EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

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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 equal sagging applied to all straw tubes, and a different randomly distributed offset applied. It is found that if the straw tubes have different sagging, the performance becomes worse significantly compared to the equal sagging for all tracking straws.

Contents

1 Introduction

1.1 SHiP Experiment

A new fixed target facility at the CERN SPS accelerator is proposed to explore the Hidden Sector particles [1]. The Search for Hidden Particle experiment (SHiP) is proposed to make measurements 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 design 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).

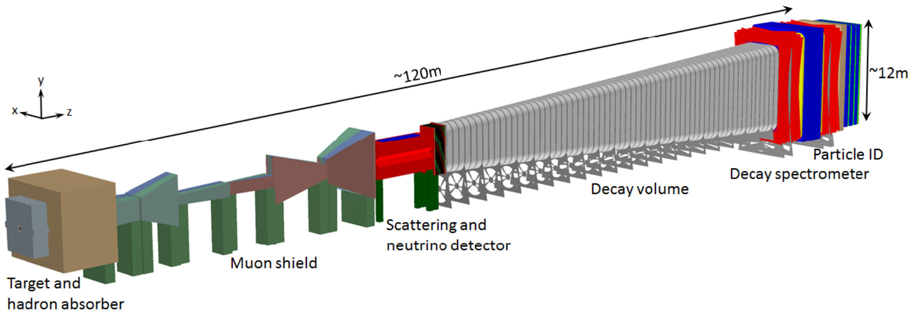


Figure 1: Sketch of the SHiP facility [3].

1.2 FairSHiP

FairSHiP is a software package based on FairRoot [1] developed for simulation and reconstruction of physics events 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 in the event is simulated. Digitization is a part where the electronic signals from the ShiP detector read out systems is simulated, based on the detector response. In a real experiment with real data, only reconstruction and analysis is performed.

1.3 Spectrometer Straw Tracker and Straw Tube

To reconstruct a vertex of the hidden particle decay and to reject background events, high accuracy is required to measure the trajectory and momentum of charged particle tracks [1]. Performance of the 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.

The SST consists of arrays of 5m long straw tubes with a diameter of 20 mm [3]. The wall of straw tubes play role of a cathode, and a thin anode wire is placed inside the straw, in 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 carriers from ionization will drift toward the wire or the cathode surface as the voltage difference is applied. Near the anode wire, where the electric potential gradient is very high, electron amplification occurs, and an electrical signal can be read out. The signals arrive at different time with respected to the moment when the particle penetrated the straw tube due to the finite drift time of the primary electrons. Fig.2 illustrates the principle of the straw tube operation. By measuring the signal time, one can get precise coordinate information.

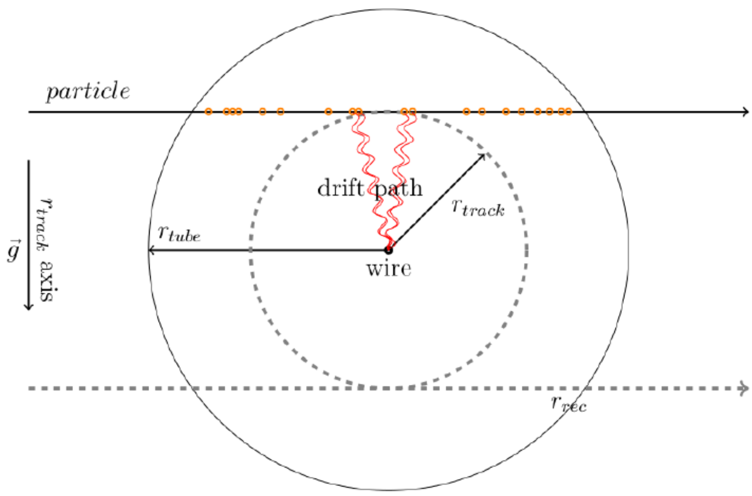


Figure 2: A graph to illustrate processes occurring when a charged particle passes through a straw tube [4].

