Strong interaction program of the NA61/SHINE experiment – recent results and plans

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Outline

1. Introduction
2. Results of the strong interaction program
3. Physics motivation for measurements beyond 2020
4. Upgrades and proposed measurements after LS2
NA61/SHINE Experiment

Beam detectors and triggering → a set of upstream scintillator and Cherenkov counters and beam Position detectors provides timing reference, charge and position measurements

Time Projection chambers → four large four small volume TPC’s serve as tracking detectors, provide PID

Time of Flight walls → used for hadron identification

Projectile Spectator Detector (PSD) → a calorimeter which measure energy of projectile fragments → collision centrality

Small Acceptance Vertex Detector → precise tracking close to the target

Beams:
- ions (Be, Ar, Xe, Pb) $\rho_{\text{beam}}=13A–150A \text{ GeV/c}$
- hadrons (n, K, p) $\rho_{\text{beam}}=13–400 \text{ GeV/c}$
- $\sqrt{s_{NN}}=5.1–16.8 \text{ (27.4) GeV}$

Large acceptance hadron spectrometer – coverage of full forward hemisphere, down to $p_T = 0$
NA61/SHINE 3D event visualization

Xe+La at 150A GeV/c
Research program: strong interactions

2D scan of energy and system size to study phase diagram of strongly interacting matter

→ search for the critical point of strongly interacting matter
→ study of the properties of the onset of deconfinement

New possibilities: direct measurement of open charm at SPS energies
Research program: measurements for neutrino and cosmic ray experiments

- Hadron production measurements for neutrino experiments
  → reference measurements for neutrino experiments for computing initial neutrino fluxes at J-PARC and FERMILAB

- Hadron production measurements for cosmic ray experiments
  → reference measurements of p+C, p+p, π+C and K+C interactions for cosmic-ray physics (Pierre-Auger, KASCADE) for improving air shower simulations
Physics motivation for 2D scan program (particle ratios)

- None monotonic behavior of $K/\pi$ ratio
- Effective temperature shows plateau in the range of SPS energy

central Pb+Pb and Au+Au (NA49, QM 2004)

$\langle K^+/\pi^- \rangle$ vs. $\sqrt{s_{NN}}$ (GeV)

$T$ [MeV] vs. $\sqrt{s}$ [GeV]

$K^+$ vs. $\sqrt{s_{NN}}$ (GeV)

beam momentum [A GeV/c]
Physics motivation for 2D scan program (fluctuations)

- Freeze-out line well established experimentally in T vs $\mu_B$ plane

- Location of the freeze-out point depends on the collision energy and system size (Phys. Rev. C 73, 044905 (2006))

- Increase of fluctuation is expected when freeze-out point is located close to the CP

\[ \text{2D scan} \]
Results on strong interactions
Particle ratios and fluctuations

$K^+ / \pi^+$ and multiplicity fluctuations change rapidly when moving from light (p+p, Be+Be) to intermediate/heavy systems.

For heavy systems they are closer to predictions of statistical models for large volume strongly interacting matter.

$\rightarrow$ beginning of creation of large clusters of strongly interacting matter (onset of fireball)
Rapid changes in $K^{+}/\pi^{+}$ (HORN) were observed in Pb+Pb collisions. It was predicted within SMES as a signature of onset of deconfinement.

NEW RESULTS:
- plateau like structure visible in p+p
- Be+Be consistent with p+p
- $\langle K^{+}/\langle \pi^{+} \rangle$ in Ar+Sc in between p+p, Be+Be and Pb+Pb
Tentative conclusions from 2D scan

Data on particle ratios and fluctuations indicate four domains of hadron production separated by two thresholds:

- **onset of deconfinement**
- **onset of fireball**

Completion of Ar+Sc analysis and new data for Xe+La awaited to verify this picture.
EM effects in Ar+Sc collisions

Strong depletion of $\pi^+/\pi^-$ ratio at beam rapidity

- first observation of spectator-induced EM effects in Ar+Sc reactions at the SPS,
- brings information on the space-time evolution of the system.

Refer to talk by Nikolaos Davis, room 3, 16:30
Physics motivation for future measurements
Model predictions for $\langle c\bar{c} \rangle$ in central Pb+Pb at 150A GeV/c

- Different models differ in predictions of $\langle c\bar{c} \rangle$ by factor $\approx 50$
- To discriminate models the $\langle c\bar{c} \rangle$ produced in full phase space is needed → measurement of open charm mesons

HSD
Linnyk, Bratkovskaya, Cassing, IJMP E17 1367

pQCD
Gavai et al. IJMP A10 2999
Braun-Munzinger, J. Stachel, PLB 490, 196

HRG, Quark Coalesc. Stat.
Gavai et al. IJMP A10 2999
Braun-Munzinger, J. Stachel, PLB 490, 196

