ACTA PHYSICA POLONICA A No. 6 Vol. **148** (2025)

2nd Symposium on New Trends in Nuclear and Medical Physics, Poland, September 24–26, 2025

The μPPET Project: Application of J-PET for Cosmic Rays Investigation

A. Porcelli[a,b,c,*]

[a] *Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, prof. Stanisława Łojasiewicza 11, 30-348 Kraków, Poland*
[b] *Centro de Investigación, Tecnologıa, Educación y Vinculación Astronómica, Universidad de Antofagasta, Avenida Angamos 601, 1240000 Antofagasta, Chile*
[c] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, Via Enrico Fermi 54, 00044 Frascati, Italy*

Doi: 10.12693/APhysPolA.148.S80 *e-mail: alessio.porcelli@uj.edu.pl

The μPPET project aims to study the cause of the observed excess of muons on the ground in extensive air showers — the so-called muon puzzle. In particular, it tests specific hypotheses that might lead to the solution of this 15-year-long-standing puzzle. The project repurposes two J-PET scanners developed by the Jagiellonian University as a muon tracker and an air-shower detection array. To make the first measurements in summer 2026, Monte Carlo simulations were used to understand the muon calibration in the muon tracker and possible array configurations. Progress achieved on these two crucial steps is presented in this work.

topics: Jagiellonian positron emission tomography (J-PET), muon puzzle, extensive air showers, mu(μ)on probe with J-PET (μPPET)

1. Introduction

Cosmic rays (CRs) are key to understanding physical phenomena in the universe, such as the mechanisms of astrophysical objects and particle acceleration, as well as the composition of the universe. Key observables are the energy and the mass of the cosmic ray. For CR with $E < 10^{15}$ eV, measurements can be performed directly through satellites and balloon-borne experiments at high altitude. At higher energies, the flux is too shallow; therefore, the measurements are made on the ground, covering large areas and using the atmosphere as a calorimeter.

Indeed, when a CR enters the atmosphere (primary particle), interactions with the air molecules occur, from strong to weak, creating an extensive air shower (EAS) of secondaries: gammas, electrons, positrons, muons, neutrinos, and a residue of hadrons. From the simplified Heitler–Matthews framework [1], the electrons and positrons collected on the ground are of particular interest for determining the energy of the primary particles, while the muons are used to estimate their mass. Due to a non-unitary efficiency of particle collection, invisible energies, and a non-trivial correlation of muon numbers and atomic mass, a hadronic interaction model must be used to establish the proper interpretation of the data in terms of the observables. Currently, three variants are widely used by the astroparticle community: QGSJet-II.04, Sibyll, and EPOS-LHC [2–4].

However, a discrepancy occurs between the mass reconstructed from the data using these models and the complementary measurements. In particular, the data show more muons than predicted by the models — this is the so-called muon puzzle [5]. This “puzzle” is an unsolved 15-year-old issue, but it is extremely compelling for the entire community in accurately and efficiently determining CR masses.

To solve the puzzle, many efforts have been made to improve the models [3–8]. Alternatively, the mu(μ)on probe with J-PET (μPPET) project proposes a geometry correction due to the polarization, inspired by the effect on the strong interaction that was recently measured by the HERMES and COMPASS experiments [9, 10]. A trajectory deflection, induced by the geomagnetic field, can change the effective lengths of the particle path, modifying the position of muon production and therefore influencing their number and density on the ground [11].

2. From J-PET to μPPET

To test the hypothesis of significant induced deflections in the secondaries due to polarization, we search for discrepancies in the muon trajectory

