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PBC CONVENTIONAL BEAMS

Executive summary

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Abstract :

This document summarises the main conclusions of the Conventional Beams Working group, which has analysed the beam related and technical requirements and requests in the proposals to the Physics Beyond Colliders study for the North Area at the CERN SPS. We present results from studies on feasibility, requirements, compatibility between proposals and, where possible, the order of magnitude of the costs. The physics interest, sensitivity reach and competitiveness world wide of the proposals is discussed in the BSM and QCD physics working groups, which work in synergy with the Conventional Beams group.

1. Introduction

The Conventional Beams Working Group (CBWG) is part of the Accelerators and Facilities Committee within the framework of the Physics Beyond Colliders study. This study shall provide input for the future of CERN's scientific diversity programme, which today consists of several facilities and experiments at the Booster, PS and SPS, spanning the period from now till 2040. The Conventional Beams study is complementary to and works in synergy with the Beyond Standard Model (BSM) and Quantum Chromodynamics (QCD) physics working groups in the Physics Beyond Colliders study, with emphasis on proposals in the North Area at the SPS.

During the PBC kick-off workshop in September 2016, a large number of fixed target proposals was presented. It was deemed important to perform pre-proposal studies in order to allow the working groups to make progress with their evaluation. The list of proposals for the CBWG is shown in Table 1.

Experiment	Comments
NA61++	Run NA61/SHINE at higher intensity and with better protection
NA64++ (e, h)	Increase electron flux and optimise hadron beams in the H4 line
NA64++ (μ)	Study the possibility to install and run a NA64-like experiment with muons in EHN2
COMPASS++	Study new requests from COMPASS, including a RF separated beam
MuonE	Study the possibility to implement the MuonE experiment in the M2 beam for operation with μ and e beams
NA62++	Optimise conditions for NA62 in beam dump mode for Hidden Sector searches
KLEVER	Study a new beam for a $K_L \rightarrow \pi^0\nu\nu$ experiment at very high proton flux in ECN3
DIRAC++	Study implementation options for a DIRAC follow-up experiment at the SPS
NA60++	Study implementation options for a NA60 follow-up experiment with heavy ion beams

Table 1: *The list of proposals to be followed by the Conventional Beams Working Group*

The North Area comprises two surface halls, EHN1 and EHN2, and an underground cavern, ECN3. EHN1 is the biggest surface hall at CERN (~330 by 50 m^2) and houses the H2, H4, H6 and H8 beam lines. EHN2 is served by the M2 beam line for muon, hadron and electron beams and houses at present the COMPASS experiment. In ECN3 the NA62 experiment for rare kaon decay measurements is served by the K12 line. The CBWG has grouped the proposals per experimental hall.

2. EHN1 proposals

2.1 Introduction

In EHN1 the NA61/SHINE experiment, installed on the H2 beam line, is for the moment driving the SPS heavy ion program. So far it has explored the phase transition to Quark Gluon Plasma. It proposes to continue after LS2 with open charm measurements as well as studies for cosmic ray physics and particle production measurements with neutrino beam replica targets. The program would profit from a significant increase (x10) of the beam intensity in the H2 beam line.

NA64 proposes to continue its search for dark photons (A') and dark matter with pure electron beam and also with various types of hadron beams in the H4 line. In order to minimize beam time, they will try increasing the electron beam intensity as much as possible, while maintaining a similar beam purity and quality. To reduce setting-up time, they have requested a dedicated beam zone for a quasi-permanent installation in the H4 line.

2.2 NA61++

NA61++ wants to continue measurements with ion and hadron beams as before, but for which 10 times higher beam intensity is necessary. Radiation measurements and simulations have been performed and it has been shown that for higher intensity the shielding around the new PSD calorimeter has to be significantly reinforced. Furthermore, NA61++ foresees several upgrades of their detectors, which imply some local modifications to the infrastructure. The SPSC committee has recommended allocating beam time to NA61/SHINE in 2021, for which part of these modifications are necessary, but the final decision is subject to NA61/SHINE funding.

In order to protect the vertex detector and TPCs from high-intensity bursts, the collaboration requests a new fast (within 1 spill) interlock that will cut the beam rapidly in case of significant intensity or position changes of the beam, to protect the new vertex detector. This system is under study and an economical solution seems feasible.

At a later stage a low-energy beam serving the NA61++ detector would be helpful. A preliminary design exists, but would imply the construction of a number of new magnets and power converters, as well as the associated cabling and cooling. A detailed cost estimate remains to be prepared, along with the NA61++ physics proposal.

