Pixel chamber: a solid-state active-target for 3D imaging of charm and beauty

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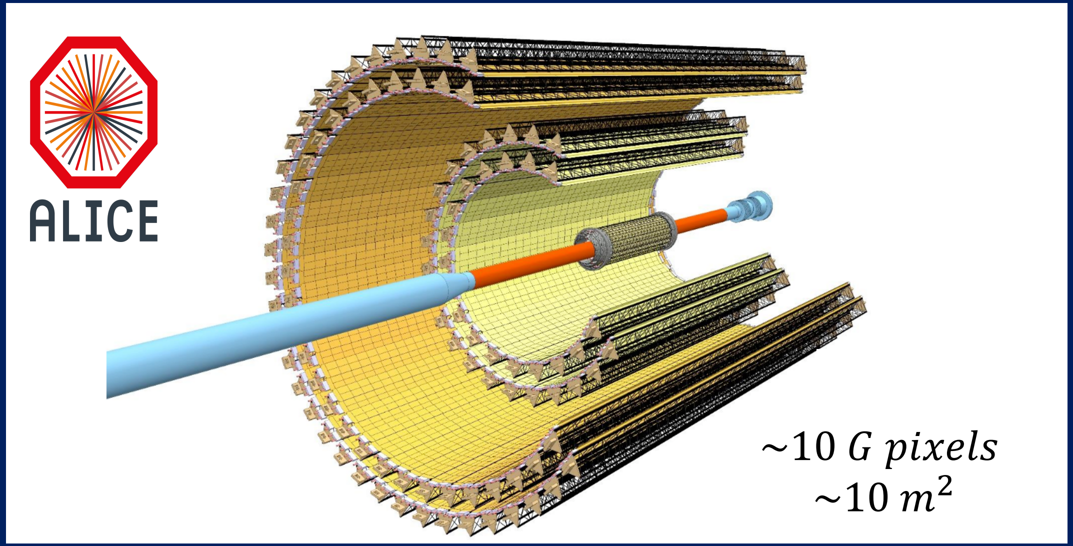
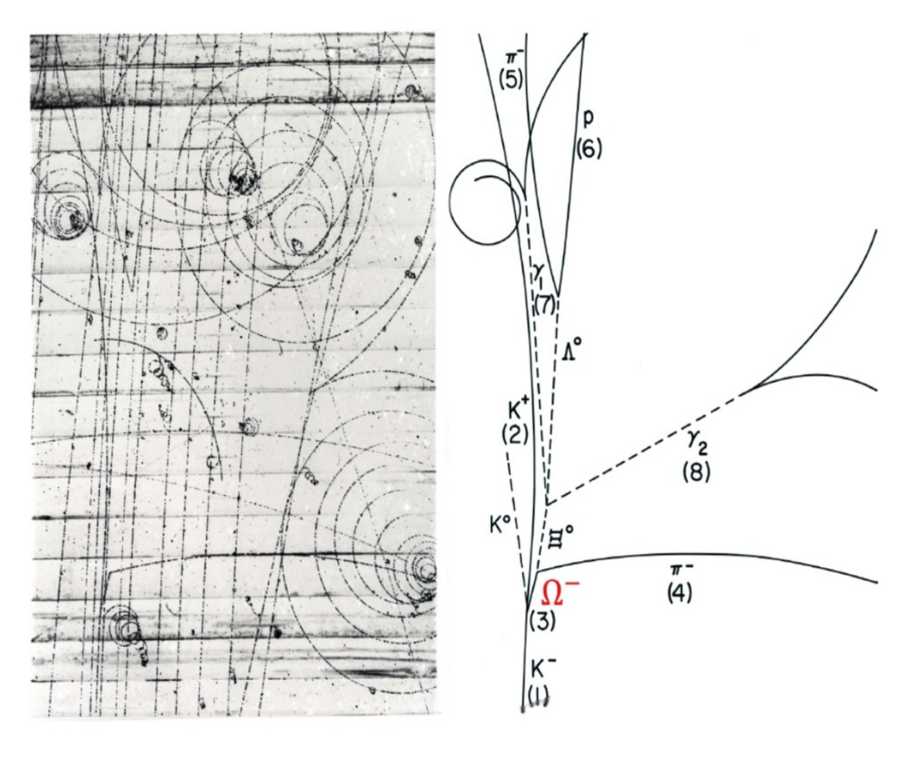
A solid-state active target

Modern vertex detectors are based on silicon sensors (pixels or strips)

- Great spatial resolution to separate primary from secondary vertices
- Fundamental for charm and beauty measurements → can travel distances from O(10-100 μm) up to mm before decay
- Limitation: always placed few centimetres away from the interaction point



