Hunting Dark Matter with the J-PET

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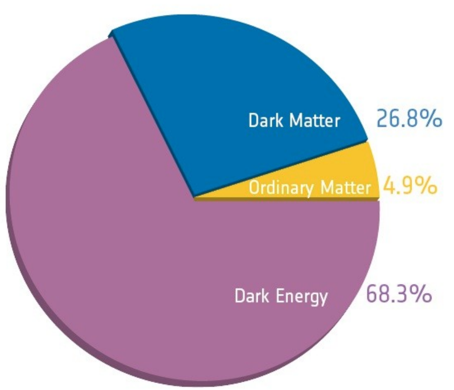
Seminar and Positronium Physics
10-01-2022

Outline

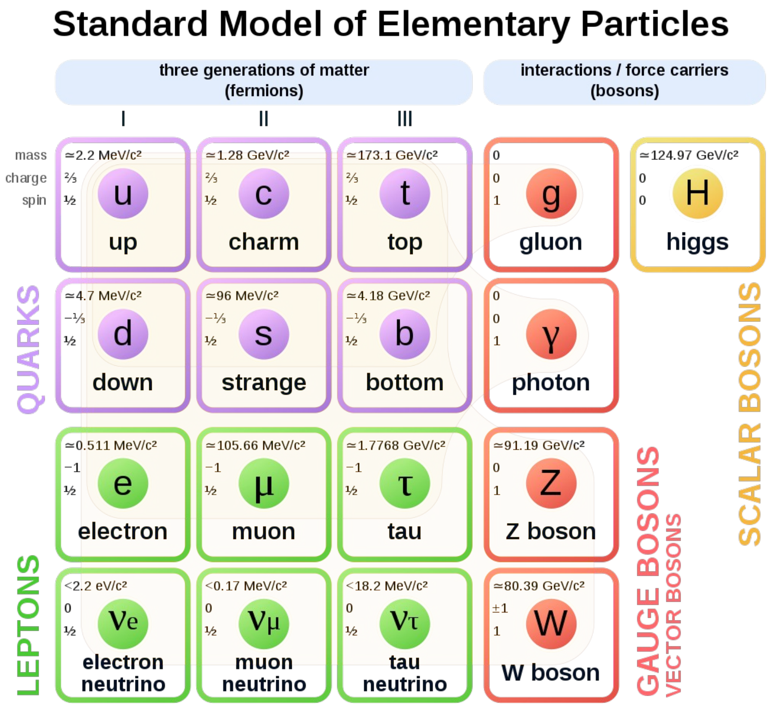
- The Standard Model
  - Physics Beyond the Standard Model (BSM)
  - **g-2** and Dark Matter
- Dark Matter
  - Minimal case and New Forces
  - Other searches
- Mirror Matter
- Ortho-Positronium life-time
- Mirror Matter in o-Ps
- J-PET search
  - Concept of the measurement
  - J-PET plans
  - Systematic Uncertainties
    - **Machine Learning** for Mirror Matter
  - Summary

Standard Model of Particles

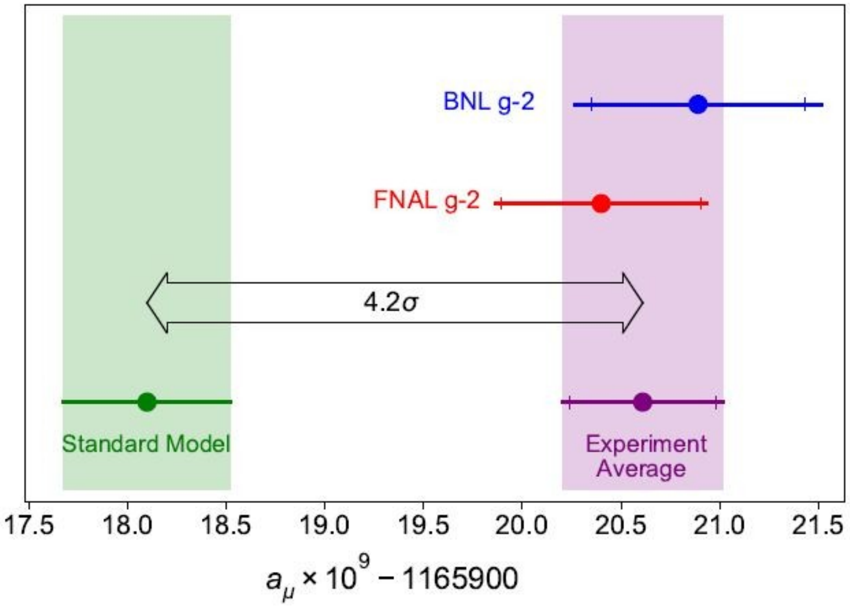
- Standard Model is now complete: 2012 LHC - Higgs boson
- Despite the highest energy reach at the LHC did not provide any convincing evidence for new degrees of freedom ... yet?
- Physics Beyond the Standard Model
    - What about gravity ?
    - Dark matter and Dark energy
    - Neutrino Masses
  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

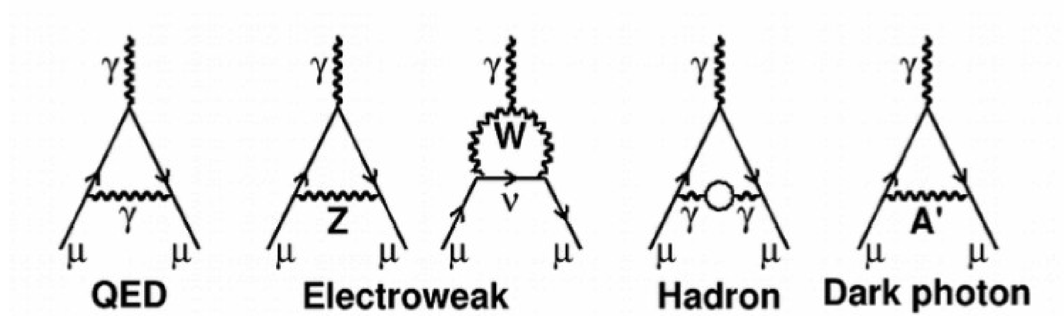


What are we searching?
How to search for it?



