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# Performance studies of strangeness production in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 8.8 GeV with the NA60+ experiment at the CERN SPS

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The NA60+ experiment is designed to study the phase diagram of strongly interacting matter by measuring thermal dimuons, charm, and strange particles produced in ultra-relativistic heavy-ion collisions. NA60+ will be installed at the CERN SPS, allowing an energy scan in the range $\sqrt{s_{NN}} \sim 5-17$ GeV and studying a region of high baryonic density little explored so far. The apparatus will be formed by a vertex telescope and a muon spectrometer. The vertex telescope will consist of layers of large area and ultra-thin state-of-the-art Monolithic Active Pixel Sensors (MAPS), which offer excellent spatial resolution with a low material budget. The vertex telescope will allow the production of strange particles, such as $\phi$, $K^0_S$, (anti-)$\Lambda^0$, $\Xi^\pm$, and $\Omega^\pm$ to be studied through exclusive reconstruction of hadronic decay channels. This paper will present the expected performances for the measurement of the $\phi$, $K^0_S$, (anti-)$\Lambda^0$, $\Xi^\pm$, and $\Omega^\pm$ production in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 8.8 GeV, using the vertex spectrometer to reconstruct their hadronic decays respectively into $K^+K^-$, $\pi^+\pi^-$, $p\pi^-$ + c.c., $\Lambda^0(p\pi^-)\pi^-$ + c.c, and $\Lambda^0(p\pi^-)K^-$ + c.c..

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## 1. Experimental setup

NA60+ is a proposed fixed target experiment at the CERN SPS designed to study the phase diagram of strongly interacting matter by measuring thermal dimuons, charm, and strange particles produced in ultra-relativistic heavy-ion collisions in the energy range $\sqrt{s_{NN}} \sim 5 - 17$ GeV. The performance studies presented in this paper are based on a vertex spectrometer composed of 5 identical silicon pixel planes positioned at 7 < z < 38 cm starting from the target considered for the simulations. The planes are embedded in the 1.5 T dipole field along the beam line that will be provided by the CERN MEP48 magnet. The stations of the telescope will be composed of is 4 large area monolithic pixel sensors of 15x15 $cm^2$. Each layer will have a very low material budget of $0.1\% X_0$ and a spatial resolution of ~5 µm. More details about the plans for the NA60+ experiment can be found in [1].

## 2. Physics motivations

The enhancement of strangeness production was proposed as a direct probe of the quark-gluon plasma formation in ultra-relativistic heavy-ion collisions [2] and then firstly observed at the SPS [3, 4]. The $\phi$, $\Xi^{\pm}$, and $\Omega^{\pm}$ are composed respectively of $s\bar{s}$, $\bar{d}\bar{s}\bar{s}$ $(dss)$ , and $\bar{s}\bar{s}\bar{s}$ $(sss)$ quarks. Therefore, they are ideal probes to study strangeness production by measuring the ratio of their yields with the one of pions or $K^0_S$, which contains a lower strange content and that can be used as a reference. High statistics studies of $K^0_S$,(anti)-$\Lambda^0$,$\Xi^{\pm}$,$\Omega^{\pm}$ and $\phi$ in A-A collison at the SPS could allow the study of multiplicities around 10-100 particles at mid-rapidity, a multiplicity region that overlaps with the high-multiplicity pp and minimum bias p–Pb collision at the the LHC. This will allow to test the models that are currently used to describe the results from RHIC and LHC. High statistics measurements of strange particles will also open the possibility to extend the measurements of the elliptic flow of strange particles at the SPS started by NA57.

## 3. Performance studies

Strangeness production via hadronic decays can be studied with the NA60+ apparatus by using the vertex telescope. The decay channel studied are $\Lambda^0 \to p + \pi^-, \bar{\Lambda}^0 \to \bar{p} + \pi^+, \Xi^- \to \Lambda^0 + \pi^-, \Xi^+ \to \bar{\Lambda}^0 + \pi^+, \Omega \to \Lambda + K, K^0_S \to \pi^+\pi^-$and $\phi \to K^+K^-$, with the $\Lambda \to p + \pi$ coming from the decay of hyperons. The decays were simulated using EvtGen [5] and the protons, kaons and pions were propagated through the vertex telescope utilizing a fast simulation framework of NA60+. The results of a Pb-Pb collisions were simulated with cocktail of prompt proton, kaons, pions and those coming from the hadronic decays the particles considered for the benchmark studies. The yield, $p_T$ and rapidity distributions of the prompt $p$, $K$ and $\pi$ and the strange particles were generated according to the measurements performed by NA49 [6–10]. The yields and kinematics of the $K^0_S$ used for the simulations are the average values of the ones of the $K^+$ and $K^-$. The signal candidates were built combining pairs, or triplets for $\Omega^{\pm}$ and $\Xi^{\pm}$, of tracks with the proper charge signs. The analysis was performed simulating $10^7$ Pb-Pb collisions in the 0-5% centrality class at $\sqrt{s_{NN}}$ = 8.8 GeV. The results obtained after the analysis were scaled to represent the expected measurements after one month of data taking with $10^{10}$ Pb ions on target. The transverse momentum spectra were fitted with the same parametrization used by NA49: $dN/dp_T \propto p_T exp(-\frac{\sqrt{m^2+p_T^2}}{T})$.

