Feasibility of the detection of $D^0$ mesons in the NA61/SHINE experiment

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Presentation Plan

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   - NA61/SHINE detector overview

2. Feasibility Studies
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   - Acceptance
   - Reconstruction
   - Cut Strategy
   - Results of $D^0$ simulation

3. Vertex detector studies
   - Parameters of Vertex detector
   - Outer dimensions
   - Fluence estimates
   - Pixel occupancy

4. Summary
Introduction

- A feasibility study of $D^0 \rightarrow K^+ \pi^-$ (BR=3.87%) channel in central Pb+Pb collisions at the CERN SPS energies will be presented. The study is done for 158 AGeV and 40 AGeV ($D^0 \rightarrow c\tau = 122.9 \, \mu m$)

- The NA61/SHINE requires upgrade with a new vertex detector that will allow precise track and vertex reconstruction at the target proximity.

- The obtained results focusing on the predicted yields of $D^0$ mesons and vertex detector optimization regarding its geometry and applied detection technologies
NA61/SHINE Experiment

NA61/SHINE at the CERN SPS
Physics motivation

→ So far no direct open charm measurements at SPS energies
→ Only J/Ψ has been measured at top SPS energy by (NA50 and NA60) experiments
→ Open charm measurement provides unique opportunity to test the validity of p-QCD based and statistical models of nucleus-nucleus collisions at higher energies (Acta. Phy. Pol. B Vol 31 (2000))

→ Differential measurements for open charm


(Int. J. Mod. Phys. E17 1367)
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 volume TPCs serve as tracking detectors

Time of Flight walls  ➔  Mainly used for Hadron Identification

Projectile Spectator Detector (PSD)  ➔  A Calorimeter which is positioned downstream of the time of flight detectors to measure energy of projectile fragments.
NA61/SHINE detector – Top view
Vertex detector Position

VERTEX DETECTOR (VD)
Feasibility Studies
Physical Input

→ AMPT (A MultiPhase Transport model) event generator used to generate 200k Pb+Pb events at 158 AGeV for 0-10% centrality

→ AMPT predicts $0.01$ of $<D^0> + <\overline{D^0}>$ per central Pb+Pb event. This seems to be under-predicted value, e.g. PYTHIA run for N-N and scaled to central Pb+Pb gives $0.21$ (P. Braun-Munzinger, J. Stachel, PLB 490 (2000) 196)

→ HSD (Hadron String Dynamic) Model predictions are consistent with scaled PYTHIA → We scaled AMPT predictions to be consistent with HSD and PYTHIA.

→ AMPT does not generate “Open Charm” at 40 AGeV, We assume open charm phase space distribution characteristic same as for 158 AGeV and yields as predicted by HSD model.

→ Rapidity distribution and Invariant mass slope parameter does not change more than 10% for Kaons while going from 158 AGeV to 40 AGeV

HSD : (Int. J. Mod. Phys. E17 1367)
AMPT Event: Pb+Pb at 158 AGeV

- VTPCs filled with Ar-CO$_2$ mixture, location and dimensions as in NA61 setup.
- Uniform magnetic field: 1.5 T in VTPC-1 and 1.1 T in VTPC-2
Design of the Future
Vertex Detector

VDS Stations are located at the distance of 5, 10, 15 and 20 cm respectively from the Target
Reconstruction

- Track distance in VTPC1 + VTPC2 > 1m
- Require hit at least in the three Vertex detector stations
- NA61/SHINE Momentum and Position resolutions are assumed

1. momentum resolution $\frac{dp}{p^2} = 7.0 \times 10^{-4} (\text{GeV/c})^{-1}$ (Nuclear Instruments and Methods in Physics Research A 430 (1999) 210 - 244)

2. position resolution is 10 μm → hits are spread in y and x around geant hit according to the Gaussian distribution (σ = 10 μm). Track line is taken from the fit to the spread points

![P Spread distribution graph with table showing statistical properties]
Background Suppression strategy

→ Combinatorial background is very large → need to apply background suppression cuts.
→ Optimized to assure good signal Acceptance.