2.3 NA64++

NA64 has been running successfully with secondary electron beams in the H4 beam line, relying on synchrotron radiation tagging and tracking, as well as calorimetry to eliminate 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 10^7 electrons per spill. The main limitation is the setting up time at the beginning of each run, due to the non-availability of a permanent location. It has been decided to prepare a new user zone PPE144, just downstream of the present NA64 location. If approved by the SPSC for 2021, NA64++ will become the first user of this new beam zone and leave the critical detectors in place and connected, eventually on rails for in/out movements.

3. EHN2 proposals

3.1 Introduction

In the EHN2 hall COMPASS proposes to continue on the shorter term a program with the existing M2 beam options, but with different physics goals from the past, such as a measurement of the proton radius R_p. For a later stage they propose using a new RF separated anti-proton and kaon beam. The feasibility and design of such a beam line must be investigated.

The NA64++ collaboration proposes to use also the M2 muon beam for dark matter searches. The required muon beam properties are within reach of the present M2 muon beam line. However, the compatibility with COMPASS++ needs detailed studies.

MuonE aims at a measurement on μ-e elastic scattering, which would provide an essential input to precision measurements of g-2 of the muon. The muon beam requirements are again within reach of the existing M2 beam line. Scenarios for installing MuonE without dismantling COMPASS have been investigated.

3.2 COMPASS

Members of the COMPASS collaboration, reinforced by some additional groups, are finalising an Expression of Interest for a QCD facility (COMPASS++), which includes a large number of possible measurements with many different beam conditions. The initial ones are standard operational conditions of the existing beam line, either hadron or muon beams. The only beam line upgrade, which is under way, is an improvement of the efficiency and rate capability of the CEDAR Cerenkov counters. A run with muon beams has been approved for 2021 by the Research Board.

One of the future options is a low-energy negative hadron beam, 12 to 20 GeV/c. As at those energies many of the pions and kaons decay over the length of the beam line (more than 1.1 km) at those energies, such a beam is quite enriched in antiproton content, hence allowing a higher antiproton rate without exceeding radiation limits due to an excessive total beam flux. However, at these low momenta, the vacuum needs serious improvement. At present the 9 magnetic collimators, each more than 5 m long, are under air and the total length of air is between 70 and 80 m.

In case of a decision to abandon the muon beam option, the magnetic collimators could be replaced by standard vacuum tubes, at modest cost. This will also greatly improve the rate of tertiary electron beams.

For the long term, COMPASS members propose to design and build an RF-separated antiproton and kaon beam at high rate and possibly at a momentum of 100 GeV/c or higher. A study has been launched to investigate the feasibility and possible performance of such a beam line. In particular for kaons, the intensity requirement is challenging as most of the kaons decay before they reach the experiment. This is a complex and long study, which will require more time to come to a plausible conclusion. A first version of a beam optics, fitting in the existing tunnel, has been developed and will serve as basis for discussions with the CERN RF group.

3.3 NA64-mu

The NA64 collaboration has started a measurement of the invisible decay mode of the dark photon A’ with an electron beam in the H4 beam line. NA64-mu proposes a similar measurement, based on a similar concept, in the M2 muon beam. The existing M2 muon beam satisfies the requirements in terms of beam momentum and flux. The contamination by other particles has been measured to be at the required level, i.e. below 10^{-6}.

However, the proposed experiment is at least 20 m long and does not fit inside the existing experimental zone without removing at least a large part of the COMPASS setup. A possible solution has been found upstream of COMPASS, at the end of the beam tunnel. By moving two quadrupoles and adding two dipoles, a 20 m long free region can be created in zone PPE211, which can house the experiment. Detailed optics calculations and simulations show that the required beam parameters can be provided, profiting from improved momentum resolution from the Beam Momentum Station. However, because of different rate requirements and lack of focusing in between NA64-mu and COMPASS++ simultaneous operation is excluded. The order of magnitude of the beam modification is about 100 kCHF, dominated by cabling cost. The change-over for the beam line is estimated to take about two weeks. If ever required, additional infrastructure can be designed and built to speed up the change between experiments, but at additional cost.

On the longer term a higher rate version of the experiment could be housed in and around the SM2 spectrometer magnet in the COMPASS++ experiment. Such an experiment could and must profit from synergy with the COMPASS++ detector.

3.4 MuonE

The MuonE collaboration proposes a measurement of μ-e elastic scattering with a detector of about 40 metres length, using the M2 muon beam at standard operating conditions. The constraints for the beam parameters are similar, though not identical to the NA64-mu requirements, although the length of the experiment is slightly longer. The proposal is to locate the experiment at the same location that is proposed for NA64-mu, but with some additional modifications. Simultaneous operation of MuonE with either COMPASS++ or NA64-mu is excluded, not only because of layout issues but also because of conflicting beam rate requirements. Similarly, MuonE and NA64-mu cannot be operated simultaneously.

