Differential Charm Cross-Section Measurement In Proton Collisions

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INTRODUCTION

MOTIVATION

- Charm production in **proton interactions** and in **hadron cascades** in the SHiP target crucial for HNL normalization and $\nu_\tau$ cross-section measurements
- Encouragement from SPSC to perform this measurement

OUTLINE

- Design of a hybrid detector for **double-differential** cross-section measurement ($d^2\sigma/dE\,d\theta$)
- Use of **nuclear emulsions** as tracking detector
  - identification of hadronic and leptonic charm decay modes
  - volume of sensitive layers $<<$ target volume
- Momentum and charge measurement by electronic detectors
- FairShip simulation:
  - detector geometry
  - charm production in primary proton interactions and in hadron cascades
- From simulation to detector layout and **run configuration**
Conceptual Design

- Proton collisions in Mo/W target instrumented with nuclear emulsions
- Identification of charm production and decay vertices
- Measurement of charm daughters charge and momentum with Spectrometer
- Muon identification with Muon Filter

not to scale
The Target Replica

- Replica of the SHiP target with smaller section: 10x10 cm²
- Exactly the same TZM, W and Ta distribution
- Ta cladding not needed: replaced by Ta slabs to preserve number of $\lambda_i$
- Water cooling not needed: 5 mm-thick PET slabs instead of 5 mm H₂O
THE TARGET REPLICA

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Characterization of the target blocks

<table>
<thead>
<tr>
<th>Block</th>
<th>Material</th>
<th>Thickness</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>M₁</td>
<td>TZM</td>
<td>78 mm</td>
<td>0.51</td>
</tr>
<tr>
<td>M₂</td>
<td>TZM</td>
<td>23 mm</td>
<td>0.15</td>
</tr>
<tr>
<td>M₃</td>
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<td>23 mm</td>
<td>0.15</td>
</tr>
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</tr>
<tr>
<td>M₉</td>
<td>TZM</td>
<td>48 mm</td>
<td>0.31</td>
</tr>
<tr>
<td>M₁₀</td>
<td>TZM</td>
<td>48 mm</td>
<td>0.31</td>
</tr>
<tr>
<td>M₁₁</td>
<td>TZM</td>
<td>63 mm</td>
<td>0.41</td>
</tr>
<tr>
<td>M₁₂</td>
<td>TZM</td>
<td>78 mm</td>
<td>0.51</td>
</tr>
<tr>
<td>M₁₃</td>
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</tr>
<tr>
<td>W₁</td>
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<td>48 mm</td>
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<td>0.78</td>
</tr>
<tr>
<td>W₃</td>
<td>W</td>
<td>98 mm</td>
<td>0.98</td>
</tr>
<tr>
<td>W₄</td>
<td>W</td>
<td>348 mm</td>
<td>3.50</td>
</tr>
</tbody>
</table>
INSTRUMENTATION OF TARGET

- Nuclear emulsions used as micrometric tracking device to identify charm production and decay
- Charm average decay length ~ 3.3 mm
- Emulsion Cloud Chamber (ECC) technique employed: sampling of target material (TZM/W) every 3 mm
- Build ECC chambers to study the charm production in different sections of the target

\[ \langle L \rangle \sim 3.3 \text{ mm} \]
Instrumentation of Target

- Instrumentation of different portions (~1λI) of the target with emulsions
- ECC always the most downstream part of the target to let charm daughters reach the spectrometer
- Target modules are retained upstream of the ECC
Position distribution along beam axis of charm production vertices in the target

**PRIMARY PROTON INTERACTIONS**

**CASCADE PRODUCTION**

Ratio between different production modes

- \( r(1^{\text{st}}\lambda_I) = \frac{\text{Primary}}{\text{Secondary}} = 2.7 \)
- \( r(2^{\text{nd}}\lambda_I) = \frac{\text{Primary}}{\text{Secondary}} = 0.8 \)

Fraction of interactions within \( 2\lambda_I \)

- **Primary** 92%
- **Secondary** 66%

Instrumentation of first and second \( \lambda_I \) allows the study of a large fraction of charmed hadrons
Run Configuration

