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Zusammenfassung

Alle fundamentalen Wechselwirkungen des Standard Modells der Teilchenphysik sind invariant unter der kombinierten Transformation von Ladungskonjugation, Parität und Zeitumkehr (CPT). Es folgt, dass die fundamentalen Eigenschaften von Teilchen und Antiteilchen betragsmäßig gleich sind. Infolgedessen sollten auch die Spektren von Atomen und deren Antiatomen gleich sein. Das einfachste stabile Atom, das gänzlich aus Antimaterie besteht, ist Antiwasserstoff. Sein Materiegegenstück, Wasserstoff, ist eines des meist untersuchten atomaren Systeme. Ein Vergleich der Spektren von Wasserstoff und Antiwasserstoff liefert daher einen der sensitivsten Tests der CPT Symmetrie.

Die ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) Kollaboration hat das Ziel die Übergangsfrequenz der Hyperfeinstruktur von Antiwasserstoff im Grundzustand in einem Rabi-ähnlichen Strahlexperiment zu messen und somit die CPT Symmetry mit höchster Präzision zu testen. Antiprotonen und Positronen werden in einer Teilchenfalle zu Antiwasserstoff kombiniert. Die neutralen Antiatome verlassen die Falle als polarisierter Strahl and treten in den Spektroskopieapparat ein, der aus einer Mikrowellenkavität und einem Sextupolmagneten besteht.

Am Ende des Aufbaus annihilieren die Antiatome in einem Detektor, der im Fokus dieser Arbeit steht. Die Aufgabe des Detektors ist, die ankommenden Antiwasserstoffatome zu zählen und somit Signal von Hintergrund zu unterscheiden. Letzterer ist von Höhenstrahlung dominiert. Der Detektor besteht aus einem positionsempfindlichen Kalorimeter im Zentrum eines zweilagigen Hodoskops zum Nachweis der Sekundärteilchen der Annihilation.

Im Zuge dieser Arbeit sind mehrere Hardware- und Softwareverbesserungen der Diskriminierung von Signal und Hintergrund durchgeführt worden. Insbesondere ist eine effiziente, auf experimentellen Daten basierende Machine Learning Analyse zur Identifizierung von seltenen Antiwasserstoffannihilationen und Hintergrundereignissen entwickelt worden. Der Algorithmus wurde mit Antiprotonannihilationen, die während dedizierten Extraktionen zum Detektor aufgenommen wurden, und Hintergrundereignissen, die während Perioden ohne Antiprotonen in den Fallen gemessen wurden, trainiert.

Das wichtigste Resultat ist die erste Messung der Hauptquantenzahlverteilung der produzierten Antiwasserstoffatome im feldfreien Raum. Das Ergebnis deutet darauf hin, dass ein Teil der Antiwasserstoffatome in niedrigen Energiezuständen produziert wird. Jedoch ist die Rate noch nicht ausreichend genug, um Spektroskopie zu betreiben, und das Ziel einer Messung des Hyperfeinübergangs mit ppm Genauigkeit noch nicht zum Greifen nah.

Des Weiteren wurde die Positionsauflösung des Hodoskops kürzlich durch ein Upgrade bestehend aus szintillierenden Fasern verbessert. Ein drei-dimensionaler Trackingalgorithmus wurde im Zuge dieser Arbeit entwickelt, mit dem Ziel, die

Vertices von Annihilationen zu bestimmen. Information über die Position der Annihilationen ist hilfreich um Antiwasserstoffereignisse, die auf dem zentralen Detektor annihilieren, von denen zu unterscheiden, die upstream vom Detektor am Strahlrohr auftreten.

Abstract

All fundamental interactions described within the Standard Model of particle physics are invariant under the combined transformation of charge conjugation, parity and time reversal (CPT). As a consequence, the fundamental properties of particles and their antiparticles are identical (mass, lifetime) or sign-opposite (charge, magnetic moment). Thus, atoms and antiatoms should also have the same characteristic spectra. The simplest stable atom composed solely of antimatter is antihydrogen and its matter counterpart hydrogen is one of the most precisely studied atomic systems. Therefore a comparison of the spectra of hydrogen and antihydrogen allows one of the most stringent tests of CPT.

In order to test CPT symmetry with high precision, the ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) collaboration aims to measure the ground state hyperfine splitting of antihydrogen in a Rabi-type beam experiment. Antiprotons and positrons form antihydrogen in a mixing trap. The antiatoms leave the trap as a polarised beam and reach the spectroscopy beamline consisting of a microwave cavity for inducing hyperfine transitions and a state-analysing sextupole magnet.

At the end of the apparatus, the antiatoms annihilate in a detector which is the focus of this thesis. Its purpose is to count the arriving antihydrogen atoms and to distinguish these signal events from the cosmic-ray dominated background. The detector is composed of a position sensitive central calorimeter which records the annihilation and a surrounding two-layered hodoscope for tracking annihilation products (pions). In the course of this thesis, improvements of the signal and background discrimination on the hardware and the software level have been carried out.

Most notably, a data-driven machine learning analysis has been developed to distinguish rare antihydrogen annihilations from background events with high efficiency. The algorithm is trained and evaluated with antiproton events recorded during dedicated direct antiproton extractions to the detector and background events gathered during periods without antiprotons in the traps. The most important result is the first measurement of the distribution of principle quantum numbers of the produced antihydrogen atoms in a magnetic field-free region. The outcome indicates that a small fraction of antihydrogen atoms in low-lying states are produced. The rate however is not yet sufficient for spectroscopy, and the goal of a relative precision for the hyperfine frequency at the ppm level is not yet within reach.

Recently, the hodoscope's position resolution has been improved by an upgrade consisting of scintillating fibres. During this thesis, a three-dimensional tracking algorithm has been developed in order to determine the vertices of annihilation events. Information on the position of the annihilation helps to distinguish antihydrogen events annihilating on the central detector from possible annihilations upstream.

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1. Introduction and theoretical background

1.1. The importance of symmetries

From time immemorial, the concept of symmetry has played a central role in mankind's view of the world and explanations of its inner workings. Symmetries observed in our surroundings inspired the idea of a defining symmetry in the heart of nature. For a long time, the notion of symmetries in physics was only used for describing objects as well as phenomena i.e. particular solutions of the equations of motion.

Classical mechanics (Newton, 1687) and electrodynamics (Maxwell, 1862) already contained symmetries due to the invariance of their laws under Galilean and Gauge transformations, respectively. Although these symmetries were recognised, their implications were not fully apprehended until the 20th century.

The concept of symmetry was revolutionised when Emmy Noether proved a profound link between symmetries and conservation laws in 1918 [1]. Conservation laws were considered before to be fundamental, but they were only thought of as a result of the dynamical laws of nature [2]. It was only found by Noether that the invariance of the action under a continuous symmetry transformation actually leads to a conservation law.

The emergence of quantum mechanics and the connection of symmetries to group theory, their mathematical description, resulted in an even greater gain of importance of symmetries. Notably, the discovery of the selection rules of atomic spectra as a result of symmetry under rotations in three dimensions which are described by the group $SO(3)$ ¹. Another important example is the exchange symmetry of identical particles which led to the classification of particles according to their spin into either bosons (integer spin) or fermions (half-integer spin).

Eventually, the development of quantum field theory, the relativistic version of quantum mechanics, marked another peak in the significance of symmetries. The most prominent example being the Standard Model, which was developed in the 1970s, encompasses our understanding of all known elementary particles and all known forces with the exception of gravity. Although it

¹The special orthogonal group $SO(3)$ can be represented by 3×3 matrices with $MM^T = M^T M = \mathbb{1}$.

is regarded as incomplete, it has had huge successes in predicting phenomena and withstanding experimental tests. The Standard Model and its two main ingredients, particles and interactions, are heavily based on symmetries. Elementary particles are associated with representations² of the Poincaré group³ and the fundamental forces can be derived by requiring local gauge invariance of the Lagrangian [3].

Apart from continuous space-time and gauge symmetries, discrete symmetries are of key importance in particle physics. The most significant discrete symmetry operations are:

- The parity transformation P which describes an inversion of space with respect to the origin i.e. $\vec{r} \rightarrow -\vec{r}$,
- the charge conjugation C under which all intrinsic charges change sign, which therefore turns a particle p into its antiparticle $\bar{p}$: $p \rightarrow \bar{p}$,
- and time reversal T : $t \rightarrow -t$.

These symmetries were believed to be exact up to the 1950s. According to C. S. Wu, who had the leading role in the experimental discovery of the P -violation by the weak interaction⁴ [5], it was “unthinkable that anyone would question the validity of symmetries under P , C and T ” and “it would have been almost sacrilegious to do experiments to test such unholy thoughts” [6].

After the discovery of P and also C violation, it was strongly assumed that at least the combined symmetry CP should hold. In 1964 however, it was experimentally demonstrated by J. Cronin and V. Fitch [7], that the weak interaction violates CP in the neutral Kaon system.

Presently, the product of all three discrete operations, CPT , is the only combination that is observed to be exact within experimental limits. CPT invariance is a direct result of any relativistic local quantum field theory (CPT Theorem) and therefore a consequence of only mild requirements [8] which strongly highlights its fundamental character. The CPT theorem has been proven first based on Lagrangian field theory by G. Lüders [9] and W. Pauli [10], by showing that all terms of the Lagrangian density are CPT symmetric. A second more general proof by R. Jost within the scope of axiomatic field theory can be found in [11].

Since CP is violated, CPT invariance essentially requires T violation, there-

²Every element of an abstract group can be represented by a corresponding matrix. The group of matrices is homomorphic.

³The Poincaré group is a space-time symmetry group and comprises translations (in time and space), rotations and boosts.

⁴In 1956, T. D. Lee and C. N. Yang proposed experiments for testing P symmetry of the weak interaction [4].

fore it was also strongly assumed that T symmetry must be broken. In 2012, it was experimentally observed by the BABAR experiment in the neutral B meson system [12].

CPT symmetry is intimately linked to antimatter since the CPT theorem implies that particles and antiparticles have the same or sign-opposite properties, which will be discussed in the next section.

1.2. Antimatter and CPT

When Dirac succeeded in combining quantum mechanics and special relativity into a single coherent theory, it came with the unexpected requirement that antiparticles existed [13, 14]. The negative energy quantum states resulting from Dirac's famous equation describing relativistic electrons lead to the prediction of "a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron. We should not expect to find any of them in nature" (Dirac in [15]).

A few years later in 1932, the positron, the electron's antiparticle was discovered by C. Anderson in cosmic rays [16]. Its discovery fuelled the search for a possible antiparticle of the proton, which was then first observed in 1955 at Lawrence Berkeley National Laboratory where it was artificially created by the the Bevatron accelerator [17].

For every particle exists a corresponding antiparticle and their properties are identical (such as the mass, lifetime) or sign-opposite to matter (charge, internal quantum numbers). When particles and antiparticles meet, they annihilate.

Since matter and antimatter were thought of as behaving symmetrically, the asymmetry observed in the close-by universe, i.e. the over-abundance of matter and the absence of large amounts of antimatter, was firstly assumed to be a result of the initial conditions of the universe. However with the increasingly stronger foothold of the Big Bang theory which firmly suggests that matter and antimatter have been produced in equal amounts at the beginning of the universe, the question arose whether there might be a difference between particles and antiparticles after all, accounting for this baryon asymmetry. In 1967, Sakharov proposed three necessary conditions that could explain the observed imbalance of matter and antimatter in the

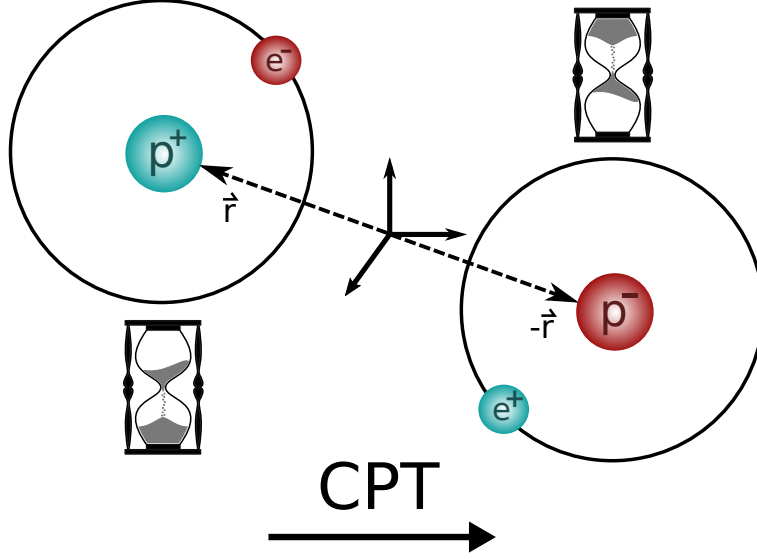


Figure 1.1.: Illustration of the CPT transformation on the hydrogen system. C exchanges particles with their corresponding antiparticles, P reflects all spatial coordinates $\vec{r} \rightarrow -\vec{r}$ and T reverses time $t \rightarrow -t$. In the case of the measurement of transition frequencies as a test of CPT, T reversal is not understood in a way that the process itself is reversed i.e. the CPT transformation is not directly applied to the experimental setup. The properties of atom and anti-atom are compared, which are predicted to be the same for both systems by the CPT theorem.

universe [18]: (1) C- and CP-violation, (2) violation of baryon number⁵ and (3) interactions outside of thermal equilibrium. C and CP violation have already been observed at that time, as mentioned in the previous section. However, the magnitude of the found violation is not sufficient to describe the baryon asymmetry in the universe. A possible violation of the CPT symmetry could have played a part in the early universe to account for this.

This motivates i.a. the experimental tests of CPT symmetry. Other motivations include the limitations of the Standard Model, which is only able to describe phenomena below the Planck mass and is expected to be superseded by a more fundamental theory combining quantum mechanics and gravity consistently. The theory is likely to include new physics and associated manifestations in the low energy region may exist [20]. CPT-violation may be one of those small effects and would be highly suppressed due to the large energy difference between low energies and the Planck scale [21]. Therefore, high precision experiments are an excellent candidate for probing for CPT-violation.

⁵Violation of baryon number has not been observed so far. A possible example would be the decay of the proton. Another possibility of baryon number violation could be realised by sphaleron processes [19].

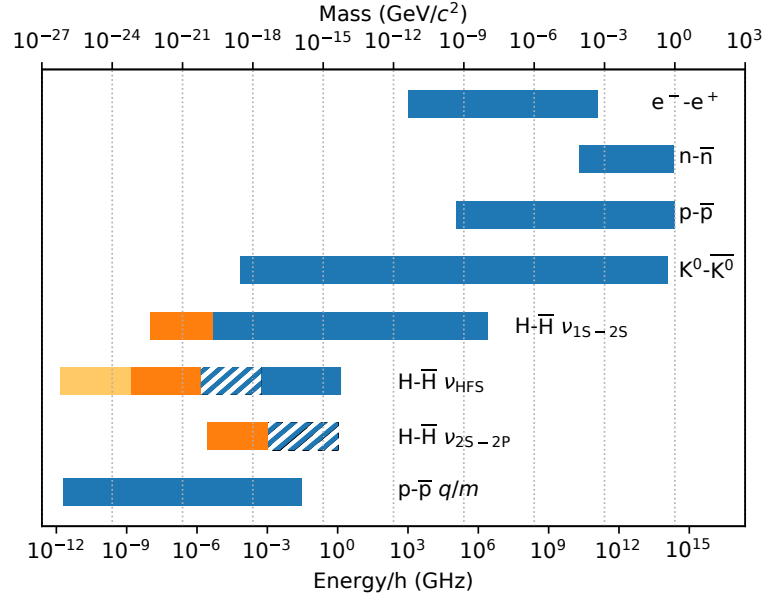


Figure 1.2.: Summary of precisions of CPT testing experiments, plot adapted from [22]. Blue bars show existing tests, labels next to them specify the compared systems. The left edge of the bars indicates the absolute precision, the right edge the measured quantity. The length of the bar gives the relative precision. Orange extensions symbolise the precision achieved for the matter system and therefore the potential sensitivity currently reachable. For hyperfine transition frequencies ν_{HFS} of $\bar{H}/H$: striped, blue extended bar symbolises the initial goal of ASACUSA. Orange marks the precision due to the line width for a fountain and the light orange extension the precision reached by the hydrogen maser experiment. For the Lamb shift ($H - \bar{H}_{2S-2P}$): estimated achievable accuracy (striped, blue extension).

A consequence of the CPT theorem is that atoms and their corresponding anti-atoms have the same characteristic spectrum and any detected differences would point to physics beyond the Standard Model. Hydrogen, as the simplest atom, contributed heavily to the understanding of atomic spectra and verification of theories. For this reason, it is one of the most studied and well-known physical systems. Its hyperfine transition frequency ν_{HFS} is one of the most accurately measured quantities and it has been measured with a relative precision of 10^{-12} (see also Figure 1.2 and Section 1.3). Therefore, a comparison of this transition frequency of hydrogen (H) and antihydrogen ($\bar{H}$) yields one of the most sensitive CPT tests. The CPT symmetry transformation applied to hydrogen is illustrated in Figure 1.1.

A summary of CPT testing experiments and their precisions is shown in Figure 1.2 [22]. The right edge of the bars indicates the measured quantity, the left edge the absolute and the length the relative precision. On a relative scale,

the experimental test with the highest precision is currently the comparison of the neutral Kaon masses ($K^0 - \bar{K}^0$) with $\Delta m/m \approx 10^{-18}$ [23].

CPT tests measuring different quantities can be compared within the Standard Model Extension (SME) acting as a common theoretical framework [24–26]. The SME Lagrangian incorporates CPT and Lorentz violating terms, their coefficients have the dimension of energy and need to be determined experimentally. Due to the dimensionality of coefficients the absolute precision of experiments becomes important. The SME in connection with antihydrogen will be discussed in more detail in Section 1.4.

Regarding the tests related to antiprotons and antihydrogen, the measurement comparing the charge-to-mass ratio of proton and antiproton via their cyclotron frequencies in a trap [27] has the largest absolute precision. The hyperfine transition of $\bar{H}$ has recently been measured with a relative precision of $\Delta\nu_{\text{HFS}}/\nu_{\text{HFS}} = 3.5 \times 10^{-4}$ in a trap by the ALPHA collaboration [28]. In Figure 1.2, the blue bar including the striped extension marked $H - \bar{H}\nu_{\text{HFS}}$ indicates the first sensitivity goal of the ASACUSA collaboration of 10^{-6} [22], see also Section 1.5. Comparing the absolute precisions of the different CPT tests, one can see that a relative precision of 10^{-6} already competes with the mass comparison of neutral Kaons.

1.3. The hyperfine structure of (anti)hydrogen

The notation (anti)hydrogen representing both, hydrogen and antihydrogen, is used in the following since considerations apply to both. Differences will be stated explicitly.

The total angular momenta of the electron (positron) and the proton (antiproton), $\vec{J}$ and $\vec{I}$ respectively, couple to the total angular momentum $\vec{F}$ of the (anti)atom. This leads to the hyperfine splitting in the energy levels. As a consequence, the ground state of (anti)hydrogen is split into a singlet state with quantum number⁶ $F = 0$ and a triplet state with $F = 1$. The transition frequency between those two states in hydrogen has been measured most precisely within a maser experiment which yielded $\nu_{\text{HFS}} = 1420405751.768 \pm 0.002$ Hz [29, 30]. The hyperfine transition frequency of H was also measured via beam spectroscopy in the 1950s with a relative precision of 5×10^{-8} [31, 32]. This result has recently been exceeded with 2.7×10^{-9} [33] by ASACUSA using the spectroscopy beamline designed for

⁶According to the eigenvalue equations $\vec{F}^2 = F(F+1)\hbar^2$ and $F_z = m_F\hbar$ with $|I - J| \leq F \leq |I + J|$ and $m_F = -F, -F+1, \dots, F$.

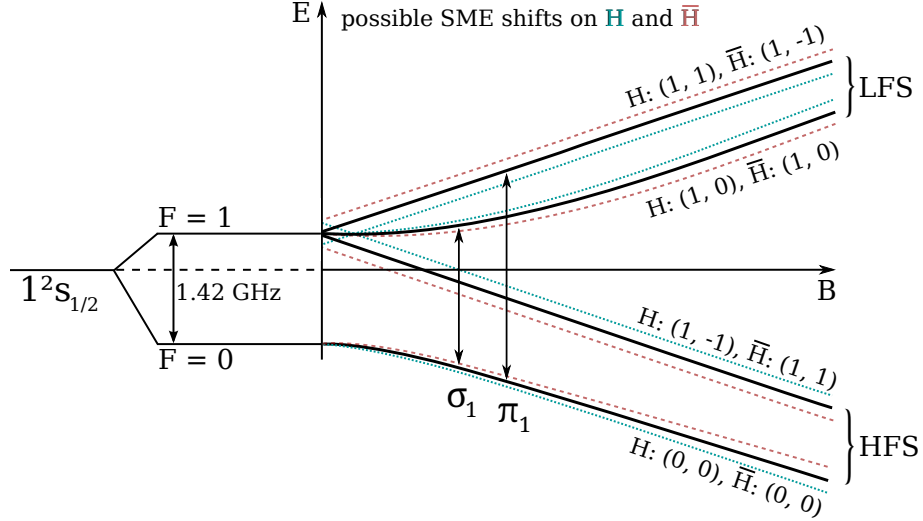


Figure 1.3.: Schematic drawing of the hyperfine splitting and Breit-Rabi diagram of H and $\bar{H}$ (black lines). The states with quantum numbers (F, m_F) are indicated for H and $\bar{H}$. The blue and red dashed lines show the spectra in the presence of Lorentz and CPT violation in context of the Standard Model Extension. Note that size and sign of the induced, additional SME shifts are not predicted by the Standard Model Extension, they need to be determined experimentally and can differ in magnitude for hydrogen and antihydrogen. The two transitions measurable within the current ASACUSA setup (σ_1 and π_1) are marked by arrows.

antihydrogen in a parallel setup for commissioning with hydrogen.

In the presence of a magnetic field $\vec{B}$, the degenerated triplet state splits and the energy levels of the resulting four states shift due to the additional interaction $-\vec{\mu}\vec{B}$ of the magnetic moment of the atom $\vec{\mu}$ with the magnetic field. This behaviour is described by the Breit-Rabi formulae [34, 35] and is depicted in Figure 1.3 (black lines). Note the different order of levels of $\bar{H}$ to H due to the opposite signs of the magnetic moments.

The four states can be classified into low- and high-field seeking (LFS and HFS) states according to their behaviour in an external inhomogeneous field. LFS atoms drift towards lower field regions since it minimises their energy, for HFS atoms the opposite applies. This behaviour is exploited in the antihydrogen experiments to achieve polarisation of a beam or to trap an $\bar{H}$ cloud.

Within the ASACUSA setup, the ground state hyperfine splitting of (anti)hydrogen can be determined via two possible methods. Firstly, several measurements of the σ_1 transition (for $\bar{H}: (F, m_F) = (1, 0) \rightarrow (0, 0)$) at different B-field strengths can be extrapolated to zero magnetic field using the Breit-Rabi formula. Secondly, the simultaneous measurement of the σ_1

and the π_1 transition (for $\bar{\text{H}}$: $(1, -1) \rightarrow (0, 0)$) at the same magnetic field strength can be used to determine ν_{HFS} via the Breit-Rabi formulae. Formulae and more details on the methods of determining the ground state hyperfine splitting of antihydrogen within the ASACUSA spectroscopy beamline can be found in [33]. Details on the spectroscopy beamline are discussed in the next chapter, in Section 2.5.

1.4. Standard Model Extension and (anti)hydrogen

The purpose of this section is to convey the idea behind the Standard Model Extension (SME) and outline its implications on the hyperfine splitting of hydrogen and antihydrogen in order to give an idea of what could be expected experimentally in presence of CPT violation. Detailed derivations of the equations can be found in [36]. First, the case of free (anti)hydrogen will be discussed and afterwards the case of the (anti)atom in a magnetic field.

The Standard Model Extension is a general theoretical test framework for studying Lorentz and CPT symmetry violation developed by Alan Kostelecký and colleagues, constructed from a few key ingredients [37]:

- It is an effective field theory comprising all established physics i.e. the Standard Model and General Relativity.
- Lorentz invariance violation (LIV) is implemented via preferred directions, which is modelled by non-dynamical background fields.
- It incorporates observer invariance i.e. the choice of the coordinate system must not affect physics.

Lorentz violation in the SME can therefore be visualised as an anisotropy of space. In the theory, this is realised by adding all possible coordinate-independent, Lorentz-violating terms to the Lagrange density:

$$\mathcal{L}_{\text{SME}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{GR}} + \delta\mathcal{L} \quad (1.1)$$

Those terms are summarised by $\delta\mathcal{L}$. For a single fermion ψ , the conventional Dirac Lagrangian is extended [38]:

$$\mathcal{L}_{\text{Dirac,SME}} = \frac{1}{2} \bar{\psi} (\gamma^\mu i \partial_\mu - m_\mu + \hat{Q}) \psi \quad (1.2)$$

where $\hat{Q}$ is the sum of all possible terms formed by contracting conventional

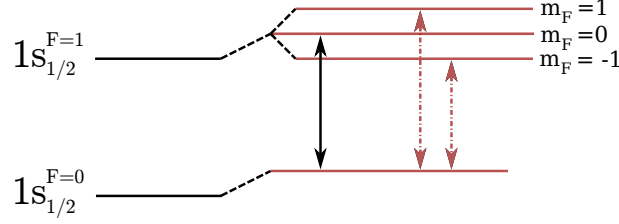


Figure 1.4.: Illustration of the Lorentz and CPT violating effects of Standard Model Extension for the ground state hyperfine level of hydrogen. Drawing adapted from A. Vargas presentation [39] at the Summer School and Workshop on the Lorentz- and CPT-violating Standard-Model Extension in 2018.

tensor operators with LIV coefficients. Here, γ^μ denotes the γ -matrices, ∂_μ the four-gradient⁷, m_μ the mass of the fermion.

In principle there exists an infinite number of such terms⁸. It is important to note, that these coefficients are not parameters of the SME, they need to be measured by appropriate experiments. If all of them would turn out to be zero, one arrives back at the conventional Lagrangian. Since in the SME Lorentz violation is included, CPT invariance is no longer ensured. In fact, roughly half of the coefficients are CPT odd and therefore also violate CPT.

Conventionally, the energy levels of hydrogen and antihydrogen, $E_{i,H}$ and $E_{i,\bar{H}}$, are identical. However, with a potential CPT violation present, the levels of both atoms might deviate resulting in a shift of transition frequencies:

$$\nu = \nu_0 + \delta\nu, \text{ with } h\nu_0 = E_i - E_j \text{ and } h\delta\nu = \delta E_i - \delta E_j \quad (1.3)$$

Here, ν_0 denotes the transition frequency without any SME effects and $\delta\nu$ a possible deviation due to a shift of the energy level E_i by δE_i . Note that the size and sign of δE_i are not predicted by the SME, they need to be determined experimentally and can differ for hydrogen and antihydrogen.

The SME coefficients are expected to be small⁹. Their effect on the spectra and the resulting energy shifts can therefore be calculated using perturbation theory [36]. The goal is to find the LIV corrections to the spectra resulting from the corrected Hamiltonian h_H^{SME} of hydrogen: $h_H^{\text{SME}} = h_H + \delta h_H$ with the Dirac Hamiltonian h_H and the leading order perturbation δh_H which consists of the electron and proton SME contributions from the Lagrangian $\delta h_H = \delta h_e + \delta h_p$. The calculations for antihydrogen are analogous.

⁷ $\partial_\mu = \frac{\partial}{\partial x^\mu}$ with x^μ being the four-position.

⁸If one only considers operators with mass dimension ≤ 4 , the model is called the minimal SME.

⁹Due to the Planck-scale suppression.

The LIV shifts are obtained by calculating the matrix elements of δh_H [36]:

$$\langle nFJLm'_F | \delta h_H | nFJLm_F \rangle = \sum_{jm} A_{jm} \underbrace{\langle Fm_Fjm | Fm'_F \rangle}_{\text{Clebsch-Gordan coeff.}} \quad (1.4)$$

where $|nFJLm_F\rangle$ are the corresponding eigenstates with principal quantum number n , the total angular momentum quantum number of the electron J , the orbital angular momentum quantum number L , the total angular momentum of the atom F and the magnetic quantum number m_F . The weights A_{jm} summarise the relevant (non-relativistic) LIV and CPT violating coefficients of the SME. The expression of A can be found in [36]. The effect on the ground state hyperfine levels results to [36]:

$$\begin{aligned} F = 0 : \quad & \delta E(n, L) = A_{00} \\ F = 1 : \quad & \delta E(n, L, \frac{1}{2}, m_F) = A_{00} + \frac{m_F}{\sqrt{2}} |\vec{A}| \end{aligned} \quad (1.5)$$

The weight A_{00} ($j = m = 0$) depends only on the quantum numbers n and L and is therefore isotropic. Consequently, isotropic SME coefficients can only be determined by measuring transition frequencies with $\Delta n \neq 0$ or $\Delta L \neq 0$. Those coefficients can therefore not be constrained with hyperfine transitions.

For the degenerated state with $F = 1$, the energy shift is a sum of the isotropic and an anisotropic contribution where $\vec{A}$ is a vector formed by anisotropic SME coefficients¹⁰. $\vec{A}$ can be thought of as a background field which couples to the total angular momentum $\vec{F}$ and lifts the conventional degeneracy of the state, therefore resulting in a splitting similar to the Zeeman effect, see Figure 1.4. The procedure for antihydrogen is analogous, A however needs to be replaced by $\bar{A}$, which has a similar composition to A , only that the CPT odd coefficients contained in A have opposite sign.

It can also be deduced from that formula, that hyperfine transitions with $\Delta m_F = 0$ are insensitive to SME coefficients, since those shifts are proportional to Δm_F :

$$\nu = \nu_0 + \Delta m_F |\vec{A}| \quad (1.6)$$

A possible scenario in case of an additional magnetic field $\vec{B}$ present is shown in Figure 1.3. The black lines in the Breit-Rabi diagram show the conventional case whereas the dashed lines show a possible scenario in case of LIV for hydrogen (blue) and antihydrogen (red). It should be pointed out again, that the figure shows only one possible example of SME shifts since their magnitude and sign are not predicted by the SME.

¹⁰ $|\vec{A}| = \sqrt{\sum_m A_{1m}^* A_{1m}}$

Since the coefficients in the SME can be thought of as a small background vector field, the earth's motion around the sun as well as its rotation around its own axis can be used to search for anisotropies in the sun-centred frame. For hydrogen, the shift of the energy levels take the following form calculated in the sun-centred inertial frame [39]:

$$\delta E \simeq A_{00}^{\text{sun}} + \vec{\beta} \cdot \vec{V}^{\text{sun}} + \frac{m_F}{B} (\vec{B} \cdot \vec{A}^{\text{sun}} + B^i T_{ik}^{\text{sun}} \beta^k) \quad (1.7)$$

where $\vec{\beta}$ denotes the velocity of the laboratory frame, $\vec{A}^{\text{sun}}$, $\vec{V}^{\text{sun}}$ and $\vec{T}^{\text{sun}}$ combinations of SME coefficients expressed in the sun-centred frame. To arrive at the expression for $\bar{\text{H}}$, the last term in equation 1.7 changes sign and $\vec{A}^{\text{sun}}$, $\vec{V}^{\text{sun}}$ and $\vec{T}^{\text{sun}}$ need to be replaced by the corresponding weights for antihydrogen $\overline{\vec{A}^{\text{sun}}}$, $\overline{\vec{V}^{\text{sun}}}$ and $\overline{\vec{T}^{\text{sun}}}$.

The term proportional to $\vec{B} \cdot \vec{A}$ would give rise to sidereal variations in the determined transition frequencies. The total angular momentum of the atom aligns to the magnetic field and additionally couples to the LIV background field $\vec{A}$. Because of the change in relative orientation of $\vec{B}$ to $\vec{A}$ due to the earth rotation around its axis, the transition frequency would vary in the course of a sidereal day. Similarly, the term $\vec{\beta} \cdot \vec{V}$ would result in annual variations due to the orbital motion of the earth around the sun and through a possible LIV background field.

Summarising, possible tests of CPT within the framework of the SME and the ASACUSA experiment using hydrogen and/or antihydrogen include: (1) a possible lift of degeneracy of the $F = 1$ state e.g. via a found line broadening, (2) direct comparisons of the transition frequencies of antihydrogen and hydrogen, (3) sidereal or (4) annual variations of transition frequencies in hydrogen and/or antihydrogen, (5) a comparison of the π_1 transition at the same absolute magnetic field, but with different orientation with respect to the background fields. More information on the subject of antihydrogen and tests within SME can be found in [36]. Details on the accessible SME coefficients within the ASACUSA hydrogen and antihydrogen programme are discussed in [40].

1.5. ASACUSA collaboration – introduction and status

The ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) collaboration is based at the Antiproton Decelerator (AD) at CERN (Conseil Européen pour la Recherche Nucléaire) and its scientific programme consists of:

- The already mentioned experiment of **production and hyperfine spectroscopy of antihydrogen**, aiming at a CPT test.
- Laser spectroscopy of antiprotonic helium, which is also a CPT test and precisely measures the mass ratio between $\bar{p}$ and electron [41].
- Study of antiproton annihilation cross sections. Measurements of atomic and nuclear collision cross sections of antiprotons at low energies (< 100 eV) [42].
- Fragmentation studies in antiproton nucleus annihilations, which is a recent addition. First measurements and experimental setup are described in Chapter 6.

The present thesis is a contribution to the ASACUSA experiment on measuring the hyperfine splitting of antihydrogen. Summarising from the last section, ν_{HFS} of $\bar{\text{H}}$ has been measured with a relative precision of 3.5×10^{-4} with trapped antihydrogen atoms. ASACUSA on the other hand uses a completely different, complementary and unique method compared to all other $\bar{\text{H}}$ experiments and employs an antihydrogen beam. The initial goal is to reach a relative precision $\Delta\nu_{\text{HFS}}/\nu_{\text{HFS}} \approx 10^{-6}$.

Trapping antihydrogen requires strong inhomogeneous magnetic fields and therefore cold antihydrogen ($\lesssim 0.5$ K) is needed. The anti-atomic beam spectroscopy method of ASACUSA has the advantage of a relatively high temperature acceptance (50 K to 100 K) [40]. Another benefit of the beam method is, that it allows a measurement in a near field-free region, since the spin-flip inducing cavity is outside of strong trap fields. This enables a more precise measurement since the hyperfine states are a magnetic phenomenon and therefore very sensitive to magnetic field gradients. The challenge however, is that a *focused* and *polarised* beam of antihydrogen atoms *in the ground state* needs to be produced. See Chapter 2 for details on the experimental apparatus and methods to combat these challenges.

The first milestone was reached in 2012 when ASACUSA succeeded in producing the first antihydrogen beam which was detected 2.7 m downstream

of the mixing region [43]. After this first major step towards antihydrogen spectroscopy, the produced $\bar{\text{H}}$ beam still needs to be characterised and the production rate increased. In 2016, the quantum state distribution of the created anti-atoms has been measured for the first time and results showed that antihydrogen in the ground state is indeed produced. This is the main subject of Chapter 4.

The number of anti-atoms however is still very low and spectroscopy of antihydrogen and the goal of achieving a relative precision at the ppm level is therefore not yet within reach. During beamtime 2017 new mixing schemes have been tested with the goal of increasing the production rate. Results showed that antihydrogen was produced with those new methods [44], but due to the highly dimensional parameter space of the trap system that can be explored, further investigations are needed to conclusively evaluate these schemes.

For the second long shut down (LS2) at CERN in the coming two years, no antiprotons will be available. Therefore it is planned to test different production schemes in the ASACUSA mixing trap with matter and reversed potentials i.e. accumulate electrons and protons and mix them to hydrogen. The advantage is that in opposition to antimatter, matter is readily available, and no restrictions due to time limitations of antiproton shifts are posed. Systematic studies of the existing schemes and investigations of new schemes will therefore also be possible during LS2.

2. The ASACUSA antihydrogen beam experiment

This chapter describes the setup of ASACUSA's experiment to measure the ground state hyperfine transition frequency of antihydrogen. Firstly, the measurement principle is described and an overview of the beamline is given. Then the different parts of the experiment are explained, starting upstream with the trap system employed for the formation of antihydrogen and continuing along the beamline in downstream direction towards the antihydrogen detector which will be discussed in the next Chapter 3. The focus will be on the synthesis scheme and necessary components that have been utilised during measurements discussed in this thesis, most notably the quantum state distribution of the produced antihydrogen atoms.

In all following chapters, the z -coordinate axis is chosen to be along the beam direction, x - and y -axis are horizontal and vertical direction. Axial and radial directions are defined as parallel and perpendicular to the z -direction, respectively.

2.1. Overview and measurement principle

The measurement principle behind ASACUSA's approach of determining the ground state hyperfine transition frequency [45] is based on an experiment initially proposed by I. Rabi in 1938 [46]. Rabi's setup employs the deflecting effect a magnetic field gradient has on traversing atoms observed by O. Stern and W. Gerlach in 1922 in their famous experiment [47]. His experiment consists of three key steps: (1) a spin-polarised source, (2) a spin-flip inducing resonator and (3) a spin selector. Figure 2.1 shows a schematic drawing of the Rabi experiment (bottom) and comparison to the ASACUSA antihydrogen spectrometer beamline (top).

The first stage of Rabi's experiment consists of an atomic hydrogen source and an inhomogeneous magnetic field region which polarises the beam due to deflection and focusing of atoms depending on their spin state. This is symbolised with red and grey dashed lines in the figure. In case of antihydrogen, (1) is achieved within one trap that both serves for producing and polarising the $\bar{\text{H}}$ atoms. Details on the mixing trap follow in Section 2.4.

Afterwards, the polarised beam enters a region with an oscillating magnetic field $\vec{B}_{\text{osc}}$ superimposed with a small, homogeneous magnetic field $\vec{B}_{\text{hom}}$.

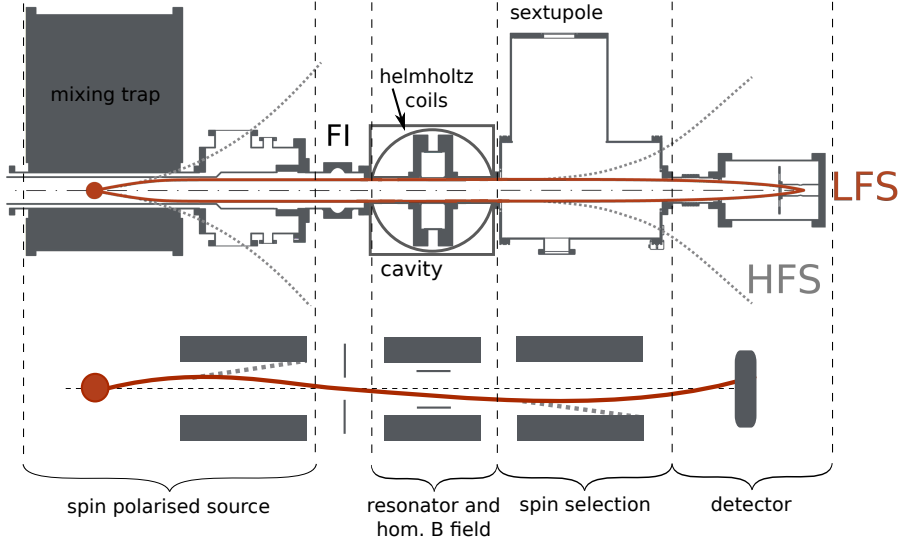


Figure 2.1.: Schematic drawing of the experimental setup of the Rabi experiment (bottom) and comparison to ASACUSA's antihydrogen experiment (top). Corresponding parts of the two setups are indicated. The beam component made up of low-field seeking (anti)atoms is indicated in red and the high-field seeking component in dashed grey.

The atom's spin aligns to $\vec{B}_{\text{hom}}$ and a spin-flip is induced if their resonance frequency is met by the oscillating magnetic field. In the third step of the experiment, the atoms are either focussed on the detector or deflected by another inhomogeneous magnetic field, depending on whether they are low- or high-field seekers.

The transition frequency can then be determined by scanning the frequency of $\vec{B}_{\text{osc}}$ and at the same time monitoring the count rate on the detector which shows a change when on resonance.

Step (2) and (3) of the measurement are not only in principle the same for matter and antimatter atoms but the same experimental equipment can be used for measurements with both. Indeed, ASACUSA has a second setup at CERN where the microwave cavity and the sextupole magnet built for antihydrogen spectroscopy have been installed and commissioned [33] with hydrogen. The spectroscopy apparatus will be discussed in more detail in Section 2.5.

The production and the detection of hydrogen and antihydrogen are however very different. Atomic hydrogen can be produced in large amounts by a microwave discharge source [48, 49]. For $\bar{\text{H}}$, the two antimatter ingredients must be produced first – in case of the antiprotons a whole accelerator complex is necessary. Afterwards they need to be contained in traps (see

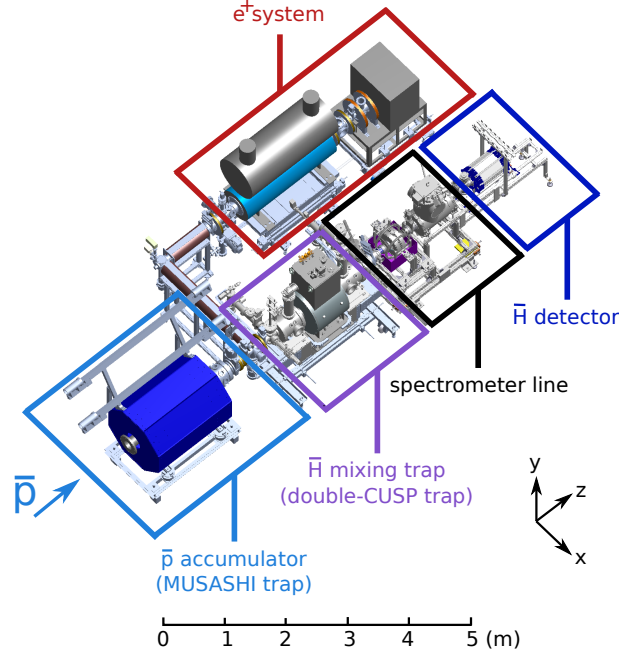


Figure 2.2.: Overview of the experimental setup of ASACUSA for antihydrogen production and spectroscopy. The antiprotons (light blue arrow) are first accumulated before being mixed with positrons (red) in the double-CUSP trap (purple). The neutral antiatoms escape the trap and enter the spectroscopy beamline (black). Afterwards they reach the antihydrogen detector (dark blue).

Figure 2.2), before being combined in ultra-high vacuum to small amounts of antihydrogen. Large parts annihilate on the trap walls and only a small fraction leaves the trap and enter the spectroscopy beamline. The production of the constituents and the formation of $\bar{\text{H}}$ will be discussed in the following sections. Figure 2.2 shows an overview of the experimental setup.

Regarding the detection of antihydrogen, the annihilation of antimatter is taken advantage of. ASACUSA’s antihydrogen detector played a central role in this thesis and will be discussed in detail in Chapter 3.

The field ioniser (FI) after the mixing trap indicated in Figure 2.1 has the purpose of rejecting antihydrogen atoms in higher quantum states and is discussed in Section 2.6.

2.2. Antiproton source

Two ingredients are needed to form antihydrogen – positrons (e^+) and antiprotons ($\bar{p}$). The first one is easily produced via radioactive decay, see Section 2.3.

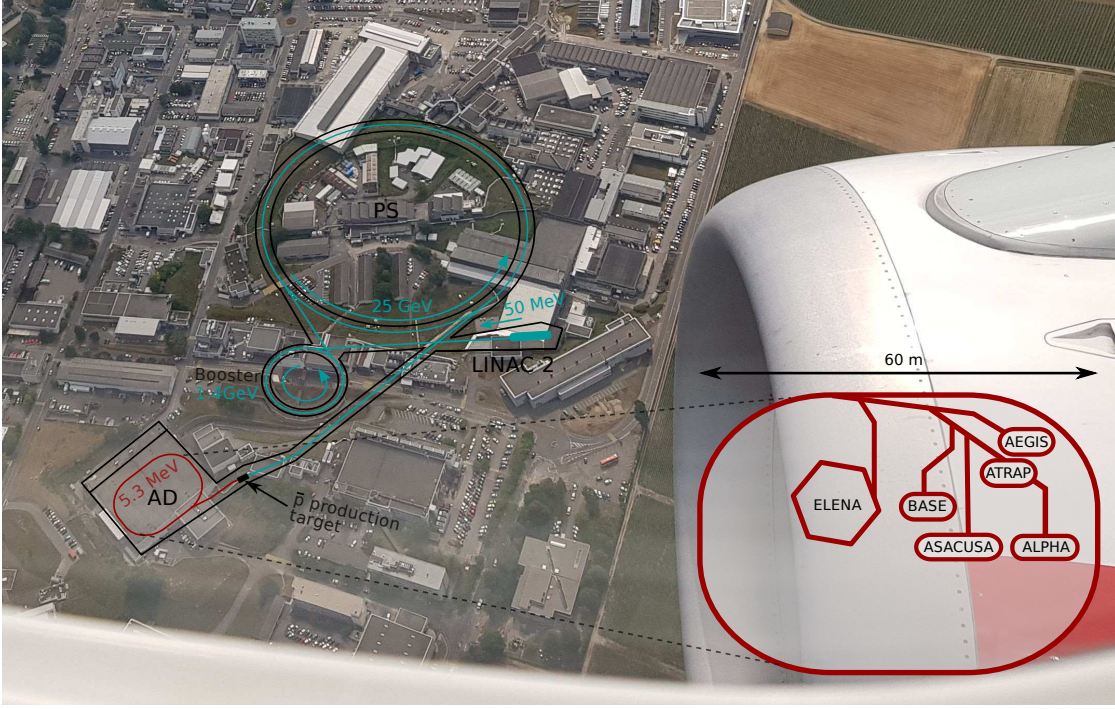


Figure 2.3.: Overview of the accelerator chain involved in the production of antiprotons. Particle paths of protons are drawn in blue, antiprotons in red. Coloured labels show the kinetic energies of the particles. The drawing of the accelerators overlaid with the photograph has been adapted from [50].

The second constituent, cold antiprotons, are harder to come by and are supplied by CERN’s Antiproton Decelerator, currently the only source in the world for slow $\bar{p}$. An overview of the accelerator complex can be seen in Figure 2.3. A bunched proton beam is first created by a linear accelerator (LINAC 2). After being accelerated by the PSB (Proton Synchrotron Booster) to 1.4 GeV, the protons are further accelerated to a kinetic energy of 25 GeV by the PS (Proton Synchrotron), which also serves as a pre-accelerator for the SPS (Super Proton Synchrotron) and in the end the LHC (Large Hadron Collider).

The protons are shot at an Iridium target and antiprotons are produced with a kinetic energy of 2.7 GeV via the reaction:

$$p(\text{beam}) + p(\text{target}) \rightarrow p + p + p + \bar{p} \quad (2.1)$$

Those antiprotons are much too energetic and need to be slowed down to the chemical energy scale in order to produce antiatoms. Firstly, they are injected into the AD, where they are slowed down in a series of deceleration and cooling steps. Deceleration causes an increase of energy and position spread of the particles in the beam, which is counteracted by stochastic and electron cooling [51].

In the end of a cycle (every ≈ 110 s), a bunch of $\approx 3 \times 10^7$ antiprotons with a length of ≈ 150 ns and a kinetic energy of 5.3 MeV is ejected into the experimental areas.

In order to trap the antiprotons efficiently, they need to be further slowed down. Most experiments use thin metal foils perpendicular to the path of the $\bar{p}$ to reduce their velocity. However, with those degrader foils most antiprotons are lost ($\approx 99.9\%$) because they either annihilate or their energy is still too high to be captured downstream in the potential well of the traps.

ASACUSA on the other hand uses an additional decelerator, an RFQD (Radio Frequency Quadrupole Decelerator) [52], which slows the $\bar{p}$ further down to ≈ 110 keV. About 30 % of the antiprotons from the AD fulfil the phase condition required for deceleration of the RFQD [53], the rest passes through and annihilates somewhere downstream in the apparatus. In the end, about 3 % of the initial number of antiprotons will be captured, resulting in a $10\times$ higher trapping efficiency compared to experiments using degrader foils.

2.3. Preparation of antihydrogen constituents

2.3.1. Antiprotons

The pulsed antiproton beam, after being slowed by ASACUSA's RFQD, is then captured, cooled and compressed in the so-called MUSASHI (Monoenergetic Ultra-Slow Antiproton Source for High-precision Investigation) trap [53]. The antiproton accumulator is a Penning-Malmberg trap consisting of multi-ring electrodes (MRE) for axial confinement and manipulation of the captured particles, and a superconducting solenoid for radial confinement.

For antihydrogen synthesis, typically a few AD shots are stacked in the MUSASHI trap before being transported to the mixing trap. In total about 3×10^6 antiprotons are accumulated. They are cooled by preloaded electrons which themselves self-cool via synchrotron radiation. Afterwards the electrons are kicked out by lifting the trapping potential for a few hundred nanoseconds which is short enough to not affect the antiproton cloud. The antiprotons are then radially compressed via rotating wall technique [54] and, in the end, extracted by dedicated electrodes.

The MUSASHI trap can be operated in two extraction modes [53]: (1) pulsed extraction for producing short-bunched beams and (2) slow extraction. For antihydrogen formation runs, mode (1) is utilised since shorter bunches

are favourable for subsequent trapping in the mixing trap. For studies of antiproton annihilation with the $\bar{\text{H}}$ detector at the end of the beamline, the slow extraction mode is used, due to the longer bunch length. Those extractions are discussed in Section 2.8.

In both cases, the antiprotons are released from the trap by ramping up the confining potential well until the antiprotons spill over the potential barrier. The kinetic energy of the $\bar{p}$ is determined by the potential difference between the potential barrier and the ground. For the antihydrogen measurements discussed in this thesis, the $\bar{p}$ were extracted with a kinetic energy of 1.5 eV. Afterwards, they are adiabatically transported with pulsed transport coils along the beamline [55] over a distance of ≈ 2.5 m to the mixing trap.

2.3.2. Positrons

The second constituent of antihydrogen, positrons, are produced via β^+ decay from a ^{22}Na source. The positrons are slowed down to a few eV by a neon moderator and transported to the buffer gas trap [56] which consists of a series of cylindrical electrodes surrounded by a superconducting magnet providing radial confinement. The positrons thermalise via inelastic collisions with the buffer gas to ≈ 25 meV. After an accumulation time of ≈ 30 s, they are ejected and magnetically guided to the mixing trap. For antihydrogen synthesis, several positron bunches are collected in the mixing trap amounting to $\approx 5 \times 10^7$ e^+ .

2.4. Antihydrogen source and formation

Positrons and antiprotons are combined and form antihydrogen in the mixing trap, the so-called double-CUSP trap [57]. Figure 2.5 shows a schematic drawing of the trap (top) as well as a typical electric potential and magnetic field configuration. Both constituents are injected from the upstream side (left in the drawing) and antihydrogen leaves the trap downstream. The mixing scheme employed will be discussed in detail in Section 2.4.1.

The production trap consists of a multi-ring electrode and a superconducting pair of anti-Helmholtz coils, see Figure 2.4 for a schematic drawing. The field configuration of the latter features two points of zero magnetic field and diverging field lines, giving the double-CUSP trap its name. The current flow of the two central coils is oriented parallel, while the current of the side coils is antiparallel to the central ones.

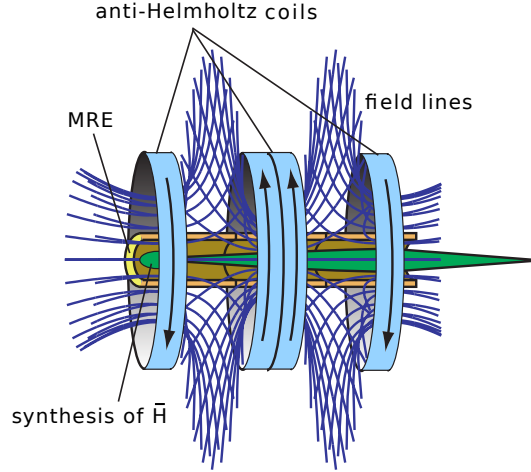


Figure 2.4.: Schematic drawing of the double-CUSP trap (figure is based on a drawing from [57]). The two sets of anti-Helmholtz coils are shown in light blue, current directions are indicated with black arrows. Magnetic field lines are drawn in dark blue. The multi-ring electrode is indicated in gold and the synthesis region and emerging low-field seeking antiatoms are drawn in green.

The electric potential configuration for antihydrogen synthesis is shown in the center of Figure 2.5. The mixing region has a nested well shape for confinement and manipulation of both constituents, a close-up can be seen to the right of the plot. A field ionisation well is located downstream from the mixing region and marked by the grey region in the figure. It is denoted as FIC (Field Ionising well in the double CUSP). Antihydrogen atoms with principal quantum number $n > 43$ are ionised by the electric field, resulting antiprotons are trapped in the well and can be counted later which gives an estimate of how many antiatoms have been produced. Opening and closing the FIC periodically during production allows to monitor the $\bar{p}$ formation in dependence of time.

The ASACUSA Micromegas Tracker (AMT) [58] is a detector situated around the mixing region between the magnet and the cold bore of the trap. It is marked in blue in Figure 2.5. The AMT is composed of two layers of Micromegas (Micro-MESh Gaseous Structure) and a layer of scintillators sandwiched in between them for triggering. The purpose of the AMT is to detect annihilations inside the trap and reconstruct their vertices [59] to distinguish annihilations on the walls of the MRE (most likely by antihydrogen atoms) and annihilations of antiprotons in the rest gas of the trap.

As mentioned in the introduction chapter, in order to perform spectroscopy with an (anti)atomic beam, a focused and polarised source is needed. Polarisation is achieved by the magnetic field gradient supplied by the anti-Helmholtz

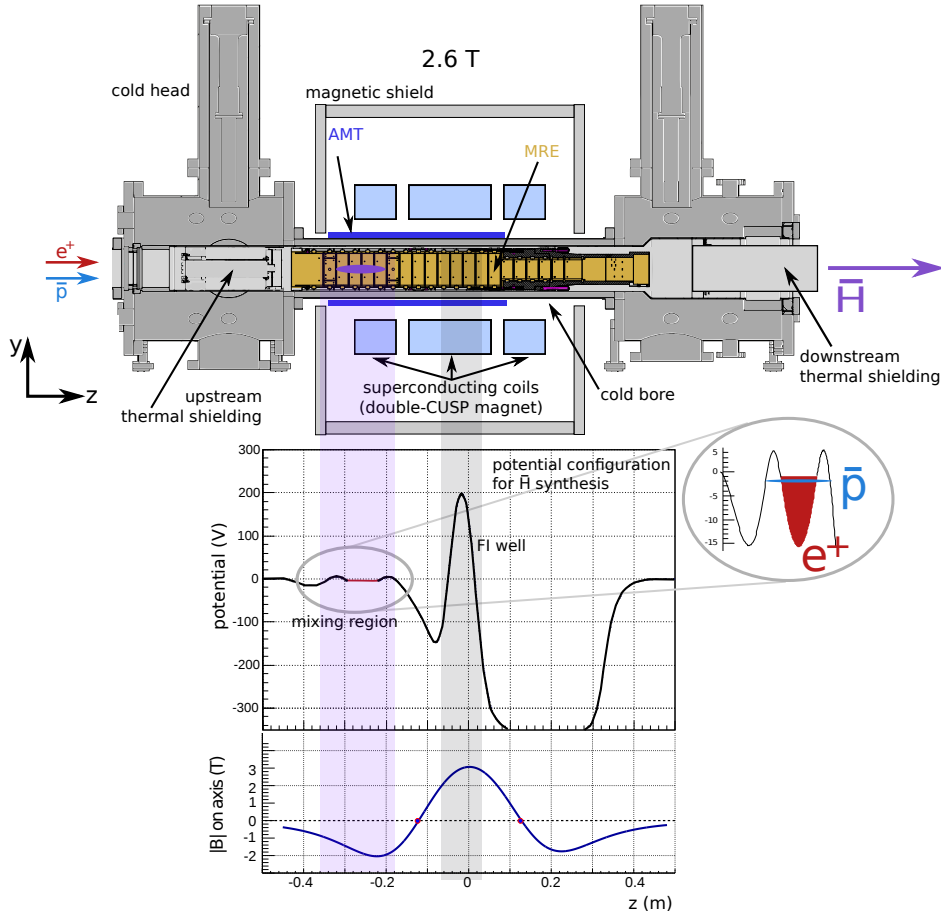


Figure 2.5.: Drawing of the double-CUSP trap (top) and electric potential (middle) and magnetic field configuration (bottom). The MRE is drawn in gold, the superconducting anti-Helmholtz coils in light blue. Direction of injection of $\bar{p}$ and e^+ is indicated, as well as the direction of emergence of antihydrogen atoms (purple arrow). The AMT detector around the mixing region is indicated in dark blue. Mixing and FIC regions are marked by purple and gray shaded areas, respectively. Drawing not to scale.

coils exerting a force on the produced antihydrogen atoms [60]. Atoms in low-field seeking states are focussed and high-field seekers are defocussed (see also Figure 2.1). The magnetic field strength distribution on axis can be seen in Figure 2.5. The mixing region is situated at the upstream minimum.

Prior to the last long shut down at CERN (years 2013 and 2014), the magnetic field of the mixing trap was produced by a single CUSP magnet [61, 62] which consists of only one pair of anti-Helmholtz coils. The trap upgrade to the double-CUSP configuration was motivated by an improved polarisation of the $\bar{H}$ atoms emerging from the trap [63, 64] and furthermore a reduction of the leak field near the spin-flip cavity.

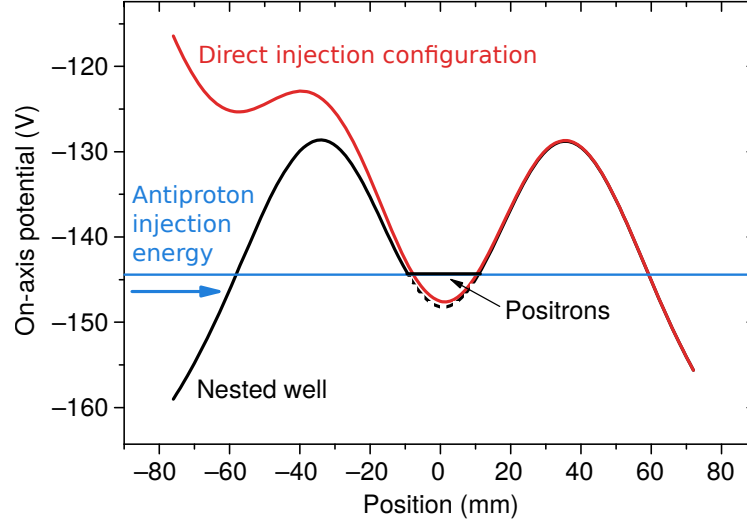


Figure 2.6.: Potential configurations during the direct injection mixing scheme [43]. The e^+ cloud is stored in the center of the nested well. The upstream potential is then opened (red line) allowing the injection of $\bar{p}$ (blue arrow) with a kinetic energy a little higher than the potential energy of the positron cloud (blue, horizontal line).

2.4.1. Direct injection mixing scheme

Producing antihydrogen atoms is a delicate and difficult procedure that requires controlled manipulation of the trapped positron and antiproton plasmas and searching a highly dimensional trap parameter space for optimum settings, maximising the antihydrogen yield. Furthermore, every mixing trial takes time i.e. antiprotons and positrons need to be accumulated and transferred, resulting in mixing cycles with lengths of 15 to 20 mins and therefore only ≈ 20 cycles per shift (eight hours).

Different production techniques are investigated and employed by ASACUSA and the other experiments at the AD [65, 66]. The scheme utilised during the measurements discussed in this thesis is called “direct injection” [43], see Figure 2.6. Firstly, several stacks of positrons are collected and then transported to the mixing trap, where they are stored in the nested well potential. Then several stacks of $\bar{p}$ are transferred adiabatically to the double-CUSP trap and directly injected into the positron cloud with a kinetic energy close to the potential energy of the e^+ and with a narrow energy spread [43].

The relevant processes of antihydrogen creation in ASACUSA are radiative recombination and three-body recombination [67], with the latter being dominant [68]. Due to energy and momentum conservation, a third body is needed for the formation of a bound state of antiproton and positron. In

mixing runs for quantum state measurement:					
# of runs	e^+ stacks	e^+ density (cm^{-3})	e^+ radius (mm)	$\bar{p}$ stacks	# of $\bar{p}$
114	25	6×10^8	0.9	4	6×10^5
high e^+ density runs:					
# of runs	e^+ stacks	e^+ density (cm^{-3})	e^+ radius (mm)	$\bar{p}$ stacks	# of $\bar{p}$
21	40	8.3×10^8	1.2	4	3×10^5
runs without e^+ :					
# of runs	e^+ stacks	e^+ density (cm^{-3})	e^+ radius (mm)	$\bar{p}$ stacks	# of $\bar{p}$
11	0	0	0	4	3×10^5

Table 2.1.: Summary of relevant mixing runs of data taking periods in 2016. A more detailed table of the 114 runs performed for determining the principal quantum state distribution can be found in the appendix (see Section A.6).

case of three-body recombination, a second positron adopts this role:



Therefore it is plausible that the production rate of $\bar{\text{H}}$ depends quadratically on the positron density. Further information on the processes involved in antihydrogen production can be found in [69, 70].

