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Search for polarization effects in the antiproton production process

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Abstract

It is proposed to study polarization effects in the production of antiprotons at the PS test beam line T11 at 3.5 GeV/c momentum. A polarization in the production process has never been studied but if existing it would allow for a rather simple and cheap way to generate a polarized antiproton beam with the existing facilities at CERN. This proposal is an update of the P349 experiment proposal which was submitted and approved in 2014 [1]. First measurements have been performed but the achieved statistics was much too low to extract any information. With an improved detector setup a longer beam time with 8 weeks data taking is proposed which will result in sufficient statistics to determine antiproton polarization if it exists in a reasonable degree.

1 Introduction

Polarization observables reveal more precise information of the structure of hadrons and their interaction, and the disentangling of various reaction mechanisms is often only possible by controlling the spin degrees of freedom. With beam and target particles both being polarized quantum states can be selectively populated. For example, in $\bar{p} - p$ reactions a parallel spin configuration of antiproton and proton ($\bar{p} \uparrow \;\; p \uparrow$) is a pure spin triplet state and with an antiparallel spin configuration ($\bar{p} \uparrow \;\; p \downarrow$) the spin singlet state is dominant. The possibility of adjusting different spin configurations is important for various topics in the regime of high as well as low energy.

While polarized proton beams and targets are routinely prepared the possibilities for the preparation of a polarized antiproton beam are still under discussion. Proposals for the generation of a polarized antiproton beam have already been presented before the first cooled antiproton beams were available. Methods that have been discussed are:
hyperon decay, spin filtering, spin flip processes, stochastic techniques, dynamic nuclear polarization, spontaneous synchrotron radiation, induced synchrotron radiation, interaction with polarized photons, Stern-Gerlach effect, channeling, polarization of trapped antiprotons, antihydrogen atoms or polarization of produced antiprotons.

Summaries of the various possibilities can be found in [2], [3], [4], [5]. Most of the methods are not usable due to the extremely low expected numbers of polarized antiprotons or the low degree of polarization and for some methods reasonable calculations are not possible since relevant parameters are not known. Due to the large required effort no feasibility studies have been performed so far.

A well known source for polarized antiprotons is the decay of $\bar{\Lambda}$ into $\bar{p}\,\pi^+$ with a $\bar{p}$ helicity of 64.2 ($\pm$ 1.3) % (the more precise value for Λ decay is taken) in the $\bar{\Lambda}$ rest frame [6]. By measuring the direction and momenta of the $\bar{\Lambda}$, the $\bar{p}$, and π^+ in the laboratory system, the decay kinematics can be reconstructed and the transversal and longitudinal antiproton polarization components in the lab system for each event can be determined. The method was used at FERMILAB in the only experiment with polarized antiprotons so far [7] studying the polarization dependence of inclusive $\pi^{\pm}\pi^0$ production. A proton beam of 800 GeV/c momentum produced antihyperons ($\bar{\Lambda}$) and their decay antiprotons with momenta around 200 GeV/c. A mean polarization of 0.45 was observed but the polarized antiprotons do not constitute a well defined beam and at lower energies the situation further deteriorates. For the preparation of a pencil beam of polarized antiprotons other methods are required.

Presently the most promising proposal is the filter method on a stored antiproton beam, by which one spin component is depleted due to the spin dependent hadronic interaction of a beam passing a polarized target. The filter method in a storage ring was first suggested 1968 in order to polarize high energy protons in the CERN ISR [9]. For filtering of antiprotons at lower momenta it was later pointed out that the new technique of phase space cooling is mandatory and the relevant parameters were shown [10], [11]. In 1993 a feasibility study of the filter method with phase space cooling was performed with a proton beam on polarized protons at the TSR in Heidelberg showing clearly the buildup of polarization [12]. A polarization of about 2% was achieved after 90 minutes filtering time. For antiprotons the filter method with cooling should also work if one can find any filter interaction with both large spin-spin dependence and cross section. Till now there are no data for the spin-spin dependence of the total $\bar{p}p$ cross section. From theoretical predictions one expects that longitudinal polarization effects are larger than transversal effects [13], [14], [15], [16]. The consequence might be that a Siberian snake is needed in the filter synchrotron. Experimental $\bar{p}p$ scattering data are needed to work out the conditions and expected properties of a polarized $\bar{p}$ beam prepared by the filter method. The PAX collaboration is working on this topic with polarized protons as filter [18], [17], [19], [14]. The spin filter method has been demonstrated at COSY for transverse polarized protons and similar studies for longitudinal polarization were planned [20]. Another filter reaction with large polarization effect, which was proposed [21] is the interaction with polarized photons but the low intensity of available photon beams together with the small cross section makes it unlikely to produce sufficient polarized antiprotons for significant experiments.

