Mirror Matter searches with the J-PET detector

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

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

QNP2022 - The 9th International Conference on Quarks and Nuclear Physics

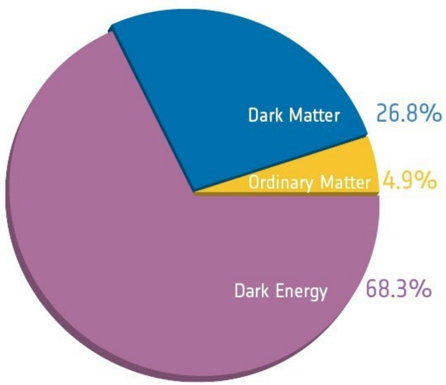
5-9 September, Florida, 2022

Outline

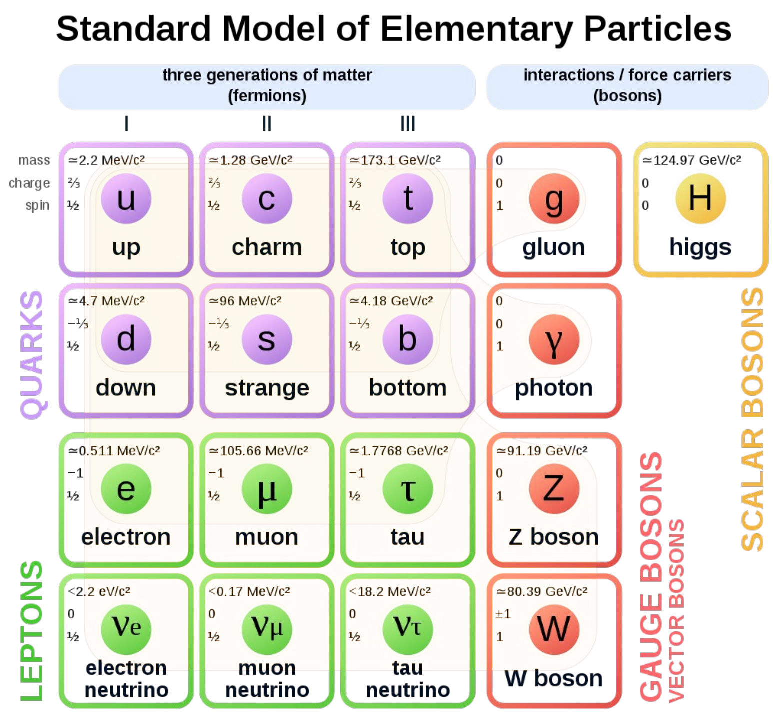
- The Standard Model
  - Physics Beyond the Standard Model (BSM)
  - **g-2** and Dark Matter
- Dark Matter
    - Minimal case and New Forces
    - Other searches
- Mirror Matter
- Ortho-Positronium life-time
- Mirror Matter in o-Ps
- J-PET search
  - Concept of the measurement
  - J-PET plans
  - Systematic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

Standard Model of Particles

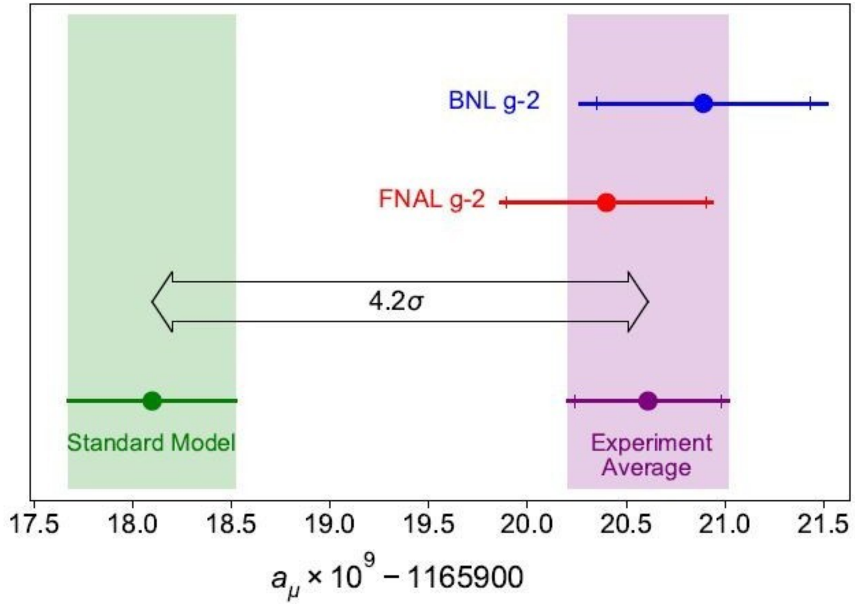
- Standard Model is now complete: 2012 LHC - Higgs boson
- Despite the highest energy reach at the LHC did not provide any convincing evidence for new degrees of freedom ... yet?
- Physics Beyond the Standard Model
  - What about gravity ?
  - Dark matter and Dark energy
  - Neutrino Masses
  - Matter-antimatter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

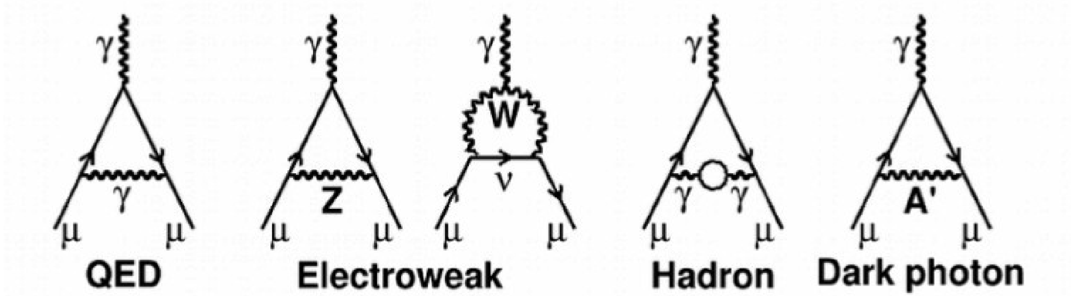


What are we searching?
How to search for it?



BSM Physics: g-2 and dark matter





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

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

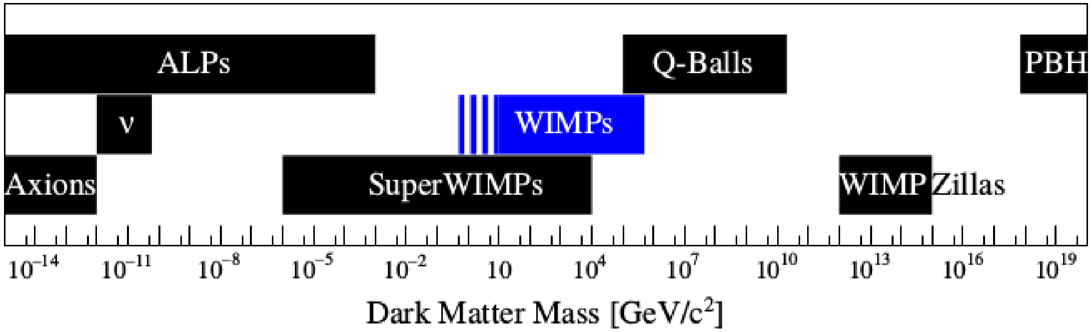
Dark matter motivated by cosmological observations could also serve as explanation to the g-2 discrepancy
$\varepsilon \sim 1\text{-}2 \cdot 10^{-3}$ and $m_V \sim 1\text{-}100$ MeV

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

arXiv:1903.03026



SM reminder:

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

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

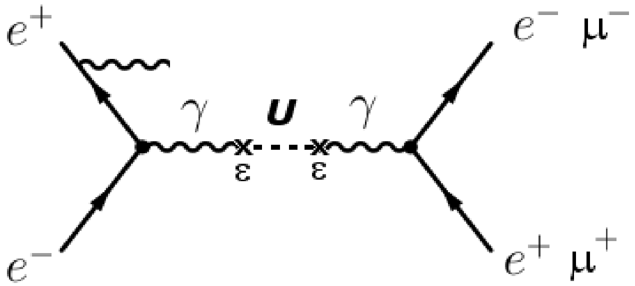
DM interacts with the same forces as in SM

