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A New QCD Facility at the M2 beam line of the CERN SPS

`Document for the 2020 update of the European Strategy for Particle Physics`

Abstract

This document summarises the physics interest, sensitivity reach and competitiveness of a future general-purpose fixed-target facility for Particle Physics research. Based upon the versatile M2 beam line of the CERN SPS, a great variety of measurements is proposed to address fundamental issues of Quantum Chromodynamics. In phase-1 of the project, operating with muons a complementary result on the average proton charge radius will be obtained and the elusive General Parton Distribution function E can be accessed, operating with pions the quark structure of the pion will be revealed, operating with antiprotons completely new results in the search of exotic XYZ states are expected, and operating with protons the antiproton production cross section will be measured as important input for future Dark Matter searches. Upgrading the M2 beam line in phase-2 of the project will provide unrivalled radio-frequency separated high-intensity and high-energy beams. Operating with kaons the virgin field of high-precision strange-meson spectroscopy becomes accessible, the Primakoff process will be used for a first measurement of the kaon polarisability, and the Drell-Yan process opens access to the nearly unknown quark-gluon structure of pion and kaon. Studying this process with an antiproton beam will allow for a complementary study of transverse-momentum-dependent parton distribution functions in the nucleon, and operating with pions new data on exclusive vector-meson production will emerge.

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In the context of the Physics-beyond-Colliders Initiative, the COMPASS collaboration enlarged by a steadily growing number of interested groups world-wide*, presently to be referred to as COMPASS++†/AMBER‡, proposes to establish the "New QCD Facility at the M2 beam line of the CERN SPS". The physics interest, sensitivity reach and competitiveness for this future general-purpose fixed-target facility are described in some detail in the Letter of Intent to the SPSC "New QCD Facility at the M2 beam line of the CERN SPS" (see [1] and references therein). This unrivalled installation will provide the site for a great variety of measurements to address fundamental issues of Quantum Chromodynamics (QCD), which are expected to lead to significant improvements in the understanding of QCD as our present theory of strong interactions. The proposed measurements cover a wide range in the squared four-momentum transfer Q^2, from lowest-Q^2 physics as the determination of the proton radius by elastic muon-proton scattering, over average-Q^2 reactions to study spectroscopy of mesons and baryons by using dedicated meson beams, to high-Q^2 studies of meson and baryon structure via the Drell-Yan process.

Over the last four decades, measurements at the world-unique M2 beam line of the CERN SPS received great attention by making a variety of measurements possible that contributed to a steady consolidation of QCD as our theory for the description of visible matter. As of today, this beam line bears great potential for future significant improvements of our understanding of hadronic matter. When operated with high-energy, the M2 beam line can be used to determine the average proton charge radius in a muon-proton elastic scattering experiment. Such a measurement constitutes a highly-welcomed complementary approach in this area of world-wide activity. When operated with pions, the M2 beam line can be used to shed new light to the light-meson structure using the Drell-Yan process, in particular by determining the widely unknown parton distribution functions (PDFs) of the pion. Operating with antiprotons, completely new results in the search for XYZ exotic states are expected. Operating with protons, the largely unknown antiproton production cross section can be measured, which constitutes important input for the upcoming activities in the Search for Dark Matter.

A completely new horizon in hadron physics would be opened by upgrading the M2 beam line to provide radio-frequency (RF) separated high-intensity and high-energy kaon and antiproton beams. Kaon beams open access to the virgin field of high-precision spectroscopy of the strange-meson spectrum and a first mea-

*The interested community list as of 18/12/2018 is provided separately in the addendum to this document

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surement of the kaon polarisability through the Primakoff process. Measurements of prompt photons allow first determinations of the parton distribution function of the gluon in the kaon. Studying the Drell-Yan process with incoming kaons opens access to the unknown kaon PDFs. Using an antiproton beam will provide a complementary approach to study the transverse-momentum-dependent (TMD) PDFs of the nucleon, which is presently under intense theoretical discussion using (mostly) the existing COMPASS data on semi-inclusive deep-inelastic scattering. Last but not least, novel data from hadron physics experiments will be required to confirm results on the structure of mesons and nucleons in terms of PDFs, which are expected to emerge from near-future computations on the QCD lattice.

