Addendum to the the NA61/SHINE Proposal SPSC-P-330

Beam momentum scan with Pb+Pb collisions
by NA61/SHINE at the CERN SPS

By the NA61/SHINE Collaboration
http://na61.web.cern.ch/

Abstract

This document presents the request of the NA61/SHINE Collaboration at the CERN SPS to perform a new beam momentum scan with Pb+Pb collisions. The new data are needed to

(i) significantly extend previous studies of collective effects due to strong and electromagnetic interactions,

(ii) improve measurements of event-by-event fluctuations and

(iii) perform the first measurements of open charm production in central Pb+Pb collisions at the SPS energies.

The charm production measurements require an upgrade of the NA61/SHINE facility by a high-precision vertex detector. The feasibility and expected performance of the proposed detector are presented.

October 15, 2015
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1 Executive summary

We propose to extend the NA61/SHINE beam momentum and system size scan programme with measurements of Pb+Pb collisions in the full CERN SPS beam momentum range $p_{\text{beam}} = 13A - 158A \text{GeV}/c$ (centre of mass energies $\sqrt{s_{\text{NN}}} = 5.1 - 17.3 \text{ GeV}$). The available statistics for Pb+Pb collisions will be increased by up to about a factor of ten compared to that collected by the NA49 experiment during the previous CERN SPS energy scan. The proposed new scan will also extend the data recorded by RHIC experiments (Au+Au collisions) by a high statistics data sample towards centre of mass energies of a few GeV ($\sqrt{s_{\text{NN}}} \sim 5 - 8 \text{ GeV}$) which are not accessible in the collider mode of RHIC operation.

The physics objectives of the new measurements of Pb+Pb collisions are:

(i) provide reference results for studying the evolution of collective effects due to strong and electromagnetic interactions when decreasing the system size and collision energy. In particular

(a) extend the anisotropic flow measurements of RHIC towards forward rapidities which is not feasible in the collider mode of RHIC but which are uniquely accessible with the fixed target set-up of NA61/SHINE,

(b) investigate the charge dependence of particle yields and anisotropic flow harmonics in the forward rapidity region which is sensitive to effects induced by the strong electric and magnetic fields generated in a heavy-ion collision.

(ii) extend the measurements of fluctuations performed in the search for the critical point of strongly interacting matter to the large acceptance of NA61/SHINE and obtain high statistics. Advantages of the NA61/SHINE acceptance which are crucial for fluctuations measurements are:

(a) the mid-rapidity coverage which is expected to be significantly larger than that of the NA49 experiment thanks to the NA61/SHINE upgrades,

(b) acceptance down to zero transverse momentum in contrast to that of the STAR experiment at RHIC,

(c) detection of projectile spectators which is important for centrality determination in the analysis of fluctuations.

(iii) perform the first measurements of $D^0$ and $D^0$ mesons in heavy ion collisions at CERN SPS energies. This requires construction of a new vertex detector for reconstruction of displaced vertices of charm meson decays with a resolution of 7 and 70 $\mu$m in the transverse and longitudinal directions, respectively. The corresponding measurements are currently not possible at RHIC. The new data on open charm production are crucial for
(a) understanding the mechanism of charm quark production in heavy ion collisions,
(b) understanding $J/\psi$ production in heavy ion collisions.

In order to reach the above goals we propose to extend the approved data taking schedule by a beam momentum scan with Pb+Pb collisions to be performed in 2016 and 2018. Namely, we request:

(i) Forty days of Pb beam at 13A, 19A, 30A, and 40A GeV/c at the end of the SPS fixed target period in 2016. This data sample will be used for study of collective effects and fluctuations. The measurements require only minor detector modifications. In addition, five days of Pb beam at 150A GeV/c in 2016 are required for a test and pilot data taking with the proposed vertex detector.

(ii) Forty days of Pb beam at 75A, and 150A GeV/c at the end of the SPS fixed target period in 2018. This data will allow to perform the first measurements of open charm production. They will also be used for the study of collective effects and fluctuations.
2 Introduction

The main physics goals of the system size and collision energy scan programme of the NA61/SHINE experiment are [1]:

(i) search for, and potentially discover, the critical point (CP) of the phase diagram of strongly interacting matter by studying the system size and collision energy dependence of fluctuations and correlations,

(ii) investigate the onset of deconfinement by studying the energy and system size dependence of its signatures.

The NA61/SHINE programme on strong interactions is driven by the evidence for the onset of deconfinement [2] observed by the NA49 Collaboration in central Pb+Pb collisions during the 1996 - 2002 beam energy scan at \( E_{\text{beam}} = 20A, 30A, 40A, 80A, 158A \text{ GeV}/c \). This observation was recently supported by the analysis [3] of the RHIC Beam Energy Scan (BES) data and that from the heavy-ion program at the LHC.

The NA49 and RHIC BES data on Pb+Pb and Au+Au collisions serve as a reference for the NA61/SHINE analyses of the collisions of lighter nuclei. However, the typical statistics for minimum bias collisions per reaction energy recorded by NA49 is about \( 4 \cdot 10^5 \). The RHIC BES experiments suffer from a limited acceptance for hadron identification in rapidity and transverse momentum. The spectator detectors of the STAR and PHENIX experiments were designed to measure spectators at top RHIC energies but at the beam energy scan energies they do not allow to measure spectator fragments which are important for collision centrality determination. Collisions below 30A GeV/c could not be registered in the collider mode of RHIC due to insufficient quality of the Au beam. These deficiencies of the existing data can be overcome by recording a new data sample of Pb+Pb collisions with the NA61/SHINE detector.

A comprehensive scan in two dimensions of the size of colliding nuclei (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La) and the beam momentum (13A, 19A, 30A, 40A, 75A, 150A GeV/c) was started by the NA61/SHINE collaboration in 2009. The current data taking schedule can be found in the Status Report submitted to the SPSC in parallel with this addendum [4]. The energy scans for p+p, Be+Be and Ar+Sc collisions are completed, while the one for Xe+La collisions is planned for 2017.

The proposed new beam momentum scan with Pb+Pb collisions at 13A, 19A, 30A, 40A, 75A and 150A GeV/c can be included into the existing program of NA61/SHINE during operation in 2016 and 2018 when Pb beams will be available at the CERN SPS. Within two 40 day Pb beam periods of data taking a full scan over the beam momenta of Pb ions can be performed. This will result in a high statistics sample of Pb-ion collisions which is up to about ten times larger than that collected by NA49. Together with the important detector upgrades, this would significantly enrich the world data for Pb+Pb collisions available in the CERN SPS energy range. The new data will allow for:

(i) new measurements at mid-rapidity which extend the NA49 acceptance,
(ii) new measurements of semi-central Pb+Pb collisions at six beam energy scan points,

(iii) new measurements of Pb+Pb collisions at lowest SPS energy of 13$A$ GeV/$c$, which is not accessible in the collider mode at RHIC,

(iv) first measurements of open charm production in Pb+Pb collisions at SPS energies.

The data samples and expected statistics from the NA61/SHINE beam momentum scan with Pb+Pb collisions are listed in Table 1. The statistics registered by NA49 for Pb+Pb collisions and by STAR at RHIC for Au+Au collisions is also shown.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target</th>
<th>$p_{LAB} (A GeV/c)$</th>
<th>Days</th>
<th>NA61/SHINE</th>
<th>NA49</th>
<th>STAR</th>
</tr>
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<tbody>
<tr>
<td>Pb</td>
<td>Pb</td>
<td>13</td>
<td>10</td>
<td>$4 \cdot 10^6$</td>
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<td>none</td>
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<tr>
<td>Pb</td>
<td>Pb</td>
<td>19</td>
<td>10</td>
<td>$4 \cdot 10^6$</td>
<td>$0.7 \cdot 10^6$</td>
<td>none</td>
</tr>
<tr>
<td>Pb</td>
<td>Pb</td>
<td>30</td>
<td>10</td>
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<td>$3.8 \cdot 10^6$</td>
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<tr>
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<td>Pb</td>
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<tr>
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<td>Pb</td>
<td>75</td>
<td>20</td>
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<td>$0.3 \cdot 10^6$</td>
<td>$10.6 \cdot 10^6$</td>
</tr>
<tr>
<td>Pb</td>
<td>Pb</td>
<td>150</td>
<td>20</td>
<td>$8 \cdot 10^6$</td>
<td>$4.0 \cdot 10^6$</td>
<td>$17.5 \cdot 10^6$</td>
</tr>
</tbody>
</table>

**Table 1:** The data samples and expected statistics from the NA61/SHINE beam momentum scan with Pb+Pb collisions. The last two columns show statistics registered by NA49 for Pb+Pb collisions and by STAR at RHIC for Au+Au collisions, respectively. The NA49 statistics is mostly for central Pb+Pb collisions with only $0.4 \cdot 10^6$ events per energy value recorded with a minimum bias trigger at 40$A$ GeV/$c$ and 158$A$ GeV/$c$. Statistics for the STAR data at $\sqrt{s_{NN}} = 7.7$ GeV and 11.5 GeV is taken from Ref. [5] and at $\sqrt{s_{NN}} = 14.5$ GeV from Ref. [6]. The 5 day long test run with 150$A$ GeV/$c$ Pb beam in 2016 is not included in the table.

In the following the expected progress resulting from the proposed beam momentum scan with Pb+Pb collisions is presented for several key physics cases, namely

(i) study of collective effects due to strong and electromagnetic interactions,

(ii) study of event-by-event fluctuations,

(iii) study of open charm production.

