PROCEEDINGS OF SCIENCE

AMBER: a new QCD facility at the CERN SPS M2 beam line

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AMBER (NA66) is a newly proposed fixed-target experiment at the M2 beam line of the SPS, devoted to various fundamental QCD measurements, with a proposal recently approved by the CERN Research Board for a Phase-1 program and a Letter of Intent made public for a longer term programme. Such an unrivaled installation would make the experimental hall EHN2 the site for a great variety of measurements to address fundamental issues of strong interactions in the medium and long-term future.

The elastic muon-proton scattering process, using high-energy muons, is proposed as a novel approach to the long standing puzzle of the proton charge radius. Such a measurement constitutes a highly-welcomed complementary approach in this area of world-wide activity.

Operating with protons, the antiproton production cross section, which is currently known with poor precision, can be measured, which constitutes important input for the upcoming activities in searches for Dark Matter.

Especially the world-unique SPS M2 beam line, when operated with high-energy pions, can be used to shed light on the emergence of hadron masses and to address the question of how we can explain the emergence of the proton mass and the nearly masslessness of the pion. The origin of hadron masses is deeply connected to the parton dynamics and their differences between baryons and mesons.

For a longer-term programme an upgrade of the M2 beam line with radio-frequency separation technique will provide kaon and antiproton beams of high purity. This will allow to perform precise spectroscopy studies and open new unique opportunities to shed new light on the light meson structure and properties.

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1. Introduction

AMBER (Apparatus for Meson and Baryon Experimental Research) is a new fixed target experiment at CERN's SPS M2 beamline. Central to AMBER's physics programme is the nature of the major part of visible matter, hadrons. Hadrons are composite particles whose substructure is made from quarks and gluons and whose interaction is governed by the underlying strong forces, theoretically described by Quantum-Chromo-Dynamics (QCD). Many features of the most fundamental hadrons and their excited states can be described by QCD or QCD–inspired effective field theories and models. While QCD as a theory is well defined in principle, the very nature of QCD as a non-Abelian gauge theory often makes real-life calculations prohibitively difficult and accurate predictions based on QCD alone are not available in many instances. This manifests most prominently in the question of how hadron masses are generated from massless gluons and nearly massless quarks and how the large differences in the mass spectra of even the most fundamental baryons and mesons like nucleons and pions can be described. This basic question, the emergence of hadron mass and related emergent properties of hadrons, linked to the dynamical breaking of chiral symmetry in QCD is at the core of AMBER's physics goals, as are detailed studies of the partonic structure of hadrons, their radii and excitation spectra[1, 2].

The experimental facility and the flagship measurements of phase-1 will be described in detail, followed by a summative outlook on the physics programme of AMBER phase-2.

2. Experimental Facility

AMBER will be located at CERN's North Area, making use of the M2 beam line which is fed by the SPS. Protons delivered by the SPS beam line on a production target create a wide range of secondary and tertiary particles for use with experiments downstream. The setup for the AMBER location at the end of the M2 beamline provides charged muon, pion, kaon and proton beams with energies ranging from 50 GeV up to 280 GeV. The beam intensity is usually only limited by radiation protection considerations.

The AMBER open geometry forward spectrometer is based on the COMPASS experiment which previously occupied this position. The setup is depicted in fig. 1. It features two spectrometer magnets, high precision tracking devices, RICH detectors for particle identification and electromagnetic as well as hadronic calorimeters. The setup is very versatile and can be adapted to a specific experimental question. Similarly, the production target in front of the spectrometer can be exchanged to match experimental needs.

This is exemplified e.g in the changes to the setup for the planned measurement of the proton radius using the form factor method. To reach the required proton target density while at the same time allowing the best possible event reconstruction, a high pressure TPC operating with pure hydrogen will be installed in the target region, acting as an active target. It will be flanked by four Universal Tracking Stations, two upstream and two downstream the TPC, equipped with ALPIDE high spatial resolution silicon tracking detectors and fast timing provided by scintillating fibre detectors read out by SiPM photosensors. This setup, unique to the proton radius measurement, provides the necessary accuracy and precision for this part of AMBER's experimental programme.