The SST has 4 stations, and each station has 4 views (Y-U-V-Y). In a view Y, the 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 allow to get information on the x-coordinate of the track hit points. The straw tubes are arranged in two planes, each of them has two layers of straws. For a direct reconstruction of a straw hit position, one needs a track pre-reconstruction done in FairShip with pattern recognition to get rough straw hit coordinate X, Y. However, currently the hit local coordinates are calculated using Monte Carlo hit information:

```
r_rec = (aDigi.GetDigi() - self.sTree.t0 - p.GetTime()
        - (stop[0]-p.GetX() )/ u.speedOfLight) * 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 time which a relativistic particle needed to reach the SST, 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 electron drift velocity in the straw.

Using results of the pattern recognition and the local hit coordinates, a precise track fitting is done. The momentum of the track can be reconstructed from the track curvature due to the existence of magnetic field. The found tracks are extrapolated backward to search for the decay vertex.

2 Straw tube sagging

2.1 Motivation

A 5 m long straw tube with the diameter 20 mm is expected to have sagging as the tube and the wire are subjected to gravitational, electrical or mechanical forces [1]. While the straw tubes are under sagging, the cylindrical symmetry will not exist. Besides the geometry and coordinates are changed, the electric field inside the tube becomes more complicated under the asymmetric geometry. The electric field will depend on the spatial coordinate, instead of the simple dependence on the distance from the wire. The time needed by charged carriers to reach the wire will be changed, as was shown in previous studies [4].

Tracks of charged particles are required to be measured with a high accuracy. A decay vertex is found by extrapolating the reconstructed tracks. It is expected that the spatial and momentum resolution will have less accuracy when the 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 SST design optimization can be done to handle sagging.

Although the design development and optimization studies are still ongoing, the sag estimation for the wire and tube is being studied by the calibration using first straw prototype [4]. If the profile of sagging can be obtained, it will be a useful information for the reconstruction studies. In this project, the profile and distribution of maximal sag values are still unknown. An ideal straw geometry is assumed in FairSHiP, and the aim of this project is to implement a simple sagging model inside the FairSHiP and to study its influence on the track reconstruction performance.