The document is organized as follows. Section 3 presents the motivation for measurements of the anisotropic flow harmonics and charge dependent correlations at CERN SPS energies, highlights the relevant experimental results from NA49 at SPS, RHIC and the LHC, and discusses the feasibility of the flow measurements with NA61/SHINE. Section 4 reviews the influence of the detector acceptance on observables sensitive to
critical fluctuations and points out the advantages of the NA61/SHINE acceptance over that of NA49. Section 5 discusses the goals of open charm measurements at SPS energies and presents the description and related performance study of the new vertex detector.
3 Collective effects due to strong and electromagnetic interactions

Fixed target experiments, such as NA61/SHINE, allow to study particle production and correlations in the full forward hemisphere of the collisions. Such coverage is difficult to achieve for collider experiments. The NA49 collaboration published results of collective flow studies with limited statistics and only for Pb+Pb reactions. For the successor experiment NA61/SHINE a new granular forward calorimeter PSD (Projectile Sp[ectator Detector) was constructed which allows an unbiased determination of the reaction plane for flow measurements. Together with the much higher event recording rate with the new DAQ system this offers the opportunity to perform studies of collective effect with better quality and precision.

Measurements of flow harmonics in Pb+Pb collisions provide a reference for studying collective flow effects in smaller systems explored by the energy and system size scan of the NA61/SHINE experiment. At the moment the only published results for $v_1$ and $v_2$ of pions, protons, and $Λ$ hyperons at 40A GeV and 158A GeV are available from the NA49 Collaboration [7, 8]. Reference heavy-ion data for studying collective effects in smaller systems at other collision energies of the system size and energy scan by NA61/SHINE are required. In addition, more statistics is necessary at collision energies previously studied by the NA49 Collaboration for differential studies of the anisotropic flow harmonics $v_n$, such as their dependence on $p_T$, rapidity, and centrality (or multiplicity).

A measurement of the charge dependence of the anisotropic flow harmonics and of spectra of produced charged particles can be used to probe effects induced by the strong electric and magnetic fields generated in a heavy-ion collision. The intense magnetic field reaches a value of $10^{14}$ T at LHC energies [9, 10]. The space-time evolution of the hot and dense strongly interacting matter created in the course of a Pb+Pb reaction [11, 12] is reflected in details of the electromagnetic (EM) interaction between the charged spectators and the produced matter (e.g. pions). The latter may result in a specific charge dependence of the anisotropic flow harmonics at forward rapidities. The charge dependence of flow harmonics provides an additional input for model calculations of the chiral magnetic [13, 14] and chiral separation [15, 16] (CME and CSE) effects which originate from local parity violation in strong interactions. The interplay of the CME and CSE may results in a Chiral Magnetic Wave [17, 18] and other possible effects due to the magnetic field [19, 20].

With the new data samples of Pb+Pb collisions proposed to be collected by NA61/SHINE it will be possible to extend the measurements of the charge dependence of the anisotropic flow, of charge dependent two particle correlations, and of charged particle spectra as a function of collision centrality for collision energies in the range of $p_{beam}$ from 13A GeV/c to 158A GeV/c, to forward rapidities which are significantly larger than what is presently accessible by RHIC experiments (see e.g. results by the STAR Collaboration [5]). The new data will also complement the ongoing measurements of charge dependent correlations at RHIC by STAR [21–23] and ALICE at the LHC [24–26].
This section is organized as follows. The data from the NA49 experiment at the CERN SPS is reviewed in Sec. 3.1. Results from the RHIC Beam Energy Scan (BES) are highlighted in Sec. 3.2. Studies of collective effects in smaller systems and the need for heavy-ion reference data are discussed in Sec. 3.3. Charge dependence of particle yields and anisotropic flow harmonics are discussed in Sec. 3.4. The feasibility of flow measurements with spectators by NA61/SHINE and projections of expected uncertainties for statistics from the requested data taking in 2016 and 2018 are presented in Sec. 3.5.

3.1 Existing results for $v_1$ and $v_2$ from NA49 at the CERN SPS

Figure 1 shows published results [7] obtained by the NA49 Collaboration for directed and elliptic flow of pions and protons at $E_b = 40A$ GeV and $E_b = 158A$ GeV.

![Figure 1: Experimental data for flow of pions and protons by the NA49 Collaboration [7]. $v_1$ at $E_b = 40A$ GeV (upper left), $v_1$ at $E_b = 158A$ GeV (upper right), $v_2$ at $E_b = 40A$ GeV (lower left), and $v_2$ at $E_b = 158A$ GeV (lower right).](image)

Figure 2 shows NA49 results for strange particle flow [27]. Only $v_2$ of $\Lambda$ hyperons was published [8]. Figures 1 and 2 demonstrate that more statistics are needed for
differential measurements of $v_n$ as a function of $p_T$ and rapidity in different centrality classes.

### 3.2 Highlights of results for $v_1$, $v_2$, and $v_3$ from the RHIC BES program

Figure 3 shows the collision energy dependence of results from the RHIC BES by STAR [5] for the slope $dv_1/dy$ of $v_1$ at midrapidity for $p$, $\bar{p}$ and net-protons (left panel) and the difference of $v_2$ for particles and anti-particles (right panel). New results by the NA61/SHINE Collaboration will complement (confirm) the STAR BES results and extend the measurements to the forward rapidity region. Spectators (forward particles) accessible with the Projectile Spectator Detector (PSD) can be used by NA61 as an advantage over STAR for the study of non-flow effects and for separating effects in flow from collision geometry and initial density fluctuations.

The higher harmonics were not measured by the NA49 Collaboration. Figure 4 shows $v_3$ vs. $p_T$ measured by STAR as a part of the BES program. Only minimum bias results are available for $v_3$. These results can be extended to the centrality dependence of $v_3$ using the new data planned to be recorded by NA61/SHINE. Another interesting aspect which can be uniquely studied by NA61/SHINE by utilizing the PSD is the role of spectators in flow fluctuations measurements.
3.3 Collective effects in collisions of heavy-ions versus smaller systems

Comparison with small systems is a hot topic at the LHC and at RHIC. Such measurements require minimum bias and high statistics data for peripheral Pb+Pb collisions. Figure 5 shows results for $v_2$ obtained by the CMS Collaboration [29]. The figure illustrates the need to measure flow in heavy-ion collisions at low multiplicities comparable to those in smaller systems (such as p+Pb in Fig. 5).

3.4 Charge dependence of particle spectra and anisotropic flow

The experimental data in the SPS energy range on the charge dependence of anisotropic flow for particles of the same isospin and mass are mostly limited to the measurements of mid-central collisions at midrapidity ($|\eta| \lesssim 1$). Figure 3 and Fig. 6 (a) show as example the elliptic and directed flow measured by the STAR Collaboration [5] during the RHIC BES. The charge dependence of directed flow shown in Fig. 6 (a) has been interpreted [19] as a hint of an effect due to a strong magnetic field which can induce charge currents inside strongly interacting matter. At the same time, the charge dependence of $v_1$ is argued to be connected to the space-time evolution of the system created in the collision via final state electromagnetic (EM) interaction between the produced charged pions and spectators [12, 30].

Figure 6 (b) shows directed flow of positively charged pions at forward (target) rapidities for mid-central Pb+Pb collisions at top SPS energy measured by the WA98 Collaboration [31]. The observed large value of $v_1$ is argued [12] to originate from EM
effects on pions produced at small distances (less than 1 fm) from the spectator remnants.

The presence of charged spectators and intense EM fields generated in a heavy-ion collision may introduce large distortions in the charged particle spectra and result in their charge dependence. Figure 7 shows the ratio of the $\pi^+ / \pi^-$ yields measured by the NA49 experiment. The ratios are plotted as a function of the reduced longitudinal momentum of the pion $x_F = p_L^*/p_{beam}$ for a given value of the transverse momentum $p_T$. A strong depletion of the $\pi^+ / \pi^-$ ratio is observed at low transverse momenta in the vicinity of $x_F = 0.15 \approx m_\pi/m_N$, which corresponds to pions moving at spectator (beam) rapidity. This depletion has been argued to have a strong dependence on the space-time evolution \cite{11} and the details of non-perturbative pion production above $x_F \approx 0$ and up to its kinematic limit of $x_F \approx 1$. The charge dependence is also sensitive to the interplay between pion production and spectator multifragmentation \cite{35}. While pions were used to study EM effects in heavy-ion collisions over a wide range of collision energies they were not used before to study the characteristic time scales of nuclear multifragmentation as was done e.g. for fragments in proton-nucleus reactions \cite{36}.
Figure 5: $v_2$ versus charged particle multiplicity in Pb+Pb collisions (left) and in p+Pb collisions (right). Results from the CMS Collaboration [29].

Figure 6: Directed flow $v_1$ of charged pions vs. particle rapidity normalized to the beam rapidity. (a) Results of the STAR Collaboration [5] (figure from [30]). (b) Data of the WA98 experiment reflected around midrapidity [31] corresponding to about 1.25M minimum bias Pb+Pb collisions [32]. The WA98 data is compared with a Monte-Carlo simulation of the EM interactions for different values of the distance $d_E$ between the spectator remnants and the formation zone of pions at freeze-out [12].

Experimental results on the charge dependence of particle spectra are mainly available for proton-nucleus and nucleus-nucleus collisions at low energies (see e.g. review [11]), while for Pb+Pb collisions at SPS energies the data is limited to that shown in Fig. 7 and in Ref. [37].

The proposed measurements by NA61/SHINE of the charge dependence of $v_1$ at for-
Figure 7: Charge dependence of pion production ($\pi^+ / \pi^-$ ratio) measured for peripheral Pb+Pb collision at 158\text{A GeV/c} [34] (NA49 data re-plotted in Ref. [33]).

ward rapidities will bring new experimental information related to EM effects and the longitudinal expansion of the system created in a heavy-ion collision [11]. Compared to the kinematic reach of the STAR experiment operating in the collider mode at RHIC, new data from the SPS energy scan with Pb+Pb collisions will allow to study the charge dependence in an extended kinematic range down to $p_T \approx 0$ and at forward rapidities as evident from Fig. 1, where EM effects are expected to be more pronounced [12].