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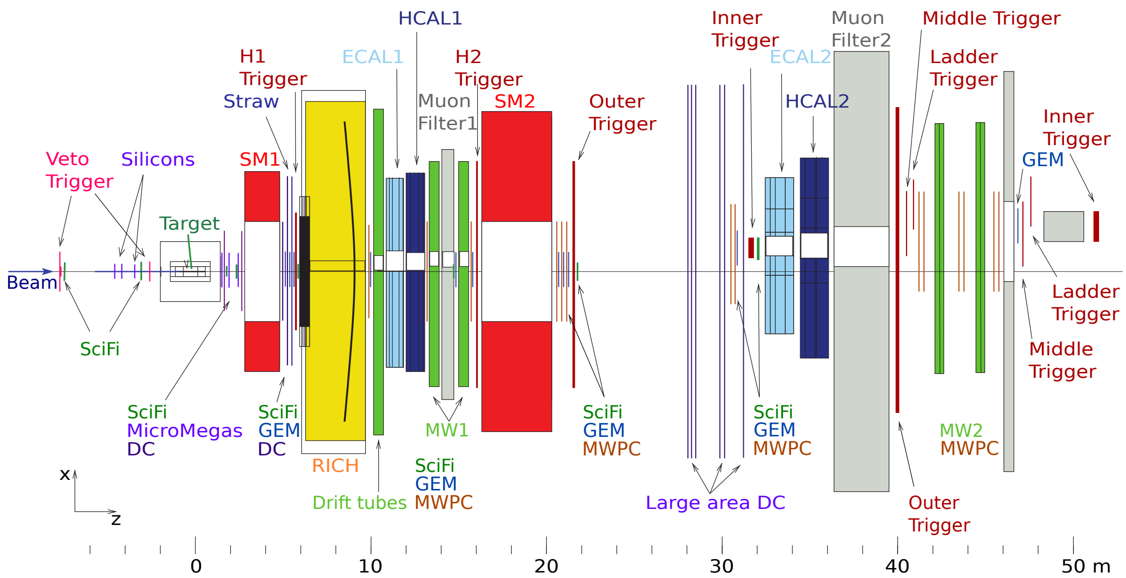

Figure 1: Sketch of a top view of the experimental setup of the open geometry forward spectrometer forming the basis of the AMBER setup. Shown is the COMPASS setup for the 2021 campaign. The target region will be specifically adapted for the measurements described in these proceedings. Note the excellent particle identification and muon tracking capabilities of this setup.

3. AMBER Phase-1

Understanding the size of the most fundamental baryon, the proton, is a crucial measurement in hadron physics and beyond. It is known for more than a decade, that measurements using electron scattering to extract the proton's electric form factor and extrapolating it to the real photon point, i.e. in the limit of the four-momentum transfer $Q^2 \to 0$, are in disagreement with high precision spectroscopic measurements using normal and muonic hydrogen atoms. Various experiments in electron scattering have been performed. The results are summarised in fig. 2. There are several reanalyses of different subsets of the electron scattering data. An overview is given in [3] with a critical discussion in [4]. The one outstanding measurement, scattering muons instead of electrons to extract the proton form factors has yet to be done. Given the presently available experimental techniques, a complete answer to this problem requires four key measurements: elastic lepton scattering to measure the Q^2–dependence of the electric form factor and atomic spectroscopy to study finite-size effects in atomic levels. Both types of experiments can be carried out with electrons or muons. To date, results are available for three types of experiments, but not yet for elastic muon–proton scattering.

The first measurement of AMBER phase-1 is a muon–proton experiment using high-energy muons of the CERN M2 beam line. The measurement will provide a new and completely independent result on the proton charge radius with a statistical accuracy of 0.01 fm or better and considerably smaller systematic uncertainty. Using muons instead of electrons is highly advantageous, as it leads to different experimental systematics as well as theoretically calculated radiation correction being considerably small.

