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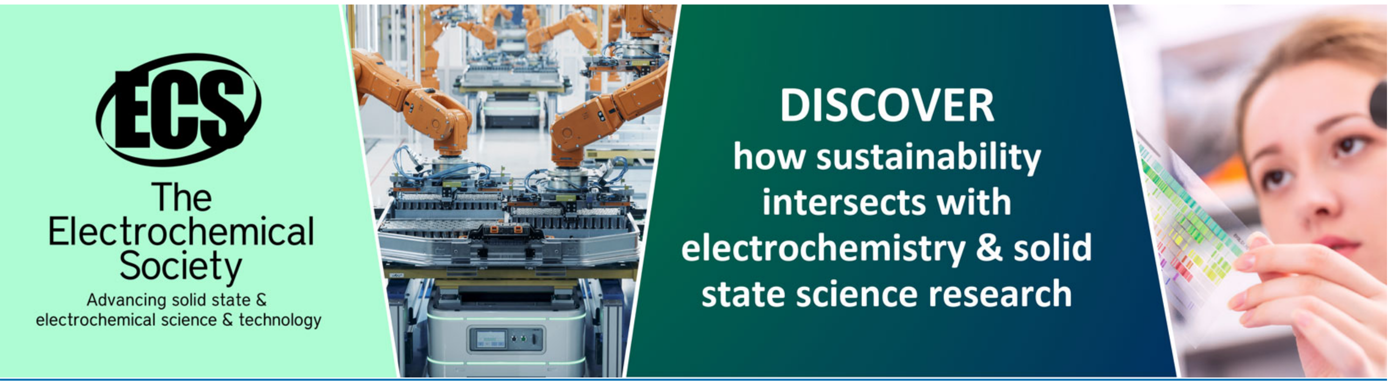

Offline Software for the PANDA Luminosity Detector

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Abstract. In 2018 data taking for hadronphysics facility PANDA is planned to commence. It will be build at the antiproton accelerator HESR, which itself is a part of the FAIR complex (GSI, Darmstadt, Germany). The luminosity at PANDA will be measured by a dedicated sub-detector, which will register scattered antiproton tracks from $\bar{p}p$ elastic scattering. From a software point of view, the Luminosity Detector is a tracking system. Therefore the most of its offline software parts are typical for a track reconstruction. The basic concept and Monte Carlo based performance studies of each reconstruction step is presented in this paper.

1. Introduction

The future fixed target experiment PANDA has an ambitious physics program. In this experiment an antiproton beam will be exploited to study different topics in Hadron Spectroscopy, Nucleon Structure, Hadrons in Matter and Hypernuclei Physics [1]. Precise luminosity information is crucial for absolute cross section measurements and scanning experiments. For the luminosity determination we will use the differential cross section of the elastic $\bar{p}p$ scattering in dependence of the scattering angle. Our measurement cannot be limited to the total scattering rate, because former experiments data, available in the PANDA energy range, has large systematic uncertainties. Hence we are going to perform measurements at very small momentum transfer t (and thus very small scattering angle), where the Coulomb part of the elastic cross section dominates. This part can be calculated very precisely. However for high energies hadronic contribution at small t cannot be ignored. Therefore parameters for the description of the differential elastic cross section will be measured in the dedicated Day-1 experiment [2] before PANDA starts data taking.

The Luminosity Detector (LMD) should have full azimuthal angle acceptance and good spatial resolution to achieve the needed precision for the luminosity measurement. Therefore the detector (Fig. 1) consists of four planes of sensors with distances of 10 or 20 cm in between. Each plane contains 10 support modules, which are made of 200 μm thick CVD-diamonds wavers. Sensors are glued on the modules from both sides. The sensors themselves are 50 μm thick silicon pixel sensors (HV-MAPS [3]) with a pixel size of 80 $\times$ 80 μm^2. In parallel to the prototype construction, this design is under study with Monte Carlo based simulations.

The LMD geometry model and reconstruction software are implemented in the PandaRoot framework [4]. This framework is the software package for the PANDA detector simulation and event reconstruction based on the FairRoot framework, which is developed by the GSI-IT, and used by all big FAIR experiments. The LMD reconstruction software includes many specific procedures like luminosity extraction, background treatment or a track-based software alignment, which are subjects of future publications. The track reconstruction part will be discussed here.

