Influence of the straw tube sagging on the SHiP Spectrometer Straw Tracker performance

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Abstract

Effect of straw tube sagging on the track reconstruction performance of the SHiP Spectrometer Straw Tracker is considered. For this study, the sagging of the tubes and wires has been implemented in FairShip, a software package developed for SHiP event simulation and reconstruction. Degradation of the track spatial and momentum resolution is observed, as expected. Two different cases are studied, which are same sagging applied to all straw tubes, and different randomly distributed offset applied. It is found that if the straw tubes have different sagging, the performance become worse significantly compared with equal sagging for all tracking straws.
1 Introduction

1.1 SHiP Experiment

A new fixed target facility at CERN SPS accelerator is proposed to explore the hidden Sector particles \[1\]. The Search for Hidden Particle experiment (SHiP) is proposed to make measurement on the hidden particles predicted beyond the Standard Model, such as dark photons, Heavy Neutral Leptons, and others, with mass in $GeV/c^2$ range \[1, 2\]. The detailed setup of the facility is under development, and optimization studies are in progress \[3\]. A schematic view of the current SHiP design is shown in Fig. 1. High energy proton beam accelerated by SPS will collide with a fixed target. Hidden particle may be produced and decay later into particles of Standard Model \[4\]. The fixed target is followed by the hadron absorber and active muon shield to suppress the background originated from Standard Model particles. Decays of the Hidden Sector particles is expected to happen in the long decay volume followed by the spectrometer straw tracker (SST) and particle identification detector (ID).

![Figure 1: Sketch of design of SHiP \[3\].](image)

1.2 FairShip

FairShip is a software package based on FairRoot \[4\] developed for simulation and reconstruction of physics in the SHiP detector. FairShip is divided into three main parts, which are simulation, reconstruction and analysis parts. Simulation is where a physics event is generated, and response of the SHiP detector to the particle produced from the event is simulated. Digitization is a part simulate the electronic signal from the response of the SHiP detector. For a real experiment, signal is obtained from real events, so only reconstruction and analysis is performed.
1.3 Spectrometer Straw Tracker and Straw Tube

To reconstruct a vertex of hidden particle decay and to reject background events, high accuracy is required to measure the trajectory and momentum of the charged particle tracks. [1] Performance of SST should satisfy this requirement. SST is composed by 4 tracking stations and a dipole magnet so that two SST stations are located before and after the magnet.

SST consists of arrays of 5m long straw tubes with diameter of 20mm. [3] The wall of straw tubes play role of cathode, and a thin anode wire is placed inside the straw, at the center of the tube under ideal situation. The tube is filled with gas. Voltage difference is applied between the tube surface and the wire. When a charged particle passes through a straw tube, it ionizes the gas filled in the tube. The charge carrier form ionization will drift to the wire or the surface as voltage difference is applied. Near the anode wire, where the electric potential gradient is very high, electron amplification occurs, and electronic signal can be read out. The signals arrive at different time with respected to the moment particle penetrate the straw tube and the finite drift time of the primary electron. Fig.2 illustrates the principle of straw tube. By measuring the signal time, one can get precise coordinate information in reconstruction.

![Figure 2: A graph to illustrate processes occurring when charged particle passes through a straw tube](image)

SST has 4 stations, and each station has 4 views (Y-U-V-Y). For the view Y, straw tubes are installed horizontally. For views U and V, the straws are slightly inclined with a stereo angle. Let x-axis and y-axis be the horizontal and vertical axis, the stereo views, in principle, can help to get information of the x-coordinate of the track hit point. The straw tubes are arranged in serval planes and layers such that y and z coordinate can be directly measured with a rough value. For a direct reconstruction of a straw hit position,
one needs a track pre-reconstruction done in FairShip with pattern recognition. However, in the version used in this work, the results of pattern recognition are not propagated to the straw hit reconstruction routine and the hit local coordinate is calculated using Monte Carlo hit information:

\[
 r_{\text{rec}} = (\text{aDigi.GetDigi()} - \text{self.sTree.t0} - \text{p.GetTime()} - (\text{stop}[0]-\text{p.GetX()})/ \text{u.speedOfLight}) \times \text{v_drift}
\]

where aDigi.GetDigi() is the signal arrived time of a digitized straw hit, self.sTree.t0 is the event time, p.GetTime() is the duration between the event and Monte Carlo hit, stop[0] is the x coordinate of the straw tube end, p.GetX() is the x coordinate of the Monte Carlo hit, u.speedOfLight is speed of light, v_drift is the drift velocity of electron in the straw.

