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Track and vertex reconstruction using moving emulsion blocks and a silicon pixel tracker for particles induced by 400 GeV/c protons on a thick target

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Abstract. The SHiP-charm experiment is designed to measure the charm production cross section, including cascade production, of 400 GeV/c protons hitting a thick, SHiP-like target. For the detection of production and decay of heavy charmed particles, emulsion films are employed in a multilayered moving target, forming an emulsion cloud chamber. While the emulsion films provide excellent spatial resolution they do not provide timing information, integrate all events, and quickly get saturated. For the charm measurement the emulsion target is thus moving at a constant speed during data-taking. A first optimization run at the CERN SPS has been performed in 2018, with the purpose to develop the required analysis tools and to fine-tune the detector layout. We report on the experiment design, track reconstruction in the pixel tracker and the track matching with the moving emulsion detector.

1. Introduction

Knowledge of the charm production cross section in a thick target is essential for the sensitivity of the proposed SHiP [1, 2] experiment. The SHiP-charm project [3] aims at measuring the double-differential cross section, $\mathrm{d}^2\sigma/(\mathrm{d}E\,\mathrm{d}\theta)$, for charm production using the 400 GeV/c primary proton beam, extracted from SPS at CERN. The target is a short replica of the SHiP target and consists of passive material interleaved with emulsion cloud chambers (ECC), with the purpose to study the different properties of the particle shower created in the target. A varying amount of absorber bricks is placed upstream of the active target to simulate different target thicknesses. The target is followed by a magnetised tracking spectrometer and by a muon tagger. In July 2018, an optimisation run took place at the H4 beam line. We address the challenge of reconstructing common tracks and events from the information recorded by the fundamentally different ECC and pixel detectors. This is complicated by the fact that the ECC detector carries no timing information and was moving relative to the beam and pixel detector in order to prevent overexposure during a given spill. We report on results of matching ECC tracks to downstream pixel tracks by means of a χ^2 minimisation of the residuals.

2. Setup and data taking

Targets of different material budget have been exposed to cover a range of 0.25 to 1.6 interaction lengths. In the following we will discuss the exposure of the shortest target brick. To record

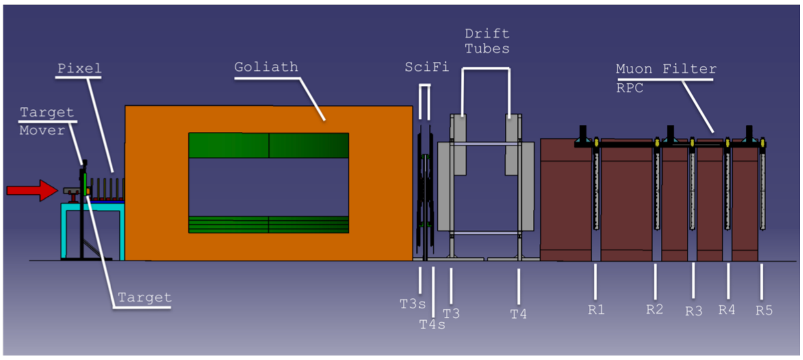

Figure 1. Setup for the optimization run. The moving ECC is first in the beam, followed by the pixel detector. The GOLIATH magnet, scintillating fiber and drift tube detectors complete the spectrometer. Most downstream is a muon filter made of resistive plate chambers.

primary and secondary interactions in the target, 28 passive tungsten sheets of 1 mm thickness alternate with 29 active emulsion films forming an ECC with an active surface of $11 \times 9\,\mathrm{cm}^2$. A simplified cross-section of two ECC layers is depicted in Figure 2. For each emulsion film two active emulsion layers are glued on a thin plastic base. In this setup each emulsion film can provide not only track position but also direction. Passing ionizing radiation will permanently ionize the two layers and may interact in the passive material, creating a cascade. After exposure the emulsion films are digitized and tracks and vertices are reconstructed with a resolution of up to 3 µm within the `FEDRA` framework [4]. Since tracklets in the emulsion layers are permanent it is required to prevent overexposure. A simple limit on the particle rate will result in a most inefficient use of beam time and emulsion surface. It therefore is more desireable to move the target during data taking, maximizing the exposed target surface. Consequently the target was moved horizontally through the beam with a constant velocity of $(2.610 \pm 0.029)\,\mathrm{cm/s}$. In between spills it was moved vertically by approximately 2 cm. The resulting strip-like pattern after exposure to five spills is shown in Figure 3.