The direction of emission of the antihydrogen atoms from the mixing region depends on the parameters of the synthesis process and the motion of the trapped particles in the trap. A spatially non-isotropic production in ASACUSA is likely. Discrepancies in numbers of $\bar{\text{H}}$ atoms are observed when comparing the recorded events by AMT detector surrounding the mixing region and the antihydrogen detector at the end of the beamline. Time distributions of the counts measured by the different detector systems during mixing are compared in Section 5.3. In any case, only a small number escapes the trap downstream, enters the spectroscopy apparatus and reaches the detector which covers a solid angle of 5×10^{-4} sr of the mixing region.

Table 2.1 summarises the conditions during mixing runs carried out during beamtime 2016. 114 runs were performed to determine the distribution of principal quantum numbers of synthesised antihydrogen atoms with the direct injection scheme. A few runs with higher positron density were also done and are listed as well as background runs without positrons in the mixing trap.

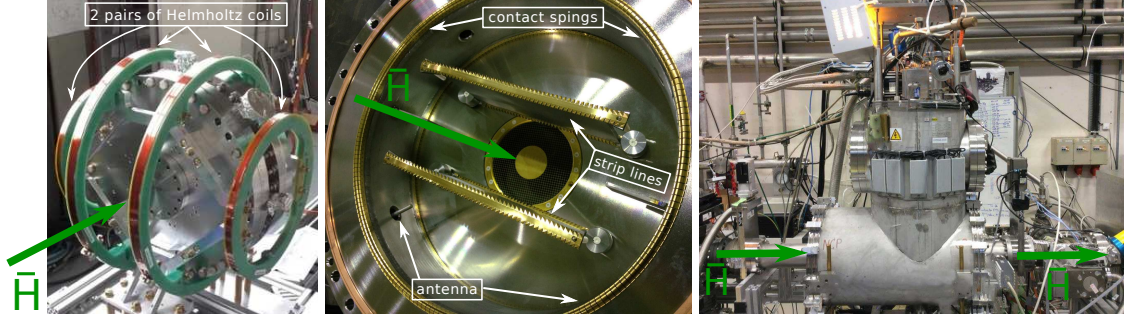


Figure 2.7.: *Left*: Picture of the cavity from outside and the two pairs of Helmholtz coils. *Center*: Photo of the inside of the cavity. *Right*: Photo of the superconducting sextupole magnet.

2.5. Spectroscopy apparatus

The spectrometer beamline downstream of the antihydrogen production trap consists of a spin-flip inducing microwave cavity and a spin state selecting superconducting sextupole magnet.

Two photographs of the cavity are shown in Figure 2.7 (left and center). On the left picture, the cavity is sealed by a flange and surrounded by two pairs of Helmholtz coils [71]. The latter provide a small, homogeneous magnetic field $\vec{B}_{\text{hom}}$ resulting in the Zeeman splitting of the atoms energy levels. In order to achieve high precision of the determined transitions, a high homogeneity of $\vec{B}_{\text{hom}}$ is required. The cavity and Helmholtz coils are therefore surrounded by three layers of cylindrical shielding to protect the spin-flip region from external fields.

The inside of the cavity can be seen in Figure 2.7 (center). The cavity has a large entrance (diameter 100 mm) compatible to the rest of the beamline in order to ensure a large acceptance of trajectories of antihydrogen atoms. This led to the design of a strip-line geometry [72, 73] which showed the best uniformity of the oscillating magnetic field strength $|\vec{B}_{\text{osc}}|$ over the large diameter, ensuring a spin-flip probability independent of the flight path of the antiatoms. Due to the cavity's large bandwidth of 12 MHz around the resonance frequency of 1420 Hz, both afore mentioned transitions, σ_1 and π_1 , can be measured. The orientation of $\vec{B}_{\text{hom}}$ to $\vec{B}_{\text{osc}}$ can be changed by rotating the cavity with respect to the Helmholtz coils. This is necessary, since the magnetic fields need to be parallel to measure σ_1 , and perpendicular to measure the π_1 transition.

Similarly to the cavity, the sextupole magnet also has a large opening diameter and needs to produce a high enough field gradient inside the

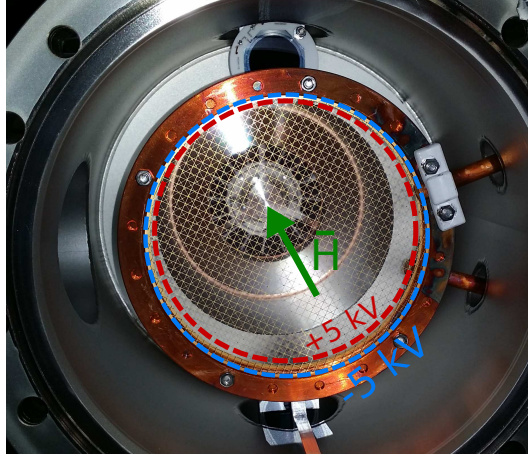


Figure 2.8.: Photograph of the external field ioniser. Mesh-electrodes are marked with circles, red for positive and blue for negative polarity. The flight direction of antihydrogen atoms (perpendicular to the meshes) is indicated by a green arrow.

beampipe to exert a focusing and defocusing effect on the antiatoms. The pole strength of the superconducting sextupole is 3.5 T.

2.6. External field ioniser

Downstream after the mixing trap, a field ioniser chamber is mounted with the purpose of evaluating the principal quantum number n of the exiting antihydrogen atoms. Depending on the electric field strength, atoms with $n > n_{\min}$ will be ionised and the resulting antiprotons deflected. The electric field $|\vec{E}|$ dissociating an atom with principal quantum number n is given by¹ [74, 75]:

$$|\vec{E}| = \frac{1}{16n^4} \quad (2.3)$$

The field ioniser is made up of two parallel copper mesh-electrodes with a distance of 1 cm placed perpendicular to the beam direction, see Figure 2.8. The meshes have a high transparency² so that as little material as possible is added to the flight path of the antiatoms.

¹The potential of a bound electron in an electric field along the z -direction is given by $V = -\frac{k}{|z|} + \vec{E}z$, with the Coulomb constant k . If the electron's energy exceeds the energy of the saddle point of the potential, the atom is ionised by the field. Equating the energy of the saddle point ($-2\sqrt{|k\vec{E}|}$) to the energy of the excited state ($-Ry/n^2$, Ry being the Rydberg constant), yields the expression for the ionising field. Conversion to atomic units gives the above stated formula for the field for ionisation.

²Each mesh has a transparency of 0.95, resulting in a total transparency of $0.95^2 = 0.90$

$\pm$ voltage (V)	$n_{\min}$	# runs
5000	14	43
400	26	31
70	40	16
40	54	24

Table 2.2.: Summary of voltages applied to the field ioniser meshes, corresponding $n_{\min}$ and the number of mixing cycles performed. A more detailed table can be found in the appendix (see Section A.6).

By applying different voltage settings to the meshes and monitoring the rate of antihydrogen atoms reaching the detector, the quantum state composition of the produced antiatomic beam can be measured. The highest voltage configuration ($|\vec{E}| \approx 10$ kV/cm) allows only atoms with $n < n_{\min}$ and $n_{\min} = 14$ to pass. Table 2.2 summarises the voltage conditions used during beamtime 2016 for measuring the quantum state distribution which will be discussed in Section 5.4.

Additionally, the chamber houses an active beam blocker downstream of the field ioniser that can be moved into the path of the antiatoms. The beam blockers purpose is to cut out the central beam component since the field strength of the state selecting sextupole magnet is close to zero in its center and traversing particles cannot be spin analysed. Furthermore, the beam blocker can be used as a normalisation counter.

2.7. Modified, short setup

During data taking periods of the last years, the experimental setup has been modified to facilitate the current main objective of increasing the production rate of $\bar{\text{H}}$ atoms. Figure 2.9 shows a drawing of the setup. The microwave cavity and the sextupole magnet have been removed from the beamline with the purpose of shortening the flight path of antihydrogen atoms to the detector which was mounted directly behind the external field ioniser. The solid angle of the detector with respect to the mixing region is therefore increased by about a factor four which facilitates monitoring changes in count rate for different mixing conditions. The distance between the mixing region and the detector is reduced to ≈ 190 cm.

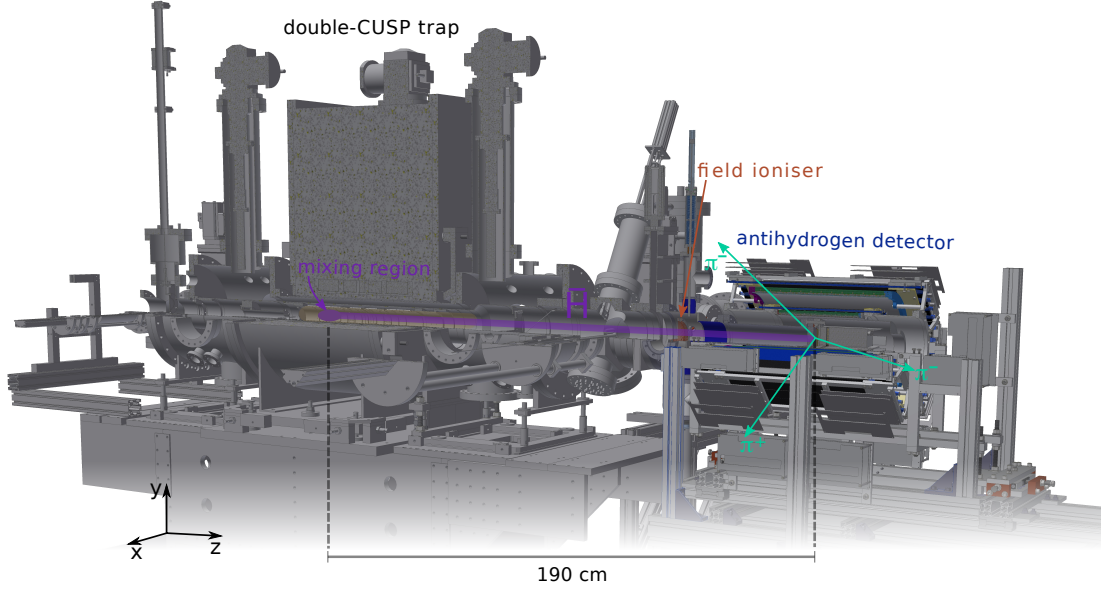


Figure 2.9.: 3D drawing of the modified experimental setup used. The mixing region and produced antihydrogen beam are indicated in purple. The field ioniser meshes downstream of the double-CUSP trap are drawn in copper colour. The resulting secondaries of the annihilation in the detector are illustrated in green.

2.8. Antiproton extractions

Studying the signal of antiproton annihilations in ASACUSA’s antihydrogen detector at the end of the beamline is of key importance in context of: (1) the afore mentioned fragmentation studies in antiproton nucleus annihilations as part of ASACUSA’s scientific programme and (2) the investigation of the antihydrogen signal in the detector since the signature of antihydrogen and antiproton annihilation are the same in the ASACUSA detector, as will be discussed in Chapter 3.

For this purposes, a single AD shot is first trapped and cooled in the MUSASHI trap before being slowly extracted with 150 eV [53]. The antiprotons are then transferred through the double-CUSP trap whose multi-ring electrodes are powered off. The magnetic field of the pair of anti-Helmholtz coils guides the antiprotons towards its exit and the detector. A fraction is defocussed when passing the zero B-field regions in the trap and annihilates on the MRE walls.

Figure 2.10 shows a histogram of event arrival times at the detector after run start during antiproton extraction. The start signal of runs is provided

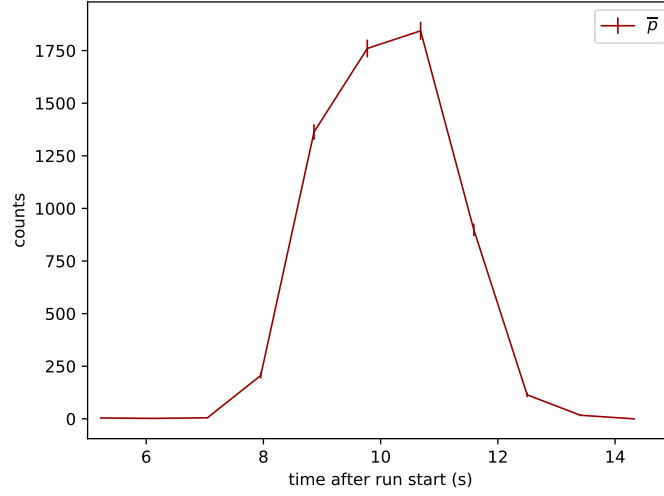


Figure 2.10.: Histogram of event arrival times during antiproton extraction runs after run start. Antiprotons arrive in a time window of ≈ 4 s.

by the trap system. It can be seen that the antiprotons arrive in a time window of ≈ 4 s.

The recorded events during extractions of beamtime 2016 are used for the data-driven machine learning analysis developed in the course of this thesis which is discussed in Chapter 4. The first data for the fragmentation studies has been recorded during data taking periods in 2017. Details of the setup and results in the context of the developed three-dimensional tracking data are discussed in Chapter 6.

2.8.1. Antiproton annihilations

Antiprotons are composite particles made up of 3 antiquarks (two anti-up and one anti-down) and additional gluons and quark-antiquark pairs responsible for binding the three valence quarks together.

When an antiproton interacts with matter, its constituents will react with the protons and neutrons of the material and the annihilation creates charged and neutral mesons (mainly pions). Depending on whether the $\bar{p}$ reacts with a proton or a neutron, an even or odd number of charged secondaries are produced due to charge conservation.

Table 2.3 summarises the secondary particles and corresponding branching ratios of the reactions $\bar{p} + p$ (top) and $\bar{p} + n$ (bottom). Since the ASACUSA tracking detector is capable of detecting charged particles only, the table is focussed on those.

$\bar{p} + p$		
secondaries		BR (%)
$2\pi^+ + 2\pi^- + N\pi^0$	$N \in [0, \dots, 3]$	47.30
$\pi^+ + \pi^- + N\pi^0$	$N \in [0, \dots, 4]$	41.53
$3\pi^+ + 3\pi^- + N\pi^0$	$N \geq 0$	4.25
$K^\pm + K^0 + \pi^\mp + \pi^0$		0.47
$K^\pm + K^0 + \pi^\mp$		0.46
$K^+ + K^- + NK^0$	$N \in [0, 1]$	0.34
$K^+ + K^- + \pi^0$		0.24
$K^+ + K^-$		0.10
$\bar{p} + n$		
secondaries		BR (%)
$2\pi^- + 2\pi^+ + N\pi^0$	$N \in [0, 1]$	59.7
$3\pi^- + 2\pi^+ + N\pi^0$	$N \geq 0$	27.6
$\pi^- + N\pi^0$	$N \geq 0$	16.4
$4\pi^- + 3\pi^+ + N\pi^0$	$N > 0$	0.39

Table 2.3.: Summary of secondaries and branching ratios of antiproton annihilations $\bar{p} + p$ (top) and $\bar{p} + n$ (bottom), information extracted from [76]. N denotes an integer number describing the number of neutral particles produced, details can be found in [76]. In case of $\bar{p} + p$, branching ratios of reactions yielding only neutral mesons have been omitted. The focus of the table lies on charged annihilation products, since neutral ones cannot be detected in the detector setup.

3. ASACUSA's antihydrogen detector

3.1. Introduction

The purpose of the antihydrogen detector at the end of the beamline is to count the arriving antihydrogen atoms. As discussed in the previous sections, the amount of produced $\bar{\text{H}}$ atoms are very small. Since the detector only sees a small solid angle, the antiatoms reaching the detector are even fewer. In the short setup mentioned previously, the solid angle was $\approx 2 \times 10^{-3}$ sr which is $\approx 0.02\%$ of 4π . Typical rates are ≈ 0.4 to 2 antihydrogen events per run, depending on the considered principal quantum state, see Section 5.4. Note that one run is about 15 to 20 mins long. Consequently, antihydrogen annihilations are very rare and the detector needs to be able to identify them efficiently in background dominated data.

The background primarily consists of cosmic rays which have, depending on the trigger condition, rates of ≈ 0.5 Hz to 1.5 Hz. Trigger generation and conditions are discussed in Section 3.4.1. Another background contribution could come from annihilations of antiatoms in high-field seeking states that are defocussed by the sextupole magnet and hit the wall of the beampipe, possibly close to the central detector, that acts as a target for the beam. Those events would have a signature in the detector very similar to low-field seeking antihydrogen atoms reaching the detector. Therefore, a high detection efficiency and very good background suppression are essential.

Antihydrogen impinging on matter simultaneously produces two annihilation events, one by the positron and one by the antiproton. The e^+ together with an e^- creates a pair of 511 keV gamma rays emerging in opposite directions, while the $\bar{p}$ annihilates with a neutron or proton and forms (on average) three charged pions. Details on low energetic antiproton annihilations can be found in Section 2.8.1.

The ATHENA experiment, which ended in 2005, used a detector system to record both annihilation events [77]. However, it became evident that antiproton annihilation with its energetic pions lead to a higher detection efficiency and differentiation from background [78].

In the ASACUSA detector, only the antihydrogen's antiproton annihilation can be detected and is therefore indistinguishable from a $\bar{p}$ annihilation alone. This is taken advantage of in the analysis for signal and background

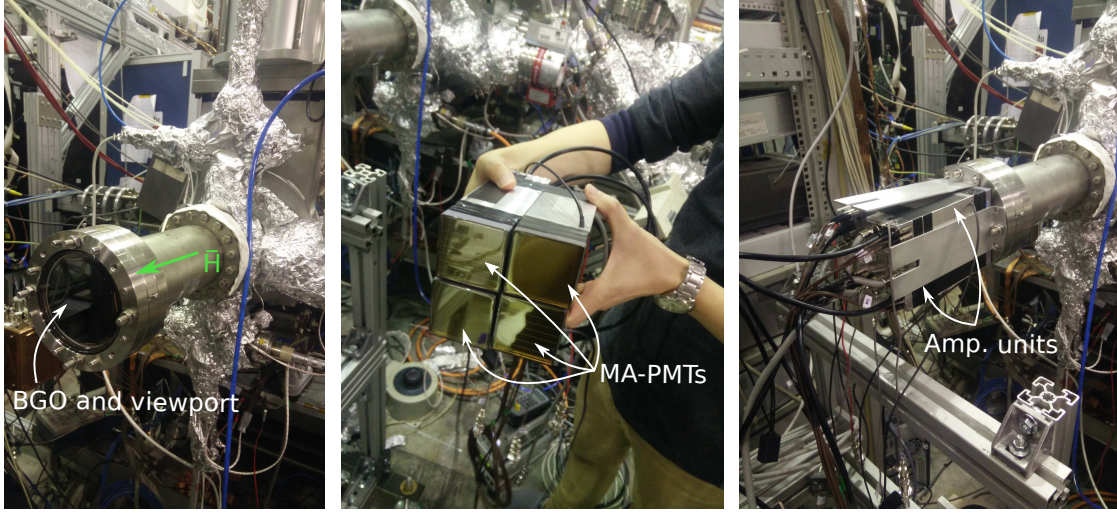


Figure 3.1.: *Left*: BGO crystal disc pressed with springs against the viewport glass at the end of the ASACUSA beamline. *Center*: four multi-anode photomultipliers with amplifier units attached. *Right*: mounted MA-PMTs and amplifier units. Afterwards, a steel cylinder will be put around the setup for additional support and to aid light tightness.

identification, see Chapter 4, since recorded $\bar{p}$ s can be used to train machine learning algorithms.

The detector is composed of a central calorimeter that detects the annihilation and a surrounding hodoscope which covers 80% of solid angle seen from its center. The purpose of the hodoscope is to track secondary and cosmic particles. The detector is discussed in detail in the next sections.

3.2. Central in-vacuum calorimeter

When the antihydrogen atom reaches the detector, it first annihilates on a central calorimeter which is a bismuth germanate (BGO) scintillating crystal disc. The BGO has a diameter of 90 mm and a thickness of 5 mm [79]. The crystal is enclosed in a vacuum vessel kept at UHV pressure and held with springs to the viewport at the end of the stainless steel CF-100 beampipe, see Figure 3.1 (left).

When particles traverse the crystal and deposit energy, scintillation photons are created and detected by four Hamamatsu H8500C multi-anode photomultipliers (MA-PMT) mounted on the opposing side of the viewport, see Figure 3.1 (center and right). Each MA-PMT has an effective area of $49 \times 49 \text{ mm}^2$ and 8×8 channels (256 channels in total). Amplifier units (Clear Pulse CP80190) are connected and directly attached to the MA-PMTs,

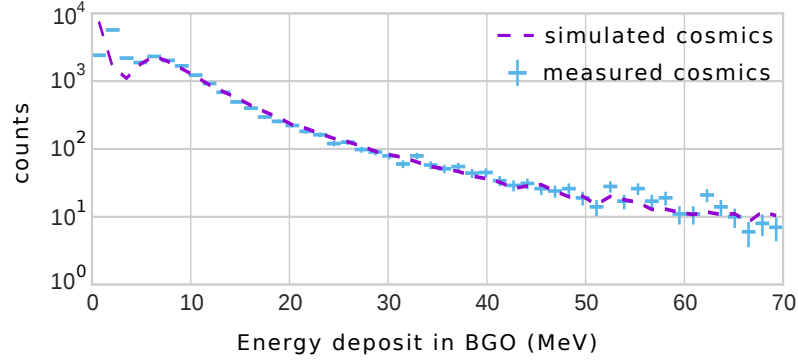


Figure 3.2.: Energy deposit distribution of simulated (purple dashed line) and measured (light blue) cosmic rays (logarithmic y -axis).

which charge-amplify, digitise and read out their signals.

The two dimensional read-out of events supplies position information, additionally to the energy information of the incident particle. The upstream face of the crystal is coated with a $0.7 \mu\text{m}$ carbon layer which was applied by sputter deposition¹. The main purpose of the carbon layer is to improve the position resolution of the annihilation point by absorbing the scintillation light reflected backwards from the downstream face of the crystal [80].

The energy calibration was performed in a two-step procedure. Firstly, the individual pixels of the four MA-PMTs were cross-calibrated by illuminating the active surface with a uniformly distributed light source in a light tight box [80]. Secondly, cosmic rays were measured with the assembled calorimeter and compared with Geant4 [81] simulations using the cosmic-ray shower library (CRY) [82]. Finally, energy calibration factors were derived by fitting the predictions of the CRY simulations to the measured data [83].

The distribution of total energy deposit in the BGO detector of measured and simulated cosmic rays is shown in Figure 3.2. For the measurements, the total energy deposit is calculated by summing over all MA-PMTs channels. The discrepancy below 4.5 MeV is attributed to light generated by charged particles passing through the optics or the viewport glass via Čerenkov effect [83] which has not been included in the Geant4 simulations.

The central calorimeter is surrounded by the tracking detector which is described in the following sections.

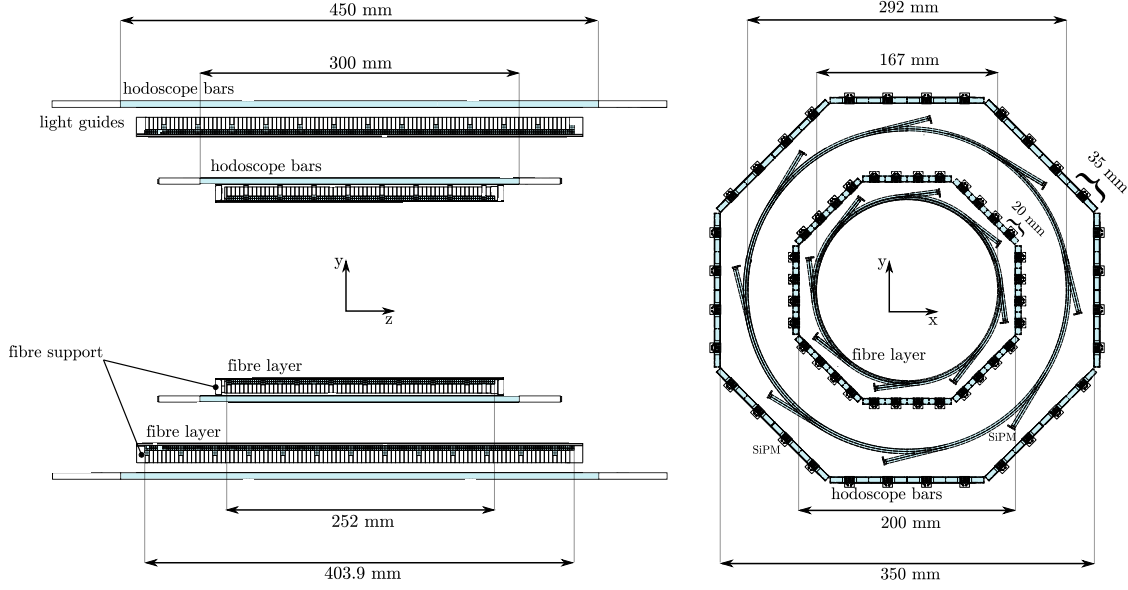


Figure 3.3.: z - y (left) and x - y (right) cross sections of the tracking detector. Scintillating bars and fibres are drawn in light blue. Light guides are drawn white. Dimensions are indicated. In the left figure, the fibre support structure is included, the right drawing also shows the silicon photomultipliers of bars and fibres.

3.3. Tracking detector

The tracking detector is composed of two individual sub-detectors, (1) two layers of hodoscope made up of scintillating plastic bars parallel to the beam direction giving the tracking detector x and y -resolution, and (2) two additional layers (one for each bar layer) of scintillating fibres perpendicular to the beam providing position resolution in the z -direction. Technical drawings of the z - y and x - y plane of the detector system can be seen in Figure 3.3.

The scintillating fibre detector is an upgrade to the already existing bar hodoscope carried out in the data taking break between beamtimes 2016 and 2017. The data analysed by the machine learning analysis in Chapter 4 was taken before the upgrade and is discussed in Section 3.6. Data taken during beamtime 2017 with the full tracking detector is discussed in Chapter 6.

In the following sections, first the bar hodoscope and then the scintillating fibre detector is described as well as improvements and measurements in the lab in Vienna that have been carried out in the course of this thesis. Section 3.4 deals with the data acquisition system.

¹The carbon coating has a purity of $> 99\%$.

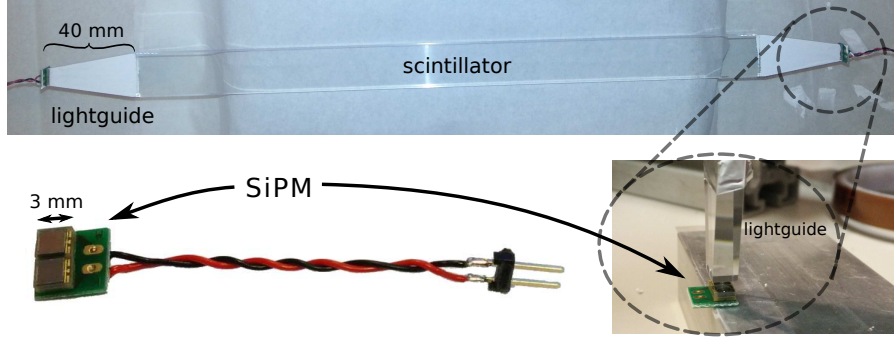


Figure 3.4.: *Top*: Scintillating bar of the inner hodoscope including painted light guides and SiPMs. *Bottom Left*: Picture of two SiPMs connected in series. Printed circuit board (green) and twisted pair cable (black and red) are also shown. *Bottom right*: Close-up of the glueing process, SiPM is being attached to the end of the light guide.

3.3.1. Two-layered bar hodoscope

The two layers of the bar hodoscope both cover the same solid angle of 80% for particles emitted from their centres, where the BGO is placed. It was initially designed and constructed in the course of C. Sauerzopf's PhD thesis [84] and A. Capon's Master thesis [85].

The diameter of the inner bar layer is 200 mm, whereas the one of the outer layer is 350 mm. Both layers have an octagonal x - y cross section and are composed of eight detachable panels accommodating four scintillating bars each. Therefore, each layer consists of 32 scintillating bars (material EJ-200) in total. The inner bars have a length of 300 mm whereas the outer bars are 450 mm long. The inner and outer bar widths are 20 mm and 35 mm, respectively. The dimensions of the detector are indicated in Figure 3.3.

Figure 3.4 (top) shows one of the bar of the inner layer. Light guides are glued² on both ends of the bars. They have the shape of trapezoidal prisms with a length of 40 mm (inner layer) and 75 mm (outer layer). They have the purpose of reducing the cross section of the bars ($width \times 5 \text{ mm}^2$) down to $8 \times 5 \text{ mm}^2$ to match the active area of silicon photomultipliers (SiPMs). The SiPMs have the purpose of detecting the photons created via scintillation by traversing charged particles.

In order to increase light collection, two KETEK 3350TS SiPMs ($3 \times 3 \text{ mm}^2$ active surface) are connected in series and glued to each light guide, see Figure 3.4 (bottom left and right). Another advantage of the double sided read-out is that requiring the coincidence of up- and downstream SiPMs

²The two-component optical cement BC-600 from Saint Gobain was used.

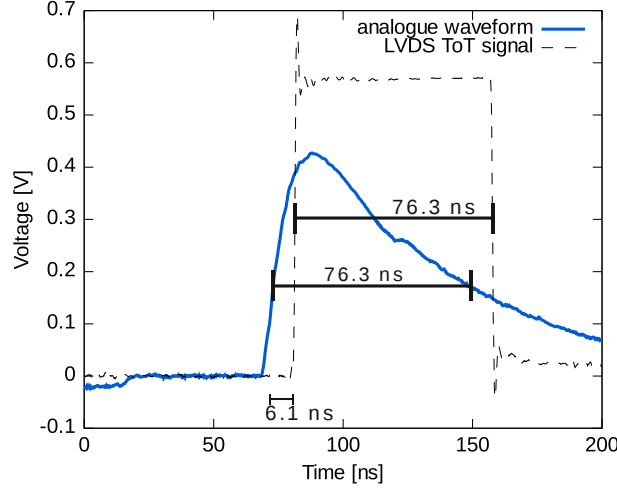


Figure 3.5.: Example of the analogue and digital LVDS signals of the SiPMs read out by the pre-amplifier electronics [84].

reduces the dark noise³ significantly.

The bars are individually wrapped in aluminium foil, before being covered with light-tight foil to block out environmental light (more details will be given in Section 3.3.1.4).

Each channel (128 in total) is connected to front-end electronics [86] which provide the SiPMs with diode bias and function as pre-amplifiers of their signals. Additionally to the amplified analogue signal, the boards output a digital time-over-threshold (ToT) signal created by an on-board time-to-digital converter via leading edge (LE) discrimination. The leading edge time is determined as the time when the amplitude of a waveform exceeds a certain threshold. The ToT is the duration for which the signal value stays above the threshold and determines the length of the digital pulse.

All signals are produced as LVDS (Low-Voltage Differential Signaling) signals which has the advantage that noise picked up is cancelled⁴. Figure 3.5 shows an example analogue and digital signal. The amplification gain and the threshold to create the time-over-threshold signals can be controlled remotely via an Arduino micro-controller [87]. Section 3.3.1.3 discusses more details of the front-end electronics.

The analogue and digital signals are transferred via 10 m long twisted pair flat band cables to the data acquisition system (DAQ) outside the

³Dark noise is the primary source of noise of SiPMs and is mainly caused by thermally generated electrons.

⁴In differential signalling, the electric pulse is split and one of the resulting signals is inverted. After transmission via twisted-pair cables to ensure equal exposure to noise, the two complementary pulses are subtracted and the original signal is recovered. The picked-up noise during transmission cancels.

experimental area. The analogue signals are fed into five waveform digitiser modules (CAEN V1742). The digital signals are connected to a CAEN V1495 FPGA (Field Programmable Gate Array) which can be used for triggering the detector system. The recorded signals are analysed by the raw data **analyser**, discussed together with the DAQ system in Section 3.4.

Apart from information on the number of tracks of a detected event, the bar hodoscope is also capable of providing a measure of the time-of-flight (ToF) of an event. A cosmic particle travelling close to the speed of light, travels ≈ 300 mm in 1 ns. The diameter of the outer layer is 350 mm. Therefore, if the time resolution for the time difference Δm between two bars the cosmic ray traverses is sufficiently small ($\lesssim 0.6$ ns), cosmics can be distinguished to a certain extent from events originating from inside the detector which show time differences of $\Delta m \approx 0$.

The time-of-flight resolution and its measurements in the laboratory for the individual hodoscope components are discussed in Section 3.3.1.2 and in Section 3.6 for the fully assembled hodoscope.

3.3.1.1. Refurbishment

The observed signal size of all channels during data taking periods in 2015 was low, causing the need for high amplification which in turn also amplified the noise picked up by the many sources at the AD of e.g. nearby traps, electronics and other experiments. Due to the low signal quality, the above mentioned time-of-flight resolution was not sufficient to discriminate cosmic events and annihilations. After beamtime 2015, the tracking detector was shipped from CERN to Vienna in order to carry out test measurements and improvements in the laboratory. The measurements described in the following were carried out in the course of this thesis and published in [88].

In order to increase the time resolution, it was necessary to improve the signal quality. Several parts of the assembly could be responsible for the low light levels collected by the SiPMs and were under investigation: (1) light guides are glued onto the bars creating a transition layer, (2) SiPMs were glued onto the light guides, (3) the light guides were coated with reflective paint (BC-620) in order to minimise light losses.

A test setup was built, which included the detector parts, pre-amplifier boards and a CAEN DT5742 desktop waveform digitiser. The binary output files were analysed by the same raw data **analyser** used also at CERN,

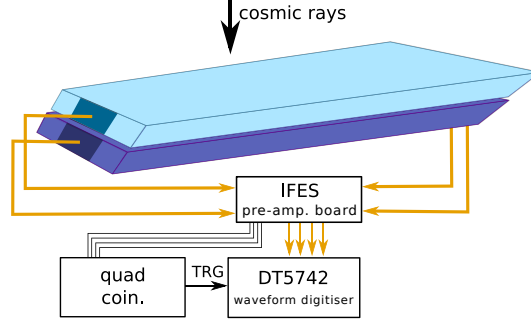


Figure 3.6.: Test setup for measuring the mean time difference of two bars (blue and purple). Drawing adapted from [88].

providing constant fraction⁵ (CF) timestamps, pulse amplitudes and deposited charges. Details of the **analyser** are discussed in Section 3.5.

One panel of the outer hodoscope (comprising four plastic scintillating bars) was dismantled and the scintillators unwrapped. The setup illustrated in Figure 3.6 was built in order to determine the resolution of time-of-flight. The measurements were done using cosmic rays. Two outer hodoscope bars were placed on top of each other and read out on both ends. In order to trigger only on cosmic rays traversing both bars, the trigger condition required a digital ToT signal of all four SiPMs.

The time-of-flight was then calculated as the mean time difference Δm of the two bars:

$$\Delta m = m_1 - m_2, \text{ with: } m_k = \frac{1}{2}(t_{k,u} + t_{k,d}), \quad k = 1, 2 \quad (3.1)$$

where $t_{k,u}$ and $t_{k,d}$ are the CF timestamps of up- and downstream SiPMs of bar k and m_k its mean time. After several hours of data taking, the resulting distribution of mean time differences obtained from CF time stamps was evaluated. A Gaussian fit showed a full width at half maximum (FWHM) of ≈ 1.6 ns which is too high to distinguish particles traversing the detector from outside from those created inside the detector.

After investigating the above listed possible causes of the low signal quality, it was found that the reflective paint on the light guides caused heavy signal attenuation. The data sheet of the applied paint confirmed the result. It states that BC-620 is a diffuse reflector and should therefore not be applied

⁵Constant fraction timestamps are independent of the amplitude of the waveform (as opposed to leading edge timestamps), since the timestamp is given as the time when the leading edge of the waveform reaches a constant fraction of the total amplitude. LE timestamps are subject to time walk which has a negative impact on the timing precision, since pulses with the same rise time but different amplitudes cross the threshold at different times.

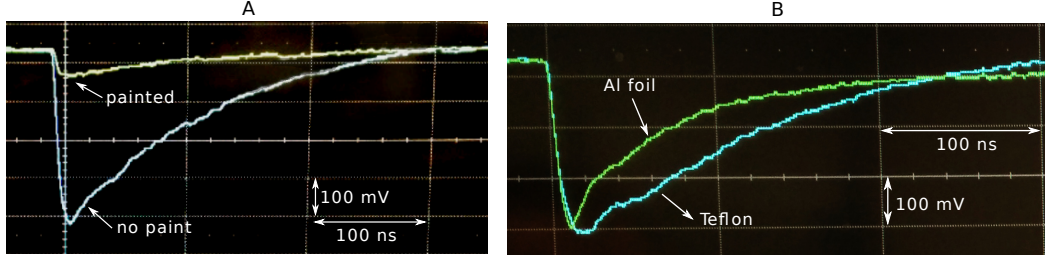


Figure 3.7.: *A*: Photograph of the oscilloscope screen showing two waveforms, one with reflective paint on the light guides (small signal) and the other one without (large signal). *B*: Waveforms using different light guide wrapping materials, Aluminium foil (green) and Teflon (blue). The oscilloscope was set to 100 mV per division (vertical axis) and 100 ns per division (horizontal axis) in both pictures.

to thin scintillator or light guides i.e. with dimensions such that their length is much longer than their thickness. Figure 3.7 (A) shows a screenshot of the oscilloscope displaying two signals from the same bar, where the small signal stemmed from the SiPM attached to a painted light guide and the other, much larger signal was recorded from the SiPM on the other end of the bar, where the reflective paint had been removed. The signal amplitude was improved by an order of magnitude by cleaning off the paint, with an amplitude of ≈ 50 mV before and ≈ 500 mV after removal.

Furthermore different wrapping materials have been tested for the light guides. Figure 3.7 (B) shows two waveforms using aluminium foil (green signal) and Teflon (blue waveform) as light guide wrapping material. The waveform of the SiPM attached to the light guide wrapped in Al foil showed a slightly shorter rise time and also shorter fall time, so aluminium was used.

3.3.1.2. Time and position resolution measurements

After improving the signal quality, the time resolution measurement was repeated with two bars whose light guides were freed from reflective paint and wrapped in Al foil. The resulting histograms of mean time differences for outer and inner hodoscope bars can be seen in Figure 3.8. A Gaussian is fitted to the histograms and the resulting width of the distributions for inner and outer bars are:

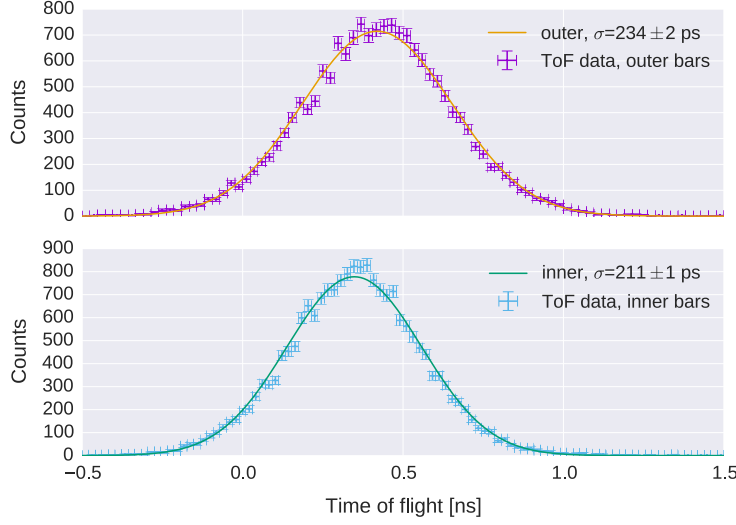


Figure 3.8.: Distributions of mean time differences for the outer (top) and the inner (bottom) hodoscope bars. Data and plot published in [88].

$$\begin{aligned}\sigma_{\text{inner}} &= (211 \pm 1) \text{ ps} & \text{FWHM}_{\text{inner}} &= (494 \pm 3) \text{ ps} \\ \sigma_{\text{outer}} &= (234 \pm 2) \text{ ps} & \text{FWHM}_{\text{outer}} &= (551 \pm 5) \text{ ps}\end{aligned}$$

which is an improvement of a factor 0.34 compared to the previous time-of-flight resolution of 1.6 ns (FWHM, outer bars) and should allow the discrimination of cosmics passing the detector from outside and secondaries from antihydrogen annihilations inside the detector. Measurements with the fully assembled hodoscope integrated into the full data acquisition system at CERN will be discussed in Sections 3.6 and 3.6.6.

As a result of the improved signals, the two-sided read out of the bars also allows the extraction of information on the hit position of a particle on the scintillating bars in beam direction. The setup for measuring the spatial resolution of the hodoscope bars in the z -direction can be seen in Figure 3.9. A small scintillator (purple) is placed perpendicular and close to the end of one of the hodoscope bars (blue). The small scintillator had a length of 27 mm, a width of 3 mm and a thickness of 1 mm and an SiPM attached to it for read out. The scintillator is thin enough that the particles emitted from a ^{22}Na source (activity of 370 kBq) placed on top of it are not stopped in it and will also enter the hodoscope bar below it. By using the triple coincidence of the up- and downstream sides of the bar and the small scintillator as a trigger, only those particles traversing both scintillators will be recorded.

The measurement is carried out at two different positions (marked pos 1 and pos 2 in the figure) which had a defined distance d to each other

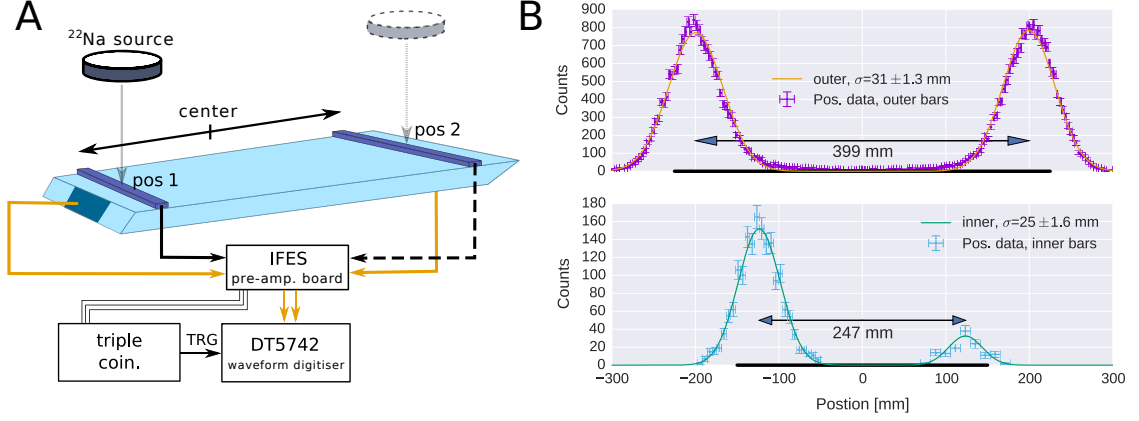


Figure 3.9.: A: Test setup for measuring the position resolution. The hodoscope bar is shown in blue and the small scintillator used for triggering in purple. Drawing adapted from [88]. B: Distributions of position measurements for outer (top) and inner (bottom) hodoscope bars. The difference in peak heights of the position measurement of the inner bar is a result of a shorter acquisition time for the second peak. Data and plot published in [88].

($d = 247$ mm for the inner and $d = 399$ mm for the outer bar) and were equidistant to the bar center.

The time difference $\Delta t = t_u - t_d$ between up- and downstream CF timestamps is calculated for the recorded events. The distributions are fitted with Gaussians and their resulting means μ_{pos1} and μ_{pos2} are determined. The time difference can then be converted to a corresponding position x via:

$$x = \alpha(\Delta t - \beta) \quad (3.2)$$

where $\alpha = d/(\mu_{\text{pos2}} - \mu_{\text{pos1}})$ and $\beta = (\mu_{\text{pos1}} + \mu_{\text{pos2}})/2$. The resulting histograms can be seen in Figure 3.9 (B) for outer (top) and inner (bottom) bars for both positions. The resulting position resolutions for inner and outer bars are then determined by extracting the widths of the Gaussian fits:

$$\begin{aligned} \sigma_{\text{inner}} &= (25 \pm 2) \text{ mm} & \text{FWHM}_{\text{inner}} &= (59 \pm 4) \text{ mm} \\ \sigma_{\text{outer}} &= (31 \pm 1) \text{ mm} & \text{FWHM}_{\text{outer}} &= (73 \pm 3) \text{ mm} \end{aligned}$$

For the outer layer, the FWHM amounts to $\approx 16\%$ of the total bar length, for the inner layer 19%. This is not enough for precise three-dimensional tracking and vertex reconstruction, which initiated the upgrade of the tracking detector using scintillating fibres (see Section 3.3.2). However, it is a useful input for the three-dimensional tracking algorithm and the necessary hit-matching between fibre and bar detector discussed in Chapter 6.

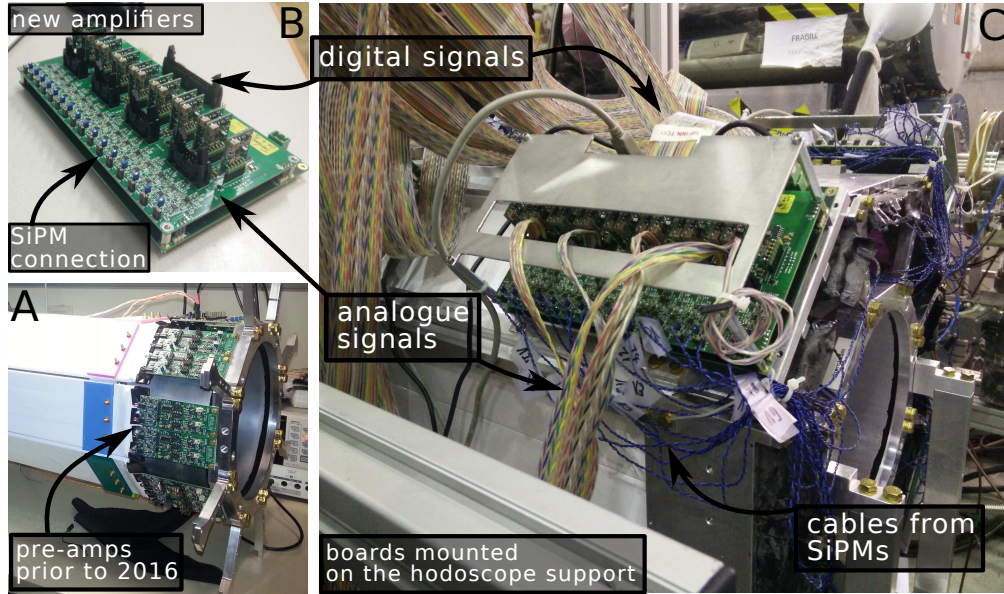


Figure 3.10.: *A*: old front-end electronics of the inner hodoscope layer. *B*: new amplifier boards. *C*: boards mounted on the hodoscope support structure, SiPMs connected (twisted pair blue and black cables) and signal cables (twisted pair flat band cables).

3.3.1.3. Pre-amplifier electronics upgrade

The afore mentioned front-end electronics used to power the SiPMs and amplify their signals were upgraded in the course of this thesis. The original boards, named Intelligent Front-End Electronics for Silicon Photomultipliers (IFES), are the basis of the pre-amplifiers and were developed at the Stefan Meyer Institute by C. Sauerzopf and H. Schneider [84, 86]. Details of the functionality and design can be found in the references. The aim of the upgrade was to make the electronics more compact and robust, since the old boards caused numerous problems during data taking periods in 2015, due to their fragility and inaccessible placement.

In order to calibrate the detector, the amplification gain and threshold settings of the pre-amplifier boards need to be adjusted for every channel. In the previous design, one board housed two hodoscope channels. The boards of the inner hodoscope layer can be seen in Figure 3.10 (A). They were closely mounted to the SiPMs since the signal quality was low and so the cables connecting the SiPMs to the electronics needed to be short. The power for the boards was distributed via daisy chain⁶. The amplification gain and the threshold of the channels could be set by a micro controller (Arduino

⁶A daisy chain is a wiring configuration, where multiple devices are connected in a sequence forming a line or ring.

Leonardo⁷). The Aduino was connected to the control buses of the first and last board in a daisy chain configuration similar to the power distribution. Commands given to the micro controller could then be sequentially transmitted to the connected boards. The Arduino Leonardo was connected to a second micro controller (Arduino Yun⁸) featuring a minimal version of Linux running on an on-board micro processor and which can be controlled via network. This allowed remote control of the front-end electronics. Additionally, the boards had an on-board potentiometer for coarse gain adjustments.

Problems during beamtime 2015 with the connections between boards of the control buses in the daisy chain prevented the signals from being sent to the individual boards. As a result, gain settings for all channels had to be done manually via the small on-board potentiometer.

Figure 3.10 (B) shows one of the new boards. Instead of two, the new electronics house sixteen channels per board. In total eight boards are needed for all SiPMs of the inner and outer hodoscope layers. Each board has its own power supply. They are mounted on the hodoscope and further away from the SiPMs, since the improved signal quality allows longer cables connecting the SiPMs to the front-end electronics. Furthermore, the new electronics have the micro-controller circuit for gain and threshold settings directly printed on-board, which can be accessed via USB connection. The daisy chain connections of power and control bus between individual IFES circuits are also directly printed on the boards.

The simple and frail two-pin connectors on the boards and two-pin plugs of the signal flat band cables have been replaced by robust IDC (Insulation-Displacement Contact) connectors and plugs that can be locked in place. Figure 3.10 (C) shows one of the mounted boards with SiPMs and signal cables connected. Additionally, a protective metal plate is mounted.

All eight boards are connected to a USB hub, that can be connected to a computer in order to adjust the channel settings. More details of the slow-control of the electronics can be found in [87].

3.3.1.4. Reassembly and light tightness of the hodoscope

After it was found out that the reflective paint on the light guides caused the signal attenuation, the whole tracking detector was taken apart i.e. all panels of inner and outer layer were dismounted and the bars unwrapped. After cleaning off the reflective paint, bars and light guides were individually

⁷https://www.arduino.cc/en/Main/Arduino_BoardLeonardo

⁸https://www.arduino.cc/en/Main/Arduino_BoardYun

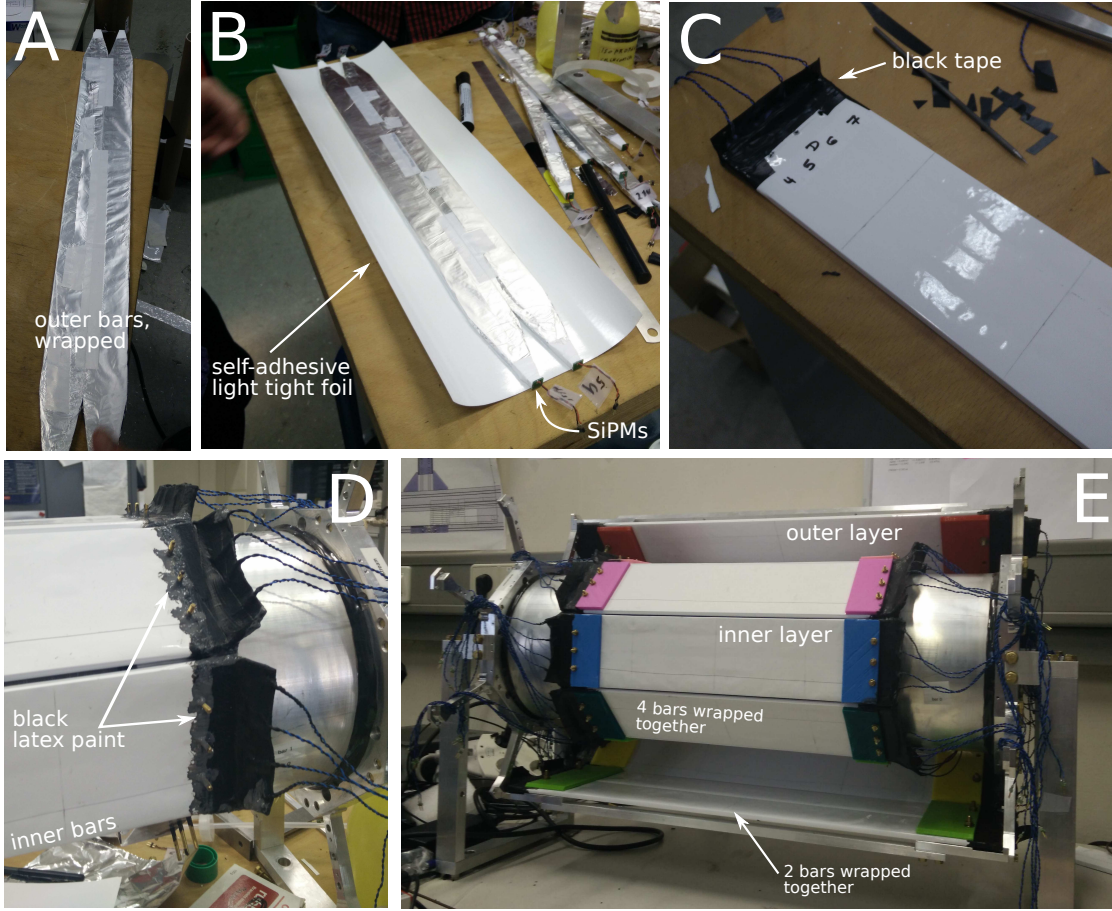


Figure 3.11.: A: Two outer bars wrapped in Aluminium foil. B: They are placed on the white, self-adhesive light tight plastic foil and wrapped in it. C: The ends of the bars where the SiPMs sit are covered with black tape. D: Additionally, black latex paint is applied to seal small gaps and mounting holes in the wrapping. E: The panels housing four bars are mounted on the support structure.

wrapped with aluminium foil. The ends of the light guides close to the SiPMs were left free of foil and were covered with Teflon tape instead to avoid the risk of a short circuit with the supply voltage of the SiPMs. Afterwards, all the hodoscope bars were made light tight to block light from the environment before being remounted onto the support structure. The steps of the process for the outer layer are shown in Figure 3.11. Two bars are wrapped individually in aluminium foil (A), before being wrapped together in light tight self-adhesive plastic foil (B). The ends where the SiPMs are attached are covered in black tape (C). The taped ends are additionally coated in black latex paint (D) which seals small gaps (especially where the SiPM cables leave the tape) and mounting holes in the wrapping, additionally it prevents the tape from coming loose. After assembling the bars onto the hodoscope support structure (E), all channels were tested for functionality and light tightness.

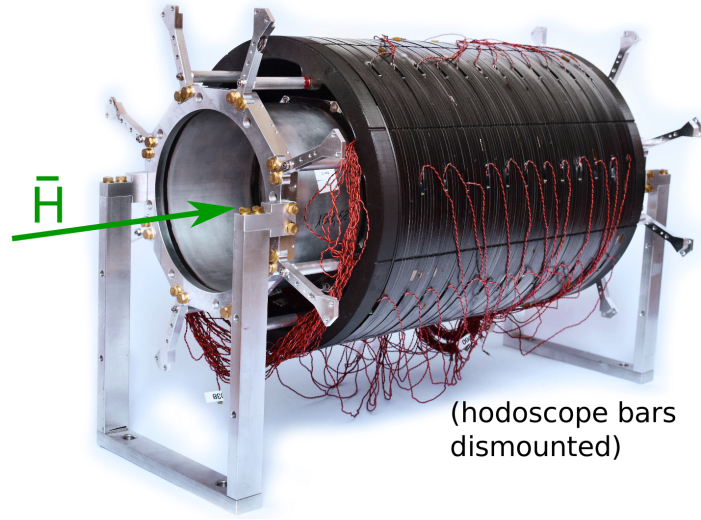


Figure 3.12.: Fibre detector mounted on the common support structure of the tracking detector. Hodoscope bar panels are not installed on the photograph.

The detector was then shipped back to CERN. Calibrations, data corrections and dedicated measurements are discussed in Section 3.6 and were done with the full detector setup at the AD. Previous data corrections relating to the waveform digitisers and corrections due to the trigger jitter in the FPGA, are discussed in [84].

3.3.2. Fibre upgrade

The ASACUSA tracking detector has been upgraded for the purpose of increasing its position resolution in z -direction [89]. As mentioned previously, the upgrade comprises two layers of scintillating fibres (material Saint Gobain BCF-12) in a cylindrical arrangement and orthogonal to the beam direction and hodoscope bars. Figure 3.12 shows the two layers of fibres mounted on the hodoscope support structure. In the picture, the panels housing the bars are removed.

The inner layer consists of 63 channels and has a diameter of 167 mm. The outer layer houses 100 channels and its diameter is 292 mm. A channel consists of four square $2 \times 2 \text{ mm}^2$ fibres arranged in a 2×2 matrix. One end of the fibre bundle is glued to an SiPM (KETEK PM3350-EB), see Figure 3.13 (A).

Figure 3.13 (B) shows a photograph taken during assembly of the fibres. The cylindrical structure is realised by winding the fibres around a supporting carbon tube, where the length of each fibre bundle is a few centimetres longer than the circumference in order to avoid loss of solid angle. They are secured

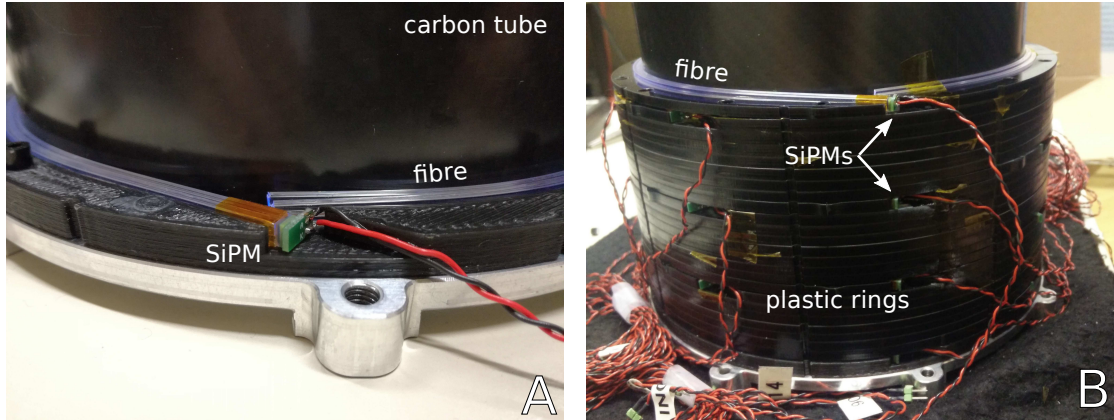


Figure 3.13.: *A*: close-up of a fibre bundle glued to an SiPM and wound around the supporting carbon tube. *B*: photograph taken during assembly of the fibres which are kept in place with black plastic rings. Red and black twisted pair cables attached to the SiPMs can also be seen.

in place by black plastic rings.

No light shielding between the individual channels is necessary, since their surface cladding prevents transmission of scintillating light of neighbouring fibres. The crosstalk was determined to be less than 1% in the laboratory [87].

In order to block environmental light, both fibre layers are covered in black tape and finally coated with several layers of black latex paint (not shown on the pictures). Further details on the construction process of the fibre detector and test measurements in the lab of the Stefan Meyer Institute are described in [87].

The SiPMs are powered and read-out by the same front-end electronics as were used for the hodoscope bars, see Section 3.3.1.3. In total 11 boards were used and mounted partly on the hodoscope and partly on its support structure.

As opposed to the hodoscope bars, only the digital time-over-threshold signals of the fibres produced by the leading edge discriminator of the front-end electronics are processed. The analogue signals were only recorded with an oscilloscope for debugging purposes during detector setup. Figure 3.14 (top) shows the analogue (yellow) and the digital (green) ToT signal of one of the fibre channels. Due to a design error, the overall amplification of the current pre-amp boards is too high, which causes waveforms with amplitudes larger than 1 V to be cut off⁹. This results in the flattening effect of the signal peak that can be seen in the figure. An upgrade with adjusted amplification

⁹The maximum output signal height of 1 V of the boards, that were originally designed for the bar hodoscope, was chosen to match the requirements of the CAEN V1742 waveform digitisers.

