Open charm measurements in NA61/SHINE experiment at the CERN SPS

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Outline

1. Introduction
2. Physics motivation for open charm measurements
3. Performance of Small Acceptance Vertex Detector
4. Upgrades and proposed measurements after LS2
Introduction
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 is positioned downstream of the time of flight detectors measure energy of projectile fragments.

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)
  \( \rho_{\text{beam}} = 13–400 \text{ GeV/c} \)
- \( \sqrt{s_{\text{NN}}} = 5.1–16.8 (27.4) \text{ GeV} \)

Large acceptance hadron spectrometer – coverage of full forward hemisphere, down to \( p_T = 0 \)
Physics motivation for open charm 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
  $\rightarrow$ 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 $\langle cc \rangle$

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>$c \bar{c}$ [μm]</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>

charm conservation

$C = \bar{C}$

violation of isospin symmetry

$D^0 \approx 2.6 \ D^+$

$D_s^+ \approx 2.6 \ D_s^-$

$31\%$  $12\%$

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

PHSD, Elena Bratkovskaya & Taesoo Song, private communication
J/ψ 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/ψ production (Matsui, Satz, PLB 178 (1986) 416)
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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 $\rightarrow$ 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 $\rightarrow$ initial state effects can reduce charmonium production rate in A+A relative to p+p collisions.
**J/ψ suppression as signal of deconfinement**


Below LHC energies in p+p 90% c¯c pairs convert to open charm, remaining 10% form charmonia states.

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Due to shadowing, parton energy loss etc., the number of c¯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.

→ the effect of the medium on c¯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!!!
Performance of Small Acceptance Vertex Detector (SAVD)
Why Vertex Detector is needed to measure open charm?

\[ D^0 \rightarrow \pi^+ + K^- \]

- Daughters of \( D^0 \) (\( \pi \) and \( K \)) are recognized as a pair forming a secondary vertex displaced from the primary vertex.
- \( c\tau(D^0) \approx 122 \mu m \), however, due to Lorentz boost (\( \beta \gamma \approx 10 \)) the displacement is on the level of 1 mm.
- This holds also for other charm mesons like \( D^+ \), \( D^- \), \( D_s^+ \).
- The Lorentz Boost makes the measurements significantly easier in fixed target experiments than in collider experiments.

Vertex detector is needed to reconstruct primary vertex and secondary vertices with high precision.
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
Main project components

System integration and project leadership:
Jagiellonian University Krakow,
supported by AGH Krakow, WUT Warsaw
Main project components (cont.)

MIMOSA-26AHR
- 1152x576 pixels of 18.4x18.4µm²
- 3.5 µm resolution, 0.05% $X_0$
- Readout time: 115.2 µs, 50µm thin
PICSEL Group, IPHC Strasbourg

ALICE ITS ladder
- Ultra light carbon fibre
- < 0.3% $X_0$ including water cooling
St. Petersburg, CERN

CBM Micro Vertex Detector Prototype
- Sensor integration
- Flex print cables, Front-end boards
- Read-out based on TRB3 FPGA Board
Goethe Universitat Frankfurt am Main
SAVD performance: $K_0^S$ and $\Lambda^0$

Results for 1.1M events of Xe+La at 150A GeV/c

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

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
5. DCA
SAVD performance: D⁰

First result for 1.1 M events of Xe+La at 150A GeV/c

Background suppression → cuts on:
1. track $p_T > 0.38$ GeV/c
2. track impact parameter $> 38$ μm
3. longitudinal distance of pair vertex to primary vertex $< 800$ μm
4. parent impact parameter $< 22$ μm
5. DCA $< 40$ μm

Analysis details:
1. Global fit (VD+TPCs) using Kalman Filter
2. PID information used but dE/dx is not calibrated yet → significant improvement expected

Next steps:
1. calibrate dE/dx
2. add full statistics (~ 3 M events)

Analysis of Pb+Pb at 150A GeV/c in progress
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

Upgrade of Projectile Spectator Detector

New Time-of-Flight detectors

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

<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 (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>

