# Characterising CCDs with Cosmic Rays

Merlin Fisher–Levine

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# Outline

- Introducing cosmic rays
  - Cosmic ray properties
    - Energy deposition & the Landau distribution
  - What measurements do the properties of cosmic rays allows?

- Gain
  - Measuring CCD gain with darks
  - Comparison with $^{55}$Fe results

- PSF
  - Measuring PSF and diffusion with cosmics

- Edge Effects
  - Examining track bending at sensor edges with cosmics

# Introduction to cosmic rays

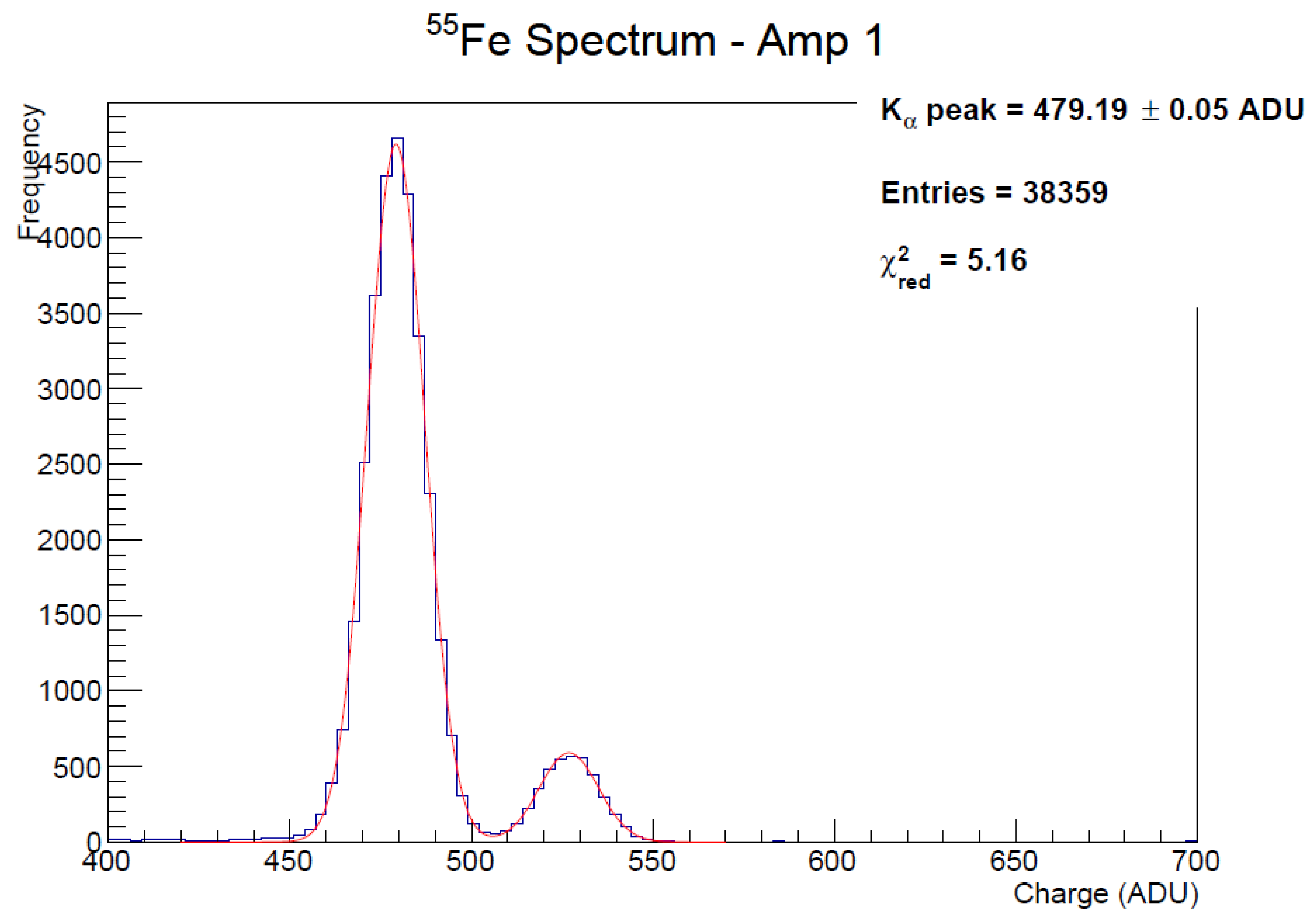
- An astronomer's enemy is a sensor scientist's best friend!
  - Cosmics need to be removed from sky images
  - However, they do provide a useful tool for characterising sensors:

- Tracks are very straight, very thin, and have a well-known energy distribution:

  - Energy distribution → Measure track fluxes → Gain measurement
  - Energy deposition in small area → Sharp tracks → PSF measurement & depth dependence
  - Track straightness → Measure deviation → Probe edge effects

# Gain measurement with $^{55}Fe$

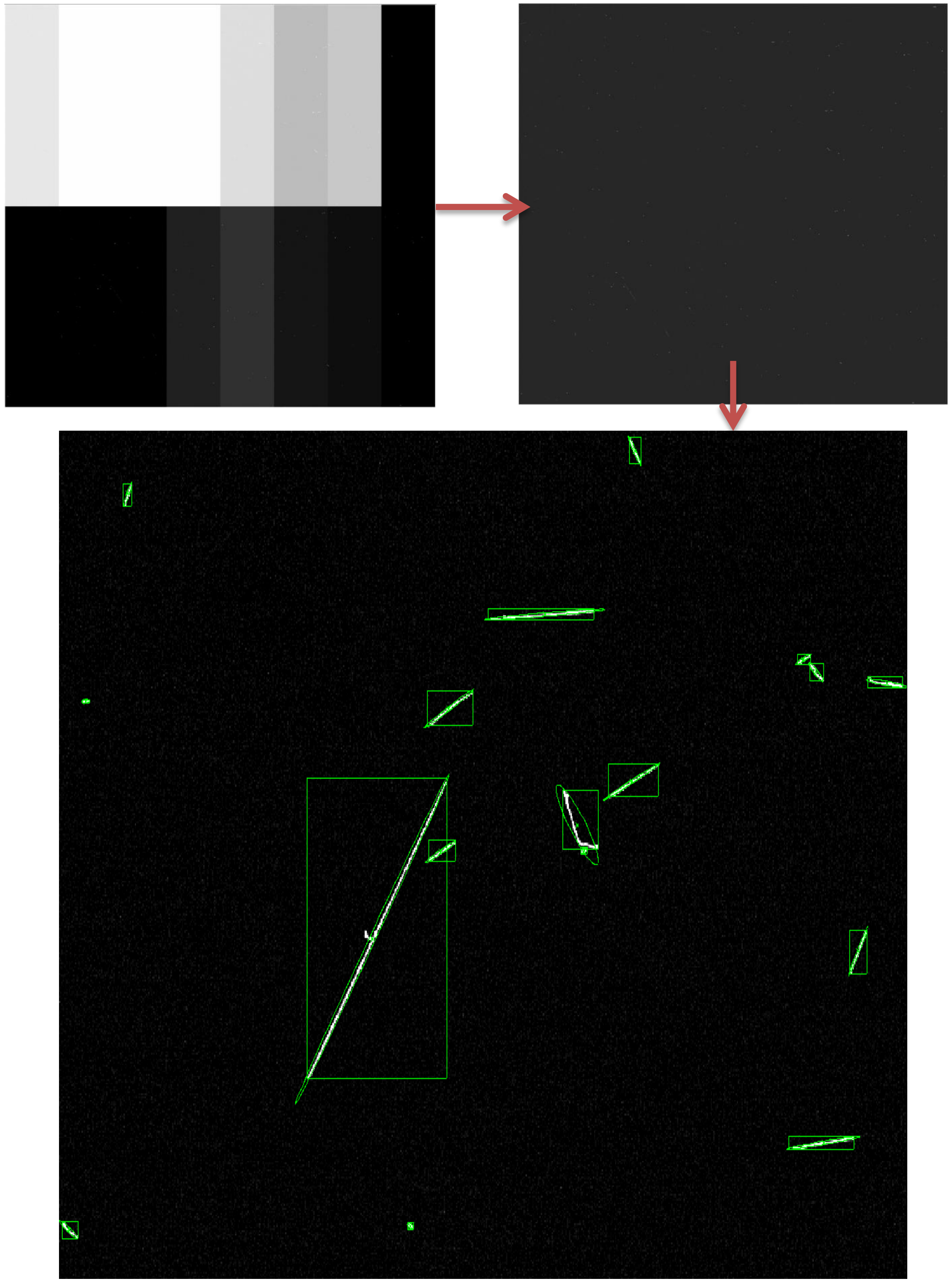
- Expose sensor to x-rays
- Histogram the charge associated with each x-ray hit
- Fit distribution with double Gaussian
  - Gain is found from pair creation energy in Si & the energy of $^{55}$Fe x-rays




- Using ~ 5 mins of data (≈ 1M x-ray hits), the gain can be calculated to ~ 0.01%
- Only problem: <u>can't do this *in-situ*</u>

# Alternative: cosmic ray gain measurement

- Take dark exposures, find tracks and classify events into three categories:
  - Worms
  - Spots
  - Cosmic rays
- Apply cuts to reject worms and spots, keeping only cosmics
- Cosmics are “minimum ionising particles”
  - Energy deposit per unit length is stochastic, but has a well known distribution
    - Landau distributed energy loss
    - Fit the Landau, get the gain



# Landau Distribution

## Landau Distribution

$$f(x,\Delta) = \phi(\lambda)/\xi$$

$$\phi(\lambda) = \frac{1}{\pi}\int_0^\infty e^{-u\ln u - u\lambda}\sin(\pi u)\,du$$

$$\lambda = \frac{1}{\xi}[\Delta - \xi(\ln\xi - \ln\epsilon + 1 - C)]$$

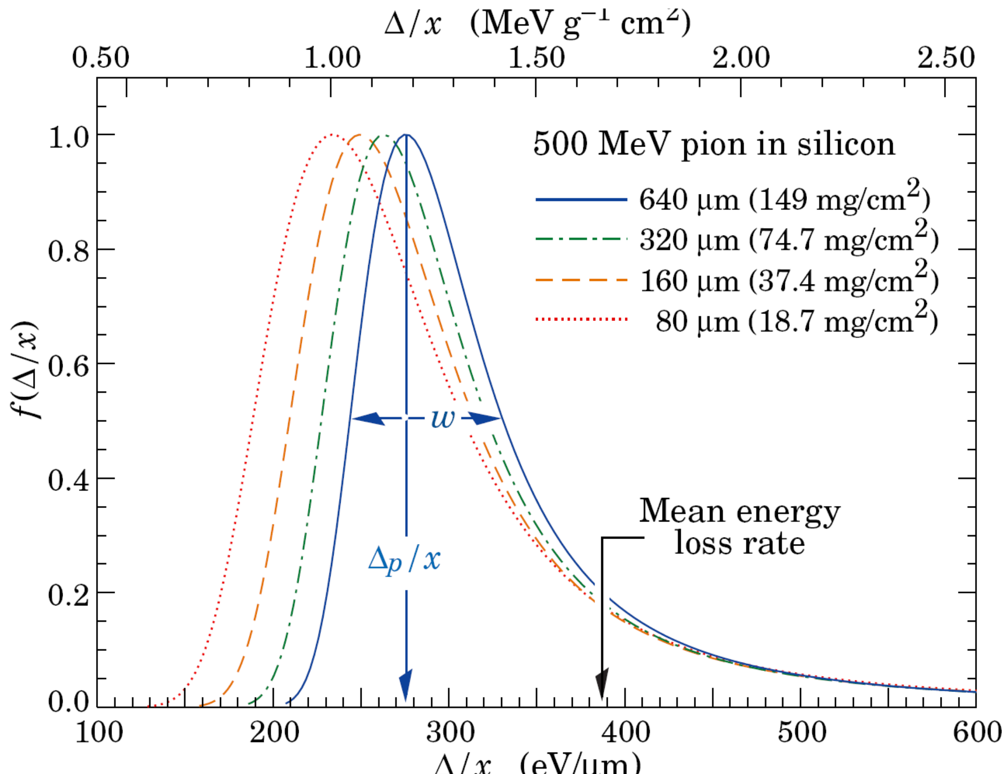
$$\ln\epsilon = \ln\frac{(1-\beta^2)I^2}{2mc^2\beta^2} + \beta^2$$

