Proposal from the NA61/SHINE Collaboration for the update of the European Strategy for Particle Physics

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Abstract

Based on the success of the currently running program and motivated by new physics needs the NA61/SHINE Collaboration proposes to continue the measurements of hadron and nuclear fragment production properties in reactions induced by hadron and ion beams after the CERN Long Shutdown 2 (LS2). These measurements are requested by heavy ion, cosmic ray and neutrino communities and they include:
(i) measurements of charm hadron production in Pb+Pb collisions for heavy ion physics to find out how the onset of deconfinement impacts open charm and J/ψ production.
(ii) measurements of nuclear fragmentation cross section for cosmic ray physics to study the origin of Galactic cosmic rays and evaluate the cosmic-ray background for signatures of astrophysical dark matter
(iii) measurements of hadron production induced by proton, pion and kaon beams for neutrino physics to improve further the precision of hadron production measurements necessary for initial neutrino flux predictions for the T2K, T2K-II, Hyper-Kamiokande, and DUNE long-baseline neutrino oscillation experiments.

The requested measurements require a substantial detector upgrade which is planned to be executed during the LS2 and the measurements are scheduled in the period 2021-2024.

Contact person: Marek Gazdzicki <Marek.Gazdzicki@cern.ch>

1 Scientific Context

NA61/SHINE [1] is a multi-purpose experiment to study hadron-proton, hadron-nucleus and nucleus-nucleus collisions at the CERN Super Proton Synchrotron (SPS). The experiment was approved by the CERN Research Board in 2007 based on the request of heavy ion, neutrino and cosmic ray communities. They argued that opportunities offered by the broad momentum range of beam particles, from pions to lead nuclei, together with the large acceptance and high resolution of the NA61/SHINE detector provide the unique opportunity to perform urgently needed measurements. The first physics data with hadron beams were recorded in 2009 and with ion beams (secondary ^{7}Be beams) in 2011. The approved program will be completed in 2018 by data taking on Pb+Pb collisions and hadron-nucleus interactions. Data have been recorded to

(i) study the properties of the onset of deconfinement and search for the critical point of strongly interacting matter not excluding also possible effects related to the chiral-symmetry-restoration phase transition expected at the CERN SPS energies.

(ii) provide precise results on hadron production for improving calculations of the initial neutrino beam flux in long-baseline neutrino oscillation experiments as well as for more reliable simulations of cosmic-ray air showers.

Among the most important physics results are:

(i) observation of a rapid change of system size dependence of hadron production properties - the onset of fireball,

(ii) reduction of systematic uncertainties of the T2K final results by a factor of about 2,

(iii) precise investigation of mechanisms for muon production in ultra-high energy cosmic-ray air showers.

It is important to stress that the beam momentum range provided to NA61/SHINE by the SPS and the H2 beam line is highly important for the heavy ion, neutrino and cosmic ray communities. Namely, it covers:

(i) energies at which the transition from a matter in which quarks and gluons are confined in hadrons to quark gluon plasma takes place in heavy ion collisions - the onset of deconfinement [2],

(ii) proton beams of momenta used to produce neutrino beams at J-PARC, Japan and Fermilab, US [3],

(iii) light nuclei at $> 10A$ GeV/c important for the understanding of the propagation of cosmic rays in the Galaxy.

Based on the success of the currently running program and motivated by new physics needs NA61/SHINE proposes to continue measurements with hadron and ion beams during the period 2021-2024 [4, 5]. The measurements are requested by heavy ion, cosmic ray and neutrino communities and include:

(i) measurements of charm hadron production in Pb+Pb collisions for heavy ion physics,

(ii) measurements of nuclear fragmentation cross sections for cosmic ray physics,

(iii) measurements of hadron production in hadron-induced reactions for neutrino physics.

