Report from the NA61/SHINE experiment

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This presentation:
- data taking
- detector status
- strong interaction physics

Next presentation:
- measurements for neutrinos and cosmic rays
- beam request for 2024

- Strong interaction physics
  - search for the critical point of strongly interacting matter
  - study of the properties of the onset of deconfinement
  - heavy quarks: direct measurement of open charm at SPS energies

- Neutrino and cosmic-ray physics
  - hadron measurements for the J-PARC neutrino program
  - hadron measurements for the Fermilab neutrino program
  - measurements for cosmic-ray physics (Pierre-Auger and KASCADE experiments) for improving air shower simulations
  - measurements of nuclear fragmentation cross-sections of intermediate-mass nuclei needed to understand the propagation of cosmic rays in our Galaxy
Strong interaction program

Critical structures:

- **Onset of deconfinement (OD)**
  Beginning of QGP creation with increasing collision energy

- **Critical Point (CP)**
  The endpoint of first-order phase transition line that has properties of second-order phase transition

- **Onset of fireball (OF)**
  Beginning of the creation of strongly interacting matter with increasing nuclear mass number. The transition from non-equilibrium strings and resonances to equilibrated hadron gas or QGP
Data-taking summary

Strong interaction physics:
- Pb-ion physics run, autumn 2022 Pb+Pb \(\approx 30M\) events
- Pb-ion physics run, autumn 2023 Pb+Pb \(\approx 150M\) events

Neutrino and cosmic-ray physics:
- Neutrino-related physics run, summer 2023
  - \(K^+ + C\) at 60 GeV/c \(\approx 86M\)
  - \(p + Ti\) \(\approx 102M\)
  - \(p + C\) \(\approx 76M\)

Number of events in target (↑)

The achieved data-taking rate is 1.2 kHz over 8.5s SPS spill
\((x30\) data-taking rate from 2018)  

42% \(\approx 38\%\) NA61/SHINE + 4% AWAKE

Beam was delivered to NA61/SHINE 59% of time
Status of open charm data-taking

- Open-charm program motivated the LS2 detector upgrade: high rate and large Vertex Detector acceptance
- Pb+Pb in 2022 and 2023 (6 weeks) 180M events
  The Pb beam program was approved in 2021 → reduced to two weeks in 2022 and four weeks in 2023 (40A GeV/c data-taking was cancelled)
- The expected number of weeks in 2024 and 2025 is 8 (7 weeks for open charm + 1 week for GCR)
- We estimate ≈ 440M events in total (goal 500M)
  Assuming similar fraction of physics data-taking time/total time
Detector

Significantly upgraded during LS2, detector was successfully used in 2022 & 2023 data taking

Cluster distribution in four planes of the new Vertex Detector
New results: strong interaction program

Spectra of identified hadrons in Xe+La interactions at 150A GeV/c

From these plots the kaon $p_T$ spectra, as well as mid-rapidity yields and total multiplicities are extracted.
New results: strong interaction program

- **Step** - the inverse slope parameters of kaon $p_T$ spectra
New results: strong interaction program

- Horn - ratio of $K^+$ to $\pi^+$ - The onset of (QGP) deconfinement

Xe+La interactions at 150A GeV/c similar to the heaviest systems (Au+Au and Pb+Pb)
New results: strong interaction program

- System size dependence and the onset of fireball - OF

Considerable difference between light and heavy systems \( \implies \text{onset of fireball} \)

SPSC-P-330-ADD-13 and SPSC-P-330-ADD-14 were submitted as proposals to extend the ion program by light ion beams before/after LS3

The two main requested ion species are \(^{16}\text{O}\) and \(^{24}\text{Mg}\)
Request for physics and test runs with light ions

Request for new measurements in Run 4:

We request SPSC to recommend these first post-LS3 measurements

<table>
<thead>
<tr>
<th>$P_{\text{beam}}$ (A GeV/c)</th>
<th>$\sqrt{S_{NN}}$ (GeV)</th>
<th>$^{10}\text{B}$ # days (# events)</th>
<th>$^{16}\text{O}$ # days (# events)</th>
<th>$^{24}\text{Mg}$ # days (# events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>5.1</td>
<td>7 (100M)</td>
<td>7 (100M)</td>
<td>7 (100M)</td>
</tr>
<tr>
<td>30</td>
<td>7.6</td>
<td>7 (100M)</td>
<td>7 (100M)</td>
<td>7 (100M)</td>
</tr>
<tr>
<td>150</td>
<td>16.8</td>
<td>7 (100M)</td>
<td>7 (100M)</td>
<td>7 (100M)</td>
</tr>
</tbody>
</table>

The oxygen beam in 2024 allows for a critical test for the proposed measurements - see SPSC-P-330-ADD-13.

Already 4 days of the O beam: setup (2 days) and data-taking (2 days), would allow us to cover and test major aspects of $\text{OF}$, fragmentation for galactic cosmic-ray physics, and a large excess of charged over neutral kaon yield (see next slides)

4 days of test oxygen beam $\approx$ 30-40M events
New results: strong interaction program

- Preliminary results on $K_S^0$ in $p+p$ interactions at 31 and 40 GeV/c

The NA61/SHINE results significantly improve the world data
New results: strong interaction program

- Preliminary results on $K_S^0$ in Ar+Sc interactions at 75A GeV/c

The mean multiplicity of produced $K_S^0$ mesons calculated as the integral of the fitted rapidity function:

$$\langle K_S^0 \rangle = 6.25 \pm 0.09 \text{ (stat)} \pm 0.73 \text{ (sys)}$$
New results: strong interaction program

- Ratio of charged to neutral kaons

Assuming collisions of $N = Z$ nuclei and the exact isospin symmetry one gets $R_K = 1$. The test run with O+O collisions ($N = Z = 8$) in 2024 may allow us to verify the hypothesis of a large isospin symmetry violation in kaon production at high energies.
Summary of strong interaction results

- **Published/submitted**
  - CP, O femtoscopy analysis in 0–20% central Be+Be collisions at 150 A GeV/c (EPJC 83, 919)
  - CP proton intermittency in Ar+Sc collisions at 150 A GeV/c (EPJC 83, 881)
  - OD, OF π±, K±, p, and p production in 0–10% central Ar+Sc collisions at 13A–150A GeV/c (arXiv:2308.16683 [nucl-ex]; submitted to EPJC)

- **Preliminary**
  - OD, OF π−, K+, and K− production in 0–20% central Xe+La collisions at 150 A GeV/c (QM 2023)
  - OD, O Λ production in 0–10% central Ar+Sc collisions at 75 A GeV/c (International School of Nuclear Physics 2023)
  - OD, O K0S production in inelastic p+p collisions at 31 and 40 GeV/c (NICA Days and MPD CM 2023)
  - OD, O K0S production in 0–10% central Ar+Sc collisions at 75 A GeV/c (QM 2023)

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The search for the critical point (CP)
The study of the onset of deconfinement (OD)
The study of the onset of fireball (OF)
Others (O)
Thank you
New results: strong interaction program

- Results on $\Lambda$ production in central Ar+Sc collisions at 75A GeV/c

$\langle \Lambda \rangle / \langle \pi^+ \rangle$ follows trend observed in $\langle K^+ \rangle / \langle \pi^+ \rangle$
Software status

Challenges ≈ 40 different reactions to reconstruct and simulate and new high-statistics data

Main activities:

- Integration of new detectors, e.g. Forward ToF, GRC (monitoring of velocity drift in TPCs)
- Upgrade to the Vertex Detector track reconstruction software
- Missing information was added for pre-LS2 time of flight detectors, the detector description software was revised and streamlined
- For 2022 runs OfflineQA service provides information on data quality. For the summer 2023 data-taking period, a new online quality-assessment service for data monitoring in real-time
Calibration status

- The Kr calibration data is fully analyzed and gain factors for TPC pads are included.
- The drift velocity calibration based on GRC measurements.
- The TPC positions and tilt angles were extracted using a new alignment procedure with field-off data.
- BPD-GEM detectors as well as ToF-F measurements were calibrated for 2022 neutrino data.