STATUS OF THE CHARM CROSS SECTION MEASUREMENT

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Motivation:

- study charm production in the SHiP target
- measure for the first time charm production in hadron cascades

Double-differential charm production cross-section measurement \( (d^2\sigma/dE_d\theta) \)

Proton collisions in Mo target instrumented with nuclear emulsions

Nuclear emulsions as tracking detector

Measurement of charm daughters charge and momentum with Spectrometer

Muon identification with Muon Filter
**INSTRUMENTATION OF TARGET**

- Use of a replica of the SHiP target with smaller section: 10x10 cm²
- Exactly the same TZM, W and Ta distribution
- Nuclear emulsions used as micrometric tracking device to identify charm production and decay

- Emulsion Cloud Chamber (ECC) technique employed: sampling of target material with nuclear emulsions
- Sampling of passive material: 1 mm, 2 mm, 3 mm
- Build ECC chambers to study the charm production in different sections of the target
- Instrumentation of first and second $\lambda_I$ allows the study of a large fraction of charmed hadrons

- Position distribution along beam axis of charm production vertices in the target

**PRIMARY PROTON INTERACTIONS**

**CASCADE PRODUCTION**

- Fraction of interactions within $2\lambda_I$
  - Primary 85%
  - Secondary 52%
CHARMED HADRONS

Charmed hadron flight length

- PRIMARY PROTONS

- CASCADE PRODUCTION

\(<L> \sim 3.3 \text{ mm}\)

\(<L> \sim 2 \text{ mm}\)
CHARMED HADRONS

Charmed hadron momentum

- PRIMARY PROTONS
  - Mean: 42.23 ± 0.3274
  - RMS: 32.01 ± 0.2315

- CASCADE PRODUCTION
  - Mean: 26.36
  - RMS: 22.19

\(<p> \sim 42 \text{ GeV}\)

\(<p> \sim 26 \text{ GeV}\)
Decay Products

Charm daughters momentum

- PRIMARY PROTONS
- CASCADE PRODUCTION

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

\[ \langle p \rangle \sim 7 \text{ GeV/c} \]
Run Configuration

- Instrumentation of different portions 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
Motion Of The Target

- Motion of target required to have protons uniformly distributed on a 10x10 cm$^2$ surface
- Optimization of the velocity of the table: - maximization of proton uniformity (minimization of a $\chi^2$ function)
  - minimization of the number of spills $N_s$

- Assumption: proton beam with gaussian shape, $\sigma = 0.5$ cm
- Motion of the target
  - along x-axis during the spill (~5s)
  - along y-axis between two spills

\[
\text{Result of optimization: } v_x = 2 \text{ cm/s} \\
\Delta y = 1.0 \text{ cm} \\
N_s = 10
\]

- Design of moving table (N. D'Ambrosio - LNGS)
  - micrometric precision
  - support ~20 kg target

- First test of a prototype for light target (~1kg) will be tested in September 2017
EXPOSURE PLAN

- Number of integrated pot per run driven by the maximum number of tracks that can be integrated in emulsion films

- Number of tracks integrated in emulsion per incoming proton

Exposure needed to observe 10k charmed pairs: ~ 8x10^7 pot

1. Density: 10^3 tracks/mm^2
   - 900 x ECC1 x 5 x 10^4 pot
   - 660 x ECC2 x 4 x 10^4 pot
   - Total emulsion surface (3mm sampling) ~ 750 m^2

2. Limit density: 3x10^3 tracks/mm^2
   - 300 x ECC1 x 1.6 x 10^5 pot
   - 220 x ECC2 x 1.2 x 10^5 pot
   - Total emulsion surface (3mm sampling) ~ 250 m^2
Integrate ~10% of total statistics

Test different samplings: 1 mm, 2 mm, 3 mm

Build 20÷40 ECC, corresponding to ~25 m² emulsion surface

Exposure with different integrated density: from $10^4$ to $10^5$ pot

Optimize beam parameters and exposure time

Test moving table

Develop and optimize of tracking/reconstruction algorithms

First physics results
Experimental Layout @H4

(implementation in FairShip by A. Iuliano)
EVENT SIMULATION

- Proton beam: gaussian shape, \( \sigma = 0.5 \text{cm} \)
- Target: ECC1 (\( \sim 0.8 \lambda_I \))
- 1 spill (5s): \( 10^4 \) protons
- 2000 protons/s
- 56\% interacting in the target
- 44\% punch-through

(implementation in FairShip by A. Iuliano)
MAGNETIC SPECTROMETER:

- **Upstream** station  
  T1: 13 x 11 cm²  
  T2: 20 x 20 cm²

- **Downstream** station  
  T3: 150 x 200 cm²  
  T4: 150 x 200 cm²

- Requirements: measurement of \((x,y)\) and \((\theta_x, \theta_y)\) in both stations

MUON FILTER:

