Pixel chamber: a silicon heavy-flavour imager with monolithic active pixel sensors for measurements of charm and beauty with unprecedented precision

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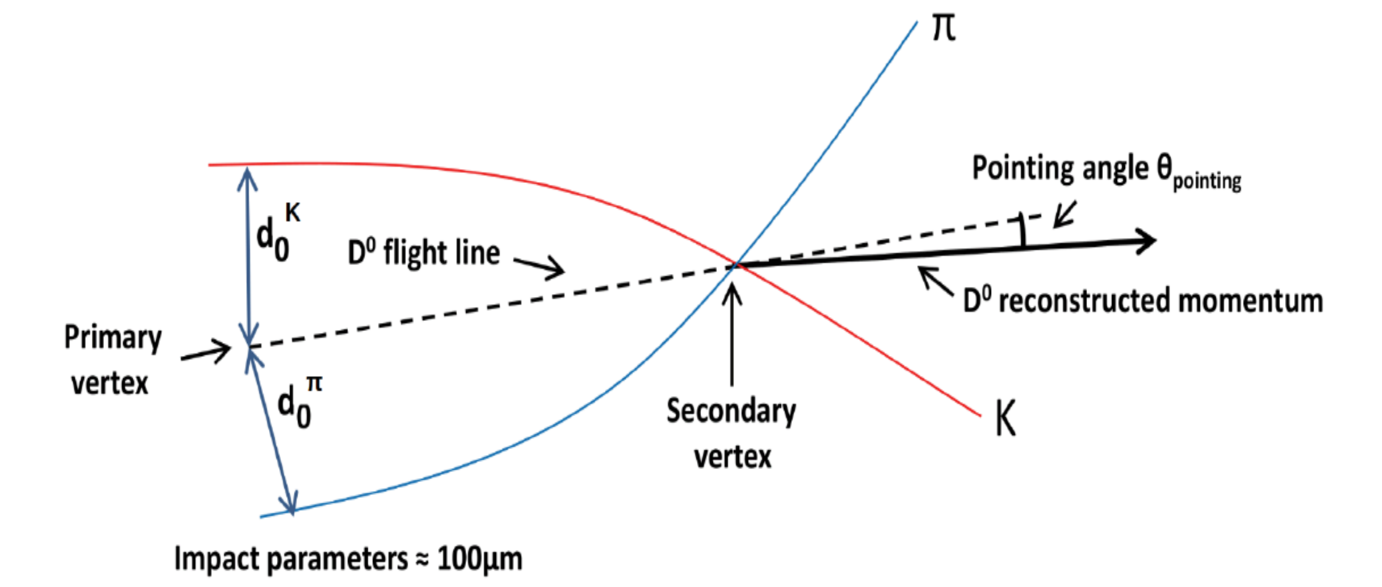
Charm and beauty

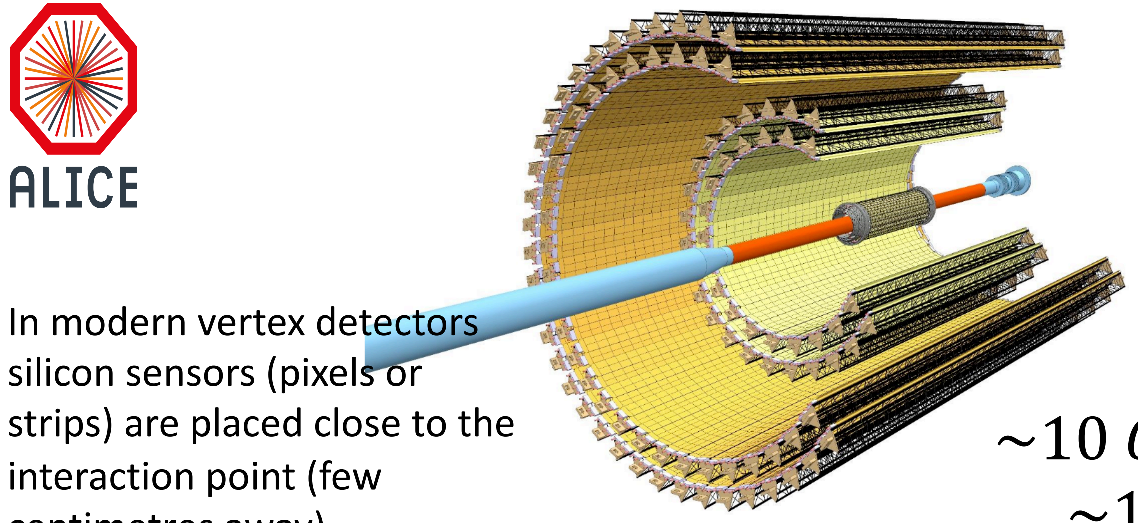
Charm and beauty quarks are very important for SM studies and for the research of new physics

