Pixel TPC simulation and reconstruction

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Outline

Readout of the ILD TPC

Baseline TPC endplate

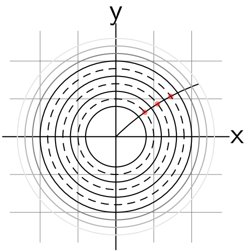
- Micromegas or GEM amplification
- Readout with $\simeq$ 6mm $\times$1mm sized pads

Endplate with timepix3 chip with integrated grid under development

- Integrated amplification grid
- Readout with a 256 $\times$ 256 grid of 55μm $\times$ 55μm pixels
- New timepix3 chip offers improved time resolution and data-acquisition

Simulation of pads within ilcsoft

version 01-17-09, ILD_o1_v5



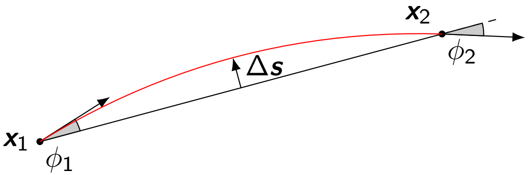
Volumes are organised as tube shaped layers, there are no pad columns

- Detector is described by DD4HEP geometry
- Pads have ideal 100% coverage
- Geant4 processes interactions of particle(s) from gun or event
- Single hit in TPC is deposited if energy is above threshold (32eV) in a single pad. Position of pad centre crossing is recorded
- Diffusion and hit resolution is simulated by smearing the hits by the expected resolution in $r\phi$ and z directions

Simulation of pixels

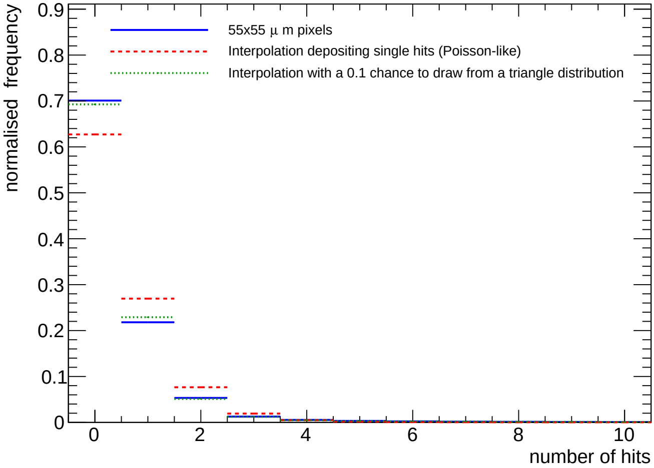
- Pixels are described by the same cylindrical volumes in DD4HEP
- Pixels also have ideal 100% coverage
- Multiple hits per row can be deposited
- In order to simulate diffusion, hits are smeared transverse to track in x, y and z directions

- Interpolate the track with a parabola over a volume of 0.99 mm (18 pixel rows)

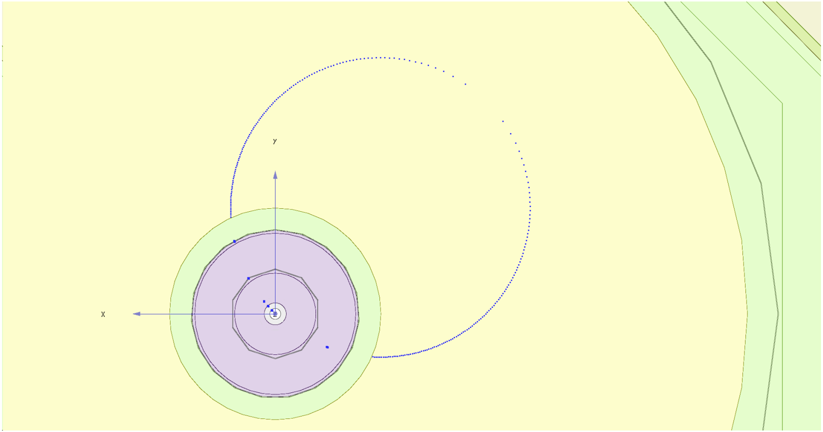


Distribution of hits along the track

- Ionization in gas follows roughly a Landau distribution
- Approximate by a combination of a Poisson and a triangle (for now)