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

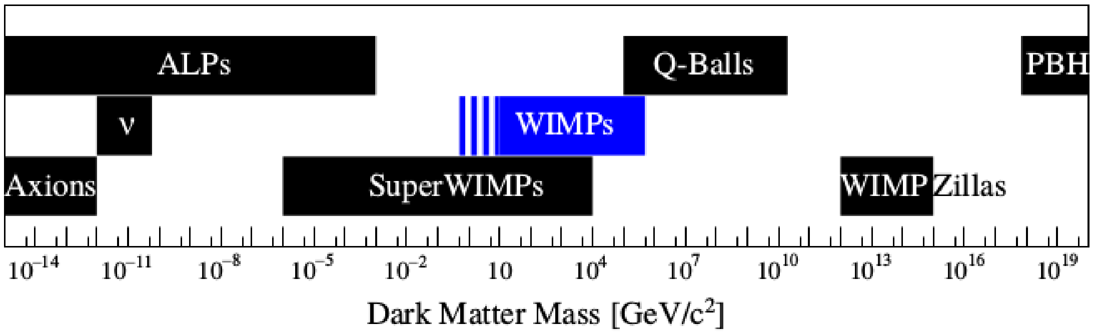
Dark Matter

- Is 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

The Dark Matter Nature

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

arXiv:1903.03026

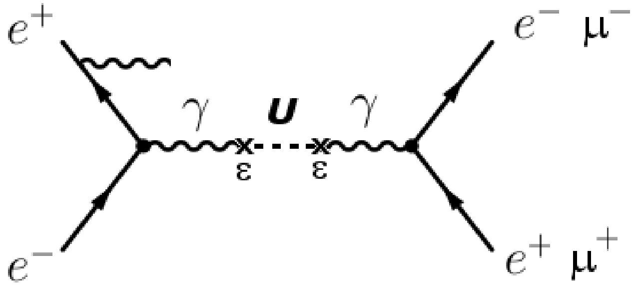


DM is a new type of matter → The DM has two possible scenarios
DM interacts with the same forces as in SM
DM iinteracts through **new forces**

Dark Matter

- “Minimal case”: Dark Matter couples to Standard Model (SM) particles through a kinetic mixing term → ***Dark Photon A’*** *(mixes with SM photon)*

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



DM is a new type of matter → The DM has two possible scenarios

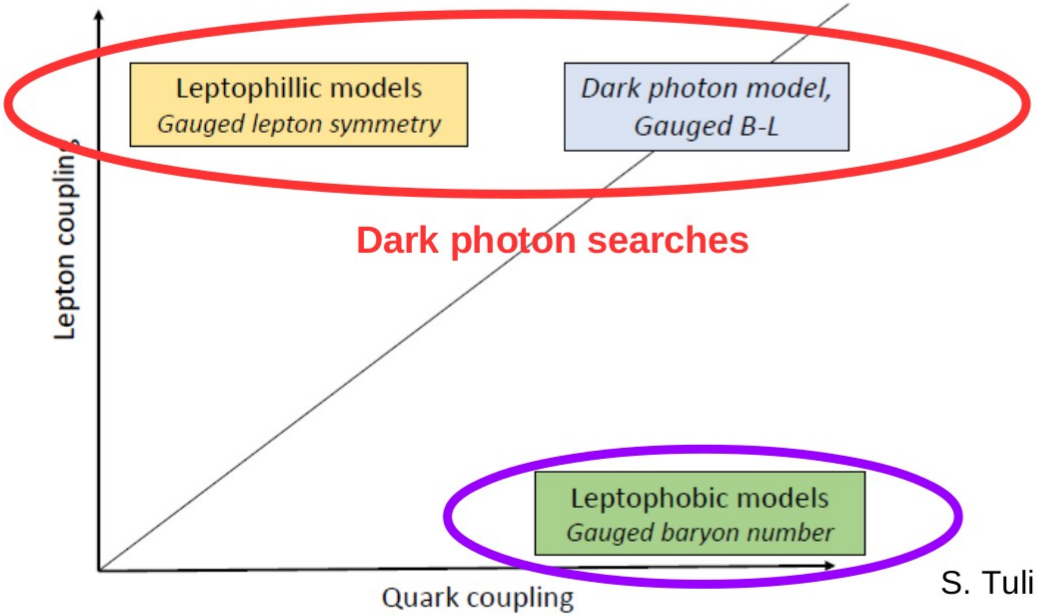
DM interacts with the same forces as in SM

DM interacts through **new forces**

- Decays depending in the mass of the mediator and decaying products

Other searches

- Not all possibilities explored
- Many models and possibilities for new gauge Boson
  - Leptophobic models → coupling to baryon number
  - Leptophilic
- Not need to introduce new interactions
  - Super-symmetric candidates: AXIONS
- **New types of matter: Mirror Matter**



S. Tulin

- Invisible decays: in 3rd axis in plot
- A' *dark photon*
- ALPs

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

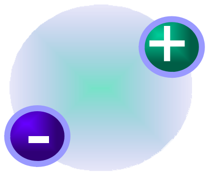
- Mirror Matter (or Alice Matter) was proposed as an explanation of Parity symmetry violation [T.D., Yang C. N. Phys. Rev. 1956. V. 104. P. 254.]
  - Each particle has a mirror partner with the same properties and opposite chirality (left/right - handed)
  - Mirror particles interact with normal matter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

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

Orthopositronium

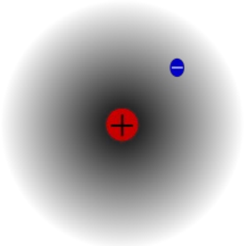
Hydrogen atom ^1H:

Positronium (Ps)



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

$^3S_1$ **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**

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

Theory QED prediction

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

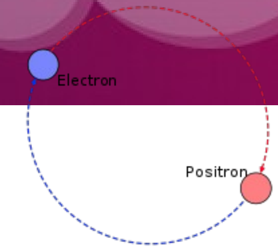
Experimental values

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

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

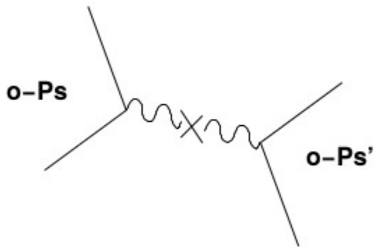
Theory predictions 100 times more precise:
10^{-6} vs 10^{-4}

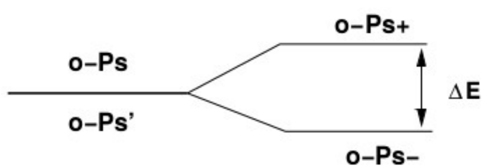
Mirror Matter in o-Ps



•o-Ps can be connected via one-photon annihilation to its mirror version (o-Ps') and can be confirmed in experiments