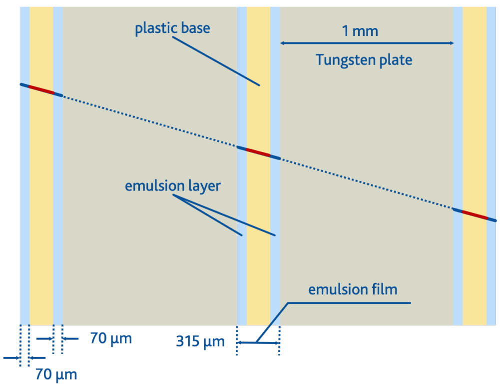

Figure 2. Passive and active layers in an ECC brick. Active emulsion is indicated in yellow, passive tungsten plates are grey. The dotted line represents a particle trajectory.

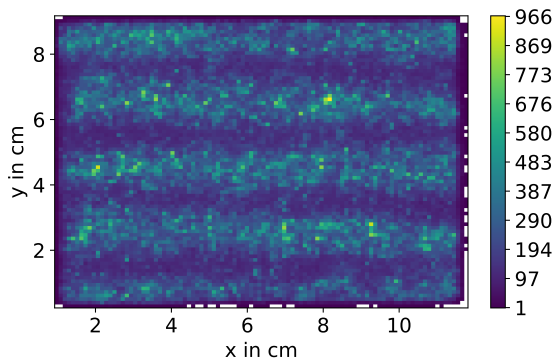

Figure 3. Positions of tracks reconstructed in the ECC at the most downstream layer. Each horizontal line represents data from one SPS spill.

The pixel detector is built from ATLAS IBL double-chip modules [5] composed of a pixelated silicon sensor and two FE-I4 read-out chips. A single pixel measures $250 \times 50\,\mathrm{\mu m}^2$. The sensor matrix on one double-chip module offers 160 columns and 336 rows, with wider pixels in the edge and central columns. The maximum timing resolution is given by the front-end chips clock of 40 MHz, allowing for 25 ns timestamping. For the tracking detector, 12 double-chip modules are arranged in six planes, where every second plane is rotated by 90° to compensate for the different resolutions in x and y dimensions. The detector layout was optimized towards a maximum angular acceptance by maximizing the active surface per plane to approximately $6.9\,\mathrm{cm}^2$ and by minimizing the distance between single tracking planes to approximately 2 cm. The distance between the first layer of the pixel detector and the moving target was reduced to (1.84 ± 0.01) cm. Similar to the approach used for the ECC, tracks are first reconstructed in the pixel detector only. A local pattern recogniton was developed, starting with a track seed formed by hits on the third and last plane. The pattern recognition only considers tracks with an opening angle within the detector acceptance of 200 mrad. A detailed description of the pixel track reconstruction can be found in Ref. [6].

3. Global alignment and track matching

To build common events from the ECC and pixel detectors and to attribute a timestamp to ECC tracks, the independently reconstructed tracks have to be machted. The common rest frame chosen is the one of the ECC. For the alignment a Newton-Raphson algorithm was developed, fitting all alignment parameters simultaneously.

First, a data selection is performed: The set of ECC tracks is limited to the spectrometer acceptance of 200 mrad and to tracks from vertices with at least six tracks. The set of pixel detector tracks is limited to events with at least 2 tracks. The pixel detector tracks are translated to the ECC rest frame using the timestamp and the alignment parameters $\boldsymbol{\alpha} = (x_0, y_0, z_0, v_x, v_y, \theta_{xz}, \theta_{yz}, \theta_{xy})$, where x_0, y_0, z_0 is the offset of the pixel detector with respect to the emulsion reference frame, the two velocities v_x and v_y characterize the target mover, and the rotations of the pixel detector about the x, y, and z axes are denoted by θ_{yz}, θ_{xz} and θ_{xy}, respectively. The origin is set at the most downstream ECC layer. The starting values for $\boldsymbol{\alpha}$ are determined from in-situ measurements of the detector positions and the velocity settings for the target mover.