A simple possibility for a polarized antiproton beam may be the production process itself.

A first proposal for the investigation of possible polarization effects in the production process of antiprotons has been submitted to the SPSC in 2014 [1] and first measurements have been performed but the achieved statistics was much too low to extract any information. With an improved detector setup a longer beam time is proposed which will result in sufficient statistics to determine antiproton polarization if it exists in a reasonable degree.

2 Search for polarization in antiprotons production

It is well known that particles, like e.g. Λ-hyperons, produced in collisions of high energy unpolarized protons show a significant degree of polarization [22]. Maybe also antiprotons are produced with some polarization but up to now no experimental studies have been performed in this direction.

The production of antiprotons is typically done by bombarding a solid target with high momentum protons. At CERN the beam momentum is about 24 GeV/c and the number of collected antiprotons is in the order of one per 10^6 beam protons. The production mechanism seems to be a rather simple quasi-free p-nucleon interaction. The $\bar{p}$ momentum spectrum which is peaked around 3.5 GeV/c is consistent with a pure phase space distribution for a four particle final state: $pp \to pp\bar{p}p$. The basic process is a creation of baryon-antibaryon out of collisional energy. If transverse polarization occurs (Fig. 1) then a polarized beam can be prepared in a rather simple and cheap way by blocking up and down events, and one side of the angular distribution. Furthermore the pure S wave region around 0 degree ($< 50\,mrad$) has to be removed. A simple modification of the extraction beam line of an existing $\bar{p}$ production and cooler facility with absorbers would be sufficient to extract a polarized beam. Of course one has to avoid polarization loss in de-polarizing resonances in the accumulator cooler synchrotron. This has to be taken into account when such a facility will be constructed. But first of all it has to be investigated whether the production process creates some significant polarization.

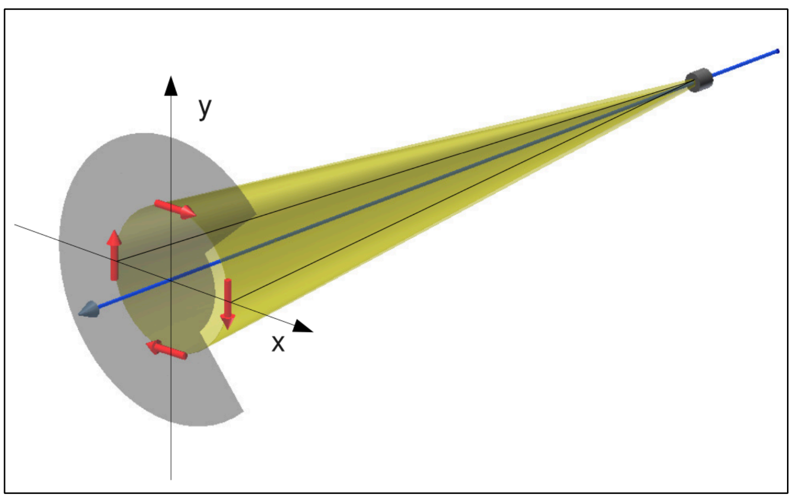

Figure 1: Possible polarization vector for a given production polar angle θ, indicated by the red arrows. In order to select an antiproton beam with transverse polarization one spin direction has to be separated by a suitably shaped absorber plate as indicated in grey.

3 Asymmetry measurement of produced antiprotons

In order to measure the polarization of the produced antiprotons a further scattering of antiprotons is necessary in a process with known and sufficient analyzing power.

Well known and calculable is the analyzing power in the pp elastic scattering in the Coulomb nuclear interference (CNI) region. The analyzing power in the CNI region at high energies is attributed to the inference between a non-spin-flip nuclear amplitude and an electromagnetic spin-flip amplitude [23],[24], [8], [27]. The maximum analyzing power is approximately given by [23], [25]: $A_N^{max} = \sqrt{3}/4 \cdot \sqrt{t_p}/m \cdot (\mu - 1)/2$, with μ=magnetic moment, m=mass. A maximum of

4-5% is reached and the four momentum transfer at the peak t_p is given by: $t_p = -8\pi\sqrt{3}\alpha/\sigma_{tot}$, with the fine-structure constant α and the total cross section σ_{tot}, which results in a value of $t_p \sim -3 \cdot 10^{-3}(GeV/c)^2$ assuming a total cross section of 40 mb. Experimentally a maximum analyzing power of about 4.5% at t= -0.0037 GeV/c was achieved which is shown in the upper part of Fig. 2. The data are from [27] taken with a 100 GeV/c proton beam at a polarized atomic hydrogen gas jet target.