- Long lifetime→can travel distances from O(10-100 μm) up to mm before decay



Ideal detectors

- great spatial resolution to separate primary from secondary vertices



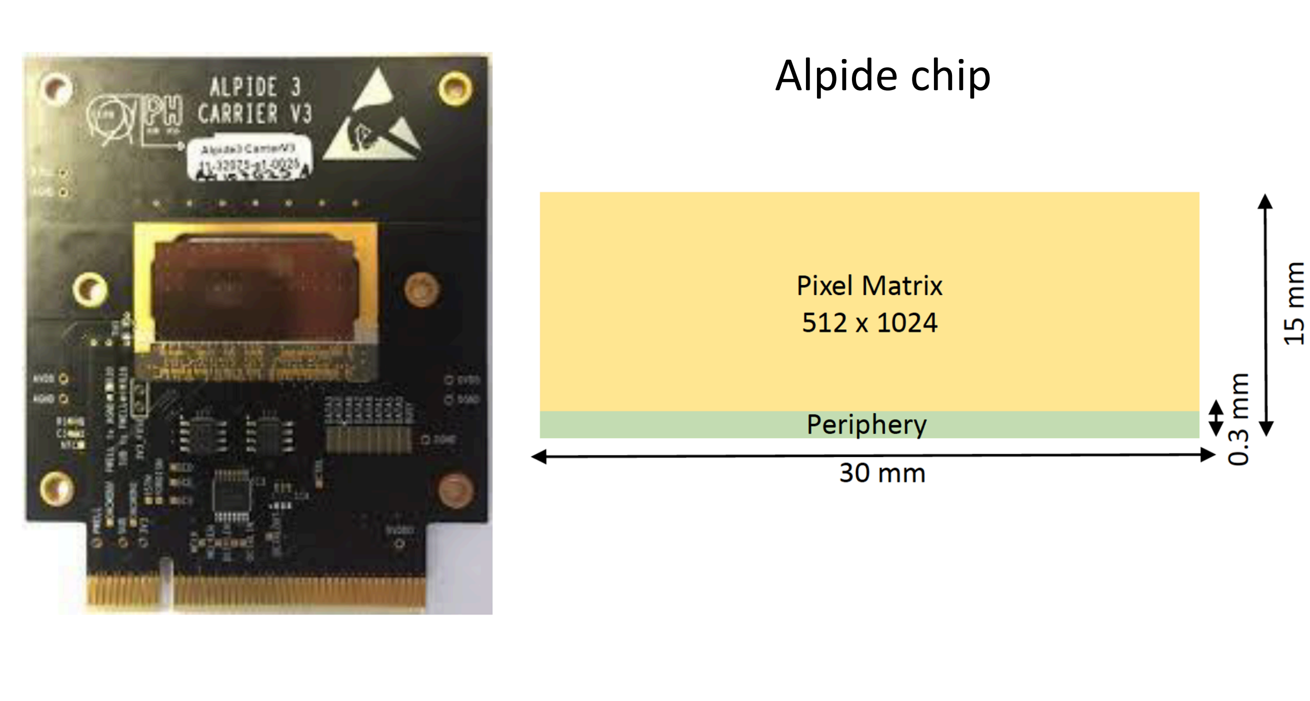
In modern vertex detectors silicon sensors (pixels or strips) are placed close to the interaction point (few centimetres away)

