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# PHYSICS BEYOND COLLIDERS: THE CONVENTIONAL BEAMS WORKING GROUP

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*Abstract*

The Physics Beyond Colliders initiative aims to exploit the full scientific potential of the CERN accelerator complex and its scientific infrastructure for particle physics studies, complementary to current and future collider experiments [1]. Several experiments have been proposed to fully utilize and further advance the beam options for the existing fixed target experiments present in the North and East Experimental Areas of the CERN SPS and PS accelerators. We report on progress with the RF-separated beam option for the AMBER experiment, following a recent workshop on this topic. In addition we cover the status of studies for ion beams for the NA60+ experiment, as well as of those for high intensity beams for Kaon physics and feebly interacting particle searches. With first beams available in 2021 after a CERN-wide long shutdown, several muon beam options were already tested for the NA64mu, MUonE and AMBER experiments.

## INTRODUCTION

The Physics Beyond Colliders (PBC) initiative is subdivided into several working groups, each with its independent, yet complementary goal. The Conventional Beams Working Group (CBWG) is a working group in the accelerators and technology sector, with the task of focusing on studies for fixed-target experiments using beams from the Super Proton Synchrotron (SPS) and the Proton Synchrotron (PS). The experiments served by the SPS are located in the two experimental halls EHN1 and EHN2, as well as in the experimental cavern ECN3 in the North Area (NA).

## EHN1

EHN1 hosts currently both the NA61/SHINE and NA64e experiments.

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### *NA60+*

The NA60+ experiment plans to receive a beam of $10^7$ lead ions per 10 s long spill at momenta of 30 – 158 A GeV/c. Operating for several weeks a year, the collaboration envisages to study the production of muon pairs and open charm final states. A new proposal of placing the detector in the H8 beam has been examined [2]. A more compact detector, additional shielding , installation of beam instrumentation, a modification of the zone access, and new beam optics have been developed by BE-EA, to be tested in 2022. A Letter of Intent by the collaboration is in preparation and expected soon.

### *NA61++*

The NA61/SHINE collaboration is focusing on studies on the onset of deconfinement and on various neutrino-relevant cross section measurements. Its intended successor, NA61++, aims at continuing measurements with ion and hadron beams as before, but with 10 times higher beam intensity. Radiation measurements and simulations have been performed and it has been shown that for higher intensities, the shielding around the new PSD calorimeter has to be significantly reinforced. Furthermore, NA61++ intends several detector upgrades, which have been partly completed during the CERN Long Stop 2 and the annual shutdowns. For the NA61++ neutrino program, a new, low-energy branch is being designed. This new branch would extend the capabilities of the current infrastructure enabling the study of particles in the 1 – 13 GeV/c momentum range. Such a beamline will enable having measurements requested by several neutrino experiments, such as T2K, Hyper-K, DUNE, and others [3].

### *NA64e*

The NA64 experiment is searching for sub-GeV dark matter candidates with the help of secondary electron beams in the H4 beam line [4], relying on synchrotron radiation tagging and tracking, as well as calorimetry to eliminate

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contamination by other particles in the beam line, usually present at the percent level. The intensity has been ramped up over the years, up to $2 \times 10^7$ electrons per spill. A new experimental area has been designed to host a semi-permanent experimental setup, which is now ready. The experiment took already first data at the new location and now is aiming for a total of $10^{12}$ electrons on target.

## EHN2

The EHN2 hall houses the COMPASS experiment [5], completing its physics program with a measurement of the d-transversity distribution by 2022. Several new ideas were submitted in the context of PBC [6], proposing to exploit the available high intensity muon and hadron beams.

### *NA64μ*

The NA64μ experiment [7] proposes to search for a dark photon and a new massive gauge boson coupling. The first phase requires a narrow 160 GeV/c muon beam with a divergence of less than 1.5 mrad with an intensity in the order of $10^5$ to $10^6$ μ/s to cover the $(g_\mu - 2)$ favoured parameter space for the new gauge boson with $5 \times 10^{10}$ μ on target. For Phase 2, the experiment will concentrate on light dark matter candidates with a requested intensity of $10^7$ μ/s. The experiment will occupy a space of 30 m length. Various compatibility and integration studies have been performed along-with optics studies for these proposals [8]. In 2021, NA64μ had their first pilot run in the M2 beamline during which a new set of muon beam optics was validated. A space 13 m upstream of the COMPASS experiment was upgraded with user infrastructure including gas, power, and DAQ space. A first test in 2021 was followed by a longer run in the beginning of 2022, collecting $4 \times 10^{10}$ μ on target.