RUN 1

ECC 1

SPECTROMETER

RUN 2

M1 M2 M3

ECC 2

SPECTROMETER

proton beam

1stλI 2ndλI

1stλI
Each ECC is made by a sequence of 3mm-thick TZM planes interleaved with 290 μm-thick nuclear emulsion films, with a total thickness of ∼1λ_I

- **ECC1**: study charm production in first λ_I
- **ECC2**: study charm production in second λ_I

### Instrumentation of Target

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<th>Plates</th>
<th>ECC1</th>
<th>ECC2</th>
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<tbody>
<tr>
<td>TZM (3mm)</td>
<td>41</td>
<td>38</td>
</tr>
<tr>
<td>λ</td>
<td>0,81</td>
<td>0,75</td>
</tr>
<tr>
<td>PET (5 mm)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Ta (1 mm)</td>
<td>6</td>
<td>10</td>
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IMPLEMENTATION IN FAIRSHIP

Beam

Instrumented Target

Magnetic Spectrometer

1 Interaction Length
ECC1

Muon Filter
IMPLEMENTATION IN FAIRSHIP

Beam

Instrumented Target

GOLIATH MAGNET

Magnetic Spectrometer

Muon Filter

1 Interaction Length

ECC1
Decay Search

- Charm decay vertex identification:
  - Impact parameter of daughter track w.r.t. primary vertex >10 μm
  - 1-prong topology: kink angle > 20 mrad
  - at least one track with >1 GeV/c
  - Fight length < 6 mm

\[<\text{IP}> \sim 170 \, \mu\text{m}\]

\[<\theta_{\text{kink}} > \sim 73 \, \text{mrad}\]
SPECTROMETER

- Stations: 2
- Planes: 4 (two per station)

- Smaller dimensions for most upstream planes

<table>
<thead>
<tr>
<th>Plane</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 &amp; P2</td>
<td>20 x 20 cm²</td>
</tr>
<tr>
<td>P3 &amp; P4</td>
<td>200 x 150 cm²</td>
</tr>
</tbody>
</table>
**Muon Identification**

MuonID criterium:
- Number of crossed layers > 3

**Diagram**:
- MUON FILTER with sensitive planes S0 to S5 and Fe layer
- Pathway for muons and hadrons

**MuonID efficiency**:
- 87%

**MuonID purity**:
- 99%

Possible improvements using momentum/range correlation
## Charm Detection Efficiency

### ECC1

<table>
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<tr>
<th>Topological Selection</th>
<th>Single-Charm</th>
<th>Double-Charm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charmed hadrons decaying in the target</td>
<td>91%</td>
<td>89%</td>
</tr>
<tr>
<td>Charmed hadrons detected in emulsion</td>
<td>51%</td>
<td>29%</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Kinematical Selection</th>
<th>Single-Charm</th>
<th>Double-Charm</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least one daughter enter in the spectrometer</td>
<td>38%</td>
<td>16%</td>
</tr>
<tr>
<td>At least one daughter cross the spectrometer</td>
<td>31%</td>
<td>11%</td>
</tr>
<tr>
<td>Charge &amp; momentum measurement</td>
<td>31%</td>
<td>11%</td>
</tr>
<tr>
<td>Particle ID</td>
<td>30%</td>
<td>11%</td>
</tr>
</tbody>
</table>

**Overall Efficiency ($\varepsilon^{\text{KIN}}$)**

- Single-Charm: 30%
- Double-Charm: 11%
Number of integrated pot per run driven by the maximum number of tracks that can be integrated in emulsion films.

Maximum density of tracks in

1st\( \lambda \) => 6.1x10^{-3}/mm²

2nd\( \lambda \) => 8.3x10^{-3}/mm²

**ASSUMPTION:** protons uniformly distributed in 10x10 cm²

Number of tracks integrated in emulsion per incoming proton.