$K = 2\pi N_0 r_e^2 m_e c^2 = 0.1535\mathrm{MeV}\,c^2/\mathrm{g}$;
$x$ is the path length in g/cm$^2$;
$r_e = \frac{e^2}{4\pi\epsilon_0 m_e c^2} = 2.8179 \times 10^{-13}$ cm is the classical electron radius;
$m_e$ is the mass of the electron;
$N_0$ is Avagadro's number, $6.022 \times 10^{23}$;
$I$ is the mean excitation energy averaged over all electrons in eV;
$Z$ is the atomic number of the medium;
$A$ is the atomic weight of the medium;
$\rho$ is the density of the medium;
$z$ is the charge of the incoming particle;
$\beta = v/c$ is the ratio of the incoming particle to the speed of light;
$\gamma$ is the Lorentz factor $\frac{1}{\sqrt{1-\beta^2}}$;
$\delta_{ion}$ is a density correction;
$C$ is a shell correction;

## Peak Energy loss

$$\Delta_p = \xi\left[\ln\frac{2mc^2\beta^2\gamma^2}{I} + \ln\frac{\xi}{I} + j - \beta^2 - \delta_{ion}(\beta\gamma)\right]$$

$$\xi = x\cdot\frac{K}{2}\frac{Z}{A}\frac{1}{\beta^2}\,\mathrm{MeV}$$



# Cosmic gain measurement

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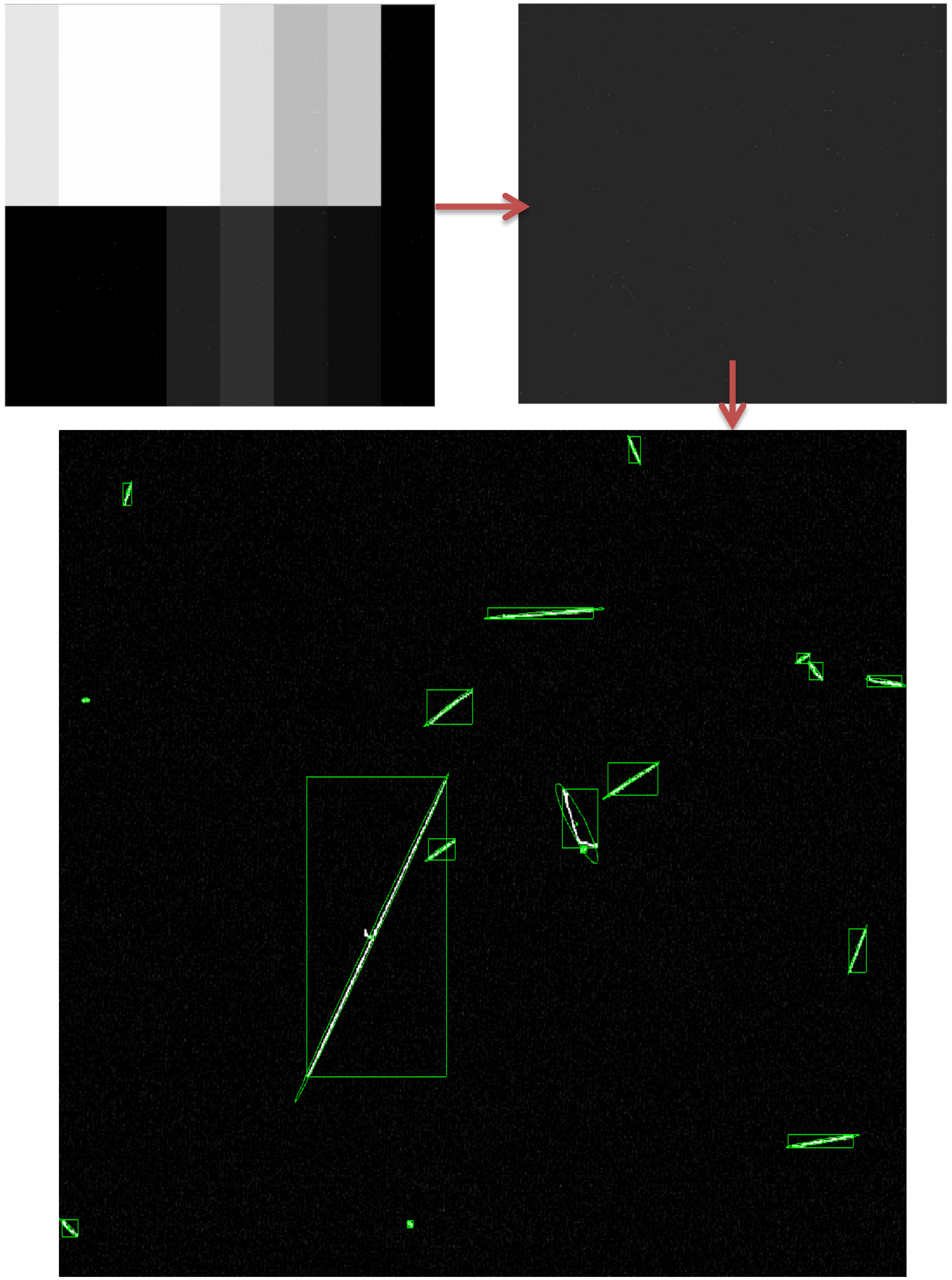
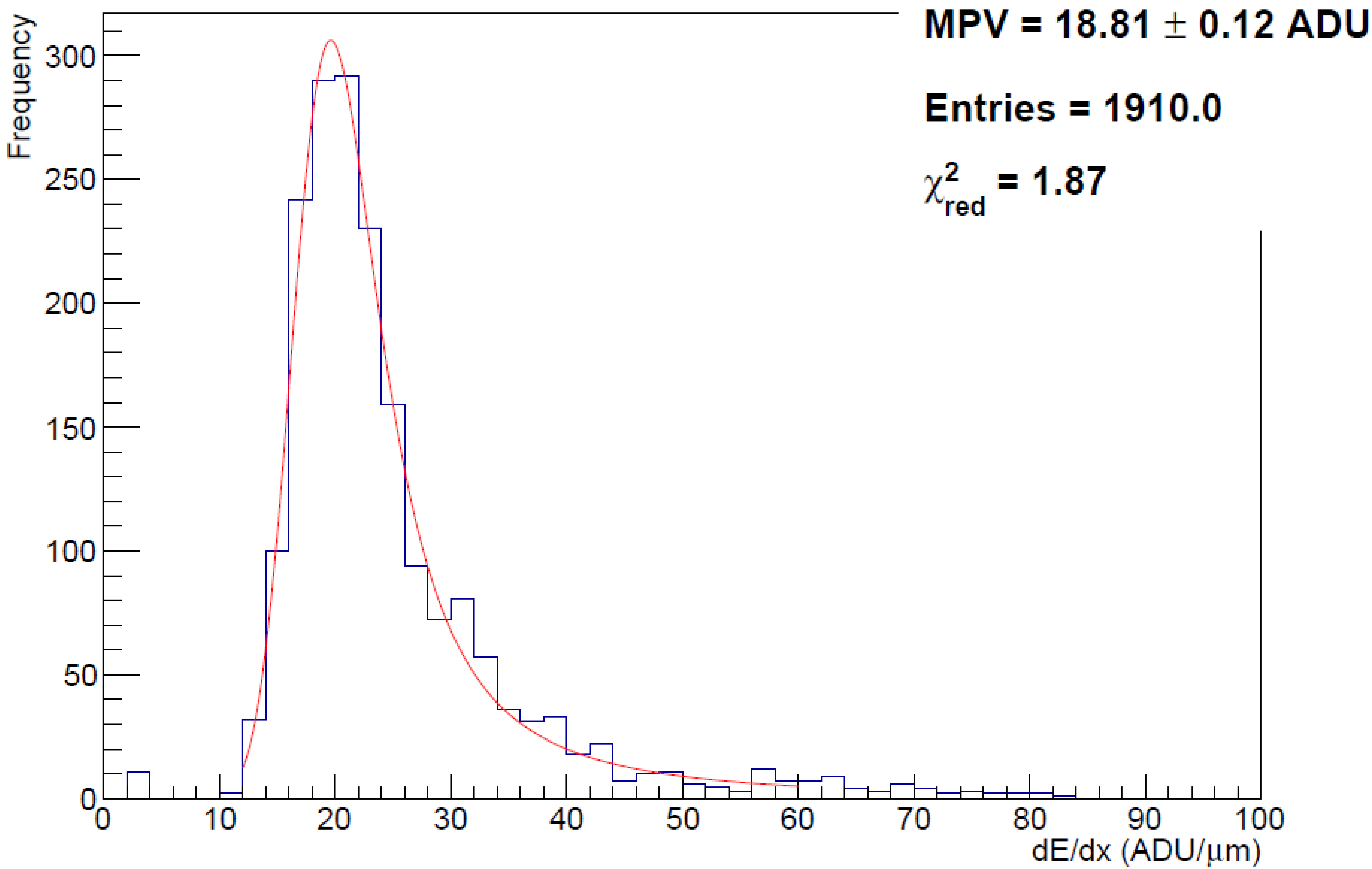


