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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.

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 ($\bar{p} \uparrow \quad p \uparrow$) is a pure spin triplet state and with an antiparallel spin configuration ($\bar{p} \uparrow \quad p \downarrow$) 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,
- polarization of produced antiprotons.

Summaries of the various possibilities can be found in [1], [2], [3], [4]. 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 (± 1.3) % (the more precise value for Λ decay is taken) in the $\bar{\Lambda}$ rest frame [5]. 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 [6] 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 popular 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 [8]. 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 [9], [10]. 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 [11]. 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 [12], [13], [14], [15]. 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. Presently the PAX collaboration is working on this topic with polarized protons as filter [17], [16], [18], [13]. The spin filter method has been demonstrated at COSY for transverse polarized protons and similar studies for longitudinal polarization are planned [19]. Another filter reaction with large polarization effect, which was recently proposed [20] 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.

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 [21]. 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.

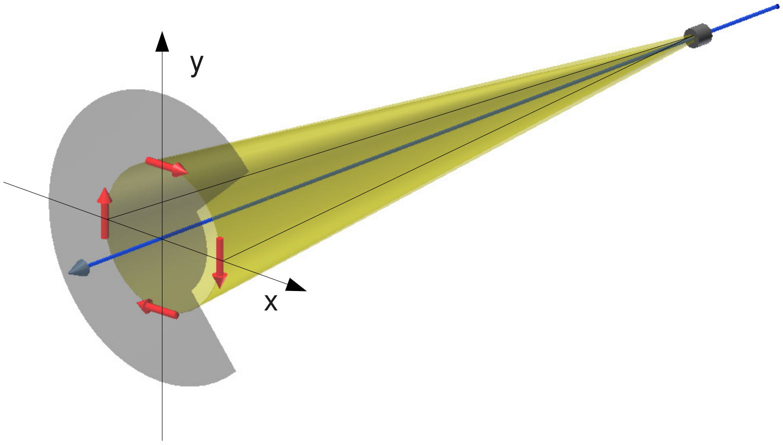

Figure 1: Possible polarization vector for a given production polar angle θ, indicated by the red arrows. In order to select an antiproton beam with transverse polarization one spin direction has to be separated by a suitably shaped absorber plate as indicated in grey.

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 [22],[23], [7], [25]. The maximum analyzing power is approximately given by [22], [24]: $A_N^{max} = \sqrt{3}/4 \cdot \sqrt{t_p}/m \cdot (\mu - 1)/2$, 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 lower part of Fig. 2. The data are from [25] taken with a 100 GeV/c proton beam at a polarized atomic hydrogen gas jet target.

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 [26] 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 an analyzing power of about 4.5%. In Fig. 3 and Fig. 4 the setup for the proposed polarization study at the T11 beam line is shown.

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 ± 3 mrad horizontally and ± 10 mrad vertically [27]. The beam line can be adjusted to momenta of up to 3.5 GeV/c for positively and negatively charged particles. For positively charged particles