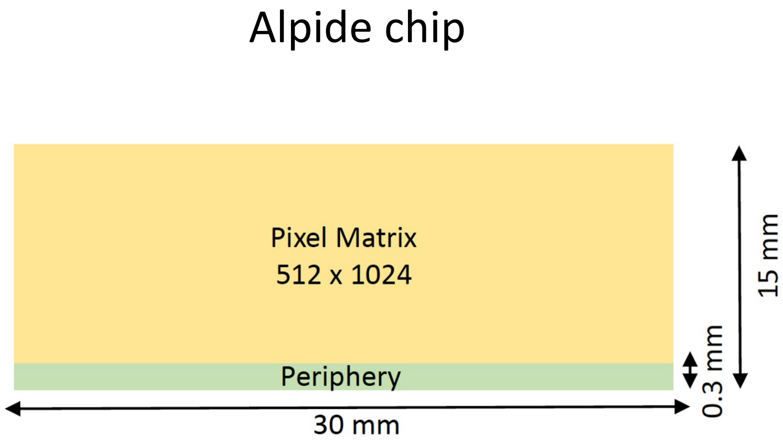


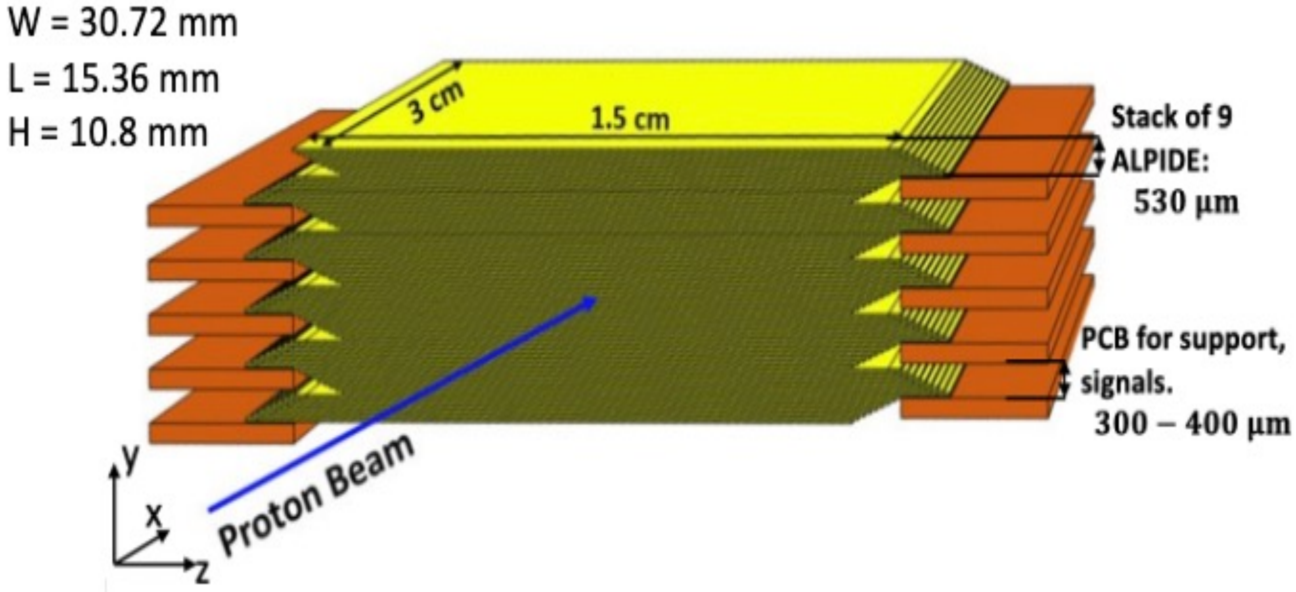
Can we build a solid-state active target providing continuous tracking as older bubble chambers to measure rare processes as charm and beauty?

Pixel Chamber

Idea:

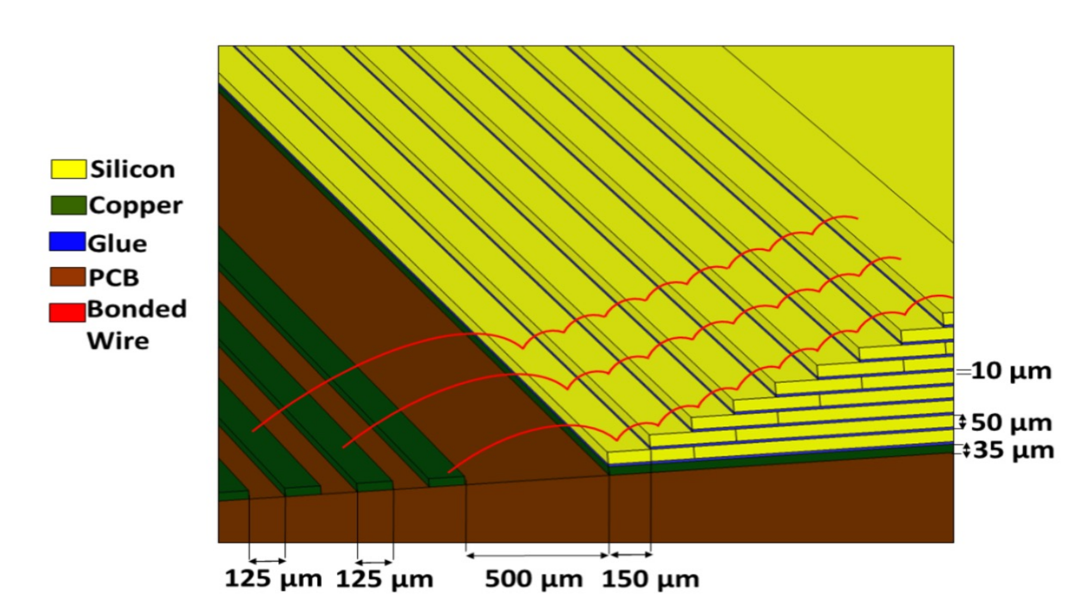
- stack of 216 ALPIDE MAPS sensors (developed for the ALICE ITS upgrade)
  - matrix of 1024x512 pixels ($\sim 29 \mathrm{x} 27 \mu\mathrm{m}^2$) in a surface of $\sim 30 \mathrm{x} 15\ \mathrm{mm}^2$
  - thickness of 50 µm
- 3D volume of 10^8pixels ($\sim 30 \mathrm{x} 15 \mathrm{x} 11\ \mathrm{mm}^3$)
- solid state bubble chamber
  - allows continuous tracking to be performed with very high precision: ~5µm spatial resolution
  - possibility to observe secondary vertices inside the detector

