Status of the c-τ factory drift chamber simulation

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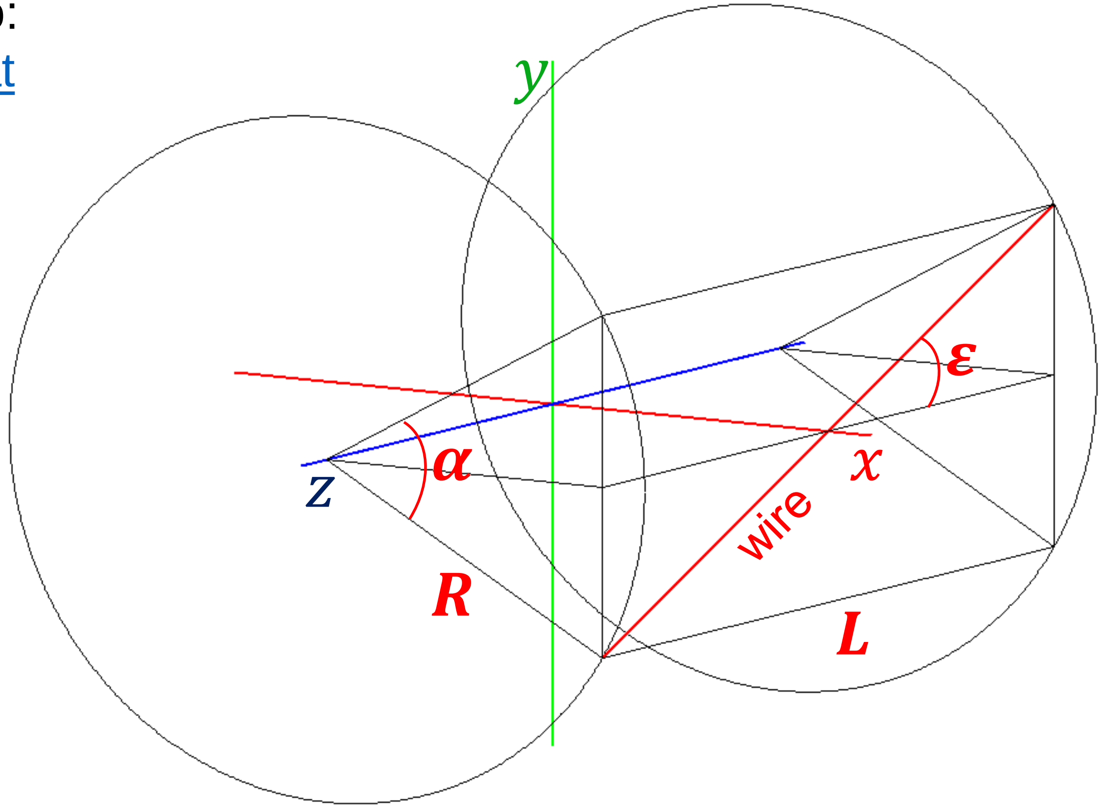
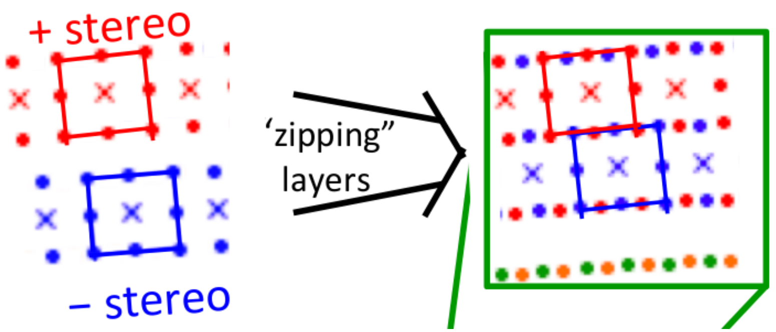
Drift Chamber Geometry

- We simulate the full-stereo drift chamber with the parameters, close to that proposed by F. Grancagnolo: https://indico.ijclab.in2p3.fr/event/4902/contributions/17030/attachments/13603/16389/SCTFDrift_Chamber.pdf

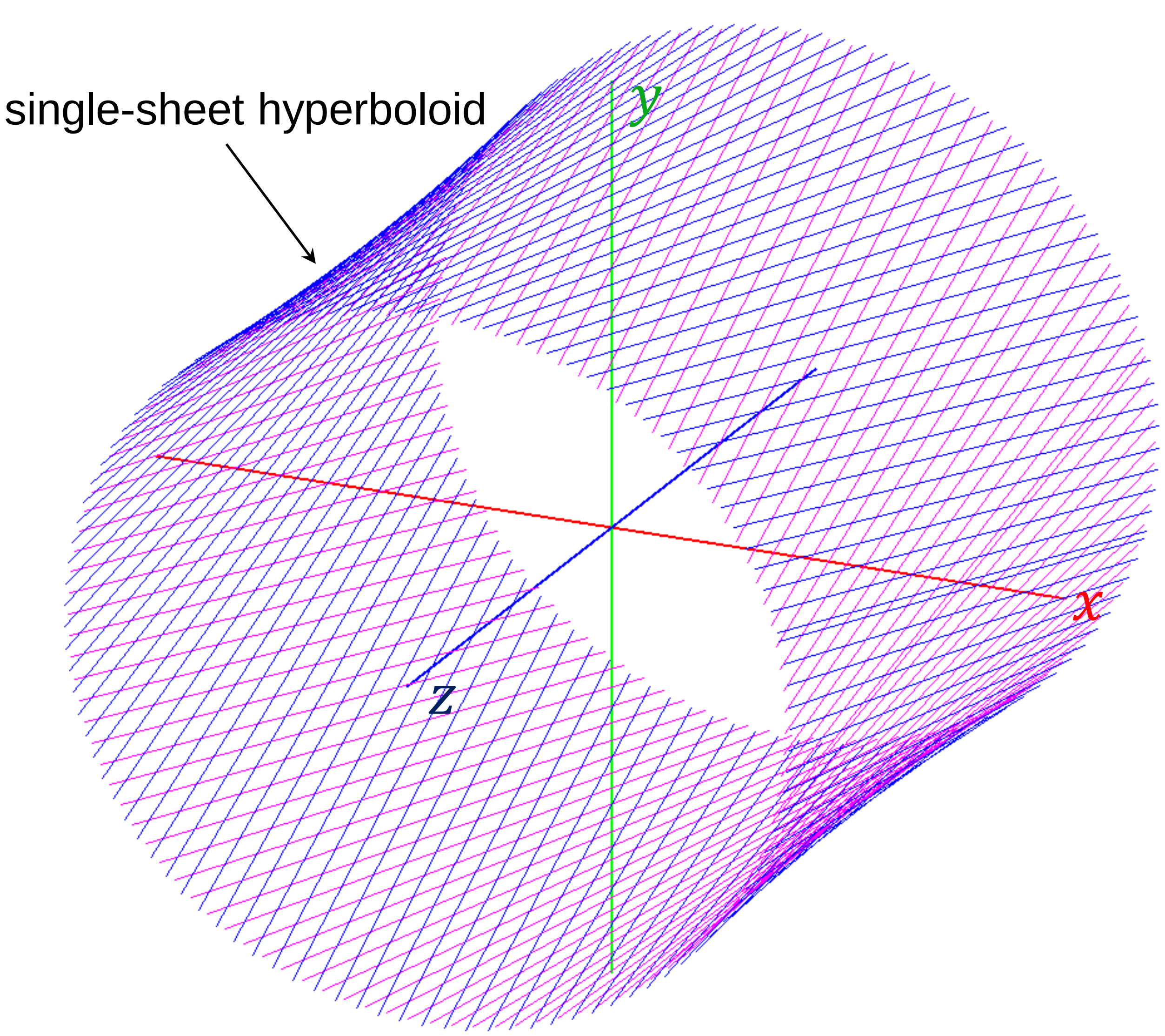
Parameter	Value
R_{in}, mm	200
R_{out}, mm	800
Length, mm	1800
Cell shape	Square
Cell size	~7-9 mm
α, rad	$\pi/6$
Stereoangle ε, rad	~60-220 mrad
$N_{superlayers}$	8
Layers in superlayer	8
Gas	90% He – 10% iC_4H_{10}
$N_{signal\ wires}$	21824
$N_{field\ wires}$	$\sim 5 \times N_{signal\ wires}$

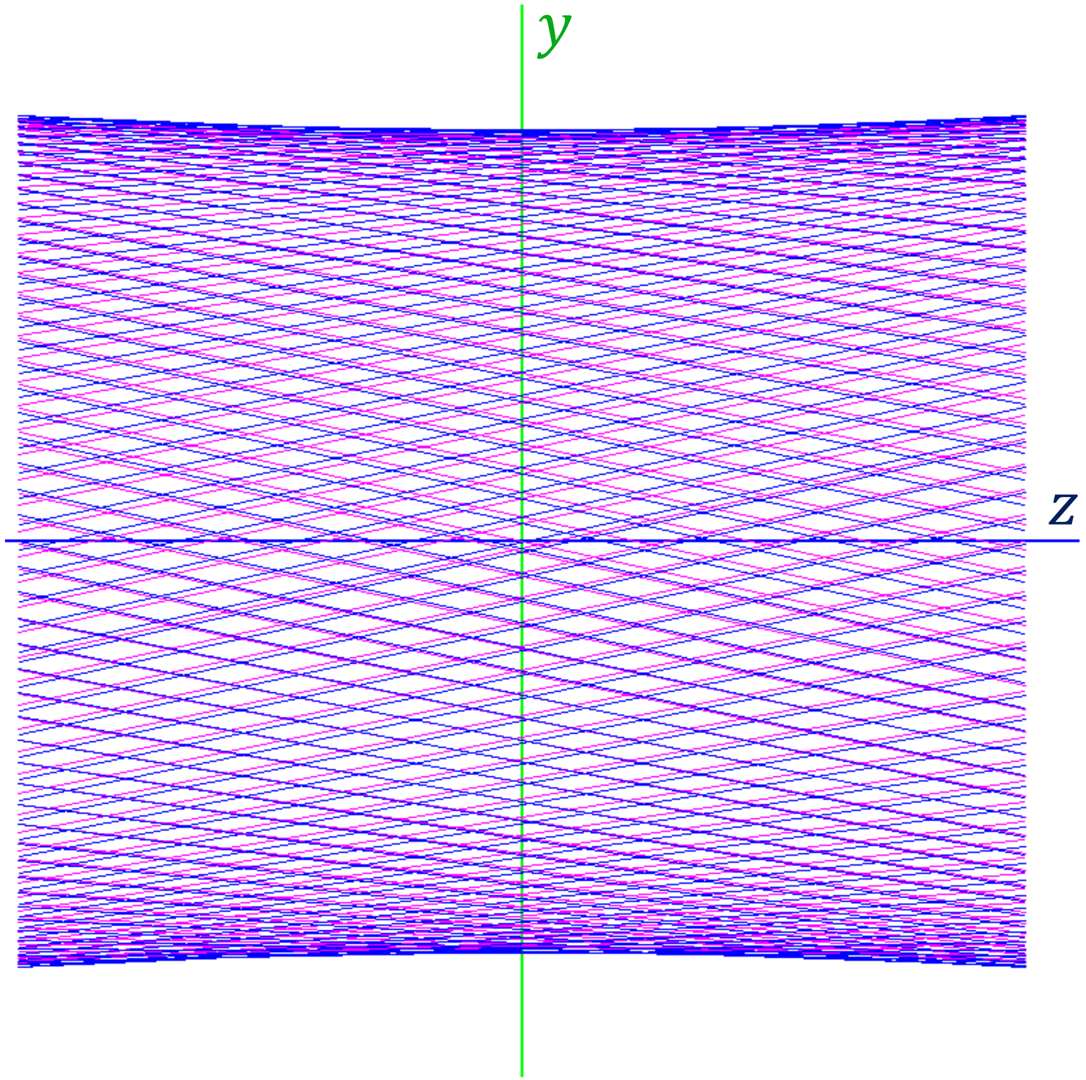


from proposal of F. Grancagnolo:



