Fast simulation of the forward tracking detector of HPLUS *

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Abstract The necessity of installing a forward tracking detector stack is discussed for the Hadron Physics LanzhoU Spectrometer(HPLUS). A local tracker is developed to solve the multi-track finding problem. The track candidates are searched iteratively via Hough Transform. The fake tracks are removed by a least square fitting process. With this tracker we have studied the feasibility of $pp\rightarrow pp+\phi(\rightarrow K^+K^-)$, a typical physical channel proposed on HPLUS. The single track momentum resolution due to the uncertainty of the positioning in FTD is 1.3%. The multiple scattering effect contributes about 20% to the momentum resolution in the FTD coverage. The width and the signal-to-background ratio of the reconstructed ϕ are 1.51 MeV and 4.36, respectively, taking into account the direct Kaon channel $pp\rightarrow pp+K^+K^-$ as background. The geometry coverage of FTD for ϕ events is about 85.4%. Based on the current fast simulation and estimation, the geometrical configuration of FTD meets the physical requirement of HPLUS under the current luminosity and multiplicity conditions. The tracker is applicable in the full simulation coming next and is extendable to other tracking component of HPLUS.

Key words simulation, track finding, event reconstruction, Hough Transform

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1 Introduction

An internal target experiment facility named Hadron Physics LanzhoU Spectrometer (HPLUS) is proposed for construction on the main ring of the Cooling Storage Ring on the Heavy ion Research Facility at Lanzhou (HIRFL-CSR). With the proton beam of 2.8 GeV delivered by HIRFL-CSR, It provides plenty of opportunities in non-perturbative QCD field research, such as hadron spectroscopy, chiral symmetry breaking restoration and mechanism of parity symmetry and breaking[1—9]. The systematic simulation for the facility is a necessary step for optimizing the setup of HPLUS and studying the feasibility of the designated physics goals.

The conceptual design of HPLUS mainly consists of the following sub-detectors: The tracking detector (TD) placed in a solenoid, the time of flight (TOF) detectors, the electromagnetic calorimeter (EMC), the forward hadronic calorimeter and the T0/Vertex detector. The tracking detector contains a time project chamber (TPC) covering a large angle and a forward tracking detector (FTD) stack covering the forward angle. Both the TPC and the FTD are placed in a uniform magnetic field along the beam axis and provide the momentum measurement and particle identification by measuring the energy loss and the curvature of the charged particles passing

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through. The purpose of installing the FTD is to compensate the low momentum resolution of the TPC at forward angle.

Two important issues should be considered in the fast simulation for the tracking detectors. (1) At the typical beam luminosity of HPLUS of 10^{32} cm^{-2}·s^{-1} (corresponding to events rate about 10^6/s), it is a real challenge to run the TPC and the FTD since they are all slow-response detectors. (2) Because any physical channel of our interest involves more than one charged particle and the successive events likely fire the detectors due to the high event rate, we have always to treat many tracks simultaneously in the detectors. A working tracker should be designed to reconstruct the multi-track event for the feasibility study and the physical analysis, and accordingly set the design parameters for the tracking detectors, like the position resolution, the geometrical configuration, the event tag and the applied cuts, etc.

This paper mainly discusses the second issue. A practical tracker is developed for the FTD and can be extended to other tracking components of HPLUS. With this tracker, we study the feasibility of a selected physical channel of interest, $pp \rightarrow pp + \phi(\rightarrow K^+K^-)$. This channel is typical and the main conclusion is also valid for another kind of physical channels, the N* channels. The structure of this paper is organized as follows: Section 2 mainly discusses the necessity of FTD for HPLUS; Section 3 gives a simple description and evaluation to the local tracker method. Section 4 then presents the application of this tracker to $pp \rightarrow pp + \phi(\rightarrow K^+K^-)$ measurement and the feasibility is discussed, including a rough estimation of the influence from noise and multiple scattering. The summary and outlook are given in Section 5. The simulation results of this paper are based on the following parameters of HPLUS: the inner and the outer radius and the length of TPC are 60, 400, 750 mm, respectively; FTD is composed of five sets of planar multi-wire drift chambers (MWDCs). The distance of each MWDCs to the target point are 800, 1050, 1300, 1550, 1800 mm, respectively. The uniform magnetic field provided by the solenoid is 1.3 T. These parameters are chosen by taking into account both the reality of the experimental site and the geometrical parameters of the sub-detectors. The fine tuning of the parameters will not change the conclusion of this paper.

