Track reconstruction of GridPix data

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DESY

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

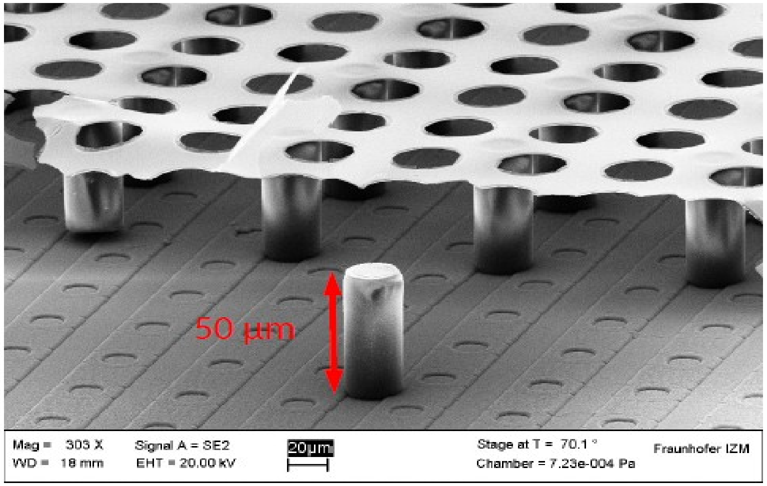
Bundesministerium für Bildung und Forschung

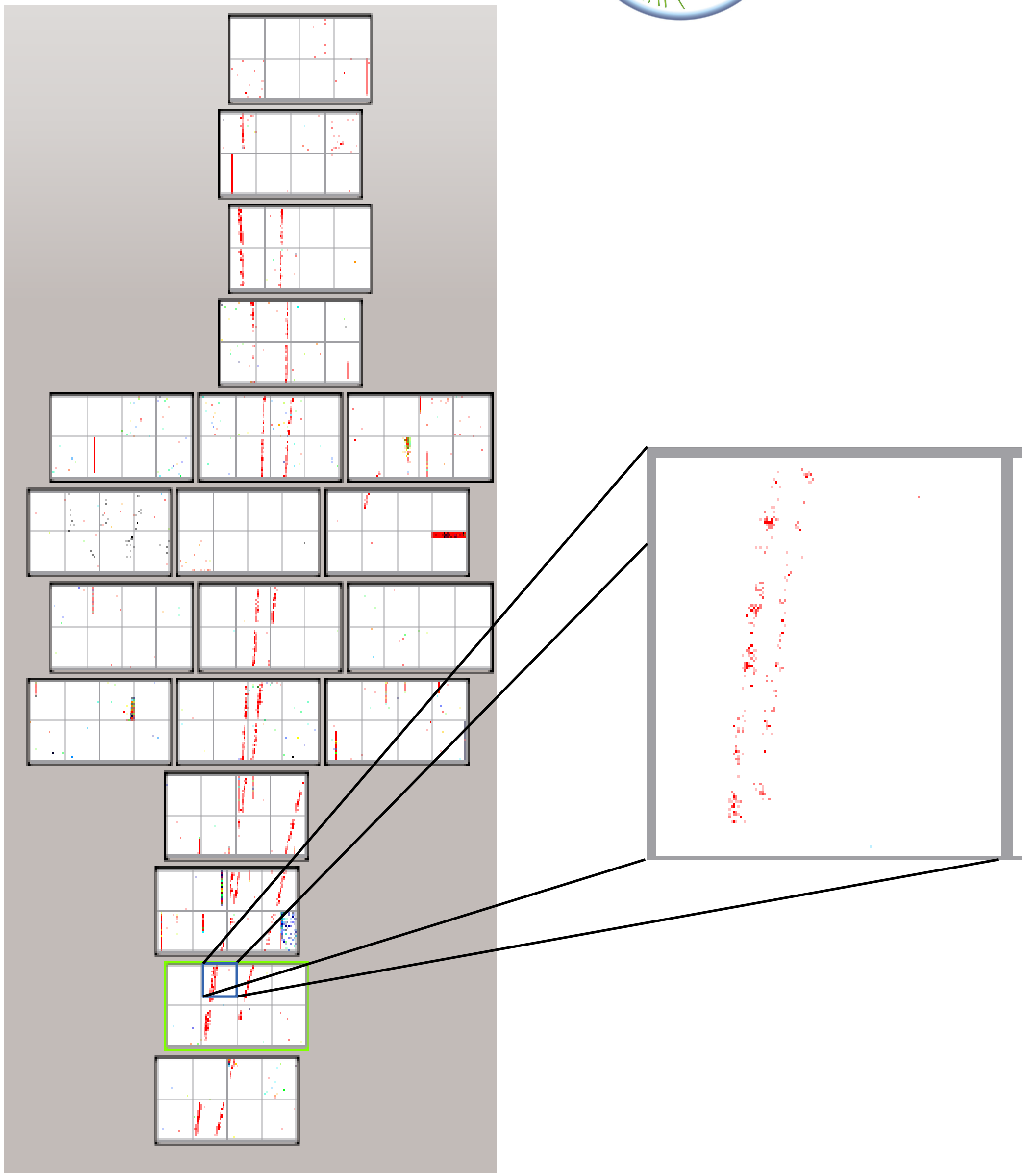
UNIVERSITÄT SIEGEN

ILC – TPC: Development of a TPC readout based on GridPix

- **Timepix:**
  - Number of pixels: 256 X 256 pixels
  - Pixel size: 55 X 55 µm²
- **InGrid:**
  - Micromegas on top of a Timepix chip
  - Mesh holes aligned with pixels of the chip:

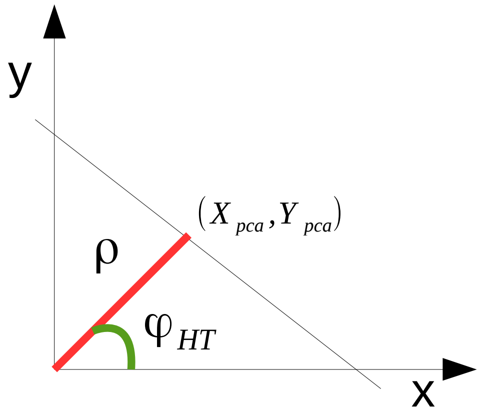
    single e⁻ measurement
  - Many hits per track's length ≈ 10 hits per mm
  - Every 8 InGrid chips are aligned in an Octoboard
  - Using the unit of the Octoboard as a segment of the track calling tracklet

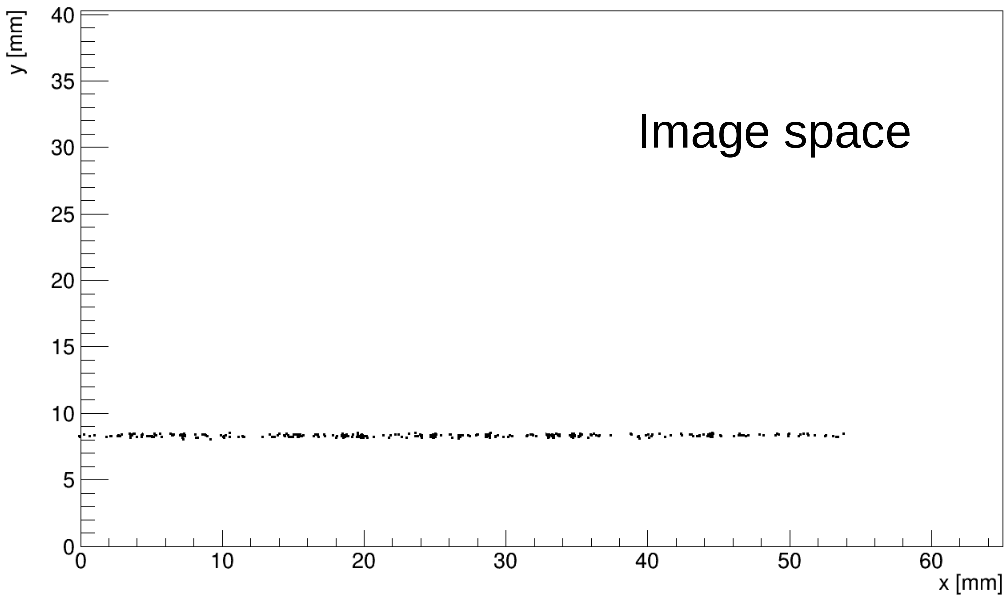


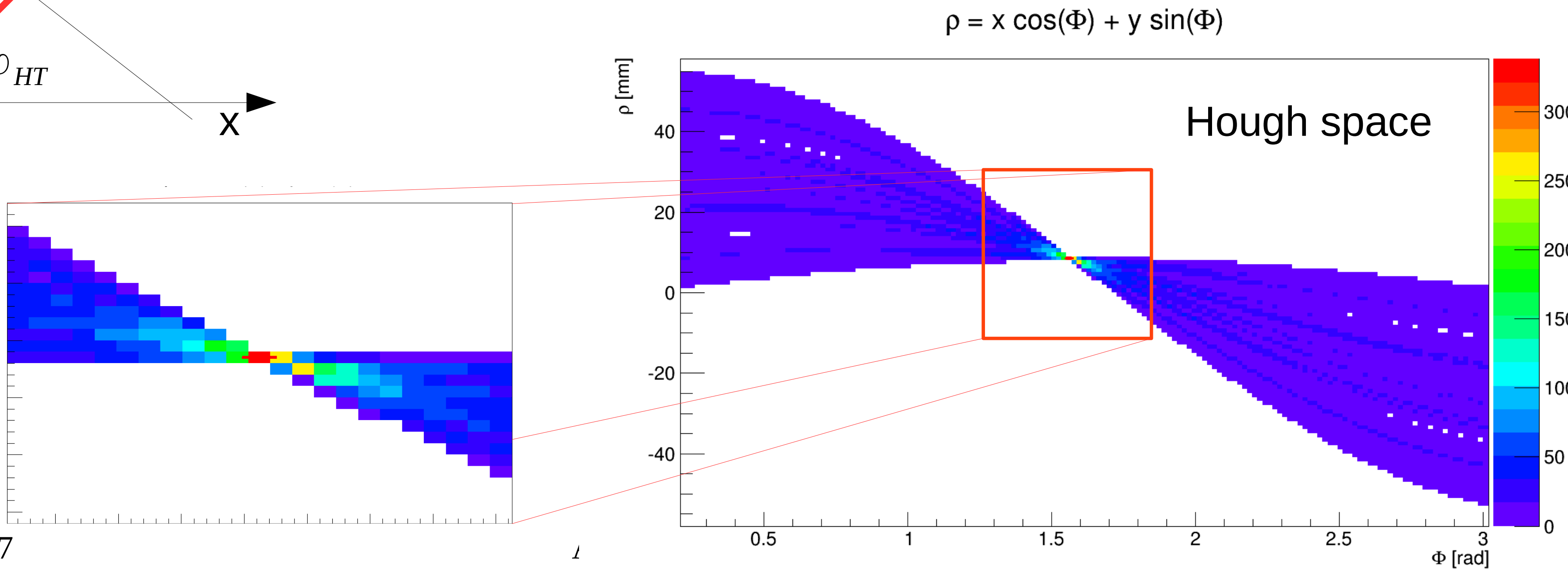


Hough Transform

- Bin with maximum entires returns φ_{HT} and ρ_{HT}
  - $\rho_{HT} = x\cos(\varphi_{HT}) + y\sin(\varphi_{HT})$
  - $d_0 = \rho_{HT}$
  - $\varphi_{track} = \varphi_{HT} - \frac{\pi}{2}$

