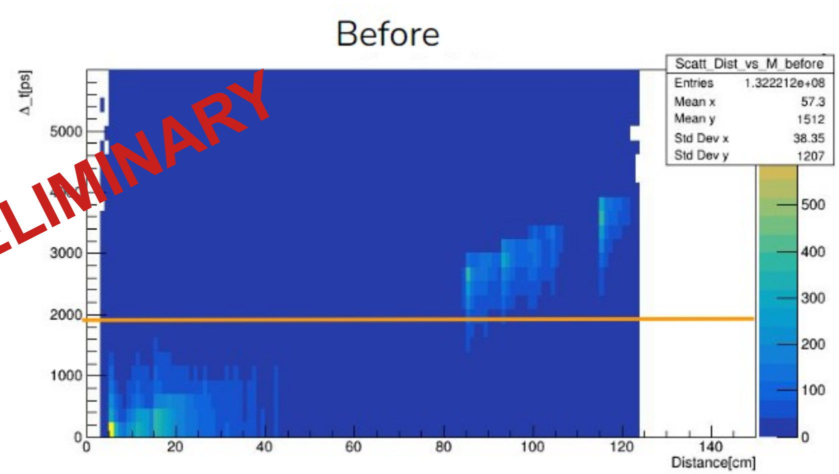
(O-Ps -> 5g)/(O-Ps -> 3g) = 1.67(99)(37) x 10^{-6}
[S. J. Freedman P. A. Vetter. Phys. Rev. A 66 (2002) 052505]

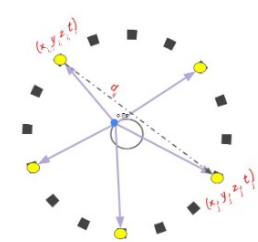
QED value(tree) = 0.9591 x 10^{-6}

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



PRELIMINARY





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

Run11 data

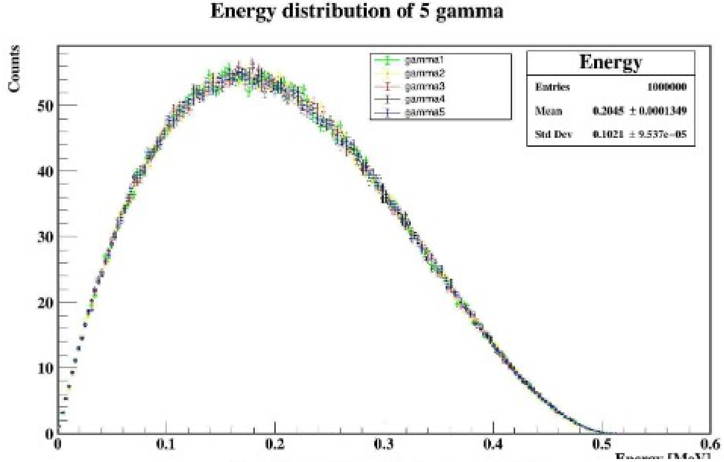
Ph.D. thesis of Pooja Tanty
In collaboration with W. Krzemien

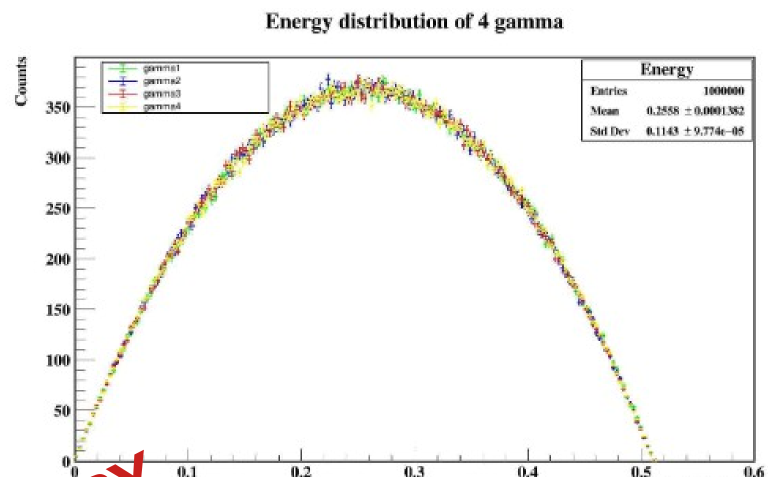
Rare decays of the oPs

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

5-gamma

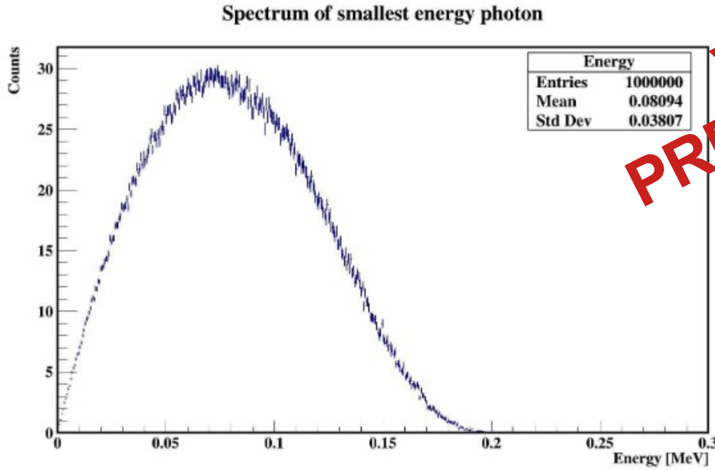
4-gamma

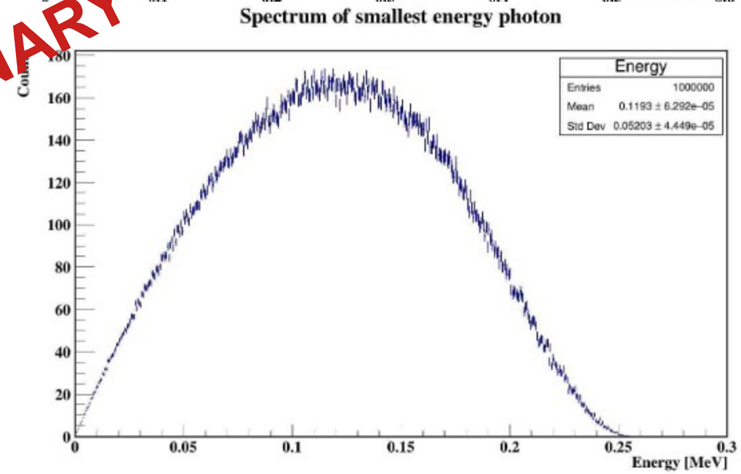




Generated true Monte Carlo

VERY PRELIMINARY





Ph.D. thesis of Pooja Tanty
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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 modelling of DM mediator and rare decays.

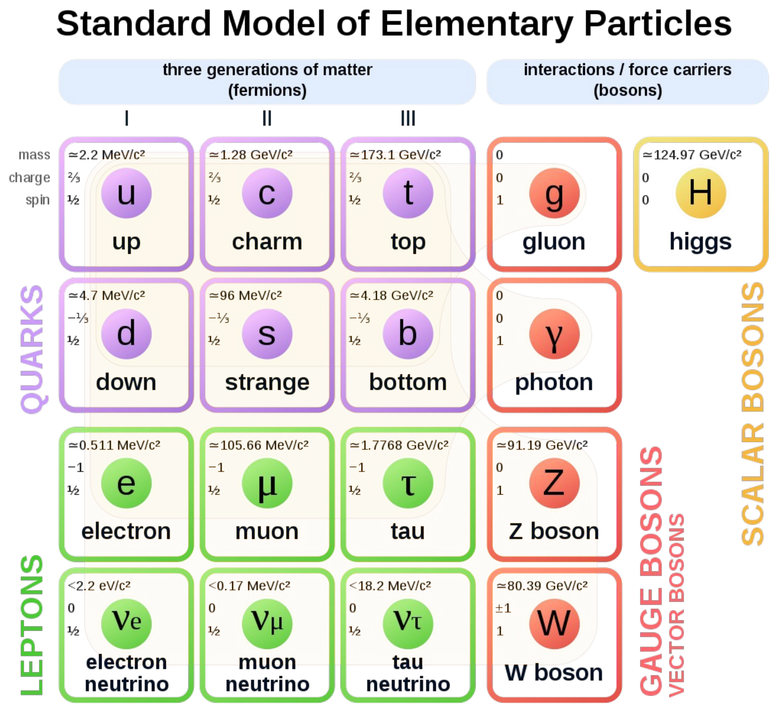
Facility: J-PET tomograph at Jagiellionan University
High performance and timing resolution with trigger-less acquisition system.
Modular/portable configuration.

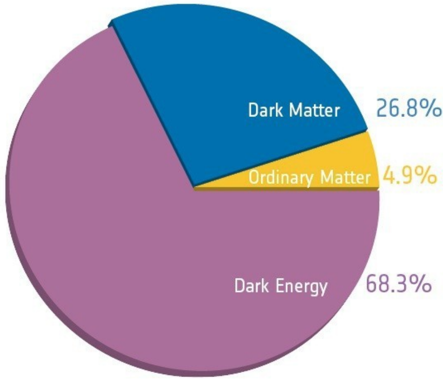
Aim: Mirror Matter search: sensitivity after two years of experiment below 10^{-5}

Thank you

Standard Model of Particles

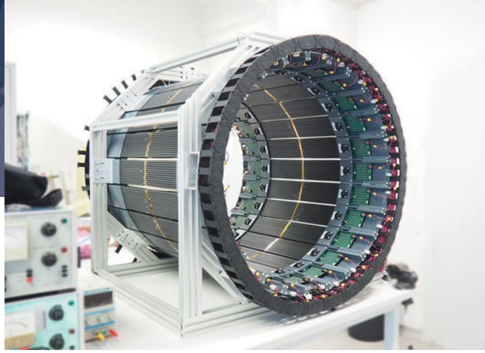
- Standard Model is now complete: 2012 LHC - Higgs boson
- Despite the highest energy reach at the LHC did not provide any convincing evidence for new degrees of freedom ... yet?
- Physics Beyond the Standard Model
  - What about gravity ?
  - Dark matter and Dark energy
  - Neutrino Masses
  - Matter-antimatter asymmetry
  - **Anomalous momentum of the muon**
  - "glueballs"
  - ....

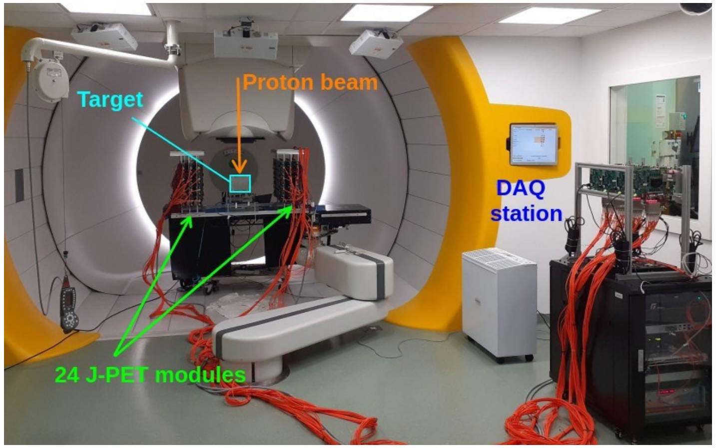


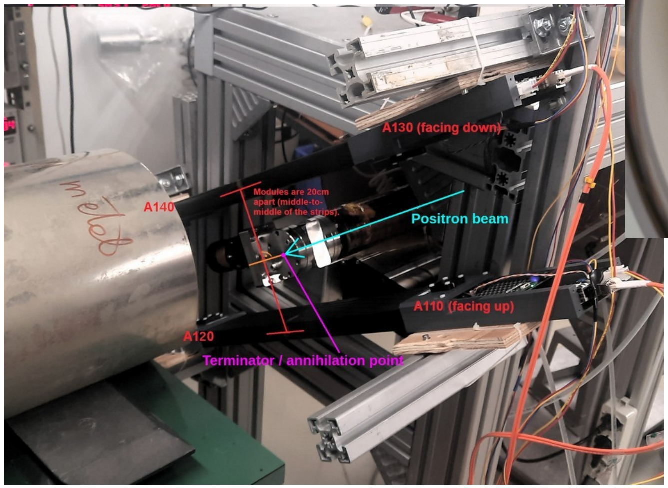


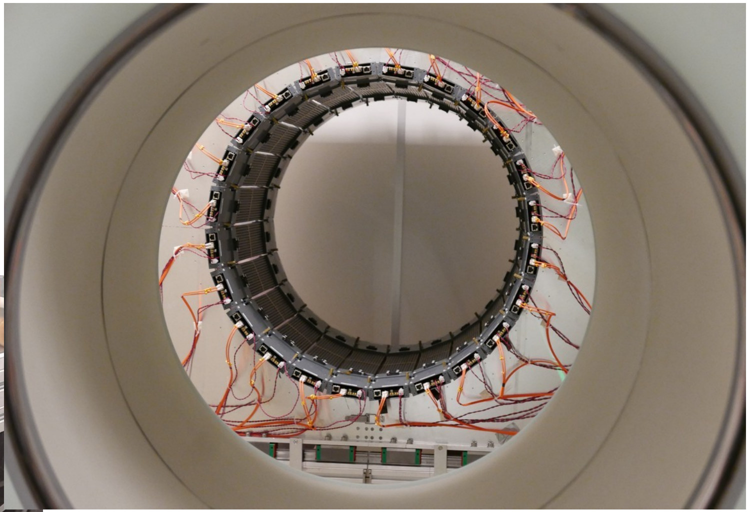
What are we searching?
How to search for it?