# Muon energy spectrum - Amp 1



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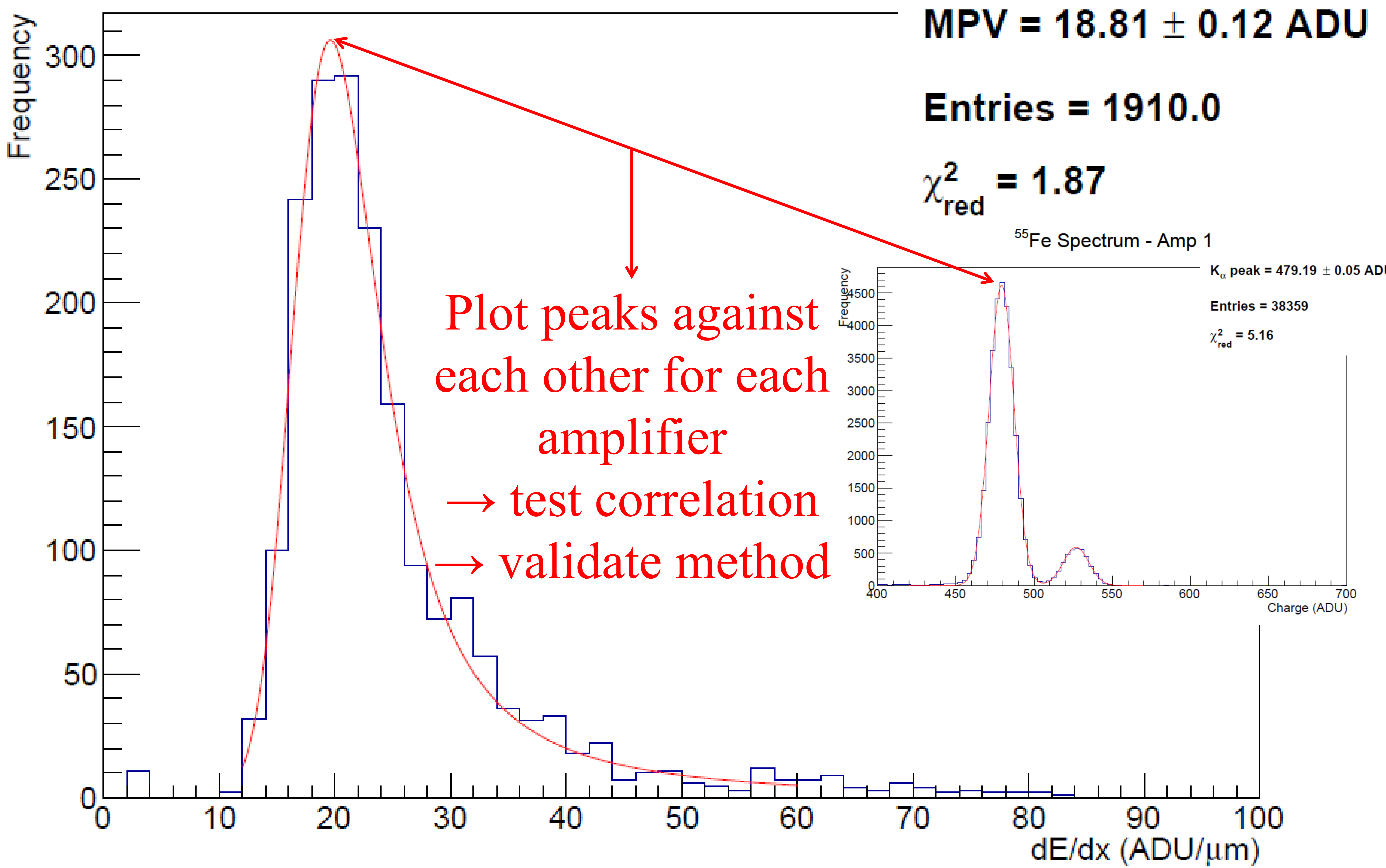
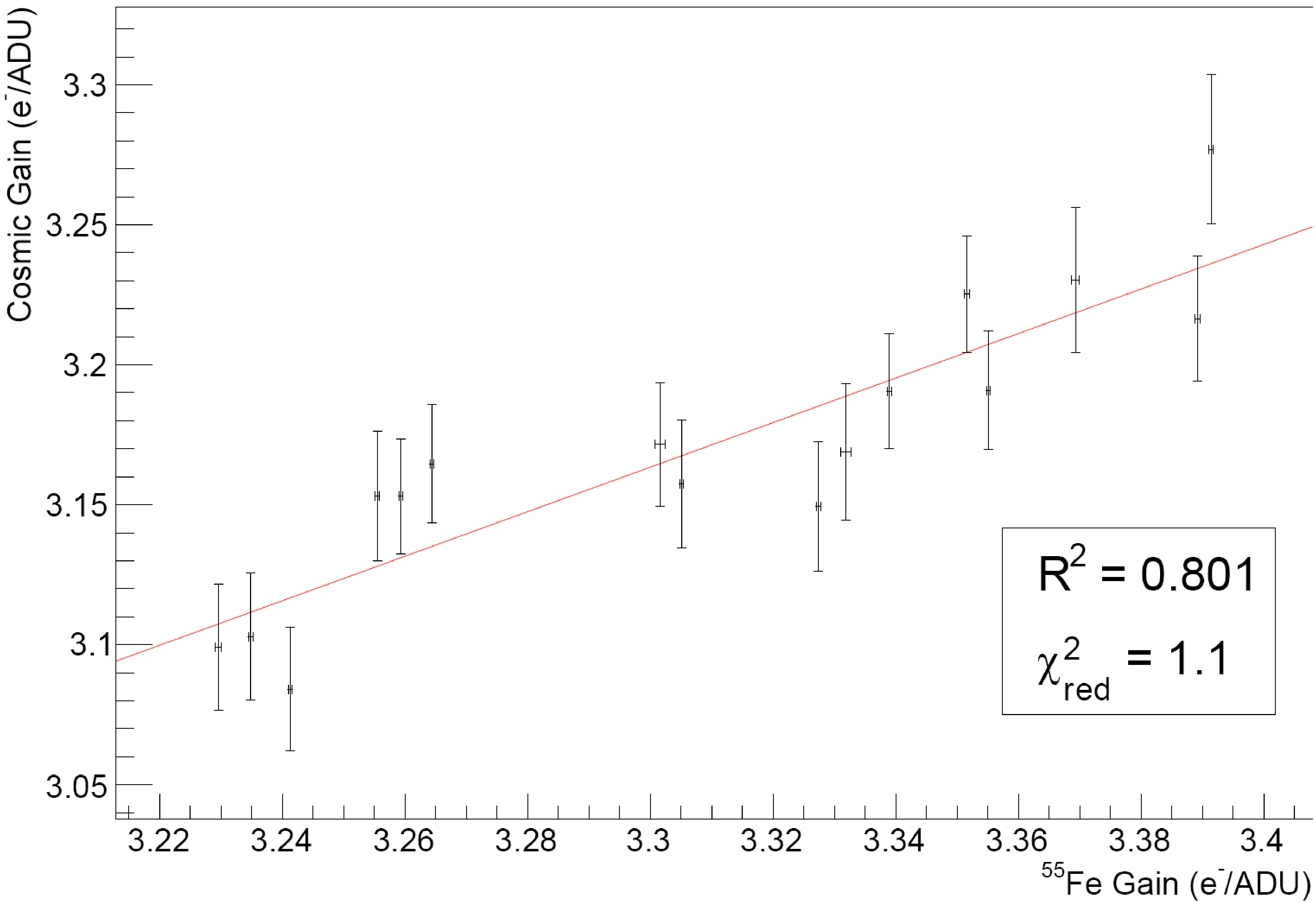
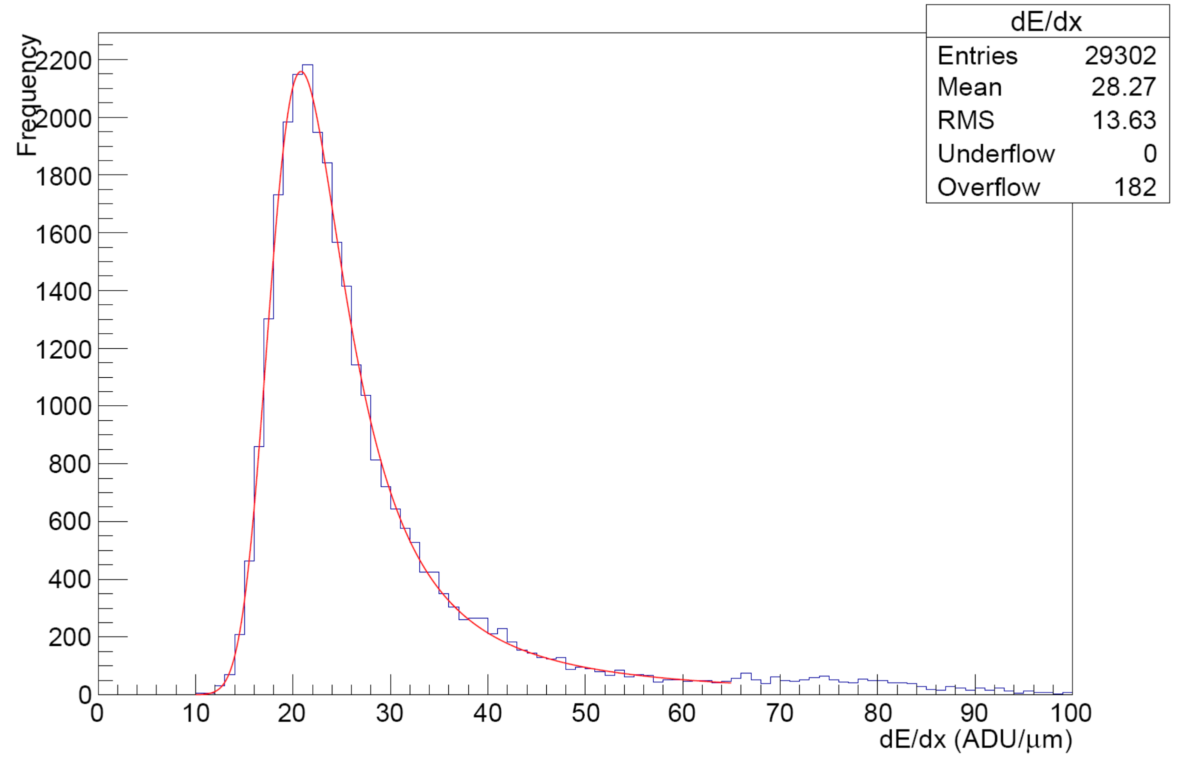


# $^{55}$Fe vs cosmic gain measurement



# Gain measurement summary

- Conclusion:
  - We can measure gain without using $^{55}Fe$ or PTC
  - We will get this information “for free” 24/7, and at twice the rate whilst on the mountain