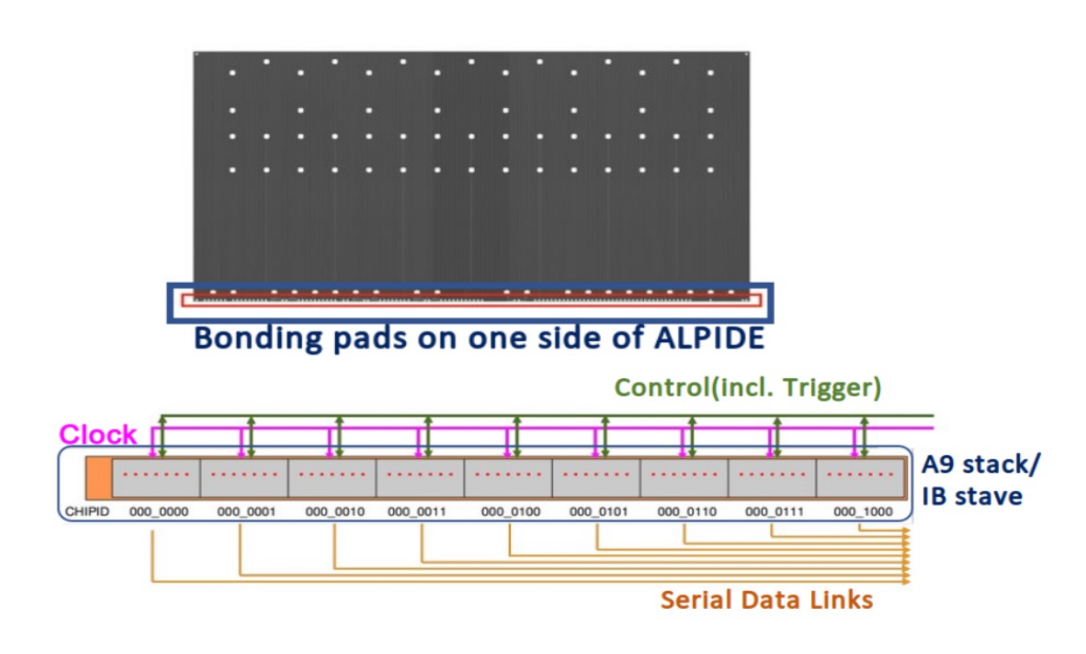




Pixel Chamber: technology

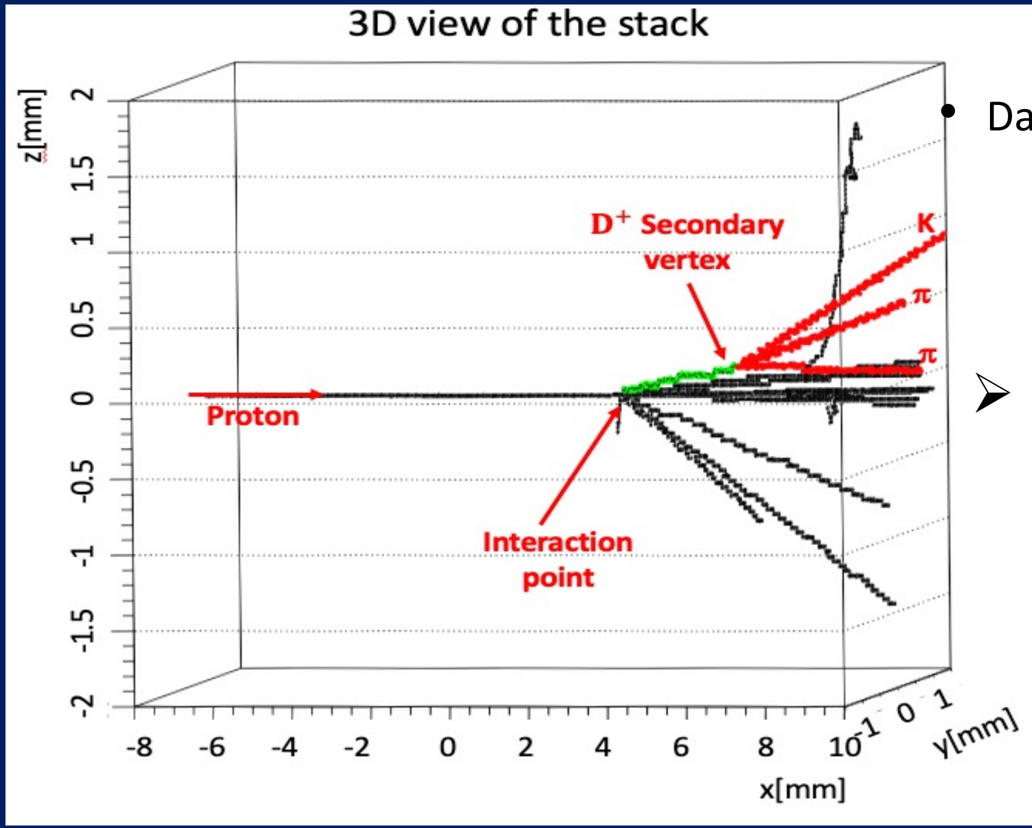
- Pixel chamber basic unit: stack of 9 ALPIDE chips → A9 stack with 530 μm thickness
  - ➢ Sensors arranged in staggered fashion (150 μm offset) to provide space for wire bonding of sensor pads
  - ➢ Pads providing access to signal and power circuits reside on one side of the sensor
  - ➢ ~10 μm layer of insulating glue between two sensors
  - ➢ Data, control, monitoring and clock interfaced on a PCB (wire bonds) → same as the ALICE ITS Inner Barrel Stave
- Pixel chamber → assembly of 24 A9 stacks
  - ➢ Active area: 30x13x10 mm^3
  - ➢ Signal and power lines distributed by combination of rigid and flex PCBs





