Report from the NA61/SHINE experiment at the CERN SPS

The NA61/SHINE Collaboration

This document reports on the status and plans of the NA61/SHINE experiment at the CERN SPS as of October 2018. The document refers to the proposal SPSC-P-330.
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1 Introduction

This NA61/SHINE annual report presents briefly the status and plans of the NA61/SHINE experiment [1] at the CERN SPS. The report refers to the period October 2017 – October 2018.

The document is organized as follows. The data taking summary is given in Section 2. A summary of facility modifications is presented in Sec. 3. Software and calibration modifications are listed in Sec. 4. New results are briefly reviewed in Sec. 5. Finally, the data-taking plan for 2021 – 2024 and the detector upgrade strategy is summarized in Sec. 6. These are fully presented in Addenda [2, 3] submitted to the SPSC earlier this year. The summary in Sec. 7 closes the report.

2 Data-taking summary

Data taking for p+Pb interactions at 40 GeV/c took place in October 2017. During one week-long period 4.3 million events were registered. This data is the last p+Pb reaction planned to be recorded by NA61/SHINE.

In October, November, and December 2017 NA61/SHINE recorded Xe+La collisions at six beam momenta. With this data taking NA61/SHINE completed its two-dimensional scan in nuclear mass number and collision momentum of colliding nuclei. Data at beam momenta of 40A, 75A, and 150A GeV/c were recorded with the Vertex Detector turned on. At lower beam momenta the large transverse size of the beam could lead to damage of Vertex Detector sensors and therefore the Vertex Detector was turned off. Table 1 presents the statistics of the data taken for each reaction.

<table>
<thead>
<tr>
<th>beam target</th>
<th>beam momentum</th>
<th>number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe La</td>
<td>13A GeV/c</td>
<td>3.0M</td>
</tr>
<tr>
<td>Xe La</td>
<td>19A GeV/c</td>
<td>3.9M</td>
</tr>
<tr>
<td>Xe La</td>
<td>30A GeV/c</td>
<td>5.1M</td>
</tr>
<tr>
<td>Xe La</td>
<td>40A GeV/c</td>
<td>4.0M</td>
</tr>
<tr>
<td>Xe La</td>
<td>75A GeV/c</td>
<td>2.6M</td>
</tr>
<tr>
<td>Xe La</td>
<td>150A GeV/c</td>
<td>4.9M</td>
</tr>
</tbody>
</table>

The NA61/SHINE beam time in 2018 started in April with a PSD calibration run. During this run tests of various PSD readout electronics including the DRS4-based readout system were also carried out.

In July 2018, data taking with a 1.3-metre-long replica of the NOvA target was performed. Problems with the cryogenics of the VERTEX-1 magnet, beam downtime and setup of the
new DRS4 readout shortened the available running time. NA61/SHINE recorded 18 million p+NOvA replica target events, 15 million of which had the full detector operational. During this data taking the Time-of-Flight Forward detector was read out by DRS4 electronics. The DRS4 readout control was included in the standard NA61/SHINE run control application for the first time. The recorded statistics were below the goal, so an additional week of NOvA target running is planned for autumn 2018.

3 Facility modifications

This section briefly presents the main modifications of the NA61/SHINE facility introduced during the last twelve months.

3.1 NOvA target replica

In July–August 2018, NA61/SHINE collected 15 million 120 GeV/c proton events on a replica of the Fermilab NOvA target. The data are intended to improve flux predictions for the NOvA and MINERvA experiments, and will complement the measurements made in 2017 with the same beam energies on a thin carbon target. The target (Fig. 1), which was provided by Fermilab, consisted of a series of contoured graphite fins held in place by an aluminium frame. The beam runs about 3 mm from the top edge of the fins; the total length of the target material is 1.25 m. Special runs were done with the target removed completely, and with the target removed but the upstream S3 trigger counter (also seen in Fig. 1) in place.
Figure 2: Reconstructed vertex positions for 120 GeV/c proton interactions on the NOvA replica target, recorded by NA61/SHINE in summer 2018. Left: Top view; Right: Side view. The boundary of the graphite target fins is shown as a black outline.

Figure 3: Reconstructed longitudinal vertex positions for 120 GeV/c proton interactions on the NOvA replica target. Red vertical lines indicate the upstream and downstream faces of the target.

Preliminary transverse and longitudinal vertex distributions have been obtained (Figs. 2 and 3 show about one day’s data collection) and show vertices being reconstructed successfully within the target material. Due to the magnet bend direction (and the preliminary nature of the field correction in tracking), the resolution is considerably better in the $y$ direction. The exponential longitudinal drop-off of vertices is also apparent. New tracking algorithms under development now will considerably improve the reconstruction, as well as integrate the forward TPCs (that were installed last year and were used for this data set) into the analysis.

The data collection period was generally successful, but was only about half as long as planned. The total number of events recorded is somewhat higher than the 10 million previously recorded on the replica T2K target (published this year [4]), which will give T2K approximately 5 % precision in the important bins for neutrino production. However, the
NOvA target lacks T2K’s azimuthal symmetry, so an additional binning dimension will be required; more events will therefore be required to achieve comparable precision per bin. Therefore, neutrino running this autumn (originally intended for measuring 60 GeV/c K⁺+C interactions) will be dedicated to additional data with the NOvA target.

3.2 PSD upgrade, tests and calibration

The Projectile Spectator Detector (PSD) is a segmented forward hadron calorimeter used by NA61/SHINE to determine the collision centrality and the orientation of the event plane. A precise characterization of the event class is of crucial importance for selection of event centrality at the trigger level as well as for the analysis of event-by-event fluctuation observables. The PSD is also important for improving the quality and kinematic range of measurements of collective flow in the collisions.

3.2.1 Performance of the PSD during the Xe+La data taking

In 2017 the PSD was used during the Xe+La beam time. It served as the trigger detector for selecting central collisions. Calibration of the central short module (module number 45) was performed with Xe ions. The energy reconstructed from the PSD measurements is shown in Fig. 4 (the upper-left plot) for different trigger types. The PSD energy is normalized to the beam energy. T1 is a beam trigger, T2 is an interaction trigger and T4 selects minimum bias interactions. Figure 4 shows correlation plots between the number of reconstructed tracks and the energy in the PSD for the T2 trigger. Results for beam momenta of 19 A GeV/c and 30 A GeV/c are shown in Fig. 4 (upper-right) and (bottom-right), respectively.

3.2.2 PSD calibration

During May 2018 the PSD was calibrated with a proton beam of 80 GeV/c. A view of the PSD is shown in Fig. 5 (left) and a sketch showing the modules used for the PSD calibration is presented in Fig. 5 (right). The calibration procedure included a scan of the PSD modules with muon and hadron beams as well as an energy scan with hadrons of 10–150 GeV/c. The PSD response linearity for all calibrated modules is presented in Fig. 6 (left) and the energy resolution is shown in Fig. 6 (right).

3.2.3 F-PSD performance test

The NA61/SHINE physics program beyond 2020 requires a tenfold increase of beam and trigger rates. This necessitates a PSD upgrade.

The increase of the Pb-beam rate by more than one order of magnitude will lead to a high radiation level in the experimental area of NA61/SHINE, because the present PSD is in effect an active beam dump. Therefore, the PSD must be shielded by additional concrete blocks. This is practically impossible for the present calorimeter because it is placed on a movable...
platform with large transverse size which facilitates the required changes of the lateral PSD position during data taking.

To solve the above problems, it is proposed to use two calorimeters, a Main (M-PSD) and a Forward (F-PSD) Projectile Spectator Detector (see Fig. 7) instead of the present PSD. The M-PSD would be based on the present PSD with the 16 small central modules replaced by four new central modules with transverse sizes $20 \times 20 \text{ cm}^2$ and with truncated edges forming a beam hole of 60 mm diameter at the center. In addition, 8 cm thick boron polyethylene blocks placed at the rear side of each of these modules will reduce the neutron fluence incident on the readout MPPCs.

The F-PSD is an additional small calorimeter placed at a distance of 4.6 m downstream of M-PSD, see Fig. 8. It consists of 9 modules with transverse sizes of $20 \times 20 \text{ cm}^2$. All F-PSD modules will have $5.6 \lambda_{\text{int}}$ interaction lengths, the same as in the M-PSD, except for a longer central module of $7.8 \lambda_{\text{int}}$. As for the M-PSD, 8 cm thick boron polyethylene blocks will be placed at the rear side of each module. According to simulations, the two calorimeter setup will decrease the hadron shower leakage for Pb+Pb interactions at 150 A GeV/c from 11% for the present PSD to 4%.