# PSF Measurement

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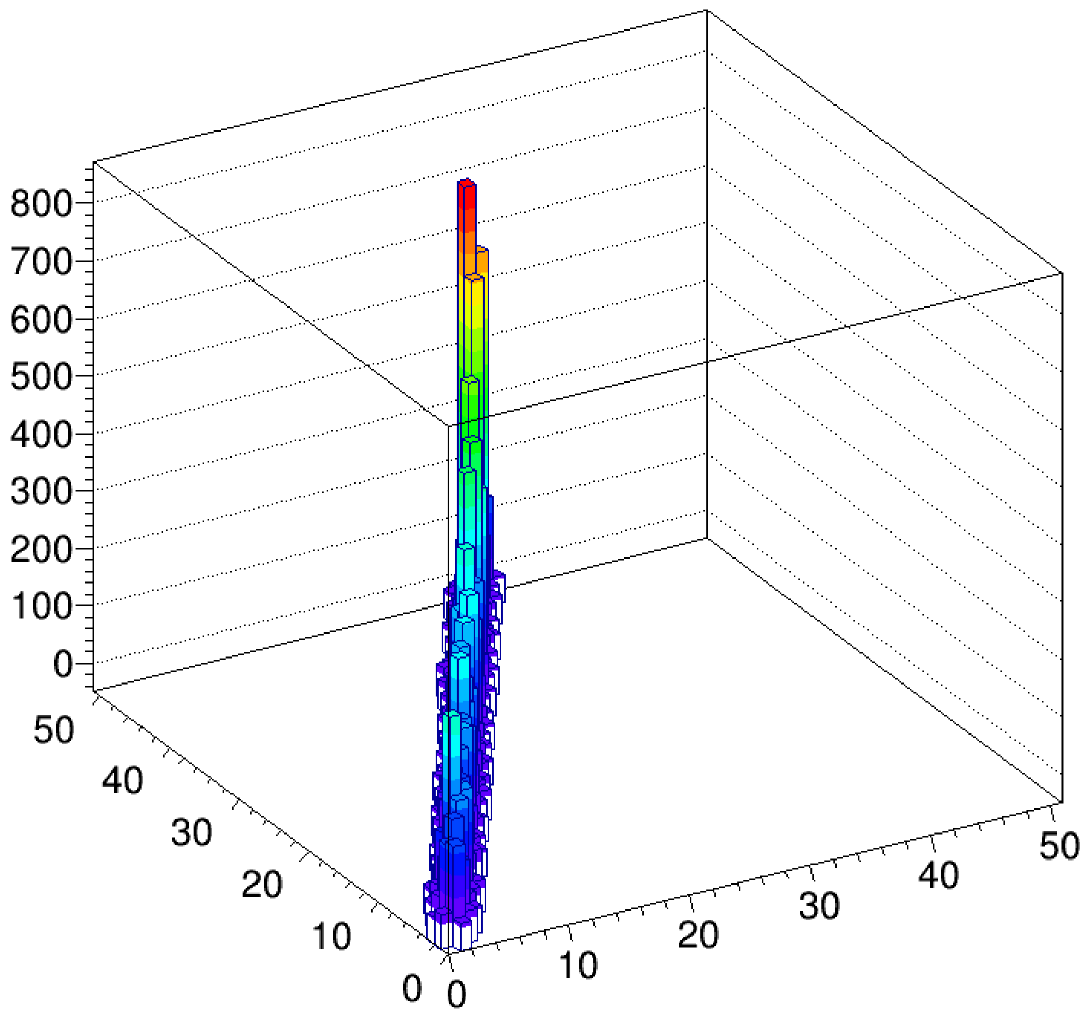
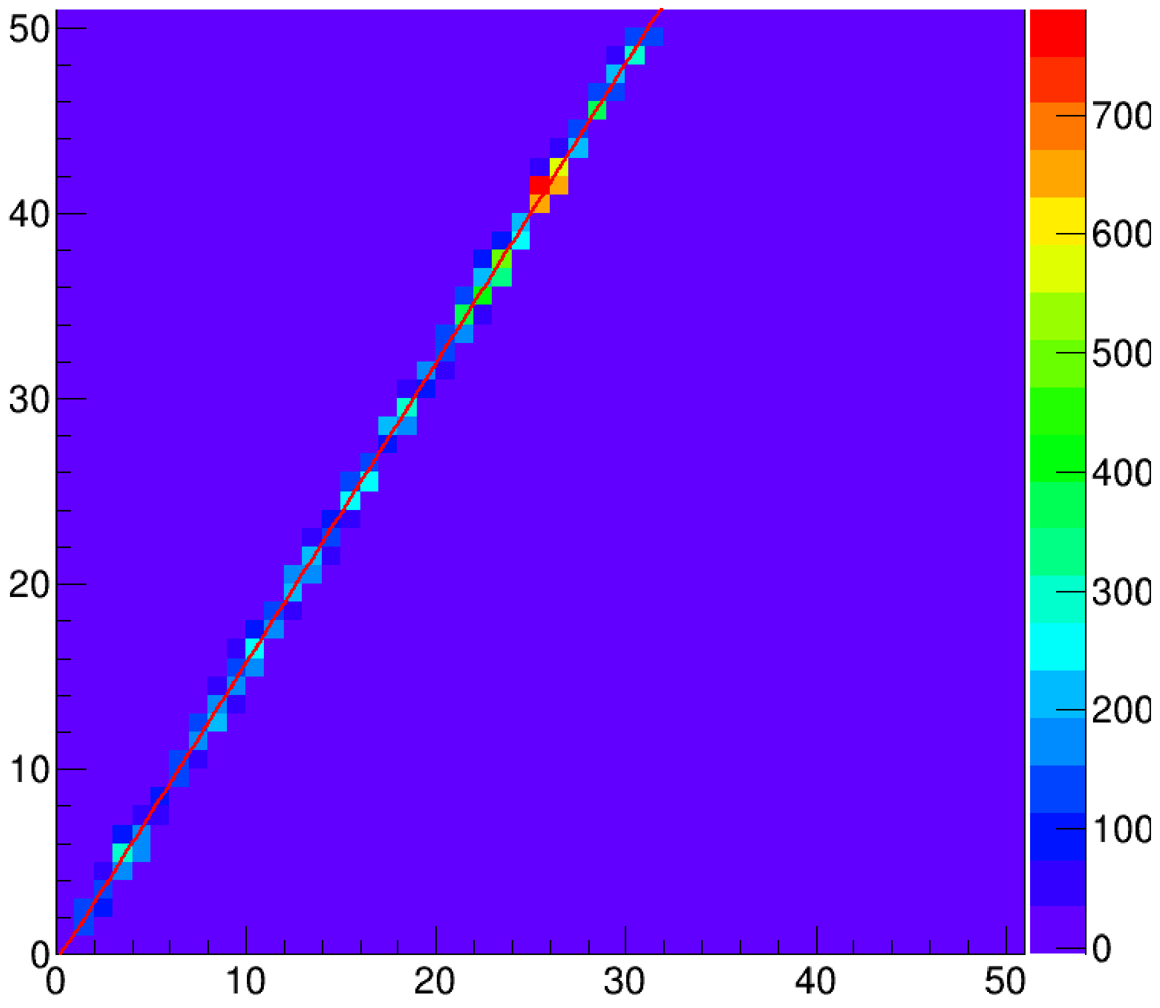
- Fit track with straight line
  - Project along line
    - Plot intensity as a function of distance to the track
  - Fit a Gaussian to get the PSF



