



Proposal for Measurements at the M2 beam line of the CERN SPS
Phase-1: 2022-2024
COMPASS++*/AMBER[†]

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Preamble

In the context of the physics-beyond-colliders initiative at CERN, the COMPASS++/AMBER (proto-) collaboration recently submitted a Letter of Intent (LoI) [1] to the SPSC in order to establish a "New QCD facility at the M2 beam line of the CERN SPS". Such an unrivalled installation would make the experimental hall EHN2 the site for a great variety of measurements to address fundamental issues of strong interactions. The proposed measurements cover a wide range in the squared four-momentum transfer Q^2 : at lowest values of Q^2 we want to determine the proton charge radius through elastic muon-proton scattering, at intermediate Q^2 we want to perform spectroscopy of mesons and baryons by using dedicated meson beams, and at high Q^2 we plan to study the structure of mesons and baryons via the Drell-Yan process. In our LoI, we have described physics goals, sensitivity reach and competitiveness for such a future general-purpose fixed-target facility at CERN.

In response to the LoI, the SPSC requested a proposal for measurements to be performed in the years 2022 to 2024. In this document, we give more details on our prioritised list of measurements proposed as phase-1 of our long-term project, using the existing muon beam and conventional hadron beams delivered by the M2 beam line. Beyond LS3, we propose an upgrade of the M2 beam line by installing a radio-frequency (RF) separation stage for kaon and antiproton beams of high energy and high intensity. Such beams allow for further unique measurements that cannot be performed elsewhere. The proposed RF upgrade of the M2 beam line is presently under study at CERN EN-EA.

The full project is expected to stretch across the next 10 to 15 years. As it continues to attract physicists world-wide, the physics scope of the facility should remain open for future exciting ideas, using either (RF-separated) hadron beams or the muon beam. Proposals for further measurements, based upon ideas already discussed in the LOI or possible new ones, will be submitted in due time.

Executive Summary

The COMPASS++/AMBER (proto-)collaboration proposes to establish a

“New QCD facility at the M2 beam line of the CERN SPS”

and perform in phase-1, *i.e.* starting in the year 2022, three experiments that will use either muons or hadrons delivered by the existing M2 beam line:

(1) Proton charge radius measurement using muon-proton elastic scattering

This experiment aims at a precision determination of the electric mean-square charge radius of the proton. The proposed measurement using elastic muon-proton scattering appears timely, since in spite of many years of intense activity the proton-radius puzzle remains unsolved up to now. The answer to this problem requires four key measurements: elastic lepton scattering and finite-size effects in atomic levels, in both cases with electrons and muons. Results are available for three types of experiments, but not yet for muon-proton scattering.

Presently, a discrepancy as large as 5 standard deviations exists between the two most recent precision measurements: $r_{\text{CREMA}}^{\text{rms}} = 0.841 \pm 0.001$ fm from line-splitting measurements in laser spectroscopy of muonic hydrogen and $r_{\text{MAMI}}^{\text{rms}} = 0.879 \pm 0.008$ fm from elastic electron-proton scattering.

We propose to perform the experiment using high-energy muons of the CERN M2 beam line. Our 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 several experimental systematic effects and also theoretical (radiative) corrections are considerably smaller. The measurement will employ a time-projection chamber filled with pure hydrogen up to pressures of 20 bar, which serves at the same time as a target and as detector gas.

The accuracy to be reached by the proposed muon-proton scattering experiment is expected to be comparable to that obtained in electron-proton scattering at MAMI. Comparing the results on the proton charge radius from these two complementary measurements performed with very similar techniques will allow to probe interpretations of the proton radius mismatch to be caused by lepton flavour effects.

(2) Drell-Yan and J/ψ production experiments using the conventional M2 hadron beam

The main objective of these measurements is to make a major step forward in the determination of the nearly unknown pion and kaon parton distribution functions (PDFs). The planned measurements will provide benchmarks for testing recent predictions of non-perturbative QCD calculations performed on the lattice or in the framework of the Dyson-Schwinger equations. At medium and large values of Bjorken- x , a quantitative comparison between the pion and the kaon valence-quark distributions will become possible. At smaller values of Bjorken- x , improved knowledge on the onset of sea-quark and gluon distributions in the meson will help in explaining the differences between the gluon contents of pions, kaons and nucleons, and shed light on the mechanism that generates the hadron masses.