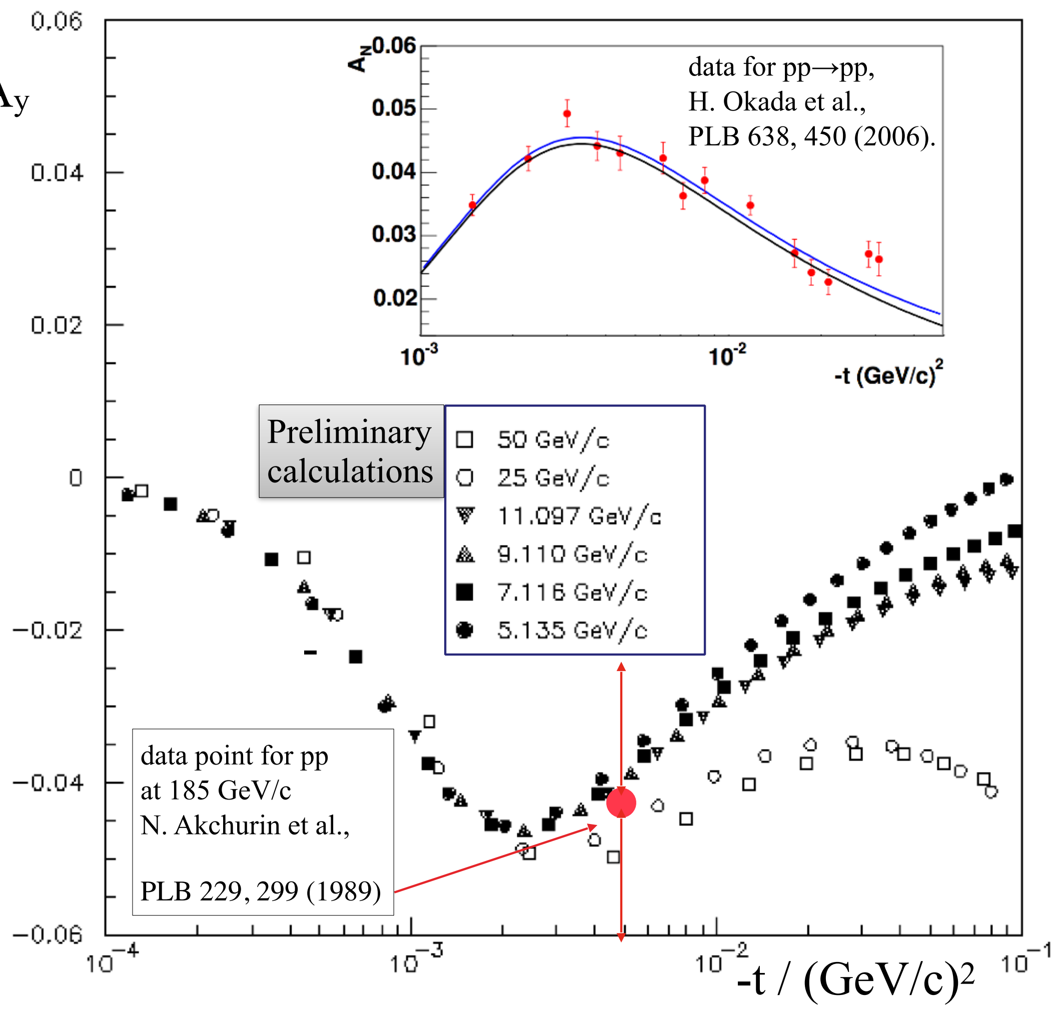

Figure 2: Analyzing power of antiproton-proton and proton-proton scattering [27] as a function of the four momentum transfer t. Data for pp-analyzing power are shown in the upper inset taken with a proton beam momentum of 100 GeV/c at a polarized atomic hydrogen target. For antiprotons only one data point is existing for a beam momentum of 185 GeV/c with a large error bar. For lower beam momenta in the range from 5 to 50 GeV/c calculations were performed by Haidenbauer [26] which are consistent with the expected value of 4.5%.

