Report from the **NA61/SHINE** experiment

Maja Maćkowiak-Pawłowska (WUT)
for the NA61/SHINE Collaboration

NA61/SHINE research program

This presentation:

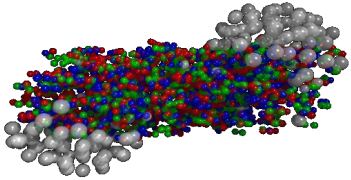
- data taking
- detector status
- strong interaction physics

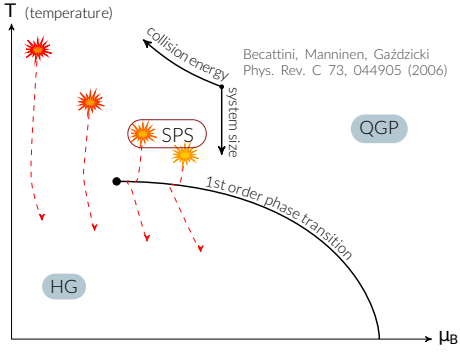
Next presentation:

- 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





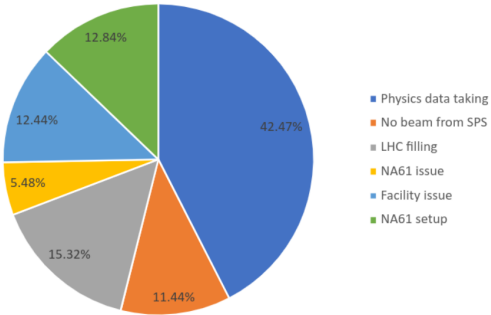
Critical structures:

- **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



Beam was delivered to NA61/SHINE 59% of time

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

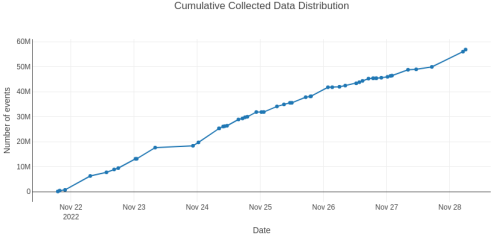
Number of events in target ($\uparrow$)

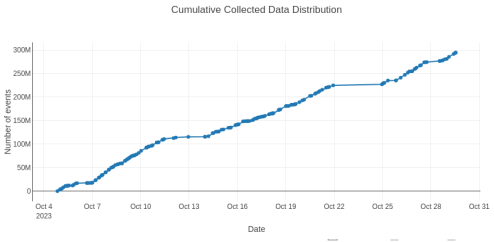
The achieved data-taking rate is 1.2 kHz over 8.5s SPS spill (x30 data-taking rate from 2018)

42% $\approx$ 38% NA61/SHINE + 4% AWAKE

Status of open charm data-taking

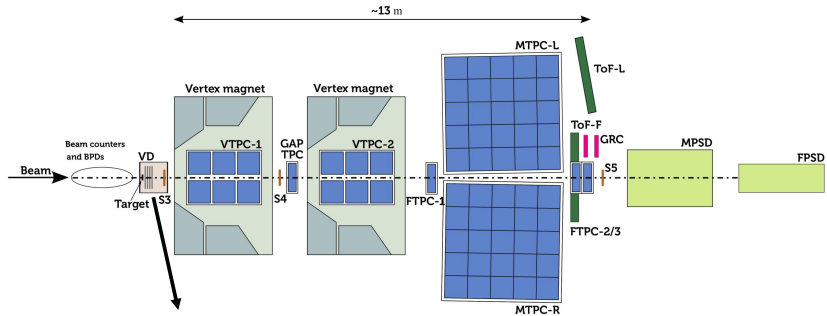
- Open-charm program motivated the LS2 detector upgrade: high rate and large Vertex Detector acceptance
- Pb+Pb in 2022 and 2023 (6 weeks) 180M events
  The Pb beam program was approved in 2021 $\longrightarrow$ reduced to two weeks in 2022 and four weeks in 2023 (40A GeV/c data-taking was cancelled)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