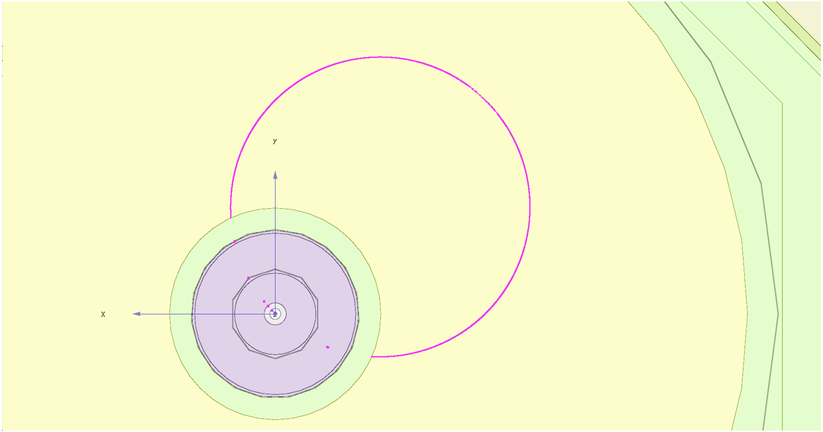


Pad simulation of a 700 MeV muon



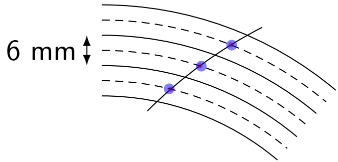
Simulated pad hits are only at layer centre crossing

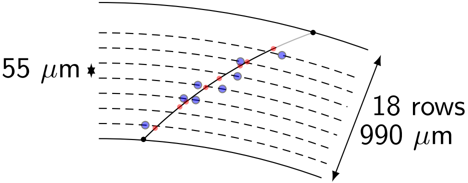
Pixel simulation of a 700 MeV muon



Interpolated pixel hits are placed everywhere along the track

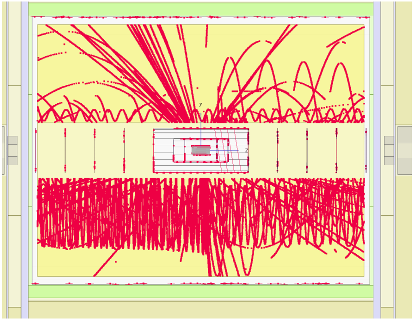
Simulation of pad hits compared to pixel hits





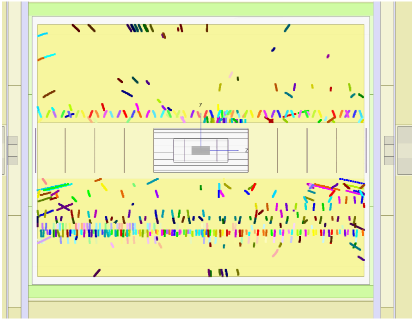
Pad hits	Pixel hits
6 mm × 1 mm	55μm × 55μm
Exactly one hit per layer	Multiple or no hits per layer
22 electrons per hit	1 electron per hit
Only diffusion in $r\phi$ and z	Diffusion in x, y and z
∼200 hits per track	∼10 000 hits per track

Track finding for pads using Clupatra



Tracker hits

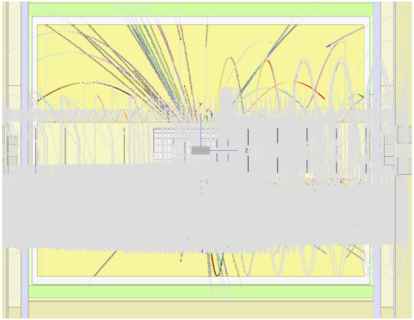
Track finding for pads using Clupatra



Seeds

1. Seed finding
   - Uses nearest neighbour clustering by distance in a pad row range of 15 rows

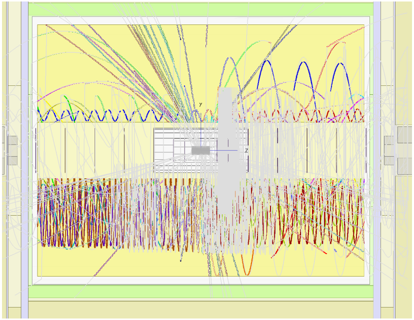
Track finding for pads using Clupatra



Seed fit and extended

1. Seed finding
   - Uses nearest neighbour clustering by distance in a pad row range of 15 rows
2. Fit track to seeds
   - use first, middle and last hit to initialise track parameters
3. Extend track inwards (and outwards)
   - Uses Kalman filter (Kaltest) in MarlinTrk