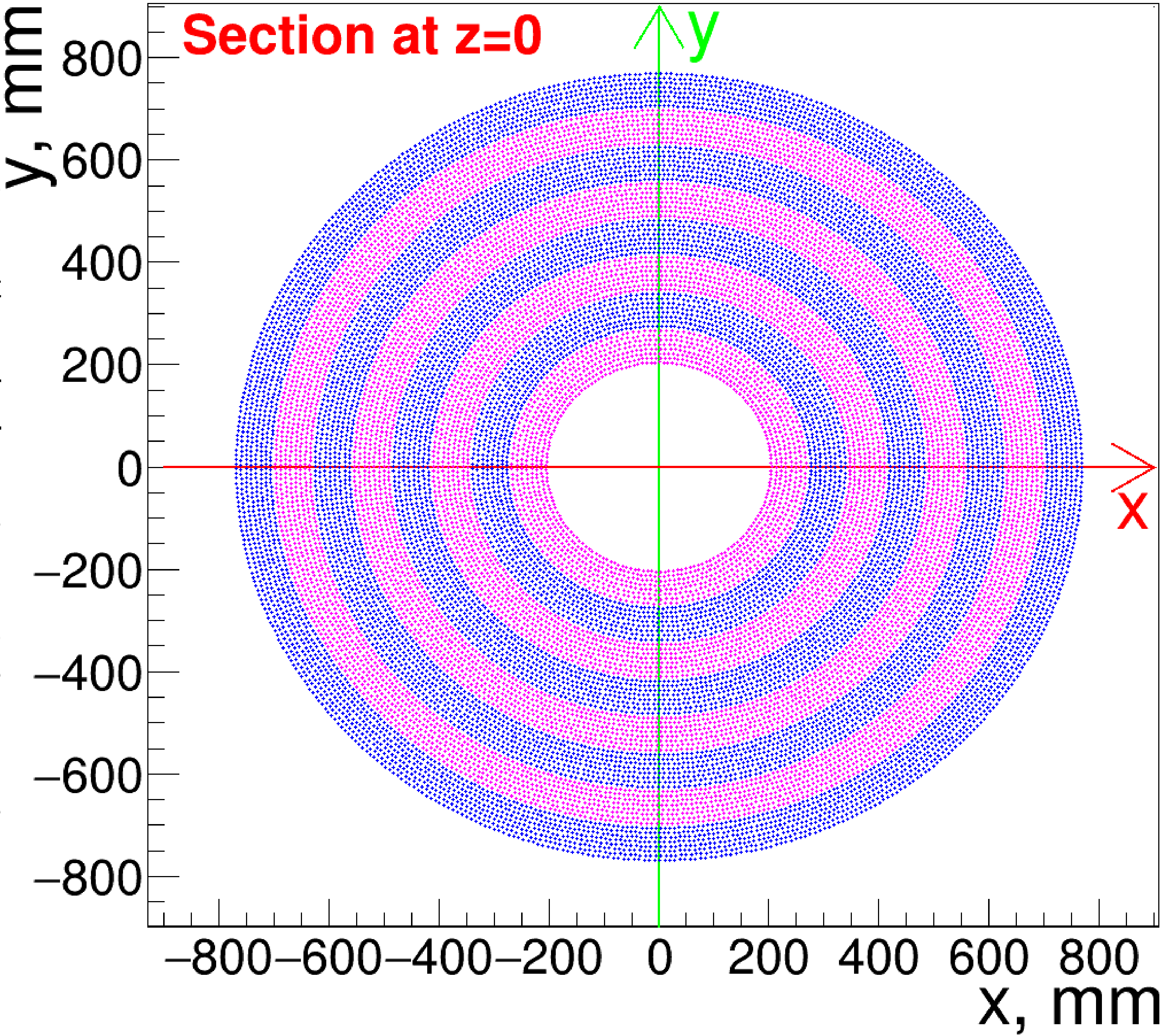
Drift Chamber Geometry





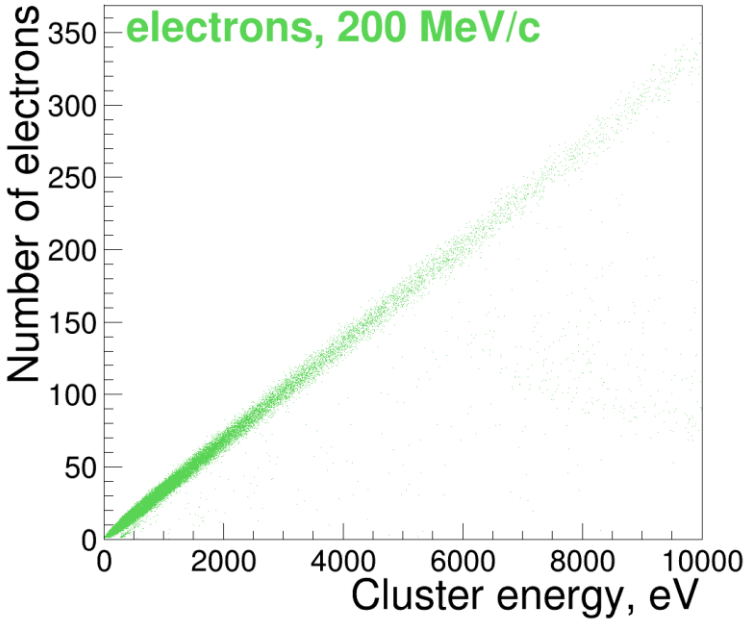
Drift Chamber Geometry

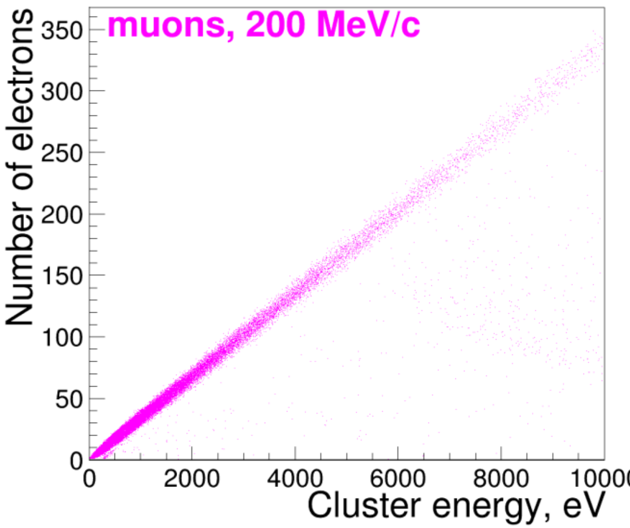
- The geometry of drift chamber is passed to **GEANT4** via the **DD4HEP** toolkit
- The material of wires is taken into account "on average"
- We do not use separate Sensitive Volumes or **DDSegmentation** to associate the **GEANT4** hits with the particular signal wire
- Instead, we developed the separate package **DriftChamberFullStereoGeomGenerator**, doing all the geometry-related stuff (hit-to-wire association, translation from the lab to wire coordinate frames, drift time and charge division coefficients calculation etc.)
- We save the drift chamber geometry using **DD4HEP DataExtensions** and invoke the geometry whenever necessary during digitization and reconstruction via the special **GaudiTool**

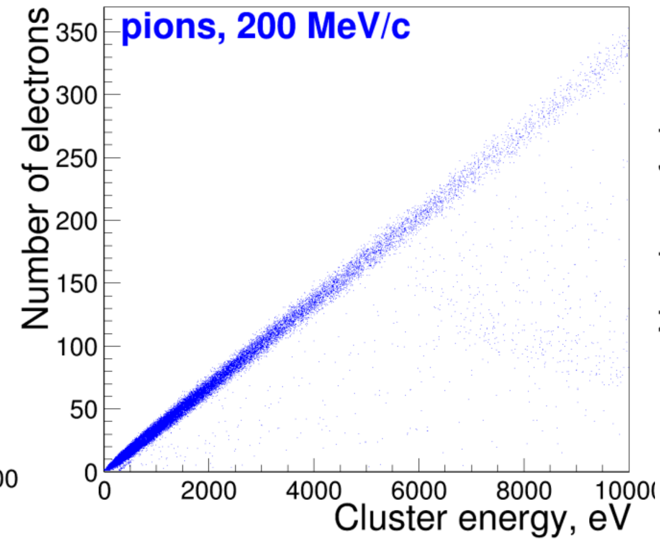


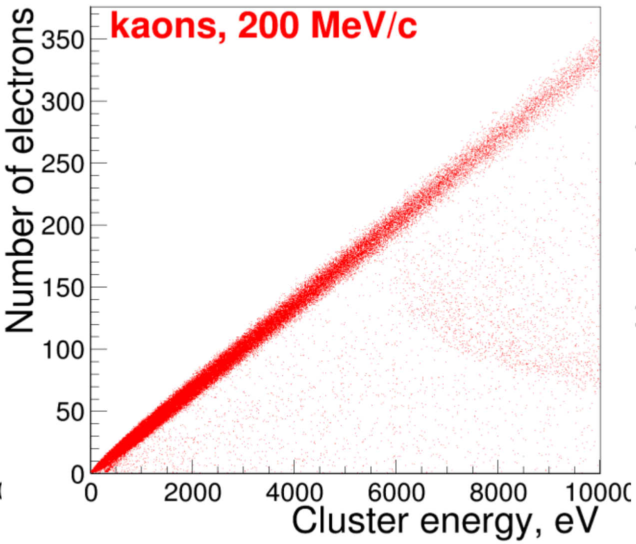
Simulation of Ionization Clusters

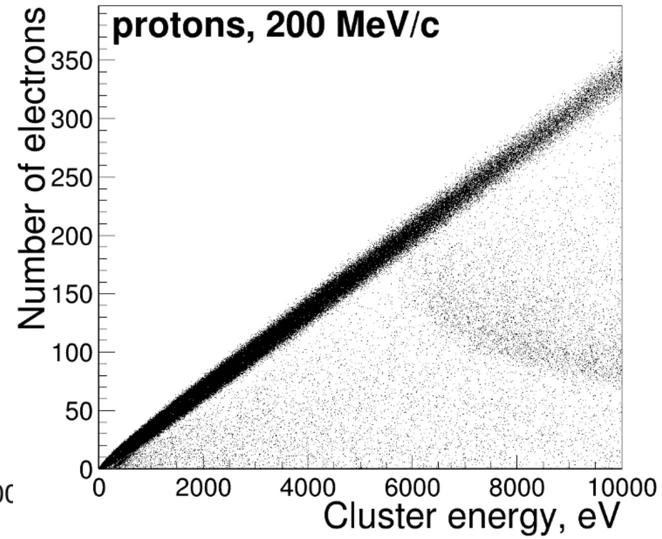
- On the spiral stretched between the beginning and the ending points of the GEANT4 hit (**G4Step**) we generate the ionization clusters until their total energy exhausts the hit energy
- The cluster energies are generated individually for $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ according to their momentum-dependent cluster energy spectra, obtained from **Garfield++** for **He:iC4H10 90:10** mixture
- Garfield predicts the average energy, required for single electron-ion pair production $\boldsymbol{W = 29.52\ \mathrm{eV}}$ and Fano factor $\boldsymbol{F = 0.19}$. For the generated cluster energy $\boldsymbol{E_{cl}}$ the average number of electrons in cluster is $\boldsymbol{E_{cl}/W}$ and the fluctuation is $\sqrt{\boldsymbol{FE_{cl}/W}}$





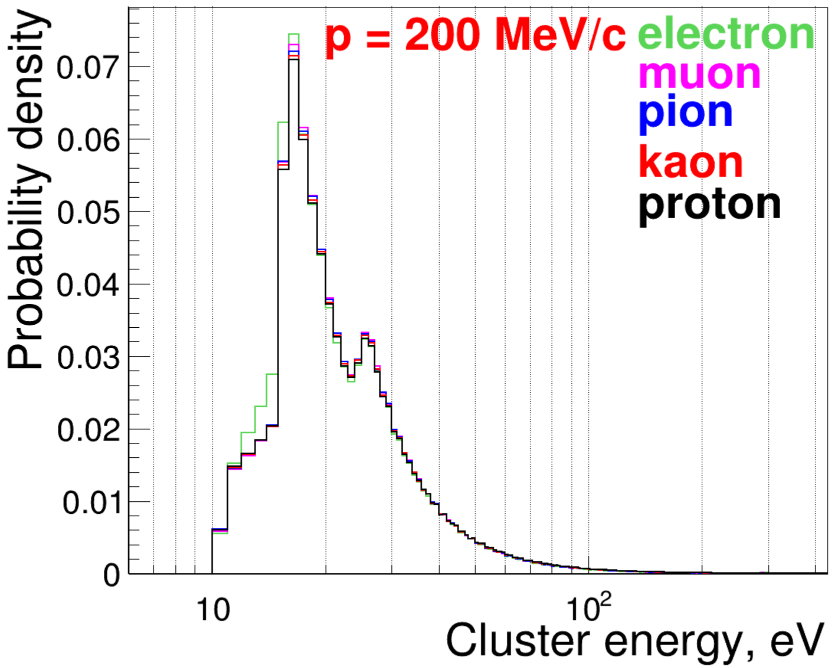


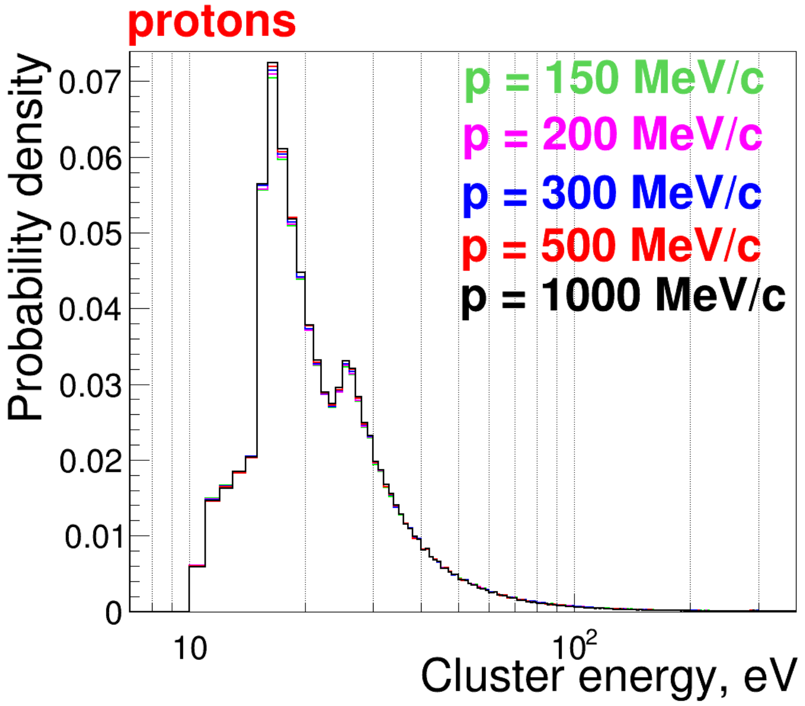


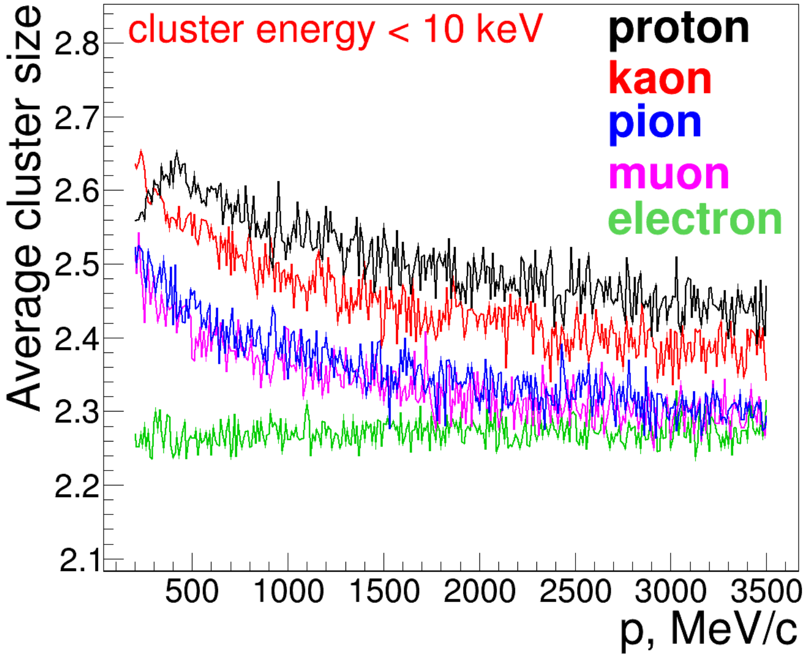


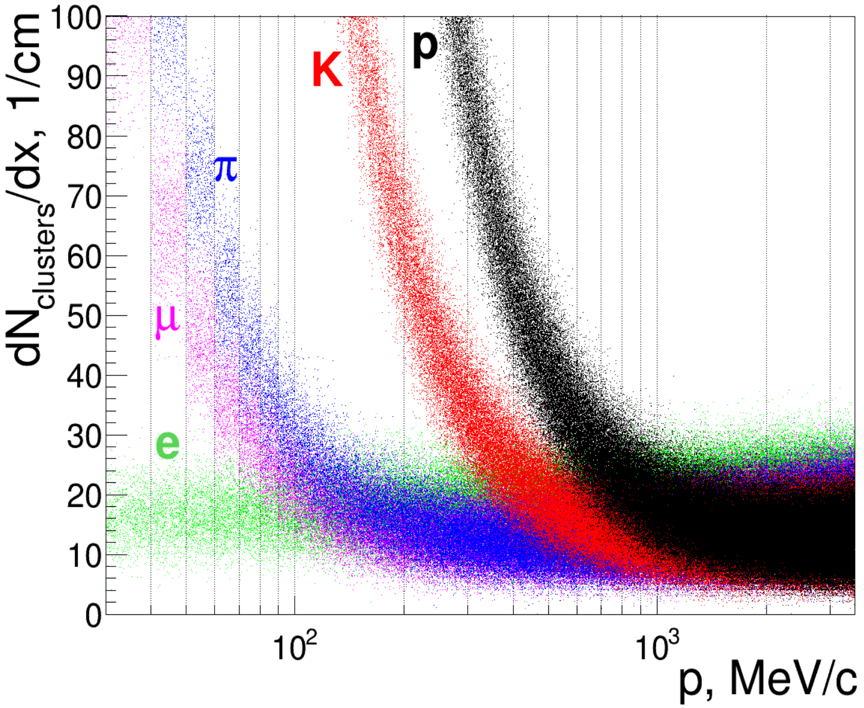
Simulation of Ionization Clusters

- The difference between the cluster energy spectra for different particle types appears to be very small
- The momentum dependence of the cluster energy spectra for give particle type is also small
- The major dependence on the particle type and momentum is seen in the number of ionization clusters per unit length