There is a world-wide effort to construct facilities providing ion and hadron beams in the CERN SPS beam momentum range, see Fig. 1 for detail. These are the fixed-target facilities at FAIR, Germany and J-PARC, Japan as well as the collider facility NICA, Russia. They will start operation after the measurements, which are requested here, are completed. The second phase of the beam energy scan at RHIC, US is planned to run in 2019 and 2020. Data will be taken in collider and fixed target modes. The fixed target facilities will operate only at energies below the onset of deconfinement. Data from collider facilities are typically complementary to the corresponding fixed target results. In particular, charm hadron measurements in a wide region of phase space are only possible at the fixed target facilities provided the collision energy and data taking rate are high enough.

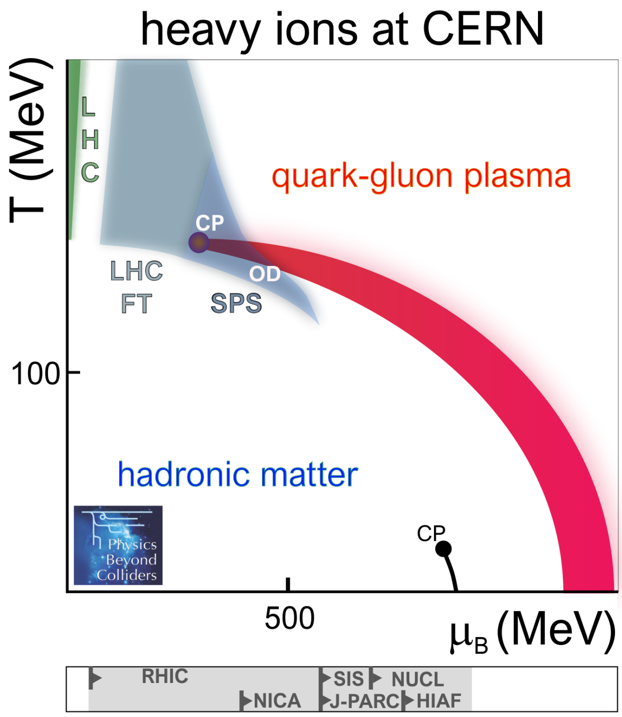

Figure 1: Phase diagram of strongly interacting matter in temperature, T, and baryo-chemical potential, μ_B, plane. The coverage of the CERN heavy ion programmes at LHC, LHC FT and SPS is indicated with the shaded areas in the diagram. The μ_B range of other heavy ion programmes is indicated in the box below the plot.

In conclusion, NA61/SHINE is the only experiment which can conduct the requested measurements in the near future. Moreover, the NA61/SHINE operation beyond the LS2 leaves open the possibility to perform new measurements which are likely to be requested in the future. In particular, measurements of hadron emission from the DUNE and Hyper-Kamiokande replica targets are expected to be requested only after the LS3 once their design will be completed. Moreover, new measurements related to the recent observation of the onset of fireball are likely to be requested soon following the growing experimental evidence.

2 Objectives

The objective of **charm hadron production measurements** in Pb+Pb collisions is to obtain the first data on the mean number of $c\bar{c}$ pairs produced in the full phase space in heavy ion collisions. Moreover, first results on the collision energy and system size dependence will be provided. This, in particular, should significantly help to answer the questions:

(i) What is the mechanism of open charm production?

(ii) How does the onset of deconfinement impact open charm production?

(iii) How does the formation of quark-gluon plasma impact J/ψ production?

NA61/SHINE physics performance with respect to the questions is illustrated in Figs. 2 – 4.