Pixel Chamber: Geant4 Simulation

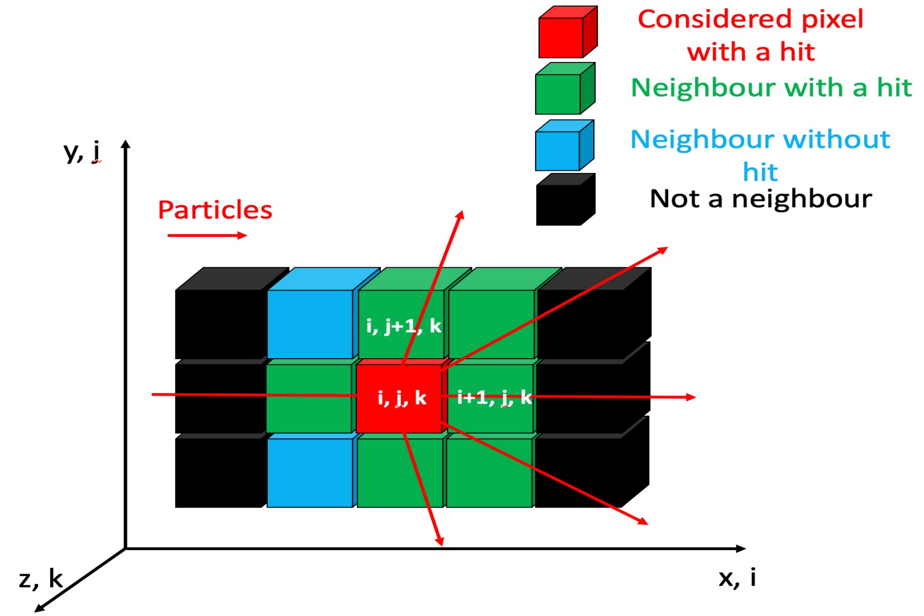
- Simulation of a protype made of 216 ALPIDE sensors
- Beam:
  - ➢ Protons at 400 GeV/c (p-Si inelastic interactions)
  - ➢ Gaussian spread for protons production coordinates
  - ➢ Angular spread of beam direction
- D mesons kinematics in 400 GeV pp interactions generated with POWHEG
- D mesons decays overlaid to p-Si interactions



- Dataset produced:
  - ➢ Digit: center coordinates of the hit pixel
  - ➢ Data for Monte Carlo truth:
    - Particle momenta
    - PDG code

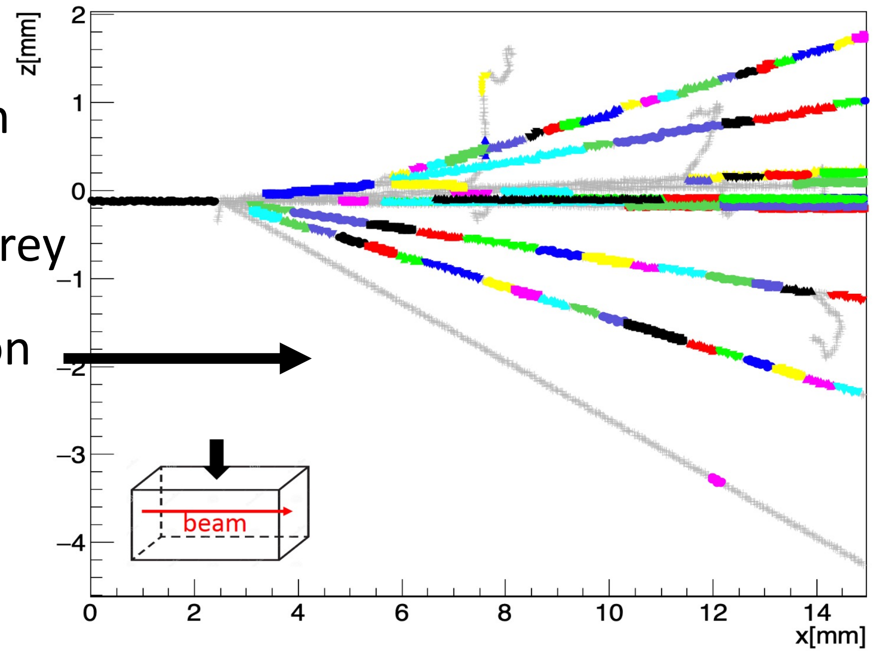
Clusterization: group hits in clusters

- Search of pixel neighbours
  - a neighbour of a hit pixel is another hit pixel for which the discrete distance is 1
- Hit clusters
  - Place a hit pixel into a cluster if it has 2 or 3 neighbours
  - Consider a hit pixel as a noise point if:
    - Number of neighbours < 2
    - Number of neighbours > 3 required to break clusters belonging to different tracks in regions with high density of hits (example figure right)