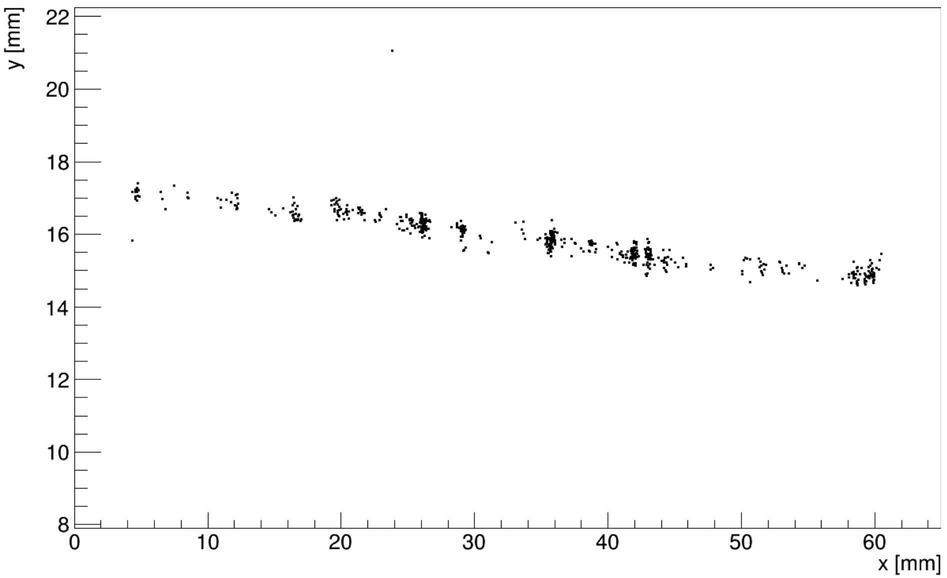


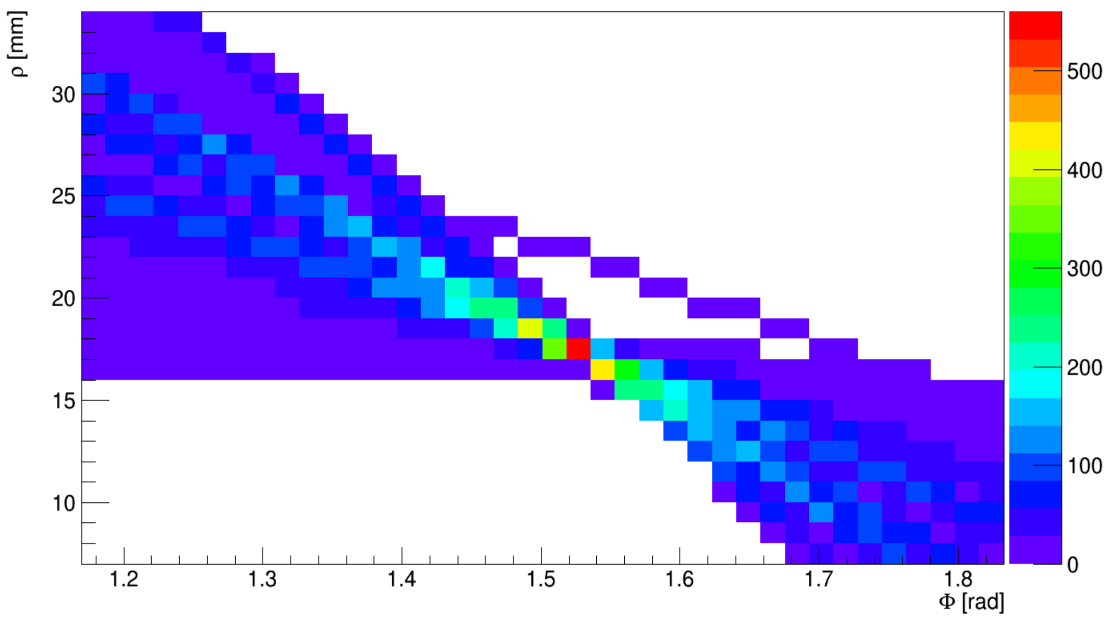




Hough Transform

- Bin size in the X-Y plane: in the ρ direction σ_D
- Bin Size in the S-Z plane: in the Z direction 2.355 σ_L
- Because of the diffusion, some lines of hits pass through other bins around the bin with maximum entries.



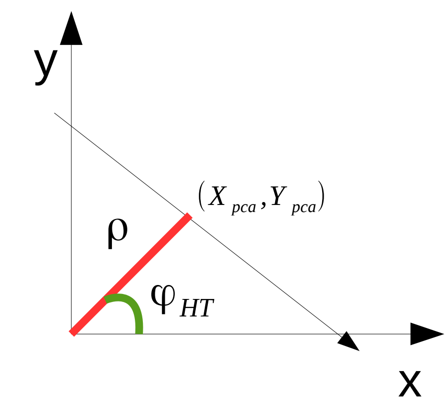


- **Calculating resolution of the track in Hough space**
- **Using Bivariate Normal Distribution for vicinity of the bin with maximum entries**

Diffusion and covariance matrix:

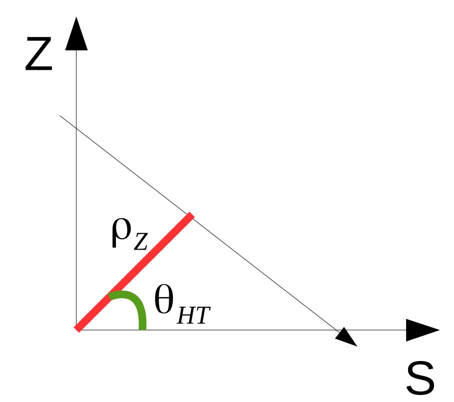
- X-Y Plane: $\rho = x\cos(\varphi) + y\sin(\varphi)$
  - Transverse resolution: $\sigma_D^2 = Z D_T^2$

$$\begin{bmatrix} \sigma_\rho^2 & \sigma_{\rho\varphi} \\ \sigma_{\varphi\rho} & \sigma_\varphi^2 \end{bmatrix} = \nabla f \begin{bmatrix} \sigma_D^2 & 0 \\ 0 & \sigma_D^2 \end{bmatrix} \nabla f^T$$

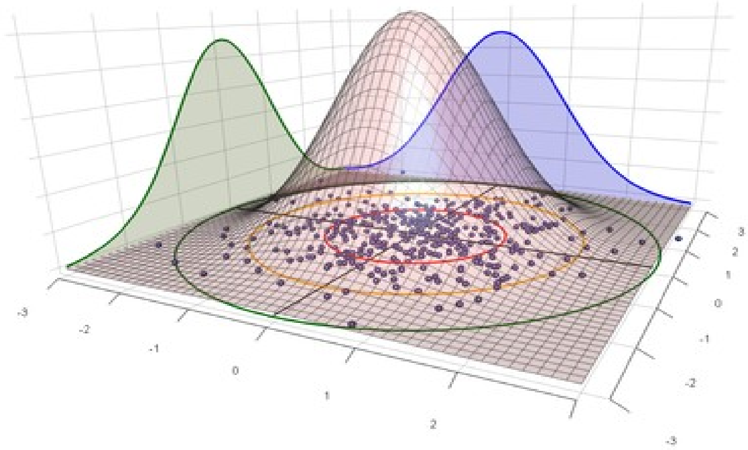


- S-Z Plane: $\rho_Z = s\cos(\theta_{HT}) + z\sin(\theta_{HT})$
  - Longitudinal resolution: $\sigma_L^2 = Z D_L^2$
  - Arc length for straight line: $S = \sqrt{(x_{hit} - x_{pca})^2 + (y_{hit} - y_{pca})^2}$

$$\begin{bmatrix} \sigma_{\rho_z}^2 & \sigma_{\rho_z\theta} \\ \sigma_{\theta\rho_z} & \sigma_\theta^2 \end{bmatrix} = \nabla f \begin{bmatrix} \sigma_S^2 & 0 \\ 0 & \sigma_L^2 \end{bmatrix} \nabla f^T$$



Bivariate Normal Distribution (BND):

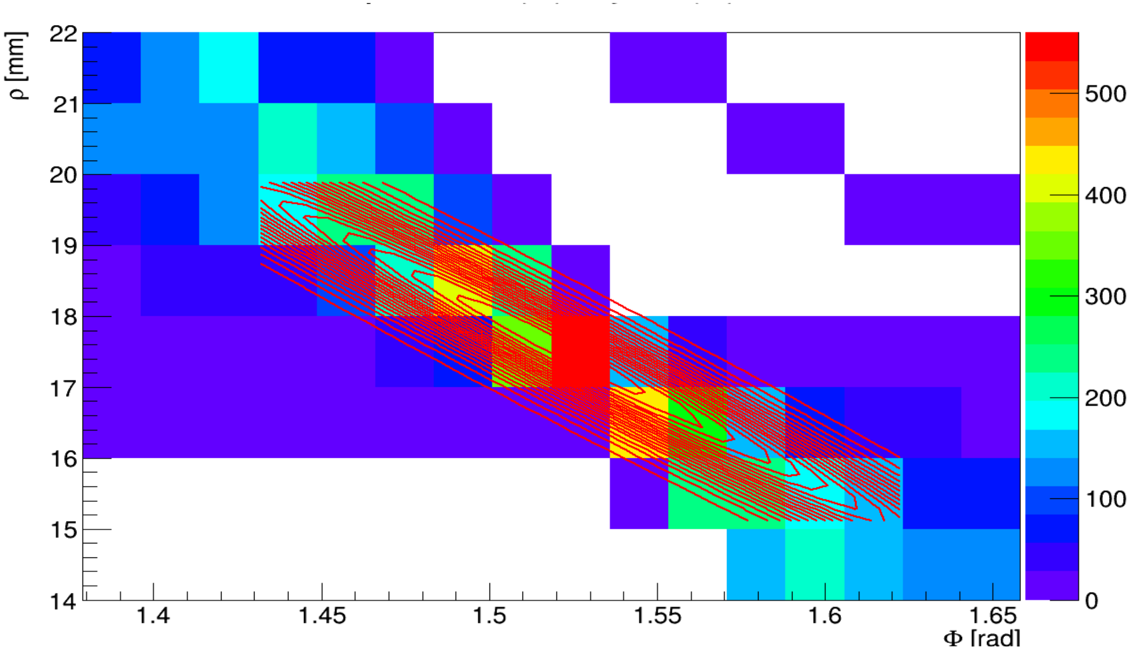


http://ballistipedia.com/index.php?title=Closed_Form_Precision

$$G(\varphi,\rho)=\frac{1}{2\pi\sigma_\rho\sigma_\varphi\sqrt{1-r^2}}\exp\left[\frac{-c}{2(1-r^2)}\right]$$

$$c\equiv\frac{(\varphi-\mu_\varphi)^2}{\sigma_\varphi^2}+\frac{(\rho-\mu_\rho)^2}{\sigma_\rho^2}-\frac{2r(\varphi-\mu_\varphi)(\rho-\mu_\rho)}{\sigma_\varphi\sigma_\rho}$$

- Correlation : $$r\equiv\frac{\sigma_{\rho\varphi}}{\sigma_\rho\sigma_\varphi}$$



Ellipse equation of 1/e of Peak of BND:

- Finding ellipse equation from BND:

$$1=\frac{(\varphi-\mu_\varphi)^2}{q\,\sigma_\varphi^2}+\frac{(\rho-\mu_\rho)^2}{q\,\sigma_\rho^2}-\frac{2r(\varphi-\mu_\varphi)(\rho-\mu_\rho)}{q\,\sigma_\varphi\sigma_\rho} \qquad (1)$$