For antiprotons the same analyzing power will result because at these energies the hadronic part is limited to the non spin-flip amplitude in the CNI region and the spin-flip Coulomb amplitude which changes the sign. This was also experimentally verified in a measurement at FERMILAB with 185 GeV/c polarized antiprotons [28] resulting in an analyzing power of -4.6 ($\pm$ 1.86) %. For a 3.5 GeV/c antiproton scattered on a proton the t-value of -0.0037 corresponds to a laboratory scattering angle of about 20 mrad where we expect the same analyzing power of about 4.5%. To verify the validity of the high energy approximations in the lower momentum region preliminary calculations were performed by Haidenbauer [26].

The investigations of antiproton polarization are foreseen at the T11 beamline where the optimum conditions for such a study are given, the momentum corresponds to the typical antiproton momentum used for the preparation of antiproton beams and the production angle is sufficiently large. The T11 beam line delivers secondary particles produced by the 24 GeV/c momentum proton beam of the PS at a production angle of about 150 mrad with an acceptance of $\pm$ 3 mrad horizontally and $\pm$ 10 mrad vertically [29]. The beam line can be adjusted to momenta of 3.5 GeV/c for positively and negatively charged particles. For negatively charged particles of momenta of 3.5 GeV/c with open collimators the momentum resolution is $\pm$ 5 % and about $1 \cdot 10^6$ particles/spill are delivered with a spill length of 400 ms.

In Fig. 3 on the left side the place for the experiment installation at the T11 area is shown. The beam comes from the left side and on the right side the CLOUD experiment is placed. For the installation the area between the first scintillator wall on the left side and the CLOUD system on the right side is required. In August 2024 some detector tests have been performed with a setup shown in Fig. 3 on the right side (viewed from the other side). In a similar way the setup for the experiment will be installed but the second scintillator wall has to be removed which was already agreed by the CLOUD collaboration.

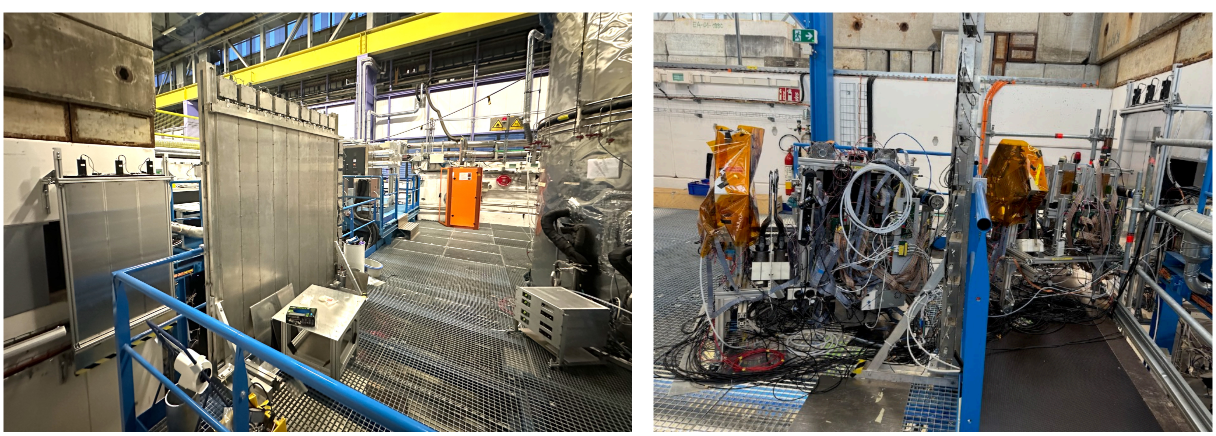

Figure 3: Area at T11 where the experiment will be installed (left) and setup for detector tests performed in August 2024 (right). The installation of the experiment will be done in a similar way after removal of the scintillator wall in the middle.

The ratios of produced pions, kaons, protons and antiprotons are assumed to be close to the values measured at a scattering angle of 127 mrad and a momentum of 4 GeV/c [30] where data exist which are given in table 1. With the ratio of produced $\bar{p}$ to the sum of negatively charged particles about 8000 $\bar{p}$ are expected to be delivered at T11.