Using the result of pattern recognition and local hit coordinates, a precise track fitting is done. The momentum of the track can be reconstructed from the curvature of the track due to the existence of magnetic field. The track is extrapolated to search for the vertex and used to find the decayed particle.

2 Straw tube sagging

2.1 Motivation

A 5m long straw tube with diameter 20mm is expected to have sagging as the tube and the wire are subjected to forces, such as gravitational, electrical or mechanical. While the straw tubes are under sagging, the cylindrical symmetry will not exist. Besides the geometry and coordinate is changed, electric field inside the tube is more complicated under asymmetric geometry. The electric field will depend on spatial coordinate, instead of simply depends on distance from the wire. The time needed by the charged carriers to reach the wire will be changed, as shown in previous studies.

Tracks of charged particles are required to be measured with high accuracy in position and momentum. In reconstruction, the decay vertex is found by extrapolating the tracks. It is expected that the resolution will have less accuracy when sagging exist. Finding tracks precisely will also help to perform background rejection. Those tracks which do not originate from the decade volume are probably background signals. The influence of the straw sagging on the reconstruction performance should be studied, so that further decision and design can be done to handle sagging.

Although the design development and optimization studies are still on going, sag estimation for the wire and tube is being studied by the calibration using first straw prototype. If the profile of sagging can be obtained, it will be a useful information for the reconstruction studies. In this project, profile and distribution of sagging are still unknown. Ideal straw is assumed in FairShip, and the aim of this project is to implement a simple sagging model inside FairShip and to study the influence on the track reconstruction performance.
2.2 Profile of sagging alone the straw tube

To understand the profile of sagging, wire sag profile under gravitation and electric field was studied previously with GARFIELD software (Fig.3). In this project, for both horizontal straw tube in view Y and stereo straw tube in view U/V, the sagging will be defined as the vertical shift from the original straw position. The two ends of a straw tube are assumed to be installed perfectly. External force that may cause sagging is assumed to be balanced at the two ends, that means zero sagging is assumed at the ends of all straw tube. The straw tube is expected to attain maximum sagging at the mid-point of the straw.

![sag profile for 5m long straw](image)

Figure 3: A graph of simulation result of wire sagging profile from [4].

In this study, a parabolic function is assumed as a profile of straw and/or wire displacement along the horizontal direction. There are other types of function that can give the same characteristics, such as quartic function, catenary for hanging wire (hyperbolic cosine), or cosine function. Parabolic function is chosen as the simplest for implementation and calculation. Parabolic function can also give an analytic solution during some step of calculation (see section 3.2). For other sagging model, numerical solution and approximation are need.
3 Implementation in FairShip

3.1 Method

As mentioned previously, FairShip can be divided as several parts, which is simulation, reconstruction, analysis, and a digitization in-between simulation and reconstruction. To avoid complicated geometry description in the GEANT-based simulation part, the straw misalignment is implemented after the simulation, just before the signal digitization part.

In FairShip, straw signal is derived from the shortest distance between the wire and the track that passes through the tube, dist2Wire. If straw or wire is sag, dist2Wire will be changed. So, a correction can be done on the value of dist2Wire to study the effect of the sagging.

There are several considerations for the choice of method. For the method of correction calculation, the main drawback is that the number of valid measurements will be reduced if the tubes have sagging. In the simulation part, ideal geometry is used, only the track that passing through the region of ideal geometry will be calculated and returned as the output. This interaction between track and detector is done by GEANT4. As Fig. 4, we can see some hit information will become useless as the tube is shifted and those hits will not be detected under sagging (the upper unshaded region). Also, the lower unshaded region is originally outside the straw tube volume, but it becomes the region of detection after sagging. However, no information will be returned from the simulation as the simulation is done based on ideal geometry.

However, for the method that changing the geometry of the GEANT4 simulation itself, it is significantly more complicated to implement. And the largest drawback of modifying geometry in simulation is that any modification in straw misalignment parameter will require repeating the simulation, which is time consuming. If the simulation is now case dependent, a new geometry file is needed, and the whole simulation should be process once again. A lot of time will be needed for repeating simulation of different set of parameters.

In this project, the method of calculating with correction is used. Although this correction can be implemented in simulation or just before digitization, correction is implemented just before digitization part with the same reason mentioned.