The expected statistics for minimum bias Pb+Pb collisions of $4 \cdot 10^6$ events (see Table 1) makes it feasible to measure the charge dependence of particle yields and flow harmonics up to $y/y_{beam} = 0.7$. This statistics is by a factor ten larger than that collected by NA49 for Pb+Pb collisions. It is comparable to the statistics collected by STAR for Au+Au collisions at lowest BES energy of $\sqrt{s_{NN}} = 7.7$ GeV, and is significantly larger than that of WA98 used for Fig. 6 (b) to study the region $y/y_{beam} \approx 1$. The statistics of NA61/SHINE will allow to extend the measurements to the region above $x_F = 0.4$ where strong EM effects on $\pi^+ / \pi^-$ ratios are expected. At the moment this region of phase space corresponding to fast pions is not studied experimentally in high energy Pb+Pb collisions. The coverage of NA61/SHINE down to the region of zero $p_T$ is an advantage over the STAR and WA98 measurements. While it was partially exploited by NA49 in Fig. 7, the new data of NA61/SHINE will allow a more differential study in the region at and above $x_F = 0.15 - 0.25$ where the charge dependence of particle yields is strongly sensitive to the longitudinal space-time evolution of the created matter and the interplay with multifragmentation of spectators [35]. The charge dependence of directed flow increases with decreasing beam energy [5]. The same is expected for EM effects, thus they should be largest at the lowest beam energy available to the scan by NA61/SHINE ($p_{beam} = 13\text{A GeV/c}$, $\sqrt{s_{NN}} = 5.1$ GeV). Such a low collision energy is not accesible to STAR at RHIC in the collider mode.
3.5 Feasibility study for flow measurements

Figure 8 shows a performance study [38] done by the CBM Collaboration for the event plane reconstruction by the PSD and the measurement of proton $v_2$ at midrapidity based on a simulation of 1M Au+Au collisions. The simulations demonstrate good event plane resolution for flow studies down to peripheral collisions (upper left panel in Fig. 8) and comparable resolution correction factors for simulations using CBM and NA61/SHINE geometry (upper right panel in Fig. 8). As shown in the lower panel of Fig. 8, the “input” model $v_2$ is recovered using the “data-driven” event plane reconstruction method based on PSD subevents (lower panel in Fig. 8).

![Graph](image)

**Figure 8:** Performance study of the PSD detector (similar to that of NA61/SHINE) done by the CBM Collaboration. Upper panel (left) shows the reaction plane resolution correction factor obtained from the CBM PSD. Upper panel (right) compares the reaction plane resolution correction factors from simulations for the CBM and NA61/SHINE geometries. Lower panel compares as function of $p_T$ the reconstructed proton $v_2$ at midrapidity with the model generated $v_2$ based on simulation of 1M of Au+Au collisions with the CBM PSD geometry (results from [38]).

Figure 9 shows a comparison of the elliptic flow $v_2$ of protons and anti-protons from the RHIC BES obtained by STAR [39] and the elliptic flow of protons measured by NA49 [7] at the SPS together with statistical errors expected for ten days of NA61/
SHINE operation. The projections for protons (upper panels in Fig. 9) are based on statistical errors of the NA49 results. There is no NA49 data available for anti-proton $v_2$ and the projections for anti-protons (lower panels in Fig. 9) are based on statistical errors of the STAR data and do not take into account the differences in the experimental setups of the NA49, STAR, and NA61/SHINE experiments. The future analysis of the NA61/SHINE data using the PSD will benefit from better sensitivity to flow measurements compared to that of the NA49 experiment. However, the strongly non-uniform azimuthal acceptance of the NA61/SHINE experiment compared to that of the STAR experiment may result in larger statistical errors than the projections shown in Fig. 9 for anti-proton $v_2$. 
Figure 9: Proton and anti-proton $v_2$ versus $p_T$. Symbols show experimental results from STAR [39] and NA49 [7]. Shaded bands indicate projected statistical errors for the ten days of proposed NA61/SHINE operation. The projections for protons (upper panels) are based on statistical errors of the NA49 data. The projections for anti-protons (lower panels) are based on statistical errors of the STAR data and do not account for the difference in the experimental setups of the NA49, STAR, and NA61/SHINE experiments.
4 Measuring fluctuations in enlarged acceptance

Among the main goals of the NA61/SHINE physics programme is the search for the critical point (CP) in the phase diagram of strongly interacting matter. Model calculations suggest that the CP may be located at energies accessible at the CERN SPS but its exact location has large theoretical uncertainties [40–43] with some of the lattice calculations suggesting that there is only a cross-over transition in the whole range of baryon chemical potential [44, 45]. Therefore experimental data is crucial for establishing the existence and locating the position of the CP.

Several experimental observables are proposed to search for the CP in heavy-ion collisions. Among them are fluctuations of transverse momentum and multiplicity [46], as well as pion-pair and proton intermittency [47, 48]. The NA49 experiment studied various measures of fluctuations: intensive quantities such as the scaled variance of multiplicity distributions $\omega$ and the strongly intensive measure $\Phi_{p_T}$ which is used to quantify $p_T$ fluctuations. For further details see Ref. [49] and references therein. For other intensive and strongly intensive measures of fluctuations which are under study by NA49 and NA61/SHINE see Refs. [50–52].

Previous measurements of fluctuations by NA49 were hampered by the large beam induced $\delta$-ray background in the VTPCs. To mitigate this problem He-filled beam pipes were installed as part of the upgrade program of NA61/SHINE. These will reduce the $\delta$-ray production from Pb ions by an order of magnitude and allow much better fluctuation measurements in Pb+Pb collisions by NA61/SHINE.

4.1 Effect of limited acceptance on fluctuations measures

The measured value of quantities which are sensitive to fluctuations in the vicinity of the CP has a strong dependence on the detector acceptance. This is shown for $\Phi_{p_T}$ in Fig. 10. The green and black lines are model calculations with a critical point located at $\mu_B = 360$ MeV and $T = 147$ MeV and two different correlation lengths $\xi = 6$ fm and $\xi = 3$ fm for the full acceptance and the NA49 acceptance limited to forward rapidities (for details of the model calculations see Refs. [46, 49, 54, 55] and references therein).

4.2 NA61/SHINE versus NA49 acceptance

Figure 11 shows the population of positively and negatively charged particles in the $p_T$-$y_\pi$ and $p_T$-$\phi$ planes for central Pb+Pb collisions recorded by the NA49 experiment. The upper row in Fig. 11 shows the particle population in the acceptance used to measure the system size dependence of $\omega$ [56] and $\Phi_{p_T}$ [57] for C+C, Si+Si and Pb+Pb collisions as well as inelastic p+p interactions at 158$A$GeV. The acceptance had to be cut even more (especially at higher energies) when comparing results at all five energies of the NA49 scan in order to achieve similar coverage at all energies. The middle and bottom rows in Fig. 11 shows the particle population in the acceptance used in the measurement
Figure 10: The measure of transverse momentum fluctuations $\Phi_{p_T}$ vs. baryon chemical potential $\mu_B$ (or collision energy which decreases with increasing $\mu_B$). Black circles show the NA49 results for central Pb+Pb collisions [53]. Lines indicate model calculations [46,49,54,55] with a critical point located at $\mu_B = 360$ MeV and $T = 147$ MeV and two different correlation lengths $\xi=6$ fm and $\xi=3$ fm for the full acceptance (green lines) and the NA49 acceptance limited to forward rapidities (black lines).

of the energy dependence of $\Phi_{p_T}$ [53]. In all cases the NA49 measurements of transverse momentum and multiplicity fluctuations were limited to forward rapidities.

There were attempts [57] by the NA49 Collaboration to measure transverse momentum fluctuations with $\Phi_{p_T}$ at mid-rapidity, $0 < y_\pi < 1$. The region near mid-rapidity was approached for the measurement of the energy dependence of $\omega$ in central Pb+Pb collisions [58]. However, strongly fluctuating background due to beam induced $\delta$-electrons makes the analysis difficult in both cases.

The problem of $\delta$-electrons is addressed in the NA61/SHINE set-up by insertion of helium filled beam pipes inside both VTPCs. This reduces the $\delta$-electron background by a factor of ten allowing to extend the acceptance to mid-rapidity. Figure 12 shows the NA61/SHINE acceptance used in the analysis [51] of transverse momentum and multiplicity fluctuations of non-identified hadrons in inelastic p+p collisions. Compared to the acceptance of the NA49 set-up shown in Fig. 11, the NA61/SHINE acceptance for $p_T$ fluctuations is significantly enlarged. The NA61/SHINE acceptance is also larger than that used by NA49 for the study of the energy dependence of multiplicity fluctuations (see Ref. [58]).

Figure 13 illustrates the improved performance of the NA61/SHINE set-up for the measurement of $\Phi_{p_T}$ in inelastic p+p interactions at $p_{beam} = 20 - 158$ GeV/c [51]. The baryon chemical potential $\mu_B$, which decreases with increasing collision energy, is assumed to be independent of the system size and for p+p collisions is taken to be the same as for Pb+Pb (see Ref. [41] for details). The panels in Fig. 13 show results for all charged hadrons (left), negatively (middle) and positively (right) charged particles. Different symbols indicate NA61/SHINE results in the acceptance shown in Fig. 12 (triangles), in the reduced NA61/SHINE acceptance to match that of NA49 (open circles),
Figure 11: Population of positively and negatively charged particles in $p_T$-$y_\pi$, and $p_T$-$\phi$ planes for central Pb+Pb collisions at 158A GeV recorded by the NA49 experiment ($y_\pi$ is the particle center-of-mass rapidity assuming the pion mass). Top: Acceptance used to measure $\omega$ [56] and $\Phi_{p_T}$ [57] in the 5% most central collisions at 158A GeV/$c$. Middle and bottom: Acceptance used to measure $\Phi_{p_T}$ [53] for 7.2% most central collisions at 20A GeV/$c$ (middle) and 158A GeV/$c$ (bottom).

and results by NA49 (solid circles).

