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M2 EXPERIMENTAL BEAMLINE OPTICS STUDIES FOR NEXT GENERATION MUON BEAM EXPERIMENTS AT CERN

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Abstract

In the context of the Physics Beyond Colliders Project, various new experiments have been proposed for the M2 beamline at the CERN North Area fixed target experimental facility. The experiments include MUonE, NA64μ and the successor to the COMPASS experiment named AMBER/NA66. The AMBER/NA66 collaboration proposes to build a QCD facility requiring conventional muon and hadron beams in a first phase of the experiment. MUonE aims to measure the hadronic contribution to the vacuum polarization in the context of the (g_μ-2) anomaly with a setup longer than 40 m and a 160 GeV/c high intensity, low divergence muon beam. NA64μ is a muon beam program for dark sector physics requiring a 100 – 160 GeV/c muon beam with a 15 m - 25 m long setup. All three experiments request similar beam times with compelling physics programs, which required launching extensive studies for integration, installation, beam optics and background estimations. The experiments will be presented along with details of the studies performed to check their feasibility and compatibility with an emphasis on the updated optics for these next generation muon beam experiments.

INTRODUCTION

Physics Beyond Colliders (PBC) is an exploratory study aiming to fully exploit the non-collider physics potential at CERN. The Conventional Beams Working Group (CBWG) was formed within the framework of PBC to study the large number of fixed target proposals for the North Area. The North Area comprises of two surface halls, EHN1 and EHN2, and an underground cavern, ECN3. This paper will focus on the muon beam experiments proposed for the EHN2 beamline [1], which delivers high intensity and high energy muon and hadron beams as well as low intensity electron beams for detector calibration towards EHN2.

THE EHN2 PROPOSALS

Currently the EHN2 hall houses the COMPASS experiment [2] which is going to complete its physics program with a measurement of d-transversity by 2022. For beyond 2021, new proposals were submitted in the context of PBC including:

- A future QCD facility (named AMBER/NA66) [3], which is the successor of COMPASS, with proposals for a proton radius measurement, Drell Yan and antiproton production cross-section amongst others. For these measurements, the collaboration aims to use the conventional muon and hadron beam with their current setup, including upgrades to their detector systems, for the first phase of their experiment.
- The MUonE experiment [4], which intends to measure the hadronic vacuum polarisation as the main contributor to the uncertainty of the $(g_\mu - 2)$ measurement. It requires a low-divergence 160 GeV/c muon beam with the maximal deliverable intensity of the M2 beamline of 5×10^7 μ/s. This limit is set by the radiation constraints. The longitudinal size of the experiment is expected to be 40 m - 60 m.
- The NA64μ experiment, [5], which proposes to search for a dark photon and a new massive gauge boson coupling predominantly to the 2nd and 3rd generation leptons in two experimental phases - Phase 1 and 2. Phase 1 requires a narrow 160 GeV/c muon beam with a divergence < 1.5 mrad and intensity in the order of 10^5–10^6 μ/s occupying a space of length 25 m, focusing to cover the $(g_\mu - 2)$ favoured parameter space for the new gauge boson. For Phase 2 the experiment will focus on the light dark matter candidate with a requested intensity of 10^7 μ/s.

THE CBWG STUDIES FOR THE EHN2 PROPOSALS

Compatibility and Integration

All the three experiments proposed for the M2 beamline have long setups in longitudinal size and strict requirements on the quality and parameters of the beam. The compatibility of NA64μ with AMBER in terms of installation and optics as well as the scenario of installing MUonE without dismantling the current COMPASS setup were the first issues that were studied by the CBWG. Two potential locations were identified for the installation of the new setups -

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1) Downstream of COMPASS; 2) Upstream of COMPASS. A 7 m long space is available downstream of COMPASS without significant modification to the COMPASS spectrometer. Due to the limited space the downstream option seemed a natural choice for test runs with short setups. Upstream of the current COMPASS setup, CEDAR detectors (Cerenkov Differential counter with achromatic ring focus) [6] are housed for their hadron beam program. For the future muon beam runs these detectors can be removed thus making the space available for the experimental setups. Without any modification to the beamline, 13 m space along the beam is available as shown in Fig. 1. In order to make the required space of 25 m – 40 m for the NA64μ and MUonE physics runs available, the beamline elements downstream of the CEDARs can be removed without any change to the COMPASS setup. However, removing the downstream elements makes it impossible to prepare the final focus of the beam for AMBER which is further downstream. Therefore, parallel running of two or more experiments was excluded. Detailed studies of the compatibility and integration are presented in Chapter 4 of Ref. [7]. In addition, optics studies were performed for the proposed experiments, which are presented below.

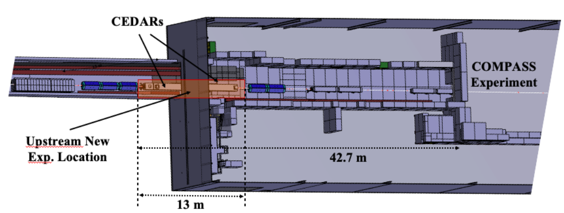

Figure 1: Upstream location of the EHN2 hall in the CERN North Area identified for the new experimental test setups of NA64μ and MUonE marked in red, the available 42.7 m space after removal of the beamline elements for the final installation of MUonE and the location of the current COMPASS experiment which will be used for AMBER/NA66.