Clusters shown in color
Noise shown in grey

After clusterization



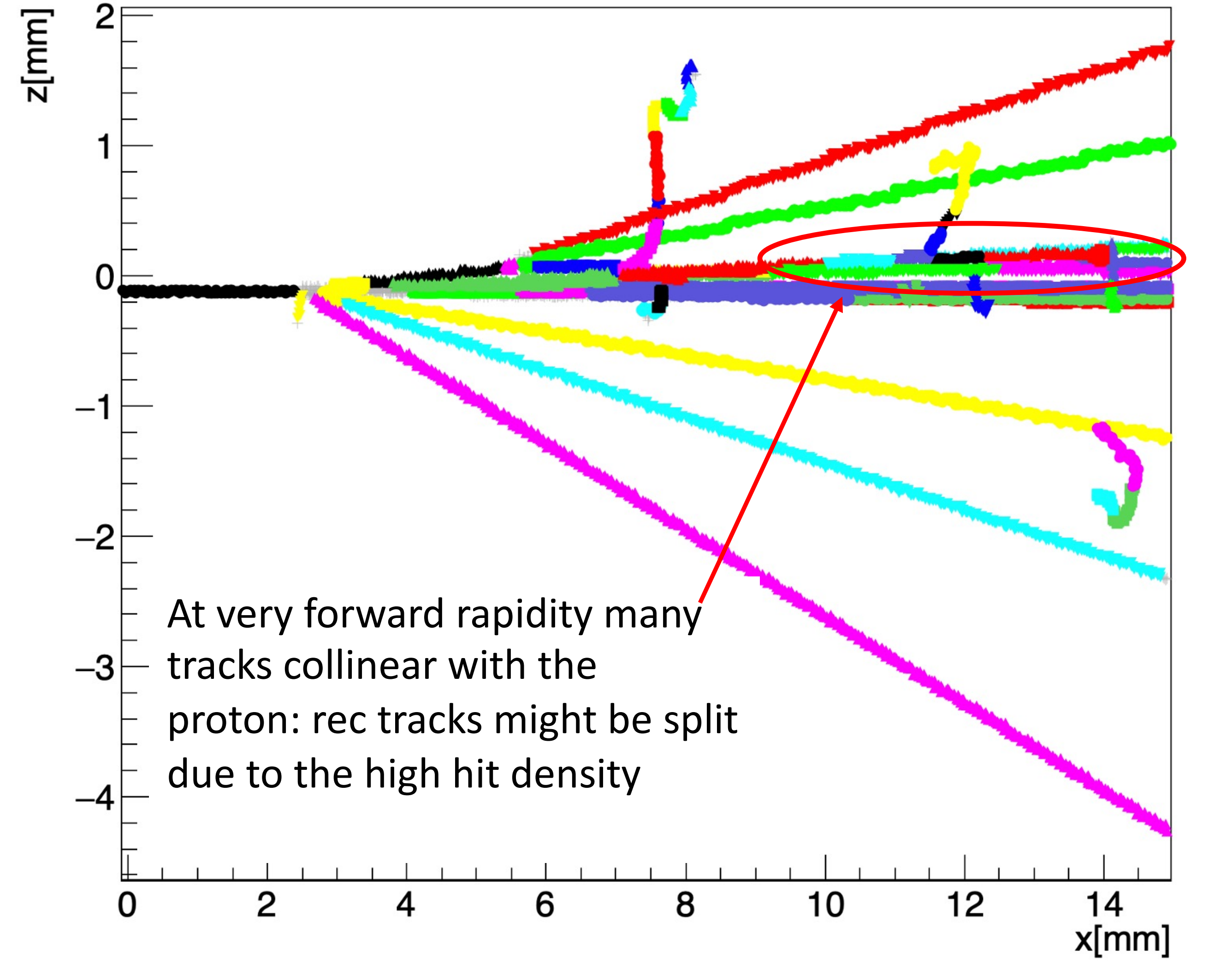
Algorithm: track finding

- Fit all reconstructed clusters with straight lines
- Merge of compatible linear clusters:
  - ➢Compatible direction cosines
  - ➢Cluster boundary points close to each other

Further clusterization for noise points:

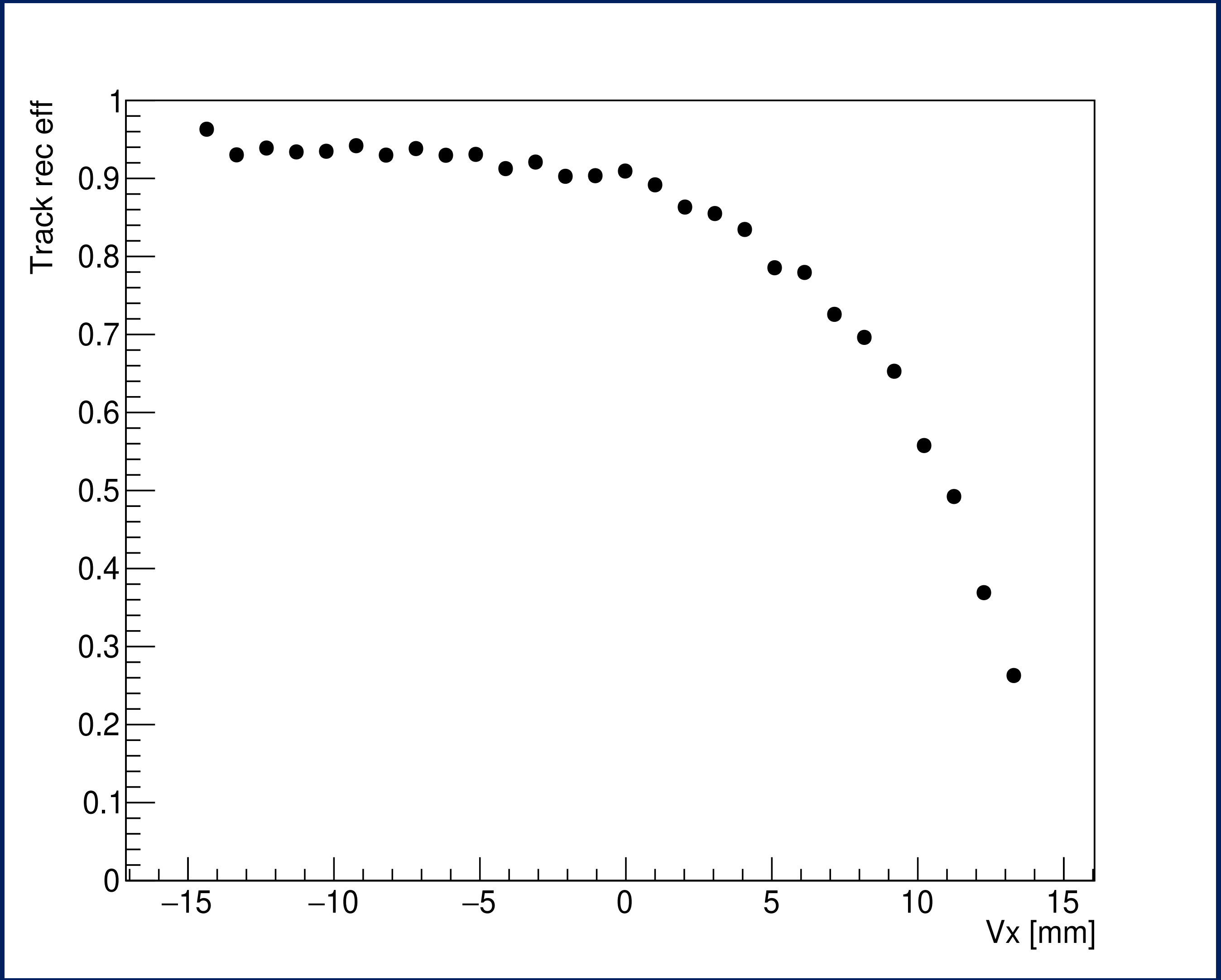
- Two more passes with less stringent neighbours condition:
  - ➢number of neighbors < 4 and <6

Satisfactory reconstruction of most hadronic tracks



Tracks reconstruction efficiency

- Track reconstruction efficiency obtained as the ratio Reconstructed/MC hadronic tracks
- Mean value of reconstruction efficiency:
  - ~90% with a cut on the primary vertex position to exclude the last 10 mm of the detector → short tracks hard to resolve close to the end of chamber



Vertex Fit

Goal: determine p-Si interaction vertex coordinates

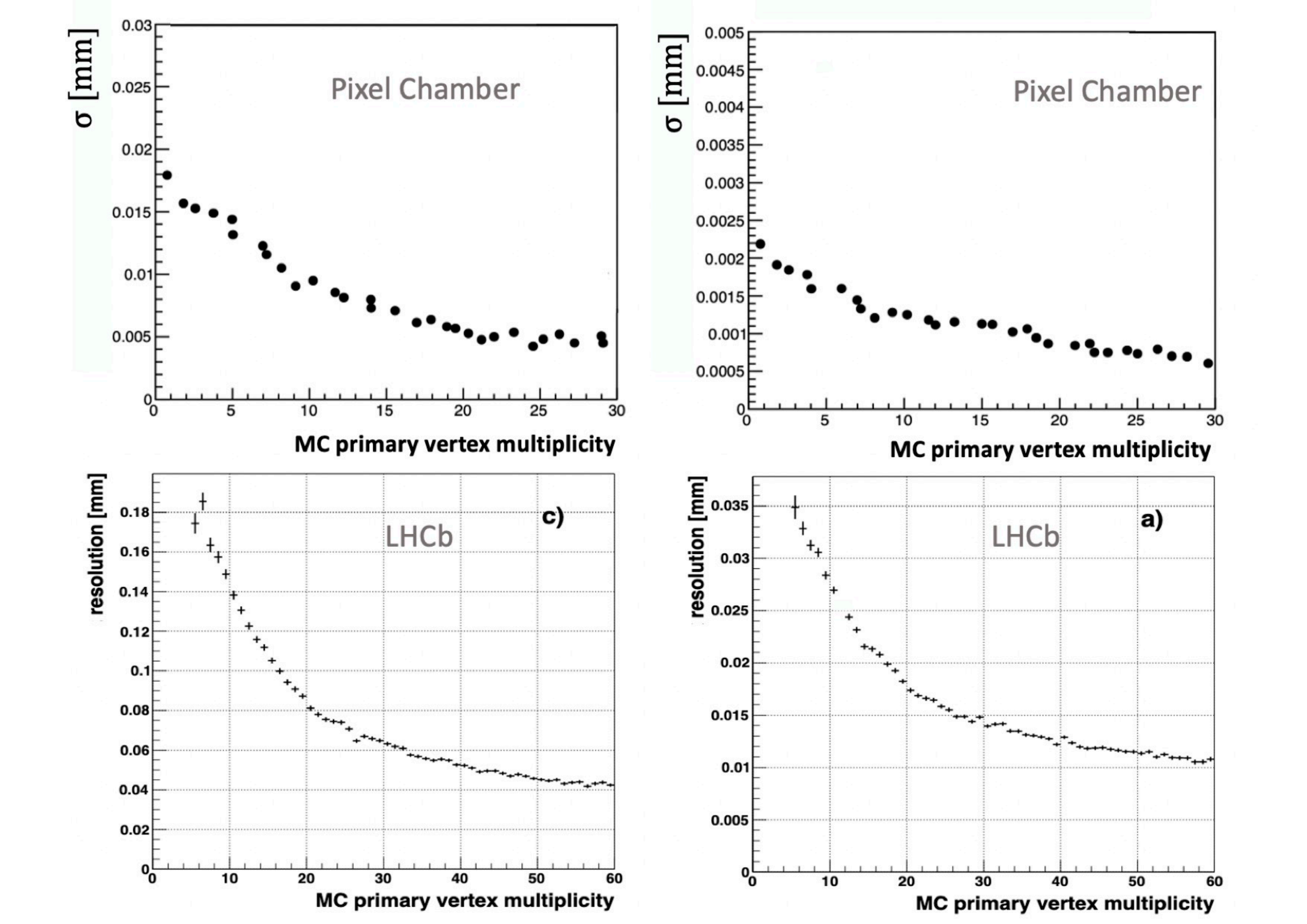
- Algorithm based on a *weighted* Least Square fit procedure (from LHCb[1], ALICE, NA45 and NA60)