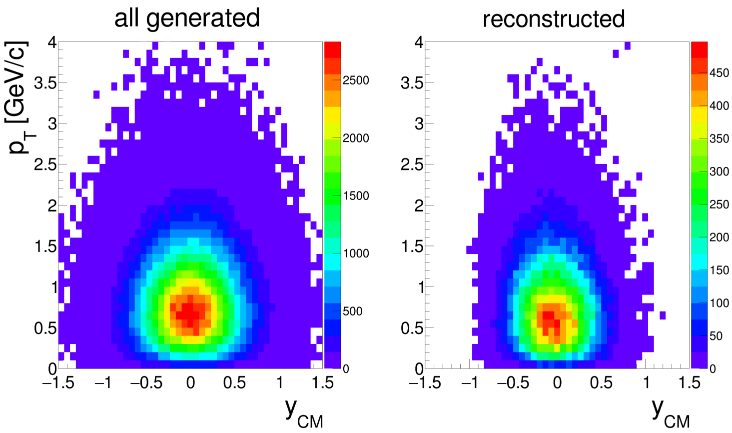

Figure 2: Transverse momentum and rapidity distribution of $D^0 + \overline{D^0}$ mesons produced in about 500M inelastic Pb+Pb collisions at 150*A* GeV/*c* to be recorded by NA61/SHINE in 2021-2024. Distributions for all produced $D^0 + \overline{D^0}$ mesons (*left*) and $D^0 + \overline{D^0}$ mesons reconstructed by NA61/SHINE *(right)* are shown.

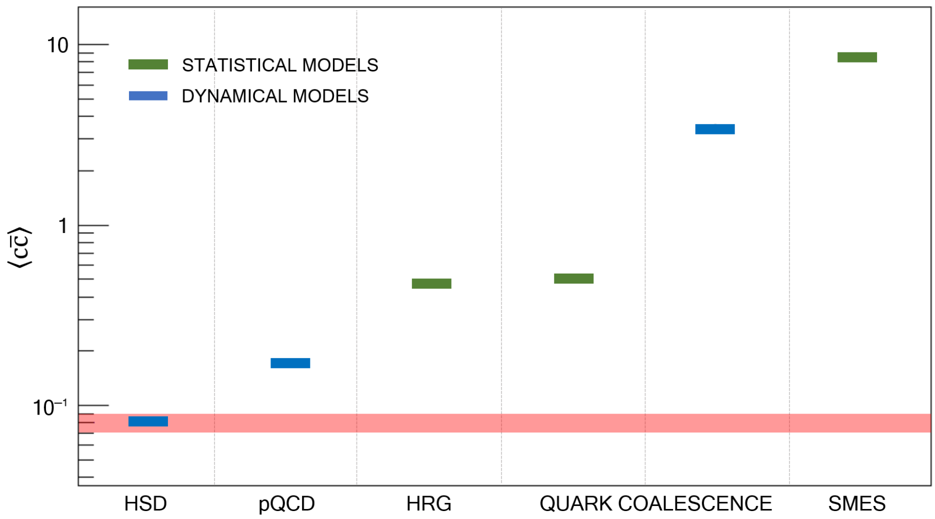

Figure 3: Mean multiplicity of charm quark pairs produced in the full phase space in central Pb+Pb collisions at 158*A* GeV/*c* calculated with dynamical models (blue bars): HSD [6, 7], pQCD–inspired [8, 9], and Dynamical Quark Coalescence [10], as well as statistical models (green bars): HRG [11], Statistical Quark Coalescence [11], and SMES [12]. The width of the red band, at the location assuming HSD predictions, shows the foreseen the accuracy of the NA61/SHINE future results.

In 2015 and 2016, a Small Acceptance Vertex Detector (SAVD) was constructed and tested. It demonstrated a successful reconstruction of the D^0 and $\bar{D}^0$ signal from Pb+Pb collision at 150*A* GeV/*c* [15]. One expects to reconstruct several thousands of D^0 and $\bar{D}^0$ decays from data