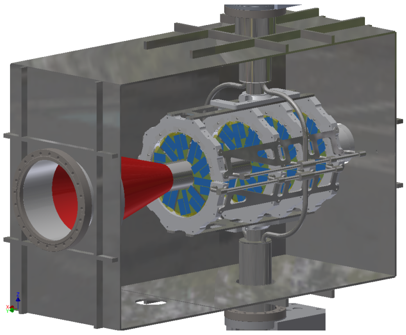


Figure 1: The Luminosity Detector

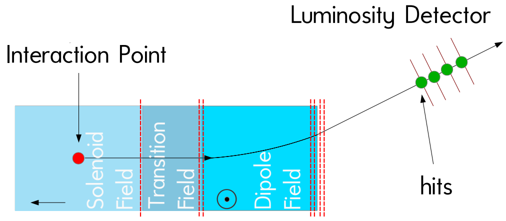


Figure 2: Illustration of the combination of the magnetic fields foreseen for PANDA (dashed red lines show steps introduced in back propagation)

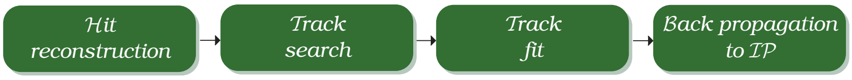


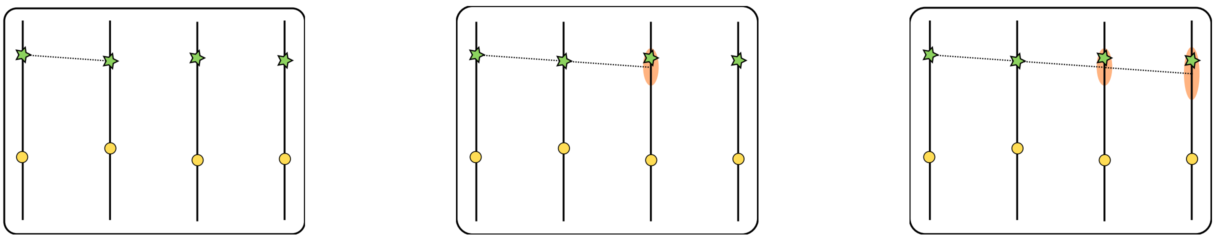
Figure 3: Illustration of the track reconstruction chain

2. Track reconstruction chain

The LMD is located outside of the magnetic field and will register hits of straight tracks. The information from the hits in the pixel sensors is given to the reconstruction chain presented in Fig. 3. After the calculation of the pixel coordinates in the global frame (hit reconstruction), the antiproton trajectory is reconstructed in a two step procedure (track search and track fit). The last part of the chain is an extrapolation of each track back to the Interaction Point through the magnetic fields of the dipole and solenoid magnet and the transition field between them (Fig. 2).

2.1. Track Search

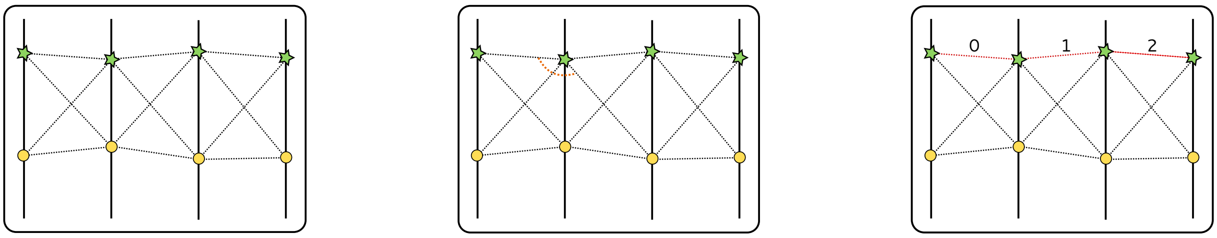
Due to the specific and very limited geometrical acceptance one does not expect very high track multiplicities in the LMD. However secondary and background particles could significantly increase track multiplicities. And even in that case the track search algorithm should be robust against hit losses and have a high track reconstruction efficiency. Therefore two competitive track search algorithms were implemented and compared in simulation tests.



(a) (b) (c)

Figure 4: Illustration of the Track Following algorithm

Track Following algorithm is a simple routine which follows the track. Here a track candidate seed is built by two hits of neighboring planes (Fig.4a) and then propagated to the next plane (Fig.4b). If the distance between the hit on the next plane and the track line lies within a certain corridor, the hit is attached to the track and the track candidate is propagated to the last plane, where it is looking for the nearest hit once again (Fig.4c). This procedure is repeated until all track candidate seeds between the first two layers are checked. Sometimes it might happen a hit on one layer is missing (e.g dead sensor). Thus a special algorithm option was implemented. In case no hit was found within the corridor on one plane, it allows further track candidate propagation and takes combinations between the second and the third layer as a candidate seed.



(a) (b) (c)

Figure 5: Illustration of the Cellular Automaton algorithm

Cellular Automaton is a more sophisticated algorithm, firstly used for a track search at the HERA-B experiment [5]. It deals with cells: segments between two hits on different planes as indicated by the lines in Fig.5a. Cells are build between all neighboring planes. To prevent missed tracks due to dead pixels in one layer, cells are also built by skipping one plane. The next step is cell evolution (the search of neighboring cells). Two cells are called neighbors if they form a straight line: they share one hit on their common plane and the breaking angle between them is small (Fig.5b). During the evolution, cells are ranked according to the number of neighbors (Fig.5c), which leads to an automatic track construction.

