EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

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Addendum to the NA61/SHINE Proposal: Request for oxygen beam in 2024

The NA61/SHINE Collaboration

This addendum presents NA61/SHINE request for oxygen beam at $13A$ GeV/c, $30A$ GeV/c and $150A$ GeV/c in 2024. The beam will be used to preform unique measurements of $^{16}O+^{16}O$ interactions needed to study diagram of high energy nuclear collisions as well as the fragmentation of ^{16}O impacting protons requested by cosmic-ray physics.

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2 Physics motivation

2.1 Diagram of high energy nuclear collisions

The request of oxygen beams in 2024 presented in this document is motivated by the newly proposed programme with ion beams at the CERN SPS. The programme aims to **uncover the diagram of high energy nuclear collisions** in the important domain of collision energies and masses of colliding nuclei. The recent results of NA61/SHINE [1–4] and the world experiments, confronted with models of hadron production in high energy nuclear collisions, ask for the proposed measurements.

The most popular models describing the hadron production process are the creation and decay of resonances or strings and the formation and hadronization of quark-gluon plasma (QGP). Domains of applicability of these approaches in the space of laboratory-controlled parameters, the collision energy and nuclear mass number of colliding nuclei, have been not well established. However, recent experimental results, in particular, the results on the K^+/π^+ ratio summarized in Figs. 1 and 2, approximately locate boundaries between them. This allows us to sketch a hypothetical diagram of high energy nuclear collisions [5] shown in Fig. 3. The data locate the transitions resonances-strings and resonances-QGP in the CERN SPS energy range. The transition strings-QGP is like to be located in collisions of light nuclei. Expected results from NA61/SHINE on Xe+La collisions soon will shed light on the diagram triple point - the region in which all three mechanisms of hadron production are equally important.

To uncover the diagram in the important range of collision energies and nuclear mass, dedicated measurements are requested with light ($A < 40$) ion beams at

(i) the top SPS momentum, $150A$ GeV/c, to locate the transition strings-QGP,

(ii) the intermediate SPS momentum, $30A$ GeV/c, to establish continuous change with the nuclear mass number (absence of transitions) below the region in which all three mechanisms mixed, resonances, strings and QGP,

(iii) the lowest SPS ion-beam momentum, $13A$ GeV/c, to establish continuous change with the nuclear mass number (absence of transitions) in the resonance domain.