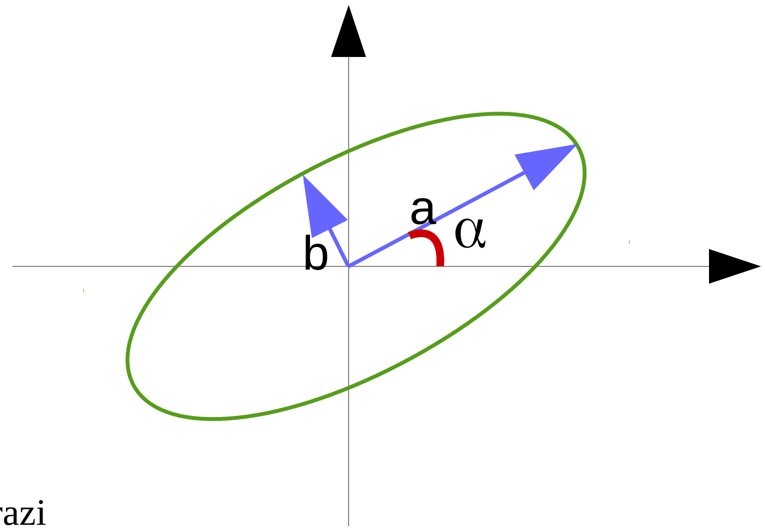
- Rotated ellipse:

$$1=\left(\frac{\cos^2(\alpha)}{a^2}+\frac{\sin^2(\alpha)}{b^2}\right)x^2-2\cos(\alpha)\sin(\alpha)\left(\frac{1}{a^2}-\frac{1}{b^2}\right)xy+\left(\frac{\sin^2(\alpha)}{a^2}+\frac{\cos^2(\alpha)}{b^2}\right)y^2 \qquad (2)$$

- From (1) and (2):

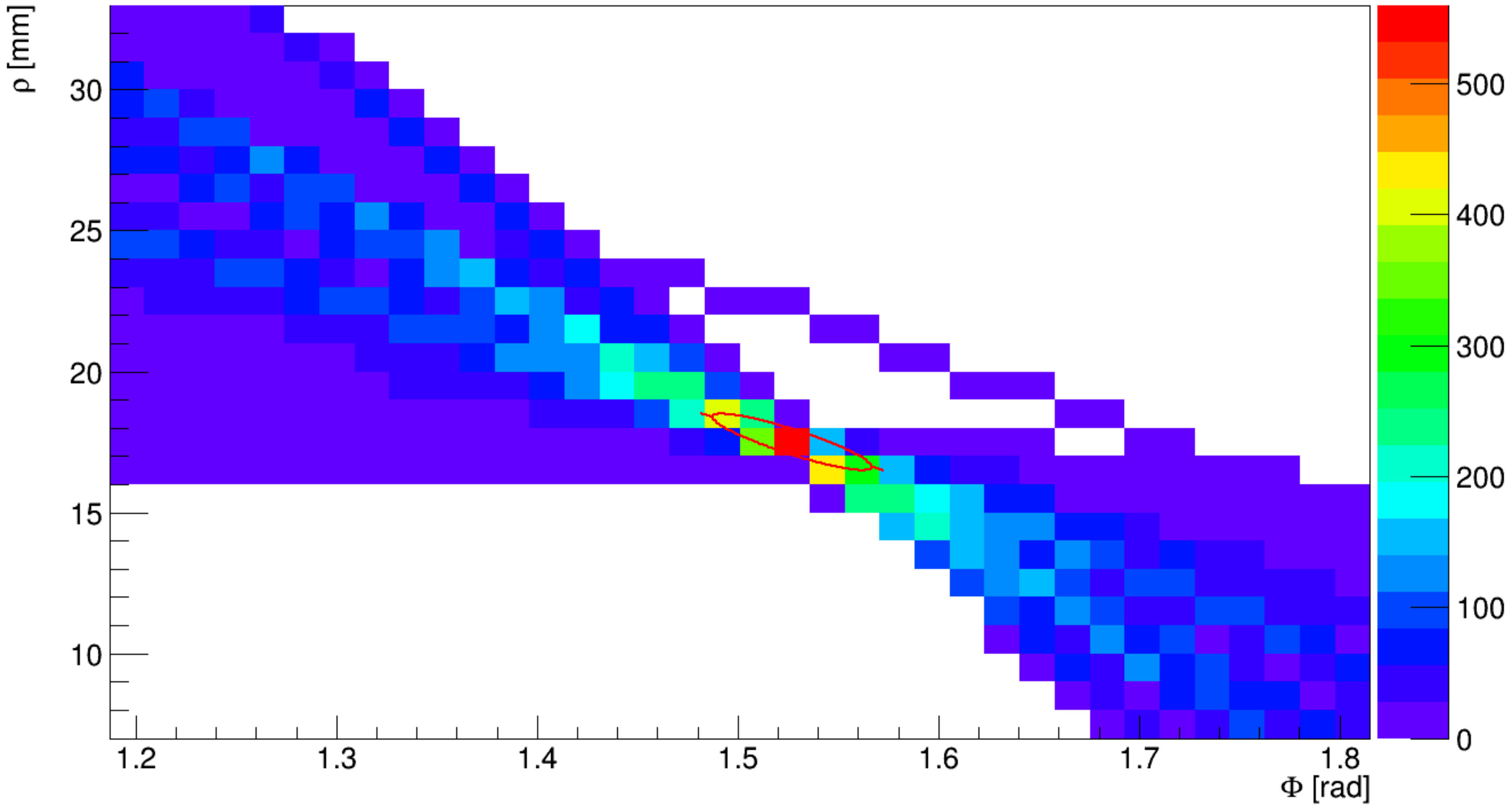
$$a^2=\frac{q\,\sigma_\varphi^2\sigma_\rho^2\cos(2\alpha)}{\sigma_\rho^2\cos^2(\alpha)-\sigma_\varphi^2\sin^2(\alpha)}$$

$$b^2=\frac{-q\,\sigma_\varphi^2\sigma_\rho^2\cos(2\alpha)}{\sigma_\rho^2\sin^2(\alpha)-\sigma_\varphi^2\cos^2(\alpha)}$$



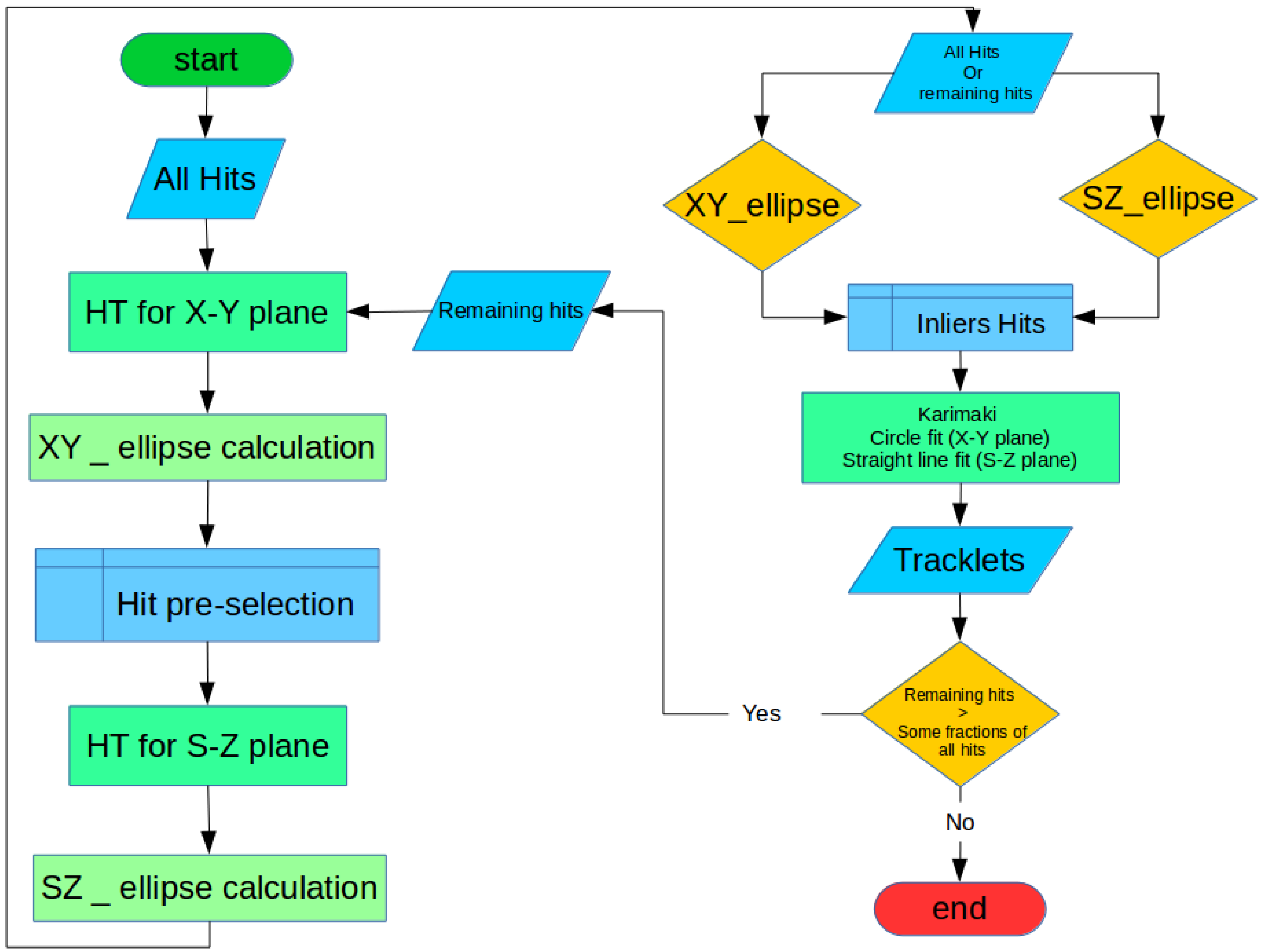
Example: XY_Plane

Inliers and 1/e of peak of BND:



- Collecting all hits inside the ellipse => **Inliers**
- The fit range and the size of the ellipse are changeable => Number of inliers is changeable too
- They are adjusted automatically based on the drift length.

