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The AMBER Experiment at CERN

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Abstract. NA66/AMBER has been approved by CERN in 2020 as a new multi-purpose facility for experiments in meson and baryon physics. In a first beam-time in 2023, data have been taken for the determination of antiproton production cross-sections in proton-helium collisions, needed for the interpretation of cosmic antimatter observations. Preparations are ongoing for a measurement of the proton charge radius in high-energy muon-proton scattering. This measurement will feature substantially different systematics than other approaches and aims at clarifying the present discrepancies. Further, experiments to study the partonic structure of mesons in Drell-Yan processes and strange-meson spectroscopy are on the menu of AMBER.

1 Introduction

Over the past decades, vast progress has been made to establish the standard model of elementary particles as the correct description of nature. Yet the predictive power of calculations remains limited especially regarding the strong interaction, and input from experiments is demanded for further exploring the large variety of effects that govern the physics of strongly interacting systems.

In that context, the AMBER (Apparatus for Meson and Baryon Experimental Research) Collaboration has been formed by about 200 physicists from 34 institutes worldwide a few years ago, and was approved to run its phase-1 program [1] by CERN as experiment NA66 in the north area at the extracted beam M2 of the super proton synchrotron (SPS). AMBER has inherited the spectrometer setup of the COMPASS collaboration [2]. About 2/3 of the COMPASS groups continue their responsibilities within AMBER, and with the joining of many new groups, the new collaboration is still growing and got ready to tackle the needed modernizations of the setup. The first measurements deliver cross-sections for antiproton production in hadron-hadron collisions, which are relevant in cosmic ray physics, since this requires the least changes of the existing detectors. Next, the setup will be changed in order to measure the proton radius in muon-proton scattering. Apart from new tracking detectors and a high-pressure hydrogen target system, the data acquisition system needs to be upgraded to a free-running mode for this measurement. The third physics case in AMBER phase-1 is the investigation of the pion and kaon partonic structure as it becomes accessible in Drell-Yan processes.

In phase-2, the collaboration plans to extend the successful COMPASS program of pion-induced light meson spectroscopy to the kaon sector, by a focus on the beam kaon component. Analogously, the study of pion-photon reactions in Primakoff processes is planned to be

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extended to kaon-photon reactions. The detector requirements for the latter ones are similar to those for the measurement of prompt photons in meson-nucleon collisions, which will shed again light on the partonic structure of mesons.

2 Spectrometer setup

The AMBER setup is depicted in Fig. 1. The setup is subdivided into two stages, which are equipped with spectrometer magnets (red), the first of maximally one, the second of four Tm. They deflect charged particles of lower and higher momenta, respectively, which are measured by means of about 300 tracking detector planes placed up- and downstream of the magnets. A ring-imaging Cherenkov detector (RICH, light grey) in the first stage allows particle identification up to about 50 GeV. Electromagnetic and hadronic calorimetry (blue) contributes to particle identification in the full momentum range, especially to distinguish electrons and hadrons, and allows for the detection of photons. Both stages feature an elaborate muon detection system (brown), placed downstream of massive absorbers. For the measurement of deep-inelastic scattering of muons off nucleons, which was one of the main physics cases of COMPASS, the muon detectors in the second stage provide fast signals to an elaborate trigger system, which allows for registering the events of interest with a rate up to 50 kHz, with beam rates of up to $2 \cdot 10^8$ muons/s. Other trigger options have been installed for the physics with hadron beams, namely a (target) proton recoil trigger, a multiplicity trigger and triggers on the electromagnetic calorimeter.