2 Necessity of FTD for HPLUS

HPLUS is a fixed target experiment and the products are dominant at forward angle according to the phase space simulation. Fig. 1(a) shows the angular distribution of the final charged products K(dotted), p(dashed), π(solid) in the reactions $pp \rightarrow p+p+\phi(\rightarrow K^+K^-)$ and $pp \rightarrow p+n+\pi^+$ with beam energy 2.8 GeV in laboratory. It is shown that about 90% charged particles are emitted within the forward polar angle 90° and the peaks of K and p sit at less than 20°. In order to study such reactions with the main products emitted at the forward angle, the design of the forward part becomes essential in the concept of the whole facility. In the conceptual design of HPLUS, the effective coverage range of TPC is about from polar angle 28° to 90°. Fig. 1(b) shows the ratio of the effective thickness experienced by a charged particle passing through the TPC over the total sensitive thickness, dubbed by R_a, as a function of the emitted angle of the charged particles. R_a is less than 1 within 28°, indicating that only part of the sensitive volume of the TPC responds to the charged particles emitted below this angle. This is a pure geometrical effect. It is expected due to this reason that the accuracy of the momentum reconstruction is much

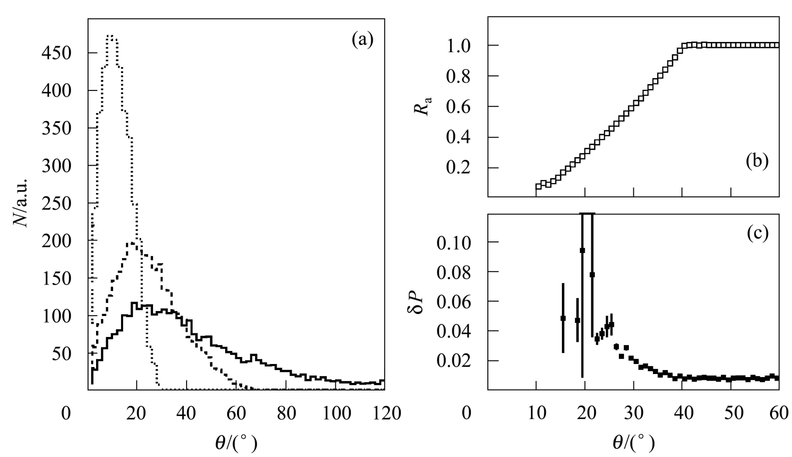

Fig. 1. (a) Angular distribution for products K(dotted), p(dashed), π(solid) of reactions $pp \rightarrow p+p+\phi(\rightarrow K^+K^-)$ and $pp \rightarrow p+n+\pi^+$; (b) Effective thickness R_a in laboratory; (c) Single track momentum resolution of TPC versus the polar angle in laboratory.

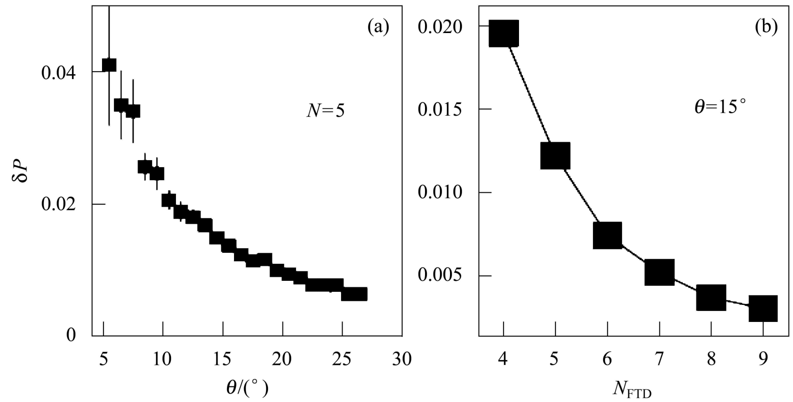

Fig. 2. (a) Single particle momentum resolution versus angle of FTD in laboratory; (b) Correlation of single particle momentum resolution and number of MWDCs being used at polar angle 15° in laboratory.