2.2 Sagging profile

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.

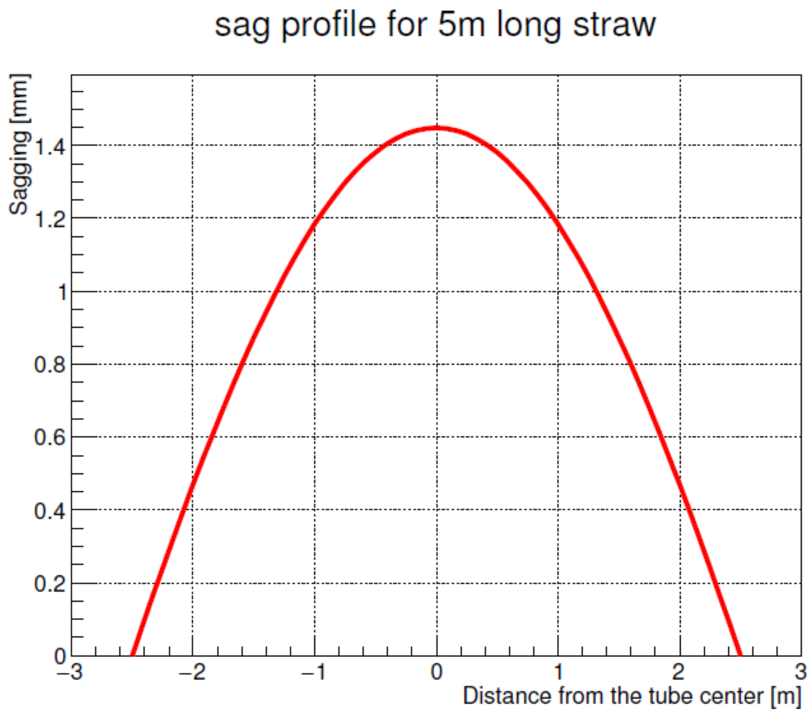


Figure 3: A graph of simulation result of wire sagging profile from [4].

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 a 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 package consists of serval parts, which are 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 was implemented after the simulation, just before the signal digitization part.

In FairSHiP, the 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 sagged, dist2Wire will be changed. So, a correction can be done on the value of dist2Wire to study the effect of the sagging.

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

However, the method which changes the geometry of the GEANT4 simulation itself, is significantly more complicated to implement. And the largest drawback of modifying the geometry in simulation is that any modification of the misalignment parameter will require repeating the simulation. So, to change a misalignment model or parameter, one needs to run the simulation part again, which is time consuming.

In this project, the correction method is used. Although this correction can be implemented in simulation or just before digitization, the correction are applied 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 a hit point, dist2Wire can be calculated. To calculate the shortest path distance from a point to the parabola describing the new geometry of a misaligned straw, an analytical solution exists. After applying differentiation, a cubic equation is obtained (Eq. 4), which can be solved analytically.

Let 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. The squared distance between a given point to the wire is a function of x:

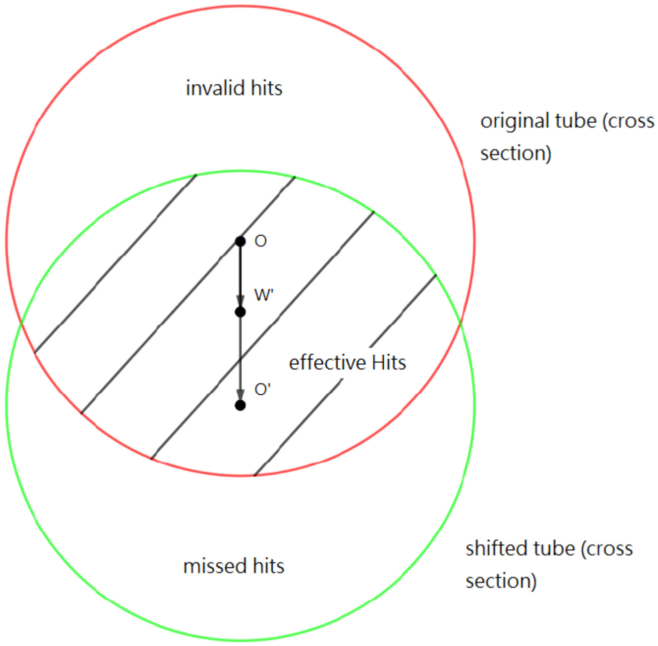


Figure 4: Cross section of the straw tube. (a) Shaded region is the region where simulated hits are available for digitization (b) Red circle is the original region of the ideal straw tube (c) green circle is the shifted tube (d) O is wire and tube center in the ideal geometry, W' the displaced wire, O' is shifted center of tube.

$$(\Delta r)^2 = (x - x_0)^2 + (y(x) - y_0)^2 + (z_w - z_0)^2, \tag{1}$$