Mirror Matter in J-PET



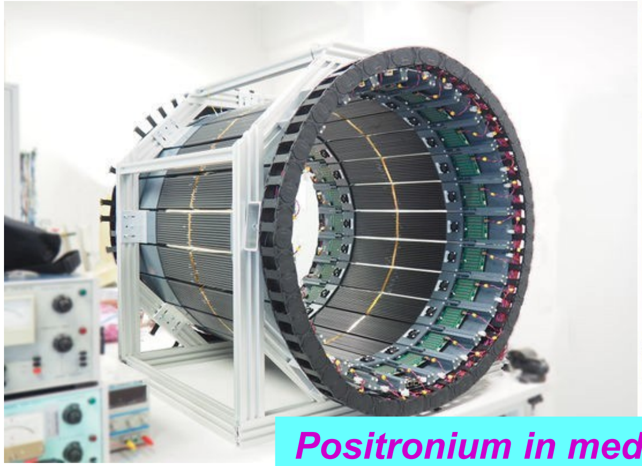


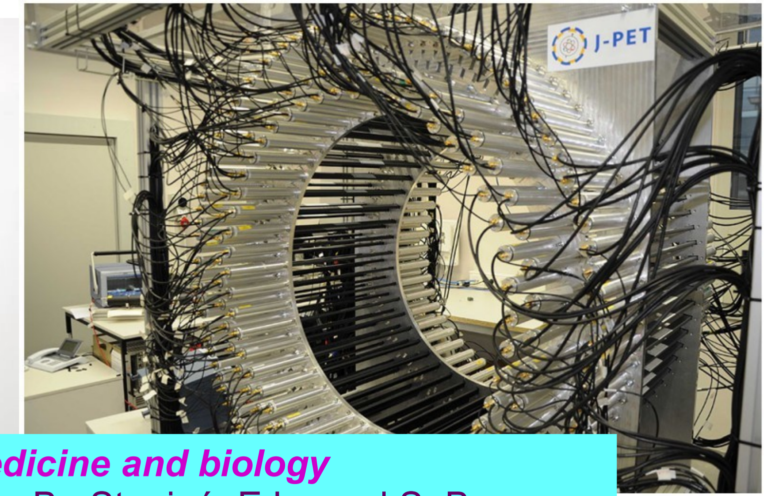


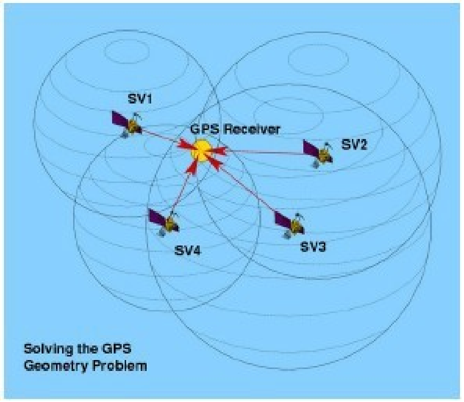


- **NCN grant Nr 2020/38/E/ST2/00112**
- **Mirror Matter search with J-PET detector**
- **Development of a tagger system**
  - **Positron tagger implementation to trigger the start of the reaction**
  - **Reduction of background**
  - **Additional start measurement**
  - **Extra measurement to trigger 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**

J-PET (Jagiellonian-PET TOMOGRAPHY)







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Nature Reviews Physics 1, pages 527-529 (2019)

First Positron Emission Tomography scanner built from plastic scintillator

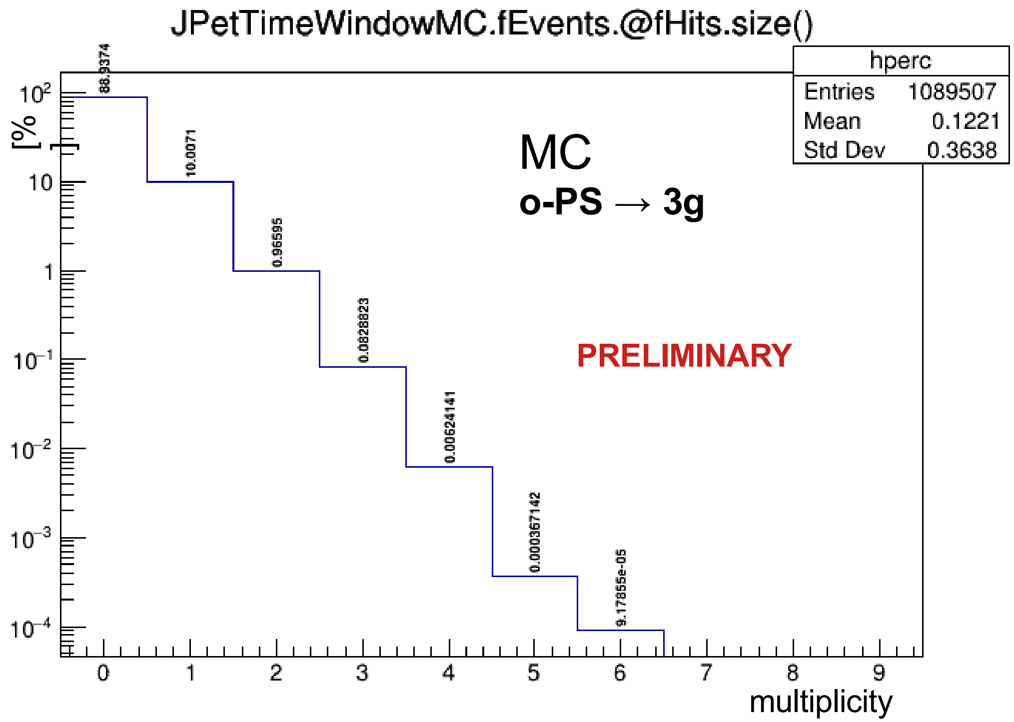
- Multidisciplinary detector
- Already involvement in the project developing analysis modules and calibration studies
- **Portable/modular prototype 2019 with higher detection probability**
- **High performance detector with high timing resolution**
- High acceptance
- **Trigger-less** and reconfigurable DAQ system
  - **Data has no filters: all data acquired is unfiltered**
- **GPS trilateration** reconstruction

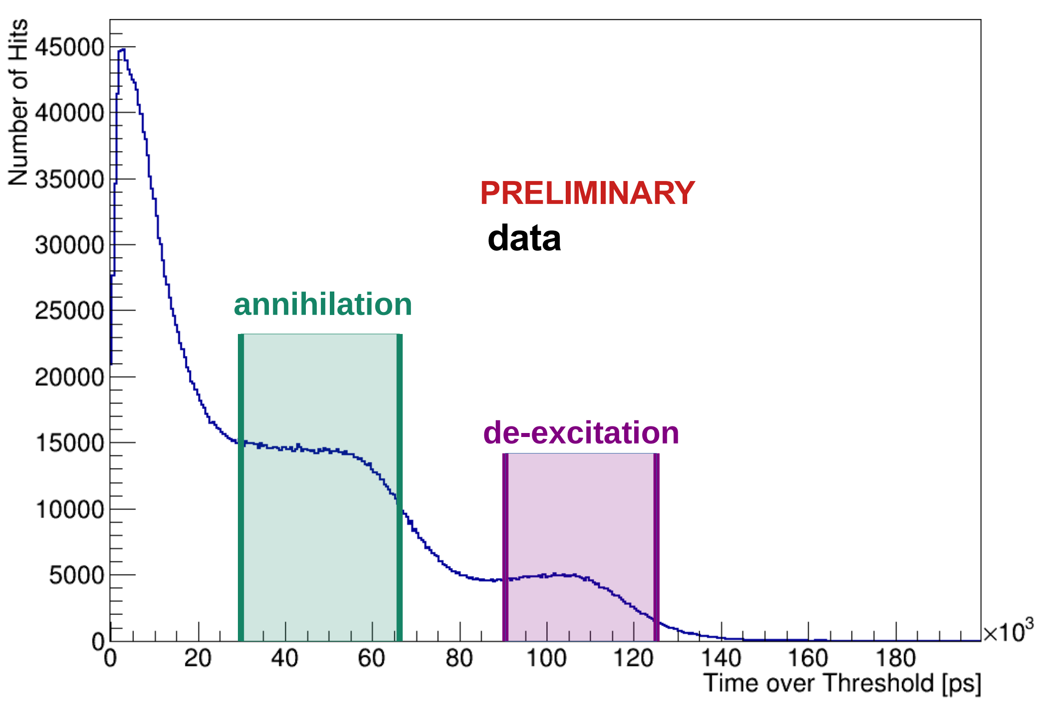
A. Gajos et al. Nucl. Instrum. Methods. A819 (2016) 54

Mirror Matter in J-PET: Studies

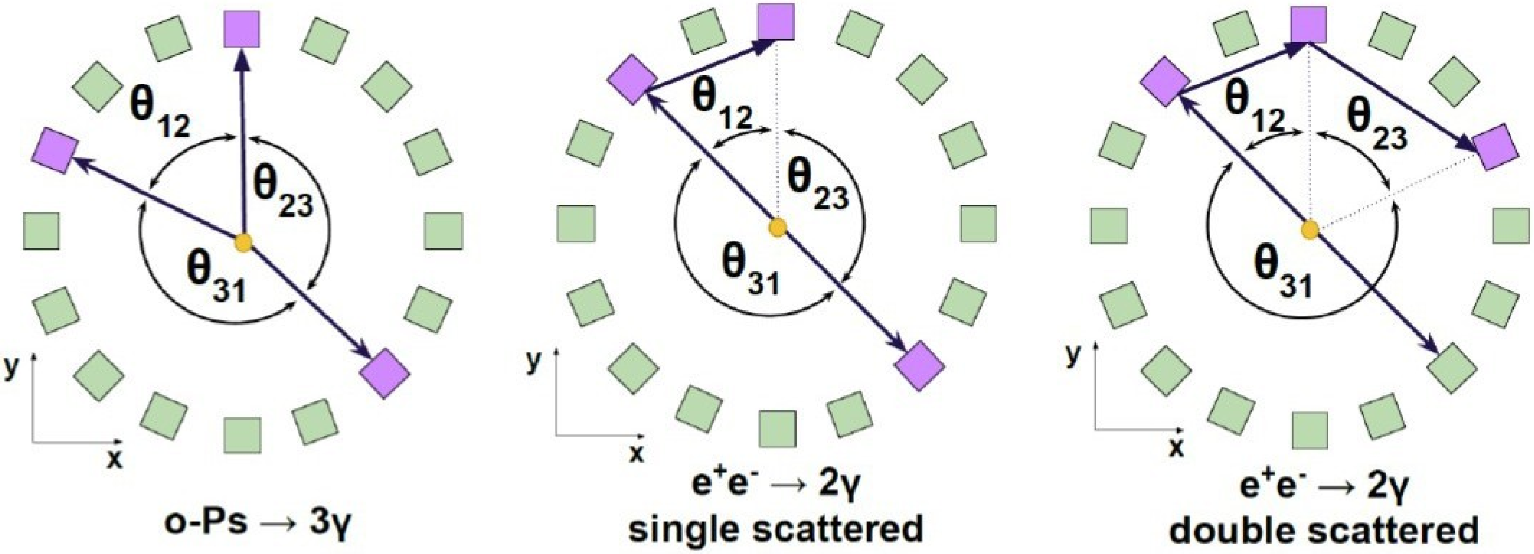
- **4-gamma events** to reconstruct the life-time
- Accurate measurement/**Precision Frontier**
  - High purity/high statistics