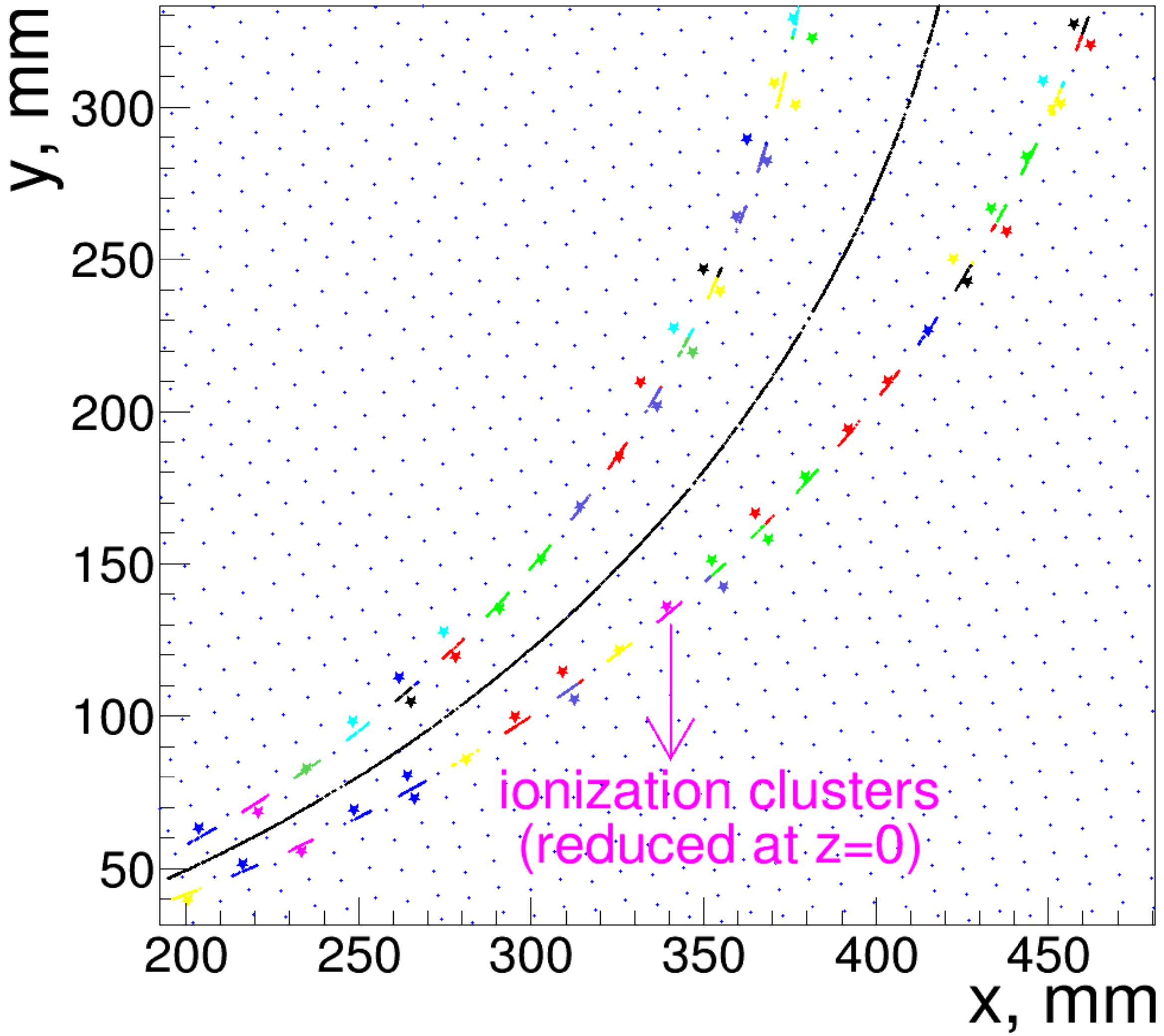


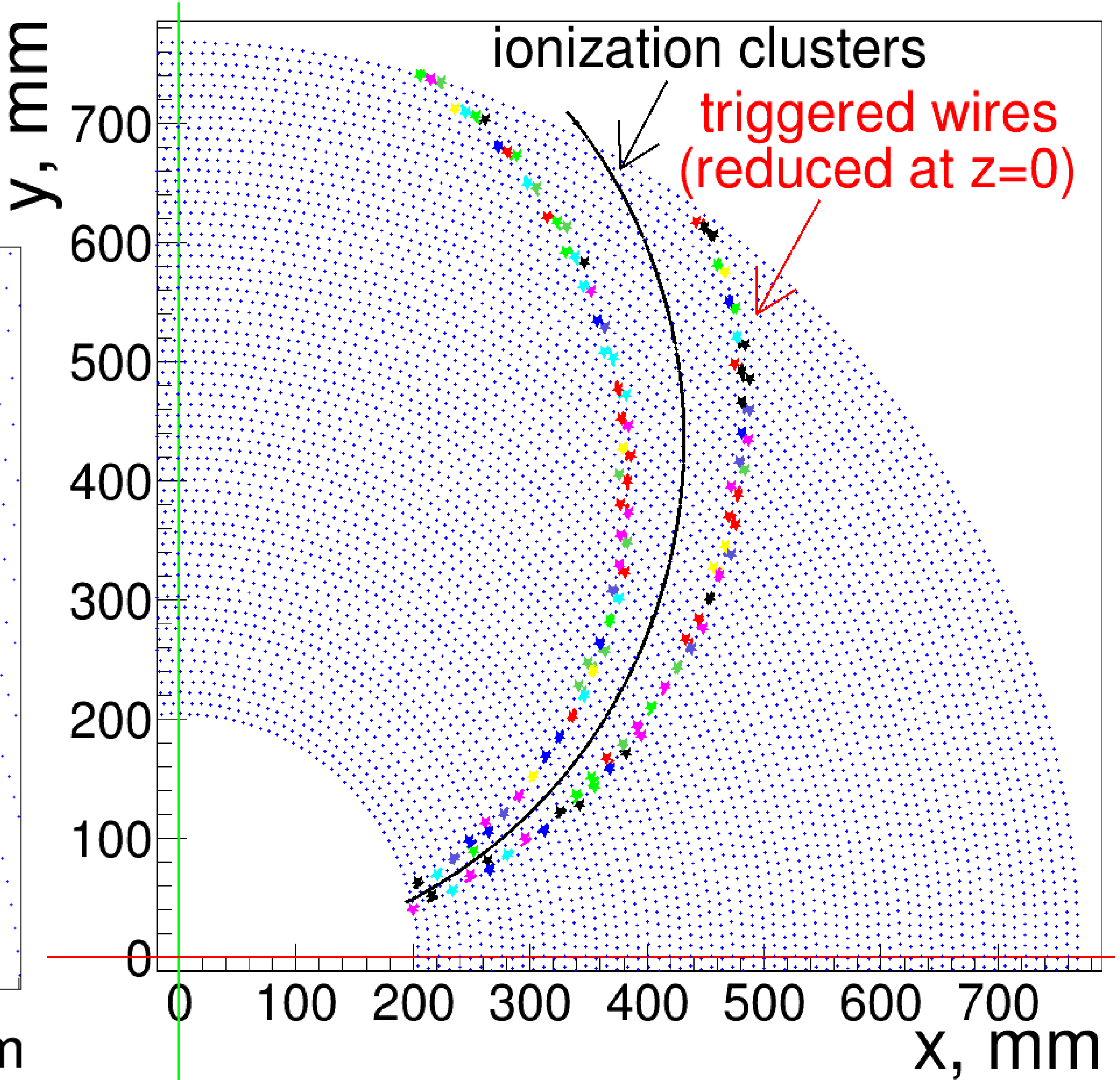




Association of Clusters with Wires

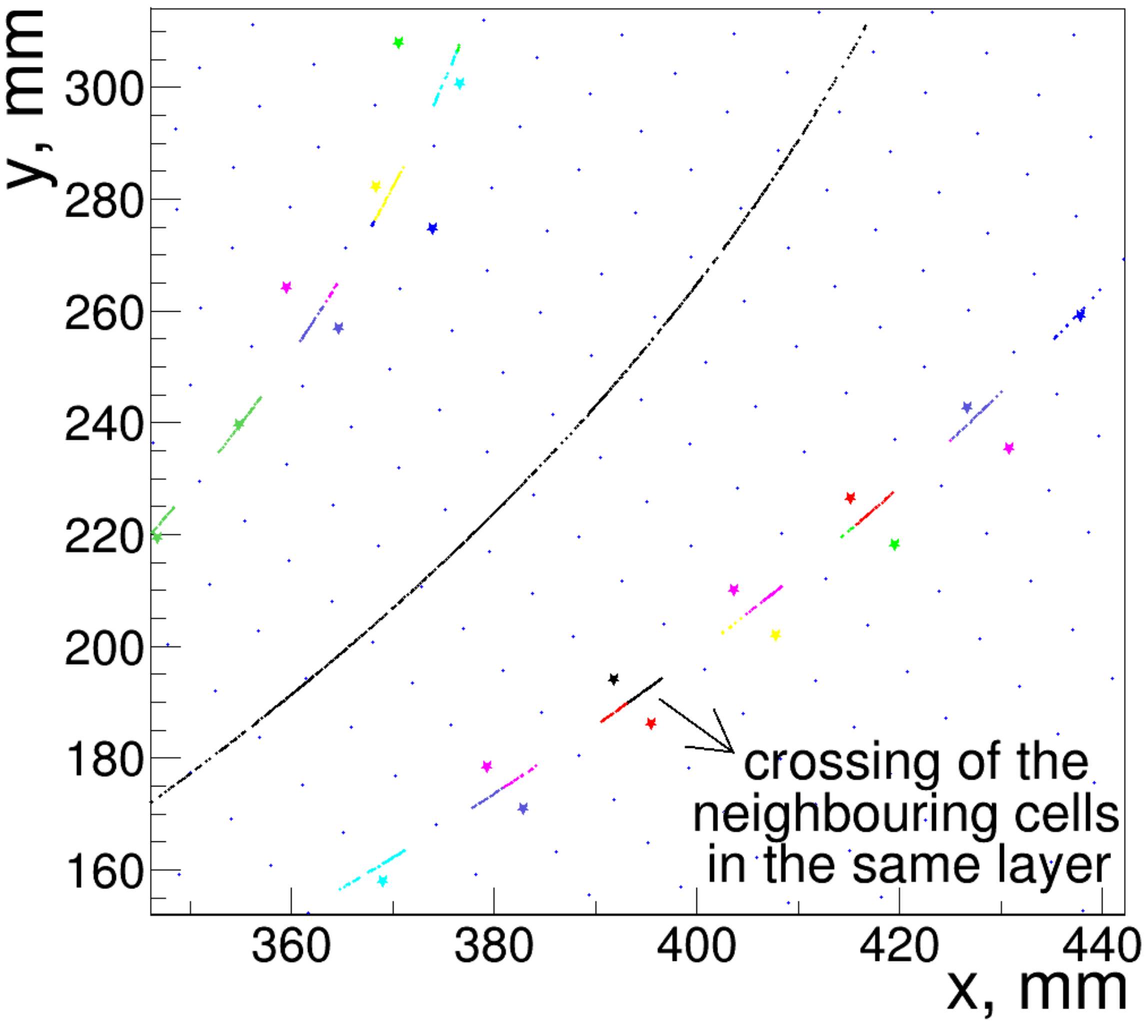
- At the first step of digitization each ionization cluster is associated with the closest signal wire
- For this purpose the reduction of cluster coordinates to the z=0 plane is performed



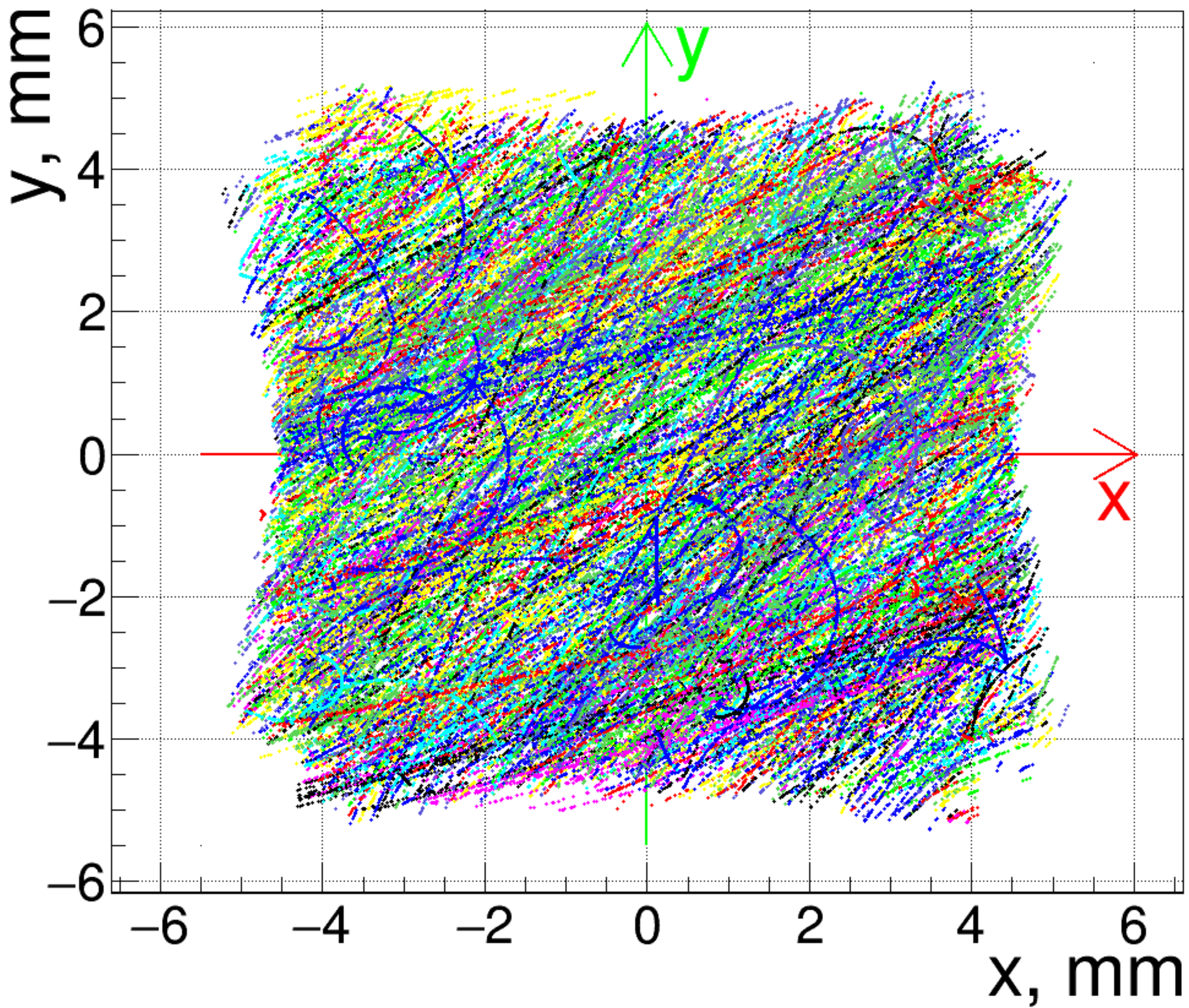


Association of Clusters with Wires

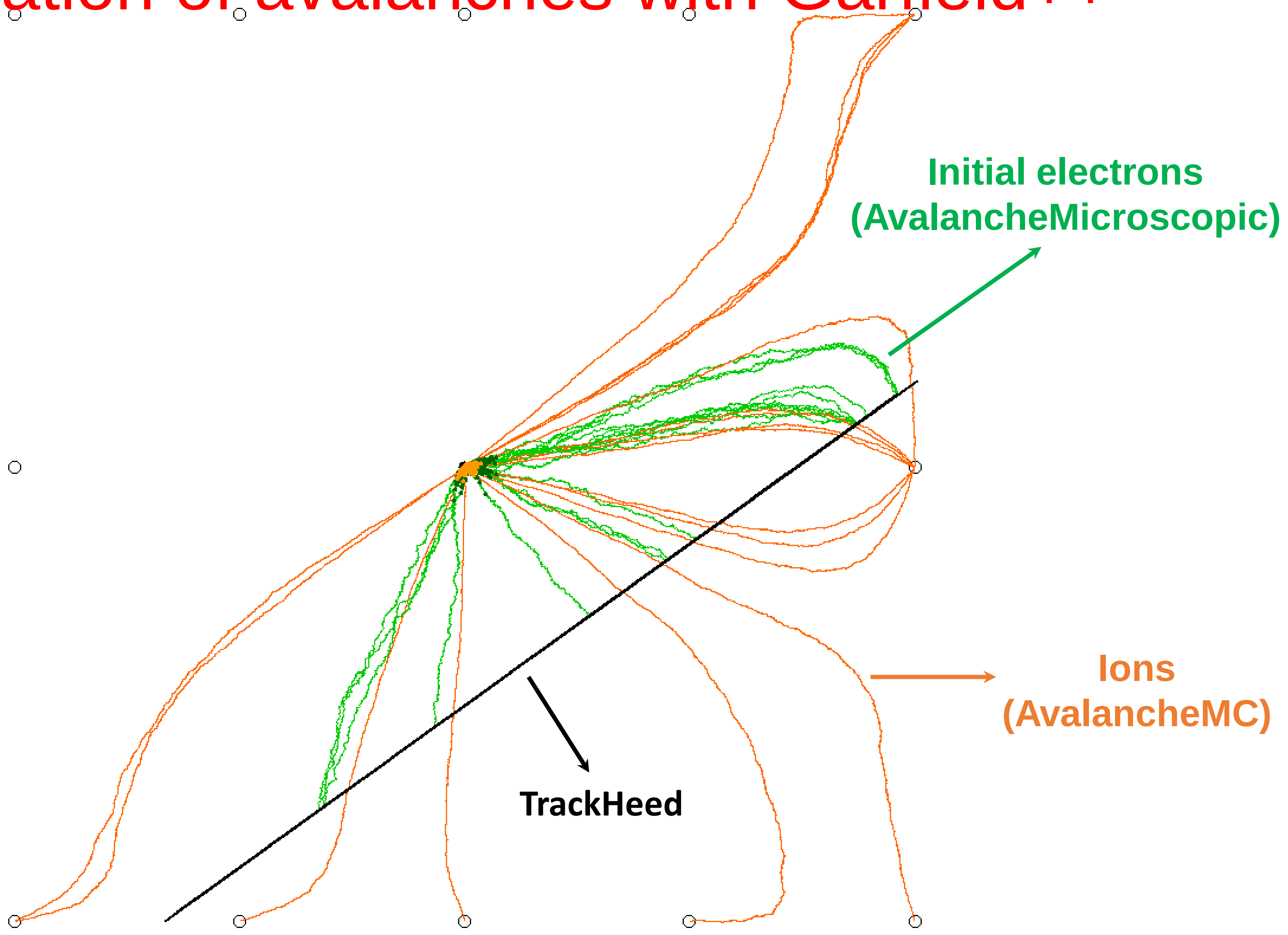
- After the cluster-to-wire association the cluster coordinates are translated to the wire coordinate frame