Track finding for pads using Clupatra



Track fit

1. Seed finding
   - Uses nearest neighbour clustering by distance in a pad row range of 15 rows
2. Fit track to seeds
   - use first, middle and last hit to initialise track parameters
3. Extend track inwards (and outwards)
   - Uses Kalman filter (Kaltest) in MarlinTrk
4. Merge split segments

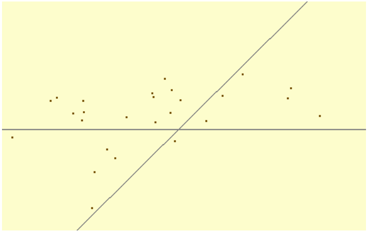
Fit tracks by Extended Kalman filter

Fit track by an Extended Kalman Filter: a recursive fitting algorithm working in steps:

- Predict state at next site using propagator $\boldsymbol{a}_k^{k-1} = \boldsymbol{f}_k(\boldsymbol{a}_k)$
  - $\boldsymbol{a}_k$ contains track parameters $(d_\rho, \phi_0, \kappa, d_z, \tan\lambda)$
- Update with measurement $\boldsymbol{m}_k$ using state-to-measurement projector $\boldsymbol{h}_k(\boldsymbol{a}_k^{k-1})$
  - Add hit and update if $\chi^2 < \chi^2_{\text{threshold}}(=35)$
  - $\boldsymbol{m}_k$ are coordinates of a cylindrical surface $(r\phi, z)$

Issues when applying pad-track-reconstruction to pixel-hits

- Seed finding: CPU time of nearest neighbour clustering scales as $\mathcal{O}(N^2)$
  Unsuitable for many thousands of pixel hits
- Track fit: initialise Kalman filter with first, middle and last hit
  3 hits do not fix the track tight enough, first hits can pull the track fit in the wrong direction

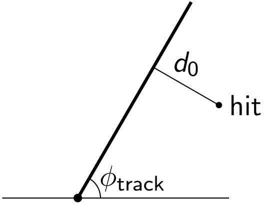


- Hits restricted to a cylindrical surface
  For pixel another representation is more suitable

Track finding for pixel TPC

- Perform clustering by ϕ (Hough-transform like)
  - Fill histogram of hits by ϕ in pad row range of 750 pixel rows
  - Maximum bin is cluster with track candidate if more than 200 hits
  - construct a straight line from the detector center to the average position
  - Cut hits on distance from this line (10mm in $r\phi$ and 3mm rz)
  - initialise track fit with this line

Track fitting for pixel hits



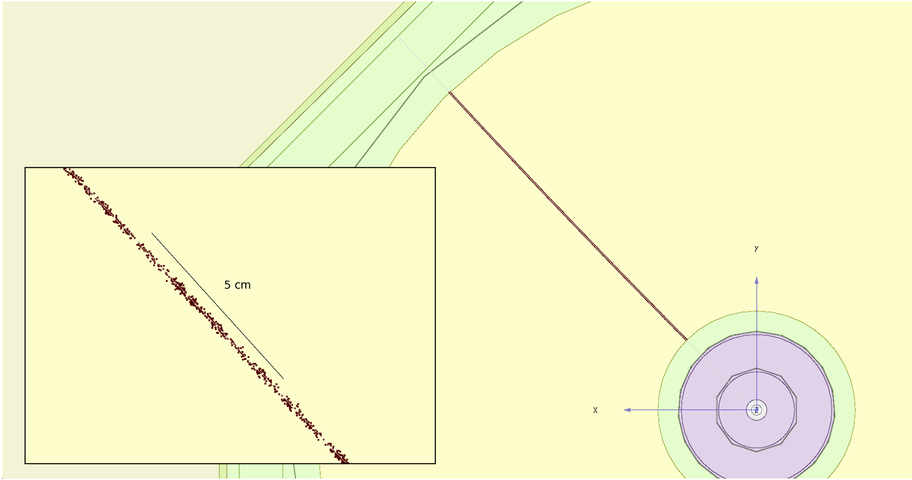
Define alternative measure with $\boldsymbol{m}_k$ as a function of $\boldsymbol{a}_k^{k-1}$