- 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

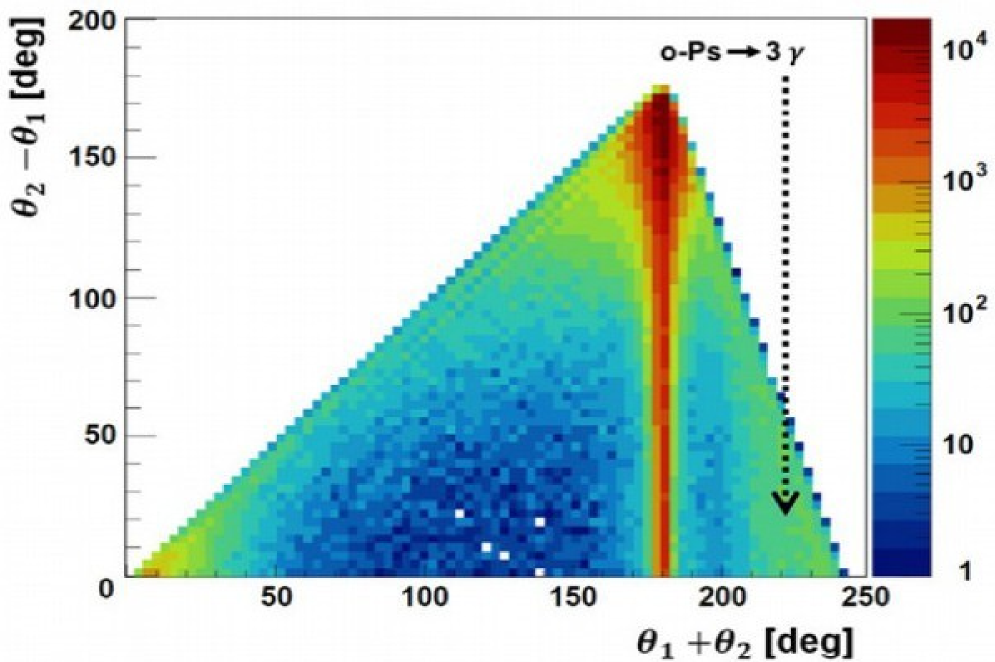




Mirror Matter in J-PET: Studies

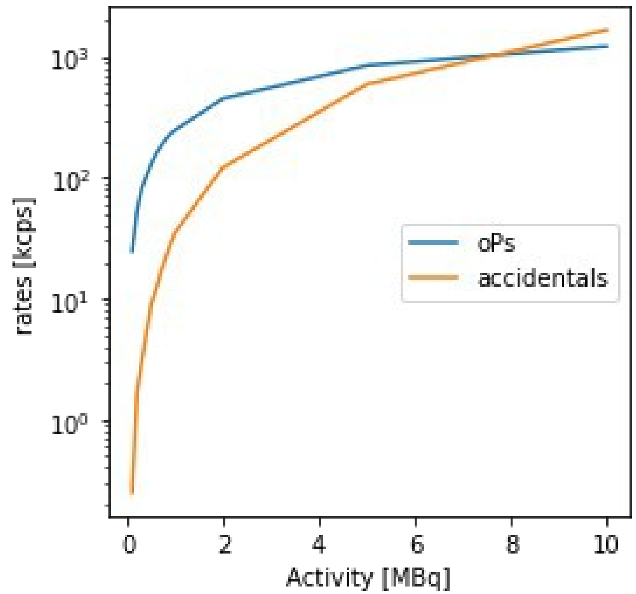


$\theta_{23} + \theta_{12} > 180$ $\quad$ $\theta_{23} + \theta_{12} = 180$ $\quad$ $\theta_{23} + \theta_{12} < 180$



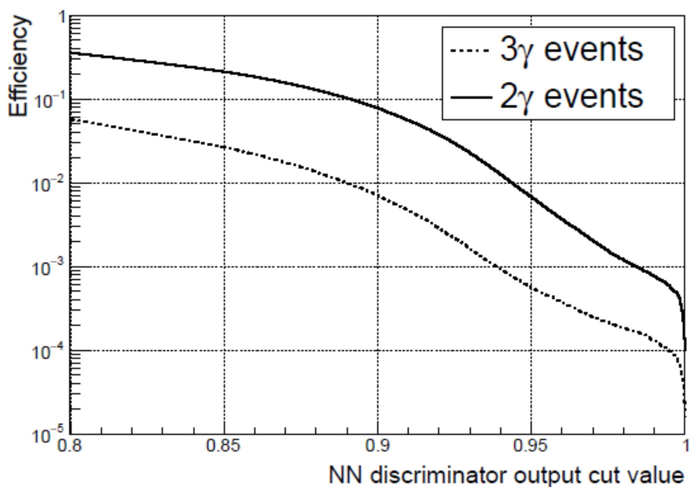
K. Dulski et al. NIM A 1008 (2021) 165452

Systematic Uncertainties



- **Accidental events**: events in coincidence but not correlated
  - Can be controlled with source activity
  - Evaluation performed in 2020 article

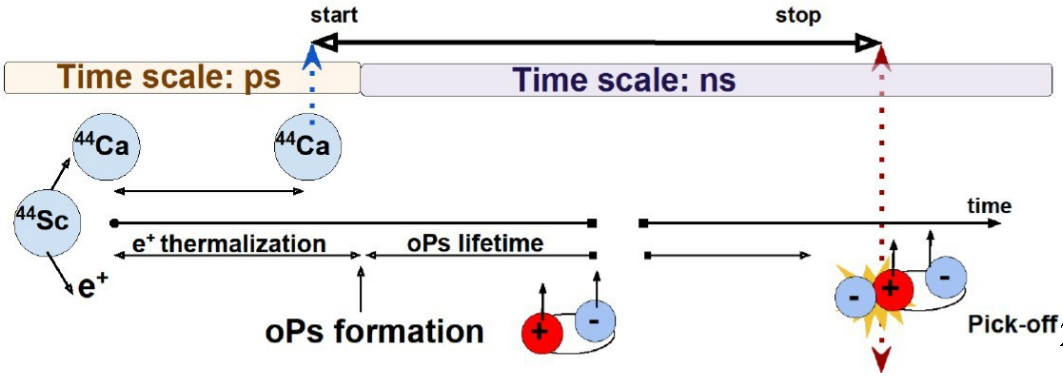
Acta Phys.Polon. B51 (2020) 165



C. Vigo et al. (2019) [805.06384v]

J. of Phys.: Conf. Series, Vol. 1138, conf 1

- **oPs interacting with the material (Pick-Off)**:
  - Can be directly evaluated from data
  - Can be used to train Machine Learning algorithms to reject the events (below 12 ppm level)



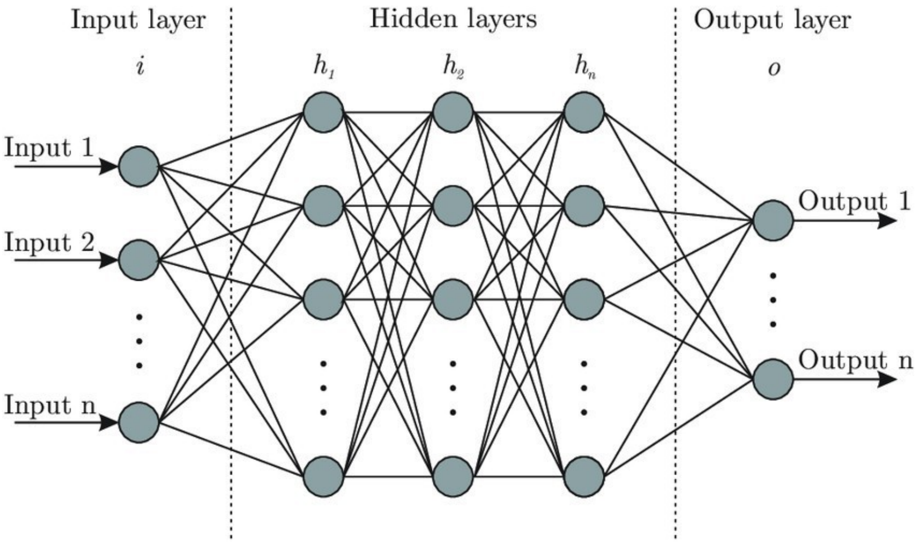
Machine Learning for background reduction

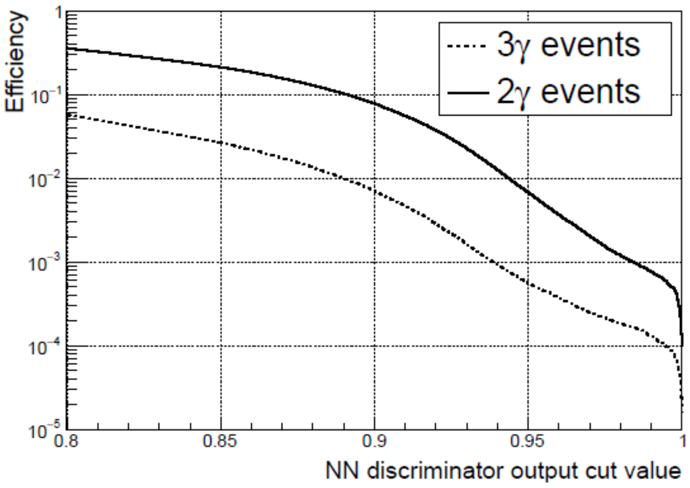
- On-going studies with
  - Random coincidences MC/data
  - **MC 3gamma/2gamma separation**
    - **Machine Learning (ML)**

Development of **Neural Network** algorithms to profit of the the excellent timing and reconstruction capabilities of the JPET detector → can be adapted in future to ***medical imaging***.

Byron P. Roe et al. Nucl.Instrum.Meth. A 543 (2005), 577–584.

Machine learning techniques, like Boosted Decision Trees and Artificial Neural Networks for background reduction