Electrons <30MeV discarded

All electrons discarded
EXPOSURE PLAN

• Maximum allowed track density in emulsion: 1000 tr/mm²
• Maximum number of pot/ECC1 = \(1.63 \times 10^5\) pot
  ECC2 = \(1.21 \times 10^5\) pot
• Number of charm pairs detected/ECC1 = 24.2
  ECC2 = 12.6

Exposure needed to observe \(1000\) charmed pairs

\[
30 \times \text{ECC1} \times 1.63 \times 10^5 \text{ pot} \\
22 \times \text{ECC2} \times 1.21 \times 10^5 \text{ pot}
\]

Total number of integrated pot = \(7.6 \times 10^6\)
Total number of emulsion films = 2466 films
Total emulsion surface = 24.7 m²
SUMMARY

• Design of a detector for the measurement of charm differential cross-section in proton interactions and in hadron cascades
• Description of run configuration and exposure plan
• Instrumentation of first two target interaction lengths with nuclear emulsions
• 1000 charm pairs expected with $7.6 \times 10^6$ pot and 25 m$^2$ emulsion surface
• Challenge: uniform proton beam on 10 x 10 cm$^2$ for runs of $\sim 10^5$ pot
• Next step: evaluation of the hadronic background contamination
Back-Up Slides
Add hadron absorber upstream of the magnet
Charm Hadron Production

Charm momentum

Angular distribution
- Charm production vertex uniformly distributed in (x,y) target plane

- Charm production along the beam axis follows exponential distribution

\[ \lambda = 1/0.006193 \sim 160 \text{ mm} \]
Charmed Hadron Production

- $\langle p \rangle \sim 42 \text{ GeV/c}$
- $\langle L \rangle \sim 3.3 \text{ mm}$

- Charmed hadron flight length
Charge measurement efficiency 98% (single track)

Charge measurement criteria

$\Delta \theta_x > 3\sigma_{\Delta \theta}$
Charmed Hadron Production

Charmed hadron flight length

- **PRIMARY PROTONS**
  - $<L> \sim 3.3$ mm
  - Entries: 10000
    - Mean: $3.297 \pm 0.0434$
    - RMS: $4.293 \pm 0.03069$

- **CASCADE PRODUCTION**
  - $<L> \sim 2$ mm
  - Entries: 964
    - Mean: $0.1954$
    - RMS: $0.2646$
CHARMED HADRON PRODUCTION

Charmed hadron momentum

- PRIMARY PROTONS
- CASCADE PRODUCTION

\[ <p> \sim 42 \text{ GeV} \]

\[ <p> \sim 26 \text{ GeV} \]

Entries: 10000
Mean: 42.23 ± 0.3274
RMS: 32.01 ± 0.2315

Entries: 964
Mean: 26.36
RMS: 22.19
DECAY PRODUCTS

Charm daughters momentum

- PRIMARY PROTONS
  \[ \langle p \rangle \sim 11 \text{ GeV/c} \]

- CASCADE PRODUCTION
  \[ \langle p \rangle \sim 7 \text{ GeV/c} \]
Cascade Production

Mother particles of charm in cascade production

- 23% neutral particles
- 77% charged particles
**Charmed Hadron Separation**

- **D**
  - Entries: 16013
  - Mean: $3.843 \pm 0.02008$
  - RMS: $2.337 \pm 0.0142$
  - <$L>$ ~ 3.5 mm

- **Ds**
  - Entries: 11458
  - Mean: $2.515 \pm 0.01908$
  - RMS: $1.992 \pm 0.01349$
  - <$L>$ ~ 2.3 mm

- **Λc**
  - Entries: 3447
  - Mean: $1.274 \pm 0.02657$
  - RMS: $1.552 \pm 0.01879$
  - <$L>$ ~ 1.2 mm
SPECTROMETER: REQUIREMENTS

- Requirement: 10 mrad angular resolution at each station
- Angle measured from the track position in two layers (P_A and P_B)

If the distance between the two layers is 1 cm

Required position resolution at each layer = 100 μm
Impact on $\nu_\tau$ yield

\[ N_{\nu_\tau + \bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \rightarrow \tau) = 2.85 \cdot 10^{-5} N_p \]

\[ \sigma_{c\bar{c}} = 18.1 \pm 1.7 \text{ \mu barn} \]

\[ Br(D_s \rightarrow \tau) = (5.54 \pm 0.24)\% \quad \text{PDG 2014} \]

\[ f_{D_s} = (7.7 \pm 0.6^{+0.5}_{-0.4})\% \quad \text{JHEP 1309 (2013) 058} \]