For all charged and positively charged particles the transverse momentum fluctuations in p+p interactions at 20-158 GeV/$c$ become significantly different from zero using the NA61/SHINE acceptance, while they are consistent with zero when additional cuts to match the NA49 acceptance in rapidity ($1.1 < y_\pi < 2.6$) and azimuthal angle are applied. Thus the extended acceptance of NA61/SHINE compared to that of NA49 provides significantly better sensitivity to fluctuations, in particular in the important midrapidity region. This represents a significant improvement in the search for the CP via fluctuation measurements.
Figure 12: Population of positively and negatively charged particles in $p_T$-$y$, and $p_T$-$\phi$ planes for inelastic p+p interactions recorded by NA61/SHINE. Top: Collisions at 20 GeV/c, bottom: collisions at 158 GeV/c.

Figure 13: The measure of transverse momentum fluctuations $\Phi_{p_T}$ versus baryon chemical potential $\mu_B$ (or collision energy which decreases with $\mu_B$) measured for p+p interactions. Triangles indicate results [51] for the full NA61/SHINE acceptance as shown in Fig. 12, open circles show results from NA49 for Pb+Pb collisions [53], and open circles are results with the NA61/SHINE acceptance reduced to that of NA49 as shown in the middle and bottom rows of Fig. 11.
5 Open charm production

The idea of measurements of open charm production in Pb+Pb collisions at the CERN SPS has a long history. First, the NA49 collaboration in 2002 [59] estimated an upper limited for the $D$ meson multiplicity via analysis of its decay topology into a pair of charged kaon and pion. Then an indirect estimate of the $D$ meson yield was obtained by the NA60 collaboration by measurements of muons which possibly originate from semi-leptonic charm meson decays [60]. Here we propose to measure $D^0$ meson production in central Pb+Pb collisions at the top SPS beam momenta with the NA61/SHINE detector. The measurements will be possible after supplementing the experimental setup with a Vertex Detector (VD) which can provide precise tracking downstream of the target.

The VD design is based on technologies developed for the corresponding detectors planned by the ALICE and CBM experiments. This should allow to have a first small, but fully operational, system ready for tests in 2016 with the possibility to reconstruct a first sample of decays of $D^0$ mesons in central Pb+Pb collisions at 150$A$ GeV/$c$. This Small Acceptance Vertex Detector (SAVD) is planned to be fully commissioned by 2018 and should allow physics data taking on open charm production in central Pb+Pb collisions at 75$A$ GeV/$c$ and 150$A$ GeV/$c$ in the fall of 2018. The final large acceptance VD (LAVD) could be operational after the Long Shutdown 2 allowing high acceptance and high statistics measurements of open charm production at the CERN SPS.

The SAVD, shown in Fig. 29, shall consist of two spectrometer arms with four sensor layers and a total active surface of $\approx 32$ cm$^2$. The sensor area of the large acceptance LAVD would be about 250 cm$^2$.

Simulation results indicate that using the SAVD detector, NA61/SHINE will observe about 1.5k $D^0 + \bar{D}^0$ meson decays during ten days of data taking on central Pb+Pb collisions at 150$A$ GeV/$c$. The corresponding number for the LAVD is 3.5k. The expected statistics is similar to that recorded by ALICE in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [61]. This holds although the cross section for $c\bar{c}$ production is about two orders of magnitude higher at the LHC than at the top SPS energy. The relatively high statistics of the future NA61/SHINE data results from the fact that the detection efficiency for $D^0 \rightarrow \pi^+ + K^-$ decays in NA61/SHINE (about 4% in the SAVD) is expected to exceed substantially the one of ALICE (less than 0.01%) $^1$. The high efficiency expected in NA61/SHINE is mainly due to the excellent pointing accuracy of the VD, the high momentum resolution and the relatively long mean decay length of $D$ mesons in the laboratory. The latter advantage is due to the Lorentz boost in the fixed target mode of NA61/SHINE operation.

Note, that the future STAR and ALICE experimental programs of heavy flavour measurement are limited to energies significantly above the top SPS energy [62–64]. There-

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$^1$The quoted efficiencies include the geometrical acceptance for $D^0 \rightarrow \pi^+ + K^-$ decays and the efficiency of the analysis quality cuts used to reduced the combinatorial background (see Sec. 5.3 for more details).
fore, the open charm measurements proposed by NA61/SHINE are complementary to
the STAR and LHC research programs.

5.1 Physics motivation

The most popular models of charm quark production in high energy collisions of hadrons
and nuclei are based on perturbative QCD [65]. It is commonly assumed that most
charm quarks are created at the early stage of the collision and their number remains
mostly unchanged during the evolution of the nuclear fireball. Charmonia are created
due to the attractive interaction between $c$ and $\bar{c}$ quarks and their production rate de-
pends in addition on the state and the space-time evolution of the surrounding mat-
ter [66, 67].

An alternative to the above mentioned approach was developed for CERN SPS en-
ergies. It is based on the unexpected observation that the $J/\psi$ yield in Pb+Pb collisions
is proportional to the mean pion multiplicity. The measured proportionality factor was
explained by statistical production of $J/\psi$ mesons at the hadronization stage [68, 69].
This motivated the development of statistical approaches to open charm and charmo-
nia production [70, 71]. The statistical estimate of the open charm yield is by more than
an order of magnitude higher than that based on pQCD-based [68]. However, both esti-
mates suffer from large systematic uncertainties. The predicted system size dependence
in these two approaches is also very different.

Up to now, only indirect measurements of open charm production in nucleus-nucleus
collisions at the SPS energies exist. They are not reliable enough to exclude either the
pQCD or the statistical model description of open charm and charmonia production.
Therefore, these quite different models coexist due to the lack of empirical data [72].
The proposed direct measurements of open charm production in Pb+Pb collisions will
help to clarify this situation.

5.2 NA61/SHINE with Vertex Detector

The layout of the NA61/SHINE detector [73] together with the planned Vertex Detector
is shown in Fig. 14. The set-up includes beam position detectors, Cherenkov counters
and the scintillation counter stations located upstream of the target. These detectors pro-
vide information on timing, charge and position of individual beam particles. For track-
ing, the experiment uses two Vertex Time Projection Chambers (VTPC1 and VTPC2), the
Gap TPC, and two main TPCs. The time-of-flight detectors, which are used for hadron
identification, are located behind the main TPCs. Finally, the projectile spectator detec-
tor PSD measures the energy of projectile spectators in order to obtain information on
the collision centrality.

The Vertex Detector together with the integrated target station is proposed to be lo-
cated upstream of the VTPC-1 as shown in Fig. 14. The distance between the target and
the front window of VTPC-1 will be about 75 cm. As mentioned before, we propose
to start with a reduced version of the vertex detector of NA61/SHINE. This Small Acceptance Vertex Detector (SAVD) is built from only 16 sensors with a total surface of \(\sim 32 \text{ cm}^2\). Despite its small surface, it is expected to detect about 4\% of all \(D^0 \rightarrow K + \pi\) decays at the top SPS energy, due to the strong forward boost of the particles at this energy.
The SAVD will consist of four sensor planes (stations) VDS1, VDS2, VDS3 and VDS4, which are located 5, 10, 15 and 20 cm downstream of the target, respectively. The stations will be equipped with silicon pixel sensors with a $\sim 2 \text{ cm}^2$ sensitive surface. The VDS1 and the VDS2 will each host two, the VDS3 four and the VDS4 8 of these sensors. The proposed configuration of sensors is shown in Fig. 15, where the position of sensors is represented by brown solid boxes.

The stations and the target are placed inside a gas vessel as shown in Fig. 29. The vessel is equipped with thin kapton windows at its front and back side and filled with helium gas at atmospheric pressure in order to minimize multiple scattering.

Each station consists of three layers: silicon (50 $\mu$m), epoxy glue (50 $\mu$m) and carbon fiber (300 $\mu$m). These layers represent the MIMOSA-26AHR silicon pixel sensors, the glue used to fix them on the mechanical support and the mechanical support itself. Thin water cooling tubes are located on the back side of the carbon fibre layer. This design was developed at CERN for the upgrade of the ALICE vertex detector and will be used for the NA61/SHINE VD (see Sec. 5.4.2).

### 5.3 Simulation of performance

For the performance studies, 200k of the 0-10% most central Pb+Pb collisions at 150 $A$ GeV/$c$ were generated using the AMPT (A MultiPhase Transport) model [74]. The model properly describes production of charged pions and kaons which contribute most of the combinatorial background in the mass distribution of pion-kaon pairs from which the open charm signal will be extracted (see Fig. 17 in Ref. [74]).

![Collision energy dependence of mean multiplicities of $\pi, \eta, \phi, K^+, K^-, D^0$, $\overline{D}^0$ and $J/\psi$ mesons produced in central Au+Au collisions predicted by the Hadron String Dynamics model [75].](image)

The AMPT model predicts an average multiplicity of about 0.01 for $D^0+\overline{D}^0$ mesons
produced in central Pb+Pb collisions at 150A GeV/c. This value is significantly lower than the corresponding predictions based on the PYTHIA (0.21) [70] and HSD (0.2, see Fig. 16) models. The latter models were tuned to properly describe data on open charm production in p+A and π+A interactions at SPS energies [76]. Therefore, it was decided to scale the AMPT mean multiplicity for \( D^0 + \bar{D}^0 \) mesons to the HSD prediction.

5.3.1 Track reconstruction

The track reconstruction is based on the hits generated by particles passing through the VD, the VTPC-1 and the VTPC-2. The presence of a uniform vertical magnetic field of 1.5 T and 1.1 T, in the volumes of VTPC-1 and VTPC-2, respectively, is accounted for. The residual magnetic field of < 0.3 T at the VD position is so far neglected.

Straight-line tracking based on the Hough-transform method is employed for stand-alone tracking in the VD. Hits in the VD are assigned to track parametrisations, to which they may potentially fit. The tracks with the largest number of “votes” are considered as true tracks, while the others are discarded as noise. In the case of the VD, a hit in each of the stations represents a vote for a track. Three or four votes (stations) are required to consider the associated hits a track candidate. Next, straight-line fits are performed on the track candidates and those with \( \chi^2 \) values below the cut limit are considered as reconstructed. The tracks reconstructed in the VD are then matched to those in the VTPCs. This is done by extending the tracks from the VD to the downstream surface of the VTPCs, and by searching for VTPC tracks with the best match both with respect to position and slope.