reduced in the forward region with only TPC. Fig. 1(c) shows the single track momentum resolution in TPC as a function of the emitting angle in laboratory. The resolution is distinctly deteriorated with the polar angle less than 30°. In the simulation, the space resolutions of x, y and z directions are parameterized as typical values of 0.2 mm, 0.2 mm and 1 mm, respectively.

In order to gain higher precision and efficiency in the forward angle, a forward tracking detector (FTD) stack is considered to be placed at the forward region in the magnetic field. The FTD in design consists of five planar multi-wire drift chambers, each of which has 4 electric planes with wire inclinations of 0°, −45°, +45° and 90°, respectively. Fig. 2(a) shows the single particle momentum resolution of the FTD in laboratory with the same fitting procedure and the same parameterized position precision as in TPC. Compared with the results of TPC in the same region, the momentum resolution of FTD is improved largely.This is expected because the track length left in FTD with such configuration is much longer than in the TPC. Fig. 2(b) shows the correlation between the reconstruction momentum resolution and the number of MWDCs being used. Obviously, the momentum resolution goes better than 1% with increasing the number of MWDCs, which gives a good compensation for low momentum resolution of TPC in forward angle. The influence of multiple scattering is not included in the fast simulation, it is estimated separately in section 4. However, increasing the number of MWDCs needs longer magnetic field and hence calls for much higher cost. In this paper, we take five multi-wire drift chambers in our simulation, which meets our detection requirement.

3 Multi-track finding

Track reconstruction is a very important task for both experimental and simulation data analysis. Generally, track reconstruction can be divided into two steps[10, 11]: track finding and track fitting. A related concept is the “hit”, namely the ionization position along the path of a charged particle. The first step, track finding, is a kind of pattern recognition. Its main function is to find out the hits assigned to a certain track candidate as called. Due to the background hits, it is possible that fake track(s) appears in the track finding process. The second step, track fitting, is to get rid of the fake tracks and calculate precisely the momenta of the real tracks by using a certain method.

The tracking detectors are placed in a homogeneous magnetic field. The trajectories of the charged particles are helices in the space coordinates. The target position is the origin of the coordinate system of HPLUS. The z-axis is along the beam line and the x-y plane is parallel to the plane of MWDCs. The wires of MWDCs collect the hit positions in x and y direction, while the positions in z direction are given by the positions of MWDCs which were fixed downstream the target, and then we can get the three-dimensional coordinator (x, y, z) of each hit. The Hough Transform method[12, 13] is applied to the hits on the MWDCs by an iterative procedure and then every hit is assigned to a certain track candidate or recognized as the noise hit.

To avoid the nonlinear problem of a normal circle fitting procedure, Riemann Transform[14, 15] is applied to fit the hits from a candidate track and determine its curvature or the momentum of the track. Due to the intensity of the event background and detector background, it is possible that fake track occurs in the track finding procedure. Many kinds of method have been developed to solve this problem, such as the linear least-squares method, the Kalman Filter[11] and so on. In this paper the linear least-squares method is applied to get rid of fake tracks by using the z direction information. If all the hits of coordinator satisfy a fitted linear function between the arc lengths of the helix projected to x-y plane and the distance on z direction, then the candidate track is recognized as a real track.

The intensity of the event background of HPLUS is estimated according to the luminosity condition at HPLUS, 10^{32} cm^{-2}·s^{-1}, the total pp reaction rate is about 10^6/s[16]. In a typical drift process 0.5 μs, a simple estimation reveals that such events contribute about 30% to the total hits and the detector background is less than 25% according to the prototype test. So to be conservative in the fast simulation, the ratio of the noise hits to the real hits is controlled lower than 60%. The influence of the noise to the timing of the hit is neglected here, since the rising time of the signal is much less than the drift time. The δ electron, which mainly contribute to the high energy part in the dE/dx spectrum, is not explicitly generated in the fast simulation because the cut to the energy loss rate is not yet implemented.