In the last two decades, the COMPASS collaboration has successfully demonstrated how to achieve a variety of different physics objectives with the same basic setup by using various beam particle species that interact with highly specialised target arrangements. We propose to follow a similar approach also for the next decade(s). Again, the CERN SPS M2 beam line will have to be used in conjunction with a multi-purpose spectrometer in the experimental hall EHN2 as experimental backbone of the new facility. The existing large-acceptance two-stage magnetic spectrometer will be upgraded by state-of-the-art detector and data acquisition equipment. For every proposed experiment, individual target-area instrumentation using modern detector architecture will be constructed and installed in EHN2.

In the first stage, we propose to perform several unique first-generation experiments that are already possible using the existing M2 beam line with muons or unseparated hadrons. In the second stage, we propose to perform a number of unique second-generation experiments that rely on high-energy high-intensity radio-frequency (RF) separated hadron beams, which could be made possible by a major upgrade of the M2 beam line. Such an upgrade, which is presently under study by CERN EN-EA in the context of the Physics-beyond-Colliders Initiative, would make the CERN SPS M2 beam line absolutely unique in the world for many years to come.

The main features of the envisaged physics programme and the anticipated hardware upgrades are summarized in Table 1. Short summaries for each of the proposed experiments are given in the following.

Proton radius measurement using muon-proton elastic scattering
The aim of this experiment is an independent precision determination of the electric mean-square charge radius of the proton using elastic muon-proton scattering. Such a measurement appears timely, since in spite of many years of intense activ-

Table 1: Requirements for future programmes at the M2 beam line after 2021. Muon beams are in blue, conventional hadron beams in green, and RF-separated hadron beams in red.

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	~100	10^8	25-50	$K^\pm$, $\overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	~100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

ity the proton-radius puzzle remains unsolved up to now. Presently, a discrepancy as large as 5 standard deviations exists between the two most recent precision measurements: $r^{rms}_{CREMA} = 0.841 \pm 0.001$ from line-splitting measurements in laser spectroscopy of muonic hydrogen and $r^{rms}_{MAMI} = 0.879 \pm 0.008$ from elastic electron-proton scattering.

We propose to perform a one-year measurement using high-energy muons of the CERN M2 beam line, which will provide a new and completely independent result on the proton radius with a statistical accuracy of 0.01 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. It has been developed by the PNPI group for several other experiments and will be adapted in a common effort to the proton-radius measurement.

Hard exclusive reactions using a muon beam and a transversely polarised target

The main goal of this experiment is to extend our fundamental knowledge on the angular-momentum structure of the nucleon, which can be accomplished by measurements of Generalized Parton Distributions (GPDs). These functions describe the correlations between longitudinal momentum fractions and transverse spatial positions of partons in the nucleon, commonly known as "3-dimensional" picture of the nucleon. Experimental data on these GPDs are required over the largest possible domain of the Bjorken-x variable, as the evaluation of the total angular momentum J^f carried by quarks of flavour f through the Ji sum rule requires an integration over the sum of the GPDs H^f and E^f. While some experimental knowledge on the GPDs H^f exists already for u and d quarks, no experimental data exists on the "elusive" GPDs E^f.

Access to the GPDs E^f is possible by measuring certain cross section asymmetries in Deeply Virtual Compton Scattering, using a polarised charged-lepton beam and a transversely polarised target. A measurement in the so-far uncharted Bjorken-x domain between 0.005 and 0.05, where phenomenological models predict a particularly large sensitivity to E^f, can only be performed using the high-energy self-polarised muon beam of the CERN SPS M2 beam line. A 2-year measurement will yield an unprecedented statistical accuracy of 0.03 for the cross section asymmetry when using four bins per variable, with the systematic uncertainty expected to be smaller. A new 3-layer Silicon detector has to be constructed and installed inside of the existing polarised target, in order to accomplish identification of the target-recoil proton by the dE/dx method and to measure its momentum and trajectory. The proposed measurement is complementary in kinematics to a JLab experiment planned for 2022, which will use a transversely-polarised HD ice target.