Detector

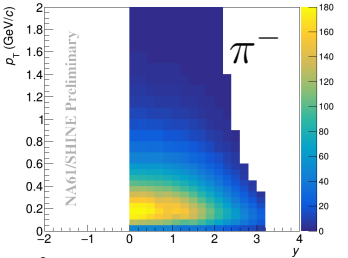
Significantly upgraded during LS2, detector was successfully used in 2022 & 2023 data taking

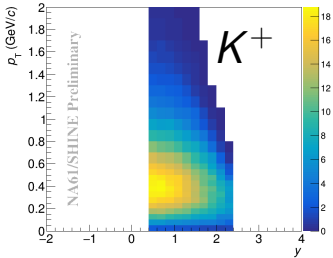


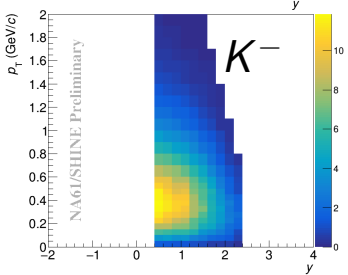
Cluster distribution in four planes of the new Vertex Detector

New results: strong interaction program

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



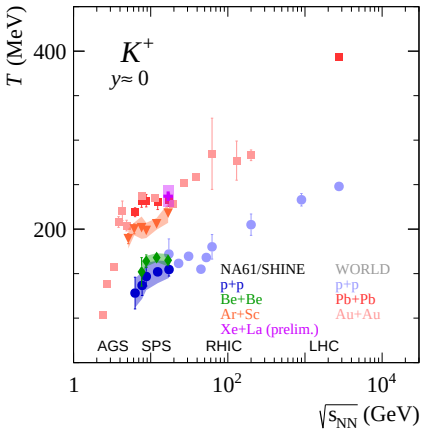


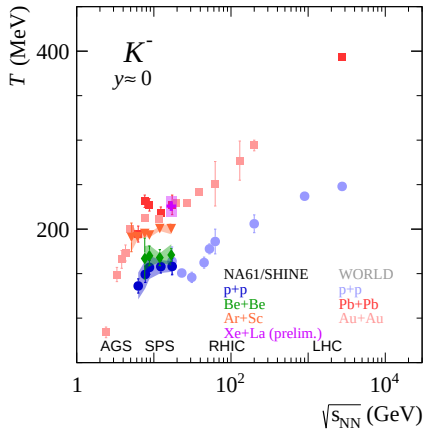


From these plots the kaon p_{T} spectra, as well as mid-rapidity yields and total multiplicities are extracted

New results: strong interaction program

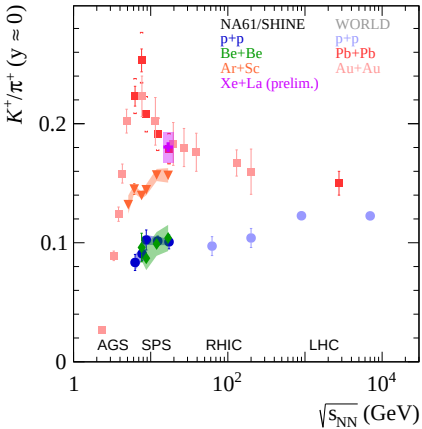
- **Step** - the inverse slope parameters of kaon p_T spectra