Figure 3 shows a typical example of the multi-track finding, with the solid squares denoting the hits of 10 real tracks and the hollow circles denoting the noise hits generated randomly as input hits. The positions of all hits are smeared in three directions according to the expected spatial resolution (testified also by the prototype test) of the detectors. Five frames shaped as octagon or dodecagon are the active areas of the five planar MWDCs. The circle in the center represents the beam pipe. All the tracks are successful found by the tracker, as shown by the circular curves determined by the tracker. It is worth mentioning that the multiplicity of the charged particles in pp collision is relatively low, typically at 3 or 4. In order to promote the applicability of track finding method, it is necessary to take a higher track multiplicity in the development of the tracker.

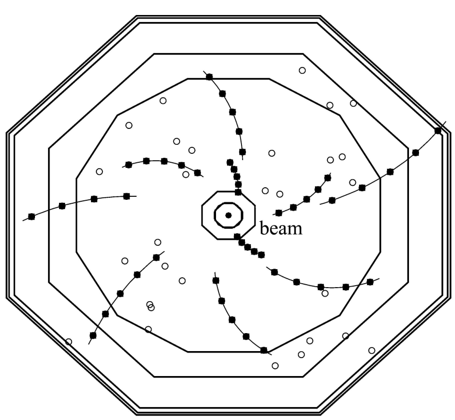

Fig. 3. Results of track finding, the solid square plots are the hits of real tracks and the hollow circles are noise hits.

Figure 4 shows the correlation between the time consuming of CPU and the number of found real tracks by using two kinds of Hough Transform methods. The computer for simulation holds 256 MB memory and 2.8 GHz CPU. The number of tracks input to the tracker is 7, 8, 9, 10 and 11, respectively. The circles and squares are time-consuming of CPU using the Hough Transform method. The track finding efficiency of the former is 100%. The latter is above 94% with the simplified iterative process, which can not find out all the real tracks when the track multiplicity is greater than 13. The triangle shows the time-consuming of CPU using the Hough Transform method supposing the tracks run cross the origin point. It is much lower than the above two methods, but the average track finding efficiency is only about 87%. It is found that, the Hough Transform method for three points has higher efficiency and takes about 5 h for 10^5 events and meets the requirement of fast simulation. This performance satisfies the need of the feasibility study for the certain physical goals on HPLUS.

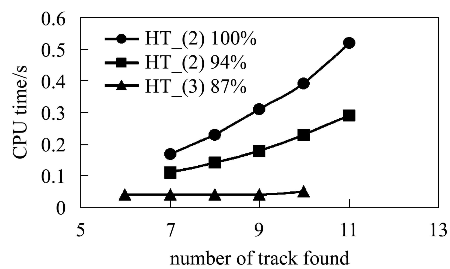

Fig. 4. Correlation of time-consuming of CPU and track number by using different type of Hough Transform method.

4 Feasibility study

4.1 Single track momentum resolution

The momentum resolution is one of the essential features of the FTD. Two facts may bring considerable uncertainty to momentum measurement, the one is the positioning error recorded by the FTD, the another is the multiple scattering in all materials on the flight path. Therefore it is important to evaluate the quality of the reconstruction program with a certain position smearing. According to a phase space simulation, the final products K^+ and K^- in the reaction $pp \rightarrow pp + \phi(\rightarrow K^+K^-)$ at 2.8 GeV mainly distribute below polar angle 30° in laboratory (see Fig. 1(a)), which is well covered by FTD. The reconstruction momentum resolution $\delta P/P_k = (P_k - P_{rec})/P_k$ for a single K^+ track from the above reaction is 1.3% under the typical parameterized space resolution and meets the physical requirement, where P_k is the origin momentum of K^+ from the event generator and P_{rec} is the reconstructed momentum. It is close to the estimation based on the following formula[17],