4. ECN3 proposals

4.1 Introduction

The NA62 experiment is now in production mode for measuring the branching ratio of $K^+ \rightarrow \pi^+\nu\nu$ with the aim to collect about 100 Standard Model signal events. In a few short runs (typically less than a day each) they have operated the beam line in 'beam dump mode', by which a relatively clean condition is created for Hidden Sector searches. One question is whether these conditions can be further optimized in terms of background rejection (e.g. by changing beam settings) and proton flux. It is also considered to accumulate 10^{18} pot in 3 months of data-taking in beam dump mode at the highest possible intensities, e.g. in 2023.
KLEVER is an independent proposal aiming at collecting a useful sample of $K_L \rightarrow \pi^0\nu\nu$ decays in a new set-up, ideally located in ECN3. This requires the design of a completely new neutral K12 beam line. A 7 times higher proton flux is needed on the T10 target, namely $2 \cdot 10^{13}$ ppp. This has potentially major implications for radiation protection, ventilation, machine protection and equipment design.
Two other experiments are proposed for high proton or heavy ion beam intensities, namely DIRAC++ or NA60++. For radiation protection reasons they can realistically only be installed in an underground facility, de facto in ECN3. One option is to install them in place of or after the completion of NA62, in which case they compete with NA62 follow-ups or KLEVER.

4.2 NA62 beam dump

The NA62 beam and experiment are designed and optimised for a measurement of the very rare decay $K^+ \rightarrow \pi^+\nu\nu$ with a branching fraction below 10^{-10}. A muon sweeping system has been installed to significantly reduce the muon rate in the main NA62 detectors, but this magnetic system is limited by the fact that it must preserve the charged kaon beam.
The NA62 experiment can also be operated in a beam dump mode, where the K^+ production target is moved out of the beam (and therefore avoiding production of kaons and pions that can decay into muons). The full primary proton beam from the SPS is dumped directly in the TAX (Target Attenuator eXperimental areas) dump-collimators, made of massive copper and steel blocks. This condition allows searching for decays of Hidden Sector particles. However, also here muons form a potentially limiting background that must be minimised. In this case the constraint from the kaon beam no longer exists.

The muon sweeping system consists of a series of three dipoles with the gap filled with iron, except for a 40 mm diameter field-free hole for the kaon beam passage. In normal beam operation these sweep muons away sideways without affecting the main beam. The positive muons from K^+ and π^+ decays downstream of these dipoles are in turn swept by a 5 m long magnetic collimator with a toroidal field. This condition is also occasionally used as such for short 'axion runs'.

It is proposed to operate for at least 3 months in beam dump mode at a later stage to collect a competitive dataset corresponding to at least 10^{18} pot. Simulations have shown that the muon background can be reduced by a factor 4 by removing the iron inserts from the dipole sweeping magnets and by changing polarities (by re-cabling) of the 3rd and 4th magnet of the so-called first achromat, a series of 4 dipoles that creates a dogleg in which the beam momentum is defined.

It has been proposed to install a new beam dump further downstream. As that dump is closer to the experiment, the angular acceptance would increase. However, extensive simulations with G4Beamline have demonstrated that the muon background will increase by at least a factor 3 and this option is not considered baseline and would need further study.

4.3 KLEVER

KLEVER is a proposal for a measurement of the rare decay $K_L \rightarrow \pi^0 \nu\nu$ with a SM branching ratio of about $3 \cdot 10^{-11}$. The measurement is extremely delicate and necessitates very high beam rates, requiring $2 \cdot 10^{13}$ protons per spill and $5 \cdot 10^{19}$ protons on target over 5 years. One potential background from $\Lambda \rightarrow \pi^0 n$ has been identified. Detailed simulations with FLUKA have demonstrated that this background can be mitigated by increasing the production angle from 2.4 to 8 mrad. This reduces the Λ production rate much more than the K_L rate and softens the Λ momentum spectrum significantly. Consequently, most Λ's will decay before the start of the fiducial region. Similarly, this shortens the average K_L decay length such that a higher fraction of K_L decay inside the length of the fiducial region. Unfortunately, the K_L production rate per incident proton decreases, but by increasing the angular acceptance of the neutral beam, the total K_L decay rate can be restored. For this one would have to bear the cost of replacing the LKr calorimeter of NA62 by a new calorimeter with larger inside aperture for the beam passage.