A sketch of the detector arrangement is shown in Fig. 4. It consists of scintillators for

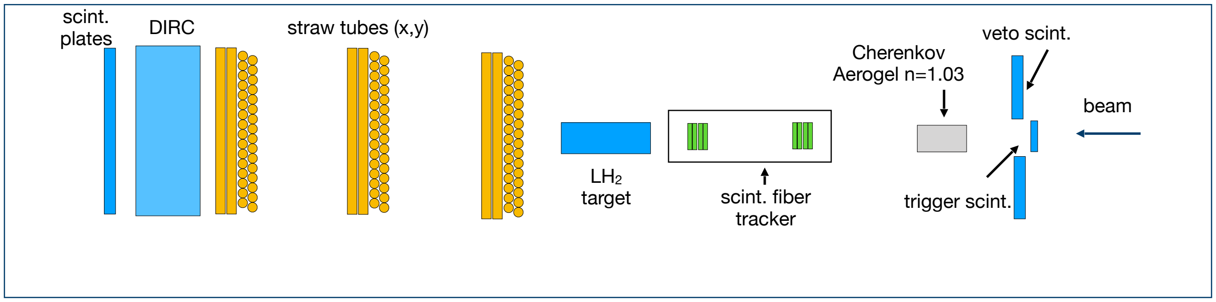

Figure 4: Sketch of the detector arrangement in the horizontal plane. The beam is entering from the right and passes through start scintillator, Cherenkov detector, scintillating fibre hodoscope, scattering target, straw tubes, DIRC, and scintillator plates. A detailed description is given in the text.

trigger signal generation, a Cherenkov detector for online pion discrimination, scintillating fibres to measure the track of the produced antiproton, an analyzer target, a set of straw tubes to reconstruct the track of a scattered antiproton and a DIRC for offline particle identification.

As analyzer target a liquid hydrogen cell with a length of 12 cm with a diameter of 6.5 cm will be used, see Fig. 5. It is placed in a vacuum chamber connected to a refrigerator cold head operated at a temperature of about 20 K. For the target cell and vacuum chamber windows Kapton foils are used.

The whole system will be operated in air. The straggling in the material between the exit window of the beam tube and the first tracking detector does not influence the measurement. The straggling in the material of the detection system including the air is below 1 mrad, the track resolution of the scintillation fibre system will be about 1 mrad and the track resolution of the straw tube system will be below 0.5 mrad. In Fig. 6 one unit of the scintillation fibre detector and a straw tube element are shown. The scintillating fibre system consists of two stations at a distance of 0.4 m each with two overlapping layers with 0.5 mm thick scintillating

Table 1: Particle production density of pions, kaons, protons and antiprotons at a laboratory angle of 127 mrad and particle momenta of 4 GeV/c induced by a 24 GeV/c proton beam for various targets normalized to the π^+ production [30]. In the last columns the ratios of produced $\bar{p}$ to the sum of positively and negatively charged particles is given.

target	π^+	K^+	p	π^-	K^-	$\bar{p}$	$\bar{p}/(\pi^+ + K^+ + p)$	$\bar{p}/(\pi^- + K^- + \bar{p})$
Be	1	0.12	0.48	0.79	0.040	0.0072	0.0045	0.0086
C	1	0.12	0.50	0.78	0.041	0.0072	0.0045	0.0087
Al	1	0.13	0.57	0.78	0.042	0.0073	0.0043	0.0088
Cu	1	0.14	0.64	0.80	0.045	0.0073	0.0041	0.0086
Pb	1	0.16	0.36	-	-	-	-	-

