Charm of NA61

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Outline

- Why open charm is important?
- First measurements in NA61/SHINE 2017-2018
- Precise open charm studies in 2021-2024
Why open charm is important?
Questions that motivate open charm measurements at the CERN SPS:

- What is the mechanism of open charm production?
- How does the onset of deconfinement impact open charm production?
- How does the formation of quark gluon plasma impact $J/\psi$ production?

To answer these questions mean number of charm quark pairs, $\langle c\bar{c}\rangle$, produced in the full phase space in A+A collisions has to be known. Up to now corresponding experimental data does not exist.
Models of open charm production

Predictions for $\langle c\bar{c} \rangle$ in central Pb+Pb at 158A GeV/$c$ differ by a factor of about 50.

- **pQCD**: Gavai *et al.* IJMP A 10 2999.
- **Braun-Munzinger, J. Stachel**: PL B 490, 196.
- **HSD**: Linnyk, Bratkovskaya, Cassing, IJMP E17 1367
- **HRG, Quark Coalesc. Stat.**: Gorenstein, Kostyuk, Stoecker, Greiner, PL B 509, 277.
- **Quark Coalesc. Dyn.**: Levai, Biro, Csizmadia, Csorgo, Zimanyi, JP G 27, 703
- **SMES**: Gazdzicki, Gorenstein, APP B30, 2705.
Charm yield as the signal of deconfinement

confined matter \( T_c \approx 150 \text{MeV} \) \( \xrightarrow{\text{deconfined matter}} \)

\[ \begin{align*}
\text{D}\bar{D} & \quad \rightarrow \quad \text{charm quarks} \\
2m_D & = 3.7 \text{ GeV} \quad \rightarrow \quad 2m_c = 2.6 \text{ GeV} \\
g_D & = 4 \quad \rightarrow \quad g_c = 12
\end{align*} \]

central Pb+Pb collisions

Statistical Model of the Early Stage

\[ \langle \bar{c}c \rangle \quad \left[ \text{Kostyuk, Gorenstein, Greiner,} \quad \text{PLB}519 \quad 207 \right] \]

QCD-inspired calculations

\[ \langle \bar{c}c \rangle \quad \left[ \text{Kostyuk, Gorenstein, Greiner,} \quad \text{PLB}519 \quad 207 \right] \]
$J/\psi$ production as the signal of deconfinement

Open charm and $J/\psi$ production within Matsui-Satz model

[PL B178 416]

Medium reduces probability of $J/\psi$ production
$J/\psi$ production as the signal of deconfinement

Calculation of $P(c\bar{c} \rightarrow J/\psi)$ requires data on:

- $\langle J/\psi \rangle$ – precise data at SPS by NA38, NA50, NA60
- $\langle c\bar{c} \rangle$ – not available up to now, NA61 has just started the corresponding measurements

中央Pb+Pb at 150-158A GeV/c

NA50

NA61

preliminary

$P(c\bar{c} \rightarrow J/\psi) \equiv \frac{\langle J/\psi \rangle}{\langle c\bar{c} \rangle} \equiv \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}}$
Data on $J/\psi$ production has been normalized by the Drell-Yan yield.

Interpreting these results one frequently assumes:

$$\langle c\bar{c} \rangle \sim \langle \text{DY} \rangle$$

This assumptions may be incorrect due to many effects: shadowing, parton energy losses, etc.
First measurements in NA61/SHINE 2017-2018
Open charm measurement concept

Vertex detector is needed to reconstruct primary vertex and secondary vertexes with high precision.

\[ D^0 \rightarrow \pi^+ + K^- \]
\[ \bar{c} \tau \approx 123 \ \mu m \]
\[ \text{BR} = 3.89\% \]
NA61/SHINE setup

Small Acceptance Vertex Detector

Diagram showing the layout of the NA61/SHINE setup with various detectors and components labeled.
Small Acceptance Vertex Detector introduced in 2016:
• 16 MIMOSA-26 sensors located on two horizontally movable arms
• Target holder integrated

Achieved goals:
• tracking in the large track multiplicity environment
• precise primary vertex reconstruction
• TPC and SAVD track matching
• first search for $D^0$ and $\bar{D}^0$ signal
Acceptance of SAVD

AMPT simulation for central Pb+Pb collisions at 150A GeV/c.
SAVD reconstructs 4% out of all $D^0 \rightarrow \pi^+ + K^-$ decays.
From the analysis of the recorded data one concludes that:

- Cluster position resolution is $\sigma_{x,y}(Cl) \approx 5 \mu m$
- Primary Vertex resolution is:
  $\sigma_x(PV) \approx 5 \mu m,$
  $\sigma_y(PV) \approx 1.8 \mu m,$
  $\sigma_z(PV) \approx 30 \mu m.$

$(\sigma_x(PV) > \sigma_y(PV) \text{ due to } B_y > B_x \approx 0)$
Search for $D^0$ and $\bar{D}^0$

First indication of $D^0$ and $\bar{D}^0$ peak

$\sigma_{D^0} = 40 \pm 15$ MeV

yield $= 55 \pm 20$
About 5M events on central Xe+La collisions at 150A GeV/c were recorded three weeks ago.

Based on simulations from Pb+Pb and p-QCD inspired system size dependence, one expects several hundred of $D^0 + \bar{D}^0$ meson decays to be reconstructed.

This should allow to obtain the first physics results on open charm production in heavy ion collisions at the CERN SPS.
Impact of Xe+La data

$J/\psi$ production in $\text{In+In (} A = 115\text{)}$ collisions at $158\text{A GeV/c}$ was precisely measured by NA60.

