



Review

Antimatter Research at the CERN Antiproton Decelerator: Legacy of Guido Barbiellini Amidei

Rafael Ferragut ^{1,2}

¹ L-NESS and Department of Physics, Politecnico di Milano, Via Anzani 42, 22100 Como, Italy; rafael.ferragut@polimi.it

² INFN, Milan Section, Via Celloria 16, 20133 Milan, Italy

Abstract: This work reviews the current research directions pursued by collaborations at CERN's Antiproton Decelerator (AD), with an outlook on future perspectives and challenges in the field. The advancement of precision studies on antimatter builds upon foundational contributions by pioneering researchers, such as Guido Barbiellini Amidei, whose early work on antimatter detection and instrumentation has profoundly influenced the design and methodologies of contemporary experiments at the AD and beyond. This review underscores the lasting impact of these early innovations on ongoing investigations into fundamental symmetries and interactions involving antimatter.

Keywords: antimatter; Antiproton Decelerator; CERN

1. Introduction

Guido Barbiellini Amidei made impactful contributions across several areas of experimental physics. He actively participated in numerous experiments, including the positron–electron collider ADONE at Frascati, where he made notable contributions [1]. He also played a key role in the development of detectors for astroparticle physics [2], contributing significantly to the Fermi Gamma-ray Space Telescope mission [3]. At CERN, he was a leading figure in the study of matter–antimatter symmetry through the DELPHI (DEtector with Lepton, Photon, and Hadron Identification) experiment. He played a central role in shaping the experiment's scientific goals and oversaw the construction of the barrel electromagnetic calorimeter. He also made essential contributions to the design of the silicon strip detectors used for precise particle tracking. More than a technical contributor, Guido was a constant source of intellectual energy within the collaboration—proposing innovative ideas in fundamental physics, particularly during LEP's transition to higher-energy operations, and fostering meaningful dialogue with both young researchers and senior colleagues (see the recent outreach article, Ref. [4]). I had the pleasure of learning about him thanks to my colleague and mentor, Alfredo Dupasquier [5], who knew him personally.

As part of the extensive DELPHI collaboration—comprising around 550 physicists from 56 universities and research institutes across 22 countries—Guido contributed to one of the four main detectors at the Large Electron-Positron (LEP) Collider at CERN. DELPHI was engineered with high granularity and nearly full 4π solid-angle coverage, enabling detailed and effective particle identification. The collaboration's scale and ambition reflected the international effort behind one of CERN's most important experiments prior to the LHC era.

The LEP collider initially operated at center-of-mass energies around 91 GeV, but over time it achieved a world-record energy of 209 GeV—high enough to produce more than



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110 proton–antiproton pairs. DELPHI was active from 1989 until 2000, when data collection ended and the detector was dismantled to make room for the construction of the Large Hadron Collider (LHC) in the same tunnel.

The DELPHI detector featured a central cylindrical structure housing multiple sub-detectors, enclosed by two end caps. A comprehensive description is provided in Ref. [6]. The detector measured 10 meters in both length and diameter and had an approximate total weight of 3500 tons. In total, DELPHI incorporated 20 subdetectors. A large superconducting magnet was positioned between an electromagnetic calorimeter (for detecting electrons) and a hadronic calorimeter. The magnet generated a field that deflected charged particles, allowing their charge and momentum to be measured. DELPHI employed the ring imaging Cherenkov technique to distinguish between secondary charged particles and featured an advanced silicon detector capable of identifying short-lived particles by extrapolating their tracks back to the collision point.

The main DELPHI result allowed the high energy e^+e^- collisions to form W^+W^- pairs to be studied for the first time. This was done by having center-of-mass energies over the threshold of W^+W^- pair production. From the data, the mass of the W boson was determined as $80.40 \pm 0.45 \text{ GeV}/c^2$, which was then combined with results from the other LEP collaborations to produce a final result compatible with other experiments [7].

At the beginning of the 2000s, matter–antimatter asymmetry physics at CERN took two important directions, that is, the construction of the LHC on the foundations of the LEP and the development of the Antiproton Decelerator (AD) to slow down antiprotons produced by the Proton Synchrotron (PS) accelerator.