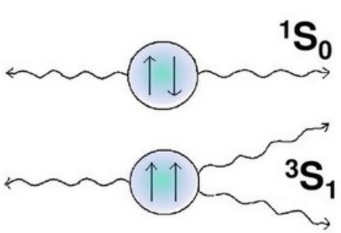
- o-Ps oscillates into its mirror partner o-Ps'
- Only mimicked by very-rare decay from Standard Model Br(oPs→ $\nu\bar{\nu}$) < O(10^{-18})
- Precision measurements of the o-Ps decay rate and compare it to QED calculations.
- **Direct searches.**





[P. Crivelli et al 2010 JINST 5 P08001]

Positronium



para-Ps τ ≈ 125 ps

Ortho-Ps τ ≈ 142 ns

Invisible decays of ortho-positronium:

- In vacuum: [Glashow S. L. Phys. Lett. B. 1986. V. 167. P. 35.]

$$Br(o-PS \rightarrow invisible) = \frac{2(2\pi\epsilon f)^2}{\Gamma_{3\gamma}^2 + 4(2\pi\epsilon f)^2}$$

where ΔE = $2h\varepsilon f$ with $f = 8.7 \cdot 10^4$ contribution of the ortho-para splitting from one-photon annihilation diagram

In a cavity

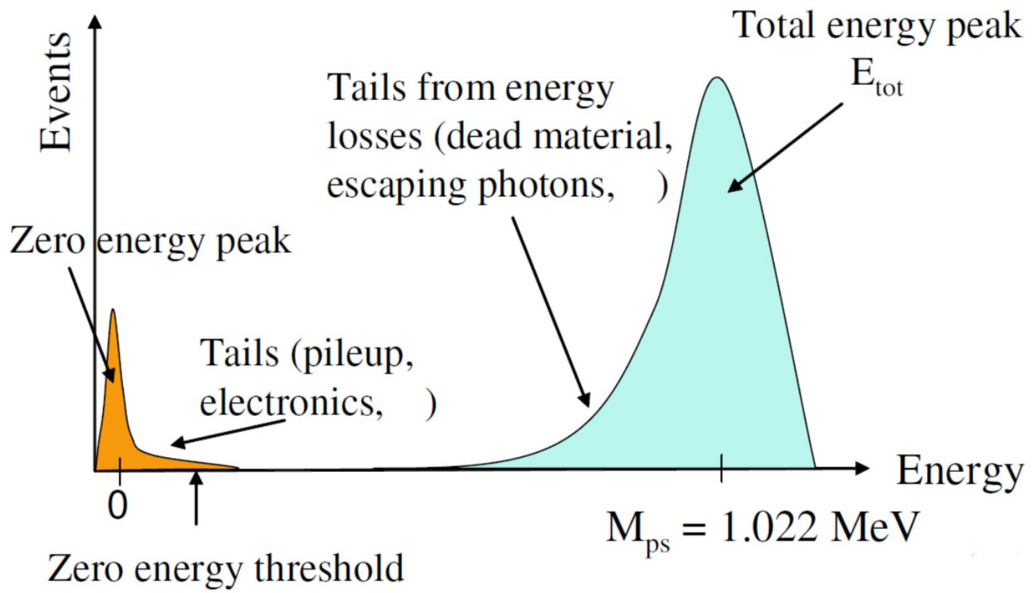
- we need to consider the rate of elastic collisions with the target - Γ_{coll}
- The collisions disrupt the ordinary-mirror oscillations (quantum decoherence)
- In the case $\Gamma_{coll} >> \Gamma_{3\gamma}$

$$\Gamma_{obs} \approx \Gamma_{3\gamma}\left(1 + \frac{2(2\pi\epsilon f)^2}{\Gamma_{coll}\Gamma_{3\gamma}}\right)$$

Mirror Matter in o-Ps

Two experiments were performed at ETH in Zurich (P. Crivelli's talk) with common characteristics:

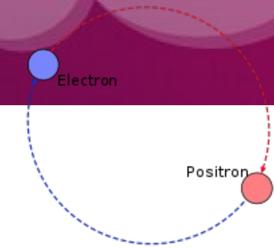
- Time measurement: time start by triggering on positron, time stop when detecting any of the annihilation photons
- Use of a calorimeter (BGO crystals) to measure the energy of γ from ortho positronium decay products and calculate $E_{tot} = \sum E_i$.
- Search for excess events (peak) in the spectrum 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 cavity* [Phys. Rev. D 75, 032004]
  - BR < 4.2 × 10^{-7} (90% C.L.)
  - Photon mixing strength
    ε < 1.55 × 10^{-7} (90% C.L.)
- *Searches in vacuum* [Phys. Rev. D 97, 09200]
  - BR < 5.9 × 10^{-4} (90% C.L.)
  - Photon mixing strength
    ε < 3.1 × 10^{-7} (90% C.L.)

Mirror Matter in o-Ps



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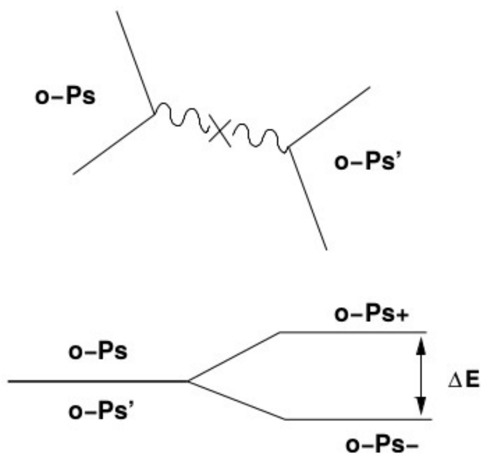
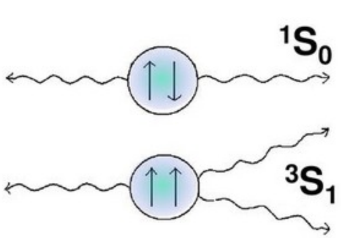
- Direct searches.