with the parabolic profile of sagging:

$$y(x) = ax^2 + bx + c, \quad y'(x) = 2ax + b. \tag{2}$$

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

$$\frac{d(\Delta r)}{dx} = \frac{(x - x_0) + (y(x) - y_0)y'(x)}{\Delta r} = 0, \tag{3}$$

$$2a^2x^3 + 3abx^2 + (2ac - 2ay_0 + b^2 + 1)x + (bc - by_0 - x_0) = 0. \tag{4}$$

To avoid involving a cubic equation, the following approximation can be applied. The maximum sag of the tube and wire is in the range of few mm. The length of the straw is 5 m. In such scale difference, a linear approximation can be used (Eq. 5). Under the linear approximation, it is a problem of the distance between a point and a straight line. So, a simple trigonometric and geometric approach can be applied to calculate the result. Fig. 5 shows the projection of the point on the plane as wire.

$$y(x) \approx y(x_0) + y'(x_0)(x - x_0). \tag{5}$$

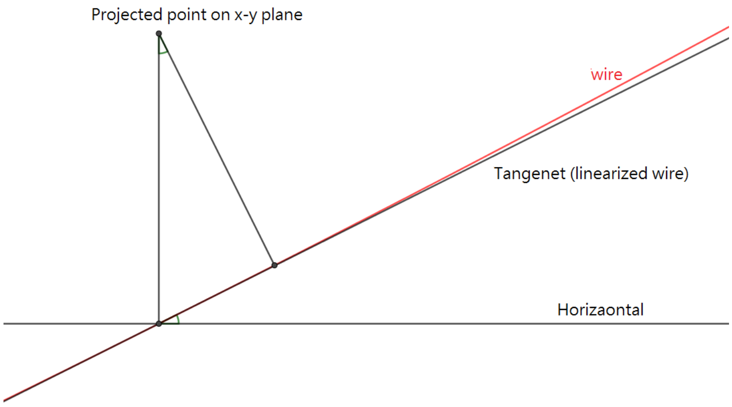


Figure 5: Projection of a hit point on x-y plane (not in scale).

Dist2Wire can be calculated with Eq. 6:

$$(\Delta r)^2 = [(y_0 - y(x_0)) \times cos(\theta)]^2 + (\Delta z)^2, \quad y'(x_0) = tan(\theta). \tag{6}$$

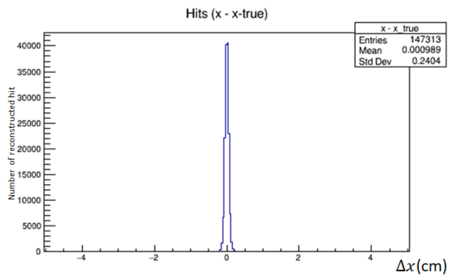
As mentioned before, misalignment of tubes and wires affects the drift time dependence. However, in this study, only the effect of the geometrical misalignment is considered. Also, it is expected that different tubes and wires may have different amount of the maximum sag. The influence of the straw misalignment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

4 Result

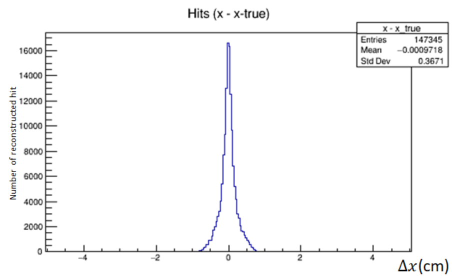
4.1 Resolution for misalignment with equal maximum wire sagging

All straw tubes are assumed to have the 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, 7 mm of the maximum displacement. While increasing the value of the maximal sagging, the distribution becomes more spread. The mean value of the hit position errors is still close to zero at the order $O(10^{-4})$ for all cases.

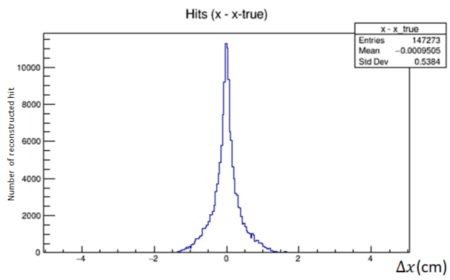
No bias in positive or negative side is observed. The standard deviation increased more than two times when 7 mm maximum sagging is applied. When the sagging is increased, the reconstruction is expected to produce a larger error as it is based on a geometry that have larger difference from the actual situation. Also, since the parabola profile used is symmetric about the middle, no bias is found at any sides, as expected.



(a) no sagging



(b) 4 mm maximum sagging