### 3.1 Long-living strange particles

$\Lambda$, $\Xi$, $\Omega$ and $K^0_S$ all have very long lifetimes ($c\tau \sim$ few $cm$) that allows to apply topological selection to reduce the combinatorial background. In order to enhance the S/B ratio, Boosted Decision Trees (BDT) [11] were employed using the python package XGBoost [12]. Since no particle identification is possible, the variables that were used for training the BDT were only the topological variables of the decay. The following variables were fed to the machine learning algorithm for the candidate selection: the rapidity of the candidate, the product of the impact parameter of decay daughters tracks, the distance of closest approach between the decay daughters tracks, the decay length and the cosine of the pointing angle. Selections on the Armenteros $\alpha$ [13] were applied to discriminate $\Lambda$ from $\bar{\Lambda}$. Further selections on invariant-mass of the candidates $\Lambda$ from $\Omega$ or $\Xi$ were applied. Out of the $10^7$ generated collisions, $10^6$ events were used for the training of the BDT, while the remaining $9 \cdot 10^6$ events were used for the analysis. The output of the BDT is a number called score that is related to probability of the candidate to be a signal. The optimal score selection is the one that maximize the expected $S/\sqrt{S+B}$. Where the number of signal candidates made it possible, the analysis was carried out in $p_T$ intervals, training different BDT models for different $p_T$ intervals. The expected measurement of the $K^0_S \to \pi^+\pi^-$, $\Lambda^0 \to p+\pi^-$, $\Xi^- \to \Lambda^0+\pi^-$ and $\Omega^- \to \Lambda^0 + K^- +$ c.c. are illustrated in Fig. 1, 2, 3, 4, 5.

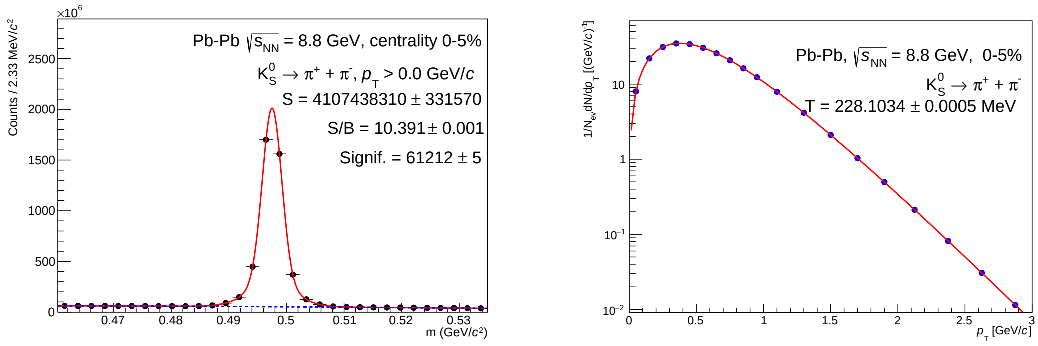


**Figure 1:** Projection for the invariant-mass distribution of $K^0_S$ candidates and $p_T$ spectrum in $10^{10}$ central Pb-Pb collisions at beam energies of 40 GeV/nucleon.