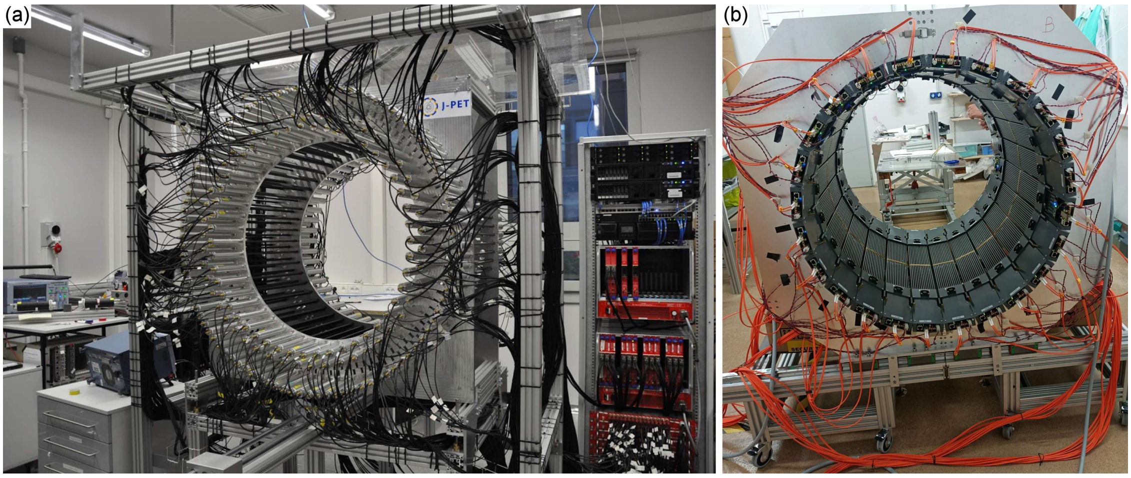

Fig. 1. Pictures of the J-PET detectors: (a) Big Barrel, (b) Modular (from [11]).

distribution compared to predictions from the current models and modified models incorporating corrections from the HERMES and COMPASS measurements. These corrections are a novelty in hadronic interaction models and are part of the goal and objective of the project, in parallel with the measurements. Therefore, there are no current predictions on how accurate the resolution must be to detect the discrepancy. Hence, we need to develop tools and methodologies to improve it as much as possible and be flexible in adapting the detection to the progress of the predictions of the new hypothesis.

The ideal location is at low altitude; we trade statistics in exchange for amplifying even slight deviations from the predicted trajectories, since muons are produced at a higher altitude than the ground. We can recover statistics optimizing the detection for cosmic rays from 10^{13} and 10^{15} eV; in this range, the energy and mass are very well known from satellite measurements, allowing for simulations with well-established parameters. The campus around the Faculty of Physics, Astronomy, and Applied Computer Science (FAIS) at Jagiellonian University, Krakow, Poland, is a suitable candidate.

Jagiellonian University has developed two scanners, named the Jagiellonian positron emission tomography (J-PET) detectors. One of them is the prototype, Big Barrel [12], shown in Fig. 1a, and the other is the Modular [13, 14], designed to be portable, shown in Fig. 1b. A J-PET detector is the first PET scanner developed using plastic scintillator strips [15, 16]; it is also cost-effective [17], suitable for scientific research [18–20], and medical applications [21–23]. Thanks to their data acquisition system (DAQ) based on a time-over-threshold (TOT) strategy [24], the position resolution is of a few mm [25].

The Big Barrel is composed of 3 concentric layers of $500 \times 19 \times 7$ mm^3 scintillator strips — 48 in each of the two innermost layers (425 mm and 467.5 mm radii, respectively) and 96 in the outermost layer (radius of 575 mm). The Modular detector is composed of 24 electronically independent modules, and each module is made of 13 scintillator strips measuring $6 \times 24 \times 500$ mm^3. Together, the modules form a single ring with a diameter of 73.9 cm.

For the µPPET project [11], the Big Barrel has been repurposed as a muon tracker. Being placed underground, it is shielded by electrons and positrons. The single modules of the Modular are, on the other hand, placed on the campus rooftops forming a scintillator array. Its purpose is to identify and reconstruct the shower induced by cosmic rays. It provides a coincidence condition for the muons in the Big Barrel and reconstructs the shower axis as a reference for the muon trajectories. The modules will be housed in pairs inside a protective cage, equipped with the necessary electronics.

3. Simulation progresses

The first data campaign is expected in the summer of 2026. In the meantime, we are making progress in the development of analysis tools and optimizing the geometry of the array. In this work, we present, in particular, the progress of muon calibration and the preliminary positions of the scintillators of the array.