Drell-Yan and charmonium production

The main objective of the proposed Drell-Yan and J/ψ production experiments 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 key benchmarks for testing the most recent predictions of fundamental, non-perturbative QCD calculations, such as lattice QCD and Dyson-Schwinger Equations formalism. At medium and large values of Bjorken-x, a quantitative comparison between the pion and the kaon valence distributions is of utmost importance. At smaller values of Bjorken-x, improved knowledge of the onset of the sea and gluon distributions in the meson will help in explaining the differences between the gluon contents of pions, kaons and nucleons, and hopefully provide clues to understand the mechanism that generates the hadron masses. Furthermore, a comparison between cross sections for positive and negative meson beams is expected to provide stringent experimental constraints on the J/ψ production mechanism, as well as an alternative way of accessing 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 partonic energy loss.

The M2 secondary hadron beam line at the CERN SPS provides an exclusive opportunity for such measurements. For both Drell-Yan and J/ψ production processes, the expected statistical accuracies reach a few 10^4 and nearly 10^6 events for the Drell-Yan and J/ψ production processes, respectively. The first part of this programme can be completed using the presently available positive (π^+, K^+, p) and negative (π^-, K^-, $\bar{p}$) hadron beams, in combination with an optimized experimental setup. A detailed study of the presently uncharted kaon structure, which is envisaged in a later stage of the programme, requires the existence of a high-intensity kaon beam that can only be produced using radio-frequency beam-separation cavities. The proposed studies need a high-performance beam particle identification. They would also greatly benefit from a novel and compact lepton absorber/detector immersed in a magnetic field. Such detector could largely improve the performances of the setup, while ensuring a large geometric acceptance and allowing for e^+/e^- detection in parallel with the muon pair.

Measurement of antiproton production cross sections for Dark Matter Search

The purpose of this experiment is the measurement of the antiproton production cross section on proton and ^4He targets for projectile energies from several ten to a few hundred GeV. In combination with similar measurements by LHCb in the TeV range, our data will provide a fundamental data set that will greatly improve the 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 or antiprotons. The new data set is expected to vastly improve the sensitivity of the very accurate AMS antiproton flux measurements to DM signals, which is presently spoiled by the poor knowledge of the antiproton production cross section.

The existing M2 beam line with its momentum range between 20−30 and 280 GeV/c is an ideal tool to perform this measurement. The double-differential antiproton production cross section will be measured in $p+p$ and $p+^4He$ collisions using the existing spectrometer in EHN2 equipped with liquid hydrogen and liquid helium targets. Measuring for several beam momenta the cross section in 20 bins each for antiproton momentum and pseudorapidity, a statistical uncertainty of 1% will be reached, with an anticipated point-to-point systematic uncertainty of less than 5%. The main challenges for these measurements are the precise determination of the efficiencies of the trigger systems and of the particle identification efficiency and purity.

Spectroscopy with low-energy antiprotons
The main objective of this experiment is a significant improvement in the understanding of the nature of the so-called X, Y, Z states, which remains so far unclear in spite of worldwide efforts in the last 15 years. The discovery of narrow resonance-like signals at e^+e^- colliders, which have masses above the open-charm threshold and decay to charmonium, had triggered a wealth of theoretical interpretations ranging from conventional excited charmonium to multi-quark states and hybrid mesons. Of particular interest is the production of states in association with a recoil particle, which opens the possibility of observing states with spin-exotic quantum numbers such as hybrids or glueballs. The annihilation of low-energy antiprotons with momenta below 20 GeV provides a unique tool to study these states.