Optics Options for the EHN2 Proposals

Currently the optics is optimised for COMPASS downstream so the beam properties at the upstream location do not fit the requirements of the proposed experiments. Therefore, studies had to be launched to finalise the optics options for the proposed runs at this location.

The M2 line is a secondary particle beamline, 1130 m long, with a front-end consisting of six high-gradient quadrupoles for high acceptance of the secondary hadrons, followed by a momentum selection in the horizontal plane with horizontal dipoles and collimators having a 10 % momentum band. The beam is then matched to a 600 m FODO section to allow the pions and kaons to either decay, or be absorbed by nine 1.1 m long Beryllium absorbers, placed inside a series of 3 vertical bends. This results in a muon beam with a hadron contamination of about 10^{-6} – 10^{-5}. The absorbers are followed by a 400 m long muon section, comprising of magnetised collimators ("scrapers") and Magnetised Iron blocks ("MIBs") with a toroidal magnetic field, which select the final muon momentum down to a momentum band of about 3.6 % and clean the muon beam halo. The scattering in the absorbers located inside the vertical bends results in a correlation between y, y' and $\frac{\Delta p}{p}$. In order to study the optics options for the upstream location, this effect was calculated at the output of the hadron section using HALO [8], a software to model the transport of muons through a beamline. The obtained correlation plots with $\frac{dy}{d(\Delta p/p)} = -0.103$ m and $\frac{dy'}{d(\Delta p/p)} = -0.018$ are shown in Figs. 2 and 3. These correlations were added as the transport matrix elements, R36 and R46, by means of an arbitrary matrix in the MADX file [9], assuming a focused beam at the start of the muon section. With the addition of this effect, two optics settings were studied for the upstream location: (1) a low divergence beam; (2) a beam with a small spot size and a divergence < 1.5 mrad. The two options are presented in Figs. 4 and 5 that show the last section of the beamline with the proposed upstream location for the experiment setups. The beam distributions for the two options are shown in Fig. 6. As seen for the low divergence beam option, a beam size of $\sigma_x = 13$ mm and $\sigma_y = 22$ mm with a divergence of $\sigma_{x',y'} = 0.2$ mrad and momentum spread of 3.7 % for a 160 GeV/c muon beam is obtained from the Gaussian fit of the distributions. This fits well with the requirements of MUonE. For the option of a more focused beam a beam size of $\sigma_x = 10$ mm and $\sigma_y = 12$ mm with a divergence of $\sigma_{x'} = 0.5$ mrad and $\sigma_{y'} = 1.3$ mrad is obtained from the Gaussian fit of the distribution. The momentum spread of 3.7 % remains the same. This fits also well with the requirement of NA64μ.

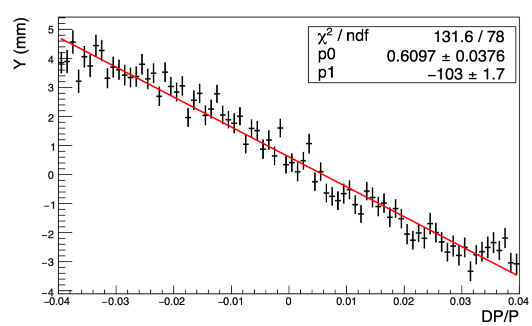

Figure 2: Correlation between y and $\frac{\Delta p}{p}$ as calculated from HALO at the end of the hadron section with the obtained value of $\frac{dy}{d(\Delta p/p)} = -0.103$ m.

2021 Test Runs

The proposed experiments requested test beam times of 2–3 weeks for 2021 with short setups to test detector performance, background levels, beam conditions and to demonstrate the physics feasibility of their searches. NA64μ aims to install a 13 m long setup with one spectrometer magnet. MUonE aims to setup two target stations, each consisting of a Beryllium target followed by 3 layers of silicon detectors, followed by an electromagnetic calorimeter with a total length

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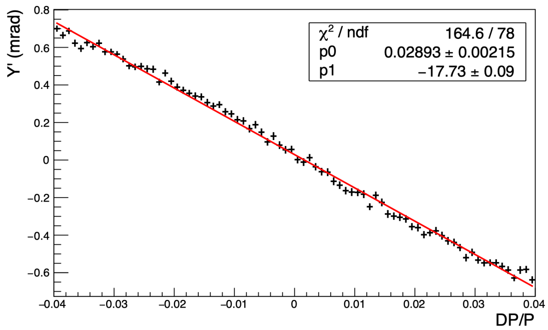

Figure 3: Correlation between y' and $\frac{\Delta p}{p}$ as calculated from HALO at the end of the hadron section with the obtained value of $\frac{dy'}{d(\Delta p/p)} = -0.018$.