### *MUonE*

The MUonE experiment [9] 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 $5 \times 10^7$ μ/s. The longitudinal size of the final experiment is expected to be 40 m, which requires substantial modifications to the end of M2. In 2021, MUonE had a parasitic run with one tracking station while NA64μ was running as the main user. In 2022, they plan to have a run towards the end of the year with three tracking station. The parallel beam optics required for MUonE have been validated during the 2021 beam commissioning. For the physics run with full setup, all downstream magnets will be moved out, for which a rail system is being designed to limit the changeover times.

### *AMBER: Phase I*

The AMBER/NA66 collaboration [10] proposes measurements of the proton charge radius, Drell-Yan, and antiproton production cross-sections amongst others. For these measurements, the available conventional muon and hadron beams with the current experimental setup of COMPASS would be used, complemented with upgrades to a set of detector systems. In 2021, AMBER tested their TPC for the Proton Radius Measurement with a 160 GeV/c muon beam. In 2022, 60 to 250 GeV/c hadron beams, required for their anti-proton cross-section measurement, have been tuned and validated.

### *AMBER: Phase II - RF-Separated Beams*

The AMBER collaboration is interested in high-intensity and high-purity Kaon beams of both charges, which is limited by the particle production spectrum from protons on target and by radiation protection limitations on the full beam. To improve the purity of Kaons in the M2 beamline, AMBER aims to use an RF-separated beam, i.e. placing two transversely deflecting RF cavities at a distance $L_{RF}$, and tuning the relative phases of the two RF waves, such that the species of interest can receive a net transverse kick, while the rest is dumped.

A first set of beam optics versions with different beam parameters have been designed [11] with special attention to the beam emittance at the cavities. A focused beam with large divergence is compared to various optics with more parallel beams. The resulting intensities and purities achieved for these different optics versions are shown in Fig. 1.

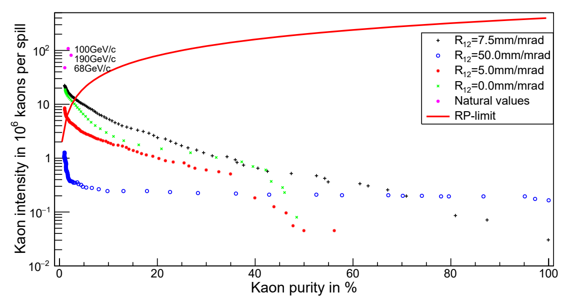


Figure 1: Intensities and purities for the RF separation in the M2 line for different beam configurations at the cavity locations. The solid red curve shows the Radiation Protection limit [11].

The Atherton parameterization [12] predicts the maximum intensity of Kaons in the conventional hadron beam at the experiment to 2.4 % of the total beam intensity, only considering losses due to decays. Given the radiation protection limit on the overall intensity, this results to about $10^7$ per spill. Figure 1 shows different beam configurations at the positions of the two sets of cavities. The advantage of the increased beam parallelism can be seen from the $R_{12} = 50\,\mathrm{mm\,mrad}^{-1}$ curve as $R_{12}$ is roughly proportional to the beam size at the cavities. Even though losses due to the small cavity iris need to be accepted, in this case the intensity remains constant at the highest purities. Therefore, the divergence needs to be limited as much as possible at the cavities. The $R_{12} = 7.5\,\mathrm{mm\,mrad}^{-1}$ optics (black crosses) has been chosen as the compromise between the beam parallelism and the transmission through the cavity aperture.

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Preliminary results for the beam optics study are promising. Further optimization of the beam optics is ongoing, including investigation of sensitivities to imperfections that influence the achievable performance. In a next step, cavities with circular polarization will be also studied.

## ECN3

The underground cavern ECN3 currently houses currently the NA62 experiment. Several proposals involving future upgrades of NA62 and complementary experiments are envisaged. The Kaon-focused experiments have been recently merged under the acronym HIKE, short for High Intensity Kaon Experiments. This includes an NA62-like setup with charged kaons with at least four times the current intensity, data taking in a dedicated beam dump mode (NA62-BD), and the neutral channel equivalent to NA62, KLEVER. Recently, also an off-axis beam dump experiment, SHADOWS, was added to the ideas for high intensity experiments at ECN3.