DELPHI contributes to characterizing matter–antimatter particles and studying their symmetry. The developed DELPHI silicon strip detectors have been used in successive experiments like the International Space Station (ISS), the LHC, and the AD hall at CERN. The LHC has contributed to the building block of the Standard Model theory, most notably with the discovery of the Higgs boson in 2012 [8,9]. This finding confirmed the mechanism proposed by François Englert and Peter W. Higgs, which plays a fundamental role in explaining the origin of mass in subatomic particles, ultimately leading to the awarding of the 2013 Nobel Prize in Physics to both scientists. Several reviews document the long list of contributions (see, for instance, [10,11]).

High-energy physics remains a central focus for the coming decades, with several major proposals for next-generation particle colliders currently under consideration to succeed the LHC [12]:

- **Future Circular Collider (FCC):** A 91 km circular collider proposed at CERN [13], potentially operational by around 2045. It aims to achieve extremely high luminosities, enabling rapid data collection (e.g., 10^{12} Z decays, 10^6 Higgs bosons), and may accommodate up to four interaction points (IPs) for parallel experiments.
- **International Linear Collider (ILC):** A mature design based on superconducting niobium RF cavities operating at 1.3 GHz, achieving gradients of approximately 35 MV/m. It features two linacs (for e^+ and e^-) and a single interaction point. The baseline energy is 250 GeV (30 km), upgradeable to 1 TeV. Although a site has been identified in Japan, political approval is still pending.
- **Compact Linear Collider (CLIC):** Uses normal-conducting RF cavities at 12 GHz, achieving higher gradients of around 100 MV/m. It is planned in stages, that is, 380 GeV (11 km) up to 3 TeV (50 km). The design employs a two-beam acceleration system, where a low-energy, high-current drive beam powers the RF cavities of the main linac. CLIC could be hosted at CERN.
- **Circular Electron Positron Collider (CEPC):** A circular collider proposed in China, with a design concept similar to the FCC.

CERN's Antiproton Decelerator (AD) program continues to advance the frontiers of physics through high-precision studies of antimatter. The experiments carried out at the AD address one of the most profound open questions in modern science: the observed dominance of matter over antimatter in the universe, despite theoretical expectations of symmetry. By enabling precision measurements on trapped antihydrogen atoms, the program allows researchers to test key principles such as CPT invariance and the gravitational behavior of antimatter. These investigations provide crucial input for refining the standard model and exploring potential extensions.

Beyond their technical accomplishments, these studies offer deep conceptual insights into the nature of mass, time, and the structure of physical laws. Antimatter serves not only as a counterpart to matter but also as a powerful tool to probe fundamental symmetries. In this context, the AD program plays a central role in both experimental and theoretical efforts to understand the universe at its most elementary level.

Future objectives—extending beyond 2040—include the development of transportable antimatter traps and new investigations into quantum field theory, gravity, and dark matter. The research agenda also encompasses hadron physics with antiprotons, including processes such as the Pontecorvo reaction, antineutron annihilation, and hypernuclei decay, reinforcing CERN's leadership in precision experimental physics.

The following summary outlines the research on matter–antimatter asymmetry conducted in CERN's AD hall, highlighting both ongoing studies and emerging directions [14]. Although this paper does not focus on detector technologies, many of the devices employed originate from earlier experiments, such as DELPHI, and continue to play a vital role in current and future investigations.

2. Physics at the AD at CERN

A new generation of antimatter experiments has been opened after the first experiments of antihydrogen production in laboratory conditions at the CERN laboratory [15] and at Fermilab [16]. These experiments produced hot antihydrogen ($\bar{H}$), i.e., relativistic, in small quantities not suited to precision $\bar{H}$ studies. Following that, a program is underway at CERN with a facility dedicated to low-energy antiproton ($\bar{p}$) and $\bar{H}$ experiments. After the first production of cold $\bar{H}$ by the ATHENA [17] and ATRAP [18] collaborations. At the moment, there are six active collaborations at the AD hall at CERN: (i) AEGIS (Antihydrogen Experiment: gravity, interferometry, and spectroscopy); (ii) ALPHA (Antihydrogen Laser Physics Apparatus); (iii) ASACUSA (Atomic Spectroscopy and Collisions Using Slow Antiprotons); (iv) BASE (Baryon Antibaryon Symmetry Experiment); (v) GBAR (Gravitational Behavior of Antimatter at Rest); and (vi) PUMA (Antiproton Unstable Matter Annihilation). The goal and direction of these experiments for the next years are summarized as follows. Many of these collaborations rely on detection technologies originally developed by earlier experiments, as discussed in Section 1.