DM interacts through **new forces**

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**

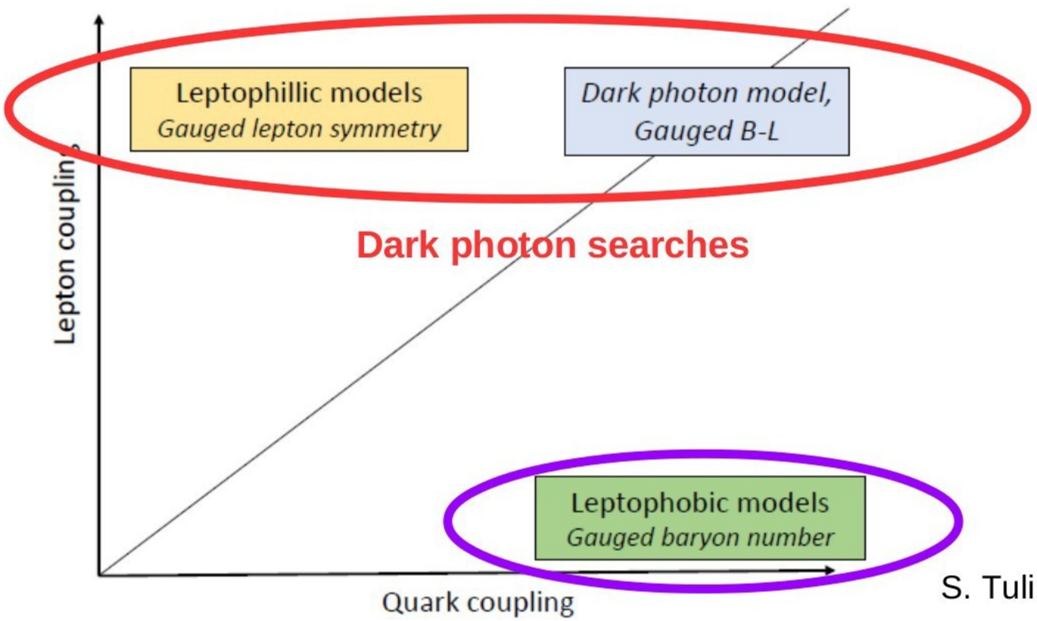
- Decays depending in the mass of the mediator and decaying products

Other searches

- Not all possibilities explored
- Many models and possibilities for new gauge Boson
  - Leptophobic models → coupling to baryon number
  - Leptophilic models

- 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

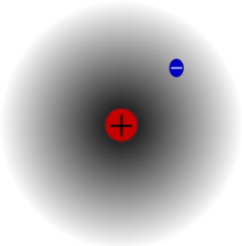
R. L. Garwin, L. Lederman and R. Weinrich
Phys. Rev. 104 (1956) 254

- 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

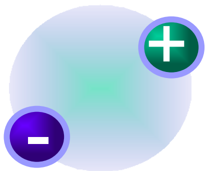
$$\mathcal{L}_{\gamma\gamma'} = -\epsilon F^{\mu\nu} F'_{\mu\nu}$$

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

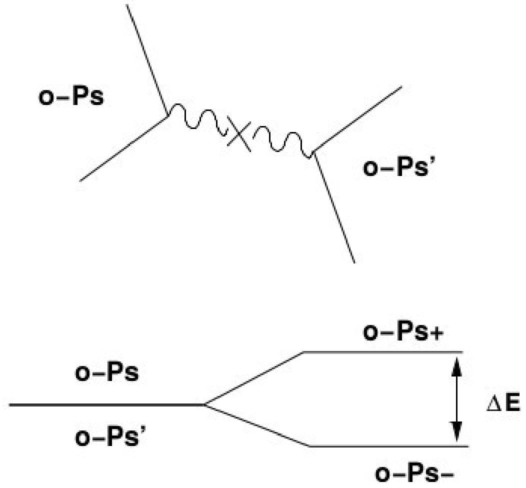
$$\Gamma = 7.0401 \pm 0.0007 \times 10^6\,\mathrm{s}^{-1}$$ Tokyo group

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

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

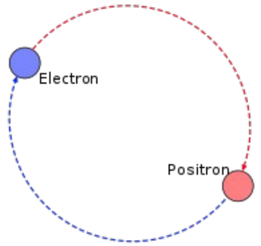
Mirror Matter in o-Ps

- 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.**

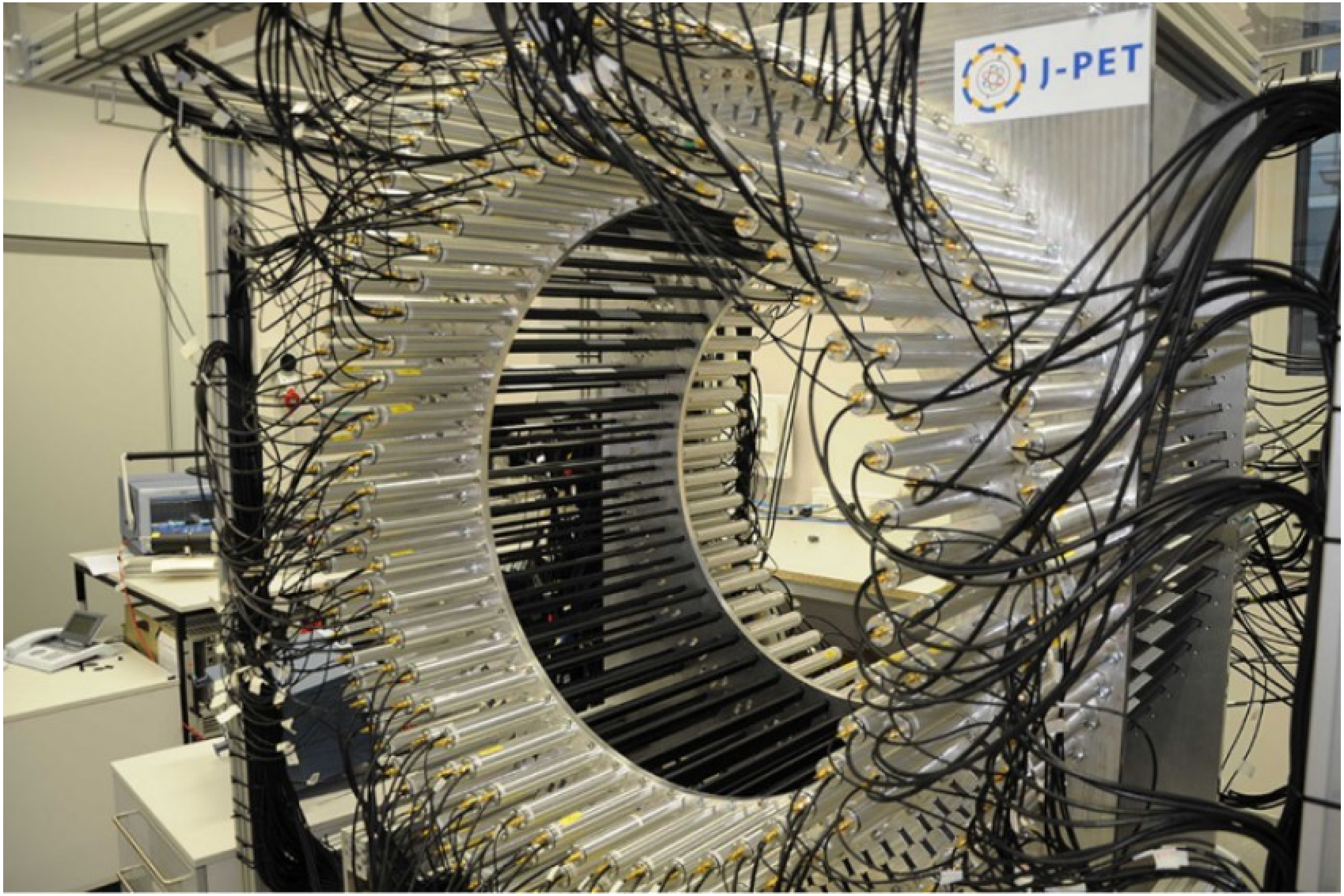


[P. Crivelli et al 2010 JINST 5 P08001]