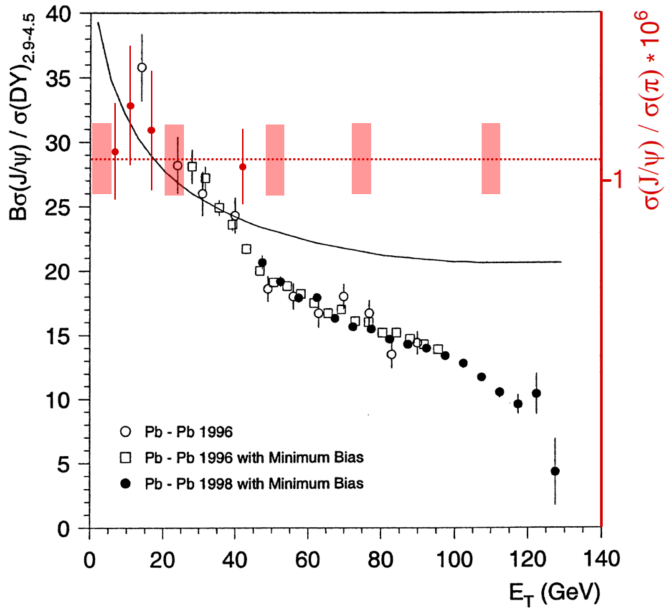

Figure 4: The ratio of $\sigma_{J/\psi}/\sigma_{DY}$ (*left*) and $\sigma_{J/\psi}/\sigma_{\pi}$ (*right*) as a function of transverse energy in Pb+Pb collisions at 158A GeV. The $\sigma_{J/\psi}/\sigma_{DY}$ ratio was measured by NA50 [13] and was used to calculate the $\sigma_{J/\psi}/\sigma_{\pi}$ ratio in Ref. [14]. Red bars mark the expected accuracy of the $\sigma_{J/\psi}/\sigma_{c\bar{c}}$ result of NA61/SHINE 2020+ assuming $\sigma_{c\bar{c}} \propto \sigma_{\pi}$ and scaled to the $\sigma_{J/\psi}/\sigma_{DY}$ ratio in peripheral collisions.

collected in 2017 and 2018 on Xe+La and Pb+Pb collisions at 150A GeV/c. Further data collection on Pb + Pb collisions and the reconstruction of decays of various open charm mesons are planned by NA61/SHINE in the years 2021-2024. The planned detector upgrades (a full acceptance Vertex Detector and ten-folod increase of the event rate) should allow to reconstruct about 100k decays of open charm hadrons [4].

The objective of **nuclear fragmentation cross section measurements** is to provide high-precision data needed for the interpretation of results from current-generation cosmic ray experiments. The proposed measurements are of paramount importance to the extraction of the characteristics of the diffuse propagation of cosmic rays in the Galaxy. A better understanding of the cosmic-ray propagation is needed to

(i) study the origin of Galactic cosmic rays,

(ii) evaluate the cosmic-ray background for signatures of astrophysical dark matter.

NA61/SHINE physics performance with respect to the questions is illustrated in Figs. 5 and 6.