Figure 4: Performance of PSD during Xe+La beam period. Upper-left: Response of PSD for different trigger types. Correlation plots of number of tracks reconstructed versus the PSD energy: at 19 A GeV (upper-right), 30 A GeV (bottom-left) and 40 A GeV (bottom-right). PSD energies are normalized to the beam energy.
During the May 2018 beam test time the F-PSD supermodule was tested with beams of momenta from 10 to 200 GeV/c. A view of the installed F-PSD is shown in Fig. 9. The measured F-PSD energy spectra and the energy resolution curve are presented in Fig. 10.

3.3 DRS4 based readout

DRS4-based readout boards were constructed and tested with the Forward Time of Flight (F-ToF) and PSD detectors. They were used for the first time to read out the F-ToF during the physics run in August 2017 and again in the summer (neutrino run) of 2018.

The F-ToF used four (out of ten) existing ToF-F modules installed behind the MTPCs and covering the gap between FTPC-2/3 and ToF-L/R. Signals from 64 photo-multipliers were readout with new DRS4 boards, custom VME backplane, and controller card. Presently the DRS4 readout is not integrated into the main DAQ and data was collected using a stand-alone system. Synchronization between both DAQs was confirmed with a preliminary time resolution of 62 ps obtained for the F-ToF system as shown in Fig. 11. Also shown in Fig. 11 is the time separation observed between protons and pions versus momentum using one
3.4 Trigger and beam counters modification

In the current setup of the beam and trigger counters for the heavy ion runs the air around the detectors has a similar interaction length as the counters. To mitigate this problem two modifications to the beam-line were carried out. The first one comprises:

(i) placement of the S2 and V0 counters in vacuum,
(ii) extending the vacuum near the target by shifting the BPD-3 detector closer to the Vertex Detector,
(iii) removal of the XWDC.021.528 wire chamber,
(iv) placement of the XSCI.021.528 scintillator on a common movable support with the XWDC.021.527 wire chamber,
(v) fabrication of a “double-T” vacuum pipe for the S2 and V0 counters.

Figure 12 shows the area of the beam-line around S2 before and after modification. The modifications lowered the number of delta electrons hitting the S2 and V0 counters which enhanced their signals. It also removed ≈ 1000 mm of air from the beam-line.

The second modification involved installing BPD-3 on a rotating support. This support allows to move BPD-3 closer to the Vertex Detector and to install additional ≈ 100 mm of vacuum pipe. The modification significantly lowers the rate of recorded out-of-target background interactions.

Together both beam-line modifications should lower the number of recorded out-of-target interactions by ≈ 20% and slightly increase the trigger rates and detector signal quality.
Figure 11: Left: Preliminary F-ToF time resolution obtained with DRS4 based readout. Right: Time separation observed between protons and pions using the F-ToF and DRS4 readout versus momentum.

4 Software and calibration modifications

4.1 Native SHINE Software

4.1.1 SHINE framework

The SHINE framework is routinely used for reconstruction of data sets collected after 2015, data quality assessment, calibration and physics analysis. As mentioned in the previous status report, it was decided that processing of older data sets should continue with the legacy software.

Over the last year, 4 releases were made, out of which 2 were small patch releases and 2 were major regular releases. The latter introduced, among other modifications, a change of the C++ standard from C++03 to C++11, preliminary native local and global tracking in the TPCs as well as the search for the main vertex. Also numerous performance improvements were introduced. The regular release v1r9p0 was the first one to be installed simultaneously in both the 32 bit mode (for running the wrapped legacy reconstruction chain) and the 64 bit mode (for all other tasks). Furthermore, tests were augmented with checks of the backward compatibility of the data structure in large data files from previous framework versions. This was in response to the bug introduced in the v1r9p0 release which caused random crashes of data reading. The bug was fixed in the next patch release.
4.1.2 Infrastructure changes

According to the CERN IT infrastructure development plan, the following tasks were performed:

(i) The version control system was changed. All SVN repositories were moved to GIT hosted in the GitLab service at CERN.

(ii) The Jira service at CERN was successfully re-introduced as the issue tracking system to improve the control over tasks that need to be done.

(iii) CERN is currently reducing its dependence on AFS and will eventually phase out this service completely. NA61/SHINE has started the transfer process for files and applications to the new storage areas (EOS and CVMFS). The services websites were transferred to the EOS file-system. Moreover the SHINE framework documentation server was moved from DFS to EOS.

(iv) For data production and reconstruction new batch scripts were prepared and the collaboration started to extensively use HTCondor as the Batch Service instead of LSF.

(v) A new system to schedule shifts was prepared and implemented.

4.1.3 Monte Carlo simulation

Since the Status Report 2017, the only major change of the SHINE Monte Carlo simulation chain was a GEANT4 version update. This allows to compare the latest model predictions on nucleus-nucleus interactions with data. Detector simulation was updated to GEANT4 version 10.4 together with C++11 implementation as described in Sec. 4.1.1. The latest version of the SHINE Monte Carlo simulation chain is being used for physics analyses, such as the study of Ar+Sc interactions.

The procedure of event reconstruction is common for data and Monte Carlo simulation and will be discussed in the next section.

The following items are under development: the vertex detector digitizer to simulate pixel-based detector response, the ToF detector digitizer to simulate scintillator-based detector response, and the fast PSD simulator to avoid time and resource consuming Geant4 simulation for mass production of high multiplicity heavy ion samples.

4.1.4 Event reconstruction

Since the Status Report 2016 the Collaboration started to use SHINE reconstruction software for production and analysis of data and Monte Carlo simulations. This new software still inherits some functions and modules from the “legacy” software, while new SHINE native reconstruction is under development. The following section focuses on the status and prospect of the new SHINE native reconstruction development.
The SHINE reconstruction chain consists of 4 main parts: cluster reconstruction, local track finding, global track merging, and main vertex finding. Cluster reconstruction had already been developed in SHINE and will not be discussed.

To reconstruct local tracks in each detector, track seeds are found by the Cellular Automaton algorithm (CA) [5]. CA was chosen because it is a fast and robust algorithm in terms of performance and dealing with detector inefficiency, and is also suitable for data reconstruction in a high multiplicity environment. Once track seeds are formed, they are merged using Kalman Filter extrapolation and fitting and local tracks are reconstructed. The merging procedure works for track segments either from upstream to downstream or vice versa.

Reconstructed local tracks are then used to form global tracks. The merging procedure works in a manner similar to local track formation. Starting from an upstream detector, tracks are extrapolated to all downstream detectors and merged using the Kalman Filter technique.

Once global tracks are reconstructed, they are used to find the main vertex. The point of closest approach (PCA) based algorithm has been developed particularly for long targets, such as the liquid hydrogen target or neutrino replica targets. For the thin target vertex finding, either the PCA based approach or the existing SHINE algorithm can be used. Vertex re-fitting will follow after finding the main vertices and is under development.

An example of the event reconstruction procedure is shown in Fig. 13. Typical performance of the new reconstruction chain for low and high multiplicity environment is summarized in Table 2.
Table 2: Reconstruction efficiency for local track finding and global track merging in low multiplicity (p+C) and high multiplicity (Pb+Pb) Monte Carlo simulated events. Performance at 1 GeV/c and above 5 GeV/c is shown.

<table>
<thead>
<tr>
<th>Track Type</th>
<th>p+C</th>
<th>Pb+Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>$\approx$90%</td>
<td>$\approx$85%</td>
</tr>
<tr>
<td>Global</td>
<td>$\approx$95%</td>
<td>$\approx$90%</td>
</tr>
</tbody>
</table>

4.2 Calibration

4.2.1 Calibration update

This subsection lists calibration activities, upgrades and modifications during the last year:

(i) Data samples collected before 2016 were reconstructed using "legacy" software and were calibrated by all currently available SHINE calibration modules using the SHOE data format.

(ii) Data samples were produced for calibration purposes both on the LXBATCH and on the HTCondor system.

(iii) Calibration of energy loss in the TPCs ($dE/dx$) is still ongoing using "legacy" calibration software but the old DSPACK format is not required any more. A new fitter for $dE/dx$ calibration and quality assessment was implemented and tested. The work on native SHINE calibration and reconstruction modules is still ongoing.

(iv) The magnetic field for the beam momentum of 13 GeV/c was carefully recalibrated using data from the TPCs ($dE/dx$), ToF (time-of-flight) detectors and the invariant mass of $\Lambda$ hyperon decay products. New scaling factors for the VTPC-1 and VTPC-2 magnetic fields were obtained and implemented in both legacy and SHINE data bases.