Single particle cuts:

1. cut on $p_T$ (< 0.4)
2. cut (track impact parameter $d$ (< 40μm))

Two particle cuts:

3. Cuts in Armenteros-Podolanski space to remove background from $K_s$ and $\Lambda$
4. Two track vertex cut $V_z$ (< 500μm)
5. Reconstructed parent impact parameter cut $D$ (> 22μm)
2. Cut on \( d \)

Relatively smooth shape of background at \( \sim 0 \) is due to uncertainly in reconstruction of track position and angle. Some uncertainly comes from multiple scattering.

\( \rightarrow \) cut on \( d < 40 \ \mu \text{m} \) as indicated
4. cut on $V_z$

$V_z \rightarrow$ cut on $V_z < 500 \ \mu m$ as require
Spectrum after selection Cuts

Reduction of Background $\approx 10^6$
Reduction of Signal $\approx 3$
Reconstructed yield for $D^0 \rightarrow K^+ \pi^-$, 200k 0-10% cent. Pb+Pb at 158 AGeV
Reconstructed yield for $D^0 \rightarrow K^+ \pi^-$, 200k 0-10% cent. Pb+Pb at 40 AGeV

<table>
<thead>
<tr>
<th>Pos. Res (μm)</th>
<th>10</th>
<th>10</th>
<th>15</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam hole (mm)</td>
<td>2.5</td>
<td>3.0</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>$S/B$</td>
<td>1.5</td>
<td>2.0</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Signal Significance (SNR)</td>
<td>33.3</td>
<td>32.7</td>
<td>8.0</td>
<td>7.3</td>
</tr>
<tr>
<td>$\langle D^0 \rangle + \langle \bar{D}^0 \rangle$</td>
<td>1846</td>
<td>1759</td>
<td>1769</td>
<td>1692</td>
</tr>
</tbody>
</table>

Results Extrapolated to 50M Events
Vertex Detector Studies
**δ-electrons** and charge particles produced in Pb+Pb interaction

Delta electrons
(averaged over 10k Pb events)

Charged particles produced in Pb+Pb interactions
Particle Flux:

- During spill the anticipated beam intensity is $10^5$ Pb ions per second.
- For 200 μm Pb target interaction probability is 0.5% which leads to 500 Hz interaction rate

**Hadronic interactions:**

flux = $(10^5 \times 0.005) \text{ event/s} \times 1.6 \text{ particles/mm}^2/\text{event}$ = $800 \text{ particles/mm}^2/\text{s} = 800 \text{ Hz/mm}^2$

**Electromagnetic interactions ($\delta$-electrons):**

flux = $10^5 \text{ event/s} \times 0.04 \text{ particles/mm}^2/\text{event}$ = $4000 \text{ Hz/mm}^2$

→ Rate of Flux is not critical, for the future detectors
Charged particles produced in Pb+Pb 0-10% central interactions

We can expect very high hit occupancy on the level of 5 hit/mm$^2$/event in the most inner part of the vertex detector.

It suggests that silicon pixel sensors would provide a good solution for us.
Outer dimensions
The figure shows hits (x,y) distribution generated by signal tracks is Vds1. The dashed boxes represent the cuts. We found that ~99.5% of signal tracks is localized within the box 2x4 cm². As you can see, to cover the remaining 0.5% we would need to extend the cut in the x direction for almost factor of 2.
For stations Vds2-Vds4 we just extend size of the boxes in proportion to their distance from the target. So we got dimensions: $4 \times 8 \, \text{cm}^2$, $6 \times 12 \, \text{cm}^2$ and $8 \times 16 \, \text{cm}^2$ for Vds2, Vds3 and Vds4, respectively. The signal lost is kept below 1% for each station.

For Pb+Pb at 40 AGeV the signal lost is on the level of 4% for the same cuts.
Signal track distribution at 158 AGeV in VDS3 and VDS4

VDS3
0.8% signal lost in outer region

VDS4
0.9% signal lost in outer region
The following conceptual drawings are based on MIMOSA-26 chip hosting sensitive area of about 1.06 x 2.12 cm$^2$ with the pixel pitch equal 18.4 µm (~663.5k pixels/chip):

These pads are for testing purpose and can be removed.