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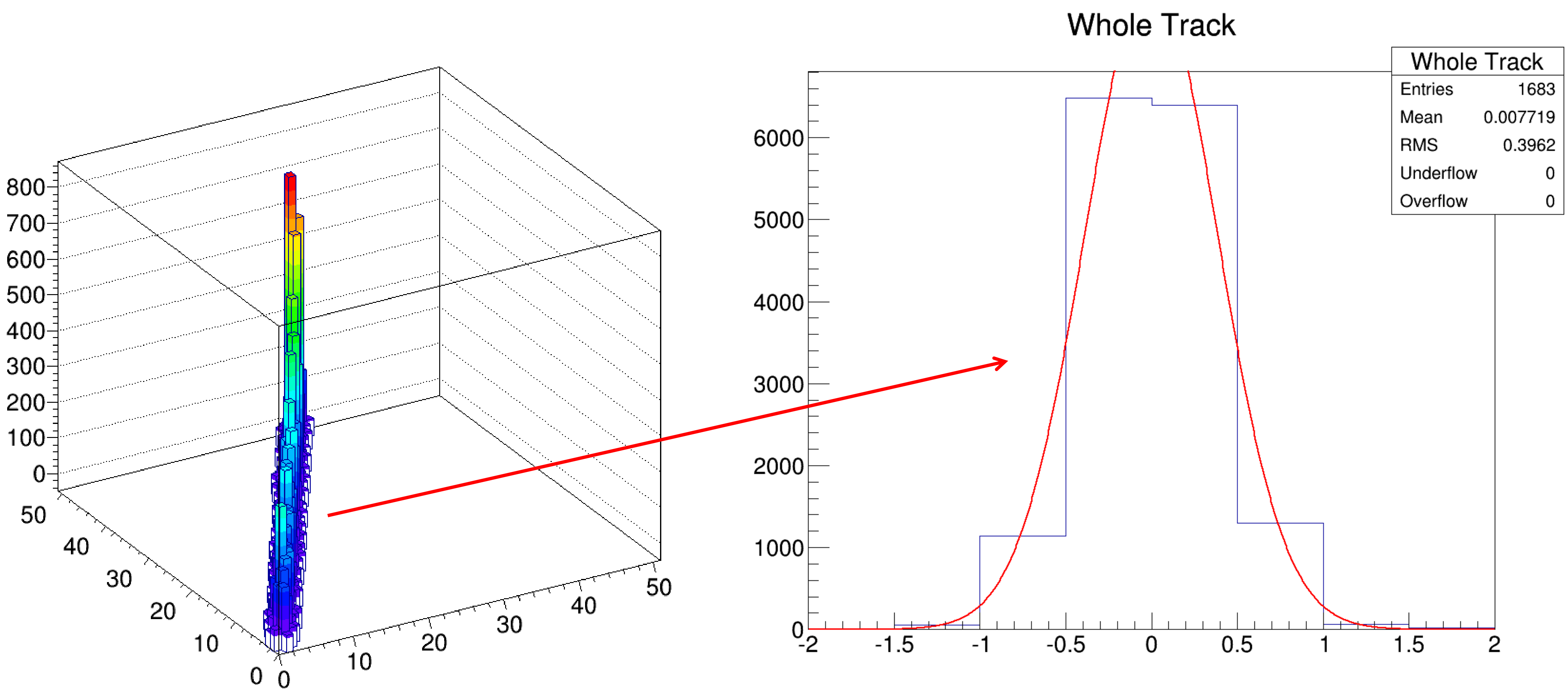
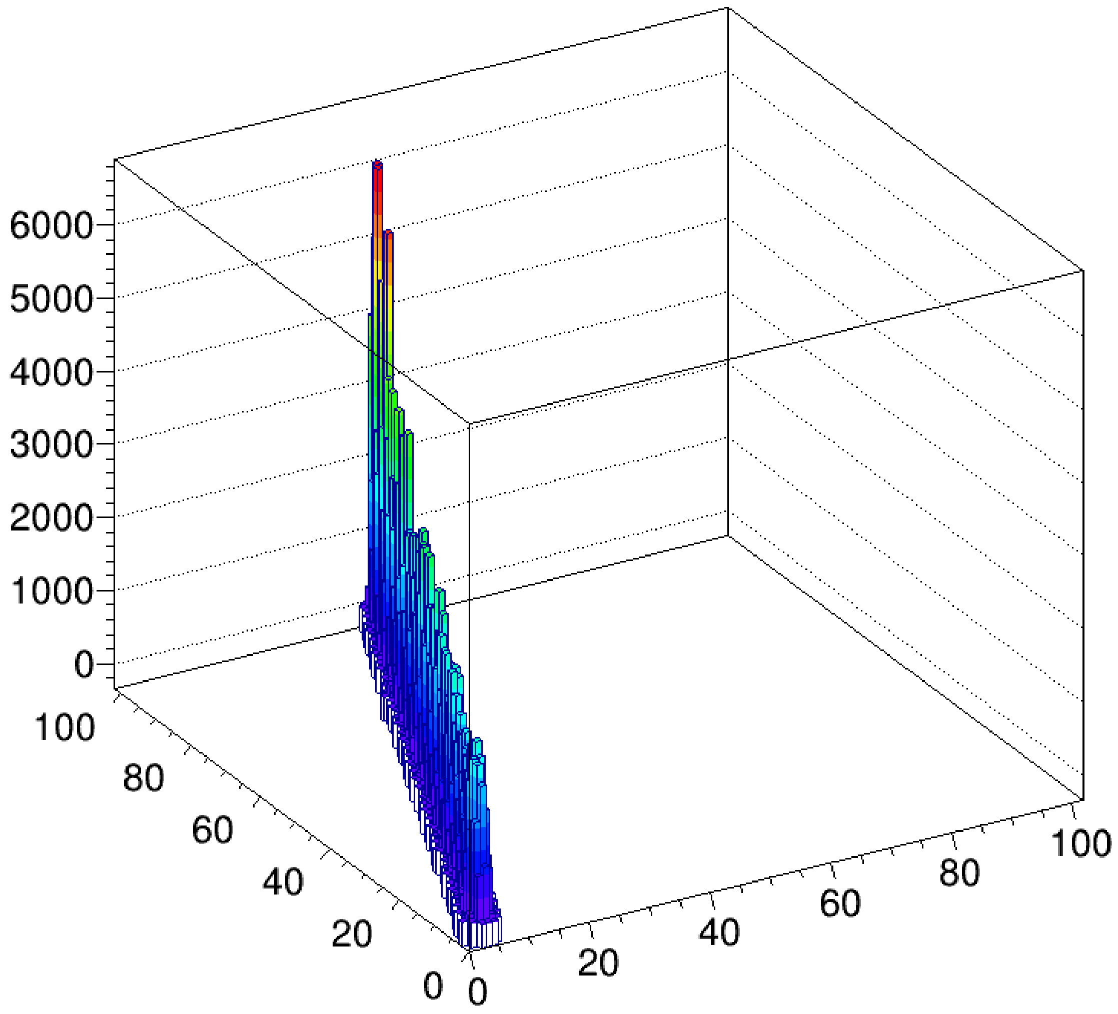
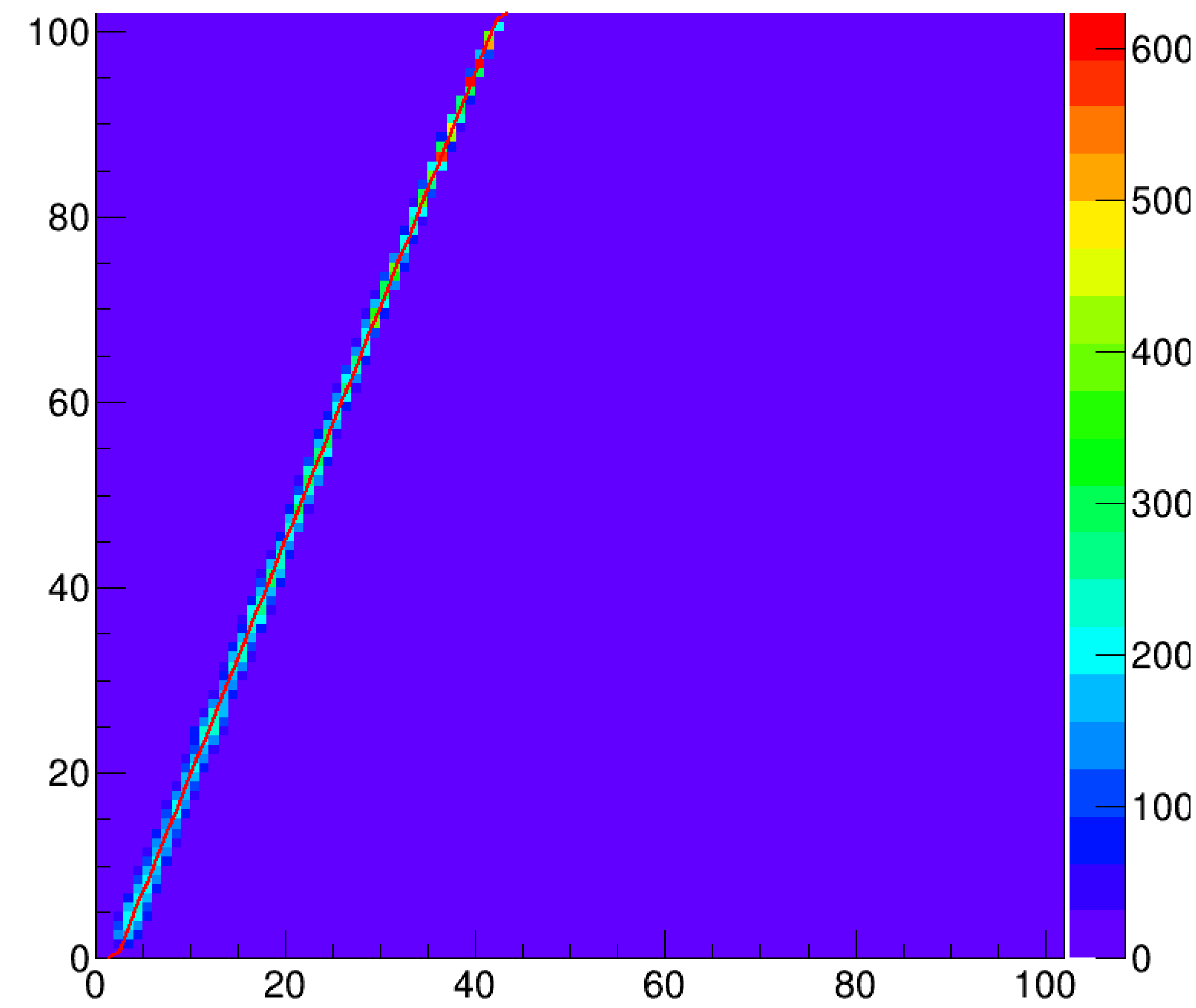


