Future Vertex Detector For
Open Charm Measurements with NA61/SHINE Experiment
at CERN-SPS

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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.

→ 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 based on the predicted yields of $D^0$ mesons and vertex detector optimization regarding its geometry and applied detection technologies
Detection Strategy

→ Distance between interaction Point and decay point is measurable

<table>
<thead>
<tr>
<th>Meson</th>
<th>Decay Channel</th>
<th>$C_{\tau}$</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$D^0 \rightarrow K^- + \pi^+$</td>
<td>122.9$\mu$m</td>
<td>(3.91±0.05)%</td>
</tr>
<tr>
<td>$D^0$</td>
<td>$D^0 \rightarrow K^- + \pi^+ + \pi^+ + \pi^-$</td>
<td>122.9$\mu$m</td>
<td>(8.14±0.20)%</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$D^+ \rightarrow K^- + \pi^+ + \pi^+$</td>
<td>311.8$\mu$m</td>
<td>(9.2±0.25)%</td>
</tr>
<tr>
<td>$D^+_s$</td>
<td>$D^+_s \rightarrow K^+ + K^- + \pi^+$</td>
<td>149.9$\mu$m</td>
<td>(5.50±0.28)%</td>
</tr>
<tr>
<td>$D^{*+}$</td>
<td>$D^{*+} \rightarrow D^0 + \pi^+$</td>
<td>-----------</td>
<td>(61.9±2.9)%</td>
</tr>
</tbody>
</table>
NA61/SHINE Experiment
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 pQCD based and statistical models of nucleus-nucleus collisions at higher energies (Acta. Phy. Pol. B Vol 31 (2000))
→ Differential measurements for open charm

(arXiv 0907. 3682 v2 [nucl-ex] 2009)

(Int. J. Mod. Phys. E17 1367)
Statistical Hadronization Model – predictions for $J/\psi$ and open charm

Note different scale factors for SPS-LHC

Quality of charm measurement not sufficient to desintangle among different models

→ needs more precise data
→ detector upgrade

We know that both STAR and ALICE (also CMS) are working on vertex detector to improve heavy flavor measurement

We can be part of the story if we succeed to build vertex detector for NA61/SHINE
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 TPC’s 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 measure energy of projectile fragments.
NA61/SHINE detector – Top view
Vertex detector Position

Position of the Future Vertex Detector
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 $<D0> + \overline{<D0>}$ 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/SHINE experimental setup.
→ Uniform magnetic field: 1.5 T in VTPC-1 and 1.1 T in VTPC-2
Reconstructed yield for $D^0 \rightarrow K^+ \pi^-$, 200k 0-10% cent. Pb+Pb at 158 AGeV

$\rightarrow S/B = 66$
$\rightarrow SNR (@50M) = 276$
$\rightarrow 77800$ detected $D^0+D^0$ bar mesons in 50M central Pb+Pb

$\rightarrow S/B = 2$
$\rightarrow SNR (@50M) = 249$
$\rightarrow 77800$ detected $D^0+D^0$ bar mesons in 50M central Pb+Pb
Reconstructed yield for $D^0 \rightarrow K^+ \pi^-$, 200k 0-10% cent. Pb+Pb at 40 AGeV

Results Extrapolated to 50M Events
Which Device Should we Use to measure open charm ??
Block diagram of MIMOSA-26

8 x analog out (obsolete)

Pixel Array
1152 x 576

Sensor array (21200 x 10600 μm²)

Readout sequencer

Coll. discriminators

Slow control interface (JTAG)

Zero suppr. computer

Output memory

Bias DACs (Threshold generation….)
Reconstructing open charm requires:

- Excellent secondary vertex resolution (~ 50 μm)
  => Excellent spatial resolution (~5 μm)
  => Very low material budget (few 0.1 % $X_0$)
- Good radiation tolerance
- Time resolution to separate 2000 coll/s => ~ 100 μs
Is MIMOSA-26 suited to measure open charm with NA61/SHINE?
## Requirements vs. sensors