3.1. Muon calibration for Big Barrel scintillators

One of the main difficulties is calibrating the energy deposited ($E_{\rm dep}$) from the muons in terms of TOT signals. The standard J-PET calibration strategy consists of measuring the TOT with sources and finding a correlation function with the corresponding simulated $E_{\rm dep}$. With muons from EAS, this

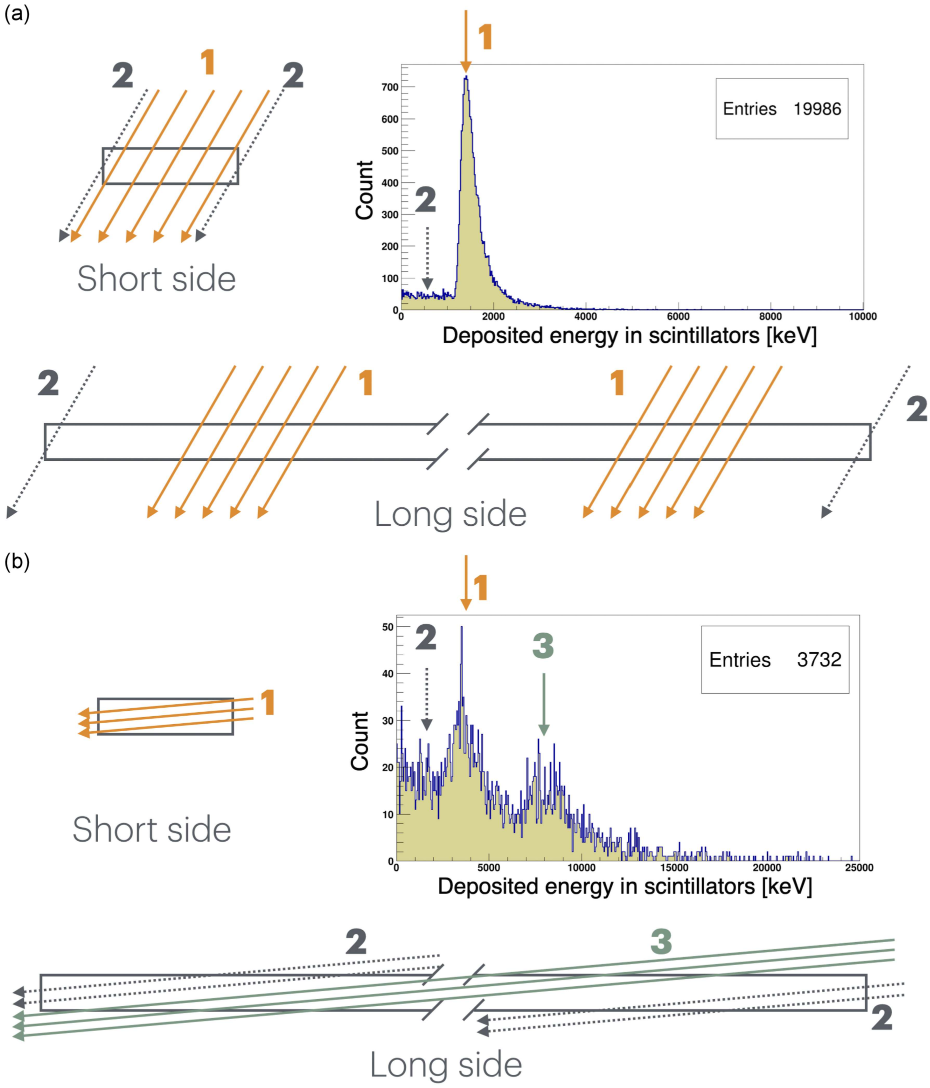

Fig. 2. Geometrical scheme of the three regions of interest (see Sect. 3.1) and the simulated energy deposited distributions. (a) The regions 1 (in orange) and 2 (in gray) are evident for small inclinations; the simulated distribution (19986 events in the detector) comprises zenithal angles between 30° and 40°. (b) For larger inclinations, region 3 appears (in green); simulations (3732 events in the detector) comprise zenithal angles between 80° and 90°. The simulated muons have random azimuthal angles and random starting points.

strategy is not possible. The difficulty arises from the CR induced muons being minimum ionizing particles. Therefore, a simple empirical conversion law is not possible, as is the case with electrons, positrons, and photons. Hence, the energy deposited from muons is mainly dependent on the inclination of the particles. This drawback will be leveraged as an advantage in a future stage of data analysis to enhance sensitivity to the muon trajectory.

The strategy for calibrating E_{dep}-TOT revolves around the creation of a three dimensional function $\mathrm{TOT} = f(E, \theta, \phi)$, where θ and ϕ are the zenithal and azimuthal angles, respectively, of the incident particle on the largest surface ($500 \times 19\ \mathrm{mm}^2$) of the scintillator. A weak dependence on particle energy E is also expected.