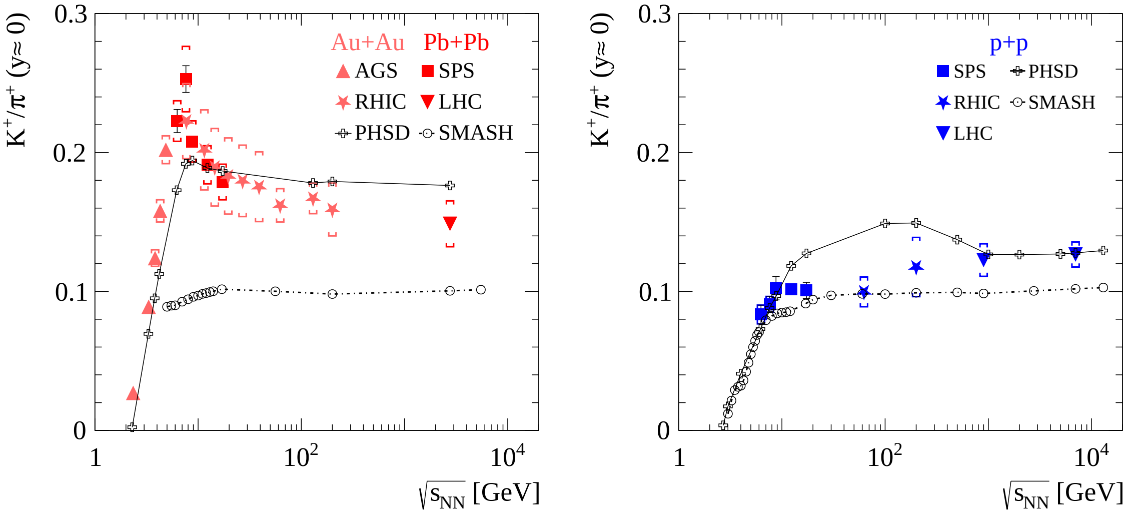

Figure 1: Energy dependence of the K^+/π^+ multiplicity ratio at mid-rapidity in central heavy-ion collisions (Pb+Pb [6–8] and Au+Au [9–13]) (*left*) and *p*+*p* interactions [1, 14–16] (*right*). Open cross points present the PHSD model predictions (QGP at high energies), while open circles - represent the SMASH model predictions (strings at high energies) for the K^+/π^+ ratio in mid-rapidity for the corresponding reaction. Lines connecting the points are plotted to guide the eye.

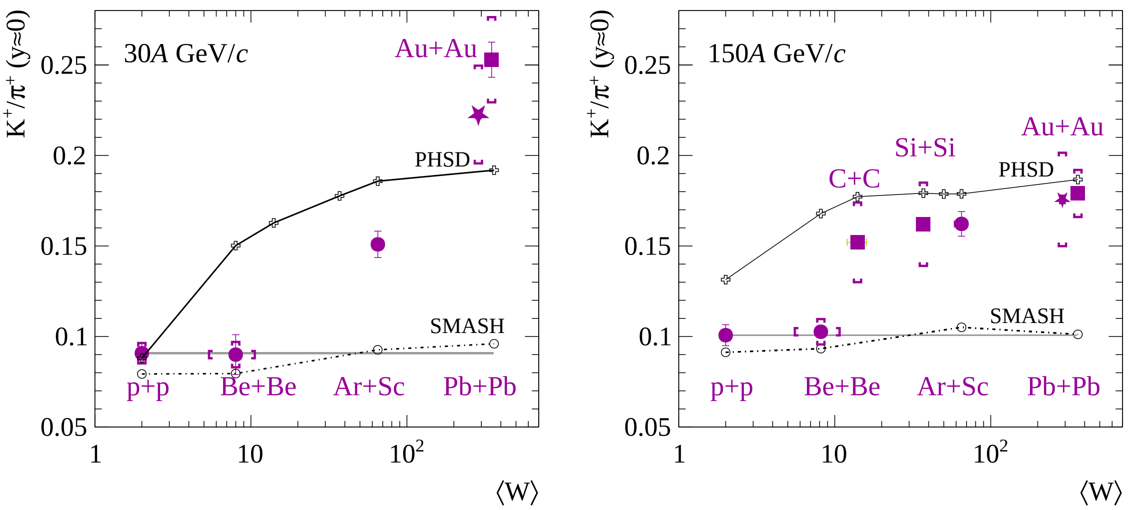

Figure 2: K^+/π^+ ratio at mid-rapidity measured at 30*A* GeV/*c* ($\sqrt{s_{NN}} \approx 7.7$ GeV) (left) and 150*A* GeV/*c* ($\sqrt{s_{NN}} \approx 17$ GeV; at $\sqrt{s_{NN}} = 19.6$ GeV for Au+Au) (right) as a function of a mean number of wounded nucleons (*p*+*p* [1], Be+Be [2], C+C [17], Si+Si [17], Ar+Sc [3, 4], Au+Au [11] and Pb+Pb [6, 7]). Star points represent results form central Au+Au collisions, they were shifted by -50 units in horizontal ($\langle W \rangle$) axis for clarity of the plot. Experimental results were compared with the PHSD (open cross points) and SMASH (open circles) predictions. Lines connecting the points are plotted to guide the eye.