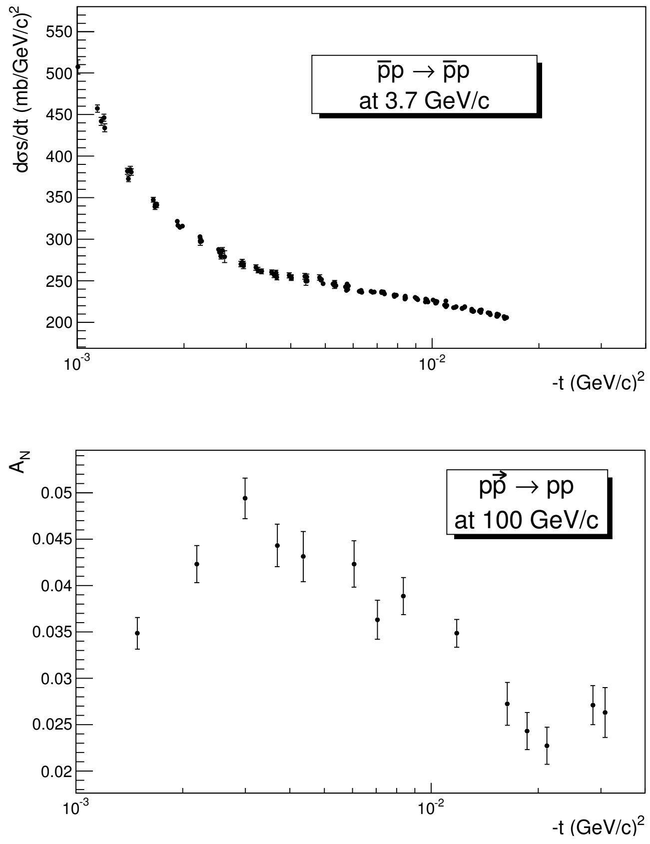

Figure 2: Cross section data for elastic antiproton proton scattering at a beam momentum of 3.7 GeV/c [31] (upper part) and analyzing power of proton-proton scattering [25] (lower part) as a function of the four momentum transfer t. The data for the analyzing power have been taken with a proton beam momentum of 100 GeV/c at a polarized atomic hydrogen target. The analyzing power of antiproton scattering is of the same size with opposite sign.

of momenta of 3.5 GeV/c with open collimators the momentum resolution is ± 5 % and up to $1 \cdot 10^6$ particles/spill are delivered with a setting for positively charged particles. The incident proton beam flux at this conditions is between $2 \cdot 10^{11}$ and $3 \cdot 10^{11}$ and the spill length is 400 ms.

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 [28] where data exist which are given in table 1. With the ratio of produced $\bar{p}$ to the sum of positively charged particles up to about 4000 $\bar{p}$ are expected to be delivered at T11 and the total flux of negatively charged particles is in the order of $5 \cdot 10^5$/spill which is about $1 \cdot 10^6$/s.

The detector arrangement is shown in Fig. 5. It consists of scintillators for trigger signal generation and beam profile measurements, a drift chamber stack to measure the track of the produced antiproton, an analyzer target, a second drift chamber set to reconstruct the track of a scattered antiproton, a Cherenkov detector for pion discrimination, a DIRC for offline