2.1. AEGIS

The AEGIS collaboration aims at determining how antimatter behaves in gravitational fields [19–21]. The experiment adopts a horizontally-boosted, free-falling pulsed beam of cold antihydrogen, probed by a high-resolution position-sensitive detector based on a series of gratings (a so-called moiré deflectometer [22]). This approach aims at transporting the antihydrogen atoms outside the magnetic field necessary to radially confine antiprotons, and conduct gravitational experiments in an electric and magnetic field-free environment. The formation process on which the pulsed, cold antihydrogen source is based is the charge-exchange reaction:



between Rydberg positronium atoms (denoted as Ps^*) impinging on an antiproton cloud. The expected Ps^* principal quantum number will be $n > 20$. The so-formed Rydberg-excited antihydrogen atoms (denoted as $\bar{H}^*$) have a momentum mostly determined by that of the initial antiproton, thanks to the small momenta of impinging Ps^* atoms. By using this method, the resulting antihydrogen atoms inherit the positronium Rydberg state, with a principal quantum number lower than that of the original n of Ps^* and approximately given by $n/\sqrt{2}$. Moreover, the cross-section of the charge-exchange reaction scales with n^4 , enhancing the efficiency of antihydrogen production at high Rydberg states.

This collaboration has yielded several significant milestones, including the first observation of antiproton deflectometry in 2014 [22], the formation of a pulsed antihydrogen beam in 2021 [23], the successful demonstration of positronium laser cooling—achieved independently and nearly simultaneously with a Japanese group in 2024 [24]—and the detection of slow antiprotons using a real-time digital vertex detector with sub-micrometer resolution in 2025 [25].

Following the ALPHA collaboration's success in determining, for the first time, the gravitational interaction between $\bar{H}$ and Earth [26] (see next subsection), AEgIS is planning, based on its recent achievements, to improve the measurement of the gravitational acceleration g with a target precision within 1%.

AEgIS has developed the key techniques required for its initial goals—antihydrogen gravity measurements and positronium spectroscopy—and is now expanding its scope to explore a broad range of physics topics, including antimatter-based gravity tests, precision QED studies, nuclear physics, dark matter searches, and antimatter-containing molecular systems.

AEgIS has laid the technological foundation for a broader program that extends well beyond its initial goals. The medium- to long-term research includes the following: (i) precision QED tests using laser spectroscopy of positronium and antiprotonic atoms; (ii) nuclear studies using antiproton annihilation on trapped atoms to access exotic radioisotopes; (iii) exploration of dark matter candidates, including uuddss sexaquarks, via $\bar{p}^3\text{He}$ annihilation; (iv) formation and spectroscopy of antiprotonic and antideuteron atoms; (v) investigations into antimatter-containing molecular ions and potential electric dipole moment (EDM) searches; and (vi) studies of antineutron interactions via charge-exchange production from antiprotons. These future advancements depend on continued access to CERN's antiproton facility beyond the programmed Long Shutdown 4.

2.2. ALPHA

The ALPHA collaboration at CERN has been a pioneer in antihydrogen research since the first successful trapping of anti-atoms in 2010 [27]. Since then, the experiment has achieved a series of groundbreaking results in precision spectroscopy, antimatter gravity, and fundamental symmetry tests. ALPHA has observed several key optical transitions [28–30] as well as microwave-induced ground-state hyperfine transitions [31,32], advancing our understanding of the internal structure of antihydrogen.

A major focus has been the 1S–2S transition, which currently achieves a precision of 10^{-12} [30], with further improvements expected thanks to ongoing upgrades including fluorescence detection optics and in situ comparison with hydrogen during the upcoming Long Shutdown 3 (LS3). ALPHA has also demonstrated laser and adiabatic cooling of antihydrogen, achieving mean kinetic energies near 1 mK and simultaneously confining over 10^4 anti-atoms using positron cooling techniques with laser-cooled Be^+ ions [29].