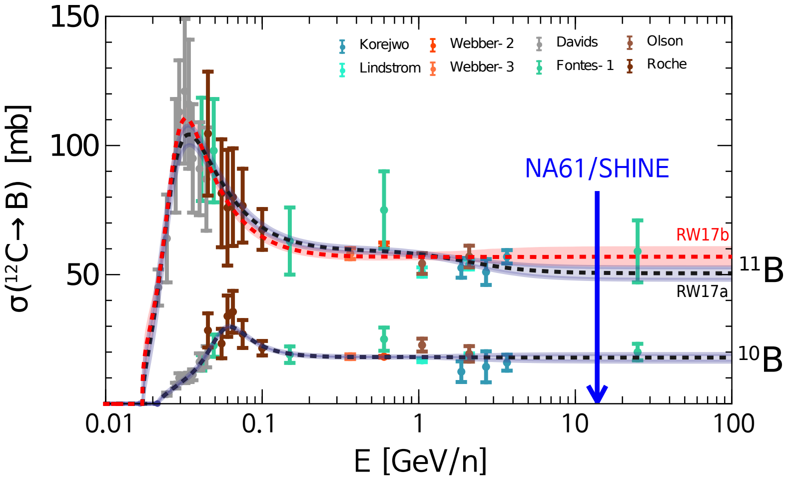

Figure 5: Current measurements of the fragmentation cross sections of $C + p \rightarrow {}^{11}B$ and $\rightarrow {}^{10}B$ as a function of energy per nucleon. Two different fits of the cross section data are shown by the red and black dashed lines. The light gray/red bands indicate the statistical uncertainty of the fits. The energy of the proposed NA61/SHINE measurements is shown as a vertical blue arrow. (Figure adapted from [16]). The energy range of main interest for cosmic-ray physics is above 1 GeV/n.

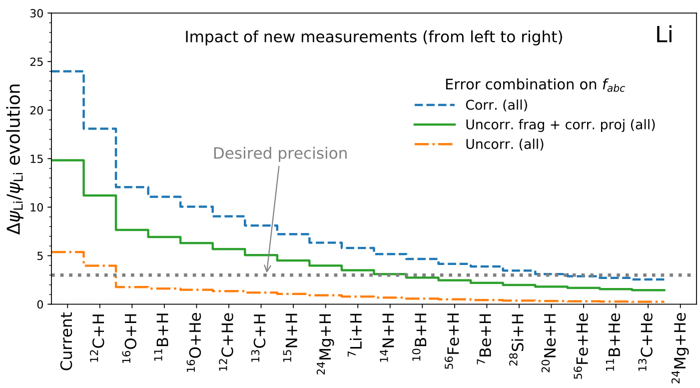

Figure 6: Evolution of uncertainty of predictions on the calculated Li fluxes at $10A$ GeV/c as a function of reaction. The plot is to be read from left to right, with the first bin giving the currently estimated uncertainty on the flux (no new cross section measurement) and consecutive bins showing the remaining uncertainty from the reactions right to the bin. The three sets of curves correspond to three different assumptions made on the cross-section errors: correlated, uncorrelated, or a mixture of these two assuming $\Delta\sigma_r^{\mathrm{current}} = 20\%$. (plots taken from Ref. [17]).

The objectives of **new hadron production measurements for neutrino physics** are

(i) to improve further the precision of hadron production measurements for the currently used T2K replica target, paying special attention to the extrapolation of produced particles to the target surface,

(ii) to perform measurements for a new target material (super-sialon), both in thin target and replica target configurations, for T2K-II and Hyper-Kamiokande,

(iii) to study the possibility of measurements at low incoming beam momenta (below 12 GeV/c) relevant for improved predictions of both atmospheric and accelerator neutrino fluxes,

(iv) to ultimately perform hadron production measurements with prototypes of Hyper-Kamiokande and DUNE targets.

Plots related to the NA61/SHINE physics performance with respect to measurements for neutrino physics are shown in Figs. 7 – 9.

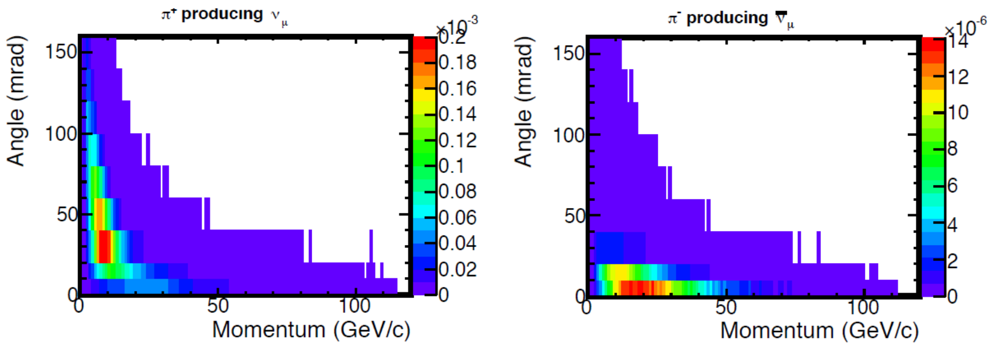

Figure 7: The secondaries that contribute to the neutrino fluxes in the LBNF beam in neutrino mode. The particles are weighted by their contribution to the flux at the DUNE far site. These are based on the November 2017 engineered design for the 3-horn optimized LBNF beam using a 120 GeV/c proton beam.