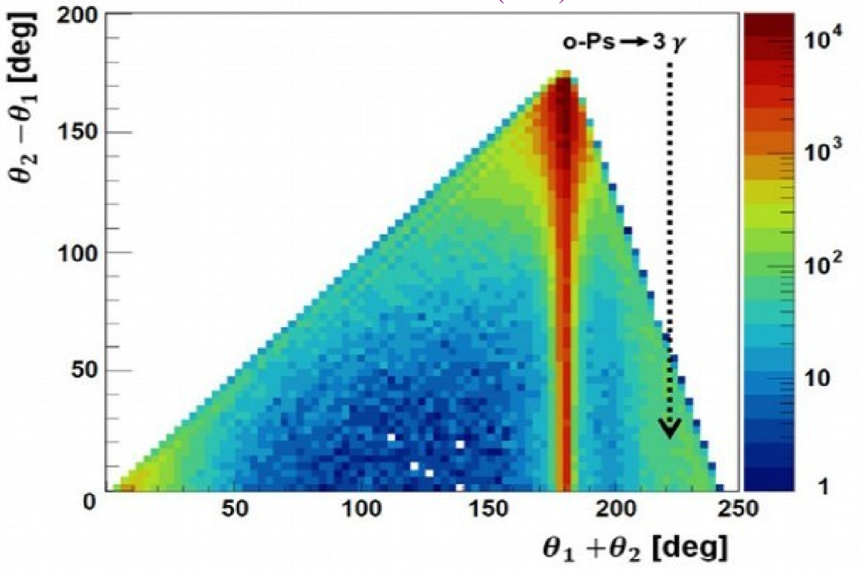


C. Vigo et al. [805.06384v]
Journal of Physics: Conference Series, Vol. 1138, conference 1

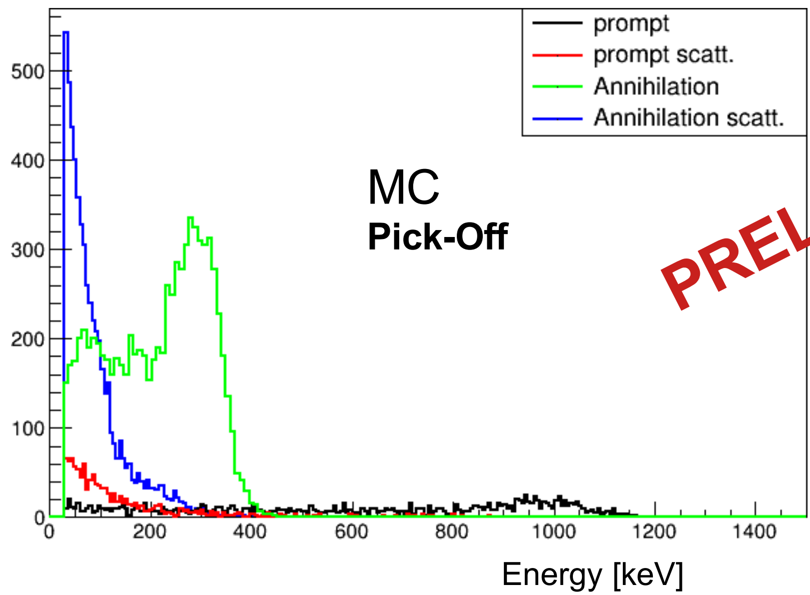
Analysis o-Ps lifetime

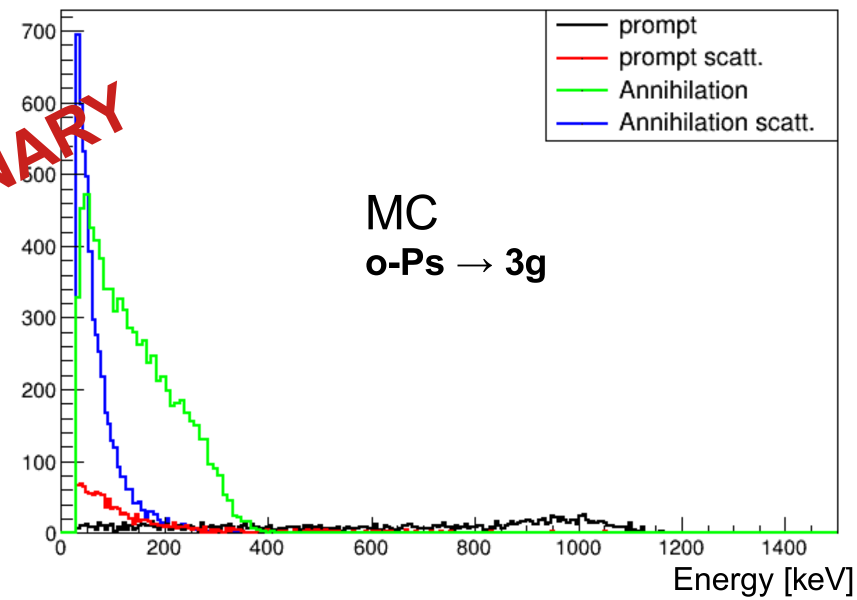
- **Machine Learning(ML) models tested for background identification and discrimination**
  - Number of features, different architectures, strategies, correlations, etc … studies on-going
  - Impemented in Keras + TensorFlow
  - Training, validation and test performed in GEANT4 Monte Carlo (MC) simulations 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**

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



- **Preliminary results**





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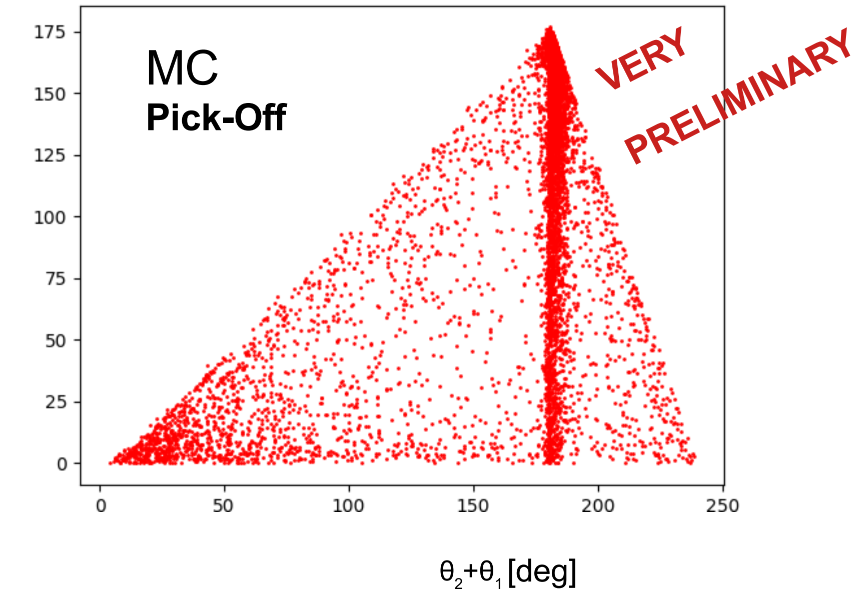
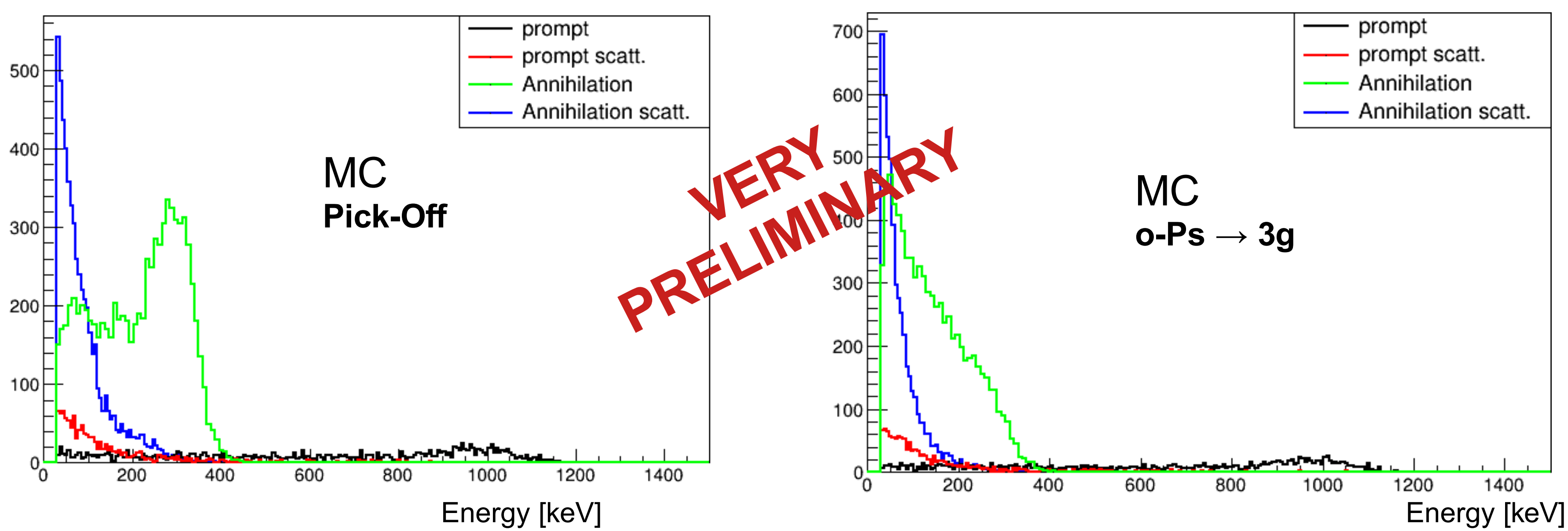
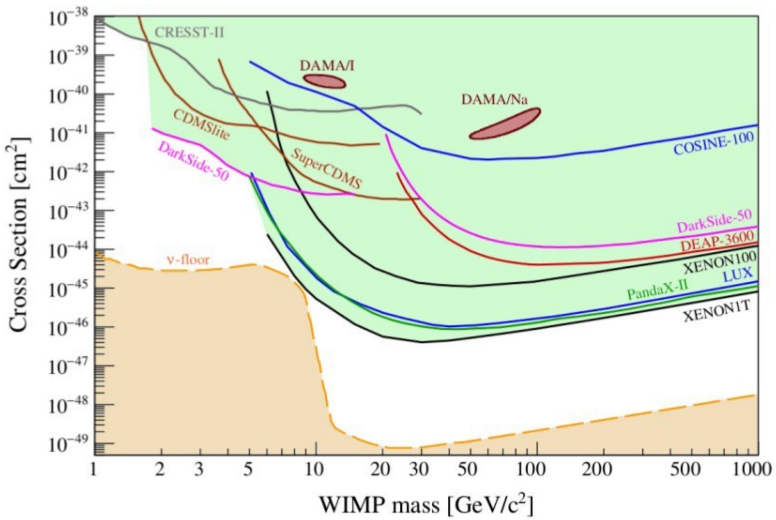


- **Preliminary results**



Dark Matter: WIMPs

- WIMPs (Weakly Interacting Massive Particles)