Comparison of the track search algorithms

For the LMD a significant amount of missed tracks as well as fake tracks could lead to changes in the shape of the scattering angle distribution and make it difficult to extract the luminosity with high precision. Therefore we tested our track search algorithms with different track multiplicity per event. The same Monte Carlo data sample was used by both algorithms to ensure that a difference in results is caused only by the searching method and not by statistical deviations. The reconstructed tracks were compared with the simulated on the hit level and sorted in 3 categories:

- Good Track: contains at least 65% of hits from one simulated track
- Missed Track: simulated track was not found
- Fake Track:
  - Clones of a track: simulated track was reconstructed twice (or even more times)
  - Ghost Track: reconstructed track contains hits from different simulated tracks

Results in terms of an average number of missed tracks per event if there was at least one track missing and percentage level of such events with missed tracks as a function of track multiplicity are presented in Fig. 6.

Due to less tight internal parameters for the Cellular Automaton algorithm in comparison to these of the Track Following algorithm, the loss of tracks is reduced for low momenta. However this also leads to a higher amount of fake tracks. For example in case of 20 tracks/event the number of events with fake tracks is $\sim 0.1\%$ for Track Following algorithm and $\sim 0.5\%$ for Cellular Automaton. Also one should mention here that for high momentum tracks both algorithms give similar results.

2.2. Track Fit

The parameters of a track candidate are defined as a line segment between the hits in the first two detector planes. To obtain more accurate description of the track, a fit based on all measured hits is performed. Since tracks in the luminosity detector are almost straight lines, the track model could be simple with only 4 parameters. However for low momentum tracks multiple scattering has to be treated rigorously. To meet this requirement, the least squares estimation with the breaking lines technique was developed. The main idea of the "breaking-lines" approach is to fit scattering angles on each plane together with the track parameters [6].

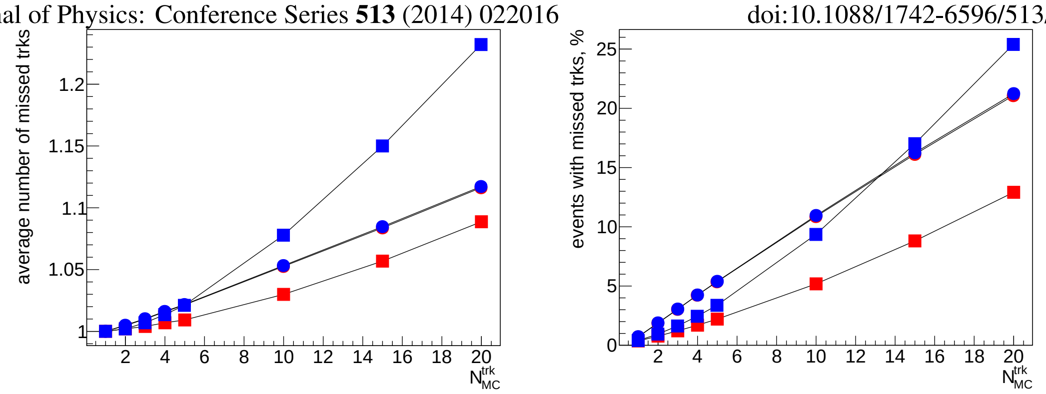


Figure 6: Average number of tracks missed per event if at least one track was missing per event (left) and average number of such events (right): Red - Cellular Automata, Blue - Track Following; ◯ - missed due to small amount of hits; □ - track search losses (1.5 GeV/c)

This leads to the following χ^2-function:

$$\chi^2 = \sum_{l=1}^{4} \left(\frac{(\xi_l^x - x_l)^2}{\sigma_x^2} + \frac{(\xi_l^y - y_l)^2}{\sigma_y^2} \right) + \sum_{J=1}^{4} \frac{(\alpha_J^x)^2 + (\alpha_J^y)^2}{\sigma_s^2} \tag{1}$$

where ξ^x and ξ^y are coordinates of the measured hits with uncertainties σ_x, σ_y; x_l and y_l are coordinates of the track on plane l; α_J^x and α_J^y are the scattering angles on plane J and σ_s is the uncertainty of the multiple scattering angle. Results of the track fit are presented in Tab. 1 in terms of pulls distributions values for the starting point (X_{start}, Y_{start}) and direction coordinates (d_x, d_y, d_z) of the track with a simulated momentum magnitude of 1.5 GeV/c. As one can see from the pull values, the fit works very well and gives an accurate parameter estimation with the corresponding error.