[1]M. Kucharczyk, P. Morawski, and M. Witek, *Primary Vertex Reconstruction at LHCb*, LHCb-PUB-2014-044

Developed in 2 main steps:

1. Choice of a vertex candidate (vertex seed):
   - Vertex candidate chosen as the last point of the proton track (the one which starts at the entrance of the detector)
2. Weighted least square method to minimize χ^2_{PV} in order to obtain the final vertex position
   - Iterative procedure repeated for every considered track
   - A χ^2_{IP} is calculated for each track expressing the distance between the vector of fitted y and z vertex coordinates and the vector of y and z track coordinates obtained from fit parameters (for $x=x_V$)
   - Weight assigned to each track depending on the χ^2_{IP} and Tuckey's constants
   - Seed position updated at each iteration
   - Iteration repeated until the χ^2_{PV} convergence

Vertex resolution vs vertex track multiplicity



Resolution: σ of the residual (Reconstructed vertex coordinates – MC vertex coordinates) distributions.

For $N_{tracks}>2$

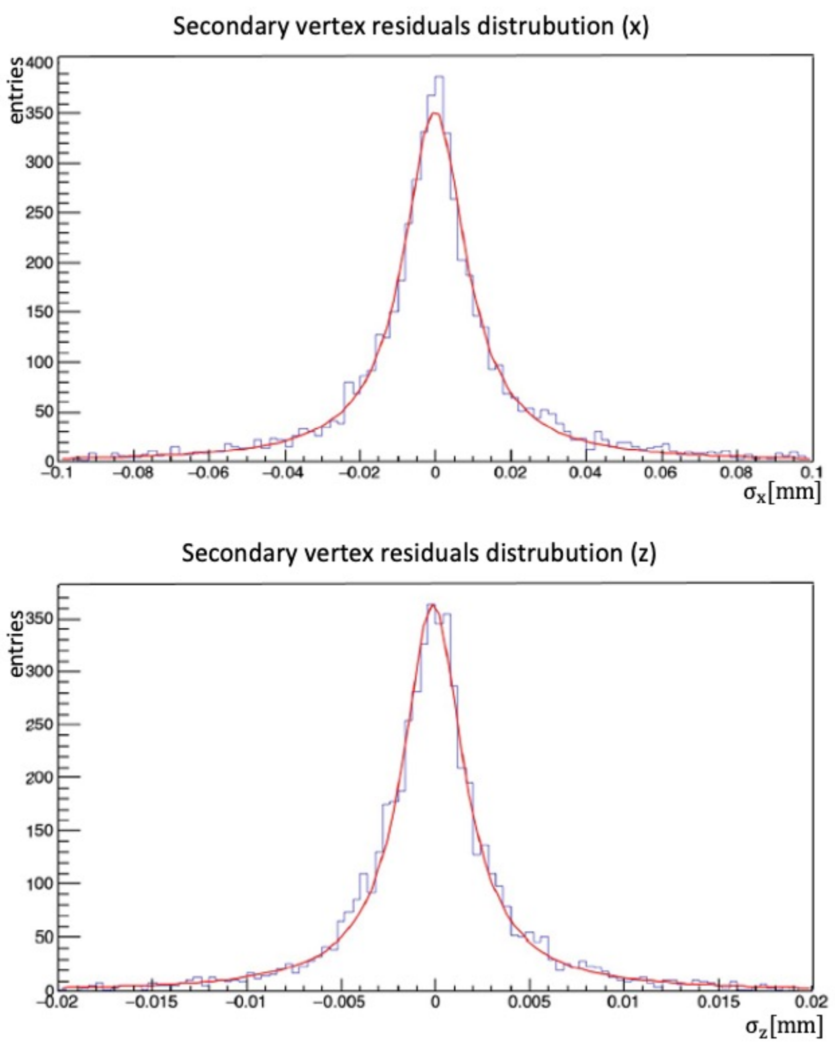
- $\sigma_x=15\ \mu m$
- $\sigma_y=2.4 \mu m$
- $\sigma_z=1.8 \mu m$

Qualitatively the resolution with PixelChamber is a factor 10 better than LHCb

LHCb note *Primary Vertex Reconstruction at LHCb*, LHCb-PUB-2014-044

Secondary vertex reconstruction for $\mathrm{D}^0 \rightarrow \mathrm{K}\pi$

- Secondary vertex reconstruction performed for events with:
  - $\chi^2_{PV}/ndf < 2.5$
  - Primary vertex tracks multiplicity > 3
- Secondary vertex fit performed applying primary vertex reconstruction algorithm on pairs of tracks not belonging to the primary vertex
- Vertex seed:
  - Closest point of one of the two tracks under test to the primary vertex
- Between all secondary vertices found, the D^0 one is selected as the closest one to the primary vertex