[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

Positronium



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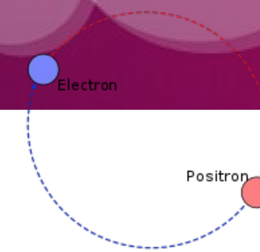
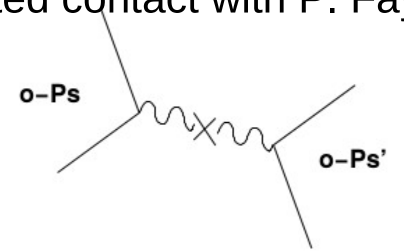
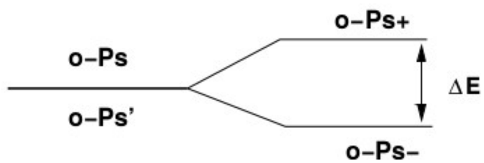


Dark Matter in o-Ps

- Other DM scenarios can be studied with the o-Ps decays
  - Search of a pseudoscalar axion particle with a mass mass range between 1μeV and 3m eV (*Baudis, 2018; Kawasaki and Nakayama, 2013*), o-Ps decays to axion + photon has BR below $O(10^{-22})$ (*S. Bass, 2019*)
  - Study of the decay of o-Ps to photon + light *dark photon* with BR up to $O(10^{-10})$ (*Ṕerez-Ŕıos and Love, 2018*)
  - Study of a possible DM candidates using a model involving a dark photon U decaying into $\upsilon\bar{\upsilon}$ *or light DM* (***P. Fayet and M. Mezard , Phys. Lett. 104B, 226-230 (1981)***)
    - Started contact with P. Fayet to study the possibility of this search with J-PET

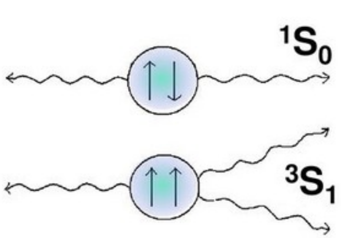




[P. Crivelli et al 2010 JINST 5 P08001]

Dark Matter hunters with J-PET

Positronium



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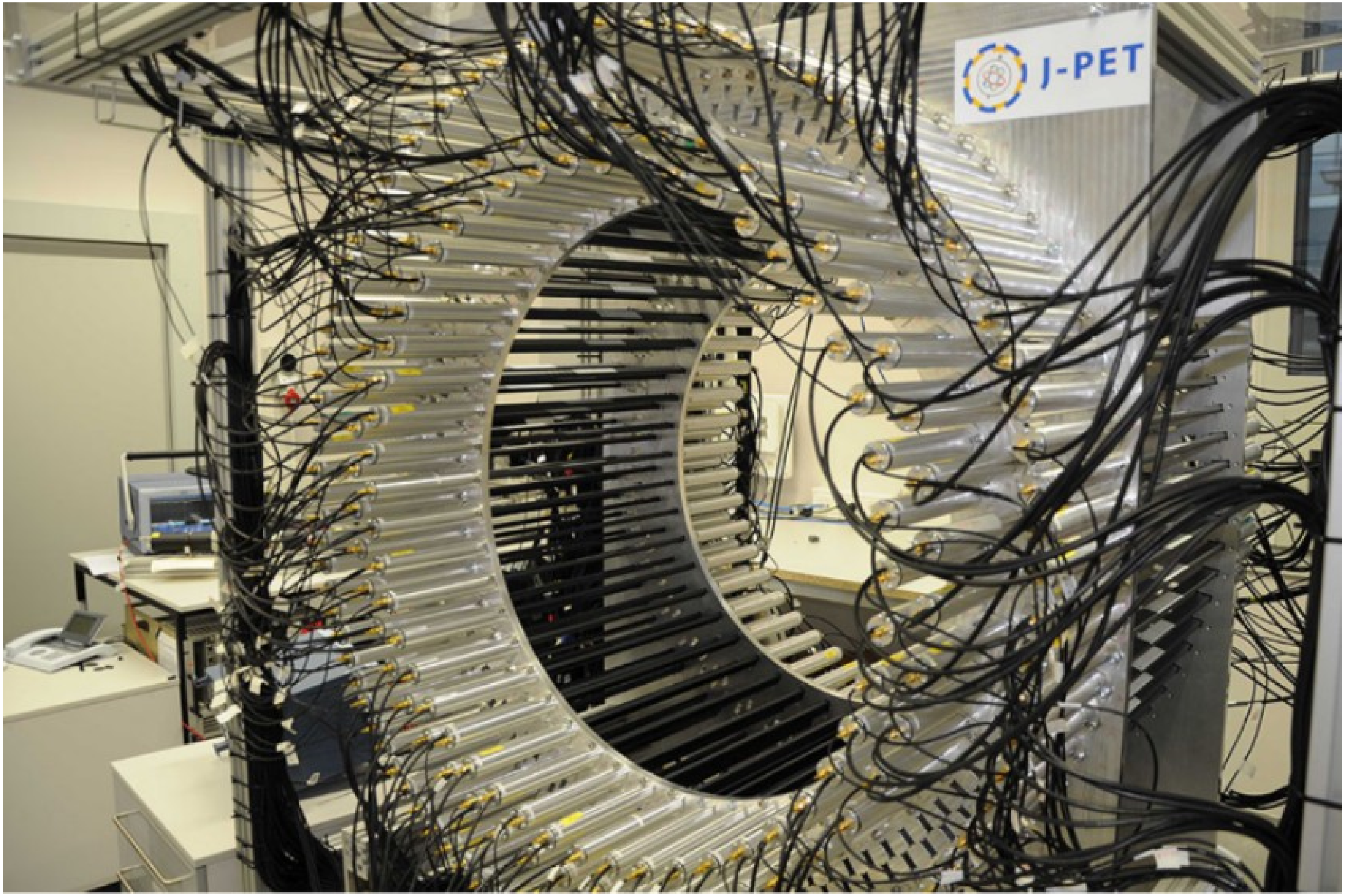
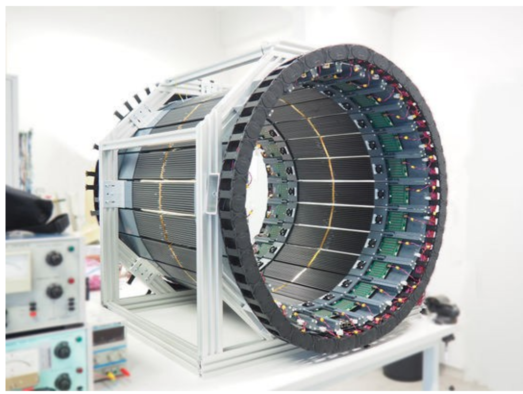
Mirror Matter in o-Ps: JPET