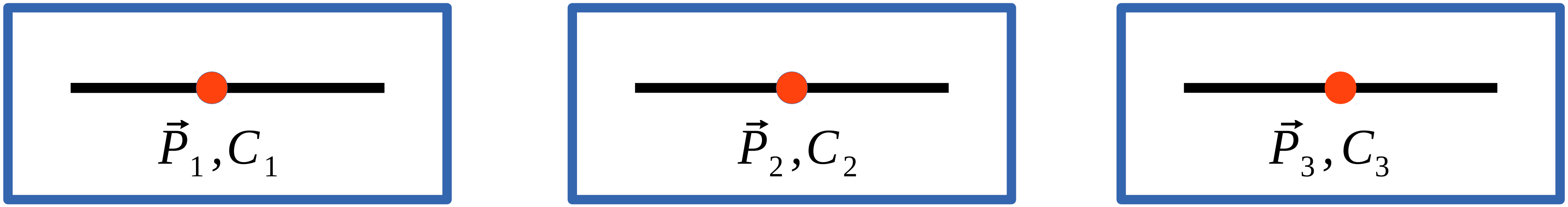
Flow chart



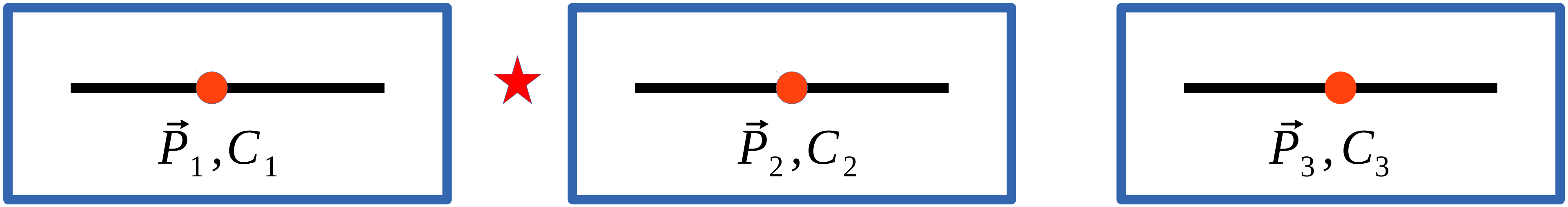
start
All Hits
HT for X-Y plane
XY _ ellipse calculation
Hit pre-selection
HT for S-Z plane
SZ _ ellipse calculation
Remaining hits
All Hits
Or
remaining hits
XY_ellipse
SZ_ellipse
Inliers Hits
Karimaki
Circle fit (X-Y plane)
Straight line fit (S-Z plane)
Tracklets
Remaining hits
>
Some fractions of
all hits
Yes
No
end

Merging Tracklets

P: parameter vector of the tracklet
C: covariance Matrix of the tracklet

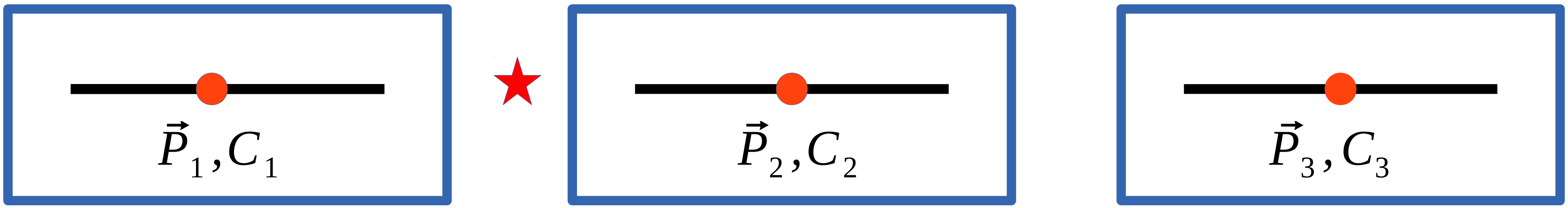


$$(\vec{P}'_1, C'_1)(\vec{P}'_2, C'_2)$$



Merging Tracklets

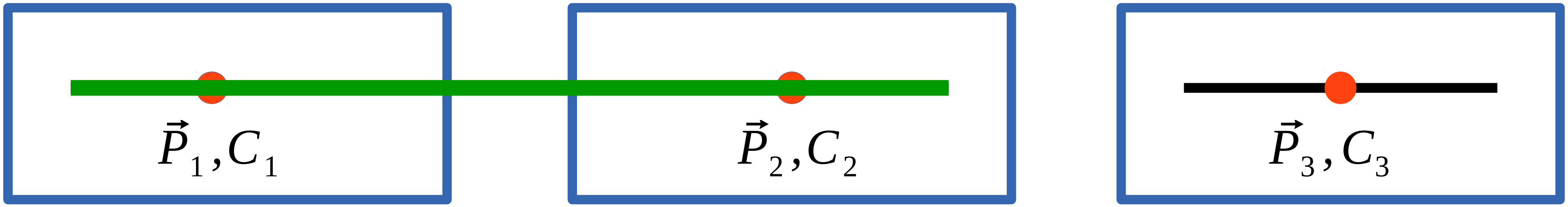
$$(\vec{P}'_1, C'_1)(\vec{P}'_2, C'_2)$$



$$\chi_1^2 = (\vec{P}'_1 - \vec{P}'_2)(C'_1 + C'_2)^{-1}(\vec{P}'_1 - \vec{P}'_2)^T$$

Merging Tracklets

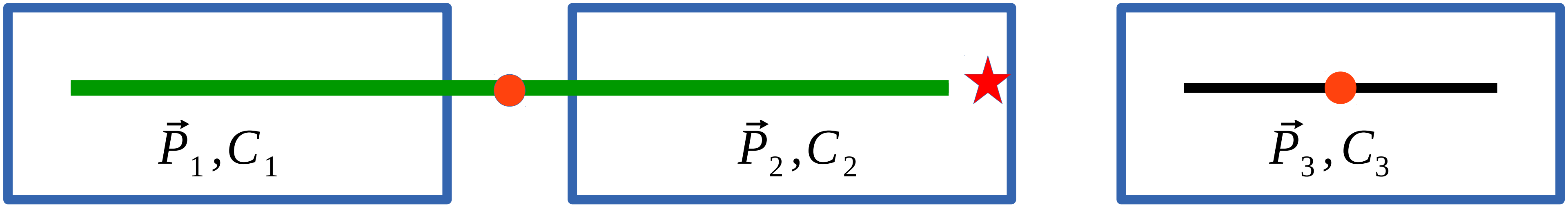
$$\left(\vec{P}'_1, C'_1\right)\left(\vec{P}'_2, C'_2\right)$$



$$\chi^2_1 = \left(\vec{P}'_1 - \vec{P}'_2\right)\left(C'_1 + C'_2\right)^{-1}\left(\vec{P}'_1 - \vec{P}'_2\right)^T \quad => \quad \left(\vec{P}_{12}, C_{12}\right)$$

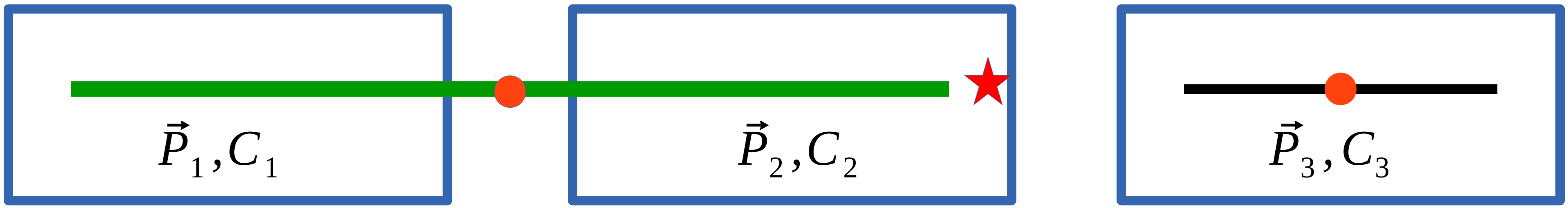
Merging Tracklets

$$(\vec{P}'_1, C'_1)(\vec{P}'_2, C'_2) \qquad (\vec{P}'_{12}, C'_{12})(\vec{P}'_3, C'_3)$$



$$\chi_1^2 = (\vec{P}'_1 - \vec{P}'_2)(C'_1 + C'_2)^{-1}(\vec{P}'_1 - \vec{P}'_2)^T \quad => \quad (\vec{P}_{12}, C_{12})$$

$$(\vec{P}'_1, C'_1)(\vec{P}'_2, C'_2) \qquad (\vec{P}'_{12}, C'_{12})(\vec{P}'_3, C'_3)$$

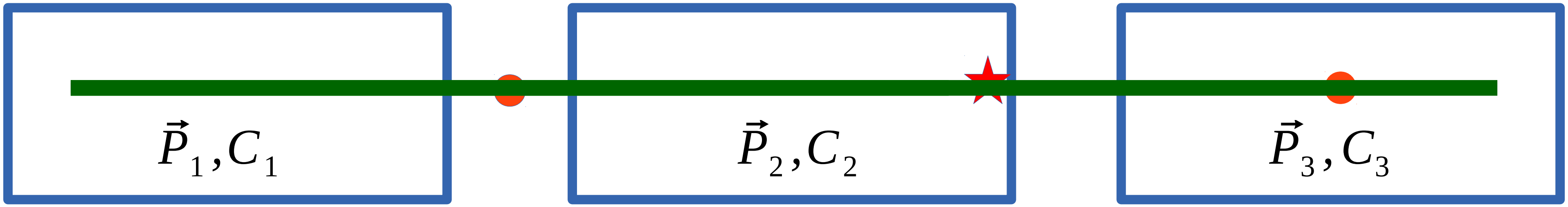


$$\chi_1^2 = (\vec{P}'_1 - \vec{P}'_2)(C'_1 + C'_2)^{-1}(\vec{P}'_1 - \vec{P}'_2)^T \quad \Rightarrow \quad (\vec{P}_{12}, C_{12})$$

$$\chi_2^2 = (\vec{P}'_{12} - \vec{P}'_3)(C'_{12} + C'_3)^{-1}(\vec{P}'_{12} - \vec{P}'_3)^T$$

Merging Tracklets

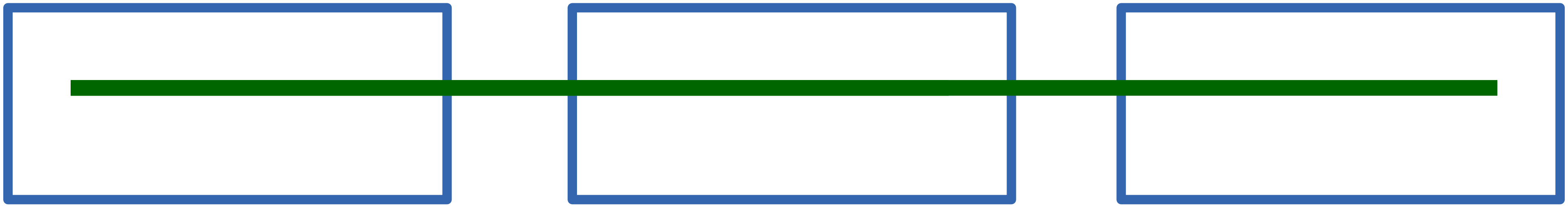
$$(\vec{P}'_1, C'_1)(\vec{P}'_2, C'_2) \qquad (\vec{P}'_{12}, C'_{12})(\vec{P}'_3, C'_3)$$



$$\chi_1^2 = (\vec{P}'_1 - \vec{P}'_2)(C'_1 + C'_2)^{-1}(\vec{P}'_1 - \vec{P}'_2)^T \quad \Rightarrow \quad (\vec{P}_{12}, C_{12})$$

$$\chi_2^2 = (\vec{P}'_{12} - \vec{P}'_3)(C'_{12} + C'_3)^{-1}(\vec{P}'_{12} - \vec{P}'_3)^T \quad \Rightarrow \quad (\vec{P}_T, C_T)$$

$$(\vec{P}'_1, C'_1)(\vec{P}'_2, C'_2) \qquad (\vec{P}'_{12}, C'_{12})(\vec{P}'_3, C'_3)$$