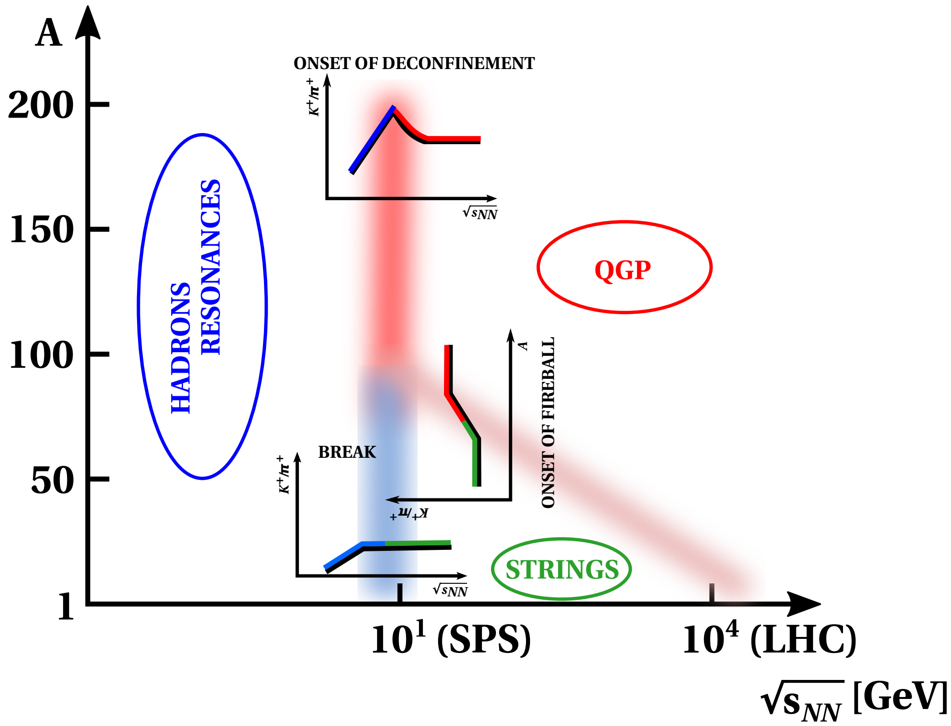

Figure 3: Schematic diagram of high energy nuclear collisions. Domains in which hadron production is dominated by resonance creation and decays, string creation and decays , as well as quark-gluon plasma formation and hadronisation are indicated as *resonances*, *strings* and *QGP*, respectively.

Table 1: Ion beams requested for the measurements on the diagram of high energy nuclear collisions. The table gives the requested number of days needed to record $\approx$ 50M good quality interactions with a beam of a given nuclear mass number and momentum per nucleon. The first numbers refer to the nominal duty cycle 0.36 (= 9/25), whereas the number in brackets correspond to the duty cycle 0.18 (= 9/50) which was used in the past. The day number includes three days for machine, beam-line and detector and trigger setup. We note that additional (not indicated in the table) two weeks of oxygen beam are needed for measurements of nuclear fragmentation cross-section for cosmic-ray physics.

p_{beam} (A GeV/c)	$\sqrt{s_{NN}}$ (GeV)	$A \approx 4$ (e.g. ^{4}He) # days	$A \approx 16$ (e.g. ^{16}O) # days	$A \approx 25$ (e.g. ^{31}P) # days	$A \approx 40$ (e.g. ^{40}Ar) # days
13	5.1	7 (11)	7 (11)	7 (11)	7 (11)
30	7.6	7 (11)	7 (11)	7 (11)	7 (11)
150	16.8	7 (11)	7 (11)	7 (11)	7 (11)

The plans concerning ion beams for the measurements on the diagram of high energy nuclear collisions are summarised in Table 1.

2.2 Nuclear fragmentation cross-sections

3 Planned measurements

3.1 Experimental setup

To reach the physics goal, precision measurements of bulk hadron production properties like identified hadron inclusive spectra and multiplicity fluctuations are needed.

The measurements will be performed using the existing NA61/SHINE detector located at the H2 beamline of EHN1.

The NA61/SHINE experimental setup upgraded during the LS2 is sufficient [18] for the measurements. The setup is schematically presented in Fig. 4.