$$(\sigma_{P_\mathrm{t}}/P_\mathrm{t})_{\mathrm{pos.}} = \frac{3.3\times10^2\times\sigma_x}{B\times L_\mathrm{t}^2}\times P_\mathrm{t}\times\sqrt{\frac{720}{N+5}}\ , \qquad (1)$$

where the field $B = 1.3$ T, p_t is transverse momentum of particle, N=5 is the number of position sample points in FTD, L_t is the length of track projected to r-ϕ plane, which is about 24.55 cm based on the average transverse and longitudinal momentum of Kaon from above reaction. The position resolution of a single MWDC for the tested prototype is about 0.2 cm, the space resolution σ_x is assigned 0.283 cm. With such parameters, it is derived from (1) that the momentum resolution due to the position uncertainty is 10.12%$\times P_\mathrm{t}$. The mean transverse momentum of Kaon in the FTD coverage is 0.133 GeV/c, corresponding to a momentum resolution of 1.34%.

The multiple scattering is not implemented in our fast simulation. Its influence is also estimated based on an empirical formula[17]. The momentum uncertainty due to the multiple scattering is written as,

$$(\sigma_{P_\mathrm{t}}/P_\mathrm{t})_{\mathrm{m.s}} = \frac{4.5}{B}\times\sqrt{\frac{1}{L\times X_0}}\ , \qquad (2)$$

The length of FTD stake is about 120 cm, the average radiation length is 82.43 m taking all the material into account, including the wires, the working gas, the air and the Kapton foil, with the working gas contributing the most. With this estimation, the contribution of multiple scattering to momentum is about 0.348%. For a low momentum at 0.2 GeV/c, it contributes about 20% of the resolution from the spatial resolution. In the following feasibility study, only the spatial resolution is explicitly taken.

4.2 pp→pp + ϕ(→$\mathrm{K^+K^-}$) feasibility study

Another essential feature for the fast simulation is the resolution and the reconstruction efficiency for a given physical channel. We take the same channel pp→pp + ϕ(→$\mathrm{K^+K^-}$) for study. Fig. 5(a) shows the invariant mass of $\mathrm{K^+}$ and $\mathrm{K^-}$ reconstructed from pure pp→pp+ϕ(→$\mathrm{K^+K^-}$) events at 2.8 GeV beam energy. It is shown that the mass of ϕ 1.02 GeV is reconstructed with a variance $\sigma = 1.30$ MeV. The total geometry efficiency is 85.40% under the current facility structure. Except the real ϕ events, the direct Kaon process pp→pp + $\mathrm{K^+K^-}$ will contribute dominantly to the background in the real experiments. According to the existing data, the ratio of the cross section between pp→pp + ϕ(→$\mathrm{K^+K^-}$) and pp→pp + $\mathrm{K^+K^-}$ is about 0.82[18] in the CSR energy region. In real experiment, there is no way in one event to distinguish whether the Kaon pair comes from a ϕ decay or from the background. Therefore in our simulation we summed these two channels with a fixed ratio. Fig. 5(b) shows the total invariant mass of $\mathrm{K^+}$ and $\mathrm{K^-}$ by summing up the real ϕ channel and the background channel with (solid) and without (dotted) the