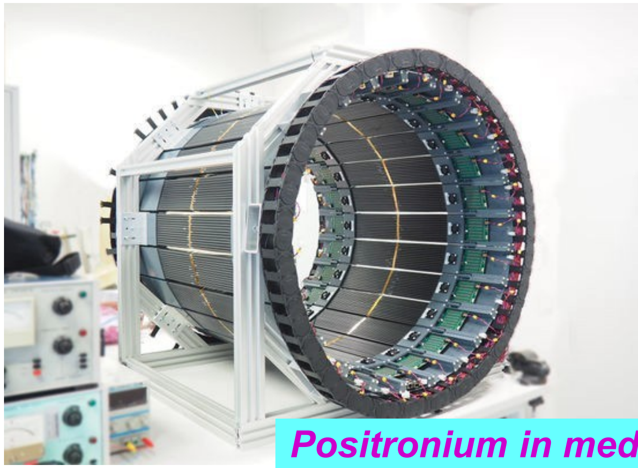
The o-Ps’ → invisible decay would manifest as an increase of the observed lifetime respect to the expected value → Precision measurement of the o-Ps lifetime

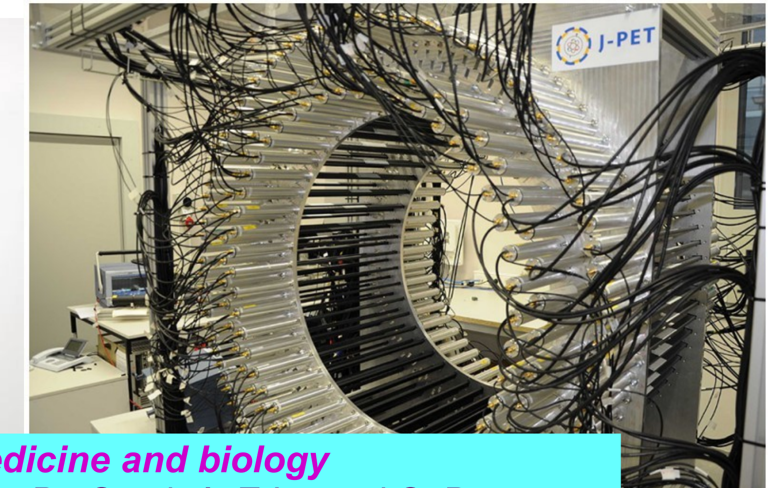


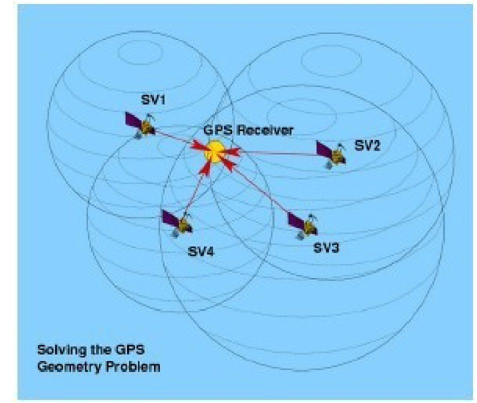
Mirror Matter in o-Ps: JPET



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

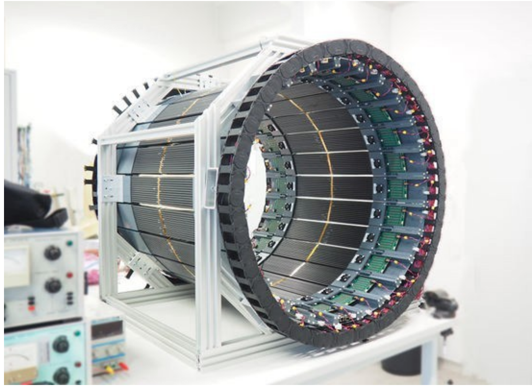
First Positron Emission Tomography scanner built from plastic scintillator

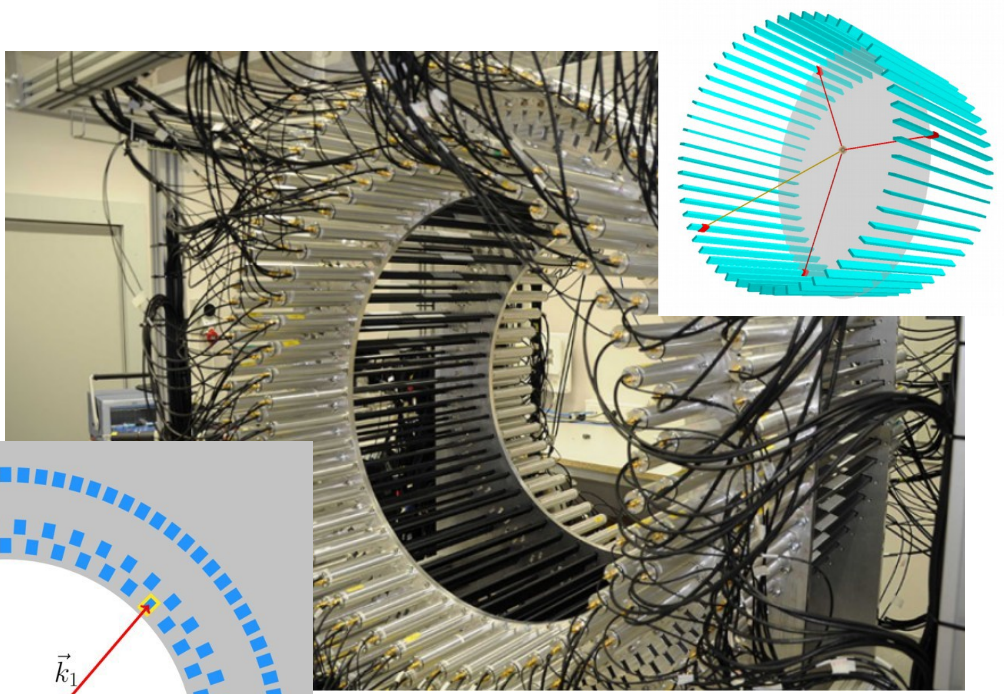
- Multidisciplinary detector
- **Portable/modular detector layer with higher detection probability High**
- **performance detector with high timing resolution**
- High acceptance
- **Trigger-less** and reconfigurable DAQ system
  - **Data has no filters: all data acquired is unfiltered**
- **GPS trilateration**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

ortho-Ps in J-PET

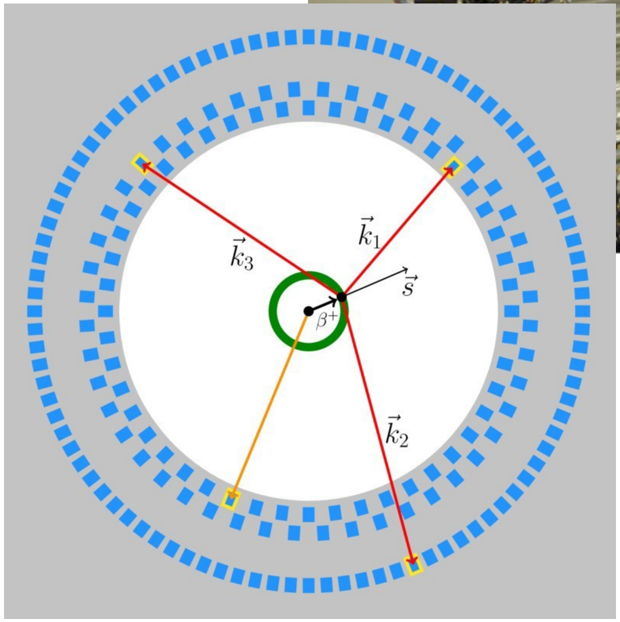
Radioactive source Na

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

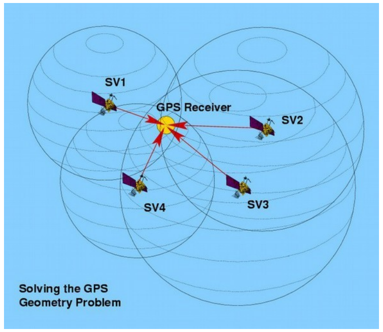




- Source activity 1 MBq = **10^6 e^+/s**
- o-Ps formed in vacuum chamber with probability 29%