**Figure 17:** Tracking efficiency and fake track contamination as a function of the \( \chi^2 \) cut for all charged particles detected in the SAVD.
Figure 17 shows the tracking efficiency and the contribution of fake tracks\(^2\) as function of the \(\chi^2\) cut. The results were obtained for the stand-alone track reconstruction in the SAVD.

One observes the tracking efficiency to exceed 90% for a cut \(\chi^2 < 1\) and to reach values of about 96% for \(\chi^2 < 3\). The fake track contamination weakly depends on the value of the \(\chi^2\) cut and stays below 4.5% for the \(\chi^2\) cut range \(< 5\).

The development of a tracking software based on curved tracks and accounting for the residual field in the SAVD is ongoing. Relying on studies of tracking carried out for the CBM experiment [77], we consider this task feasible. Moreover, we expect the more realistic tracking not to cause qualitative changes in the simulation results shown below.

5.3.2 The strategy for reconstructing open charm

The invariant mass distribution for kaon-pion pairs accepted in the SAVD is shown in Fig. 18. The combinatorial background is several orders of magnitude higher than the \(D^0 + \overline{D^0}\) signal shown in red color.

\[\begin{align*}
\text{all } \pi, K \text{ pairs in SAVD} \\
\text{D}^0 \, \pi, K \text{ pairs}
\end{align*}\]

\textbf{Figure 18:} The invariant mass distribution of pion-kaon pairs from \(D\) meson decays (in red), and for all pion-kaon pairs (in black) for central Pb+Pb collisions at 150A GeV/c.

\(D^0\) mesons typically decay tens to hundreds of microns downstream of their production point. To select pion and kaon pairs that originate from \(D^0\) decays, one needs to reconstruct the decay vertex with a precision of about 50 \(\mu\)m. This precision can be reached only with a VD added to the NA61/SHINE set-up.

\(^2\)A fake track is a reconstructed track which can not be matched to a corresponding GEANT track.
In order to reduce the large combinatorial background, four kinematical and topological cuts are applied:

(i) A cut on the track transverse momentum $p_T$,

(ii) a cut on the track impact parameter $d$,

(iii) a cut on the longitudinal distance $V_z$ between the $D$ decay candidate and the interaction point,

(iv) a cut on the impact parameter $d_P$ of the back-extrapolated $D$ candidate momentum vector.

Figure 19 shows distributions of the cut variables. The cut values used in the performance study are indicated by the vertical dashed lines. We select tracks with $p_T > 0.31 \text{ GeV/c}$, $d > 31 \text{ \mu m}$, and track pairs with $V_z > 400 \text{ \mu m}$, $d_P < 20 \text{ \mu m}$. These values were chosen to maximize the signal to noise ratio (SNR) of the reconstructed $D^0$ peak.

Figure 19: Distributions of cut variables $p_T$, $d$, $V_z$ and $d_P$ for background (blue) and signal (red). The cut values selected for the analysis are indicated by the vertical dashed lines.

Figure 20 shows the invariant mass distribution (black) for all pion-kaon pairs and the distributions after the cuts, namely, after the $p_T$ cut (in magenta), $p_T$ and $d$ cuts (in green), $p_T$, $d$ and $V_z$ cuts (in blue) and finally $p_T$, $d$, $V_z$ and $d_P$ cuts (in red). The cuts reduce the number of signal pairs by a factor of 2, while the number of background pairs in the signal region is reduced by a factor of $2 \times 10^5$. The distributions were obtained assuming perfect particle identification.
5.3.3 Simulation results

The invariant mass distributions after the four cuts are shown in Fig. 21 assuming perfect PID (left) as well as no PID information (right). Both studies represent an upper and a lower limit of the PID capabilities of NA61/SHINE. The fitted curves represent a sum of an exponential (background) and a Gaussian (signal) function. They are used to derive the $D^0 + \bar{D}^0$ yields of the signal (S) and the background in the signal region (B) by integrating the fitted functions over a $\pm 3\sigma$ range around the $D^0$ mass.

The total number of measured $D^0 + \bar{D}^0$ decays in 4 millions central Pb+Pb collisions (statistics after 10 days of data taking in 2018) is estimated to be about 1500. The signal to background ratio (S/B) is 5 (0.5) and the SNR is 34 (22) assuming perfect PID (without PID).

Figures 22 and 23 show the distribution of $D^0$ mesons in rapidity ($y$) and transverse momentum $p_T$ for all generated particles, within the SAVD acceptance and after the cuts. The presented plots refer to 4M of the 0-20 % most central Pb+Pb collisions at 150A GeV/c.

The simulation for Pb+Pb collisions at 75A GeV/c is in progress and quantitative results will be available soon. To obtain a first guess of the feasibility of open charm measurements at 75A GeV/c, we scaled the results obtained for 150A GeV/c with the open charm production multiplicities predicted for 75A GeV/c (as shown in Fig. 16). According to this scaling, the SAVD is expected to reconstruct 350 $D^0 + \bar{D}^0$ from 4 million central Pb+Pb collisions at 75A GeV/c. Given that the multiplicity of the background is smaller at the lower energy, we assume that this yield is sufficient to create a significant
Figure 21: The invariant mass of pion-kaon pairs measured in the SAVD after all cuts applied. The red curve represents the fit with a sum of an exponential (background) and Gaussian ($D^0$ signal) function. Left: perfect PID is assumed, Right: no PID information is used.

Figure 22: Population of $D^0$ mesons in transverse momentum $p_T$ and rapidity $y$. Left: all generated, middle: within the SAVD acceptance, right: within the SAVD acceptance and after all cuts. Results are plotted for the 0-20 % most central Pb+Pb collisions at 150$A$ GeV/c and correspond to 4 million events.

peak in the invariant mass spectrum.

Simulation results for the large acceptance VD In the large acceptance VD (LAVD) the stations are located at the same distances as in the SAVD. The transverse dimensions
Figure 23: Rapidity (left) and $p_T$ (right) distributions of $D^0$ mesons. Dots: all generated, triangles: within the SAVD acceptance, squares: within the SAVD acceptance and after all cuts. Results are plotted for the 0-20 % most central Pb+Pb collisions at 150$A$ GeV/c and correspond to 4 million events.

of the stations are $2 \times 4$ cm$^2$ (VDS1), $4 \times 8$ cm$^2$ (VDS2), $6 \times 12$ cm$^2$ (VDS4) and $8 \times 16$ cm$^2$ (VDS4). Each station has a square beam hole of $(3 \times 3$ mm$^2$) in the centre. These dimensions allow to detect 28% of the $D^0$ mesons decaying into charged pions and kaons. The LAVD area will be covered by 126 sensors.

Figure 24: The invariant mass of pion-kaon pairs after the cuts for the LAVD. The red curve represents the fit with a sum of exponential (background) and Gaussian function ($D^0$ signal). Left: perfect PID is assumed, right: no PID information is used. The same vertical scale is used as in Fig. 21 to allow for a comparison.

The invariant mass spectra measured by the LAVD after the cuts are shown in Fig. 24.
The number of measured $D^0 + \bar{D^0}$ in 4 millions central Pb+Pb events at 150A GeV/c is expected to be 3600. The signal to background ratio is estimated to be 3 (0.35) and the SNR 53 (30) with the perfect (without) PID information.

Figure 25: Population of $D^0$ mesons in transverse momentum $p_T$ and rapidity $y$. Left: all generated, middle: within the SAVD acceptance, right: within the LAVD acceptance and after all cuts. Results are plotted for the 0-20 % most central Pb+Pb collisions at 150A GeV/c and correspond to 4 million events.

Figure 26: Rapidity (left) and $p_T$ (right) distributions of $D^0$ mesons. Dots: all generated, triangles: within the LAVD acceptance, squares: within the LAVD acceptance and after all cuts. Results are plotted for the 0-20 % most central Pb+Pb collisions at 150A GeV/c and correspond to 4 million events.
5.4 NA61/SHINE vertex detector

5.4.1 Design concept of the vertex detector

The design of the NA61/SHINE VD is based on that of the CBM-MVD [78]. In both cases, four layers of ultra-granular and very light silicon pixel counters are employed. The first layer is located 5 cm downstream of the target. This position represents a compromise between the need to reach good secondary decay vertex resolution of $\sim 50 \mu m$, which favours closeness to the target, and the need to handle the high track density generated by a heavy ion collision, which favours increasing the distance. The four consecutive stations are required to perform stand-alone track finding in the VD in order to help matching with the tracks found in the VTPCs. The distance between the stations is kept small in order to minimize the impact of the high track density and multiple scattering on the tracking process. Otherwise, more than one hit might be found in the search window of the tracking. Taking account of this argument and of engineering aspects, a distance of 5 cm between the stations is considered a good solution.

To reach the required secondary vertex resolution the individual layers of the vertex detector have to feature a very small material budget (few 0.1% $X_0$) and a spatial resolution of a few $\mu m$. These requirements are met by the novel CMOS Monolithic Active Pixel Sensors (MAPS), which are successfully operated in the STAR experiment [79]. Moreover, they form the technology of choice for the Micro Vertex Detector (MVD) of the CBM experiment and the ALICE ITS [80].

The ultra-thin and granular MIMOSA-26AHR sensors [81, 82] and the integration techniques developed for the prototype of the CBM-MVD [83, 84] and the ALICE ITS are suitable for building the VD for NA61/SHINE. As discussed in more detail in Sec. 5.3.3, it is currently foreseen to initially construct the so-called Small Acceptance Vertex Detector (SAVD). This device is shown in Fig. 15. It integrates sensors with a total surface of 32 cm$^2$. In spite of its modest size it will allow first physics measurements of open charm production at SPS beam momenta. In addition, the SAVD will be a valuable test bench for understanding in detail how to operate MAPS in fixed target experiments.