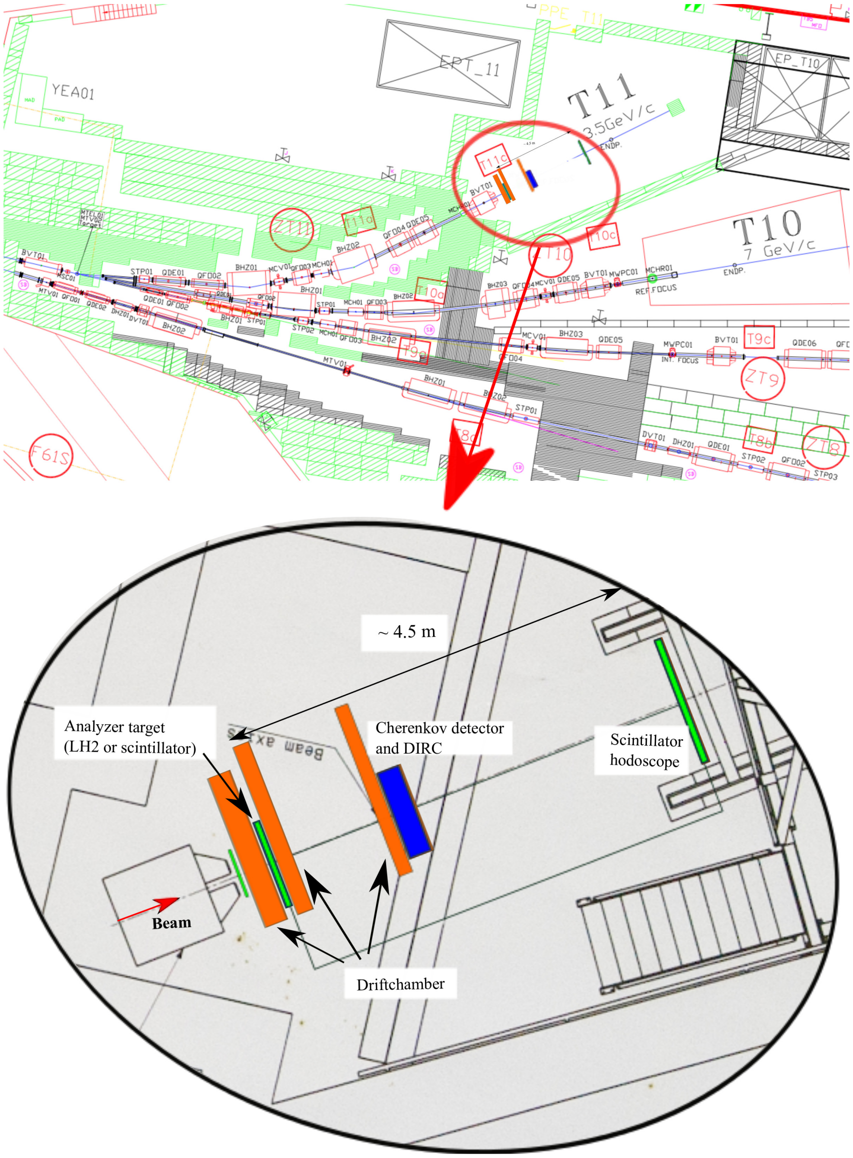

Figure 3: Experimental setup to measure the polarization of produced antiprotons. The upper part shows the test beam area with the detector components at the T11 beam line. In the lower part the area of the detector setup at the T11 exit is shown.

particle identification, and another scintillator hodoscope for trigger and $\bar{p}/\pi^-$ distinction by time of flight. At the exit of the dipole a scintillation detector is mounted which belongs to the CERN installation at T11. A scintillation fibre hodoscope follows which will be used to determine the beam profile. The drift chambers foreseen for these studies have been used in the COSY-11 experiments at the cooler synchrotron COSY in Jülich [29]. The first chamber D1 has a hexagonal drift cell structure, optimized for low magnetic field sensitivity, with 3 straight and 4 inclined (± 10 deg.) wire planes [30]. The drift chamber set for the measurement of scattered

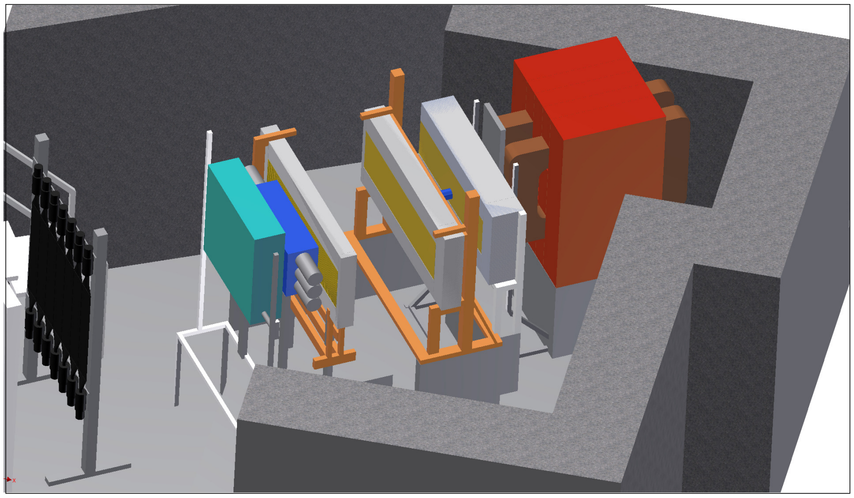

Figure 4: T11 area with installed detector components in front of the CLOUD installation. On the right side the last dipole of the beam line (BVT01) is seen and the CLOUD experiment is located on the left side (not shown in the figure).

antiprotons include 4 (2) straight and 4 (4) inclined (± 10 deg.) planes for D2 (D3). A track resolution in the order of 1 mrad was achieved with 1 GeV/c protons for D1 and the D2, D3 set.