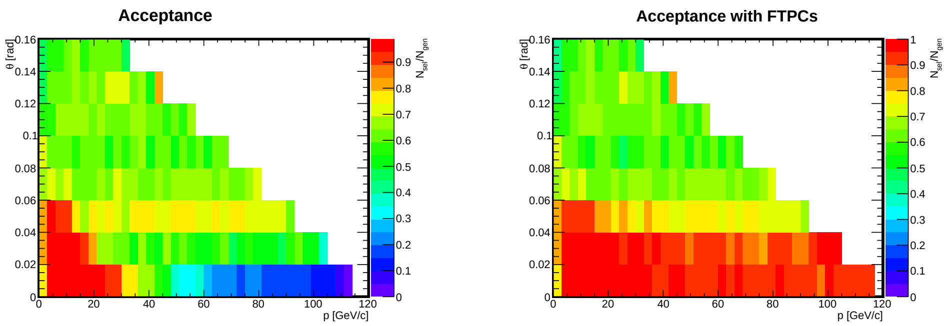

Figure 8: Acceptance of the NA61/SHINE spectrometer for charged pions with a magnetic field of 4.63 Tm (half of the maximum value). Particles were not simulated in the white regions. The plot on the left only includes track hits in the VTPCs, GTPC, and MTPCs (see Fig. 10). The plot on the right also includes hits in the newly installed FTPCs.

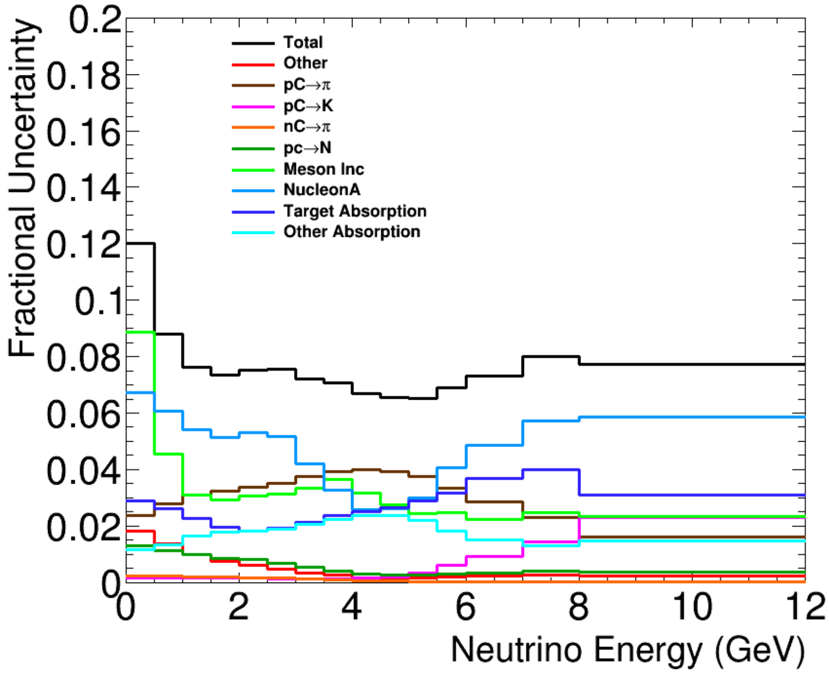

Figure 9: Current estimated uncertainties on the LBNF neutrino mode ν_μ flux at the DUNE far detector due to hadron production. This is for the optimized 3-horn beam configuration with an 80 GeV primary proton beam [18]. These errors are expected to be similar for a 120 GeV primary proton beam.