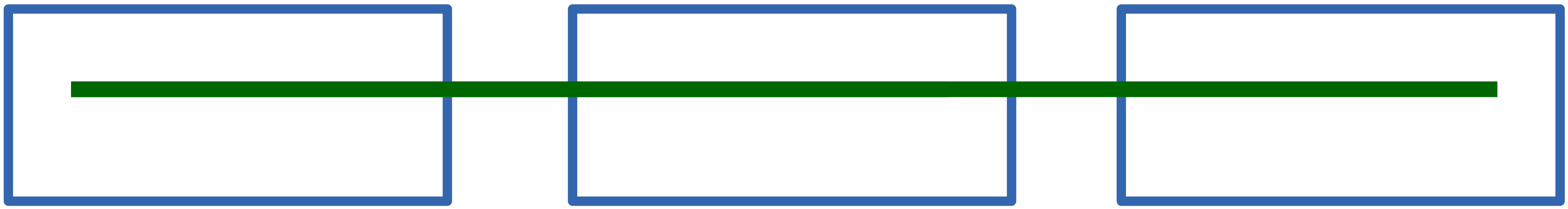


$$\chi_1^2 = (\vec{P}'_1 - \vec{P}'_2)(C'_1 + C'_2)^{-1}(\vec{P}'_1 - \vec{P}'_2)^T \quad \Rightarrow \quad (\vec{P}_{12}, C_{12})$$

$$\chi_2^2 = (\vec{P}'_{12} - \vec{P}'_3)(C'_{12} + C'_3)^{-1}(\vec{P}'_{12} - \vec{P}'_3)^T \quad \Rightarrow \quad (\vec{P}_T, C_T)$$

- Using General Broken lines (GBL) for fitting

$$(\vec{P}'_1, C'_1)(\vec{P}'_2, C'_2) \qquad (\vec{P}'_{12}, C'_{12})(\vec{P}'_3, C'_3)$$



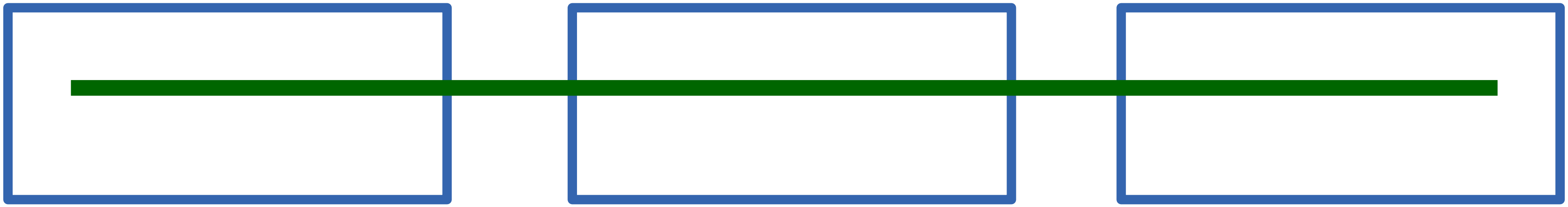
$$\chi_1^2 = (\vec{P}'_1 - \vec{P}'_2)(C'_1 + C'_2)^{-1}(\vec{P}'_1 - \vec{P}'_2)^T \quad => \quad (\vec{P}_{12}, C_{12})$$

$$\chi_2^2 = (\vec{P}'_{12} - \vec{P}'_3)(C'_{12} + C'_3)^{-1}(\vec{P}'_{12} - \vec{P}'_3)^T \quad => \quad (\vec{P}_T, C_T)$$

- Using General Broken lines (GBL) for fitting
- Recollection remaining hits

Merging Tracklets

$$(\vec{P}'_1, C'_1)(\vec{P}'_2, C'_2) \qquad (\vec{P}'_{12}, C'_{12})(\vec{P}'_3, C'_3)$$



$$\chi_1^2 = (\vec{P}'_1 - \vec{P}'_2)(C'_1 + C'_2)^{-1}(\vec{P}'_1 - \vec{P}'_2)^T \quad \Rightarrow \quad (\vec{P}_{12}, C_{12})$$

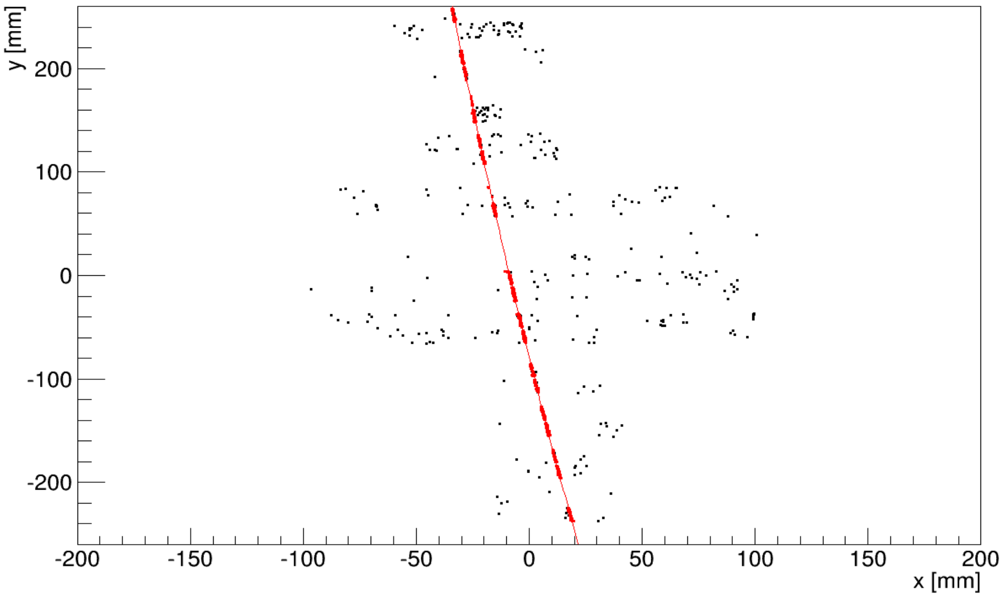
$$\chi_2^2 = (\vec{P}'_{12} - \vec{P}'_3)(C'_{12} + C'_3)^{-1}(\vec{P}'_{12} - \vec{P}'_3)^T \quad \Rightarrow \quad (\vec{P}_T, C_T)$$

- Using General Broken lines (GBL) for fitting
- Recollection remaining hits
- Using GBL again for the final fit