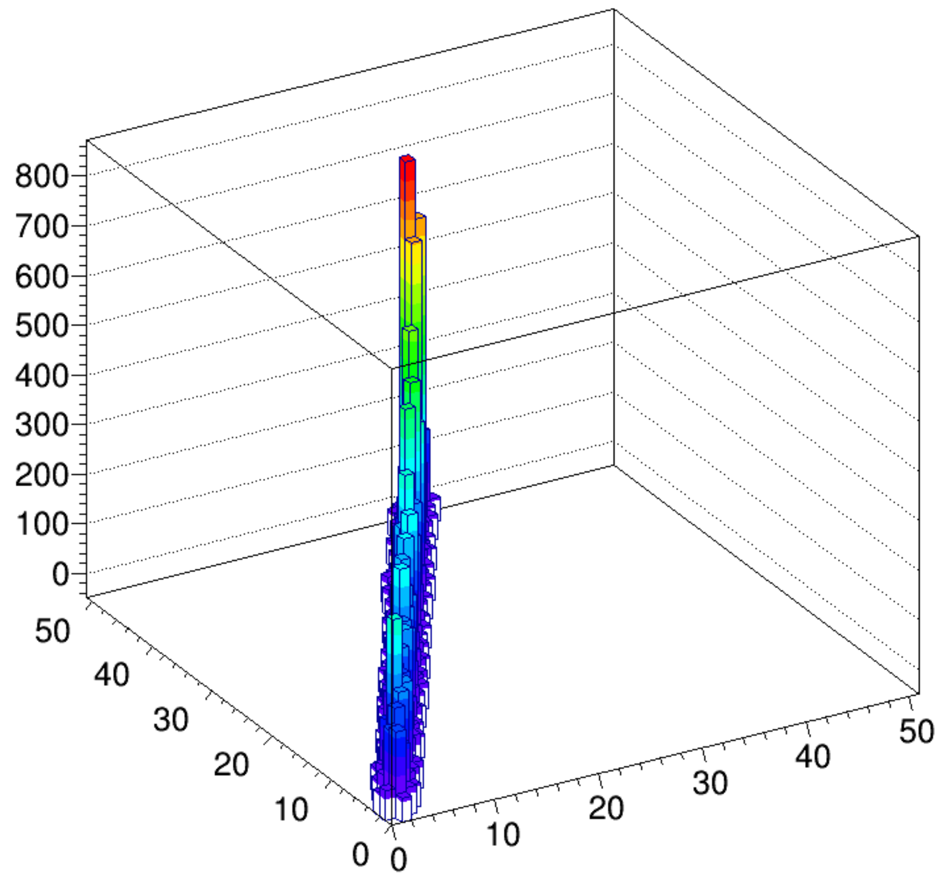
# Example of PSF changing with depth

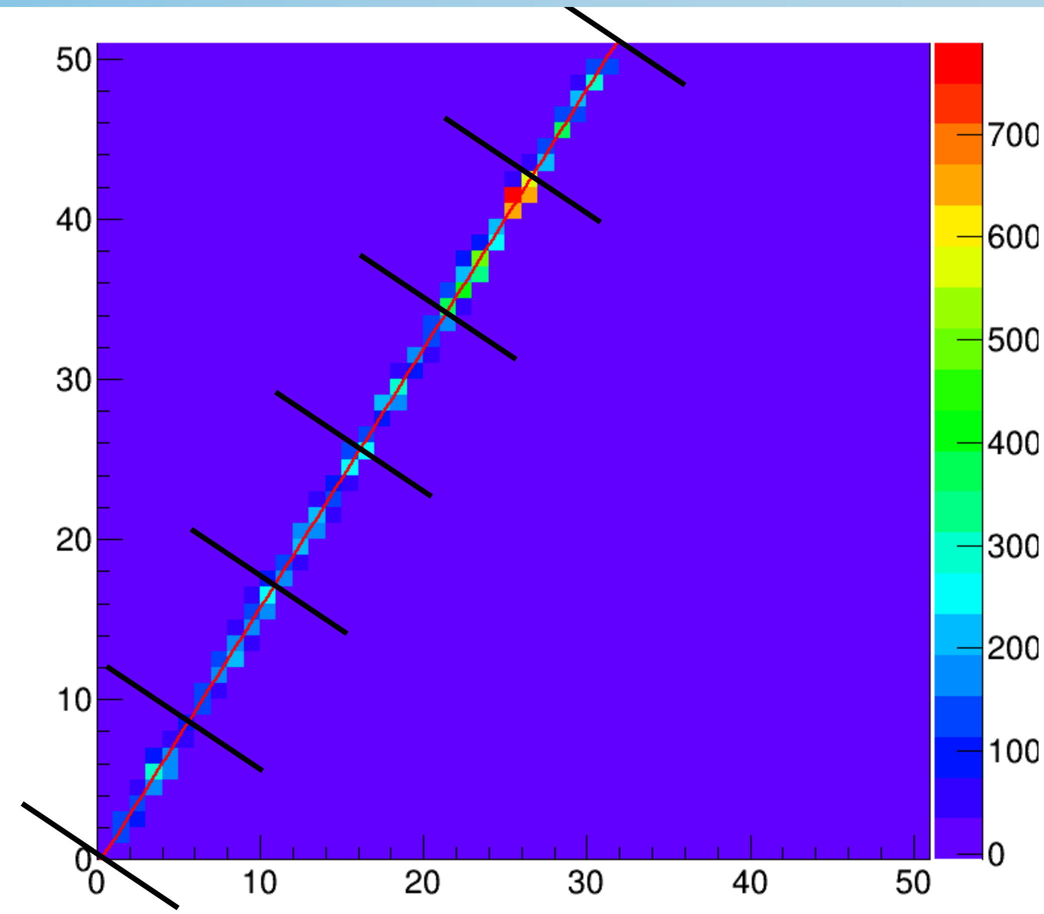
- Eye-candy:
  - Nice example of a track visibly changing in PSF whilst traversing the sensor:



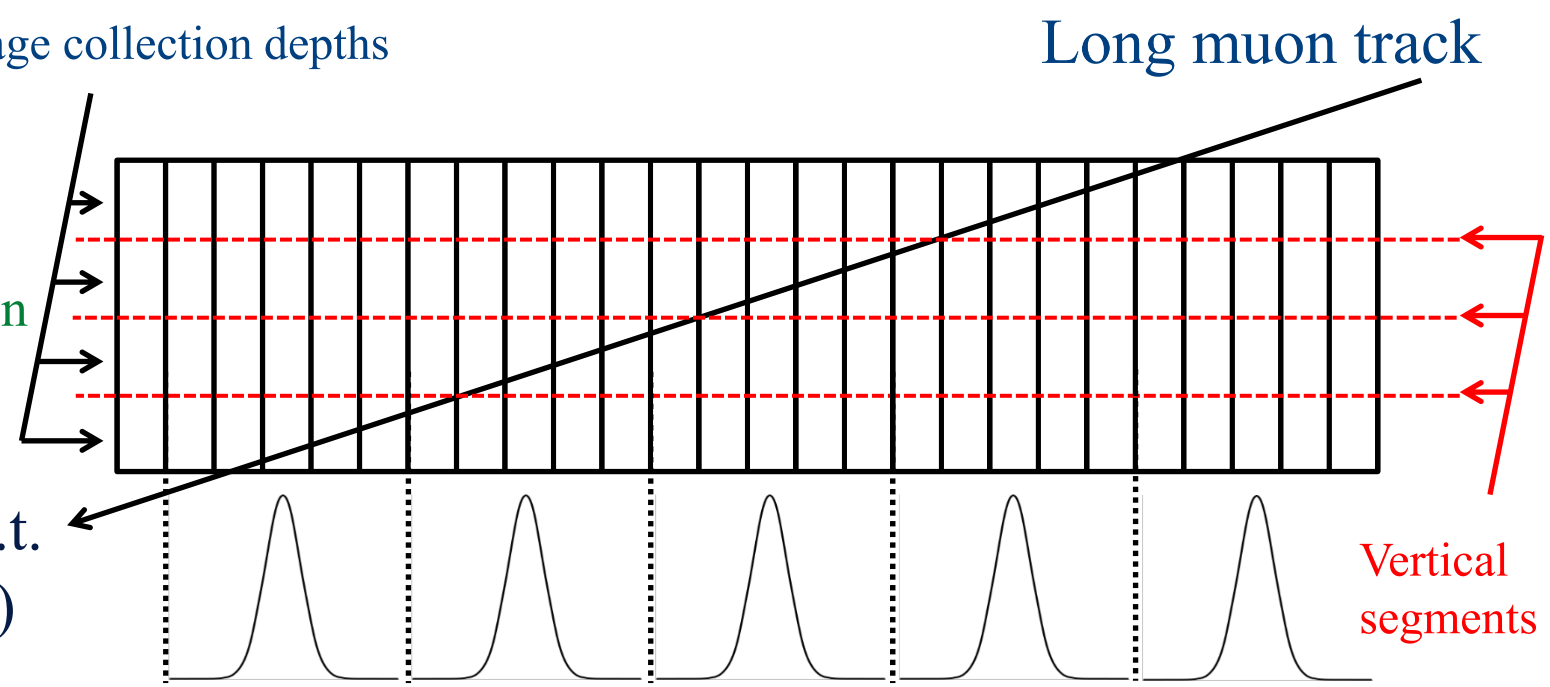



# PSF vs Depth: Track Segmentation



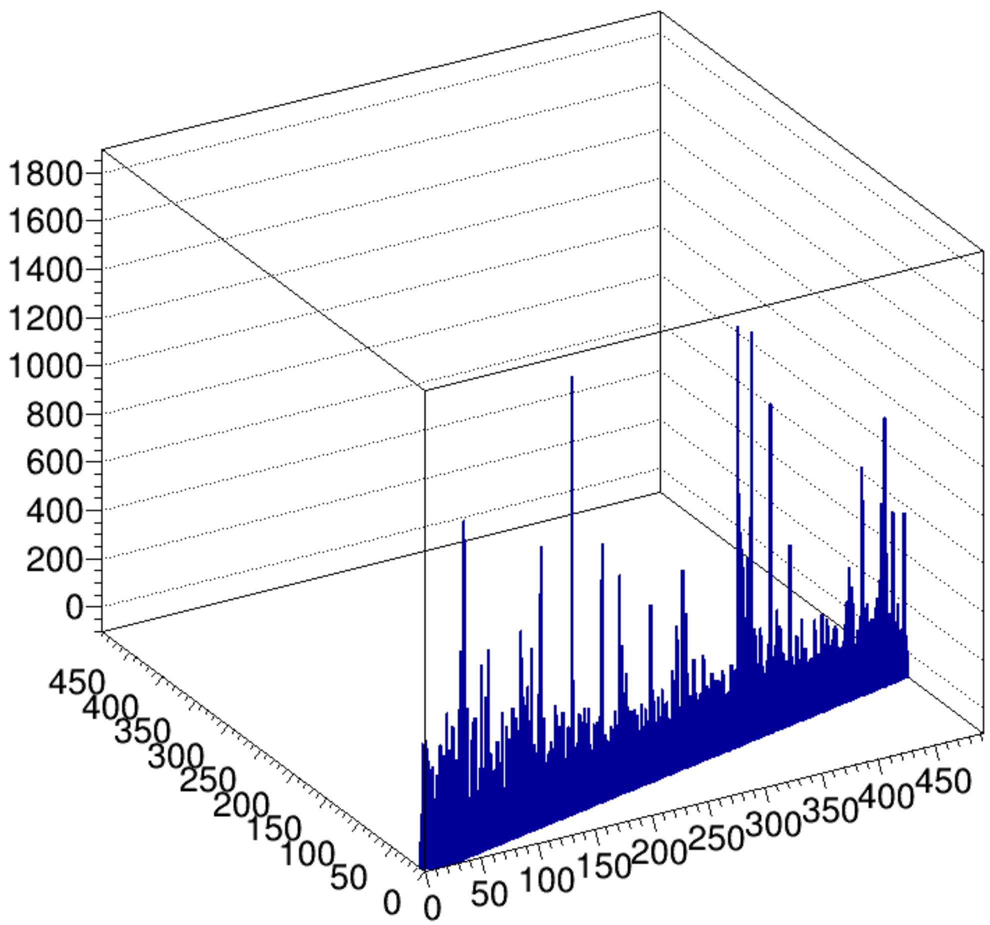

- Take a long track
  - Divide track into several segments
  - For each segment:
    - Produce histogram of intensity as a function of distance to the track as before
    - Again, fit Gaussian to get the PSF
  - Plot the widths of these Gaussians w.r.t. track segment number (i.e. depth in Si)

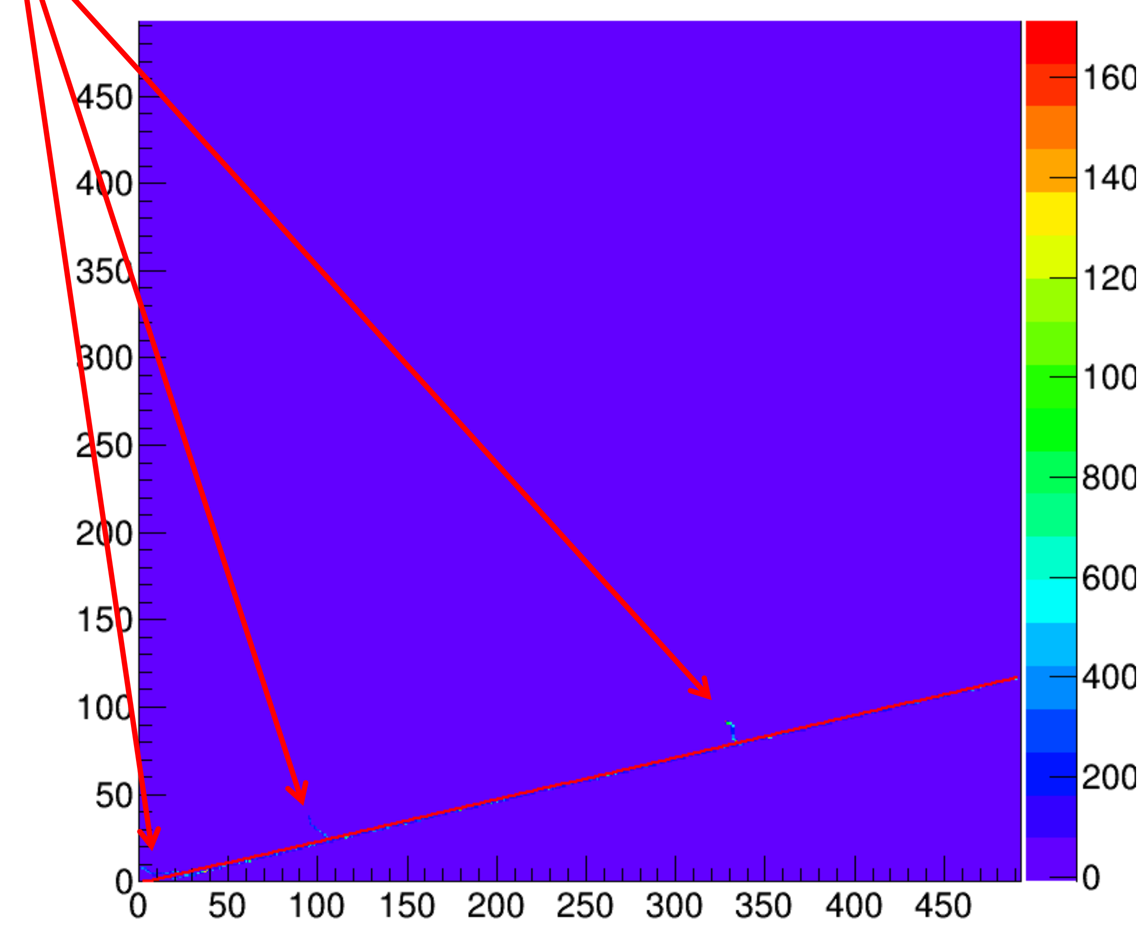


# PSF Track selection

- Here, however, unlike for gain measurements, when measuring PSF the δ-rays must be ***excluded***
  - They will ruin the PSF measurement for the depth at which they occur