Secondary vertex resolutions
(Reconstructed vertex coordinates – MC vertex coordinates) :

- $\sigma_x \sim 25\ \mu m$
- $\sigma_y \sim 5\ \mu m$
- $\sigma_z \sim 4\ \mu m$

Outlook

- ✓ According to Geant4 simulations it is possible to reach very high efficiency for the reconstruction of hadronic tracks produced from p-Si interactions inside Pixel Chamber
- ✓ Primary vertices and D^0 secondary vertices coordinates can be reconstructed with very high precision
- Improvement of the track finding algorithm:
  - Kalman filter to take into account multiple scattering
  - Machine learning (neural network) for 3D imaging
- Finalize development of secondary vertex reconstruction algorithm (reconstruction of other charm and beauty states)
- Full reconstruction of charmed particles:
  - ➢ Momentum measurements of decay products with a silicon telescope
  - ➢ Detailed performance study of charm production at CERN SPS

Backup slides

Track fit

- Tracks are fitted with a linear model of parametrized line:

$$x = x_0 + v_x t$$
$$y = y_0 + v_y t$$
$$z = z_0 + v_z t$$

$\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix}$ →direction cosines vector

- Fits of the projections of the line in the x-y and x-z planes considering y and z as functions of x:

$$y(x) = y_0 + \alpha(x - x_0)$$
$$z(x) = z_0 + \beta(x - x_0)$$

x_0 fixed arbitrarily (x coordinate of the track starting point)

$\alpha = v_y/v_x \quad \beta = v_z/v_x$

Track fit

- χ^2 function to be minimized:

$$\chi^2 = \sum_{i=1}^{n_{points}} \frac{\left(y_i - y(x_i)\right)^2}{\sigma_y^2 + \alpha^2 \sigma_x^2} + \frac{\left(z_i - z(x_i)\right)^2}{\sigma_z^2 + \beta^2 \sigma_x^2}$$

- If the track is perpendicular to the x axis the fit reduces to the y-z projection:

$$\chi^2 = \sum_{i=1}^{n_{points}} \frac{\left(z_i - z(y_i)\right)^2}{\sigma_z^2 + \beta^2 \sigma_y^2}$$

- In the χ^2 functions the effective variance formula is considered to take into account the x error

Track fit

- The errors used for the fit are the pixel pitch / $\sqrt{12}$:
  - $\sigma_x = 29.24/\sqrt{12}\ (\mu\text{m}) = 8.44\ (\mu\text{m})$
  - $\sigma_y = 50/\sqrt{12}\ (\mu\text{m}) = 14.43\ (\mu\text{m})$
  - $\sigma_z = 26.88/\sqrt{12}\ (\mu\text{m}) = 7.75\ (\mu\text{m})$

- Parameters obtained from the fit are:

$$q_i = \begin{pmatrix} \alpha \\ y_0 \\ \beta \\ z_0 \end{pmatrix}$$

$$\alpha = v_y/v_x \qquad \beta = v_z/v_x$$

$$v_x = \frac{1}{\sqrt{(1+\alpha^2+\beta^2)}}$$

- For a track of N points there are 2N-4 degrees of freedom

Vertex Fit

Goal: determine x_v, y_v, z_v vertex coordinates

- ➢Algorithm based on a *weighted* Least Square fit procedure (from LHCb[1], ALICE, NA45 and NA60)

[1]M. Kucharczyk, P. Morawski, and M. Witek, *Primary Vertex Reconstruction at LHCb*, LHCb-PUB-2014-044

1. Mandatory proton track: the track at the entrance of the sensor
2. First guess for the vertex coordinates (vertex seed):
   - end point of the proton track → reasonably close to the primary vertex
3. All other tracks with χ^2/ndf< 1.5 from the linear fit and with more than 50 points included in the vertex fit
4. A χ^2_{IP} is calculated for each track that expresses the distance between the vector of fitted y and z vertex coordinates (h_i) and the vector of y and z track coordinates obtained using fit parameters and imposing $x=x_v$ (q_i)

$$\chi^2_{IP} = \sum_{i=1}^{n_{tracks}} (q_i - h_i)^T V_i^{-1} (q_i - h_i)$$

Steps of vertexing algorithm for primary vertex

5. Biweighted correlation used to assign a weight (W_T) to each track under test according to their χ^2_{IP} and some constants called Tukey's constants, in order to avoid the worsening of the vertex resolution due to tracks not well reconstructed

$$W_T = \left(1 - \frac{\chi^2_{IP}}{C_T^2}\right)^2 \rightarrow \text{if } \chi^2_{IP} < C_T$$

$$W_T = 0 \rightarrow \text{if } \chi^2_{IP} \geq C_T$$

6. Minimization of primary vertex χ^2_{PV}:

$$\chi^2_{PV} = \sum_{i=1}^{n_{tracks}} \chi^2_{IP\,i}\, W_{T\,i}$$

8. Iterative procedure repeated for different decreasing values of C_T
   - initially set to a large value (10^6) to avoid convergence to a local minimum and decreased iteratively → iteration stopped upon convergence to final χ^2_{PV}
9. Updated vertex position used to recalculate χ^2_{IP} and W_T at each iteration:
   - Tracks with a zero weight at a certain iteration are not excluded → weight recalculated at the following iteration and attached to the PV if the updated weight is different from zero