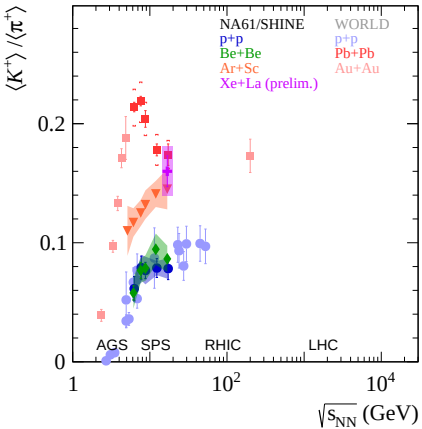




New results: strong interaction program

- **Horn** - ratio of K^+ to π^+ - **The onset of (QGP) deconfinement**

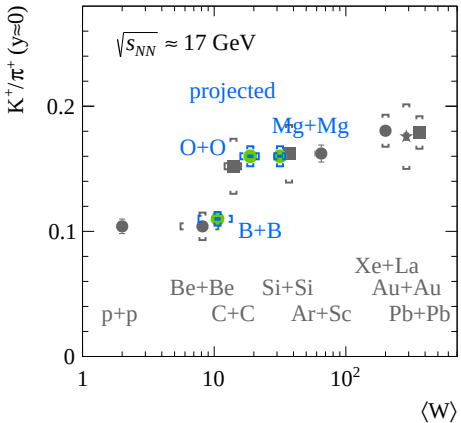




Xe+La interactions at 150A GeV/c similar to the heaviest systems (Au+Au and Pb+Pb)

New results: strong interaction program

- **System size dependence and the onset of fireball - OF**



Considerable difference between light and heavy systems $\Longrightarrow$ **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}O and ^{24}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

p_{beam} (A GeV/c)	$\sqrt{s_{NN}}$ (GeV)	^{10}B # days (# events)	^{16}O # days (# events)	^{24}Mg # days (# events)
13	5.1	7 (100M)	7 (100M)	7 (100M)
30	7.6	7 (100M)	7 (100M)	7 (100M)
150	16.8	7 (100M)	7 (100M)	7 (100M)

SPSC-P-330-ADD-14

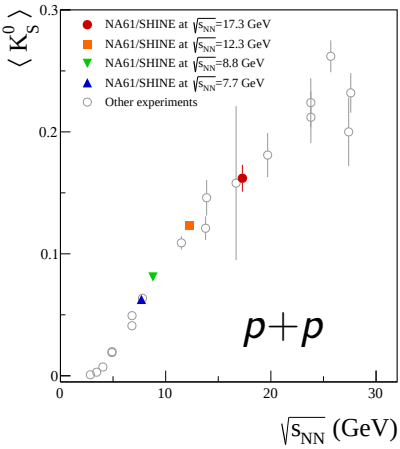
The oxygen beam in 2024 allows for a critical test for the proposed measurements - see SPSC-P-330-ADD-13.

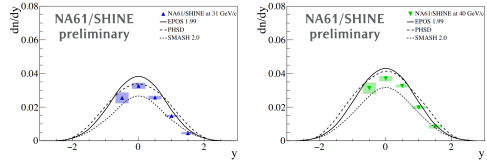
Already 4 days of the O beam: setup (2 days) and data-taking (2 days), would allow us to cover and test major aspects of **OF**, **fragmentation for galactic cosmic-ray physics**, and **a large excess of charged over neutral kaon yield** (see next slides)