(v) The reconstruction of p+p and Ar+Sc collisions at 13A GeV/c beam momentum were redone using the new magnetic field scaling factors.

(vi) The vD-PA SHINE calibration module which provides the TPC calibration parameters for the drift velocities, the time offsets and and vertical shifts of all chambers was tested on several data samples and validated. The module was used for the calibration of Pb+Pb data samples collected at 13A and 30A GeV/c beam momentum. The calibration of other data samples is ongoing.

(vii) The PSD modules were recalibrated for Be+Be collisions using experimental data. The procedure was based on proper energy reconstruction of single nucleon clusters. The recalibration was done on the module level, i.e. the correction parameters were determined for each PSD module (see dedicated sub-section).

(viii) The PSD detector modules were calibrated using dedicated calibration runs with muon beams and proton beams at various momenta (see dedicated sub-section).
5 New results

5.1 New results for strong interactions physics

This section summarizes new physics results from the programme on physics of strong interactions and reports on analysis progress. The most recent results on spectra and yields as well as fluctuations and correlations are presented.

5.1.1 $K^*(892)^0$ meson production in $p+p$ interactions at 158 GeV/c

The first NA61/SHINE measurement of $K^*(892)^0$ meson production via its $K^+\pi^-$ decay mode in inelastic $p+p$ collisions at beam momentum 158 GeV/c ($\sqrt{s_{NN}} = 17.3$ GeV) was obtained and presented at the 2018 workshop on the Critical Point and Onset of Deconfinement [6]. The template method was used to extract raw $K^*(892)^0$ signals. In this method the background is described as a sum of two components: mixed events and Monte Carlo generated templates which describe the contribution of $K^+\pi^-$ pairs coming from sources other than the $K^*(892)^0$. The template method was found to be much more effective in estimating the background than the standard procedure relying on mixed events only. Values of the mass and width of the $K^*(892)^0$ were obtained from fits to the background subtracted invariant mass spectra in several transverse momentum bins. The results are in agreement with the values given in the PDG tables.

With the large statistics of NA61/SHINE data (about 53M recorded interaction trigger events, combining data from the years 2009, 2010 and 2011) it was possible to obtain the double differential transverse momentum and rapidity spectra of $K^*(892)^0$ mesons. The double differential yields of $K^*(892)^0$ in inelastic $p+p$ events at 158 GeV/c are presented in bins of ($y, p_T$) in Fig. 14. In the left panel the shown uncertainties are statistical, in the right panel systematic.

![Figure 14](image)

Figure 14: Double differential yields of $K^*(892)^0$ in (GeV/c)$^{-1}$ in bins of ($y, p_T$) for inelastic $p+p$ collisions at 158 GeV/c. The left plot presents the results with statistical and the right plot with the systematic uncertainties.

The rapidity spectra of $K^*(892)^0$ mesons in inelastic $p+p$ collisions at 158 GeV/c are shown in Fig. 15 and compared with published NA49 results [7] for the same system and energy. The mean multiplicity of $K^*(892)^0$ mesons in full phase-space ($4\pi$) was obtained from summing the measured points and adding the contribution from a Gaussian fit in the unmeasured
region (red line in Fig. 15, right). The point for \( y < 0 \) was calculated only to check the symmetry of the rapidity distribution and was not included in the procedure of mean multiplicity determination. The value of the mean multiplicity of \( K^*(892)^0 \) mesons was found to be \( 0.08058 \pm 0.00059 \pm 0.0026 \), where the first uncertainty is statistical and the second is systematic. This result is similar to the NA49 measurement \( (0.0741 \pm 0.0015 \pm 0.0067) \) for the same system and energy [7], however the NA49 multiplicity was obtained for the range \( 0 < p_T < 1.5 \text{ GeV}/c \) instead of \( 4\pi \) acceptance as in NA61/SHINE.

The NA61/SHINE result was also compared with predictions of statistical Hadron Resonance Gas models in Canonical (CE) and Grand Canonical (GCE) formulations. Surprisingly, the GCE model [8, 9] (multiplicity \( \langle K^*(892)^0 \rangle = 0.0805 \)) provides a very good description of NA61/SHINE result for the \( K^*(892)^0 \) multiplicity in p+p interactions. The CE model [10] also agrees (multiplicity \( \langle K^*(892)^0 \rangle = 0.0741 \)) provided that the \( \phi \) meson is excluded from the fits.

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**Figure 15:** Left: Rapidity distribution of \( K^*(892)^0 \) for one wide transverse momentum bin \( (0 < p_T < 1.5 \text{ GeV}/c) \). NA49 points are taken from Ref. [7]. Only statistical uncertainties are shown. Right: \( p_T \)-integrated and extrapolated rapidity distribution (NA49 points are the same as in the left panel). Red bands correspond to NA61/SHINE systematic uncertainties. Solid lines correspond to Gaussian fits.

### 5.1.2 \( \Xi^- \) production in p+p interactions at 158 GeV/c

Hyperons are excellent probes of the dynamics of proton-proton interactions as constituent strange quarks are not present in the initial state of this process. Therefore hyperon production has been studied in a long series of experiments in elementary hadron+hadron interactions. However, the experimental situation in this field remains inconclusive.

This report presents new data from p+p collisions on \( \Xi^- \) hyperon production. The event sample consists of 60 million registered collisions obtained at 158 GeV/c beam momentum corresponding to \( \sqrt{s_{NN}} = 17.3 \text{ GeV}/c \). Final results refer to primary \( \Xi^- \) produced in strong and electromagnetic processes and are corrected for detector geometrical acceptance and reconstruction efficiency.

To find the \( \Xi \) candidates, all \( \Lambda \) candidates are combined with pion tracks of appropriate charge (daughter track). A fitting procedure is applied, using as parameters the decay position of the \( V^0 \) candidate, the momenta of both the \( V^0 \) decay tracks, the momentum of the daughter track, and finally the \( z \) position of the \( \Xi \) decay point. The \( x \) and \( y \) position of the
Figure 16: Invariant mass of $\Lambda - \pi^-$ candidate pairs in p+p interactions at mid-rapidity ($-0.25 < y < 0.25$) calculated assuming $\Xi^-$-decay hypothesis in a transverse momentum bin from 0.4 to 0.6 GeV/c. For explanation of curves and lines see text.

$\Xi$ decay position are not subject to the minimization, as they are determined from the parameters using momentum conservation. This procedure yields the decay position and the momentum of the $\Xi$ candidate.

To reduce the background in the invariant mass distribution several selection criteria where applied:

(i) The $\Xi^-$ candidate originates from the main vertex.

(ii) The $\Lambda$ vertex is located downstream from the $\Xi^-$ vertex.

(iii) The extrapolated impact parameter of the $\Xi^-$ in the $x$ and $y$ direction at the main vertex $z$ position $\sqrt{b_{\Xi x}^2 + (b_{\Xi y}/0.5)^2}$ is smaller than 1.0 cm.

(iv) A rapidity dependent cut on the distance between the primary and the secondary $\Xi$ vertex:

<table>
<thead>
<tr>
<th>$\Xi$ rapidity</th>
<th>$y &lt; -1.75$</th>
<th>$-1.75 &lt; y &lt; 0.75$</th>
<th>$0.75 &lt; y &lt; 1.25$</th>
<th>$1.25 &lt; y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum decay length</td>
<td>0 cm</td>
<td>5 cm</td>
<td>12 cm</td>
<td>20 cm</td>
</tr>
</tbody>
</table>

About half of the background is removed with these cuts, with the signal effectively unchanged.

An example of the invariant mass distribution of $\Xi^-$ candidates is plotted in Fig. 16 for a selected transverse momentum bin around mid-rapidity. The black curve shows the fitted function consisting of a Lorenzian for the signal and a polynomial (up to 4th order) for the background. Additionally, the signal component of the fit is shown in magenta and the background as a blue line. The gray dashed lines delimit the area of signal integration and the solid gray line shows the PDG value of the $\Xi$ mass. The same analysis was performed on simulated events in order to obtain corrections for geometrical acceptance and reconstruction efficiency.
Preliminary results derived from two dimensional spectra \( y \) vs \( p_T \) are presented as transverse momentum distributions in bins of rapidity in Fig. 17. Statistical uncertainties are shown as vertical bars and preliminary estimates of systematic uncertainty are indicated by shaded bands. The solid red lines present results of exponential fits to the data binned in \( m_T \).