We began the identification of the E_{dep} features due to the geometry of the scintillator. Three regions of interest are classified:

(i) A primary Landau distribution (indicated in orange in Fig. 2). The deposited energy mode (i.e., the peak position) and the width will increase with increasing muon inclination as a result of a longer path across the scintillator. After a certain zenithal angle ($\mathrm{arccot}(7/19) \simeq 70°$), it will not change significantly, reaching approximately a plateau of deposited energy, and region 3 will appear.

(ii) Some traces fall in the “corners” of the scintillators, resulting in a collection of shorter paths (indicated in gray in Fig. 2). That is expected to be represented by an exponentially

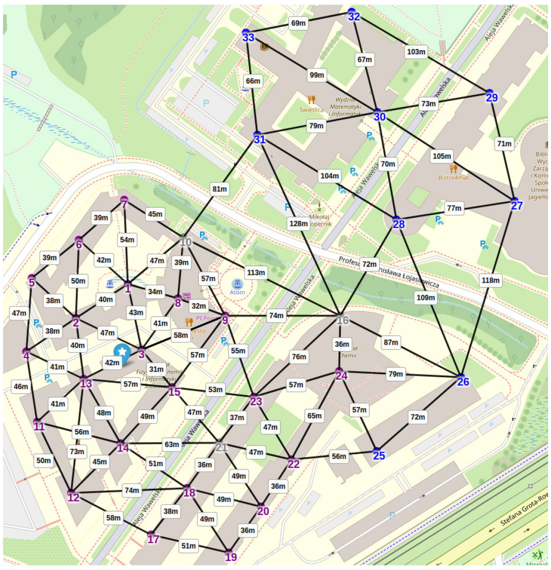

Fig. 3. Map of the cage positions (dots labeled with identification numbers). The black lines are the dimension lines with the reported distance. The purple stations are the main array (from 1 to 24), while the blue stations are the possible future larger array (25 to 32); in gray are the stations shared by the two arrays (10, 16, 21). A cyan pin with a white star indicates the position of the Big Barrel.

distributed initial tail. The more inclined the muon, the more statistically evident this tail becomes due to more volume considered "corners"; however, once the region 3 appears, the volume occupied by "corners" decreases, and this tail starts to be statistically reduced as well.

(iii) After a certain zenithal angle ($\mathrm{arccot}(7/19) \simeq 70^\circ$), a second Landau distribution appears (indicated in green in Fig. 2) to describe the few trajectories that cross the longer side of the scintillator. The inclinations are such that a small increase results in a significant increase in the Landau mode and width. Similarly to region 1, the distribution will reach approximately a plateau of deposited energy for zenithal angles greater than $\mathrm{arccot}(7/500) \simeq 89^\circ$.

In future work, we will present the calibration function, which will be fundamental also for the J-PET group to study the background induced by muons.

3.2. Scintillator array configuration

The choice of the distribution of the scintillators across the area depends on the desired energy range, where a larger distance between the scintillators corresponds to a higher detected energy. This is due to the size of the footprint (the higher the energy, the larger the footprint) and the statistical efficiency of capturing a particle. In our case, the ideal distance is between 40 and 60 m. In Fig. 3, the positions identified for the cages to house the scintillators are shown by purple and gray dots, labeled 1 to 24, covering an area of approximately 40000 m^2. We plan a campaign with a "larger array", approximately doubling the area to explore higher energies (distance between 75 and 150 m), indicated by blue dots — labeled 25 to 32 — and gray dots. The gray dots are the cages shared by the two types of arrays.

To have enough detection surface, a pair of scintillators will be housed in a cage, creating 12 active stations per campaign. In particular, to adapt to the progress on the prediction of the new hypothesis, we plan to study different possible distances of shower cores from the Big Barrel (cyan pin with a white star in Fig. 3). This is the reason why we have planned 24 cages. In future work, we will present the final configurations once the cage is positioned, which might slightly differ from the presented plan.

4. Conclusions

Among the many projects associated with J-PET, we are developing the first cosmic ray project. The J-PET detectors are repurposed efficiently to study the 15-year-long muon puzzle. This is a fundamental issue that needs to be solved to properly interpret the cosmic ray data in terms of the mass of the primary particles and, consequently, to understand the source and the acceleration mechanisms of the cosmic rays.