5.4.2 Technological implementation

The MIMOSA-26AHR sensor (see Fig. 27) is the smaller and decisively faster version of the sensor used for the STAR-Heavy Flavor Tagger. It is routinely thinned to 50 $\mu m$ and provides a very fine pixel pitch of $18.4 \times 18.4 \mu m^2$ resulting in a measured spatial resolution of $3.5 \mu m$. The 2 cm$^2$ active surface of the sensor is covered by 1156 columns made each from 576 pixels. The readout of the pixel is done by means of a rolling shutter and the readout time is 115.2 $\mu$s. The sensor is suited for room temperature operation and tolerates an integrated non-ionizing dose of $> 10^{13}$ n$_{eq}$/cm$^2$ [82] and an integrated ionizing dose of $> 150$ krad [85].

It is equipped with a slow control system based on the JTAG standard. Internal analog and digital data processing circuits perform pedestal correction, signal discrim-
Figure 27: Schematic view of the MIMOSA-26AHR displaying the basic architecture of the sensor.

Figure 28: Ladder to be used for the NA61-SAVD. The sensors will be glued on the middle part of the ladder and cooled via the integrated micro channels.

...ination and zero suppression. The pre-processed data is read out by two digital links of 80 Mbps transfer rate each [86].

The sensors for the SAVD were purchased from the PICSEL group of IPHC Strasbourg and probe tested by the Institute for Nuclear Physics (IKF) of the Goethe University Frankfurt. They will be mounted on ultra-light, actively cooled carbon fibre ladders. It was realized that 30 cm long ladders developed for the upgrade of the ALICE Inner Barrel [80] fit to the NA61/SHINE VD design concept. The involved ALICE group agreed to support NA61/SHINE efforts in the mechanical integration of the devices based on their experience with building the mechanics and the alignment system of the present ALICE-ITS. Figure 28 shows 20 pre-fabricated ladders dedicated to be used in the SAVD.

A thin (0.1% X₀) layer of laminated carbon fibres will hold the sensors and will be glued on top of this ladder structure. This additional layer was introduced as a simple means to increase the width of the ladder to match the size of MIMOSA-26AHR. Moreover, it allows to integrate the sensors on a solid and planar layer, which offers the option to reuse the tools and procedures known from the CBM-MVD prototype for this purpose. Overall, an average material budget of 0.4% X₀ will be reached in the active area.

The sensors will be controlled and read out by means of a local DAQ system. This
The system was developed based on the HADES TRB standard [87] and operated during a successful beam test within the CBM-MVD prototype project [88]. The sensors will be connected by means of thin flex print cables, which transport the data via some intermediate PCBs toward a TRB3 FPGA board. This board steers the slow- and fast-control of the sensors, pre-processes the data received and communicates it to the central DAQ system by means of Ethernet.

The local readout and DAQ system will be slightly modified compared to the CBM solution. The modifications include the adaptation of the back-end of the FPGA code of the TRB-boards in order to operate together with the NA61-DAQ. Moreover, the flex print cables needed to operate the sensors will be lengthened in order to adapt them to the needs of NA61/SHINE.

![Image](image.png)

**Figure 29:** View of the helium vessel containing the SAVD (**left**). Mounting structure of the detector ladders (**right**).

The SAVD will operate in a vessel filled with helium (see Fig. 29, **left**), in order to reduce multiple scattering. The detector ladders will be mounted into C-frames (see Fig. 29, **right**), which also host the cables and the front end boards of the sensors (not shown) as well as the coolant distribution system. The coolant needed for supplying the micro cooling pipes of the ladders will be provided by a cooling system based on an industrial chiller. The geometry of the vessel and the C-frame is optimized to minimize the material budget in the active area of the downstream NA61/SHINE experiment.

The connection between the ladders and the frames will rely on the ruby ball connector technology known from the ALICE-ITS [80]. Each detector arm is mounted on a positioning stage (e.g. the PI M-683 Dynamic Micropositioning Stage), which is tolerant to magnetic fields and provides a < 1 µm positioning accuracy. This allows to move the ladders by up to 5 cm into a protected position, which is required to avoid hitting the SAVD with the beam during beam tuning.
5.4.3 Compatibility with the running conditions

**Figure 30:** Occupancy of the first station of the SAVD due to delta electrons (*left*) and 0-10% central 158A GeV/c Pb+Pb collisions (*right*). A 200 µm (about 0.5%) instead of a 5% Pb target was used during the simulations of the delta electrons. The occupancies per event shown in the left figure have therefore to be multiplied by a factor of ten. From Refs. [89, 90].

**Anticipated running scenario and trigger strategy** The robustness of the SAVD in terms of occupancy, trigger strategy and radiation doses was estimated according to the following running scenario: NA61/SHINE will be operated with a 10 kHz Pb beam, which impinges on a 5% interaction target. This results in 500 collisions/s from which a maximum of (100 Hz) will be selected by the DAQ system of NA61/SHINE.

The MIMOSA-26AHR sensors are read out by means of a rolling shutter within 115.2 µs and with a frame rate of 8.68 kHz. The data is internally discriminated and compressed. Then it is combined with a frame number generated by an internal frame counter, packed into a high level protocol and pushed toward the controlling FPGAs on the TRB3 board. In the FPGA, the data is checked for corruption by means of comparing frame numbers and checking for the fixed length of a correctly submitted data train. Finally, potential idle bits are removed and the data is sent to a PC via optical Ethernet.

The sensors and the above mentioned readout chain is operated continuously. The trigger logic is integrated by means of selecting two frames once a trigger signal is provided. Selecting two frames is required as, once a collision occurs, the rolling shutter is in a random position. Therefore, a part of the related hits are found in front of the shutter and recorded in the frame being read out in the moment of the collision. The remaining hits are located behind the shutter. These pixels sample and hold the hits but they are only read out during the next passage of the rolling shutter. Consequently, the data is found in the related, consecutive, frame.
The hardware platform for performing the trigger handling and the frame selection is not yet finally decided. Besides putting this logic into the FPGAs of the TRB3 boards, one might consider to employ a powerful PC for this purpose.

**Sensor bandwidth and occupancy** MIMOSA-26AHR is designed to record up to 9 data strings of maximum 4 active pixels each per row. The global memory allows to store 1152 strings, which is sufficient to record about 380 hits per frame (depending on the precise multiplicity and relative position of the hit clusters). In case the hit density exceeds this limit, the data is truncated and an overflow is indicated.

The internal bandwidth of MIMOSA-26AHR was compared with the occupancy generated by the two main sources of tracks in a 158 A GeV/c Pb+Pb collision system. These are the products of the heavy ion collision and the non-negligible number of delta electrons, which are knocked out from the target by the primary beam. The related hit distributions are shown in Fig. 30. A 200 µm (about 0.5%) Pb target was used for the simulations of the delta electrons.

Delta electrons, which are knocked out of the target by the primary beam, provide about 30 hits to each frame of the most exposed sensor of the first VD station. Moreover, the sensor receives about 150 hits in case a central collision occurs. Therefore, less than 50% of the sensor bandwidth is used. This holds even if the data of the central collision is concentrated exclusively in one of the two frames related to the collision. The remaining bandwidth is sufficient for accommodating fluctuations in the hit number. Moreover, one may handle an increase of the delta electron flow by a factor of five, which might be caused by beam intensity fluctuations. In principle, the sensors should also be able to handle a pile-up of two heavy ion collisions. However, this scenario is unlikely as we expect on average 0.06 collisions per frame. The sensors should therefore be able to separate the collisions even if the beam intensity increases temporarily by a factor of five (0.3 collisions per frame).

The peak occupancy of the VD in the most exposed square millimetre of its surface is estimated to amount to 4 hits/mm\(^2\) for central Pb+Pb collisions plus an additional 2 hits/mm\(^2\) from delta electrons (which includes the mentioned factor 5 security margin for beam fluctuations and takes into account the 5% target foreseen for data taking). Assuming (conservatively) a hit multiplicity of 4 fired pixels per hit, one obtains 24 fired pixels/mm\(^2\). Due to the high granularity of MIMOSA-26AHR, namely 2950 pixels/mm\(^2\), the resulting maximum occupancy is 0.8%.

**Radiation doses** An upper limit of the radiation tolerance required for operating the VD in NA61/SHINE is estimated with the following, simple arguments. From the simulations shown in Fig. 30, one finds that the most exposed mm\(^2\) of the VD has to face about 4 hits per cm\(^2\) and central collision. Assuming pessimistically that all collisions are central and that all hits cause a damage of 1 n\(_{eq}\), this corresponds to \(\sim 400 n_{eq}/cm^2\) per collision. Moreover, it is assumed that the VD will operate a maximum of 40 days with Pb+Pb collisions before being replaced (e.g. by exchanging the most irradiated lad-
ders against the identical and mostly not irradiated ladders of the 4th station). Taking into account the effective duty cycle of 30% of the accelerator, one finally finds an integrated non-ionizing radiation dose of $2.6 \times 10^{11} \text{ n}_{eq}/\text{cm}^2$. The delta electrons add about 0.35 hits/mm$^2$ and beam particle, which leads to a dose of $4.5 \times 10^{11}$ electrons/cm$^2$. As each electron, however, creates a bulk damage of only $< 0.1 \text{ n}_{eq}$, their contribution to the non-ionizing dose is small. One concludes that the expected non-ionizing radiation dose during the 40 day-long run is about $3 \times 10^{11} \text{ n}_{eq}/\text{cm}^2$ corresponding to 3% of the radiation tolerance of the sensors.

When estimating the integrated ionizing dose, it is assumed that all charged particles impinging on the detector are minimum ionizing. Based on this assumption, one finds that one minimum ionizing particle per cm$^2$ creates a radiation damage of $2.86 \times 10^{-11}$ krad [91]. From the above mentioned particle densities, one concludes that the most exposed mm$^2$ of the VD will have to tolerate about 25 krad, which is once more only a fraction of the $> 150$ krad radiation tolerance of the sensor.

Additional radiation damage is expected from ions from the Pb beam halo.