The presented \( p_T \) spectra were used to calculate the rapidity spectrum of \( \Xi^- \) production as the sum of measured points and extrapolation to the unmeasured region of \( p_T \). The result is displayed in Fig. 18. Vertical bars show statistical, the shaded band systematic uncertainties. The rapidity distribution was fitted by a Gaussian function for extrapolation into the unmeasured regions. Based on summing the data points and the extrapolation of the fitted function resulted in the mean multiplicity \( \langle \Xi \rangle = 0.0033 \pm 0.0001 \pm 0.0006 \).

The results on \( \Xi^- \) spectra in p+p interactions at 158 GeV/c were presented for the first time at 2018 workshop on the Critical Point and Onset of Deconfinement [11]. The analysis of \( \Xi^+ \) production is ongoing and should be released in the near future.
Figure 18: Rapidity spectrum of $\Xi^-$ hyperons produced in inelastic p+p interactions at 158 GeV/c fitted by a Gaussian function (red line).
5.1.3 $\pi^\pm$, $K^\pm$ and proton spectra in Be+Be collisions at 19A–150A GeV/c

Preliminary $\pi^\pm$, $K^\pm$ and proton spectra from the 20% most violent Be+Be collisions at 19A–150A GeV/c were obtained via the dE/dx identification method. Results refer to primary particles produced in strong and electromagnetic processes and are corrected for geometrical detector acceptance and reconstruction efficiency as well as contamination from weak decays and secondary interactions. Additionally, a preliminary study of systematic uncertainties was performed. Estimates are typically around 5% for charged pions, 10% for charged kaons and around 8% for protons.

Two-dimensional rapidity–transverse momentum distributions of charged hadrons produced in the 20% most violent Be+Be collisions at 30A GeV/c obtained with the dE/dx identification method.

Figure 19: Double differential spectra $d^2N/d^2p_t$ of $\pi^\pm$, $K^\pm$ and protons produced in strong and electromagnetic processes in the 20% most violent Be+Be collisions at 30A GeV/c obtained with the dE/dx identification method.

Two-dimensional rapidity–transverse momentum distributions of charged hadrons produced in the 20% most violent Be+Be collisions at 30A and 150A GeV/c are presented in Fig. 19 and Fig. 20 respectively. The new results extend the acceptance of the $tof$-dE/dx identification method to the forward hemisphere.

Together with kaon spectra previously obtained at mid-rapidity with the $tof$-dE/dx identification method [12] the new results allow to determine the charged kaon rapidity spectrum. Rapidity distributions of positively and negatively charged kaons produced in the 20% most violent Be+Be collisions at 19A–150A GeV/c using the dE/dx and $tof$-dE/dx identification methods are shown in Fig. 21. Data points in each rapidity bin are obtained by summing the measured points and extrapolating with an exponential fit to the unmeasured regions. Due to the limited acceptance of the dE/dx identification method at mid-rapidity, the data points in this region at 30A and 40A GeV/c were taken from the $tof$-dE/dx analysis. Statistical un-
Figure 20: Double differential spectra $\frac{d^2n}{dydp_{T}}$ of $\pi^{\pm}$, $K^{\pm}$ and protons produced in strong and electromagnetic processes in the 20% most violent Be+Be collisions at 150A GeV/c obtained via the $dE/dx$ identification method.

certainties are plotted as vertical bars and preliminary systematic uncertainties are shown as shaded bands.

Results shown in Fig. 21 were reflected around mid-rapidity and fitted by two Gaussian functions symmetrically displaced around mid-rapidity to obtain the mean multiplicities of charged kaons. Finally, symmetry between production of $\pi^{-}$ and $\pi^{+}$ was assumed in the calculation of the ratio $\langle K^{+} \rangle / \langle \pi^{+} \rangle$. This assumption is justified in the limited acceptance of the $dE/dx$ identification method in Be+Be interactions. The mean multiplicity $\langle \pi^{+} \rangle$ was taken to be the same as $\langle \pi^{-} \rangle$, the latter obtained from the $h^{-}$ analysis method [13].

Figure 22 presents the $\langle K^{+} \rangle / \langle \pi^{+} \rangle$ ratio in full $4\pi$ phase space as well as the $K^{+} / \pi^{+}$ ratio at mid-rapidity [12] as a function of collision energy. For comparison the new Be+Be results are shown together with measurements in p+p and A+A collisions. The ratios in the 20% most violent Be+Be collisions show similar values and energy dependence like those observed in p+p interactions. Thus no horn structure is observed, in contrast to the behaviour seen in heavy Pb+Pb or Au+Au systems.

Another indication for the similarity of p+p and Be+Be collision systems can be seen in the rapidity distribution of protons presented in Fig. 23. The shape of the distributions is qualitatively similar for Be+Be and p+p reactions. This is contrary to results for proton, net-proton or net-baryon distributions in Pb+Pb collisions [14] which exhibit a significant evolution of shape between AGS energies (stopping) and top SPS energies (partial transparency).

The recent results on $\pi^{\pm}$, $K^{\pm}$ and proton spectra in Be+Be collisions were presented for the
Figure 21: Rapidity distributions of positively (left) and negatively (right) charged kaons produced in the 20% most violent Be+Be collisions at 19A–150A GeV/c using the dE/dx and tof-dE/dx identification methods. Statistical uncertainties are plotted as vertical bars and preliminary systematic uncertainties are shown as shaded bands. Results are scaled for better separation.

Figure 22: \(\langle K^+ \rangle / \langle \pi^+ \rangle\) ratio in full 4\(\pi\) phase space (left) and the \(K^+ / \pi^+\) ratio at mid-rapidity [12] (right) as function of collision energy for p+p, Be+Be, Ar+Sc, and Pb+Pb/Au+Au collisions.

first time at the 2018 workshop on the Critical Point and Onset of Deconfinement [11, 16].
Figure 23: Rapidity distributions of protons measured in inelastic p+p interactions [15] and the 0-20% most central Be+Be collisions.
5.1.4 Electromagnetic effects in Ar+Sc collisions at 150A GeV/c

Figure 24: $\pi^+ / \pi^-$ ratio in central (a) and intermediate (b) Ar+Sc collisions (data points are connected by curves to guide the eye). Right panel: The ratio $\pi^+ / \pi^-$ compared to model calculations (curves) described in the text, with the distance between the spectator and the pion at freeze-out set to $d_E = 0$ (c) and $d_E = 0.5$ fm (d). Only statistical errors are shown (from Ref. [17]).

Preliminary data on the spectator-induced electromagnetic (EM) distortion [18] of charged pion ratios were obtained for Ar+Sc collisions at 150A GeV/c beam momentum. These are presented in Figs. 24 (a) and (b). The data were taken with a semi-central trigger. The ratio of produced positive over negative pions ($\pi^+ / \pi^-$) was determined using dedicated identification cuts on the specific energy loss ($dE/dx$) of charged particles. Biases for relevant detector effects were estimated to remain below ±0.06. Centrality was defined by the forward energy deposited in the PSD detector. The mean number of wounded nucleons ($N_w$) and the number of projectile spectator nucleons ($N_A^{\text{Ar}}$) were estimated by a Glauber simulation and cross-checked with the EPOS [19] event generator.

For Ar+Sc collisions at intermediate centrality, the $\pi^+ / \pi^-$ ratio drawn as a function of $x_F = p_T(\text{pion}) / p_T(\text{beam nucleon})$ in the collision c.m.s., shows a significant depletion at low transverse momenta. The largest effect is observed for $x_F = 0.15 = m_\pi / m_p$ which corresponds to pions moving at spectator rapidity. This distortion of the $\pi^+ / \pi^-$ ratio is caused by the final state electromagnetic repulsion (attraction) of positive (negative) pions by the spectator system. This is the first observation of this effect in small systems at the SPS. The effect strongly decreases with centrality although interestingly, some lowering of the ratio at $x_F \approx 0.15$ is still suggested by the central Ar+Sc data.

It is known that the spectator-induced EM effect provides information on the space-time evolution of the reaction [20] (see also Ref. [21]). Figures. 24 (c) and (d) show the results of a Monte Carlo model simulation of charged pion propagation in the EM field of the Ar spectator system. The model applied is similar to that described in Ref. [18]. The assumption of a stable spectator system ($\beta=0$) cannot describe the experimental data. The optimal description corresponds to the spectator expansion surface velocity of $\beta = 0.3$ in its own c.m.s., in combination with the distance $d_E = 0.5$ fm in the collision c.m.s. between pions emitted at freeze-out and the Ar spectator. The latter indicates that similarly to what was established for heavy ion collisions [22], fast pions in Ar+Sc collisions are emitted less than 1 fm behind the spectator. The former points at a significant spectator expansion velocity,
and may provide an interesting test for corresponding model calculations [23].