As analyzer target a liquid hydrogen cell with a length of 15 cm will be used. The reconstructed tracks of primary and scattered antiproton allow to determine the reaction vertex with some uncertainty due to the limited track precision. For the analysis only the central part with a length of about 10 cm will be taken into account in order to discriminate reactions from the target windows. As alternative an analyzer target consisting of several layers of 4 mm thick scintillators will be prepared. The carbon nuclei from the scintillator material will introduce a rather high background level but the scintillators can act as trigger for elastic $\bar{p}p$ scattering events in the relevant forward angular range. An antiproton passing a scintillator will result in

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 [28]. In the last column the ratio of produced $\bar{p}$ to the sum of positively charged particles is given.

target	π^+	K$^+$	p	π^-	K$^-$	$\bar{p}$	$\bar{p}/(\pi^+ +$ K$^+$+p)
Be	1	0.12	0.48	0.79	0.040	0.0072	0.0045
B_4C	1	0.12	0.50	0.78	0.041	0.0072	0.0045
Al	1	0.13	0.57	0.78	0.042	0.0073	0.0043
Cu	1	0.14	0.64	0.80	0.045	0.0073	0.0041
Pb	1	0.16	0.36	-	-	-	-

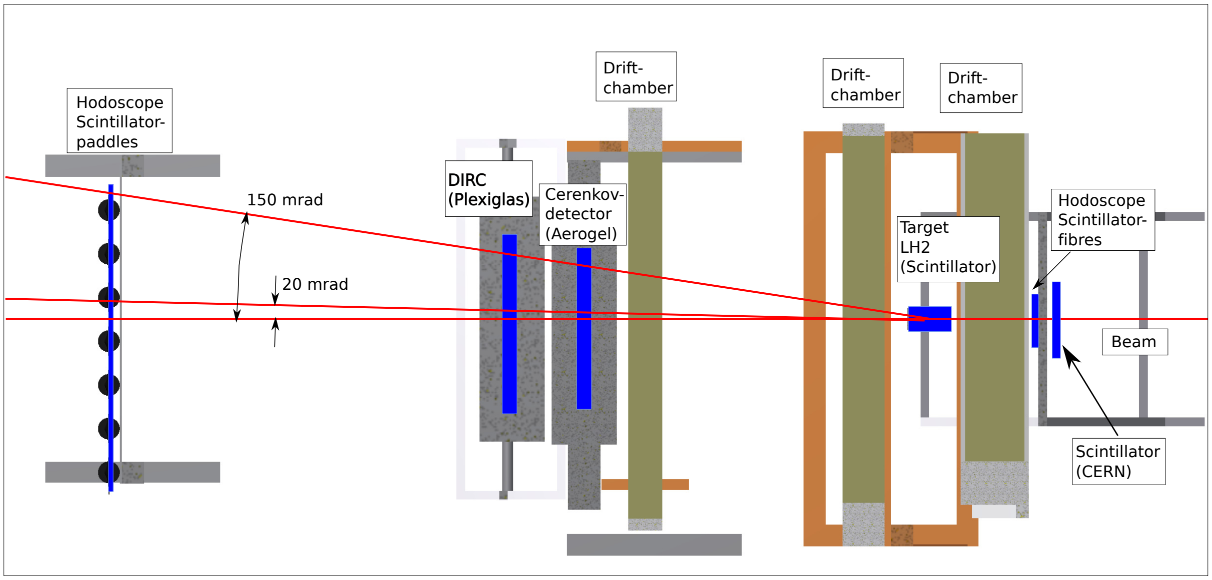

Figure 5: Sectional drawing of the detector arrangement in the horizontal plane. The beam is entering from the right and hits start scintillator, beam hodoscope, first drift chamber, scattering target, drift chamber pair, Cherenkov detector, DIRC, and scintillator hodoscope. A detailed description is given in the text. The relevant scattering angle for the asymmetry measurement of 20 mrad is indicated by the red line. In total a scattering angular range of about 150 mrad is covered by the system. A similar angular range is covered in vertical direction.