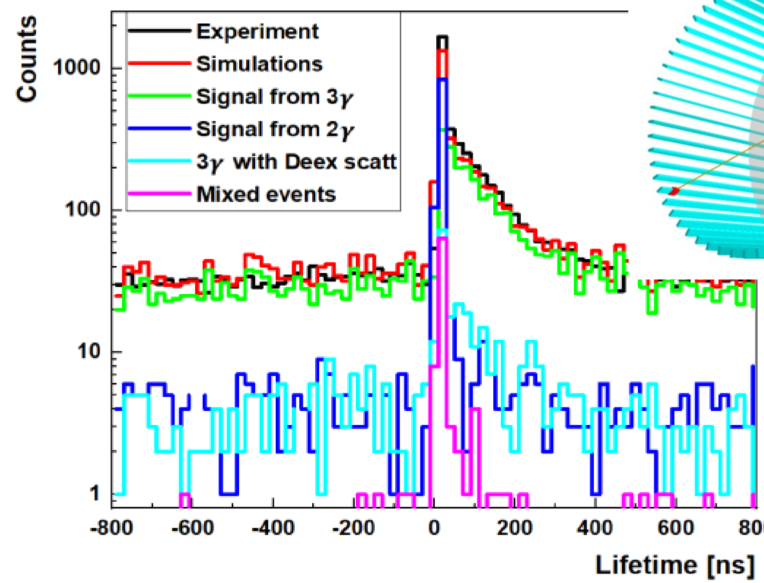


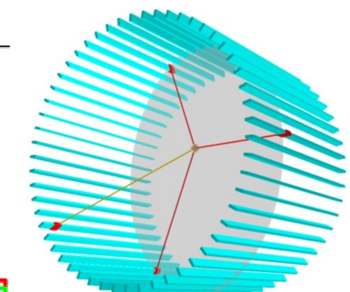
ortho-Ps in J-PET

Radioactive source Na



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





[arXiv:2006.07467 [physics.ins-det]]

- 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

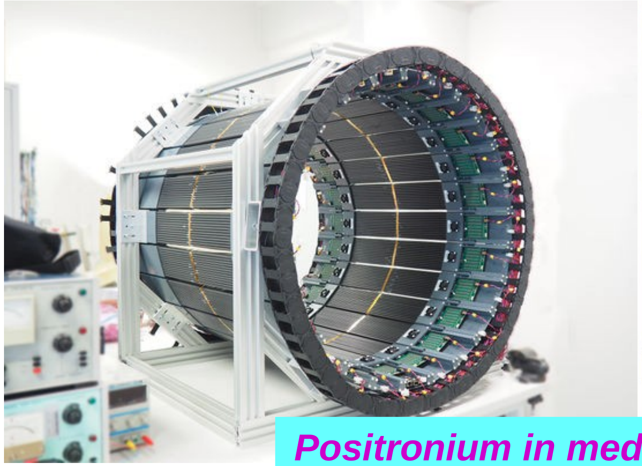
Sensitivity below $O(10^{-5})$

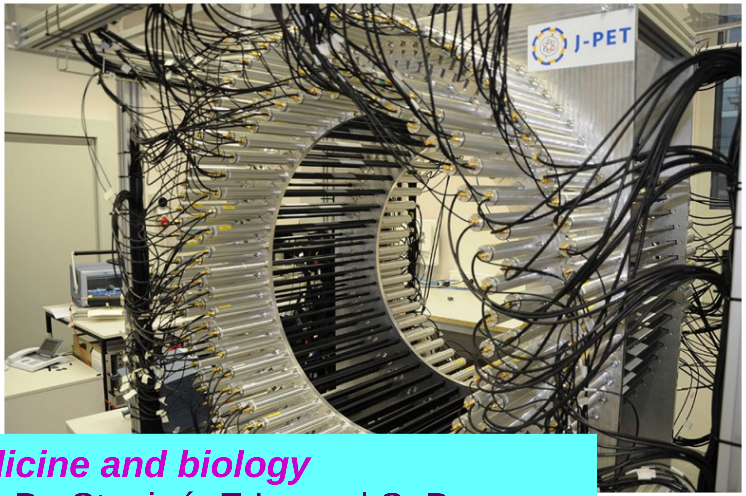
Photon mixing strength $\varepsilon < O(10^{-7})$

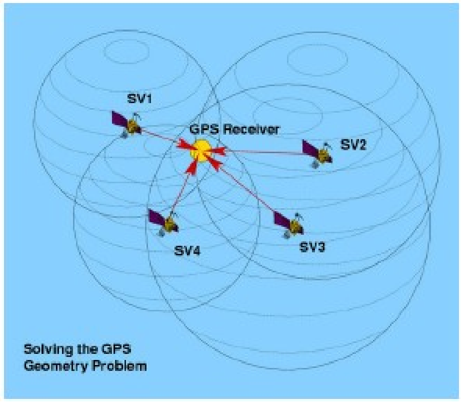
Already available statistics

- **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*]**

J-PET (Jagiellonian-PET TOMOGRAPHY)