5.1.5 Reconstruction of $D^0 + \bar{D}^0$ signal with improved resolution in Pb+Pb collisions at 150A GeV/c

The successful reconstruction of the $D^0$ and $\bar{D}^0$ signal is the most important result of the feasibility studies of the new charm physics programme of the NA61/SHINE experiment [2]. The reconstruction chain for data collected with the Small-Acceptance Vertex Detector (SAVD) consists of the following steps:

(i) cluster finding,
(ii) geometry calibration,
(iii) track finding,
(iv) primary vertex reconstruction,
(v) SAVD-TPC track matching.

All the steps are described in detail in Ref. [12]. In order to improve the resolution of the $D^0$ and $\bar{D}^0$ signal, a new method of SAVD-TPC track matching was implemented, the so-called method via interpolation. In the previous method, via extrapolation, the SAVD and TPC tracks were extrapolated to a common transverse plane (VTPC front surface) and the matching tracks were found by comparing the directions and the extrapolated positions of candidate tracks. The new interpolation method consists of the following steps:

(i) refit the TPC track to the SAVD primary vertex$^1$,
(ii) interpolate refitted TPC track to the SAVD stations and collect sufficiently close clusters,
(iii) remove primary tracks from further analysis,
(iv) refit the TPC track to the matched SAVD cluster from the second station,
(v) interpolate the refitted track to other SAVD stations and collect clusters,
(vi) save secondary tracks for further analysis.

As the second step of the algorithm, the tracks refitted to SAVD primary vertex are interpolated to all SAVD stations in order to collect the matching clusters. For each station the distribution of the distances between interpolated tracks and all SAVD clusters were created. Figure 25 presents the comparison of such a distribution for tracks before (left) and after (right) refitting to the SAVD primary vertex. Only the right panel, obtained with the interpolation method, shows the correlation peak from matched tracks and clusters, but on a huge combinatorial background. For each sensor, after reducing the background, the correlation peak was fitted with a Gaussian function and the standard deviation value ($\sigma$) was used for the matching cut. If the distance between interpolated track and cluster is smaller than $2\sigma$ for primary tracks and $3\sigma$ for secondary tracks (in the fifth step of the matching algorithm), the cluster is accepted as matched.

$^1$ the primary vertex reconstructed from data registered by the Small-Acceptance Vertex Detector
In order to obtain the $D^0$ and $\bar{D}^0$ signal, the secondary track candidates were grouped into pairs. Then, for each pair the invariant mass was calculated assuming that the first particle is a pion and the second a kaon and vice versa. In order to reduce the combinatorial background cuts on the following quantities were applied:

(i) transverse momentum: $p_T > 0.42 \text{ GeV}/c$,  
(ii) track impact parameter: $d > 42 \mu m$,  
(iii) longitudinal position of the secondary vertex (reconstructed from the track pair) relative to the primary vertex: $V_z > 450 \mu m$,  
(iv) parent particle impact parameter: $d_p < 400 \mu m$.

The comparison of the final $D^0$ and $\bar{D}^0$ signal obtained from both methods of SAVD-TPC track matching is presented in Fig. 26. Comparing these methods, one finds that the interpolation method not only confirmed the previously obtained $D^0$ and $\bar{D}^0$ signal, but also improved the signal resolution by a factor of about 3. The new results for the $D^0$ signal were presented, for example, in Refs. [24–34]. Identification of pions and kaons is planned for the future and is expected to further reduce the combinatorial background.

5.1.6 Method of studying high $p_T$ (charged) particles in p+p and p+Pb collisions

In NA49, the $p_T$ spectra of identified hadrons were measured up to 4 GeV/c in Pb+Pb collisions, but only up to 2 GeV/c in p+p and p+Pb interactions, due to the limited statistics. One of the goals of NA61/SHINE is to extend these measurements, and study the behaviour of the nuclear modification factor at higher transverse momenta.

For the track selection the same method was used as in the NA49 high $p_T$ analysis. The first step was to reject the misfitted tracks which give a large background at $p_T > 2$ GeV/c. For this purpose distributions of track properties, such as the number of potential clusters or the ratio of measured and calculated clusters were studied, and a 3 dimensional cut was applied.
in the $\phi$ - $p_T$- rapidity phase space to select a clean region dominated by well-measured and well-reconstructed particles.

Figure 27 shows the acceptance corrected spectra of positively and negatively charged particles at mid-rapidity in p+p and p+Pb interactions at 158 GeV/$c$ beam momentum, obtained by the described method. In Fig. 28, comparisons to the existing NA61/SHINE results on identified charged particles in p+p collisions [15] are shown.

**Particles with negative charge**

![Graph](image1)

**Particles with positive charge**

![Graph](image2)

**Figure 27:** Acceptance corrected transverse momentum spectra of charged particles at mid-rapidity in p+p and p+Pb interactions at 158 GeV/$c$ beam momentum.
Figure 28: Transverse momentum spectra of charged particles (this analysis) compared to the existing NA61/SHINE results [15] on identified hadron spectra at mid-rapidity in p+p interactions at 158 GeV/c beam momentum.

5.1.7 Pseudo-rapidity dependence of multiplicity and transverse momentum fluctuations in p+p at 20–158 GeV/c

A search for the critical behavior of strongly interacting matter was done by studying the pseudorapidity dependence of event-by-event multiplicity and transverse momentum fluctuations. The analysis presents results [35] referring to all charged hadrons with $p_T < 1.5$ GeV/c produced in the analysis acceptance of NA61/SHINE [36] in inelastic proton-proton collisions at beam momenta of 20, 31, 40, 80 and 158 GeV/c with corrections for off-target interactions applied.

The intensive quantity $\omega[N]$ [37] and the strongly intensive quantities $\Sigma[P_T, N]$ and $\Delta[P_T, N]$ [38] were studied as functions of the width of the chosen pseudorapidity interval, which corresponds to changing the rapidity averaged baryo-chemical potential at the freeze-out stage [10]. Moreover, a search for short- and long-range correlations was performed via study of the dependence of the strongly intensive quantity $\Sigma[N_F, N_B]$ [39] on the distance between two separated pseudorapidity windows in which the Forward and Backward multiplicities are evaluated. $\Sigma[N_F, N_B]$ is considered to be sensitive to the initial conditions of particle production such as string fragmentation and fusion [40].

One finds that multiplicity and transverse momentum fluctuations significantly depend on the width and/or location of the chosen pseudorapidity intervals (see Fig. 29). The event generator EPOS1.99 describes well the measurements of the $\omega[N]$, $\Sigma[P_T, N]$ and $\Sigma[N_F, N_B]$ measures [35]. In contrast, a significant discrepancy between data and EPOS1.99 is observed for $\Delta[P_T, N]$ at all collision energies. The deviation grows with the width of the pseudorapidity window. An increase of the value of $\Sigma[N_F, N_B]$ with the distance between forward and backward pseudorapidity intervals is predicted by the model of independent quark-gluon string production [40].
Figure 29: Dependence on the width of the pseudorapidity window of a) $\omega[N]$, b) $\Sigma[P_T,N]$, c) $\Delta[P_T,N]$ compared to EPOS 1.99 model predictions and d) dependence of $\Sigma[N_F,N_B]$ on the distance between the Forward and the Backward pseudorapidity window.

Figure 30: Detector effects in $\Delta\eta\Delta\phi$ correlations for all charged pairs of particles at beam momentum 75A GeV/c. Left: Correlations before applying corrections. Middle: Magnitude of detector effects (corrections) shown at the same scale as correlations. Right: Correlations after applying corrections. Details of the analysis and the correction procedure can be found in Ref. [42].

5.1.8 Corrected results on $\Delta\phi, \Delta\eta$ correlations in Be+Be at 19A–150A GeV/c

In the last Status Report [12], first uncorrected results on two-particle correlations in azimuthal angle and pseudorapidity in Be+Be collisions were reported (and presented at the CPOD 2017 conference [41]). During the current reporting year, the results were corrected for detector effects and the systematic and statistical uncertainties were calculated.

The effect of corrections is presented in Fig. 30 for the example of 75A GeV/c beam momentum. In general, the corrections are small and usually do not exceed 2%. The only region with larger corrections is near $(\Delta\eta, \Delta\phi) \approx (0, 0)$. This structure is a result of some inefficiencies in matching tracks between simulated (EPOS) events and the same events processed through detector simulation and reconstruction. These inefficiencies contribute to detector effects mostly but they change the eventual corrected results only slightly. The only exception where corrections are larger than 2% is the case of negatively charged pairs for lower beam momenta where they reach 5% for higher values in $\Delta\eta$. This is mostly due to large statistical fluctuations in the data at lower beam momenta.

