Implementation of signal digitization for the SHiP Spectrometer Straw Tracker simulation

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***Abstract*—The report describes simulation of straw tube response to a charged particle penetrating the SHiP Spectrometer Straw Tracker (SST), and proposes optimization of the straw signal description.**

A new signal parametrization has been added into the FairSHiP software framework [1] to achieve a more realistic SST performance prediction. A comparison of the SST hit resolution obtained with the old and new parametrization versions is presented.

***Index Terms*—SHiP experimental facility, Spectrometer Straw Tracker, straw-tubes.**

I. Introduction

SHiP (Search for Hidden Particles) – a fixed target experiment proposed at the CERN SPS accelerator for exploring the domain of hidden particles and measuring τ neutrinos. Hidden particles are predicted by a large number of models beyond the Standard Model (BSM) [2]. One of possible strategies of extending the SM is to explain the phenomena that cannot fit the SM by minimal means, introducing the smallest possible number of new particles without adding any new physical principles (such as supersymmetry or extra dimensions) or new energy scales (like the Grand Unified scale).

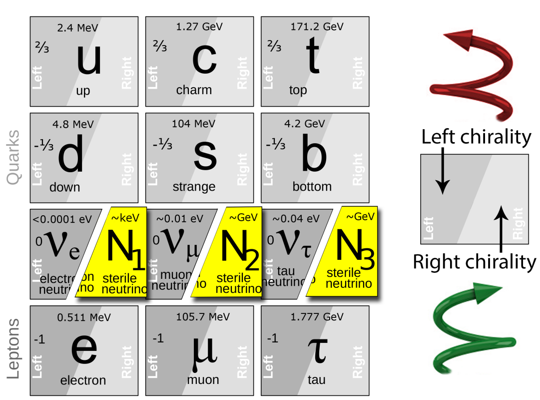

Fig. 1. SM extension by three heavy neutral leptons (HNLs).

An example of such a theory is a renormalizable extension of the SM, the νMSM (neutrino Minimal Standard Model), where three light singlet right-handed fermions (also known as heavy neutral leptons or sterile neutrinos) are introduced (Fig. 1). Every left-handed fermion in the leptonic sector of the theory has its right-handed counterpart. This model is consistent with the data on neutrino oscillations, provides a candidate for a dark matter particle – the lightest singlet fermion, and can explain the baryon asymmetry of the Universe. A crucial feature of this theory is the relatively small mass scale of the new neutral leptonic states, which opens a possibility for a direct search of these particles [3].

High intensity of the SPS 400 GeV proton beam allows to produce the heavy neutral leptons (HNLs) with masses in the GeV range [4]. In the SHiP experiment HNLs can be produced from D and D_s decays, as shown in Fig. 2:

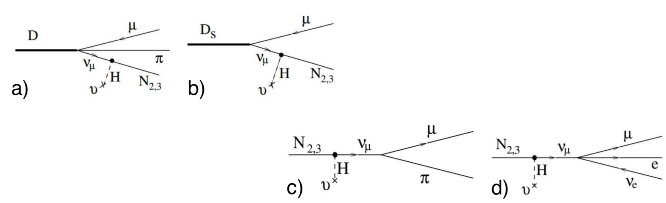

Fig. 2. HNL production from D (a) and D_s (b) mesons. Examples of HNL decay channels are shown in (c) and (d).

Decay of D_s meson is also a principal source of τ neutrinos. The D meson decays are also a source of e and μ neutrinos. Though the optimisation of the facility is driven by the requirements of the hidden particle searches, the experimental setup is ideally suited for measurements of neutrino scattering, including recently observed τ neutrinos.

II. Overview of the SHiP experiment

SHiP will consist of the proton target, followed by a hadron stopper and an active muon shield that deflects muons produced in the beam dump out of the detector acceptance [5]. The SHiP detector itself incorporates two complementary apparatuses, the Scattering and Neutrino Detector (SND) and the Hidden Sector (HS) spectrometer. The SND will search for Light Dark Matter (LDM) scattering and serve the neutrino physics studies. It is made of an emulsion spectrometer located inside a long single magnet with a field above 1.2 T in the entire volume and a muon identification system. The emulsion spectrometer is a hybrid detector consisting of alternating layers of an absorber, nuclear emulsion films and fast trackers. The absorber mass totals ~ 10 tonnes.