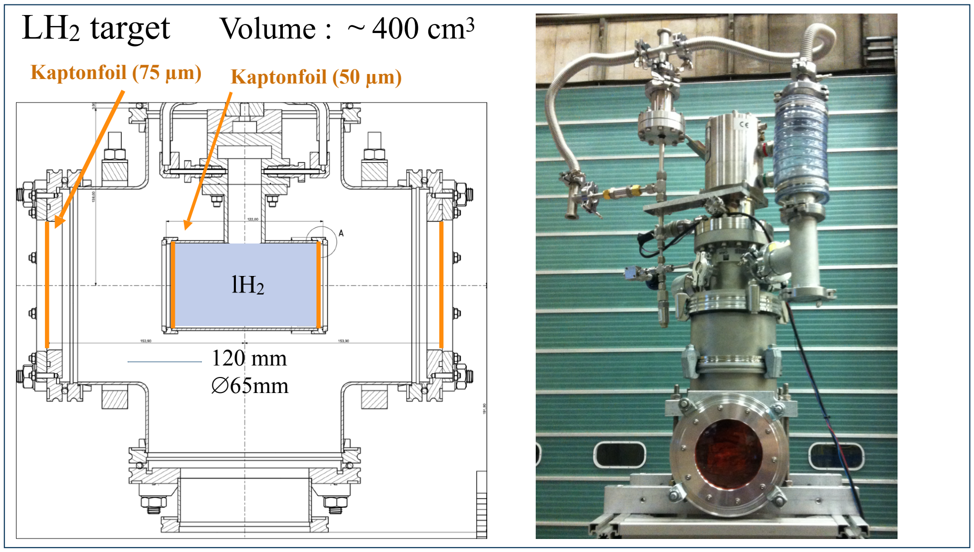

Figure 5: LH_2 - target system with the target cell and the vacuum chamber.

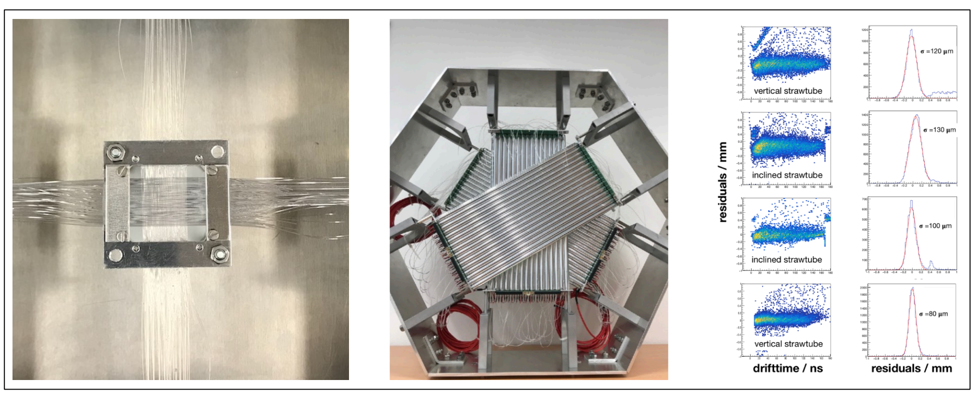

Figure 6: Scintillating fiber detector with two overlapping double layers of 0.5 mm scintillating fibres (left) and a straw tube station with (middle) with drift time distributions and residuals (right).

fibres. The straw tubes have a diameter of 10 mm and are operated with an $Ar(90\%)/CO_2(10\%)$ mixture at an overpressure of 1 bar. The drift time measurement results in a position resolution in the range of 100 - 150 μm.

The aerogel Cherenkov detector (n $\sim$ 1.03) will discriminate the high pion background by including the Cherenkov signals in the trigger as veto. When the event selection is reduced to single tracks at small scattering angles most background channels are suppressed and the momenta of the scattered particles are close to the momenta of the primary particles. Antiprotons with 3.5 GeV/c momentum have a velocity of $\beta_{\bar{p}}(3.5\ \mathrm{GeV/c}) = 0.966$, i.e. the threshold for Cherenkov light emission is at n = 1.035. For pions, which will be the main background source, the velocity is close to c ($\beta_\pi(3.5$ GeV/c$) = 0.9992$) with a threshold refractive index of n = 1.0008. Therefore a threshold Cherenkov detector with n $\sim$ 1.03 will strongly suppress the large pion background.

The DIRC with Plexiglas as radiator [34] is used for offline particle identification. In Fig. 7 a sketch of the DIRC is shown. Pions and antiprotons produce Cherenkov light which is detected with a PMT-matrix resulting in a Cherenkov arc as shown in the right upper part of Fig. 7 for a sample of events. The plot in the right lower part of Fig. 7 shows the separation of pions and antiprotons in a distribution of arc height vs. arc center.