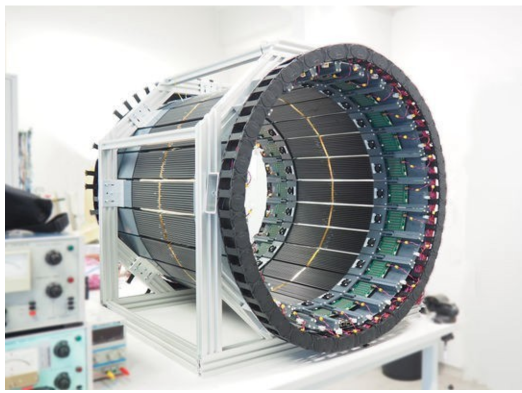


P. Moskal et al., Acta Phys. Pol. B 47 (2016) 509
A. Gajos et al. Nucl. Instrum. Methods. A819 (2016) 54



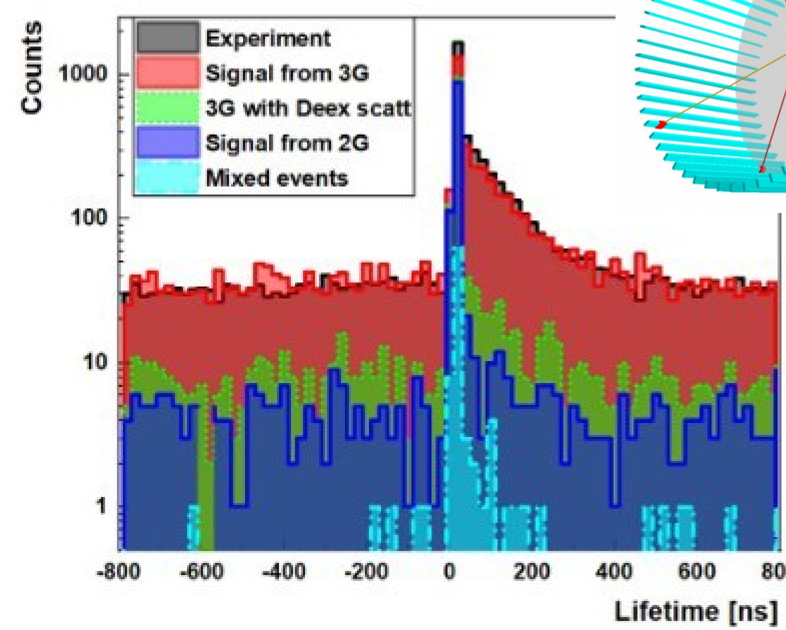
ortho-Ps in J-PET

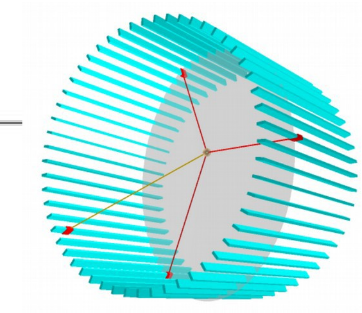
Radioactive source Na



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

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





- 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})

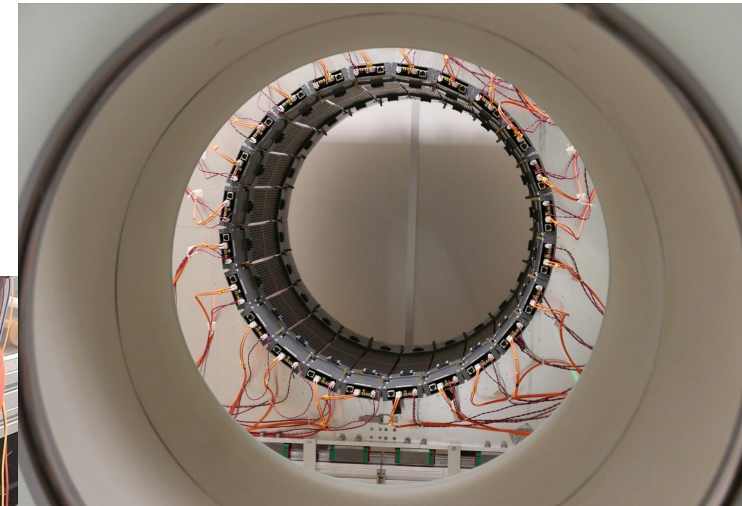
Already available statistics

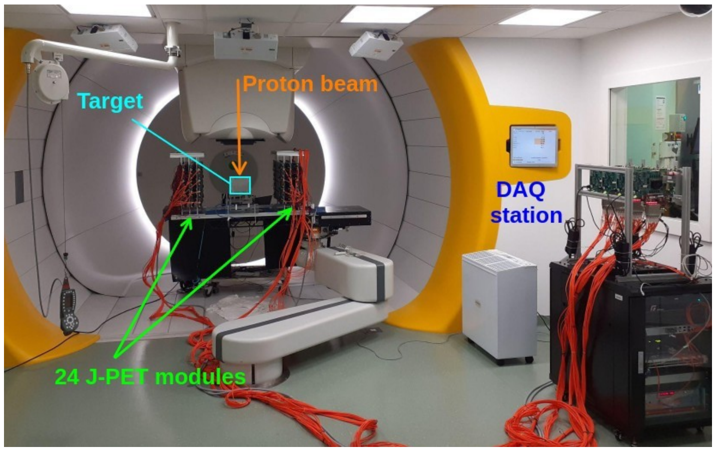
- **E.g. 7.3 × 10^6 event candidates in a continuous 26-day measurement using a 10 MBq ^{22}Na positron source. [*Nature Communications 12 (2021) 5658*]**