The FLUKA simulations have been extended to include the neutral beam line itself and to optimise the muon sweeping. A detailed design has been made. A primary proton beam sloping down at an angle of 8 mrad impinges on a new T10 target with 2 mm radius producing the K_L beam and other secondaries. It is immediately followed by a vertical sweeping magnet that bends the protons further downward by 5.6 mrad, and a TAX dump-collimator with a hole for the K_L beam passage. Another horizontal sweeper reduces the background further.

Two more passive collimators, followed by sweeping magnets and a final active collimator define the neutral beam. The sweeping fields have been optimised to minimise muon backgrounds. An oriented tungsten crystal, located at the level of the TAX converts the photons into electron positron pairs, which are swept away. The overall beam performance is considered adequate for the experiment.

The main issues are related to the high proton flux required on the T10 target. FLUKA and ANSYS simulations have shown that the present T10 target design would be unsuitable, since its thin aluminium mounting cannot stand the desired rate of $2 \cdot 10^{13}$ ppp. However, there exist designs capable of fulfilling the requirements of KLEVER beam. For instance, some concepts of the target design developed for the fast extracted CNGS beam of $4 \cdot 10^{13}$ ppp can be implemented.

Similar calculations show that the K12 TAX are already close to the limit in K12 beam dump mode with $3 \cdot 10^{12}$ ppp hitting the TAX. The same arguments apply to the P42 TAX. Here a new design is needed with optimised block materials and optimised cooling. This is not considered a fundamental show-stopper, as the TAX in the M2 beam has survived many years of operation with $1.5 \cdot 10^{13}$ ppp impinging on the T6 target upstream of it. But a re-design of the TAX and its construction is needed and will require additional investment of resources.

The beam to T10 passes through the T4 target. It is proposed to not focus the primary beam on T4, but to have a wide and parallel beam in the vertical plane that mostly misses the 2 mm thick T4 target plate. The small fraction that hits the target will be sufficient to produce the H6 and H8 beams without damaging the target head. On the other hand, most of the beam is not attenuated by T4 and therefore the total beam intensity on T4 is not nearly as high as for a focused beam. Depending on the requirements on the other targets, this could be within reach for a 4.8 second flat top.

There was initially a concern that the air containment in the TCC8 cavern would be insufficient for KLEVER operation with the existing ventilation approach. However, the air flow inside the TCC8 target cavern was measured to be very small, thus explaining the low air activation measured outside. The current expectation is that the air contamination can be kept under control, possibly at the cost of installing an air lock in the access gallery to the TCC8 target cavern (like in the accesses from the NA62 control room to ECN3).

However, for the charged beam for NA62, the prompt dose on the surface is still within limits for a supervised area, but would exceed the limits if scaled up to KLEVER intensities. On the other hand, the primary proton beam for KLEVER incident on the T10 target has a downward angle of 8 mrad and is further deflected downward by an additional sweeping magnet following the target. This is much more favourable than the 0 mrad production angle for NA62 today. FLUKA simulations for the prompt dose on the surface above ECN3 are under way. If necessary, it can presumably be mitigated by more front-end shielding inside TCC8 or by better fencing outside around the ECN3 area.

4.4 NA60++ and DIRAC++

As long as the NA62 or KLEVER beam lines and experiments are installed, all the lateral space is taken, in particular along the T10 target and front-end where massive shielding is required. There is no way to transport a second beam line into ECN3 without seriously limiting the front-end shielding, excluded by radiation protection constraints. However, one can revive the old H10 beam towards the old NA60 location and also, in parallel, re-establish a new beam line in place of the present K12 beam, but the NA62 beam and experiment must then be dismantled. A design for a new P12 primary proton beam for a new DIRAC-like experiment has been prepared and has the required parameters. There will be an associated cost for new magnets and power converters that remains to be estimated.

New beam dumps must be installed inside ECN3 and their design must be carefully studied to minimise activation of the air and equipment inside ECN3. It may require a modification of the ventilation system in ECN3.

5. Costs

Cost estimates are mostly very preliminary. In Table 2 the present estimates are listed in four cost categories as a first indication. Consolidation costs are not included (e.g. consolidation of electrical, cooling, ventilation or civil engineering infrastructure). Also, these costs refer only to beam and infrastructure upgrades and do not include the experiments themselves.