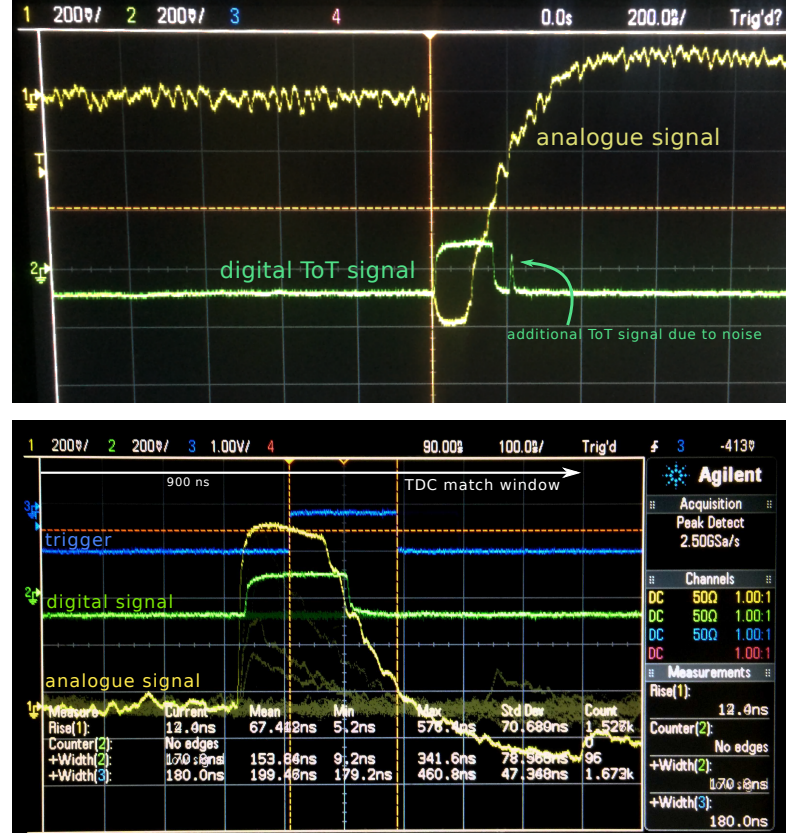


Figure 3.14.: *Top*: Photograph of the oscilloscope screen showing analogue (yellow) and digital (green) time-over-threshold signals of a fibre channel. Oscilloscope settings: 200 mV/div (vertical axis) and 200 ns/div (horizontal axis). *Bottom*: Fibre signals and trigger signal (blue). Oscilloscope was in persistence mode (past few waveforms are displayed in faded colours). Oscilloscope settings for fibre signals: 200 mV/div (vertical axis). Settings for trigger signal: 1 V/div (vertical axis). 100 ns/div (horizontal axis) for both.

is foreseen.

The digital pulses of the 163 fibre channels are then transferred as LVDS signals via twisted pair flat-band cables to the crate containing the DAQ modules. They are fed into two Time-to-Digital Converters (TDCs), a CAEN V1190B with 64 channels and a CAEN V1190A with 128 channels. Additionally, the trigger signal (see Section 3.4.1) is fed into one of the channels of each TDC to record it with higher precision.

The correct configuration of the so-called time match window of the TDCs is essential which is defined with respect to the trigger signal. All hits of a channel that fall into the time window associated to a trigger are recorded. Therefore, it is important to make it long enough to record both, leading and trailing edge of the signal. The time offset (relative to the leading edge of

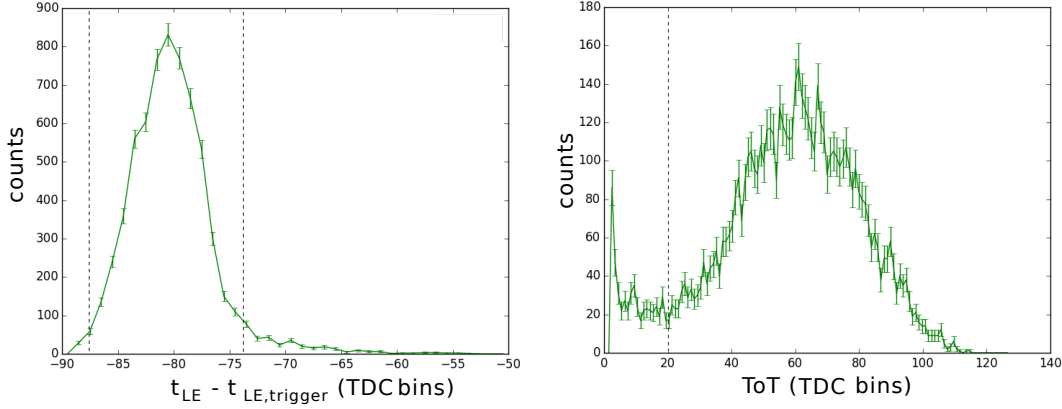


Figure 3.15.: *Left*: Distribution of leading edge timestamps of channel 45 of the outer fibre detector. Timestamp of the trigger signal has been subtracted. The bin width of the recorded LE timestamps was 1.6 ns. *Right*: ToT distribution of the same channel. The bin width of the recorded ToT was 3.2 ns, the highest bin value is 127 which corresponds to 409.6 ns (128×3.2 ns). Vertical dashed lines mark cuts for noise reduction.

the trigger) and the width (added to the offset) of the match window can be chosen. The trigger signal and fibre analogue and digital signals are shown on the oscilloscope recording in Figure 3.14 (bottom). The window width and position is indicated by the white arrow, with a total width of 900 ns and an offset of -500 ns in order to capture data before the trigger.

The TDCs are operated in so-called “pair mode” which means that the leading edge timestamp and the width of the digital signals of each channel are recorded. LE timestamps and ToTs are recorded with 7 bit resolution and bin widths of 1.6 ns and 3.2 ns, respectively.

Example histograms of LE timestamps and ToT of one of the outer fibre channels can be seen in Figure 3.15. The data contains cosmic events, that have been recorded in the fully assembled detector at CERN. The trigger condition was set to hodoscope only i.e. a trigger is issued if one or more bar of inner and outer layer show a hit (see Section 3.4.1 for details). For the distribution of LE timestamps (left), the trigger signal has been subtracted which results in a peak.

The peak in the LE timestamp distribution has a width of ≈ 8 ns as a consequence of the time walk effect due to the leading edge discriminator. The ToT distribution (right) shows a peak around 60 TDC bins which corresponds to a pulse length of 192 ns.

Noise on the waveforms can result in digital signals with several pulses which can be seen for example in the top picture of Figure 3.14 (small

additional digital signal after the main pulse). Therefore, for every channel, LE timestamps and ToT of all pulses arriving in the trigger window of the TDCs are recorded. Later, the pulse with the highest ToT is selected for further analysis.

Furthermore, in order to reduce noise hits, cuts on the recorded leading edge timestamp and time-over-threshold are applied before further analysis e.g. tracking. The cuts are based on the individual distributions of the channels, see vertical dashed lines in Figure 3.15 for an example.

3.4. Data acquisition system

This section provides a compact outline of the DAQ¹⁰ system of ASACUSA's antihydrogen detector. Details can be found in [84, 87].

An overview of cabling and setup is shown in Figure 3.16. The diagram is grouped into three spatially separated areas (marked by dashed dark grey lines): (1) the ASACUSA beam area where the traps, spectrometer line and detector are located, (2) a rack housing NIM¹¹ and VME¹² electronics on a platform above the experimental area and (3) the counting house where the DAQ server is situated.

The NIM logic is mainly utilised to create the event trigger, while the VME modules are responsible for DAQ control and data recording. The VME crate contains a VME controller (SIS3100) that is connected via an optical fibre cable to the DAQ server in the counting house. The server communicates with the VME crate and manages the DAQ process. The data acquisition software used is MIDAS (Maximum Integrated Data Acquisition System) [90] and it comprises four main components: (1) a core server responsible for managing the other components, (2) a data logger which handles data storage, (3) a web server which allows easy monitoring and run control via a web interface and (4) a frontend program which needs to be provided by the user. The frontend interacts directly with the VME modules and is in charge of the initialising and monitoring of the modules, trigger handling and subsequent data reading.

Data read-out and storage is event-based. The most important event type

¹⁰The DAQ system has been developed in the course of C. Sauerzopf's PhD thesis [84], and was further progressed by M. Fleck (master thesis [87]).

¹¹Nuclear Instrumentation Module (NIM) is an electronics standard widely used in particle and nuclear physics.

¹²Versa Module Europa (VME) is a bus system with interrupt management.

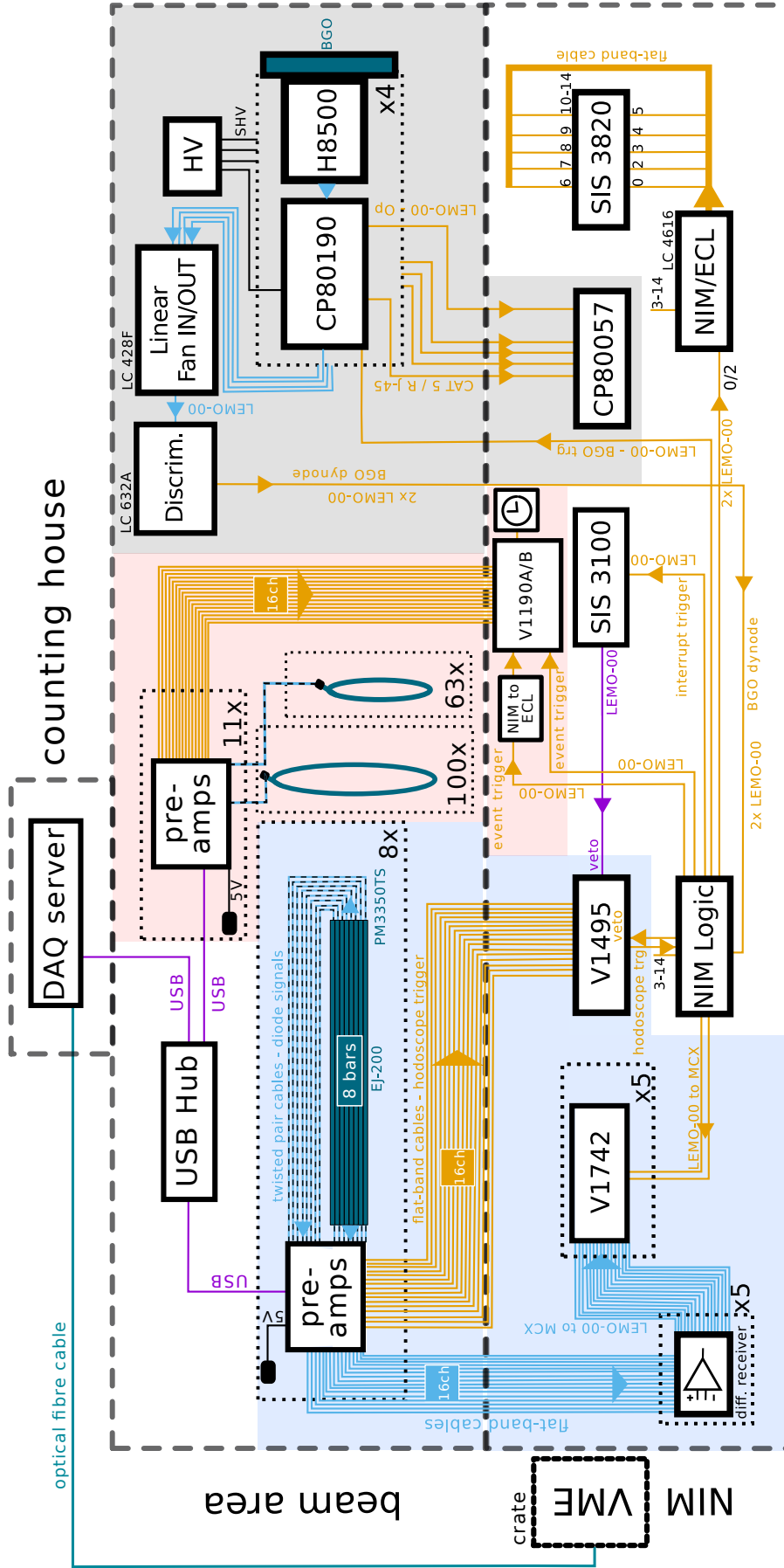


Figure 3.16.: Overview of the DAQ system of the antihydrogen detector. The drawing is based on Figure 5.3 of [84]. Rectangles with dashed, dark grey contours mark different spatial areas e.g. the counting house. Shaded areas mark components belonging to the same detector system i.e. blue for the bar hodoscope, red for the fibre detector and grey for the BGO. Scintillators are drawn in dark turquoise. Twisted pair diode signals from SiPMs are indicated as dashed light blue and black lines. Analogue signals are drawn in light blue, digital signals in gold. Purple connections indicate control signals. Power cables are shown in black.

is the “ $\overline{H}$ event” which is created when an interrupt trigger is issued. Trigger conditions will be discussed in Section 3.4.1. When an interrupt from the VME controller is sent to the DAQ server, a veto gate is created (called *deadtime veto* in the following) to prevent triggering during the data read-out process. Furthermore, signals created in the detectors during injection of the antiprotons into the ASACUSA area are vetoed.

The maximum rate of the DAQ is between 50 and 100 Hz which is sufficient for rates during antihydrogen production which are in the order of the cosmic rate. The raw data is saved in binary format and needs to be converted into a data format suitable for data analysis by the **analyser**, discussed in Section 3.5.

The flow of signals and cabling is depicted in Figure 3.16 as well. Following the signals from each sub-detector, starting in the experimental area:

- ▷ **Bar hodoscope** (blue shaded area):
 - Amplified analogue signals are transferred via flat-band cables to the platform, where they are fed into differential to single-ended converters (marked as *diff. receivers*). Afterwards they are sent to the waveform digitisers (V1742).
 - Digital time-over-threshold signals are fed into the FPGA (V1495) where they are used to create the “hodoscope trigger” (discussed below in Section 3.4.1) which is then sent to the NIM logic.
- ▷ **Fibre detector** (red shaded area):
 - Digital ToT signals are transmitted via flat-band cables to the TDCs (V1190A/B) in the VME crate on the platform. The TDCs are synchronised by an external 40 MHz clock (CERN’s TTCvi). They are triggered by the event trigger which is additionally fed into one of the channels of each TDC in order to record it with higher precision.
- ▷ **BGO calorimeter** (gray shaded area):
 - The four dynode signals provided by the MA-PMTs are first combined by a linear fan-in and then fed into a discriminator which creates then a trigger pulse from the BGO detector. The signal is sent to the NIM Logic and will henceforth be referred as “BGO trigger”. When an event trigger is issued, the pulses of the MA-PMTs are digitised and the output sent to the VME crate for read-out.

Furthermore, the scaler (SIS3820) is read out periodically for trigger counting, recording of detector rates and mixing start and stop signals supplied by

the trap control system.

3.4.1. Event trigger

The event or $\bar{\text{H}}$ trigger is created from a combination of the afore mentioned “hodoscope” and “BGO trigger”. For clarification, the $\bar{\text{H}}$ trigger does not mean that the recorded event is automatically an antihydrogen event. It is merely the minimal condition that needs to be fulfilled for an event to be recorded.

For the hodoscope trigger, the digital pulses of all channels as well as the deadtime veto from the VME controller are fed into the FPGA. The 128 digital signals are organised in two arrays for each layer, containing the up- (U_I and U_O) and downstream (D_I and D_O) responses of the SiPMs. The FPGA is configured as follows. Firstly, the coincidence of up- and downstream SiPM signals is checked for both layers: $C_I = (U_I \& D_I)$ and $C_O = (U_O \& D_O)$, where $\&$ symbolises a logical “and” and C_I and C_O the resulting boolean arrays. If both coincidence arrays contain at least one positive value and the deadtime veto permits it, then a trigger signal is generated by the FPGA. Therefore, a hodoscope trigger is created if one or more bars of inner and outer layer show a hit. A diagram of the FPGA logic can be found in the Appendix A.5 in Figure A.3.

The output signal is then transferred to a coincidence unit (NIM, LeCroy 465). Additionally to the FPGA signal, the veto and the BGO dynode trigger signal are fed into the coincidence unit. Depending on which of its input channels is activated, an event trigger signal consisting of just hodoscope, just BGO or the combination of hodoscope and BGO can be generated. Detailed trigger flow diagrams can be found in Appendix A.5 in Figure A.4.

Typical rates during cosmic ray recording are 1.5 Hz for BGO, 2 Hz for hodoscope and 0.5 Hz for combined triggering.

3.5. Raw data analyser

The recorded raw data files are then pre-analysed and converted to ROOT [91] files. ROOT is a scientific software tool-kit developed at CERN intended for data storing, processing and analysing.

A file contains the data of events recorded in the period of a MIDAS run whose start and stop can be controlled manually via the MIDAS web interface or automatically by setting a time or byte limit for a run and automatic run

3.5. Raw data analyser

Detector	Data per channel	Format	Notes
Bar hodoscope (128 channels)	LE timestamp (ns)	double	Integral of waveform
	LE ToT (ns)	double	
	CF timestamp (ns)	double	
	Amplitude of waveform (V)	double	
	Charge (204.8e ⁹ Vs)	double	
Fibre detector (163 fibres + 2 trigger ch.)	LE timestamps (ADC bins)	int[128]	Width of digital signal
	ToT (ADC bins)	int[128]	
BGO (256 channels)	Charge (ADC bins)	double	12 bit resolution
General run and event information	CUSP run number	int	Run number of trap system
	AD pulse (bool)	bool	Antiproton injection
	MIDAS mixing time stamp	int	With sec. precision
	MIDAS mixing time stamp	double	With milli-sec. precision
	ADC mixing time stamp (ns)	double	From waveform digitisers

Table 3.1.: Relevant detector data and general run and event information stored in the `HbarEventTree`.

restart. The detector runs are therefore in principle independent from the trap cycle. However, during mixing runs they are synchronised via start and stop signals that are sent from the control system of the traps.

Each ROOT file comprises trees where data can be organised and stored in branches and leaves. The two most important trees for the ASACUSA detector are the `HbarEventTree` and the `ScalerDataTree` which contain the $\bar{H}$ event data and the scaler data, respectively.

In case of the BGO and the fibre raw data, the `analyser` first decodes the binary data from the MIDAS files and then stores them in the corresponding leaves of the ROOT tree. Calibration and data corrections are applied afterwards.

The analysis of the bar hodoscope data is more sophisticated and implemented in the `waveform library` [84, 92]. It uses a Fast-Fourier filter to remove high-frequency noise and allows pulse shape fitting with templates of waveforms. Afterwards, LE and CF timestamps, as well as amplitude and charge are calculated and stored in the ROOT tree. The relevant quantities are summarised in Table 3.1.

Further run and event information that is saved are also listed. Notably, the mixing start signal, that is supplied by the trap control system 21 ms before the antiprotons are injected into the double-CUSP trap. The mixing signal is recorded with both second and millisecond precision by the scaler and additionally fed into the spare waveform digitiser, and therefore using the internal clock of the waveform digitisers, for a higher accuracy (≈ 10 ns).

Detailed description of the ROOT file structure of the ASACUSA detector

data can be found in the above mentioned references.

3.6. Commissioning of the $\bar{\text{H}}$ detector and cosmic and $\bar{\text{p}}$ measurements

The data discussed in this section was collected with the bar hodoscope and BGO calorimeter set up in ASACUSA's experimental area at CERN (as opposed to the measurements in the lab in Vienna discussed before). Note, that this was before the fibre upgrade of the tracking detector was realised. The data consists of two sets (1) cosmic rays acquired during beam-off periods i.e. no antiprotons were injected into ASACUSA's area and (2) antiproton annihilation events accumulated during dedicated extractions from the MUSASHI trap.

In the first two sections, detector calibration and data corrections are discussed. Recorded cosmic events have been used for this purpose. Afterwards, distributions of mean times and z -positions for the fully assembled hodoscope are evaluated with cosmic rays.

Then, distributions of deposited energy in the BGO by cosmic rays and $\bar{\text{p}}$ s are studied. Time-of-flight distributions for both data sets are compared. A two-dimensional tracking algorithm to determine the number of charged particle tracks in the hodoscope is described and resulting histograms are shown.

Furthermore, the discussed data forms the basis of the data-driven machine learning analysis for signal and background discrimination described in Chapter 4.

3.6.1. Calibration

Calibration of the central BGO calorimeter was carried out by Y. Nagata and is briefly described in Section 3.2. Details can be found in the mentioned references.

The hodoscope calibration is done by adjusting gain and threshold settings of the pre-amplifier electronics of all 128 channels. For the amplification gain, in an initial step, a coarse adjustment was done using the on-board potentiometer of the front-end electronics. All channels were set to a nominal value, measuring the current drawn during operation of the channels with a multimeter ($\approx 7 \mu\text{A}$). The thresholds cannot be set on-board and need to be

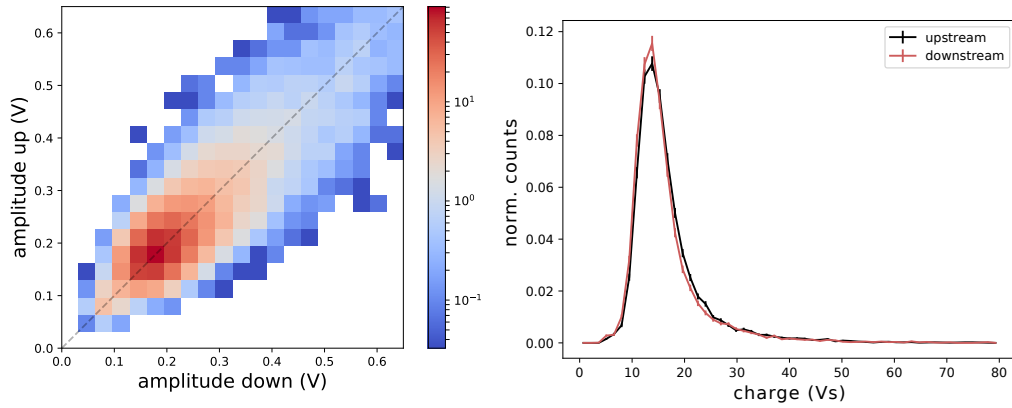


Figure 3.17.: *Left*: Normalised two -dimensional histogram of up- and downstream amplitudes of outer hodoscope bar channel 10. The dashed line has an angle of 45° with both axes, symbolises perfect positive linear correlation. Histograms of all inner and outer hodoscope channels can be found in Appendix A.4 in Figure A.1 and Figure A.2. *Right*: Landau distributions of up- and downstream SiPMs (outer layer channel 10).

measured with an oscilloscope. Initial settings were gauged by examining a few channels via an oscilloscope and adopting the settings to the remaining channels.

After the first rough adjustments, cosmic rays were recorded for about an hour. Events producing one or more hits in the hodosocpe and a hit in the BGO were recorded (see Section 3.4.1 for details on the trigger conditions). Subsequently, the correlation of signal amplitudes of up- and downstream SiPMs, as well as the distribution of deposited charges, calculated as the area under the waveform, were inspected. Example distribution can be seen in Figure 3.17. The left plot shows a two-dimensional histogram of pairs of up- and downstream amplitudes. The desired linear correlation is nicely visible.

The charge deposit in the scintillators is expected to follow a Landau distribution¹³ [93], which can be seen in Figure 3.17 (right). Due to the BGO in the trigger, cosmic particles traverse through approximately the same amount of scintillating material of the bars and the Landau distributions are therefore expected to look the same for all channels. This can be used as an additional gauge during calibration.

Gain settings were then fine tuned by consecutive adjustment remotely via slow-control and examining the resulting distribution after taking more

¹³The distribution of deposited energy of charged particles traversing detectors of finite thickness resembles a Gaussian with a tail towards higher energies due to fluctuations in energy loss.

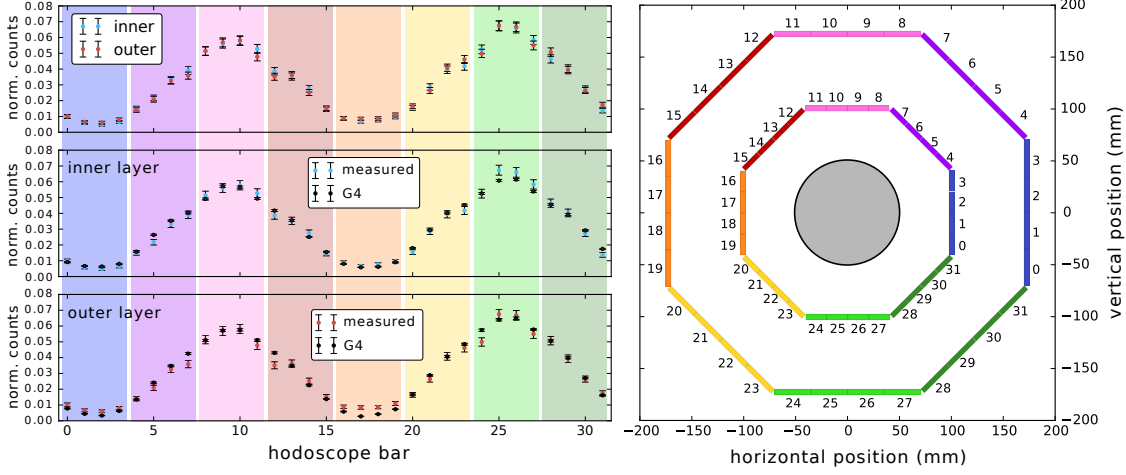


Figure 3.18.: *Left*: angular distribution of inner and outer layer (top), as well as comparison to Geant4 simulations (middle and bottom). Light blue points indicate measurements of the inner, red points the outer layer. Simulation results are shown in black. The coloured, shaded areas correspond to bars sharing the same panel. *Right*: x - y cross section of the detector showing the channel numbering and panel colours [84]. The grey circle in the center symbolises the BGO calorimeter.

cosmic data. Additionally, the angular distribution of cosmic rays in the hodoscope and a comparison to simulations was used to assess the channel settings. The angular distribution of cosmic rays is expected to follow a distribution proportional $\cos^2\theta$ [94] with θ being the zenith angle. It can be seen in Figure 3.18 (left) for the inner and outer hodoscope layer after calibration. The data consists of about 20000 cosmic events recorded over a few hours. A cut on the BGO energy deposit of $E_{\text{BGO}} > 7$ MeV has been applied. The top plot shows a comparison of the distributions for inner (light blue) and outer (red) layer, the middle and bottom plot show comparisons to simulations for both layers. The x -axis shows the channel number of the bar. The shaded vertical areas mark bars sharing the same panel. Figure 3.18 (right) shows the x - y plane of the detector and the channel numbering for orientation. The simulations have been carried out in Geant4 employing the afore mentioned CRY library for cosmic ray generation. The cut $E_{\text{BGO}} > 7$ MeV was applied as well.

The bars on top (pink panel) and bottom (light green panel) show the highest counts since their effective area facing upwards is the largest. The expected $\cos^2\theta$ distribution is nicely visible for both layers and the data agrees well with simulations.

3.6.2. Cable length corrections

The bar hodoscope has been characterised by ToF and z -position resolution measurements using its individual components at the Stefan Meyer Institute in Vienna (Section 3.3.1.2). ASACUSA's experimental area at CERN is a much noisier environment and since the DAQ system is located outside the experimental area, the full detector setup involves longer cable lengths (≈ 10 m).

The ToF resolution measured in the lab yielded 494 ps and 551 ps (FWHM) for inner and outer bars, respectively. At this level of precision possible differences in cable lengths of the individual bar hodoscope channels need to be corrected for. The correction of cable lengths has been done using cosmic data taken over a week and the combined trigger condition of BGO and hodoscope. An additional cut of $E_{\text{BGO}} > 7$ MeV on the deposited energy in the BGO calorimeter has been applied.

The implemented procedure of calculating the corrections results in additive values for up- and downstream timestamps of all 64 bars. For every bar channel i , events with a hit on the currently considered bar and additionally a hit on the neighbouring channel j are selected e.g. $[i, j] = [0, 1]$. Constant fraction timestamps of up- and downstream SiPM signals of both channels, i and j , are saved. If two neighbouring channels show a signal in cosmic runs, it is very likely that they come from the same particle hitting both scintillating bars.

Firstly, mean times and time differences¹⁴ of bars i and j are calculated via:

$$m_k = \frac{1}{2}(t_{k,u} + t_{k,d})$$

$$d_k = \frac{1}{2}(t_{k,u} - t_{k,d})$$

where $k = \{i, j\}$, $i, j \in [0, \dots, 31]$ and $j = i + 1$. Firstly, corrections for mean times and for time differences are calculated, which can then be used to determine the corrections for up- and downstream timestamps.

Starting with the corrections on the mean times, histograms of the differences of the mean times $\Delta m_{ij} = m_i - m_j$ are created and fitted with Gaussian distributions yielding their means $\mu_m(ij)$. Assuming the cables of the two considered channels i and j have the same length, the distribution of

¹⁴The factor $\frac{1}{2}$ in the calculation of the time difference has been added because it simplifies the terms of the corrections.

Δm_{ij} should be centred around zero. Furthermore, in case of no cable length differences, summing up all $\mu_m(ij)$ for a layer should give zero. The reason for this is that due to the sum, both m_i and $-m_i$ are represented and their contributions cancel each other out. From this, a first overall time correction for each layer can be calculated and is subtracted from the $\mu_m(ij)$:

$$\tilde{\mu}_m(ij) = \mu_m(ij) - \frac{\sum \mu_m(ij)}{32} \quad (3.3)$$

Corrections c_{mk} for the mean times m_k for a layer are then calculated by:

$$c_{m0} = 0 \quad (3.4)$$

$$c_{m1} = c_0 + \tilde{\mu}_m(01) \quad (3.5)$$

$$c_{m2} = c_1 + \tilde{\mu}_m(12) \quad (3.6)$$

$$\dots \quad (3.7)$$

$$c_{mj} = \sum_{\substack{i,k \\ i < k; i \neq k}}^j \tilde{\mu}_m(ik) \quad (3.8)$$

The correction for one arbitrary channel (in this case channel 0) can be set to zero, since we are only interested in the relative cable length differences.

The same procedure is applied for time differences. Histograms of the differences of the time differences $d_{ij} = d_i - d_j$ are determined, and subsequently, their means $\mu_d(ij)$ are extracted from Gaussian fits and c_{dk} are calculated analogously to above.

Corrections for the up- and the downstream timestamps for a channel k are then determined by:

$$c_{k,u} = c_{mk} + c_{dk} \text{ (upstream)} \quad (3.9)$$

$$c_{k,d} = c_{mk} - c_{dk} \text{ (downstream)} \quad (3.10)$$

which are then finally added to the timestamps of bar k :

$$\tilde{t}_{k,u} = t_{k,u} + c_{k,u} \quad (3.11)$$

$$\tilde{t}_{k,d} = t_{k,u} + c_{k,d} \quad (3.12)$$

The cable length corrections were then tested by determining the distributions of mean times and z -positions of the individual channels using cosmic rays. Example distributions of four channels of the outer hodoscope layer comparing the z and mean time distributions with and without corrected timestamps are shown in Figure 3.19 and 3.20, respectively. Two of the

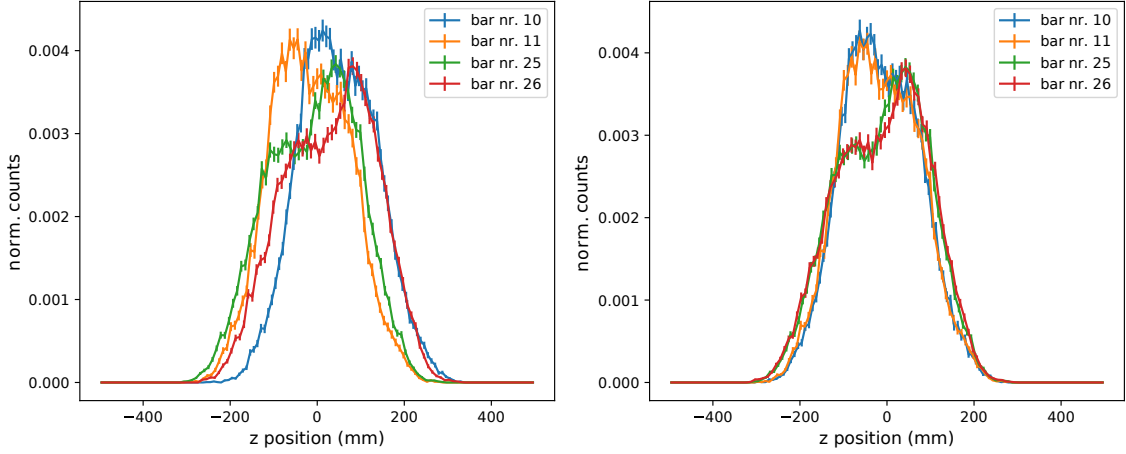


Figure 3.19.: Distributions without (left) and with (right) cable corrections of the hit position of cosmic rays in z -direction on four selected bars of the outer hodoscope. Bars 10 and 11 are situated on the very top panel of the hodoscope, bars 25 and 26 on the very bottom.

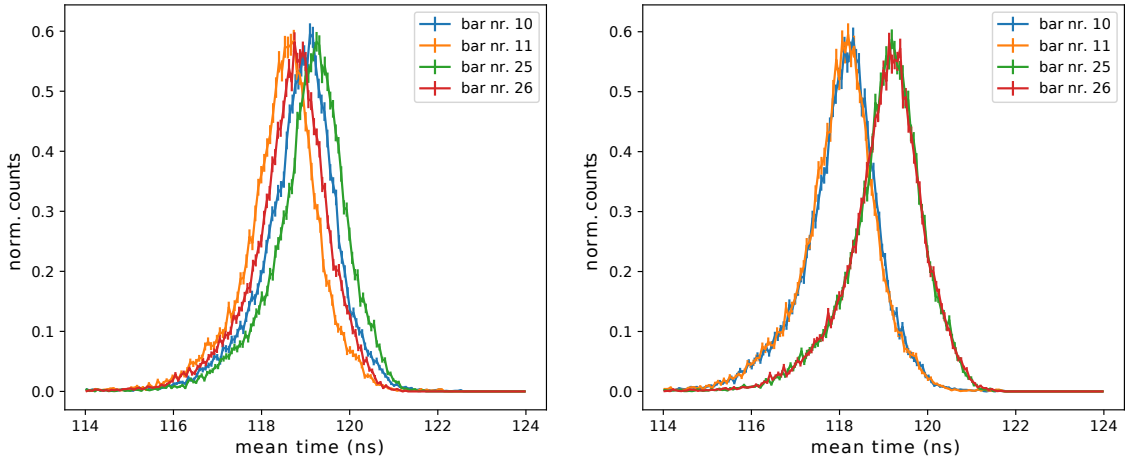


Figure 3.20.: Distributions without (left) and with (right) cable corrections of the mean times of cosmic rays of four selected bars of the outer hodoscope. Bars 10 and 11 are situated on the very top panel of the hodoscope, bars 25 and 26 on the very bottom.

selected channels (10 and 11) lie on the top panel of the hodoscope and the other two (25 and 26) on the very bottom panel. It can be seen that, after the cable length correction, the z -distributions lie nicely on top of each other and are centred around zero. Noticeably, there is a dip in the center of the distributions resulting in two asymmetric peaks, that will be discussed at the end of this section.

Comparing the distributions of the mean times for the four channels, one can see that after cable correction the histograms of bars on top of the hodoscope (blue and orange) overlay, as well as the ones of the bottom bars (green and red). The shift between bars on bottom and top is a result of

the cosmic particles hitting first the upper bars before traversing the lower scintillating bars. The latter have therefore higher mean times.

3.6.3. Mean time and z -position distributions

Figure 3.21 shows the total z -position distributions of the inner and outer layers. The presented data consists again of the above described recorded cosmic ray data triggering on both, BGO and hodoscope. It features the afore mentioned dip in the center which is especially visible for the outer layer, but washed out for the inner layer.

This has been investigated with simulations of cosmic events using Geant4 and the CRY library. The implemented geometry consists of the carbon-coated BGO crystal housed in a beampipe including its flange and both arrays of plastic scintillators of the bar hodoscope. The z -positions of cosmic particles hitting the hodoscope bars have been extracted. The resulting distributions for the inner and outer hodoscope can be seen in Figure 3.22 (top). The cut $E_{\text{BGO}} > 7$ MeV has been applied as well. Furthermore, the convolution of the histogram with a Gaussian distribution representing the detector z -resolution is shown in orange. The standard deviation of the Gaussian is $\sigma = 31$ mm for the outer and $\sigma = 25$ mm for the inner layer. For comparison, the distributions without a cut on E_{BGO} are shown in Figure 3.22 (bottom).

The dip in the z -position distribution in the measurements is a geometrical effect and stems from the requirement of a hit on the thin BGO disc. The effective area of the BGO that cosmic “see” is larger if they arrive with a slight angle to the vertical axis.

Simulated histograms without the energy cut on E_{BGO} show a flat distribution. Additionally, a slight asymmetry is observed in the measured distributions. For the outer hodoscope, the two peaks next to the dip show different heights. The asymmetry is especially visible in the distributions of the individual bars (Figure 3.19). Furthermore, the effect is antisymmetric for bars on top and in the bottom.

The above stated observations lead to the conclusion that the asymmetry is a consequence of a slight tilt of the hodoscope with respect to the BGO caused by the imprecise alignment of the detectors which has been done by eye and a spirit level. Another misalignment, namely a deviation of the BGO position from the center of the hodoscope, manifests itself in a slight shift of the distribution to negative positions, see also Table 3.2 which summarises

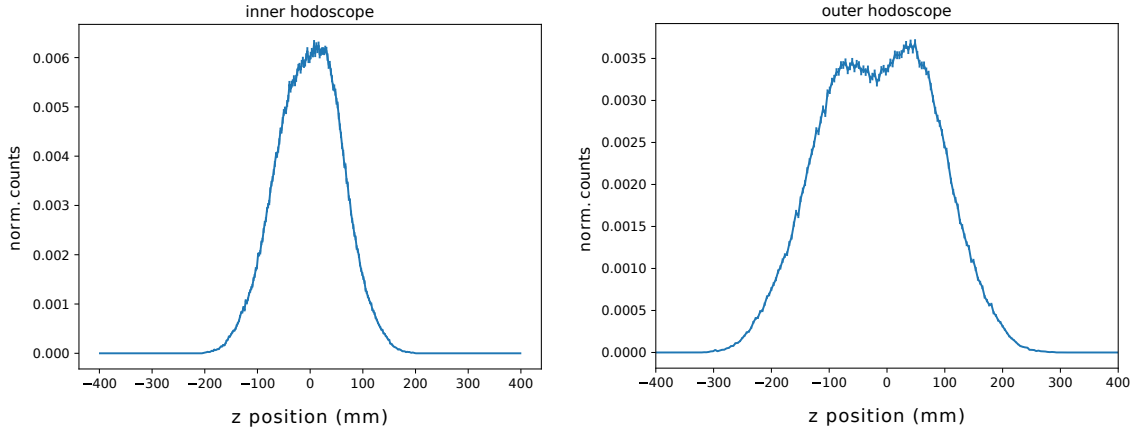


Figure 3.21.: Total distributions of the hit positions of cosmic rays in z -direction for the inner (left) and the outer (right) layer of the hodoscope.

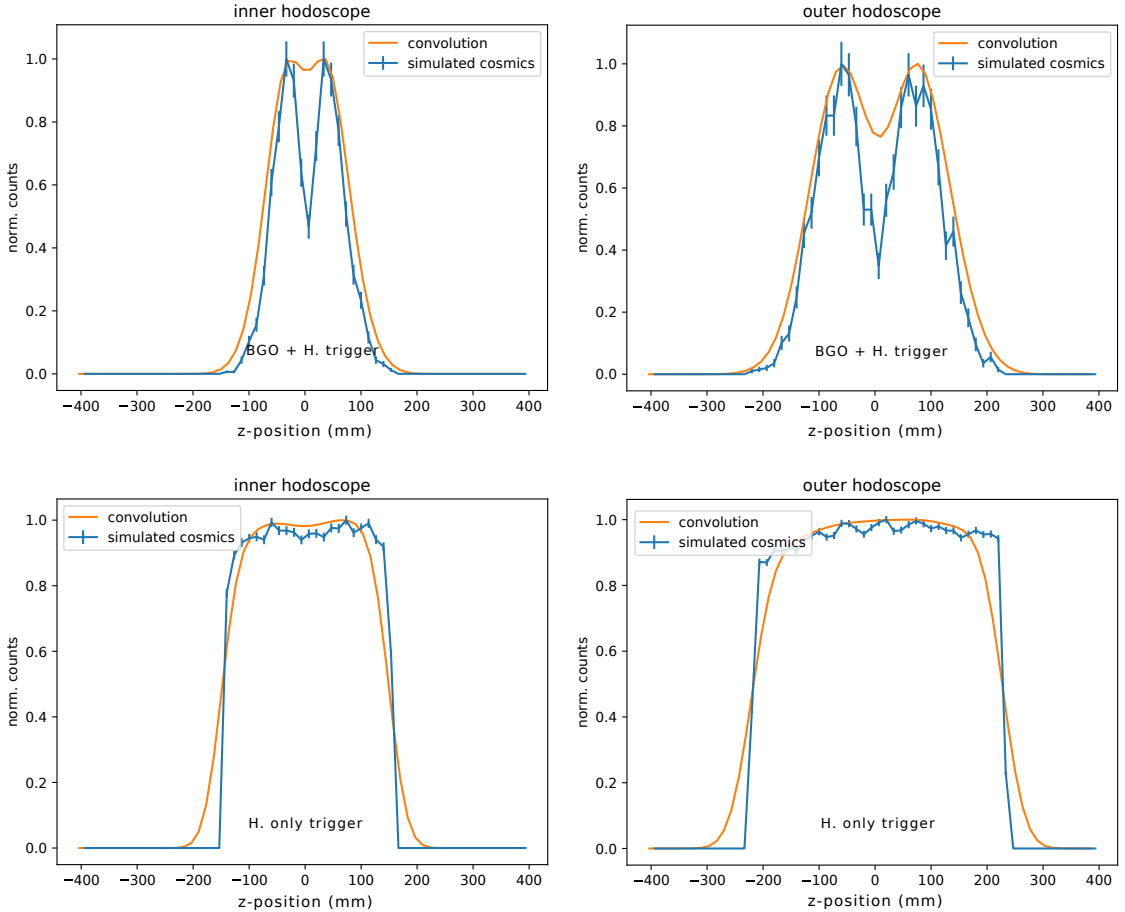


Figure 3.22.: Total distributions of the hit positions of simulated cosmic rays in the z -direction for the inner (left) and the outer (right) layer of the hodoscope. The histogram is shown in blue and the convolution with a Gaussian with $\sigma = 25$ mm for the inner and $\sigma = 31$ mm for the outer layer, in orange. *Top*: A cut on the deposited energy in the BGO calorimeter of $E_{\text{BGO}} > 7$ MeV has been applied. *Bottom*: No cut on the BGO energy deposit has been applied.

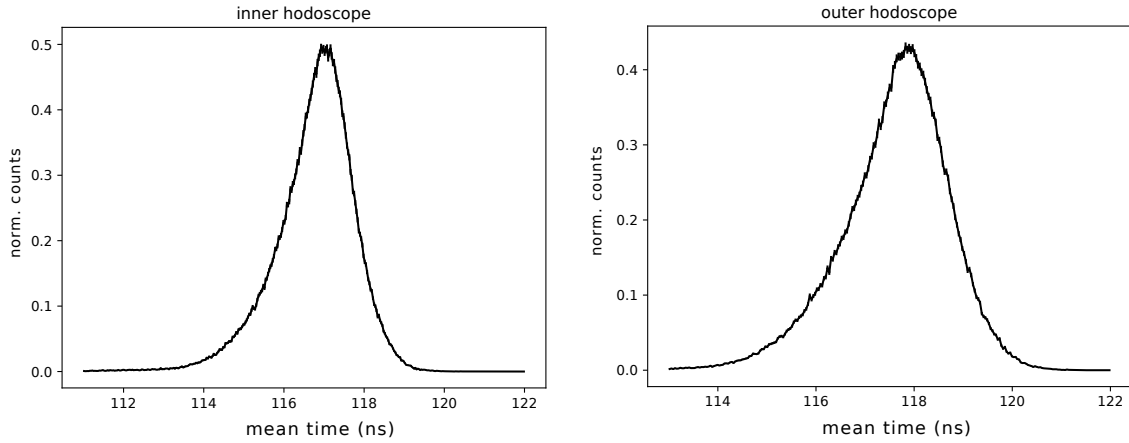


Figure 3.23.: Total distributions of the mean times of cosmic rays of the inner (left) and the outer (right) layers of the hodoscope.

mean time				
	mean (ns)	median (ns)	σ (ns)	skewness
inner layer	116.76	116.88	1.00	-0.122
outer layer	117.82	117.94	1.11	-0.109
z -position				
	mean (mm)	median (mm)	σ (mm)	skewness
inner layer	-1.8	-0.2	60.5	0.027
outer layer	-15.1	-13.3	97.0	0.018

Table 3.2.: Summary table of sample mean, median, standard deviation and skewness of measured mean time and z -position distributions of the inner and the outer hodoscope layer (Figures 3.23 and 3.21). The skewness was calculated via $(\text{median} - \text{mean})/\sigma$.

the sample statistics such as the mean.

The distributions of mean times of the inner and outer hodoscope layers exhibit a slight skew to smaller mean times, see Figure 3.23. This has already been observed in [84] and was accredited to a small contamination of the data, the source of it being uncertain. Table 3.2 lists the sample statistics of the mean time distributions.

The distributions are also used to place cuts on z -positions and mean times of events in order to further reduce noise hits. Hits that show values of m_k and d_k outside of $\mu \pm 3\sigma$ of the distributions are discarded and not considered for subsequent analyses.

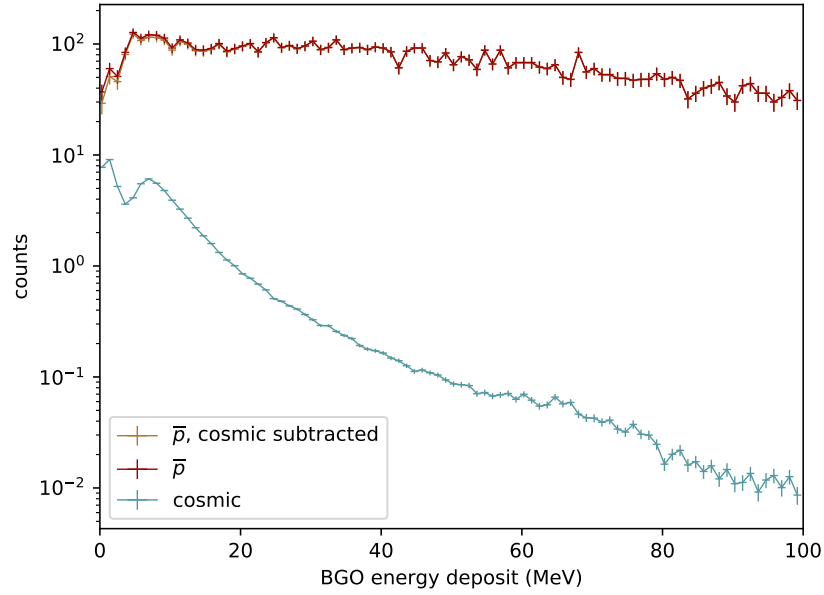


Figure 3.24.: Distributions of energy deposit in the BGO calorimeter for antiproton (red) and cosmic events (blue). The cosmic distribution has been scaled to the measuring time and the hit area of the antiprotons. Their difference (orange) is also shown.

3.6.4. Energy deposit and hit position on the BGO calorimeter

The deposited energy E_{BGO} in the central calorimeter is one of the most important event characteristics for distinguishing antiproton annihilations from cosmic rays. On average, the energy deposit of antiproton annihilations is higher than of cosmic events. Figure 3.24 shows the distributions of E_{BGO} for recorded cosmic (blue) and $\bar{p}$ (red) events. Both data sets were recorded with the trigger condition including BGO and hodoscope. Details of the antiproton extractions are explained in Section 2.8 of the previous chapter. The cosmic distribution is scaled to the measuring time and the hit area (discussed below) of the antiproton data. The difference between the two histograms is shown in orange.

The cosmic distribution features a peak at ≈ 7 MeV. The path length of cosmic particles is determined to be around 8 mm [83] on average and since the energy loss of a MIP (minimum ionising particle) in bismuth germanate is 9 MeV/cm [94], the peak in the cosmic distribution is accredited to MIPs.

Prior to the fibre upgrade and three-dimensional tracking, the hit position of particles on the central calorimeter has been determined using the two-

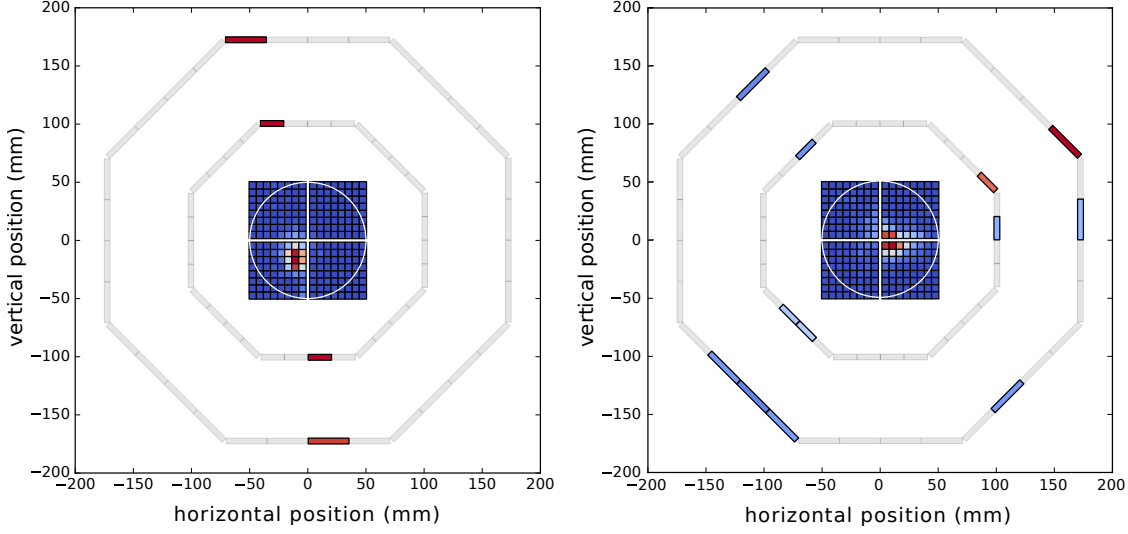


Figure 3.25.: Example two-dimensional read-out of events. *Left*: cosmic event passing straight through the detector. *Right*: antiproton annihilation of an antihydrogen event. The star pattern resulting from pions emerging from the annihilation point is faintly visible. The energy deposition is normalised and represented by ranging colours, from red (high) to blue (low). The white circle marks the position of the BGO crystal, the four pixel squares show the two-dimensional read-out of the MA-PMTs.

dimensional read-out of the BGO. Figure 3.25 shows the x - y plane of the detector of two example events, a cosmic particle passing straight through (left) and an antiproton annihilation (right). In the center of the plots, the position of the BGO crystal disc is indicated by a white circle. The charge distribution recorded by the MA-PMTs is shown by the four pixelated squares.

In order to determine the hit position on the BGO, a cluster finding algorithm has been employed. Firstly, the pixel with the highest energy $E_{\text{pixel}}^{\text{max}}$ deposit is found. Afterwards, the 16×16 pixel map containing the energy information is converted into a binary matrix, where pixels with $E_{\text{pixel}} > 0.5 E_{\text{pixel}}^{\text{max}}$ are represented with 1, others with 0. Clusters consisting of pixels that are horizontally, vertically and diagonally connected are then found with the Python image processing function `ndimage.label` that can be used to find and label connected regions in an image. The particle's hit position on the BGO is defined as the energy weighted mean center of the largest cluster.

Results of the described analysis can be seen in Figure 3.26. For cosmics (left plot), the distribution of hit positions is uniformly distributed over the area of the BGO. The circular shape of the BGO is nicely visible, as well as the blind “cross” where the four MA-PMTs meet.

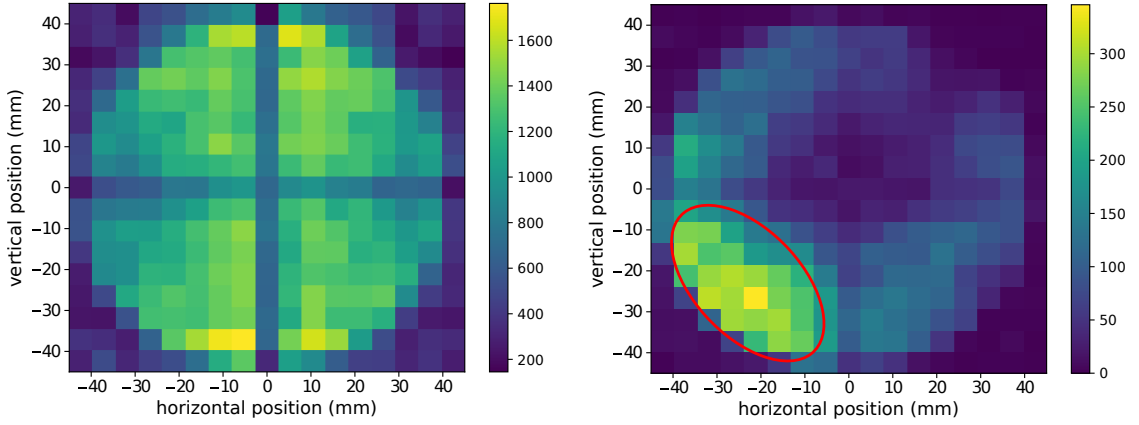


Figure 3.26.: Two-dimensional histograms of hit positions on the BGO determined via the cluster finding algorithm. The left plot shows the hit position distribution for cosmic events while the right plot shows results for the antiproton annihilation data.

The hit positions of antiproton events show a broad off-center distribution (right plot), indicating that the extracted antiprotons hit the BGO on the bottom side. The reason for this is most likely a possible misalignment between the double-CUSP trap with respect to the downstream beamline.

The red ellipse encloses the hit pattern of the extracted antiprotons and illustrates the cut for antiproton event selection to reduce the background contribution in the data sample.

3.6.5. Event multiplicites

Distributions of the number of bars with a hit for cosmic and antiproton events for inner (n_I) and outer (n_O) hodoscope layer are shown in Figure 3.27. Cosmic rays produce mostly events with two hits per layer, since they pass straight through the detector. Antiproton annihilations on the other hand typically show a higher number of bar hits. A better method for extracting the number of charged particles passing the hodoscope is achieved by a tracking algorithm.

Since the precision on the z -position of the bar hodoscope is not sufficient for three-dimensional tracking, the number of tracks N_{tracks} of an event is found using the two-dimensional information of the detector perpendicular to the beam axis.

The z -position information of the bar hodoscope is however used for finding clusters in the hodoscope stemming from the same particle. If neighbouring bars are hit and their z -positions are close, than they are regarded as belonging

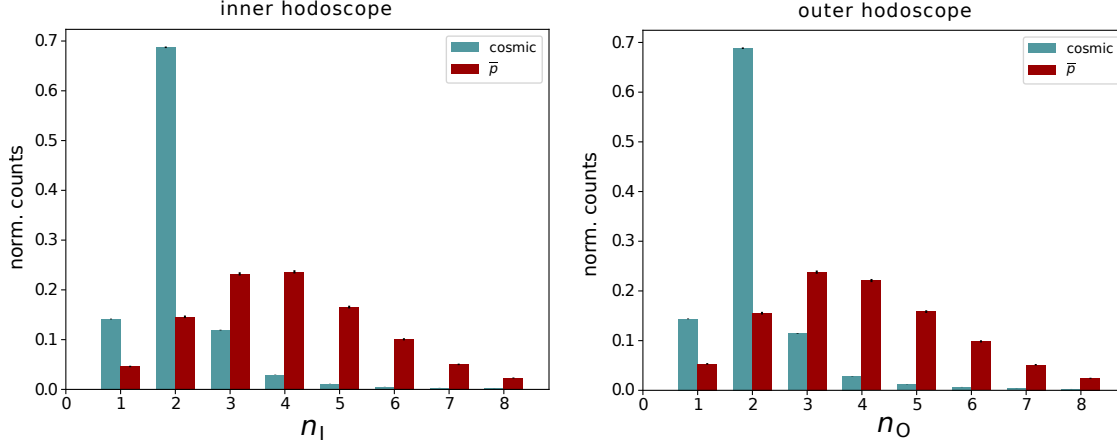


Figure 3.27.: Number of bar hits for cosmic (blue) and antiproton (red) events for the inner (left) and the outer (right) hodoscope layer.

to the same track. This is done by checking whether their z -positions show an overlap considering $\pm 2\sigma$. Secluded hits are excluded from the track finding algorithm e.g. a hit in the outer layer and no hit in the inner layer close by. This is implemented by checking whether the interval $[ch_j - 2, ch_j + 2]$ with ch_j being the channel number of layer j has a overlap with the list of channels of the other layer.

In this analysis a track is defined as having its origin in the BGO and passing both layers of hodoscope once. Firstly, the hit position on the BGO is determined by finding the largest cluster in the BGO pixel map, as described in Section 3.6.4. Tracks are afterwards found by rotating straight lines about pivot points drawn uniformly from the (x, y) distribution of the found cluster. The process is depicted in Figure 3.28. The total number of pivot point n_{tot} used is proportional to the number of pixels in the cluster to ensure good coverage.

For every rotation step, hodoscope bars lying on the current line are saved in a collection of track candidates. Additionally, for every possible track candidate (= combination of inner and outer bars), the compatible number of lines n_{lines} out of n_{tot} is stored.

Afterwards, the found track candidates are sorted in descending order by $n_{\text{lines}}/n_{\text{tot}}$. Track candidates with the highest ratio are then selected and all other candidates which include bar hits of tracks already accepted are removed from the track collection.

The number of tracks for cosmic and antiproton events can be seen in Figure 3.29. Since tracks determined by the described algorithm are defined as originating from the BGO and passing each hodoscope layer once, most cosmic events show two tracks. For antiproton events, the expected average of 3

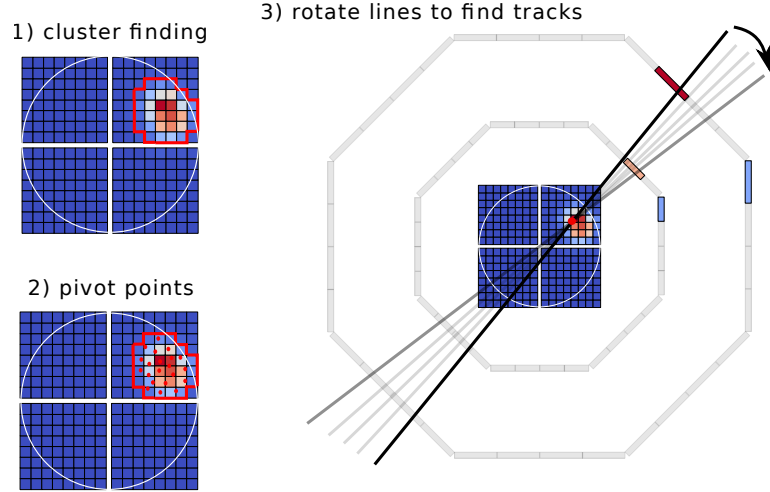


Figure 3.28.: Sketch of the two-dimensional track finding process. 1) cluster in the BGO pixel map are found. 2) pivot points are drawn from the area covered by the MA-PMT pixel of the found cluster. 3) straight lines are rotated about those points.

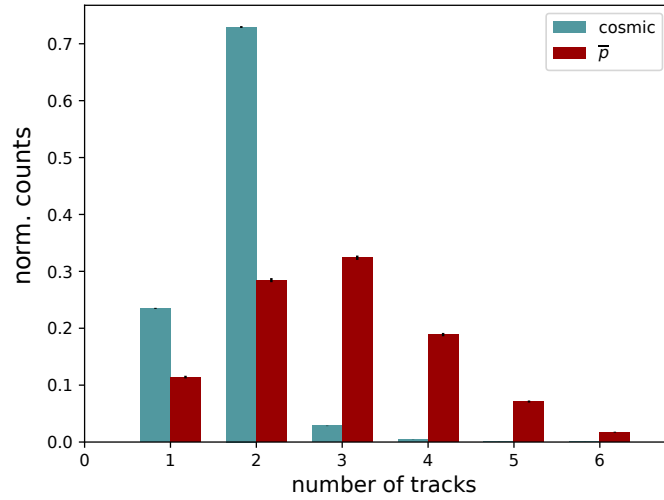


Figure 3.29.: Histograms of number of tracks for cosmic (blue) and antiproton (red) events for the inner (left) and the outer (right) hodoscope layer determined by the two-dimensional tracking algorithm.

secondaries from the branching ratios from the previous section is reproduced by the distribution.

3.6.6. Time of flight

It is recalled, that the time information gained from the tracking detector are the afore discussed constant fraction timestamps of the up- and downstream

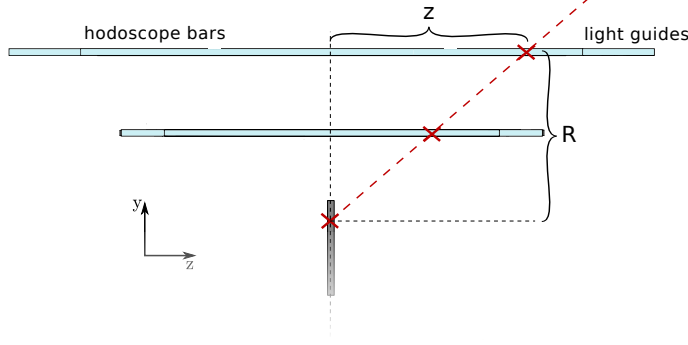


Figure 3.30.: Sketch illustrating the correction of $m_{k,n}$. The hodoscope bars are drawn in light blue and the BGO crystal in dark grey. The red dashed line symbolises a track, R the radial distance of the hit on the bar to the hit on the BGO and z the distance of the hit on the bar to the center of the bar.

SiPMs. The time of the hit on a scintillating bar k is determined by calculating the mean time m_k of the up- and downstream timestamps via $m_k = \frac{1}{2}(t_{k,u} + t_{k,d})$. Section 3.3.1.2 discusses the measurements for determining the time-of-flight resolution of the hodoscope components. A setup consisting of only two bars was used. The time-of-flight has been calculated as the mean time difference Δm of particles traversing both bars.