The HS decay spectrometer is purposed for measurements of visible decays of HS particles by reconstructing their decay vertices in a 50 m long decay volume. To minimize multiple scattering and to eliminate the background from neutrinos

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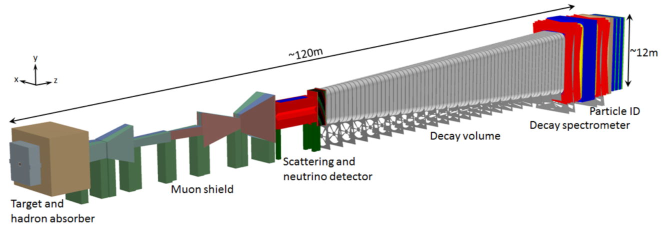

Fig. 3. Overview of the SHiP experiment as implemented in FairSHiP.

interacting in the decay volume, it is maintained at the pressure of $O(10^{-3})$ bar. The decay volume is followed by a large spectrometer with a rectangular acceptance of 5 m in width and 10 m in height.

A. Spectrometer Straw Tracker

The purpose of the Spectrometer Straw Tracker (SST) is to measure track parameters and momentum of charged particles with high efficiency and accurate enough to reconstruct a decay vertex and invariant mass of hidden particles, and to reject background events. The track extrapolated position must be well matched with a corresponding segment of the timing detectors such that the high accuracy time measurement can be used to reject combinatorial background. The invariant mass, vertex quality, timing, matching to the background veto taggers and vertex projection are crucial tools for rejecting background.

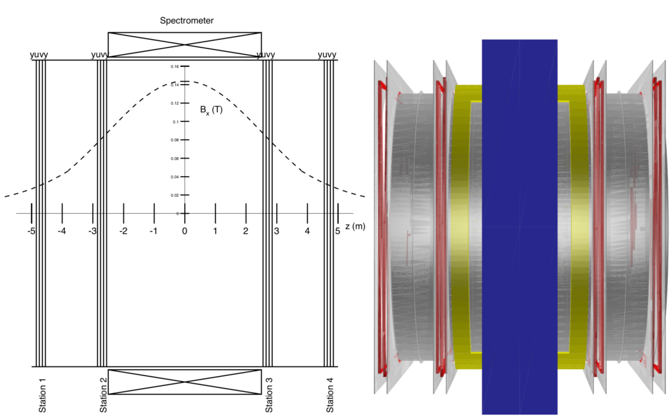

Fig. 4. Spectrometer layout. Left: position of the tracking stations (each with four views) and dipole magnet, overlaid with magnetic field component B_x as a function of the longitudinal coordinate z. Right: 3D view of the spectrometer as implemented in the FairSHiP simulation [2].

The spectrometer consists of a large aperture dipole magnet and two tracking telescopes, one on each side of the magnet and each composed of two tracking stations (Fig. 4). The four stations are identical with a nominal acceptance of 5 m in X and 10 m in Y, and consist of ultra-thin straw drift tubes oriented horizontally. Each station contains four views, in a $YUVY$ arrangement, where U and V are stereo views tilted by a small angle $\pm\theta_{\text{stereo}}$ around the z-axis with respect to the horizontal straws of Y views.

B. Straw-tubes

Straw-tube is a cylindrical drift tube with a small diameter [6]. The main idea that primary electrons, created when an ionizing particle traverses the tube, drift towards the anode Fig. 5(a). In vicinity of the anode wire, electrons are accelerated in a strong electric field and can gain a sufficient amount of energy to produce further gas ionisation. At this moment the avalanche formation starts (b).

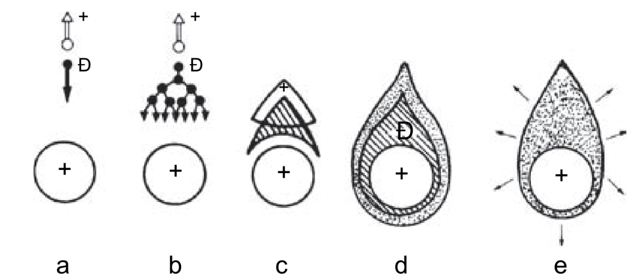

Fig. 5. Temporal and spatial development of an electron avalanche [6].

During the avalanche production of charge carriers, the electron and ion clouds drift apart (c). In last two steps the avalanche formation is completed and the ion cloud recedes radially and slowly drifts to the cathode (d, e).