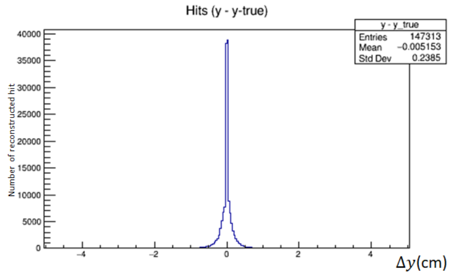


(c) 7 mm maximum sagging

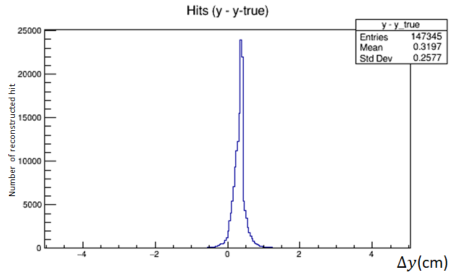
Figure 6: Error on x-coordinates of the reconstructed hit for different values of the maximum sagging.

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

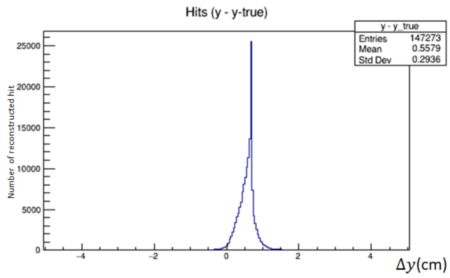
The error of reconstructed track momentum is also shown in Fig. 8 as relative errors $\frac{\Delta p}{p}$. The shape of the distribution has no large change. Most of the distribution is still within the range of 5% error. It is observed that the standard deviation is increased, but still remains at the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



(a) no sagging



(b) 4 mm maximum sagging



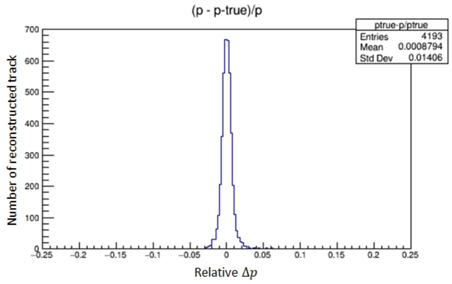
(c) 7 mm maximum sagging

Figure 7: Error on y-coordinates of the reconstructed hit for different values of the maximum sagging.

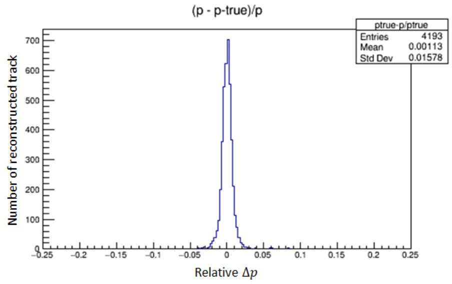
4.2 Resolution for misaligned straws with different maximum wire offset

A uniform distribution of the maximal sag values was applied to the straw tubes. Two cases were studied: the maximal sag distributed in range 3-5 mm, and between 2 and 6 mm. In both cases, the mean value was equal to 4 mm. The results were compared to the cases with equal maximal sag values applied, which the values are 4 and 7 mm. Fig. 9 shows the error on reconstructed x-coordinate for those cases. The standard deviation increased significantly for a wider distribution, and the maximal error increased also. It is noticed that Fig 9(b) and 9(c) show more spread than Fig. 9(d) even though all tubes in the case with 3-5 mm and 2-6 mm have a maximal less than 7 mm. When straws have different sagging, the resolution is degraded. The reason shall be studied.

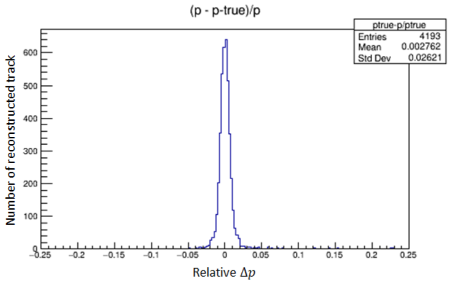
Similar graphs for y-coordinate are plotted in Fig. 10. For error on y-coordinate, the plots show a different pattern than Fig. 9. The standard deviation of Fig. 10(a), 10(b), 10(c) is almost the same, and it is not strictly increasing, while the mean value even decreased. Compared to the 7 mm case,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



(a) no sagging



(b) 4 mm maximum sagging



(c) 7 mm maximum sagging

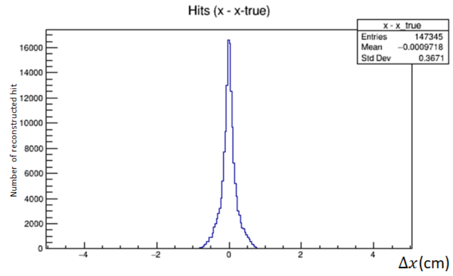
Figure 8: Relative error on the reconstructed momentum for different value of maximum sagging.