Quark Coalesc. Dyn.
Levai, Biro, Csizmadia, Csorgo, Zimanyi, JP G27, 703

SMES
Gazdzicki, Gorenstein, APP B30, 2705
Measurements of $\langle c\bar{c} \rangle$

0-20% Pb+Pb at 150A GeV/c

Hadrons containing charm considered for measurements in NA61/SHINE

<table>
<thead>
<tr>
<th>Hadron</th>
<th>Decay channel</th>
<th>$c\bar{\tau}$ [\mu m]</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$\pi^+ + K^-$</td>
<td>123</td>
<td>3.89%</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$\pi^+ + \pi^+ + K^-$</td>
<td>312</td>
<td>9.22%</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>$\pi^+ + K^- + K^+$</td>
<td>150</td>
<td>5.50%</td>
</tr>
<tr>
<td>$\Lambda_c$</td>
<td>$p + \pi^+ + K^-$</td>
<td>60</td>
<td>5.00%</td>
</tr>
</tbody>
</table>

Measuring $D^0$, $\bar{D}^0$, $D^+$, $D^-$ provides good $\langle c\bar{c} \rangle$ estimate

PHSD, Elena Bratkovskaya & Taesoo Song, private communication
$J/\psi$ suppression as signal of deconfinement


Data was interpreted in terms of final state interaction in the deconfined medium created in nucleus-nucleus collisions.

Medium reduces probability of $J/\psi$ production (Matsui, Satz, PLB 178 (1986) 416)
**J/ψ suppression as signal of deconfinement**

**NA50**

- Observed anomalous suppression
- $\sigma(\text{abs}) = 4.18 \text{ mb (GRV 94 LO)}$

**Data**

- Medium reduces probability of $J/\psi$ production
  (Matsui, Satz, PLB 178 (1986) 416)

**NA60 in 2005**

- QM05
$J/\psi$ suppression as signal of deconfinement


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Medium reduces probability of $J/\psi$ production (Matsui, Satz, PLB 178 (1986) 416)
$J/\psi$ suppression as signal of deconfinement


Below LHC energies in p+p 90% $c\bar{c}$ pairs convert to open charm, remaining 10% form charmonia states.
J/ψ suppression as signal of deconfinement

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In A+A color screening reduces charmonia production → reduction of fraction of $c\bar{c}$ pairs going into charmonia in respect to p+p at the same energy

**J/ψ suppression as signal of deconfinement**


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In A+A color screening reduces charmonia production → reduction of fraction of $c\bar{c}$ pairs going into charmonia in respect to p+p at the same energy.

Due to shadowing, parton energy loss etc., the number of $c\bar{c}$ pairs produced in A+A may well be less than the scaled number from p+p → initial state effects can reduce charmonium production rate in A+A relative to p+p collisions.
**J/ψ** suppression as signal of deconfinement


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→ the effect of the medium on $c\bar{c}$ binding can only be determined by comparing the ratio of $\langle J/\psi \rangle/\langle c\bar{c} \rangle$ in A+A to that in proton-proton collisions.

→ measurements of open charm in A+A needed!!!

\[ P (c\bar{c} \rightarrow J/\psi) \equiv \frac{\langle J/\psi \rangle}{\langle c\bar{c} \rangle} \equiv \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}} \]
Vertex Detector tests with Pb+Pb at 150A GeV/c

SAVD:
- 16 MIMOSA-26 sensors located on 2 horizontally movable arms.
- Target holder integrated with SAVD base plate

Achieved goals:
- tracking in the large track multiplicity environment
- precise Primary Vertex reconstruction
- TPC and SAVD track matching
- first search for $D^0$ signal
Highlights of SAVD performance

First results for 140k events of Pb+Pb at 150A GeV/c

Background suppression
→ cuts on:
1. track $p_T$
2. track impact parameter
3. longitudinal distance of pair vertex to primary vertex
4. parent impact parameter

Analysis details:
1. Global fit (VD+TPCs) using Kalman Filter
2. PID not used yet (should reduce background by factor of 5)

Allocated beam time in 2018: 10M 0-20% central Pb+Pb → 2.5k $D^0 + \bar{D}^0$

- Large statistic Xe+La data taken in 2017 at 150A and 75A GeV/c.
- Segmented target was used (tree 1mm thick La blocks squeezed together). The structure of the target seen in the data.
- Primary vertex spatial resolution: 1.3, 1.0 and 15 μm in x, y and z coordinate, respectively.

Refer to talk by Anastasia Merzlaya (5.07)
Motivation: NFCS of intermediate mass nuclei are needed to understand the propagation of cosmic rays in our Galaxy

→ background for dark matter searches with space-based experiments as AMS and PAMELA.
NFCS measurements: goals and performance

- One week test run in 2018 is proposed:
  - establish capability of NA61/SHINE to measure NFCS.
- No major modifications to the experimental setup are needed.
- The comprehensive measurement program (beyond 2020) will be formulated based on experience gained in 2018.
- The test data on carbon-proton and oxygen-proton at 13A GeV/c should already improve the current cross section uncertainties.