III. TEST BEAM 2017

In 2017 JINR manufactured a prototype of SST straw tube for tests at the SPS (CERN) special experimental line. The straw tube had the following parameters:

Parameter	Value
Diameter	20 mm
Walls	PET (36 μm) coated with Cu (50 nm) and Au (20 nm)
Wire	W coated with Au (30 μm)
Gas mixture	Ar (70%) and CO_2 (30%)
Pressure	1.05 bar
Operation voltage	2200 V

A 150 GeV pion beam with intensity of $(1.0 - 1.3) \cdot 10^5$ π/spill was used in the test beam. The main goal of these tests was to estimate the spatial resolution of the straw as a function of the anode wire displacement. During the test the straw signal arrival time was measured with respect to the trigger signal. The track coordinate inside the tube was measured using a reference silicon tracker [7]. It consisted of 8 detecting layers and had a spatial resolution of 60 μm.

The dependence of the straw signal arrival time t on the radial distance of the point Y of closest approach of the track to the wire (often called the "V-shape") was studied (Fig.6).

It was found that the average resolution of a straw tube does not depend on anode wire displacement, but the spatial resolution is non-uniform along the tube diameter. It increases significantly near the anode wire and strongly depends on the track position.

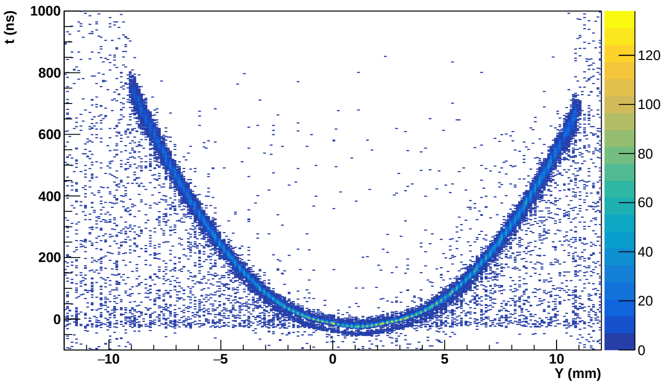

Fig. 6. An example of the V-shape measured with the test beam [8].

IV. SIGNAL PARAMETRIZATION

In parallel with the test beam measurements, special studies of the drift time parameterisation were made [9]. Since the SST consists of 18000 straw-tubes, it is impossible to implement Monte Carlo simulation of the straw signal development for the every tube. So it was decided to make a model which will consider the displacement of the anode wire from the axis of the tube and the distance from the anode to the particle track. These studies were made using GARFIELD package [10].

The arrival time t of the straw signal was parameterised with the Landau function:

$$P(t) = Landau(t, t^{\text{MPV}}, \sigma_t) \tag{1}$$

where t^{MPV} is the most probable value of the drift time for a given shortest distance between the wire and the track passing through the tube, σ_t – is the width of this distribution and $P(t)$ is the probability to get a signal exceeding a given threshold at the time t after the track passage.

In equation (1) σ_t is a function of the distance between the anode and the particle track Y. Using the GARFIELD studies, $\sigma_t(Y)$ was parameterised as

$$\sigma_t(Y) = \frac{t^{\text{MPV}}}{100} \cdot \left(8.52 \cdot e^{-0.466 \cdot Y} + 31.81 \cdot e^{-2.392 \cdot Y} + +0.419\right) \tag{2}$$

where t^{MPV} is given in [ns] and Y in [cm].

Fig. 7 shows that the chosen model agrees quite well with the test beam data. This parameterisation was implemented in the FairSHiP framework.

V. REALISTIC SIMULATION IN FAIRSHIP

In the baseline version of FairSHiP the $Y(t)$ relation is based on the idea that the drift time linearly depends on the distance between the track and anode wire. Another assumption is that the straw-tube has the spatial resolution of 120 μm. Based on this, the drift time is obtained as a smeared coordinate divided by the constant drift velocity:

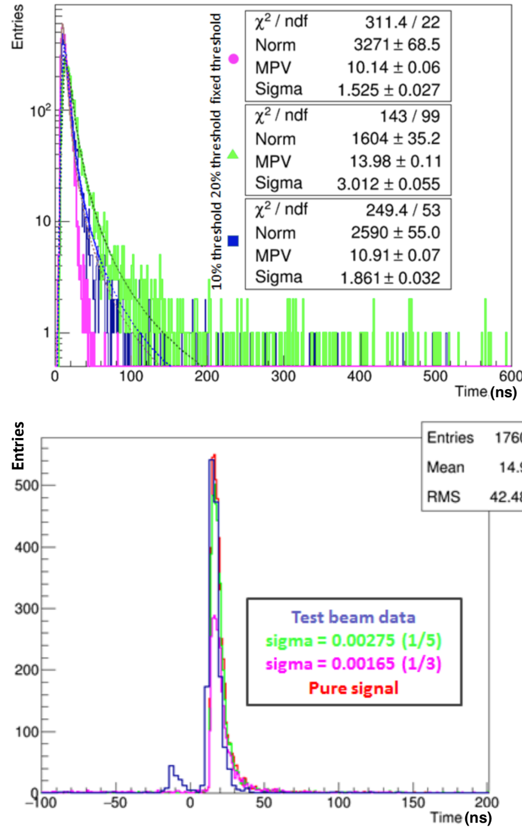

Fig. 7. Examples of the simulated and real drift time distributions fitted with the Landau distribution (1) [9].

$$t = Y^{\text{smear}}(Y, \sigma_Y)/v_{\text{drift}} \tag{3}$$

where Y^{smear} is a random coordinate obtained using a Gaussian probability density function $P(Y^{\text{smear}}) = Gauss(Y^{\text{smear}}, Y, \sigma_Y)$, σ_Y – is the predicted spatial resolution of the straw and v_{drift} – is a drift velocity of electrons to the anode.

This assumption does not agree with the test beam results (Fig. 6). More realistic parameterisation based on GARFIELD simulation was implemented in a test branch of FairSHiP. A fit of the V-shape gives the $t^{\text{MPV}}(Y)$ relation for (1) and (2). For ideal straw geometry this dependence can be parameterised as it was shown in [11]:

$$t^{\text{MPV}}(Y) = 622.8 \cdot Y^2 + 5.285 \tag{4}$$

where t^{MPV} is given in [ns] and Y in [cm].

The plots in Fig. 8 show the drift time distributions of simulated hits as a function of the distance between the hit and the straw center. For the top plot the baseline simulation was used. The bottom plot is obtained with the improved signal parameterisation.

The spatial resolution can be obtained by comparing the true and reconstructed coordinates of the hits, Y and Y^{reco}. The residuals $(Y - Y^{\text{reco}})$ for the baseline (top) and realistic (bottom) straw signal parameterisations cases are shown in Fig. 9.

The results obtained with the realistic signal parameterisation better agree with measurement results.

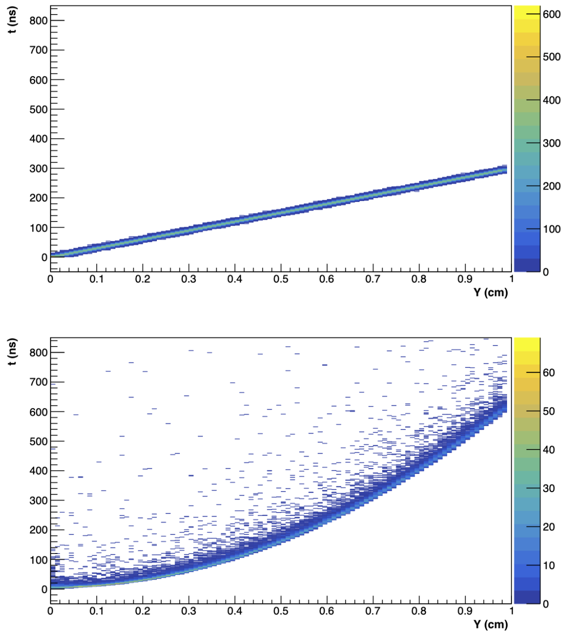

Fig. 8. Comparison of $t(Y)$ relations for straw hits simulated with the baseline (top) and updated (bottom) signal parameterisations.