Remove tracks with deltas



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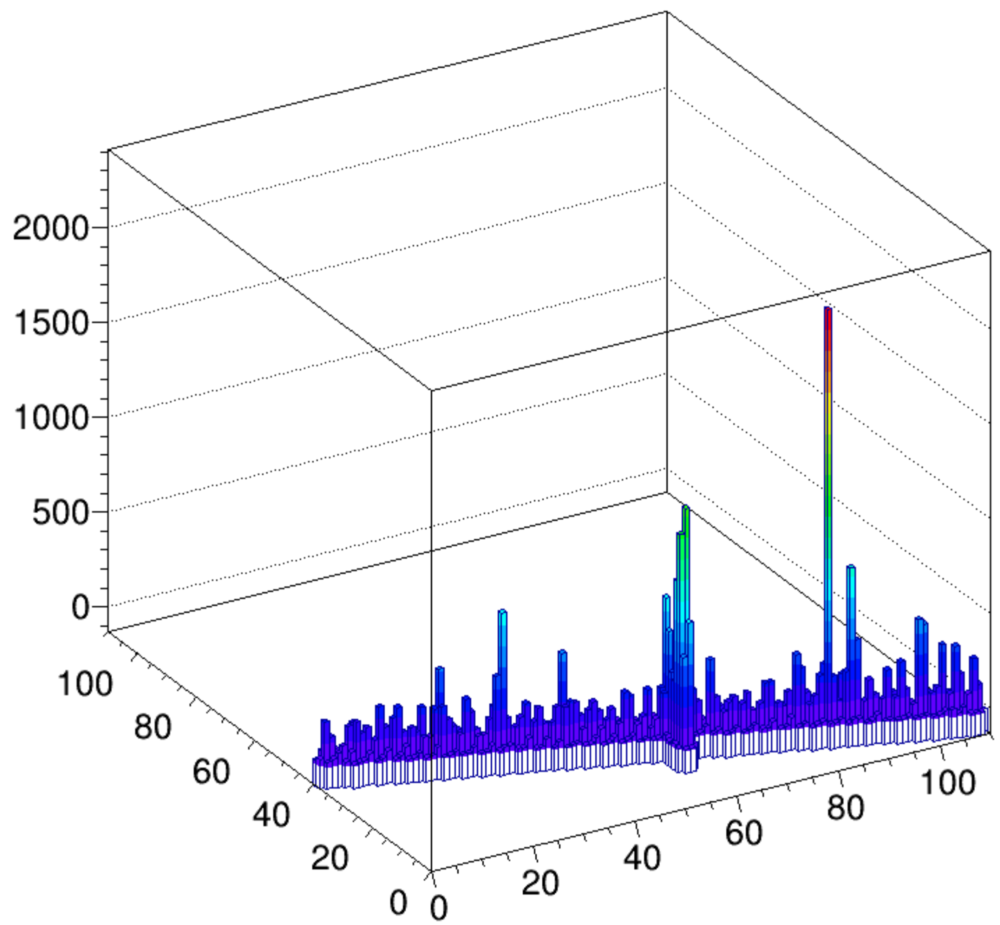
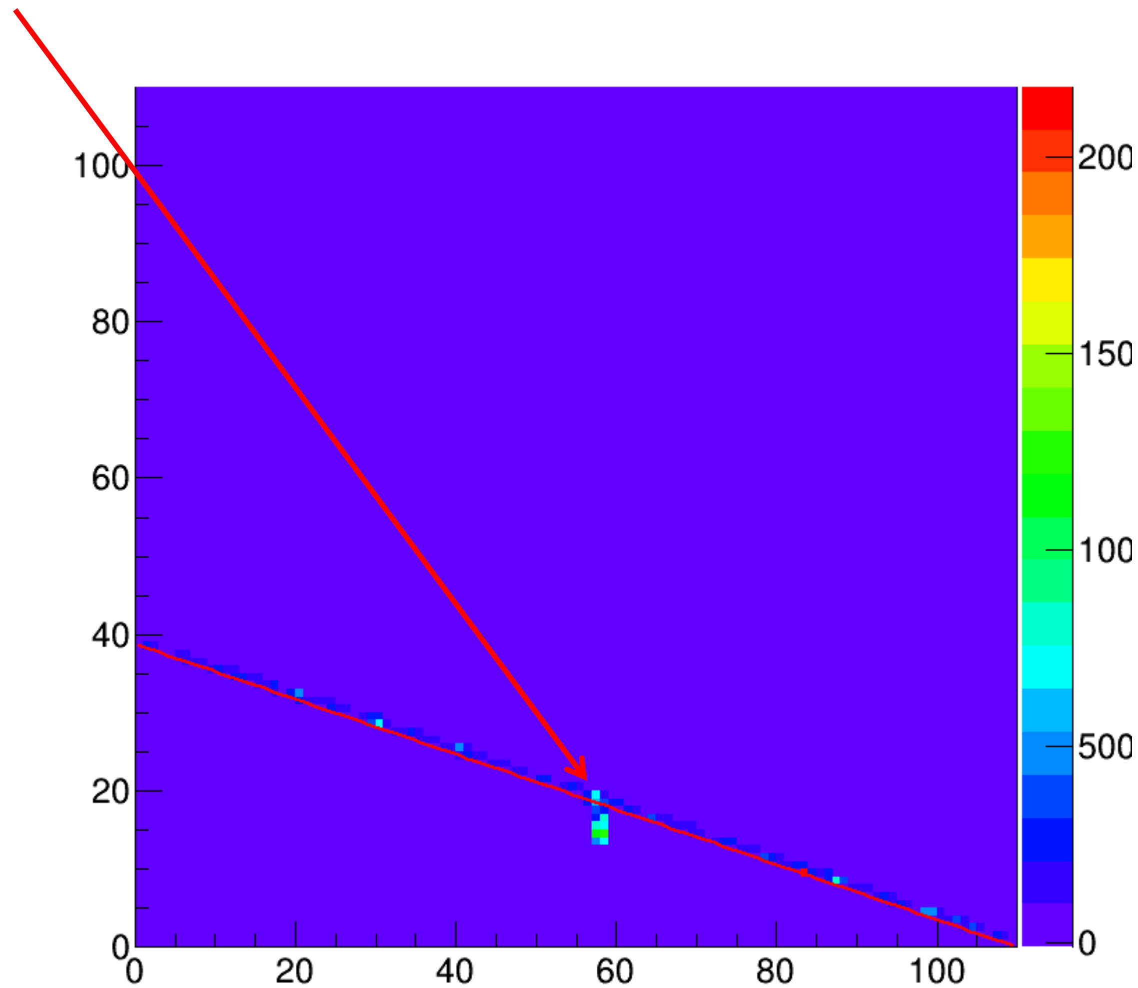
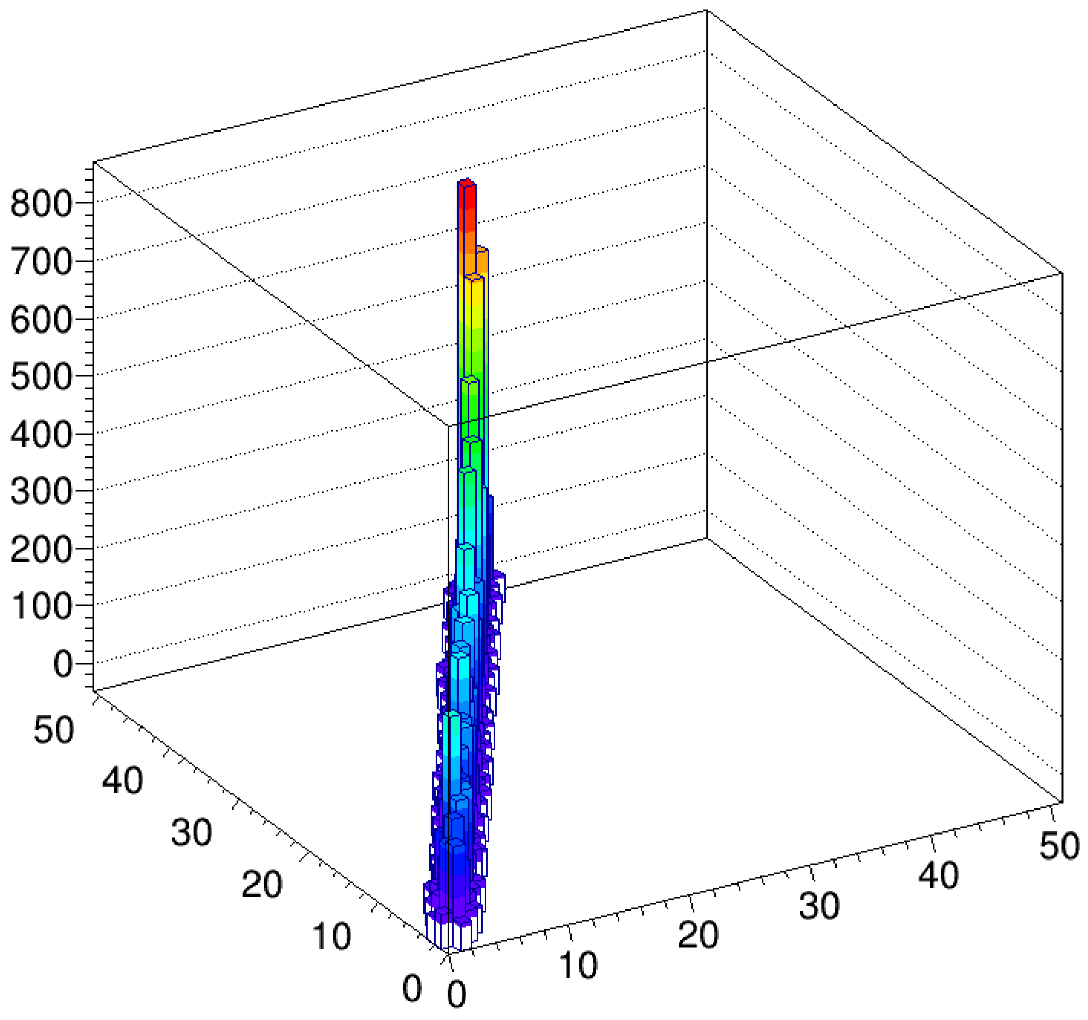
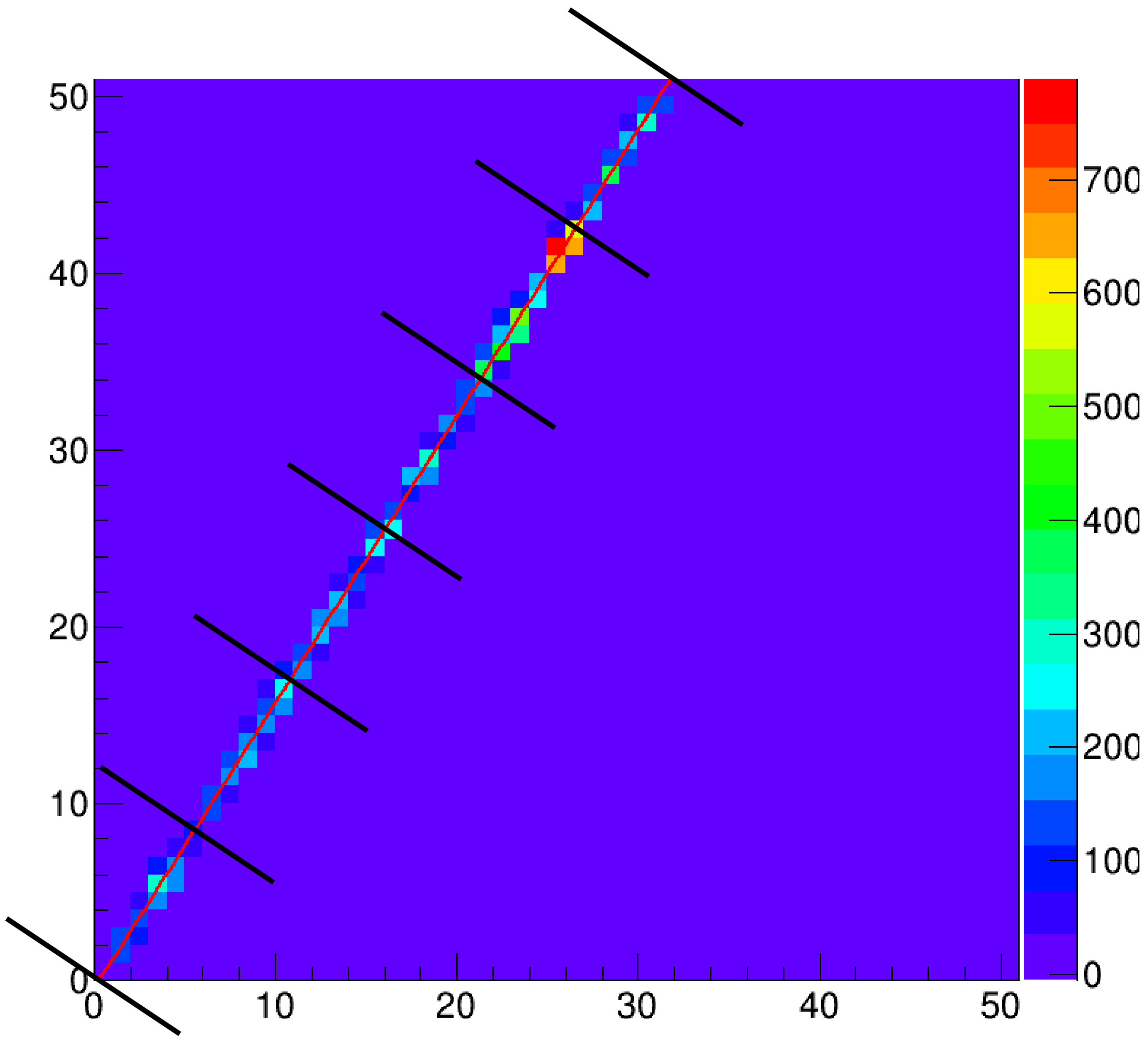