Ionization clusters in the coordinate frames of the wires

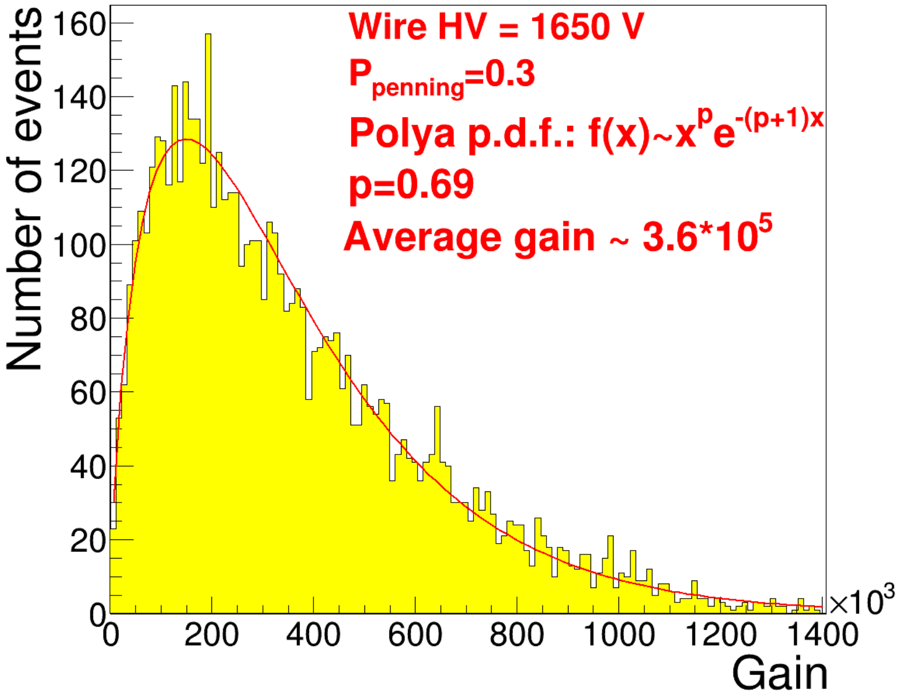


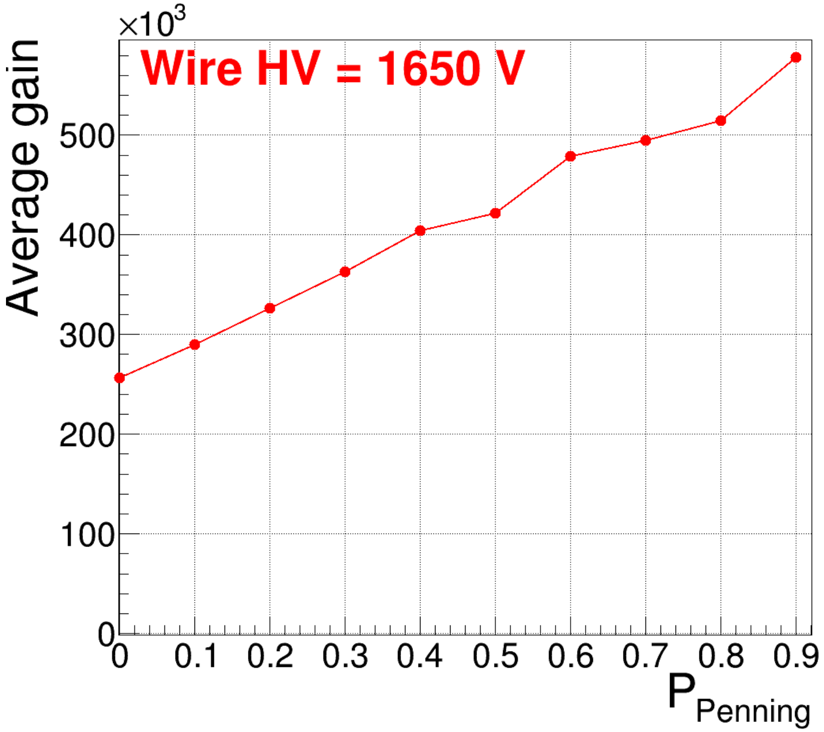
Simulation of avalanches with Garfield++

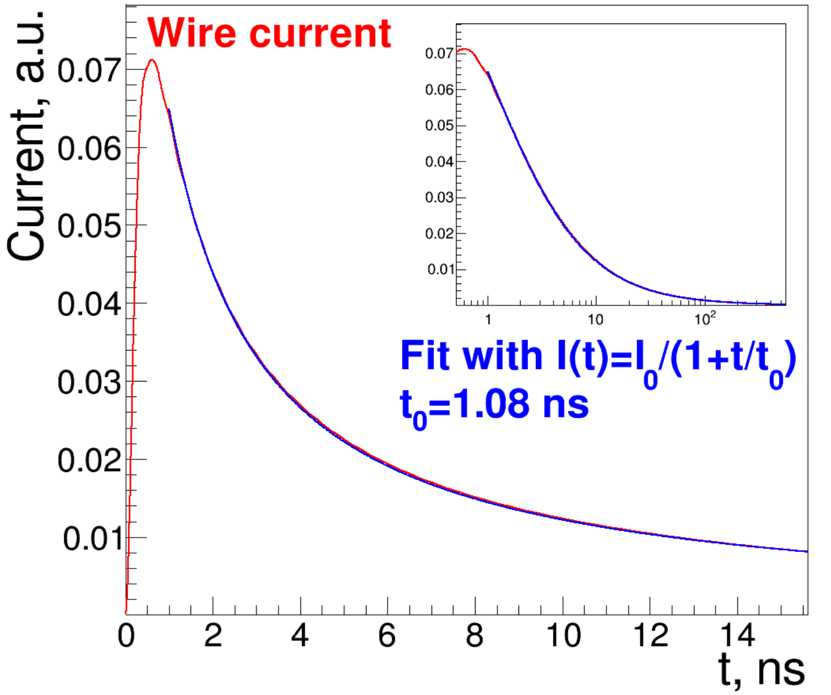


Determination of the wire high voltage

- The attainment of the desired signal/noise ratio requires the average avalanche gain to be **few** $\mathbf{10^5}$
- The average probability P_{Penning} of the Penning/Jesse energy transfers for the mixtures with helium is unknown (we didn't find any data), so we scanned over this parameter
- We have chosen the **HV=1650 V** to be a working point, the P_{Penning} is fixed at **0.3** in further studies. The average gain in this case is $\mathbf{3.6 \cdot 10^5}$
- From the fit of the gain spectrum with the Polya distribution we obtained the parameter of the latter $\boldsymbol{p = 0.69}$
- At the given working HV by averaging the signals from many avalanches we determined the characteristic signal decreasing time $\boldsymbol{t_0 = 1.08}$ **ns**