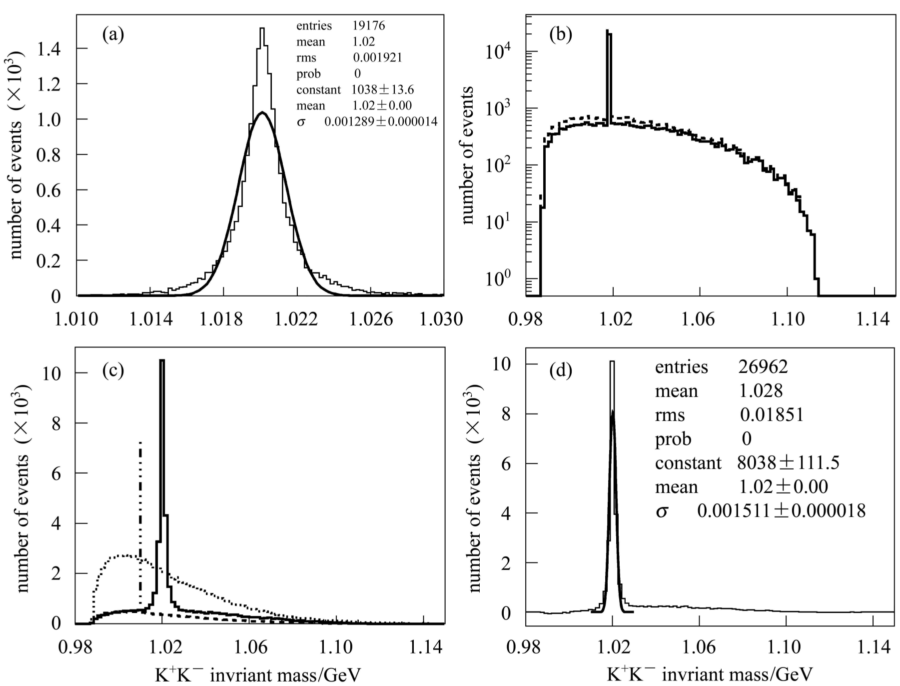

Fig. 5. (a) Invariant mass reconstructed by $\mathrm{K^+K^-}$from pure reaction pp→pp+ϕ(→$\mathrm{K^+K^-}$); (b) The invariant mass of $\mathrm{K^+}$ and $\mathrm{K^-}$ from mixed events (dashed) and with the required FTD geometrical filter (solid); (c) The solid curve denotes the summed invariant mass spectrum of $\mathrm{K^+}$ and $\mathrm{K^-}$, the dotted and the dashed curve denote the background invariant mass spectrum and normalization result, respectively; (d) The final invariant mass of ϕ after the background subtraction.

FTD geometrical filter. In order to extract the pure ϕ events, we subtract the background from the summed invariant spectrum, where the background is obtained from a mixing technique in our reconstruction. As shown in Fig. 5(c), the solid curve denotes the summed invariant mass spectrum of K^+ and K^-, while the dotted curve denotes the background reconstructed by the K^+ and K^- from different event. The background is then normalized (dashed) in the left region of the vertical dash-dot line. Fig. 5(d) further shows the final invariant mass of ϕ after the background subtraction. The mass of ϕ is 1.02 GeV fitted by the gauss function with the mass resolution $\sigma = 1.51$ MeV. The signal-to-noise ratio determined from (c) and (d) is about 4.36.

5 Summary and outlook

The forward track detector stack (FTD) is a critical part in HPLUS for detecting the charged particles. FTD is composed of five multi-wire drift chambers. For the fast simulation we have developed a local tracker for multi-track finding in C++ environment, the candidate tracks are searched in iteration via the Hough Transform method with a least square fitting process to eliminate the fake tracks. The tracker is applied for the feasibility study of $pp \to pp + \phi(\to K^+K^-)$. The single momentum resolution of K^+ is 1.3% with the typical parameterized position accuracy of such detector. The influence of the multiple scattering is not implemented in the fast simulation, but estimated via an empirical formula. It contributes about 20% to the total resolution for the Kaons in the FTD coverage. The geometry coverage of FTD for ϕ events form reaction $pp \to pp + \phi(\to K^+K^-)$ is about 85.40% , the invariant mass of ϕ has also been reconstructed by taking the direct Kion process as background. The reconstruction results demonstrate that the tracker method and the geometry construction of FTD satisfy the requirement of the facility under the current luminosity and multiplicity conditions. The performance of the tracker which is tested satisfies the requirement of the fast simulation works even without the optimization of the data storage structure in its current version. Furthermore, the tracker can be applied to other tracking device in HPLUS. It is worth mentioning that despite the $pp \to pp + \phi(\to K^+K^-)$ is a typical channel in the isospin symmetry physics. We also found that the conclusion of this fast simulation is also valid for the other kind of physics, the N^* channels for instance. Further full simulation of the response of the detector to the passing particles, including the effect of multiple scattering, δ electrons and other selection cuts as well as the inhomogeneity of the magnetic field, are instantly required to draw a solid conclusion in the feasibility study.

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