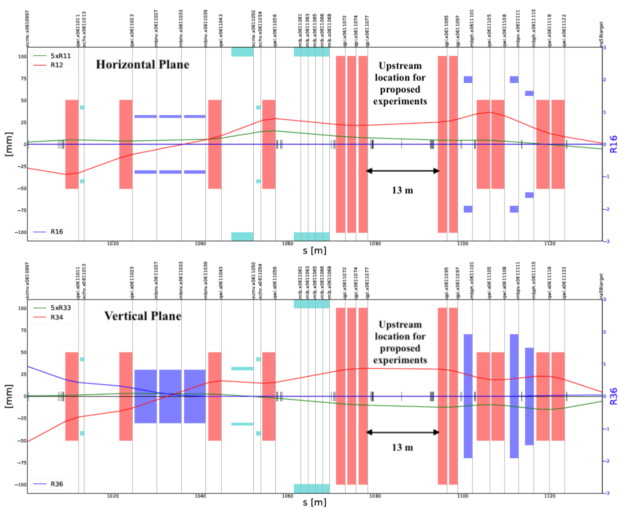

Figure 4: Updated optics option for a parallel beam as required by MUonE at the proposed upstream location (the downstream part is not matched). The red, blue and green rays correspond to the transport matrix elements as given by the legends. Red Box – Quadrupoles ; Blue Box – Bends ; Cyan – Collimators.

of 7 m. AMBER aims to test their Time Projection Chamber (TPC) setup for the proton radius run with a 2.2 m long TPC and tracking stations, with a total length of 9 m. Due to unforeseen delays because of COVID the test beam schedule for the three experiments is currently being re-evaluated. Preparations for the test runs are being undertaken by the EHN2 Working Group (EHN2-WG) under supervision of BE-EA. Installation of all three setups is compatible with the available upstream location without any change to the beamline. A rail system is also planned to be installed for easy removal and installation of the detector components, spectrometer magnet and the CEDARs which helps to reduce the change-over time to and from the different configurations. The small beam size optics option for the upstream location fits well with the requirements of NA64μ and the AMBER test run. The parallel beam option fits well with the requirement of MUonE. The time and cost estimates for the required infrastructure changes in the zone, e.g. installation

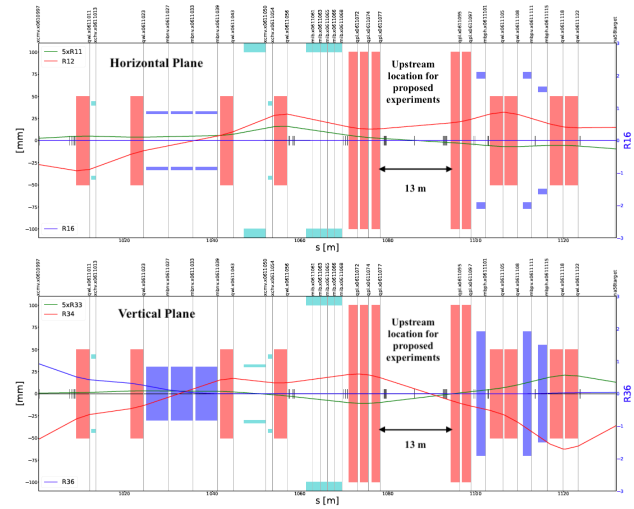

Figure 5: Updated optics option for a small beam with divergence <1.5 mrad as required by NA64μ at the proposed upstream location (the downstream part is not matched). The red, blue and green rays correspond to the transport matrix elements as given by the legends. Red Box – Quadrupoles ; Blue Box – Bends ; Cyan – Collimators.

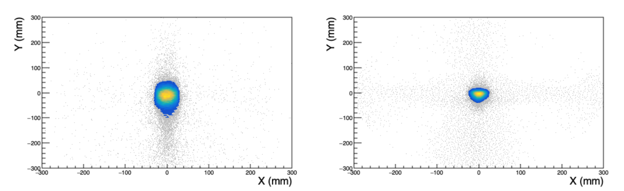

Figure 6: Beam size for a low divergence beam optics – σ_x = 13 mm, σ_y = 22 mm (left panel) and that for a focused beam optics – σ_x = 10 mm, σ_y = 12 mm (right panel) from the Gaussian fit of the distributions.

of a gas line, power and ethernet ports, installation of the magnet etc., have been calculated and documented to initiate the changes. The works are scheduled to be completed by the end of June. The test runs are crucial for the approval of the experiments and to determine the next steps for the final installation that will include potential optimisation of the beam parameters and integration of the final setups in the beamline.

CONCLUSIONS

The EHN2 WG of the CBWG has completed various optics studies for the new proposals at the M2 line [10] and finalised the different options given the varied requirements of the experiments. It has also studied the feasibility and implications of the beam and infrastructure modifications associated with the proposed experiments and finalised the test installations in 2021. All studies are included and discussed in detail in the PBC report [7]. The updated optics options are presented in this paper. Further studies will continue as more detailed requests become available for the future runs.

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