- 6 planes 200 x 200 cm²
- A “typical” charm event in T1

- Momentum distribution in T1

- High occupancy in the first spectrometer plane due to low energy electrons
- Necessary to deflect/absorb electrons before they reach T1
Solution under investigation: magnetic field between target and T1

- Magnetized region 8 cm-thick (highlighted in yellow)
- 1T uniform field along y-axis

- Reduction of electrons in T1: ~factor 3x
- Larger distance between ECC and T1 and therefore makes the pattern matching more challenging

- MISiS University (Moscow) is working at the magnet design

Track density (average): 0.7 tracks/cm²
Track density (central region): 10 tracks/cm²

- The magnetic field would imply a larger distance between ECC and T1 and therefore makes the pattern matching more challenging
Detector option under investigation:

**Atlas FE-I4** silicon detectors (M. Cristinziani, Bonn University)

- 50 µm × 250 µm pixel size
- position resolution (2 layers): ∼ 10 µm
- total width: ∼ 400 µm
- high rate capability
- high occupancy capability
- sensor surface ∼ 4 cm²
- array 3x3: 6x6 cm²
- possible configuration -> T1: 4 layers, T2: 2 layers
MAGNETIC SPECTRO - DOWNSTREAM STATION

- Detector options under investigation:
  1) Scintillating fiber trackers (A. Malinin, V. Shevchenko)
  2) Drift Tubes used for muon flux measurement
     • with the addition of high granularity detector in the central high occupancy region

- Solution under investigation:
  • insert GEM chambers in the central region
  • COMPASS triple-GEM trackers 30x30 cm
  • 400 μm pitch
  • position resolution: <100 μm
  • in contact with A. Bressan for chambers availability in 2018 run

- Track density (average): 0.002 tracks/cm²
- Track density (central region): 0.2 tracks/cm²

A “typical” charm event in T3

LEGEND
- Muon
- e+/e-
- hadron

Track density (average): 0.002 tracks/cm²
Track density (central region): 0.2 tracks/cm²
MUON FILTER

- Central hole (R=2.5 cm) foreseen in the Muon Filter slabs
  1) Rejection of proton punch-through interactions
  2) Avoid high density area in RPC planes

- 6 planes 2 x 2 m²
- Sensitive planes: RPC
- Passive material: 34 cm-thick iron slabs

FRONTAL VIEW

RPC CONSTRUCTION

- Joint project between INFN and KODEL from Korea University (S. Park and K.S. Lee)
- KODEL: RPC construction
- INFN (Bari and Napoli): readout electronics
Average number of hits in RPC planes per **interacting** proton

- Several charged particles per event
- em/had showers not totally absorbed in iron slabs
- Muon track non the unique in the downstream layers
- Tracking algorithm to be implemented for performances evaluation
- Detector layout in terms of passive material thickness and position of sensitive planes under optimization
BACKGROUND STUDIES
Background Evaluation

- Dominant background for charm search: hadronic re-interactions

**SIGNAL**
- TZM plate
- Emulsion film
- Proton
- Ds-
- D+
- h
- h
- h

**BACKGROUND**
- TZM plate
- Emulsion film
- Proton
- h
- h
- h
- h

- Lever arms for signal/background discrimination:
  - Observation of nuclear fragment at the hadron interaction point
  - Exploit kinematical features (MVA analysis)
Hadronic Re-Int. Simulation

- FLUKA simulation of hadronic re-interactions in TZM/emulsion ECC chamber (A. Iuliano)

- Monte Carlo simulation used in OPERA: FLUKA with PEANUT model

- Validation with test beam data: \( \pi^- \) at 2, 4, 10 GeV/c in ECC brick

- Simulated beam: \( \pi^- \)
- Energy spectrum: pions produced in proton interaction in FairShip
Fragment: - at least 1 emulsion film crossed
- \( \tan(\theta) < 3.0 \)
- \( \beta < 0.7 \)

Forward-going track: - at least 3 emulsion film crossed
- \( \tan(\theta) < 1 \)
- \( \beta > 0.7 \)
**KINEMATICAL SELECTION**

- **Impact parameter (signal region)**
  - CHARM SIGNAL
  - HAD BACKGROUND

- **Kink angle (1 prong)**
  - CHARM SIGNAL
  - HAD BACKGROUND

**NB:** signal and background distribution normalized to unity
**Background-Yield Evaluation**

- Charm decay channels: $c \rightarrow 1h, c \rightarrow 3h$

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path length $&lt; 6$ mm</td>
<td>3.4%</td>
</tr>
<tr>
<td>Impact parameter $&gt; 10$ μm</td>
<td>2.9%</td>
</tr>
<tr>
<td>Kink angle $&gt; 20$ mrad</td>
<td>2.8%</td>
</tr>
<tr>
<td>1 or 3 forward-going tracks</td>
<td>1.0%</td>
</tr>
<tr>
<td>no nuclear fragments</td>
<td>0.45%</td>
</tr>
</tbody>
</table>