Track momentum resolution is also studied, and the result are shown in Fig. 11. For equal offset shown in Fig. 8, the resolution is almost unchanged even when the varaible 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 serval times compared to Fig 11(a). A bias toward the positive values is also observed. Tracks with momentum reconstruction errors more than 10% are observed more frequently. This shows that a distribution of the maximal sag values will significantly reduce the performance of the track momentum reconstruction.

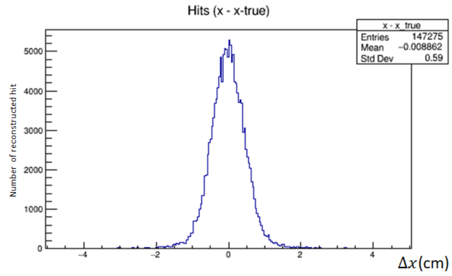
4.3 Track fit quality

To study the degradation of the track reconstruction performance, the track fit quality should be considered. Fig. 12 shows the χ^2 per the number of degree of freedom of reconstructed tracks for the different misalignment cases. For the cases with the same maximal sag value, the mean χ^2 and its standard deviation increased when the sagging increased. It is also observed that in the case with distributed misalignment, Fig. 12(c), they are more spread and the mean value is larger than in all the other cases. It shows that variable misalignment causes worse fitting and reconstruction performance.

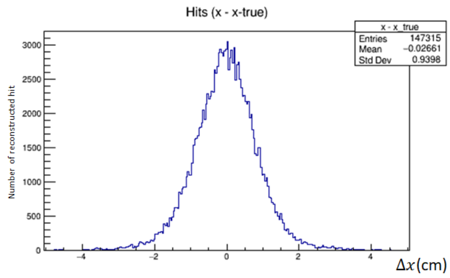
Also, the number of reconstructed hits per a track is considered. Fig. 13 shows the number of hits in each case. The distributions of the number of hits per a track are almost



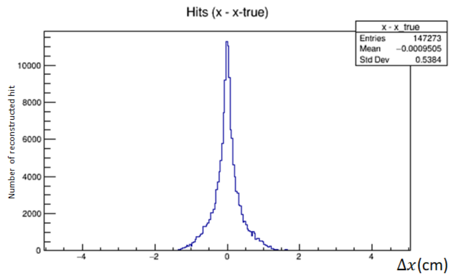
(a) 4 mm maximum sagging



(b) 3-5 mm maximum sagging



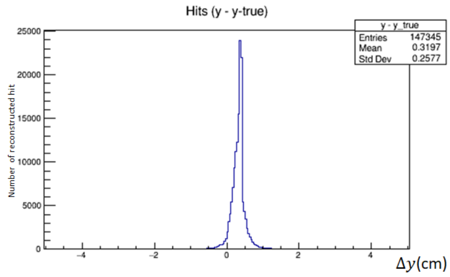
(c) 2-6 mm maximum sagging



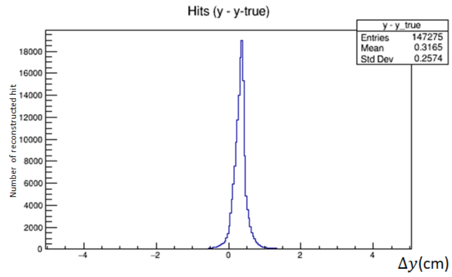
(d) 7 mm maximum sagging

Figure 9: Error on x-coordinates of the reconstructed hits for different ranges of the maximal sagging.

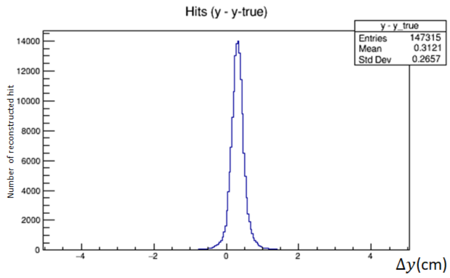
the same for the cases with same maximal sag values applied (Fig. 13(a), 13(b), 13(d)). The mean value is decreased also. It is observed that the number is decreased more than by a half when maximal sagging is randomly distributed, which is significantly different from the other cases. It is unknown 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.



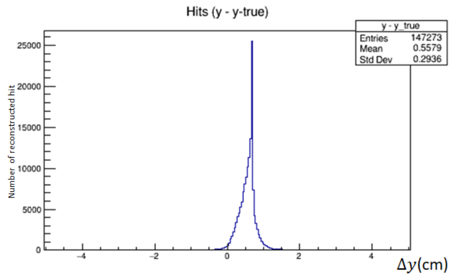
(a) 4 mm maximum sagging



(b) 3-5 mm maximum sagging

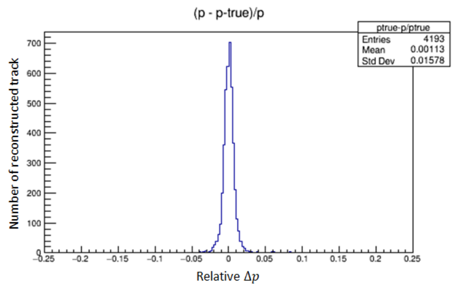


(c) 2-6 mm maximum sagging

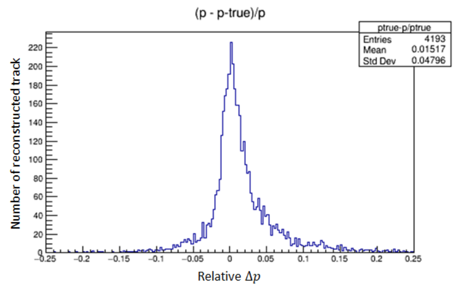


(d) 7 mm maximum sagging

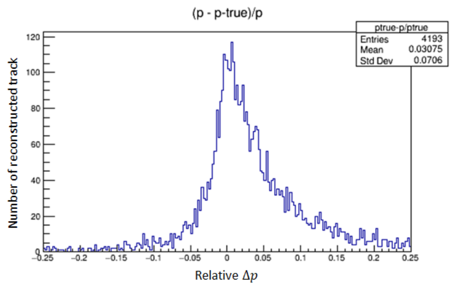
Figure 10: Error on y-coordinates of the reconstructed hits for different ranges of the maximal sagging.



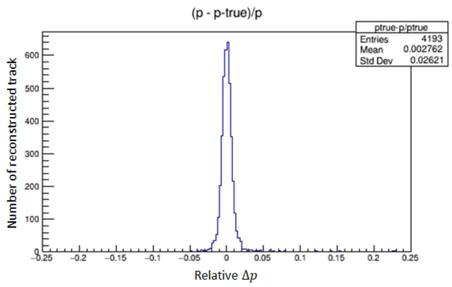
(a) 4 mm maximum sagging



(b) 3-5 mm maximum sagging