Although the first light is expected in the summer of 2026, numerous preparations must be completed. We have presented the current state of the understanding of muon calibration and the planned geometry of the scintillating array. The study of muon calibration will have a significant impact on all J-PET activities, since the muon background remains incompletely understood.

Acknowledgments

We thank the Dean of the Faculty of Physics, Astronomy, and Computer Science, Professor Zbigniew Postawa, and the Vice-Dean for Research and Development, Professor Leszek Motyka, for supporting the J-PET experiment and the μPPET project. We thank the support of the Ministry of Education and Science and the SciMat and qLife Priority Research Area budgets under the Programme Excellence Initiative-Research University at the Jagiellonian University. We acknowledge the technical and administrative support of A. Heczko,

M. Kajetanowicz, W. Migdał, and A. Wach. Finally, we thank the Polish high-performance computing infrastructure PLGrid (HPC Center: ACK Cyfronet AGH) for providing computer facilities and support within the computational grant no. PLG/2024/017688.

This research is funded by the National Science Centre (NCN) grant no. 2023/50/E/ST9/00576.

References

[1] J. Matthews, *Astropart. Phys.* **22**, 387 (2005).

[2] L.G. Dedenko, A.V. Lukyashin, T.M. Roganova G.F. Fedorova, *J. Phys. Conf. Ser.* **934**, 012017 (2017).

[3] T. Pierog, *Proc. Sci.* **301**, 1100 (2018).

[4] F. Riehn, R. Engel, A. Fedynitch, T.K. Gaisser, T. Stanev, *Phys. Rev. D* **102**, 063002 (2020).

[5] J. Albrecht, L. Cazon, H. Dembinski et al., *Astrophys. Space Sci.* **367**, 27 (2022).

[6] S. Baur, H. Dembinski, M. Perlin, T. Pierog, R. Ulrich, K. Werner, *Phys. Rev. D* **107**, 094031 (2023).

[7] S. Acharya, A. Agarwal, G. Aglieri Rinella et al., *J. Cosmol. Astropart. Phys.* **2025**, 009 (2025).

[8] L.A. Anchordoqui, C. García Canal, F. Kling, S.J. Sciutto, J.F. Soriano, *J. High Energy Astrophys.* **34**, 19 (2022).

[9] A. Airapetian, N. Akopov, Z. Akopov et al., *Phys. Rev. Lett.* **103**, 152002 (2009).

[10] B. Parsamyan, *Proc. Sci.* **249**, 007 (2015).

[11] A. Porcelli, K.V. Eliyan, G. Moskal et al., *Universe* **11**, 180 (2025).

[12] S. Niedźwiecki, P. Białas, C. Curceanu et al., *Acta Phys. Pol. B* **48**, 1567 (2017).

[13] F.T. Ardebili, S. Niedźwiecki, P. Moskal, *Bio-Algorithms Med-Syst.* **19**, 132 (2023).

[14] F.T. Ardebili, P. Moskal, *Bio-Algorithms Med-Syst.* **20**, 1 (2024).

[15] P. Moskal, Sz. Niedźwiecki, T. Bednarski et al., *Nucl. Instrum. Methods Phys. Res. A* **764**, 317 (2014).

[16] P. Moskal, P.0 Kowalski, R.Y. Shopa et al., *Phys. Med. Biol.* **66**, 175015 (2021).

[17] P. Moskal, E. Stępień, A. Khreptak, *Bio-Algorithms Med-Syst.* **20**, 55 (2024).

[18] P. Moskal, E. Czerwiński, J. Raj et al., *Nat. Commun.* **15**, 78 (2024).

[19] P. Moskal, A. Gajos, M. Mohammed et al., *Nat. Commun.* **12**, 5658 (2021).

[20] P. Moskal, D. Kumar, S. Sharma, *Sci. Adv.* **11**, 3046 (2025).

[21] P. Moskal, K. Dulski, N. Chug et al., *Sci. Adv.* **7**, 4394 (2021).

[22] P. Moskal, J. Baran, S. Bass, *Sci. Adv.* **10**, 2840 (2024).

[23] M. Das, R. Bayerlein, S. Sharma et al., *Bio-Algorithms Med-Syst.* **20**, 101 (2024).

[24] G. Korcyl, P. Białas, C. Curceanu et al., *IEEE Trans. Medical Imaging* **37**, 2526 (2018).

[25] L. Raczyński, W. Wiślicki, K. Klimaszewski et al., *Phys. Med.* **80**, 230 (2020).