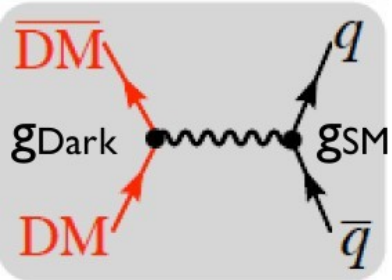
arXiv:1903.03026

- 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

↓

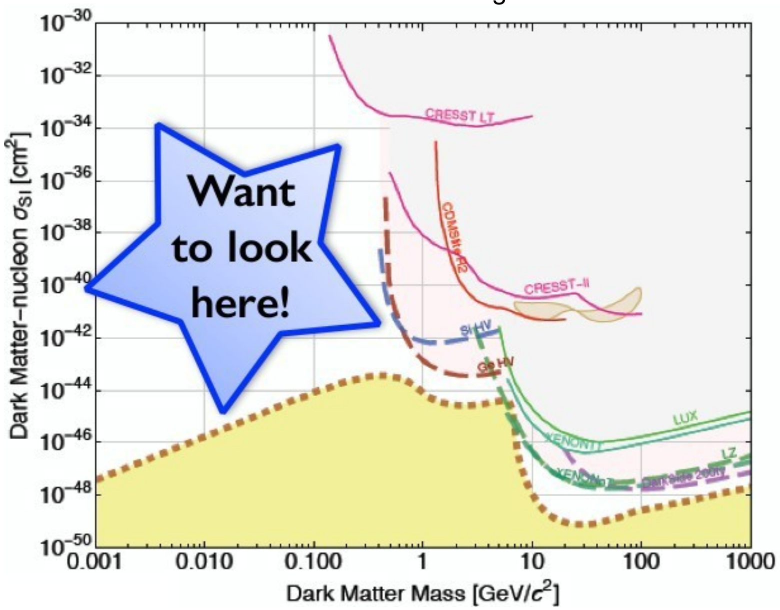
New Force

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

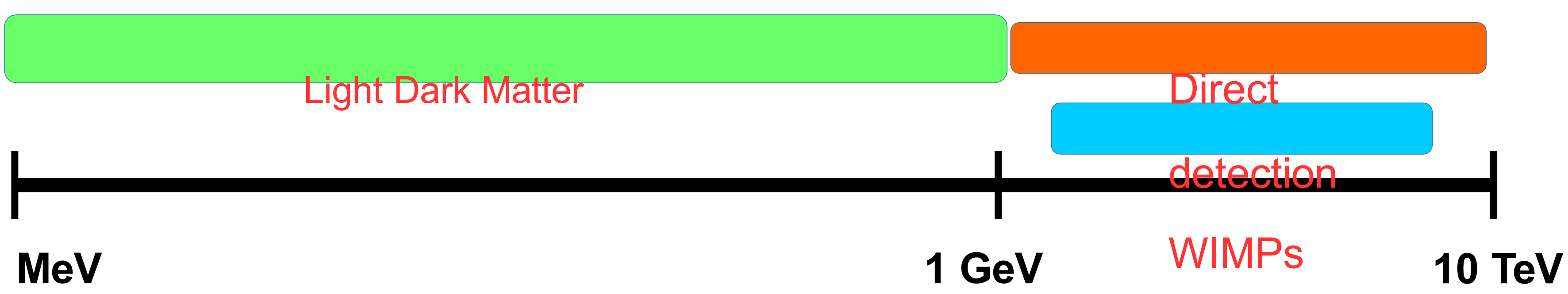
Light Dark Matter

- **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

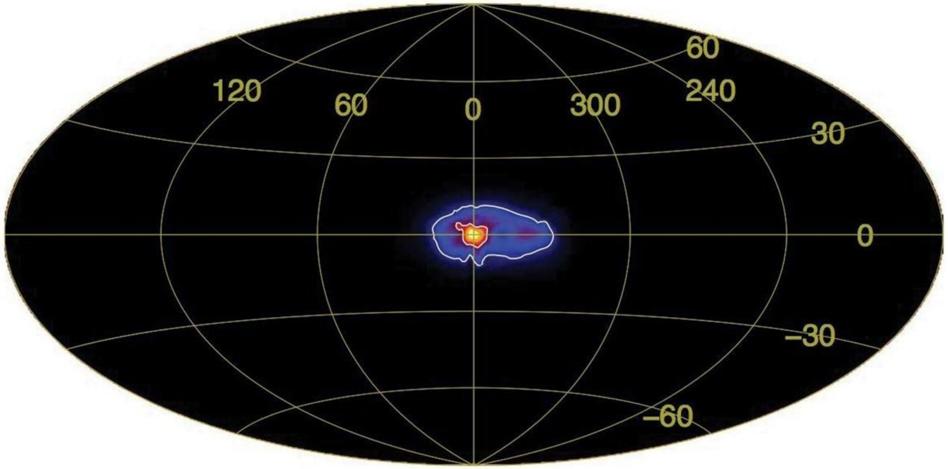
M.Battaglieri talk

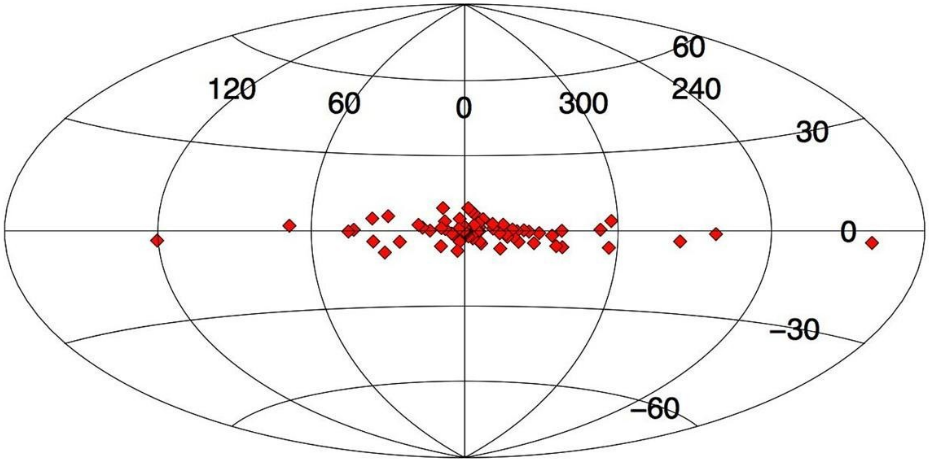


Dark Sector or Hidden Sector (DM not directly charged under SM interactions)



Motivations for new GeV-scale forces





The left-hand panel shows the glow of 511 keV gamma rays coming from the annihilation of electrons by their antimatter counterparts, the positrons of the Milky Way observed by SPI. The map shows the entire sky, with the galactic centre at the middle. The emission can be seen extending towards the right-hand side of the map. The color code shows the intensity of the signal (white more intense). The right-hand panel shows the distribution of hard low mass X-ray binary stars detected by IBIS/ISGRI telescope on board INTEGRAL satellite. This stellar population has a distribution that matches the extent of the 511 keV map.
(Credits: Integral CEA and CESR team)

Motivations for new GeV-scale forces

CoGeNT scattering cross sections with nucleus

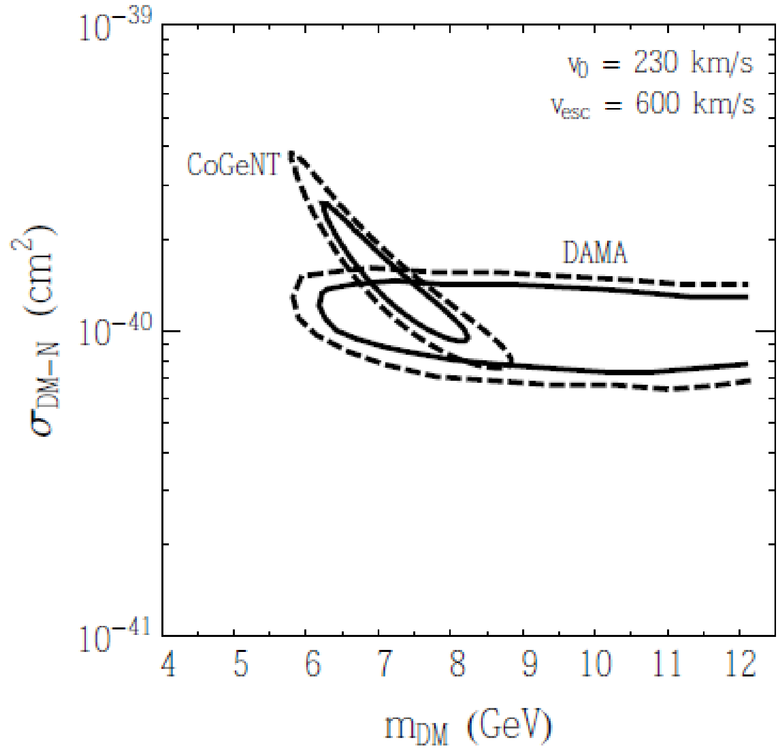
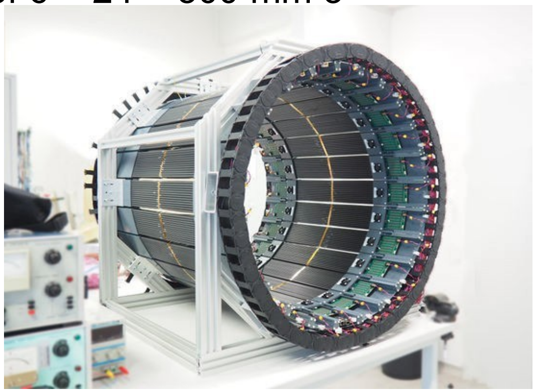
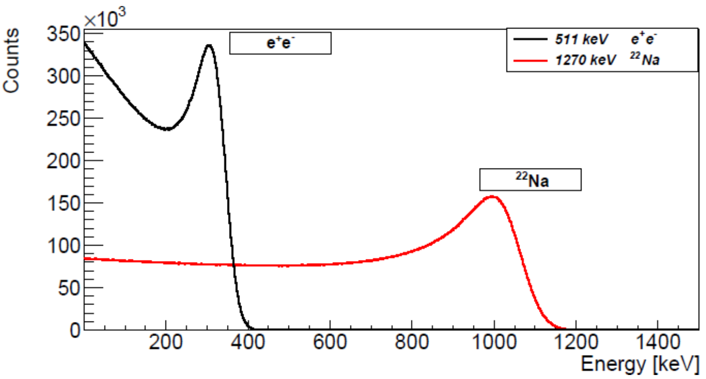


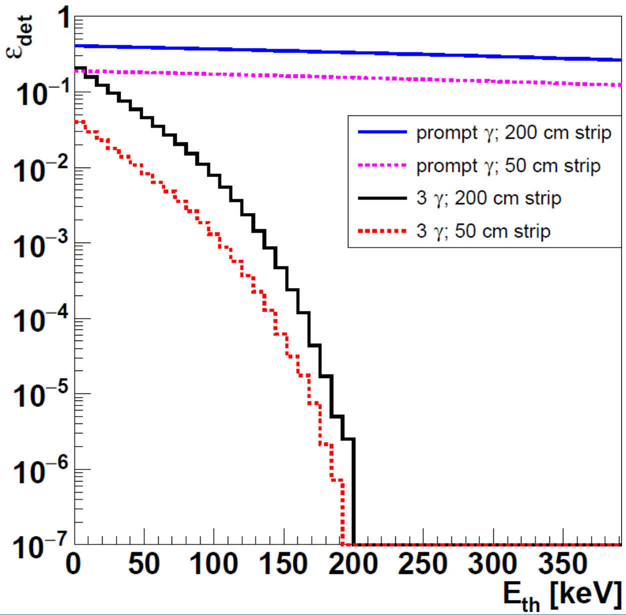
FIG. 6: A comparison of the parameter space favored by the CoGeNT spectrum with that favored by the modulation spectrum reported by DAMA/LIBRA [7]. Good agreement is found, but somewhat large quenching factors for low energy nuclear recoils on sodium are required ($Q_{Na} \sim 0.40-0.45$) [7].

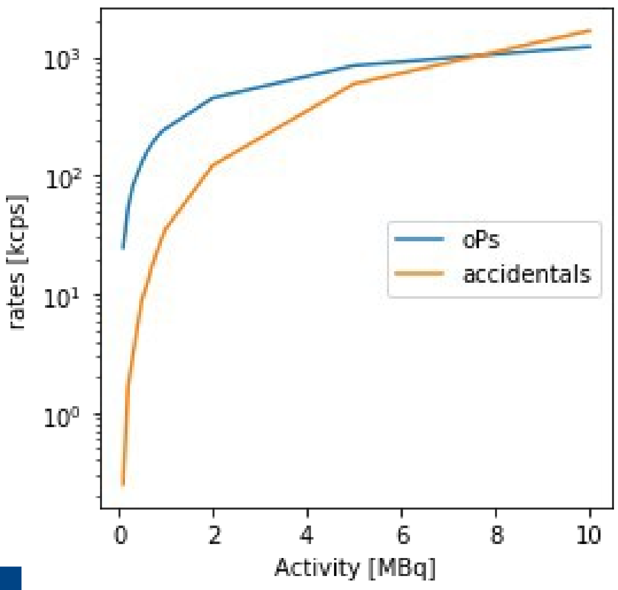
J-PET (Jagiellonian-PET TOMOGRAPHY)

- 3 + 1 layer arrangement
  - 192 scintillator modules 7 × 19 × 500 mm 3 arranged in 3 layers read out by vacuum tube photomultipliers (PMs) with radius of 42.5 cm and length of 50 cm
  - 4-th layer modular JPET: 312 plastic scintillator strips in 24 modules with dimensions of 6 × 24 × 500 mm 3 read out by matrices of silicon photomultipliers (SiPM)
- Novel digital front-end electronics probing signals at multiple thresholds
- Trigger-less and reconfigurable DAQ system
- Annihilation gamma quanta hit time measurement: σ_t (0.511 MeV) ~ 125 ps
- Gamma quanta energy resolution: $\sigma_E/E = 0.044/\sqrt{E(\mathrm{MeV})}$
- Resolution of photon relative angles measurement ~ 1◦
- Possibility of o-Ps spin and photon polarization measurement
- Increased detection efficiency and improved time resolution with layer 4





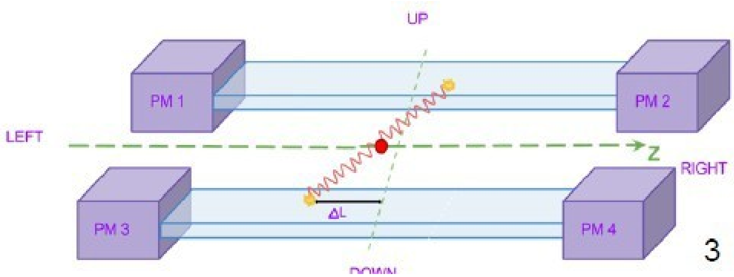




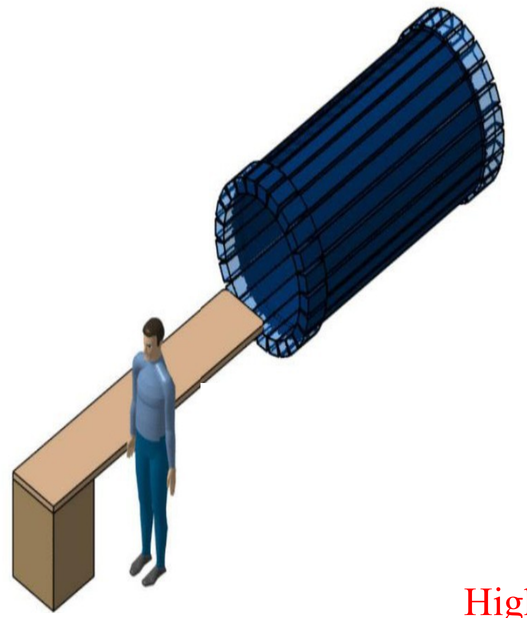
P. Moskal, D. Kisielewska et al. Phys. Med. Biol. 64 (2019)