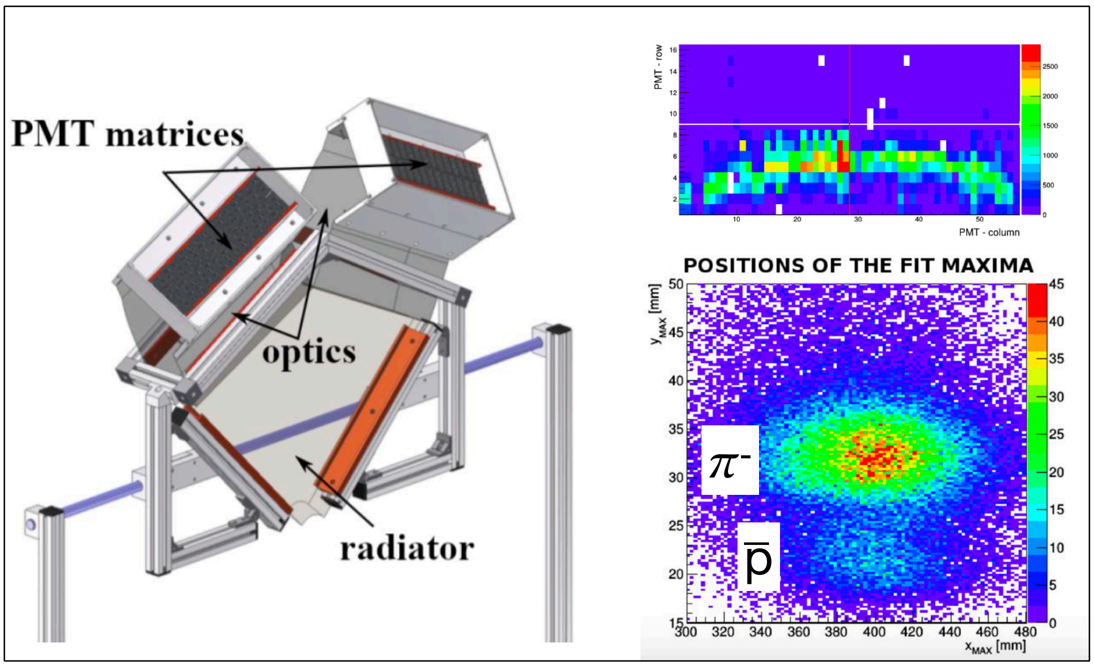

Figure 7: Sketch of the DIRC (left), Cherenkov arcs for an event sample detected by the PMT-matrices (up right) and $\pi^-/\bar{p}$ separation (down right) in a distribution of arc height (y_{max}) vs. arc center (x_{max}).

Behind the DIRC a scintillator hodoscope to trigger on single track events is placed consisting of scintillator paddles with a width of 20 cm readout on both ends by photomultipliers.

4 Beam time estimate

The cross section for elastic $\bar{p}p$ scattering is about 1.35 mb in the t-range from -0.002 to -0.007 [33], which is considered as a reasonable range with sufficiently high analyzing power to be included in the analysis, see Fig. 8. With the expected 8000 antiprotons/spill and an effective 12 cm long LH_2 target about 7 useful analyzer scattering events/spill are expected. In the typical operating conditions 2 spills every 30 s are ejected to the T11 beam line which sums up to 5760 spills/day. The mean spill rate over some weeks of beam time will be somewhat lower. A reasonable number for the mean spill rate is 4000 spills/day which gives 224000 spills

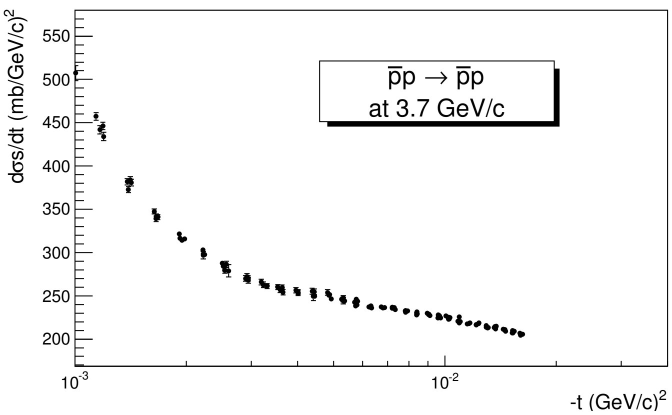

Figure 8: Cross section data for elastic antiproton proton scattering at a beam momentum of 3.7 GeV/c [33].

in 56 days and about $1.6{\cdot}10^6$ expected scattering events useful for the polarization analysis. In order to determine the achievable precision for the given statistics simulation studies have been performed. In Fig. 9 the extracted asymmetry is shown as a function of the number of scattering events taking into account events in a scattering angular range from 6 to 42 mrad and an assumed polarization of 100%. A high statistics event sample is required to extract a useful value for the asymmetry. Fig 10 shows the analysis result of a sample of $1.6{\cdot}10^6$ scattering events generated in a GEANT4 setup as a function of the assumed polarization. Given is the error of the determined asymmetry in σ-units for various ranges of scattering angles indicated by the different symbols. For a polarization of 12% the asymmetry can be determined with a precision of 5σ and for a polarization of 7% the precision is 3σ.