### *NA62 High Intensity*

The NA62 experiment is expected to reach its goal of a 10 % measurement of the branching ratio of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ until the next Long Stop at CERN. So far, the measurements are compatible with standard model predictions, for which recently a better precision at the level of 5% has been reached. Thus, data taking at higher intensities is envisaged to match the theory error, including an extensive upgrade of the NA62 apparatus. In order to withstand higher intensities in the order of a factor 4 to 6 higher than currently being delivered, beam intercepting devices have to be upgraded, such as the T10 production target and the proton dump (TAX) . Studies for this are complemented by radiation protection considerations as well as a bypass beam option around the T4 target, after which the proton transfer line towards T10 starts.

### *KLEVER*

KLEVER aims to measure the branching ratio of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ to a precision of around 20%, supplementing the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ measurement currently being performed by NA62. This will allow for a set of strong constraints on new physics models, potentially further illuminating the anomalies being observed in the flavour sector. An extensive design study for the beamline and detector has been made in terms of signal yield, background rejection and radiation protection concerns. It was found that a prohibitive background from $\Lambda^0$ decays necessitates displacement of the target upstream and lengthening of the cavern downstream, subject to further study.

### *NA62-BD*

Employing the possibility to move in the proton beam dump of the NA62 transfer line, NA62 is also able to run in beam dump mode. Such an experiment uses the available NA62 detectors to search for dark matter candidates. Since test runs and simulations showed that the dominant background is caused by muons, current studies evaluate the optimal magnetic field configuration to maximally reduce this background at the relevant veto-detectors [13, 14]. In a recent beam test in the end of 2021, the newly developed concept for mitigation of muons showed a reduction by a factor 200 with respect to the original configuration. There are further ideas for background reduction using all available magnets in the K12 beam line that are currently being followed-up.

### *SHADOWS*

Complementary to NA62-BD, an off-axis experiment located besides the K12 beam line is currently under consideration, tentatively named SHADOWS [15,16]. The experiment would run fully parasitically to NA62-BD and focus on the search for feebly interacting particles shortly after the beam dump, thereby potentially enhancing the physics reach of the setup. Strong synergies are expected between the two beam dump experiments, which share the main backgrounds of muons and neutrinos. First simulations suggest that the SHADOWS experiment will benefit from a magnetic muon sweeping system as shown in Fig. 2 [13]. Possible design options for such a system are studied as well as its impact on NA62-BD and potentially also on NA62 data taking.

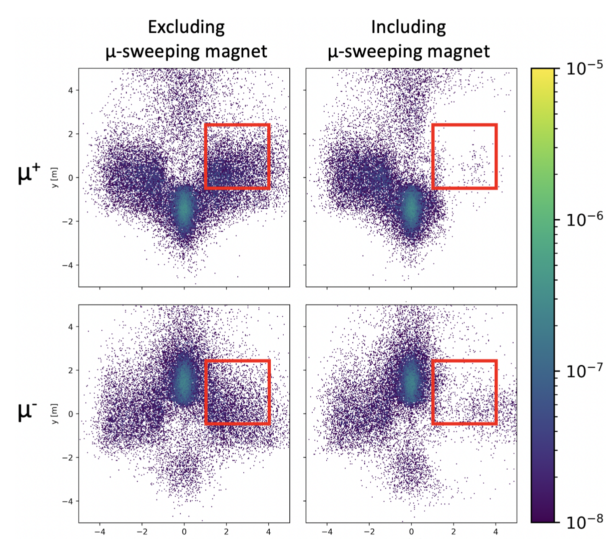


Figure 2: Simulated muon-induced background at the SHADOWS detector (marked in red) excluding (left) and including (right) a dedicated muon sweeping magnet.

## CONCLUSION

We have highlighted the large diversity of new experiments that are currently being studied by the Conventional Beams Working Group of Physics Beyond Colliders. Many of these experiments have already been approved while some others are nearing the proposal stage. The experiments range from upgrades of currently existing ones to brand new proposals complimentary to LHC and HL-LHC with relatively minor modifications to the existing infrastructure.