Systematic and statistical uncertainties were also studied. Statistical uncertainties normally
do not exceed 5% except for like-sign pairs of particles at lower beam momenta in regions of higher \( \Delta \eta \) where they can reach 25%. Such high uncertainties are a result of low statistics. Systematic uncertainties were estimated for two beam momenta: 30\( A \) and 150\( A \) GeV/c by repetition of the entire analysis for two different sets of cuts and selections. These uncertainties are at the level of 0.5% with exception of negatively charged pairs of particles for 30\( A \) GeV/c where they reach 2%.

The detailed description of the calculation of statistical uncertainties and the estimation of systematic uncertainties can be found in Ref. [42]. The results of this analysis, with comparison to EPOS model predictions and to already published results of \( \Delta \eta \Delta \phi \) correlations in p+p collisions, were presented at the Quark Matter 2018 conference in form of a poster [43].

5.1.9 Intermittency of protons in Ar+Sc collisions at 150\( A \) GeV/c

In the Status Report for 2016 [12], first results were reported on intermittency analysis in transverse momentum space of protons produced in the 0-12% most central Be+Be collisions at 150\( A \) GeV/c at mid-rapidity. This year the analysis was continued for Ar+Sc collisions at 150\( A \) GeV/c for several centrality selections. The \( dE/dx \) method was used for the identification of protons. Centrality was determined using the information on energy deposited in the PSD detector. The Second Scaled Factorial Moments (SSFMs) \( F_2(M) \) of candidate proton momenta were calculated as a function of number of bins \( M \) in \( p_x \) and \( p_y \) components of transverse momentum. The correlator \( \Delta F_2(M) \), derived by subtracting the moments \( F_2(M) \) of mixed events from data moments, was fitted with a power-law. The resulting exponent (intermittency index \( \phi_2 \)) was compared to the theoretically expected [44] critical value \( \phi_2 = 5/6 \).

Figure 31 (upper panel) presents the SSFMs for data and mixed events in the 0-12% most central Be+Be as well as the 5-10% and 10-15% central Ar+Sc collisions at 150\( A \) GeV/c. For Ar+Sc collisions protons were selected with at least 90% purity (see Ref. [45] for more details and other proton purities). They are compared (lower panel) to older NA49 results for 0-12% central ‘C’+C and ‘Si’+Si and 0-10% central Pb+Pb interactions [46].

The overlap of \( F_2(M) \) for data and mixed events seen in NA61/SHINE Be+Be collisions and NA49 ‘C’+C and Pb+Pb interactions indicates that \( \Delta F_2(M) \) fluctuates around zero, and suggests that no intermittency (scaling of SSFMs) is observed. In contrast, an indication of an intermittency effect is seen in mid-central Ar+Sc collisions at 150\( A \) GeV/c. This is similar to the effect seen by NA49 in central ‘Si’+Si collisions at 158\( A \) GeV/c. The result seen in Ar+Sc collisions is a first possible evidence of a critical point signal in the NA61/SHINE experiment. The analysis of Xe+La at 150\( A \) GeV/c as well as Ar+Sc at 75\( A \) GeV/c has the highest priority in NA61/SHINE as it might strengthen the evidence for the expected non-monotonic system size and collision energy dependence of an intermittency signal from the critical point.

The results of this analysis were presented for the first time at the 2018 workshop on the Critical Point and Onset of Deconfinement [45].
Figure 31: $F_2(M)$ of protons at mid-rapidity measured in the 0-12% most central Be+Be and 5-10% and 10-15% central Ar+Sc collisions at 150 A GeV/c (upper panel) as well as in the 0-12% most central ‘C’+C and ‘Si’+Si and the most central 0-10% Pb+Pb interactions [46] studied by the NA49 experiment (lower panel).

5.1.10 Anisotropic flow relative to the spectator plane in Pb+Pb collisions at 30 A GeV/c

This subsection presents an analysis of the anisotropic flow harmonics in Pb+Pb collisions at beam momentum 30 A GeV/c collected by the NA61/SHINE experiment in the year 2016. Directed and elliptic flow coefficients were measured relative to the spectator plane estimated with the Projectile Spectator Detector (PSD). The flow coefficients are reported as a function of transverse momentum in different classes of collision centrality. The results are compared with a new analysis of the NA49 data for Pb+Pb collisions at 40 A GeV using forward calorimeters (VCal and RCal) for event plane estimation.

A sample of Pb+Pb collisions at 30 A GeV/c was used for the analysis. Events with fitted vertex position close to the target region were selected. Events overlapping in time were rejected. After event selection, the available statistics was 1.1 M events for the minimum bias trigger (T4) and 0.6 M events for the central trigger (T2) which was fully efficient in the 0-15% centrality class. Charged particle tracks with total number of clusters in the TPCs larger than 30 and number of clusters in the vertex TPCs larger than 15 were accepted for flow analysis. To avoid track splitting, the number of hits associated to the track was required to be more than 55% of the maximum possible number of points along the particle trajectory. Primary tracks were selected based on the distance of closest approach to the primary vertex, which was required to be less than 2 cm in x direction and less than 1 cm in y direction. Charged pion and proton identification was based on specific energy loss dE/dx in the TPCs. The Projectile Spectator Detector (PSD) was used for event (centrality) classification and reaction plane determination following the procedure described in Ref. [47]. For event plane determination PSD modules were subdivided into 3 groups (PSD1, PSD2, PSD3) with approximate coverage in pseudo-rapidity $\eta \in \{(5.1, \infty), (4.4, 5.1), (4.0, 4.4)\}$. Azimuthal asymmetry of the measured distributions was described in terms of two dimensional flow vectors $q_n$ and...
Figure 32: Charged pion and proton directed (left) and elliptic (right) flow coefficient as a function of transverse momentum for the 15-35% centrality class.

$Q_1$ determined event-by-event from the TPC tracks and the PSD sub-events. The results were corrected for detector non-uniformity following procedures described in Refs. [48–50].

Results for $\pi^-$, $\pi^+$ and proton directed ($v_1$) and elliptic ($v_2$) flow for the 15-35% centrality class are presented in Fig. 32. For both harmonics, a strong mass dependence is observed. Comparison to a new analysis of the NA49 Pb+Pb data at 40A GeV for directed flow of negatively charged pions can be found in Refs. [51–53].

In future, measurements will be extended to other collision energies (13A and 150A GeV/c) and collision systems, such as Xe+La, Ar+Sc, and Be+Be collisions, which are available from the system size scan of the NA61/SHINE program. The developed measurement technique using spectators in a fixed target geometry is also relevant for physics performance studies of the future CBM experiment at FAIR at beam momentum of 12A GeV/c and below. CBM is constructing a projectile spectator detector with a design similar to that of the PSD of NA61/SHINE and the latest flow performance studies were presented recently in Ref. [54].

5.2 New results for neutrino physics

The NA61/SHINE collaboration has recently prepared papers on hadron production measurements using the T2K replica target and thin targets at energies that are relevant for the Fermilab neutrino physics programme. Analyses are in progress for additional hadron production spectrum measurements.

5.2.1 Final T2K replica-target measurements

The double differential yields of $\pi^+$, $\pi^-$, $K^+$, $K^-$ and protons emitted from the surface of a 90 cm-long carbon target (T2K replica) with incoming 31 GeV/c protons were released and
submitted for publication recently [4]. These measurements were performed using data collected during the 2010 run [55]. Yields of $\pi^+$ and $\pi^-$ were measured with improved precision compared to the previously published NA61/SHINE results [56], while $K^+$, $K^-$ and proton yields were obtained for the first time.

These new measurements are crucial for reducing the hadron production component of the T2K (anti)neutrino flux error [57], which is the dominant component in the flux uncertainty. Any reduction of the flux uncertainties will directly improve measurements of the (anti)neutrino-nucleus cross sections as well as of the (anti)neutrino oscillation parameters in T2K. A simple method of using these results in T2K which avoids problems with the dependence on the incident proton beam profile is proposed in the paper.

![Figure 33](image-url): Double differential yields of protons for the downstream target face ($z = 90$ cm). Vertical bars represent the total uncertainties. Predictions from the NuBeam (red) and QGSP (blue) physics lists from GEANT4.10.03 [58, 59] are overlaid on top of the data.

The results were also compared with the NuBeam and QGSP physics lists from GEANT4.10.03 [58, 59] and show that none of the models predicts accurately the measured proton yields, see Fig. 33 as an example. This information can be used by model builders to improve hadronic Monte Carlo generators.
Figure 34: Summary of production cross section measurements. The results are compared to previous results obtained with a beam momentum of 60 GeV/c by Carrol et al. [60].