<table>
<thead>
<tr>
<th></th>
<th>NA-61</th>
<th>Hybrid</th>
<th>CCD</th>
<th>MIMOSA-26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>&lt; 5 μm</td>
<td>30 μm</td>
<td>&lt;5 μm</td>
<td>3.5 μm</td>
</tr>
<tr>
<td>Material Budget</td>
<td>few 0.1 $X_0$</td>
<td>~ 1% $X_0$</td>
<td>~0.1% $X_0$</td>
<td>0.05% $X_0$</td>
</tr>
<tr>
<td>Rad. Tol. (¹)</td>
<td>$3 \times 10^{10} n_{eq}/cm^2$</td>
<td>$&gt;10^{14} n_{eq}/cm^2$</td>
<td>$&lt;10^9 n_{eq}/cm^2$</td>
<td>$&gt;10^{13} n_{eq}/cm^2$</td>
</tr>
<tr>
<td>Rad. Tol. (²)</td>
<td>~1 krad</td>
<td>&gt;10 Mrad</td>
<td>~1 Mrad</td>
<td>&gt; 300 krad</td>
</tr>
<tr>
<td>Time res.</td>
<td>~100 μs</td>
<td>20 ns</td>
<td>~ 100 μs</td>
<td>115.2 μs</td>
</tr>
</tbody>
</table>

(¹) non ionizing dose per week beam on target  
(²) ionizing dose per week beam on target

All numbers extrapolated from CBM simulations assuming 2000 Au+Au coll./s
Vertex Detector
VD in geant4

MIMOSA-26 sensors
Carbon fiber support
Water cooling tubes

Vessel:
Rectangular top/bottom plates
Trapezoidal left/right plates

→ same length of carbon leader
→ similar distance between top/bottom plates and VDS1-VDS4

→ flat micro cables variation in length +/- 2cm

VDS1: 5 cm
VDS2: 10 cm
VDS3: 15 cm
VDS4: 20 cm
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: 4x8 cm², 6x12 cm² and 8x16 cm² 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
Read-out connections scheme

Inside helium vessel

outside helium vessel

Aluminum frame

Standard cables/connectors

TRBv3
Summary

The simulations have shown that the measurements of the D0 and D0 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 (on going)

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)
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NA61 Collaboration
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BACK UP SLIDES
Reconstruction

- Track distance in VTPC1 + VTPC2 > 1m
- Require hit at least in the three Vertex detector stations
- NA61/SHINE Momentum resolutions is 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 (\( \sigma = 10 \text{ μm} \)). Track line is taken from the fit to the spread points
Reconstructed yield for $D^0 \rightarrow K^+\pi^-$, 200k 0-10% cent. Pb+Pb at 158 AGeV
VDS Stations are located at the distance of 5, 10, 15 and 20 cm respectively from the Target
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 $d$ ($< 40\mu m$))

**Two particle cuts:**
3. Cuts in Armenteros-Podolanski space to remove background from Ks and Λ
4. Two track vertex cut $Vz$ ($< 500\mu m$)
5. Reconstructed parent impact parameter cut $D$ ($> 22\mu m$)
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 $d < 40 \, \mu m$ as indicated
4. cut on $V_z$

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

Reduction of Background $\approx 106$
Reduction of Signal $\approx 3$
For the studies at 40 AGeV energy the whole phase space (physical input) was not available by AMPT event generator.

Rapidity distributions for kaons at both energies 40 and 158 AGeV and for D0 meson at 158 AGeV respectively.

\[ \frac{\Sigma K(158)}{\Sigma K(40)} = \frac{\Sigma D(158)}{\Sigma D(40)} \]

Temperature from transverse mass distributions by fitting exponential function \( A \exp(-mt/T) \)

**Parameters for 40 AGeV**

\[
\begin{align*}
\chi^2 / \text{ndf} & = 54.74 / 19 \\
\text{Const} & = 286.4 \pm 18.7 \\
T & = 0.2412 \pm 0.0087
\end{align*}
\]

