STATUS OF SHiP-CHARM
DATA ANALYSIS

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On behalf of the SHiP-charm working group

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INTRODUCTION

› SHiP-charm optimization run performed in summer 2018 at H4 beam line of SPS
› Hybrid setup to measure the double-charm production cross-section in a thick target
› Emulsion Cloud Chamber used to identify charm-decay topology
› Electronic detectors: **Pixel** + **SciFi** + **Drift Tubes** to measure the momentum of charged charm daughters, **RPC** to identify penetrating muons

![Track reconstruction in RPC](image1.png)

**Track and vertex reconstruction in Pixel**

![Track reconstruction in RPC](image2.png)

**Track reconstruction in RPC**

Run 2793
Spill1f22ae29
Trigger 1

X1 -2.66 cm
Y1 -22.31 cm
sx 0.0041
sy 0.0042
PIXEL DATA ANALYSIS & SIMULATION

PIXEL DETECTOR SIMULATION

- Full implementation FairShip
- Plane geometry, material budget
- Timestamp, digitization (FairShip integration ongoing)
- Tracking outside FairShip

Z of 2-track vertex (cm)

REFINING ALIGNMENT

- Further improve parameters, focus on rotation around z

Old

New
SHiP-CHARM & SND@LHC

<table>
<thead>
<tr>
<th>SIGNAL</th>
<th>SHiP-Charm</th>
<th>SND@LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Charmed hadrons produced in 400 GeV/c proton interactions and secondaries</td>
<td>Neutrino interactions and LDM scattering</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>Secondary interactions of hadrons and electromagnetic showers produced in 400 GeV/c proton interactions</td>
<td>Background muons from IP</td>
</tr>
</tbody>
</table>

SHiP-charm as a proof of principle for SND@LHC:
- Both measurements search for interaction vertices in ECC target modules
- Both measurements have to cope with an unprecedented flux of charged particles
- Analysis tools developed/under development for SHiP-charm can be applied for the analysis of emulsion data from SND@LHC
EMULSION TARGET CONFIGURATION

- Position of charmed hadron production vertices in the target along the beam direction

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHARM1</td>
<td>41701</td>
<td>10.97</td>
<td>10.68</td>
</tr>
<tr>
<td>CHARM2</td>
<td>54299</td>
<td>29.99</td>
<td>21.34</td>
</tr>
</tbody>
</table>

Six configurations

- CHARM1: 28 mm lead
- CHARM6: 56 mm lead

Target Mover

Emulsion Detector

Beam positions: pl1, pl29, pl1, pl57
PROTON BEAM CHARACTERISATION

› CHARM1-RUN6
  › Number of integrated spills: 5
  › Pot counts from the scaler: $4 \times 10^4$

› CHARM1-RUN2
  › Number of integrated spills: 10
  › Pot counts from the scaler: $11 \times 10^4$
EVENT RECONSTRUCTION

Challenges:
1) Track reconstruction in high density environment
2) Identify interaction vertices in the *mare magnum* of reconstructed vertices
   (required rejection power: $10^2$
3) Identify charm decay topology
   (required rejection power: $10^4$

Reconstructed tracks in 1x1 cm$^2$, 29 emulsion films
TRACK RECONSTRUCTION

- Film-by-film base-track efficiency
- Selection: penetrating proton tracks

**CHARM1-RUN6**

Mean base-track efficiency
82±2 %

**CHARM1-RUN2**

Mean base-track efficiency
92±2 %
EVENT RECONSTRUCTION

CHARM1-RUN6

- Volume of the ECC: 10x12.5x3.6 cm$^3 = 450$ cm$^3$

- $10^4$ proton interaction vertices expected in 450 cm$^3$:
  - (cf. 1 interaction/1000 cm$^3$ in OPERA)

- Event multiplicity
  - Average number of charged interaction products: 21
  - Average momentum of charged interaction products: 11 GeV/c
  - Average number of photons: 11
  - Average momentum of photons: 5 GeV (with long tails)

- $\sim 4 \times 10^5$ reconstructed vertices in 450 cm$^3$
INTERACTION VERTEX IDENTIFICATION

- **CHARM1-RUN6**

- Excess in data at low multiplicity due to random combination of instrumental background/cosmic rays segments (not included in the simulation)
- The background induced by proton interactions is dominant at low multiplicity and in the downstream region of the ECC
INTERACTION VERTEX IDENTIFICATION

- Multivariate analysis approach based on 4 variables:
  1) vertex probability
  2) angular distance between of tracks
  3) impact parameter
  4) fill factor

Proton interaction vertex reconstructed in CHARM1-RUN6
INTERACTION VERTEX IDENTIFICATION

- Selection criteria for interaction vertex identification:
  1) BDT-value-1ry > 0.04
  2) Multiplicity > 4
  3) Z<-3900 (at least 3 downstream films)

- Data/MC comparison after the application of selection criteria for the identification of interaction vertices
- Good agreement in normalization and shape
- Selected interaction vertices: 7582 out of 425650
- Selection efficiency: ~90% - Purity: 77%

Results demonstrate the capability to reconstruct interaction vertices in high density environment.
Search for decay in a ~55 mm$^3$ volume downstream of the interaction vertex.
Search for decay in a \( \sim 55 \text{ mm}^3 \) volume downstream of the interaction vertex.