The readout speed of the whole fame in ~100 µs (10 kHz), zero suppression circuit.
The chips are available. We can just buy them from IPHC (Institut Pluridisciplinaire Hubert Curien), Strasbourg.
Preliminary design of the 1\textsuperscript{st} station

\rightarrow \text{Drawn blue boxes have dimensions of the sensitive area of MOMOSA-26 sensor} (~1x2 \text{ cm}^2)

\rightarrow \text{Size of the dashed box is } ~ 2x4 \text{ cm}^2. \text{ We have to cover this area to loose less than 0.3\% / 3\% of signal particles for 158 / 40 GeV}
Preliminary design of the 2\textsuperscript{nd} station

→ Size of the dashed box is \( \sim 4 \times 8 \text{ cm}^2 \)

→ full coverage of Vds2 area with MOMOSA-26 requires 20 sensors

→ Including Vds3 (6x12 cm\(^2\)) and Vds4 (8x16 cm\(^2\)) we will need about 120 sensors for the whole detector.
Fluence estimates
Performance of MIMOSA-26 → test on beam

Temperature: + 30°C
Readout Time: 125 µs
Pitch size: 20.7 µm
Irradiated with to
fluence = $3 \times 10^{12} n_{eq}/cm^2$

For disc. Threshold= 5 mV:
detection efficiency ~ 99.8%,
fake hits < $10^{-4}$
resolution ~ 3.5 µm

(M.Winter, CBM Progress Report 2010)
Displacement Damage Function

Bulk damage exclusively depends upon non ionizing energy lose (NIEL). This is described by the displacement damage functions $D(E)$

Hadronic interactions:
- flux = $(10^5 \times 0.005) \text{ event/s} \times 1.6 \text{ particles/mm}^2/\text{event}$ = 800 Hz/mm$^2$

Electromagnetic interactions ($\delta$ - electrons):
- flux = $10^5 \text{ event/s} \times 0.04 \text{ particles/mm}^2/\text{event}$ = 4000 Hz/mm$^2$

(A. Vasilescu, ROSE Internal Note ROSE/TN/97-2 (1997))
Fluence Calculations

\[ \Phi_{eq}^{1\text{MeV}} = \kappa \Phi \]
\( \kappa \) - radiation hardness parameter
\( \kappa = 0.62/5 \) for electrons
\( \kappa = 0.62 \) for particles from hadronic interactions

Fluence for electrons in [for 1 month] (upper limit):

\[
= 4 \times 10^5 /\text{cm}^2/\text{sec} \times 0.62/5 \times 2592000 \text{ sec} = 1.28 \times 10^{11} \text{n}_{eq}/\text{cm}^2
\]

For Spill of the beam (20%) = \( 2.57 \times 10^{10} \text{n}_{eq}/\text{cm}^2 \)

\( \rightarrow \) \( \Phi \) for charge Particles = \( 800 \text{ Hz/mm}^2 \)

Fluence for charged particles [for 1 month] (upper limit):

\[
= 8 \times 10^4 /\text{cm}^2/\text{sec} \times 0.62 \times 2592000 \text{ sec} = 1.28 \times 10^{11} \text{n}_{eq}/\text{cm}^2
\]

For Spill of the beam (20%) = \( 2.57 \times 10^{10} \text{n}_{eq}/\text{cm}^2 \)

Factor of 40 below the tested range
Pixel Occupancy
As usually looking at the most critical area of Vds1 where the track occupancies are:

1. 5 tracks/mm²/event for central Pb+Pb collisions
2. 1.6 tracks/mm²/event from averaging over minimum bias Pb+Pb collision
3. 0.04 δ-electrons/mm²/event for Pb ion on 200 μm target

P(0) = 95% - empty frame
P(1) = 4.7% - single event
P(2) = 0.12% (pile-up P(2)/P(1) = 2.5%)

Beam intensity of 100kHz will lead to 10 ions in 100 μs

Single Pixel Occupancy = 0.25% (+0.01% contribution from fake hits)

→ Not very dense environment → probability of overlap low, however we need full simulation to prove the reconstruction feasibility
Summary

The simulations have shown that the measurements of the $\bar{D}^0$ and $D^0$ mesons in NA61 experiment with a dedicated vertex detector is feasible.