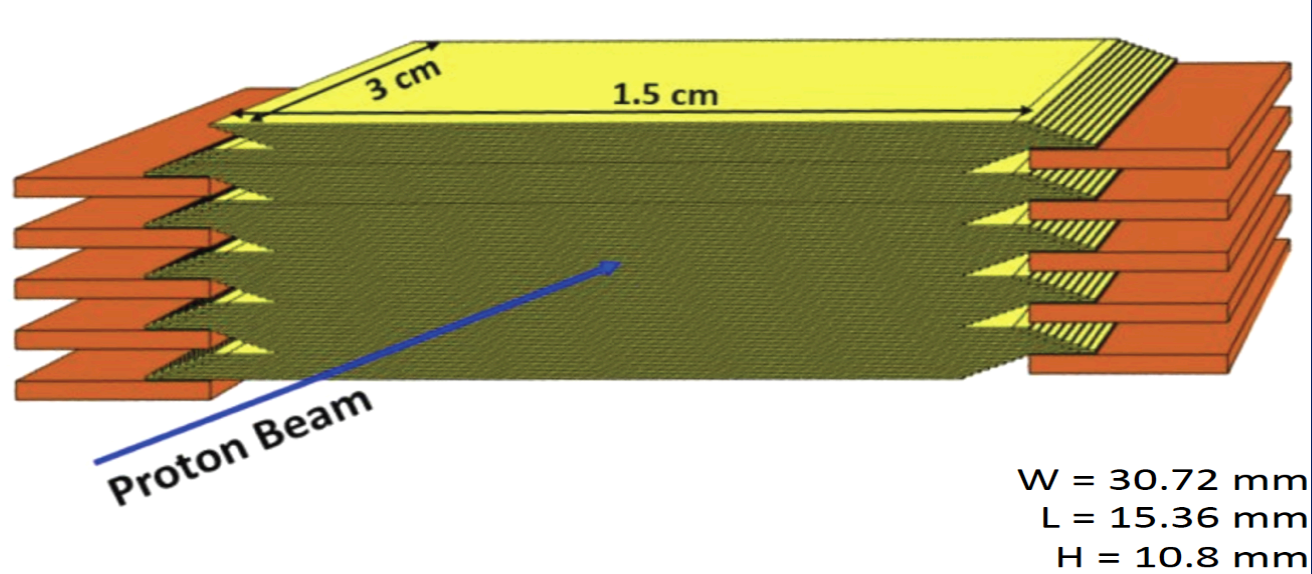
$\sim 10\ G\ pixels$
$\sim 10\ m^2$

Pixel Chamber

Idea:

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





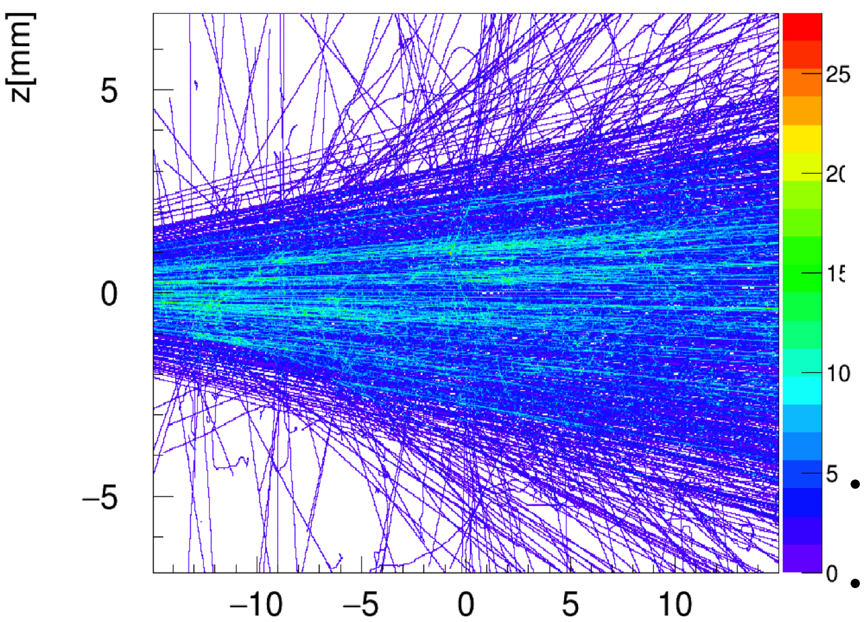
Pixel Chamber: Geant4 Simulation

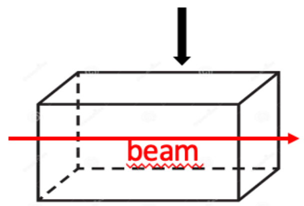
- Simulation of a protype made of 216 ALPIDE sensors
- Each sensor is a matrix of 1024x512 pixels
- 10^4 p-Si inelastic interactions at 400 GeV/c:

➢ Beam simulation:

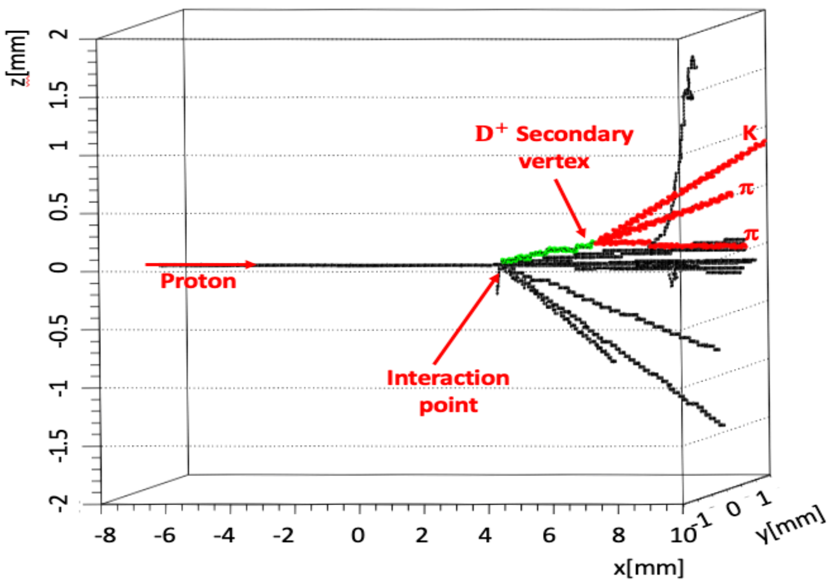
- ✓ Gaussian y,z production coordinates with σ=0.2 mm
- ✓ Considered some angular spread of beam direction