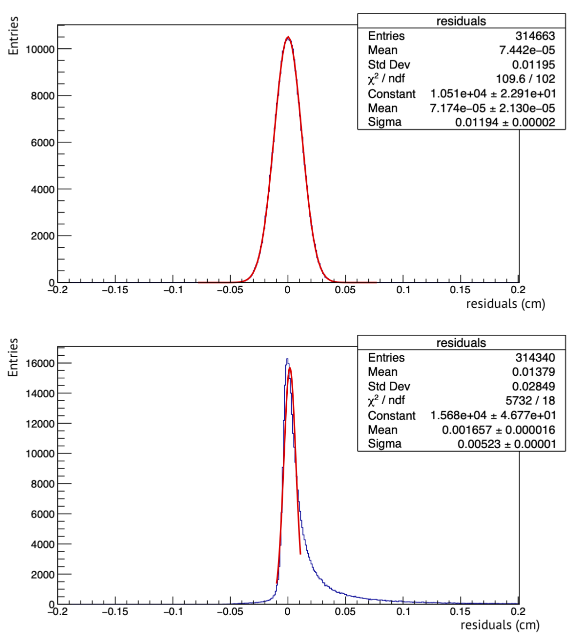

Fig. 9. Hit coordinate residuals for the baseline (top) and updated (bottom) signal parameterisations fitted with a Gaussian.

During the test beam data analysis it was shown that $t(Y)$ relation strongly depends on wire and tube sagging. The idea how straw tube and anode wire misalignment can be implemented in FairSHiP framework is described in [12]. It is assumed, that only vertical misalignment can be significant in a reasonable SST design.

The displacement of the wire in a tube makes the electric field inside the straw to be distributed asymmetrically. So the $t(Y)$ relation becomes asymmetric also (Fig. 10).

To implement this in the simulation, the inner space of the tube can be divided into two areas: the smaller and the larger ones. It is assumed that each of these areas has its own $t(Y)$ relation. In Fig. 11 these regions are above and below the center of the displaced wire (the blue dot line).

Using the test beam results and assuming that the left and right branches of the V-shape (Fig. 10, bottom) can be fitted by a second degree polynom ($t = a(\Delta) \cdot Y^2$), where Δ is the value of wire displacement and has dimension of $[cm]$. Two graphs (Fig. 12), which show how $a(\Delta)$ changes with increasing wire sagging were made.

The following parameterisation of $a(\Delta)$ was found from the test beam measurements:

$$a(\Delta) = 83.11 \cdot \Delta \tag{5}$$

From Fig. 12 it can be seen that the $a(\Delta)$ coefficient varies symmetrically for both branches of the V-shape. So it is possible to implement the wire offset Δ as an additional parameter $a(\Delta)$ in relation (4).

$$t^{\mathrm{MPV}}(Y, \Delta) = (622.8 \pm a(\Delta)) \cdot Y^2 + 5.285 \tag{6}$$

where $\pm a(\Delta)$ in this equation will take a negative sign if the particle track intercept the smaller area and a positive sign if the larger one.

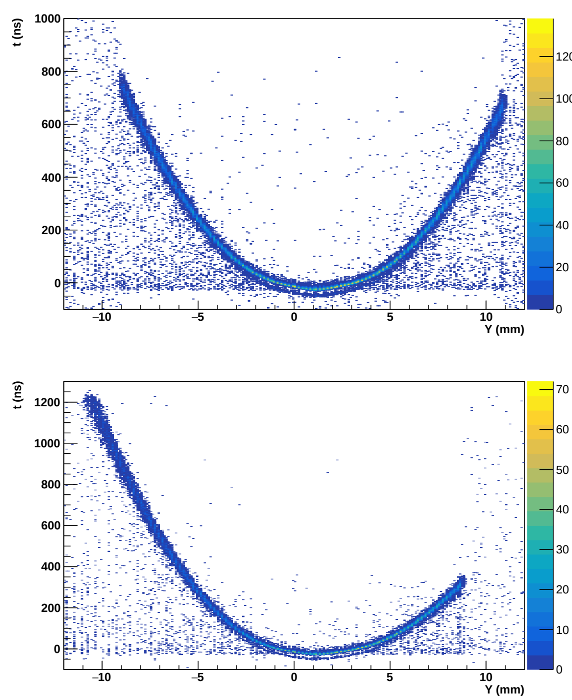

Fig. 10. Examples of $t(Y)$ relations measured at the test beam for the ideal geometry (top) and for the dataset with a 2.4 mm wire sagging (bottom).

The parameter σ_t mostly depends on the distance between the track and anode wire and, at first approximation, does not need the additional parameterisation.