In the fully assembled hodoscope, an event will consist of several hits in both layers stemming from either a cosmic particle or secondaries from an antiproton annihilation. A method needs to be applied in order to calculate a measure for the time-of-flight for events in the detector.

For every track n of N_{tracks} total tracks of the regarded event, the mean times m_k of all bars are corrected via:

$$m'_k = m_k - \sqrt{R_k^2 + z_k^2}/c, \quad k \in [\text{bars of track } n] \quad (3.13)$$

using the distance from the vertex to the center of the bar R_k and the distance z_k from the hit position in z -direction to the center of the bar¹⁵. c is the speed of light. Figure 3.30 illustrates this. In case a cluster has been found in the hodoscope (a particle hitting more than one bar) and is part of track n , the average of all bars belonging to the cluster is calculated for inner and outer layer respectively:

$$m_{I,n} = \frac{1}{n_{I,n}} \sum_k^{n_{I,n}} m_k \quad (3.14)$$

$$m_{O,n} = \frac{1}{n_{O,n}} \sum_k^{n_{O,n}} m_k \quad (3.15)$$

¹⁵(0,0,0) is defined as the BGO center.

where $n_{I,n}$ are the bars of the inner layer belonging to track n and $n_{O,n}$ the bars of the outer layer. Previously, the time-of-flight calculations have been done for the inner and the outer layer separately. Since the two-dimensional tracking algorithm supplies the information of which inner hits belong to which outer hits, the time informations can be combined. Therefore, the average of inner and outer mean times belonging to the track is calculated:

$$t_n = \frac{1}{2}(m_{I,n} + m_{O,n}) \quad (3.16)$$

One possible method of calculating the ToF of the events can be achieved by finding the smallest and the largest t_n of the event, $t_{\min}$ and $t_{\max}$, respectively, and calculating the difference:

$$ToF_{\min\max} = t_{\max} - t_{\min} \quad (3.17)$$

Since annihilation events originate from inside the detector and their secondaries should reach the hodoscope at approximately the same time, their ToF is considerably smaller compared to cosmic particles that pass the detector from outside. The resulting normalised distributions for cosmic and antiproton events can be seen in Figure 3.31 (right). They are fitted by Gaussian distributions (black, solid lines) and the resulting μ and σ are listed in boxes in the upper right corner of the plot.

Only cosmic and antiproton events with $N_{\text{tracks}} > 1$ are included. A time interval cut has been applied to the antiproton data, since they arrive during extractions in a time window of a few seconds, see Section 2.8. Additionally, a cut on the deposited energy in the BGO of $E_{\text{BGO}} > 20$ MeV has been applied to the antiproton data, and a cut of $E_{\text{BGO}} > 7$ MeV to the cosmic data.

Another method calculates first the mean of all t_n , $\bar{t}$, then the time-of-flight by:

$$ToF_{\text{std}} = \sqrt{\frac{1}{N_{\text{tracks}} - 1} \sum_{n=1}^{N_{\text{tracks}}} (t_n - \bar{t})^2} \quad (3.18)$$

The time-of-flight distributions determined via ToF_{std} are shown in Figure 3.31 (left), the coloured histograms show the ToF_{std} for cosmic (blue) and antiproton (red) events, respectively. They are normalised to their area and fitted with Gaussian distributions (black, solid lines). The resulting mean μ and σ are again listed in the boxes in the upper right corner of Figure 3.31.

The two methods, $ToF_{\min\max}$ and ToF_{std} , have been compared by calculating the area of overlap of the cosmic and antiproton distributions. The

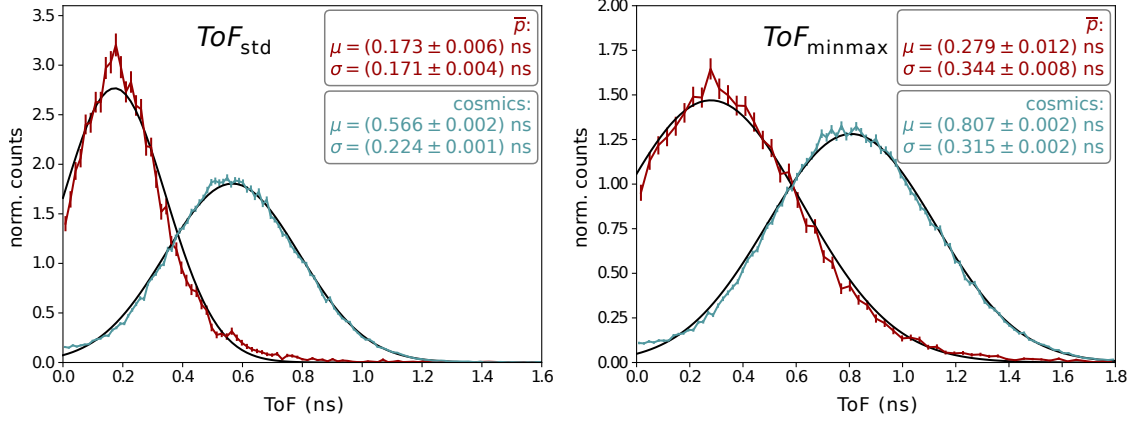


Figure 3.31.: *Left:* Time-of-flight distributions calculated via ToF_{std} (see equation 3.18). *Right:* Time-of-flight distributions calculated via ToF_{minmax} (see equation 3.17). Blue histograms show the distributions of cosmic and red histograms of antiproton events. Black lines show Gaussian fits, the resulting mean μ and σ are listed in the boxes in the upper right corner. All histograms are normalised to their area.

overlap of the ToF_{std} distributions amounted to 0.328 which is smaller by a factor of 0.71 compared to the ToF_{minmax} method which yielded an overlap area of 0.462. The former has therefore been chosen as an estimate for the time-of-flight of an event since it results in a better separation of cosmic and antiproton events. It is used as one of the event characteristics fed into the machine learning analysis discussed in the next chapter.

4. Event identification using machine learning

This chapter discusses the classification of recorded events, the foundation of an analysis for counting experiments. The aim is to efficiently categorise events observed by the ASACUSA antihydrogen detector into either signal and background events i.e. antiproton annihilations of antihydrogen atoms or any other events. This is crucial since the number of produced antihydrogen atoms is small and the number reaching the detector even smaller.

In order to carry out this task, a data-driven supervised machine learning analysis has been developed, evaluated and employed. An analysis based on gradient-boosted decision trees is discussed which has been used for the analysis of the measurement of the principal quantum number distribution of the produced antihydrogen atoms. At the end of the chapter, an alternative analysis utilising a profoundly different approach called anomaly detection is described. Results of both analyses are discussed and compared in the next chapter (Chapter 5).

Previously, a cut-based analysis was employed by ASACUSA for event identification [43]. This sequential and separate application of rectangular cuts on different characteristics of the event e.g. energy deposit in the BGO calorimeter, treat those characteristics (called *features* in the machine learning jargon) independently and disregard correlations. On the contrary, multivariate classification methods exploit the multi-dimensional feature space. Furthermore, instead of appointing an event to a single class, it is usually possible to assign a measure of probability of belonging to a class.

In supervised learning a so-called training data set is chosen, containing a balanced mixture of signal and background events the classes of which are known. The algorithm learns from this data what signal and background events look like. The common approach of training with simulation data has been discarded since none of the comparisons made between data and available annihilation simulation models showed satisfying agreement. For example, previous studies [95, 96] at the AD have found deviations of the multiplicity and energy distribution predicted by the Geant4 physics models and recorded antiproton annihilations at rest.

Since the $\bar{p}$ annihilation signature in the ASACUSA detector is identical to the one of antihydrogen atoms and the available number of antihydrogen events is small, the recorded annihilations during antiproton extractions to

the detector described in Section 2.8 are used as signal sample of the training data set.

The background is dominated by cosmic rays, other possible, much rarer sources are pions from upstream annihilations and annihilations in the direct vicinity of the detector. The background data used for this analysis was acquired during ASACUSA beam-off periods i.e. no antiprotons or positrons in the traps, and will be addressed as “cosmic background” in the following. Upstream annihilations and annihilations on the beampipe close to the detector are not included in the background sample. Due to the poor position resolution of the bar hodoscope discussed in Section 3.3.1.2, it is only possible to identify this events with the hodoscope fibre upgrade which was not yet installed during the measurement period of the data discussed in this chapter. Table 4.1 summarises the background contributions for the antihydrogen detector.

Furthermore, those events share basically all characteristics with annihilations on the detector apart from the vertex. Therefore, it is more efficient to employ a two step procedure and determine the vertex of events after they have been selected by a machine learning analysis.

Background contribution	acquisition procedure	before fibre upgrade (this chapter, 2016)	with fibre upgrade (2017 –)
cosmic rays	easy to record	–	–
upstream annihilations	mixed into $\bar{p}$ and $\bar{H}$ measurements	cannot be distinguished, no information on z -position of annihilation	can be distinguished with 3D tracking and vertex

Table 4.1.: Summary of background contributions for the antihydrogen detector before and after the fibre upgrade.

4.1. General remarks and strategy of supervised learning

The purpose of this section is to explain the general set-up of a supervised machine learning analysis and to introduce the used terminology.

In machine learning, the features of an event i are usually summarised to a feature vector $\vec{x}_i$ with d entries. Events are then combined to a data set $X \in \mathbb{R}^{N \times d}$ where N is the total number of events. Analogously, their corresponding class labels y_i which can be 0 (background) or 1 (signal), will be summarised to a target vector Y . The aim is to learn the underlying, unknown function that maps the known information about the data, quantified in X ,

to their corresponding classes Y :

$$f(\vec{x}_i) = y_i, \forall i = 1 \dots N \quad (4.1)$$

$$f(X) = Y \quad (4.2)$$

where f denotes the predicting function of interest. In supervised machine learning a training data set (X_t, Y_t) containing labelled signal and background events is used to infer f which can then be used to predict the class of new, unseen data. Therefore, it is essential that the algorithm generalises well from the X_t to new data e.g. in this case from recorded antiproton annihilations and cosmic events to data taken during mixing runs. Ultimately, a model is desired which minimises the *true expected risk*. The expected risk of a classifying function f is defined by [97]:

$$R(f) = \int (f(x) - \hat{f}(x))^2 p(x, y) dy dx \quad (4.3)$$

where $f(x)$ corresponds to the model prediction of x , and $\hat{f}(x)$ denotes the true outcome. $p(x, y)$ is the probability density function of x and y . Since $p(x, y)$ is usually unknown and so is therefore also the true expected risk, one has to rely on the *empirical risk* which is an estimation of the true risk based on our training sample [97]:

$$R_e(f) = \frac{1}{N} \sum_{i=1}^N (f(x_i) - y_i)^2 \quad (4.4)$$

Table 4.2 summarises the terms used in the following.

Generally, the strategy for solving a classification problem via supervised machine learning requires the following steps: (1) define the data set X , (2) choose an evaluation metric, (3) choose a model, (4) choose features, (5) hyper-parameter tuning, (6) training and evaluation. The steps are discussed below to give the reader an overview, and are described in more detail and in light of the present problem of antihydrogen event identification in the next sections.

1. Define the data set X and the corresponding Y vector. This is then split into a training (X_t, Y_t) , a validation set (X_v, Y_v) and a test set $(X_{\text{test}}, Y_{\text{test}})$. The algorithm learns from the training set. During training, the performance is monitored with the validation test. Afterwards, the algorithm is tested using $(X_{\text{test}}, Y_{\text{test}})$ which contains events the algorithm has not seen before.

	description
Dimension N of the data	total number of events used (training, validation and test set)
Dimension d of an event	number of used features of an event
Feature of an event	property of an event (e.g. number of tracks, $ToF...$)
Input data set X	$N \times d$ matrix containing all events and features
Target/class vector Y	$N \times 1$ vector containing the classes of the data set X
$\vec{x}_i$	input data vector of event i
y_i	target value of event i
$\hat{y}_i$	predicted target value of instance i
Training set (X_t, Y_t)	entries of X and Y used for training the algorithm
Validation set (X_v, Y_v)	entries of X and Y used for validation during training
Test set $(X_{\text{test}}, Y_{\text{test}})$	entries of X and Y used for testing the trained algorithm
Signal/antiproton data set X_i^1	entries of X with class 1
Background/cosmic data set X_i^0	entries of X with class 0
$(X_m, ?)$	mixing data set with unknown class vector
$(X_m^q, ?)$	mixing data set of the runs dedicated to the quantum state distribution measurement
H	set of model specific hyper-parameter (see Section 4.3.3)
f	predicting function

Table 4.2.: List of terms and their explanation/definition used in this chapter.

2. Furthermore, a performance measure needs to be chosen. A common metric for classification problems is the ROC (Receiver Operator Characteristics) curve and the A_{ROC} (ROC area under curve). The ROC curve shows the background rejection as a function of the signal efficiency and the A_{ROC} is simply the area under this curve. An example can be seen in Figure 4.1. The dashed diagonal line shows the ROC curve for a random guessing algorithm (A_{ROC} is 0.5). Points above the diagonal represent good classification results (better than random), points below the line represent poor results (worse than random). A perfect classifier would yield the point (1, 1) and a A_{ROC} of 1.
3. The choice of the underlying model depends on the size N and dimension d of the data set X , but also on other properties of the data such as the type of input features e.g. continuous or discrete data or whether the a feature includes missing values. This is further discussed in Section 4.3.1.
4. When using a finite set of training data, the choice of the number of dimensionality d of the data becomes important. Every event can be seen as a point in a d dimensional feature space and the more features are considered, the more sparse the available data becomes. This is known as the curse of dimensionality [98]. Since the amount of antiproton events is limited, the number of and also choice of features should be studied. Therefore, feature selection has been performed and

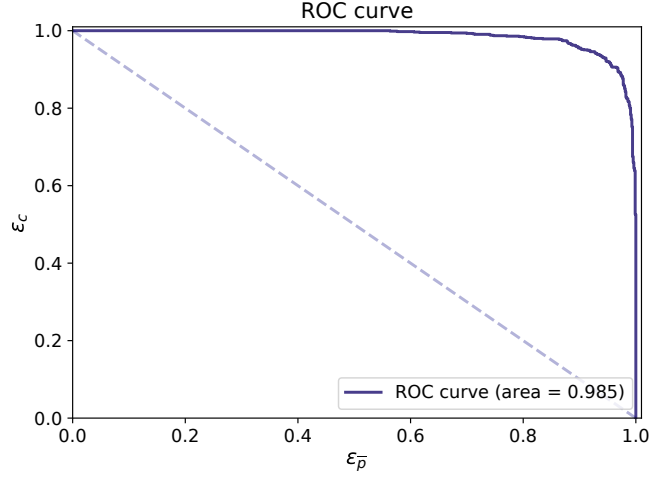


Figure 4.1.: Example of a ROC curve (dark blue). $\varepsilon_{\bar{p}}$ denotes the signal efficiency, ε_c the background rejection. The grey, dashed line shows the ROC curve for a random guessing algorithm (A_{ROC} is 0.5). The ROC curve resulted from one of the training and testing rounds of the gradient-boosted decision trees ensemble discussed below in Section 4.3.4.

is described in Section 4.3.2.

5. The hyperparameters H of the model need to be optimised, see Section 4.3.3. Hyper-parameters define the architecture of the model and need to be set prior to training.
6. Training and testing of the model, see Section 4.3.1.2. For every event, the algorithm returns a so-called prediction score, a value between zero and one, indicating whether the event is more signal-like (closer to one) or more background-like (closer to zero). A cut-off value on the score needs to be set to classify events. This determines cosmic rejection and antiproton efficiency which, by setting this cut, both can be made arbitrarily large in expense of the other becoming small. Details will be discussed in Sections 4.3.4 and 5.1.
7. Finally the model is used to predict the class of unknown instances, such as events recorded during mixing runs, denoted in the following as $(X_m, ?)$ with Y_m denoted as $?$ since the class of the events is unknown. Results of the data set from the runs dedicated to the quantum state distribution measurement, $(X_m^q, ?)$, are discussed in the next chapter, in Section 5.1 to Section 5.4.

4.2. Data selection and preparation

4.2.1. Cosmic and antiproton data

Recorded cosmic particle data during beam-off periods and the recorded annihilations of antiproton extraction described in Section 2.8 are used for training and testing the algorithm. Note again, that the scintillating fibre detector upgrade was installed in 2017 and the data studied in this chapter has been recorded during beamtime 2016. The trigger condition for both data sets was a hit on the BGO and at least one hit in both hodoscope layers (see Section 3.4.1 for more information on triggering).

Due to the possible impurity of the recorded “signal” data, residual background events are reduced with careful cuts on the recorded antiproton data. The following cuts were applied: (1) cut on the arrival time of events since antiprotons arrive during extractions in a time window of ≈ 4 s, (2) events with several separated hits on the BGO are removed due to the possibility of being upstream annihilations and (3) a cut on the hit position on the BGO. Cut (3) is necessary due to the broad off-center hit distribution of the antiprotons on the central detector, see Figure 3.26 (right) in Section 3.6.4 of the previous chapter. Thus, contributions from cosmics and pions from upstream annihilation are reduced.

It is important to emphasise, that no cuts have been made on event features that will later be used in the machine learning procedure.

cosmic events N_{tot}^c (background sample)	282935
antiproton events $N_{\text{tot}}^{\bar{p}}$ (signal sample, after cuts)	6481
estimated cosmics in signal sample n_{est}^c (percentage of $N_{\text{tot}}^{\bar{p}}$)	24 (0.37%)

Table 4.3.: Number of events of signal and background samples.

The number of events after the cuts are listed in Table 4.3. No cuts have been applied on the cosmic background sample. The total recorded time for cosmics is 603659 s (cosmic rate $f_{\text{cosmic}} = 0.4687$ Hz) and for antiprotons $t_{\bar{p}} = 372$ s (4 s $\times$ 93 runs). The estimated residual cosmic events left in the antiproton data after cuts are also listed, these are normalised to the recorded time $t_{\bar{p}}$ and hit area A_{hit} considered i.e. $n_{\text{est}}^c = f_{\text{cosmic}} t_{\bar{p}} \frac{A_{\text{hit}}}{A_{\text{BGO}}}$ with the area of the BGO A_{BGO} .

4.2.2. Imbalanced data

Comparing event numbers in Table 4.3, it is noticeable that there are much more cosmic events than antiproton events – this is of course due to the fact that shifts used for recording antiprotons are limited and cosmics come “for free”.

When classes are not equally represented in a data set, it is called imbalanced. This can lead to a biased analysis model. It can be understood with the following example: assume an imbalanced data set consisting of 90% events of class 1 and only 10% of class 2 is used to train an algorithm. The trained algorithm might report an accuracy of 90% (90% of the events have been correctly classified) but this is simply because the model decided that a high accuracy can be achieved by predicting class 1 for every instance.

There are several methods to combat this problem, such as e.g. under- and oversampling. In random under-sampling for example, instances of the class with higher abundance are randomly selected until their number equals the number of the less frequent class. In one of the over-sampling approaches, synthetic data points are created to restore class balance.

In order to overcome the class imbalance of the training data set at hand, a combination of under- and over-sampling has been employed. Firstly, the cosmic data set is randomly under-sampled to 40% of its original size. Afterwards, the antiproton training data is over-sampled using an algorithm called SMOTE (synthetic minority oversampling technique) [99] implemented in the python package `imbalanced-learn` [100].

Shortly, the idea of SMOTE is the following: for an event s_i with m features of a data sample, consider its k nearest neighbours who also belong to the same class in the m dimensional feature space. One of the k neighbours is chosen randomly, then the m dimensional vector between s_i and the neighbour is multiplied by a random number $x \in (0, 1)$ to create a synthetic data point.

Note, that this method of creating synthetic events is only used on the training data sample, NOT the test data sample. The test sample stays untouched and the results such as background rejection etc. discussed in the next sections result from presenting only the test sample to the trained algorithm.

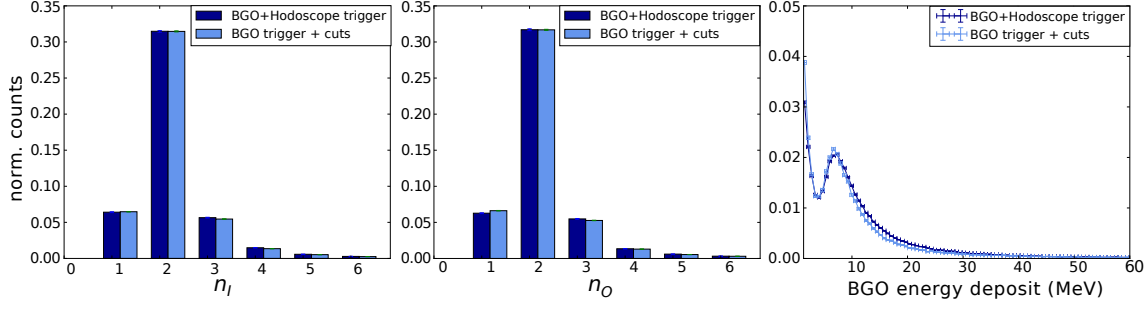


Figure 4.2.: Comparison of distributions with BGO+hodoscope trigger (dark blue) and distributions with BGO trigger and software cuts applied (light blue). *Left*: histogram of the number of hits in the inner hodoscope layer. *Middle*: histogram of the number of hits in the outer hodoscope layer. *Right*: BGO energy deposit distribution. All histograms are normalised to the acquisition time. Error bars show the Poisson error.

4.2.3. Antihydrogen data preparation

As mentioned in the previous section, signal and background data sets used for training and testing were recorded with a trigger condition of a hit on the BGO and as well as a hit in both hodoscope layers.

However, during mixing runs the hodoscope has been removed from the trigger. Therefore the trigger condition was applied to the antihydrogen data by software afterwards in order to avoid feeding the trained algorithm data with distributions different from the train and test data.

As discussed in Section 3.4.1, the hardware hodoscope trigger is generated by an FPGA. Digital signals created by the pre-amplifier boards are fed into the FPGA which is programmed to send a trigger signal if one of the inner and one of the outer bars shows a digital signal from the up- as well as from the downstream SiPMs.

Cosmic data of a few days recorded with BGO trigger only has been studied under cuts on the signal amplitudes recorded by the waveform digitisers. Cuts on the amplitudes of up- and downstream signals of both layers have been scanned in order to find the appropriate threshold values to artificially mimic the additional hodoscope trigger. In total 250165 events in 192388 seconds have been used. Afterwards the resulting distributions and rate have been compared to data containing a few days of cosmic runs with BGO and hodoscope trigger (the same data as used for training and testing, described in Section 4.2.1). The amplitude¹ (A) cut has been scanned in the range of [0.15 MeV, 0.19 MeV] with a step size of 0.001 MeV.

¹Energy calibration of the hodoscope channels was carried out in the course of A. Capons Master thesis, see [85] for more information.

With cuts of $A > 0.169$ MeV and $A > 0.177$ MeV for the inner and outer layer, respectively, the rate of 0.468700 cosmons per second is closest reproduced with a value of 0.468725 (difference $\approx 2 \times 10^{-4}$). Figure 4.2 shows a comparison of distributions of events recorded under the trigger condition BGO+hodoscope (dark blue) with events under BGO only trigger and software cuts applied afterwards (light blue). Histograms of the number of hits in inner and outer layer and the distribution of BGO energy deposit are displayed and normalised to the acquisition time. They are in very good agreement.

In the following, the discussed trigger cuts are applied on the mixing data set before analysis by the trained machine learning models.

4.2.4. Event features

As stated previously, discriminating observables of an event, the so-called features, are summarised to a feature vector. The potential input features for the analysis are: (1) BGO energy deposit E_{BGO} , (2,3) number of hits in the inner and outer hodoscope (n_{I} and n_{O}), (4) number of tracks N_{tracks} , (5) time-of-flight ToF , (6) mean of all angles of tracks with the vertical axis α_{Y} , (7,8,9) maximum of all angles between tracks α_{max} and the second and third largest angle (α_2 and α_3), (10,11,12) the number of horizontal tracks and tracks in the upper and lower hodoscope halves N_{h} , N_{u} , N_{d} respectively.

(6) can only be determined with $N_{\text{tracks}} > 0$, (5) and (7) can only be calculated for events with $N_{\text{tracks}} > 1$ and (8,9) are only available for $N_{\text{tracks}} > 2$. Therefore not all entries of the feature vector are filled in those cases. Later on in this chapter it is explained how those so-called *missing values* are treated. The features are discussed in more detail below.

(1) BGO energy deposit Sum of energies of all MA-PMT channels. Antiproton annihilation events have on average a higher energy deposit than cosmic events, see again Figure 3.24.

(2,3) Inner and outer hodoscope hits (n_{I} and n_{O}) Number of bars with a hit in the inner layer and the outer layer of hodoscope. Coincidence of up and downstream SiPM is required. Also, only hits falling within 3σ of the meantime and z-position distributions of inner/outer hodoscope count as hits (Section 3.6.3). The majority of cosmic events will pass the detector on a straight track, resulting into mostly two hits in inner and outer hodoscope

layer, while antiproton annihilations have mostly higher multiplicities, see Section 3.27 for histograms of n_I and n_O .

(4) Number of tracks N_{tracks} is found using the 2D information of the detector perpendicular to the beam axis, see Section 3.6.5 and Figure 3.29 for a histogram of the number of tracks.

(5) Time of flight (ToF) Since annihilation events originate from inside the detector and their secondaries should reach the hodoscope at approximately the same time, their ToF is considerably smaller compared to cosmic particles that pass the detector from outside. Distributions are shown in Figure 3.31 of the previous chapter.

(6,7,8,9) Angles The angle between two 2D tracks is defined as the angle between the connecting lines between hit position on the BGO and the midpoint of the outer hodoscope bars of a track. Angles take values between 0° and 180° . Cosmic events have a maximum angle between tracks of around 180° , while the distribution for antiprotons is much broader, see Figure 4.3 (left). Furthermore, the majority of cosmic rays enters the detector from above, explaining the use of the mean of angles with respect to the horizontal axis, α_Y , see Figure 4.3 (right).

(10,11,12) Number of horizontal and vertical tracks A track is classified as being horizontal, if its angle with the y -axis is larger than 70° i.e. hitting the vertical panels of the hodoscope. All other tracks will be grouped into N_u and N_d , depending whether they pass the bottom or lower part of the hodoscope.

Using all listed features might not result in the best classifier. The feature selection process is described in Section 4.3.2.

4.3. Supervised machine learning with measured data

4.3.1. Model selection – Gradient-boosted decision trees

The choice of the classifier for a given classification problem depends very much on the given task and the available data i.e. its size and quality. The un-

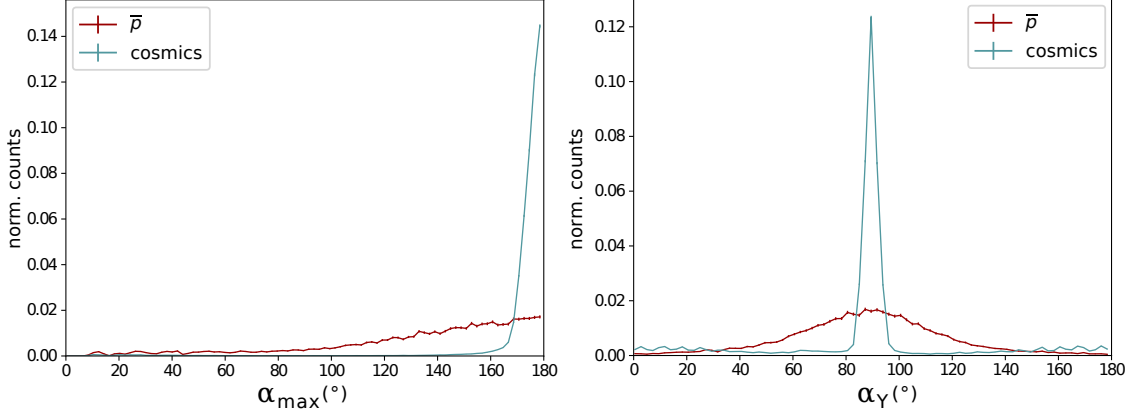


Figure 4.3.: *Left*: distribution of the maximum angle between tracks $\alpha_{\max}$. *Right*: distribution of α_{γ} . Blue histograms show cosmic data and red histograms antiproton data.

derlying algorithm selected for this analysis is gradient-boosted decision trees (GBDT) and the implementation used is the python library of **XGBoost** [101]. The following list summarises the reasons for choosing GBDT over other machine learning algorithms such as neural networks [102–104]:

- Due to the simple nature of their building blocks, the advantage of algorithms based on decision trees is that they are easy to use and interpret compared to e.g. neural networks.
- Tree ensembles perform in general better for smaller data sets than neural networks. This is crucial for the classification problem at hand, since the number of antiproton events is small.
- Algorithms using GBDT do not require a lot of data preprocessing i.e. they can deal with continuous, discrete and categorical data without any initial rescaling as it is the case for many other algorithms. This applies to the analysis at hand, since the events have continuous features such as the BGO energy deposit and discrete features such as the number of tracks, all with different value ranges.
- GBDT can deal naturally with missing values. A missing value can occur if a certain quantity i.e. an entry in an event’s input vector $\vec{x}_i$ could not be calculated or measured. An example would be the angle between tracks for events with only one track. For more details, see Section 4.3.1.2.
- GBDT are robust to outliers in the input data. This makes GBDT preferable for the classification task at hand considering that measured data is used for training and testing.
- The selection procedure of the features of the input data is not as critical

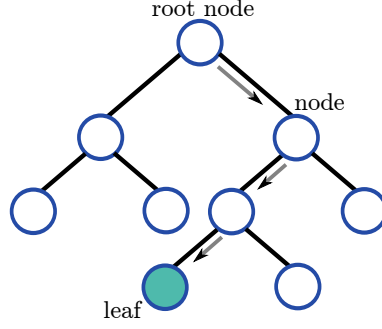


Figure 4.4.: Illustration of a binary decision tree.

as for e.g. neural nets. GBDT perform feature selection intrinsically, since during the construction of a tree, for every split the best feature is determined.

- Since trees are added sequentially in tree ensembles, the performance of the ensemble on training and validation data set can be monitored while the forest is growing. When the performance on the validation does not increase after a certain number of trees has been added, the forest growth can be terminated in order to avoid over-fitting.
- Forests are easy to parallelise and are therefore fast(er) to train.

A drawback of gradient-boosted decision trees, is that they have more hyper-parameters compared to other classification techniques. The tuning of the hyper-parameters are discussed in Section 4.3.3.

4.3.1.1. Principles of tree ensembles

Gradient-boosted decision trees fall into the category of tree ensemble methods. The building blocks of these so-called *forests*, are binary decision trees. Figure 4.4 shows a sketch of a binary tree for illustration. Starting from the root node the event vectors $\vec{x}_i$ flow through the nodes where each tests one of the event features e.g. whether the BGO energy deposit of the event is above or below a certain value, and redirects $\vec{x}_i$ to one of the two connected nodes. Depending on which leaf the event i terminates, a class prediction $\hat{y}_i$ of the event is made based on the leaf score. For simple decision trees, the leaf score can be 1 or 0. For classification and regression trees (CARTs), the leaf scores are continuous values in a certain interval and are also called prediction scores. In case of forests, the prediction is a superposition of the responses of K trees:

$$\hat{y}_i = \sum_{k=1}^K f_k(\vec{x}_i), \quad f_k \in \mathfrak{F} \quad (4.5)$$

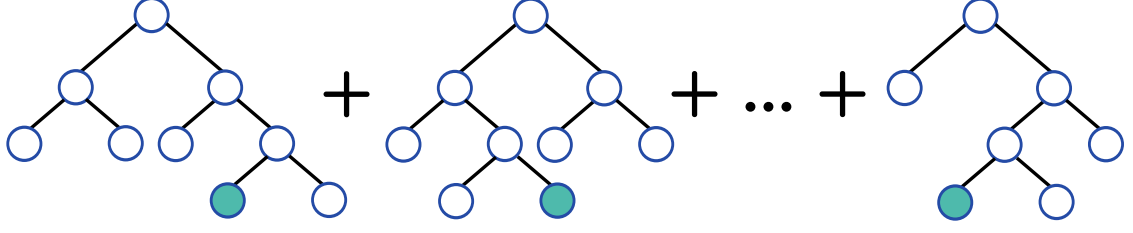


Figure 4.5.: Illustration of a tree ensemble.

where f_k describes one of the trees and the class prediction of $\vec{x}_i$ is a sum of all the predictions of the K trees. $\mathfrak{F}$ is the space of possible CARTs. Figure 4.5 shows an illustration of a tree ensemble.

The forest is build incrementally using *boosting* which is described in the following. In the first iteration $k = 1$, the training set (X_t, Y_t) is used to construct the first tree. For the second instance, training events $\vec{x}_i$ that have been misclassified by the previous tree are emphasised by assigning higher weights to them; lower weights are assigned to $\vec{x}_i$ correctly classified. After K iterations, the final classifier is a linear combination of the constructed trees. The next section addresses the question of how to find the “best” trees i.e. how a tree ensemble is trained.

4.3.1.2. Training – building a forest

In order to find the best combination of trees to solve e.g. the classification problem at hand, an objective function L is defined to evaluate the performance of the ensemble of a particular set of trees F [101]:

$$L(F) = l(F) + \Omega(F) = \sum_i l(y_i, \hat{y}_i) + \sum_k \Omega(f_k) \quad (4.6)$$

The first term of the objective function is the training loss l which gives a measure of the differences between predicted classes $\hat{y}_i$ and the target values (actual class) y_i . The regularisation term Ω measures and penalises the complexity of the tree ensemble and helps therefore to avoid over-fitting.

The goal is to optimise the objective function during training which happens in an additive fashion. With every iteration t , a new tree f_t is added to minimise L . At iteration t , this results in [101]:

$$L_t = \sum_i l(y_i, \hat{y}_{i,t-1} + \epsilon f_t(\vec{x}_i)) + \sum_k \Omega(f_k) \quad (4.7)$$

where ϵ is called the shrinkage. Setting it to a value < 1 i.e. not allowing for a full optimisation in each step reduces the impact of an individual f_t and

therefore leaves room for further improvement of the model by later trees.

At every iteration, the f_t that minimises L needs to be found. In principle, this can be done by enumerating all possible trees and picking the one resulting in the lowest L . However, since there can be an infinite amount of possible trees, in practice the trees are grown *greedily* which means:

- Start at a tree with depth zero.
- At each node of the tree, try to add a split.
- Find the best split by scanning over all features and all possible splits along the feature.
- Check the change of the objective function L after the split.
- Stop adding a new split when the user defined maximum depth of the trees is reached.

After the desired number of trees K is reached, the model is finished.

Throughout this sections, parameters that need to be set by the user before the training starts have been mentioned. Examples are the total number of trees K , the allowed maximum depth of a tree, the shrinkage ϵ as well as regularisation parameters that characterise Ω which was not described in depth (further detail can be found in the literature [101]). Such model specific parameters are called *hyper-parameters* and they are discussed in Section 4.3.3. Their optimal values depend on the problem and data at hand and need to be carefully tuned in order to achieve optimised results with the model.

The total number of trees K is additionally controlled by “early stopping rounds” which is a built in feature of **XGBoost**. During training, the performance measure is monitored in dependence of the added number of trees. For the training set (X_t, Y_t) the classification error becomes smaller and smaller since the model gets to know the training set better and better. Although this might not be the case for a new data set, that the model has not seen before. Characteristically, the error on the new data set falls at first but starts rising again after a certain number of iterations when the model learns the training data *too well* – and starts to overfit. In order to avoid this, the error of the training set (X_t, Y_t) as well as a validation set (X_v, Y_v) is monitored. If the error of the validation set does not decrease after a certain number of rounds, the model stops early before the total number of K trees has been reached. Figure 4.6 shows the A_{ROC} , the chosen performance metric, in dependence of the number of added trees to the forest.

Given a new unclassified event, starting from the root node, it travels along

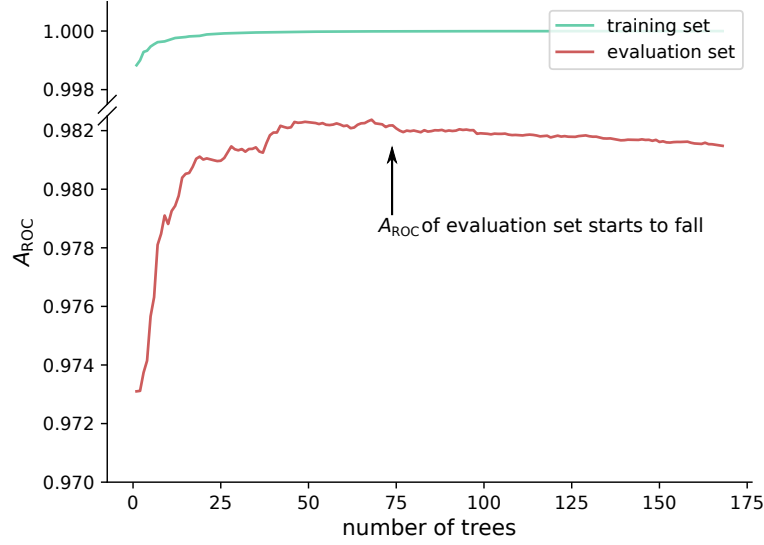


Figure 4.6.: A_{ROC} of training and evaluation set versus number of trees. The A_{ROC} of the evaluation set rises until a certain number of trees and then slowly falls again when the model starts to overfit.

the path determined by the nodes tests on the event features. The leaf node it ends up in determines the classification of the event depending on the training events that reached the leaf. The algorithm returns a prediction score which takes a value in $[0, 1]$ and is closer to one if the event is signal-like and closer to zero if it is background-like. The prediction score of the new event is calculated from the distribution of training events, it is however not necessarily a good estimate of probability. The distribution of scores for of the antiproton and cosmic test set needs to be considered to define a threshold value s_{thres} for the score. Events with scores $\leq s_{\text{thres}}$ are then classified as cosmic and events with $> s_{\text{thres}}$ as signal. Score distributions and the determination of the cut value are discussed later in Section 5.1.

Another advantage of **XGBoost** that has been mentioned, is tagging of missing values i.e. making the algorithm aware of missing entries in the event feature vectors $\vec{x}_i$. Missing values must be marked, for example by a numerical value such as 999 which will not appear naturally in the data set. If an event arrives at a node where a split happens on the variable that is missing, **XGBoost** handles the event by classifying it into a default direction i.e. the direction that minimises the chosen metric e.g. accuracy or A_{ROC} [101].

4.3.2. Feature selection

When using a finite set of training data, the choice of number of event observables (dimensionality d) becomes important. Every event can be seen as a point in a d dimensional feature space and the more features are considered, the more sparse the available data becomes (curse of dimensionality). Especially since the amount of signal input data is small, the number and also choice of features is important. Therefore, an extensive feature study and selection has been performed and is described in this section.

With **XGBoost**, the chosen algorithm for the analysis, it is possible to tag missing feature values which makes the algorithm aware of absent feature values. With many common feature selection algorithms tagging is not possible and therefore conclusions of feature importance results cannot be directly translated to **XGBoost**. Consequently, wrapper feature selection methods have been employed which optimise the performance of a chosen model by evaluating and comparing scores of different feature sets.

Finding the combination of best input features involves an exhaustive evaluation of possible feature subsets which is computationally often infeasible since for every subset the model needs to be trained and evaluated in order to compare performance measures of the subsets.

Sequential feature selection [105] overcomes this by removing and/or adding one feature at a time based on the best model performance. This is done until a desired number of features is reached. There are two possible strategies in sequential feature selection:

- **Sequential forward selection (SFS):** Starting from an empty set, features are sequentially added. In every step, the feature resulting in the best performance is added when combined with the features that have already been selected. This strategy is most effective when the optimal subset is small since closer to the empty set more features are accessible.
- **Sequential backward selection (SBS):** Here the search starts from the full set, and features are removed sequentially in a way, that results in the smallest decrease of the performance measure.

The disadvantage of the two mentioned sequential selection methods is obviously that features, once removed or added, will not be accessible anymore and will not be re-evaluated again. This shortcoming can be overcome by Sequential *Floating* Selection methods which are capable of backtracking. Those algorithms also allow features to be removed/added once they were

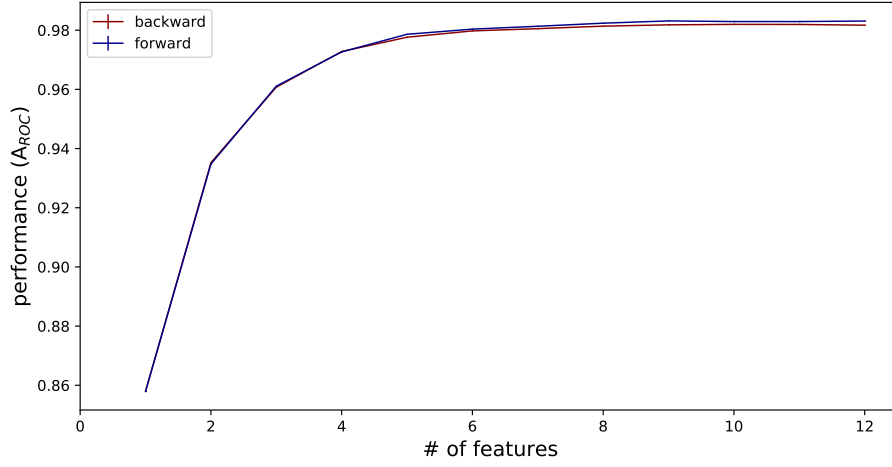


Figure 4.7.: Performance measure (A_{ROC}) as a function of the number of features used in the analysis for sequential forward and backward floating selection.

included (or excluded), so that a larger number of feature subset combinations can be sampled. In case of the SFFS for example, after each forward step (adding of a feature), backward steps (removing a feature) are performed as long as the performance of the model improves.

4.3.2.1. Results

The implementation of SFFS and SBFS of the python package `MLxtend` (Machine Learning extensions) [106] has been used to find the combination of event features listed in Section 4.2.4 that results in the best performance i.e. highest area under the ROC curve of the gradient-boosted decision tree analysis.

Firstly, a training set and evaluation set are randomly chosen. The training set is then re-sampled as described in Section 4.2.2. The evaluation set stays untouched to avoid any intervening effects of re-sampling with the feature selection process. The best feature combination within a range of zero to twelve (all) possible features has then been determined by SFFS and SBFS.

Figure 4.7 shows the performance of `XGBoost` (A_{ROC}) in dependence of the number of features used. The highest A_{ROC} value has been achieved with SFFS and the following nine features, in order of addition: largest angle between tracks $\alpha_{\max}$, E_{BGO} , ToF , mean angle with the y -axis α_Y , number of hits in the outer hodoscope n_O , α_3 the third largest angle between tracks, number of hits in the inner layer n_I , horizontal number tracks N_h and the total number of tracks N_{tracks} .

# features	A_{ROC}	list of selected features
1	0.8579	α_{max}
2	0.9358	α_{max} E_{BGO}
3	0.9611	α_{max} E_{BGO} ToF
4	0.9727	α_{max} E_{BGO} ToF α_Y
5	0.9786	α_{max} E_{BGO} ToF α_Y n_O
6	0.9804	α_{max} E_{BGO} ToF α_Y n_O α_3
7	0.9813	α_{max} E_{BGO} ToF α_Y n_O α_3 n_I
8	0.9824	α_{max} E_{BGO} ToF α_Y n_O α_3 n_I N_h
9	0.9831	α_{max} E_{BGO} ToF α_Y n_O α_3 n_I N_h N_{tracks}
10	0.9829	α_{max} E_{BGO} ToF α_Y n_O α_3 n_I N_h N_{tracks} N_u
11	0.9829	α_{max} E_{BGO} ToF α_Y n_O α_3 n_I N_h N_{tracks} N_u N_d
12	0.9830	α_{max} E_{BGO} ToF α_Y n_O α_3 n_I N_h N_{tracks} N_u N_d α_2

Table 4.4.: Best feature combinations using SFFS for fixed total numbers of features.

A summary of the best combinations of features for a fixed number of features is shown in Table 4.4. This states that, if the model would be trained with only one feature, α_{max} would be the best choice and so on. So by interpreting the choice of best features for the different fixed number of input features used, it can be deduced that α_{max} , E_{BGO} and ToF are the three top features.

4.3.3. Hyper-parameter tuning

Hyper-parameters are model specific parameters that determine the architecture of the model and need to be defined before the training. As mentioned earlier, in case of GBDT this can be for example the maximum tree depth, the learning rate or the number of trees. Table 4.5 shows a list of **XGBoost**'s hyper-parameters that have been tuned for the antihydrogen analysis discussed here. The optimal values of the hyper-parameter depend on the data set and need to be tuned to result in the best performance for the problem at hand. The tuning process can be depicted as:

$$H^* = \underset{H \in \mathcal{H}}{\operatorname{argmax}} \hat{O}(H) \quad (4.8)$$

where $\hat{O}$ is an objective function depending on the hyper-parameter H . In this case, evaluation of the objective function involves training and testing of GBDT which then returns a performance score p_s i.e $p_s = \hat{O}(H)$. H^* denotes the set of H that results into the optimised performance score. For the tree

ensemble **XGBoost**, the hyper-parameters can be grouped into tree boosting parameters and optimisation parameters.

Boosting parameter:	Range	Scanned range	Description
<code>n_estimators</code>	$[0, \infty]$	$[200, 5000]$	Number of trees
<code>max_depth</code>	$[0, \infty]$	$[2, 30]$	Maximum depth of the trees
<code>eta</code>	$[0, 1]$	$[0, 1]$	Learning rate avoids over-fitting by shrinking the weights on trees added at each step
<code>max_delta_step</code>	$[0, \infty]$	$[0.01, 5]$	
<code>gamma</code>	$[0, \infty]$	$[0, 1]$	Minimum loss reduction required to make a split
<code>colsample_bytree</code>	$(0, 1]$	$[0.3, 1]$	Fraction of features to be randomly sampled for each tree
<code>subsample</code>	$(0, 1]$	$[0.01, 1]$	Fraction of events to be randomly sampled for each tree
<code>lambda</code>	$[0, 1]$	$[0, 1]$	Regularisation parameter of Ω , see ref. [101]
<code>alpha</code>	$[0, 1]$	$[0, 1]$	Regularisation parameter of Ω , see ref. [101]
Optimisation parameter:			Description
Objective function			Function the algorithm tries to optimise e.g. logistic loss
Metric			Metric used for evaluating the performance of the model on the given data set (A_{ROC})

Table 4.5.: List of hyper-parameters of **XGBoost** and their description as well as possible range and range used for parameter tuning.

The optimisation parameters are chosen first, depending on the learning task at hand. For binary classification problems such as the discrimination of signal and background, the objective function “binary:logistic” is recommended.

The boosting parameters have different optimum values depending on the data set (X, Y) . A common and the conceptually simplest method for finding those values, is grid search. A set of values are defined for each hyper-parameter and the model is then trained and tested for all possible parameter combinations and in the end, the best combination is chosen. This method however is very computational intensive and only a good choice if the training of the model is quick and the number of parameters is small. This is not the case for **XGBoost** and the present data set².

Other possibilities would be a manual search (scanning parameter sequentially or in lower dimensional subspace of the grid), random search (does not cover full parameter space, still very computational intense) or more efficient algorithms which base their decision of evaluating the next parameter set on

²Assuming we choose 10 possible values for the 9 parameter, the model needs to be trained 9^{10} times where training takes on average about 10 minutes, resulting in a total amount of computation time of 66k years. Even if this is sped up by parallelising the process, it would still take much too long.

previous evaluations and do not waste time evaluating bad hyper-parameter regions. An example are Bayesian optimisation techniques.

Search by hand, as well as two Bayesian optimisation methods: Gaussian processes and the Tree Parzen Estimator [107] were tried. The best parameters were found with the Tree Parzen Estimator (TPE) and the implementation provided in the python library `hyperopt` [108]. Therefore only the latter is described here and for discussions of the others the reader shall be referred to the literature.

In Bayesian hyper-parameter optimisation methods, first a probability model P of the objective function is build that is cheaper to evaluate than $\hat{O}$ itself. This surrogate model $P(p_s|H)$ maps H to the corresponding performance score p_s and is based on past evaluations of the true objective function. From that model, a promising hyper-parameter set is predicted and used for the next evaluation of $\hat{O}$. After the evaluation of $\hat{O}$ using the promising set H , P is updated and the above discussed steps are repeated. The following list gives an overview of the ingredients needed before the optimisation starts:

- Firstly, prior distributions for the hyper-parameters are defined. In the analysis at hand, all of them were chosen to be equally distributed in the intervals listed in Table 4.5.
- The objective function which takes in a set of parameters, trains `XGBoost` with this set and returns the corresponding performance score (A_{ROC}) is set up.
- A surrogate model needs to be chosen – TPE in this case, since it showed the best results. It is discussed next.
- A criterion needs to be defined in order to obtain the next H from the surrogate model $P(p_s|H)$. Commonly [107], the expected improvement is used:

$$EI_{p_s^*}(H) := \int_{-\infty}^{\infty} \max(p_s^* - p_s, 0) P(p_s|H) dp_s \quad (4.9)$$

where p_s is the score of the objective function $\hat{O}$ using H and p_s^* a threshold of the objective function. The goal is to find the best H under the surrogate model.

The choice of the surrogate model for the Bayes optimisation determines the way $P(p_s|H)$ is calculated. In TPE it is calculated via the Bayes rule:

$$p(p_s|H) = \frac{p(H|p_s)p(p_s)}{p(H)} \quad (4.10)$$

where $p(H|p_s)$, the probability of H given the score p_s , is represented by:

$$p(H|p_s) = \begin{cases} l(H), & p_s < p_s^* \\ g(H), & p_s \geq p_s^* \end{cases} \quad (4.11)$$

$l(H)$ is the distribution over H which yield a score of the objective function smaller than the threshold p_s^* whereas $g(H)$ is the one with scores higher than the threshold. Inserting this into equation 4.9, results in [107]:

$$EI_{p_s^*}(H) \propto \left(\gamma + \frac{g(H)}{l(H)}(1 - \gamma) \right)^{-1} \quad (4.12)$$

with $\gamma = p(p_s < p_s^*)$. In order to maximise the expected improvement, the ratio $\frac{l(H)}{g(H)}$ needs to be maximised i.e. the goal is to find H s with high probability under l and low under g (which is also intuitive). The Tree Parzen Estimator for hyper-parameter optimisation undergoes the following steps:

1. An initial surrogate model is built by evaluating the objective function via random search. So in practice, **XGBoost** is trained a few (hundred) times with random sets of H .
2. From the resulting H , the two distributions $l(H)$ and $g(H)$ are made and TPE draws samples from $l(H)$, evaluates the ratio $l(H)/g(H)$ and returns the set that gives the highest expected improvement.
3. $\hat{O}$ is evaluated with that new set of H .
4. With the outcome, the surrogate model P is updated and steps 2-5 are repeated until the maximum number of iterations is reached.

The resulting H^* found are summarised in Table 4.6.

n_estimators	3773
max_depth	20
eta	0.09
max_delta_step	5.00
gamma	0.05
colsample_bytree	0.80
subsample	0.92
lambda	0.10
alpha	0.22

Table 4.6.: Optimal set H^* found via TPE.

4.3.4. Training and evaluation

After defining the data set (X, Y) , choosing features and tuning the hyperparameter of the model as has been discussed in the previous sections, the model is trained and evaluated. The principle of training of gradient-boosted decision trees is described in Section 4.3.1.2. Due to fluctuations in the train and test data samples by randomised splitting, there are also variations in the predictions of algorithms based on those data sets. Hence a bootstrap method³ is employed where an ensemble of 500 algorithms is built, each with a randomly chosen training and test sample. Results are then determined by averaging over the ensemble outcomes. This has also the advantage that an error on quantities such as cosmic rejection and antiproton efficiency can be calculated. Every round consists of the following steps:

1. Firstly, the data set (X, Y) is split into a training set (X_t, Y_t) and a test set $(X_{\text{test}}, Y_{\text{test}})$. In order to have a balanced test set, a third of the antiproton data sample is randomly selected and as well as an equal number of cosmic events. The rest is used for training.
2. In order to create a validation sample (X_v, Y_v) for monitoring the performance of the algorithm during training, the training set is split again, before oversampling. A fraction of 0.2 is used and the number of background events in the validation sample reduced by random undersampling to establish class balance in (X_v, Y_v) .
3. Since the training data set is imbalanced it is re-sampled prior to training, as described in Section 4.2.2.
4. Afterwards, the model is build based on (X_t, Y_t) and its performance evaluated after every tree addition by (X_v, Y_v) . If the performance measure does not improve for the validation set after the addition of 20 trees, the best iteration is chosen as the final number of total trees.
5. The model faces the test set, the data sample it has not seen before, and returns a prediction score that is closer to 1 for events belonging to the signal class and closer to 0 if they belong to the background class. This score is also called a probability estimate but should not be used blindly as a probability since it is not ensured that it is a good probability estimate⁴.
6. After defining a threshold value for the score s_{thres} i.e. events below the

³Bootstrap methods are statistical approaches that employ random sampling with replacement [98].

⁴However, the score can be calibrated. This is not done in the current work.

threshold are categorised as background and above as signal, cosmic and antiproton efficiency are determined by:

$$\varepsilon_c = \frac{N_{\text{test},0}^c}{N_{\text{test}}^c} \quad (4.13)$$

$$\varepsilon_{\bar{p}} = \frac{N_{\text{test},1}^{\bar{p}}}{(N_{\text{test}}^{\bar{p}} - n_{\text{est}}^c)} \quad (4.14)$$

Thus they are defined by the ratio of the number of correctly identified events, $N_{\text{test},0}^c$ and $N_{\text{test},1}^{\bar{p}}$, and the number of total events, N_{test}^c and $N_{\text{test}}^{\bar{p}}$, of the respective classes. From the total number of antiprotons in the test set, the estimated number of cosmics n_{est}^c (see Table 4.3) is subtracted. The false positive rate is calculated via:

$$f_{\text{fp}} = (1 - \varepsilon_c) f_{\text{cosmic}} \quad (4.15)$$

with the rate of cosmic rays f_{cosmic} .

7. The area under the ROC curve for the test set is determined.
8. Finally, the trained model is used on the mixing data set ($X_m, ?$) and returns a prediction score for every event. This is discussed in detail in the next chapter in Section 5.1.

4.3.5. Feature importance

Gradient-boosted decision trees perform an intrinsic feature selection during training since for every split the best feature is determined. **XGBoost** has therefore also a build-in function which determines feature importance scores which give a measure of how useful an event feature was during the construction of the forest. More precisely, the importance of a feature is calculated as the number of times it has been used in a node to split the data across all trees. A bar plot showing the feature importances averaged over the ensemble of 500 algorithms is shown in Figure 4.8. The error bars shown are the sample standard deviations of the individual features.

Note, that this definition of feature importance does not take the number of events into account that are concerned by a split. For example are features, that are chosen for splits closer to the root of the tree due to their higher separation power of the data sub set into signal and background, intuitively more important but could still be used a similar amount of times for splitting and their importance is therefore underestimated. The results in Section 4.3.2 are therefore more meaningful and significant in terms of

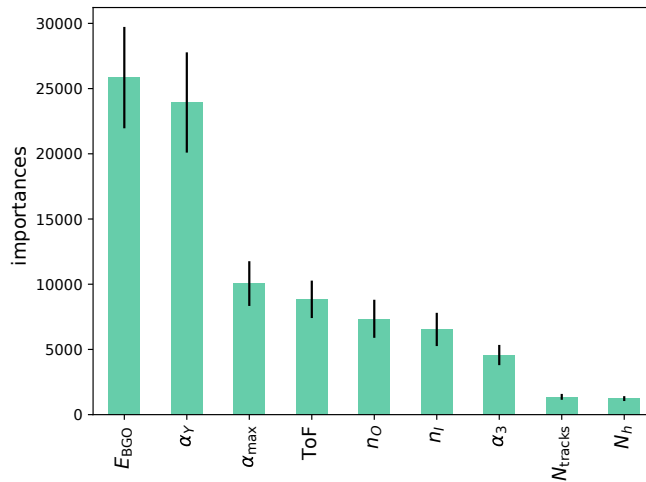


Figure 4.8.: Feature importance scores averaged over the ensemble. The error bars shown are the sample standard deviations for the individual features.

feature importance estimates since they are based on optimising the models performance. Nevertheless, both methods have the top four features in common.

4.3.6. Benchmark

In order to benchmark the developed GBDT analysis, its performance is compared with an ensemble of simple rectangular cuts. For this purpose, ROOTs TMVA (Toolkit for Multivariate Data Analysis) [109] has been used. “Rectangular cuts” is TMVA’s simplest method for signal and background discrimination and is commonly used by particle physicists for benchmark purposes.

The algorithm finds a set of rectangular cuts on the event features by optimising the cut placement and also the order in which the cuts are applied on the data. The optimisation of cuts performed by TMVA maximises the background rejection at given signal efficiency, and scans over the full range of the latter quantity. Note, that this is not a multivariate analysis method but a series of univariate cuts.

Unfortunately, handling of missing feature values is not realised for TMVA. One possibility would be to use only features that can be calculated for all events. This however, would make the resulting performance measure not comparable to the one archived by the multivariate analysis discussed later in this chapter due to missing key features.

Since the features that can be calculated are dependent on the number

of tracks, the data set is split up into groups with equal number of tracks. Afterwards, TMVAs rectangular cuts can be used on the individual groups and the obtained A_{ROC} s can then be averaged. The in this way obtained A_{ROC} amounts to 0.84. The achieved result using the analysis based on gradient-boosted decision trees is $A_{\text{ROC}} = 0.984$, see Section 5.1. The benchmark test shows, that a multivariate analysis for the classification task at hand is justified and results in a significant improvement.

4.4. Anomaly detection

Anomaly detection is a profoundly different type of machine learning technique compared to the supervised machine learning technique discussed in the last sections. The goal is to find instances that have different characteristics than the majority of instances in a data set. Those instances are called anomalies or outliers, such as rare antihydrogen annihilation events during mixing runs when the majority of the events are cosmic rays.

In order to perform anomaly detection on the antihydrogen data, a novel algorithm called *isolation forest* [110] was chosen and the implementation of the python library `scikit learn` [111] was used. Isolation forest (IF) is another tree based algorithm that relies on the fact that anomalies are rare and different compared to normal instances. It is also an *unsupervised* algorithm i.e. it is not trained with labelled data sets of signal and background in contrast to the gradient-boosted decision tree analysis discussed in the previous sections.

The isolation forest is build on a data set containing a mixture of normal events and anomalies. Here, the data of all mixing runs in Table 2.1 is used for building the isolation forest. Including data sets of all mixing runs, not only $(X_m^a, ?)$, is sound since the detection conditions for all mixing runs were the same and the antihydrogen event signature in the detector does not depend on mixing condition. The final results of quantum state distribution and time distribution are of course determined with event candidates of $(X_m^a, ?)$ only.

Training the IF with a mixed data set has the advantage that one does not rely on any background or signal samples for training and therefore also no data re-sampling is needed.

On the other hand, a possible disadvantage might be that the algorithm classifies everything that does not look similar to the majority class (cosmic events) as an outlier which does not automatically make it an antihydrogen

event. However, antiproton and cosmic data are available for testing the anomaly detection algorithm and predictions can be compared with the results of the gradient-boosted decision tree analysis in order to evaluate the classification power of the IF. Also, no other background contributions are expected, apart from a small contribution of possible upstream annihilations which also cannot be distinguished with the GBDT analysis.

4.4.1. Principle of the isolation forest algorithm

Isolation Forest is a tree ensemble constructed out of random trees. A random tree is a binary tree where at every node the feature to split on is selected randomly as well as the split value (between maximum and minimum value of the feature).

An event is called isolated, if it ends up alone in a leaf node. The number of splittings it takes to isolate an event is a measure of (ab)normality of the event since for random partitioning of the feature space, a smaller number of splits is needed to isolate anomalies compared to normal events, see Figure 4.9 for a sketch of an isolation free. Therefore, for anomalies, the random forest will on average generate a lower *anomaly score* a which is defined as [110]:

$$a(x, N) = 2^{-\frac{\overline{h(x)}}{c(N)}} \quad (4.16)$$

where x is the event, N is the total number of events, $\overline{h(x)}$ the average number of splittings for x and the normalisation factor $c(N)$ which is the average of $h(x)$ given N .

The hyper-parameters of the isolation forest as well as their used values are listed in Table 4.7. A disadvantage of the implementation of the isolation forest algorithm⁵ used is that it does not support tagging of missing values. Therefore, only features available for all events will be used which are: (1) BGO energy deposit E_{BGO} , (2,3) hits in inner and outer hodoscope layer n_{I} and n_{O} , (4) number of tracks N_{tracks} , (5,6,7) the number of horizontal tracks and tracks in the upper and lower hodoscope halves N_{h} , N_{u} , N_{d} . Note that some features that had a high importance score in the analysis using GBDT are therefore excluded, such as the ToF , α_{Y} or α_{max} .

The **contamination** parameter has been set to 0.01, the fraction of anti-hydrogen candidates found by the GBDT analysis of the total number of events in the mixing data set (no time cut applied). Values in [0.05, 0.001]

⁵There is not yet one that supports tagging of missing values.