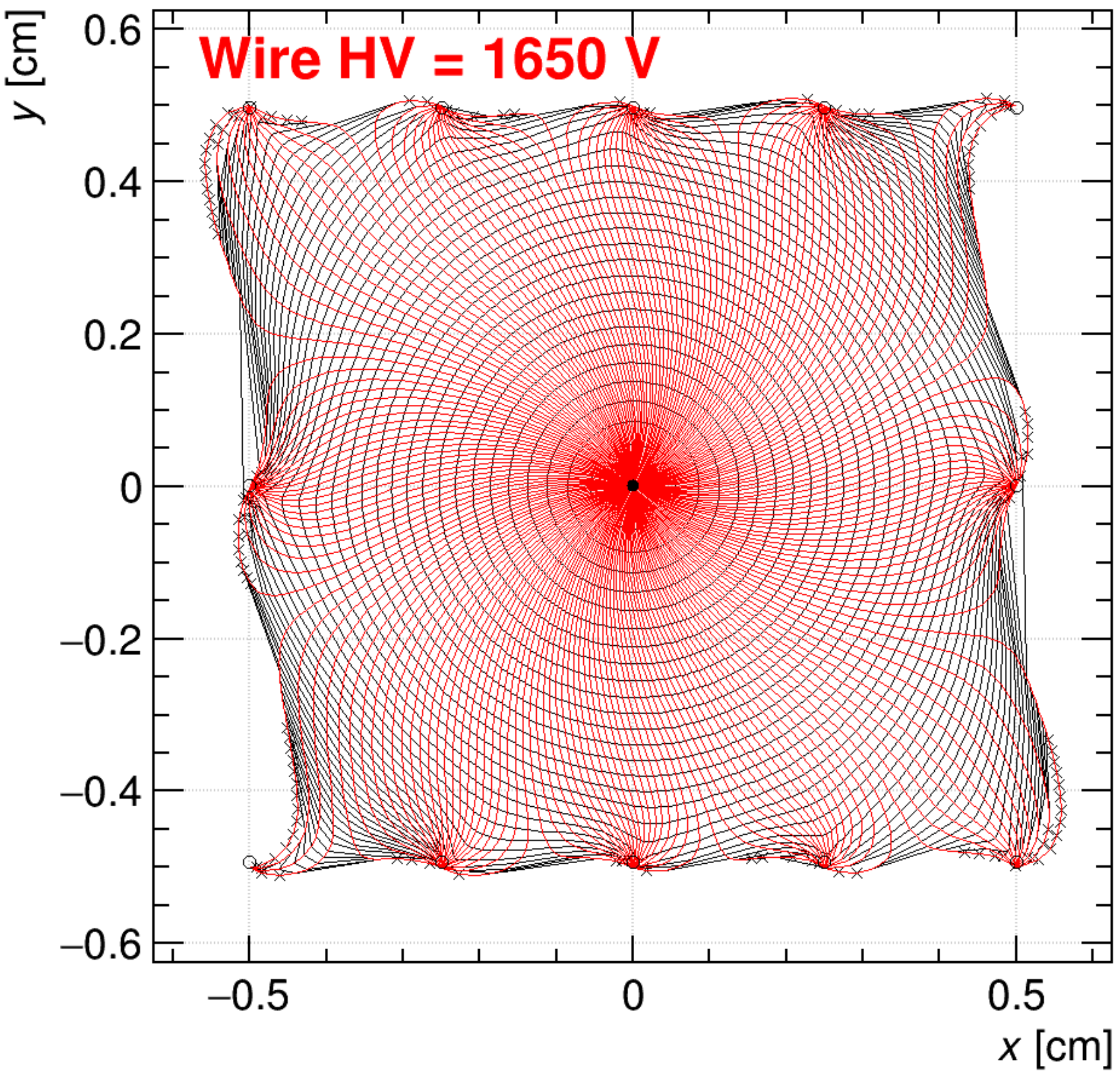


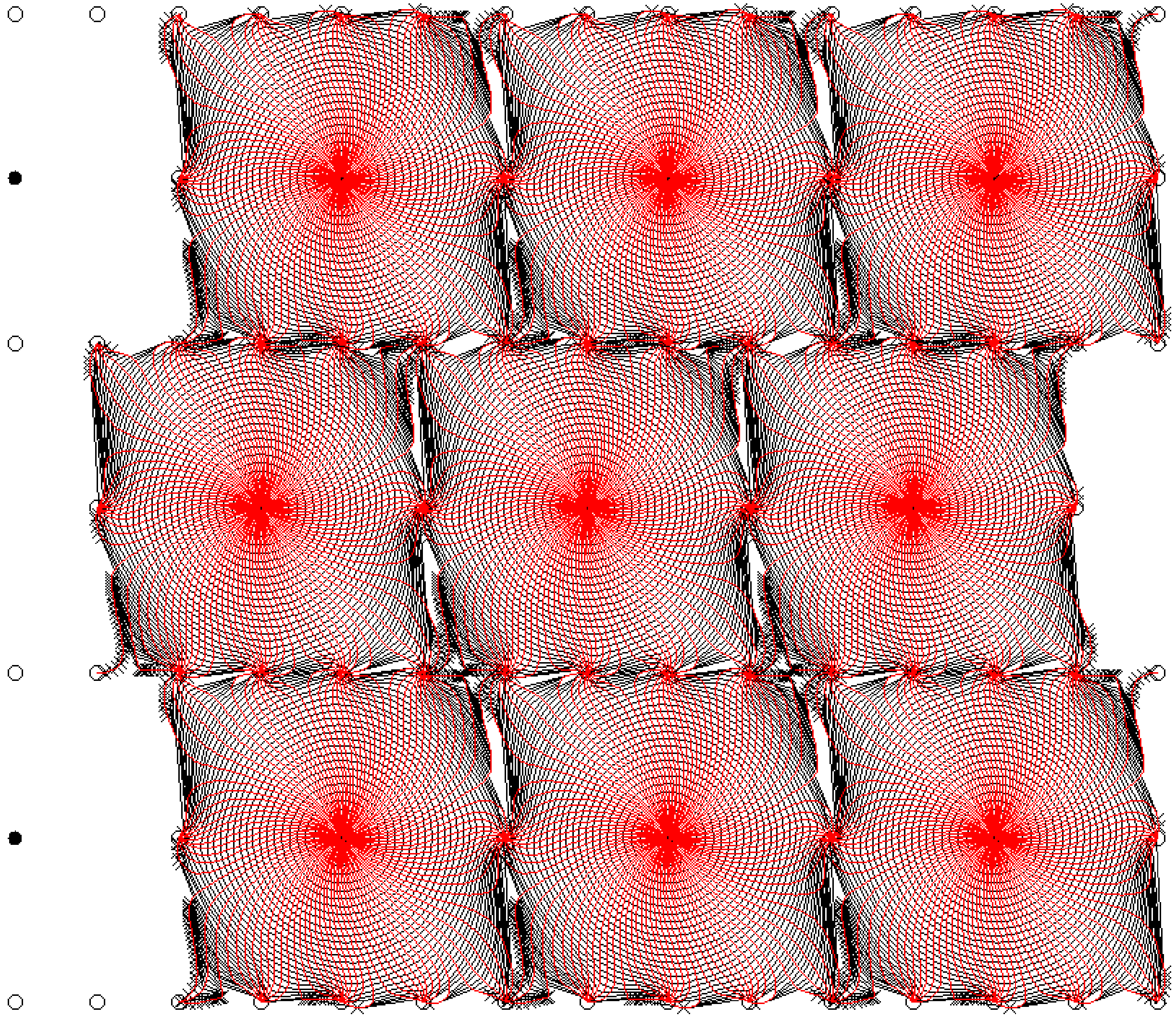




Simulation of isochrones

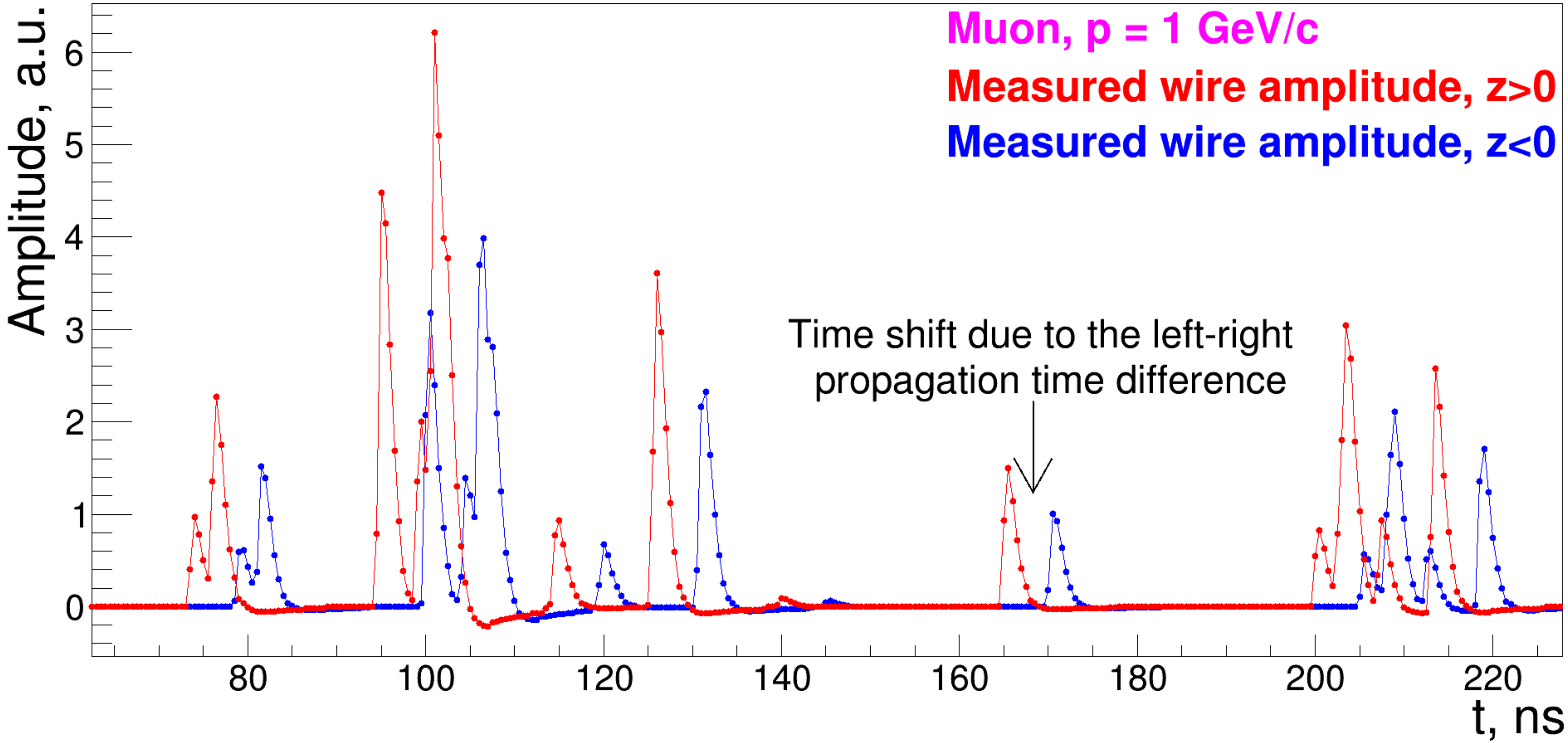
- We obtained from **Garfield++** the isochrones for $10 \times 10\ \mathrm{mm}^2$ 2D square cell and use them as the first approximation for all cells





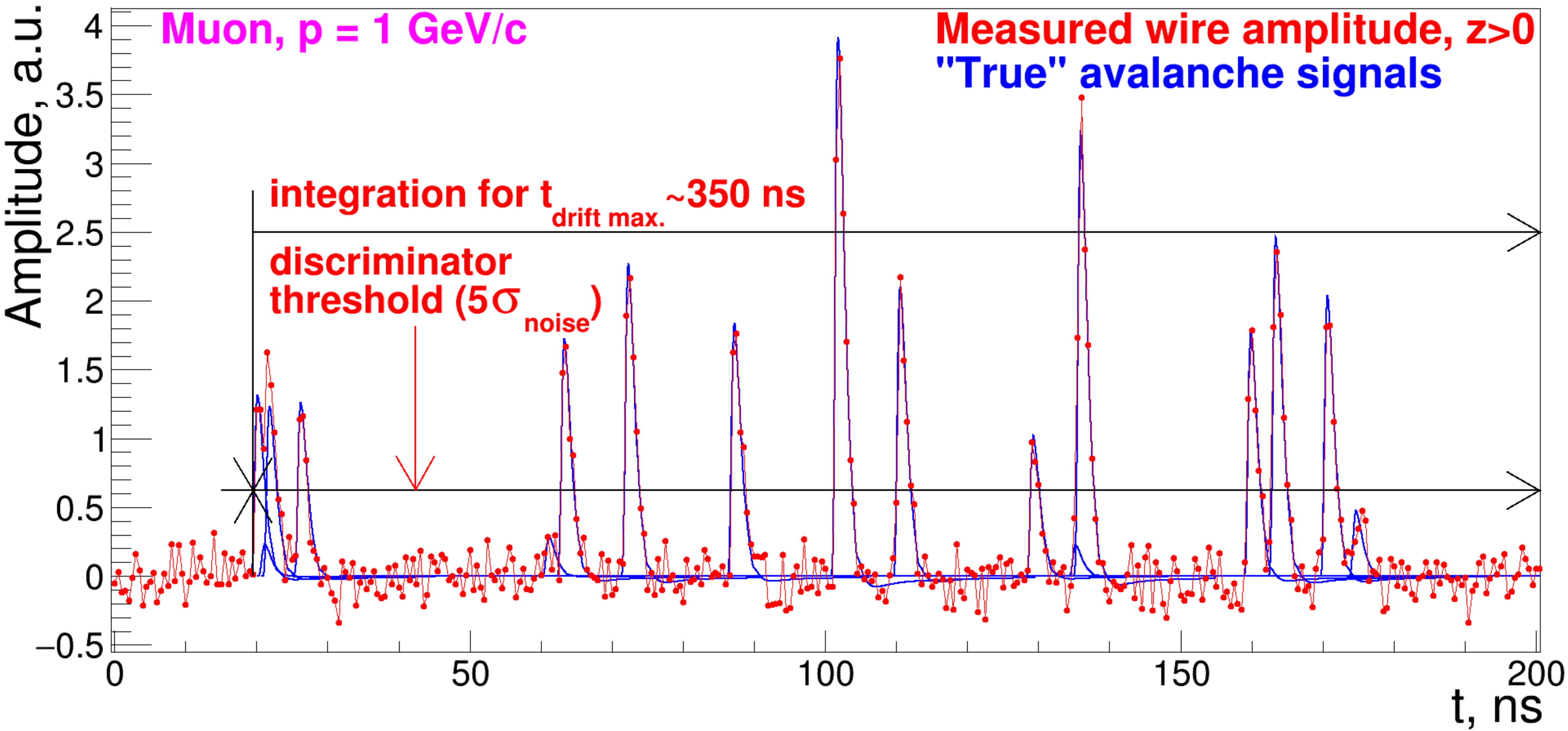
Wave form scan

- The waveform for all wires is scanned with 2 GHz frequency (for cluster counting)
- The signal shape is provided by the V.M. Aulchenko, signal/noise ratio is estimated to be ~1/8



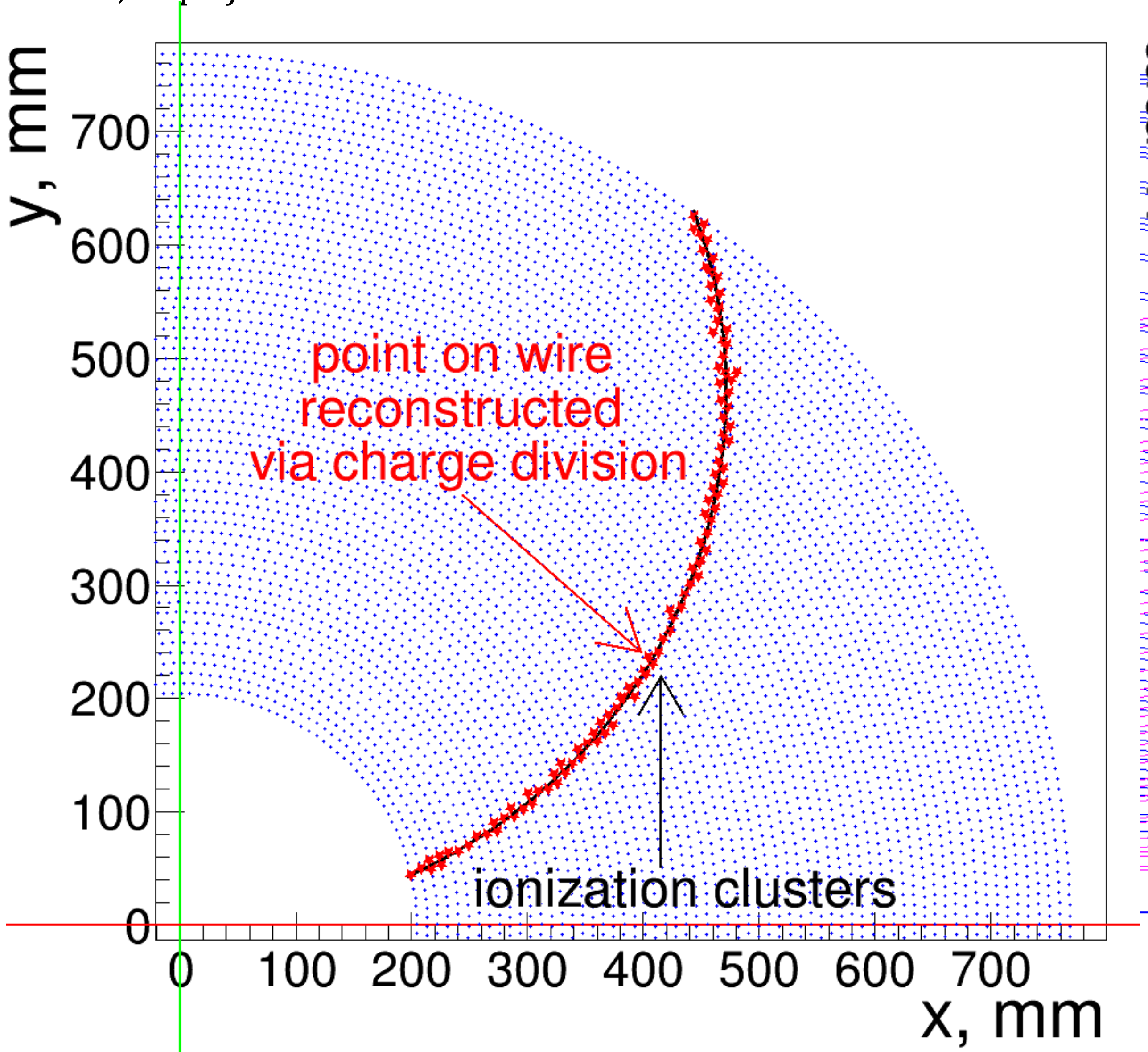
Wave form scan

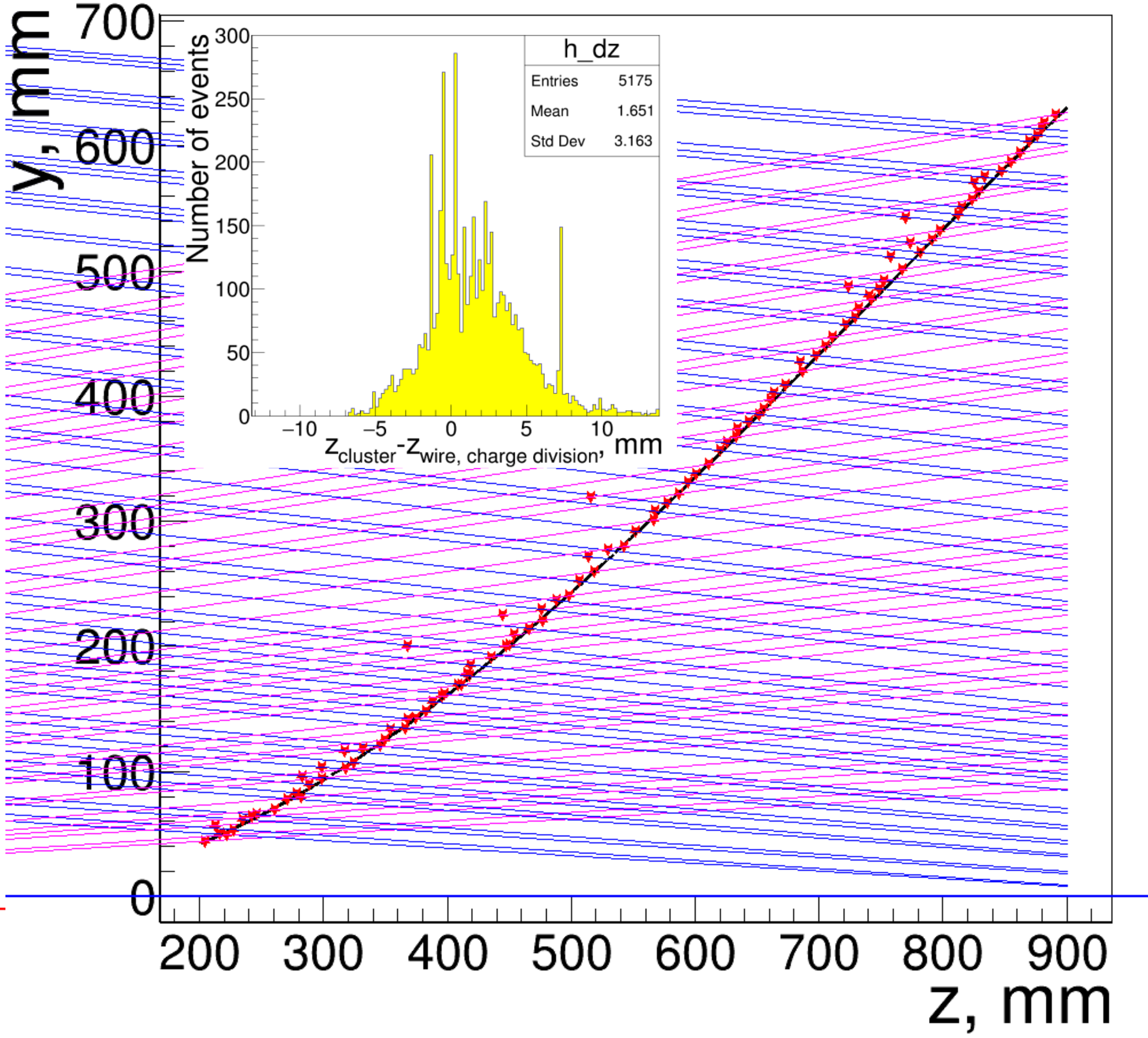
- The charge integration starts from the discriminator threshold ($5\sigma_{\mathrm{noise}}$) crossing