3.2 Water target

Magda/Tomek/Maciek

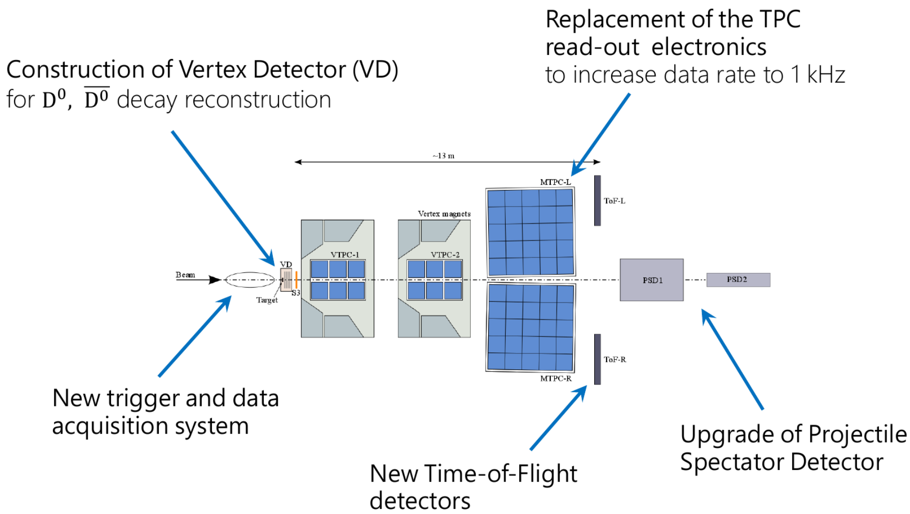

Figure 4: Schematic view of the NA61/SHINE experimental setup with indicated upgrades for the post-LS2 measurements. This setup will be used for the proposed post-LS3 measurements with ion beams.

3.3 Oxygen beams

Nikos/Reyes

The measurements would profit from an improvement of the spot-size of the beams at 13A GeV/c and 30A GeV/c. This can be achieved by an improvement of the ion emittance / spot-size of the beam already at T2 target. This would require studies from the machine side and possibly at the H2 beam line in order to understand the possibilities that exist for this purpose. BE-EA and BE-OP experts will follow up the necessary studies for an improvement at this front from 2023 onwards.

3.4 Possibility of parallel running proton and ion experiments in NA

Reyes/Nikos

A very rich and diverse physics programme using beams of ions is being proposed by different fixed target experiments like NA61/SHINE, NA60++ as well as the LHC experiments beyond Run 3. The beam requirements target different ions species and rigidites during the same operational year, which will have to be delivered in parallel or even interleaved with the proton beams. Currently the way the North Area ion interlock has been designed and implemented, prevents to send protons and ions as primary beams within the same supercycle. This interlock, therefore, heavily limits the capability of the complex to fulfill the diverse beam requirements over an operational year and penalizes the overall CERN physics programs for ions and protons. For the CERN accelerator complex to be up to demands of the physics community beyond Run 3, a redesign of the NA ion Interlock system would be absolutely needed to lift the current limitation and allow protons and primary ion beams to be sent to the North Area experiments. This redesign would be also extremely beneficial for other experimental facilities, like HiRadMat or AWAKE that could continue taking protons more efficiently during the ion run, which is not the case today. In other words, it would constitute an important improvement of the CERN injector complex towards delivering more efficiently ion beams.

3.5 Data taking conditions

Data is expected to be recorded under the following conditions:

(i) SPS cycle length: from 25.2 s to ≈ 50 s, flat top: ≈ 9 s,
average duty cycle: $\approx 0.18 - 0.36$,

(ii) primary-ion beam intensity at the NA61/SHINE target: $\approx 10^5$ ions/s,

(iii) targets: $\approx 5\%$ interaction probability, rate of all inelastic events 5000 Hz, rate of 30% most violent collisions 1500 Hz,

(iv) recorded event rate during the spill: 800 Hz,

(v) fraction of time for physics data taking
(includes planned and the unplanned detector and machine interruptions): $\approx 80\%$,

(vi) mean of the number of recorded events: $\approx 9 - 18$M events/day.

The mean number of recorded A+A collisions after off-line quality cuts (mostly off-time rejection) is about $7 - 14$ M events/day, where the numbers refer to 0.18 and 0.36 duty cycle respectively.

Data on O+water collisions will be recorded using three on-line event selections:

(i) selection of 30% of inelastic collisions with the smallest energy recorded in the PSD (80% events),

(ii) minimum bias event selection (15% events) and

(iii) ion beam selection (5% events).

The minimum bias event selection will be provided by anti-coincidence of the incoming beam particle with the signal from a scintillator detector located downstream of the target. This should minimise the contamination by non-target interactions. The detector will work as a threshold detector with the threshold set just below the beam-ion signal.

4 Physics performance

5 Summary

Acknowledgments

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