3. The built forest is used to calculate anomaly scores of the events in the antiproton and cosmic data set (discussed in Section 4.2.1), X^1 and X^0 , and their distributions are compared to the one for the $(X_m^{\text{tot}}, ?)$ data set. Studying the response to the two labelled data sets gives a measure of the ability of the isolation forest of discriminating cosmic and annihilation events.
4. A cut value a_{thres} on the anomaly score needs to be determined in order to select antihydrogen events with $a < a_{\text{thres}}$. For further analysis and comparison to the GBDT results, only events in the mixing runs dedicated to the measurement of the quantum state distribution, $(X_m^q, ?)$, are used.

Results such as cosmic rejection, antiproton efficiency and antihydrogen candidate events as well as the quantum state distribution determined by the IF analysis are presented in the next chapter in Section 5.5.

5. $\overline{\text{H}}$ beam characterisation results

In this chapter, the results of the developed data-driven machine learning analyses described in the previous chapter are discussed. The focus of this chapter lies on the results of the GBDT analysis which yields a higher observed significance for the number of antihydrogen candidates in low-lying states, as is discussed in the following sections. Firstly, the GBDT analysis is evaluated, cosmic rejection and antiproton efficiency are calculated. The procedure of antihydrogen candidate event selection is discussed and important results are shown. Most notably the principal quantum number distribution of the produced antihydrogen atoms is presented. The distribution of arrival times of antihydrogen candidates at the detector is discussed, as well as a comparison to the time distribution recorded by the detector surrounding the mixing area of the double-CUSP trap.

At the end of this chapter, the analysis based on the isolation forest algorithm is evaluated and results are compared to those of the GBDT analysis.

5.1. Background rejection, antiproton efficiency and $\overline{\text{H}}$ events

The next step after building the ensemble consisting of 500 trained and evaluated algorithms as described in the last chapter, is to study the prediction score distributions of cosmic, antiproton and mixing events. Based on them, an appropriate cut value s_{thres} on the score is determined that defines cosmic rejection ε_c , antiproton efficiency $\varepsilon_{\overline{\text{p}}}$ and dictates which events are accepted as antihydrogen candidates in the mixing data set ($X_{\text{m}}^{\text{q}}, ?$).

Figure 5.1 shows the distribution of scores for the $(X_{\text{test}}, Y_{\text{test}})$ of all 500 rounds. The blue histogram shows results for cosmic events and the red one antiproton events. As expected, scores of cosmic events tend towards values of 0 and antiprotons towards 1. Figure 5.2 (left) shows cosmic rejection ε_c and antiproton efficiency $\varepsilon_{\overline{\text{p}}}$ in dependency of the cut value s_{thres} . The ROC curve of the ensemble is shown in Figure 5.2 (right), averaging over the 500 ensemble outcomes results in an A_{ROC} of 0.9840 ± 0.0015 . Picking a point of operation on the ROC curve fixes the cut on the prediction score and vice

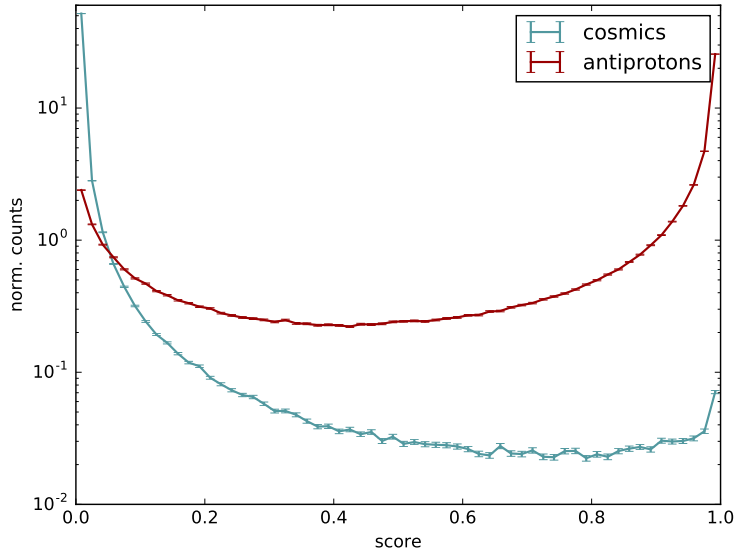


Figure 5.1.: Distribution of the prediction scores of cosmic (blue) and antiproton (red) test sets (logarithmic y -axis). The histograms are normalised to their area.

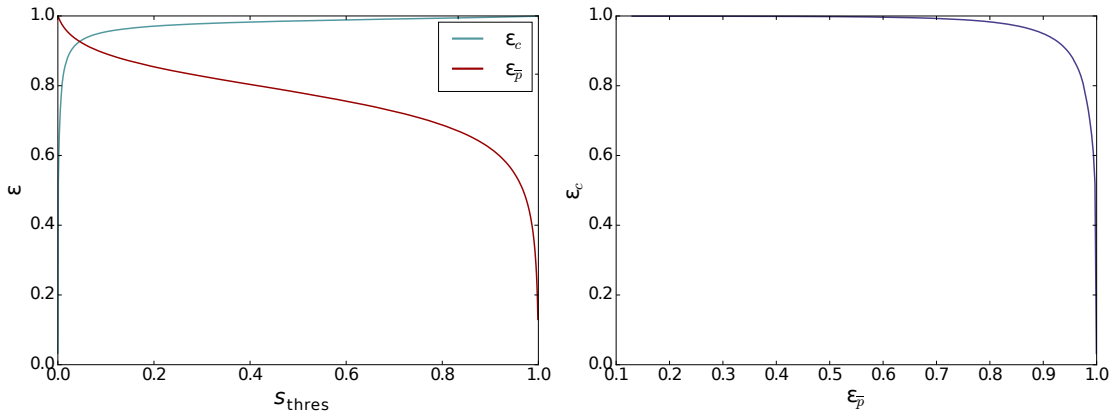


Figure 5.2.: *Left*: Cosmic and antiproton efficiencies averaged over the ensemble in dependence of the cut s_{thres} on the prediction score. *Right*: ROC curve of the ensemble (antiproton efficiency versus cosmic rejection).

versa. This is done later on by finding the point that results in the lowest p-value/highest significance of the observed antihydrogen candidates.

For the mixing events in $(X_m^q, ?)$ that are used for determining the principle quantum state distribution, the prediction score distributions determined from the 500 outcomes, can be studied for every event individually and provide some insight into how confident the algorithm is about the class of the candidate events. Figure 5.3 shows examples of four different score distributions to illustrate this. The normed histograms of the scores (light

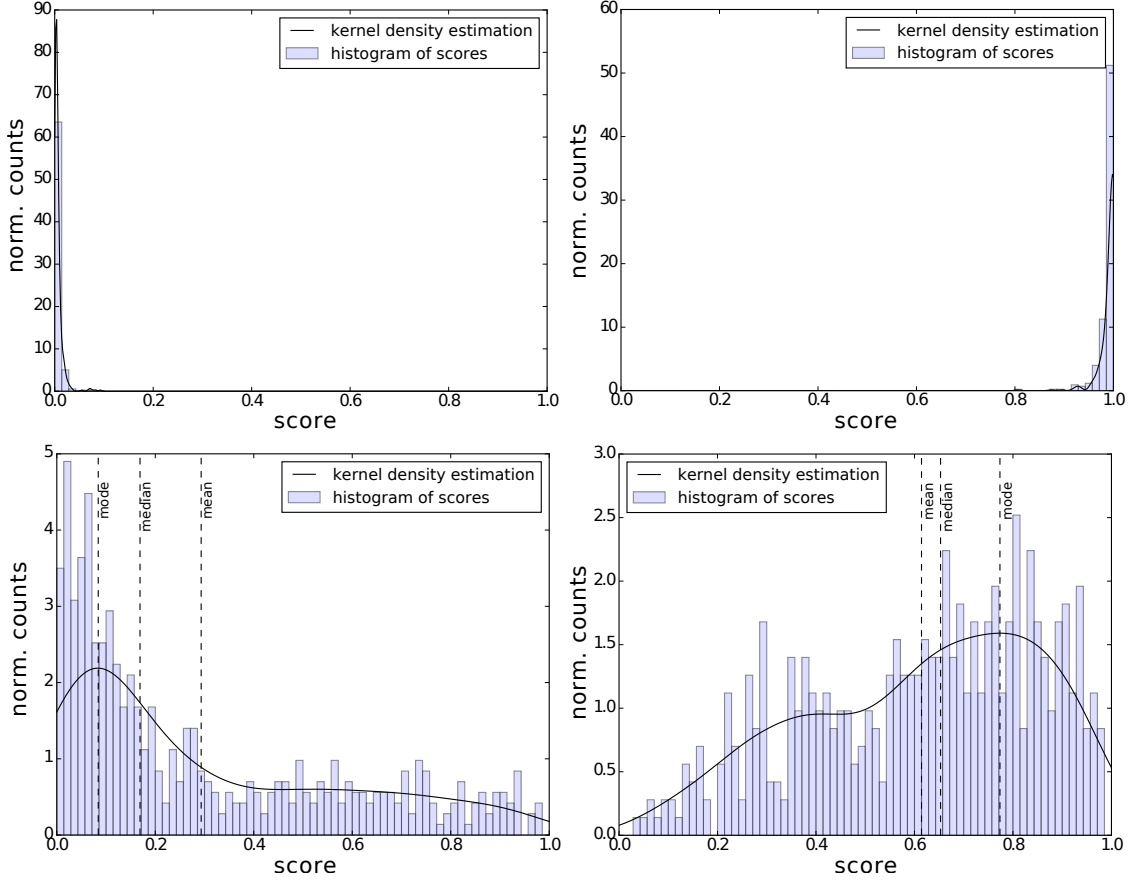


Figure 5.3.: Distributions of the prediction scores of the gradient-boosted decision tree ensemble of four different events. *Top row*: events with very narrow score distribution: left probably cosmic (distribution around zero), right probably an antihydrogen (distribution around one). *Bottom row*: events with broad distributions. Vertical dashed lines show mean, mode and median.

blue) as well as the kernel density estimations¹ (black) are plotted.

The left column of Figure 5.3 shows cases of score distributions which have a maximum close to zero indicating that the event is more likely classified as a background event. The right column shows a similar case for events with scores closer to one. The general shape of the score distributions is skewed with the mode close to one or zero and a tail. For most events in $(X_m^q, ?)$, the width of the distribution tends to be narrow, see the histogram of standard deviations σ in Figure 5.4 (left). For some events though, the model shows a high variance depending on the randomly selected training and test sets.

Figure 5.4 (right) shows the distributions of the median of the score

¹The kernel density estimation has been determined using the implementation `KernelDensity` of `sklearn.neighbours` via $\rho_K(y) = \sum_{i=1}^N K((y - x_i)/h)$. A gaussian kernel form K was used. h denotes the bandwidth, which has been determined by minimising the bandwidth of the mean integrated squared error as in [112].

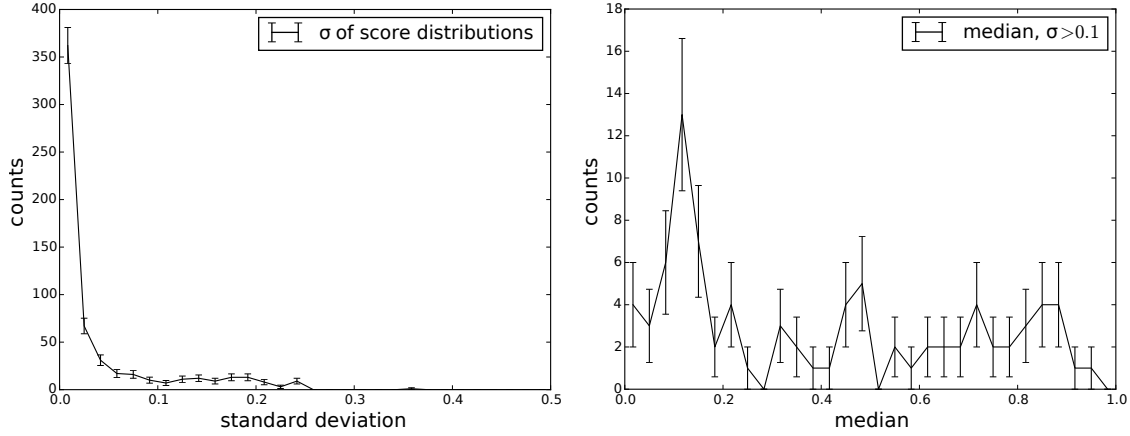


Figure 5.4.: *Left*: Histogram of the standard deviation of score distributions of events in the mixing runs. *Right*: Histograms of the median of score distributions of events in mixing runs with $\sigma > 0.1$.

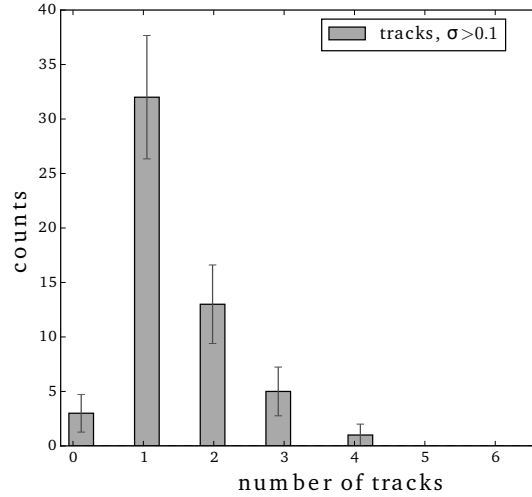


Figure 5.5.: Histogram of number of tracks of events with a standard deviation of scores of $\sigma > 0.1$.

distributions of mixing run events with $\sigma > 0.1$ ($\approx 10\%$ of total number in $(X_m^q, ?)$). Most events with broader distributions seem to be background-like, since the peak for the median is closer to zero, although this is most likely due to the underlying event class distribution in $(X_m^q, ?)$ i.e. the dominating cosmic rate over the low antihydrogen rate.

In order to investigate events with larger σ , their feature distributions have been studied and it was found that the majority of events with large σ have only a single track, see Figure 5.5. This findings are plausible because events with one track are the hardest to place due to missing decisive features e.g. ToF , $\alpha_{\max}$, α_2 and α_3 which have a non-negligible importance score.

In order to assign a single score to the events in the mixing runs for further

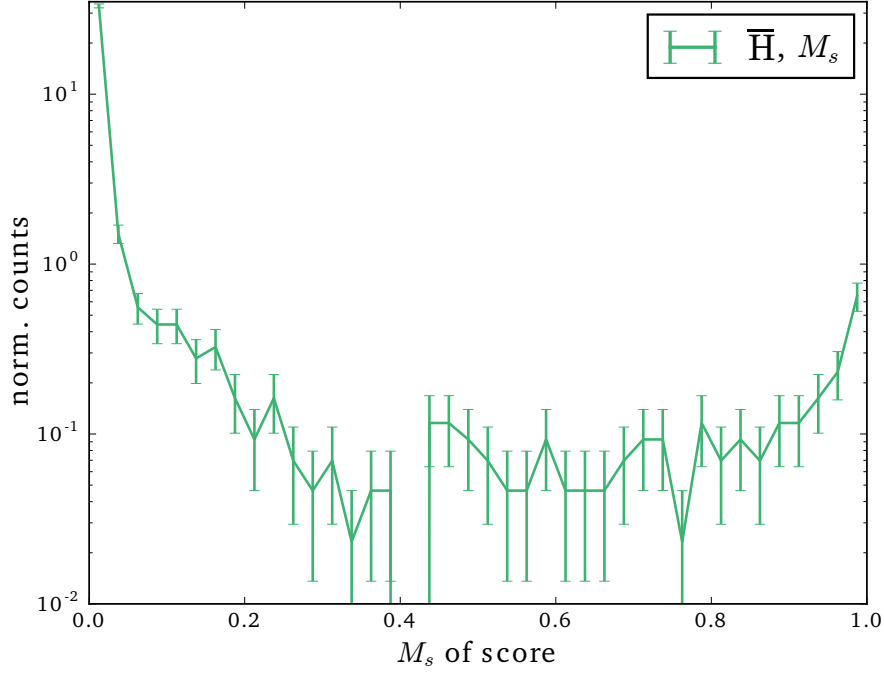


Figure 5.6.: Histograms of the median of scores of events in mixing runs in $[t_{\text{start}}^{\text{mix}}, 25 \text{ s}]$.

analysis, the median M_s has been chosen as a measure of central tendency. The distribution of scores for events in $(X_m^q, ?)$ is displayed in Figure 5.6.

Now a suitable value for the score threshold s_{thres} has to be determined to classify events. For this purpose, s_{thres} is scanned while monitoring the p-value of the found candidates considering the false positives resulting from the cut. The p-value is a measure of the deviation of the found number of events n_{obs} from the number of expected number of events in the background only case n_b . More precisely, it is the probability to observe n_{obs} or more. For counting experiments as the one at hand, the p-value is calculated using Poisson statistics [113]:

$$p(\Delta t) = P(n \geq n_{\text{obs}} | n_b) = 1 - F_{\text{Poisson}}(n_{\text{obs}}, n_b) \quad (5.1)$$

where Δt is the considered time interval and F the cumulative distribution function given by:

$$F_{\text{Poisson}}(n_{\text{obs}}, n_b) = \sum_{k=0}^{n_{\text{obs}}} \frac{e^{-n_b} n_b^k}{k!} \quad (5.2)$$

The p-values can also be translated into an observed significance which is the number of standard deviations of the standard normal distribution [113]. Via the inverse cumulative functions of the standard normal distribution F_{normal}^{-1} , the p-value can be converted into units of sigma s :

$$s = F_{\text{normal}}^{-1}(1 - p) \quad (5.3)$$

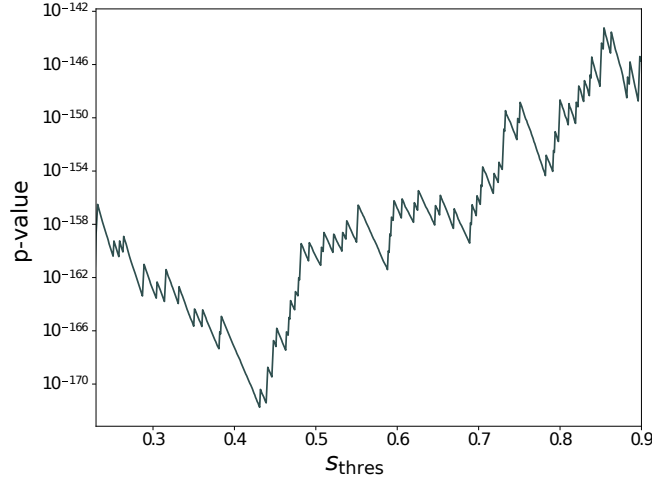


Figure 5.7.: P-value in dependence of the cut value s_{thres} on the prediction score, using the median of the score distributions of the events in the mixing runs.

$s_{\text{thres}} = 0.431$	
cosmic rejection ε_c	0.9836 ± 0.0031
false positive rate (Hz)	0.0077 ± 0.0015
$\bar{p}$ efficiency $\varepsilon_{\bar{p}}$	0.800 ± 0.0111

Table 5.1.: Summary Table of cosmic rejection, false positive rate and antiproton efficiency for $s_{\text{thres}} = 0.431$.

where s denotes the significance in numbers of σ .

The cut value producing the lowest p-value (highest significance) is chosen to fix the discrimination of signal and background and the selection of antihydrogen candidates. The considered time interval Δt is $[t_{\text{start}}^{\text{mix}}, 6 \text{ s}]$, since most antihydrogen counts have been observed in the first few seconds, on the antihydrogen detector.

The scan has been done considering all mixing runs dedicated to the quantum state measurement. Figure 5.7 shows the p-value in dependence of s_{thres} . The jagged form of the functions is due to the low number of antihydrogen events. The minimum is found at 0.431.

The resulting cosmic rejection ε_c , antiproton efficiency $\varepsilon_{\bar{p}}$ and false positive rate are summarised in Table 5.1 for $s_{\text{thres}} = 0.431$. Note, that those values are dependent on the rate of produced antihydrogen since they are found via optimising the p-value. The process of finding the optimum s_{thres} has to be repeated for a new mixing data set.

The second, independent analysis done in ASACUSA which does not employ machine learning but two dimensional cuts on event features [83], achieved a detection efficiency of 81% and a false positive rate of 0.012 Hz. A similar

$\Delta t = [t_{\text{start}}^{\text{mix}}, 25 \text{ s}]$					
n_{min}	runs	n_{obs}	$n_{\text{obs}}/\text{run}$	n_b	n_b/run
14	43	31	0.721	8.247 ± 1.560	0.192 ± 0.036
26	31	24	0.774	5.946 ± 1.124	0.192 ± 0.036
40	16	35	2.188	3.069 ± 0.580	0.192 ± 0.036
54	24	69	2.875	4.603 ± 0.871	0.192 ± 0.036
$\Delta t = [t_{\text{start}}^{\text{mix}}, 6 \text{ s}]$					
14	43	17	0.395	1.979 ± 0.374	0.046 ± 0.009
26	31	19	0.613	1.427 ± 0.270	0.046 ± 0.009
40	16	27	1.688	0.737 ± 0.139	0.046 ± 0.009
54	24	54	2.250	1.105 ± 0.209	0.046 ± 0.009

Table 5.2.: Summy of run numbers, their corresponding n_{min} , found event numbers and false positives for $\Delta t = [t_{\text{start}}^{\text{mix}}, 25 \text{ s}]$ (top) and $\Delta t = [t_{\text{start}}^{\text{mix}}, 6 \text{ s}]$ (bottom).

detection efficiency is achieved but the false positive rate is almost twice as large demonstrating the effectiveness of a data-driven multivariate analysis. Furthermore, the analysis in [83] is based on Monte-Carlo simulations using Geant4 and since discrepancies of multiplicities and energy deposit between Geant4 simulation results and measured data for low energy antiproton annihilations has been observed previously [95, 96], the two analyses are not directly comparable.

In the following sections, event numbers, time distribution and the quantum state distribution using the described analysis of the $(X_m^q, ?)$ data set are discussed.

5.2. Time distribution of $\bar{H}$ events

The number of events found with a prediction score $s > s_{\text{thres}}$ for the runs dedicated to the measurement of the quantum state distribution (see Table 2.1 in Section 2.4.1) are summarised in Table 5.2. The minimum n state n_{min} , the associated number of runs taken at that external field ioniser (FI) settings, determined antihydrogen event candidates n_{obs} and expected background events n_b are listed. Note, that for the runs with $n_{\text{min}} = 54$ the field ionisation well in the double-CUSP (FIC) was turned off, since the FIC ionises antiatoms down to $n = 43$. In total, 159 $\bar{H}$ candidates have been found.

In order to help understand the mixing process, it is important to study the arrival time of the antihydrogen events at the detector after the start of the mixing at $t_{\text{start}}^{\text{mix}}$ and also to compare this distribution to the time distribution

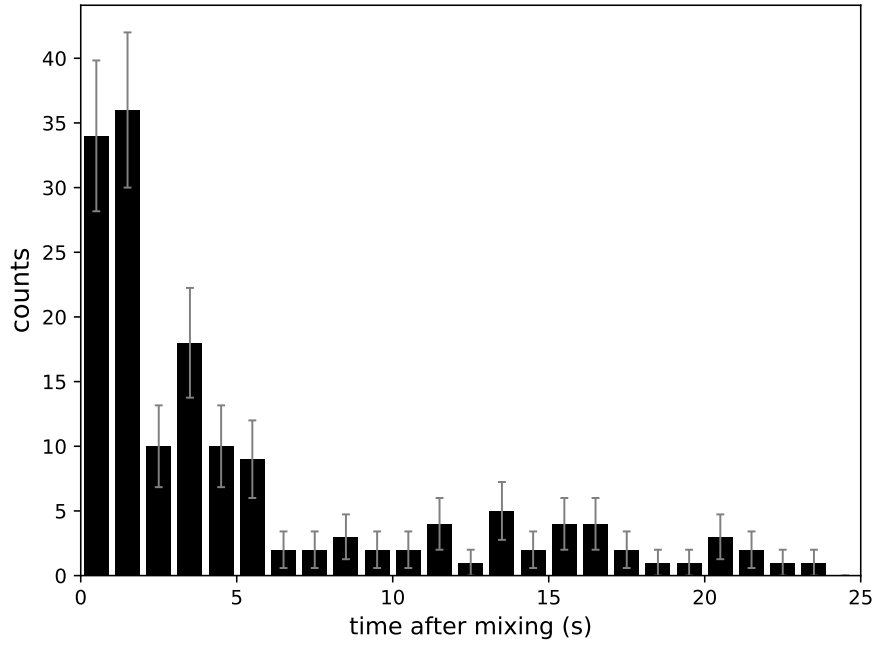


Figure 5.8.: Distributions of arrival times after mixing start signal of antihydrogen candidate events for all runs dedicated to the measurement of the quantum state distribution. The error bar shown is the Poisson error.

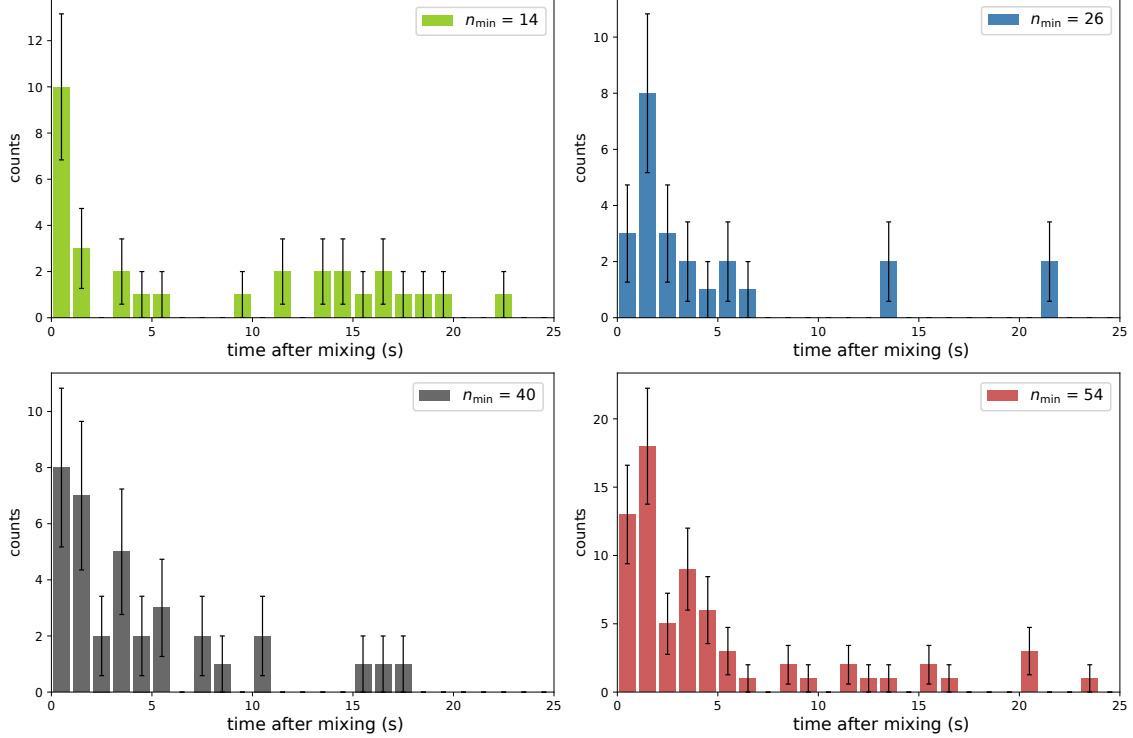


Figure 5.9.: Distributions of arrival times after mixing start signal of antihydrogen candidate events for the different FI settings. The error bar shown is the Poisson error.

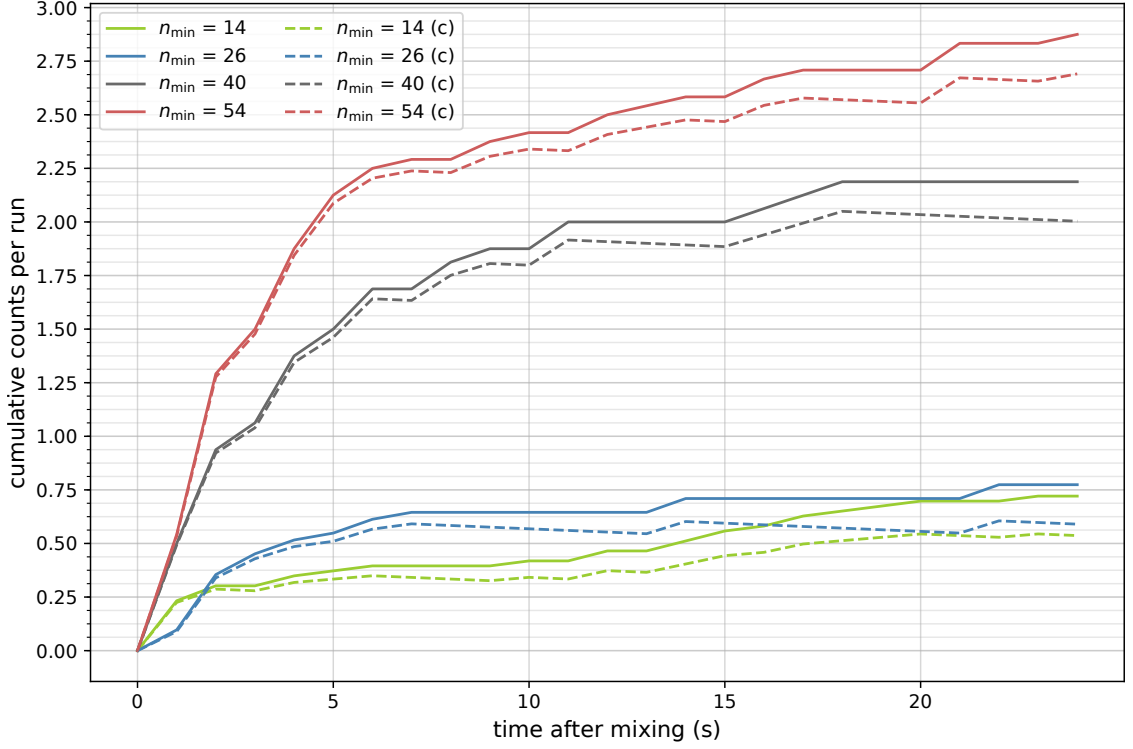


Figure 5.10.: Cumulative counts per run for 25 seconds after the mixing start signal for the different FI settings: $n_{\min} = 14$ in green, $n_{\min} = 26$ in blue, $n_{\min} = 40$ in grey and $n_{\min} = 54$ in red. The step size used is 1 seconds. Continuous lines show results for total counts, dashed lines show counts with the expected cosmic background subtracted.

of annihilation events measured by the detectors around the mixing trap (see next section).

Figure 5.8 shows the distribution of arrival times of antihydrogen candidates at the detector of all runs. The bin width is 1 s and the errorbars shown are Poisson errors. The distribution shows that most events were detected in the first few seconds. Comparing to the total number of events $n_{\text{obs}}^{\text{tot}}$, 74.2% arrived at the detector in the first 6 s and of those, 59.5% in the first 2 s (44.2% of $n_{\text{obs}}^{\text{tot}}$). Figure 5.9 shows the histograms of arrival times at the $\bar{H}$ detector for the different $n_{\min}$ data sets that show that the pronounced count rate in the first few seconds arises for all four field ioniser settings.

To further study the process, Figure 5.10 shows the cumulative counts for the data sets with different $n_{\min}$. Continuous lines indicate the total cumulative counts while the dashed lines show counts with the expected cosmic background subtracted. As expected, the steepest increase of counts arises in the first few seconds while afterwards the cosmic contribution dominates which becomes apparent due to the downwards tilt of the cumulative counts with higher times. Only for the FI settings with the highest $n_{\min}$, the corrected

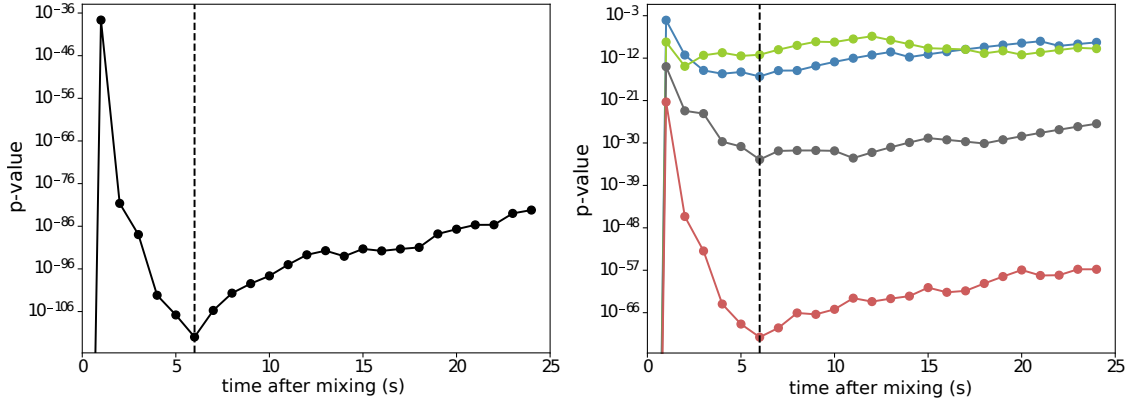


Figure 5.11.: p-value of counts in $\Delta t = [t_{\text{start}}^{\text{mix}}, t_{\text{cut}}]$ in dependence of t_{cut} (logarithmic y -axis). *Left*: for all FI runs. *Right*: for the different FI settings: $n_{\text{min}} = 14$ in green, $n_{\text{min}} = 26$ in blue, $n_{\text{min}} = 40$ in grey and $n_{\text{min}} = 54$ in red. The dashed, black horizontal line shows the selected time around the minimum.

cumulative counts still seem to rise towards later times.

From the insight gained so far it seems that the production of antihydrogen stops after a few seconds. Therefore, in order to keep the number of false positive events without any significant gain in $\bar{H}$ event numbers with later times low, a cut on the arrival time is chosen before determining the principal quantum number distribution. The p-value of counts in $\Delta t = [t_{\text{start}}^{\text{mix}}, t_{\text{cut}}]$ in dependence of t_{cut} can be seen in Figure 5.11.

The minimum for $n_{\text{min}} = 26$, $n_{\text{min}} = 40$ and $n_{\text{min}} = 54$ is around 6 s and 7 s, for $n_{\text{min}} = 14$ it is at 2 s, though the rise afterwards until 6 s is not dramatical. Looking at the p-value versus arrival time after mixing for all FI runs, the minimum is found at 6 s which is the chosen cut off value for further analysis.

5.3. Comparison with AMT and FIC time distribution

The time distribution of antihydrogen atoms produced has been measured additionally by two other methods. A comparison to the distribution obtained by the antihydrogen detector is given in the following.

As described in Section 2.4, the AMT detector is placed around the mixing region of the trap in order to monitor antihydrogen synthesis in the double-CUSP trap. Furthermore, the mixing trap features a field ionisation well FIC (Field Ioniser in the CUSP) downstream of the mixing region which ionises antihydrogen atoms with $n > 43$, the resulting antiprotons are trapped in the

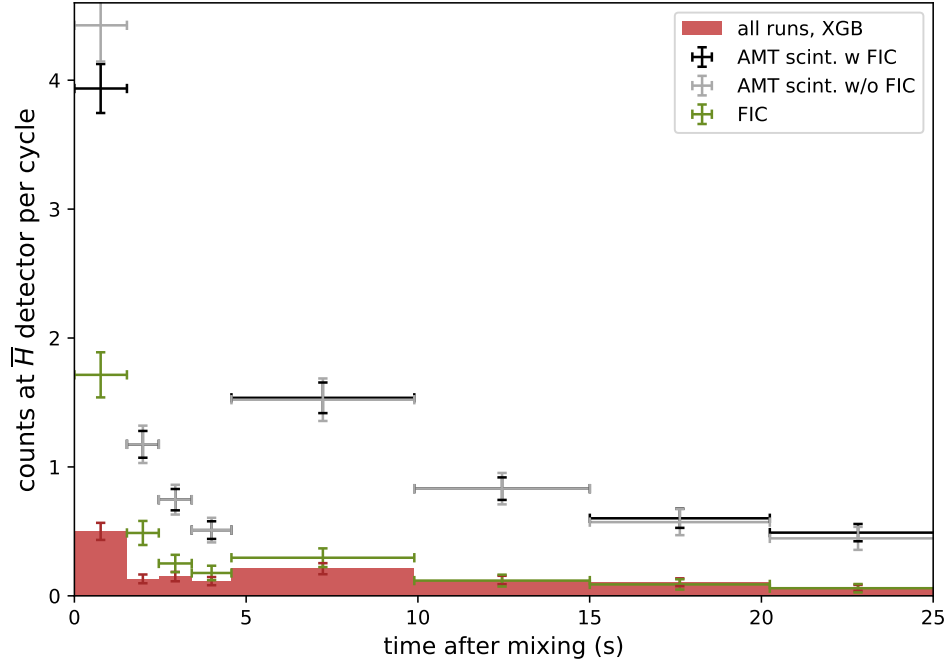


Figure 5.12.: Time distribution of antihydrogen events after mixing start signal at the antihydrogen detector: Estimation from the observed time distribution of the AMT detector during mixing runs with and without FIC (grey, black). Estimation from ionised antihydrogen atoms trapped in the FIC are shown in green and measured distribution by the antihydrogen detector in red. AMT and FIC data have been extracted from Figure 3.41 in Ref. [55], run numbers are listed in Appendix A.8.

well (potentials can be seen in Figure 2.5 in Section 2.4). When the trapped antiprotons are released, they annihilate and can be counted.

Therefore, the time distribution of synthesised antihydrogen atoms can be measured by three different methods: (1) counting the ionised antihydrogen atoms trapped in the FIC well, (2) counting the antihydrogen atoms annihilating at the inner wall of the MRE via the AMT detector and (3) via the antihydrogen detector as discussed in the previous section.

In order to compare the results of the different detection methods, their relative solid angles need to be considered. This has been determined by M. Tajima with Monte-Carlo simulations, see Ref. [55]. The full double-CUSP geometry and the electric-field distribution inside have been simulated and antihydrogen atoms have been emitted isotropically from the mixing region. The principal quantum number distribution of the simulated antiatoms has been estimated from the measurements. The relative detection efficiencies have then been calculated from the fraction of the total number of events reaching the AMT, the antihydrogen detector and antiatoms being trapped in

the FIC. From this, the expected number of $\bar{H}$ at the antihydrogen detector has been estimated from the measured FIC and AMT time distributions.

Results compared to the time distribution determined at the detector in this thesis can be seen in Figure 5.12. The green crosses show the estimated counts at the $\bar{H}$ detector determined from the FIC counts. The FIC measurement requires opening and closing of the ionisation well during mixing. When the ionisation well is closed, antiprotons from ionised antihydrogen atoms are accumulated. When the well is opened those antiprotons escape and can be counted. In order to cover the whole time span of the mixing process, two measurements with reversed opening and closing periods were performed [55]. The FIC measurement includes 56 runs (run numbers are listed in Appendix A.8). The varying bin width of the histograms arises from the varying time intervals chosen for the field ionisation cycle of the FIC. The red histogram shows the time distribution determined by the discussed machine learning analysis using the same binning. Black and grey histogram shows the expected time distribution estimated from the events detected by the AMT scintillators (double coincidence) during mixing runs with and without FIC well, respectively.

The estimation from the AMT detector shows much higher counts for all time intervals after the mixing start, especially for the first second. Above $t \gtrsim 3$ s, the observed counts by the FIC estimation and the antihydrogen detector agree, meaning that their Poisson error bars show an overlap. For $t \lesssim 3$ s however, the counts predicted from the measurements by the FIC show much higher counts than have been measured by the detector at the end of the beamline.

This large discrepancy in antihydrogen numbers observed by the different detectors which see different angles of the mixing process gives rise to the assumption of a possible spatially non-isotropic production of antihydrogen atoms. A possible explanation of this apparent asymmetric emittance from the mixing region could be a radial component of the produced antiatoms that could stem from the rotation of the plasmas in the trap. Monte-Carlo simulations assuming a non-isotropic production have been carried out in [55]. In those simulations, a certain axial component of the produced antiatoms has been removed by neglecting antihydrogen atoms emerging from the mixing region that have trajectories with a small angle θ to the beam axis. Afterwards, resulting time distributions of the three detection methods have been compared again and it was found that the best agreement between them can be achieved by removing antihydrogen atoms emerging with an angle of

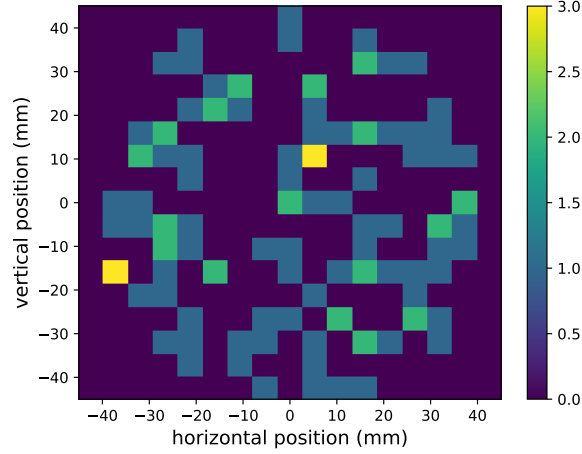


Figure 5.13.: Two-dimensional histogram of hit positions on the BGO central calorimeter of antihydrogen candidate events of the mixing runs dedicated to the measurement of the quantum state distribution. Events arriving within the first 6 s after mixing start have been considered (117 events in total).

$\theta \leq 1.15^\circ$ to the beam axis. The reason for a possible radial component is still under investigation.

Figure 5.13 shows a two-dimensional histogram of the hit positions of antihydrogen candidates on the BGO calorimeter (determined by the cluster finding algorithm discussed in Section 3.6.4). Events of the $(X_m^q, ?)$ data set arriving within 6 s after the mixing start signal have been considered. However, due to the low statistics, no conclusions about the beam shape can be drawn.

5.4. Quantum state distribution

The resulting principal quantum number distribution is displayed in Figure 5.14, the count values per run can be found in Table 5.2. The x -axis shows $n_{\min}$, the minimum principal quantum number that is ionised by the corresponding voltage setting of the external field ioniser. Therefore, counts per run on the y -axis include atoms with $n < n_{\min}$. As explained in the last section, only events arriving within the first 6 s after the mixing start signal are considered. Note, that the quantum state distribution has been published earlier in [40] and the result presented in this thesis is an updated version.

Clearly a higher fraction of atoms reaching the entrance of the spectroscopy beamline are in Rydberg states which is expected for 3-body-recombination [67], the dominant creation process in ASACUSA. However,

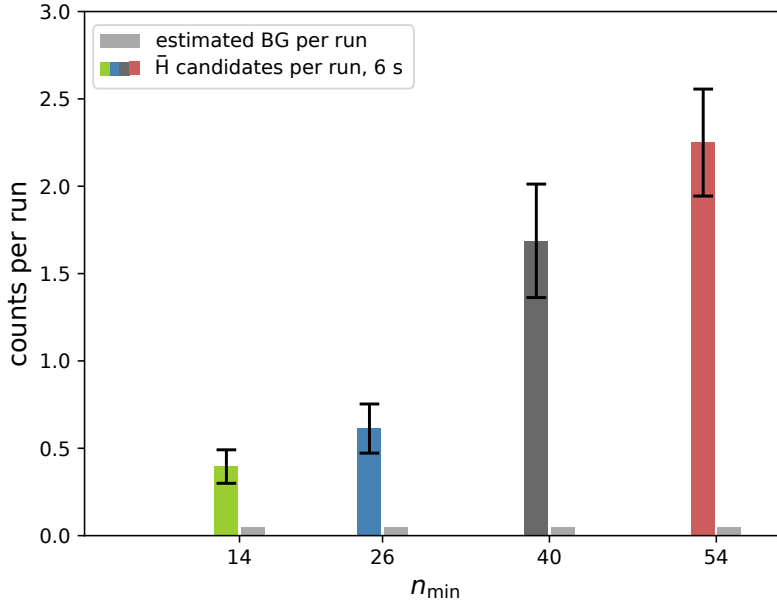


Figure 5.14.: Principal quantum number distribution: counts per run as a function of $n_{\min}$, the minimum principal quantum number that is ionised by the corresponding voltage setting of the external field ioniser. Events arriving in 6 s after mixing start signal in colours and the estimated background events in grey. The error bar shown is the Poisson error.

since the counts per run are plotted in dependence of $n_{\min}$ and bins corresponding to higher principal quantum numbers therefore include also contributions of antiatoms displayed in bins of the lower $n_{\min}$ values, the rise towards higher n s appears stronger.

The distribution in dependence of n instead of $n_{\min}$ can be obtained by considering the difference between the bins and their lower neighbouring bins of Figure 5.14, e.g. the number of antihydrogen atoms per run with principal quantum numbers in the interval $[14, 26)$ can be calculated by subtracting the bin of $n_{\min} = 14$ from the one of $n_{\min} = 26$. The results are shown in Figure 5.15. The error bars have been calculated from the Poisson errors of Figure 5.14 and error propagation. Due to the low statistics and the resulting large error bars, no meaningful conclusions about the shape of the distribution can be drawn.

Most important for ASACUSA's measurement of the ground state hyperfine transition frequency, are the number of antihydrogen candidate events in the lowest-lying quantum states. The rate of candidate events in states with $n < 14$ is 0.395 ± 0.096 (Poisson error) per run with an observed significance

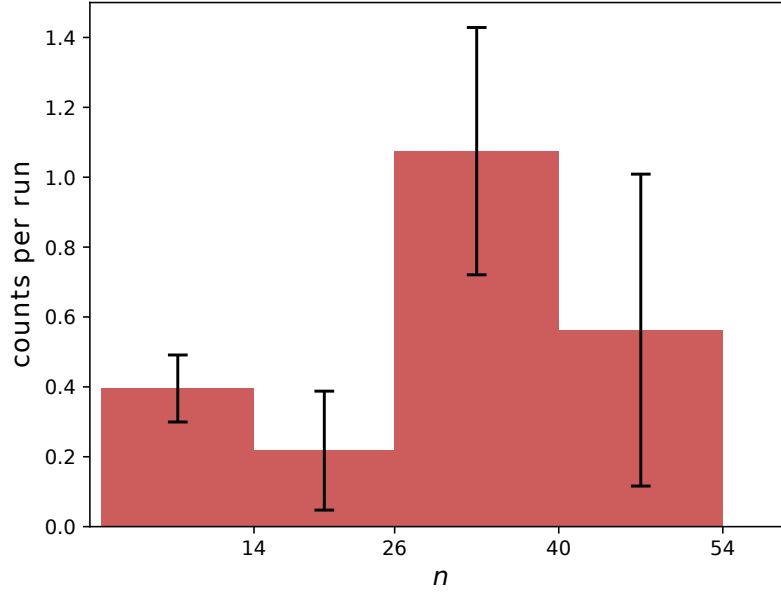


Figure 5.15.: Antihydrogen candidate events per run as a function of n . The error bars have been calculated via error propagation from the Poisson errors shown in Figure 5.14.

of 6.8σ determined via equation 5.3. Considering velocities² of 1000 m/s and that their longest decay channel to the ground state is $\approx 100 \mu\text{s}$ [40], it follows that those states have a good chance to decay into the ground state before reaching the cavity³.

ASACUSA reached their first milestone towards antihydrogen spectroscopy in 2012, the production and observation of cold antihydrogen atoms 2.7 m away from the mixing region [114]. The employed mixing scheme was direct injection, as described in Section 2.4.1. The measurement of the principal quantum number distribution is the first characterising measurement and a next big step towards spectroscopy. However, it also shows that, in order to reach the goal of a ppm measurement of the ground state transition frequency, the production rate of atoms with $n < 14$ needs to be increased by 1 to 2 orders of magnitude⁴ in order to perform spectroscopy and reach ppm precision on the ground state hyperfine transition frequency in the typical amount of beamtime available.

Therefore, ASACUSA’s focus for the subsequent beamtimes was on im-

²1000 m/s is the limit of accepted velocities of the spectroscopy setup.

³Except for antiatoms decaying to the metastable 2S state.

⁴based on estimations from the results of measurements with hydrogen and the ASACUSA spectroscopy apparatus, see Ref. [33]

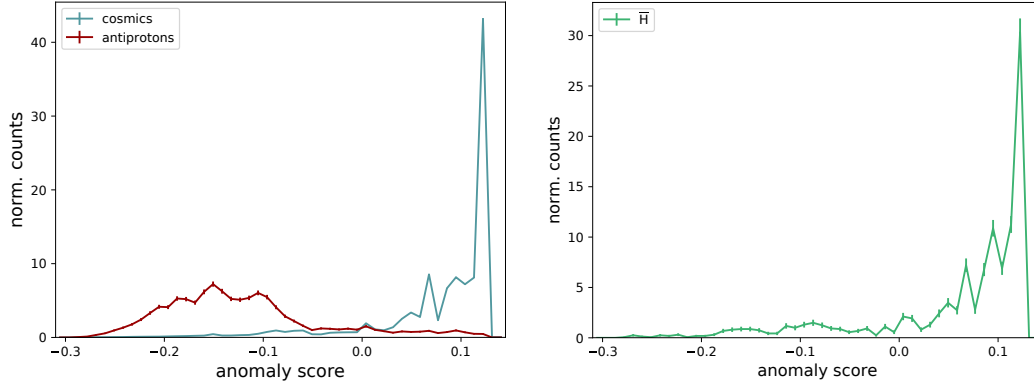


Figure 5.16.: Histogram of the anomaly score. *Left:* for events in the mixing data set ($X_m^q, ?$). *Right:* for cosmic (blue) and antiproton events (red) The histograms are normalised to their area.

proving beam intensity and quantum states. New mixing schemes have been investigated to overcome the low rates. Also, efforts on improving the density and temperature of the positrons have been made since a strong dependence on the positron plasma properties is expected [68].

Note, that this is also the first measurement of the quantum state distribution of antihydrogen atoms produced in 3-body-recombination *in a field-free region*. The quantum distribution has been measured before by the ATRAP collaboration down to $n = 48$. [75]. ASACUSA’s measurement is therefore the first one down to quantum numbers as low as $n = 14$. Also, ATRAP’s measurement was performed inside a large B-field of 5.4 T, where the assumed dependence of n on the ionising electric field is not valid [115]. This leads to a large uncertainty of their result and the ASACUSA measurement discussed here gives therefore a more reliable result of the quantum state distribution of produced antihydrogen atoms.

5.5. Comparison to results of the IF analysis

As opposed to the GBDT analysis, which is a supervised machine learning method, the IF analysis belongs to the category of anomaly detection. As discussed in Section 4.4, the IF algorithm is trained with an unlabelled data set consisting of abundant “normal” events (cosmics) and rare outlier (antihydrogen events). It returns an anomaly score a for events that predicts its class.

The resulting distributions of anomaly scores a for events in the mixing data set and for cosmic and antiproton data are displayed in Figure 5.16. Scores

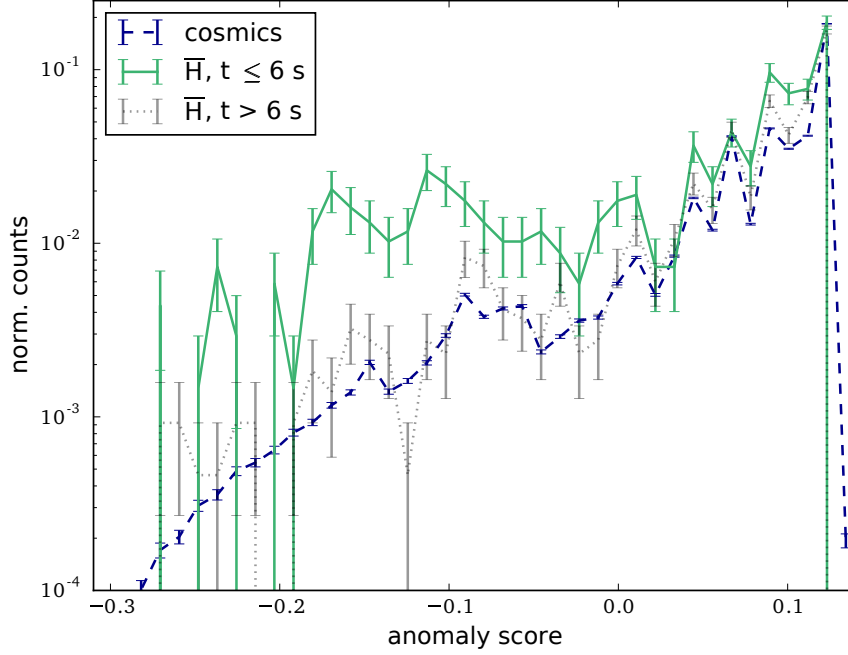


Figure 5.17.: Histograms of the anomaly score for cosmic test set (dashed, dark blue) and mixing data with logarithmic scale of the y -axis. Events at the detector in $[0, 6 \text{ s}]$ (dotted, gray) and events in $(6 \text{ s}, 25 \text{ s}]$. The histograms are normalised to their acquisition time.

are distributed in a range of $[-0.28, 0.18]^5$ and histograms are normalised to their area.

Cosmic and antiproton distributions show a nice separation. This is especially notable since only a few event features have been used and the training is only based on the unlabelled mixing data set, a mixture of cosmic particles and a small fraction of antihydrogen annihilations.

The cosmic distribution shows a tall narrow peak at high anomaly scores and a few smaller peaks next to it followed by a tail. The peak structure is a result of events with very similar characteristics resulting into similar scores a . For example, the highest peak contains events with two tracks, $N_u = N_d = 1$ and $N_h = 0$, which are the characteristics of a typical cosmic event passing the detector from above. Antiproton annihilation events result in a broad peak at lower scores and a tail towards higher scores.

The mixing data set exhibits a structure very similar to the cosmic distribution which naturally results from the dominance of cosmic events in the set. The contribution to higher scores can be clearly seen in the logarithmic

⁵The algorithm returns $0.5 - a$.

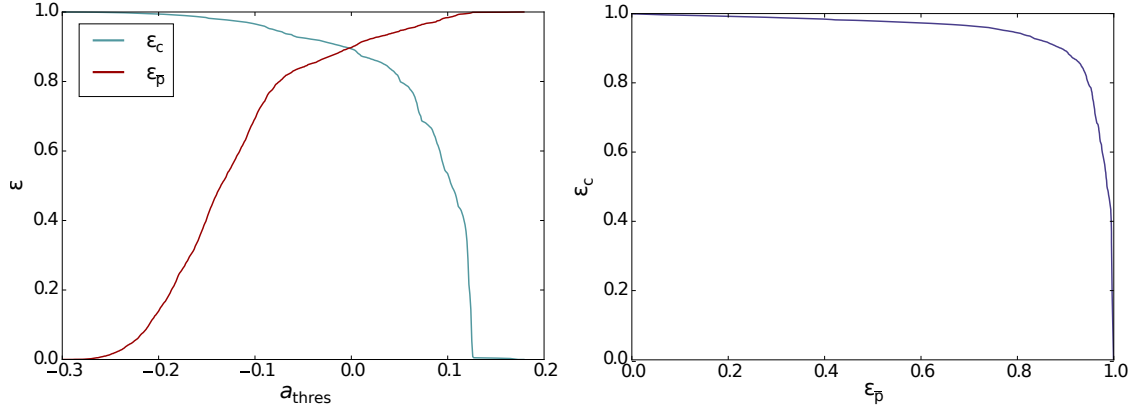


Figure 5.18.: *Left*: cosmic (blue) and antiproton (red) efficiency in dependence of a_{thres} . *Right*: ROC curve of the isolation forest.

plot, see Figure 5.17, and indicates the presence of antihydrogen events. The histograms in this plot are normalised to their acquisition time. Since it is known from the GBDT analysis that most antihydrogen events reach the detector in the first few seconds after mixing start, the data can be split in events with $t > 6$ s and $t \leq 6$ s and compare their anomaly score distributions, see Figure 5.17.

The data containing events below 6 s after mixing start (green) clearly shows an excess for lower anomaly scores while the events after 6 s (grey) closely resemble the background distribution (dark blue). Also, the excess of events between -0.2 and -0.1 in the green histogram lies in the same anomaly region as the peak of the antiproton distribution.

The cosmic and antiproton efficiency in dependence of a_{thres} is shown in Figure 5.18 (left) and the resulting ROC curve in Figure 5.18 (right). The achieved A_{ROC} amounts to 0.94.

Antihydrogen candidate events can now be selected by setting a cut a_{thres} on the anomaly score and considering events below. In order to determine an appropriate a_{thres} , the procedure as applied for the GBDT analysis is used. The cut value is scanned in the range of the anomaly score $[-0.28, 0.18]$ and the p-value of the found counts is monitored.

The p-value of the found candidate events in dependence of the anomaly cut value a_{thres} is presented in Figure 5.19. Its minimum is found at -0.034 and the resulting cosmic rejection ε_c , false positive rate and antiproton efficiency ε_p are summarised in Table 5.3. The antihydrogen candidate events and false positives for the runs dedicated to the measurement of the quantum state distribution are summarised in Table 5.4.

Comparing A_{ROC} of the IF and the GBDT analysis, shows that the IF is

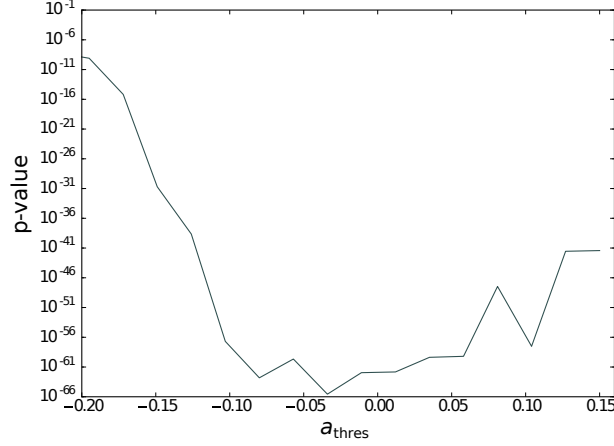


Figure 5.19.: P-value versus the cut value a_{thres} on the anomaly score.

$a_{\text{thres}} = -0.034$	
cosmic rejection ε_c	0.9175 ± 0.0025
false positive rate (Hz)	0.0386 ± 0.0012
$\bar{p}$ efficiency $\varepsilon_{\bar{p}}$	0.8597 ± 0.0050

Table 5.3.: Summary Table of cosmic rejection, false positive rate and antiproton efficiency for $a_{\text{thres}} = -0.034$.

a bit less efficient. However, surprisingly not by a lot considering that it is based on only a mixed data set. Furthermore, only the 7 most basic features have been used (E_{BGO} , n_I , n_O , N_{tracks} , N_h , N_u and N_d) which makes the achieved results quite impressive. Of course, without applying the analysis to additional signal and background data sets, no estimation of cosmic rejection, antiproton efficiency and false positive rate can be made.

The analysis still needs a fair amount of total number of events in the mixed data set in order to work, so it can only be used after a few weeks of data taking, but it can still serve as an alternative if no signal data set is at hand and as a cross check to other analysis methods.

With a cut of $a_{\text{thres}} = -0.034$, the isolation forest analysis finds 154 candidate events in $(X_m^q, ?)$ considering events arriving at the detector in the first 6 s after mixing start. The GBDT analysis found 112, but has a higher cosmic rejection. Comparing found events directly, the two methods have 107 candidate events in common which is 95.5% of the total number of events of the GBDT analysis. The agreement is quite impressive.

Taking a closer look at the five events that were not selected by the isolation forest algorithm, but by the GBDT algorithm, it is found that all of them are events with two tracks (key characteristic for cosmics) but with

$\Delta t = [t_{\text{start}}^{\text{mix}}, 25 \text{ s}]$					
n_{min}	runs	n_{obs}	$n_{\text{obs}}/\text{run}$	n_b	n_b/run
14	43	65	1.512	41.487 ± 1.236	0.965 ± 0.029
26	31	53	1.710	29.910 ± 0.891	0.965 ± 0.029
40	16	51	3.188	15.437 ± 0.460	0.965 ± 0.029
54	24	95	3.958	23.156 ± 0.690	0.965 ± 0.029
$\Delta t = [t_{\text{start}}^{\text{mix}}, 6 \text{ s}]$					
14	43	29	0.674	9.957 ± 0.297	0.232 ± 0.007
26	31	33	1.065	7.178 ± 0.214	0.232 ± 0.007
40	16	31	1.938	3.705 ± 0.110	0.232 ± 0.007
54	24	61	2.542	5.557 ± 0.166	0.232 ± 0.007

Table 5.4.: Summary of run numbers, their corresponding n_{min} , found event numbers and false positives for $\Delta t = [t_{\text{start}}^{\text{mix}}, 25 \text{ s}]$ (top) and $\Delta t = [t_{\text{start}}^{\text{mix}}, 6 \text{ s}]$ (bottom).