Reconstruction of the wire hit via the charge division

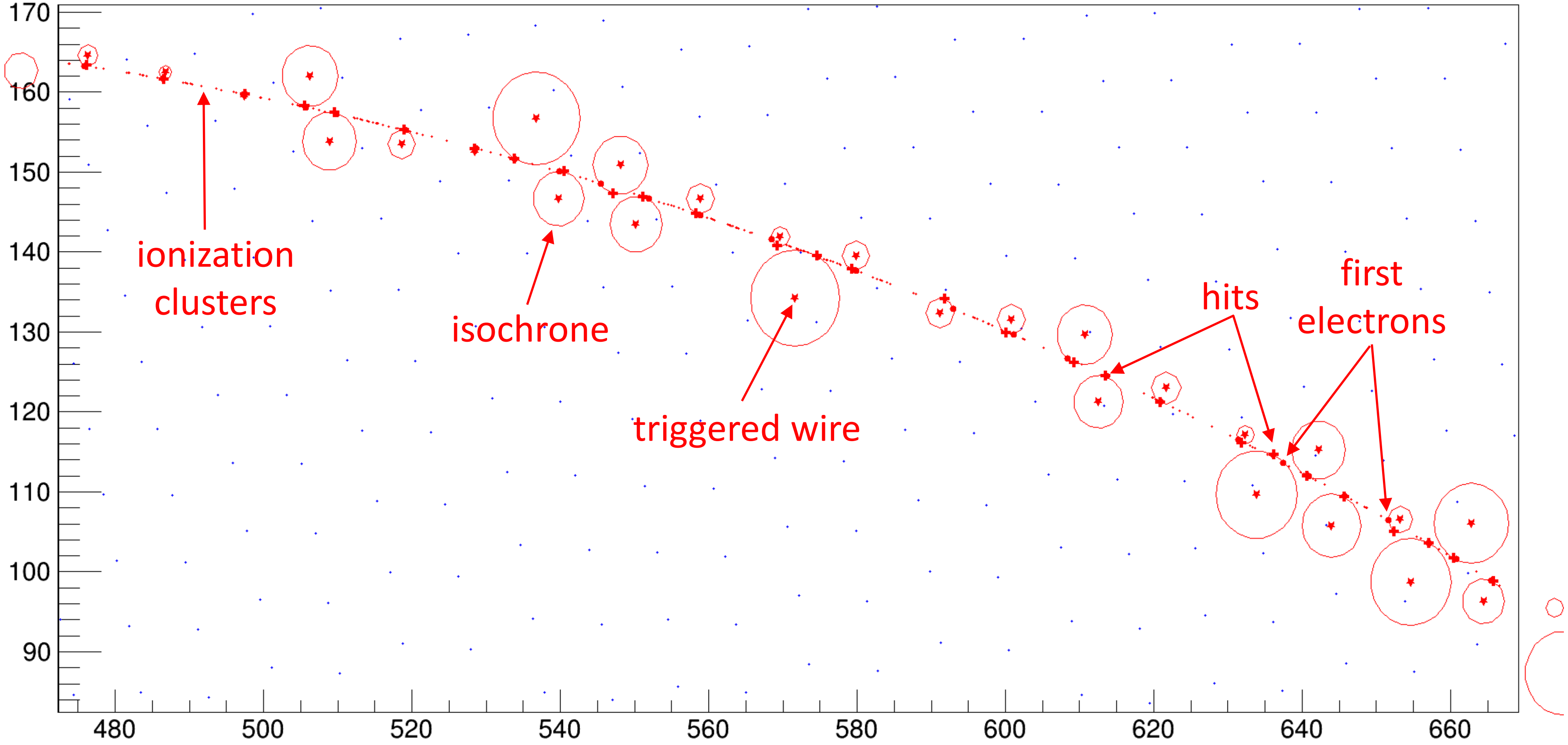
- z −coordinate of the hit on wire is reconstructed via the charge division formula, taking by default $R_{in,amplifier} = 373\ \Omega$, $\rho_{wire} = 0.112\ \Omega/\text{mm}$





«Reconstruction» of hits using the Monte-Carlo truth

- In order to bypass the track searching algorithm, we use the Monte-Carlo truth (MCtruth)
- We select the ionization electron with the smallest drift time in the cell ($t_{\mathrm{first.el.}}$), assuming that it causes the wire triggering
- We place the *hit* on the isochrone (assumed to be circular), corresponding to the $t_{\mathrm{first.el.}}$, in the point where the tangent to the isochron is parallel to the direction of flight of the particle, known from the MCtruth (the latter will also be known from the track searching algorithm)



Riemann circle fit

- We use the Riemann fit as the pre-fit for the forthcoming fit with Kalman filter

- The hits in the transversal plane are mapped on the surface of the circular paraboloid

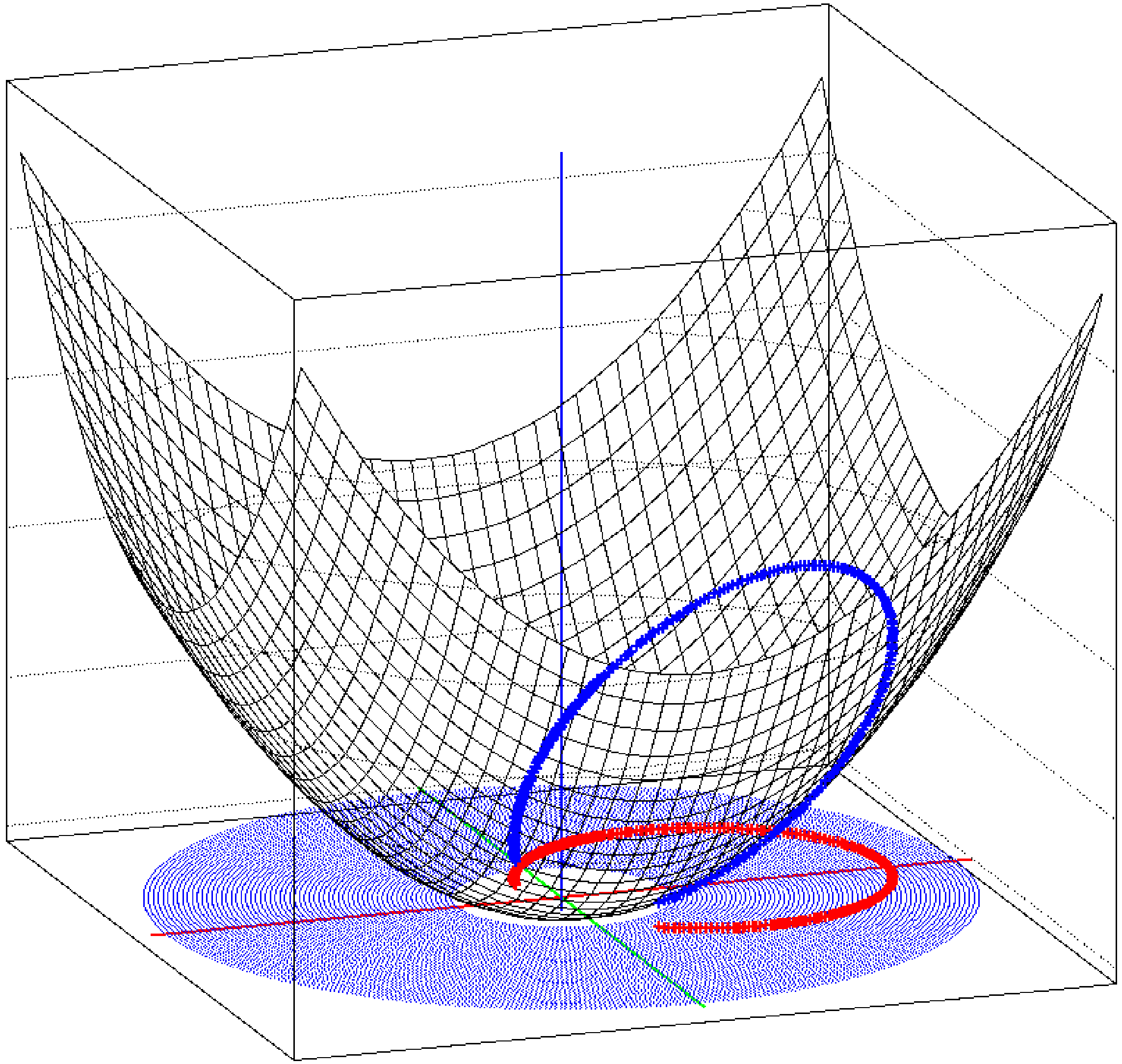
$$x_i = u_i$$
$$y_i = v_i$$
$$z_i = u_i^2 + v_i^2$$

- The **circle** on plane maps to the **ellipse** on the paraboloid, which is the intersection of some **plane** $\vec{n}^T \vec{r} + c = 0$ with the paraboloid

$$(u - u_0)^2 + (v - v_0)^2 = \rho^2$$
$$z - 2xu_0 - 2yv_0 = \rho^2 - u_0^2 - v_0^2$$

- The fit is performed by the minimization of the cost function ***S*** – the weighted sum of squared distances from the **mapped hits** to the fitting **plane**

$$S = \sum_{i=1}^{N} w_i d_i^2 \quad w_i \propto 1/\sigma_i^2, \quad \sum_{i=1}^{N} w_i = 1$$



Riemann circle fit

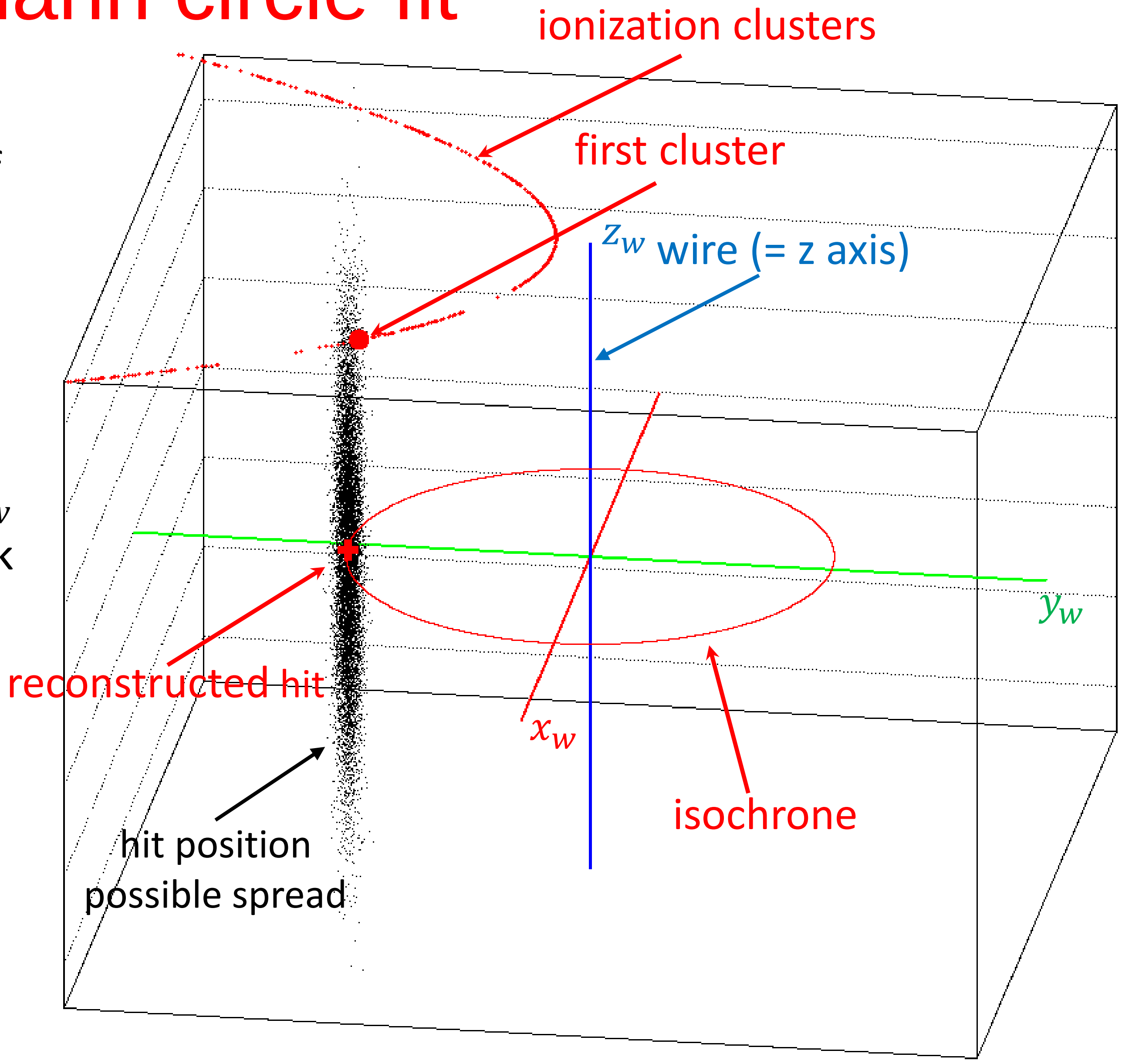
- The calculation shows that the uncertainties σ_i^2 of the distances from the mapped hits to the fitting plane are actually the uncertainties of the distances from the hits in xy −plane to the fitting circle
- To estimate this uncertainties we calculate the hit covariance matrix
- $Ox_wy_wz_w$ - the coordinate system with Oz_w parallel to given wire and Ox_w is parallel to track direction in the PCA to the wire. In this frame

$$cov(x_w, y_w, z_w) = \begin{bmatrix} \delta^2 & 0 & 0 \\ 0 & \sigma_\rho^2 & 0 \\ 0 & 0 & \sigma_z^2 \end{bmatrix}$$

$\delta^2 = 0.01\sigma_\rho^2$ - small factor introduced to make the covariance matrix positive-definite

$\sigma_\rho^2 = \sigma_{diffusion}^2 + \sigma_{clusters}^2$

$\sigma_{clusters} = A \cdot sin\left(\text{atan}(B/t_{diffusion})\right), A, B$ – tunable parameters



Riemann circle fit

- Uncertainty propagation to the lab system is done via the Jacobian

$$J = \begin{bmatrix} cos\varphi_w cos\tilde{\varphi}_{tr} - sin\varphi_w sin\tilde{\varphi}_{tr} cos\varepsilon & -cos\varphi_w sin\tilde{\varphi}_{tr} - sin\varphi_w cos\tilde{\varphi}_{tr} cos\varepsilon & -sin\varphi_w sin\varepsilon \\ sin\varphi_w cos\tilde{\varphi}_{tr} + cos\varphi_w sin\tilde{\varphi}_{tr} cos\varepsilon & -sin\varphi_w sin\tilde{\varphi}_{tr} + cos\varphi_w cos\tilde{\varphi}_{tr} cos\varepsilon & cos\varphi_w sin\varepsilon \\ -sin\tilde{\varphi}_{tr} sin\varepsilon & -cos\tilde{\varphi}_{tr} sin\varepsilon & cos\varepsilon \end{bmatrix}$$

where φ_w - wire azimuthal angle at z_{hit}, $\tilde{\varphi}_{tr}=\varphi_{tr} - \varphi_w$, φ_{tr} - azimuthal angle of track at z_{hit}, ε - stereo angle

- $Oxyz$ - the lab coordinate system: $cov(x,y,z) = J \cdot cov(x_w, y_w, z_w) \cdot J^T$
- Uncertainty of the hit distance to the track circle in xy-plane:

$$\sigma^2_{hit} = sin^2\varphi_{tr} \cdot cov(x,y,z)_{11} + cos^2\varphi_{tr} \cdot cov(x,y,z)_{22} - 2sin\varphi_{tr} cos\varphi_{tr} \cdot cov(x,y,z)_{12}$$

- The minimization of cost function ***S*** gives the value of $c = -\vec{n}^T \vec{r}_0$, where $\vec{r}_0 = \sum_{i=1}^{N} w_i \vec{r}_i$
- Then the normal to the plane $\vec{n}$ is obtained as the unit eigenvector of the sample covariance matrix A, corresponding to the smallest eigenvalue (<= principal component analysis)

