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

Yasir Ali

For NA61/SHINE Collaboration

Strangeness in Quark Matter SQM 2013
22nd - 27th July 2013 Birmingham, United Kingdom
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Introduction

→ A feasibility study of $D^0 \rightarrow K^- \pi^+$ (BR=3.91%) 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**

### Meson Decay Channels

<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>122.9μm</td>
<td>(3.91±0.05)%</td>
</tr>
<tr>
<td>$D^0$</td>
<td>$D^0 \rightarrow K^- + \pi^+ + \pi^+ + \pi^-$</td>
<td>122.9μm</td>
<td>(8.14±0.20)%</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$D^+ \rightarrow K^- + \pi^+ + \pi^+$</td>
<td>311.8μm</td>
<td>(9.2±0.25)%</td>
</tr>
<tr>
<td>$D^+_s$</td>
<td>$D^+_s \rightarrow K^+ + K^- \pi^+$</td>
<td>149.9μm</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>
Physics motivation

→ So far no direct open charm measurements at SPS energies
→ But there are experimental initiatives which measure charmonia states at SPS energies (Town Meeting "Relativistic Heavy-Ion Collisions" Fleuret and Usai)
→ Simultaneous measurements of charmonia and open charm
   1. are needed to construct charm observables that are model independent.
   2. will allow to disentangle between initial and final state effects
Physics motivation cnt.

- Measurement of $J/\psi$ at top SPS energy (NA50, NA60) was performed.
- Anomalous suppression of $J/\psi$ for central A+A collisions ($N_{\text{part}}>200$).
- Attributed to QGP formation but other scenarios cannot be ruled out.
- If anomalous behavior of charm production is present in the open charm channel we will be able to characterize this effect versus centrality and energy.

![Graph showing measured J/psi yield vs. N_part](graph.png)

- $\bullet$ InIn
- $\Delta$ PbPb

(arXiv 0907.3682 v2 [nucl-ex] 2009)
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> + <D0̅> per central Pb+Pb event. This seems to be an under-predicted value.

→ The prediction of the HSD model is ~0.2. HSD model was tuned to properly describe available p+A and π+A charm production data at SPS energies. (Nucl. Phys. A 691, 753 (2001)).

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

→ AMPT does not generate “Open Charm” at 40 AGeV.

→ Width of the rapidity distribution and Invariant mass slope parameter does not change by more than 10% for Kaons while going from 158 AGeV to 40 AGeV.

→ We assumed similar changes for D0 as we observe for Kaons and its yield as predicted by HSD model.

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

→ VTPCs filled with Ar-CO₂ mixture, location and dimensions as in NA61/SHINE experimental setup.
→ magnetic field: 1.5 T in VTPC-1 and 1.1 T in VTPC-2
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 $p_T$ ($< 0.325$)
2. cut (track impact parameter $d$ ($<0.032$)

**Two particle cuts:**

3. Track pair vertex cut $V_z$ ($< 0.4$)
4. Parent impact parameter cut $D$ ($> 0.02$)

$p_T$ in GeV/c
topological cuts are in mm.
Summary of Cuts

Reduction of Background $\approx 10^6$
Reduction of Signal $\approx 1.8$

![Graph showing data points and cuts](image-url)
Reconstructed yield for $D^0 \rightarrow K^- \pi^+$, 200k 0-10% cent. Pb+Pb at 158 AGeV

→ $S/B = 17$
→ $SNR(@50M) = 246$
→ 64300 detected $D^0 + D^0\bar{b}$ar mesons in 50M central Pb+Pb (PID)

→ $S/B = 1$
→ $SNR(@50M) = 197$
→ 64300 detected $D^0 + D^0\bar{b}$ar mesons in 50M central Pb+Pb (PID)
Reconstructed yield for $D^0 \rightarrow K^- \pi^+$, 200k 0-10% cent. Pb+Pb at 40 AGeV

$\rightarrow$ $S/B = 1.0$
$\rightarrow$ $SNR(@50M) = 11.3$
$\rightarrow$ 2000 detected $D^0+D^0\bar{b}$ bar mesons in 50M central Pb+Pb (PID)

$\rightarrow$ $S/B = 0.07$
$\rightarrow$ $SNR(@50M) = 2.1$
$\rightarrow$ 2000 detected $D^0+D^0\bar{b}$ bar mesons in 50M central Pb+Pb (no PID)
Vertex Detector studies
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 ladder
→ 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
We used developed simulation to determine requirements for the detector which are:

- 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.
**Estimates of NA61/SHINE requirements and limits for different chip technologies**