An early experiment at the M2 beamline of the SPS using low-energy antiprotons and a liquid hydrogen target can reach luminosities of the order of $10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. It is expected to make important contributions to the production and spectroscopy of these long sought-after states even before the start of PANDA at FAIR, where such a measurement is in the planning state. Our measurements will at the same time provide vital input for PANDA, e.g. by measuring production cross sections for X, Y, Z states in $\overline{p}p$ reactions, for which theoretical estimates range from 0.1 nb to 10 nb. Owing to the low beam momentum, the experiment requires a dedicated target spectrometer including charged-particle tracking and electromagnetic calorimetry, in addition to the forward spectrometer in EHN2.

Spectroscopy of kaons
The goal of the kaon spectroscopy programme is to map out the complete spectrum of excited kaons with unprecedented precision using novel analysis methods. A more precise knowledge of the kaon spectrum will have a broad impact not only on low-energy QCD, but also on many processes in modern hadron and particle

physics where excited kaons appear, e.g. in the study of CP violation in heavy-meson decays, which are studied at LHCb and Belle II.

The high-intensity RF-separated kaon beam of the upgraded M2 beam line is an unrivalled place to accumulate a large data set for kaon spectroscopy as most of the planned or proposed measurements in the strange-meson sector elsewhere can either not compete with the measurement proposed here or are complementary to it. Taking data over one year with a beam energy of at least 50 GeV, about 20×10^6 events can be collected, which allows us to keep systematic effects under control. The main experimental challenges are high-precision vertex reconstruction, photon detection with electromagnetic calorimeters for reconstructing neutral hadrons, and final-state particle identification, i.e. kaons have to be distinguished from pions with high efficiency over a broad kinematic range.

Study of the gluon distribution in the kaon via prompt-photon production

The purpose of this experiment is the study of the gluon content of charged kaons. This is of fundamental importance for understanding the internal structure of light mesons and may also shed light onto the mechanism that generates their mass. In contrast to the well-known gluon distribution of the nucleon, our knowledge on the gluon distribution in light mesons is rather limited. It can be considerably improved by studying prompt-photon production in hadronic collisions using a high-energy meson beam.

The high-intensity RF-separated kaon beam of the upgraded M2 beam line is an unrivalled site to investigate the gluon content of the kaon. Using a beam of positive kaons with an energy of at least 100 GeV over 1-2 years, the gluon PDF in the charged kaon will be measured using the dominant hard gluon Compton scattering process in the range of x_g above 0.05 and for $Q^2 \sim p_T^2 > 7$ (GeV/c)^2. A separate data set will have to be taken with a beam of negative kaons in order to allow for a separation of the subdominant quark-antiquark annihilation process. For systematic studies and also to improve the knowledge on the gluon structure of the pion, it is foreseen to also collect data with incoming pions. This can be done either in parallel or separately in a preceding running period. The basic requirements for the proposed measurement are a sufficiently high transparency of the experimental setup for the produced photons, a wide kinematic range of photon detection by the system of electromagnetic calorimeters, efficient beam hadron identification, and a dedicated calorimeter-based trigger on high-p_T photons. We are not aware of plans to study the gluon structure of charged kaons at other laboratories.

Low-energy tests of QCD using Primakoff reactions
The main objective of this experiment is the first measurement of the kaon polarisability. Electric and magnetic polarisabilities, which describe the rigidity against deformation by an external electromagnetic field, constitute fundamental quantities of low-energy QCD. Apart from a quite vague experimental upper limit, presently only model predictions exist for the electric polarisability of the kaon, e.g. by chiral perturbation theory (χPT) or the quark-confinement model. It can be determined using the so-called Primakoff reaction, $K^- Z \rightarrow K^- \gamma Z$, using a high-energy high-intensity kaon beam. Such an experimental approach allows the parallel determination of another fundamental quantity of low-energy QCD, i.e. the lifetime of the neutral pion, which is related to the chiral-anomaly hypothesis.