Cost-effective total body solution

$$\Delta l = \frac{(t_2 - t_1) \cdot v}{2} \cong \frac{(t_2 - t_1) \cdot c}{4}$$



$$\Delta x = \frac{(t_l - t_r) \cdot c}{2} \Longrightarrow \Delta x = \frac{\Delta t}{2} \cdot c$$

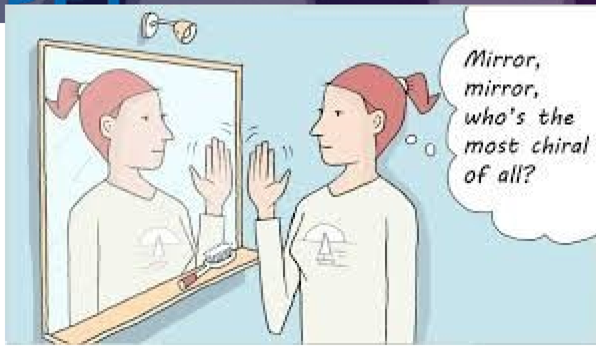


Change of the paradigm

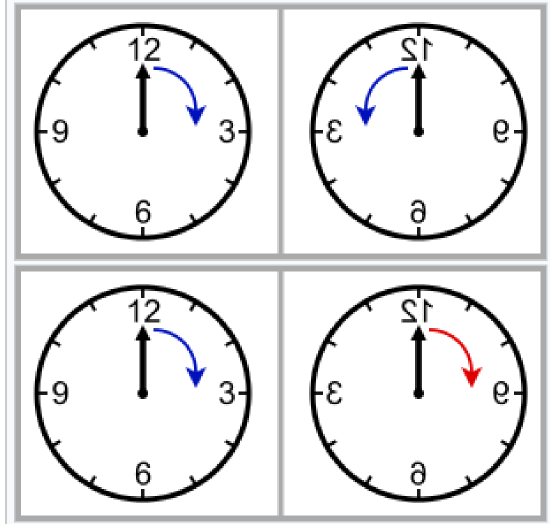
Crystal	→	**Plastic**
Energy	→	Time
High efficiency	→	Low efficiency
Photoeffect	→	Compton scattering
Low acceptance	→	High acceptance
Analo	→	Digital electronics
g electronics	→	No master trigger
Trigge		
ring		

P. Moskal, P 388 555 [WIPO ST 10/C PL388555] (2009), PCT/PL2010/00062 (2010), WO2011008119, US2012112079, JP2012533734, EP2454612.

J-PET: P. Moskal et al., Nucl. Inst. and Meth. A 764 (2014) 317-321
J-PET: P. Moskal et al., Nucl. Inst. and Meth. A 775 (2015) 54-62
J-PET: P. Moskal et al., Phys. Med. Biol. 61 (2016) 2025-2047



Mirror Matter



Top: P-symmetry: A clock built like its mirrored image behaves like the mirrored image of the original clock.
Bottom: P-asymmetry: A clock built like its mirrored image does *not* behave like the mirrored image of the original clock.

*from Parity article in wikipedia

Weak interactions violates parity. Experimental confirmations:

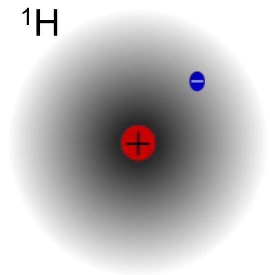
C. S. Wu et al.
Phys. Rev. 105 (1956) 1413

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

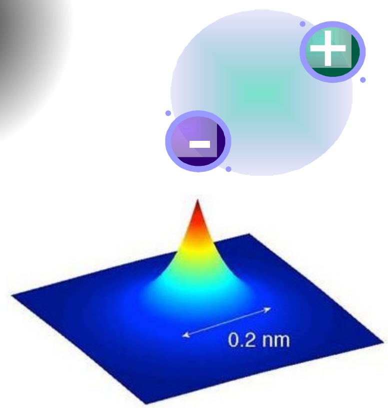
- Mirror Matter (or Alice Matter) was proposed as an explanation of Parity symmetry violation [T.D., Yang C. N. Phys. Rev. 1956. V. 104. P. 254.]
  - Each particle has a mirror partner with the same properties and opposite chirality (left/right - handed)
  - Mirror particles interact with normal matter 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)



$S = 0$ $\quad \downarrow\uparrow - \uparrow\downarrow \quad$ $^{1}S_{0}$ **Para-positronium**

$\uparrow\uparrow$

$S = 1$ $\quad \uparrow\uparrow + \downarrow\downarrow \quad$ $^{3}S_{1}$ **Ortho-positronium**

$\downarrow\downarrow$

	$^{1}S_{0}$	$^{3}S_{1}$
L	**0**	**0**
S	**0**	**1**
J	**0**	**1**

$C\,|Ps\rangle = (-1)^{L+S}\,|Ps\rangle$

$C\,|n\gamma\rangle = (-1)^{n}\,|n\gamma\rangle$

	$^{1}S_{0}$	$^{3}S_{1}$
C	+	-
P	-	-
CP	-	+

Decay modes

$^{1}S_{0}$ **Para-positronium** $\quad$ **p-Ps** $\rightarrow$ **2n γ** $\quad$ **τ (p-Ps) ≈ 125 ps**

$^{3}S_{1}$ **Ortho-positronium** $\quad$ **o-Ps** $\rightarrow$ **(2n+1) γ** $\quad$ **τ (o-Ps) ≈ 142 ns**

oPs in JPET tomograph

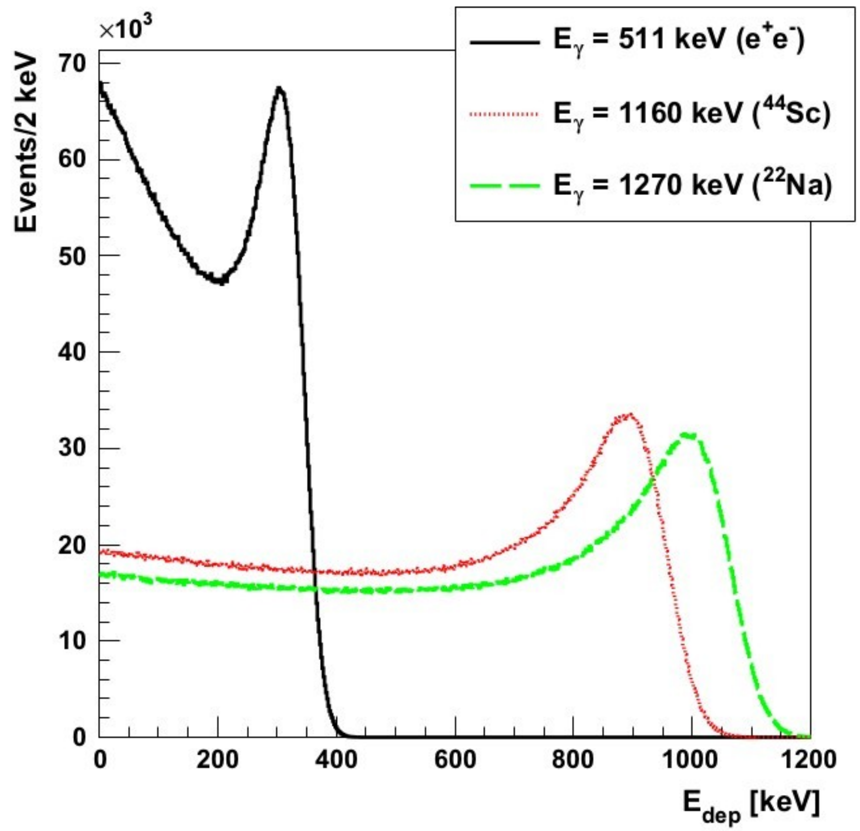
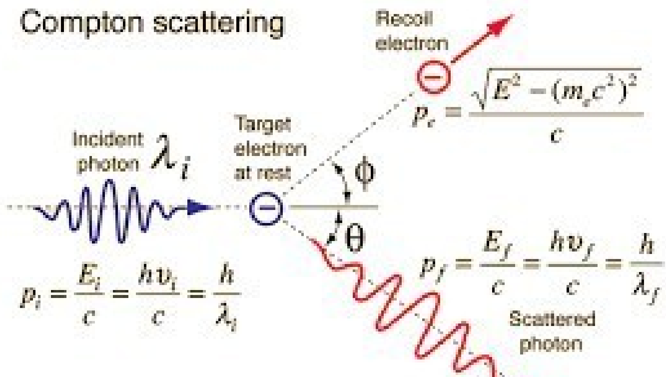


Fig. 3 Simulated spectra of deposited energy in plastic scintillators for gamma quanta from $e^+e^- \rightarrow 2\gamma$ annihilation and for de-excitation gamma quanta originating from isotopes indicated in the legend. The spectra were simulated including the energy resolution of the J-PET detector [20] and were normalized to the same number of events

Gamma quanta interact in detector via Compton scattering

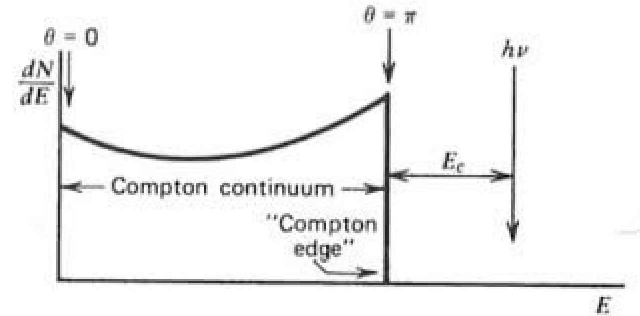


$$p_e = \frac{\sqrt{E^2 - (m_e c^2)^2}}{c}$$

$$p_i = \frac{E_i}{c} = \frac{h\nu_i}{c} = \frac{h}{\lambda_i}$$

$$p_f = \frac{E_f}{c} = \frac{h\nu_f}{c} = \frac{h}{\lambda_f}$$

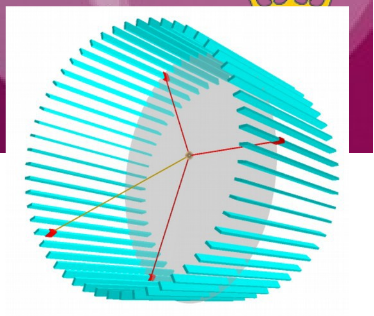
$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$



Radioactive sources

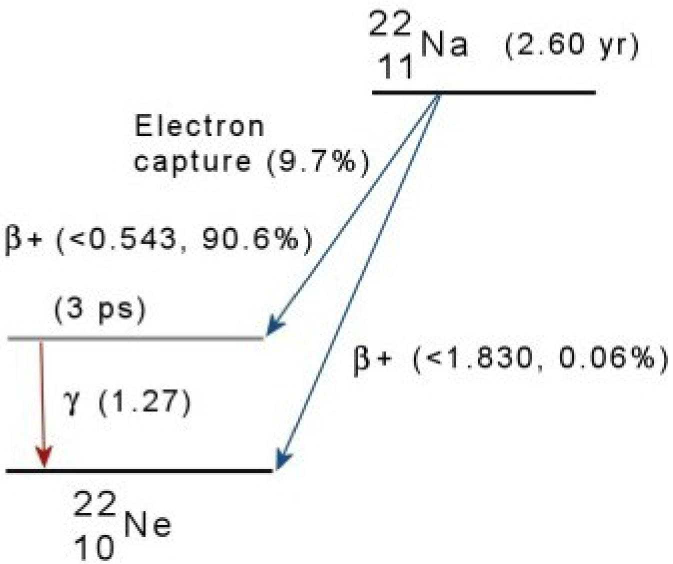
Table 1 Summary of major physical characteristics of beta-plus isotopes useful for PET imaging and positron annihilation lifetime spectroscopy (PALS) investigations. For isotopes that decay into excited states the properties of emitted gamma quanta are denoted. Data were adapted from [27]