In the next stage of the study, need to include:

1. Full simulation:
   Realistic track reconstruction in VD & matching with VTPC

2. Building Prototype and Tests (on beam) to show that keeping sensors in flowing and conditioning helium will ensure reasonably low and stable sensor temperature (to keep fake hits low)
Thank you!

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BACK UP SLIDES
Parameters for 40 AGeV

For the studies at 40 AGeV energy the whole phase space (physical input) was not available by AMPT event generator.

Sigma → From the rapidity distributions for kaons at both energies 40 and 158 AGeV respectively.

Sigma K(158)/Sigma K(40) = Sigma D(158)/Sigma D(40)

Temperature From transverse mass distributions By Fitting
Exponential Function A Exp(-mt/T)
Acknowledgments

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→ NA61 Collaboration

→ Division of Hot Matter Physics
M. Smoluchowski Institute of Physics, Jagiellonian University, Krakow Poland
Detection Strategy

“Distance between interaction Point and decay point is measurable”

\[ d_0^K \]

<table>
<thead>
<tr>
<th>Meson</th>
<th>Decay Channel</th>
<th>( C \tau )</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D^0 )</td>
<td>( D^0 \to K^\pi^+ )</td>
<td>122.9 ( \mu m )</td>
<td>(3.91 ± 0.05)%</td>
</tr>
<tr>
<td>( D^0 )</td>
<td>( D^0 \to K^\pi^+\pi^+\pi^- )</td>
<td>122.9 ( \mu m )</td>
<td>(8.14 ± 0.20)%</td>
</tr>
<tr>
<td>( D^+ )</td>
<td>( D^+ \to K^-\pi^+ )</td>
<td>311.8 ( \mu m )</td>
<td>(9.2 ± 0.25)%</td>
</tr>
<tr>
<td>( D^+_s )</td>
<td>( D^+_s \to K^-K^\pi^+ )</td>
<td>149.9 ( \mu m )</td>
<td>(5.50 ± 0.28)%</td>
</tr>
<tr>
<td>( D^{*+} )</td>
<td>( D^{*+} \to D^0\pi^+ )</td>
<td>( \text{----------} )</td>
<td>(61.9 ± 2.9)%</td>
</tr>
</tbody>
</table>

The average multiplicity for 158AGeV is 0.01 * 1/0.0378 = 0.26 (consistent with HSD) for 40 AGeV it is 0.01
→ VTPCs filled with Ar-CO$_2$ mixture, location and dimensions as in Na61 setup.
→ Uniform magnetic field: 1.5 T in VTPC$_1$ and 1.1 T in VTPC$_2$
Background suppression strategy (Need to discuss)

List of cuts in the order they are applied

**Single particle cuts:**

1. track $p_T$ cut
2. track $d$ cut (track impact parameter)

**Two particle cuts:**

3. cuts in Armenteros-Podolanski space to remove background from $K_s$ and $\Lambda$
4. two track vertex cut $V_z$
5. reconstructed parent impact parameter cut $D$
1. cut on $p_T$

Background $p_T$ spectrum has maximum around ~ $0.2\text{GeV/c}$, whereas maximum of signal distribution is at around $1\text{GeV/c}$

$\rightarrow$ cut on $p_T<0.4$ as indicated
3. cut on D

$V_z$ cut reduces background at $D \sim 0$, where the signal is located. $V_z$ and $D$ cuts are nicely complementary to each other.

→ cut on $D > 0.022$ mm
Charged Particle Fluxes

Sources of particles hitting VD:
   - during spill the anticipated beam intensity is $10^5$ Pb ions per second.
   - for 200 $\mu$m Pb target interaction probability is 0.5% which leads to 500 Hz interaction rate
   - used AMPT to generate 100k min. bias Pb+Pb at 158 AGeV

2. Delta electrons produced mostly in target
   - study 10k Pb ions passing through the lead target
   - soft particles – surrounding material might be important
   - production threshold cut in geant4: minimum distance that produced particle will travel in a given material → translates to cut on energy
     If the distance is (too) small – a lot of soft particles is produced (CPU consumption)
     If the distance is (too) large – important component might not be described

→ the influence of the production threshold cut has to be studied