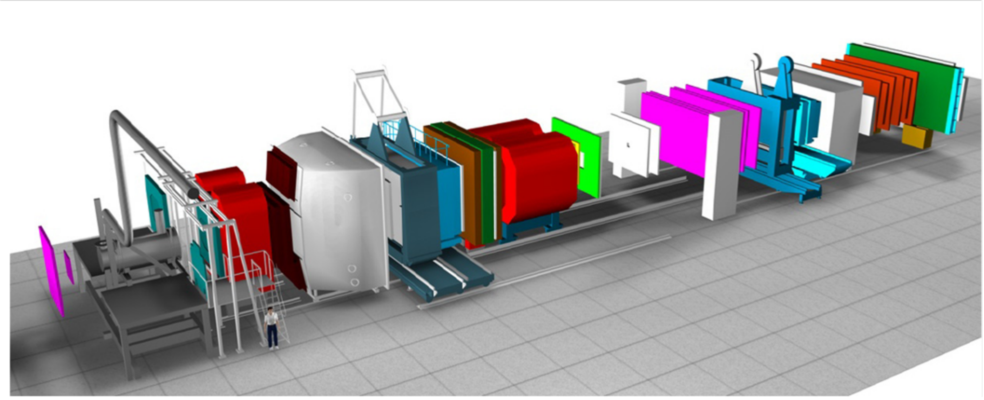

Figure 1. The setup of the AMBER experiment. Beam is entering from the left. The target region is equipped with the polarized target, visible as large cylindric solenoid and the L-shaped helium supply line, both in dark grey. It has been used in 2023 for providing a liquid-helium target in the antiproton production measurements of AMBER.

For the diverse physics program of AMBER, those trigger options turned out to be insufficient to reach the needed count rates. Most versatile and modern is the implementation of a readout system that does not feature a trigger selection in the first stage, but processes all detector data to a higher stage, where the information of interest can be filtered out based on more complex algorithms on a computer farm. This is refered to as *streaming* or *free-running* data acquisition (DAQ). Many of the old COMPASS detectors are not ready for this new readout scheme, and thus need to be upgraded or replaced. This is one of the major efforts for the AMBER hardware projects.

3 Antiproton production cross-sections

The measurement of the antiproton yield for protons of different incoming energies impinging on helium and proton targets could be done as first experiment of the newly installed Collaboration already in the year 2023, as it does not require the new streaming DAQ or other new detector components. Key for this measurement is the identification of the incoming protons, which represent about 70% of the hadron beam, and the identification of antiprotons as reaction products.

For the incoming particles, this is achieved by ring-imaging Cherenkov detectors with a specific optics that allows to separate the rings, which differ for the main beam components (pions, kaons and protons) in radius only on sub-millimetre level (CEDAR detectors, cf. [3]).

The identification of the produced antiprotons is done by the RICH detector, cf. Fig. 2. In this sample data set there are much less antiprotons in the final state than protons, as expected from the matter-antimatter asymmetry of the initial state. The measurements cover the momentum range of the incoming protons from 60 to 250 GeV/c, and will be subdivided into angular bins. The obtained cross-sections can be used in the estimations by astrophysical models for the spectrum and intensity of antiprotons in the cosmic rays, and thus can help to clarify whether there are significant discrepancies of such models and the spectra observed e.g. by AMS-02 [4] and PAMELA [5].

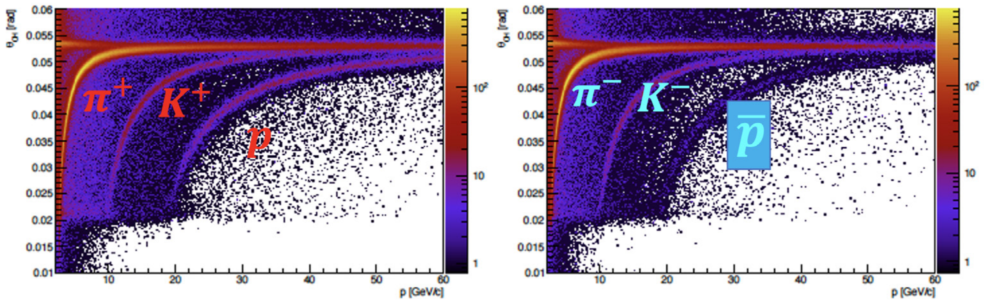

Figure 2. First data from the antiproton production measurement in the year 2023. The Cherenkov angle, calculated from the radius of the ring of Cherenkov photons that is projected on the detector plane by the employed mirror system, is drawn versus the momentum of the associated charged particles. The left plot is for positive, the right one for negative particles.

For the measurement in 2023, the polarized target of COMPASS was used [2], filled exclusively with liquid helium (He-4), replacing the normal filling with polarized material and a He-3/He-4 dilution-cooling mixture. From these data on a pure He-4 target, production cross-sections of proton-helium collisions are obtained. For a future beam time in the year 2024, it is planned to install a liquid hydrogen target and measure production cross-sections in proton-proton collisions. Here, data exist from NA61 [6] for proton-proton collisions, however an independent cross-check and a higher precision at higher transverse momenta is particularly desirable. In addition, filling the target with deuterium allows to determine also antiproton production on the deuteron and thus on the neutron, which is an important input in order to understand the precision of the estimations made for heavier nuclei.