<table>
<thead>
<tr>
<th></th>
<th>NA61</th>
<th>Hybrid</th>
<th>CCD</th>
<th>MIMOSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>&lt; 5 μm</td>
<td>30 μm</td>
<td>&lt; 5 μm</td>
<td>&lt; 3.5 μm</td>
</tr>
<tr>
<td>Mat. Budg.</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>$3 \times 10^{10}$ neq/cm$^2$</td>
<td>$&gt;10^{14}$ neq/cm$^2$</td>
<td>$&lt;10^{9}$ neq/cm$^2$</td>
<td>$&gt;10^{13}$ neq/cm$^2$</td>
</tr>
<tr>
<td>Rad. Tol (2)</td>
<td>~1 krad</td>
<td>~10 Mrad</td>
<td>~1 Mrad</td>
<td>~300 krad</td>
</tr>
<tr>
<td>Time resolution</td>
<td>~100 μs</td>
<td>~20 μs</td>
<td>~100 μs</td>
<td>~115.2 μs</td>
</tr>
</tbody>
</table>

Rad. Tol (1) and (2) refers to non ionizing and ionizing dose per week beam on Target

→ MIMOSA-26 seems to be very much feasible device
Preliminary design of the 1st station

→ Drawn blue boxes have dimensions of the sensitive area of MOMOSA-26 sensor (~1x2 cm$^2$)
→ Size of the dashed box is ~ 2x4 cm$^2$. We have to cover this area to loose less than 0.3% / 3% of signal particles for 158 / 40 GeV
Preliminary design of the 2nd station

→ Size of the dashed box is ~ 4x8 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.
Test of Prototype in 2015 (Ar + Ar/Ca)

Simulation results: prototype setup geometry

500k 0-10% central Ar+Ar at 158 GeV

Again cuts are optimized to central Pb+Pb at 158 AGeV (cuts may be relaxed for Ar+Ar/Ca)

~ 20 $D^0 + D^{0\text{bar}}$

For “no Pid” analysis S/B=11 and SNR= 4.6

Measurement with the setup geometry seems to be feasible if we collect ~500k central events (and if HSD yields are not significantly over-predicted)
Read-out connections scheme

Inside helium vessel

outside helium vessel

Aluminum frame

Standard cables/connectors

TRBv3
Summary

→ The measurements of the D0 and \( \bar{D}_0 \) mesons in NA61 experiment with a dedicated vertex detector equipped with MIMOSA-26 sensors as detection units is feasible.

→ Full simulation:
Realistic track reconstruction in VD & matching with VTPC (on going)

→ 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)

→ Differential measurements for open charm
Thank you!

ETH, Zurich, Switzerland
Fachhochschule Frankfurt, Frankfurt, Germany
Faculty of Physics, University of Sofia, Sofia, Bulgaria
Karlsruhe Institute of Technology, Karlsruhe, Germany
Institute for Nuclear Research, Moscow, Russia
Institute for Particle and Nuclear Studies, KEK, Tsukuba, Japan
Jagiellonian University, Cracow, Poland
Joint Institute for Nuclear Research, Dubna, Russia
Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Budapest, Hungary
LPNHE, University of Paris VI and VII, Paris, France
University of Silesia, Katowice, Poland
Rudjer Boskovic Institute, Zagreb, Croatia
National Center for Nuclear Research, Warsaw, Poland
St. Petersburg State University, St. Petersburg, Russia
State University of New York, Stony Brook, USA
Jan Kochanowski University in Kielce, Poland
University of Athens, Athens, Greece
University of Bergen, Bergen, Norway
University of Bern, Bern, Switzerland
University of Frankfurt, Frankfurt, Germany
University of Geneva, Geneva, Switzerland
University of Warsaw, Warsaw, Poland
Warsaw University of Technology, Warsaw, Poland
The Universidad Tecnica Federico Santa Maria, Valparaiso, Chile

NA61/SHINE Collaboration
Acknowledgments

→ We acknowledge the support by the Foundation for Polish Science - MPD program, co-financed by the European Union within the European Regional Development Fund.