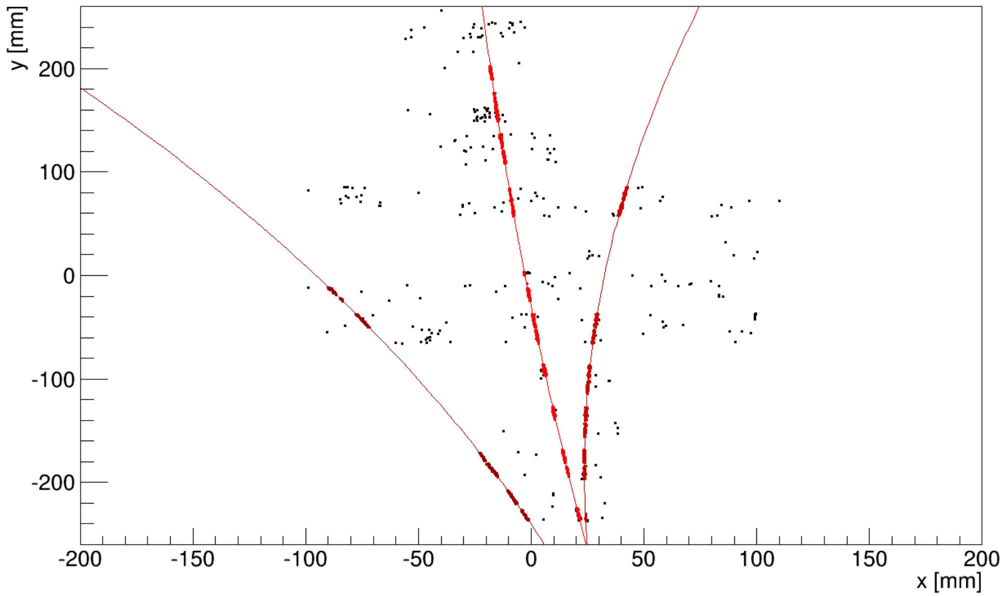
Testbeam data 2015

- Run_136
- B = 1T
- 5 GeV

Event_2_Drawing_1_Tracks_3036_Hits

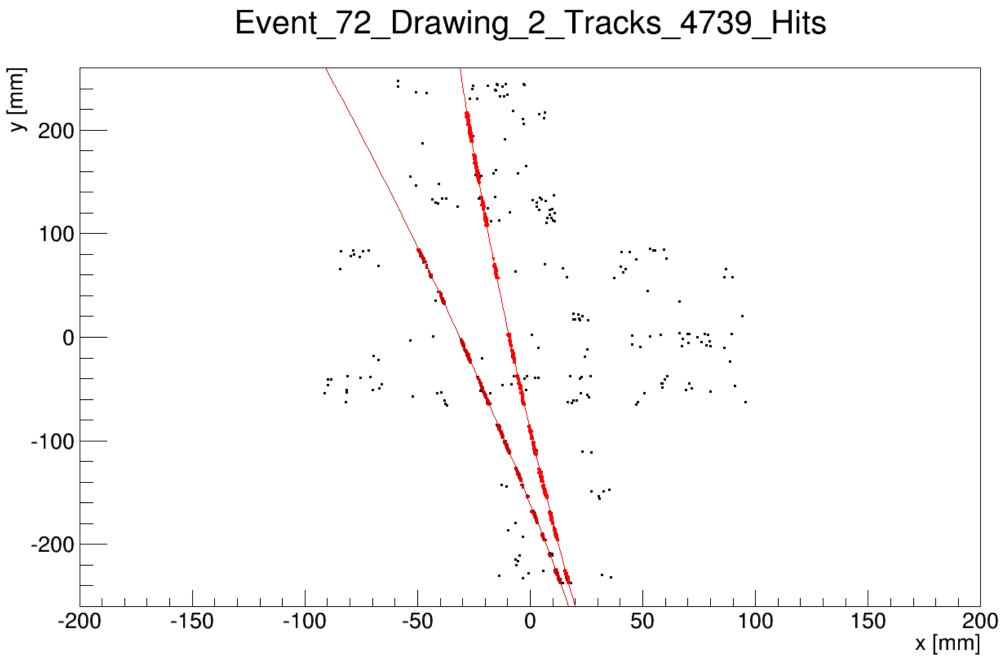


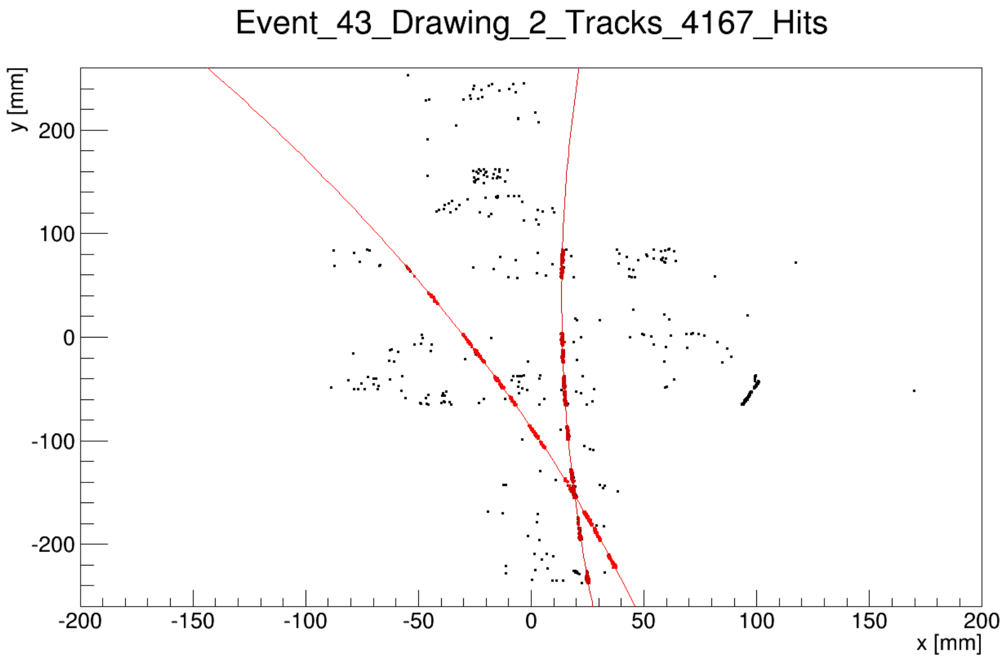
Event_39_Drawing_3_Tracks_5819_Hits



Testbeam data 2015

- Run_136
- B = 1T
- 5 GeV





Testbeam data 2015

- Run_136
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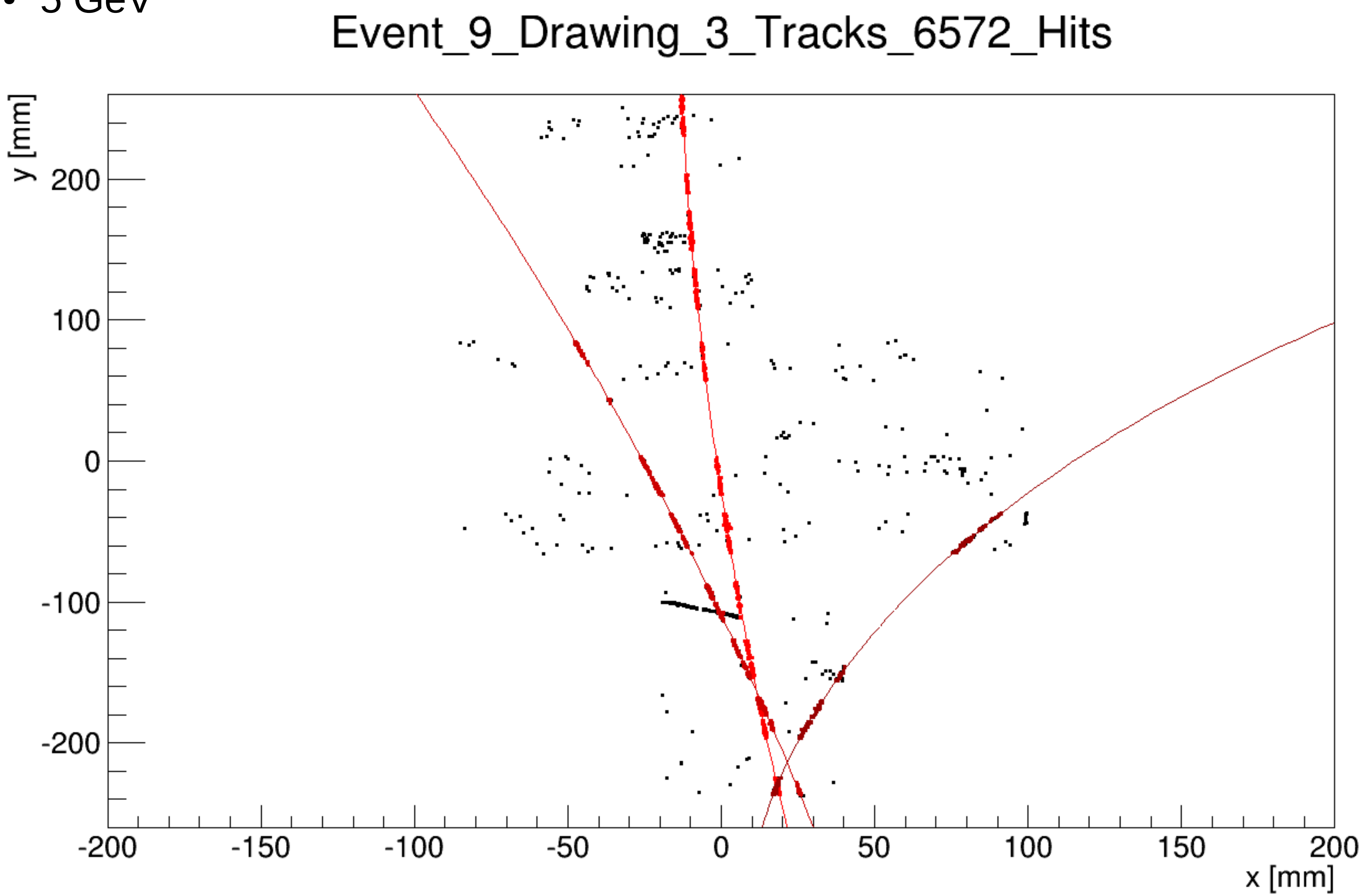
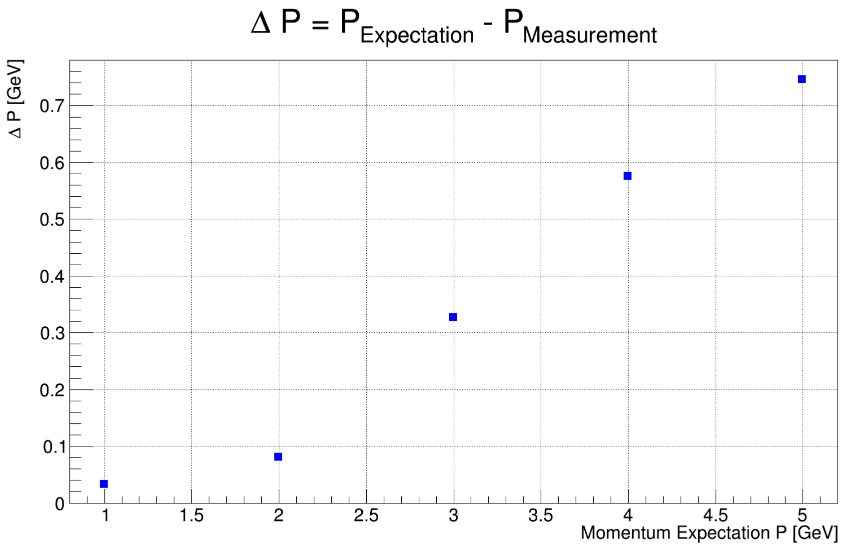
- 5 GeV



Testbeam data 2015

- Transverse Momentum Resolution: $\frac{\sigma_{P_t}}{P_t^2}$
  - Transverse Momentum for Real data
  - Each run: **10000** events
  - Plot 1/Pt and using Crystal Ball function for fit
  - Pt=1 / Mean of fit
  - Momentum Resolution= σ of fit



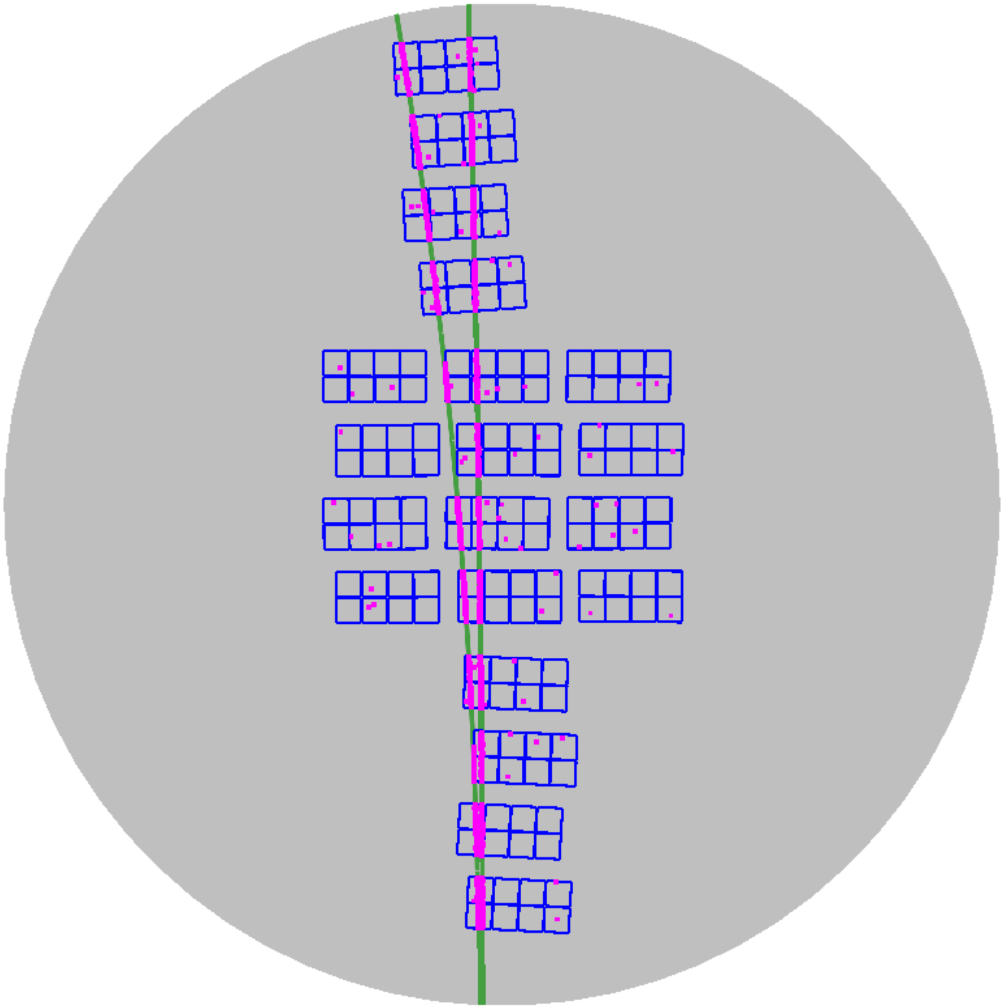
Run	Energy (GeV)	Pt	Momentum Resolution $(GeV)^{-1}$
140	1	0.983	**0.06169**
139	2	1.949	**0.01783**
138	3	2.773	**0.01422**
137	4	3.510	**0.01069**
136	5	4.261	**0.00868**

Summary and Outlook:

- Collecting inliers directly in the Hough space by a bivariate normal distribution fit in the Hough space
- Merging tracklets to have full track
- Recollecting remaining hits along the track
- Analysis of testbeam data is ongoing

Acknowledgment:

- I sincerely thank **Claus Kleinwort** for all his guidance and help.
- I also thank all my colleagues in Siegen, DESY, Bonn and Nikhef.