4 Proton radius measurement with muon beam

The size of the proton, the most abundant hadron in the universe, plays a key role in many fields of science, foremost in the quantitative understanding of quantum chromodynamics

(QCD). Within QCD the proton is identified with the lowest-lying bound state of three valence quarks, and this state may be calculated by continuum or lattice methods.

Since the first SLAC measurements of the proton radius by R. Hofstadter and colleagues, the measurements have been continuously refined and thus the precision increased. The progress over the past 10 years is summarized in Fig. 3. Hofstadter gave a value for the proton charge radius of about 0.80 fm [8]. Linking the proton-photon interaction to the vector meson spectrum, dispersion relations were exploited to calculate the prediction of 0.84 fm in 1975 [9]. Simon *et al.* did a precision measurement at the Mainz accelerator [10] in 1980 and found the proton radius to be 0.862 fm. Revisions of the dispersion calculations [11, 12] confirmed the discrepancy with Simon's value. In order to clarify and further increase the precision, besides new electron scattering experiments, atomic spectroscopy has been refined to the point where level splitting could be used for determining the nuclear charge radius. For the particularily difficult case of the proton, this has been pursued by the CREMA collaboration with muonic hydrogen [13], in which the nuclear size effect is much amplified. They extracted the value for the proton radius of 0.841 fm with extremely small experimental uncertainties.

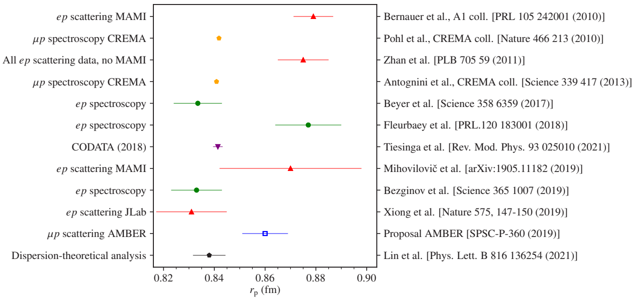

Figure 3. Determinations and calculations of the proton charge radius since 2010. The measurement with the highest precision comes from spectroscopy of muonic hydrogen atoms, as investigated by the CREMA collaboration. The most elaborate electron scattering experiment has been done at MAMI. The upcoming AMBER measurement with high-energy muon beam aims at a competitive precision as the existing electron scattering data. Plot adapted from [7].

At about the same time, a high-statistics experiment for electron scattering has been done at MAMI [14], and the result of 0.88 fm even increased the discrepancy with dispersion theory and muonic atom spectroscopy. At Jefferson Lab, the PRad experiment has studied electron scattering on a windowless hydrogen gas target [15], measuring without a momentum-selecting magnetic field, but instead with calorimetry. This alternative approach led to a value of 0.83 fm, however with quite large uncertainties. The tension of these data, already on the cross-section level, between the PRad and the MAMI data, is depicted in figure 4.

An approach that has not been exploited so far is muon scattering off the proton. It is more elaborate to provide a muon beam as compared to electron beams, muons however come with much different systematic effects and thus they are promising to shed light on apparative effects that may explain the different measured values. The MUSE experiment [17] at PSI is pursuing this idea with low-energy muons up to about 200 MeV.

AMBER will measure the scattering of high-energy muons of about 100 GeV off protons in a pressurized target cell for a proton radius measurement (PRM). In order to safely identify the elastic scattering events of interest, the target volume is built in form of a time-projection chamber (TPC), with the hydrogen constituting also the detector gas. For the de-

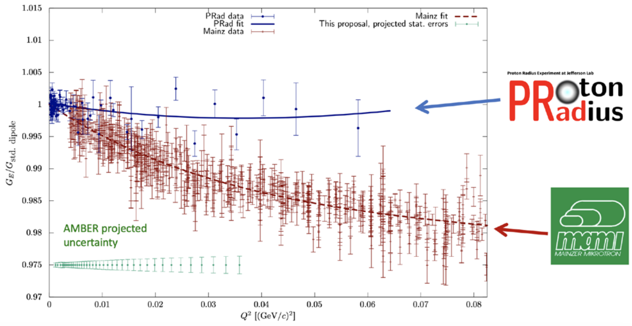

Figure 4. Electron scattering data from MAMI [14] and PRad [15]. The proton radius is proportional to the slope of the electric form factor $G_E(Q^2)$. The data points at higher values of Q^2 up to about 0.04 give rise to the discrepancy between the two experiments. AMBER aims to clarify with high-energy muon scattering, projected to deliver data points with the shown uncertainties. Plot courtesy of [16].

termination of the muon scattering angle with high precision, dedicated detector telescopes will be installed upstream and downstream of the TPC. They will be equipped with silicon pixel detectors (ALPIDEs) and fast scintillating-fiber detectors, both newly developed for the streaming DAQ. This is particularily important for PRM, since there is no way to distinguish the elastically scattered muons at low momentum transfer from the undeflected beam muons. An interesting additional option is the operation of the electromagnic spectrometer in forward direction, since it allows to determine the occurence of bremsstrahlung photons. Those are rare for muons, according to the suppression of radiative effects for more massive particles. This is a particular advantage of the measurement with muons, and it is worth to prove this point by the experiment.