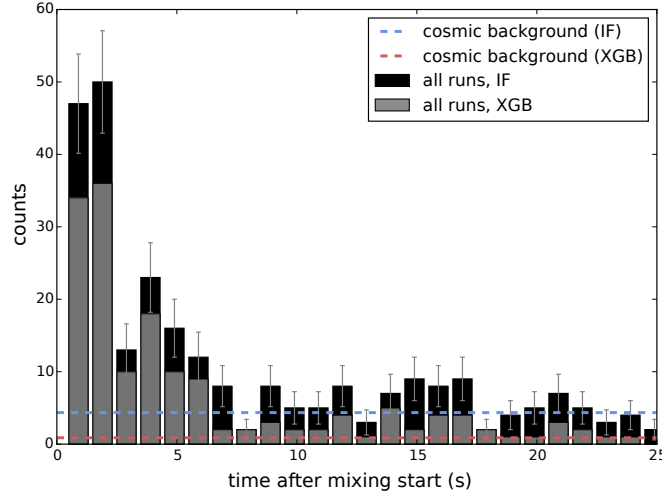


Figure 5.20.: Detector arrival time distribution for antihydrogen candidates recorded during FI mixing runs (data set $(X_m^q, ?)$). Histograms of the isolation forest (black) and the XGB analysis (grey) are overlaid. The dashed, blue line shows the estimated cosmic background of the isolation forest for the 114 runs considered. The dashed, red line shows the estimated background for the GBDT analysis.

a low ToF indicating that they originated from the inside of the detector. Since the isolation forest was trained without the ToF feature, it has an expected tendency of assigning two track events a higher anomaly score. The 47 events the isolation forest analysis sees more, seem to have mostly cosmic-like characteristics. Also the comparison of the arrival time distributions indicates this conclusion, see Figure 5.20. The excess in the histogram of isolation forest (black) over the GBDT histogram (grey) seems mostly in accordance with the estimated background (dashed, blue line).

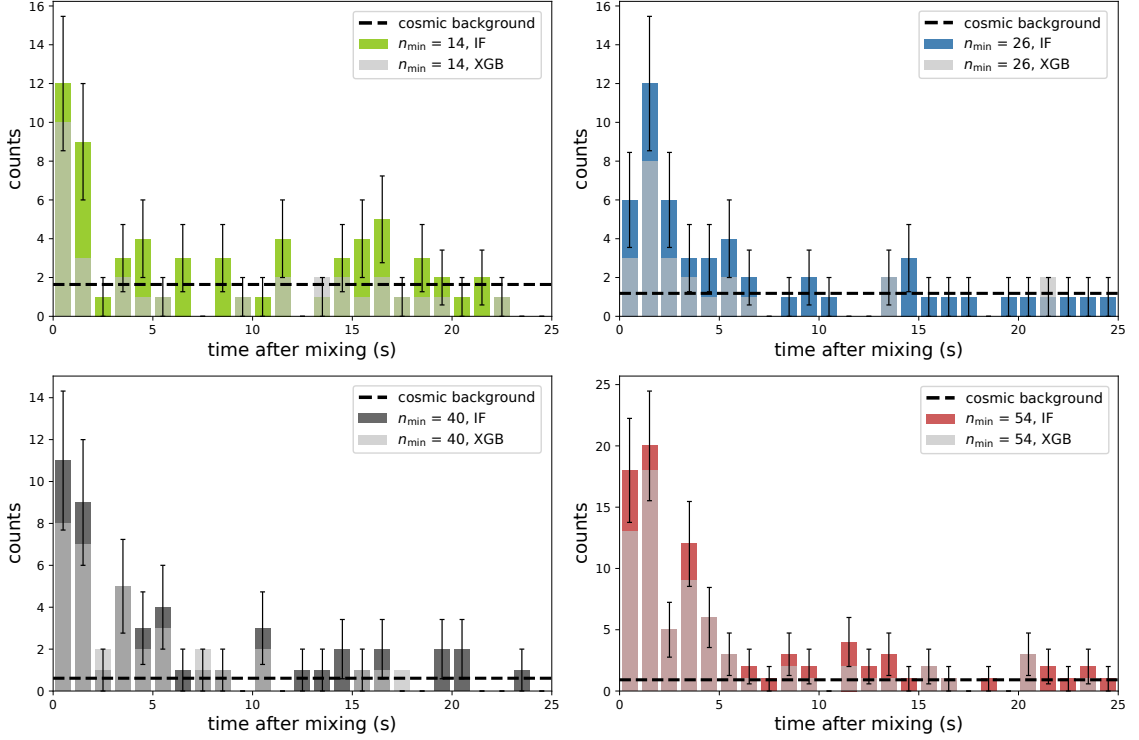


Figure 5.21.: Detector arrival time distribution for antihydrogen candidates recorded during mixing runs (X_m^q , ?) for the different FI settings. The coloured histograms show IF results, the gray, overlaid histogram show the GBDT results. The dashed, black line shows the estimated cosmic background of the IF analysis for the 114 runs.

Interestingly, the only excess of candidate events not in agreement with the estimated background is found in the first two seconds after mixing start. As mentioned earlier, most annihilations in the FI well in the CUSP are seen in the very first second. Figure 5.21 shows the individual time distributions of the four external field ioniser settings in comparison with the GBDT analysis.

The resulting quantum state distribution of the isolation forest analysis is displayed in Figure 5.22 (colours). For comparison, the GBDT results are also shown (faded colours). In order to facilitate the comparison, the estimated background has already been subtracted for both results and is shown below as negative bins (grey). The two agree well, the Poisson error bars show an overlap for all four $n_{\min}$.

The rate of antihydrogen events with $n < 14$ for the IF algorithm is 0.674 ± 0.125 (Poisson error) per run with an observed significance of 5.0σ . Therefore, the analysis based on gradient-boosted decision trees is favoured since it shows a higher significance, namely 6.8σ , for found antihydrogen candidates $n < 14$.

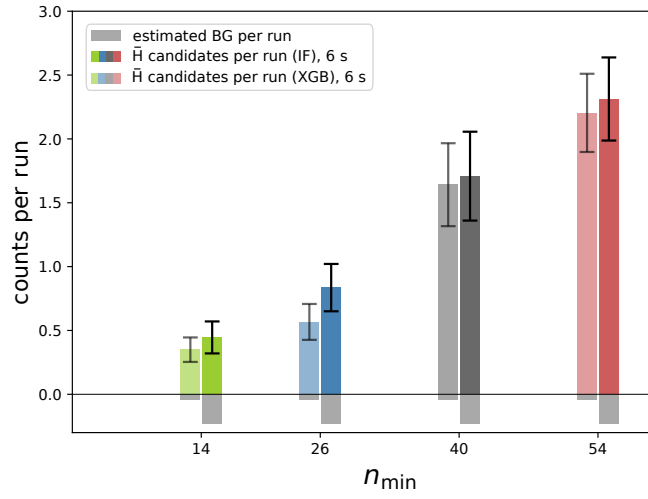


Figure 5.22.: Principal quantum number distribution of the produced antihydrogen atoms. Isolation forest analysis (coloured) and GBDT analysis (faded colours). estimated background counts have been subtracted to facilitate comparison. The grey negative bins show the estimated background for the two analysis method. The errorbars show the Poisson error.

6. Three-dimensional tracking

The fibre upgrade of the tracking detector enables the study of charged particle tracks in three dimensions. The main purpose of the upgrade is to enhance the vertex capability of the detector in order to discriminate annihilations on the central BGO calorimeter (or any other target) inside the tracking detector from annihilations close by on the beampipe. During mixing runs, this additional background source could stem from antihydrogen atoms in high-field seeking states defocussed by the sextupole magnet. Currently conducted fragmentation studies in antiproton nucleus annihilations by ASACUSA have been briefly mentioned in the introduction chapter in Section 1.5. For those measurements, the central BGO calorimeter is replaced by a Timepix3 [116] detector (more details follow in Section 6.5.1) downstream of a thin target foil. It is important to identify antiproton annihilations on and outside the target material of interest. For both cases, knowing the z -position of the events helps to reduce the contribution of those upstream annihilations.

This chapter describes the three-dimensional tracking algorithm developed in the course of this thesis in order to find tracks and vertices of antihydrogen and antiproton annihilations with higher precision. Track finding, fitting, selection and vertex determination are discussed. A short overview of the strategy shall be given here: (1) Track candidates are found first by combining all position measurements i.e. detector hits in the fibre and bar detector into possible subsets, then (2) a track model is fitted to all candidates in the track collection and (3) those candidates that best fit the model are selected. In the end (4), the tracks are used for determining the vertex of the events. Note, that the hit position on the central detector has not been included in the discussed algorithm in order to avoid assumptions about the vertex position and therefore to prevent an induced bias.

The algorithm is first tested with simulated data generated with the particle physics simulation tool-kit Geant4. The setup used for the simulations includes the tracking detector geometry and the BGO central detector. Afterwards, measured data taken during the Timepix3 annihilation studies is analysed and compared to simulations using a simple setup where the BGO detector is replaced by a carbon target foil.

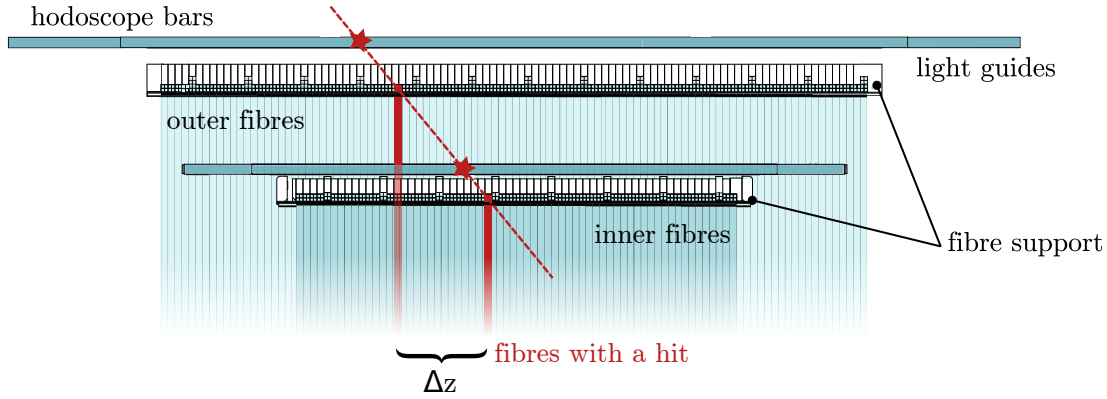


Figure 6.1.: z - y plane of the tracking detector. Two fibres with a hit are highlighted in red. Possible corresponding hit positions on the bars of the same particle track are marked with red stars.

6.1. Associating bar and fibre detector hits

Firstly, hits in the four detector layers that belong to the same track need to be identified. Every event yields a collection of bar hodoscope and fibre detector hits. The challenge lies now in associating hits of the two independent sub-detectors to the correct track of their origin.

The fibre detector has no resolution in x - and y -direction. As discussed in Section 3.3.2, the time resolution of the fibres is ≈ 8 ns, due to the time walk effect of the leading-edge discriminator. This is unfortunately not good enough to correlate the hits in time. Therefore, only the z -positions of bar and fibre detector give guidance for matching hits in the two detectors.

An intuitive way of finding possible bar and fibre hits belonging to the same track is sketched in Figure 6.1. The z - y cross section of the tracking detector is shown with two fibre channels highlighted in red symbolising possible hits. The z -position of the bar hits compatible to these fibres can be guessed by using the difference in z -position of fibres and the known distances between detector layers. They are marked by red stars in the figure. If hits in the bar hodoscope are found with agreeing z -positions, then the found combination of fibre and bar hits can be further investigated as a potential track candidate.

However, with increasing track number and due to the coarse z -resolution of the bar hodoscope ($\text{FWHM}_z = 73$ mm for the outer and 59 mm for the inner layer), the described approach loses its advantages over a simple combinatorial approach. It is therefore also faster, to simply consider all possible combinations of fibre and bar hits that have agreeing z -position measurements before doing a track selection by best fit.

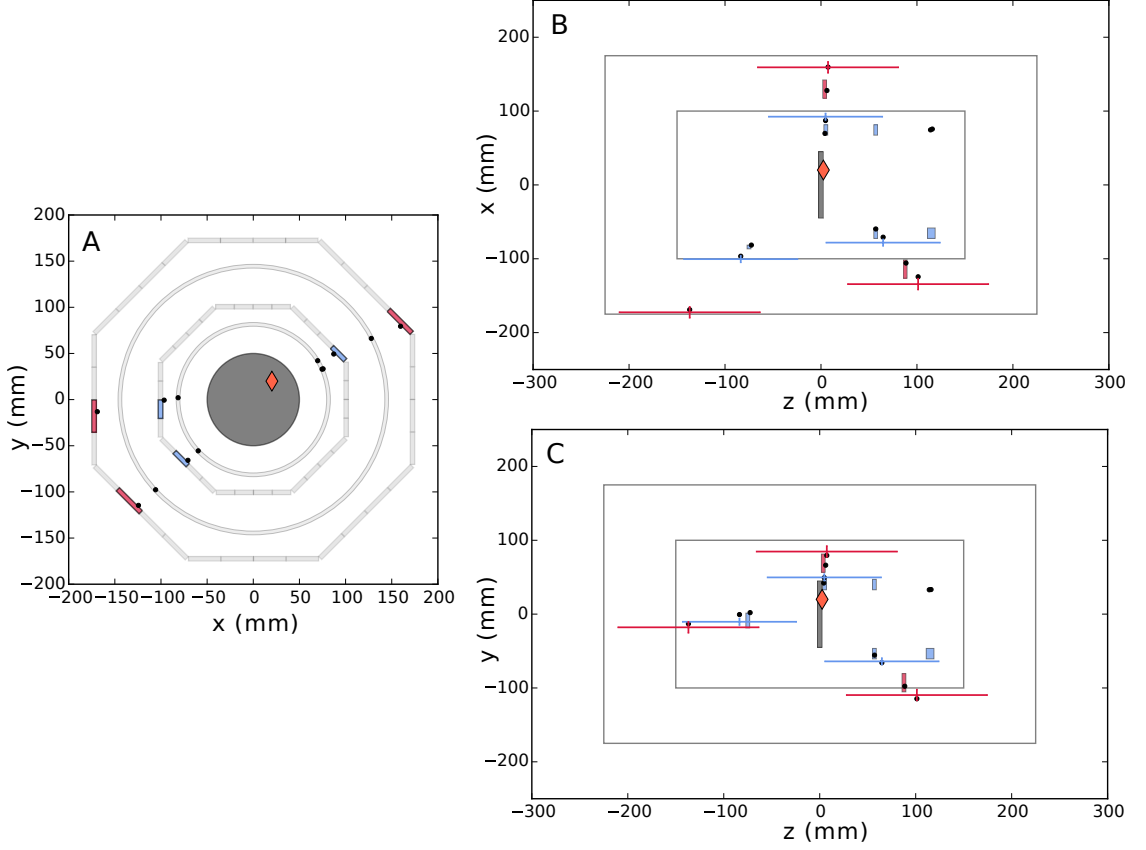


Figure 6.2.: Simulated antiproton event. x - y (A), z - x (B) and z - y (C) plane of the detector, where z is the direction of the beam. A: The circle in the center symbolises the BGO crystal, the grey octagons the bar hodoscope layer and the grey rings the fibre layers. The coloured bars are those with a hit, blue for the inner and red for the outer layer. B and C: The two grey rectangles indicate the inner and outer bar hodoscope, the dark grey narrow box in the center symbolises the BGO. Red and blue crosses show hits in the outer and inner bar hodoscope, respectively. Their width in x - and y -direction is determined by the bar geometry, in z -direction by the measured position resolution. The small blue and red rectangles represent hits in the fibre detector, their dimension in x - and y -direction is determined by the hodoscope bar the fibre overlaps in z , and by the width of the fibre (4 mm) in z -direction. The black dots show hit positions on the sensitive detector parts extracted from the simulations. The orange diamond shows the annihilation position on the BGO.

As a first step, fibre and bar combinations are found in pairs for inner and outer layer separately. If their position measurements overlap, i.e.:

$$[z_b - 2\sigma_{z,b}, z_b + 2\sigma_{z,b}] \cap [z_f - 2\sigma_{z,f}, z_f + 2\sigma_{z,f}] \neq 0 \quad (6.1)$$

they are matched. Here, z_i is the position in z -direction and $\sigma_{z,i}$ the corresponding standard deviation for bars ($i = b$) and fibres ($i = f$). For the fibres a uniform distribution is assumed with standard deviation in z of $\sigma_{z,f} = \frac{w_z}{\sqrt{12}}$ with the width of a fibre bundle $w_z = 4$ mm.

Every found pair consists then of a bar hit ($x_{\text{bar}}, y_{\text{bar}}, z_{\text{bar}}$) and a fibre hit ($x_{\text{bar}}, y_{\text{bar}}, z_{\text{fibre}}$), where the x - and y -information of the associated bar are used since the fibres do not yield any x - and y -position information. The pairs are then added to a collection of associated hits for the corresponding layer.

Figure 6.2 shows an example of a simulated antiproton event where hits in the fibre and bar detector are indicated in colour, blue for the inner and red for the outer layer. The coloured squares in the z - x and z - y cross sections mark the intersection of fibres with bars they have been matching with.

For events with many tracks and due to the poor z -resolution of the bar hodoscope, the problem of double (or multiple) assignment complicates the track finding which is discussed in the next section. Double assignment can be seen for the inner hodoscope layer in Figure 6.2 *B* and *C* where the fibre at $z \approx 60$ mm could be associated to two of the bar hits (blue crosses) due to the overlap in z . The position information extracted from the simulation (black dots) shows the true fibre to bar assignment.

6.2. Track finding and fitting

In the next step, possible hit pairs of outer and inner layer are combined to track candidates that consist of four hits:

$$\text{track candidate} = \begin{pmatrix} x_{i,\text{bar}}, y_{i,\text{bar}}, z_{i,\text{bar}} \\ x_{i,\text{bar}}, y_{i,\text{bar}}, z_{i,\text{fibre}} \\ x_{o,\text{bar}}, y_{o,\text{bar}}, z_{o,\text{bar}} \\ x_{o,\text{bar}}, y_{o,\text{bar}}, z_{o,\text{fibre}} \end{pmatrix} \quad (6.2)$$

where index i denotes hits of the inner layer and o hits of the outer layer. In order to rule out non-physical track candidates, only combinations of inner and outer hits that are close to each other are considered i.e. if the channel number of the hit in the outer layer n_{outer} is in the interval $[n_{\text{inner}} - 2, n_{\text{inner}} + 2]$.

Fibre hits with no matching bar partner are omitted, since for those hits no x - and y -information needed for 3D fitting can be associated. Bars with no matching fibre are added to the collection, resulting in track candidates with only three instead of four hits.

Afterwards, all track candidates are fitted. The errors on the detector hits used for the fit are summarised in table 6.1. For the hodoscope bars, the z -error is the measured standard deviation. As in the pair matching procedure, for the fibres a uniform distribution across the fibre width is assumed. For x - and y -positions also a uniform distribution is used. Depending on which of the eight panels of the hodoscope layers the considered bar is positioned i.e. what angle α the bar has with respect to the x -axis, the standard deviations for x and y are calculated by:

$$\begin{pmatrix} \sigma_x \\ \sigma_y \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} w_{\text{bar}}/\sqrt{12} \\ t_{\text{bar}}/\sqrt{12} \end{pmatrix} \quad (6.3)$$

with the width of the bars w_{bar} (20 mm and 30 mm for inner and outer layer, respectively) and the bar thickness t_{bar} which is 5 mm for both layers.

Coordinate	inner bars	outer bars	fibres
x and y	$\begin{pmatrix} \sigma_x \\ \sigma_y \end{pmatrix} = R(\alpha) \begin{pmatrix} 20 \text{ mm}/\sqrt{12} \\ 5 \text{ mm}/\sqrt{12} \end{pmatrix}$	$\begin{pmatrix} \sigma_x \\ \sigma_y \end{pmatrix} = R(\alpha) \begin{pmatrix} 30 \text{ mm}/\sqrt{12} \\ 5 \text{ mm}/\sqrt{12} \end{pmatrix}$	same as bars
z	25 mm (σ_z)	31 mm (σ_z)	4 mm/ $\sqrt{12}$

Table 6.1.: Table summarising the errors in x , y and z on the detector hits used for the fit. $R(\alpha)$ is the rotation matrix defined in equation 6.3.

Subsequently all track candidates are fitted with a track model, in this case a straight line with the following parametrisation:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} p_0 \\ 0 \\ p_1 \end{pmatrix} + t \begin{pmatrix} \cos(p_2) \sin(p_3) \\ \sin(p_2) \sin(p_3) \\ \sin(p_3) \end{pmatrix} \quad (6.4)$$

Parameter p_0 and p_1 are x - and z -coordinate of a point on the line and p_2 and p_3 are the angles used for the spherical representation of the direction vector of the parametrisation. t is a free parameter with $t \in \mathbb{R}$. For fitting, ROOTs minimiser `Minuit2` is used [117]. Parameters, their start values and errors, step sizes and function to minimise need to be defined by the user.

In order to find good start values for the fit, the vector from the inner most to the outer most detector hit is determined and used to calculate the

corresponding polar and azimuth angle which are used as starting values for p_2 and p_3 ; for p_0 and p_1 simply zero is used.

The merit function to be minimised is chosen as follows:

$$\chi^2 = \sum_{i=0}^N \frac{d_i^2}{\sigma_{x,i}^2 + \sigma_{y,i}^2 + \sigma_{z,i}^2} \quad (6.5)$$

where N denotes the number of points to fit, d_i the distance between point $\vec{x}_i$ to the line, and $\sigma_{j,i}$ with $j = x, y, z$ the errors on the x -, y -, z -coordinates of the point. The distance d is determined simply via $(\vec{x}_i - \vec{x}_0) \times \vec{u}_{\text{dir}}$, with $\vec{x}_0$ being a point on the line and $\vec{u}_{\text{dir}}$ a unit vector pointing in the direction of the line.

The left column of Figure 6.3 shows a simulated example antiproton event and the fits of all possible track candidates (dashed lines). After fitting all track candidates, only those with convergence and full covariance matrix of the fit are further looked into. They are sorted by the found minimum value of the merit function in ascending order. Then they are successively added to the final track collection while removing tracks from the candidate collection that contain bar and fibre hits that are already contained in a track of the final collection. The right column of Figure 6.3 shows the tracks selected (coloured, solid lines) in the described manner for the simulated antiproton event.

Note, that in order to make the simulations more accurate and realistic, the coarse z -resolution of the hodoscope bars needs to be included in the simulations by adding a Gaussian distributed random number with a standard deviation of $\sigma_{\text{bar},z}$ to the z -position of the hit of secondaries on the bars. This has not been done for the simulated events displayed in the plots in this section for reasons of comprehensibility of the plots, but are included in the tracking results discussed in Sections 6.4.2 and 6.4.3.

Note, that due to the missing x - and y -position resolution of the fibre detector and the assignment of bar information to the fibres instead, a bias on the vertex (x, y) position towards the center of the BGO is induced. This effect is illustrated in Figure 6.4. The Figure shows the x - y view of a simulated $\bar{p}$ event with two tracks. The tracks found in the above described fashion are indicated with sold lines (orange and yellow). They pass through the center of the bars and therefore meet in the center of the BGO. Exact hit positions on the bars and fibres are marked with black dots and black lines show the actual tracks. The only way of eliminating this bias would be to add x - and y -capability to the fibre detector by e.g. improving its time resolution.

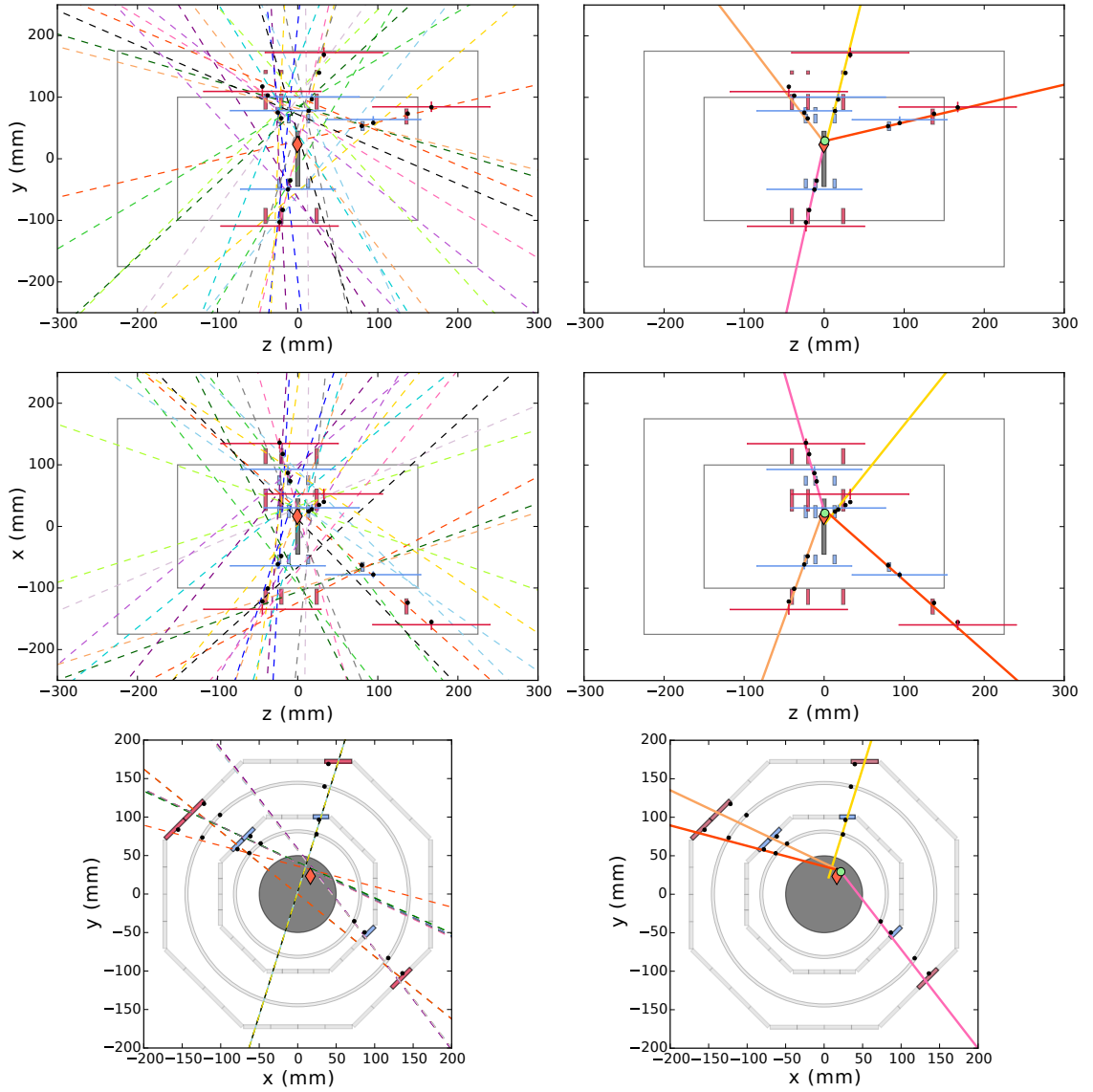


Figure 6.3.: Simulated antiproton event. x - y , z - x and z - y planes of the detector showing hits in the outer layers of the detector in red and in the inner layer in blue. Black dots mark hit position information extracted from simulations. Crosses show bar hodoscope hits and rectangles fibre hits. Lines show fitted track candidates where each track has the same colour in all three projections. The orange diamond marks the annihilation position of the simulated $\bar{p}$. *Left column:* Dashed lines show all fitted track candidates before selection (31 for this particular event). They are drawn over the whole range of the plot. *Right column:* solid lines show the selected tracks. The green dot shows the reconstructed vertex, see Section 6.3.

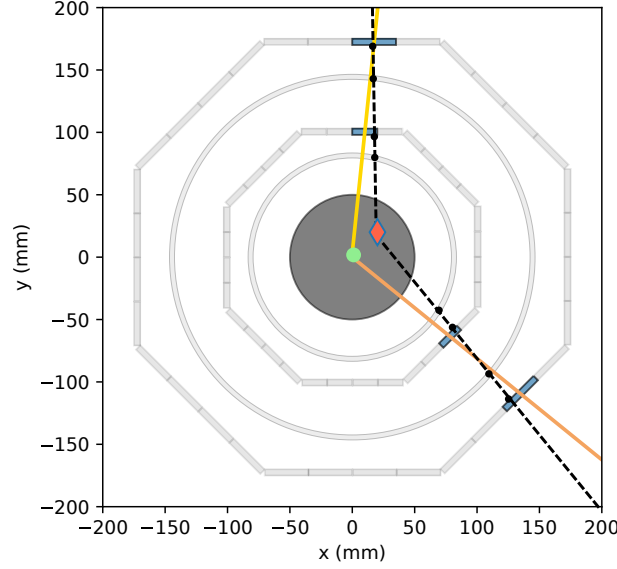


Figure 6.4.: x - y view of a simulated antiproton event. Tracks found by the developed 3D tracking algorithm are shown with solid lines (orange and yellow). Exact hit positions of secondaries in the scintillators extracted from simulations are marked with black dots and the tracks with black, dashed lines. The orange diamond shows the simulated annihilation position and the green dot the vertex determined by the algorithm.

6.3. Vertex reconstruction

The next step after finding and fitting the tracks, is determining the vertex. Firstly, the shortest distance between pairs of tracks and the corresponding nearest points on the two straight lines are found. For a pair of fitted tracks with the following parametrisations:

$$\vec{x}_k = \vec{p}_k + t\vec{d}_k \quad (6.6)$$

where $\vec{p}_k$ is a point and $\vec{d}_k$ the direction vector of the line, the nearest point on line i to line j is calculated by [118]:

$$\vec{p}_{c,i} = \vec{p}_i + \frac{(\vec{p}_j - \vec{p}_i) \cdot \vec{n}_j}{\vec{d}_i \cdot \vec{n}_j} \vec{d}_i \quad (6.7)$$

with $\vec{n}_j = \vec{d}_j \times (\vec{d}_i \times \vec{d}_j)$. The midpoint of the nearest points of a pair of lines i and j is calculated by $\vec{m}_{ij} = \frac{1}{2}(\vec{p}_{c,i} + \vec{p}_{c,j})$. Figure 6.5 shows an example antiproton event and the corresponding nearest points (coloured dots) and midpoints (black crosses).

The vertex can then be defined e.g. as the mean of all the midpoints, or a better approximation can be determined by a cluster finding algorithm

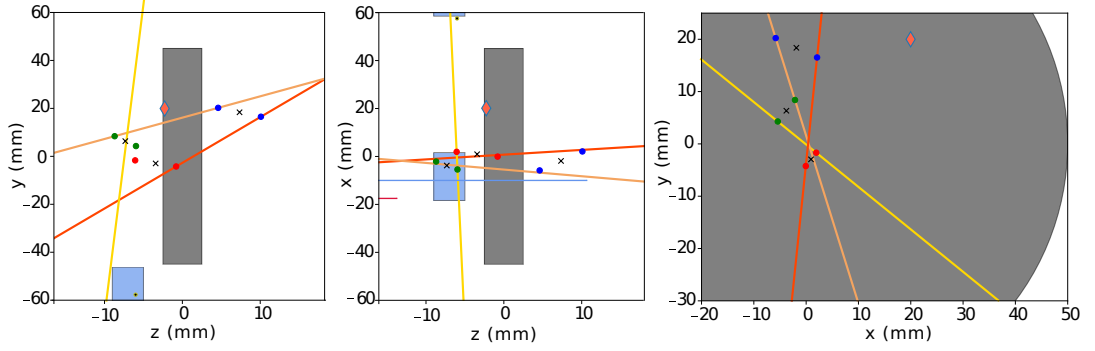


Figure 6.5.: z - y , z - x and x - y view of the detector showing a simulated antiproton event (zoomed in). The fitted tracks are shown as solid lines (yellow, orange, red). The nearest points on a track pair is indicated by dots of the same colour (red, blue, green) and their midpoints as black crosses.

applied to the cloud of midpoints. This helps to exclude wrongly selected tracks e.g. when there are many hits and the association problem of fibre and bar hits lead to a wrong track, see Figure 6.6. For the orange track, the bars have been matched with the wrong fibres and result into the midpoints highlighted with the dashed ellipses. Note also, that for the orange track, the algorithm has successfully matched the correct hits for inner and outer bar layer.

The python implementation of DBSCAN (Density-Based Spatial Clustering of Applications with Noise) [119] has been used to find clusters in the collection of midpoints. In a nutshell, DBSCAN categorises points that are closer together than a certain distance `eps` into clusters of minimum size `min_samples`. Points that cannot be classified to one of the clusters are marked as outliers. For a more detailed explanation of the DBSCAN algorithm, see reference [119].

The two parameters `eps` and `min_samples` need to be set by the user. The minimum number of points of a cluster depends in principle on the number of tracks. It can be simply set to 1, since if several clusters have been found, the largest one is selected for determining the vertex estimation.

In order to find an appropriate value for the minimum distance parameter `eps`, the distances between midpoints are studied with simulations. The antiprotons have been generated with trajectories parallel to the z -axis, with a distance of 11 cm from the BGO surface and hitting the BGO in the center. Details of the simulations are discussed in the next section.

After finding, fitting and selecting the tracks in the above described fashion, the resulting collection of midpoints has been investigated. The distribution of the average of the distances between midpoints $\bar{d}$ per event can be seen

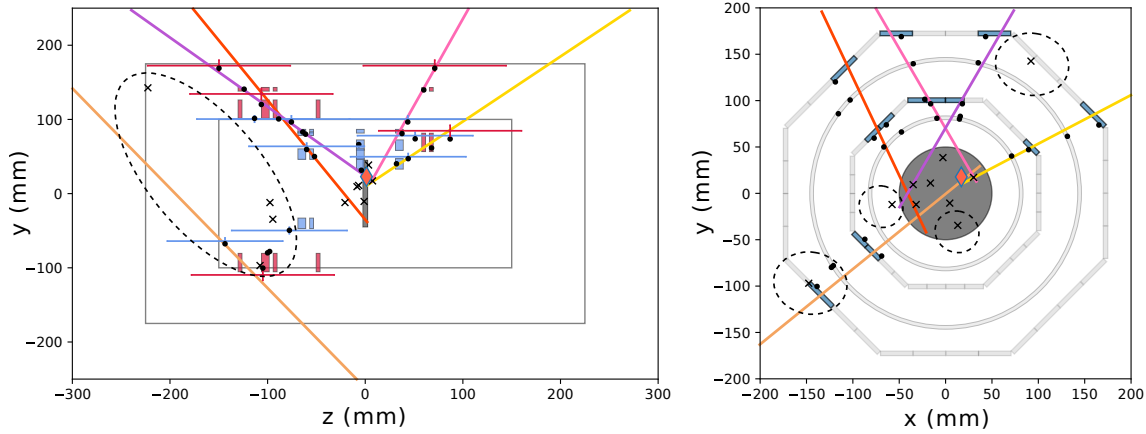


Figure 6.6.: Simulated antiproton event. z - y plane on the left and x - y plane on the right. The orange track has been wrongly selected, causing midpoints (highlighted by the black, dashed circles) that are away from the other points from the correctly identified tracks. The orange diamond marks the actual annihilation position. Note again the bias towards zero in x and y .

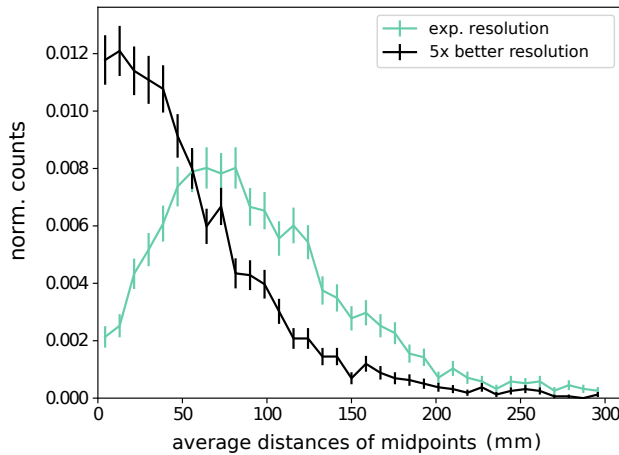


Figure 6.7.: Histograms of the mean distance of all midpoints per event of simulated antiproton events.

in Figure 6.7. Two histograms are shown, one of simulations including the current z -position resolution of the hodoscope bars (green) and the other histograms shows results of simulations assuming a five times better z -resolution. An increased z -resolution of the hodoscope bars would improve the track selection process based on the best fit and lowers the probability of selecting a track with a wrong fibre-bar match. Therefore the distances between line pair midpoints is smaller. The medians of the distributions are ≈ 90 mm and ≈ 45 mm respectively, and have been used for the parameter `eps` of DBSCAN.

The vertex is then estimated by calculating the weighted average of the

midpoints in the largest cluster found:

$$\vec{v}_{\text{cl}} = \frac{1}{\sum_{ij} 1/d_{ij}} \sum_{ij} \frac{1}{d_{ij}} \vec{m}_{ij} \quad (6.8)$$

i.e. the average position of the largest found cluster weighted by the inverse of distances d_{ij} of their corresponding closest points. Weighting by d_{ij} reduces the impact of midpoints from lines with greater distance on the estimated vertex.

6.4. Algorithm evaluation with simulations

The above discussed analysis is first applied to simulated antiproton and cosmic simulations to evaluate its expected accuracy and capability of finding the correct tracks of secondaries in the hodoscope and reproducing the predisposed vertex position.

Firstly, the simulation conditions and implemented detector geometry are described. Afterwards, the obtained results of number of tracks and found vertices are discussed for cosmics and antiproton annihilations on the central BGO detector. Simulated antiprotons annihilating on the beampipe in the vicinity of the detector are studied as well.

6.4.1. Simulation conditions

The simulations discussed in this section have been carried out using the particle physics tool-kit Geant4¹. Geant4 allows to combine the event generation with the full beamline simulation, and is therefore heavily used by the ASACUSA collaboration [120, 121].

Previous studies [95, 96] at the AD have found discrepancies in the multiplicity and energy distribution between the prediction of the Geant4 physics models and recorded antiproton annihilations on silicon at rest. In these studies the CHiral Invariant Phase Space (CHIPS) model [122] and the FRITIOF model [123] were compared with data taken at the AD at CERN.

Due to this observed discrepancies, a phenomenological model (SMI model) was introduced by Bertalan Juhasz and further developed by Clemens Sauerzopf [84]. The SMI model is tailored to reproduce the measured low energy antiproton annihilations on protons and neutrons of [76] (see also Table 2.3). Further details can be found in [84].

¹geant4-10-00-patch-03

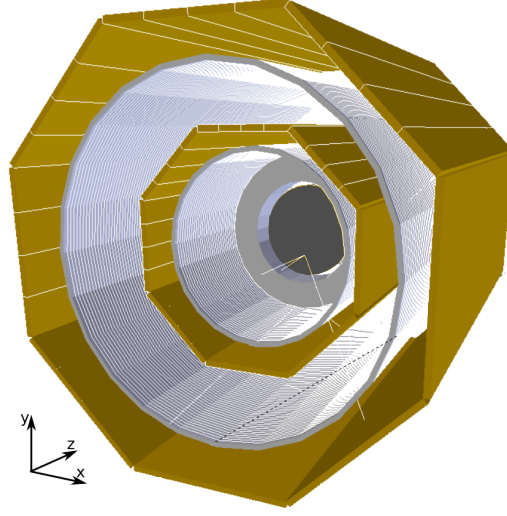


Figure 6.8.: Screen-shot of the detector geometry visualised with the 3D graphics software tool-set Blender [124]. The carbon coated BGO disc (dark grey) where the annihilation of antiprotons takes place, is surrounded by a flange (grey). The central part of the detector is encompassed by two layers of fibres (grey) and two layers of the octagonal bar hodoscope (gold).

All simulations described in this section are performed using the SMI model. The center of the BGO crystal is chosen to be at $(x, y, z) = (0, 0, 0)$. The energy of the generated antiprotons was set to 150 eV (mono energetic), the extraction energy used for antiproton annihilation studies during measurements. Antiproton annihilations with different hit positions on the central detector as well as on the beampipe have been performed. The particles were created in a narrow beam with parallel trajectories in order to generate a well defined annihilation vertex for vertex resolution studies.

For simulations of antiprotons annihilating solely on the BGO, $\bar{p}$ with trajectories parallel to the z -axis are generated with two different positions in x and y , once hitting the BGO in the center at $(x, y) = (0 \text{ cm}, 0 \text{ cm})$ and once off-center with a source position of $(x, y) = (2 \text{ cm}, 2 \text{ cm})$.

In order to study the tracking algorithm's response to wall annihilation, antiprotons were generated with trajectories perpendicular to the z -axis and parallel to the y -axis and three different distances, 11 cm, 5 cm and 2 cm, from the BGO surface.

For cosmic background simulations, the afore mentioned CRY library [82] is used. Cosmic events are generated in an area of $3 \times 3 \text{ m}^2$ and height of 0.5 m above the detector.

Table 6.2 summarises the different beam conditions of the simulated an-

beam properties			
run	# of initial particles	direction (x, y, z)	source position (x, y, z)
$\bar{p}$	3000	(0, 0, 1)	(2 cm, 2 cm, -11 cm)
$\bar{p}$	3000	(0, 0, 1)	(0 cm, 0 cm, -11 cm)
$\bar{p}$	10000	(0, 1, 0)	(0 cm, 0 cm, -11 cm)
$\bar{p}$	6000	(0, 1, 0)	(0 cm, 0 cm, -5 cm)
$\bar{p}$	6000	(0, 1, 0)	(0 cm, 0 cm, -2 cm)
cosmics	10^5	—	area $3 \times 3 \text{ m}^2$, 0.5 m

Table 6.2.: Table summarising the Geant4 simulation conditions.

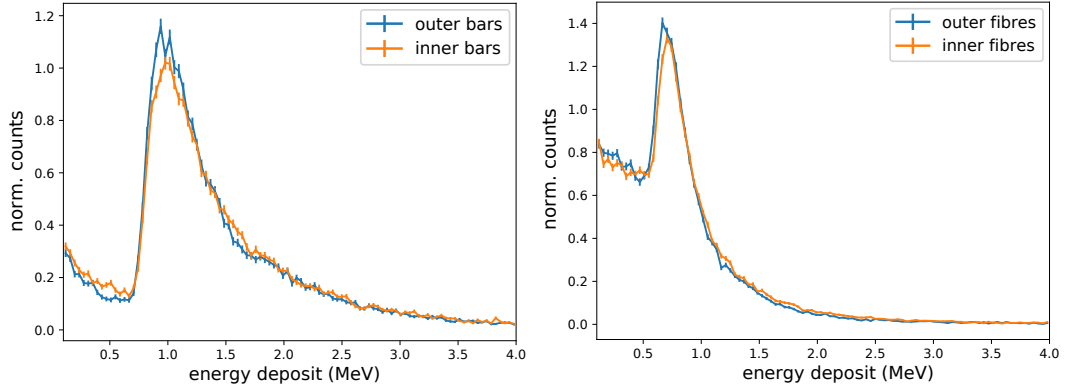


Figure 6.9.: Distributions of deposited energy in the scintillating bars (right) and fibres (left) using simulated antiproton events.

tiprotons and cosmics. A screen-shot of the implemented detector geometry can be seen in Figure 6.8. The BGO detector including its carbon coating can be seen in dark grey in the center. It is surrounded by a stainless steel flange (light grey). Scintillating fibres are displayed in light grey, hodoscope bars in gold. Input dimensions of the geometry have been gathered from technical drawings and material properties found in data sheets of the detector components have been used. The simulated stainless steel vacuum pipe in which the antiprotons are generated has been removed from the picture. It is surrounded by air and contains vacuum.

Figure 6.9 shows a histogram of the deposited energy in scintillating bars and fibres from antiproton simulations. In order to eliminate noise, a cut on the deposited energy in bars of 0.7 MeV and of 0.55 MeV for fibres is applied.

Also, in order to mimic the coarse z -position resolution of the hodoscope bars, a random number drawn from a Gaussian distribution with standard deviation equal to the measured σ_z^{bar} for the respective layer is added to the

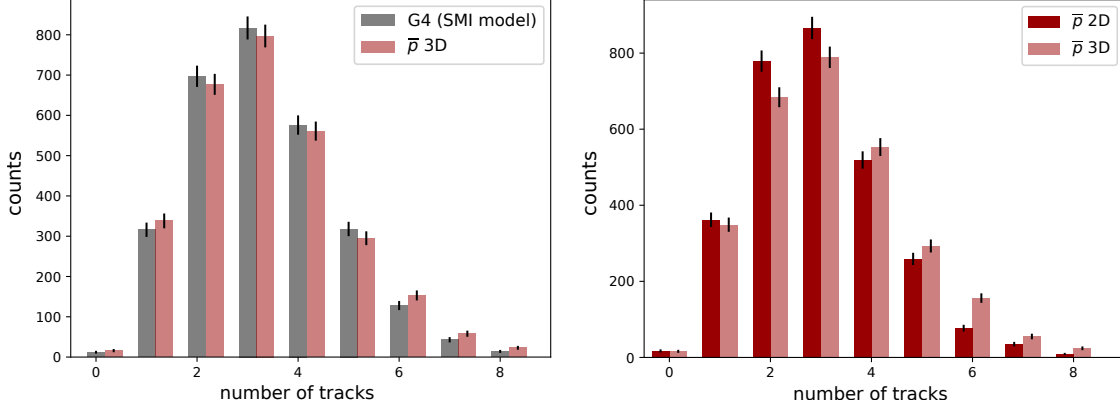


Figure 6.10.: Histograms of number of tracks for simulated antiproton events. *Left*: comparison of number of secondaries traversing both layers of hodoscope as extracted from the simulation N_{G4} (grey) and number of found tracks by the three dimensional tracking algorithm N_{3D} (light red). *Right*: comparison of N_{3D} (light red) and N_{2D} (dark red). The error bars indicate Poisson errors.

z -position extracted from the simulation. The effect of an improved σ_z^{bar} is studied in the following sections.

6.4.2. Tracking results – number of tracks

In this section, the found number of tracks in three dimensions N_{3D} is discussed and compared to results of the two-dimensional tracking algorithm N_{2D} (Section 3.6.5) as well as the actual number of secondaries traversing both layers of hodoscope N_{G4} extracted from the simulations. The distributions in this section show results from simulated antiprotons annihilating in the center of the BGO detector. In case of cosmic events, only those depositing a non-zero energy in the BGO are considered. Furthermore, cuts on the number of inner bar hits $n_I > 0$ and on the number of outer bar hits $n_O > 0$ are applied for antiproton and cosmic events.

Figure 6.10 (right) shows a histogram of the number of found tracks in three (light red) and two dimensions (dark red) of antiproton annihilations. In order to test the track finding capability of the algorithm, the number of secondary particles traversing both layers of hodoscope, N_{G4} , has been extracted from simulations. A comparison with N_{3D} can be seen in Figure 6.10 (left). The number of tracks N_{3D} using the discussed tracking algorithm is in very good agreement with the simulations. The number of tracks determined by the two-dimensional tracking shows an overestimation of lower track numbers and an underestimation of higher numbers of tracks.

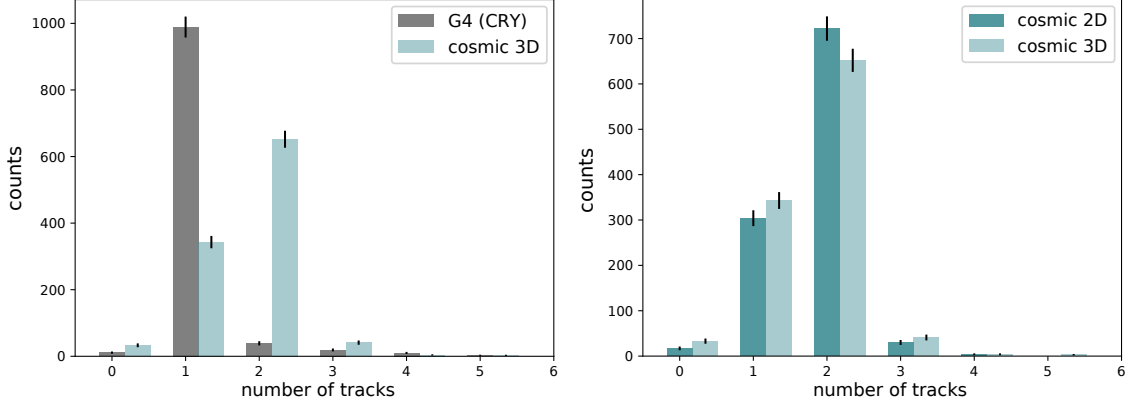


Figure 6.11.: Histograms of number of tracks for simulated cosmic events. *Left*: comparison of N_{G4} (grey) and N_{3D} (light blue). Note that, in context of the algorithm, a track is defined as passing the two layers of hodoscope only once and therefore a muon passing the whole detector is counted as two tracks. In the simulation, the actual number of particles traversing the detector is counted. *Right*: comparison of N_{3D} (light blue) and N_{2D} (medium blue). The error bars indicate Poisson errors.

For cosmic rays, the comparison of N_{3D} to N_{G4} is not so straightforward, since the tracking algorithm at hand defines a particle track as passing through each hodoscope layer once. A muon for example, traversing the hodoscope from top to bottom, is counted as two tracks. In the simulations, the number of particles traversing the detector N_{G4} is extracted and therefore counts the muon as one track. A direct comparison cannot be made. Nevertheless for completeness, Figure 6.11 (left) shows a comparison of the distributions of N_{3D} and N_{G4} for cosmic rays. Found events with one and two tracks by the tracking algorithm (light blue) should in total match the number of traversing cosmons with one track (first bin in Figure 6.11 (left)). This agreement is observed. Figure 6.11 (right) shows a comparison of N_{3D} (light blue) and N_{2D} (medium blue) dimensional tracking algorithms.

6.4.3. Tracking results – vertices

In this section the reconstructed vertices and achieved z -resolution are discussed. Expected event types i.e. antiprotons annihilating on the BGO, annihilations on the beampipe and cosmic events are investigated. Recall, that the vertex is estimated as the weighted average of points in the largest cluster found in the cloud of midpoints of track pairs and is denoted as $\vec{v}_{cl}$.

The biggest influence on the vertex resolution is naturally the limitation of the position resolution of the detector. Particularly, the coarse z -resolution of the hodoscope bars which is the only guidance to correlate fibre and bar hits.

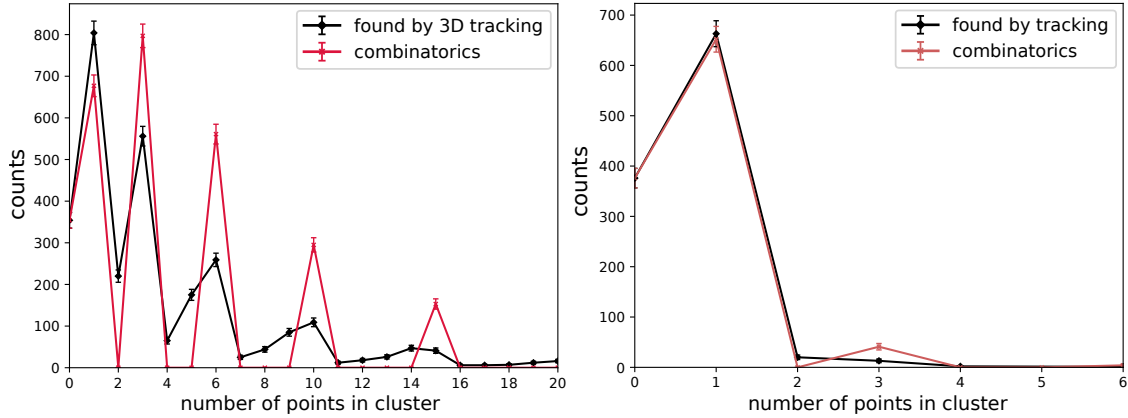


Figure 6.12.: Histograms of the number of midpoints in the largest cluster found for simulated antiprotons (left) and cosmes (right) in black and the calculated number of points that should be in a cluster based on the found number of tracks (see Figure 6.10) in red. The error bars indicate Poisson errors.

During the tests with simulations it was observed that without adding the random number to the z -positions of the bars, the algorithms track finding capability was very good. By adding the Gaussian smearing to mimic a more realistic scenario, the probability of a wrong bar to fibre association rises since the track selection by best fit fails if the wrong hit combination results in a smaller χ^2 than the actual track hits.

Another factor is the missing x - and y -resolution of the fibre detector. As mentioned earlier, the assignment of x - and y -position of the bar hits to the associated fibre hits induces a bias on the x - and y -position of the vertex. The z -resolution of the vertex should stay unaffected by this bias due to the fact that there is position information on z available from all four layers, as opposed to x and y . Therefore, the error on the z -component of $\vec{v}_{cl}$ is governed by the errors on the midpoints which can be calculated by error propagation from errors on the fit parameters.

The errors on the fit parameters are especially influential for tracks which have direction vectors with a small angle to each other. In this case, the error on the fit parameters has a bigger effect on the error of the found midpoint. This is especially important for two track events, since the “cluster” is only made up of one point.

Also the number of (correctly) identified tracks influences the vertex resolution which increases with the number of tracks as discussed later in this section.

The number of midpoints in the cluster that should be found in an ideal case (all tracks meet in the same vertex, no misidentified tracks) can be

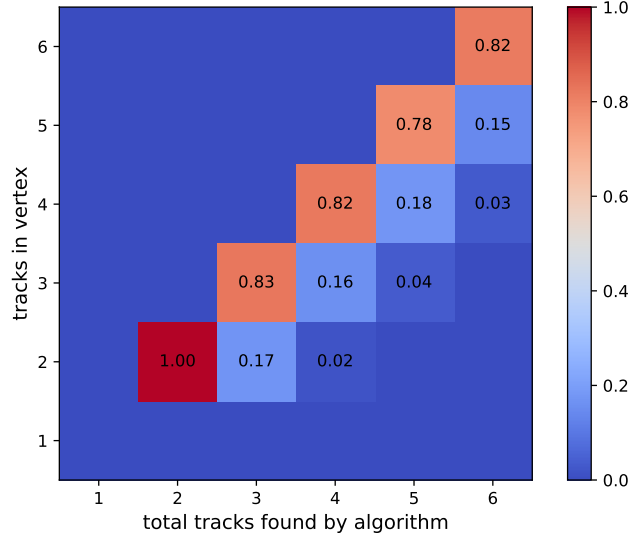


Figure 6.13.: Two-dimensional histogram of $(N_{3D,v}, N_{3D})$ i.e. the number of tracks that meet in the vertex and the number of total tracks found for simulated antiproton events. The histogram is normalised column-wise to their corresponding N_{3D} .

determined by calculating the number of midpoints for a given number of tracks N_{3D} via $\frac{N_{3D}!}{2!(N_{3D}-2)!}$, which is denoted as “combinatorics” in the following. Figure 6.12 shows histograms of the number of points in the largest cluster (black) compared to the calculated number of points by combinatorics (red) for antiproton events (left) and cosmic events (right). The majority of cosmic has two tracks and shows therefore only one midpoint. Their tracking results agree well with the expected number of midpoints. For $\bar{p}$ annihilations, the predicted peak structure (red) is visible but washed out with tails towards lower numbers. The effect is stronger for larger track numbers most likely due to the discussed increasing difficulty of bar and fibre matching with higher track number.

Figure 6.13 shows a two-dimensional histogram of pairs $(N_{3D}, N_{3D,v})$ i.e. the total number of tracks N_{3D} on the x -axis and $N_{3D,v}$, the number of tracks that meet in the vertex (their midpoints are part of the largest cluster found), on the y -axis.

The columns of the histogram are normalised to their corresponding total number of tracks N_{3D} i.e. in the ideal case of all tracks meeting in the vertex, only the diagonal bins of the histogram would be filled and have value one.

For all N_{3D} , the highest bin is located in the diagonal of the histogram. The bins below the diagonal show events with a certain N_{3D} , but not all of the tracks where associated with the largest cluster. The gap at one track

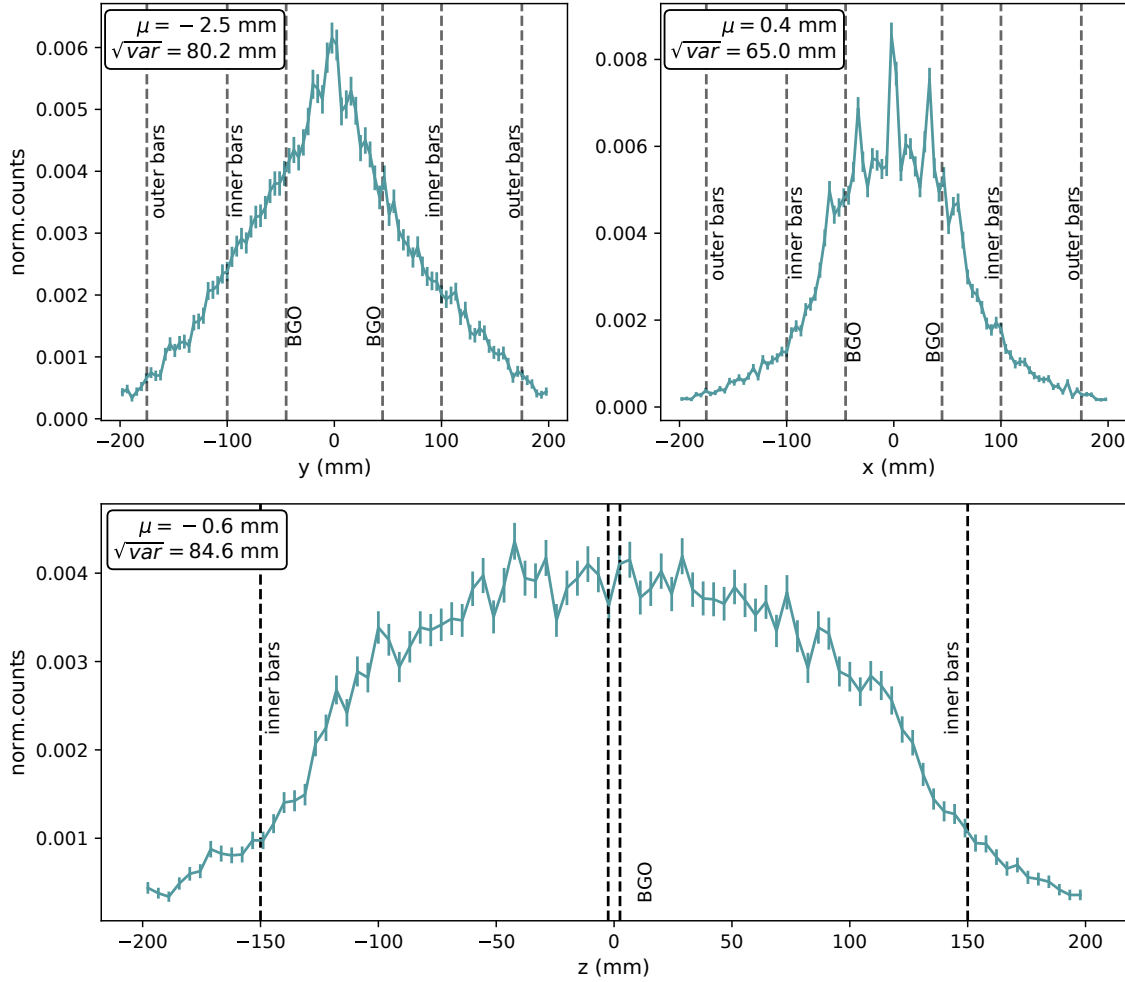


Figure 6.14.: Histograms of the y - (top left), x - (top right) and z -components (bottom) of the determined vertices. Dashed lines mark the extent of BGO crystal and hodoscope bar layers. The text boxes in the left corners show sample mean and standard deviation of the displayed data. The error bars indicate Poisson errors.

naturally arises from the condition that there always needs to be more than one track in order to calculate the vertex. The bin at (2, 2) has value one, since in this case the cluster of midpoints contains only one point.

6.4.3.1. Cosmic events

Cosmic events do not have an actual vertex in the detector, since they traverse it from outside. In the following, the algorithm's response to cosmic rays is studied. The determined “vertices” are therefore expected to be broadly distributed. Figure 6.14 shows histograms of the x -, y - and z -components of the vertices for cosmic rays. Note, that all cosmic events are considered traversing both layers of bar hodoscope, no cut on the energy deposited in

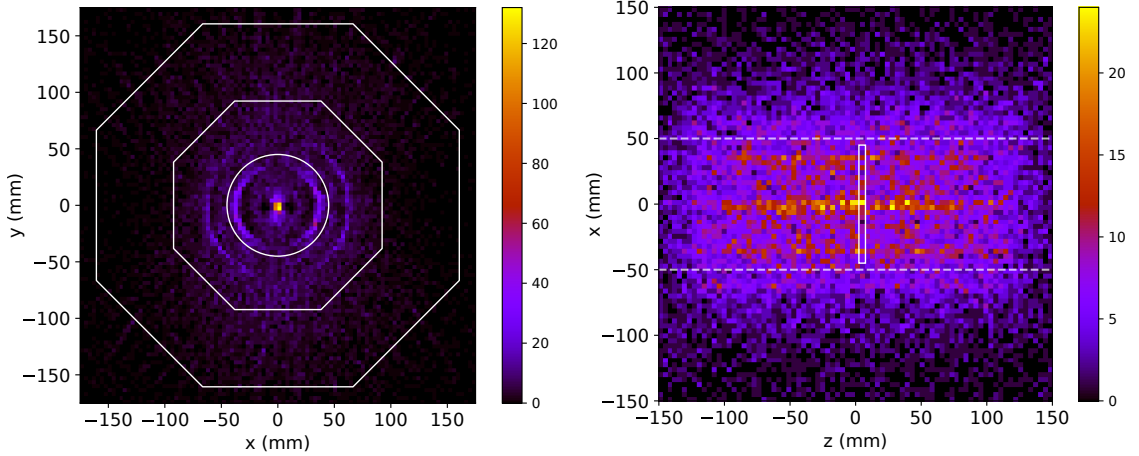


Figure 6.15.: Two-dimensional histograms of vertices of simulated cosmic events. *Left:* x - y plane of the detector with the BGO marked as a white circle and the two bar hodoscope layers as two white octagons. *Right:* z - y plane of the detector. The BGO is marked as a white rectangle and the position of the wall of the beampipe by two dashed lines.

the BGO is made. The z -coordinate (bottom plot) shows a wide, almost uniform distribution spanning over the length of the inner layer of hodoscope. Since only tracks that traverse both layers are accepted, this agrees with expectations.