Simulation of fragments reconstruction in the NA61/SHINE detector
Upgrades and proposed measurements beyond LS2
LS2 upgrades of NA61/SHINE setup

Construction of Vertex Detector (VD) for $D^0$, $\bar{D}^0$ decay reconstruction

Replacement of the TPC read-out electronics to increase data rate to 1 kHz

New trigger and data acquisition system

New Time-of-Flight detectors

Upgrade of Projectile Spectator Detector

Upgrades are needed to increase rate capability of NA61/SHINE by one order of magnitude to 1 kHz
Upgrade of Vertex Detector

- Mimosa 26AHR will be replaced by ALPIDE developed for ALICE-ITS
- $16 \rightarrow 46$ sensors
- Increase surface $32 \text{ cm}^2 (\text{SAVD}) \rightarrow 190 \text{ cm}^2$

<table>
<thead>
<tr>
<th></th>
<th>MIMOSA-26AHR</th>
<th>ALPIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor thickness ($\mu$m)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Spatial resolution ($\mu$m)</td>
<td>3.5</td>
<td>5</td>
</tr>
<tr>
<td>Dimensions ($\text{mm}^2$)</td>
<td>$10.6 \times 21.2$</td>
<td>$13.8 \times 30$</td>
</tr>
<tr>
<td>Power density (mW/cm$^2$)</td>
<td>250</td>
<td>40</td>
</tr>
<tr>
<td>Time resolution ($\mu$s)</td>
<td>115.2</td>
<td>10</td>
</tr>
<tr>
<td>Detection efficiency (%)</td>
<td>$&gt;99$</td>
<td>$&gt;99$</td>
</tr>
<tr>
<td>Dark hit occupancy</td>
<td>$\lesssim 10^{-4}$</td>
<td>$\lesssim 10^{-6}$</td>
</tr>
</tbody>
</table>

- Reuse mechanics and infrastructure of SAVD
- Minor modifications are required:
  - modifications of feedthrough
  - modification of ladders fixation bars
Upgrade of TPC

- New readout used in ALICE TPC will allow for 1 kHz operation (MoU between ALICE and NA61/SHINE)

- Major challenges:
  → Development of dedicated FPC
  → Flexible connection between FEC and ROU.

<table>
<thead>
<tr>
<th></th>
<th>NA61/SHINE</th>
<th>ALICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>dynamic range</td>
<td>120:1</td>
<td>900:1</td>
</tr>
<tr>
<td>MIP S:N ratio</td>
<td>14:1</td>
<td>14/20/18:1</td>
</tr>
<tr>
<td>noise</td>
<td>e</td>
<td>1100</td>
</tr>
<tr>
<td>ADC number of bits</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>number of time slices</td>
<td>512</td>
<td>1000</td>
</tr>
<tr>
<td>power consumption</td>
<td>mW/ch</td>
<td>51</td>
</tr>
<tr>
<td>sampling rate</td>
<td>MHz</td>
<td>5, 10</td>
</tr>
<tr>
<td>readout frequency</td>
<td>MHz</td>
<td>0.1</td>
</tr>
<tr>
<td>integrated non-linearity</td>
<td>%</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>
Upgrade of PSD

- **Main PSD** (MPSD) – 44 modules with beam hole in center ($\phi=60\text{mm}$)
- **Forward PSD** (FPSD) – 9 modules w/o beam hole
  - $\sigma_b/b \approx 0.1$, reaction plane resolution $\approx 40\text{ deg}$
- Beam rates up to 50 kHz
Upgrade of DAQ

- Inhomogeneous Nodes → flexible choice of sub-detector readout system.
- Homogeneous Core → data from all subsystems treated in the same way.
- For 1 kHz expected data rate is 160 Gb/s
- Other features:
  - Extendibility
  - Transparency
  - Use of commercial components
  - Robustness
Request for Open Charm measurements