$$\boldsymbol{m}_k(\boldsymbol{a}_k^{k-1}) = \begin{pmatrix} d_0 \\ z \end{pmatrix} = \begin{pmatrix} \Delta x \sin(\phi_{\text{track}}) - \Delta y \cos(\phi_{\text{track}}) \\ z_{\text{hit}} + \tan\lambda(\Delta x \cos(\phi_{\text{track}}) + \Delta y \sin(\phi_{\text{track}})), \end{pmatrix}$$

The distance to the track d_0 better represents the measurement

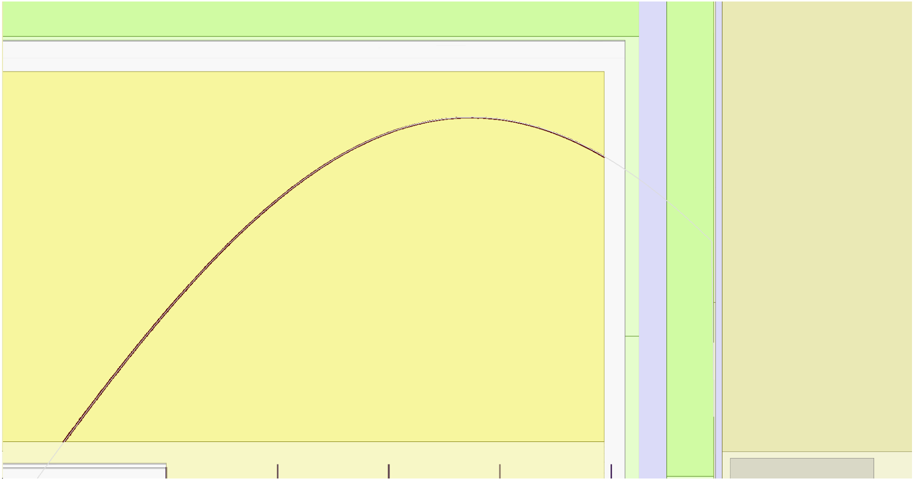
Fit of straight track

50 GeV muon



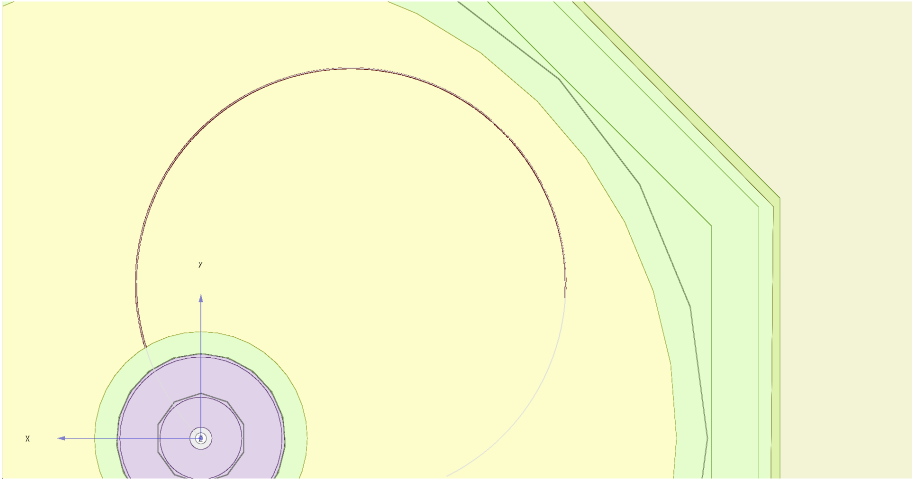
Fit of curled track

1 GeV muon without energy loss



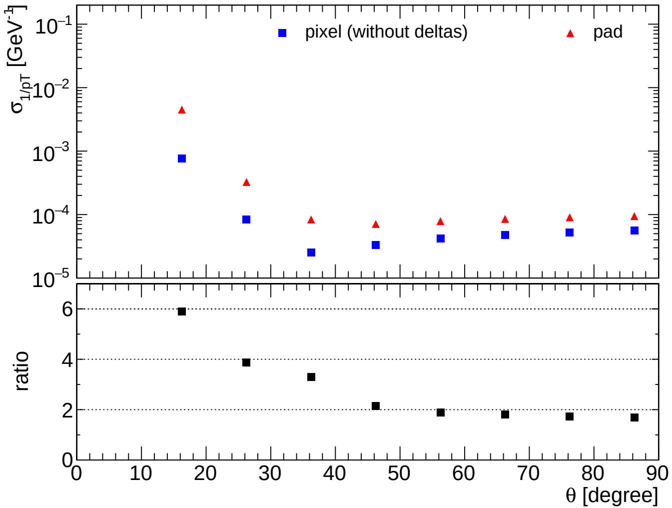
Fit of curled track

1 GeV muon without energy loss