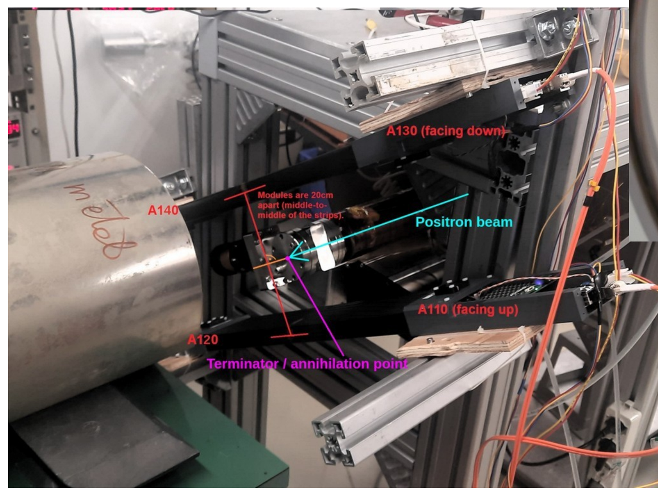
Main competitor ETH Zurich

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

Mirror Matter in J-PET





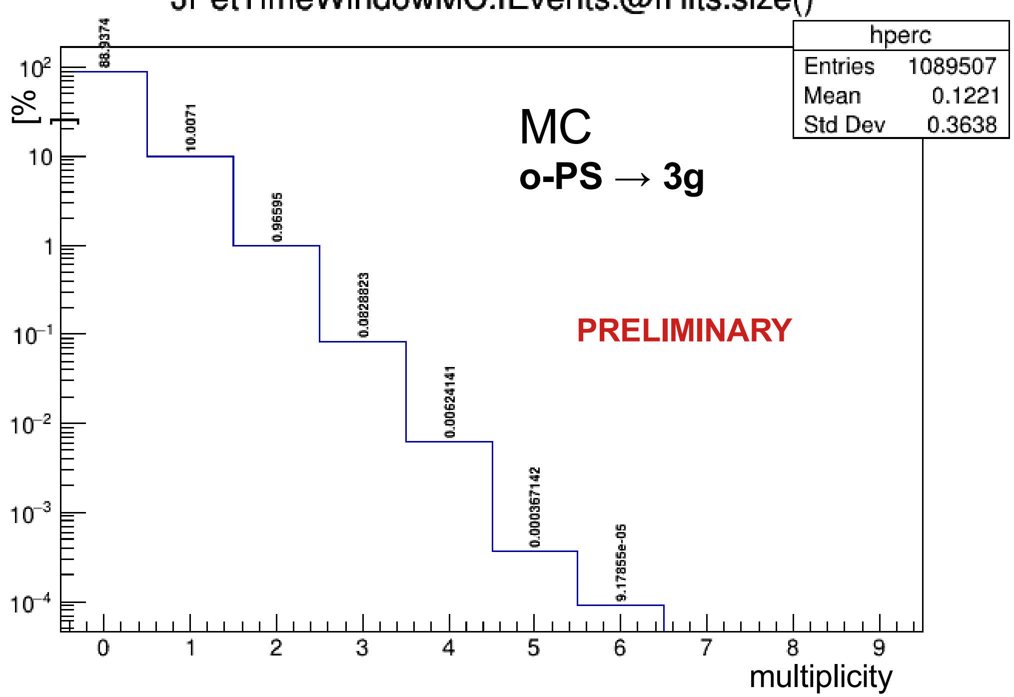


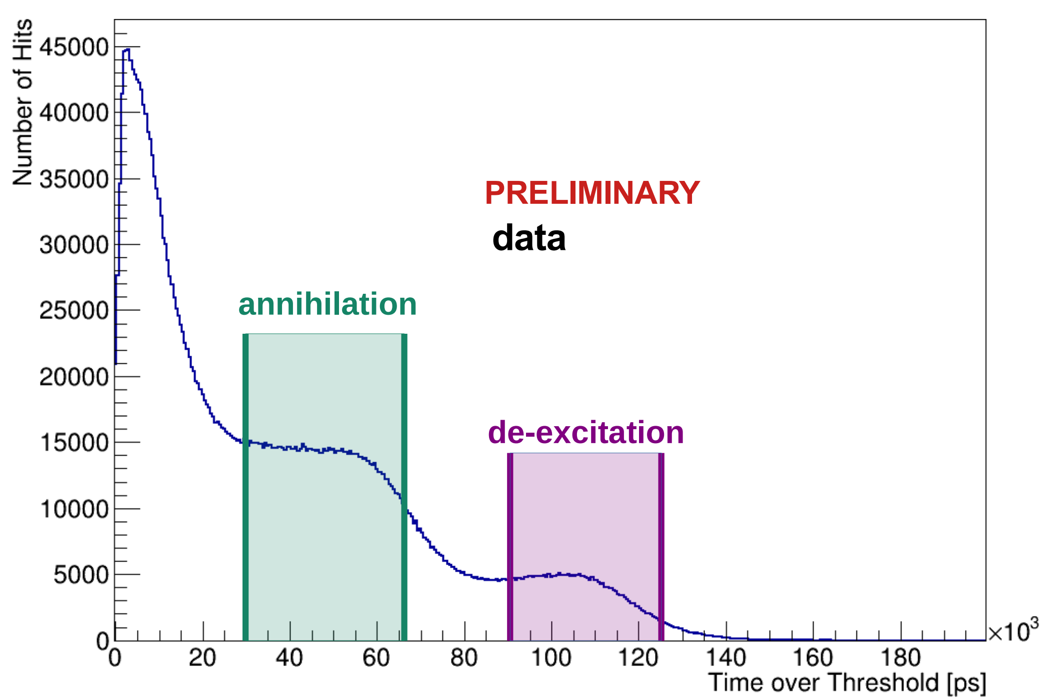
- NCN grant Nr 2020/38/E/ST2/00112
- Mirror Matter search with J-PET detector
- Development of a tagger system
  - Positron tagger implementation to trigger the start of the reaction
  - Reduction of background
  - Additional start measurement
  - Extra measurement to trigger the formation of positronium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

Mirror Matter in J-PET: Studies

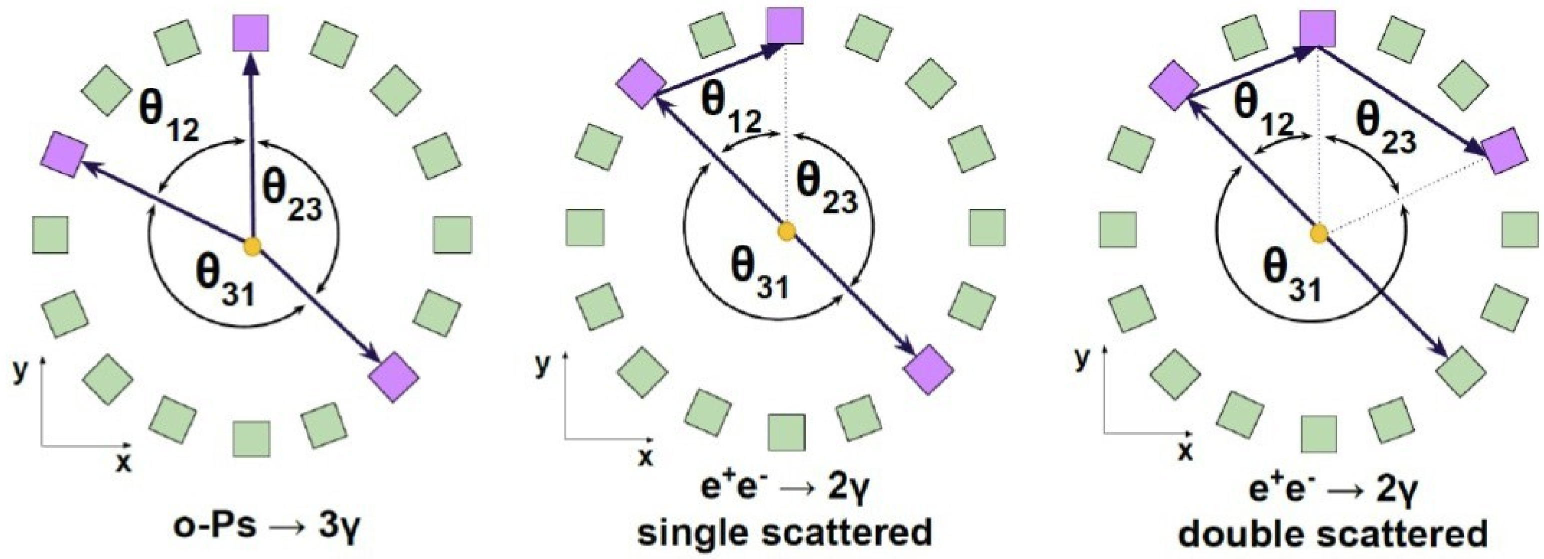
- **4-gamma events** to reconstruct the life-time
- Accurate measurement/**Precision Frontier**
  - High purity/high statistics