Top view of the stack





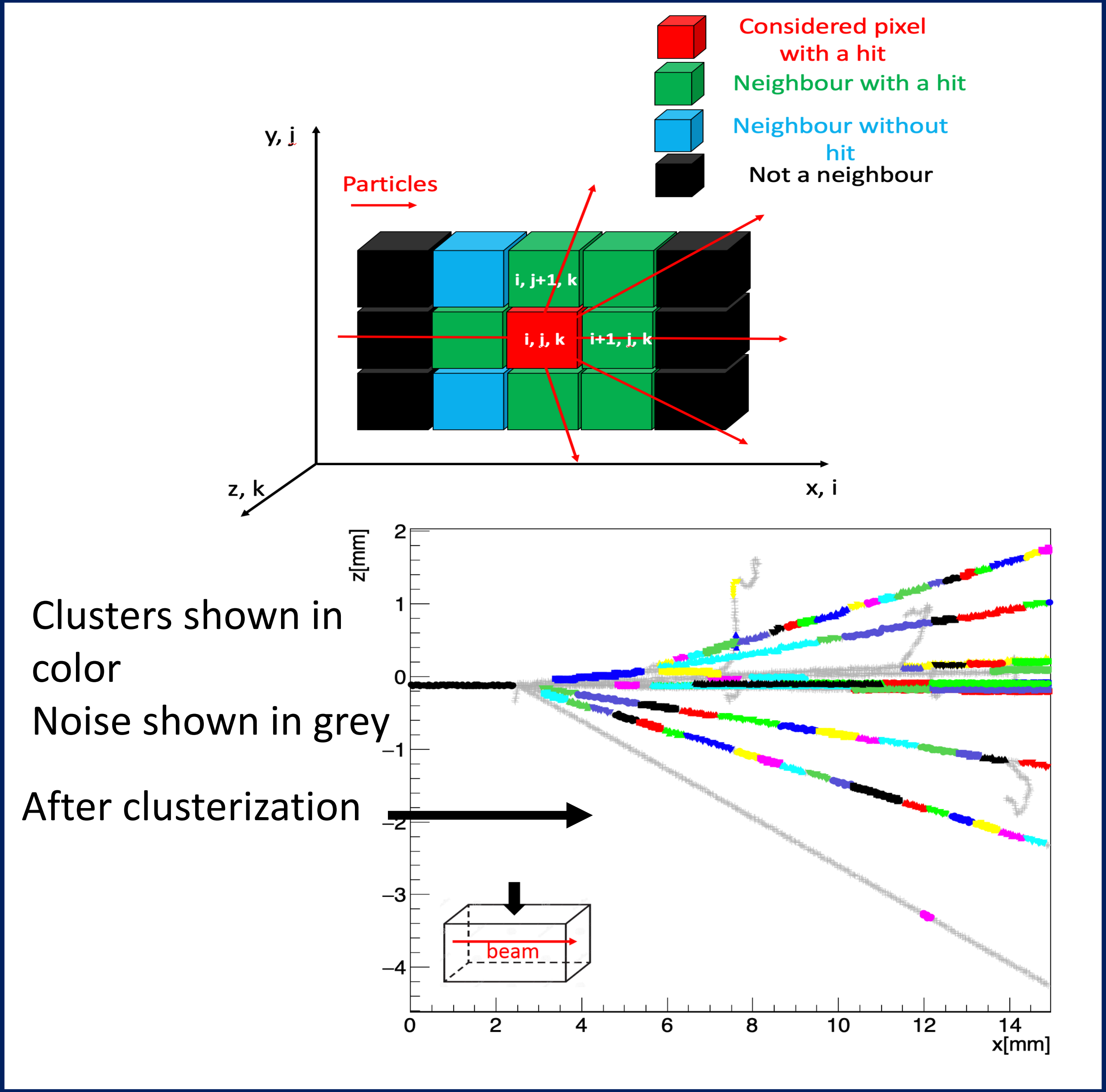
3D view of the stack



- 400 GeV p-Si interactions generated using Geant4 physics-list
- D meson 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)