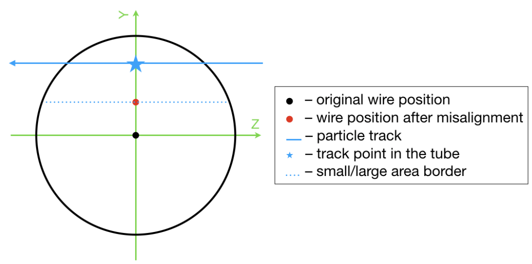

Fig. 11. SST straw tube sketch.

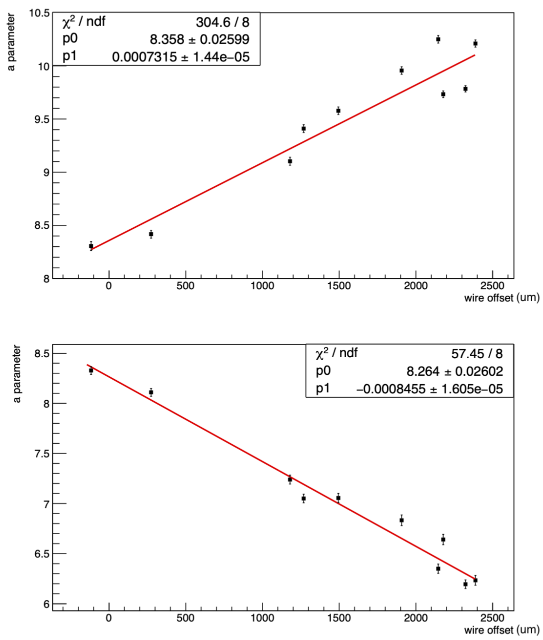

Fig. 12. Linear fits of $a(\Delta)$ relation for the left (top) and right (bottom) branches of V-shapes measured at the test beam.

VI. Proposal for a future improvement of the SST simulation and reconstruction procedure

The baseline version of FairSHiP simulates a hit in a SST straw tube in 4 steps, as illustrated in Fig. 13. At the beginning it is only a MC point, which has (X, Y, Z) coordinates and the calculated distance between the simulated track and the anode (dist2wire). This distance is used as a parameter Y in the formula (3). It is assumed that the straw spatial resolution σ_Y and v_{drift} are already known. The distance to the wire is smeared by the value of resolution and divided by the constant drift velocity to estimate the drift time.

At the next step the time measurements are emulated. Currently in the baseline version of FairSHiP *t_0* is the beginning of a readout frame, which is common for all SHiP detectors, *p–>GetTime( )* – returns the time when the track intersects the tube and *(stop[0]-p–>GetX( )) / speedOfLight* estimates the signal propagation time in the tube.

At step 3 the distance to the wire is reconstructed from the measured signal time. In the real case the signal arrival time will be the only data read out from a straw. However, currently the reconstruction directly uses a Monte Carlo hit coordinates for it. At the last step this reconstructed distance to the wire is collected into a list to propagate the future Pattern Recognition (PR) and Track Reconstruction procedures.

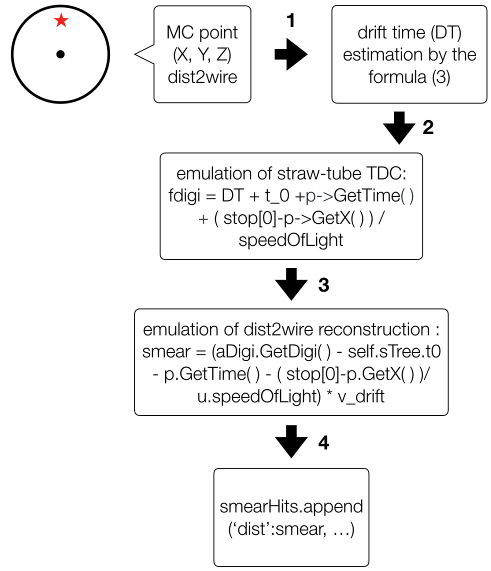

Fig. 13. FairSHiP baseline straw-tube hit simulation and reconstruction.

The baseline logic makes it impossible to run PR without results of the smearing step (Fig. 14), even through PR uses a straw identificator number only. However, in the reconstruction of real data the hit reconstruction step requires PR results to define the signal propagation time and t_0 as well.