The RF-separated beam of the upgraded M2 beam line is a unique place for these measurements. One year of data taking with a 100 GeV beam delivering 5×10^6 kaons per second will allow to determine the electric kaon polarisability with a statistical accuracy of $0.03 \times 10^{-4}\text{fm}^3$, with the total systematic uncertainty estimated to be smaller. This accuracy is even smaller than that of the prediction of χPT in the one-loop approximation and will clearly allow us to distinguish between models for the kaon polarisability. The neutral pion lifetime will be measured in parallel using those beam pions that remain in the RF-separated kaon beam. Here, the resulting statistical accuracy of about 1% will be smaller by more than a factor of two compared to the accuracy of the theoretical prediction and that of existing measurements. The proposed measurement requires advanced beam particle identification, excellent tracking capabilities at small angles and precise electromagnetic calorimeters. All these expectations are estimated to be met by the upgraded spectrometer that is planned to be available in EHN2 at the time of running. The proposed measurements have presently no competitors in the world.

Production of vector mesons and excited kaons off nuclei
The main goal of this measurement is to study pion-induced exclusive vector-meson production off various nuclei in order to determine the nuclear dependence of the cross section for longitudinally polarised vector mesons ($\rho^0(770)$, $K^{0*}(892)$). The absorption strength for a vector meson produced in a nuclear environment is predicted to strongly depend on its polarisation and also on the beam energy. However, neither existing data nor phenomenological models allow presently for a satisfactory description of nuclear transparency. Of particular interest is a clarification of a possible colour screening effect, as predicted by the colour transparency model. When using incoming kaons, the absorption of polarised K^* mesons can be studied, which is a topic of increasing interest.

About one year of running using pions and kaons produced by the M2 beam line is required to reach a sufficient accuracy of the cross section measurement. The beam energy should be higher than about 50 GeV to avoid effects related to meson decays in the nuclear medium and lower than about 100 GeV as the cross section for the charge-exchange reaction decreases with energy. In this energy range, the cross section is sufficiently large, so that parallel running with other physics programmes can be considered. The proposed measurements are kinematically fully complementary to the studies that are planned to be performed at JLab.

Tentative schedule of the CERN M2 beam line

A tentative schedule of the CERN M2 beam line is outlined in table 2 according to the information given on https://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm.

Table 2: Tentative schedule of the CERN M2 beam line for the time between LS2 and LS3.

Year	Activity	Duration	Beam
2019 2020	Long Shutdown 2	2 years	-
2021	COMPASS-II transversity with polarised deuteron target	1 year	muon
2022	proton radius	1 year	muon
2023 2024	Drell-Yan for π and K PDFs and charmonium production mechanism Antiproton cross section for Dark Matter Search	$\lesssim$ 2 years 2 month	p, K^+, π^+ $\bar{p}$, K^-, π^- p
2025	Long Shutdown 3 (for SPS)		

Outlook

The New QCD Facility at the M2 beam line of the CERN SPS is proposed as site for a great variety of measurements to achieve significant improvements in the understanding of QCD as our theory of strong interactions. This can be accomplished in a similar way as already successfully demonstrated by the COMPASS collaboration in the past two decades, by using for different experiments various beam particle species that interact with highly specialised target arrangements in conjunction with the upgraded multi-purpose spectrometer in EHN2. We expect a total budget in the range of 10-20 MCHF, although at the present stage of the project it is difficult to give solid cost estimates for new detectors and for the upgrade of the spectrometer. A major challenge will be the upgrade of the M2 beam line by radio-frequency beam separation for phase-2 of the project, in order to produce high-intensity kaon and antiproton beams for several unique measurements to study hadron structure and spectroscopy. Design and cost of this upgrade are being studied by the PBC Conventional Beam subgroup. The complete long-term physics programme would require about 11 to 12 years of running time. The earliest starting year of the programme is 2022, as a one-year extension of the COMPASS-II programme is scheduled to run in 2021. According to previous experience of the COMPASS collaboration, a collaboration of approximately 250 physicists is required to carry out the proposed long-term physics programme.

References

[1] *Letter of Intent (Draft 2.0): A New QCD Facility at the M2 beam line of the CERN SPS*, Letter of Intent working group, arXiv:1808.00848, 2018.