The distributions of the x - and y - coordinates show a bias towards the center of the detector. This is a consequence of the track candidate selection procedure of combining hits in the inner and outer bar layer with the outer channel number fulfilling $n_{\text{outer}} \in [n_{\text{inner}} - 2, n_{\text{inner}} + 2]$ and additionally, the association of the x and y bar positions to the fibre hits.

Moreover, the distribution of the x -component of the vertex shows a peak structure which can be understood when looking at two-dimensional histograms of the vertex components, see Figure 6.15 (left). The peak structure in x is due to the bias towards the center of the detector (central peak) and additionally, two “rings” can be observed at the border of the BGO and around it. The explanation for this is given by Figure 6.16 (left) which shows the x - y plane of the detector with scintillators in light blue. The black lines show all possibilities for straight tracks passing the detector when applying the track candidate selection procedure used.

Some areas show a higher density of lines crossing each other which illustrates the bias of the x and y vertex positions towards the center and the ring structure observed in cosmic events.

To further investigate this effect, the simulated cosmic events have also been analysed assuming an increased z -position resolution of the bar hodoscope.

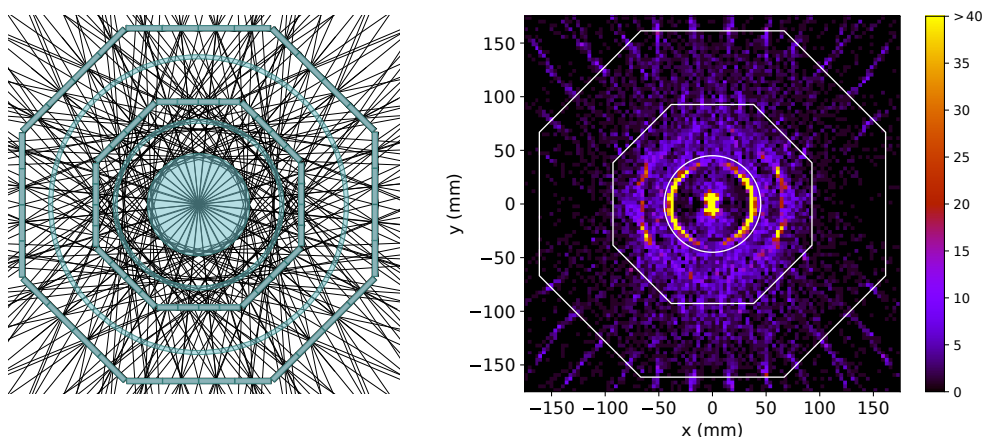


Figure 6.16.: x - y plane of the detector. *Left*: Sensitive detectors are drawn in light blue. Black lines show all possibilities for straight tracks when connecting the centres of inner bars to outer bars with channel numbers $[n_{\text{inner}} - 2, n_{\text{inner}} + 2]$ i.e. the search window for finding hit combinations for track candidates. The pattern shows areas of higher density, illustrating the bias of the x and y vertex positions towards the center and the ring structure observed in cosmic events. *Right*: two-dimensional histogram of the x - and y -positions of the vertices. A ten times better z -resolution of the hodoscope bars has been assumed. Note the modified colour map to better visualise the observed structure.

Adopting a ten times better position resolution, the resulting vertex distributions show the vertex bias in x and y even more clearly, see Figure 6.16 (right). Note that the colour map of the plot has been modified for better visualisation.

With essentially only two points in the x - y plane, no unbiased vertex can be determined by a straight line fit. Therefore, only the z -position gives reliable information on the origin of events. Its resolution will be investigated with simulated antiproton annihilations in the next sections.

6.4.3.2. Antiproton annihilation on the BGO

The vertex resolution for annihilations on the central detector has been investigated by simulating two well defined hit positions on the BGO crystal. Figure 6.17 shows histograms of the x -, y - and z -components of the determined vertex for antiprotons hitting the BGO at the center $(x, y) = (0, 0)$ (grey) and at $(x, y) = (2 \text{ cm}, 2 \text{ cm})$ (red). The histograms are normalised to their area and their mean and standard deviations are listed in the boxes in the top left of the plots. Note, that the distributions contain all vertices of events with $N_{3D} > 1$.

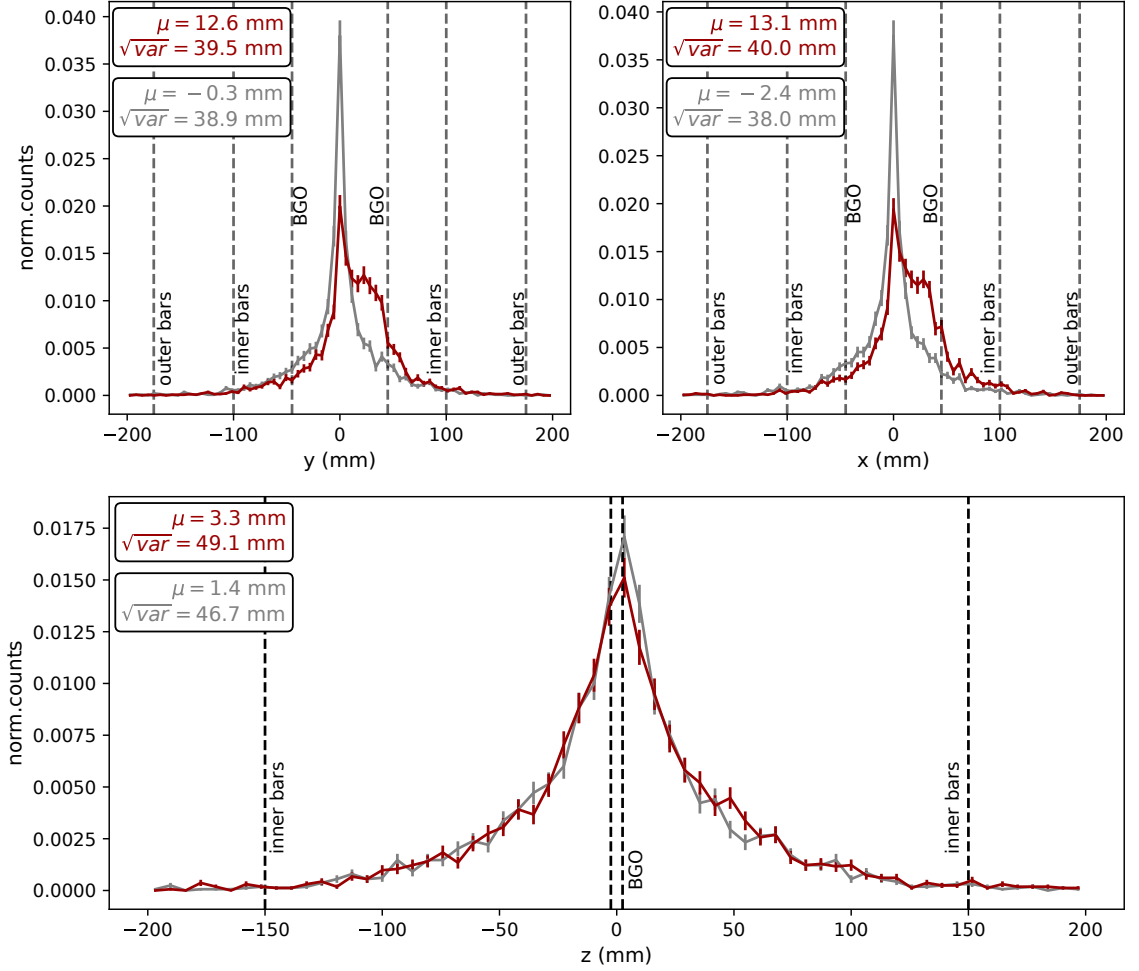


Figure 6.17.: Histograms of the y - (top left), x - (top right) and z -component (bottom) of the determined vertices for hit positions on the BGO of $(x, y) = (0, 0)$ in grey and $(x, y) = (2 \text{ cm}, 2 \text{ cm})$ in red. Dashed lines mark the extent of BGO crystal and hodoscope bar layers. The text boxes in the left corners show sample mean and standard deviation of the displayed data. The error bars indicate Poisson errors.

The determined x - and y -positions of the annihilations have a clearly visible bias towards the center, see especially the red histogram of the simulation with hit position $(x, y) = (2 \text{ cm}, 2 \text{ cm})$ on the BGO crystal.

The determined z -position of the annihilation is almost unaffected by the (x, y) position of the annihilation on the BGO. The simulation with off-center hit position show a slightly higher standard deviation. This indicates that the x - and y -positions of the annihilation and their bias also has a small influence on the properties of the midpoint cluster due to the impact on distances between midpoints.

Figure 6.18 shows the two-dimensional histograms of the determined vertices in the x - y and the z - y plane for annihilations at $(x, y) = (0, 0)$ (top row) and

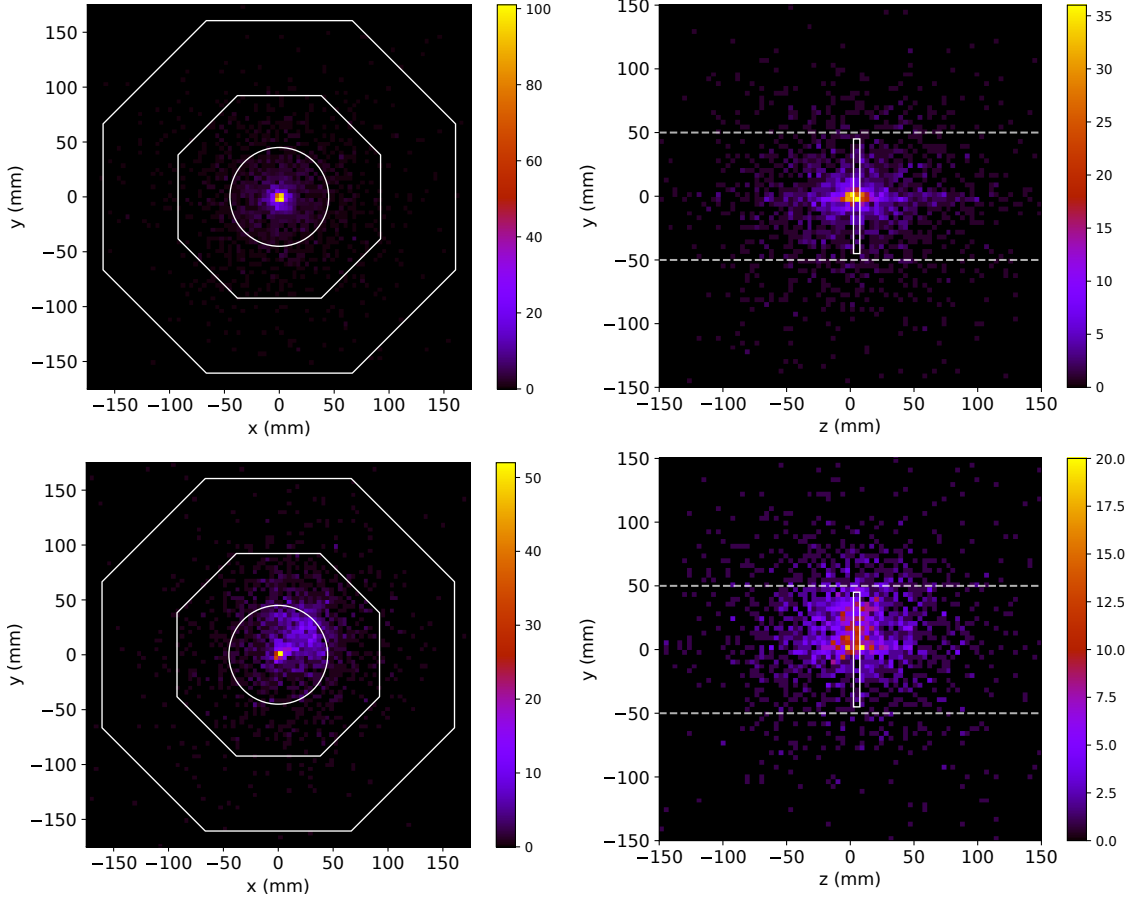


Figure 6.18.: Two-dimensional histograms of vertices of simulated antiproton events hitting the center of the BGO (top row) and hitting the BGO at (2 cm, 2 cm) (bottom row). *Left*: x - y plane of the detector with the BGO marked as a white circle and the two bar hodoscope layers as two white octagons. *Right*: z - y plane of the detector. The BGO is marked as a white rectangle and the position of the wall of the beampipe by two dashed lines.

$(x, y) = (2 \text{ cm}, 2 \text{ cm})$ (bottom row). Again, the bias in x and y is visible for hit positions away from the center of the BGO.

The standard deviation σ_z of the z -position distributions is 46.7 mm (antiprotons annihilating at $(x, y) = (0, 0)$), its full width at half maximum (FWHM) is 32.3 mm. A ratio of 0.76 of all events lie within a bandwidth of one σ_z around the mean. However, σ_z is not necessarily the best estimate for the vertex z -resolution due its dependence on the number of tracks and the errors on the fit parameters of the tracks. Figure 6.19 (blue triangles) shows σ_z as a function of the number of tracks in the vertex. The width of the distribution drops with increasing track number.

As previously mentioned, the error on the z -component of $\vec{v}_{cl}$ can be calculated by error propagation of the fit parameter errors to the midpoints

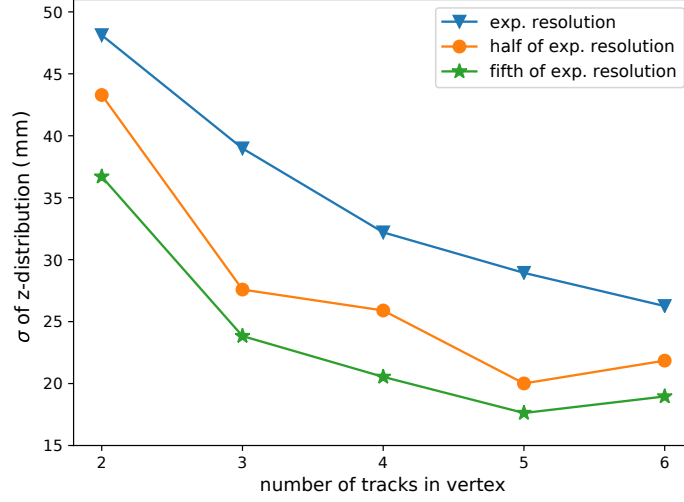


Figure 6.19.: Standard deviation σ_z of the z -position distribution of simulated antiproton events in dependence of $N_{3D,v}$. Results are shown for measured z -resolution of hodoscope bars (blue triangles) and improved bar resolution of two times (orange dots) and five times (green stars) better resolution.

and their average. This allows also to give an error on the z -position of the annihilation for every event individually. Note, that the described method below only gives a reliable error estimate on the z -component of the vertex. For x and y it does not necessarily, because there is not enough information in x and y for a three-dimensional fit to give results without bias.

The error on the midpoint m of line i and line j is estimated by error propagation via $C_m = J V J^T$, where C_m is the resulting covariant matrix of the midpoint. $J = \frac{1}{2}(J_i + J_j)$ denotes the Jacobian of the midpoint i.e. the mean of the Jacobians J_i and J_j of the two closest points on the line. The matrix V contains the covariance matrices of the fits of lines i and j in the diagonal $\begin{pmatrix} C_i & 0 \\ 0 & C_j \end{pmatrix}$. The derivatives of the closest points (see Equation 6.7) necessary for the Jacobians have been calculated using the python package **SymPy** for symbolic mathematics [125].

After calculating C_m for all midpoints contained in the cluster, the covariance matrices are averaged to:

$$\overline{C} = \frac{1}{\sum_m d_m} \sum_m \frac{1}{d_m} C_m \quad (6.9)$$

analogously to the averaging of the midpoints to the vertex estimate $\vec{v}_{cl}$. The diagonal elements of $\overline{C}$ give the variances of x , y and z . The vertex error on z is therefore calculated as the square root of the corresponding diagonal element of $\overline{C}$ which gives the standard deviation σ_z^v :

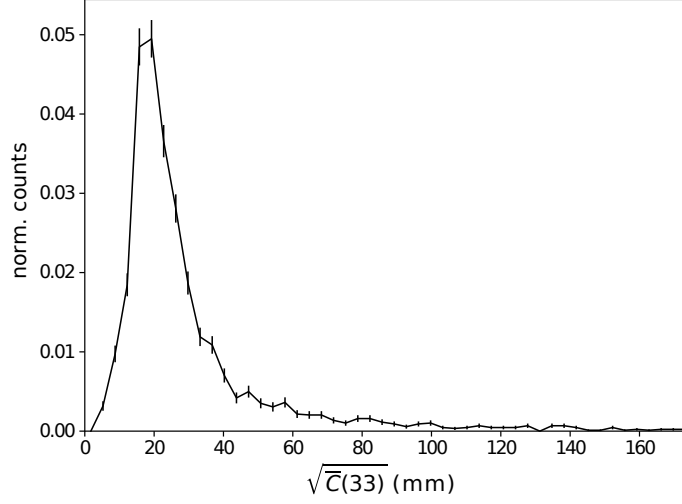


Figure 6.20.: Histogram of $\sigma_z^v = \sqrt{\overline{C}(33)}$ of simulated antiproton events hitting the BGO. The histogram is normalised to the area. The error bars indicate Poisson errors.

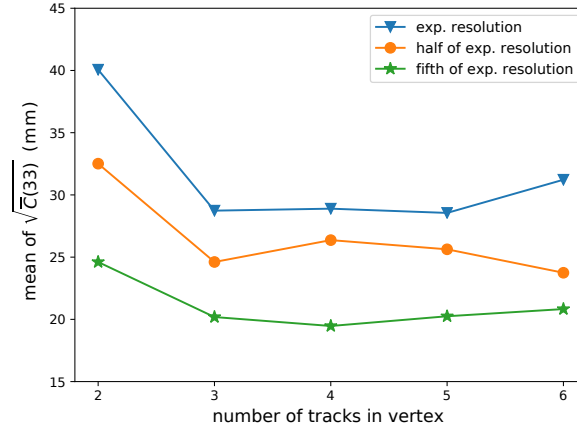


Figure 6.21.: Mean of the σ_z^v distributions in dependence of the number of tracks in the vertex for varying z -resolution of the hodoscope bars: current resolution (blue), two times better (orange) and five times better (green).

$$\overline{C} = \begin{pmatrix} \overline{C}(11) & \overline{C}(12) & \overline{C}(13) \\ \overline{C}(21) & \overline{C}(22) & \overline{C}(23) \\ \overline{C}(31) & \overline{C}(32) & \overline{C}(33) \end{pmatrix} \text{ and } \sigma_z^v = \sqrt{\overline{C}(33)} \quad (6.10)$$

Figure 6.20 shows the distribution of σ_z^v , the error estimated on the z -position of the vertex calculated by the described method. The mean of the distribution is 33.4 mm and the median 22.2 mm.

The mean of the distribution of σ_z^v in dependence of the numbers of tracks in the vertex is displayed in Figure 6.21 (blue triangles). For only two tracks meeting in the vertex, the mean of σ_z^v is ≈ 40 mm, for $N_{3D,v} > 2$, σ_z^v drops to around 29 mm.

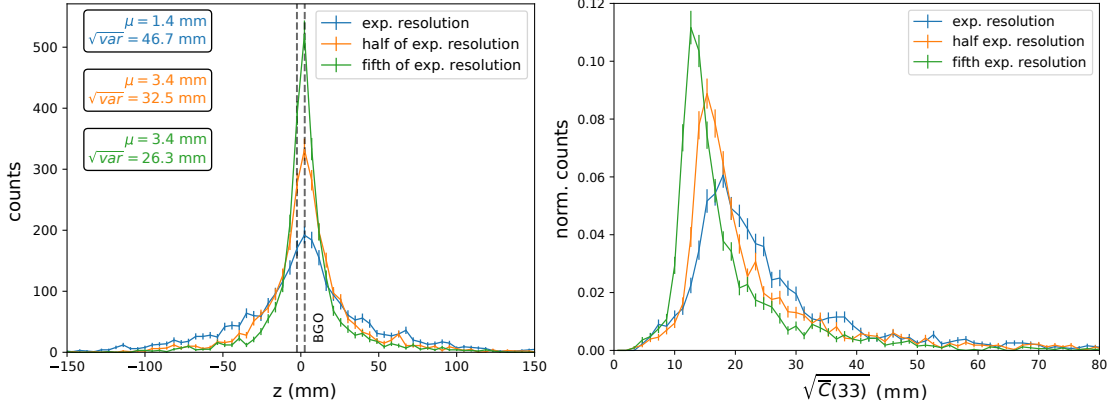


Figure 6.22.: *Left*: Distributions of the z -position of the determined vertex for different z -position resolution of the hodoscope bars: current resolution (blue), 2 times better (orange) and 5 times better (green). *Right*: Corresponding distribution of the resolution $\sigma_z^v = \sqrt{C(33)}$ of the vertex in z .

An improvement of the vertex resolution can be achieved by increasing the z -position resolution of the bar hodoscope. Recall, that the coarse z -position resolution of the hodoscope bars is included in the simulations by drawing a random number from a Gaussian with standard deviation equal to the measured σ_z^{bar} for the respective layer and is then added to the z -position extracted from the simulation. The effect on the determined vertex of a decreased σ_z^{bar} has been studied.

The determined z -position of antiprotons annihilation on the BGO for different values of σ_z^{bar} is shown in Figure 6.22 (left). The means and standard deviations of the distributions are listed in the boxes in the top left corner.

The corresponding distributions of the vertex resolution σ_z^v are plotted in Figure 6.22 (right). The means of the σ_z^v distributions in dependence of the number of tracks in the vertex are displayed in Figure 6.21. Comparing the means of σ_z^v for varying hodoscope bar resolutions, shows a decrease of a factor of ≈ 0.83 for half the σ_z^{bar} and ≈ 0.69 for a fifth of $\sigma_z^{\text{bar}2}$.

The improved z -resolution of the vertices is a result of several benefits that come with an increased bar resolution. The track selection via best straight line fit becomes more effective and reliable and also the errors on the fit parameters are smaller and therefore result in a smaller propagated error on the midpoints of line pairs. As a consequence, the average distance between midpoints is decreased, which was shown in Figure 6.7.

However, the largest improvement of the vertex resolution would probably be achieved by adding x - and y -resolution to the fibre hits. The bias towards

²The improvement factors are averaged over all number of tracks.

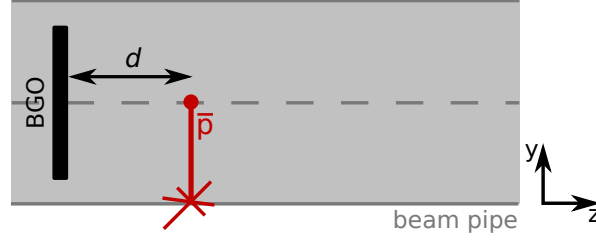


Figure 6.23.: sketch of the setup in the Geant4 simulations for testing the tracking algorithms response to upstream annihilations on the beampipe.

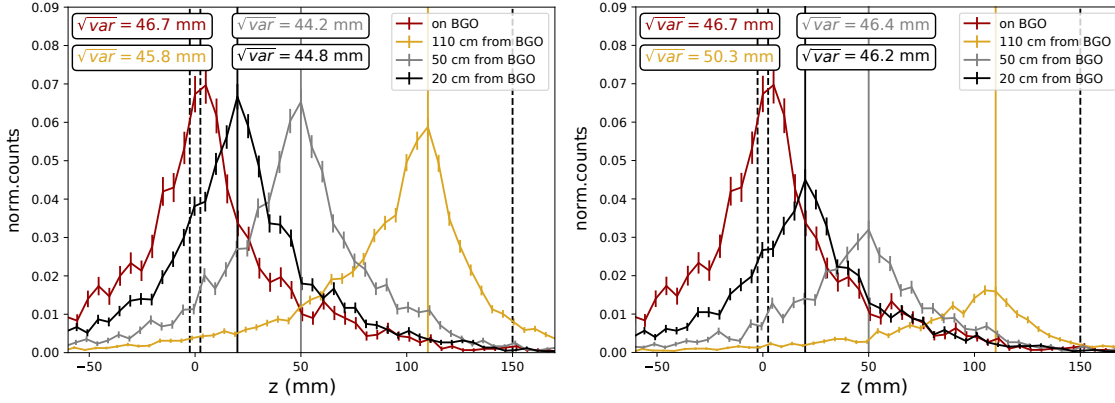


Figure 6.24.: Distributions of the z -position found by the algorithm of antiproton annihilations on the BGO (red) and different annihilation positions on the wall: 2 cm (black), 5 cm (grey) and 11 cm (gold) from the BGO surface. The exact z of the annihilations is marked by the vertical coloured lines. The histograms are normalised to the initial number of $\bar{p}$ generated. The experimental FWHM_z of the bars has been used. *Left*: without any cuts. *Right*: considering only events with non-zero energy deposit in the BGO, $E_{\text{BGO}} > 0$.

the center in x and y would be eliminated and no assignment of bar x - and y -positions to fibres would be required. This has not been tested in the course of this thesis, since it would require major and time consuming changes of the algorithm. Furthermore, an entirely different track finding approach would probably be more efficient in that case.

6.4.3.3. Upstream annihilations

The main motivation for the fibre upgrade of the tracking detector was to enable discrimination against annihilations upstream of the central detector. These could stem from antihydrogen atoms in high-field seeking states or in case of annihilation studies, antiprotons annihilating in the apparatus before reaching the target material.

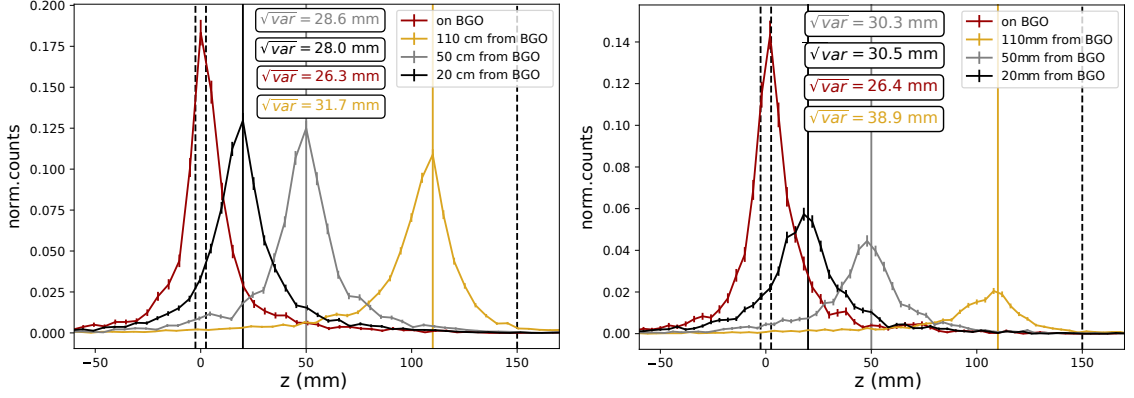


Figure 6.25.: Distributions of the z -position found by the algorithm of antiproton annihilations on the BGO (red) and different annihilation positions on the wall: 2 cm (black), 5 cm (grey) and 11 cm (gold) from the BGO surface. The exact z of the annihilations is marked by the vertical coloured lines. The histograms are normalised to the initial number of $\bar{p}$ generated. The FWHM_z of the bars has been assumed to be five times smaller than the experimental one. *Left*: without any cuts. *Right*: considering only events with non-zero energy deposit in the BGO, $E_{\text{BGO}} > 0$.

In the last section, it was evaluated that for the current position resolutions of the detector hardware, the determined z -position of annihilations in the central detector showed a standard deviant of 46.7 mm. The z -resolution was then estimated for events individually by error propagation of the errors on the fit parameters. The mean and median of the distribution of σ_z^v are 33.4 mm and 22.2 mm respectively.

In order to study the signal of wall annihilations in the detector, antiprotons were generated with trajectories perpendicular to the z -axis and annihilating at well defined positions on the stainless steel beam pipe, see sketch in Figure 6.23. The antiprotons were generated with different distances $d = \{2 \text{ cm}, 5 \text{ cm}, 11 \text{ cm}\}$ from the BGO surface. The resulting z -position distributions determined by the algorithm can be seen in Figure 6.24. The histograms have been normalised to the number of generated antiprotons which is also the number of antiprotons annihilating on the wall. The left plot shows the z -distribution for all events without a cut on the deposited energy in the BGO. For the right plot, a cut of $E_{\text{BGO}} > 0$ has been applied. The peak of the distributions nicely matches with the simulated annihilation position marked by the solid vertical lines in the figures.

Figure 6.25 shows the z -position distributions of the wall annihilations but with an improved z -resolution of the bar hodoscope of $0.2\sigma_z^{\text{bar}}$ which reduces the overlap of the distributions significantly.

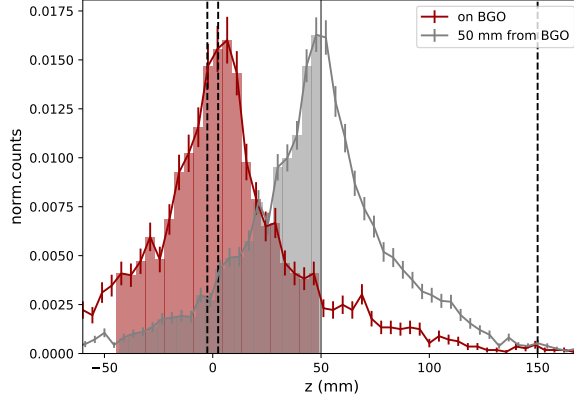


Figure 6.26.: Normalised z -position distributions i.e. probability density functions (PDFs), of antiproton annihilations on the BGO (red) and on the beampipe 5 cm away from the BGO surface (grey). The dashed black lines show the z -position of the BGO (± 2.5 mm). The red shaded area shows the area under the PDF_{BGO} for $\bar{z} - \sigma_z \leq z \leq \bar{z} + \sigma_z$ with the mean $\bar{z}$. The grey shaded area is the area under $\text{PDF}_{5\text{cm}}$ for z in $\bar{z} \pm \sigma_z$, i.e. the fraction of total events that will be accepted as annihilating on the BGO in the given case. The error bars indicate Poisson errors.

For the purpose of giving a quantitative example, Figure 6.26 shows the distributions of $\bar{p}$ annihilating on the BGO (red) and 5 cm away on the beampipe (grey). The histograms are normalised to their area. The shaded red region shows the area under the red histogram within $(\bar{z} - \sigma_z \leq z \leq \bar{z} + \sigma_z)$, which contains a fraction of 0.76 of the total number of antiprotons annihilating on the BGO. If events with z -position within $1\sigma_z$ of the mean are accepted, a fraction of 0.53 of events annihilating 5 cm away will be accepted as well, see the grey shaded area in the figure. Analogously, for 2 cm and 11 cm away from the detector, the probabilities of accepting those events are 0.74 and 0.14 respectively. In case of assuming a better z -resolution of the hodoscope bars of $0.2\sigma_z^{\text{bar}}$, 0.84 events are contained within $1\sigma_z$ around the mean and for the three simulated cases of wall annihilations at 2 cm, 5 cm and 11 cm, a fraction of 0.68, 0.17 and 0.04 of events will be falsely accepted.

The results in this and the last section lead to the conclusion that, to a certain extent, the improved z -resolution of the detector helps to discriminate against annihilations away from the central detector (or any target in the center). Events that create several tracks in the hodoscope and look like an annihilation on the target, can partly be distinguished from annihilation events on the actual target. However, the distributions of annihilations close

to the target show a large overlap with the central distribution. Disregarding events without any energy deposit in the central detector certainly helps.

The improvement of the z -resolution of bars and its impact on the vertex was studied in this and the previous section. An increase of the time resolution (and therefore also of the z -resolution) could be achieved by removing the lightguides of the bars and glueing the SiPMs directly on the scintillating bars. This is currently tested in the lab.

For measurements with the combined detector setup of hodoscope and Timepix3 which is discussed in the next section, additional three dimensional track information from the Timepix3 can be considered. Combined with the hodoscope track information, this would lead to an increased z -resolution of the events and would help to discriminate between annihilations in the direct vicinity of the target foils and on the target.

6.5. Measured antiproton annihilations with the Timepix3 setup

The upgraded ASACUSA tracking detector has first been used during measurements in beamtime 2017 within the combined Timepix3 and hodoscope setup for antiproton annihilation studies. Therefore a short overview of the detector setup is given before the results of the tracking algorithm on measured data are discussed and compared to simulations.

6.5.1. Motivation and detector setup

The main motivation for the discussed experimental study is validation and testing of simulation models for annihilations of low energetic antiprotons in matter and resulting fragmentation. The main simulation tools available and used for antiproton annihilations are FLUKA [126] and Geant4. Geant4 has two models for antiproton annihilations, CHIPS (CHiral Invariant Phase Space) [127] and FRITIOF [128]. The CHIPS model is no longer supported by Geant4 and has been removed since version 10. FRITIOF is tuned to high energy physics and uses only extrapolations to low energies. The few experimental studies of low energy antiproton-nuclei annihilations that have been carried out, showed discrepancies in distributions of multiplicity and energy deposit compared to simulations [95, 96]. Therefore, the aim is a systematic study of multiplicities of nuclear fragments such as protons, alpha particles and heavier fragments, and charged pions using various target

materials with different atomic numbers.

Antiproton annihilation studies were carried out in ASACUSA during beamtime 2017 and 2018 using a modified detector setup. The central BGO detector read out by MA-PMTs was replaced by a detector consisting out of a quad array of Timepix3 chips arranged in a 2×2 matrix. One of the four chips has 256×256 square pixels (with $55 \mu\text{m}$ pitch). In total, the quad array covers an area of $2.8 \times 2.8 \text{ cm}^2$. The spatial x - and y -coordinates and their resolution are given by the segmentation of the Timepix3 sensor. The z -position can be reconstructed from the drift time of the charge carriers to the pixel electrodes. Therefore, information on the three-dimensional tracks in the Timepix3 could be extracted and used for a future upgrade of the tracking algorithm discussed here.

The Timepix3 is capable of discriminating between minimum ionising particles, such as pions, and heavily ionising particles produced in the annihilation. Combined with the hodoscope which covers a larger solid angle (0.80 of 4π seen from center point of the hodoscope), the setup makes it possible to study both charged pion multiplicity and nuclear fragments. Foils of different materials can be placed in front of the Timepix3 and act as the target. In 2017, a carbon target foil was used and measurements with other materials (gold, molybdenum) were performed in 2018.

Pictures of the Timepix3 setup can be seen in Figure 6.27. The vacuum chamber in *D* encloses target foil and Timepix3 array (right hand side of the picture) and is directly mounted after the double CUSP trap and surrounded by the tracking detector.

Picture *A* shows the lens system placed in a vacuum tube between double-CUSP trap and detector for beam focusing and steering. It has an adapted Einzel lens geometry made out of five individual electrodes. The entrance and exit electrodes of the conventional three-electrode Einzel lens geometry are segmented and voltage differences can be applied to steer the beam in the x - y plane.

Pictures *B* shows the mounted Timepix3 quad array which is mounted on a Silicon sensor and *C* the carbon foil fixed in front of the Timepix3 with a distance of 1 cm.

6.5.2. Beam characterisation

Previous extractions to the detector showed an off-center position distribution of the annihilating antiprotons, see Figure 3.26 in Section 3.6.4. For a

6.5. Measured antiproton annihilations with the Timepix3 setup

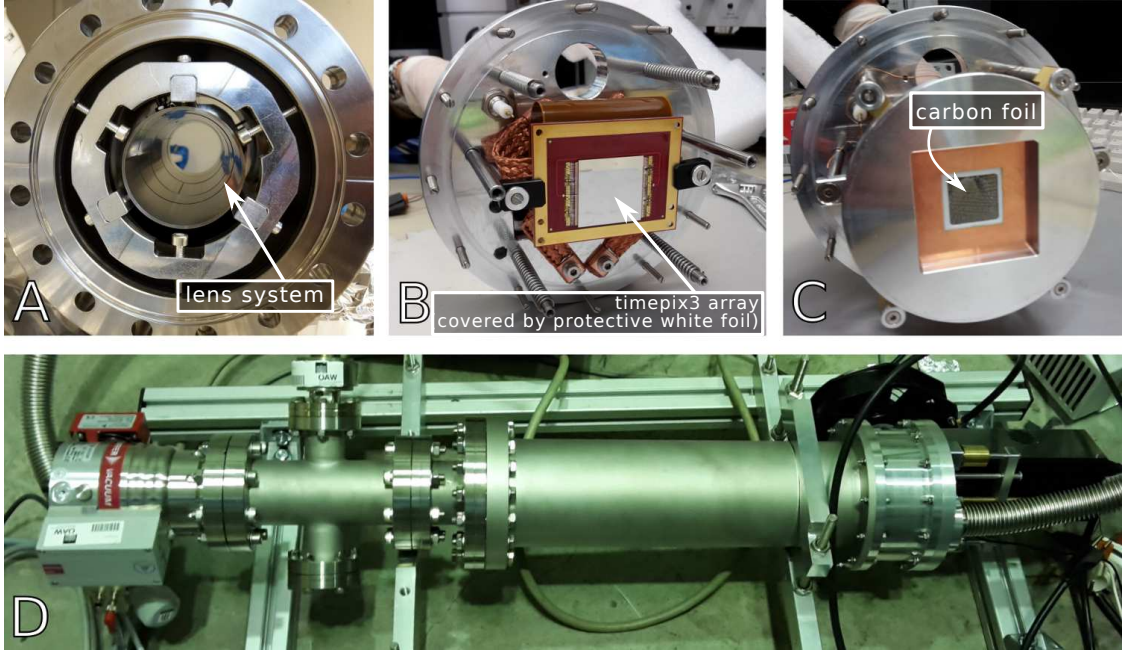


Figure 6.27.: Pictures taken during preparations for the Timepix3 measurements in beam-time 2017 (picture by courtesy of Johann Zmeskal and Angela Gligorova). *A*: Einzel lens inside its beampipe. *B*: mounted Timepix3 sensor. *C*: Carbon target foil mounted in front of Timepix3. *D*: Beampipe housing the Timepix3 setup which was inserted later into the hodoscope and connected to the antiproton beamline.

systematic study of annihilations it is important to have a data sample as clean as possible i.e. antiprotons should in an ideal case only annihilate on the target material of interest. Therefore the mentioned lens system has been placed between double-CUSP trap and Timepix3 detector to steer and focus the beam.

Prior to the measurements and in order to characterise the size of the beam in x and y , extractions of antiprotons using the position sensitive BGO detector have been carried.

The x - and y -position distribution of the annihilating antiprotons after tuning of lens system can be seen in Figure 6.28. The optimum settings of the lens system found showed a FWHM of the beam of around ≤ 30 mm.

Additionally, in order to further focus the antiprotons, a voltage between 500 V and 1000 V was applied to the carbon foil. Simulations carried out by D. Murtagh in SIMION 8.0 [129] showed, that this further decreases the width of the annihilation profile in x - y to about $\text{FWHM} = 25$ mm. According to those simulations, 97.5% of all antiproton events annihilate in the foil when applying a voltage of 1000 V to the foil.

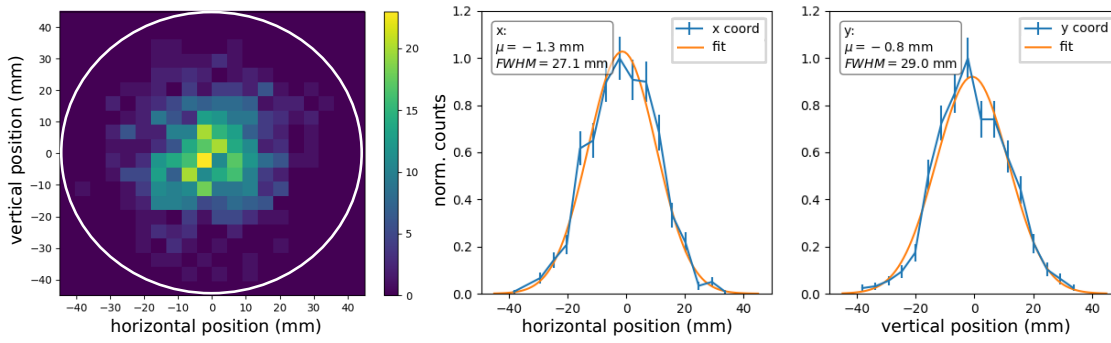


Figure 6.28.: Recorded antiproton events during one extraction from the MUSASHI trap to the BGO detector. 808 events in total using rough cuts of $E_{\text{BGO}} > 20$ MeV and a time window cut of 40 seconds in which the detector showed a high trigger rate indicating when the antiprotons arrived at the detector. *Left*: two-dimensional histogram of (x, y) hit position of the recorded events. The hit position has been determined using the cluster finding algorithm described in Section 3.6.4. *Middle*: histogram of the x -coordinate (horizontal position) of the events (blue) and Gaussian fit (orange). *Right*: histogram of the y -coordinate (vertical position) of the events (blue) and Gaussian fit (orange). The error bars indicate Poisson errors.

The found beam parameters have been used for Geant4 simulations to compare the tracking and vertex reconstruction results of simulations and measurements. A simple setup has been simulated where the BGO is replaced by a target carbon foil. More accurate simulations including a detailed geometry and electronics of the Timepix3 array are currently on-going.

6.5.3. Tracking and Vertex reconstruction of measured antiproton annihilations

The measured data discussed in the following has been taken during 28 runs in the last shift of beamtime 2017 (17th December). The antiprotons were slowly extracted from MUSASHI through the double-CUSP trap to the Timepix3 chamber with an energy of 150 eV. The start and stop of the detector DAQ was synchronised with the trap system resulting to run duration of 70 s. The antiprotons arrived in a time window of about 20 s.

After an event initiated a hodoscope trigger, the trigger signal was sent to the Timepix3 detector causing the current event to be marked by a time stamp in the continuous Timepix3 readout. About 1000 triggers were issued per run. Time between two consecutive triggers was limited by the hodoscope DAQ which has a maximum rate of about 100 Hz.

6.5. Measured antiproton annihilations with the Timepix3 setup

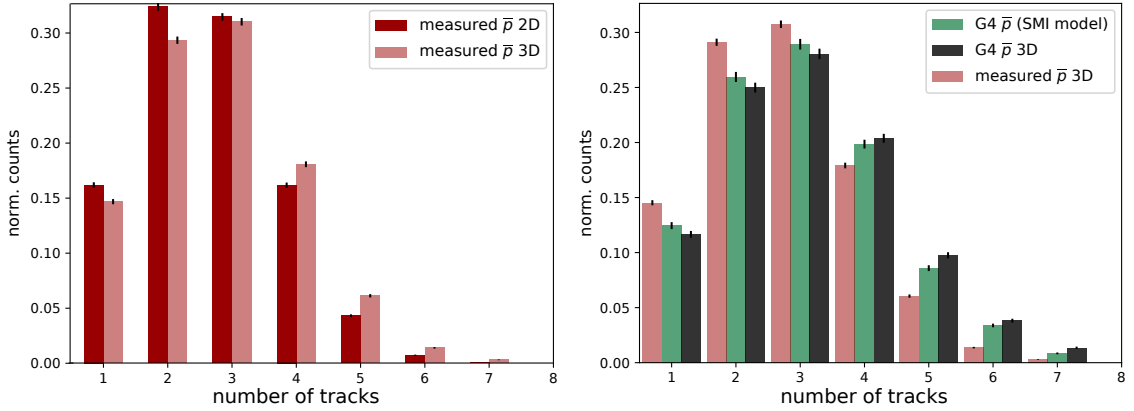


Figure 6.29.: Histograms of number of tracks for the measured antiproton annihilations with the Timepix3 and hodoscope setup. *Left*: comparison of number of tracks found by the three-dimensional (light red) and the two-dimensional (dark red) tracking algorithms. *Right*: comparison of number of tracks by the three-dimensional tracking algorithm for measured (light red), simulated (dark grey) antiproton events and tracks passing both bar hodoscope layers extracted from the simulations (green). The error bars indicate Poisson errors.

A cut on the arrival time at the detector was applied to reduce background from cosmic rays. In total 34450 events were recorded and will be considered in the analysis of number of tracks. The cosmic rate was ≈ 1.3 Hz. The total number of cosmic events in the data set is therefore estimated by $28 \times 20 \text{ s} \times 1.3 \text{ Hz}$ resulting to 728 cosmic events, which is only 2.1% of the total number of recorded events and therefore negligibly small. For the vertex reconstruction, 29818 events with $N_{3D} > 1$ are taken into account.

The number of tracks of the measured antiproton events determined by the two- and the three-dimensional tracking algorithms as well as a comparison to simulations can be seen in Figure 6.29. N_{3D} of the measurements is shown in light red in both plots in Figure 6.29. As has been found also with simulations, the two-dimensional tracking (dark red) overestimates the number of tracks for lower track numbers and underestimates higher number of tracks.

The number of secondaries traversing both layers of hodoscope in the simulations (N_{G4}) is shown in green and the number of reconstructed tracks by the algorithm in dark grey.

The charged multiplicity distribution of the measurements shows a shift towards lower number of tracks compared to simulations. Note, that the simulations done here lack detailed geometry of the Timepix3 setup and their purpose is mainly testing the tracking and vertex reconstruction algorithm. A detailed comparison to the simulation models will be done at a later stage.

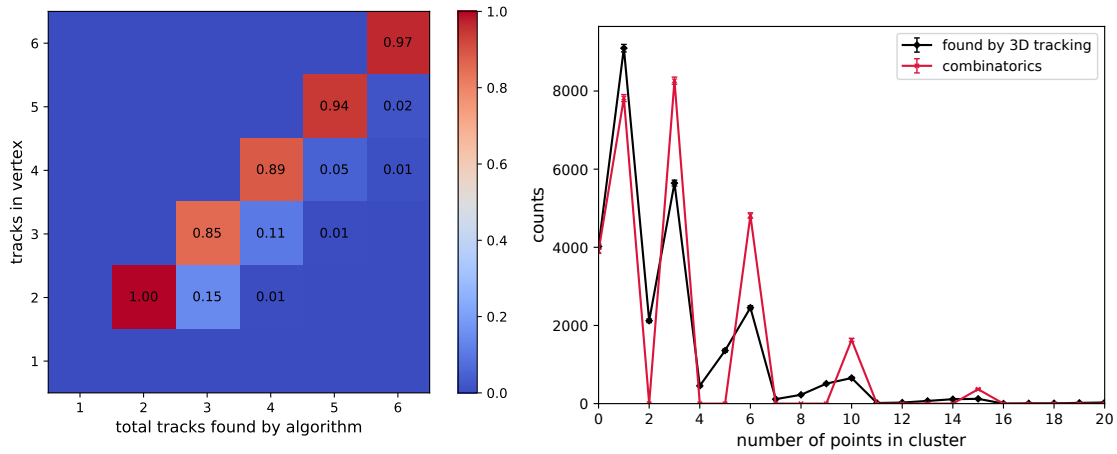


Figure 6.30.: *Left*: two-dimensional histogram of the number of tracks that meet in the vertex $N_{3D,v}$ (i.e. their midpoints contribute to the largest cluster) versus the number of total tracks found (N_{3D}) for measured antiproton events. The histogram is normalised column-wise to their corresponding N_{3D} . *Right*: Histograms of the number of midpoints in the largest cluster found for measured antiproton annihilations (black) and the calculated number of points that should be in a cluster based on the found number of tracks (see Figure 6.29) in red.

Figure 6.30 (left) shows a two-dimensional histogram of $(N_{3D}, N_{3D,v})$ for measured data i.e. a comparison of found tracks in total and tracks meeting in the vertex. The histogram is normalised column-wise, the the column's corresponding N_{3D} . For all track numbers, the highest bins are located in the diagonal. It is also in good agreement with expectations from simulations, cf. also Figure 6.13.

A histogram of the number of midpoints found in the largest cluster for measured antiproton events can be seen in black in Figure 6.30 (right). The expected number of midpoints in an ideal case deducted from the number of tracks is plotted in red. It shows a very similar structure as found with simulations earlier in this chapter, see Figure 6.12.

Figure 6.31 shows the normalised distributions of x -, y - and z -components of the determined vertices for measured (red) and simulated data (grey). The histograms have been centred around zero by subtracting the means from the z -positions. Their standard deviations are again listed in the top left corners. The x - and y -distributions of simulations and measurements look very similar, the simulations show a slightly higher variance in x . The central peak of the measurements is a bit narrower compared to simulations. This could be an indication that the beam width was slightly smaller than assumed during measurements. The measured z -distribution is in good agreement

6.5. Measured antiproton annihilations with the Timepix3 setup

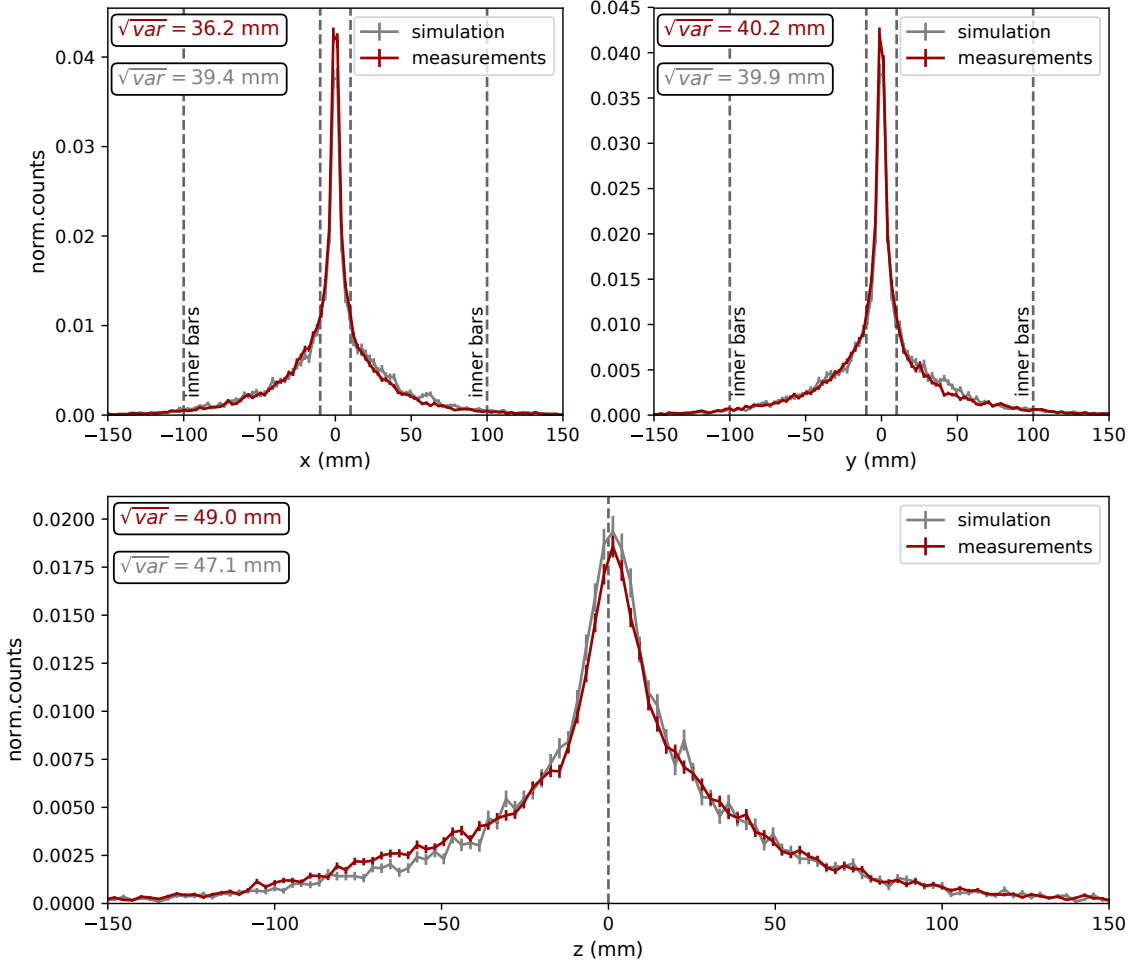


Figure 6.31.: Histograms of the x - (top left), y - (top right) and z -components (bottom) of the determined vertices for measured data (red) and simulations (grey). Both histograms have been normalised to their area. Dashed lines mark the extent of carbon foil and the inner hodoscope layer. The text boxes in the left corners show sample mean and standard deviation of the displayed data.

with simulations. It shows a slightly higher variance of $\sigma_z = 49$ mm than the simulations ($\sigma_z = 47.1$ mm).

Figure 6.32 shows a comparison of the distributions of the error on the z -positions estimated by error propagation of the errors of the fit parameters σ_z^v for measured (red) and simulated antiprotons (grey). The measured distribution is only slightly broader and shifted to higher σ_z^v , the overall agreement is very good. The measured distribution has a mean of 31.5 mm and a median of 20.8 mm, compared to the simulations which show 30.0 mm and 20.8 mm.

Summarising, the vertex reconstruction results of measurements and simulations are in good agreement. Additional three-dimensional track information

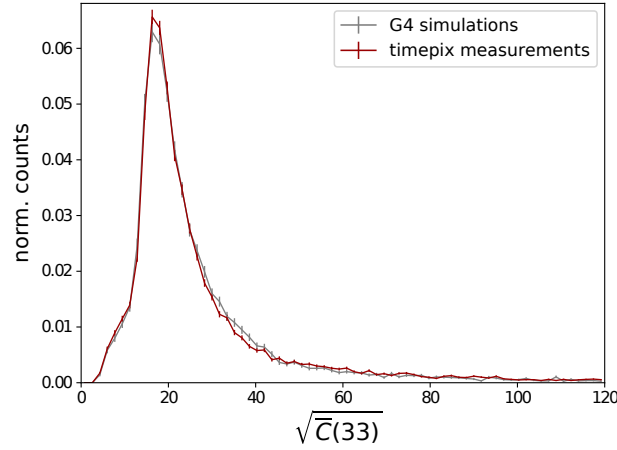


Figure 6.32.: Histogram of $\sigma_z^v = \sqrt{C(33)}$ of simulated (grey) and measured (red) antiproton events. The histograms are normalised to their area.

from the Timepix3 detector could help to improve the vertex resolution. This is planned for a future upgrade of the analysis.

The next steps are implementing a detailed geometry of the Timepix3 quad array and related parts such as its support structure in Geant4 and performing simulations with the combined detector setup. Afterwards, the measured data recorded with the three different target materials (carbon, gold and molybdenum) can be compared to simulations using different models for antiproton annihilations.

7. Summary and conclusions

In the course of this thesis, several improvements of the antihydrogen detection hardware and analysis have been carried out which lead to an improved signal and background discrimination. In the following, the results of the four main parts of this thesis are summarised: detector hardware (Chapter 3), event identification employing machine learning (Chapter 4), the results of the developed analysis (Chapter 5) and three-dimensional tracking (Chapter 6). Conclusions and an outlook for possible further improvements are given as well.

7.1. Detector hardware

The purpose of the antihydrogen detector at the end of the Rabi-like spectrometer line is to count the arriving antihydrogen atoms. Due to the low production rate of antihydrogen atoms, a high efficiency for annihilations and a high background suppression are essential. Several hardware improvements of the existing tracking detector surrounding the central calorimeter have been carried out during this thesis.

The signal quality of the bar hodoscope was greatly improved by increasing the pulse amplitudes by an order of magnitude. The signals were heavily attenuated in the previous setup due to paint on the light guides. As a result, the time-of-flight resolution of the hodoscope has been improved which aids the discrimination of events originating from inside the detector (antihydrogen annihilations) from background stemming from outside (cosmic particles). The time-of-flight resolution of hodoscope bars have been measured to be (494 ± 3) ps (FWHM) for the inner and (551 ± 5) ps (FWHM) for the outer layer (Section 3.3.1.2). In the context of the machine learning analysis, investigations of the importance of event characteristics have been carried out. Those showed, that in terms of discrimination power of signal and background, the time-of-flight of events is one of the top three event features.

Furthermore, the improved signal quality allows for obtaining coarse z-position information of particles hitting the hodoscope bars.

The front-end electronics of the hodoscope, responsible for setting amplification gains and thresholds for generating digital signals, have been upgraded to be more robust and ensure stable operation during beamtime (Section 3.3.1.3). Additionally, contributions to the development and construction of the scintillating fibre upgrade of the tracking detector were made in order to improve

its position resolution (Section 3.3.2). The upgrade was successfully installed into the existing setup and made operational during beamtime 2017.

A future improvement of the tracking detector could be achieved by increasing the time resolution of the hodoscope bars further. This would enhance the separation of signal and background due to resulting improved time-of-flight resolution and additionally aid the three-dimensional tracking greatly.

Another possible upgrade would be to increase the time resolution of the fibre detector and therefore potentially allow for determining the x - and y -position of the particle's hit position on the fibre. This could be achieved by replacing the leading edge discriminators that create the digital signals of the fibres with constant fraction discriminators.

7.2. Event identification and $\bar{\text{H}}$ beam characterisation results

A major part of this thesis was dedicated to the development of a data-driven machine learning analysis for antihydrogen event identification (Chapter 4). Two analysis methods based on different machine learning algorithms have been realised: (1) gradient-boosted decision trees (Section 4.3) and (2) isolation forest (Section 4.4). The former is chosen for final results since it showed a higher cosmic rejection and higher significance of the number of antihydrogen atoms in the lowest-lying states. It shall be discussed first in the following.

The analysis employs supervised machine learning and the underlying algorithm is gradient-boosted decision trees (Section 4.3.1). The measured data that has been used to train and validate the algorithm consists of recorded antiproton annihilations (signal sample) and cosmic rays (background sample) (Section 4.2.1).

In order to find the combination of event characteristics resulting in the best performance, input feature selection has been performed (Section 4.2.4). For this purpose, sequential feature selection methods have been employed which showed that the best performance could be achieved with the nine features listed in Table 4.4, the three top features being the largest angle between tracks, the energy deposit in the BGO, and the time-of-flight. Furthermore, the hyper-parameter of the gradient-boosted decision trees have been tuned employing a Bayesian optimisation method, namely the Tree Parzen Estimator (Section 4.3.3).

In order to calculate background and signal efficiency, the algorithm's response to cosmic and antiproton events that it has never seen before, was used (Section 4.3.4). It assigns a prediction score s with a value between 0 (background) and 1 (signal) to every event. Setting a cut on s allows to classify events into signal ($s > s_{\text{thres}}$) and background ($s \leq s_{\text{thres}}$) and therefore to calculate signal efficiency and background rejection.

Antihydrogen mixing runs dedicated to the measurement of the quantum state distribution of the produced antiatoms have been analysed (Chapter 5). In total, 114 runs were performed and analysed. A suitable value for the afore mentioned cut s_{thres} on the prediction score needs to be determined in order to select $\bar{H}$ candidates. s_{thres} has been tuned by optimising the observed significance of the found number of antihydrogen candidates in the first 6 s after mixing start (Section 5.1), which is the time interval when the majority of them arrive at the detector.

The resulting antiproton efficiency is 0.800 ± 0.0111 and the background rejection 0.9836 ± 0.0031 . The false positive rate amounts to (0.0077 ± 0.0015) Hz. In total, 117 $\bar{H}$ candidates have been found considering the first 6 s after the mixing start, which is the time interval when most candidate events have been observed. The resulting distribution of principal quantum numbers of the produced antihydrogen atoms shows, that a higher fraction of atoms reaching the entrance of the spectroscopy beamline are in Rydberg states as expected for 3-body-recombination, the dominant creation process in ASACUSA (Section 5.4). The observed rate of the lowest-lying quantum states, $n < 14$, amounts to 0.395 ± 0.096 (Poisson error) per run with an observed significance (defined in Equation 5.3) of 6.8σ . The longest decay channel of antiatoms with $n < 14$ to the ground state is $\approx 100 \mu\text{s}$. Hence when considering velocities of 1000 m/s which is the limit of accepted velocities of the spectroscopy setup, those antiatoms are likely to decay into the ground state before reaching the cavity.

This first characterising measurement of the produced antihydrogen beam shows that a small fraction of antihydrogen atoms in low-lying states reach the spectroscopy line. However, in order to reach the goal of a ppm measurement of the ground state transition frequency in the typical amount of beamtime, the production rate of $\bar{H}$ atoms with $n < 14$ needs to be increased by 1 to 2 orders of magnitude. The primary goal of subsequent beamtimes is therefore to focus on increasing beam intensity and optimise the quantum state distribution. Further characterisation of the beam, such as measurements of its polarisation and velocity, will also be necessary.

It shall be emphasised again that ASACUSA's measurement of the quantum state distribution is the first one of antihydrogen atoms produced in 3-body-recombination in a magnetic field-free region. It is also the first measurement down to quantum numbers as low as $n = 14$. In the past, the ATRAP collaboration has measured the n -distribution only down to $n = 48$. Furthermore, their measurement was done inside a Penning trap with a magnetic field of 5.4 T. However, the assumed dependence of n on the ionising electric field is not valid in large B-fields leading to a large uncertainty of their results.