\~10 background vertices (induced by physics processes) in the selected volume.
Multivariate analysis approach based on 4 variables:
1) angular difference between segments of the same track
2) kink angle
3) impact parameter
4) transverse distance between 1ry and 2ry vertices
5) sum of daughters momenta

Cut applied for decay vertex classification
## SELECTION EFFICIENCIES - SIGNAL

- FairShip simulation + reconstruction algorithms (FEDRA)
- Starting sample: **2500** proton interactions with **double charm production**
- Detector: submodule 6x5cm², 28 mm W (1/4 of CHARM1-RUN6)

<table>
<thead>
<tr>
<th>SIGNAL EVENTS</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fiducial volume</strong></td>
<td>2230</td>
</tr>
<tr>
<td><strong>1ry vertex visibility</strong></td>
<td>1911</td>
</tr>
<tr>
<td><strong>1ry vertex identification</strong></td>
<td>1745</td>
</tr>
<tr>
<td><strong>2ry visibility</strong></td>
<td>1187</td>
</tr>
<tr>
<td><strong>2ry vertex identification</strong></td>
<td>735 (123 double, 612 single)</td>
</tr>
<tr>
<td><strong>Decay search</strong></td>
<td>584 (69 double, 515 single)</td>
</tr>
</tbody>
</table>

- Geometrical efficiency, vz<-3900
- Reconstructed primary vertices
- Decay vertex identification with multivariate analysis (*BDT-1ry*)
- Long decay, secondary vertex reconstructed
- Decay vertex identification with multivariate analysis (*BDT-2ry*)
- Search for decay topology (*BDT-decay*)
FEATURES OF CHARM DECAYS

2ry vertex visible

2ry vertex selected by decay search
SELECTED EFFICIENCIES - BACKGROUND

- FairShip simulation + reconstruction algorithms (FEDRA)
- Starting sample: 2500 proton interactions w/o charm production
- Detector: submodule 6x5cm², 28 mm W (1/4 of CHARM1-RUN6)

<table>
<thead>
<tr>
<th></th>
<th>BACKGROUND EVENTS</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial volume</td>
<td>2225</td>
<td>89%</td>
</tr>
<tr>
<td>1ry vertex identification</td>
<td>1983</td>
<td>79%</td>
</tr>
</tbody>
</table>

Total number of vertices reconstructed in the full volume: **106412**

Total number of 2ry vertices selected in the fiducial volume around 1ry vertex: **18708**

Total number of 2ry vertices selected by decay search: **787**

Achieved rejection power: **~130**
EXPECTATIONS

- Configuration: CHARM1-RUN6
- Protons interaction in the target: $10^4$
  [Charm production cross-section: $2 \times 10^{-3}$]
- Double-charm events produced in the target: 19 [FairShip simulation]

- **Expected signal events:** 4.4 (3.8 single-charm + 0.6 double-charm)
- **Expected background events:** 2072 (1328 single-charm + 516 double-charm + 228 triple-charm)
- **Noise/signal ratio:** 480
BACKGROUND

Background events that survive the selection criteria show the same topology of charmed hadron decays

1) HADRONS RE-INTERACTIONS
   - Average momentum of hadrons produced in proton interactions: 11 GeV
   - Further background suppression requires kinematic analysis at the decay vertex
   - Multiple Coulomb Scattering in the ECC reliable up to 8 GeV
   - Higher momentum daughters requires electronic detector data

2) ELECTROMAGNETIC SHOWERS INDUCED BY PHOTON CONVERSION
   - Average number of electromagnetic showers per event: 11
   - Further background suppression requires the identification of showers in the brick
Topological variables used in the decay search show very similar distributions.

Kinematic variables could improve considerably the rejection power, but they can be evaluated on a small sample of events.

Momentum measurement in ECC based on Multiple Coulomb Scattering is reliable up to 8 GeV.