3.2 Calculation with correction

A set of hit points is produced in detector response simulation and is used for signal digitization. Based on the position of hit point, dist2Wire can be calculated. To calculate the shortest distance from a point to the parabola describing the new geometry of the misaligned straw, an analytical solution exists. After applying differentiation, a cubic equation is obtained (Eq. 4), which can be solved analytically.

$x_0, y_0, z_0$ be coordinates of a hit point. $z_w$ is the z coordinate of the anode wire, which does not depend on x. And, Square of the distance between a given point to the wire is a function of x:
Figure 4: Cross section of the straw tube. (a) Shaded region is the region will be detected from simulation and will be valid in digitization (b) Red circle is the original region of straw tube (c) green circle is the shifted tube (d) O is origin wire and tube center, W’ is shifted wire, O’ is shifted center of tube

\[(\Delta r)^2 = (x - x_0)^2 + (y(x) - y_0)^2 + (z_w - z_0)^2\]  \hspace{0.5cm} (1)

with the parabolic profile of sagging:

\[y(x) = ax^2 + bx + c, \quad y'(x) = 2ax + b\]  \hspace{0.5cm} (2)

For the closest distance between a hit and the wire, the derivative will be zero:

\[d(\Delta r) \over dx = (x - x_0) + (y(x) - y_0)y'(x) \over \Delta r = 0\]  \hspace{0.5cm} (3)

\[2a^2x^3 + 3abx^2 + (2ac - 2ay_0 + b^2 + 1)x + (bc - by_0 - x_0) = 0\]  \hspace{0.5cm} (4)

To avoid involving cubic equation, the following approximation can be applied. The maximum sagging of the tube and wire is in the range of few mm. The length of the straw is 5m. In such scale difference, locally linearized is assumed (Eq. 5). Under linear approximation, it is a problem of point to straight line. So, simple trigonometric and geometric approach can be applied to calculate the result. In Fig. 5, it shows the projection of the point on the plane as wire.
\[ y(x) \approx y(x_0) + y'(x_0)(x - x_0) \]  

(5)

Figure 5: Sketch of projection of hit point on x-y plane as the wire, not in scale

Dist2Wire can be calculated by Eq. (6):

\[
(\Delta r)^2 = \left[ (y_0 - y(x_0)) \times \cos(\theta) \right]^2 + (\Delta z)^2, \quad y'(x_0) = \tan(\theta)
\]

(6)

As mentioned before, misalignment of tube and wire affects the drift time dependence. However, in this study, only the effect by the geometry misalignment is considered. Also, it is expected that different tubes and wires may have different amount of maximum sagging. The influence of the straw misalignment was studied for two cases, when all SST straw have the same misalignment parameters, and when maximum sag is distributed randomly for different straws. In this case, a uniform distribution of the maximum sag is used.

4 Result

4.1 Resolution for misalignment with equal maximum wire sagging

All straw tubes are assumed to have same maximum sagging. The reconstructed hit coordinates were compared to the hit position available from the Monte Carlo simulation. The difference between those two values were studied for different value of maximum sagging. Fig. 6 shows the result for 0, 4, 7mm of the maximum displacement. While increasing the value of maximum value of the sagging, the distribution become more separated. The mean value of error is still approximately to zero with order \( O(10^{-4}) \). All cases have peak at zero. No bias in positive or negative is observed. The standard
deviation increased more than two times when 7 mm maximum sagging is applied. When the sagging is increased, the reconstruction is expected to produce larger error as it is based on a geometry that have larger difference from the actual situation. Also, the parabola profile used is symmetric about the middle, no bias is found on any sides, as expected.

![Graph](image)

(a) no sagging  
(b) 4mm maximum sagging  
(c) 7mm maximum sagging

Figure 6: Error of reconstructed hit in x-coordinates for different values of the maximum sagging

In Fig. 7, similar graph is plotted for y-coordinate. A shift toward positive value is observed when wire sagging is applied. And the shift increases when the maximum sagging increase. The standard deviation is increased also, but with less increase compared to the x-coordinate case. The result is expected since the reconstruction assumes the ideal straw geometry.