**In progress:** Kinematical selection based on total momentum, transverse momentum, invariant mass
Overall experimental layout outlined

Magnetic field immediately downstream of the target helps reducing the electron multiplicity

Challenge: track connection between moving target and fixed spectrometer, with a gap of a few cm

Magnetic spectrometer: new detector options to cope with high occupancy under investigation

Muon filter: RPC technology, sampling to be optimized

2018 exposure will act as “optimization run” for the charm cross-section measurement

Hadronic background simulation performed in FLUKA. Exploit kinematical features to reduce hadronic background contamination
Back-Up Slides
Spatial distribution of muons produced by charmed hadron decay
HITS IN RPC CELL: 2x2 mm$^2$
**Hits In The RPC**

- Number of hits in RPC strips (2 cm-wide) along x and y axes

![Graphs showing x and y distributions for RPC planes R2 and R5](image-url)
To be done: analysis of nuclear emulsions from E653 experiment (Fermilab, ‘90)

- Density: $10^3$ tracks/mm$^2$
- Limit density: $3 \times 10^3$ tracks/mm$^2$

600 GeV negative pions

800 GeV protons
Motion of the target required to have protons uniformly distributed on a 10x10 cm$^2$ surface

- Design of a moving table in progress (details in N. D’ambrosio’s talk)

Motion of the target
- along x-axis during the spill (~5s)
- along y-axis between two spills
Motion of the Target

- Motion of target required to have protons uniformly distributed on a 10x10 cm² surface
- Design of a moving table in progress (details in N. D’ambrosio’s talk)
- Optimization of the velocity of the table: - maximization of proton uniformity (minimization of a $\chi^2$ function)
  - minimization of the number of spills $Ns$
- Assumption: proton beam with gaussian shape, $\sigma=0.5\text{cm}$
INSTRUMENTATION OF TARGET

- 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 $\sim 1\lambda_I$.
- **ECC1**: study charm production in first $\lambda_I$
- **ECC2**: study charm production in second $\lambda_I$

<table>
<thead>
<tr>
<th>Plates</th>
<th>ECC1</th>
<th>ECC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TZM (3mm)</td>
<td>41</td>
<td>38</td>
</tr>
<tr>
<td>$\lambda$</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>
</tr>
<tr>
<td>Emulsion (0.29 mm)</td>
<td>47</td>
<td>48</td>
</tr>
</tbody>
</table>
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
HITS IN THE SPECTROMETER

- A “typical” charm event as seen in the four spectrometer planes
Zoom in the most central region of the first Spectrometer plane \textbf{P1}

- Pitch: 200 \times 200 \mu m^2 (size of the histogram bin)
**MOTIVATION**

- Charm production in **proton interactions** and in **hadron cascades** in the SHiP target crucial for HNL normalization and $\nu_\tau$ cross-section measurements
- Current knowledge of inclusive associated charm cross-section measurement

\[ \sigma_{CC} = (18.1 \pm 1.7) \mu\text{barn} \ (\text{NA27}^*) \]

- Missing information: charm production in **hadron cascades** (factor>2) and charm hadron spectra

- Angular and energy spectra available only for 500 GeV pions in E791

\[ \text{* Phys.Rept. 433 (2006) 127} \]
\[ \text{* Z. Phys. C40 (1998) 321} \]

- Comparison between Pythia 6.4 generator and NLO calculations, **JHEP 0709 (2007)**: discrepancy in $p_T$ spectra

\[ \text{Entries} \ 104542 \]
\[ \text{Mean} \ 1.011 \]
\[ \text{RMS} \ 0.6015 \]

\[ \text{Entries} \ 80274 \]
\[ \text{Mean} \ 1.111 \]
\[ \text{RMS} \ 0.6404 \]

\[ \text{*Phys. Lett. B462 (1999) 225.} \]
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 \( \sim 1\lambda_I \)

- ECC1: study charm production in first \( \lambda_I \)
- **ECC2**: study charm production in second \( \lambda_I \)
Charmed Detection Efficiency

**TOPOLOGICAL SELECTION**
- Charmed hadrons decaying in the target: 91% (91%) vs. 89% (89%)
- Charmed hadrons detected in emulsion: 51% (51%) vs. 29% (29%)

**KINEMATICAL SELECTION**
- At least one daughter enter in the spectrometer: 38% (38%) vs. 16% (16%)
- At least one daughter cross the spectrometer: 31% (31%) vs. 11% (11%)
- Charge & momentum measurement: 31% (31%) vs. 11% (11%)
- Particle ID: 30% (30%) vs. 11% (11%)

**OVERALL EFFICIENCY (ε^KIN)**
- Single-Charm: 30%
- Double-Charm: 11%
Detector options under investigation:

1) Scintillating fiber trackers (A. Malinin, V. Shevchenko)
2) Atlas FE-I4 silicon detectors (M. Cristinziani, Bonn University)
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   - possible configuration -> T1: 4 layers, T2: 2 layers

(see M. Cristinziani's slides)