With this setup, the goal is to collect a sample of 70 million elastic muon-proton scattering events in the momentum transfer Q^2 range from 0.001 to 0.04 GeV^2. This will take about one beamtime of 140 days, foreseen in the year 2025. From these data, we aim at determining the Q^2 dependence of the proton form factor as indicated in Fig. 4.

5 Pion structure from Drell-Yan processes and Charmonium Production

The quark-gluon structure of mesons is of particular interest in the context of the emergence of the hadron mass (EHM) [18]. Since deep-inelastic scattering (DIS) is not possible in that case, the way to learn about meson structure is the production of lepton pairs in the collision with nucleons whose structure is much better known from DIS, namely, in Drell-Yan processes. Previous data are from experiments at Fermilab and CERN [19–21], dating back to the 1980s, with limited accuracy and partly considered in tension with each other [22]. The data that COMPASS has taken with negative pion beam on a polarised ammonia target [23] may help to clarify once the cross-sections on the secondary aluminium and tungsten targets are available. With those data, however, it is not possible to clarify how sea and valence quarks contribute to the cross-section, and thus to constrain their respective structure functions.

AMBER plans to measure the Drell-Yan process with pions of both negative and positive polarity, which allows for the separation of sea and valence quark contributions. In two beam

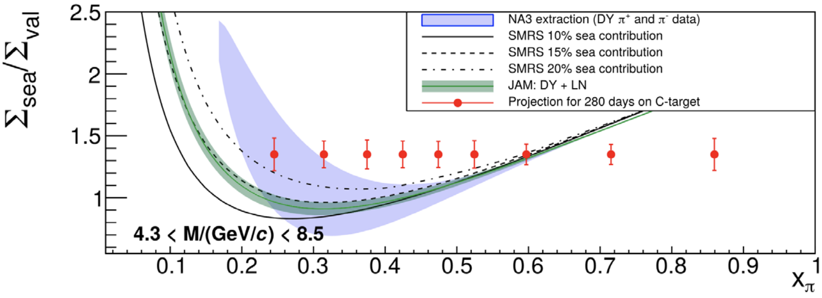

Figure 5. The ratio of the sea $\Sigma_{sea} = 4\sigma^+ - \sigma^-$ and valence $\Sigma_{val} = -\sigma^+ + \sigma^-$ quark contribution to the cross-section of pions on an isoscalar target, such as carbon. The uncertainty of the only available data [20] is indicated as blue band.

times, with in total 280 days of beam, the achievable accuracy is indicated as red error bars in figure 5, when the beam time is shared between π^- and π^+ beams in the ratio 1:3.

Within the dimuon sample that will be taken by AMBER, there will be the whole charmonium spectrum with decays into leptons, most prominently from J/Ψ and $\Psi(2S)$. Their inclusive production comes mainly from $q - \bar{q}$ annihilations and from gluon-gluon fusion. Exploiting the polarisation state of these vector mesons and the dependence on the production kinematics, allows to separate those contributions and thus gives insight in the gluon distribution of the pion.

6 Conclusion and Outlook

In its phase-1 the AMBER Collaboration operates a modernized two-stage spectrometer setup at the CERN SPS, for measurements of antiproton production cross-sections, the proton radius and the pion structure via the Drell-Yan mechanism. While the first data have been taken in 2023 already, this program will take up to about 2029.

For the longer term future, the setup is planned to be upgraded for measurements that will be described in the phase-2 proposal. They will mainly focus on the usage of the kaon component of the hadron beam. This will allow to extend the successful COMPASS light-meson spectroscopy program to the strange-meson sector, and to study photon-kaon interactions in Primakoff processes. While the Drell-Yan program of phase-1 may already profit from this kaon component with respective enhancements in the beam line, it will be promising to pursue it in phase-2. A further idea to access the gluonic part of the meson structure is the measurement of prompt photons, in a similar configuration as the Primakoff program with electromagnetic calorimetry.

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