**Protection with respect to ions from the primary beam** The SAVD will have a gap of ±3 mm with respect to the beam axis. In this position the sensors are also exposed to beam ions. The impact of these ions was considered in two different scenarios. First, an accidental impact of the beam into the SAVD, as might be caused by a mistake during beam tuning or by a failure in one of the magnets of the beam line. Second, continuous impact of a smaller number of ions, which are part of the beam halo.

In both cases, the ions are considered to generate an integrated radiation damage. Moreover, a large number of electron/hole pairs caused by impinging heavy ions may generate local malfunctions in the sensors, which are referred to as Single Event Upsets (SEU). These may cause for example an accidental switching of the state of a memory cell, which might turn into an unexpected modification of the detector settings. Moreover, the sensors may be affected by so-called latch-ups. These are reversible short-circuits, which may be generated by heavy ions in CMOS structures forming a parasitic thyristor. The electron/hole pairs excited by the ion switch those thyristors into their conductive state and a power cycling of the sensors is needed in order to switch them off again. Latch-ups are considered as a particular risk for the SAVD and are considered as the origin of a loss of a significant number of sensors in the STAR-PXL detector [79].

A number of measures are being undertaken in order to protect the SAVD against beam ions. As a first step, the detector will be installed on the already mentioned positioning tables, which allow to move them into a protected position during beam tuning. This is expected to reduce the risk of an accidental hit of the detector substantially. Moreover, the tables allow to adapt the position of the SAVD with respect to the real beam position, if needed.

A potential accidental displacement of the beam will be detected by the beam detectors of NA61/SHINE. Once detected, the SAVD will be moved into its protected position, which may be carried out within two seconds. Moreover, a signal requesting
Figure 31: Measured profile of the primary Ar beam at 150A GeV/c at the NA61/SHINE target. The tails are suppressed by the veto counters around the beam. The gap of the SAVD (±3 mm) and the anticipated position of the sensors is shown. The numbers are normalized to one beam ion.

A fast beam abort will be sent to the SPS accelerator control. This signal will trigger an automatic beam stop within a fraction of a second.

In order to prevent damage from SEUs and latch-up, the current consumption of each sensor will be monitored. An over-current as generated by a latch-up will be detected and the bias voltage of the sensor will be cut within a few milliseconds. This system, which is improved compared to its equivalent in the STAR-PXL, will reliably prevent a damage of the sensors due to the thermal overload caused by the latch-up.

SEU-like bit flips may modify the state of the slow control registers of the sensors and eventually confuse the internal counters. In order to minimize the consequences of such bit flips, the sensors will be routinely reset and reconfigured between the spills.

The integrated radiation dose due to halo ions was estimated for the Ar beam at 150A GeV/c based on the beam spot measurements shown in Fig. 31. The most exposed surface of the sensor may be hit by about $1.2 \times 10^{-3}$ ions per beam ion and square millimetre. For beam intensity of $10^4$ ions per second, a duty cycle of 30% and an operation time of a maximum of 40 days, this results in a total flux of $1.3 \times 10^9$ ions per square centimetre and per run of 40 days.

The radiation damage caused by 150A GeV/c Pb ions is poorly known. To estimate the non-ionizing radiation damage, we used the NIEL hypothesis and the theoretical estimates provided in Ref. [92]. As these estimates cover only beam energies up to 2 GeV and ions up to the mass of iron, we extrapolated the NIEL as shown in Fig. 32. Knowing that $1 \text{ n}_{eq}/\text{cm}^2 \approx 2.1 \text{keV} \cdot \text{cm}^2 \cdot \text{g}^{-1}$, one concludes that the hardness factor is
Figure 32: Non Ionising Energy Loss (NIEL) as a function of atomic number and energy of the ion. The extrapolation employed for estimating the non-ionizing radiation damage (see text for details) is shown by the red dot. Plot from Ref. [92].

about 200-300 and the non-ionizing radiation damage is about $4 \times 10^{11} \text{n}_{\text{eq}}/\text{cm}^2$, which is 4% of the radiation tolerance of MIMOSA-26AHR.

To estimate the ionizing radiation dose, it was assumed in accordance with the Bethe-Bloch formula, that this dose is proportional to $Z^2$. Starting from the energy deposit of a minimum ionizing particle one estimates an ionising dose of $1.9 \times 10^{-7} \text{krad} \cdot \text{cm}^2$ for Pb ions ($Z = 81$). By multiplying this factor with the integrated ion flux, one obtains an estimated integrated ionizing radiation dose of about 235 krad, which exceeds the radiation tolerance of the sensors by a factor of two. It is therefore concluded that the sensors have to be protected against beam ions.

The studies on how to protect the sensors have started only recently. Among the options are:

(i) Increase the gap of the SAVD, which may be carried out even during run time thanks to the positioning tables. This step will however change the acceptance for open charm particles, which remains to be worked out in a quantitative way.

(ii) Collimate the beam by a collimator installed upstream of the target. Interactions in the collimator will produce fragments and secondary particles and a fraction of them will hit the VD. The radiation load for the SAVD will be reduced as the damage created by the fragments is smaller than the one of the ions. Moreover, it is distributed over a larger surface. It is currently expected that the VD is able to handle the additional load provided a veto counter in front of the target is employed to request a fast beam abort in case of malfunction of the beam line. Again, the scenario has to be worked out in detail.
(iii) Improve the focusing of the beam, which may however be limited by the hardware of the beam line.

(iv) Employ a next generation sensor technology, e.g. the FSBB [93]. However, this would require significant efforts as a different/additional DAQ system has to be developed.

The November 2015 test run with Pb beam at $30AGeV/c$ will be used to test some of these options.

**Operating MIMOSA-26AHR above its nominal radiation tolerance** As shown in Fig. 31, the beam ions hit a relatively small area of the sensitive surface of the sensors. It might therefore be possible to sacrifice this area and to operate the sensors beyond their nominal radiation tolerance. This requires however that the damaged pixels do not disturb the operation of the non-irradiated part of the sensor.

It was therefore studied in how far radiation damage on this restricted surface would affect the operation of the remaining pixels. According to our preliminary results, applying a radiation dose of 300 krad to a part of the pixel matrix causes a slight drop of the dark signal of the irradiated pixels. Given that the signal of the irradiated and the non-irradiated pixels is discriminated with a common threshold, this represents an effective rise of the threshold of the affected pixels and therefore leads to a loss of sensitivity. Moreover, one observes an increased thermal noise, which may create additional fake hits. However, the non-irradiated pixels are found to operate without radiation induced artefacts.

In case a significant number of fake hits are produced, this may saturate the bandwidth of the sensors. If so, the data is truncated in a controlled way. The data from the non-irradiated part of the sensor will remain available as, according to the direction of the rolling shutter, those pixels are read out first.

It is known that ionizing radiation damage in MAPS may be cured by thermal annealing [94]. It is found that this method can be applied to MIMOSA-26AHR [95]. This opens the option to eliminate a part of the radiation damage on the sensors during beam breaks by means of increasing the coolant temperature for example to $+80^\circ C$.

### 5.5 Status and plans toward the completion of the SAVD

The SAVD is being constructed by a collaboration formed from members of four Universities and CERN. These groups participate in the upgrade of the ALICE-ITS and in the CBM-MVD project and provide their know-how and their solutions to implement the SAVD for NA61/SHINE.

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3 The AGH University of Science and Technology, Krakow; the Institute für Kernphysik, Goethe University Frankfurt (IKF); the Jagiellonian University, Krakow; the St. Petersburg State University, St. Petersburg.
Table 2: Status of and responsibilities for different work packages concerning the detector R&D and integration. The difference between the groups performing the initial R&D within their experiment and the responsibilities within the SAVD-project reflects the technology transfer towards NA61/SHINE. Remarks: (1) Remains to be adapted to the needs of NA61/SHINE

<table>
<thead>
<tr>
<th>Issue</th>
<th>Status</th>
<th>R&amp;D by</th>
<th>Responsible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor, rad. tolerance, thinning</td>
<td>Completed</td>
<td>IPHC / IKF</td>
<td>IKF</td>
</tr>
<tr>
<td>Sensor, handling and integration</td>
<td>Established</td>
<td>IKF</td>
<td>IKF</td>
</tr>
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<td>Sensor, probe test</td>
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<td>IKF</td>
</tr>
<tr>
<td>Sensor, bonding</td>
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<td>IKF</td>
</tr>
<tr>
<td>Detector ladders, construction</td>
<td>Completed</td>
<td>ALICE-ITS</td>
<td>St. Petersburg</td>
</tr>
<tr>
<td>Detector ladders, cooling</td>
<td>Completed</td>
<td>ALICE-ITS</td>
<td>St. Petersburg</td>
</tr>
<tr>
<td>Cooling plant</td>
<td>Established</td>
<td>–</td>
<td>Krakow</td>
</tr>
<tr>
<td>Cooling plant</td>
<td>Under design</td>
<td>Krakow</td>
<td>Krako</td>
</tr>
<tr>
<td>Micro cables</td>
<td>Demonstrated</td>
<td>IKF</td>
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<tr>
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<td>Krakow</td>
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<tr>
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<td>Krakow</td>
</tr>
<tr>
<td>Local DAQ, interface to NA61</td>
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<td>Krakow</td>
</tr>
<tr>
<td>LV-System</td>
<td>Under design</td>
<td>Industrial</td>
<td>–</td>
</tr>
<tr>
<td>LV-System</td>
<td>Under design</td>
<td>Krakow</td>
<td>Krakow</td>
</tr>
<tr>
<td>Helium box</td>
<td>Under design</td>
<td>Krakow</td>
<td>Krakow</td>
</tr>
<tr>
<td>Detector frame</td>
<td>Under design</td>
<td>Krakow</td>
<td>Krakow</td>
</tr>
<tr>
<td>Position tables</td>
<td>Under design</td>
<td>Industrial</td>
<td>–</td>
</tr>
<tr>
<td>Alignment system (mechanical)</td>
<td>Demonstrated</td>
<td>ALICE-ITS</td>
<td>St. Petersburg</td>
</tr>
<tr>
<td>Alignment system (track alignment)</td>
<td>Demonstrated</td>
<td>IKF</td>
<td>NA61/SHINE</td>
</tr>
<tr>
<td>Digitizer software</td>
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<td>IKF</td>
<td>NA61/SHINE</td>
</tr>
<tr>
<td>Data analysis (cluster analysis)</td>
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<td>Krakow</td>
</tr>
<tr>
<td>Data analysis (tracking)</td>
<td>Demonstrated</td>
<td>NA61/SHINE</td>
<td>NA61/SHINE</td>
</tr>
</tbody>
</table>

The suitability of the chosen sensor technology was demonstrated by the operation of a mostly identical sensor in the STAR-PXL detector. Members of the involved project team at the IPHC Strasbourg are regularly consulted. As far as the sensor integration and the DAQ-system is concerned, the SAVD is a slightly enlarged and improved version of the prototype of the CBM-MVD [84]. The carbon fibre ladders are being mass produced for the ALICE-ITS upgrade.