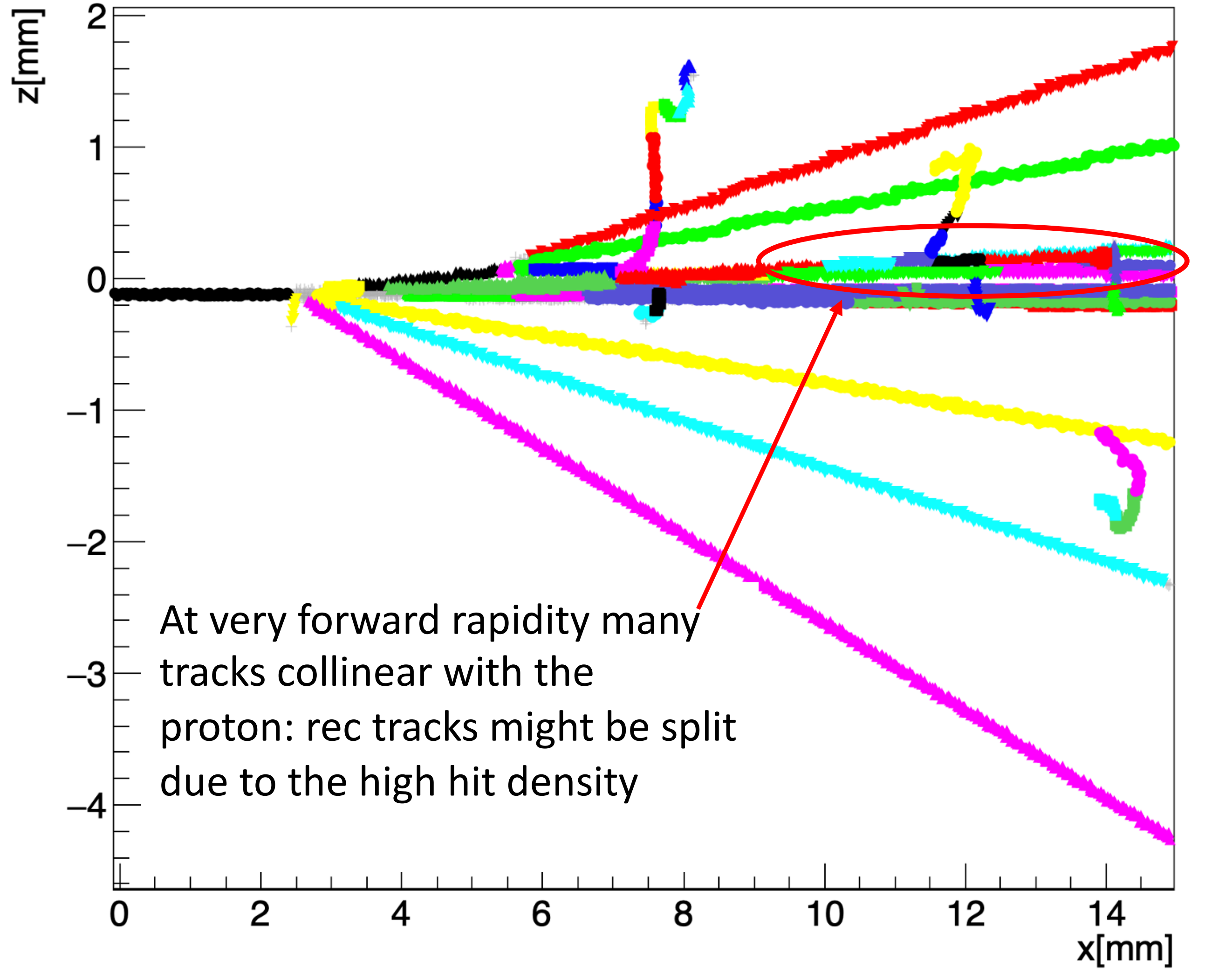
Algorithm: track finding

- 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:

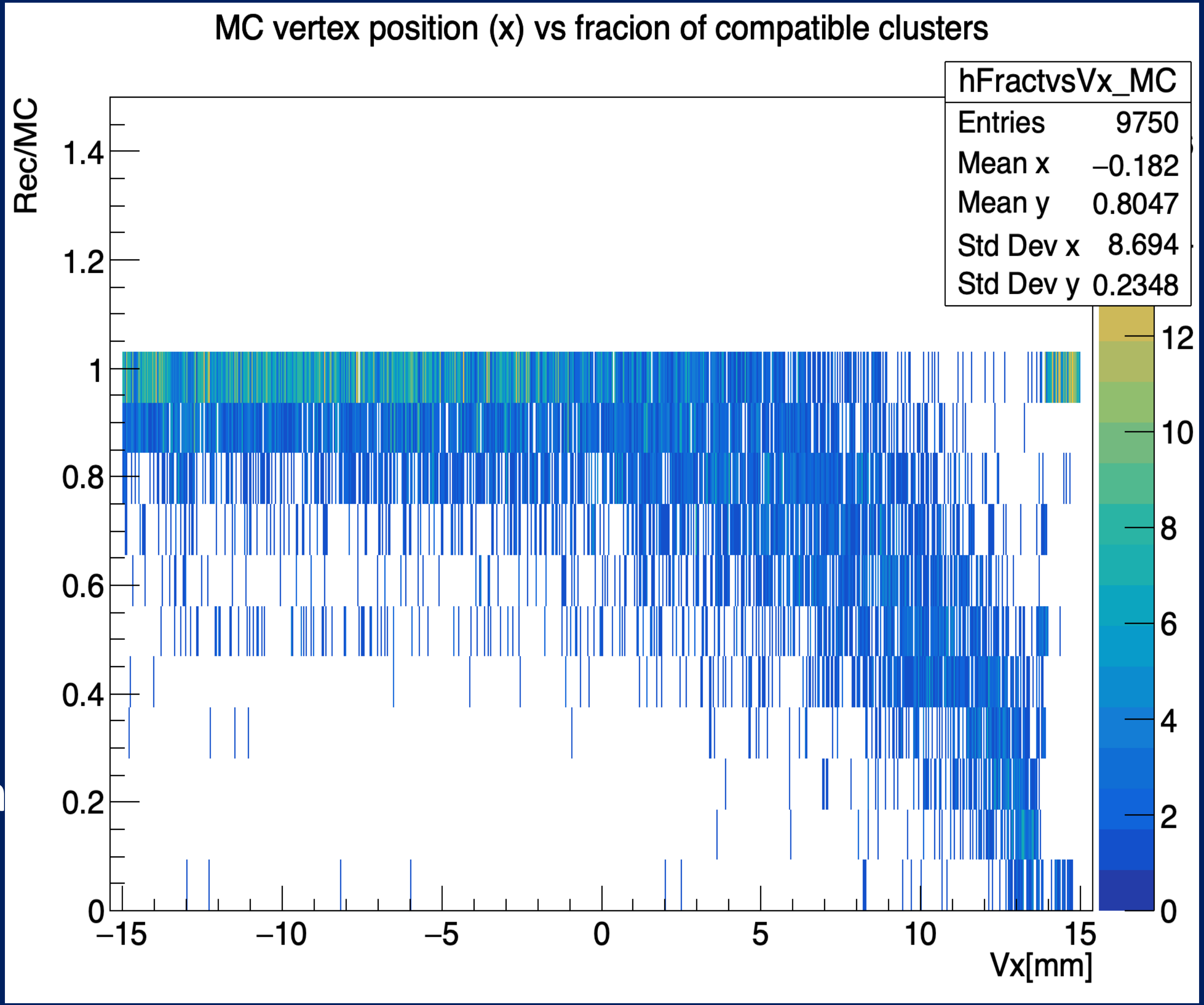
- Two more passes with less stringent neighbours condition:
  - ➢number of neighbors < 4 and <6

Satisfactory reconstruction of most hadronic tracks



Tracks reconstruction efficiency

- The efficiency of the track reconstruction (Reconstructed/MC tracks) gets worst at the end of the detector
- Mean value of efficiency reconstruction:
  - ~80% with no cuts on the vertex position
  - ~90% with a cut on the vertex position along x < 5 mm



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:
   - 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 fitted vertex and the calculated one (obtained from the track fit)
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

Steps of vertexing algorithm for primary vertex

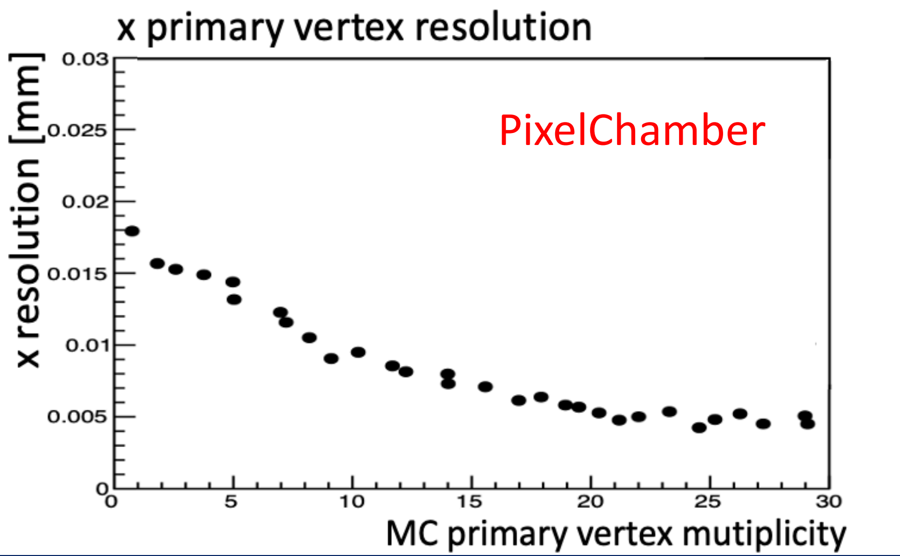
5. Minimization of primary vertex χ^2_{PV}:

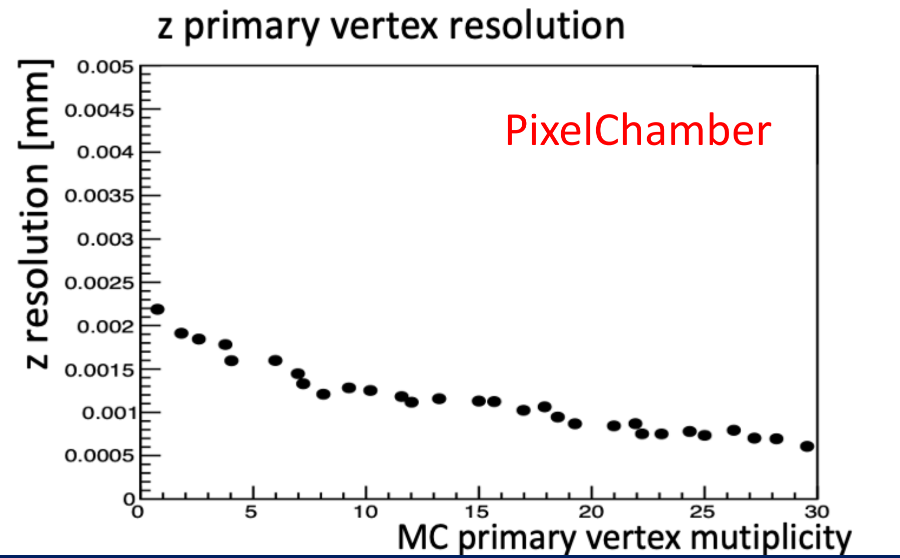
$$\chi^2_{PV} = \sum_{i=1}^{n_{tracks}} \chi^2_{IP\,i}\, W_{T\,i}$$

6. 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 down iteratively → iteration stopped upon convergence to final χ^2_{PV}

7. 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

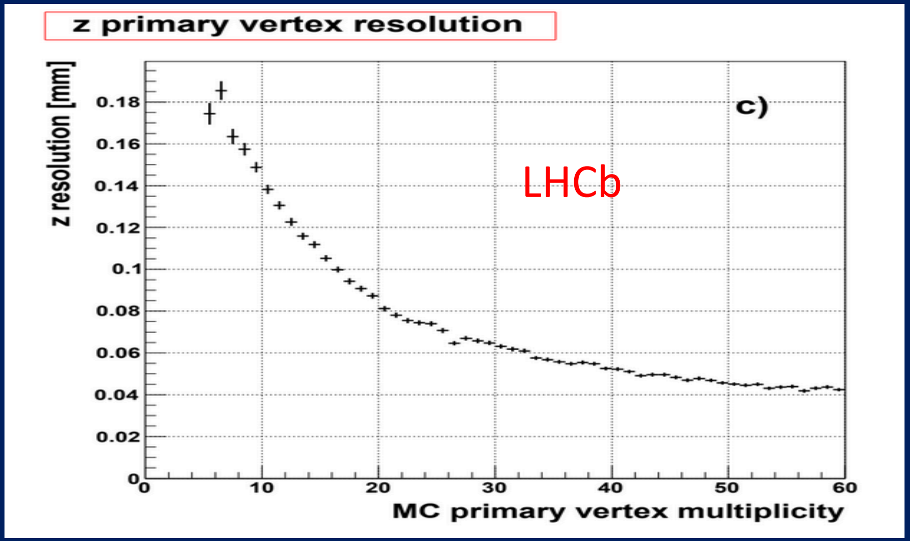
Vertex resolution vs #tracks associated to vertex

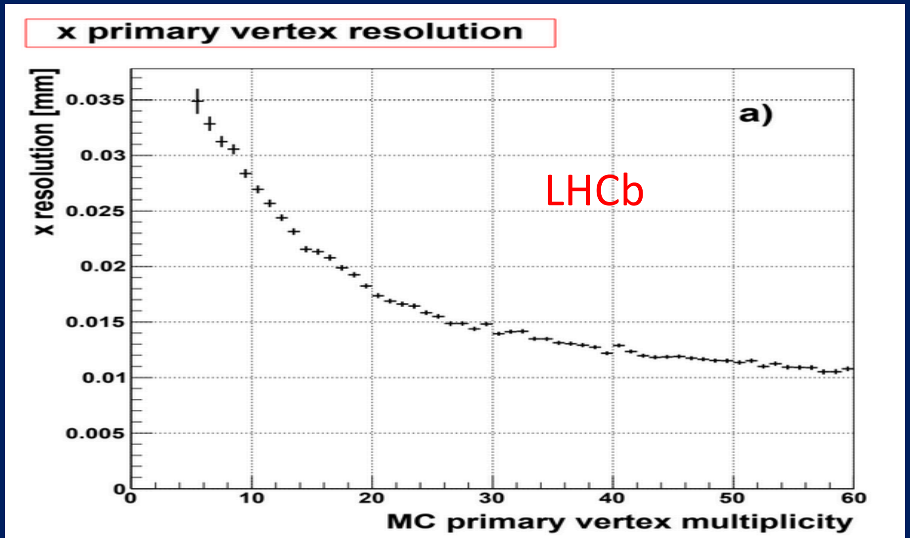




Resolution: σ of the residual (Reconstructed vertex coordinates – MC vertex coordinates) distributions. For $N_{tracks}>2$