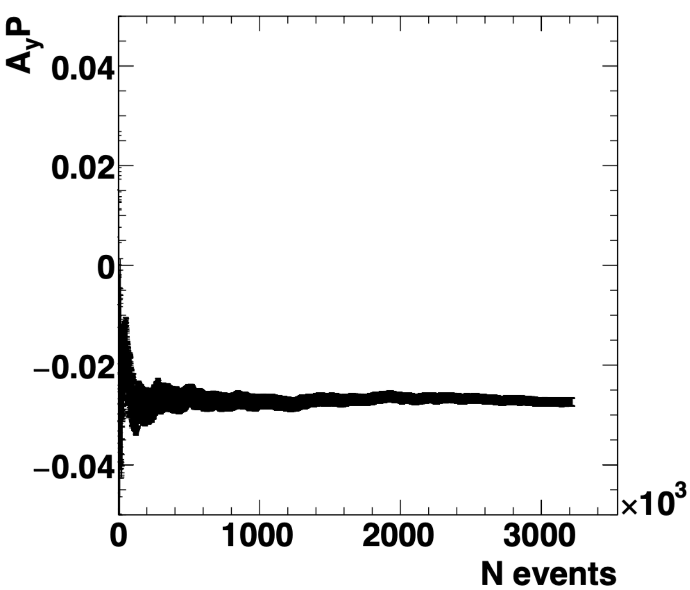

Figure 9: Asymmetry as a function of the number of scattering events in the angular range from 6 to 42 mrad assuming a polarization of 100 %.

Therefore we ask for 8 weeks of beam time at the T11 beam line adjusted for negatively charged particles of 3.5 GeV/c momentum which corresponds to the statistics of the performed

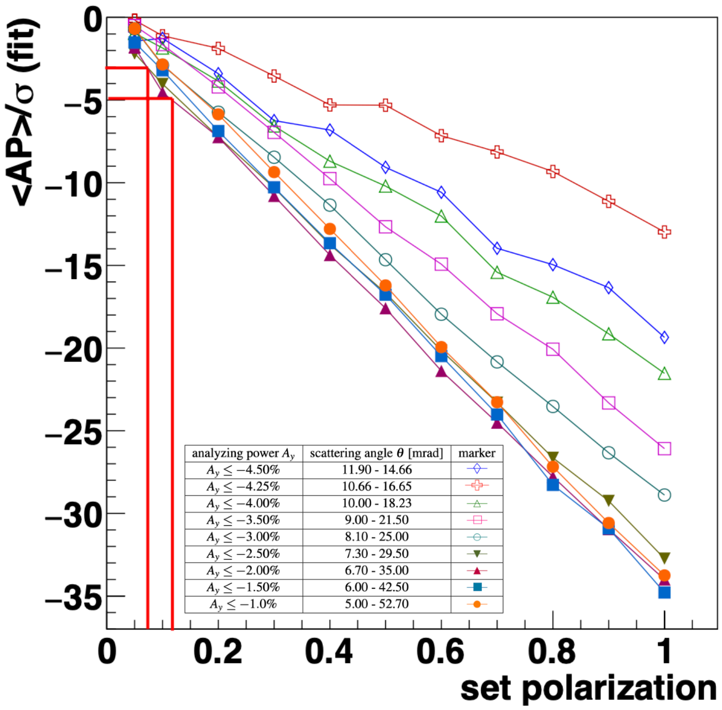

Figure 10: Precision of the determined asymmetry in σ for $1.6 \cdot 10^6$ scattering events generated in a GEANT4 setup for various ranges of the scattering angles. The red lines mark two examples for an assumed polarization of 12% and 7% resulting in a precision for the determination of the asymmetry in a value of 5σ and 3σ.

simulation studies with $1.6 \cdot 10^6$ scattering events.

5 Resources

All components of the detection system as well as the electronics and data acquisition system are provided by the collaboration. The resources requested from CERN are beside the delivery of beam at T11, a few hours of crane operation to install the detector system, a power line (3 x 16A) to operate the system, and a network connection for control and data taking. Furthermore a scaffold has to be installed as support for the detection system as it was done for the test measurement in August 2024 and the scintillator wall of CLOUD has to be removed for the experiment.

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