Furthermore, an analysis that simultaneously accounts for the differential cross section and for the degree of polarization of the charmonia resonances produced is expected to provide stringent experimental constraints on their production mechanisms. J/ψ production provides an alternative access to both quark and gluon distributions in the incoming meson.

In parallel to meson structure measurements, the availability of heavier nuclear targets in the setup will allow the study of cold nuclear effects such as nuclear PDFs and parton energy loss.

(3) Measurement of proton-induced antiproton production cross sections for dark matter searches

The purpose of this experiment is the measurement of the antiproton production cross sections in proton-proton and proton- ^4He scattering for projectile energies from several ten 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 of the predicted natural

flux of antiprotons in the galactic cosmic rays. This is of great importance as the indirect detection of dark matter (DM) is based on the search for products of DM annihilation or decay, which are expected to appear as distortions in the spectra of rare cosmic ray components like positrons, antiprotons, or even antideuterons. Our new data set will thus substantially improve the sensitivity of existing (and future) very accurate antiproton flux measurements to DM signals, which is presently limited by the poor knowledge of the antiproton production cross sections.

The existing M2 hadron beam line with its momentum range between 20 and 280 GeV/c is an ideal place to perform this measurement. The double-differential antiproton production cross section will be measured using the spectrometer in EHN2 equipped with liquid-hydrogen or liquid-helium targets and using the antiproton-identification capabilities of the RICH detector. Measuring for several beam momenta the cross section in 20 bins each for 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%.

Novel **instrumentation** using modern detector architecture will be constructed and installed in the experimental hall EHN2, where the upgraded multi-purpose two-stage magnetic spectrometer will serve as experimental backbone of the new facility. Upgrades will be designed to serve for as many individual experiments as possible and installed along the lifetime of the facility according to actual needs and availabilities.

A **tentative schedule of the measurements proposed in this document at the M2 beam line** is outlined in Tab. 1, according to the information given on <https://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm>.

The proposed measurements are attributed to beam times in the years 2021-24. In the present estimate, the total requested time will exceed the available beam time in Run 3, such that the Drell-Yan measurements may have to be continued after LS3.

Year	Activity	Duration	Beam
2021	Proton radius test measurement	20 days	μ
2022	Proton radius measurement	120 (+40) days	μ
	Antiproton production test measurement	10 days	p
2023	Antiproton production measurement	20(+10) days	p
	Proton radius measurement	140 (+10) days	μ
2024 2024+	Drell-Yan: pion PDFs and charmonium production mechanism	$\lesssim 2$ years	$p, K^+, \pi^+, \bar{p}, K^-, \pi^-$

Table 1: Tentative schedule for the proposed measurements at the M2 beam line for the time period between LS2 and LS3. The proton radius test measurement in 2021 has been agreed with the COMPASS collaboration. The numbers of days in parentheses are times for setting up and commissioning. For the proton radius measurement, the proposed running time is based on the conservative estimate discussed in the main text along with Eq. 13.

The **Outlook** of the proposal recapitulates the future plans of COMPASS++/AMBER in accordance with what was already sketched in our Letter of Intent [1]. Beyond phase-1, we propose an upgrade of the M2 beam line by installing a radio-frequency (RF) separation stage for kaon and antiproton beams of high energy and high intensity. Such an upgrade is presently under study by CERN EN-EA in the framework of the Physics-beyond-Colliders Initiative. Once realised, it would make the CERN SPS M2 beam line unique in the world for many years to come.

As an overview, brief descriptions are provided of all presently available ideas for further experiments to be performed at the M2 beam line, either with RF-separated hadrons or with muons:

Drell-Yan physics and hadron spectroscopy with high-intensity kaon and antiproton beams

- Valence-quark distributions in the kaon
- Separation of valence and sea-quark contributions in the kaon
- J/ψ production mechanism and gluon distribution in the kaon
- Measurement of the electric polarisability of the kaon via the Primakoff reaction
- High-precision strange-meson spectroscopy
- Study of the gluon distribution in the kaon via prompt-photon production
- Studies of the spin structure of the nucleon with antiproton beam and a transversely polarised target
- Heavy-quark meson spectroscopy with low-energy antiprotons
- Direct measurement of the lifetime of the neutral pion
- Vector-meson production off nuclei by pion and kaon beams

Hard exclusive reactions with muon beam and transversely polarised target

- Measurement of the GPD E in Deeply Virtual Compton Scattering
- Measurements of Deeply Virtual Meson Production