Consequently, most of the R&D needed for the SAVD was performed in the past, in great part in the framework of the dedicated R&D programs of the experiments mentioned above (see Table 2 for an overview). Comprehensive strategies for completing the remaining work packages in the near future were worked out in the process of applying for project money. The application was submitted to the Polish National Science Center in December 2014 and was accepted for funding in June 2015. The grant will cover costs
of purchasing MIMOSA26-AHR sensors and most of the design, construction as well as travel costs related to tests of the SAVD at CERN. Complementary resources are being requested from German funding agencies.

The remaining open work packages will finalize the mechanical design of the helium box, the detector frames and the coolant distribution system. Moreover, adapting the existing DAQ and the slow control of the CBM-MVD prototype to the needs of NA61/SHINE is still ongoing. In all cases, the complex points of the related work packages and systems were successfully addressed during the R&D for CBM and ALICE. The remaining design and implementation tasks are considered moderately complex on the scale of experienced engineers and DAQ experts. The design of the latch-up and temperature protection of the sensors is progressing based on existing and tested hardware.

On the software side, the necessary digitizer [96] and cluster finder codes were provided by the CBM-MVD group and are being implemented into the NA61/SHINE simulation and data analysis framework. Progress of this activity will allow to improve the simulations, tracking codes and particle reconstruction codes, in order to account for the 0.1-0.3 T residual magnetic field in the SAVD region.

It is intended to finalize construction of ladders of the SAVD by February 2016. In parallel, the adaptation of the DAQ and the design of the helium box will be completed. The box will be constructed while the ladders are tested with cosmic muons.

In May 2016 we plan to transport the fully integrated detector to CERN and install the device in the NA61/SHINE experimental environment. This will include the mounting of the mechanical structure on the movable platform in the interaction zone, the integration with the NA61/SHINE central DAQ and connection with the detector infrastructure like voltage supplies, helium gas flow system and water cooling system.

For commissioning of the complete set-up we request two weeks of proton beam at 150 GeV/c to produce interactions in the Pb target installed inside the SAVD vessel. The goals of the test period are:

(i) test the performance of the SAVD subsystems in the experimental hall environment,

(ii) test the SAVD readout integrated with the NA61/SHINE central DAQ,

(iii) commission data synchronization and track reconstruction in the SAVD.

After the data of this test run will have been analysed and potential weaknesses in the SAVD are eliminated, we intend to carry out a pilot run with Pb+Pb collisions at 150 A GeV/c in November 2016. This will validate the performance of the SAVD in the Pb beam and the associated high track density. Moreover, during the pilot run about 1M central Pb+Pb collisions are expected to be recorded. The analysis is expected to show a SNR for the $D^0 + \overline{D^0}$ signal of about 12 which is sufficient to demonstrate the physics capabilities of the SAVD.

Physics data taking with the SAVD is planned in 2018. Pb beams at 75 A and 150 A GeV/c for 40 days in total are requested for this purpose.
The upgrade to the large acceptance vertex detector is planned to be ready by 2020 and then precise measurements of open charm production at the CERN SPS could follow.
6 Data taking

Data is planned to be recorded under conditions similar to those used for Ar beams:

(i) SPS cycle length: 26.4 s, flat top: 8.5 s and thus a duty cycle: ≈0.3,

(ii) Pb beam intensity at the NA61/SHINE target: ≈10^4 ions/s,

(iii) Pb target: ≈5% interaction probability (about 0.25 cm thickness),

(iv) recorded event rate during the spill: 50 Hz,

(v) mean number of recorded events per day: ≈400k (the averaging includes beam, detector, trigger set-up time as well as machine stops).

Data will be recorded using two on-line event selections:

(i) minimum bias event selection and

(ii) central collision event selection.

The ratio of central to minimum bias events will be 1:4 for data on Pb+Pb collisions at 13A, 19A, 30A, 40A GeV/c and 1:1 for data on collisions at 75A and 150A GeV/c.

The central collision event selection was used for data taking with Be and Ar beams. About ≈30% of all inelastic interactions with the smallest energy measured by the Projectile Spectator Detector were recorded.

The minimum bias event selection will be provided by anti-coincidence of the incoming beam particle with the signal from a scintillator detector located just downstream of the target holder. This should minimize the contamination by non-target interactions. The detector will work as a threshold detector with the threshold set just below the Pb-ion signal. Two of the possible solutions for this minimum bias detector are considered:

(i) plastic scintillator detector

(ii) Cherenkov counter with thin quartz glass as radiator

In both cases the light signal will be read by a PMT. The detector will work in the area where a fringe magnetic field exist and thus it is planned to use a PMT designed to work in a magnetic field environment. Moreover it is considered to install a light guide between the plastic or quartz and the PMT in order to position the PMT in a reduced field region. Both possible solutions for the minimum bias trigger (scintillator and Cherenkov detector) are planned to be tested during the 2015 November test period with Pb beam at 30A GeV/c.

The NA61/SHINE data taking plan which includes the requested runs with primary Pb beams is shown in Table 3. The same table is presented in the 2015 Status Report submitted to the SPSC in parallel to this document. Following the current accelerator
<table>
<thead>
<tr>
<th>Beam Primary</th>
<th>Secondary</th>
<th>Target</th>
<th>Momentum ($A \text{ GeV}/c$)</th>
<th>Year</th>
<th>Days</th>
<th>Physics</th>
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<tbody>
<tr>
<td>P</td>
<td>h$^+$</td>
<td>A</td>
<td>400</td>
<td>2016</td>
<td>4x7 days</td>
<td>installation/tests</td>
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<tr>
<td>P</td>
<td>P</td>
<td>p</td>
<td>400</td>
<td>2016</td>
<td>28 days</td>
<td>SI</td>
</tr>
<tr>
<td>P</td>
<td>h$^+$</td>
<td>A</td>
<td>30–120</td>
<td>2016</td>
<td>42 days</td>
<td>$\nu$</td>
</tr>
<tr>
<td>Pb</td>
<td>Pb</td>
<td>13, 19, 30, 40</td>
<td>2016</td>
<td>40 days</td>
<td>SI</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>Pb</td>
<td>150</td>
<td>2016</td>
<td>5 days</td>
<td>SI</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>P</td>
<td>p/Pb</td>
<td>13, 19, 30, 40, 75</td>
<td>2017</td>
<td>35 days</td>
<td>SI</td>
</tr>
<tr>
<td>P</td>
<td>h$^+$</td>
<td>A</td>
<td>30–120</td>
<td>2017</td>
<td>42 days</td>
<td>$\nu$</td>
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<tr>
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<td>60 days</td>
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<tr>
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<td>P</td>
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<tr>
<td>Pb</td>
<td>Pb</td>
<td>75, 150</td>
<td>2018</td>
<td>40 days</td>
<td>SI</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3:** The NA61/SHINE data taking plan revised in 2015. The following abbreviations are used for the physics goals: SI – measurements for physics of strong interactions, $\nu$ – measurements for the Fermilab neutrino beams.

The schedule the plan assumes that the data taking with primary Xe beam will take place in 2017 and with Pb beam in 2016 and 2018.

Figure 33 schematically illustrates status and plans concerning data taking for the NA61/SHINE (beam momentum)-(system size) scan.

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Figure 33: The NA61/SHINE data taking schedule for the (beam momentum)-(system size) scan and its proposed extension for the period 2016-2018 with data taking on Pb+Pb collisions (in gray).

Sciences, the Polish Ministry of Science and Higher Education (grants 667/N-CERN/2010/0, NN 202 48 4339 and NN 202 23 1837), the National Science Centre, Poland (grants 2011/03/N/ST2/03691, 2012/04/M/ST2/00816, 2013/11/N/ST2/03879, 2014/14/E/ST2/00018 and 2014/14/B/ST2/02537), the Foundation for Polish Science — MPD program, co-financed by the European Union within the European Regional Development Fund, the Federal Agency of Education of the Ministry of Education and Science of the Russian Federation (SPbSU research grant 11.38.193.2014), the Russian Academy of Science and the Russian Foundation for Basic Research (grants 08-02-00018, 09-02-00664 and 12-02-91503-CERN), the Ministry of Education, Culture, Sports, Science and Technology, Japan, Grant-in-Aid for Scientific Research (grants 18071005, 19034011, 19740162, 20740160 and 20039012), the German Research Foundation (grant GA 1480/2-2), the EU-funded Marie Curie Outgoing Fellowship, Grant PIOF-GA-2013-624803, the Bulgarian Nuclear Regulatory Agency and the Joint Institute for Nuclear Research, Dubna (bilateral contract No. 4418-1-15/17), Ministry of Education and Science of the Republic of Serbia (grant OI171002), Swiss Nationalfonds Foundation (grant 200020117913/1) and ETH Research Grant TH-0107-3.
References


[38] F. Guber et al., [CBM Collab.] http://repository.gsi.de/record/109059 (2015).


[54] M. Stephanov, “private cummunication.”.


[56] M. Stephanov, “private cummunication.”.