Table 1: Pull distributions values after the Track Fit procedure (1.5 GeV/c)

Parameter	Pull Mean	Pull Sigma
X_{start}	$-1.3 \cdot 10^{-3} \pm 2 \cdot 10^{-3}$	$0.96 \pm 8 \cdot 10^{-3}$
Y_{start}	$+2.3 \cdot 10^{-3} \pm 8 \cdot 10^{-4}$	$0.97 \pm 8 \cdot 10^{-3}$
d_x	$+6.5 \cdot 10^{-3} \pm 3 \cdot 10^{-3}$	$1.1 \pm 7 \cdot 10^{-3}$
d_y	$+3.9 \cdot 10^{-3} \pm 2 \cdot 10^{-3}$	$1.1 \pm 6 \cdot 10^{-3}$
d_z	$-3.4 \cdot 10^{-3} \pm 1 \cdot 10^{-3}$	$1.1 \pm 7 \cdot 10^{-3}$

2.3. Back propagation to Interaction Point

The extraction of the luminosity value is done by comparing the measured angular distribution of the tracks with the theoretical model at the Interaction Point (IP). This is necessary because the angular distribution of the elastic scattered antiprotons at LMD is distorted by the magnetic fields which the antiprotons have to pass on their way to the LMD (11 m behind the IP). Therefore the tracks measured in LMD have to be extrapolated back to the IP. GEANE package [7] and the Runge-Kutta method from the GenFit package [8] were included in our software and tested with simulated data to find out the best suitable tool and allow cross checks between them. The back propagation is done in steps (see dashed red line in Fig. 2), because both tools cannot deal accurately enough with a fast change of the magnetic field.

From the results of simulation studies it is difficult to judge which back propagator is better in general. The extrapolation of the parameters looks quite similar, however the extrapolation of the covariance matrix gives different results. Tab. 2 shows the values of the pull distributions after back propagation with GEANE or GenFit for the simulation with an antiproton momentum of 1.5 GeV/c. The resolution for all parameters is the same, but the widths of the pull distributions are different. The reason for the difference is currently under investigation.

Table 2: Pull distributions values after back propagation (1.5 GeV/c)

	GEANE		GenFit	
Parameter	Pull Mean	Pull Sigma	Pull Mean	Pull Sigma
X_{start}	$+1.1 \cdot 10^{-2} \pm 3 \cdot 10^{-3}$	$0.91 \pm 2 \cdot 10^{-3}$	$+3.1 \cdot 10^{-3} \pm 5 \cdot 10^{-3}$	$1.53 \pm 3 \cdot 10^{-3}$
Y_{start}	$+1.0 \cdot 10^{-3} \pm 3 \cdot 10^{-3}$	$0.86 \pm 2 \cdot 10^{-3}$	$+8.0 \cdot 10^{-3} \pm 5 \cdot 10^{-3}$	$1.44 \pm 3 \cdot 10^{-3}$
d_x	$-2.8 \cdot 10^{-3} \pm 4 \cdot 10^{-4}$	$1.03 \pm 2 \cdot 10^{-3}$	$+1.2 \cdot 10^{-2} \pm 3 \cdot 10^{-3}$	$0.98 \pm 2 \cdot 10^{-3}$
d_y	$+8.3 \cdot 10^{-3} \pm 2 \cdot 10^{-3}$	$0.65 \pm 1 \cdot 10^{-3}$	$-1.3 \cdot 10^{-2} \pm 2 \cdot 10^{-3}$	$0.67 \pm 1 \cdot 10^{-3}$
d_z	$+7.4 \cdot 10^{-3} \pm 5 \cdot 10^{-4}$	$0.14 \pm 4 \cdot 10^{-4}$	$+3.1 \cdot 10^{-2} \pm 3 \cdot 10^{-3}$	$0.86 \pm 4 \cdot 10^{-4}$

3. Conclusions
The Luminosity Detector will determine the luminosity in the fixed target experiment PANDA by analyzing the elastic $\bar{p}p$ scattering at very small momentum transfer. For this measurement a small tracking system will be inserted downstream from the Interaction Point. Although material budget of the LMD is very low, multiple scattering affects the resolution of low momentum tracks. To overcome this problem, the Cellular Automaton algorithm was implemented in addition to the more simple Track Following algorithm for the track search. In the Track Fit, multiple scattering is taken into account by the "breaking-lines" approach.

Another feature of our reconstruction chain is the back propagation of the tracks to the IP. The back propagation of the track parameters works fine, however it was shown that none of the existing tools (GEANE and GenFit) are accurate enough in the extrapolation of the covariance matrix and should be studied more carefully.

The track reconstruction chain was checked in different simulation tests and is used for the next step, the extraction of the luminosity from (simulated) data.

Acknowledgments
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