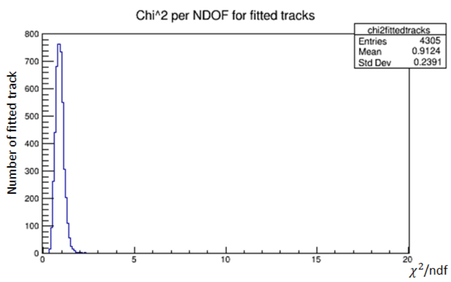


(c) 2-6 mm maximum sagging

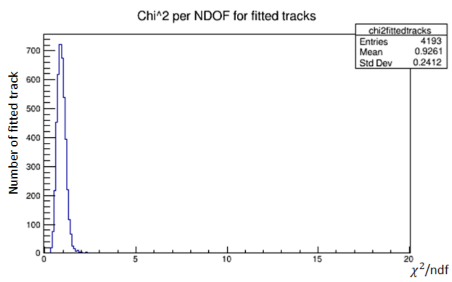


(d) 7 mm maximum sagging

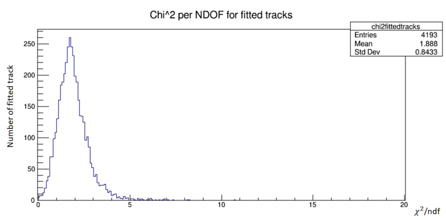
Figure 11: Relative error on the reconstructed track momentum for different ranges of the maximal sagging.



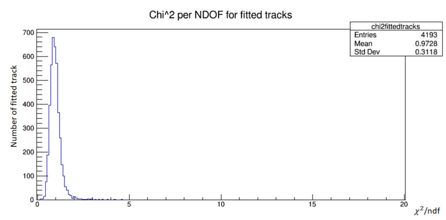
(a) no sagging



(b) 4 mm maximum sagging

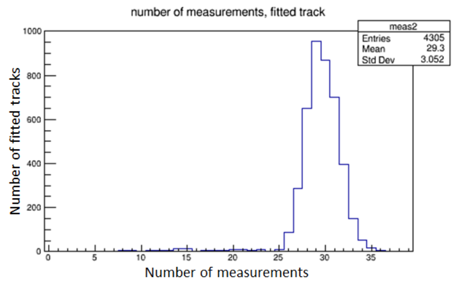


(c) 2-6 mm maximum sagging

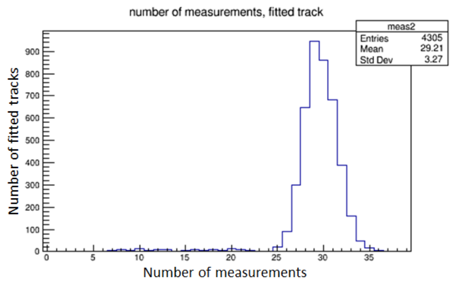


(d) 7 mm maximum sagging

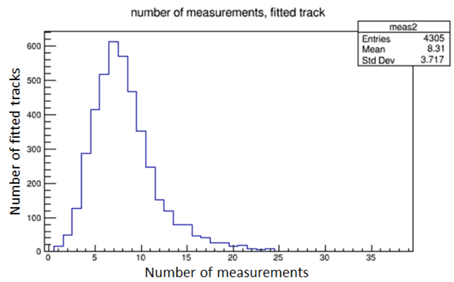
Figure 12: χ^2 per the number of degree of freedom for the reconstructed tracks.



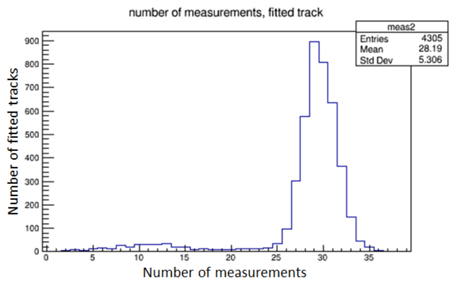
(a) no sagging



(b) 4 mm maximum sagging



(c) 2-6 mm maximum sagging



(d) 7 mm maximum sagging

Figure 13: The number of reconstructed hits per a track.

4.4 Hit spatial resolution as a function of the track x-coordinate

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 track x-coordinate as the reconstruction performance is affected by the amount of sagging. The hit spatial resolution is studied as a function of the track x-coordinate.

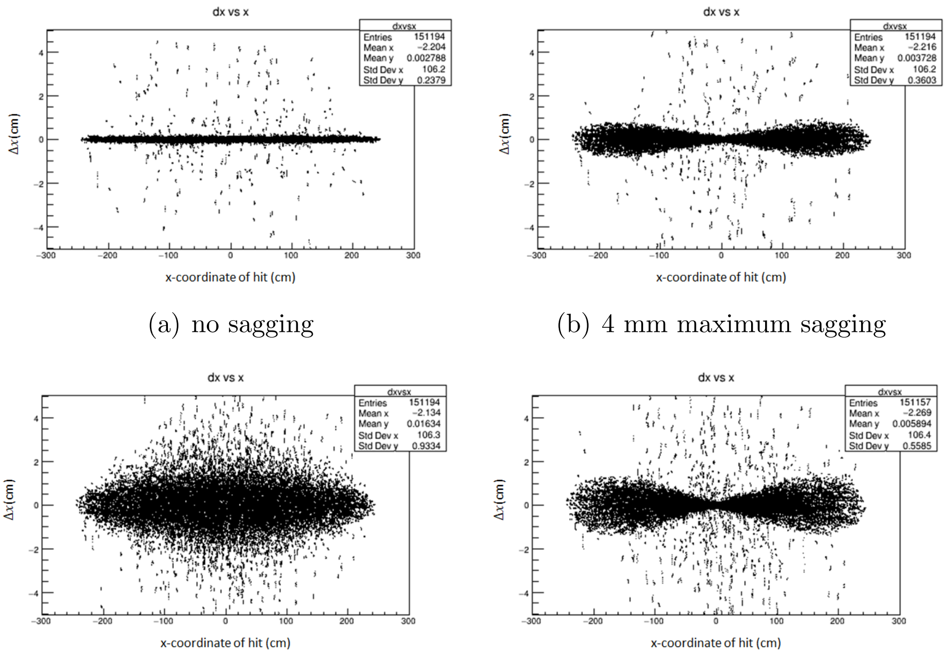
Fig. 14, 15 show the spatial resolution as a function of the x-coordinate for different misaligned cases. The x-axis of the graph is the x-coordinate along the straw tube, and the y-axis is the hit spatial resolution. For the case with no sagging (Fig. 14(a)), the error along the x- coordinate is almost the same. Reconstructed from many hits, 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 maximal sag 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 for larger misalignment. Comparing 7 mm and 4 mm case, the whole distribution become more spread along the y-axis for larger misalignment. It is expected that the performance becomes poor when the sag increased. However, for the case of the distributed maximal 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. 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 the y-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 that the error on y is strongly depends on the amount of sagging.

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 equal sagging. In this report, a fake pattern recognition was used. The performance of different pattern recognition algorithms and fitting should be studied in the future. The performance may be improved with different reconstruction methods.