3 Methodology

The new measurements require upgrades of the NA61/SHINE detector (see Fig. 10) and DAQ that shall increase the data taking rate to about 1 kHz. These are:

(i) construction of a new Vertex Detector,

(ii) replacement of the TPC read-out electronics,

(iii) construction of a new trigger and data acquisition system,

(iv) upgrade of the Projectile Spectator Detector.

Furthermore, the construction of new Time-of-Flight detectors would be highly desirable for potential future measurements of hadron production in C+C and Mg+Mg collisions which are expected to be needed to understand the onset of fireball phenomenon.

4 Readiness and Expected Challenge

The collaboration consists of about 150 physicists from 30 institutions and 14 countries. The NA61/SHINE request for the data taking in 2021 which would start the new measurements was recommended by the CERN SPSC in June 2018 and approved by the CERN Research Board provided resources needed for the detector upgrades will be acquired by the Collaboration. The

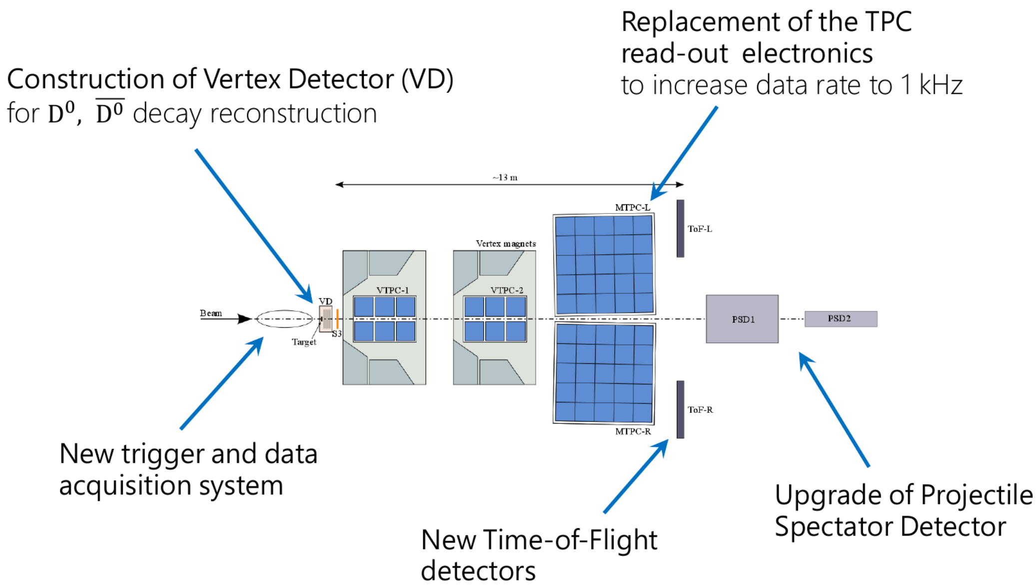

Figure 10: Schematic layout of the NA61/SHINE experiment at the CERN SPS (horizontal cut in the beam plane, not to scale) in its configuration for open charm measurements. Planned upgrades to be completed during the LS2 period are indicated.

work on the detector upgrades has already started and is planned to be finished at the beginning of 2021. The hardware cost is estimated to be about 1.5M CHF. Up to now 0.9M CHF was allocated and a number of grant requests are planned and in preparation to cover all needs.

The operation of the experiment during the data taking period 2021-2024 will require:

(i) proton and Pb beams to be delivered from the CERN SPS several months per year: NA61/SHINE operates in parallel with other fixed target experiments and with LHC,

(ii) the CERN IT resources: about 10 PB per year storage and 50 kHS06 CPU,

(iii) operation and maintenance of the detector including data taking and expert shifts: about 500k CHF per year to be covered by the Collaboration)

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