The error of reconstructed track momentum is also plot (Fig. 8). The shape of the distribution has no large change. Most of the distribution is still within the range of 5% error. It is observed that the standard deviation is increased, but still remains in the order $O(10^{-2})$. The mean value is also increased for larger maximum sagging. It is observed that little number of tracks is reconstructed with a relatively large error while sagging is applied. For 7mm case, some tracks momenta are found with error larger than 20%, however the event statics does not allow to make good comparison of the amount of outlier for the considered cases. Compared to the spatial resolution behavior, the momentum resolution is less affected by the misalignment.
4.2 Resolution for misalignment straws with different maximum wire offset

A uniform distribution of maximum sagging is applied to the straw tubes. Mean value of maximum sagging 4mm is used in the study. The Fig. 9 shows the error in reconstructed x-coordinate for different cases. The standard deviation is increased significantly for a wider range of distribution. And the maximum error is increased as the distribution become spread. It is noticed Fig 9(b) and 9(c) show more spread than Fig. 9(d) even though all tubes in the case with 3-5mm and 2-6mm have a maximum sagging less than 7mm. When straws have different sagging, the resolution is degraded. The reason shall be studied.

Similar graphs for y-coordinate are plotted as Fig. 10. For error in y-coordinate, the plots show a different pattern than Fig. 9. The standard deviation of Fig. 10(a), 10(b), 10(c) is almost the same, and it is not strictly increasing. While the mean value is even decreased. Compared to the 7mm case, the peak, the mean and the standard deviation are smaller. It is observed that the performance is better if the wires have lesser sagging. The algorithm used for pattern recognition and fitting shall be studied with the sagging applied. The behaviour in reconstructed x-coordinate and y-coordinate is different. The reconstruction algorithm may influence to the result.

Track momentum resolution is also studied, the result are shown in Fig. 11.
equal offset shown in Fig. [8] the resolution is almost unchanged even different maximum sagging is applied. However, in Fig. [11] the distribution is significantly worse. From Fig. [11(b), 11(c)] the standard deviation is seen to be increased several times compared to Fig [11(a)]. A bias toward positive direction is also observed. Tracks with momentum reconstruction errors more than 10% are observed more frequently. This shows that a distribution on the maximum sagging will significantly reduce the performance of track momentum reconstruction.

4.3 Track fit quality

To study the reconstruction performance degradation for non-equal misalignment distribution, the fitting quality should be considered. Fig. [12] shows the $\chi^2$ per the number of degree of freedom of the tracks for the different misalignment cases. For the cases with same maximum sagging, the mean $\chi^2$ and the standard deviation increased when the sagging increased. It is also observed that in the case with misalignment distribution, Fig. [12(c)] they are more spread and the mean value is larger than all the other cases. It shows that distribution cause the fitting and reconstruction performance worse.

Also, the number of reconstructed hits per track is considered. Fig. [13] shows the number of hits in each case. The distributions of the number of hits per track are almost the same for the cases with same maximum sagging applied (Fig. [13(a), 13(b), 13(d)]. The mean value is decreased also. It is observed that the number is decreased more than
Figure 9: Error of reconstructed hit in x-coordinates for different ranges of the maximum sagging

(a) 4mm maximum sagging  (b) 3-5mm maximum sagging  
(c) 2-6mm maximum sagging  (d) 7mm maximum sagging

a half when maximal sagging is randomly distributed, which is significantly different from the other cases. It is unknown whether it is simply due to the existence of sagging or due to the performance of the fitting procedure. Maybe some limit or cut off based on ideal geometry is used so that the result become poorer. Further study should be done on the quality of fitting while sagging is applied.
Figure 10: Error of reconstructed hit in y-coordinates for different ranges of the maximum sagging

Figure 11: Relative error in momentum for different ranges of the maximum sagging
(a) no sagging  
(b) 4mm maximum sagging  
(c) 2-6mm maximum sagging  
(d) 7mm maximum sagging  

Figure 12: $\chi^2$ per the number of degree of freedom

(a) no sagging  
(b) 4mm maximum sagging  
(c) 2-6mm maximum sagging  
(d) 7mm maximum sagging  

Figure 13: the number of reconstructed hits per a track
4.4 Study of x-coordinate of hit influence on resolution

The profile of the applied sagging is a parabolic function of x-coordinate, which is along the straw. The resolution performance may also depend on the x-coordinate as the performance is affected by the amount of sagging. The spatial resolution is studied as a function of the x-coordinate.