Momentum resolution from track fit

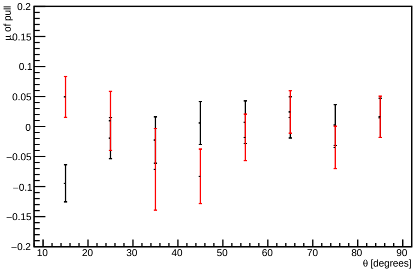
50 GeV muon

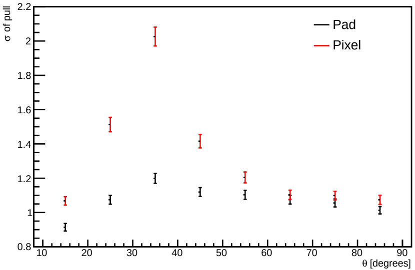


Pixels hits simulated with delta's, but rejected before reconstruction

Pull of $1/p_T$

from 8×1000 tracks of 50 GeV muons

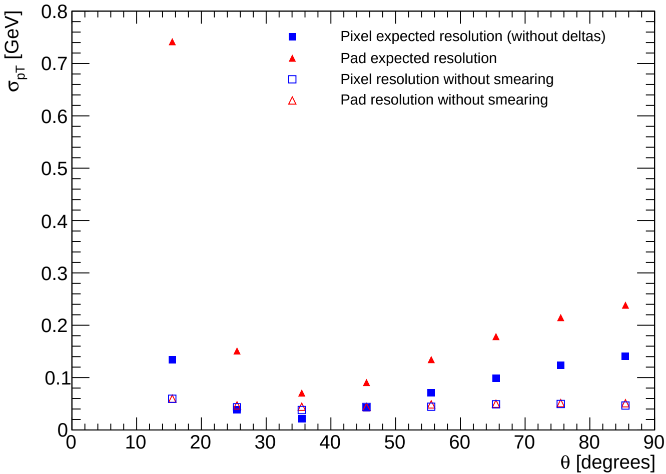




Mean μ does not indicate any biases

σ of pull is too large at angles with the best momentum resolution

Distortion of σ of pull



p_T difference between input and fit to unsmeared hits is $\sim$ 40 MeV

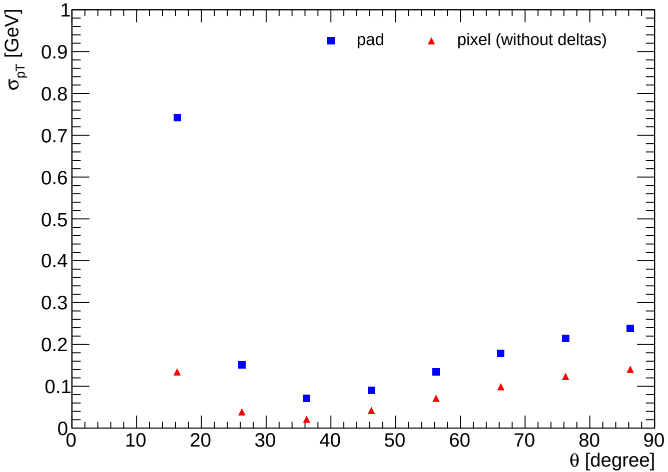
σ of pull is increased by precision settings or a bug in the code