### 3.2 $\phi \to KK$

The $\phi$ meson has a very short lifetime $\tau = (1.55 \pm 0.01) \times 10^{22} s$ [14] that does not allow to extract the signal applying topological selections. Therefore, the event mixing was used to subtract the background. The background has been reproduced building candidates $\phi$ pairing the tracks of an event with the tracks of the next four events. The event mixing background was normalized to the counts of in the simulated data outside the peak region ($0.98 < m < 0.99$ GeV$/c^2$ and $1.04 < m < 1.06$ GeV$/c^2$). The process was repeated for each $p_T$ interval. The resulting invariant

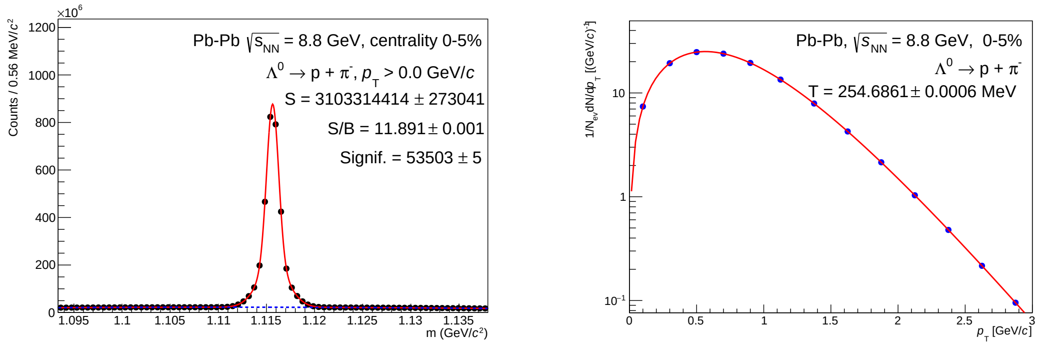


**Figure 2:** Projection for the invariant-mass distribution of $\Lambda^0$ candidates and $p_T$ spectrum in $10^{10}$ central Pb-Pb collisions at beam energies of 40 GeV/nucleon.

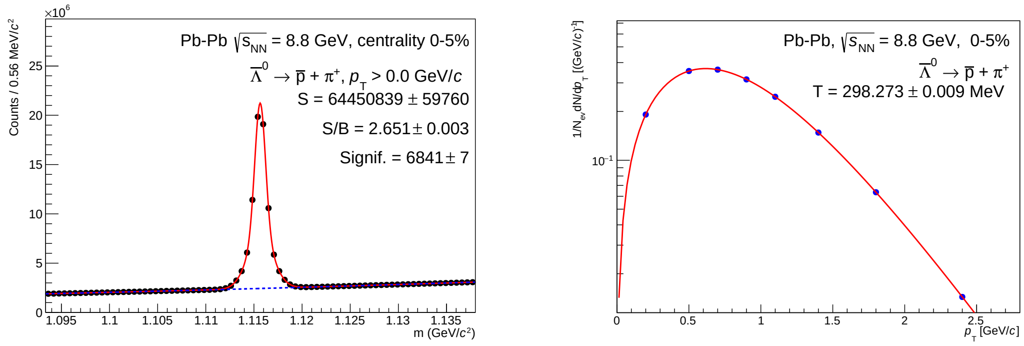


**Figure 3:** Projection for the invariant-mass distribution of $\bar{\Lambda}^0$ candidates and $p_T$ spectrum in $10^{10}$ central Pb-Pb collisions at beam energies of 40 GeV/nucleon.

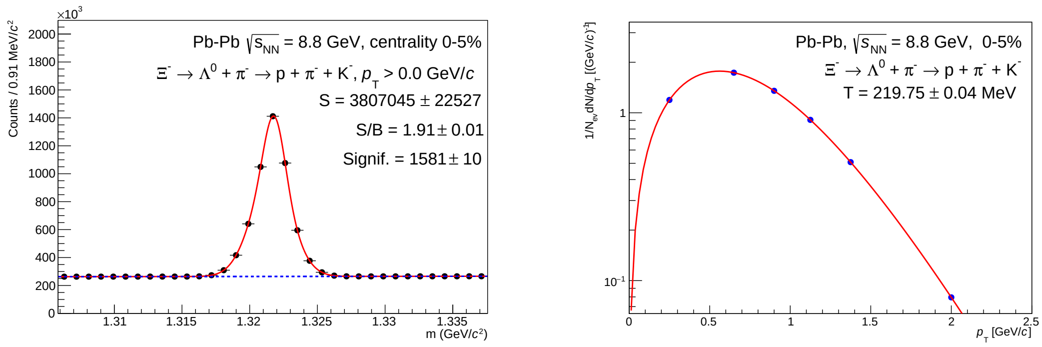


**Figure 4:** Projection for the invariant-mass distribution of $\Xi^-$ candidates and $p_T$ spectrum in $10^{10}$ central Pb-Pb collisions at beam energies of 40 GeV/nucleon.