Furthermore, the time distribution of antihydrogen atoms arriving at the detector has been compared to results of the AMT detector and of the FIC measurements (Section 5.3). A large discrepancy in numbers of produced antiatoms is observed for the three different detection methods which see different solid angles of the mixing region. A spatially non-isotropic production is therefore likely which could be explained by a radial component of the produced antiatoms that could arise from the rotation of the plasmas in the mixing trap.

A second, profoundly different machine learning analysis has been developed which is based on the anomaly detection algorithm isolation forest (Section 4.4) and is trained by only one data sample consisting of a mixture of unlabelled signal and background events with the requirement that the signal events are different and rare. This perfectly suits the data gathered during mixing runs which is dominated by cosmics and contains only a few antihydrogen events.

Similarly to the optimisation procedure used to determine a cut on the prediction score s of the GBDT analysis, the cut on the anomaly score was also chosen to maximise the observed significance of the found antihydrogen candidates (Section 5.5). The IF analysis shows a lower cosmic rejection (0.9175 ± 0.0025) and a slightly higher antiproton efficiency (0.8597 ± 0.0050). The events found by GBDT and IF analysis agree well, 95.5% of the total number of events of the GBDT analysis are included in the 154 candidate events the IF analysis identified. The rest of the events only selected by IF have been investigated and show mostly cosmic-like characteristics. The rate of antihydrogen events with $n < 14$ for the IF algorithm is 0.674 ± 0.125 (Poisson error) per run with an observed significance of 5.0σ . Although the IF analysis has the advantage that it only relies on one data set and less event input features, the analysis based on gradient-boosted decision trees is favoured since it shows a higher significance for found antihydrogen candidates with $n < 14$.

7.3. Three-dimensional tracking

The scintillating fibre upgrade of the tracking detector of ASACUSA's antihydrogen detector enables three-dimensional tracking and vertex reconstruction in order to discriminate against the possible background contribution of upstream annihilations. During mixing runs, those could stem from antihydrogen atoms in high-field seeking states being defocussed by the sextupole magnet. During antiproton extractions for the fragmentation studies in antiproton nucleus annihilations with the Timepix3 detector, it is important to identify antiprotons annihilating on and outside the target material.

A three dimensional track finding and -fitting as well as a vertex estimating algorithm was developed and tested with Geant4 simulations (Chapter 6). Cosmic events, as well as antiproton annihilations on the central calorimeter and on the beampipe walls have been simulated and studied.

The found number of tracks N_{3D} is in good agreement with the extracted number of charged secondaries N_{G4} from the simulations (Section 6.4.2). The vertex reconstruction based on the found tracks shows that due to the missing x - and y -position information of the fibres, a bias in x and y is induced. However, the distributions of the reconstructed z -position is unbiased and nicely centred around the actual annihilation position known in the simulations.

The standard deviation σ_z of the z -position distributions for antiprotons annihilating on the center of the BGO is 46.7 mm (Section 6.4.3.2). The error on the vertices has been calculated for events individually by error propagation of the track fit errors. The distribution of errors for events hitting the BGO in the center considering all events with $N_{3D,v} > 1$ showed a mean of 33.4 mm and a median of 22.2 mm. Discrimination against annihilation on the beampipe and direct vicinity of the central detector is therefore only possible to a certain extent (Section 6.4.3.3).

The algorithm has been used to analyse antiproton annihilations recorded with the Timepix3 as a central detector surrounded by the tracking detector (Section 6.5). The results have been compared to simulations and the distributions of vertex components show very good agreement.

The algorithm uses at the moment only the information of the tracking detector for the vertex determination. For a future improvement, the data of the central detector could be included. In case of the BGO calorimeter, the determined hit position could be included as a track hit without making assumptions about the vertex, since the BGO hit could stem from a pion

from an annihilation in the direct vicinity of the central detector. For antiproton extractions using the Timepix3 detector, additional three-dimensional track information can be gained from it and could be incorporated into the algorithm.

The most limiting factor of the tracking and vertex determination results from the difficulty of assigning bar and fibre hits of the two independent sub-detectors. A possible way of increasing the vertex resolution would therefore be to improve the detector hardware e.g. as already mentioned additional x and y information from the fibres and a better z -resolution of the hodoscope bars.

Furthermore, on the analysis side, the vertex determination could be upgraded by using a vertex fitting method. In the discussed analysis the vertex is estimated by finding the largest cluster in the collection of midpoints of the closest points of track pairs. The vertex fit on the other hand, aims at finding the spatial point that minimising the sum of squared distances between tracks weighted by the variances of the fits¹. More information and impetus for future improvements can be found in [130].

¹Actually, the vertex fit was implemented for the analysis at hand, did however run into minimisation problems that could not be resolved in a reasonable amount of time.

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A.3. List of acronyms and abbreviations

AD	Antiproton Decelerator
ADC	Analogue to Digital Converter
AMT	ASACUSA Micromegas Tracker
ASACUSA	Atomic Spectroscopy And Collisions Using Slow Antiprotons
BGO	Bi ₄ Ge ₃ O ₁₂ (Bismuth germanate)
CART	Classification And Regression Tree
CRY	Cosmic-RaY shower library
CERN	Conseil Européene pour la Recherche Nucléaire
CF	Constant Fraction
CHIPS	CHiral Invariant Phase Space
DAQ	Data AcQuisition
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
FI	Field Ioniser
FIC	Field Ionizing well in the double CUSP
FPGA	Field Programmable Gate Array
FWHM	Full Width at Half Maximum
Geant4	GEometry ANd Tracking, version 4
GBDT	Gradient Boosted Decision Trees
IDC	Insulation-Displacement Contact
IF	Isolation Forest
IFES	Intelligent Front-End Electronics for Silicon Photomultipliers
LE	Leading Edge
LHC	Large Hadron Collider
LS2	Long Shutdown 2
LIV	Lorentz Invariance Violation
LVDS	Low-Voltage Differential Signaling
MA-PMT	Multi-Anode PhotoMultiplier Tube
Micromegas	Micro-MESh Gaseous Structure
MIDAS	Maximum Integrated Data Acquisition System
MIP	Minimum Ionising Particle
MRE	Multi-Ring Electrode

MUSASHI Monoenergetic Ultra-Slow Antiproton Source for High-precision Investigation
NIM Nuclear Instrumentation Module
PS Proton Synchrotron
PSB Proton Synchrotron Booster
RFQD Radio Frequency Quadrupole Decelerator
ROC Receiver Operator Characteristics
SBS Sequential Backward Selection
SBFS Sequential Backward Floating Selection
SFFS Sequential Forward Floating Selection
SFS Sequential Forward Selection
SiPM Silicon PhotoMultiplier
SME Standard Model Extension
SPS Super Proton Synchrotron
SMOTE Synthetic Minority Oversampling TEchnique
TDC Time-to-Digital Converter
TMVA Tool-kit for MultiVariate data Analysis
ToF Time of Flight
ToT Time over Threshold
TPE Tree Parzen Estimator
VME Versa Module Europa

A.4. Bar hodoscope amplitudes

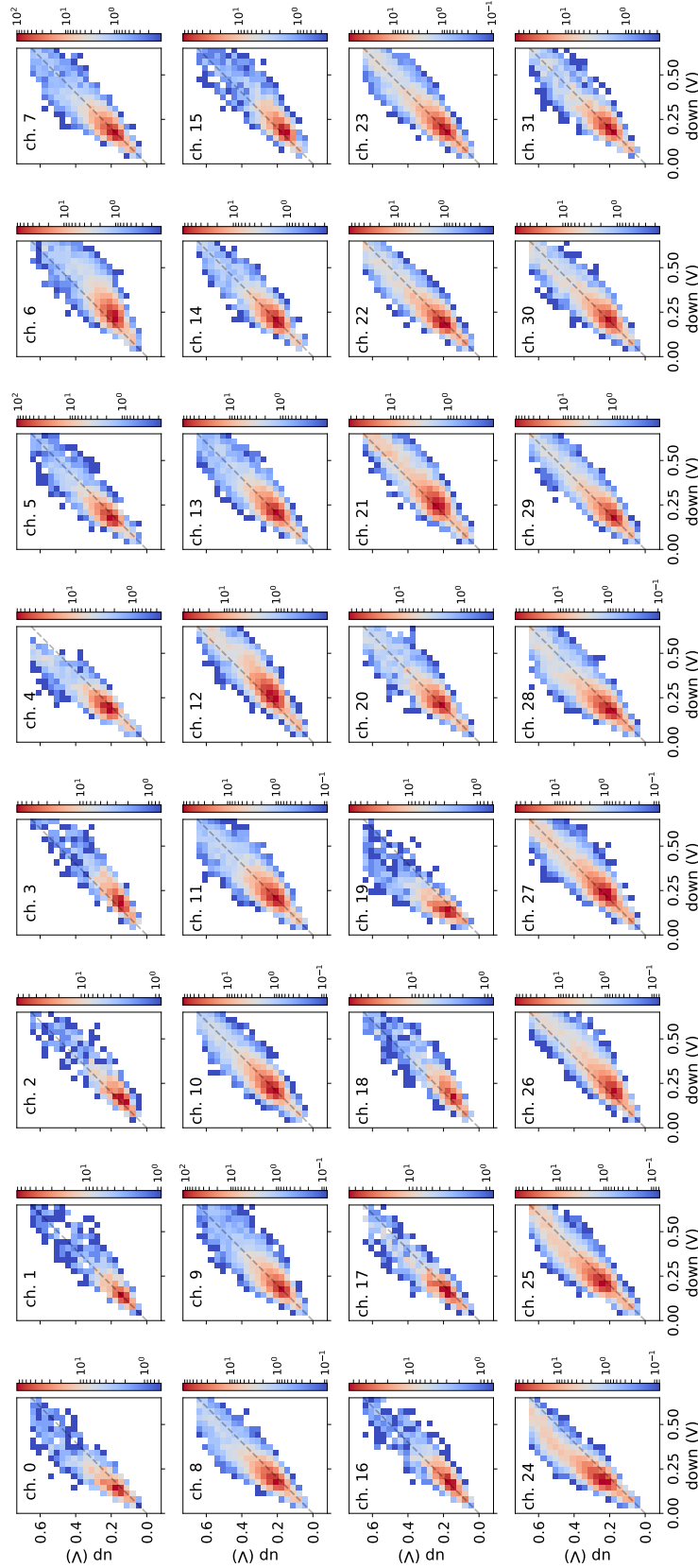


Figure A.1.: Two-dimensional histograms of up- and downstream amplitudes of the inner hodoscope.

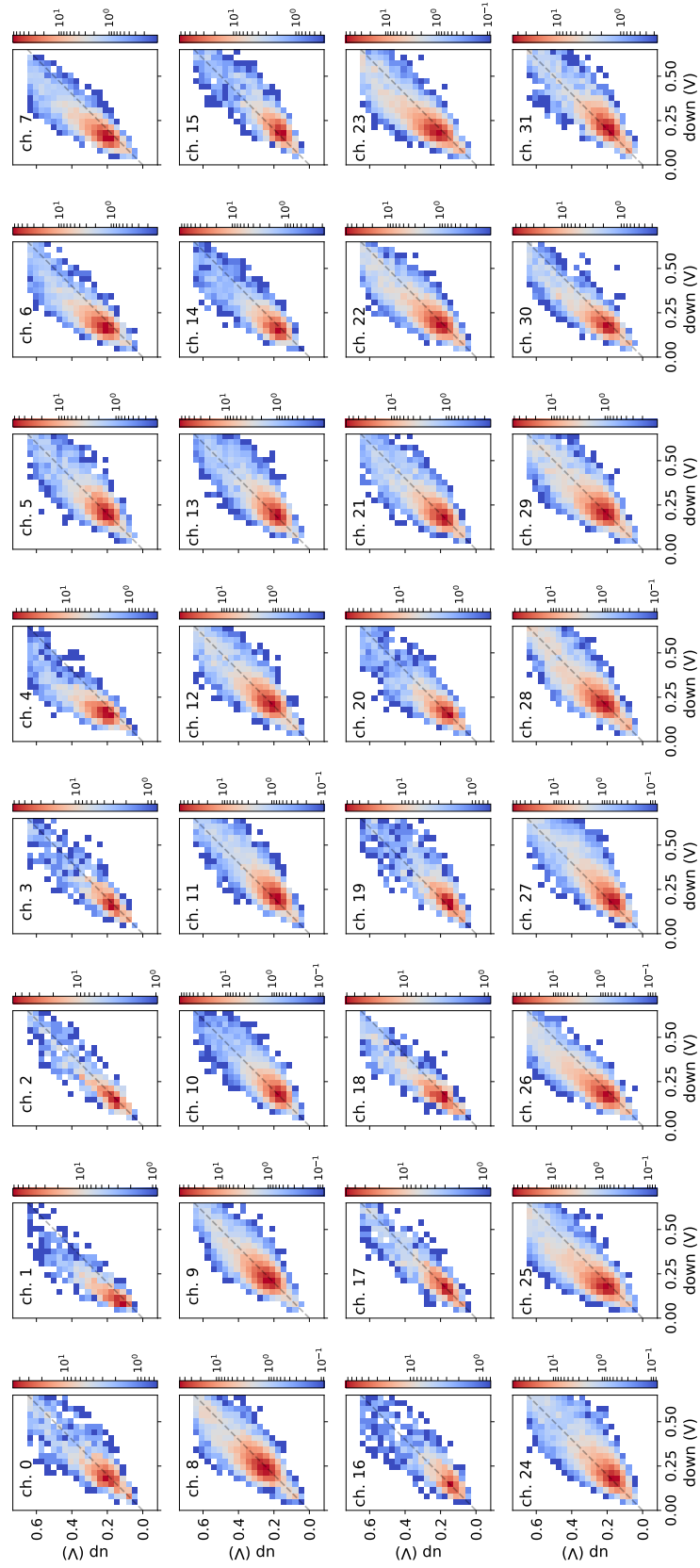


Figure A.2.: Two-dimensional histograms of up- and downstream amplitudes of the outer hodoscope.

A.5. Trigger diagrams

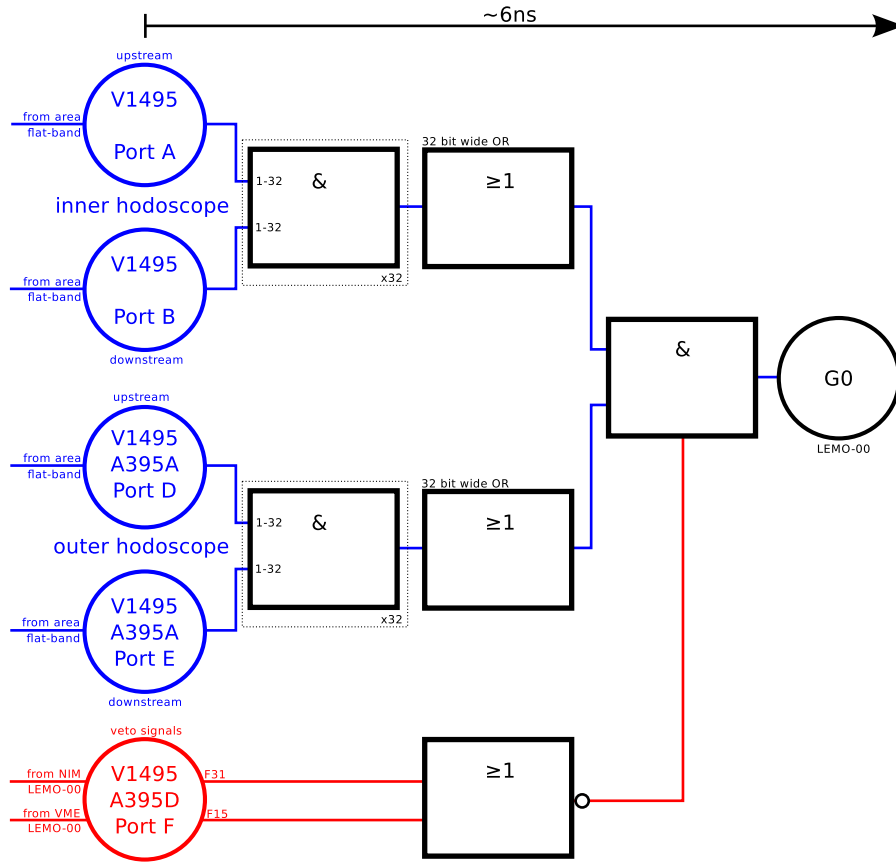


Figure A.3.: The FPGA logic [84]. Trigger signals are shown in blue and veto signals in red. The small circle of the veto signal symbolises inversion. G0 is the output of the FPGA.

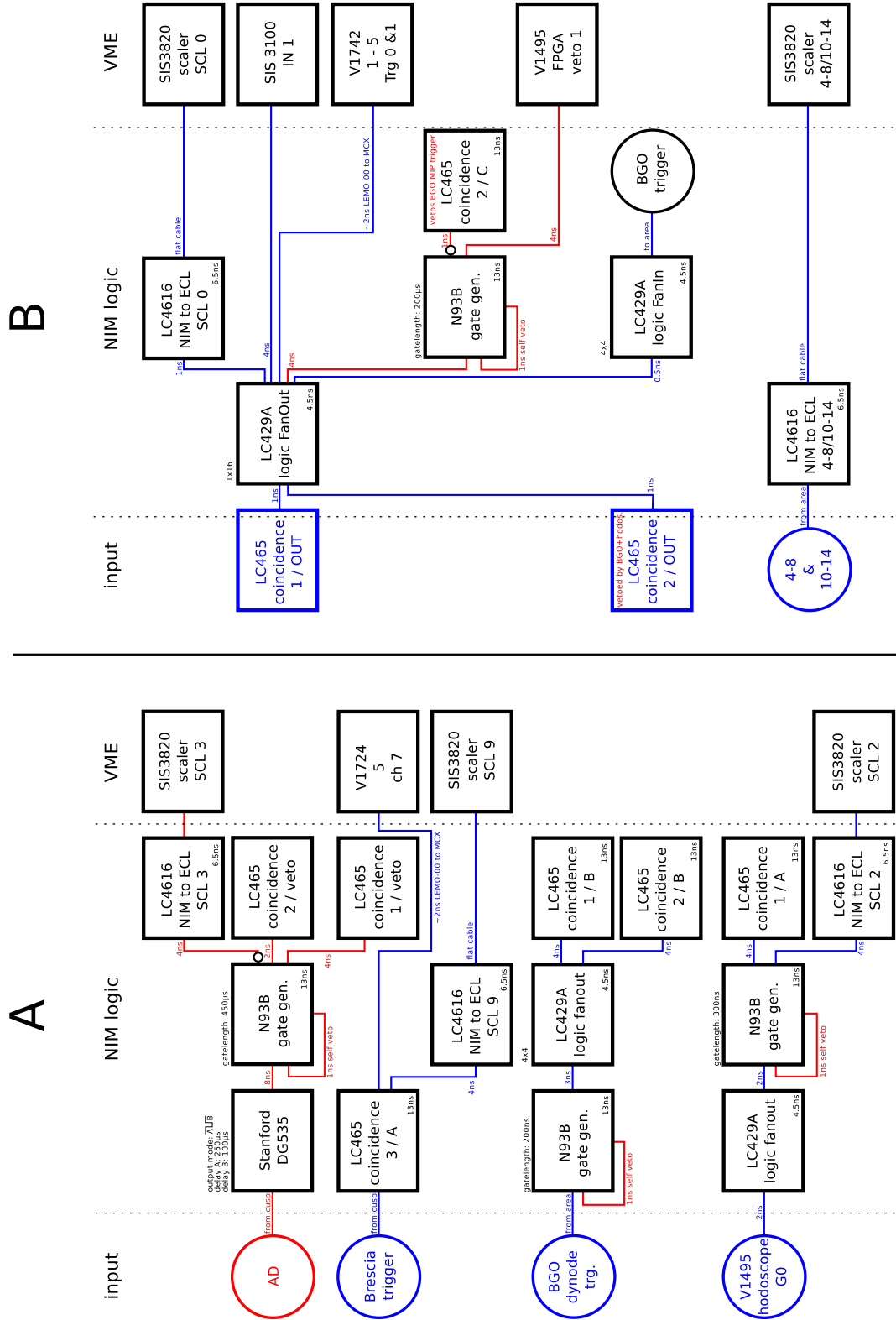


Figure A.4.: Trigger flow diagrams [84]. A: first part of the diagram, before the coincidence unit that generates the event trigger from BGO and hodoscope trigger. B: signal flow after the coincidence unit. Blue indicates trigger signals, red veto signals. Coloured circles symbolise signals coming from or going to the experimental area. Labels indicate delays. Modules are drawn with black rectangles in which model, functionality, and used input channel are listed.

A.6. List of mixing runs

Table A.1.: Mixing runs dedicated to the measurement of the principal quantum number distribution and used in the analysis. The total number of runs is 114. “planned $\bar{p}$ stacks” lists the number of planned antiproton AD shots accumulated in the MUSASHI trap. The actual number of stacks is listed in “actual $\bar{p}$ stacks”. The number of positron stacks is indicated in column “ e^+ stacks”. The column “transport” lists the extraction energy of the antiprotons from MUSASHI to the double-CUSP. “FIC” indicates whether the field ioniser in the mixing trap was turned on. The last column lists the applied voltages to the external field ioniser meshes.

CUSP	MIDAS	planned $\bar{p}$ stacks	actual $\bar{p}$ stacks	e^+ stacks	transport	FIC	Field ioniser (up, down)
2640	3966	4	4	27	1.5 eV	false	(0 V, -40 V)
2642	3970	4	4	30	1.5 eV	true	(400 V, -400 V)
2644	3972	4	4	30	1.5 eV	false	(0 V, -40 V)
2646	3974	4	4	30	1.5 eV	true	(400 V, -400 V)
2652	3982	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2653	3984	4	4	25	1.5 eV	true	(400 V, -400 V)
2654	3985	4	4	25	1.5 eV	false	(0 V, -40 V)
2655	3986	4	3	25	1.5 eV	true	(5000 V, -5000 V)
2656	3987	4	3	25	1.5 eV	true	(400 V, -400 V)
2657	3988	4	4	25	1.5 eV	false	(0 V, -40 V)
2658	3989	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2659	3990	4	2	25	1.5 eV	true	(400 V, -400 V)
2660	3991	4	4	25	1.5 eV	false	(0 V, -40 V)
2661	3992	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2662	3993	4	4	25	1.5 eV	true	(400 V, -400 V)
2663	3994	4	4	27	1.5 eV	false	(0 V, -40 V)
2664	3995	4	4	27	1.5 eV	true	(5000 V, -5000 V)
2665	3996	4	4	27	1.5 eV	true	(400 V, -400 V)
2666	3997	4	4	27	1.5 eV	false	(0 V, -40 V)
2667	3998	4	4	27	1.5 eV	true	(5000 V, -5000 V)
2668	3999	4	3	27	1.5 eV	true	(400 V, -400 V)
2669	4000	4	3	27	1.5 eV	false	(0 V, -40 V)
2671	4002	4	4	27	1.5 eV	true	(5000 V, -5000 V)
2672	4003	4	4	27	1.5 eV	true	(400 V, -400 V)
2673	4004	4	3	27	1.5 eV	false	(0 V, -40 V)
2674	4005	4	4	27	1.5 eV	true	(5000 V, -5000 V)
2675	4006	4	4	27	1.5 eV	true	(400 V, -400 V)
2682	4011	4	4	25	1.5 eV	true	(400 V, -400 V)

Table A.1.: Mixing runs dedicated to the measurement of the principal quantum number distribution and used in the analysis. The total number of runs is 114. “planned $\bar{p}$ stacks” lists the number of planned antiproton AD shots accumulated in the MUSASHI trap. The actual number of stacks is listed in “actual $\bar{p}$ stacks”. The number of positron stacks is indicated in column “ e^+ stacks”. The column “transport” lists the extraction energy of the antiprotons from MUSASHI to the double-CUSP. “FIC” indicates whether the field ioniser in the mixing trap was turned on. The last column lists the applied voltages to the external field ioniser meshes.

CUSP	MIDAS	planned $\bar{p}$ stacks	actual $\bar{p}$ stacks	e^+ stacks	transport	FIC	Field ioniser (up, down)
2683	4012	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2684	4013	4	4	25	1.5 eV	false	(0 V, −40 V)
2685	4014	4	4	25	1.5 eV	true	(400 V, −400 V)
2686	4015	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2687	4016	4	4	25	1.5 eV	false	(0 V, −40 V)
2688	4017	4	4	25	1.5 eV	true	(400 V, −400 V)
2689	4018	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2690	4019	4	4	25	1.5 eV	false	(0 V, −40 V)
2691	4020	4	4	25	1.5 eV	true	(400 V, −400 V)
2692	4021	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2693	4022	4	4	25	1.5 eV	false	(0 V, −40 V)
2694	4023	4	3	25	1.5 eV	true	(400 V, −400 V)
2695	4024	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2696	4025	4	4	25	1.5 eV	false	(0 V, −40 V)
2697	4026	4	4	25	1.5 eV	true	(400 V, −400 V)
2698	4027	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2699	4028	4	4	25	1.5 eV	false	(0 V, −40 V)
2700	4029	4	4	25	1.5 eV	true	(400 V, −400 V)
2701	4030	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2702	4031	4	4	25	1.5 eV	false	(0 V, −40 V)
2703	4032	4	4	25	1.5 eV	true	(400 V, −400 V)
2704	4033	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2705	4034	4	4	25	1.5 eV	false	(0 V, −40 V)
2706	4035	4	4	25	1.5 eV	true	(400 V, −400 V)
2707	4036	4	1	25	1.5 eV	true	(5000 V, −5000 V)
2708	4037	4	1	25	1.5 eV	true	(5000 V, −5000 V)
2715	4042	4	0	25	1.5 eV	true	(5000 V, −5000 V)
2716	4043	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2717	4044	4	4	25	1.5 eV	true	(400 V, −400 V)
2718	4045	4	4	25	1.5 eV	false	(0 V, −40 V)
2719	4046	4	4	25	1.5 eV	true	(5000 V, −5000 V)

Table A.1.: Mixing runs dedicated to the measurement of the principal quantum number distribution and used in the analysis. The total number of runs is 114. “planned $\bar{p}$ stacks” lists the number of planned antiproton AD shots accumulated in the MUSASHI trap. The actual number of stacks is listed in “actual $\bar{p}$ stacks”. The number of positron stacks is indicated in column “ e^+ stacks”. The column “transport” lists the extraction energy of the antiprotons from MUSASHI to the double-CUSP. “FIC” indicates whether the field ioniser in the mixing trap was turned on. The last column lists the applied voltages to the external field ioniser meshes.

CUSP	MIDAS	planned $\bar{p}$ stacks	actual $\bar{p}$ stacks	e^+ stacks	transport	FIC	Field ioniser (up, down)
2720	4047	4	4	25	1.5 eV	true	(400 V, -400 V)
2721	4048	4	4	25	1.5 eV	false	(0 V, -40 V)
2722	4049	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2723	4050	4	4	25	1.5 eV	true	(400 V, -400 V)
2724	4051	4	4	25	1.5 eV	false	(0 V, -40 V)
2725	4052	4	3	25	1.5 eV	true	(5000 V, -5000 V)
2726	4053	4	3	25	1.5 eV	true	(400 V, -400 V)
2727	4054	4	4	25	1.5 eV	false	(0 V, -40 V)
2728	4055	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2729	4056	4	3	25	1.5 eV	true	(400 V, -400 V)
2730	4057	4	4	25	1.5 eV	false	(0 V, -40 V)
2731	4058	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2732	4059	4	4	25	1.5 eV	true	(400 V, -400 V)
2742	4095	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2743	4096	4	4	25	1.5 eV	false	(70 V, -70 V)
2744	4097	4	3	25	1.5 eV	false	(70 V, -70 V)
2745	4098	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2746	4099	4	4	25	1.5 eV	false	(70 V, -70 V)
2747	4100	4	3	25	1.5 eV	false	(70 V, -70 V)
2748	4101	4	4	25	1.5 eV	false	(0 V, -40 V)
2749	4102	4	4	25	1.5 eV	false	(70 V, -70 V)
2750	4103	4	1	25	1.5 eV	false	(70 V, -70 V)
2751	4104	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2752	4105	4	4	25	1.5 eV	false	(70 V, -70 V)
2753	4106	4	4	25	1.5 eV	false	(70 V, -70 V)
2754	4107	4	4	25	1.5 eV	false	(0 V, -40 V)
2755	4108	4	1	25	1.5 eV	false	(70 V, -70 V)
2756	4109	4	4	25	1.5 eV	false	(70 V, -70 V)
2768	4146	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2769	4147	4	2	25	1.5 eV	true	(5000 V, -5000 V)
2845	4227	4	3	25	1.5 eV	true	(5000 V, -5000 V)

Table A.1.: Mixing runs dedicated to the measurement of the principal quantum number distribution and used in the analysis. The total number of runs is 114. “planned $\bar{p}$ stacks” lists the number of planned antiproton AD shots accumulated in the MUSASHI trap. The actual number of stacks is listed in “actual $\bar{p}$ stacks”. The number of positron stacks is indicated in column “ e^+ stacks”. The column “transport” lists the extraction energy of the antiprotons from MUSASHI to the double-CUSP. “FIC” indicates whether the field ioniser in the mixing trap was turned on. The last column lists the applied voltages to the external field ioniser meshes.

CUSP	MIDAS	planned $\bar{p}$ stacks	actual $\bar{p}$ stacks	e^+ stacks	transport	FIC	Field ioniser (up, down)
2846	4228	4	4	25	1.5 eV	true	(400 V, -400 V)
2847	4229	4	4	25	1.5 eV	false	(70 V, -70 V)
2848	4230	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2849	4231	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2850	4232	4	4	25	1.5 eV	false	(70 V, -70 V)
2851	4233	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2852	4234	4	4	25	1.5 eV	true	(400 V, -400 V)
2853	4235	4	4	25	1.5 eV	false	(70 V, -70 V)
2854	4236	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2855	4237	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2856	4238	4	4	25	1.5 eV	true	(400 V, -400 V)
2857	4239	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2858	4240	4	4	25	1.5 eV	true	(400 V, -400 V)
2859	4241	4	4	25	1.5 eV	false	(70 V, -70 V)
2860	4242	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2861	4243	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2863	4246	4	4	25	1.5 eV	false	(70 V, -70 V)
2864	4247	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2865	4248	4	4	25	1.5 eV	true	(400 V, -400 V)
2866	4249	4	3	25	1.5 eV	false	(70 V, -70 V)
2867	4250	4	3	25	1.5 eV	true	(5000 V, -5000 V)
2868	4251	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2869	4252	4	4	25	1.5 eV	true	(400 V, -400 V)
2870	4253	4	4	25	1.5 eV	true	(5000 V, -5000 V)

A.7. List of antihydrogen candidates

Table A.2.: Table listing the antihydrogen candidates of the mixing runs dedicated to the n -distribution measurement. The prediction score s , CUSP run number, MIDAS run number, event number, time after mixing start, energy deposit in the BGO (E_{BGO}), hits in inner and outer layer (n_{I} and n_{O}), the number of tracks (N_{tracks}), largest angle between tracks (α_{max}), mean angle of track with vertical axis (α_{Y}) and the time-of-flight (ToF) are listed. Entries showing “999” mark missing features of the event (e.g. such as α_{max} for events with only 1 track).

s	CUSP	MIDAS	Event	time (s)	E_{BGO} (MeV)	n_{I}	n_{O}	N_{tracks}	α_{max} (°)	α_{Y} (°)	ToF (ns)
0.82	2,654	3,986	1,092	1.59	69.78	4	5	3	175.6	61.67	0.09
0.55	2,654	3,986	1,128	16.1	9.47	6	4	3	59.62	51.26	0.01
1	2,657	3,989	1,919	0.01	22.64	3	4	3	149.41	82.12	0.1
0.97	2,657	3,989	1,940	5.53	9.03	6	6	4	177.23	86.24	0.26
1	2,660	3,992	1,034	0.85	10.11	5	5	4	164.07	79.12	0.25
0.72	2,666	3,998	1,030	0.16	6.14	3	2	2	136.32	68.29	0.3
0.75	2,666	3,998	1,031	0.17	0.35	3	3	3	131.21	117.47	0.04
0.47	2,666	3,998	1,037	0.9	6.33	2	2	2	145.49	72.75	0.38
0.81	2,666	3,998	1,079	14.12	13.24	2	2	2	68.9	70.52	0.46
0.51	2,673	4,005	2,003	19.62	35.55	12	9	7	158.56	106.41	0.39
0.59	2,682	4,012	1,810	13.52	5.59	3	2	2	149.23	103.48	0.18
1	2,685	4,015	971	14.34	64.8	4	4	3	126.74	120.1	0.1
0.45	2,688	4,018	872	3.78	2.36	4	4	3	62.74	60.42	0.18
0.62	2,688	4,018	887	11.55	8.68	9	7	5	169.58	107.95	0.29
0.53	2,700	4,030	926	16.96	10.05	2	2	2	84.78	137.61	0.43
0.85	2,707	4,036	780	0.95	123.51	3	2	2	11.17	158.26	0.09
0.51	2,707	4,036	819	22.69	33.21	1	1	1	999	99.65	999
0.72	2,707	4,037	1,640	11.44	25.41	1	1	1	999	22.05	999
0.8	2,714	4,042	2,302	13.47	13.85	3	3	2	49.9	84.73	0.12
0.65	2,718	4,046	949	3.06	5.24	2	2	2	68.63	34.32	0.35
0.96	2,724	4,052	1,004	15.21	7.16	3	4	3	133.83	46.98	0.33
0.91	2,730	4,058	929	0.93	22.89	6	3	3	166.63	120.65	0.04
1	2,744	4,098	1,005	0.69	33.13	3	4	3	160.35	69.08	0.27
0.46	2,744	4,098	1,063	18.95	4.7	1	1	1	999	115.49	999
0.44	2,750	4,104	1,276	0.11	4.59	4	3	2	131.41	65.7	0.55
1	2,768	4,147	2,557	1.34	61.49	3	4	3	128.76	81.53	0.23
0.48	2,768	4,147	2,599	17.37	7.46	2	2	2	138.53	110.73	0.27
1	2,848	4,230	1,018	4.69	107.31	8	7	5	167.81	73.35	0.11
0.43	2,854	4,237	2,514	0.74	42.34	5	6	4	159.82	112.13	1.17
0.67	2,863	4,247	1,931	1.56	2.37	4	3	3	152.19	95.25	0.17
1	2,866	4,250	1,045	9.13	25.84	5	5	4	115.13	90.6	0.2
1	2,655	3,987	984	1.18	140.18	3	3	3	124.97	110.01	0.23
0.99	2,655	3,987	1,004	5.17	38.84	3	4	3	169.65	73.9	0.17
0.49	2,664	3,996	1,000	1.57	38.59	8	9	7	177.53	76.9	0.39
1	2,667	3,999	1,871	1.19	99.54	4	3	3	134.67	94.66	0.19
0.52	2,667	3,999	1,887	6.95	96.8	1	2	1	999	131.67	999
0.98	2,684	4,014	1,119	0.02	47.81	2	3	2	47.61	139.22	0.2
0.94	2,696	4,026	1,206	1.46	96.38	5	8	3	143.24	101.83	0.12
0.48	2,696	4,026	1,207	1.81	34.24	4	5	2	148.58	105.71	0.33
0.47	2,699	4,029	989	0.32	23.01	6	4	2	80.92	46.84	0.01
0.85	2,699	4,029	1,007	4.76	20.32	3	3	3	158.46	72.56	0.46

Table A.2.: Table listing the antihydrogen candidates of the mixing runs dedicated to the n -distribution measurement. The prediction score s , CUSP run number, MIDAS run number, event number, time after mixing start, energy deposit in the BGO (E_{BGO}), hits in inner and outer layer (n_{I} and n_{O}), the number of tracks (N_{tracks}), largest angle between tracks (α_{max}), mean angle of track with vertical axis (α_{Y}) and the time-of-flight (ToF) are listed. Entries showing “999” mark missing features of the event (e.g. such as α_{max} for events with only 1 track).

s	CUSP	MIDAS	Event	time (s)	E_{BGO} (MeV)	n_{I}	n_{O}	N_{tracks}	α_{max} (°)	α_{Y} (°)	ToF (ns)
0.99	2,702	4,032	1,763	1.93	126.11	6	5	4	179.73	65.72	0.15
1	2,702	4,032	1,765	2.11	164.71	6	7	6	147.77	101.89	0.28
0.44	2,702	4,032	1,768	3.19	6.32	3	4	2	39.03	130.42	0.09
0.8	2,705	4,035	983	5.26	11.93	4	4	2	74.2	136.45	0.14
0.96	2,705	4,035	1,011	13.83	110.82	5	6	5	159.35	71.37	0.51
0.75	2,719	4,047	894	0.02	19.57	4	8	4	122.81	73.39	0.54
1	2,722	4,050	1,222	1.96	59.98	4	4	2	107.44	126.28	0.06
0.99	2,845	4,228	2,145	2.9	15.18	7	5	5	132.63	91.42	0.44
0.73	2,851	4,234	1,247	2.57	25.81	4	3	2	162.86	98.57	0.02
0.69	2,851	4,234	1,305	21.57	4	2	2	2	128.12	115.94	0.13
1	2,855	4,238	1,192	1.65	112.31	5	5	3	151.86	100.17	0.29
1,000	2,855	4,238	1,200	3.29	12.49	4	4	4	159.32	111.91	0.27
0.88	2,855	4,238	1,254	21.76	21.68	3	2	2	144.4	72.2	0.02
0.59	2,857	4,240	1,183	13.52	4.27	4	5	3	171.9	74.85	0.32
0.84	2,742	4,096	2,241	0.03	10.27	2	2	2	71.45	144.27	0.12
1	2,742	4,096	2,249	1.85	31.69	5	5	4	158.8	110.81	0.16
0.65	2,742	4,096	2,264	3.71	72.54	1	1	1	999	85.95	999
0.78	2,742	4,096	2,279	10.06	2.72	5	4	3	111.27	41.59	0.02
0.97	2,743	4,097	1,175	0.09	9.31	3	4	3	137.64	73.34	0.07
0.99	2,743	4,097	1,181	0.98	113.39	7	8	5	104.29	89.65	0.56
1	2,743	4,097	1,200	4.86	45.36	3	3	3	127.73	99.84	0.01
0.97	2,743	4,097	1,204	5.59	61.11	4	6	4	167.78	106.29	0.46
1	2,745	4,099	1,430	2.83	87.79	4	5	4	162.3	121.19	0.18
1	2,745	4,099	1,433	3.38	27.47	4	4	3	132.22	117.48	0.17
0.91	2,745	4,099	1,442	5.63	66.44	3	3	2	23.36	72.2	0.49
1	2,748	4,102	1,179	1.14	65.16	3	3	3	165.71	91.83	0.16
0.9	2,748	4,102	1,181	1.39	41.02	3	3	3	168.76	67.33	0.09
0.94	2,748	4,102	1,192	4.55	81.84	5	4	3	179.28	97.72	0.27
0.7	2,748	4,102	1,199	7.4	39.47	1	1	1	999	162.04	999
0.98	2,748	4,102	1,200	7.91	6.32	4	4	4	169.5	91.99	0.26
0.45	2,748	4,102	1,201	8.13	14.1	3	2	2	71.26	36.58	0.01
1	2,748	4,102	1,230	16.85	57.99	3	3	3	149.11	83.19	0.25
1	2,749	4,103	1,994	1.53	22.06	5	5	3	114.11	139.38	0.21
0.86	2,749	4,103	2,002	3.69	50.2	7	7	3	80.6	110.88	0.38
1	2,751	4,105	1,144	1.37	22.15	4	3	3	128.46	126.88	0.03
0.94	2,751	4,105	1,152	3.44	38.65	4	4	3	175.09	75.15	0.32
0.7	2,752	4,106	1,182	17.69	10.53	3	3	2	155.35	77.68	0.17
0.7	2,755	4,109	962	0.26	82.98	2	3	1	999	133.55	999
1	2,755	4,109	963	0.47	43.66	6	5	4	136.06	99.09	0.15
0.83	2,755	4,109	983	5.22	128.99	2	1	1	999	87.65	999
0.99	2,755	4,109	998	10.48	7.54	2	2	2	130.62	65.31	0.16
0.45	2,846	4,229	1,239	0.02	54.37	3	2	2	10.39	44.72	0.03
0.63	2,846	4,229	1,249	0.51	71.15	1	1	1	999	84.54	999
1	2,846	4,229	1,258	1.74	26.99	3	3	3	122.36	100.29	0.13
0.48	2,846	4,229	1,292	15.66	7.77	3	2	2	86.06	69.61	0.36

Table A.2.: Table listing the antihydrogen candidates of the mixing runs dedicated to the n -distribution measurement. The prediction score s , CUSP run number, MIDAS run number, event number, time after mixing start, energy deposit in the BGO (E_{BGO}), hits in inner and outer layer (n_{I} and n_{O}), the number of tracks (N_{tracks}), largest angle between tracks (α_{max}), mean angle of track with vertical axis (α_{Y}) and the time-of-flight (ToF) are listed. Entries showing “999” mark missing features of the event (e.g. such as α_{max} for events with only 1 track).

s	CUSP	MIDAS	Event	time (s)	E_{BGO} (MeV)	n_{I}	n_{O}	N_{tracks}	α_{max} (°)	α_{Y} (°)	ToF (ns)
0.95	2,858	4,241	1,121	0.32	4.42	6	7	4	104.52	83.88	0.43
1	2,858	4,241	1,128	1.43	53.03	4	3	3	146.84	77.49	0.17
0.98	2,862	4,246	2,949	2.94	47.08	2	3	2	153.82	103.09	0.08
0.98	2,865	4,249	1,169	3.68	32.24	5	5	3	161.57	82.17	0.12
0.99	2,639	3,966	3,281	1	15.51	7	8	5	106.68	84.03	0.21
0.82	2,639	3,966	3,295	2.73	15.17	4	3	3	41.5	120.89	0.23
0.84	2,639	3,966	3,323	13.77	14.61	3	2	2	51.1	114.76	0.14
1	2,643	3,972	960	0.95	27.96	4	3	3	137.3	75.95	0.09
0.97	2,643	3,972	978	3.52	92.51	8	6	6	173.1	71.85	0.35
0.9	2,643	3,972	985	4.89	34.81	3	4	2	175.73	92.13	0.32
0.98	2,653	3,985	1,060	3.03	92.51	4	4	3	169.07	69.29	0.06
0.99	2,653	3,985	1,081	9.41	61.12	4	4	4	169.7	58.87	0.08
1	2,653	3,985	1,089	12.8	62.4	4	4	4	174.87	95.45	0.2
0.9	2,656	3,988	1,078	1.18	33.13	2	3	2	57.05	61.63	0.23
0.9	2,656	3,988	1,091	3.13	94.19	7	7	6	136.94	100.61	0.89
1	2,656	3,988	1,095	3.92	78.34	2	2	2	150.41	104.8	0.18
0.73	2,656	3,988	1,096	4.68	16.12	4	5	2	123.27	76.3	0.13
1	2,656	3,988	1,099	5.29	48.51	3	4	3	166.52	94.13	0.06
1	2,656	3,988	1,102	5.91	10.47	4	3	3	154.78	104.79	0.22
0.55	2,659	3,991	1,043	0.12	3.76	5	5	3	171.71	87.01	0.17
1	2,659	3,991	1,047	0.64	96.4	4	5	3	145.71	72.36	0.43
0.94	2,659	3,991	1,050	1.12	7.93	2	3	2	119.49	59.75	0.11
0.91	2,659	3,991	1,112	20.63	18.19	3	2	2	110.01	55.01	0.15
1	2,662	3,994	1,914	0.06	48.06	3	3	3	165.68	99.26	0.34
0.92	2,662	3,994	1,924	2.79	31.94	6	3	2	163.9	81.95	0.1
0.99	2,662	3,994	1,926	3.1	91.77	4	3	3	139.36	89.23	0.51
1	2,662	3,994	1,927	3.36	94.21	6	5	5	140.36	96.95	0.2
0.61	2,665	3,997	981	1.13	12.04	2	2	2	158.21	100.89	0.17
0.47	2,665	3,997	982	1.16	10.19	5	6	3	157.29	108.36	0.29
0.94	2,665	3,997	1,013	11.31	22.67	4	3	2	62.28	73.89	0.42
0.98	2,672	4,004	1,000	1.57	12.8	4	3	3	168.78	89.27	0.17
1	2,672	4,004	1,019	5.83	52.5	5	5	5	157.27	122.71	0.09
0.79	2,672	4,004	1,027	11.21	17.67	3	3	2	22.04	89.32	0.08
0.6	2,672	4,004	1,055	20.94	12.95	4	5	3	77.85	28.11	0.02
1	2,686	4,016	920	1.19	38.27	3	3	3	84	136.28	0.22
1	2,686	4,016	923	1.63	36.41	5	5	4	147.19	87.56	0.29
1	2,686	4,016	924	1.68	65.26	3	4	3	130.13	95.14	0.37
0.79	2,686	4,016	925	1.76	95.51	2	3	1	999	122.26	999
0.99	2,686	4,016	930	2.33	15.18	3	3	3	161.04	95.08	0.28
0.98	2,689	4,019	1,012	1.18	16.61	3	3	3	168.54	81.87	0.3
0.98	2,689	4,019	1,024	4.07	12.52	4	4	4	159.77	119.05	0.15
0.59	2,692	4,022	1,826	0.02	94.58	6	5	3	177.57	81.12	0.47
0.98	2,692	4,022	1,851	4.42	17.27	3	3	3	176.86	94.19	0.1
1	2,695	4,025	1,030	0.03	49.66	7	6	5	166.86	58.31	0.2
0.96	2,695	4,025	1,052	3.96	12.82	5	4	3	163.25	81.2	0.2

A.8. List of runs for FIC $\bar{H}$ time distribution

Table A.2.: Table listing the antihydrogen candidates of the mixing runs dedicated to the n -distribution measurement. The prediction score s , CUSP run number, MIDAS run number, event number, time after mixing start, energy deposit in the BGO (E_{BGO}), hits in inner and outer layer (n_{I} and n_{O}), the number of tracks (N_{tracks}), largest angle between tracks (α_{max}), mean angle of track with vertical axis (α_{Y}) and the time-of-flight (ToF) are listed. Entries showing “999” mark missing features of the event (e.g. such as α_{max} for events with only 1 track).

s	CUSP	MIDAS	Event	time (s)	E_{BGO} (MeV)	n_{I}	n_{O}	N_{tracks}	α_{max} (°)	α_{Y} (°)	ToF (ns)
0.99	2,695	4,025	1,056	4.69	55.88	3	4	2	130.69	114.65	0.03
1	2,695	4,025	1,103	20.62	24.63	7	5	5	123.93	111.21	0.14
0.96	2,698	4,028	975	1.2	49.43	6	2	2	103.94	128.03	0.33
1	2,698	4,028	988	4.15	38.06	3	3	3	158.91	91.34	0.22
0.85	2,698	4,028	1,024	16.17	8.12	2	3	2	45.31	121.77	0.12
1	2,701	4,031	996	2.84	89.16	4	4	3	145.75	85.62	0.25
1	2,701	4,031	998	3.76	64.95	3	3	3	157.14	113.17	0.21
1	2,701	4,031	1,011	8.1	18.83	5	5	5	104.49	86.93	0.17
0.54	2,704	4,034	999	1.11	5.53	9	5	4	125.42	79.37	0.22
1	2,704	4,034	1,002	1.32	50.4	4	3	3	165.5	61.8	0.12
0.69	2,704	4,034	1,011	3.23	21.56	3	3	3	120.39	70.02	0.66
0.94	2,704	4,034	1,031	8.15	13.47	3	4	3	163.6	81.18	0.26
0.93	2,704	4,034	1,063	23.27	52.04	2	2	2	23.91	124.67	0.06
1	2,717	4,045	957	0.41	83.64	3	3	3	139.93	93	0.1
1	2,720	4,048	1,605	0.17	62.43	6	6	4	143.86	105.88	0.33
1	2,720	4,048	1,619	1.36	46.63	3	3	3	158.84	102.73	0.27
0.73	2,723	4,051	1,000	15.46	85.14	8	10	5	154.03	105.15	0.11
1	2,726	4,054	1,418	15.49	63.18	3	4	3	164.49	78.63	0.22
1	2,729	4,056	1,493	1.46	206.35	7	4	4	104.96	104.04	0.19
1	2,729	4,057	6,696	0.28	77.84	6	6	4	123.06	89.13	0.19
0.97	2,729	4,057	6,697	0.52	82.71	4	4	3	171.32	100.37	0.51
1	2,729	4,057	6,704	1.18	34.89	5	3	3	168.6	116.23	0.07
0.89	2,729	4,057	6,710	2.77	77.32	9	6	6	173.25	43.68	0.3
1	2,747	4,101	1,124	0.01	22.19	6	6	4	155.07	94.5	0.24
1	2,747	4,101	1,131	1.33	61.42	8	8	5	143.21	101.15	0.12
1	2,747	4,101	1,149	6.5	28.09	7	4	3	136.52	115.57	0.04
0.99	2,753	4,107	936	0.07	122.97	3	2	2	100.32	121.82	0
1	2,753	4,107	941	0.74	18.57	6	7	4	115.68	94.94	0.24

A.8. List of runs for FIC $\bar{H}$ time distribution

Table A.3.: Mixing runs used for the analysis in [55] for determining the FIC time distribution of antihydrogen events (see Figure 5.12). 56 runs in total.

CUSP	MIDAS	planned $\bar{p}$ stacks	actual $\bar{p}$ stacks	e^+ stacks	transport	FIC	Field ioniser (up, down)
2642	3970	4	4	30	1.5 eV	true	(400 V, −400 V)
2643	3971	4	4	30	1.5 eV	true	(8700 V, −8700 V)
2645	3973	4	4	30	1.5 eV	true	(8700 V, −8700 V)

Table A.3.: Mixing runs used for the analysis in [55] for determining the FIC time distribution of antihydrogen events (see Figure 5.12). 56 runs in total.

CUSP	MIDAS	planned $\bar{p}$ stacks	actual $\bar{p}$ stacks	e^+ stacks	transport	FIC	Field ioniser (up, down)
2646	3974	4	4	30	1.5 eV	true	(400 V, −400 V)
2652	3982	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2653	3984	4	4	25	1.5 eV	true	(400 V, −400 V)
2655	3986	4	3	25	1.5 eV	true	(5000 V, −5000 V)
2656	3987	4	3	25	1.5 eV	true	(400 V, −400 V)
2658	3989	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2659	3990	4	2	25	1.5 eV	true	(400 V, −400 V)
2661	3992	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2662	3993	4	4	25	1.5 eV	true	(400 V, −400 V)
2664	3995	4	4	27	1.5 eV	true	(5000 V, −5000 V)
2665	3996	4	4	27	1.5 eV	true	(400 V, −400 V)
2667	3998	4	4	27	1.5 eV	true	(5000 V, −5000 V)
2668	3999	4	3	27	1.5 eV	true	(400 V, −400 V)
2671	4002	4	4	27	1.5 eV	true	(5000 V, −5000 V)
2672	4003	4	4	27	1.5 eV	true	(400 V, −400 V)
2674	4005	4	4	27	1.5 eV	true	(5000 V, −5000 V)
2675	4006	4	4	27	1.5 eV	true	(400 V, −400 V)
2716	4043	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2717	4044	4	4	25	1.5 eV	true	(400 V, −400 V)
2719	4046	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2720	4047	4	4	25	1.5 eV	true	(400 V, −400 V)
2722	4049	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2723	4050	4	4	25	1.5 eV	true	(400 V, −400 V)
2725	4052	4	3	25	1.5 eV	true	(5000 V, −5000 V)
2726	4053	4	3	25	1.5 eV	true	(400 V, −400 V)
2728	4055	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2729	4056	4	3	25	1.5 eV	true	(400 V, −400 V)
2731	4058	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2732	4059	4	4	25	1.5 eV	true	(400 V, −400 V)
2739	4092	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2742	4095	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2745	4098	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2751	4104	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2769	4147	4	2	25	1.5 eV	true	(5000 V, −5000 V)
2845	4227	4	3	25	1.5 eV	true	(5000 V, −5000 V)
2846	4228	4	4	25	1.5 eV	true	(400 V, −400 V)
2848	4230	4	4	25	1.5 eV	true	(5000 V, −5000 V)
2849	4231	4	4	25	1.5 eV	true	(5000 V, −5000 V)

A.8. *List of runs for FIC $\bar{H}$ time distribution*

Table A.3.: Mixing runs used for the analysis in [55] for determining the FIC time distribution of antihydrogen events (see Figure 5.12). 56 runs in total.

CUSP	MIDAS	planned $\bar{p}$ stacks	actual $\bar{p}$ stacks	e^+ stacks	transport	FIC	Field ioniser (up, down)
2851	4233	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2852	4234	4	4	25	1.5 eV	true	(400 V, -400 V)
2854	4236	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2855	4237	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2856	4238	4	4	25	1.5 eV	true	(400 V, -400 V)
2857	4239	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2858	4240	4	4	25	1.5 eV	true	(400 V, -400 V)
2860	4242	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2861	4243	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2864	4247	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2865	4248	4	4	25	1.5 eV	true	(400 V, -400 V)
2867	4250	4	3	25	1.5 eV	true	(5000 V, -5000 V)
2868	4251	4	4	25	1.5 eV	true	(5000 V, -5000 V)
2869	4252	4	4	25	1.5 eV	true	(400 V, -400 V)
2870	4253	4	4	25	1.5 eV	true	(5000 V, -5000 V)

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CURRICULUM VITAE

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PERSONAL INFORMATION

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EDUCATION

University of Vienna: PhD Physics Nov 2014 – Present

Focus Particle physics, antimatter, precision physics, particle detectors, statistical data analysis, machine learning, simulations.

Thesis “Machine Learning for Antihydrogen Detection in ASACUSA”

Supervisor Prof. Dr. Eberhard Widmann

Funding Doctoral program “Doktoratskolleg for Particles and Interactions” (DK-PI), ERC Advanced Grant of Prof. Widmann.

University of Vienna: Physics, MSc Oct 2011 – Jun 2014

Focus Particle physics, computational physics.

Thesis “Numerical Simulations of Hyperfine Transitions in Antihydrogen”

Supervisor Prof. Dr. Eberhard Widmann

University of Vienna: Physics, BSc Oct 2007 – Sep 2011

Thesis “Optical Properties of Metal Cluster”

Supervisor Prof. Dr. Markus Arndt

High School Sep 1998 – Jun 2006

Gymnasium des Instituts Neulandschule Grinzing, Vienna

EMPLOYMENT HISTORY

Stefan Meyer Institute, Austrian Academy of Sciences Nov 2014 – Present

Position Researcher, PhD Student

Secondary Workplace CERN

Stefan Meyer Institute, Austrian Academy of Sciences Feb 2013 – Jun 2014

Position Researcher, Master Student

**Institute for High Energy Physics,
Austrian Academy of Sciences** Jul 2012 – Aug 2012

Position Researcher, Summer Student

Funding FEMtech program (Austrian Research Promotion Agency)

SKILLS AND INTERESTS

Languages	German (mother tongue), English (fluent), French (basics)
Software	– <i>Programming</i>: Python(advanced), C(advanced), C++(advanced), Bash(advanced) – <i>Tools/Frameworks</i>: Scikit-learn, Hyperopt, ROOT, ROOT's TMVA, Geant4 – <i>Operating Systems</i>: Linux(advanced), Windows(advanced), Mac OS(intermediate)
Hardware	Data acquisition hardware (NIM/VME) (intermediate), FPGA programming with VHDL (basics), Arduino programming (intermediate)
Communication	– Gained many experiences presenting scientific work at international conferences, collaboration meetings and internal group meetings. – Enjoys networking and successfully built international connections in research environment. – Gathered experiences in training other students and working in and organising teams within the collaboration.
Hobbies	Creative writing (writing fantasy novels, short stories and world building), painting, travelling, sports (hiking, skiing, ice skating)
Other	Clean driving license

CONFERENCE CONTRIBUTIONS

Posters:

- Meeting: Antiproton physics in the ELENA Era, September 2017, UK
Title: Machine Learning for Antihydrogen Detection
- Meeting on CPT and Lorentz Symmetry, June 2016, Bloomington, Indiana
Title: A Detector for Measuring the Ground State Hyperfine Splitting of $\bar{H}$
- LEAP (Low Energy Antiproton Physics) Conference, March 2016, Kanazawa, Japan
Title: A Detector for Measuring the Ground State Hyperfine Splitting of $\bar{H}$

Talks:

- (Invited) PSAS (Precision Physics of Simple Atomic Systems) Conference, May 2018, Vienna, Austria
Title: Measuring the Ground State Hyperfine Structure of Antihydrogen
- RECFA (Restricted European Committee for Future Accelerators) Meeting, April 2018, Vienna, Austria
Title: The students perspective on particle physics in Austria
- LEAP Conference, March 2018, Paris, France
Title: A Detector for Measuring the Ground State Hyperfine Splitting of $\bar{H}$

- EXA (Exotic Atoms) Conference, September 2017, Vienna, Austria
Title: A Detector for Measuring the Ground State Hyperfine Splitting of $\bar{H}$
- SPS/OEPG Meeting, August 2017, CERN, Geneva, Switzerland
Title: A Detector for Measuring the Ground State Hyperfine Splitting of $\bar{H}$
- INPC (International Nuclear Physics Conference), Sep. 2016, Adelaide, Australia
Title: Measuring the Ground State Hyperfine Structure of Antihydrogen
- Workshop Connecting the Dots, February 2016, Vienna
Title: Tracking for ASACUSA – Detecting Antihydrogen

AWARDS AND SCHOLARSHIPS

- Young Academics article** Mar 2018
Selected for an article about my PhD work, published online (www.oeaw.ac.at).
- Nature Physics Poster Prize** Mar 2016
Poster: A Detector for Measuring the Ground State Hyperfine Splitting of Antihydrogen
Conference: LEAP (Low Energy Antiproton Physics) 2016, Kanazawa, Japan
- PhD Scholarship in the DK-PI doctoral programme** Nov 2014
“Doktoratskolleg for Particles and Interactions”

EXTRA-CURRICULAR

Schools and further training:

- Machine learning course at the Technical University of Vienna,
Winter semester 2017
- INFN School of Statistics, *May 2017, Ischia, Italy*
- Summer School on the Lorentz- and CPT-violating Standard Model Extension (SME), *June 2015, Bloomington, Indiana*

Outreach:

- Round table with young austrian scientists and the president of Austria
27 February 2018, CERN
- Lab tour for the president of Austria and the Minister of Education, Science and Research of Austria, *27 February, CERN*
- Lab tour for school children at International Particle Physics Masterclasses
6 March 2017, Stefan Meyer Institute, Vienna
- European Researchers Night, *30 September 2016, Vienna*
- Demonstrator for school girls at FIT days (“Frauen in die Technik” – women into science), *27 January 2016, SMI, Vienna*

Committee Memberships/Administrative Activities:

- Member of the local organising committee of the PSAS Conference
May 2018, SMI, Vienna
- Institute speaker of the Stefan Meyer Institute of the DK-PI (2014 - 2018)
- Member of the Young Minds ÖPG, treasurer for a year (2016)
- Member of the local organising committee of and chair at the Connecting the Dots Workshop, *February 2016, HEPHY, Vienna*

List of publications

1. C. Malbrunot et al. “A hydrogen beam to characterize the ASACUSA antihydrogen hyperfine spectrometer”. In: *submitted to NIM* (2018). arXiv: [1812.06736](#)
2. E. Widmann et al. “Hyperfine spectroscopy of hydrogen and antihydrogen in ASACUSA”. in: *Hyperfine Interactions* 240.1 (2019), p. 5. DOI: [10.1007/s10751-018-1536-9](#). arXiv: [1809.00875](#)
3. Y. Nagata et al. “Monte-Carlo based performance assessment of ASACUSA’s antihydrogen detector”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 910 (2018), pp. 90–95. DOI: [10.1016/j.nima.2018.09.013](#)
4. B Kolbinger et al. “Recent Developments from ASACUSA on Antihydrogen Detection”. In: *EPJ Web of Conferences* 181 (2018), p. 01003. DOI: [10.1051/epjconf/201818101003](#)
5. Y. Nagata et al. “The Development of the Antihydrogen Beam Detector: Toward the Three Dimensional Tracking with a BGO Crystal and a Hodoscope”. In: *Proceedings of the 12th International Conference on Low Energy Antiproton Physics (LEAP2016)*. Vol. 011038. Journal of the Physical Society of Japan, 2017, pp. 1–6. DOI: [10.7566/JPSCP.18.011038](#)
6. Y. Nagata et al. “Progress of Antihydrogen Beam Production Using a Double Cusp Trap”. In: *Proceedings of the 12th International Conference on Low Energy Antiproton Physics (LEAP2016)* 011007 (2017), pp. 1–10. DOI: [10.7566/JPSCP.18.011007](#)
7. C. Malbrunot et al. “The ASACUSA antihydrogen and hydrogen program: results and prospects”. In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376.2116 (2018), p. 20170273. DOI: [10.1098/rsta.2017.0273](#)
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9. Clemens Sauerzopf et al. “Annihilation detector for an in-beam spectroscopy apparatus to measure the ground state hyperfine splitting of antihydrogen”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 845 (2017), pp. 579–582. DOI: [10.1016/j.nima.2016.06.023](#)

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