4 days of test oxygen beam ≈ 30-40M events

New results: strong interaction program

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

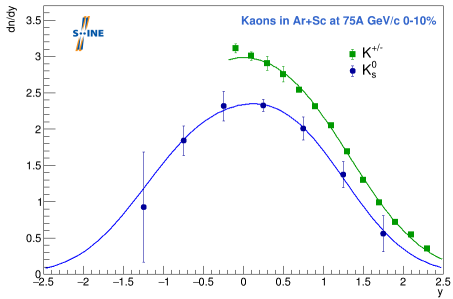


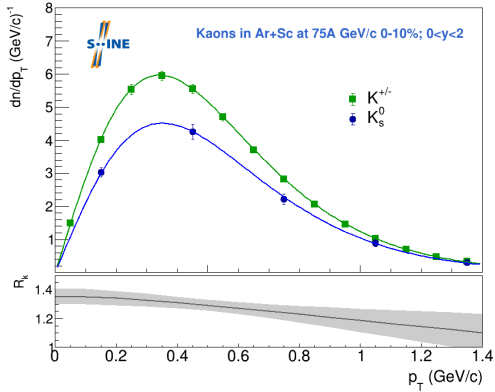


The NA61/SHINE results significantly improve the world data

New results: strong interaction program

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





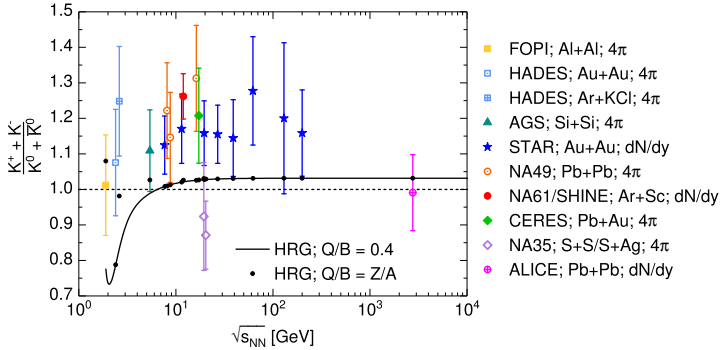
The mean multiplicity of produced K_S^0 mesons calculated as the integral of the fitted rapidity function:

$$R_K = \frac{K^+ + K^-}{2K_S^0}$$

$$\langle K_S^0 \rangle = 6.25 \pm 0.09\ (\text{stat}) \pm 0.73\ (\text{sys})$$

New results: strong interaction program

- **Ratio of charged to neutral kaons**



Large excess of charged over neutral kaon yield in A+A collisions

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 150A GeV/c (EPJC 83, 919)

CP proton intermittency in Ar+Sc collisions at 150A GeV/c (EPJC 83, 881)

OD, OF $\pi^{\pm}$, $K^{\pm}$, p, and $\overline{p}$ 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 150A GeV/c (QM 2023)

OD, O Λ production in 0–10% central Ar+Sc collisions at 75A GeV/c (International School of Nuclear Physics 2023)

OD, O K^0_S production in inelastic p+p collisions at 31 and 40 GeV/c (NICA Days and MPD CM 2023)

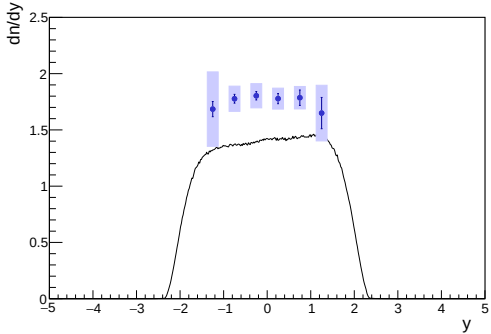
OD, O K^0_S production in 0–10% central Ar+Sc collisions at 75A GeV/c (QM 2023)

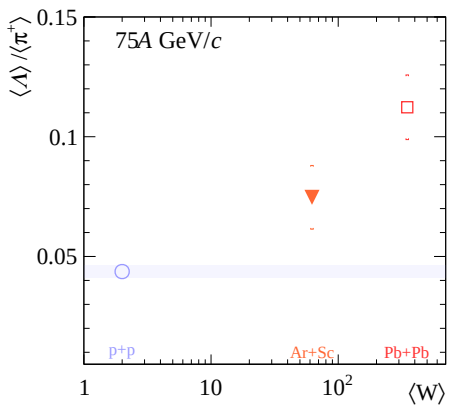
The search for the critical point (**CP**)
The study of the onset of deconfinement (**OD**)
The study of the onset of fireball (**OF**)
Others (**O**)

Thank you

New results: strong interaction program

- Results on Λ 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 $\approx$ 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