In the gravitational domain, ALPHA performed the first direct measurement of the gravitational acceleration of antimatter ($\bar{H}$) due to the Earth's gravitational field, reporting a value of $(0.75 \pm 0.13 \text{ (stat. + syst.)} \pm 0.16 \text{ (sim.)})g$ for antihydrogen [26], consistent with

an attractive interaction with Earth. The ALPHA-g apparatus is poised to improve this measurement, aiming for 1% precision and beyond through techniques such as atomic interferometry and antihydrogen extraction.

ALPHA's comprehensive program aims to test CPT invariance and the Weak Equivalence Principle with increasing sensitivity over the next decades. The collaboration is expanding its spectroscopic reach to transitions such as Lyman- α (1S–2P), 2S–2P, 2S–3S, and 2S–4P, and aims to determine quantities like the anti-Rydberg constant and the antiproton charge radius. These efforts solidify ALPHA's role at the frontier of antimatter research and fundamental physics.

2.3. ASACUSA

The ASACUSA collaboration at CERN investigates fundamental symmetries between matter and antimatter through high-precision spectroscopy of systems containing antiprotons. These include hybrid matter–antimatter systems such as antiprotonic helium, and pure anti-atoms like antihydrogen. The research also extends to studies of antiproton annihilation and collisions.

A central focus is the measurement of the ground-state hyperfine structure (GS-HFS) of antihydrogen using Rabi spectroscopy [33,34], with the goal of achieving ppm-level precision and, in the future, part per billion-level (ppb) sensitivity by upgrading to a Ramsey-type setup. The AD-ELENA facility upgrade and innovations in plasma manipulation techniques have enabled a two-order-of-magnitude increase in beam intensity. This paves the way for further improvements in beam properties—such as polarization, spatial distribution, and velocity—which are crucial for high-precision experiments. Additional approaches, including beam focusing, deceleration, and new formation methods, are under development. Spectroscopy of other antihydrogen states using microwaves or, eventually, lasers is also planned, potentially yielding insights into quantities like the anti-Rydberg constant and the antiproton radius [35,36].

The collaboration has achieved remarkable precision in determining the antiproton-to-electron mass ratio via laser spectroscopy of antiprotonic helium [37,38], yielding $M_{\bar{p}}/m_e = 1836.1526734(15)$. These results provide stringent tests of QED and constraints on possible new interactions such as fifth forces and exotic axion-like couplings. To improve this test by up to two orders of magnitude, ASACUSA is implementing two-photon laser spectroscopy techniques. Related initiatives at the Paul Scherrer Institute include similar methods for mesonic atoms, targeting the masses of charged pions and kaons [39]. Observations of antiprotonic helium in superfluid environments suggest potential applications in probing condensed matter phenomena [40].

Collision and annihilation studies with low-energy antiprotons (10–20 keV) aim to measure ionization cross-sections for helium, argon, and hydrogen molecules, exploiting the antiproton as a clean, non-exchange particle probe of atomic electron structure. Plans include extending these measurements to sub-keV energies and benchmarking annihilation models via thin foil targets [41], as well as measuring antiproton-nucleus annihilation cross-sections at 100 keV using ELENA in mini-bunch mode [42].

Looking ahead, future accelerator upgrades may facilitate studies at energies exceeding 5.3 MeV, allowing investigations of elastic scattering and annihilation dynamics [43]. ASACUSA also proposes exploring the Pontecorvo reaction [44] and conducting antimatter interferometry experiments, building upon recent positron-based results by the QUPLAS collaboration [45]. These efforts are fundamental for exploring quantum interference effects such as the Aharonov–Bohm phenomenon with antiprotons.

2.4. BASE

The BASE collaboration employs advanced Penning trap techniques to perform high-precision comparisons of the fundamental properties of protons and antiprotons, providing stringent tests of CPT symmetry in the baryon sector. Notably, the experiment has achieved a comparison of the charge-to-mass ratios of the proton and antiproton with a fractional uncertainty of just 16 parts per trillion (ppt) [46]. These results also function as clock-comparison tests, placing bounds on violations of the weak equivalence principle. In addition, BASE has set new benchmarks in measuring magnetic moments: the proton magnetic moment has been determined with a precision of 300 ppt [47], while the antiproton magnetic moment has been measured with a precision of 1.5 ppb [48], improving previous results by more than three orders of magnitude. These high-precision results have enabled direct limits on couplings between antimatter and dark matter [49], outperforming astrophysical constraints by over five orders of magnitude.