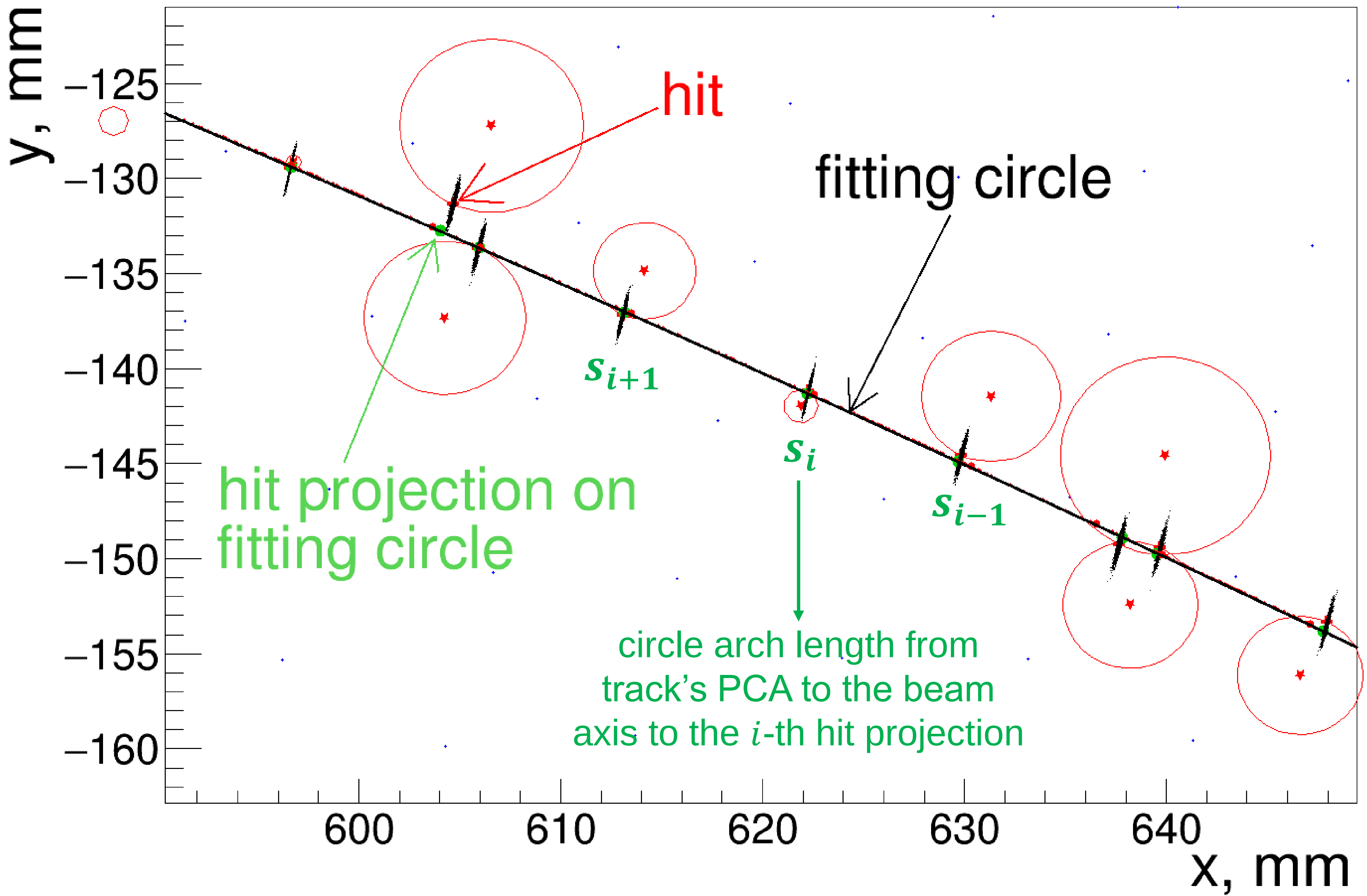
$$\boldsymbol{A} = \sum_{i=1}^{N} w_i(\boldsymbol{r}_i - \boldsymbol{r}_0)(\boldsymbol{r}_i - \boldsymbol{r}_0)^\mathsf{T}$$

- Finally, the obtained parameters of the plane are mapped back to the parameters of the fitting circle

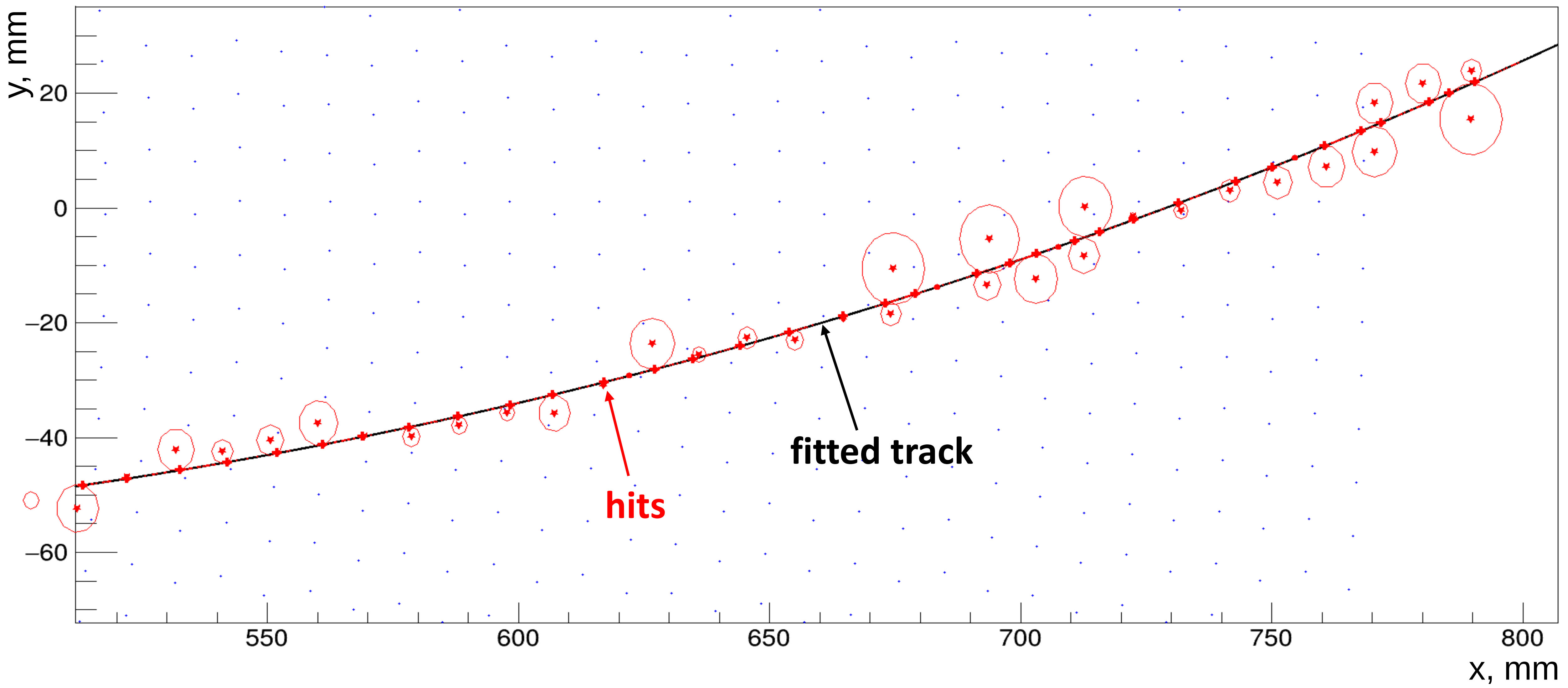
$$u_0 = -\frac{n_1}{2n_3} \quad v_0 = -\frac{n_2}{2n_3}$$

$$\rho = \frac{\sqrt{1 - n_3^2 - 4cn_3}}{2n_3}$$

Riemann circle fit

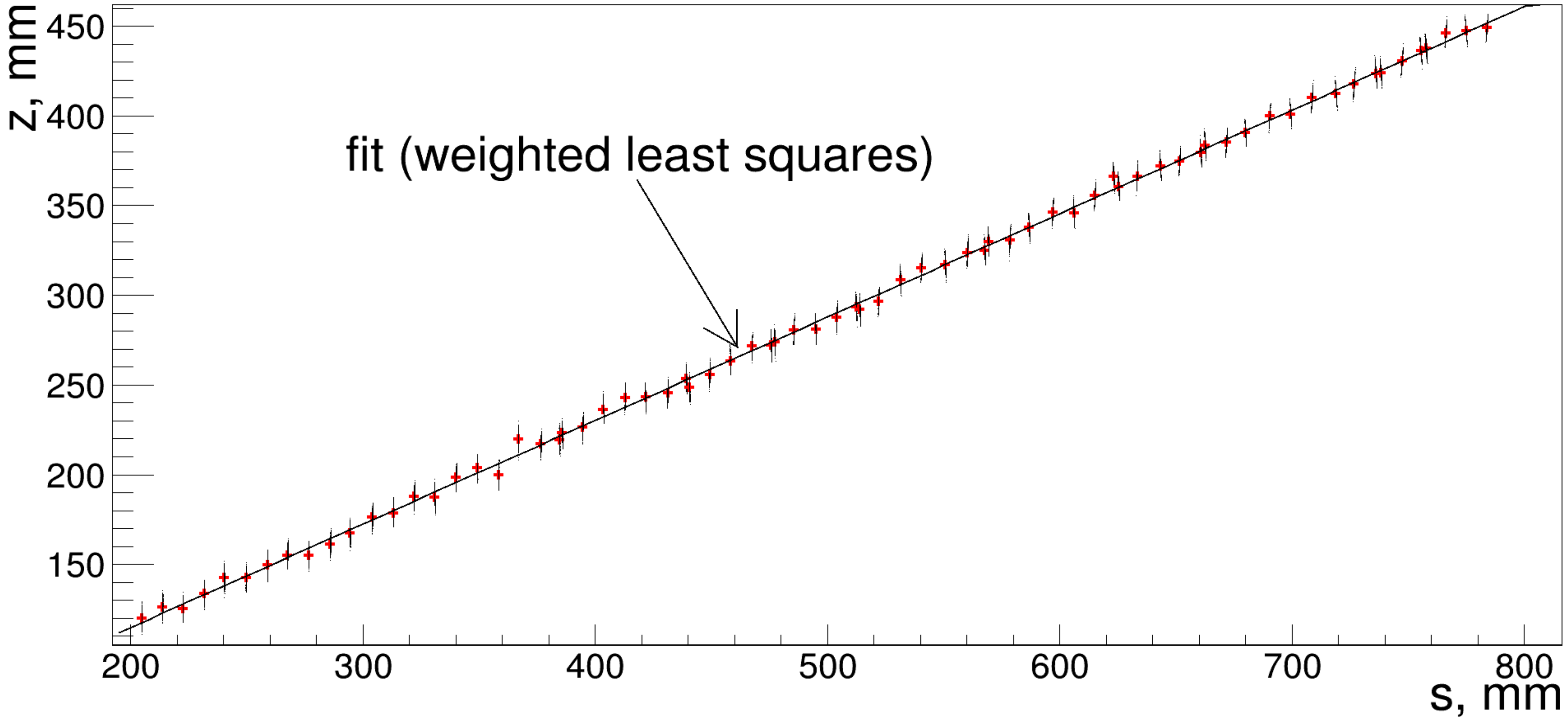


Riemann circle fit

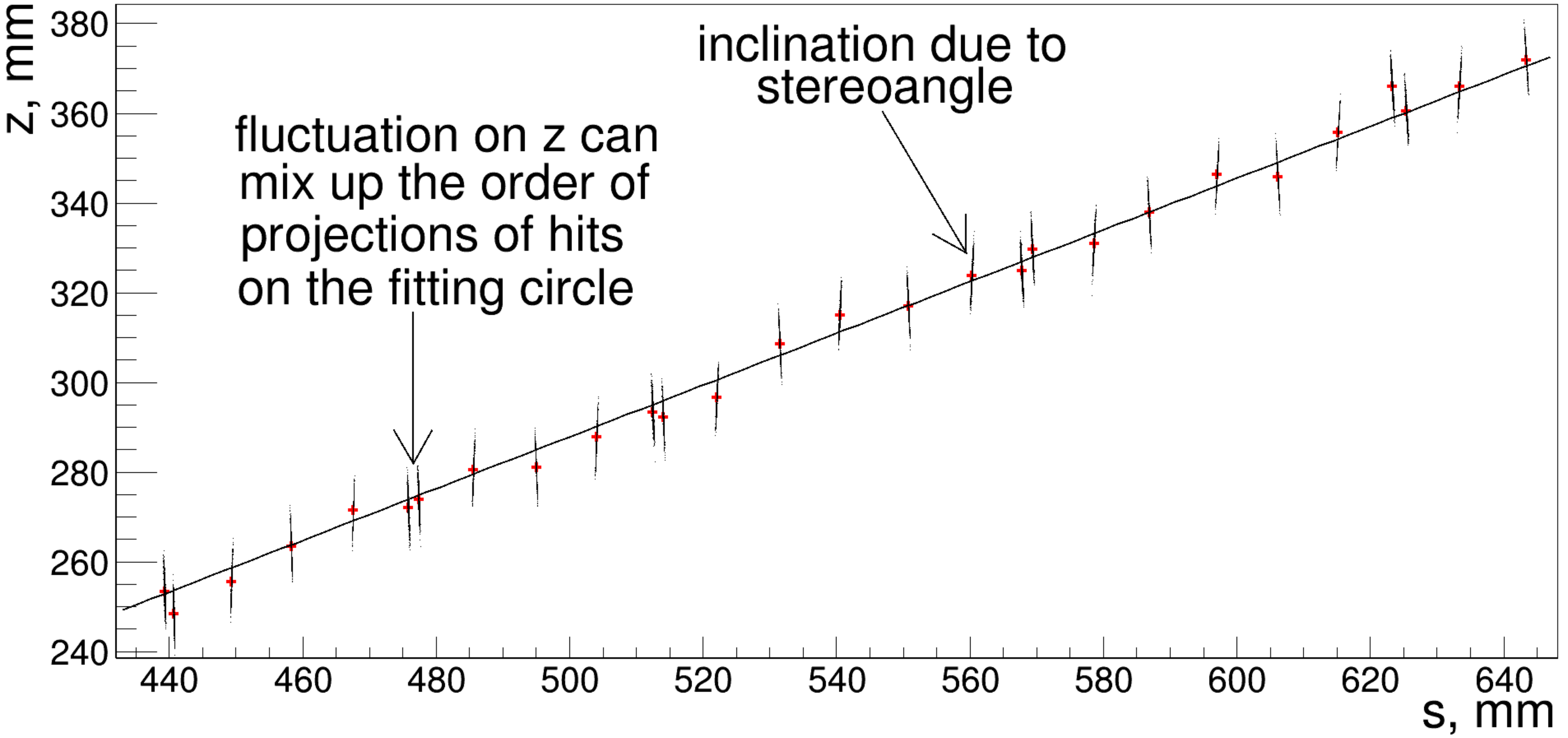


Line fit

- To determine the $\cot(\theta)$ and z_{PCA} of the track we perform simple weighted least squares line fit of the hits in sz −plane. For simplicity, only the uncertainties on z are taken into account