For fitting the alignment parameters a track χ^2_{track} of residuals between the emulsion and pixel detectors is defined as

$$\chi^2_{\mathrm{track}} = \boldsymbol{r}^{\mathrm{T}} \boldsymbol{V}^{-1} \boldsymbol{r}, \tag{1}$$

where $\boldsymbol{r} = \boldsymbol{x}^{\mathrm{pix}} - \boldsymbol{x}^{\mathrm{emu}} = (\Delta x, \Delta y, \Delta\theta_x, \Delta\theta_y)$ is the vector of residuals and $\boldsymbol{V} = \boldsymbol{V}^{\mathrm{pix}} + \boldsymbol{V}^{\mathrm{emu}}$ is the covariance matrix of residuals evaluated at the matching plane of $z = 0$. For each possible track combination the χ^2_{track} is calculated and the best combination is considered. The sum of all χ^2_{track} is evaluated for a Newton-Raphson fit of $\boldsymbol{\alpha}$ according to Ref. [7]. After convergence of $\boldsymbol{\alpha}$, all unique track pairs with $\chi^2_{\mathrm{track}}/\mathrm{ndf} \leq 25$ are considered a match. The resulting distribution can be observed in Figure 4. By calculating the residual $r_i = x_i^{\mathrm{pix}} - x_i^{\mathrm{emu}}$ one can estimate the matching resolution. The residual distribution for the x coordinate is shown in Figure 5. Table 1 shows all estimated resolutions.

Table 1. Matching resolutions extracted from the residual's fit.

parameter	resolution
σ_{x}	40 µm
σ_{y}	72 µm
$\sigma_{\theta\mathrm{xz}}$	3.5 mrad
$\sigma_{\theta\mathrm{yz}}$	2.9 mrad

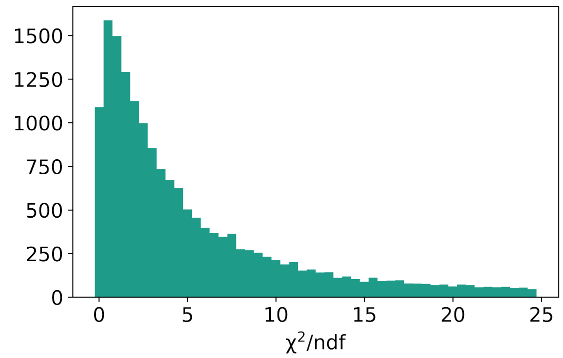

Figure 4. χ^2/ndf distribution for matched track pairs.

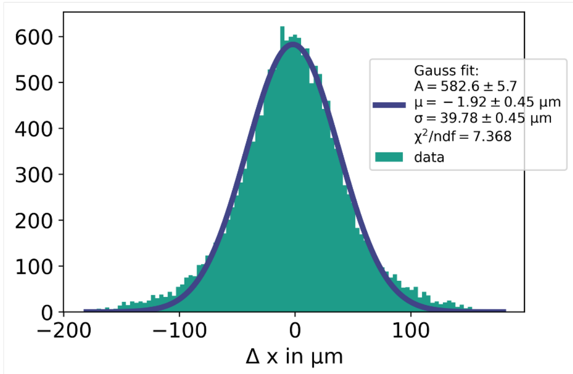

Figure 5. Residuals in x for matched track pairs.

4. Summary and outlook

We developed an alignment and event-building procedure for the moving emulsion target without timing information and the pixel tracking detector as first instance of the spectrometer in a high occupancy environment. Two aspects were crucial for the succesful alignment: The introduction of an (unwanted) velocity in y direction, and a set of adequate input paramters for the algorithm. With this procedure, more than 62 % of the selected emulsion tracks were assigned a timestamp, corresponding to 82 % of all recontructed vertices in the emulsion.
Software and detector setup will be further optimized for a dedicated charm cross section measurement at the CERN SPS after the LHC Long Shutdown 2.

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