- 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

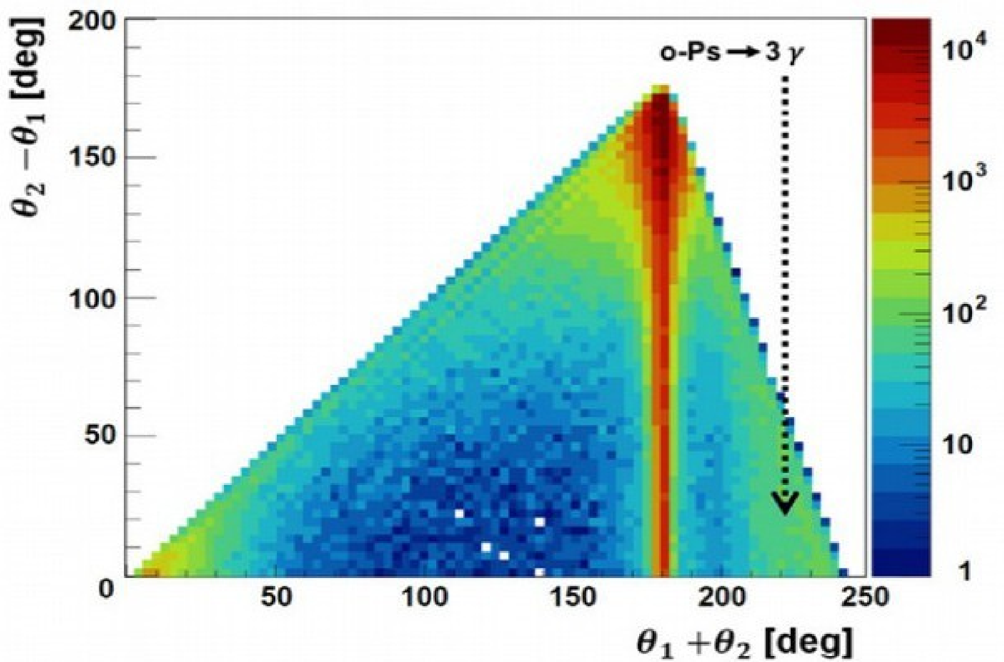




Mirror Matter in J-PET: Studies

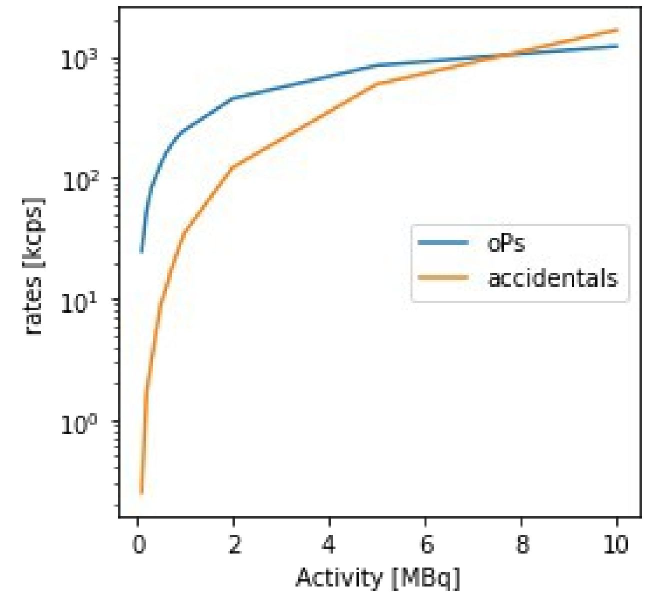


$\theta_{23} + \theta_{12} > 180$ $\theta_{23} + \theta_{12} = 180$ $\theta_{23} + \theta_{12} < 180$



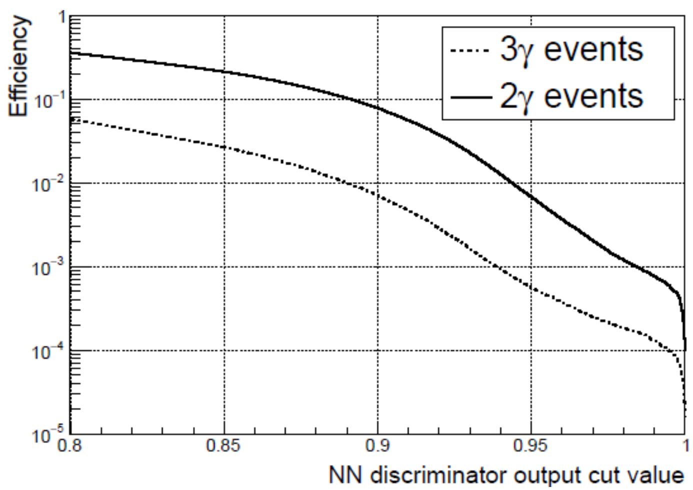
K. Dulski et al. NIM A 1008 (2021) 165452

Systematic Uncertainties



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

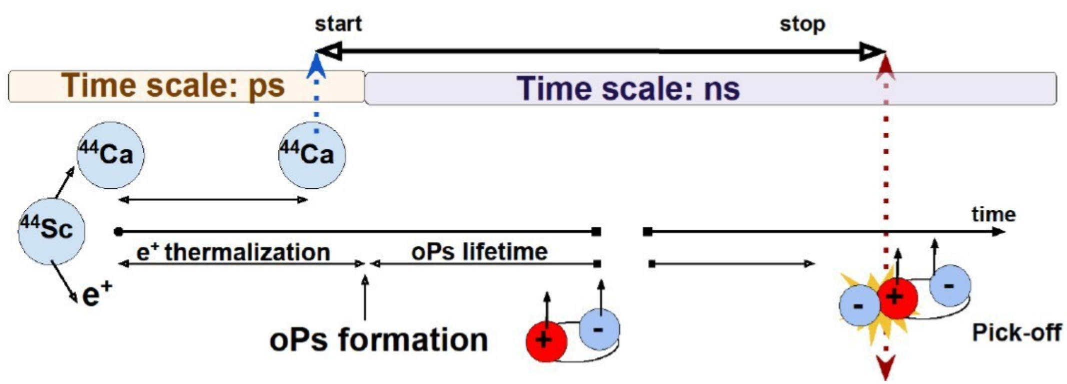
Acta Phys.Polon. B51 (2020) 165



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)



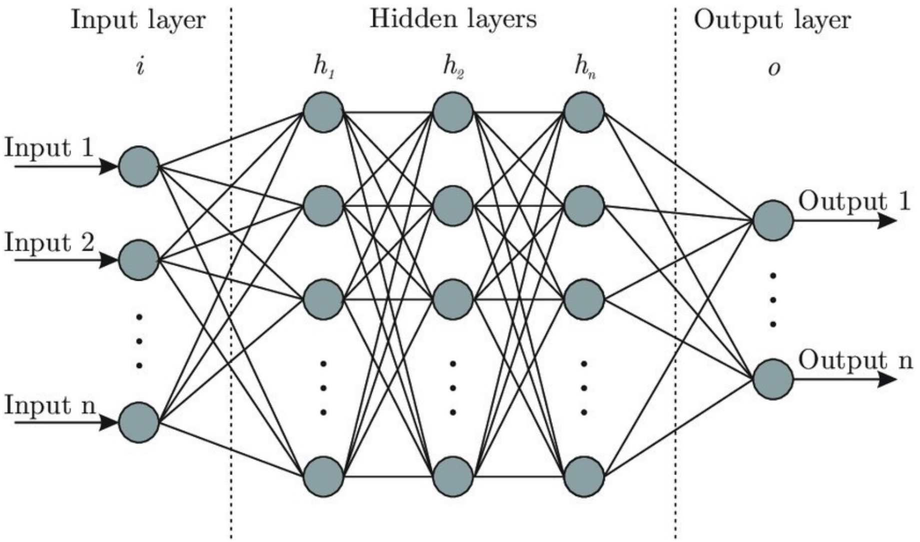
Machine Learning for background reduction