This data together with NA61 results on open charm production in Xe+La ($A = 129, A = 139$) collisions at $150\text{A GeV/c}$ will strongly challenge theoretical models.
Pilot data on Pb+Pb at 150A GeV/c in 2018

Data taking in 2018 on central Pb+Pb collisions for open charm measurement recommended by CERN SPSC in October 2017.

Three weeks of data taking:
• 10M central collisions recorded
• 4000 $D^0$ and $\overline{D^0}$ decays is expected to be reconstructed
Precise open charm studies in 2021-2024
Upgrades of NA61/SHINE setup

Construction of Large Acceptance Vertex Detector (LAVD) 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
Large Acceptance Vertex Detector

General requirements:
• Precise vertex measurement
• Fast detectors with high granularity
• The low material budget
• Large acceptance

Technology developed for ALICE ITS:
• CMOS ALPIDE pixel sensors
• Carbon fiber support structure
• Read-out electronics

6 stations with about 200 sensors
# Beam request for 2021-2024

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam</th>
<th>Duration</th>
<th>Purpose</th>
<th>$D^0 + \bar{D}^0$ stat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>p at 150 GeV/c</td>
<td>4 weeks</td>
<td>detector tests</td>
<td></td>
</tr>
<tr>
<td>2022</td>
<td>Pb at 150A GeV/c</td>
<td>2 weeks</td>
<td>charm in central collisions</td>
<td>40k</td>
</tr>
<tr>
<td>2022</td>
<td>Pb at 150A GeV/c</td>
<td>4 weeks</td>
<td>charm in peripheral collisions</td>
<td>8k</td>
</tr>
<tr>
<td>2023</td>
<td>Pb at 150A GeV/c</td>
<td>2 weeks</td>
<td>charm in mid-central collisions</td>
<td>20k</td>
</tr>
<tr>
<td>2024</td>
<td>Pb at 40A GeV/c</td>
<td>4 weeks</td>
<td>charm in central collisions</td>
<td>2k</td>
</tr>
</tbody>
</table>
Performance for open charm measurements

Two weeks in 2022 (1kHz + LAVD) \( \approx 40\,000 \, D^0 + \bar{D}^0 \) decays reconstructed in 40M central Pb+Pb collisions at 150\( A \) GeV/c

LAVD reconstructs 12% out of all \( D^0 \rightarrow \pi^+ + K^- \) decays.

Based on AMPT one estimates that fully corrected results will cover most of the phase space.

Total systematic uncertainty of \( \langle D^0 \rangle \) and \( \langle \bar{D}^0 \rangle \) is expected to be about 10%.
Uniqueness of NA61 open charm program

Landscape of present and future heavy ion experiments

- **LHC and RHIC at high energies**: measurements in small phase space due to collider geometry and kinematics
- **RHIC BES collider**: measurement not possible due to collider geometry and kinematics
- **RHIC BES fixed-target**: measurement require dedicated setup, not under consideration
- **NICA (< 80 A GeV/c)**: measurement during stage 2 under consideration
- **J-PARC (< 20 A GeV/c)**: maybe possible after 2025
- **FAIR (< 10 A GeV/c)**: not possible

Only NA61/SHINE is able to measure open charm production in heavy ion collisions in full phase space in the near future.
Impact of open charm measurements

accuracy of NA61 2020+ result assuming HSD yield
Impact of open charm measurements

\[ m_Q^c = 1.3 \text{ GeV} \]

\[ g_w^c = 10 \]

accuracy of NA61 2020+ result assuming SMES yield
Impact of open charm measurements

accuracy of NA61 2020+
result assuming
\langle c\bar{c} \rangle \sim \langle \pi \rangle
and scaling to
\langle J/\psi \rangle / \langle \text{DY} \rangle
for peripheral collisions
NA61 charm program addresses following questions:

- What is the mechanism of open charm and $J/\psi$ production?
- How does the onset of deconfinement impact open charm production?
- How does the formation of quark gluon plasma impact $J/\psi$ production?

To answer these questions, the mean number of charm quark pairs produced in heavy ion collisions will be measured in 2017-2018 and in 2021-2024.

Only NA61/SHINE can perform this measurement in the near future.
Backup slides
Distribution of charm

charm conservation

\[ c = \bar{c} \]

isospin symmetry

\[ D^+ \approx D^0 \]
\[ D^- \approx \bar{D}^0 \]

high baryon density

\[ \Lambda_c \]
\[ \bar{\Lambda}_c \]
Replacement of the TPC electronics

Will increase the read-out rate by a factor of about 10 (up to 1 kHz)

ALICE will transfer to NA61/SHINE its present TPC electronics that will be replaced during the long shutdown LS2
Upgrade of the trigger and data acquisition

Need for 1kHz readout frequency
Search for $D^0$ and $\bar{D}^0$

Huge combinatorial background is suppressed by cuts on:
- track transverse momentum
- track impact parameter
- longitudinal distance between secondary and primary vertices
- pair impact parameter
LHC open charm and $J/\psi$
LAVD acceptance
Charm in h+A collisions

![Graphs showing charm cross-sections as a function of beam energy and s^{1/2}]

- Linnyk, Bratkovskaya, Cassing, JWMPE17 1367
- Alves et al., [E769 Collab.] PRL 77 (1996) 2388
- QCD prediction for total charm cross-section (x_f > 0)
NA49 open charm upper limit
HSD predictions

[Image of a graph showing multiplicity as a function of energy for Au+Au collisions. The graph includes data points for different hadrons and energies, with markers for AGS, SPS, and RHIC.]
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 dpx and dpz

Matching with TPC provides: momenta and PID to VD tracks → invariant mass distribution