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam</th>
<th>#days</th>
<th>#events</th>
<th>#(D^0 + \bar{D}^0)</th>
<th>#(D^+ + D^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2022</td>
<td>Pb at 150,A GeV/c</td>
<td>42</td>
<td>250M</td>
<td>38k</td>
<td>23k</td>
</tr>
<tr>
<td>2023</td>
<td>Pb at 150,A GeV/c</td>
<td>42</td>
<td>250M</td>
<td>38k</td>
<td>23k</td>
</tr>
<tr>
<td>2024</td>
<td>Pb at 40,A GeV/c</td>
<td>42</td>
<td>250M</td>
<td>3.6k</td>
<td>2.1k</td>
</tr>
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<table>
<thead>
<tr>
<th></th>
<th>0–10%</th>
<th>10–20%</th>
<th>20–30%</th>
<th>30–60%</th>
<th>60–90%</th>
<th>0–90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>#(D^0 + \bar{D}^0)</td>
<td>31k</td>
<td>20k</td>
<td>11k</td>
<td>13k</td>
<td>1.3k</td>
<td>76k</td>
</tr>
<tr>
<td>#(D^+ + D^-)</td>
<td>19k</td>
<td>12k</td>
<td>7k</td>
<td>8k</td>
<td>0.8k</td>
<td>46k</td>
</tr>
<tr>
<td>⟨W⟩</td>
<td>327</td>
<td>226</td>
<td>156</td>
<td>70</td>
<td>11</td>
<td>105</td>
</tr>
</tbody>
</table>
Anticipated results

- Precise measurements of charm hadron production by NA61/SHINE are expected to be performed in 2022-2024.

- The Lorentz boost makes the measurements significantly easier than in case of collider experiments.

- Unlike in a typical collider experiment the acceptance extends down to $p_T=0 \rightarrow$ accurate measurements of total charm meson yields.

The proposed program will allow to perform systematic study of $D^0$, $\bar{D}^0$, $D^+$, $D^-$, $(D^+_s)$ production versus collision energy and centrality.
Summary

**Tentative conclusion from 2D scan:** four domains of hadron productions separated by two thresholds:

the onset of deconfinement and the onset of fireball

**NA61/SHINE started measurements of open charm in 2017 → expected first physics results soon**

- After LS2 high statistic Pb+Pb data taking with upgraded detector is proposed. The results from high statistic runs are expected to:
  - distinguish between many existing models of charm production in Pb+Pb collisions
  - initiate a measurement of collision energy dependence of open charm yield
  - verify signal of the QGP formation by measurements centrality dependence of charm production

- We will continue with strong interaction program which is not related to charm

- NA61/SHINE plans to continue measurements for neutrino physics

- Request of dedicated secondary beams for measurements of NFCS

Details in CERN document: SPSC-P-330-ADD-10
The NA61/SHINE Collaboration


Addendum on the NA61/SHINE program after LS2 submitted to SPSC

Got SPCS recommendation for data taking in 2021 !!!
Backup slides
Performance of anisotropic flow measurements in Pb+Pb

- The results promise an extended rapidity coverage for flow measurements in comparison to the RHIC BES program,

- improvements in respect to NA49 results due to reaction plane orientation measurement with the PSD
Models fail to describe $\rho^0$ and $K^{0*}$ inclusive production
→ important input for modeling air showers generated by cosmic ray
NA61/SHINE program: complementarity and uniqueness

- **LHC** and **RHIC** at high energies ($\sqrt{s}_{NN} \geq 200$ GeV): significantly limited acceptance due to collider kinematics and related detector geometry

- **RHIC BES** collider and fixed-target ($\sqrt{s}_{NN} = 3-39$ GeV): measurement not considered in the current program

- **NICA** ($\sqrt{s}_{NN} < 11$ GeV): measurements during stage 2 (after 2023) are under consideration (overlap in energy with NA61/SHINE)

- **J-PARC-HI** ($\sqrt{s}_{NN} \leq 6$ GeV): under consideration, may be possible after 2025.

- **FAIR SIS-100** ($\sqrt{s}_{NN} < 5$ GeV): sub-threshold charm production measurements are considered. Systematic charm measurements are planned with SIS-300

→ only NA61/SHINE is able to measure open charm in heavy ion collisions in full phase space in the near future
Simulated results on $D^+ + D^-$
Anticipated results

SMES predictions
Measurements for Fermilab neutrino beams

Preliminary cross sections from data taken in 2015 and 2016.

Data taken in 2016 and 2017 (with magnetic field) are under calibrations and analysis with the aim to obtain particle spectra.
NFCS: performance of test

- **Secondary ion beam**: nuclear fragments from SPS, Pb ions on primary Be target, selection of $A/Z = 2$ and $p = 13A$ GeV/c,
- **target**: thin polyethylene foil and carbon targets,
- **beam PID**: $A$ from Time of Flight at 140 m, $Z$ from Cherenkov quartz plate based detector (see figure below),
- **fragment PID**: $Z$ from scintillator downstream of the target and energy deposited in TPCs. $A/Z$ from from the bending in the NA61 superconductiong magnets (9 Tm).
NFCS: current situation

Precise measurement of the cross sections at around 13 A GeV/c can improve situation dramatically.

Similar situation is for $^{16}\text{O} + p \rightarrow ^{11}\text{B}$

Main uncertainties to the cumulative flux are related to uncertainty on NFCS for C+p and O+p.