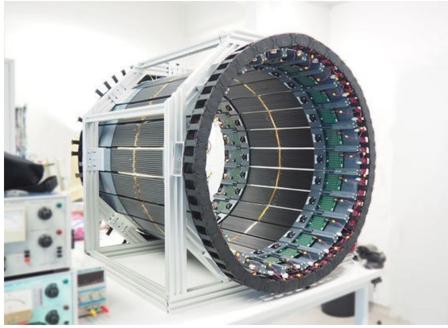
Isotope	Half-life	β^+ decay	E_γ (MeV)	$E_{e^+}^{max}$ (MeV)	Excited nuclei lifetime
Isotopes for PALS and PET imaging					
^{22}Na	2.6 (years)	$^{22}\text{Na} \rightarrow ^{22}\text{Ne} + e^+ + \nu_e + \gamma$	1.27	0.546	3.63 (ps)
^{68}Ga	67.8 (min)	$^{68}\text{Ga} \rightarrow ^{68}\text{Zn} + e^+ + \nu_e + \gamma$	1.08	0.822	1.57 (ps)
^{44}Sc	4.0 (h)	$^{44}\text{Sc} \rightarrow ^{44}\text{Ca} + e^+ + \nu_e + \gamma$	1.16	1.474	2.61 (ps)
Isotopes for PET imaging					
^{68}Ga	67.8 (min)	$^{68}\text{Ga} \rightarrow ^{68}\text{Zn} + e^+ + \nu_e$	–	1.899	–
^{11}C	20.4 (min)	$^{11}\text{C} \rightarrow ^{11}\text{B} + e^+ + \nu_e$	–	0.961	–
^{13}N	10.0 (min)	$^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu_e$	–	1.198	–
^{15}O	2.0 (min)	$^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu_e$	–	1.735	–
^{18}F	1.8 (h)	$^{18}\text{F} \rightarrow ^{18}\text{O} + e^+ + \nu_e$	–	0.634	–



- 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

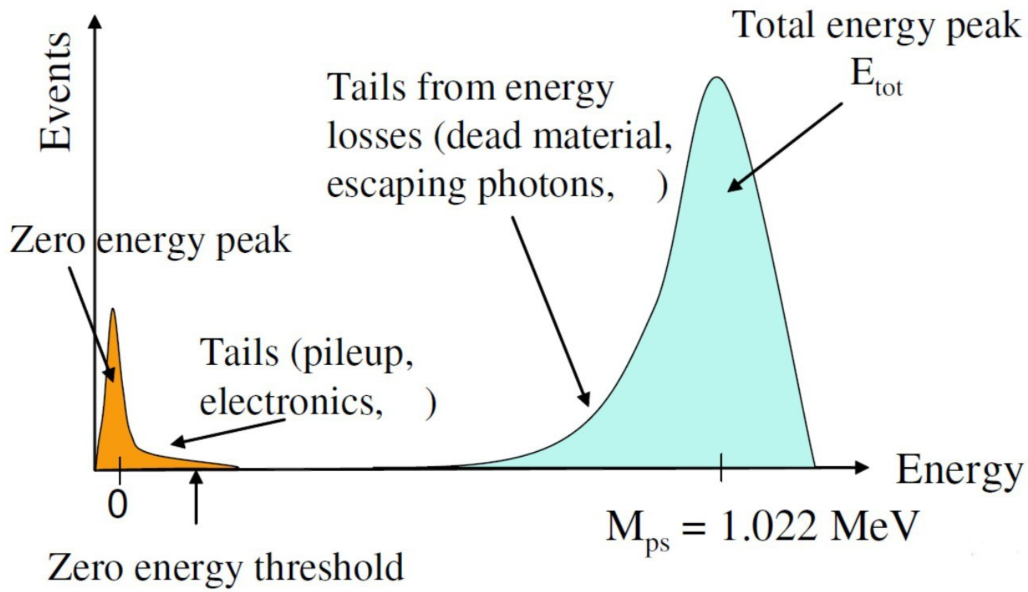
- *Searches in vacuum* [Phys. Rev. D 97, 09200]
  - Slow positron beam (15000 e^+/s)
  - BR < 5.9×10^{-4} (90% C.L.)
  - Photon mixing strength $\varepsilon < 3.1 \times 10^{-7}$ (90% C.L.)

- 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 $\varepsilon < O(10^{-7})$**

“zero-signal” experiment

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

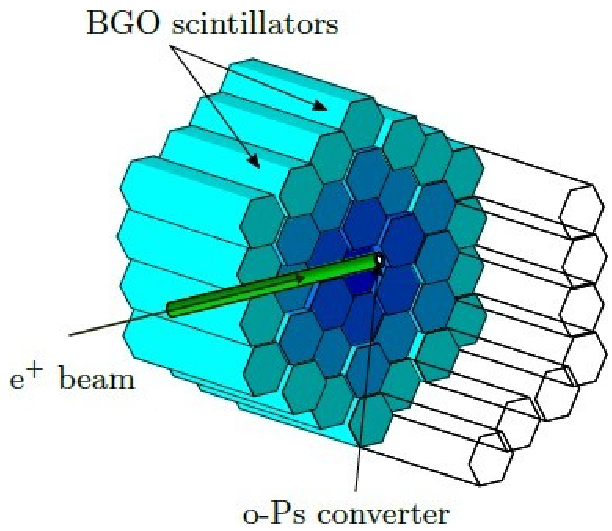
- Time measurement: time start by triggering on positron, time stop when detecting any of the annihilation photons
- Use of a calorimeter (BGO crystals) to measure the energy of γ from ortho positronium decay products and calculate $E_{tot} = \sum E_i$.
- Search for excess events (peak) in the spectrum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



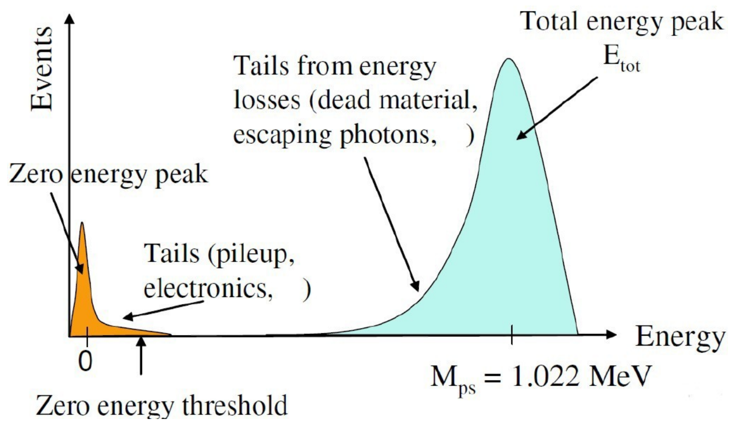
Decay not observed
UL calculated for BR

- *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

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

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

GPS trilateration

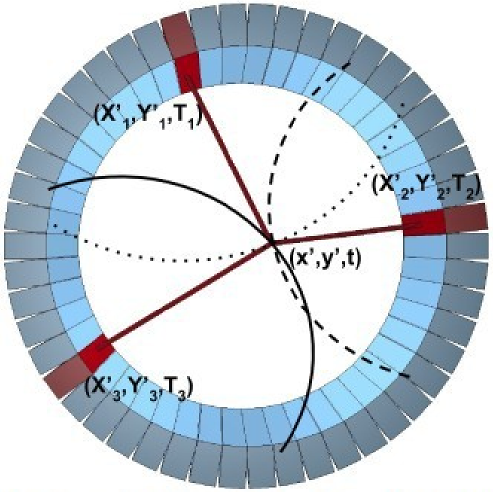
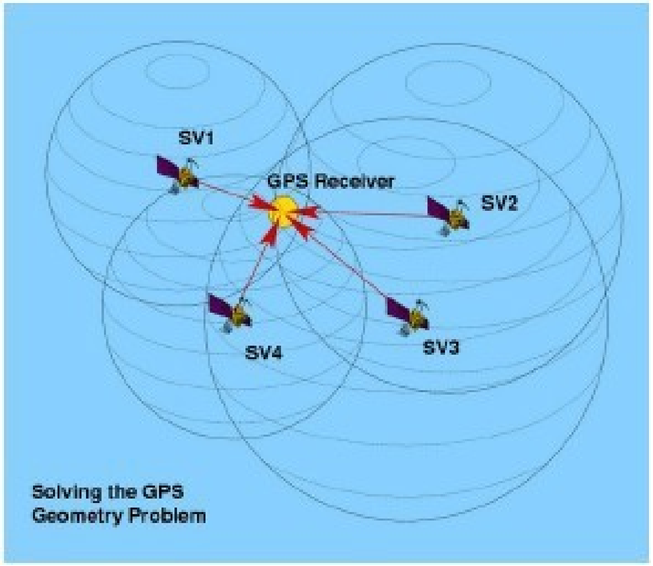


Figure 5: A scheme of the detector showing o-Ps $\rightarrow 3\gamma$ annihilation. For clarity only a single layer with registered hits is shown. Red lines represent the gamma photons from ortho-positronium annihilation. The trilateration method is used to determine the annihilation position and time (x', y', t) along the annihilation plane. For each recorded photon a circle, which is a set of possible photon origin points, centered in the hit-position and parameterised with the unknown o-Ps annihilation time is considered. The intersection of the three circles corresponds to the o-Ps $\rightarrow 3\gamma$ annihilation point.



2 gamma background

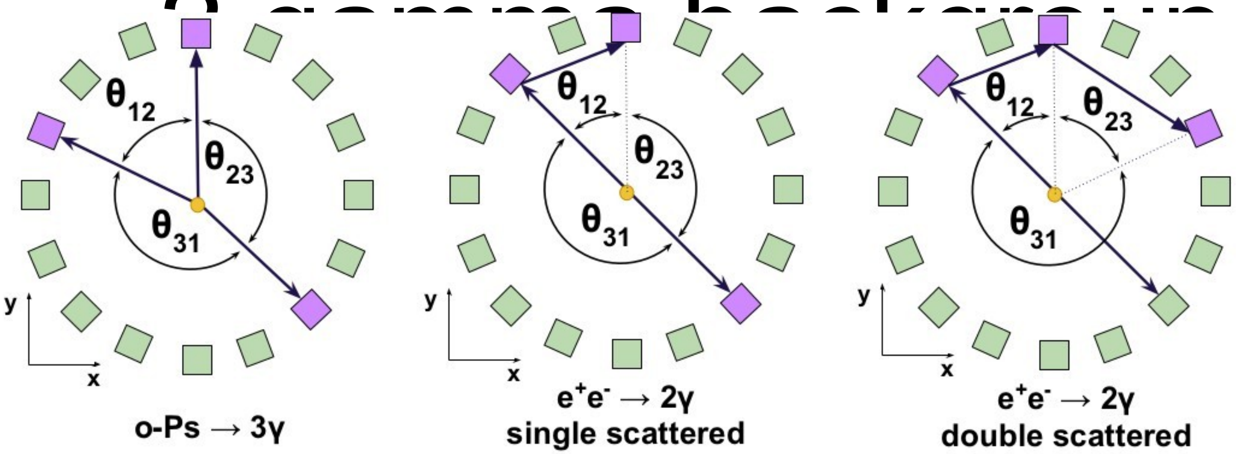


Fig. 13 Pictorial illustration of the possible response of the detector to o-Ps → 3γ and e^+e^- annihilation into 2γ. Arranged circularly *squares* represents scintillator strips—*purple* and *green* colors indicate strips where the gamma quanta were or were not registered, respectively. The *arrows* represents gamma quanta occurring in the events, while *dotted lines* indicate naively reconstructed gamma quanta. Examples of primary and secondary scatterings are depicted