Electronic detectors information is required to improve the rejection power.
SHOWER IDENTIFICATION

- High density of electromagnetic showers in small angular region
- Charged charm daughters fall within the cone of the shower
- Shower-identification algorithms not optimised for the SHiP-charm case
SUMMARY AND PERSPECTIVES

- SHiP-charm measurement sets two challenges:
  
  1) reconstruct tracks and interaction vertices in a high density environment:
     - Rejection power ~50 achieved
     - Good agreement between data and Monte Carlo simulations
     - Capability of reconstructing interaction vertices demonstrated
  
  2) search for rare decays of charmed hadrons:
     - Rejection power ~130 achieved exploiting topological variables measured in ECC
     - Kinematic analysis and shower identification required to reduce the background

- SHiP-charm as a proof of principle for SND@LHC:
  - Both measurements search for interaction vertices in ECC target modules
  - Both measurements have to cope with an unprecedented flux of charged particles
  - Analysis tools developed/under development for SHiP-charm can be applied for the analysis of emulsion data from SND@LHC
BACKUP SLIDES
## EXPOSURE

<table>
<thead>
<tr>
<th>Configuration</th>
<th>#runs</th>
<th>Passive material</th>
<th>Emulsion Cloud Chamber</th>
<th># Emulsion Films</th>
<th>Integrated pot</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHARM 1</td>
<td>x6</td>
<td>-</td>
<td>28 mm Pb +29 emulsion films</td>
<td>174</td>
<td>5.4 x 10^5</td>
</tr>
<tr>
<td>CHARM 2</td>
<td>x6</td>
<td>28 mm lead</td>
<td>28 mm Pb +29 emulsion films</td>
<td>174</td>
<td>5.2 x 10^5</td>
</tr>
<tr>
<td>CHARM 3</td>
<td>x3</td>
<td>56 mm lead</td>
<td>56 mm Pb +57 emulsion films</td>
<td>171</td>
<td>1.0 x 10^5</td>
</tr>
<tr>
<td>CHARM 4</td>
<td>x3</td>
<td>2x56 mm lead</td>
<td>56 mm Pb +57 emulsion films</td>
<td>171</td>
<td>0.8 x 10^5</td>
</tr>
<tr>
<td>CHARM 5</td>
<td>x3</td>
<td>3x56 mm lead</td>
<td>56 mm Pb +57 emulsion films</td>
<td>171</td>
<td>1.6 x 10^5</td>
</tr>
<tr>
<td>CHARM 6</td>
<td>x3</td>
<td>4x56 mm lead</td>
<td>56 mm Pb +57 emulsion films</td>
<td>171</td>
<td>1.6 x 10^5</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>24</strong></td>
<td></td>
<td><strong>1032</strong></td>
<td><strong>1.56 x 10^6</strong></td>
<td></td>
</tr>
</tbody>
</table>

- Emulsion scanning performed in Napoli and Zurich

~12 m²
MC SIMULATION: Charmed had decays

- Double-charm production in 400 GeV proton interactions

\[ D^0 \quad \langle L \rangle = 3.0 \text{ mm} \]

\[ D_s^+ \quad \langle L \rangle = 4.0 \text{ mm} \]

\[ D^+ \quad \langle L \rangle = 7.7 \text{ mm} \]

\[ \Lambda_c^+ \quad \langle L \rangle = 2.6 \text{ mm} \]
MC SIMULATION: Charmed had decays

- Simulation of double-charm production in proton interaction in a Emulsion/Tungsten target (CHARM1-RUN6 configuration)
- Application of tracking and vertexing algorithms as in data (FEDRA software)
- Selection of good-quality primary vertices

**CHARM1: D^0**
- Decay length: 12.3 mm
- Daughters: $k^-$ (26 GeV/c) and $\pi^+$ (14 GeV/c)

**CHARM2: anti-D^0**
- Decay length: 3.4 mm
- Daughters: $\pi^-$ (15 GeV/c) and $n^+$ (2 GeV/c)
SEARCH FOR CHARMB DECAYS

- Charm decay topologies are classified in two categories:

**SHORT DECAYS**: primary and secondary vertex in the same passive layer
   - No visible segment for the charmed hadron

**LONG DECAYS**: primary and secondary vertex in two different passive layers
   - >1 visible segment for charged charmed hadrons

![Graph showing distributions of short and long charm decays](image)
SEARCH FOR CHARM DECAYS

- Definition of a decay search procedure to select charm-like topologies
- For the moment, we focus on LONG topology
- Variables characterising the decay topology: impact parameter, longitudinal distance, kink angle

**Impact Parameter**
Mean 148.9 ± 5.974
Std Dev 145.3 ± 4.224

**Longitudinal Distance**
<dz> = 4 mm

**Kink angle**
<kink> = 100 mrad