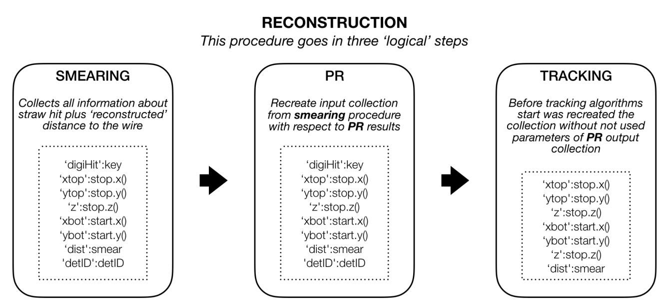

Fig. 14. FairSHiP baseline reconstruction procedure scheme.

To make the reconstruction procedure identical for the real data and Monte Carlo simulation results, the following procedure was proposed (Fig. 15).

As well as in the baseline version, the starting point is a MC point with (X, Y, Z) coordinates and a calculated distance to the wire. At the first step also the straw and wire misalignment can be introduced. The output of this procedure is a new

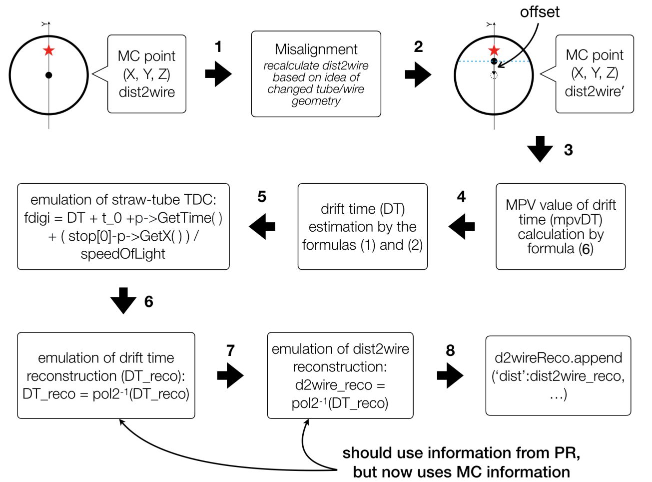

Fig. 15. FairSHiP updated straw-tube hit simulation and reconstruction.

distance to the wire (dist2wire'), recalculated with respect to the new straw position inside the tube. In contrast to the baseline version, the distance to the wire is not smeared anymore. It used to calculate the most probable value of the drift time t^{MPV} and the width of the drift time distribution σ_t by the formulas (6) and (2). At the next step this value will be smeared by the Landau distribution (1) to create a realistic signal. Next steps use only the signal time information as in the real data case.

To provide more intuitive names for the software functions and variables the following renaming is proposed:

Baseline name		New name
smearHits( )	→	strawHitReconstruction( )
smear	→	dist2wire
SmearedHits[ ]	→	d2wireReco[ ]

The next step would be to improve the reconstruction procedure. It is important to split the straw hit reconstruction and PR. That means it should be a special collection for the PR procedure which does not include the reconstructed distance to the wire. A routine which creates a collection for the PR independent of the straw hit reconstruction was created, and the only input parameter per a straw hit which is passed to the PR procedure is the identificator of the straw with a signal.

With this logic it is possible to run the straw hit reconstruction after the PR as it is supposed to be in the reconstruction of real SHiP data.

VII. CONCLUSION

The reported software optimisation was introduced into a FairSHiP test branch. Influence of the realistic signal parameterisation on the SST hit resolution prediction was studied.

In future steps the parameterisation (6) should be replaced by a more realistic one with respect to the test beam data.

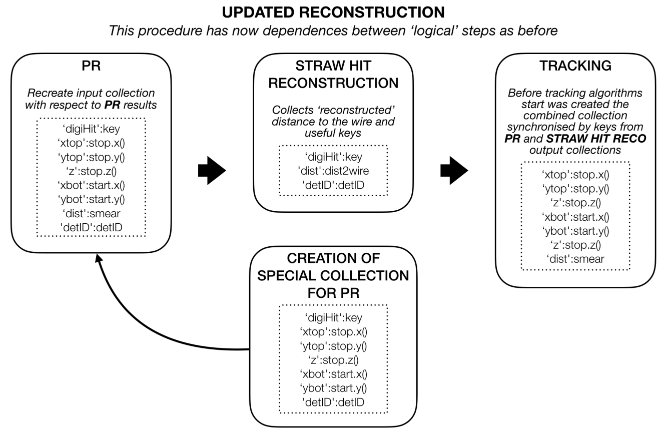

Fig. 16. FairSHiP updated reconstruction procedure scheme.

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