Conclusion

- A muon track was successfully simulated and reconstructed with a pixel readout
- First estimates of the pixel readout performance show a factor $\sim 2-6$ improvement over to the pad readout
- Next steps:
  - Fix pull of track fit
  - Do delta rejection using an algorithm
  - Continue studies of performance of pixel readout
  - Investigate dE/dx performance
  - Implement an endplate layout with more realistic coverage ($\sim 80\%$)
  - Simulate and reconstruct physics events with a pixel readout

Momentum resolution from track fit covariance matrix

50 GeV muon



Extended Kalman filter

Recursive fitting algorithm to find state vector $\boldsymbol{a}_k$ and covariance $\boldsymbol{C}_k$ at site k from a series of measurements $\boldsymbol{m}_k$ by procedure:

- Predict
  - $\boldsymbol{a}_k^{k-1} = \boldsymbol{f}_{k-1}(\boldsymbol{a}_{k-1})$, where $\boldsymbol{f}_k(\boldsymbol{a}_k)$ is the state-propagator
  - $\boldsymbol{C}_k^{k-1} = \boldsymbol{F}_{k-1}\boldsymbol{C}_{k-1}\boldsymbol{F}_{k-1}^T + \boldsymbol{Q}_{k-1}$, where $\boldsymbol{F}_{k-1} = \frac{\partial \boldsymbol{f}_{k-1}}{\partial \boldsymbol{a}_{k-1}}$, and $\boldsymbol{Q}_k$ the covariance of the process noise
- Update
  - $\boldsymbol{a}_k = \boldsymbol{a}_k^{k-1} + \boldsymbol{K}_k\left(\boldsymbol{m}_k - \boldsymbol{h}_k(\boldsymbol{a}_k^{k-1})\right)$, where $\boldsymbol{h}_k(\boldsymbol{a}_k)$ the projector, $\boldsymbol{K}_k = \boldsymbol{C}_k^{k-1}\boldsymbol{H}_k^T(\boldsymbol{V}_k + \boldsymbol{H}_k\boldsymbol{C}_k^{k-1}\boldsymbol{H}_k^T)^{-1}$, $\boldsymbol{H}_k = \frac{\partial \boldsymbol{h}_k}{\partial \boldsymbol{a}_k^{k-1}}$, and $\boldsymbol{V}_k$ the coveriance of the measurement noise
  - $\boldsymbol{C}_k = \left((\boldsymbol{C}_k^{k-1})^{-1} + \boldsymbol{H}_k^T\boldsymbol{G}_k\boldsymbol{H}_k\right)^{-1}$, where $\boldsymbol{G}_k = (\boldsymbol{V}_k)^{-1}$
- (Smooth...)

See: Keisuke Fujii, Extended Kalman Filter, The AFCA-SIM-J Group

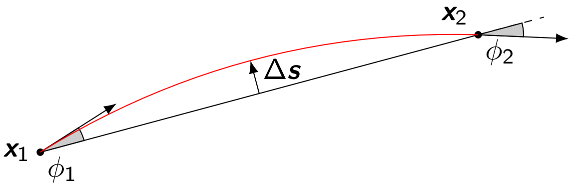
Parabolic interpolation

The position $\boldsymbol{x}(t)$ between the points $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ is parametrised as a function of $0 \geq t \geq 1$

$$\boldsymbol{x}(t) = \boldsymbol{x}_1 + t(\boldsymbol{x}_2 - \boldsymbol{x}_1) + 4t(1-t)\Delta\boldsymbol{s}, \quad (1)$$

where $\Delta\boldsymbol{s}$ is the deflection midway given by

$$|\Delta\boldsymbol{s}| = \frac{|\boldsymbol{x}_2 - \boldsymbol{x}_1|}{4} \sin(\Delta\phi_{12}/2). \quad (2)$$