a minimum ionizing energy loss signal. In case of an elastic $\bar{p}p$ scattering process an additional energy loss from the scattered proton will be seen. In figure 6 the energy losses as a function of the t-value in plastic scintillators of 4 mm and 10 mm thickness are shown for Monte Carlo data of 3.5 GeV/c $\bar{p}p$ and $\bar{p}C$ scattering in addition to the expected energy loss of a minimum ionizing particle. In the relevant t-range around $t = -0.0037$ GeV/c^2 a clear separation of $\bar{p}p$ events is visible but quasi elastic processes like $\bar{p}C \to \bar{p}pX$ are not included in the MC data and will give rise to additional background signals. About 20 layers of scintillator modules are foreseen which result in a thickness comparable to the liquid hydrogen target.

The whole system will be operated in air. The straggling in the material between the first drift chamber and exit window of the beam tube does not influence the measurement. The straggling in the material of the detection system is below the expected track resolution of the drift chambers. For 3.5 GeV/c momentum antiprotons the radiation length up to the target including D1 and the flight path of $\sim$ 0.5 m in air is about 30 g/cm^2 with a mean thickness of 0.13 g/cm^2 which introduces a straggling of about 0.2 mrad. The tracking system for the scattered antiprotons gives a straggling of below 0.8 mrad and the hydrogen target adds another 0.7 mrad straggling. With a 10 cm CH target the straggling will be increased to 2 mrad, which would still be low enough to measure the region of scattering angles around 20 mrad.

At the exit of the tracking system, an aerogel Cherenkov detector (n $\sim$ 1.03) to discriminate the expected high pion background will be installed. The Cherenkov signals will be included

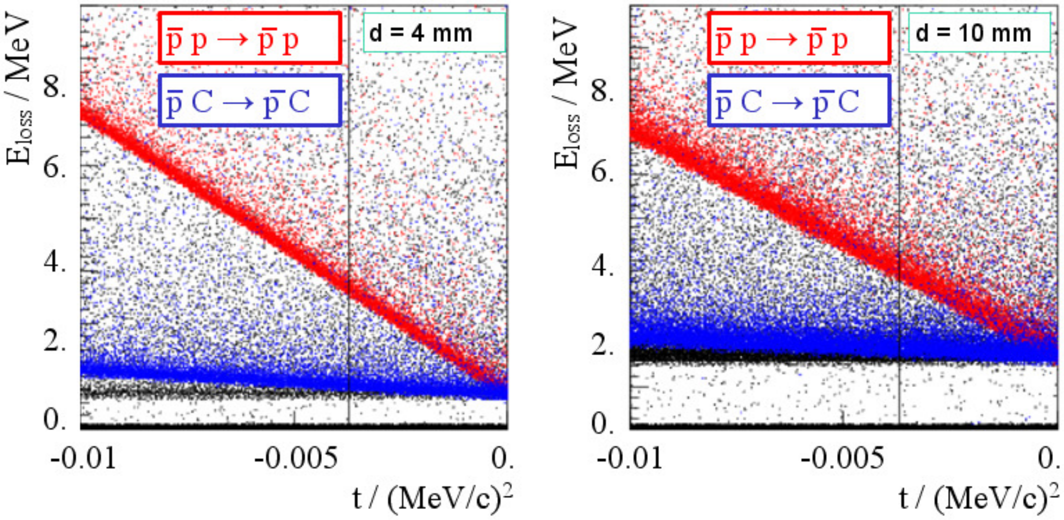

Figure 6: Simulation of the energy loss in plastic scintillators of 4 mm and 10 mm thickness for 3.5 GeV/c antiprotons passing the scintillator without reaction (black dots), elastically scattered on a Carbon nucleus (blue dots) or elastically scattered on a proton (red dots) in the relevant t-range around $t = -0.0037$ GeV/c^2.