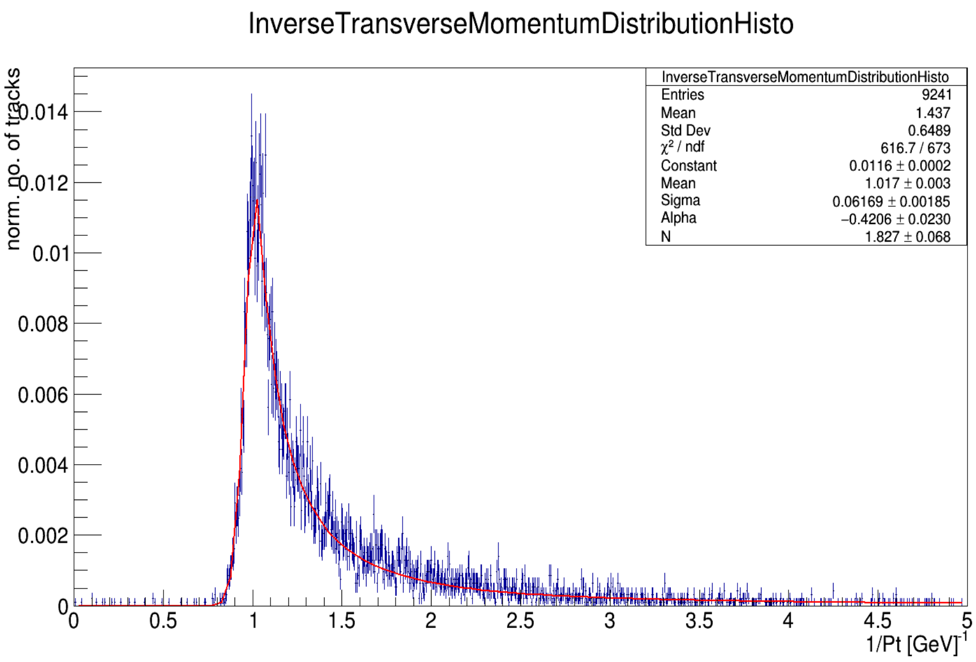


Thank you for your attention

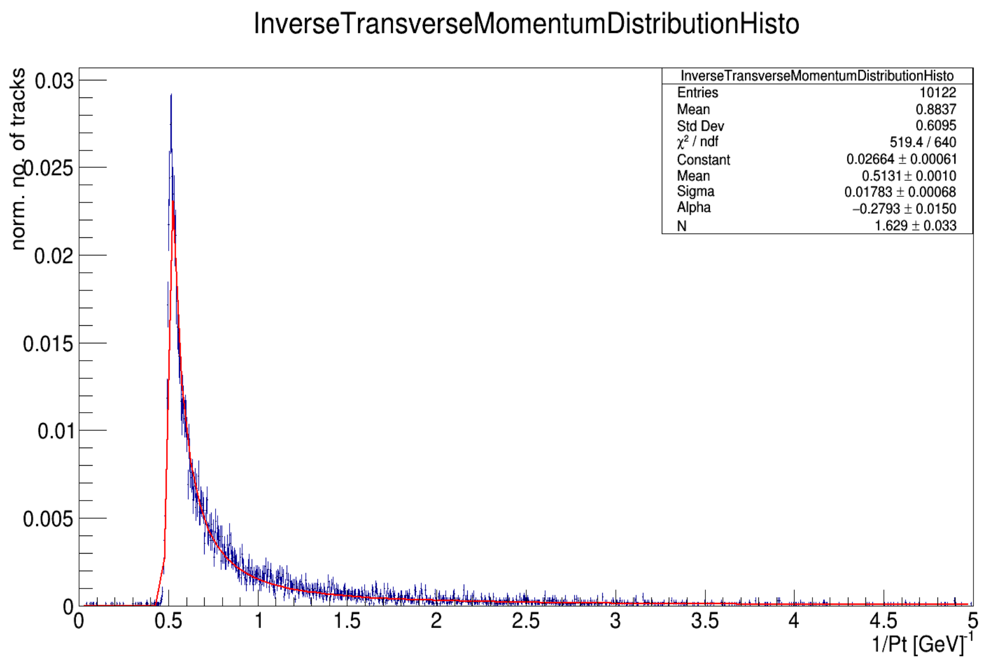
Backup

Testbeam data

Inverse Momentum



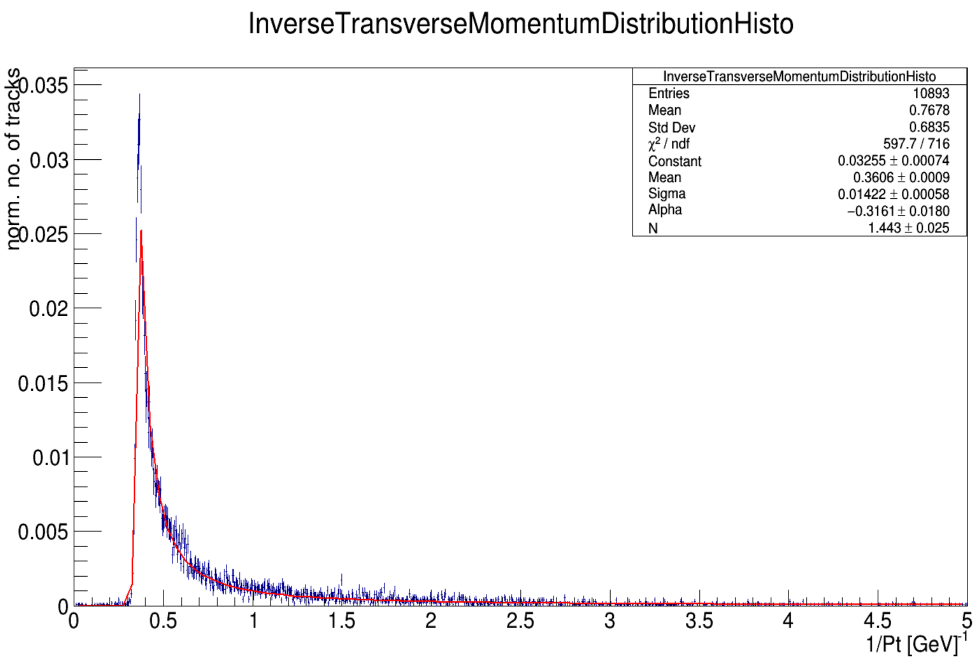
Run_140: 1 GeV



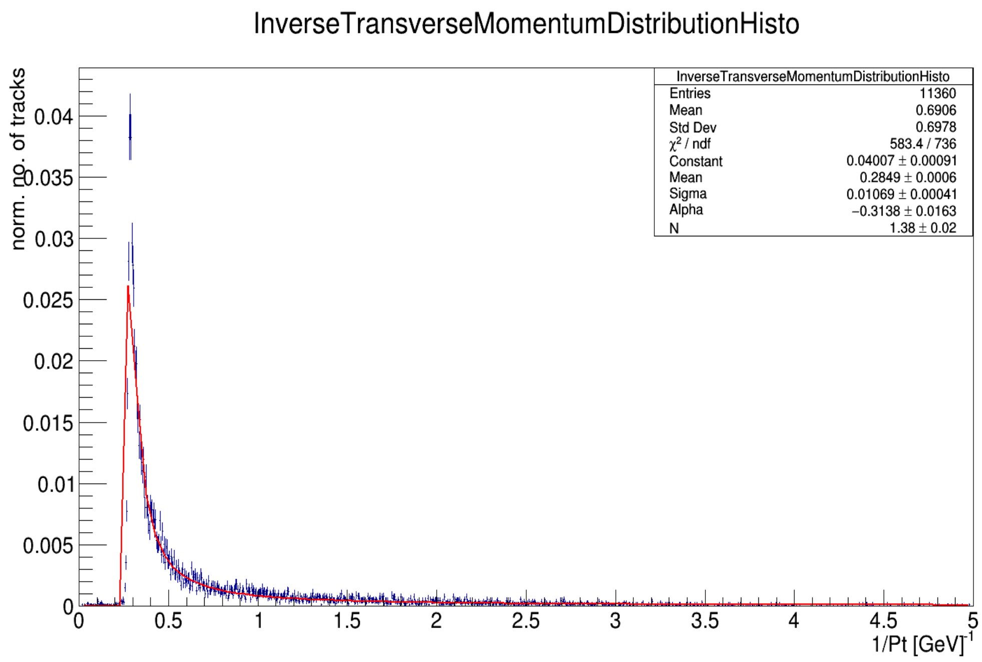
Run_139: 2 GeV

Testbeam data

Inverse Momentum



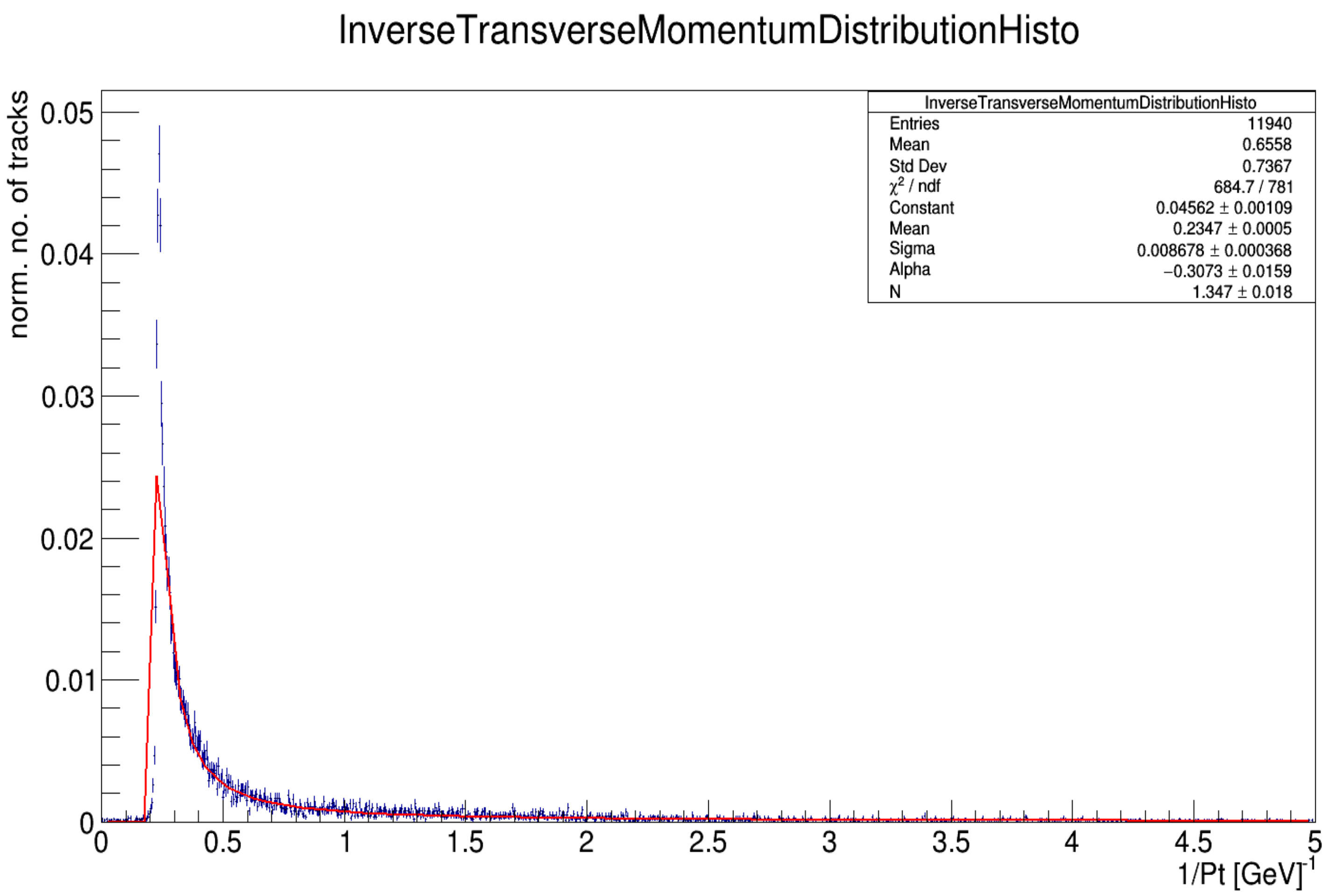
Run_138: 3 GeV



Run_137: 4 GeV

Testbeam data

Inverse Momentum



Run_136: 5 GeV

Definition: Efficiency and Purity

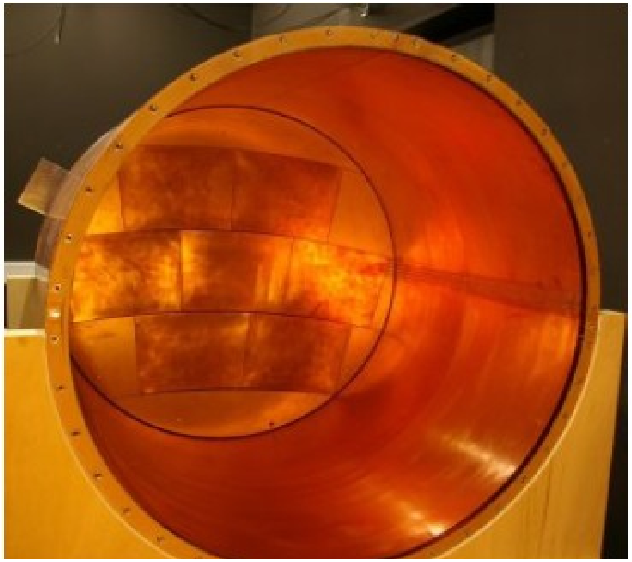
- **True Track:** is associated to the MC particle with the most hits on the track and more than some percentages (60% , 70%) of MC particle hits .
- **Track Efficiency:** Number of true track to number of all MC particle
- **Track Purity:** Number of true track to sum over number of true track, ghost and clone tracks
- **Right Hits:** Number of hits on the track from the associated MC particle
- **Hit Efficiency:** Number of right Hits to number of associated MC particle hits
- **Hit Purity**: Number of right hits to all hits of the true track