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

see also report by Grigori Feofilov at this conference

- Reuse mechanics and infrastructure of SAVD
- Minor modifications are required:
  - modifications of feed through
  - modification of ladders fixation bars
# Request for Open Charm measurements

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam</th>
<th>#days</th>
<th>#events</th>
<th>#(D⁰ + D̄⁰)</th>
<th>#(D⁺ + D⁻)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2022</td>
<td>Pb at 150A GeV/c</td>
<td>42</td>
<td>250M</td>
<td>38k</td>
<td>23k</td>
</tr>
<tr>
<td>2023</td>
<td>Pb at 150A GeV/c</td>
<td>42</td>
<td>250M</td>
<td>38k</td>
<td>23k</td>
</tr>
<tr>
<td>2024</td>
<td>Pb at 40A GeV/c</td>
<td>42</td>
<td>250M</td>
<td>3.6k</td>
<td>2.1k</td>
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</tbody>
</table>

<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>#(D⁰ + D̄⁰)</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>\langle W \rangle</td>
<td>327</td>
<td>226</td>
<td>156</td>
<td>70</td>
<td>11</td>
<td>105</td>
</tr>
</tbody>
</table>
Anticipated results ($D^0$)

- 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 $p_T=0$ → 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

NA61/SHINE open charm production measurements started in 2017 with SAVD → 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 of centrality dependence of charm production

Details in CERN document: SPSC-P-330-ADD-10
Backup slides
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 planed with SIS-300

→ only NA61/SHINE is able to measure open charm in heavy ion collisions in full phase space in the near future
**Vertex Detector performance**

Spacial resolution of the sensor < 5μm as expected

\[
\sigma_{x/y} = \sqrt{\frac{2}{3}} \sigma_{dev_{x/y}}
\]

Reconstruction of primary vertex allows to separate **in-** and **out-target** interactions

Spacial primary vertex resolution:

\[
\begin{align*}
\sigma_x &= 5 \mu m \\
\sigma_y &= 1.8 \mu m \\
\sigma_z &= 30 \mu m
\end{align*}
\]

Worse resolution in \( x \) due to presence of magnetic field (\( B_y \))
VD – TPC track matching

Extrapolate SAVD tracks to TPC volume.

Pre-selection: cut on y-slopes of tracks.

After cuts on dx and dy clear correlation peaks are seen in $d p_x$ and $d p_z$.

Matching with TPC provides:

- momenta and PID to VD tracks

  $\rightarrow$ invariant mass distribution
Performance for Xe+La at 150A GeV/c

- Large statistic Xe+La data taken in late 2017 at 150A and 75A GeV/c for minimum bias and 0-20% central events.
- Segmented target was used (tree 1mm thick La blocks squeezed together). The structure of the target can be well seen in the $z_{\text{prim}}$ distribution plot.
- Obtained primary vertex resolution: 1.3, 1.0 and 15 $\mu$m in $x$, $y$ and $z$ coordinate, respectively. Significant improvement as compared to test measurement due to better setup of sensor thresholds.
- Xe+La data should allow for reinterpretation of $J/\psi$ yields measured by NA60 for medium size systems.
Measurement program with SAVD

2016: Pb+Pb at 150A GeV/c
• Detector commissioning
• Good detector performance
• $D^0$ likely seen

2017: Xe+La at 75 and 150A GeV/c
• Improved sensor efficiency
• Improved primary vertex resolution ($dx=1.3\mu m$, $dy=1.0\mu m$, $dz=15\mu m$)
• Large statistics collected:
  5.1 MEvents@150AGeV/c
  4.0 MEvents @75A GeV/c
• Analysis ongoing, expected good data quality
• Expected open charm data suited for comparison with NA61/SHINE

2018: Pb+Pb at 150A GeV/c run scheduled
Simulated results on $D^+ + D^-$
Anticipated results

SMES predictions
Particle ratios and fluctuations (2)

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
- $<K^+>/<\pi^+>$ 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
and
onset of fireball

Completion of Ar+Sc analysis and new data for Xe+La awaited to verify this picture
We would like to thank the CERN EP, BE, EN and IT Departments for the strong support of NA61/SHINE

The NA61/SHINE Collaboration