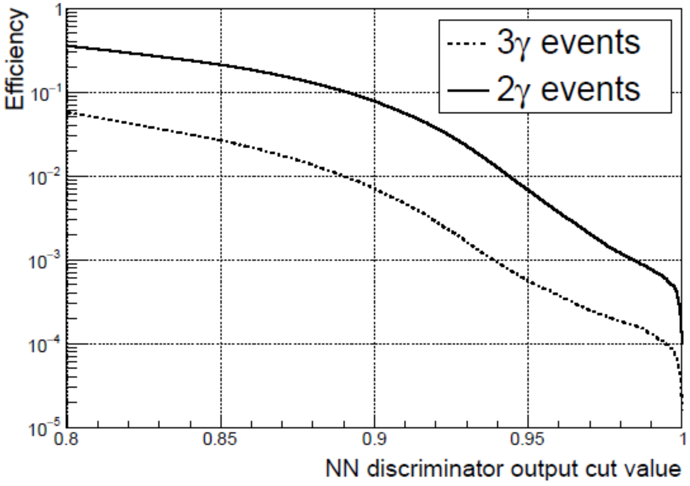
- On-going studies with
  - Random coincidences MC/data
  - **MC 3gamma/2gamma separation**
    - **Machine Learning (ML)**

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





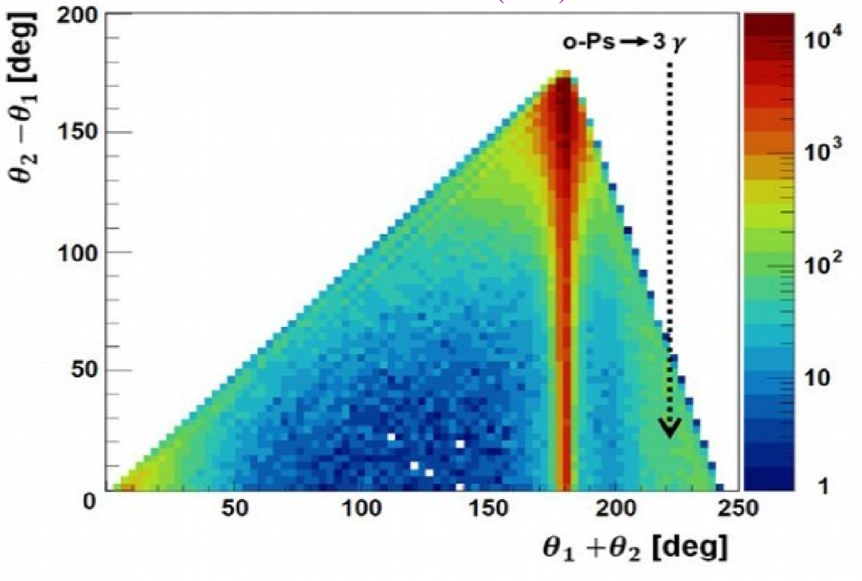
C. Vigo et al. [805.06384v]

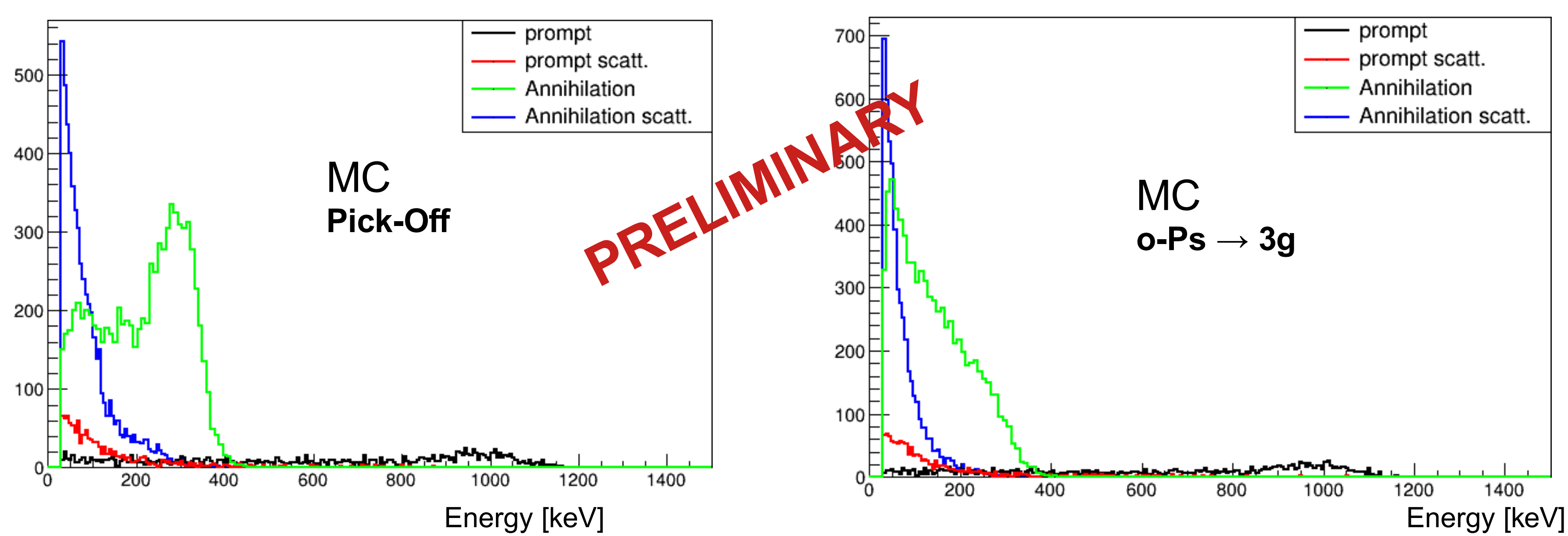
Journal of Physics: Conference Series, Vol. 1138, conference 1

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**
- **Preliminary results**