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## REFERENCES


[1] R. Alemany *et al.*, "Summary Report of Physics Beyond Colliders at CERN", *Journal of Physics G: Nuclear and Particle Physics*, vol. 47, no. 1, p. 010501, 2019. doi:10.1088/1361-6471/ab4cd2

[2] A. Gerbershagen, C. Ahdida, J. Bernhard, V. Clerc, Vincent, S. Girod, E. Scomparin, G. Usai, and H. Vincke, "Integration Studies and Beam Physics for the Project of the NA60+ Heavy-Ion Experiment at CERN", Rep. CERN-PBC-Notes-2022-005, 2022. https://cds.cern.ch/record/2806698

[3] Y. Nagai, "Addendum to the NA61/SHINE Proposal: A Low-Energy Beamline at the SPS H2", Rep. CERN-SPSC-2021-028, SPSC-P-330-ADD-12, 2021. https://cds.cern.ch/record/2783037

[4] D. Banerjee *et al.*, "Dark Matter Search in Missing Energy Events with NA64", *Phys. Rev. Lett.*, vol. 123, no. 12, p. 121801, 2019. doi:10.1103/PhysRevLett.123.121801

[5] J. Friedrich, O. Denisov, and A. Vorobyev, "Addendum to the COMPASS-II Proposal", Rep. CERN-SPSC-2017-034, SPSC-P-340-ADD-1, 2018. https://cds.cern.ch/record/2286954

[6] J. Bernhard *et al.*, "Studies for New Experiments at the CERN M2 Beamline within "Physics Beyond Colliders": AMBER/COMPASS++, NA64μ, MuonE", *AIP Conference Proceedings*, vol. 2249, p. 030035, 2020. doi:10.1063/5.0008957

[7] S. Gninenko *et al.*, "Addendum to the NA64 Proposal: Search for the A'→invisible and X→e+e- decays in 2021", Rep. CERN-SPSC-2018-004, SPSC-P-348-ADD-2, 2018. https://cds.cern.ch/record/2300189

[8] D. Banerjee *et al.*, "M2 Experimental Beamline Optics Studies for Next Generation Muon Beam Experiments at CERN", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 4041–4044. doi:10.18429/JACoW-IPAC2021-THPAB143

[9] G. Abbiendi *et al.*, "Letter of Intent: The MUonE Project", Rep. CERN-SPSC-2019-026,SPSC-I-252, 2019. https://cds.cern.ch/record/2677471

[10] O. Denisov *et al.*, "Letter of Intent: A New QCD facility at the M2 beamline of the CERN SPS", Rep. CERN-SPSC-2019-003, SPSC-I-250, 2019. http://cds.cern.ch/record/2653603

[11] A. Gerbershagen, V. Andrieux, J. Bernhard, M. Brugger, O. Denisov, J. Friedrich, L. Gatignon, F. Gerigk, A. Guskov, B. Ketzer, F. Metzger, W.-D. Nowak, C. Quintans, and S. Schuh-Erhard, "RF-Separated Beam Project for the M2 Beam Line at CERN", Rep. CERN-PBC-Notes-2022-004, 2022. https://cds.cern.ch/record/2806692

[12] H. W. Atherton, C. Bovet, N. Doble, G. von Holtey, L. Piemontese, A. Placci, M. Placidi, D. E. Plane, M. Reinharz, and E. Rossa, "Precise Measurements of Particle Production by 400 GeV/c Protons on Beryllium Targets", Rep. CERN-YELLOW-80-07, p. 25, 1980. doi:10.5170/CERN-1980-007

[13] F. Stummer, A. Gerbershagen, J. Schieck, "Studies and Optimization for Future Beam Dump Experiments in the K12 and P42 Beams at CERN", diploma thesis, Technische Universität Wien, 2021. doi:10.34726/hss.2021.83255

[14] L. Gatignon *et al.*, "Report from the Conventional Beams Working Group to the Physics Beyond Collider Study and to the European Strategy for Particle Physics): Expression of Interest", Rep. CERN-PBC-REPORT-2018-002, 2018. https://cds.cern.ch/record/2650989

[15] W. Baldini *et al.*, "SHADOWS (Search for Hidden And Dark Objects With the SPS)", 2021. doi:10.48550/arXiv.2110.08025

[16] W. Baldini *et al.*, "SHADOWS (Search for Hidden And Dark Objects With the SPS): Expression of Interest", Rep. CERN-SPSC-2022-006, SPSC-EOI-022, 2022. https://cds.cern.ch/record/2799412