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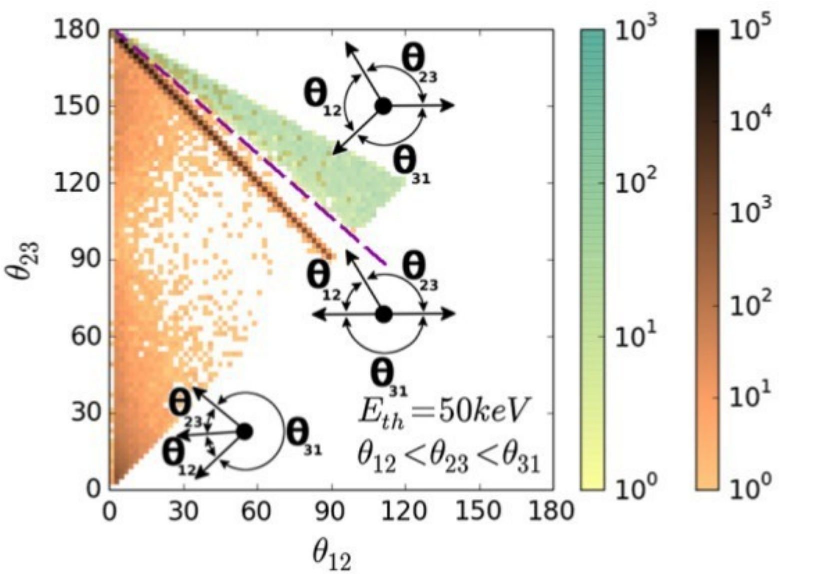
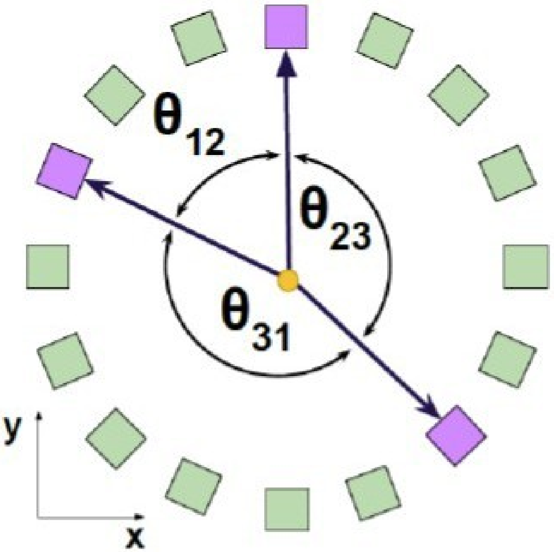
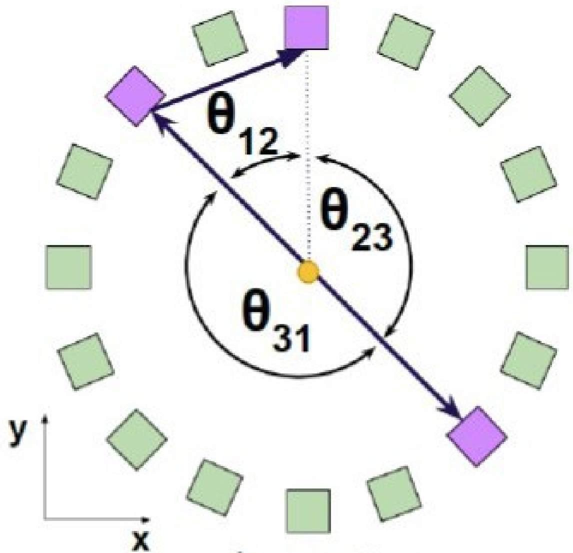




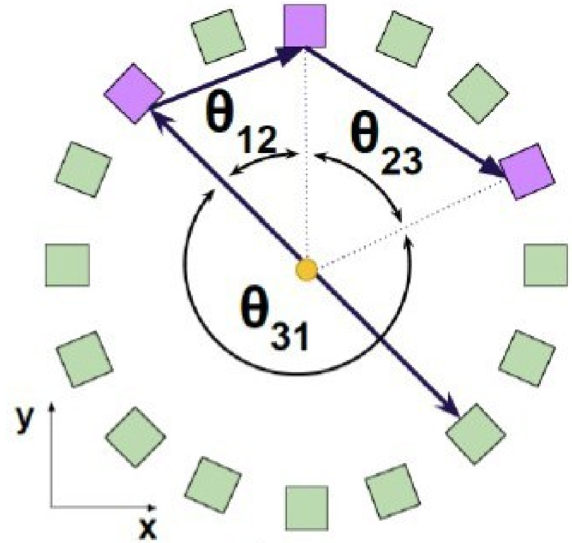
o-Ps → 3γ

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



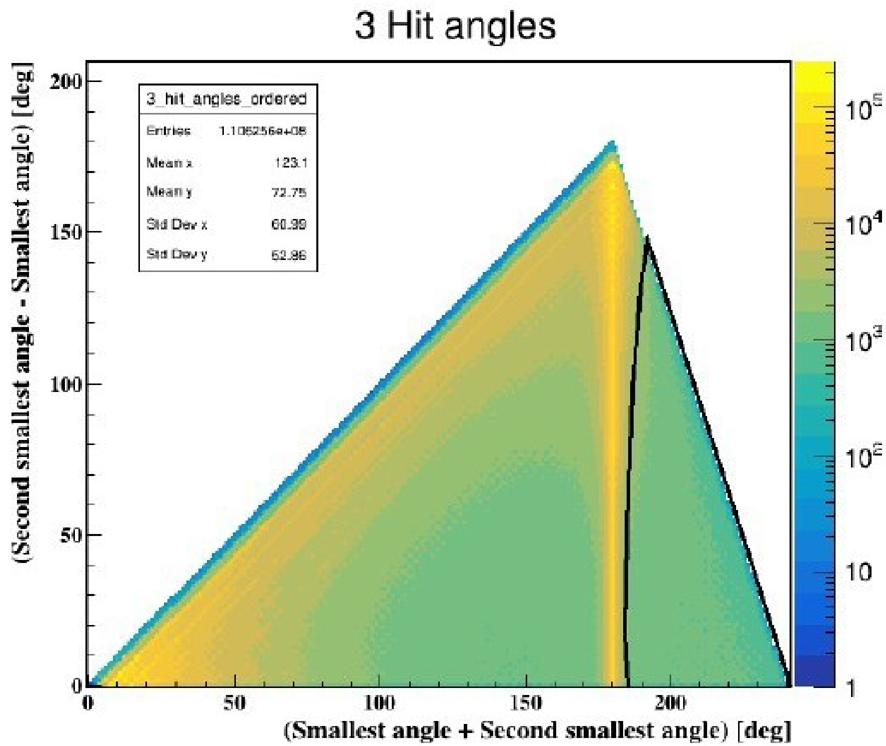
e⁺e⁻ → 2γ
single scattered

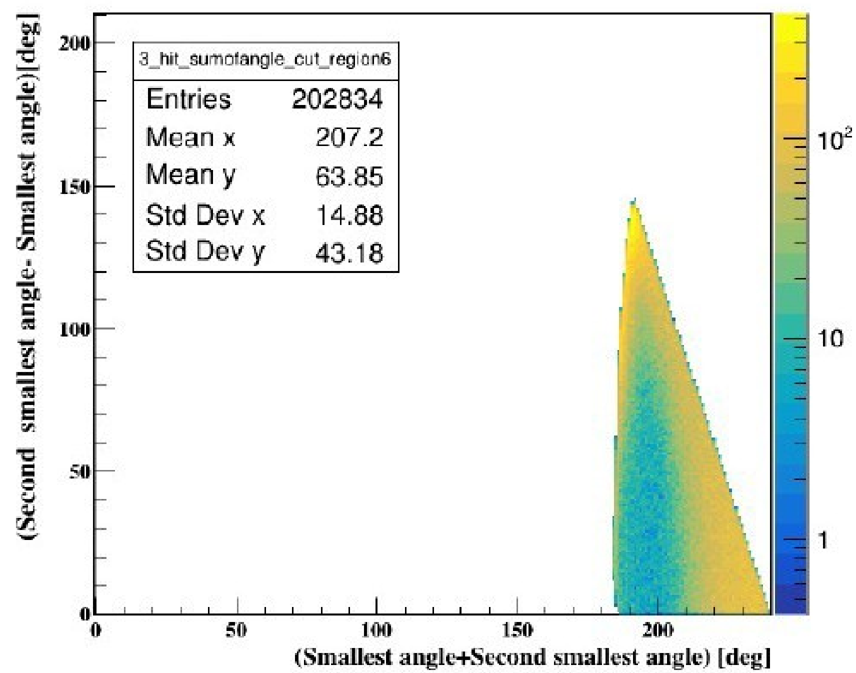
$$\theta_{23} + \theta_{12} = 180$$



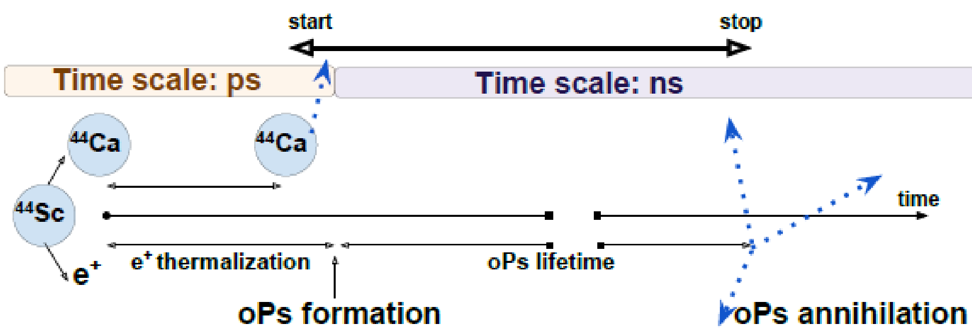
e⁺e⁻ → 2γ
double scattered

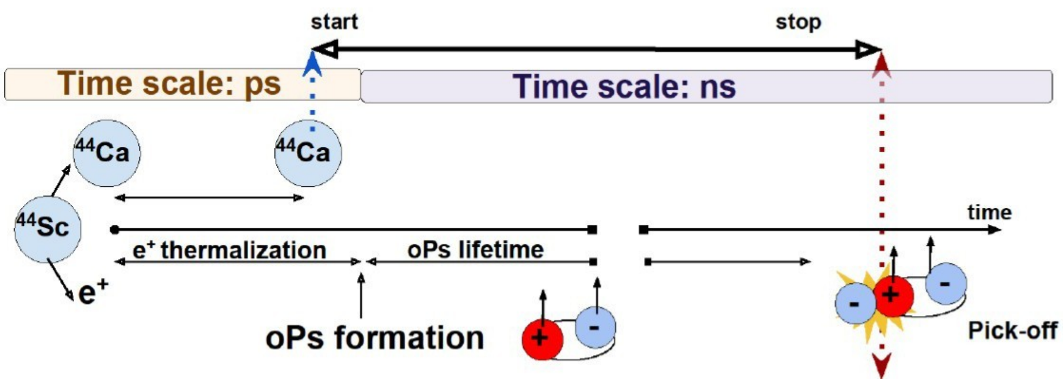
$$\theta_{23} + \theta_{12} < 180$$





The main experimental challenge: pick-off effect





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

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

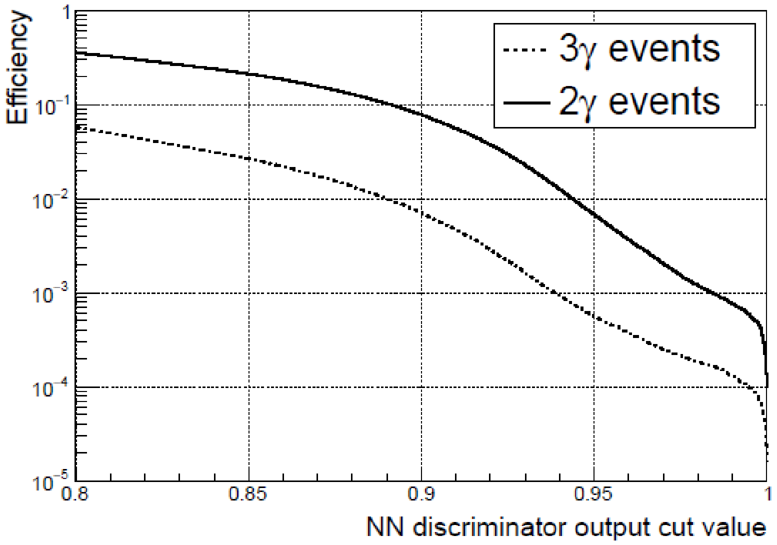
velocity of o-Ps

target density

annihilation cross-section

Neural network classifier for pick-off $\lambda_{pick}(t)$ determination

ETHZ method proposal



C. Vigo et al. (2019) [805.06384v]

J-PET

- very good timing resolution
- very good angular resolution (~1 deg)
- vertex determination with trilateration methods

- very good topological cut

+

- reasonable energy resolution