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 $\beta_{\bar{p}}(3.5 \text{ GeV/c}) = 0.966$, i.e. the threshold for Cerenkov light emission is at n = 1.035. For pions, which will be the main background source, the velocity is close to c ($\beta_\pi(3.5 \text{ GeV/c}) = 0.9992$) with a threshold refractive index of n = 1.0008. Therefore a threshold Cerenkov detector with n $\sim$ 1.03 will drastically suppress the expected large pion background.

Behind the Cherenkov counter a DIRC with Plexiglas as radiator [32] is mounted for offline particle identification. The separation between antiprotons and pions at 3.5 GeV/c is expected to be 7.8 σ deduced from recently performed test measurement with a proton beam at COSY. And finally a scintillator hodoscope to trigger on single track events is positioned at a distance of about 4.5 m from the analyzer target. It consists 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 [31], which is considered as a reasonable range with sufficiently high analyzing power to be included in the analysis, see Fig. 2. With the expected 4000 antiprotons/spill and an effective 10 cm long LH_2 target or a 10 cm CH analyzer target about 3 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 84000 spills in 21 days and about $2.5{\cdot}10^5$ expected scattering events which is sufficient to measure a polarization of 20% with a statistical precision of about 25%.

A rough estimate of the accuracy for an asymmetry measurement $\delta\epsilon$ with N events is calculated by $\delta\epsilon = \sqrt{(\frac{\delta\epsilon}{\delta L})^2 + (\frac{\delta\epsilon}{\delta R})^2}$ with $L = R = N/4$ for the events on the left (L) and right (R) side used to calculate $\epsilon = \frac{L-R}{L+R}$. With 20% polarization i.e. $\epsilon = P \cdot A_y = 0.009$, an error $\delta\epsilon$ of ~ 30 % results. In Fig. 7 the ϕ angular distribution of $2.5{\cdot}10^5$ Monte Carlo events is given assuming an analyzing power of 0.045 and a polarization of 20% from which an asymmetry of $\epsilon = 0.012 \pm 24\%$ is extracted.

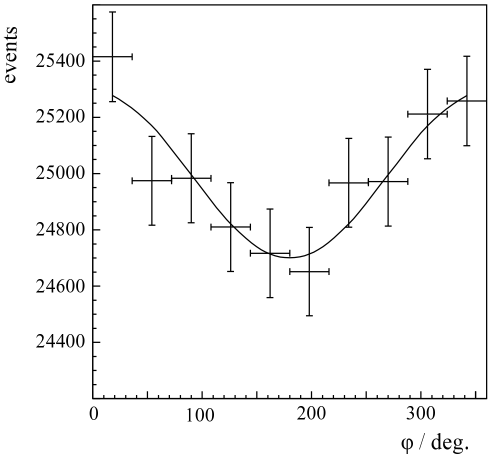

Figure 7: Expected asymmetry with $2.5{\cdot}10^5$ MC scattering events assuming an analyzing power of 0.045 and a polarization of 20%. The solid line is a fit to the angular distribution by $N(\phi) = N_0{\cdot}(1{+}A_y P{\cdot}cos(\phi))$ resulting in an asymmetry of $\epsilon = 0.012 \pm 24\%$.

Therefore we ask for three weeks of beam time at the T11 beam line adjusted for negatively charged particles of 3.5 GeV/c momentum. The measurements will be done essentially with the liquid hydrogen target. In order to check the background and performance of a scintillator target we want to spend two days for measurements with scintillator target.

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.

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