Recent upgrades to the experimental apparatus have allowed BASE to demonstrate coherent magnetic moment spectroscopy with 16-fold narrower linewidth and improved signal-to-noise compared to earlier measurements [48]. These advancements pave the way for an order-of-magnitude improvement in the determination of the antiproton magnetic moment and allow exploration of possible antiproton–axion interactions. Upcoming plans include simultaneous two-particle measurements in a single trap to enhance the charge-to-mass ratio precision to the ppt level. To extend measurements beyond the accelerator operation period, BASE developed a reservoir trap capable of storing antiprotons [50], enabling experiments during the annual CERN shutdown. The successful off-site transport of protons [51] marks a milestone toward relocating the experiment to a low-noise precision laboratory, where BASE aims to continue and expand its research program.

The long-term vision includes coordinated infrastructure at multiple institutions—Mainz, Hannover, Heidelberg, Düsseldorf, and CERN—designed to facilitate synchronized and complementary measurements in various trap configurations. These efforts aim to improve fundamental constant determinations and enable precision studies of antiproton properties by at least two orders of magnitude before 2040. For instance, BASE-Mainz has achieved record-low temperatures via sympathetic cooling of single protons [52], and BASE-Hannover is advancing quantum logic spectroscopy methods [53], both of which may be extended to antiprotons. Other initiatives include deuteron magnetic moment measurements and a high-precision search for antiproton decay with a target sensitivity improvement of up to three orders of magnitude [54].

Finally, BASE's exceptional control of trap environments has enabled novel research directions in fundamental physics. The collaboration has observed ultra-low heating rates in spin-state detection traps [55], facilitating the search for milli-charged dark matter particles [56] and axion-like particles [57]. A dedicated experiment is under development to exploit these detectors, aiming to improve existing axion limits by at least two orders of magnitude, demonstrating BASE's broad impact on both precision metrology and the search for new physics.

2.5. GBAR

The GBAR collaboration aims to measure the gravitational acceleration of antihydrogen by producing and cooling the antihydrogen ion, composed of one antiproton and two positrons. This anti-ion can be sympathetically cooled using laser-cooled Be^+ ions, then photo-neutralized near threshold to create ultra-cold antihydrogen with minimal kinetic energy [58]. The free fall of these neutral anti-atoms can be studied over distances of a few centimeters, and eventually at the sub-millimeter scale where quantum effects from surface interactions, such as Casimir–Polder reflection, may give rise to gravitational

quantum states. The targeted relative precision on the measurement of gravitational acceleration is of the order of 10^{-5} [59]. Although the antihydrogen ion has not yet been produced, it represents a powerful new tool for antimatter physics. It would enable further developments such as optical trapping of ultracold antihydrogen [60] and the production of molecular ions [61], opening up new avenues to test Lorentz and CPT symmetries with unprecedented sensitivity.

To generate the anti-ion, a two-step charge exchange process involving positronium is employed—first, antiprotons react with positronium to form antihydrogen, and then antihydrogen reacts with positronium to form the anti-ion. This process requires high numbers of antiprotons ($\sim 10^7$) and positrons ($\sim 10^{10}$) per event. GBAR currently traps up to 5×10^6 antiprotons from ELENA and 6×10^8 positrons every two minutes, with record achievements of 7×10^7 antiprotons in 35 min and nearly 10^{10} positrons in 30 min. The successful production of antihydrogen was demonstrated in 2022 [62], and subsequent upgrades in 2023 have boosted production rates by a factor of 30, with further improvements expected as transport efficiency to the interaction region is optimized.