mass distribution an the reconstructed $p_T$ spectra are shown in Fig. 6. The invariant mass resolution is in the interval 1-2.5 MeV depending on the $p_T$ bin, smaller than the natural width of the resonance

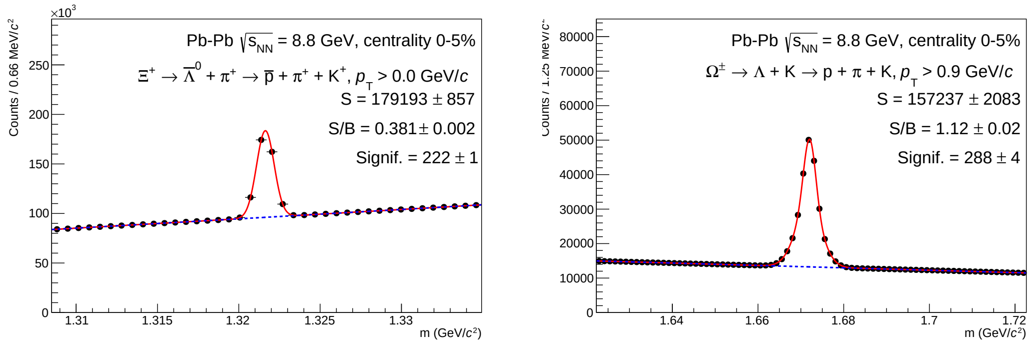


**Figure 5:** Projection for the invariant-mass distribution of $\Xi^{+}$ (left) and $\Omega^{-} + \Omega^{+}$ (right) candidates in $10^{10}$ central Pb-Pb collisions at beam energies of 40 GeV/nucleon.

$\Gamma_{\phi}$ = 4.26 MeV [14]. The high resolution and low statistical uncertainty could allow to observe modifications of the mass that may be induced by the medium [15, 16]. Moreover, it will be possible to extract the $\phi$ signal down to low $p_T$, allowing the comparison of the decay channels into kaons and muons by the same apparatus and in the same $p_T$ region. This will allow to finally solve the so called $\phi$-puzzle, a discrepancy in the inverse T slopes and yields measured by NA49 and NA50 in the kaons [17, 18] and muons [19, 20] channel, respectively.

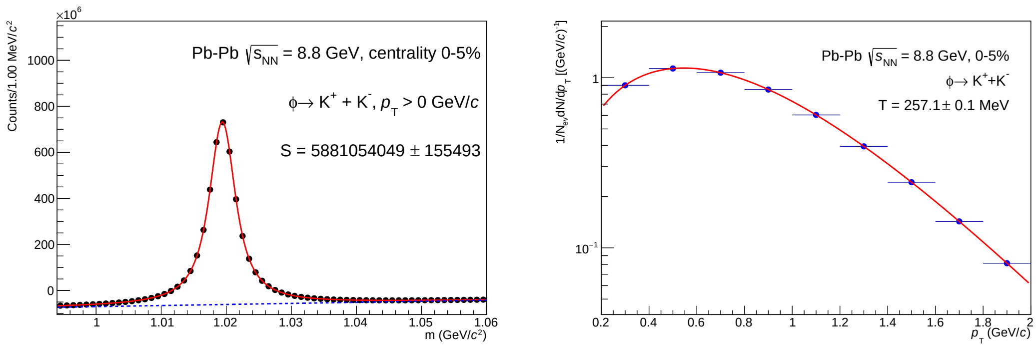


**Figure 6:** Projection for the invariant-mass distribution of $\phi$ candidates in $10^{10}$ central Pb-Pb collisions at beam energies of 40 GeV/nucleon.

## 4. Summary

The expected invariant mass distributions of $K^0_S$, $\phi$, $\Lambda^0$, $\bar{\Lambda}^0$, $\Xi^-$, $\Omega^+ + \Omega^-$ and $\Xi^+$ and the $p_T$ spectra measurements for $K^0_S$, $\Lambda^0$, $\bar{\Lambda}^0$, $\Xi^-$, $\phi$ in Pb-Pb collisions with $\sqrt{s_{NN}}$ = 8.8 GeV collected in one month of data taking with $10^{10}$ ions on target were presented. The high-statistics measurements that NA60+ will allow to perform a systematic and fully differential study of the strangeness production, in particular for channels that in past measurements suffered from statistical uncertainties like the $\Omega$. Furthermore, the elliptic flow might be studied with precision measurements.

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