5.2.2 New production cross section measurements

NA61/SHINE is engaged in a series of hadron production measurements to benefit the Fermilab neutrino programme. The current NuMI beam uses 120 GeV/c protons on a graphite target to produce neutrinos for the Minerva and NOvA experiments (and previously MINOS and MINOS+). The proposed future LBNF beamline from Fermilab to South Dakota for the DUNE experiment [62] will provide an even higher intensity beam using protons with an energy between 60-120 GeV/c (still to be determined) on a graphite target. In addition to measurements of the particles produced by the interactions of the primary beam protons, the hadrons produced by secondary interactions of lower-energy protons, pions, and kaons in the target and aluminium horns also contribute significantly to the neutrino flux. NA61/SHINE is well suited to make measurements that can reduce the flux uncertainties for the Fermilab neutrino experiments.

Data was collected for the Fermilab experiments in 2015, but the vertex magnets were not operational at that time. While this data set could not be used for spectrum measurements, NA61 has used it to measure the total inelastic and production cross sections. The total cross section of hadron-nucleus interactions $\sigma_{tot}$ can be defined in terms of the inelastic $\sigma_{inel}$ and coherent nuclear elastic $\sigma_{el}$ cross sections:

$$\sigma_{tot} = \sigma_{inel} + \sigma_{el}.$$  \hspace{1cm} (1)

Production processes are defined as those in which new hadrons are produced. Since inelastic processes include quasi-elastic interactions which only result in the disintegration of the
target nucleus, the production cross section $\sigma_{\text{prod}}$ is defined as:

$$\sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{qe}}.$$  \hfill (2)

Data were collected for the following configurations: $\pi^+ + C$, $\pi^+ + Al$, $K^+ + C$, and $K^+ + Al$ at 60 GeV/c and $\pi^+ + C$ and $\pi^+ + Al$ at 31 GeV/c. These cross section results have recently been published [63], and the results are summarized in Figures 34 and 35. Data was also collected for p+C at 31 GeV/c, as a crosscheck of earlier NA61 results [64], and good agreement was found there.

5.3 New results for cosmic-ray physics

5.3.1 Air Shower Physics

The analysis of hadronic production cross sections in $\pi^- + C$ needed for the understanding of cosmic-ray induced air showers has been finalized in the last year. The last missing piece was the measurement of the production cross sections of $V^0$ particles ($\Lambda$, $\bar{\Lambda}$ and $K^0_S$) for a data-driven calculation of feed-down correction of pion and proton spectra from weak decays. The $V^0$ yields were measured as a function of $p$ and $p_T$ at 158 and 350 GeV/c and the spectra were released for the HEP conference in January 2018. The $p_T$-integrated spectra for the 158 GeV/c data set are shown in Fig. 36 and compared to the predictions from hadronic interaction models.
Figure 36: $p_T$-integrated spectra of $V^0$ particles as a function of $p$ for the 158 GeV/$c$ data set. The black data points show the measurements, the black vertical lines denote the statistical uncertainties and the gray bands denote the systematic ones. The colored curves show the predictions of hadronic interaction models.

A publication on the measurement of $\pi^\pm$, $K^\pm$, $p^\pm$ and $V^0$ spectra in $\pi^-\text{C}$ interactions at 158 and 350 GeV with NA61/SHINE is currently being drafted and submission to a journal is expected before the end of this year.

5.3.2 Cosmic-Ray Propagation and Dark Matter

The existence of dark matter is established on very different length scales from galaxies to galaxy clusters to the cosmic microwave background [65]. Little is known about dark matter particles except that they are gravitationally interacting, but other than that only very weakly interacting - if at all - with regular matter.

Anti-deuterons may also be generated in dark matter annihilations or decays, offering a potential breakthrough in unexplored phase space for dark matter. The unique strength of searching for low-energy anti-deuterons lies in the ultra-low astrophysical background [66–71]. Low-energy anti-deuterons from a wide range of viable dark matter models [68, 69, 72] exceed the astrophysical background [73] by $O(100)$ below a few GeV/nucleon. This is in strong contrast to positrons, anti-protons, and $\gamma$ rays where only a small contribution on top of the background is expected in optimistic scenarios.

5.3.3 Anti-deuteron Formation

Although the predicted low-energy flux of antideuterons from dark matter annihilations or decays is much higher in many models, the uncertainties of anti-deuteron formation and propagation are on the order of a factor of 10 and should be reduced for a more powerful dark matter interpretation. The formation of nuclei in hadronic interactions is described by different models. It is an important question whether (anti)deuterons are produced at chemical freeze-out from a quark-gluon plasma or at a later stage via coalescence. The conclusion of the following short overview is that more experimental data and better modelling of (anti)deuteron formation are needed.
5.3.4 Coalescence Model

The fusion of an anti-proton and an anti-neutron into an anti-deuteron can be described by the simple coalescence model, which is based on the assumption that any pair of (anti-)proton and (anti-)neutron within a sphere of radius $p_0$ in momentum space will coalesce to produce an (anti)nucleus. The coalescence momentum $p_0$ is a phenomenological quantity and cannot be calculated from first principles. Therefore, it has to be determined through fits to experimental data [74]. In this approach, the (anti-)deuteron spectrum is given by:

$$\gamma_d \frac{d^3 N_d}{dp_d^3} = \frac{\pi}{6} p_0^3 \left( \gamma_p \frac{d^3 N_p}{dp_p^3} \right) \left( \gamma_n \frac{d^3 N_n}{dp_n^3} \right),$$  (3)

where $p_i$ and $dN_i/dp_i$ are, respectively, the momentum and the differential yield per event of particle $i$ ($d=$(anti-)deuteron, $p=$(anti-)proton, $n=$(anti-)neutron). The coalescence momentum is a critical value because it enters to the third power and directly scales the yield, and as such the cosmic-ray flux. The state-of-the-art technique is to apply the coalescence condition to $p\bar{p}$ pairs on a per-event basis in Monte Carlo simulations. Tuning to experimental data typically yields best-fit $p_0$ values in the range of about 100 MeV/$c$, which is smaller than the typical scale at which the perturbative theory of Quantum Chromodynamics breaks down. As a result, the coalescence model is sensitive to non-perturbative effects in the hadronic generators. $p_0$ heavily depends on the hadronization model because it also describes all other differences between antiproton and antideuteron production.

A recent study [75] combined results from existing anti-deuteron measurements. The left panel of Fig. 37 illustrates the best current understanding of the coalescence momentum $p_0$ for anti-deuteron production as a function of energy in the laboratory frame. The underlying data sets come from many different experiments, some dating back several decades. The different points are derived from mostly poorly constrained production cross section spectra. Due to the shape of the primary cosmic-ray spectrum, especially interesting for the understanding of cosmic-ray anti-deuterons is the steep increase of the coalescence momentum between 10 to 100 GeV/$c$ of beam momentum.

5.3.5 Thermal model

The production of light nuclei in $p+p$ interactions can also be discussed in a thermal model approach, where the hadronization happens in fireballs [77–79]. The resulting particle spectra can be used to examine the conditions at freeze-out. In this model, the particle yields depend approximately exponentially on the chemical freeze-out temperature $T_{\text{chem}}$ and the mass $m$: $dN/dy \propto \exp\left(-m/T_{\text{chem}}\right)$. Due to their large masses, the abundance of nuclei is very sensitive to $T_{\text{chem}}$. The value of $T_{\text{chem}}$ obtained from data is about 170 MeV and shows a low energy dependence.
Figure 37: Left: Coalescence momentum \( p_0 \) (see Ref. [75]) for anti-deuterons as function of collision kinetic energy (T) for two different hadronic generators. Fits for EPOS-LHC (long-dashed red line) and FTFP-BERT (dashed blue line) are shown. Additionally, the \( p_0 \) values obtained from the analytic coalescence model and the parametrization of Korsmeier et al. are included. [76] The Geant4 FTFP-BERT model could not be used to simulate the highest energies. Right: Estimates from EPOS-LHC simulations for differential invariant anti-deuteron production cross sections in p+p interactions at 158 GeV/c for 60 and 600 millions, respectively.