→ NA61 Collaboration
NA61/SHINE Experiment

NA61/SHINE at the CERN SPS
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 $\frac{d\rho}{\rho^2} = 7.0 \times 10^{-4}(\text{GeV}/c)^{-1}$ (Nuclear Instruments and Methods in Physics Research A 430 (1999) 210 - 244)
  2. position resolution is 10 $\mu$m → hits are spread in y and x around geant hit according to the Gaussian distribution (σ = 10 $\mu$m). Track line is taken from the fit to the spread points
AMPT-MODEL
Reconstructed yield for $D^0 \rightarrow K^+ \pi^-$, 200k 0-10% cent. Pb+Pb at 158 AGeV
Design of the Future Vertex Detector

VDS Stations are located at the distance of 5, 10, 15 and 20 cm respectively from the Target
NA61/SHINE detector

- **Large acceptance:** \( \approx 50\% \)
- **High momentum resolution:**
  \( \sigma(p)/p^2 \approx 10^{-4} \text{(GeV/c)}^{-2} \) (at full \( B = 9 \text{ T} \cdot \text{m} \))
- **ToF walls resolution:**
  ToF-L/R: \( \sigma(t) \approx 60 \text{ ps} \); ToF-F: \( \sigma(t) \approx 120 \text{ ps} \)
- **Good particle identification:**
  \( \sigma(\text{dE/dx})/\langle \text{dE/dx} \rangle \approx 0.04 \); \( \sigma(m_{\text{inv}}) \approx 5 \text{ MeV} \)
- **High detector efficiency:** \( > 95\% \)
- **Event rate:** 70 events/sec

- **Four large volume Time Projection Chambers (TPCs):** VTPC-1, VTPC-2 (inside superconducting magnets), MTPC-L, MTPC-R; measurement of \( \text{dE/dx} \) and \( p \). **Time of Flight (ToF) detector walls.**

- **Projectile Spectator Detector (PSD) for centrality measurement (energy of projectile spectators) and determination of reaction plane; resolution of 1 nucleon (!) in the studied energy range (important for fluctuation analysis).**

- **Helium beam pipes** inside VTPC-1 and VTPC-2 (to reduce \( \delta \)-electrons).

- **Z-detector** (measures ion charge for on-line selection of secondary ions), **A-detector** (measures mass composition of secondary ion beam).

- **Low Momentum Particle Detector (LMPD)** for centrality determination in \( p+A \); measures target nucleus spectators.
2. Cut on $d$

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

$\rightarrow$ cut on $d < 40 \, \mu m$ as indicated
4. cut on $V_z$

→ cut on $V_z < 500 \ \mu m$ as required
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.

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

Transverse mass distributions By Fitting Exponential Function A \(\exp(-mt/T)\)

Parameters for 40 AGeV

### Parameters for 40 AGeV

\[ \chi^2 / \text{ndf} \quad 54.74 / 19 \]
\[ \text{Const} \quad 286.4 \pm 18.7 \]
\[ T \quad 0.2412 \pm 0.0087 \]

**Kplus @ 40 AGeV**
→ 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
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 2\times 4 \text{ cm}^2. As we 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
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 Ks and $\Lambda$
4. two track vertex cut $Vz$
5. reconstructed parent impact parameter cut $D$

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

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

→ 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 $\rightarrow V_z$ and $D$ cuts are nicely complementary to each other

$\rightarrow$ cut on $D > 0.022$ mm
Charged Particle Fluxes

Sources of particles hitting VD:

   - during spill the anticipated beam intensity is 105 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
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):

These pads are for testing purpose and can be removed.

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.
**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 105 Pb ions per second.
- For 200 μm Pb target interaction probability is 0.5% which leads to 500 Hz interaction rate

**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):**
\[
\text{flux} = 105 \text{ event/s} \times 0.04 \text{ particles/mm}^2/\text{event} = 4000 \text{ Hz/mm}^2
\]

The rate of flux is not critical, for the future detectors.
Fluence estimates
Performance of MIMOSA-26 → test on beam

Temperature:  $+30^\circ C$
Readout Time:  $125 \mu s$
Pitch size:  $20.7 \mu m$
Irradiated with to
fluence:  $3 \times 10^{12} n_{eq}/cm^2$

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

(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):

\[
\text{flux} = 105 \text{ event/s} \times 0.04 \text{ particles/mm}^2/\text{event} = 4000 \text{ Hz/mm}^2
\]

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

\[ \Phi_{eq \, 1\text{MeV}} = \chi \Phi \quad \chi \text{ - radiation hardness parameter} \]
\[ \chi = 0.62/5 \text{ for electrons} \]
\[ \chi = 0.62 \text{ for particles from hadronic interactions} \]

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

\[ = 4 \times 105 \text{ /cm}^2/\text{sec} \times 0.62/5 \times 2592000 \text{ sec} = 1.28 \times 10^{11} \text{ neq/ cm}^2 \]

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

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

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

\[ = 8 \times 104 \text{ /cm}^2/\text{sec} \times 0.62 \times 2592000 \text{ sec} = 1.28 \times 10^{11} \text{ neq/ cm}^2 \]

For Spill of the beam (20%) = 2.57 \times 10^{10} \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