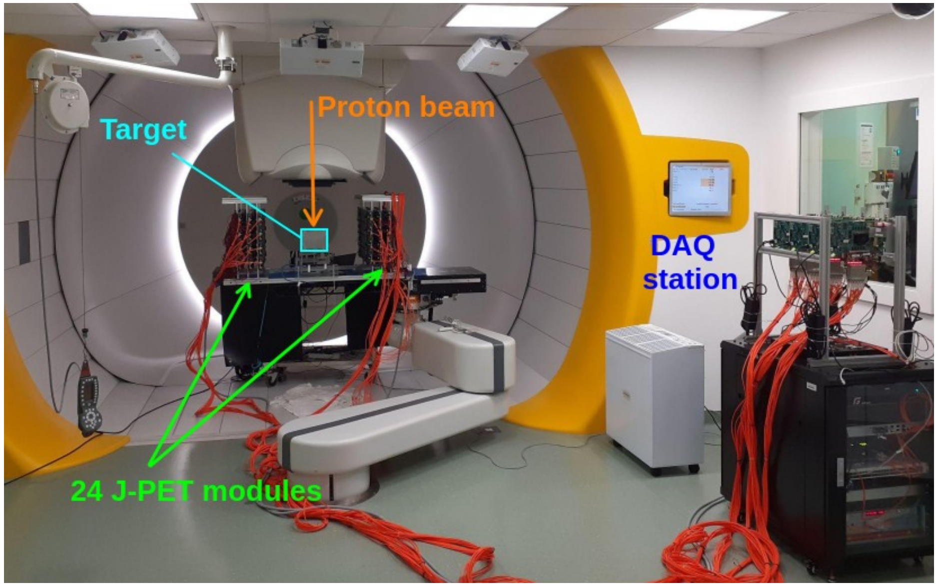


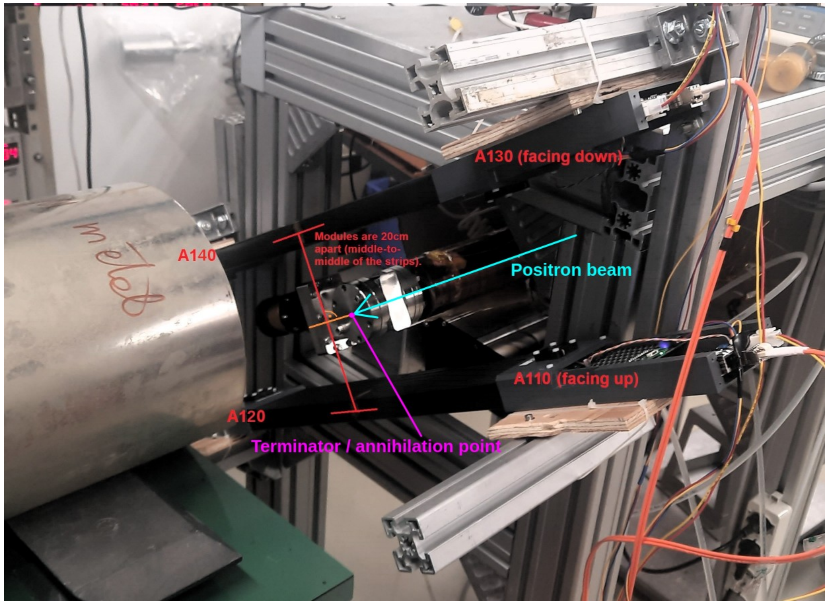
Positronium in medicine and biology
Moskal, P., Jasińska, B., Stępień, E.Ł., and S. Bass.
Nature Reviews Physics 1, pages 527-529 (2019)

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**
- **Data acquisition ensured for the next years: Agreement with J-PET collaboration and Physics department + preexistent data from 2017-2020**
- **GPS trilateration** reconstruction

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

Mirror Matter in J-PET



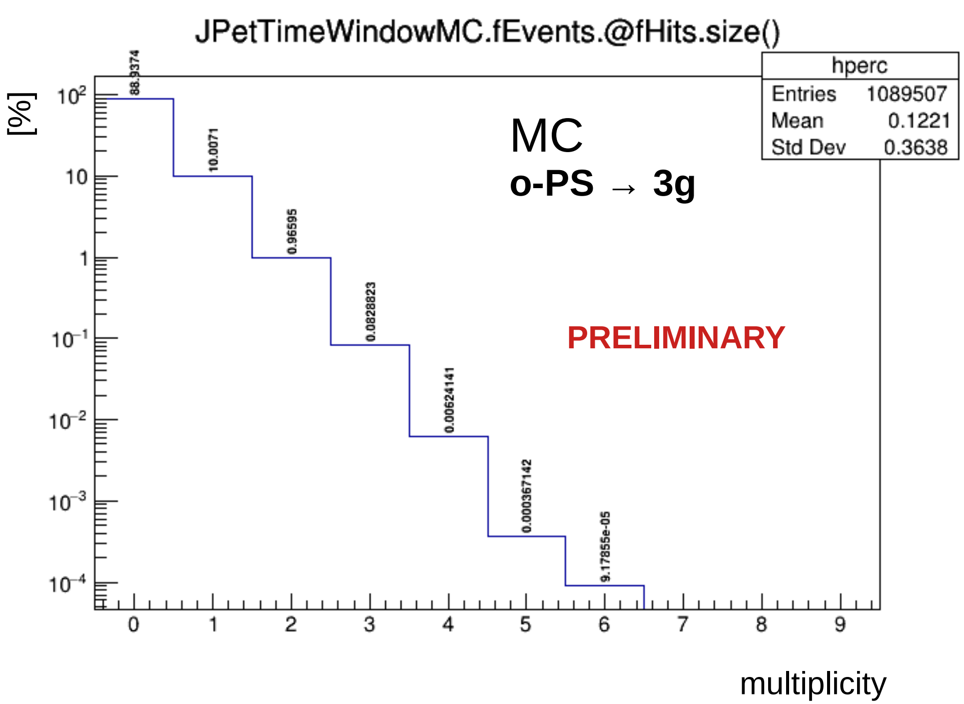


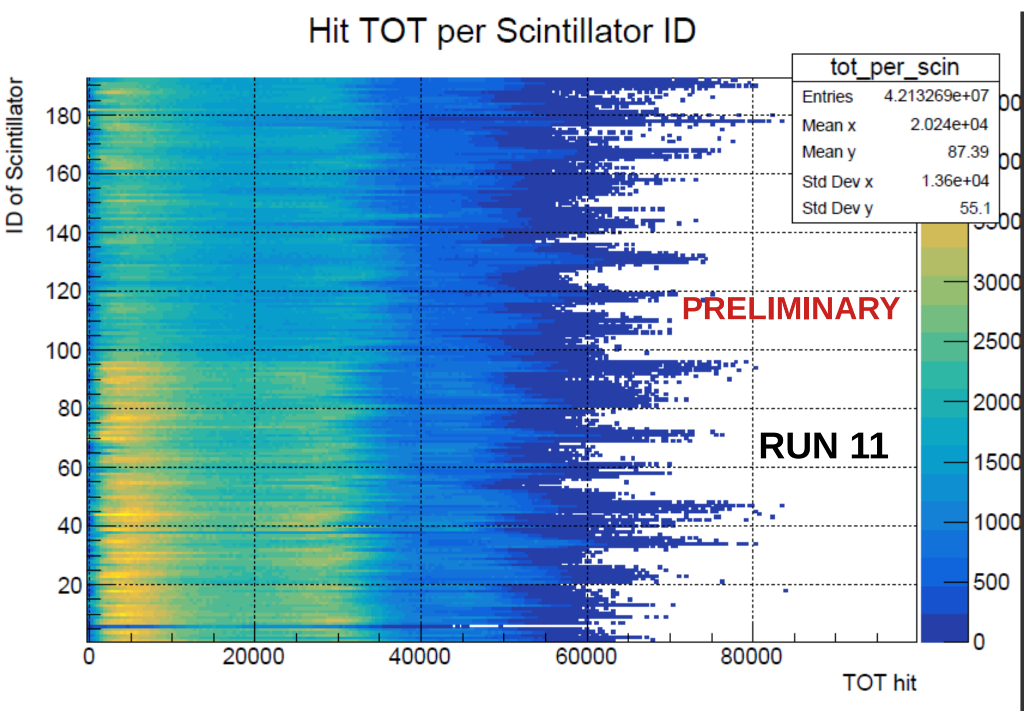
- **SONATA BIS 10 – NCN grant 2021/2026**
- **Mirror Matter search with J-PET detector**
- **Development of a tagger system**
  - **Positron tagger implementation to trigger the start of the reaction**
  - **Reduction of background**
  - **Additional start measurement**
  - **Extra measurement to trigger 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 with some modules already performed at The Cyclotron Centre Bronowice and Trento (INFN)**