The error on spatial coordinates shows a dependence on the hit position along the straw. The error on x-coordinate shows a different behaviour compared to the error on y-coordinate. This is also a property that should be studied.



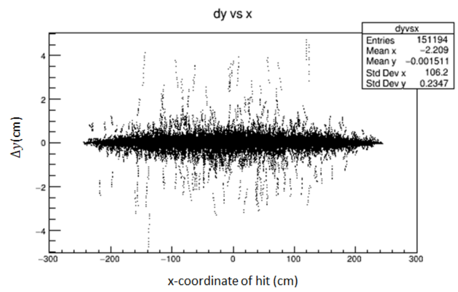
(a) no sagging

(b) 4 mm maximum sagging

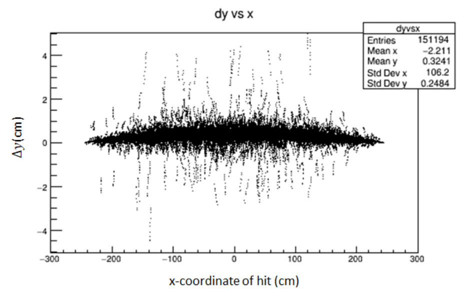
(c) 2-6 mm maximum sagging

(d) 7 mm maximum sagging

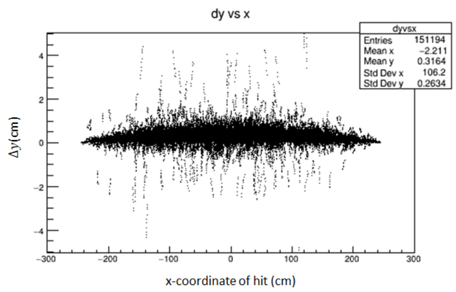
Figure 14: Error on the reconstructed x-coordinate as a function of the horizontal track coordinates.



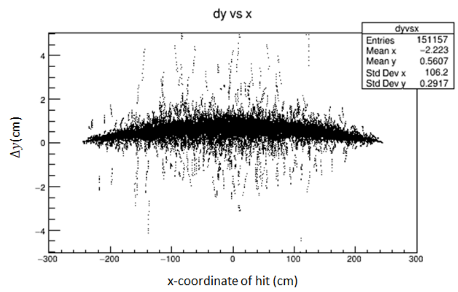
(a) no sagging



(b) 4 mm maximum sagging



(c) 2-6 mm maximum sagging



(d) 7 mm maximum sagging

Figure 15: Error on the reconstructed y-coordinate as a function of the horizontal track coordinates.

References

[1] The SHiP Collaboration, *Technical Proposal. An Experiment to Search for Hidden Particles (SHiP) at the SPS*, CERN-SPSC-2015-016, SPSC-P-350, 8 April 2015.

[2] The SHiP Collaboration, *A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case*, CERN-SPSC-2015-017, SPSC-P-350-ADD-1, 09 April 2015.

[3] The SHiP Collaboration, *SHiP Experiment - Progress Report*, CERN-SPSC-2019-010, SPSC-SR-248, 25 January 2019.

[4] I. Bereziuk , O. Bezshyyko and M. Ferro-Luzzi, *Initial design studies of the SHiP straw detector*, CERN-SHiP-NOTE-2015-001, 31 March 2015.

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*. A member of the class will be used for setting up reconstruction. In order to have reconstruction results for different sagging setup, the 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 of 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 misalignment corrections. True is used for turning on.

randType is a variable to set the type of distribution applied to the maximal sag. 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 tube sag for tube. If no distribution is used, then all tubes will have this value of the maximal sag. 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 tube misalignment with 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 maximal sag value will be between (*maxTubeSagging* - *tubeUnifDelta*) and (*maxTubeSagging* + *tubeUnifDelta*).

wireUnifDelta is similar to *tubeUnifDelta*, but it is for wires.

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 default calculation. To test each module individually, this flag is used to choose the way of drift time calculation. True is used for default setting, where the drift time is calculated from constant drift velocity.