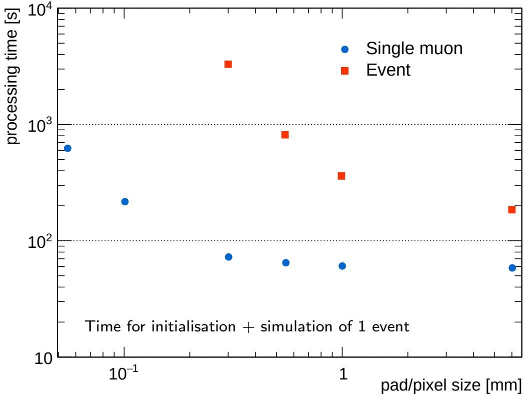
Diffusion and hit resolution is simulated by smearing the hits by the expected resolution in TPCDigiProcessor

$$
\begin{aligned}
a &= \sigma_{r\phi 0}^2 + \sigma_{\phi 0}^2 \sin^2(\phi_{\text{pad}}) \\
b &= \frac{D_{r\phi}^2}{N_{\text{Eff}}} \sin(\theta_{\text{pad}}) \left(\frac{6\ \text{mm}}{h_{\text{pad}}}\right) \left(\frac{4.0\ \text{T}}{B}\right) \\
\sigma_{r\phi} &= \sqrt{a + bL} \\
\sigma_z &= \sqrt{\sigma_{z0}^2 + D_z^2 L}
\end{aligned}
$$

,

$$
\begin{aligned}
\sigma_{r\phi 0} &= 0.05\ \text{mm} & \sigma_{z0} &= 0.4\ \text{mm} & \sigma_{\phi 0} &= 0.9\ \text{mm} \\
D_{r\phi} &= 0.025\text{mm}/\sqrt{\text{cm}} & D_z &= 0.08\text{mm}/\sqrt{\text{cm}} & N_{\text{Eff}} &= 22.
\end{aligned}
$$

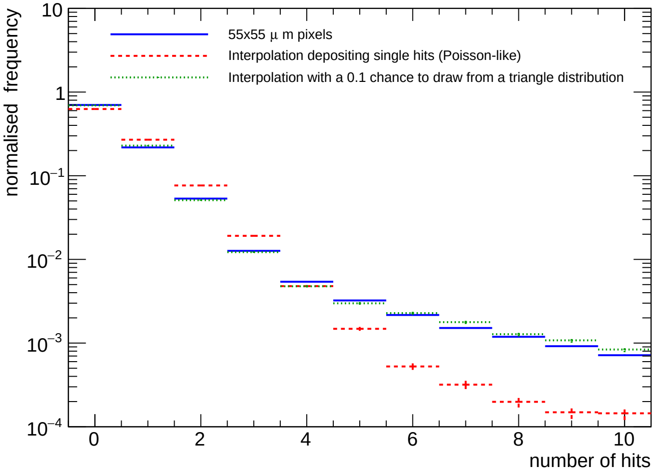
Simulating 55 × 55 μm^2 pixels as small pads costs too much processing time



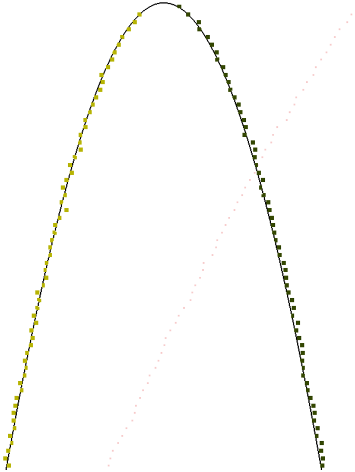
- Processing time increases rapidly at smaller pixel sizes

Distribution of hits along the track

Distribute hits with a $P(N_{\text{hits}} = N) \simeq 0.1 \cdot \frac{2N}{N_{\text{total}}^2}$ chance to deposit multiple hits



Track fitting for pads



Track fit: For curled (low momentum) tracks, cluster inward and outward parts separately and merge

Curled segements in schematic pad layout