5.3.6 Anti-deuteron Formation Studies

The improvement in measuring the anti-deuteron production cross-sections at different beam momenta, by having much larger p+p data sets, was studied. This was motivated by the potential data sets of 600 million p+p events at different collision energies with NA61/SHINE after the 2020 upgrades. The right panel of Fig. 37 illustrates the impact on the error bars of the anti-deuteron production cross section using EPOS-LHC simulations and reasonable estimates for NA61/SHINE detection efficiencies. Overall, a factor of four improvement is seen in 600 million collisions compared to the estimates for existing data from 2010/2011 with 60 million collisions. This directly translates into a factor of four better understanding of the coalescence momentum, reducing an important uncertainty for the cosmic-ray anti-deuteron understanding significantly.

5.3.7 Correlation Studies

The underlying mechanisms of hadronic generators are very different and it cannot be expected that two-particle correlation models agree. There is also no a-priori reason to expect the two-particle correlations from one generator to be more reliable than from another. Therefore, an important study is to compare angular correlations between (anti-)protons and (anti-)neutrons for different generators. For this purpose the differences in azimuthal angle \( \Delta \phi \) and in pseudo-rapidity \( \Delta \eta \) of nucleon pairs will be investigated. Like many fixed-target experiments, NA61/SHINE does not have experimental access to (anti-)neutron spectra. Therefore, only pp, p\( \bar{p} \), and \( \bar{p} \) \( \bar{p} \) correlations will be studied experimentally and compared
Figure 38: Left: Efficiency uncorrected proton and deuteron differential invariant cross sections in p+p interactions at 158 GeV/c as measured with NA61/SHINE. Right: EPOS LHC prediction for the frequency of channels of interest for p+p interactions at 158 GeV/c. Channels shown in red can contribute to production of deuterons, and those in blue can also produce anti-deuterons.

to simulations. This is a crucial step for validating and/or tuning the underlying hadronic models.

5.3.8 Path Onwards

Between 2009 and 2011, nearly 60 million events on p+p interactions with the target inserted and about 5 million events with the target removed were recorded. The identification of low-momentum deuterons is based on the truncated mean of the energy depositions in the TPCs along the track. Combining estimates for the detection efficiency with the EPOS LHC simulations, about 300 000 protons, 13 000 anti-protons, 1100 deuterons, and 10 anti-deuterons are expected in the low-momentum range.

More than 1000 clean low-momentum deuterons were detected with high statistical significance in the 2009 to 2011 p+p data sets. A preliminary step for the cross section calculation (without acceptance correction) is shown in the left panel of Fig. 38. Monte-Carlo studies to estimate detector acceptance and efficiencies for protons and deuterons as a function of transverse momentum and rapidity are currently going on. Further momentum range widening will be achieved by using time-of-flight information. Measuring charge, momentum, and velocity, mass reconstruction in NA61/SHINE is possible up to a maximum momentum of about 10 GeV/c (restricted by timing resolution), which corresponds to the momentum range accessible for deuterons by the cosmic-ray experiment AMS-02.

Measurement of Nucleon Production Channels: A lot of the data that were used for the development of the modified coalescence model dates back several decades [75]. Therefore, it is important to add new results from experiments with up-to-date techniques in hardware and data analysis to reduce systematic errors. As was already started with lower statistics
NA61/SHINE p+p data [15], detailed measurements of various (anti-)proton production channels will be performed to tune hadronic generators. The right panel of Fig. 38 shows the EposLHC prediction for the number of particles and particle pairs produced per collision for p+p interactions at 158 GeV/c. Only channels that may contribute to production of (anti)deuterons are shown. As (anti)deuterons are composed of two (anti-)nucleons, it is most interesting to study channels with at least two (anti-)nucleons in the final state.

Deuteron production is dominated by production in association with pions (p+p → p+n+π⁺ above √s ≈ 2.0 GeV) while anti-deuteron production requires at least six final-state nucleons (p+p → p̅+n+p+p+p+p above √s ≈ 5.6 GeV). Production of anti-deuterons in association with only pions is not possible for interactions of (anti-)protons with the interstellar medium. Therefore, a detailed accounting of the number of pions, protons, anti-protons, etc. in association with deuterons will be carried out to study if and how the deuteron spectrum changes. Two channels are especially important: The deuteron production in association with one proton p+p → d+n+p) is relevant because the production of anti-deuterons in p̅ +p → d̅+n+p should show the same energy dependence. In addition, production of deuterons in association with a single anti-proton (p+p → d+p̅ +n+p+p) will be searched for. Clean anti-deuteron events should have three additional protons in the final state (p+p → d̅+n+p+p+p).

**Measurement of ratio of production cross-section** The d/p and d̅/p̅ ratios as a function of transverse momentum will be determined and used as tools to tune hadronic generators as well as to test the coalescence and thermal model approach. The analysis of ALICE data [80] suggests that the thermal model works well for Pb+Pb interactions, but that the d/p ratio is over-predicted for p+p interactions. As it is more relevant to cosmic rays, this finding will be tested with the lower SPS energies.

6 Data-taking plan for 2021 – 2024 and detector upgrade strategy

Detailed description of the newly proposed NA61/SHINE physics programme beyond 2020 was presented to the SPSC in Refs. [2,3]. Here a brief summary is given.

NA61/SHINE proposes to continue measurements of hadron and nuclear fragment production properties in reactions induced by hadron and ion beams after the Long Shutdown 2. The measurements are requested by heavy ion, cosmic ray and neutrino communities and they will include:

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

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

(iii) measurements of hadron production induced by proton and kaon beams for neutrino physics.

NA61/SHINE is the only experiment which will conduct such measurements in the near future.
The objective of charm hadron production measurements in Pb+Pb collisions is to obtain the first data on 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 $J/\psi$ production?

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

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.

The new measurements require upgrades of the NA61/SHINE detector 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. The detector upgrade is planned to be executed during the LS2 and the measurements are scheduled in the period 2021-2024.
7 Summary

This NA61/SHINE annual report briefly presents the status and plans of the NA61/SHINE experiment [1] at the CERN SPS. The report refers to the period October 2017 – October 2018.

The summary of this report is as follows:

(i) Recorded physics data (see Section 2):

(a) Data on p+Pb interactions at 40 GeV/c for the strong interaction programme were recorded in October 2017 as scheduled.

(b) Data on Xe+La collisions at 13 A, 19 A, 30 A, 40 A, 75 A and 150 A GeV/c were recorded in October, November and December 2017 as scheduled. These data complete the NA61/SHINE (system-size) – (beam-momentum) scan.

(c) Data on p+(NOvA replica target) interactions at 120 GeV/c for the Fermilab neutrino beams were recorded in July 2018 as scheduled.

(ii) Facility modifications (see Section 3), in particular, include:

(a) The NOvA target replica was constructed by Fermilab and delivered to NA61/SHINE. The target consists of a series of contoured graphite fins held in place by an aluminium frame. The target was used during the July data taking.

(b) The Forward PSD calorimeter needed for data taking with the increased beam intensity after 2020 was installed and tested with proton beams from 10 to 200 GeV/c.

(c) Several modifications of beam and trigger counters were introduced resulting in about 20% decrease of the background of off-target interactions.

(iii) Software modifications (see Section 4), in particular, include:

(a) Significant progress in the development of the native SHINE reconstruction software. This software is now routinely used for off-line data quality assessment,

(b) NA61/SHINE software infrastructure changes following the CERN IT infrastructure development plan.

(iv) New physics results, final and preliminary, were released, see Section 5. They include results highly relevant for the NA61/SHINE search for the critical point and the study of the onsets of deconfinement and fireball:

(a) first observation of intermittent fluctuations of protons produced in Ar+Sc collisions at 150 A GeV/c,

(b) charged pion, kaon and proton spectra in Be+Be collisions at 19 A-150 A GeV/c,

(c) anisotropic flow relative to the spectator plane in Pb+Pb collisions at 30 A GeV/c.
In particular, proton intermittency in Ar+Sc collisions at 150\,A\,GeV/c may be the first NA61/SHINE indication of the critical point at the transition to the quark-gluon plasma.

Further new physics results concern:

(a) \(K^*(892)^0\) production in p+p interactions at 158\,GeV/c,
(b) \(\Xi^-\) production in p+p interactions at 158\,GeV/c,
(c) electromagnetic effects in Ar+Sc collisions at 150\,A\,GeV/c,
(d) pseudo-rapidity dependence of multiplicity and transverse momentum fluctuations in p+p interactions at 158\,GeV/c,
(e) final spectra of hadrons emitted from the T2K replica target,
(f) new production cross section measurements for several hadron-nucleus reactions,
(g) identified hadron spectra in \(\pi^-+C\) interactions at 150 and 350\,GeV/c.

(v) The data taking plan for 2021 – 2024 and the detector upgrade strategy (see Section 6) presented in Addenda 10 and’11 [2,3] are briefly summarized in this document.

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