- σ_x=15 μm
- σ_y=2.4μm
- σ_z=1.8μm





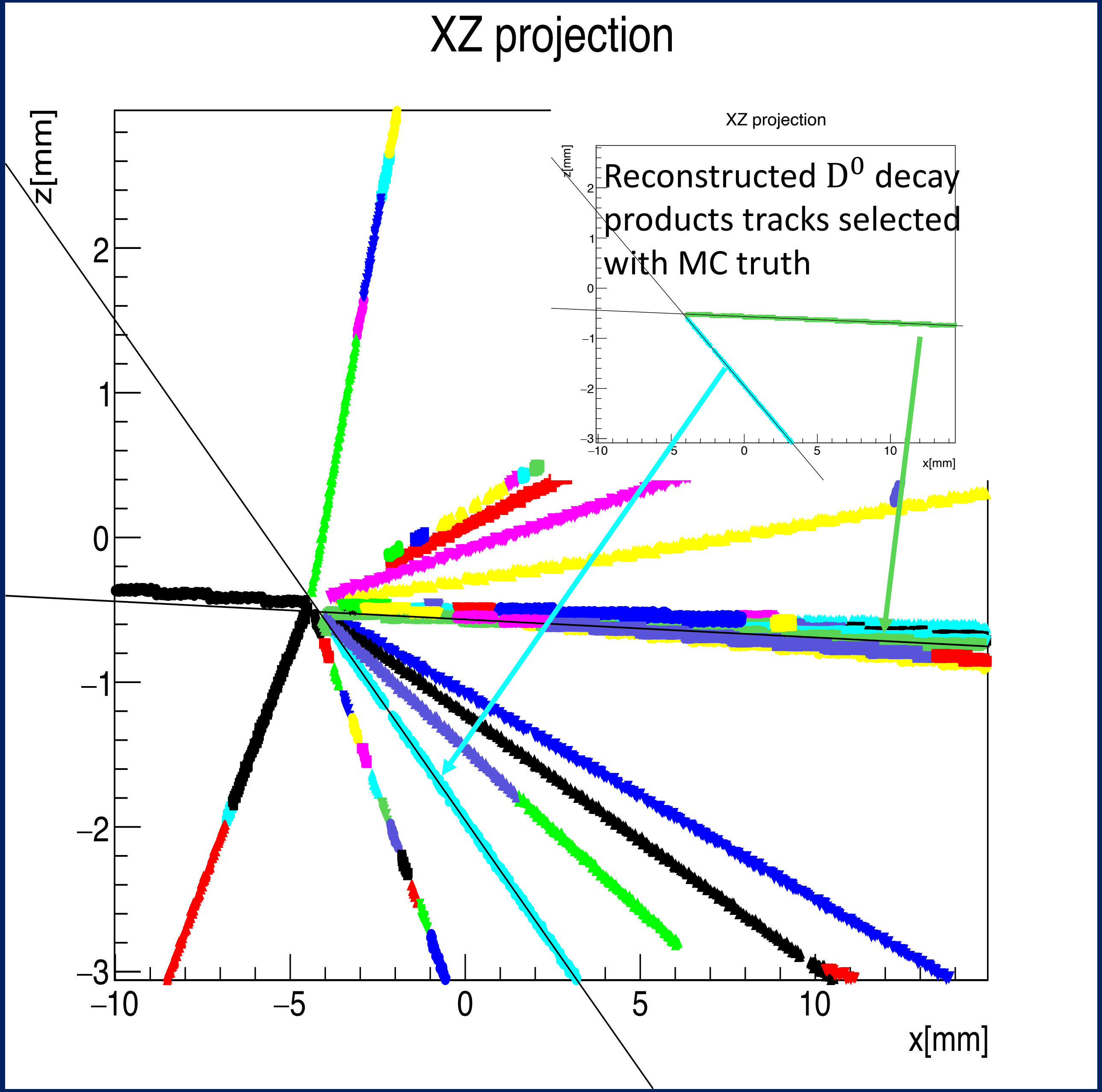
Qualitatively the resolution with PixelChamber is a factor 10 better than LHCb

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

Example of reconstructed D^0 secondary vertex

Preliminary studies on secondary vertices for $D^0 \rightarrow K\,\pi$:

- ➢ vertex searched testing two tracks at a time usining the same algorithm described for primary vertex
- Monte Carlo truth for D^0 vertex:
  - X_v = -4.160679 mm
  - Y_v = 0.202199 mm
  - Z_V = -0.514571 mm
- Reconstructed secondary vertex:
  - X_v = -4.170620 ± 0.002387 mm
  - Y_v= 0.204738 ± 0.000817 mm
  - Z_V = -0.513834 ± 0.000612 mm
- Residuals:
  - ΔX= -0.009941 mm
  - ΔY= 0.002539 mm
  - ΔZ= 0.000737 mm



Outlook

✓ Improvement of the track finding algorithm:
- Kalman filter to take into account multiple scattering
- Machine learning (neural network) for 3D imaging (in collaboration with M. Marchesi and R. Tonelli from Dipartimento di informatica)

✓ 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

- Construction of a detector prototype