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





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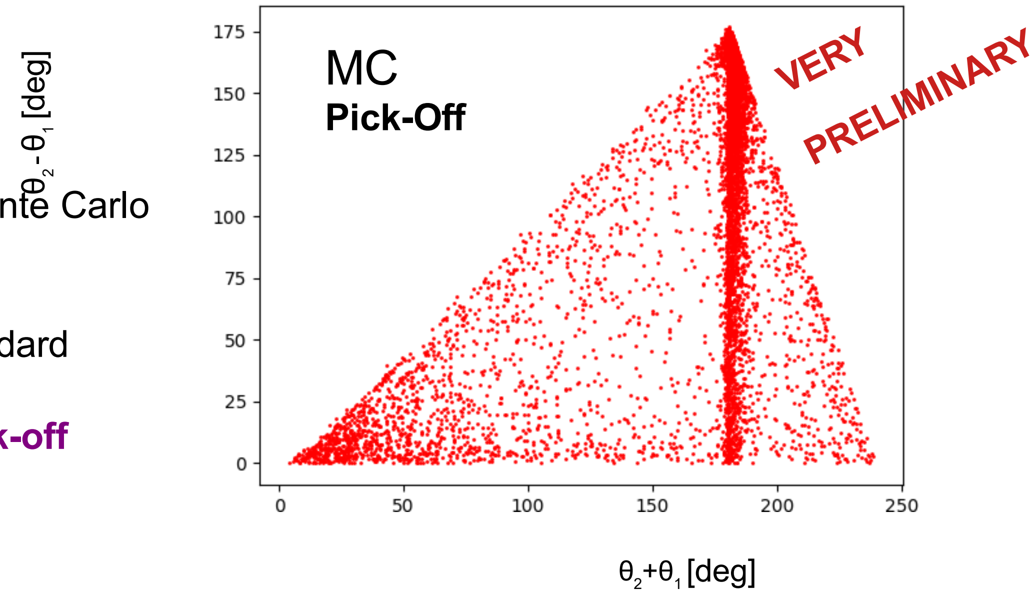
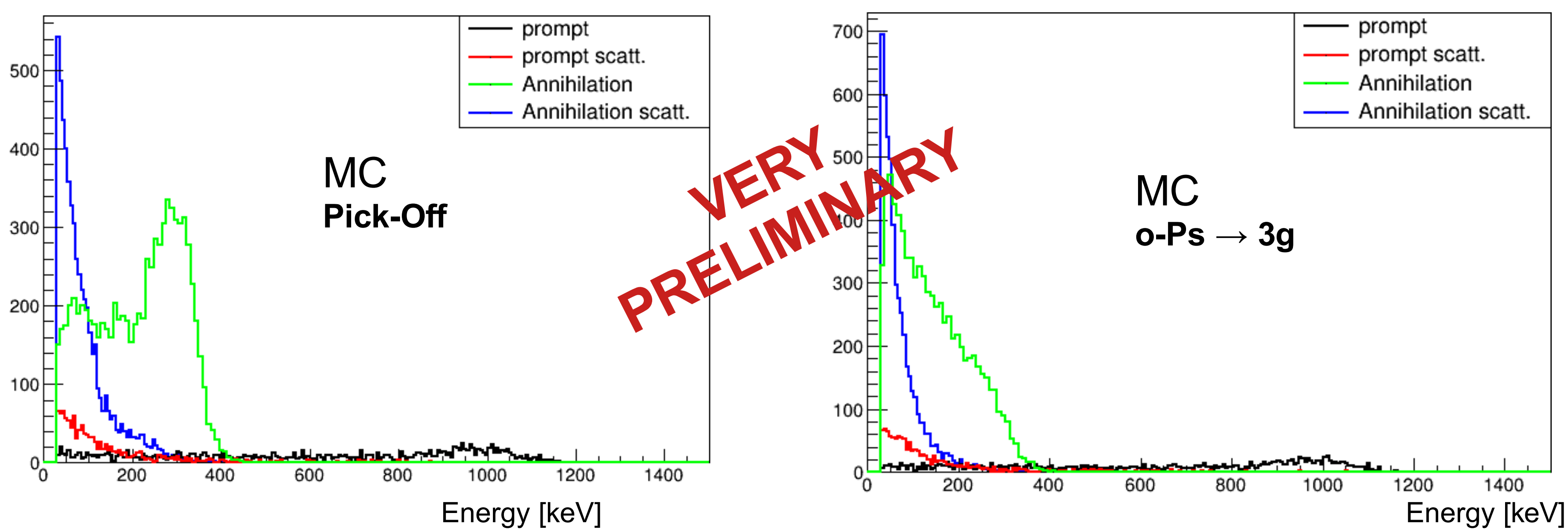
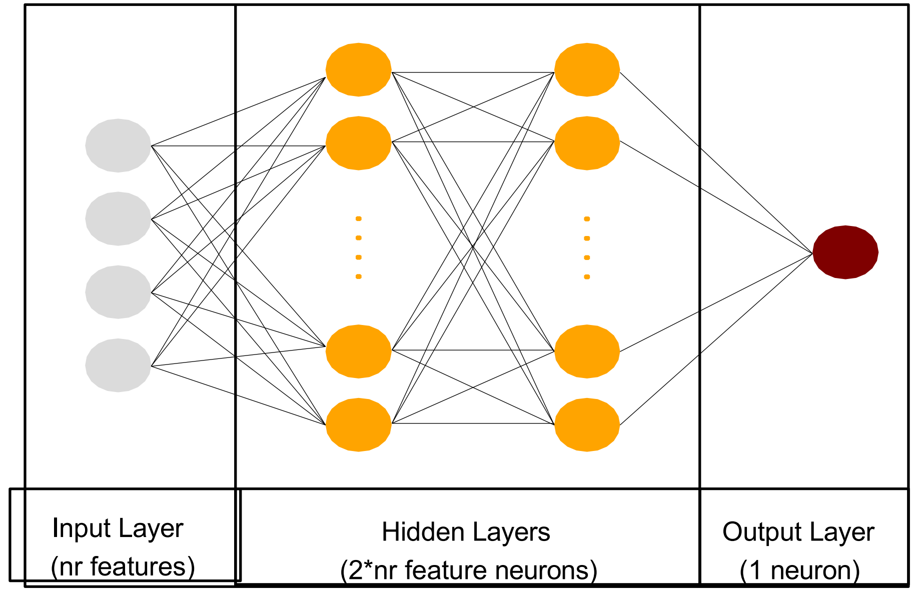


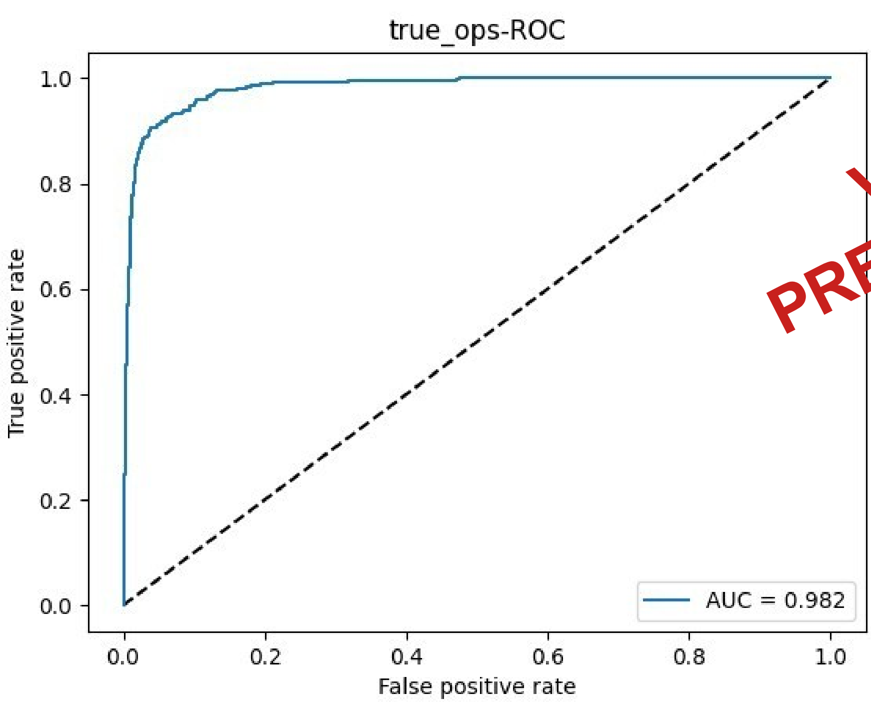
- **Preliminary results**



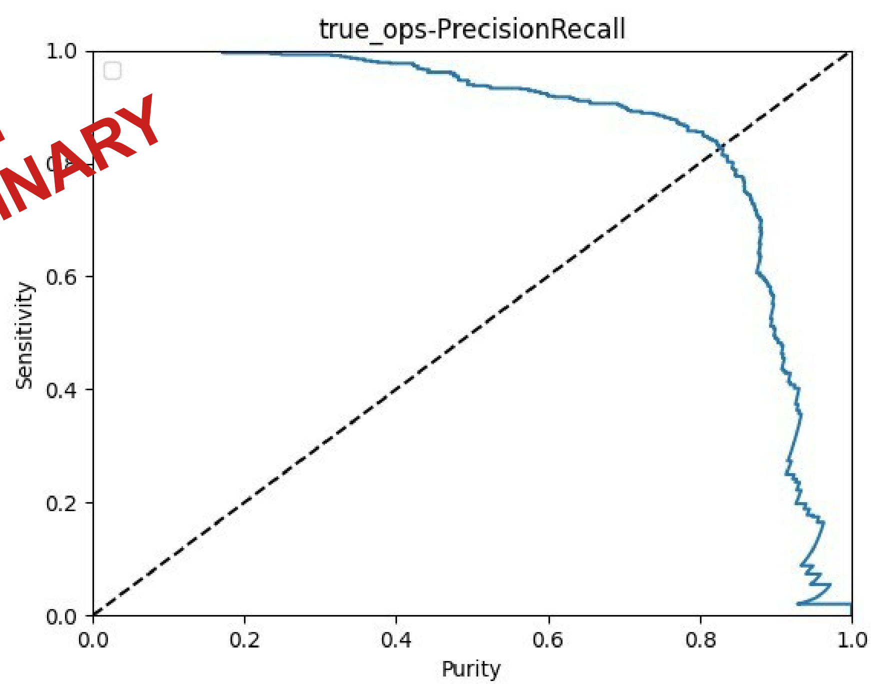
Analysis o-Ps lifetime

- ML 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





VERY PRELIMINARY



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