Mirror Matter in J-PET: Studies

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

- On-going studies with
  - TOT calibration (started for run 11)
  - Random coincidences MC/data
  - **MC 3gamma/2gamma separation**
    - **Machine Learning (ML)**

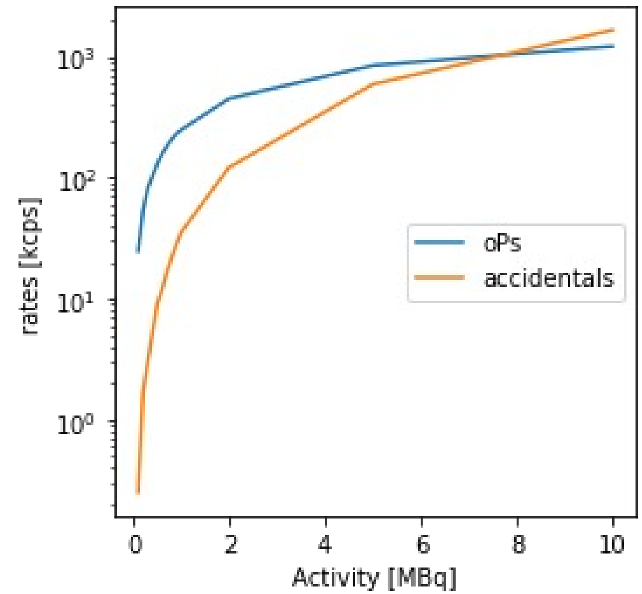


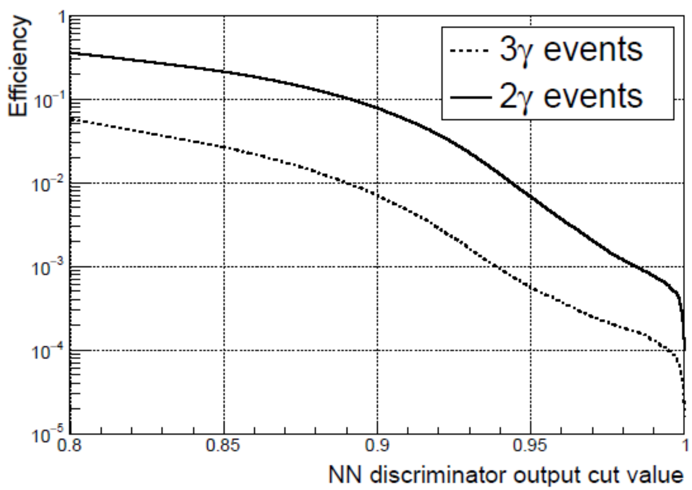


Systematic Uncertainties

- **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

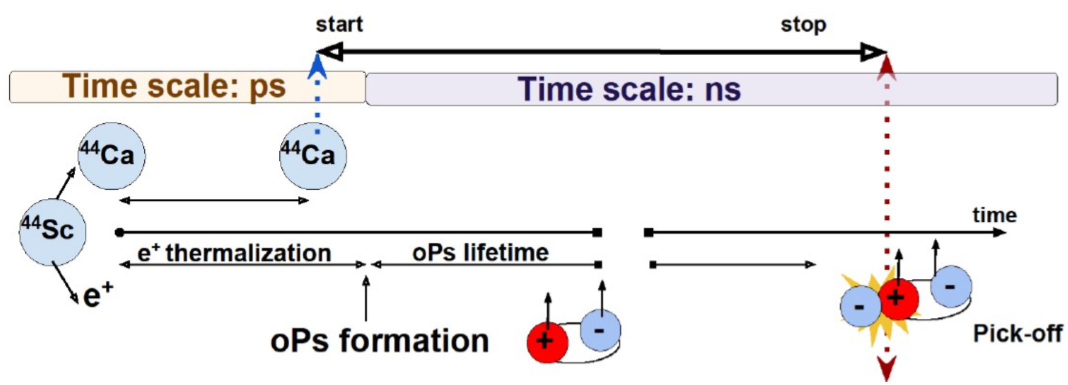




C. Vigo et al. (2019) [805.06384v]

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

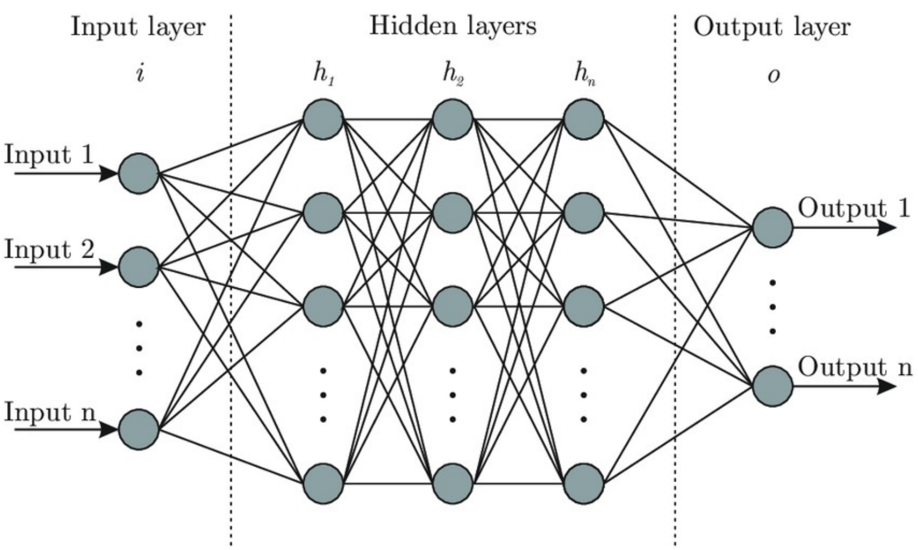
- **oPs interacting with the material**:
  - Can be directly evaluated from data
  - Can be used to train Machine Learning algorithms to reject the events (below 12 ppm level)