Experimental measurements of the antihydrogen and anti-ion formation cross-sections from positronium, informed by recent theoretical predictions, are planned for 2025 using the GBAR setup with a pulsed hydrogen beam [63]. If favorable cross-sections are confirmed, GBAR aims to begin its weak equivalence principle tests after CERN's Long Shutdown 3, culminating in a first free-fall measurement at 1% precision. Subsequent phases will aim for the first observation of quantum reflection and gravitational quantum states of antihydrogen. By CERN's Long Shutdown 4 (around 2034), the experiment may evolve toward precision spectroscopy and interferometry with cold antihydrogen, achieving sensitivities below 10^{-5} . In parallel, GBAR plans to pursue complementary studies, including Lamb shift measurements in magnetic-field-free environments [64], and cross-section measurements for charge exchange with excited positronium. An in-flight microwave spectroscopy program, running concurrently with ion production, may also target transitions such as the fine structure of antihydrogen, offering additional tests of CPT and Lorentz symmetry. Looking further ahead, if antideuterons become available at CERN, GBAR could adapt its setup to study antideuterium using similar techniques [65].

2.6. PUMA

The PUMA experiment is designed to probe the neutron and proton distributions in nuclei through antiproton annihilation. Neutron-rich nuclei develop a neutron skin—an excess of neutrons at the surface—which reflects underlying effective nuclear forces derived from quantum chromodynamics (QCD), shell structure, and the nuclear equation of state relevant to neutron stars. Despite intensive research, experimental knowledge of neutron skin thickness remains limited due to challenges in accessing neutron density profiles.

PUMA exploits the formation of antiprotonic atoms when low-energy antiprotons are captured by nuclei. These atoms offer unique sensitivity to the peripheral nuclear density where neutron skins reside. By detecting the charged pions resulting from antiproton annihilation, PUMA aims to extract neutron-to-proton annihilation ratios. The total pion charge and multiplicity are key observables, although final-state interactions with the residual nucleus remain a significant source of uncertainty. Originally proposed by Wada and Yamazaki in 2004 [66], the technique can achieve a 10% precision for 10^4 annihilations, and is implemented for the first time in the PUMA setup [67].

PUMA consists of Penning traps within a 4-T solenoid, surrounded by a time-projection chamber for pion detection. Stable isotope experiments will be conducted at ELENA, while short-lived radioactive nuclei will be studied at ISOLDE. The setup is

transportable: antiprotons will be trapped and stored at ELENA, then moved to ISOLDE for interactions with exotic isotopes.

Accepted in 2021, the experimental setup is nearing completion and will be installed at ELENA in 2025. Initial milestones include the demonstration of antiproton storage and transport (with a target of 10^7 trapped antiprotons) and successful mixing with isotopes.

At ELENA, PUMA will (i) measure neutron-to-proton annihilation ratios in light systems (p, d, ^3He , ^4He) and along the oxygen, neon, and xenon isotopic chains; and (ii) characterize neutron skins in $^{40-48}\text{Ca}$, $^{112-124}\text{Sn}$, and $^{206-208}\text{Pb}$ using a new laser-ablation ion source.

At ISOLDE, the focus will shift to isotopic dependencies, particularly the following: (i) neutron halo nuclei such as ^6He , ^8He , ^{11}Li ; (ii) proton-rich candidates like ^8B , $^{17,18}\text{Ne}$; (iii) deformed and potentially haloed nuclei like $^{26-30}\text{Ne}$, $^{28-33}\text{Mg}$; (iv) neutron skin evolution in $^{14-22}\text{O}$, exotic Xe, and Sn isotopes. The most challenging cases, like ^{11}Li (with a 9 ms half-life and beam intensities of $\sim 10^3$ ions/s), will demand PUMA's full performance capabilities.

3. Summary

The present achievements and future prospects of antimatter research at CERN's Antiproton Decelerator (AD) are firmly grounded in the technical innovations and experimental expertise developed over decades. As a member of the AD community for more than fifteen years, I have had the privilege of witnessing how current advances stand on the shoulders of earlier contributions. Guido Barbiellini Amidei serves as a symbol of the many dedicated scientists and engineers who, often working quietly behind the scenes, helped to shape the detection techniques and instrumentation that remain central to our experiments. Beyond the sophisticated and costly apparatuses, it is ultimately the talent, perseverance, and collaborative spirit of numerous individual persons—and the unique value each of them brings—that make meaningful scientific progress possible. Their collective efforts continue to expand the frontiers of human knowledge.

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