The cost categories are defined as follows:

C1: Up to a few 100 kCHF
C2: From few 100 KCHF to 1 or 2 MCHF
C3: From 1 or 2 MCHF to 5 to 10 MCHF
C4: Of the order of ≥ 10 MCHF

Building	Beam	Proposal	Upgrades foreseen	Cost
EHN1	H2	NA61++	Shielding, interlocks	C1
	H2	NA61++	New very low energy beam (2nd phase)	C2
	H4	NA64-e	New permanent location	C1
EHN2	M2	NA64-mu	New location on beam	C1
		NA64-mu	Phase 2	C1
	M2	MuonE	Installation on M2 beam	C2
	M2	COMPASS++	Low-energy beam	C2
		COMPASS++/RF	New RF-separated beam	C4
ECN3	K12	NA62++ (BD)	Re-cabling for μ sweeping	C1
	K12	KLEVER	Upgrades and new beam	C3
	K12	NA60++	Revive H10 beam line	C2
	K12	DIRAC++	New K12 beam line	C3

Table 2: *Preliminary cost estimates where available. Cost categories are explained in the text.*

6. Final remarks and conclusions

The CBWG has made studies for all future options attributed to this working group. A common feature of all the proposals is the need for ever higher proton fluxes, with the exception of EHN2. In the framework of the BDF study, significant progress has been made by the SLAWG working group, in reducing losses in the region of extraction and splitting. However, if the Beam Dump Facility is operated, there will be competition for the SPS duty cycle. In the CNGS era this was mitigated by doubling the flat top length. This will again be an option, but not so much with KLEVER in case the same instantaneous rate has to be maintained over much more than 4.8 seconds.
The Conventional Beams Working Group has made significant progress in the specific studies of all proposals submitted to the group and concepts are available or in many cases worked out. Only the RF-separated beam study is still in early stages, but making steady progress. Detailed information and conclusions are described in the full report of the working group, which is available in [1]. It is also clear that, as expected, most of the many studies need further work, in particular studies leading to more precise cost estimates.
Among the BSM (Beyond Standard Model) proposals, the NA62 beam dump run for dark matter searches is rather straightforward to set up, at modest re-cabling cost. It could be combined in the same year with a low-intensity neutral beam test run for KLEVER.
The beam line for KLEVER itself, a measurement of the very rare decay $K_L \rightarrow \pi^o \nu\nu$, is a new installation, mostly with existing equipment. However, the target and TAX have to be replaced and adequate machine protection systems must be implemented.

On the other hand, the ventilation system and civil engineering infrastructure can be maintained in its present form, apart from very minor local improvements. This would have an associated cost for the installation of the charged beam lines.
NA64-e can continue running in the H4 electron beam for an A' search without significant upgrades, but it is foreseen to move the setup to a new zone, further downstream, which will allow much faster reinstallation and recommissioning. NA64-mu can be integrated rather easily in the M2 muon beam upstream of COMPASS++ for a complementary A' search, but cannot operate simultaneously with COMPASS++. The changeover time is a few weeks. The same holds for MuonE, which could use the same location as NA64-mu. It will measure μ-e elastic scattering that provides an essential input for g_{μ}-2. The cost of the beam line modifications remains at a modest level. At a later stage, NA64-mu could use higher fluxes, once installed in and around the SM2 spectrometer magnet of COMPASS++ and in synergy with part of the COMPASS++ apparatus and readout.
For the QCD physics, a new Expression of Interest is in preparation for a COMPASS++ QCD Facility, exploiting initially the M2 muon and hadron beam in basically its present form. Once the muon beam operation is completed, the 9 magnetic collimators could easily be replaced by standard vacuum to allow better electron beams and in particular a low-energy hadron beam, enriched (by the decay of pions and kaons before they would reach the experiment) in antiproton content. At a later stage an RF-separated kaon or antiproton beam would greatly enhance the physics potential of the QCD facility, but its feasibility, performance and (high) cost are still under evaluation.
In EHN1, NA61++ can continue the NA61/SHINE hadron program, for particle production for cosmic ray studies and neutrino beams, as well as its ion beam program for open charm production and fragmentation studies, with local improvements of shielding and interlocks against intensity and beam position variations. A dedicated and local low-intensity beam is under study to improve somewhat the beam characteristics at low beam momenta, but the cost-benefit ratio remains to be evaluated.
DIRAC++, a study of pionic atoms (and similar systems), and NA60++, open charm measurements with ion beams, can only be housed in an underground area, but are both incompatible with the presence of the NA62/NA62++ or KLEVER installation. However, they can be installed, at the same time, in case none of the kaon experiments would be present. But their operation must be in alternation.

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Reference

1. D.Banerjee et al., Report of the Conventional Beams Working Group to the Physics Beyond Collider Study and to the European Strategy for Particle Physics, to be published as CERN-PBC-Report-2018-002, advanced draft available from 18 December 2018 as EDMS No. 2053962