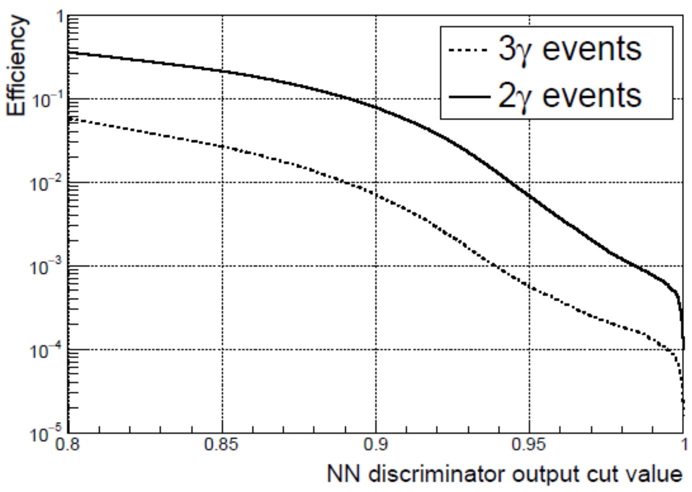
Machine Learning for background reduction

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



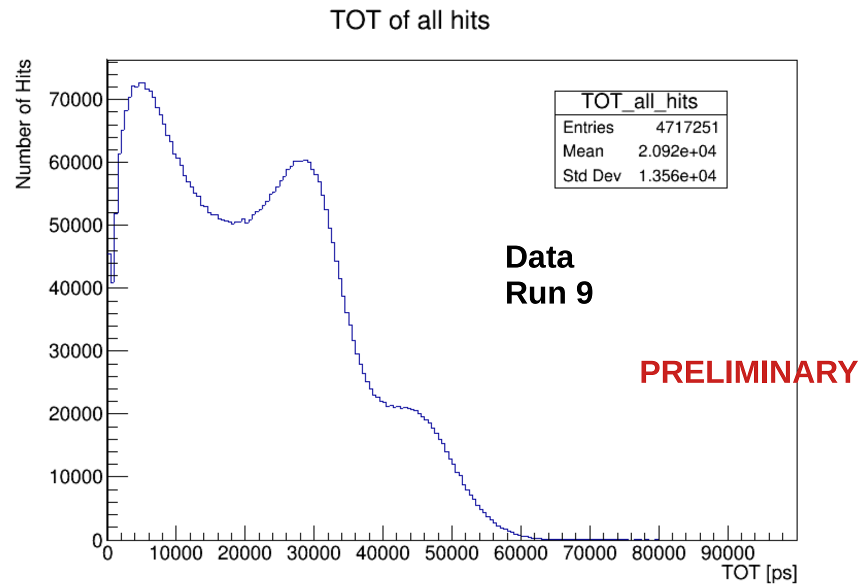
Development of **Neural Network** algorithms to profit of the the excellent timing and reconstruction capabilities of the JPET detector → can be adapted in future to ***medical imaging***.

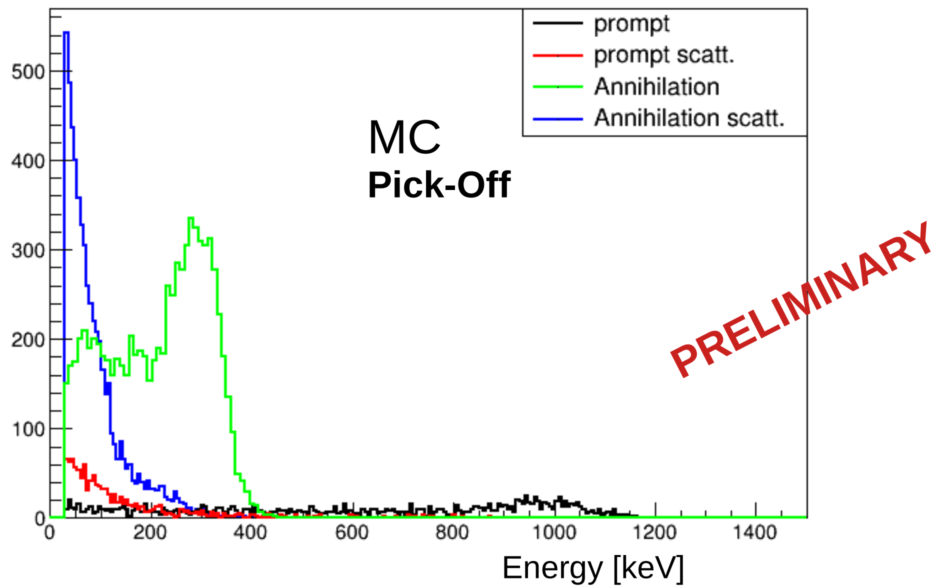


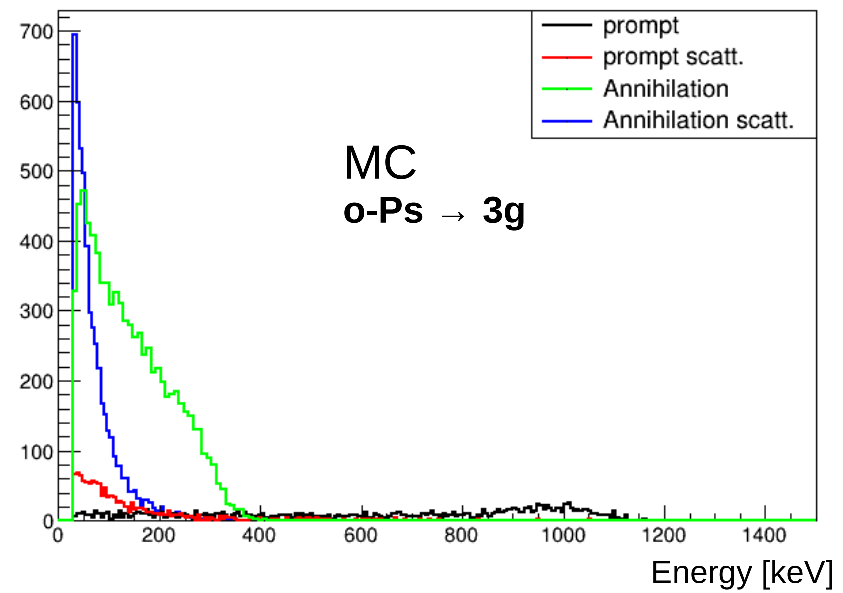
C. Vigo et al. (2019) [805.06384v]
Journal of Physics: Conference Series, Vol. 1138, conference 1

Analysis o-Ps lifetime

- MC used to find features to be used in the ML algorithms
  - Work started in collaboration with Dr. Wojciech Krzemien
- Exploration studies with Run 9 to defined the analysis strategy







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.

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.

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

Aim: **Sensitivity after two years of experiment below 10^{-5}**

Thank you