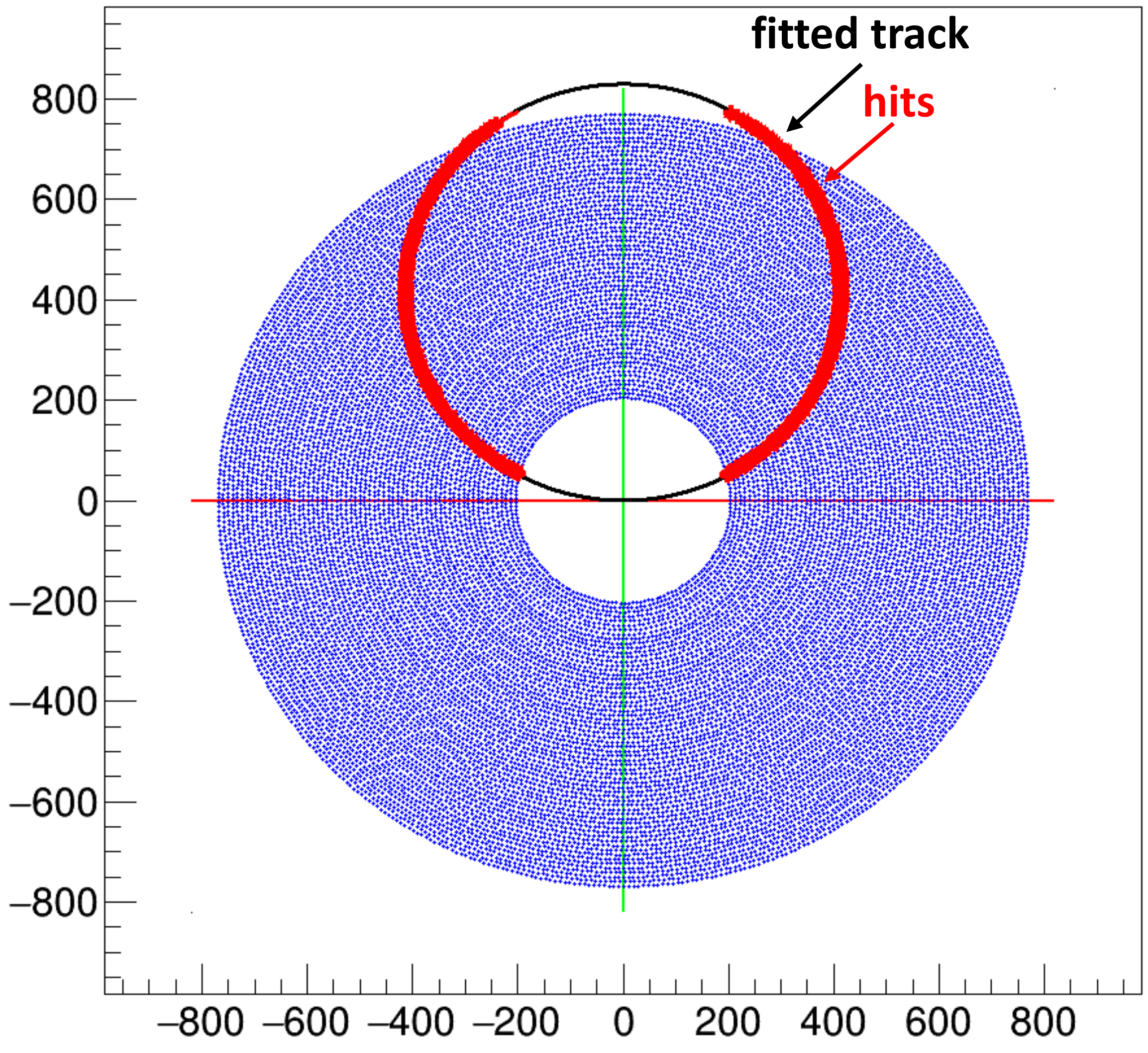


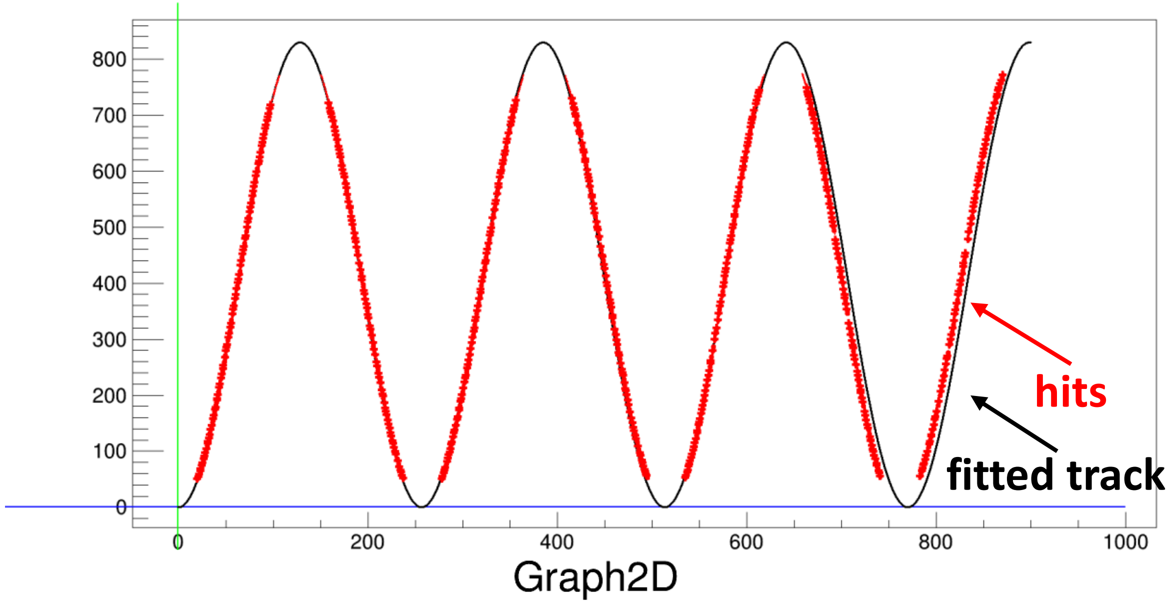
Line fit

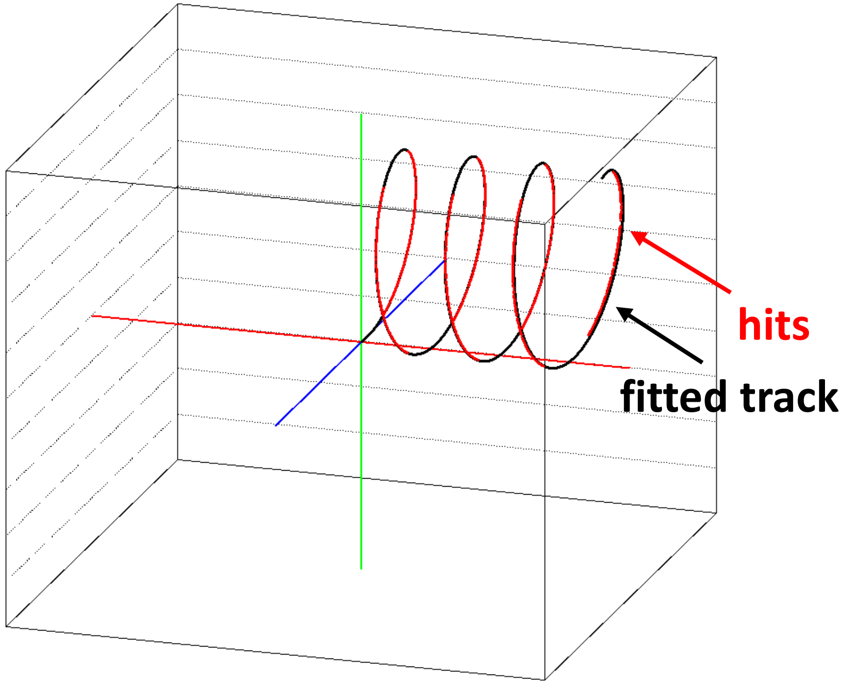


z, mm
380
360
340
320
300
280
260
240
440
460
480
500
520
540
560
580
600
620
640
s, mm
fluctuation on z can mix up the order of projections of hits on the fitting circle
inclination due to stereoangle

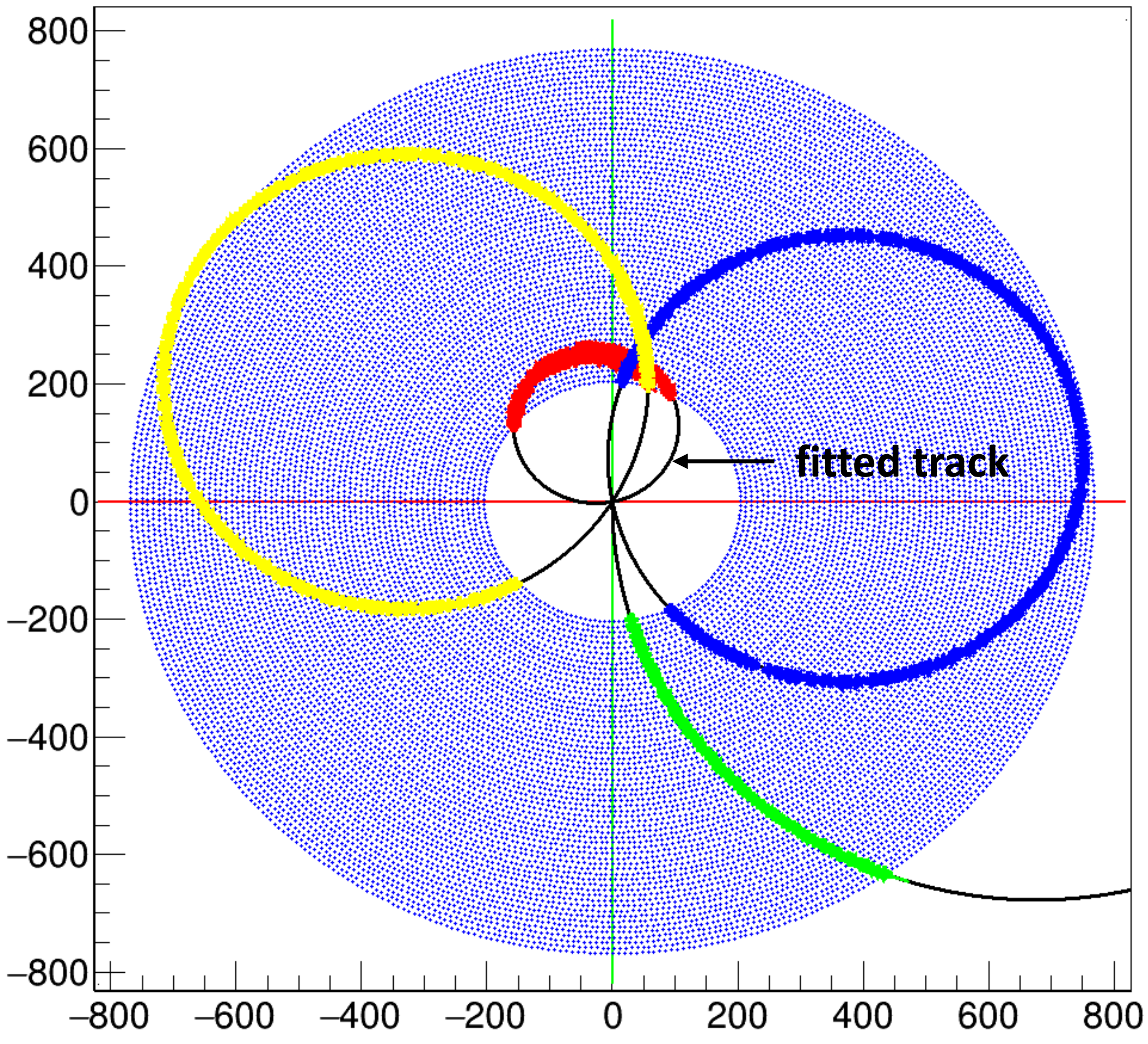
Fit results: single track

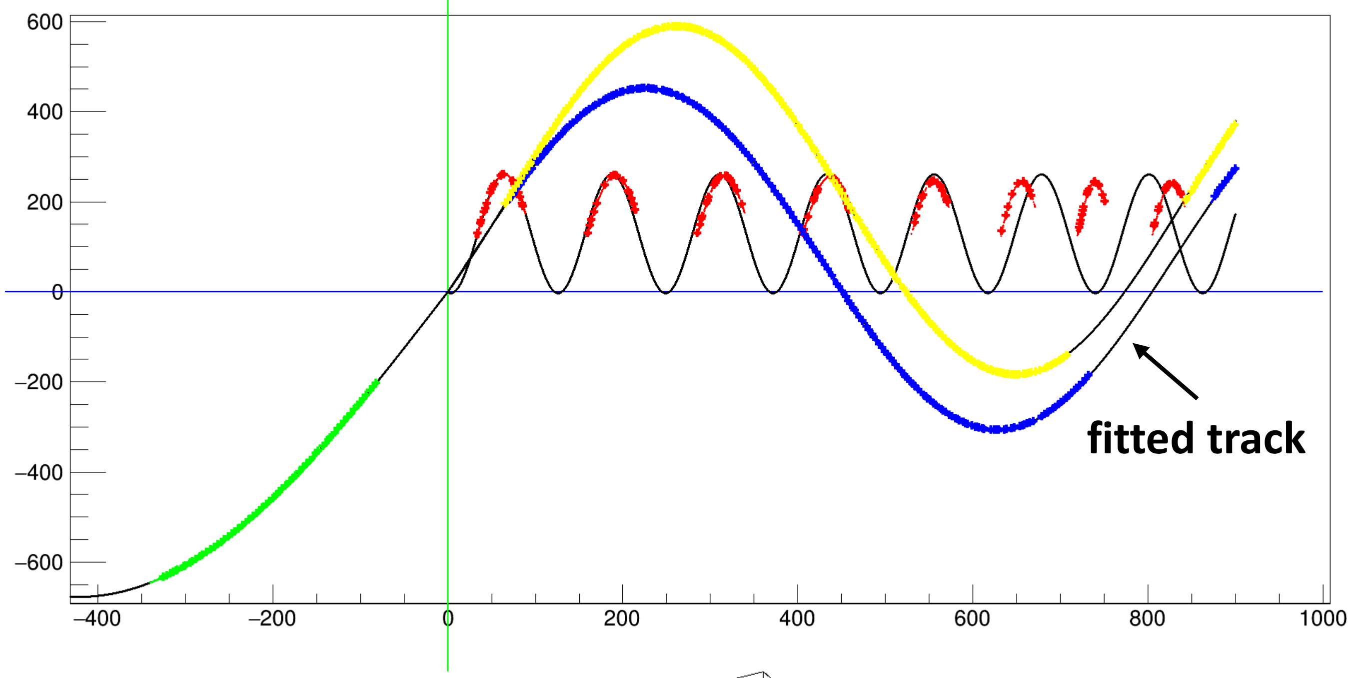


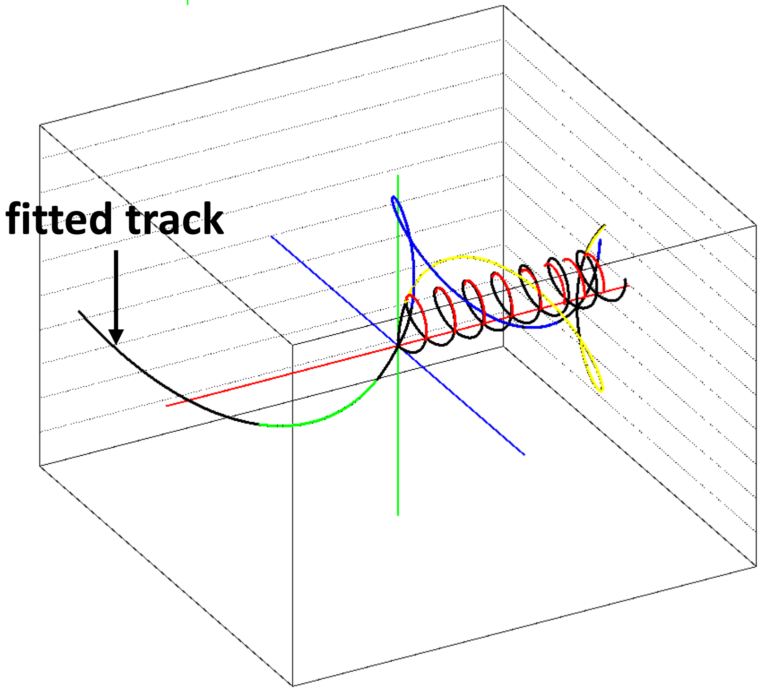




Fit results: many tracks







Plans

- Learn more about the practical ways of the hit reconstruction in the stereo geometry (we are still noobs here)
- Track fit using Kalman filter (GenFit or ACTS)
- Development of the algorithm of track finding
- Vertex reconstruction using RAVE
- Kinematic fit with TPC & Calorimeter
- Wave form analysis, cluster counting & cluster timing