**Kplus @ 40 AGeV**

\[
\begin{align*}
\chi^2 / \text{ndf} & = 311.4 / 26 \\
\text{Constant} & = 20.63 \pm 0.14 \\
\text{Mean} & = 0.003231 \pm 0.005150 \\
\text{Sigma} & = 0.9138 \pm 0.0033
\end{align*}
\]
→ VTPCs filled with Ar-CO2 mixture, location and dimensions as in Na61 setup.
→ Uniform magnetic field: 1.5 T in VTPC1 and 1.1 T in VTPC2
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 $D$

The average multiplicity for 158AGeV is $0.01 \times 1/0.0378 = 0.26$ (consistent with HSD) for 40 AGeV it is 0.01
1. cut on pT

Background pT spectrum has maximum around ~ 0.2GeV/c, whereas maximum of signal distribution is at around 1 GeV/c

→ cut on pT<0.4 as indicated
Charged Particle Fluxes

Sources of particles hitting VD:
   - during spill the anticipated beam intensity is 105 Pb ions per second.
   - for 200 μm 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
The following conceptual drawings are based on MIMOSA-26 chip hosting sensitive area of about 1.06 x 2.12 cm² with the pixel pitch equal 18.4 µm (~663.5k pixels/chip):

The readout speed of the whole frame in ~100 µs (10 kHz), zero suppression circuit.

The chips are available. We can just buy them from IPHC (Institut Pluridisciplinaire Hubert Curien), Strasbourg.
Drawn blue boxes have dimensions of the sensitive area of MOMOSA-26 sensor (~1x2 cm²).

Size of the dashed box is ~ 2x4 cm². We have to cover this area to lose less than 0.3% / 3% of signal particles for 158 / 40 GeV.
$\delta$-electrons and charge particles produced in Pb+Pb interaction

Delta electrons (averaged over 10k Pb events)

Charged particles produced in Pb+Pb interactions
We can expect very high hit occupancy on the level of 5 hit/mm²/event in the most inner part of the vertex detector.

It suggests that silicon pixel sensors would provide a good solution for us.
Hadronic interactions:
\[ \text{flux} = (105 \times 0.005) \text{ event/s} \times 1.6 \text{ particles/mm}^2/\text{event} = 800 \text{ particles/mm}^2/\text{s} = 800 \text{ Hz/mm}^2 \]

Electromagnetic interactions (δ-electrons):
\[ \text{flux} = 105 \text{ event/s} \times 0.04 \text{ particles/mm}^2/\text{event} = 4000 \text{ Hz/mm}^2 \]

Rate of Flux is not critical, for the future detectors
Preliminary design of the 2nd station

- Size of the dashed box is ~ 4x8 cm²
- Full coverage of Vds2 area with MOMOSA-26 requires 20 sensors

- Including Vds3 (6x12 cm²) and Vds4 (8x16 cm²) 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 = $3 \times 10^{12} \text{n}_{eq}/\text{cm}^2$

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:
\[
\text{flux} = (105 \times 0.005) \text{ event/s} \times 1.6 \\
\text{particles/mm}^2/\text{event} = 800 \text{ Hz/mm}^2
\]

Electromagnetic interactions ($\delta$ - electrons):
\[
\text{flux} = 105 \text{ event/s} \times 0.04 \\
\text{particles/mm}^2/\text{event} = 4000 \text{ Hz/mm}^2
\]
Fluence Calculations

\[ \Phi_{eq\ 1\text{MeV}} = \chi \Phi \]  
\[ \chi \text{ - radiation hardness parameter} \]

\[ \chi = 0.62/5 \] for electrons

\[ \chi = 0.62 \] for particles from hadronic interactions

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

\[ = 4 \times 105 \text{ /cm}^2\text{/sec} \times 0.62/5 \times 2592000 \text{ sec} = 1.28 \times 1011 \text{ neq/cm}^2 \]

For Spill of the beam (20%) = 2.57 \times 1010 \text{ neq/cm}^2

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

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

\[ = 8 \times 104 \text{ /cm}^2\text{/sec} \times 0.62 \times 2592000 \text{ sec} = 1.28 \times 1011 \text{ neq/cm}^2 \]

For Spill of the beam (20%) = 2.57 \times 1010 \text{ neq/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