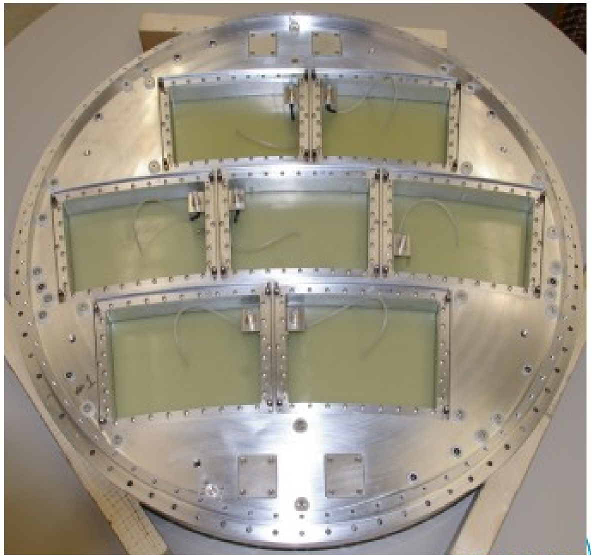
ILCTPC – DESY: Large Prototype TPC

- Test beam area at DESY(1-6 GeV e^- beams)
  - Infrastructure includes a large bore 1T magnet on a movable stage

- Large Prototype (LP) built and installed to test scaling up of technologies and to compare different readout technologies on equal footing

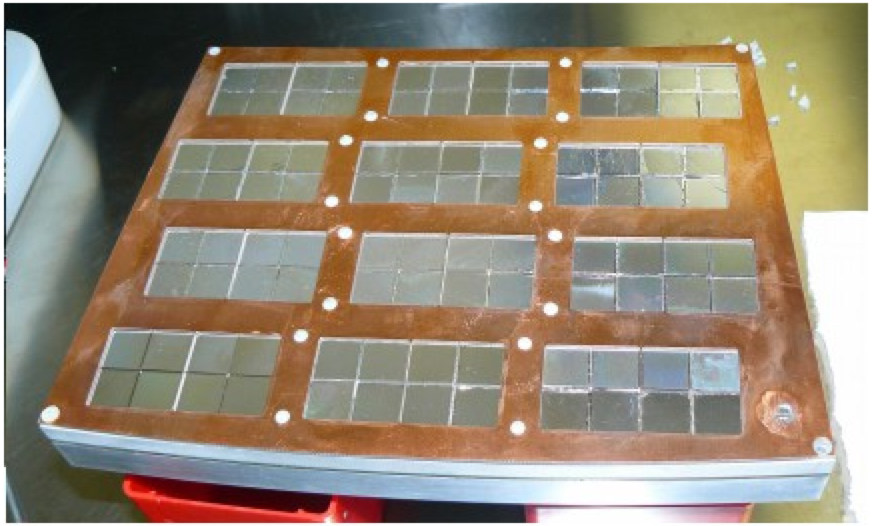
- LP field cage parameters:
  - Length: 61 cm, Diameter: 72 cm
  - Up to 25 kV => E_{drift} up to 350 V/cm
  - Wall material budget: 1.3% X_0
- Endplate is able to host 7 readout modules (dimensions ~22 X 17 cm^2)





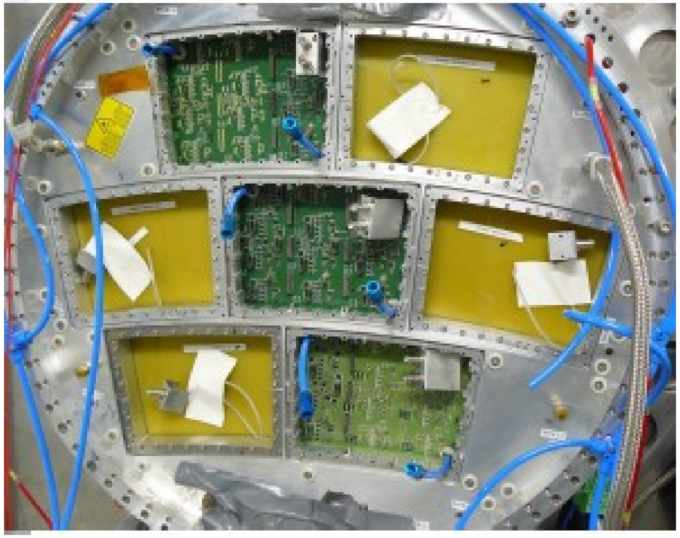
Infrastructure for test beam, TPC and Endplate from DESY group

- Test beam with 160 InGrid chips:
  - Central module with 96 chips (coverage 50 %)
  - 2 outer modules with 32 chips each



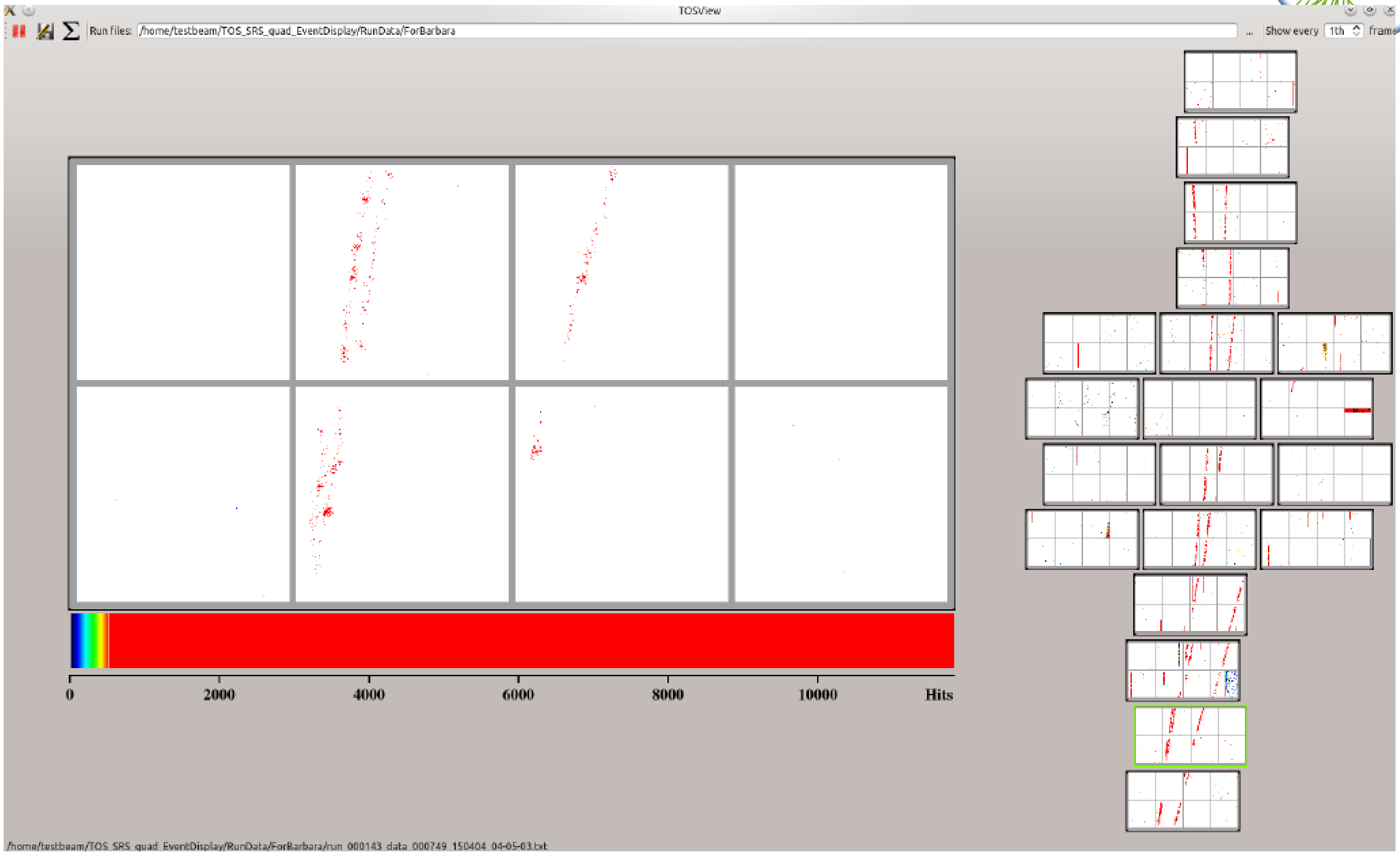
- Some Challenges:
  - InGrid production
  - Synchronized readout
  - Bonding on boards
  - LV distribution (up to 85 A @ 2.2 V)
  - Cooling

- The test beam was successful. During the test beam ~10^6 frames at a rate of around 5 Hz were collected.



- Test beam program:
  - Voltage scans (gas gain)
  - Z-scan
  - Momentum scan
  - Different angles
  - With and without magnetic field (B = 1 T)
  - Two different electrical drift fields

ILCTPC – Bonn: Preliminary results for Test beam



Further information about test beam results:

- Michael Lupberger, “Preliminary results from the 160 InGrid test beam”,University of Bonn, LCTPC-WP Meeting 10.09.2015,
- Jochen Kaminski,”Large Area Coverage of a TPC Endcap with GridPix Detectors”, University of Bonn,For the LCTPC collaboration , MPGD 2015, Trieste 12-15.10.2015,

- LC-TPC parameter

Parameter			
Geometrical parameters	r_{in} 329 mm	r_{out} 1808 mm	z $\pm$ 2350 mm
Solid angle coverage	up to $\cos\theta \simeq 0.98$ (10 pad rows)		
TPC material budget	$\simeq 0.05\ X_0$ including outer fieldcage in r		
	$< 0.25\ X_0$ for readout endcaps in z		
Number of pads/timebuckets	$\simeq$ 1-2 $\times 10^6$/1000 per endcap		
Pad pitch/ no.padrows	$\simeq 1\times$ 6 mm^2 for 220 padrows		
σ_{point} in $r\phi$	$\simeq 60\ \mu$m for zero drift, $<100\ \mu$m overall		
σ_{point} in rz	$\simeq 0.4 - 1.4$ mm (for zero – full drift)		
2-hit resolution in $r\phi$	$\simeq 2$ mm		
2-hit resolution in rz	$\simeq 6$ mm		
dE/dx resolution	$\simeq 5$ %		
Momentum resolution at B=3.5 T	$\delta(1/p_t) \simeq 10^{-4}$/GeV/c (TPC only)		