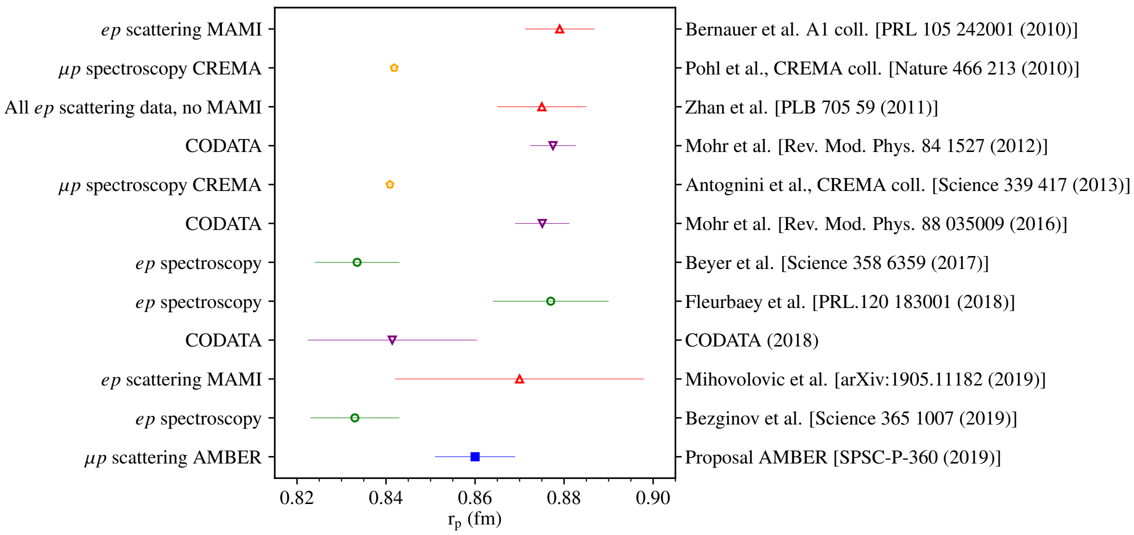

Figure 2: Compilation of data on the proton radius puzzle, sorted by time. Electron-proton scattering and spectroscopy (red/green), muon-proton spectroscopy (orange) and summary data (purple) is shown with the value of this proposed measurement (blue) arbitrarily placed at 0.86 fm, with the projected uncertainties. Error bars represent statistical and systematic uncertainties added in quadrature. Reproduced from [2].

Uncertainties in the standard nuclear physics production cross sections are a dominant source of error in the hunt for dark matter, especially when considering experiments measuring the composition of cosmic rays. Several experiments are ongoing or planned to remedy that situation and increase the precision of current cosmic ray experiments. AMBER will perform precise production cross section measurements in the kinematic range where current AMS-2 data suffers most from nuclear cross section uncertainties.

The purpose of this experiment is the measurement of the antiproton production cross sections in proton- proton and proton- He scattering for projectile energies from several tens to a few hundred GeV. In combination with similar measurements by LHCb in the TeV range, our measurements will provide a fundamental data set that is expected to allow for a significantly higher accuracy for the predicted natural flux of antiprotons in galactic cosmic rays.

The existing M2 hadron beam line with a proton momentum range between 20 and 280 GeV/c is an ideal place to perform this measurement. The antiproton production cross section will be measured using the spectrometer in EHN2 equipped alternatively with liquid-hydrogen and liquid-helium targets, relying on the antiproton-identification capabilities of the RICH detector. The cross section will be measured for several beam momenta in 20x20 intervals of antiproton momentum and pseudorapidity. A 1% statistical uncertainty will be reached for the cross section, with an anticipated point-to-point systematic uncertainty of less than 5%.