Fig. 14, 15 shows the spatial resolution as a function of the x-coordinate for different misaligned cases. The x-axis of the graph is the x-coordinate along the straw tube, and the y-axis is the spatial resolution. For the case with no sagging (Fig. 14(a)), the error along the x-coordinate is almost the same. Reconstructed with many, the fitted track will have an error near zero. The distribution is concentrated along $y = 0$. Since no sagging is used in this case, it is expected that there is no explicit dependence on x-coordinate. The error shall not depend on x-coordinate also, what agrees with the result. For the case with the same maximum sagging applied, Fig. 14(b), 14(d), they both show a similar distribution. The distribution is of a dumbbell shape. Near the center, the error is close to zero. The error near the two ends is more spread along the y-axis. Comparing 7mm and 4mm case, the whole distribution become more spread along the y-axis. It is expected as the performance become poor when the sagging is increased. However, for the case of distributed maximum sagging, the shape is like an ellipse (Fig.14(c)). The performance on the middle become much poorer. The reason why they show a dumbbell shape or an elliptical shape is unknown. It is possible that the error of x is related to the slope of the wire, so that they show a dumbbell shape. When the sagging distribution is applied, the hits in the middle of the tracker are more sensitive to the sagging because only the middle can attain the largest value of sagging. It is one of the possible reasons why the performance is poorer around the middle.

For they-coordinate reconstruction, a different dependence was obtained. The distribution for no sagging is inconclusive for the dependence on x. The mean value of error is still close to zero. For the other cases, the distribution around $x = 0$ is more spread and shifted along y-axis. The reason may be the error on y is strongly dependent on the amount of sagging at the hit position.

5 Discussion

Different models of straw misalignment are tested. The performance is decreased when the sagging is increased. It is an expected result. When different maximal sagging values are applied to straws, the performance become worse compared with the case that all straw tubes have same sagging. In this report, a fake pattern recognition was used. The performance of different ways for pattern recognition and fitting should be studied in the future. The performance may be improved with different methods.

The error of spatial coordinate shows a dependence on the hit x-coordinate. The error on x-coordinate shows a different result compared to the error on y-coordinate. This is also a property that can be studied.
Figure 14: Error on the reconstructed x-coordinate as a function of horizontal position

Figure 15: Error on the reconstructed y-coordinate as a function of horizontal position
References


A Appendix: Code implemented for the misalignment studies

In FairShip, a python file strawDigi_conf.py is added under the directory FairShip/python. After running the simulation part by following the instruction of FairShip, the sagging setting for reconstruction can be changed by modifying strawDigi_conf.py. In the python file, there are two class, which are StrawtubesMisalign and DriftTimeCalculate. The member of the class will be used for the setting of reconstruction. In order to have reconstruction results for different sagging setup, modification of strawDigi_conf.py is needed before reconstruction. There is no need to do the simulation again, as mentioned in section 3.1. Also, the member in strawDigi_conf.py will be passed to a C++ function by python code. So, there is no need to compile the FairShip again after any modification in strawDigi_conf.py

For StrawtubesMisalign,

misalign is a flag to turn on/off the calculation with correction. True is used for turning on.

randType is a variable to set the type of distribution applied to the maximum sagging. It is applied to both the wire and tube. The choice implemented are "None" and "Unif". "None" is used for the case when all straw tubes have a same maximum sagging. "Unif" is used for a uniform distribution. "Gaus" is prepared for gaussian distribution, but gaussian distribution is not implemented yet.

maxTubeSagging is the value of the maximal sagging for tube. If no distribution is used, then all tubes will have this value for the maximum sagging. If any distribution is used, this will be the mean or the most probable value.

maxWireSagging is similar to maxTubeSagging, but it is used for wire.

tubeUnifDelta is used for the uniform distribution. If the distribution is not uniform, it has no effect. This is the value equal to a half of the range where the distribution is defined. It means that the maximum sagging of tubes will be between the range from (maxTubeSagging - tubeUnifDelta) to (maxTubeSagging + tubeUnifDelta).

wireUnifDelta is similar to tubeUnifDelta, but it is for the wire.

tubeGausSigma is used for Gaussian distribution only. For a Gaussian distribution, a mean value and a sigma are needed.

wireGausSigma is similar to wireUnifDelta, but it is for the wire.
For DriftTimeCalculate,

defaultDriftTime is a flag to turn on the use of default calculation or not. To test each module individually, this flag is used to choose the way of drift time calculation. True is used for using default setting, which is calculation from constant drift velocity.