Drell-Yan reactions provide access to the partonic structure of unstable hadrons if the latter can be provided as beam particles. This puts AMBER into a prime position to study the structure of charged pions and kaons with unprecedented precision , the third pillar of AMBER phase 1.

This inclusive measurement of lepton pairs and the high statistics runs possible for AMBER using isoscalar targets will provide excellent opportunities to study the quark and gluon content inside pions and kaon, investigating commonalities and differences, hence shedding light on the crucial question of emergent hadron mass in QCD.

The main objective of these measurements is to study the structure of the pion, i.e. to determine the poorly known pion valence and sea-quark parton distribution functions (PDFs). Modern theory reveals that the properties of the nearly-massless pion are the cleanest expression of the mechanism that is responsible for (almost) all the visible mass in the Universe [5].

The associated theory simultaneously reconciles the emergence of the proton mass with the masslessness of the pion in the chiral limit [6]. It shows, too, that a determination of the valence-quark PDF of the pion provides the needed sensitivity to the mechanism(s) responsible for the emergence of mass in QCD. The planned measurements will also provide benchmarks for testing recent predictions of non-perturbative QCD calculations performed on the lattice or in the framework of the Dyson-Schwinger equations.

4. AMBER Phase-2

AMBER is currently preparing a physics proposal for phase-2 of its experimental programme. Phase-2 aims to extend the physics reach of AMBER by increasing the beam intensities of the charged meson beams available through RF seperation techniques, especially focusing on exploiting the physics opportunities of a high intensity $K^{\pm}$ beams. Drell–Yan measurements with kaon beams will give unprecedented access to their structure, including but not limited to measuring the quark structure functions, their gluon structure functions via direct photon production and measuring their charge radius in elastic kaon–electron scattering.

Similarly, the intense kaon beam delivered to AMBER will allow ground-breaking experiments in the spectroscopy of strange mesons and exploration of kaon low-energy parameters in ultra-soft collisions with nuclei, so-called Primakoff reactions. Primakoff reactions give access to properties of the beam particle via the interaction with a photon from the electric field of the scatterer and e.g. allow determining the particle's polarisability.

The search for a complete picture of meson states has never been more topical. Possibilities allowed within QCD beyond the simple quark models include tetraquarks, mesonic molecules, glueballs and hybrid states. Strong candidate for glueballs and hybrids exist experimentally, but the evidence is still not overwhelming. Progress hinges on large, bespoke data sets with very small statistical and systematic uncertainties. AMBER's predecessor COMPASS has been instrumental in clarifying the nature of a hybrid meson candidate, the π_1, the first of a expected nonet of hybrid mesons. AMBER in phase-2 will provide the much needed reduction in experimental uncertainties, aiming at major step in completing not only this nonet, but a better understanding of exotic states in general.

This promising physics programme will be accompanied by the development of new detector system for the characterisation of the beam as well as the reaction products, especially at high fluxes and high rates and the higher fraction of kaons and (anti-)protons in the beam due to RF-separation
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5. Summary

AMBER (NA66) is a recently approved fixed target experiment making use of SPS M2 beamline in the North Area of CERN. AMBER will make use of the versatile beam delivery available at that beam line, exploiting $\mu^{\pm}, \pi^{\pm}, K^{\pm}$ and proton beams with energies ranging from 50 GeV to 280 GeV.

AMBER's physics programme, divided into two phases, consists of rich topics in hadron structure and hadron spectroscopy, making the best use of the versatile beam and target configurations. The approved first phase will concentrate of measuring the proton radius using elastic scattering of muons off protons following the form-factor method. This will be followed by measuring the production cross section for anti-protons off proton and helium targets with high precision over the entire available energy range to provide crucial input for dark matter searches. This first phase will be completed by a series of Drell–Yan measurements using charged pion beams at 190 GeV.

The second phase aims at much higher beam intensities for meson beams, especially for $K^{\pm}$, providing unique opportunities for studying the structure of Kaons including its gluonic structure, Primakoff reactions and a very rich programme in light meson spectroscopy.

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