# Segment Measurement

- Fit each track with straight line
  - Divide track into n segments
  - For each segment:
    - Produce histogram of intensity as a function of distance to the track
    - Fit a Gaussian to get the PSF



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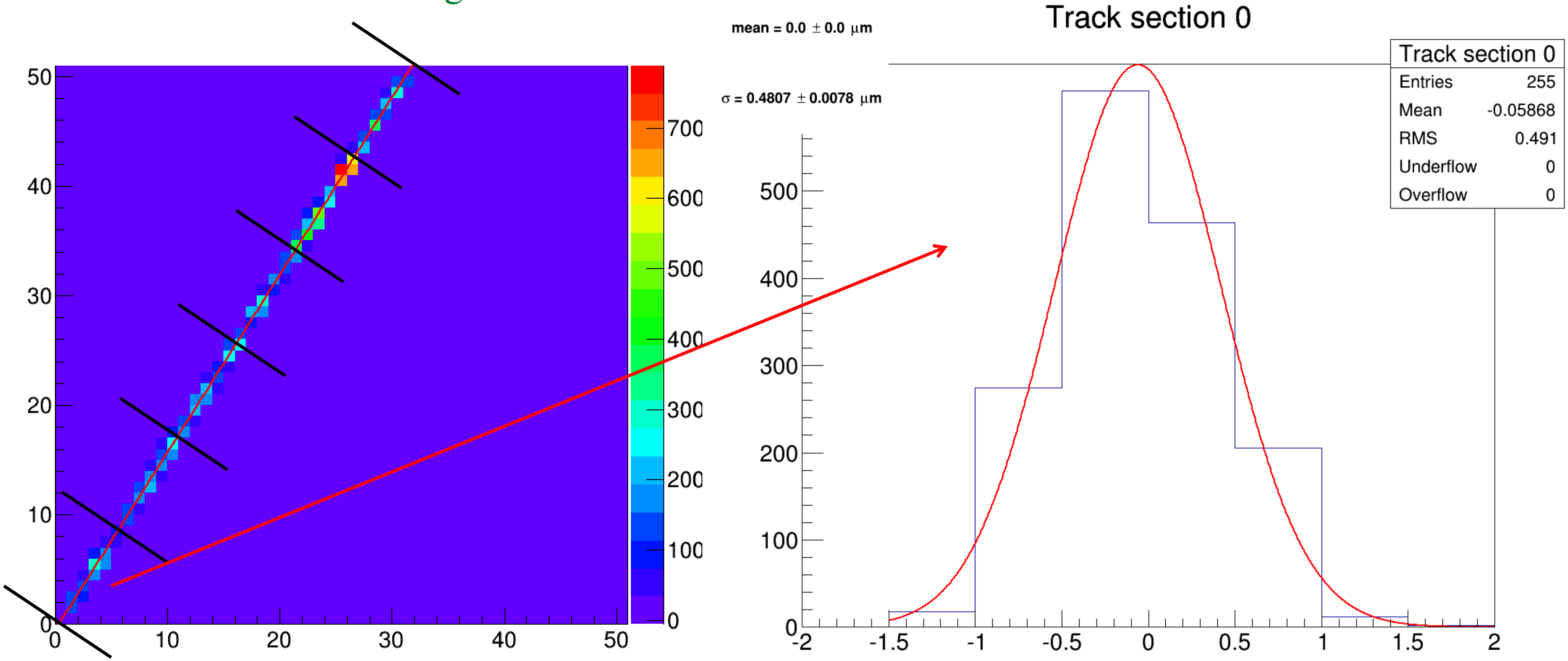

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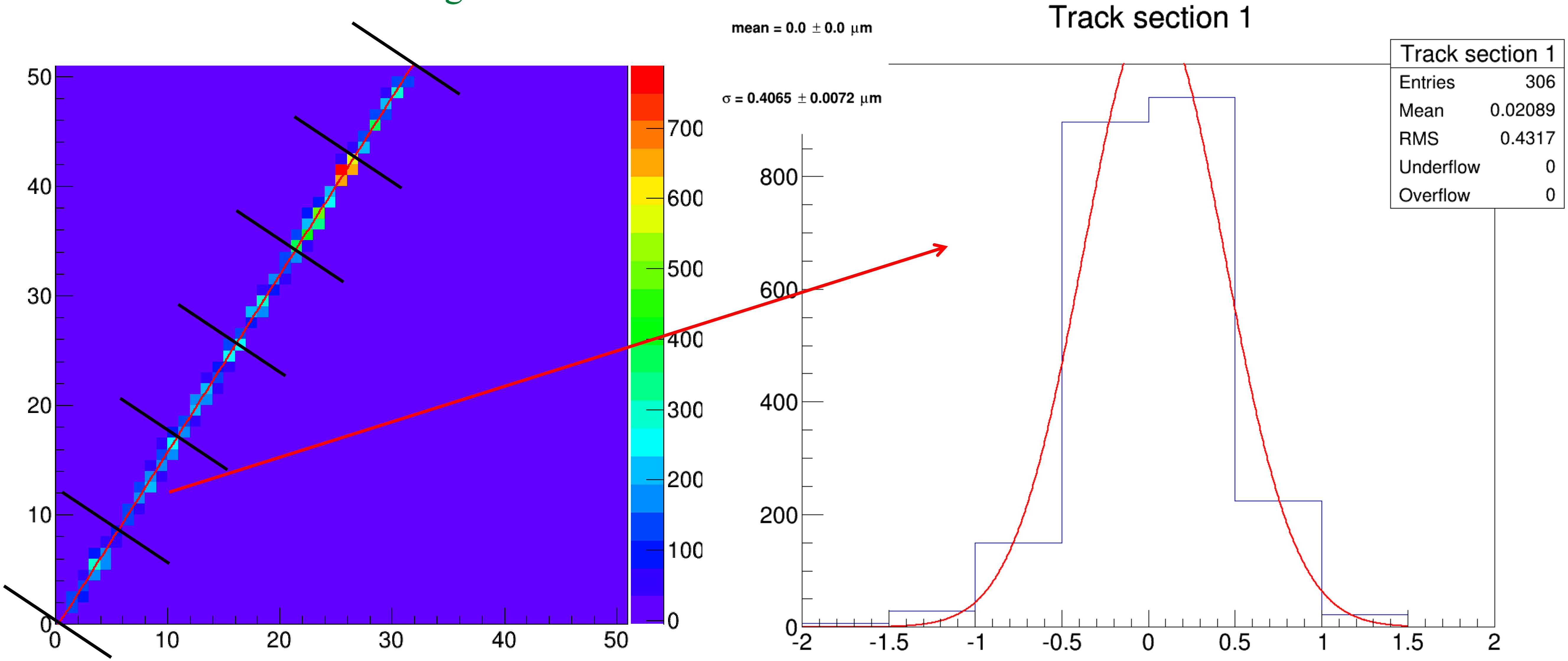

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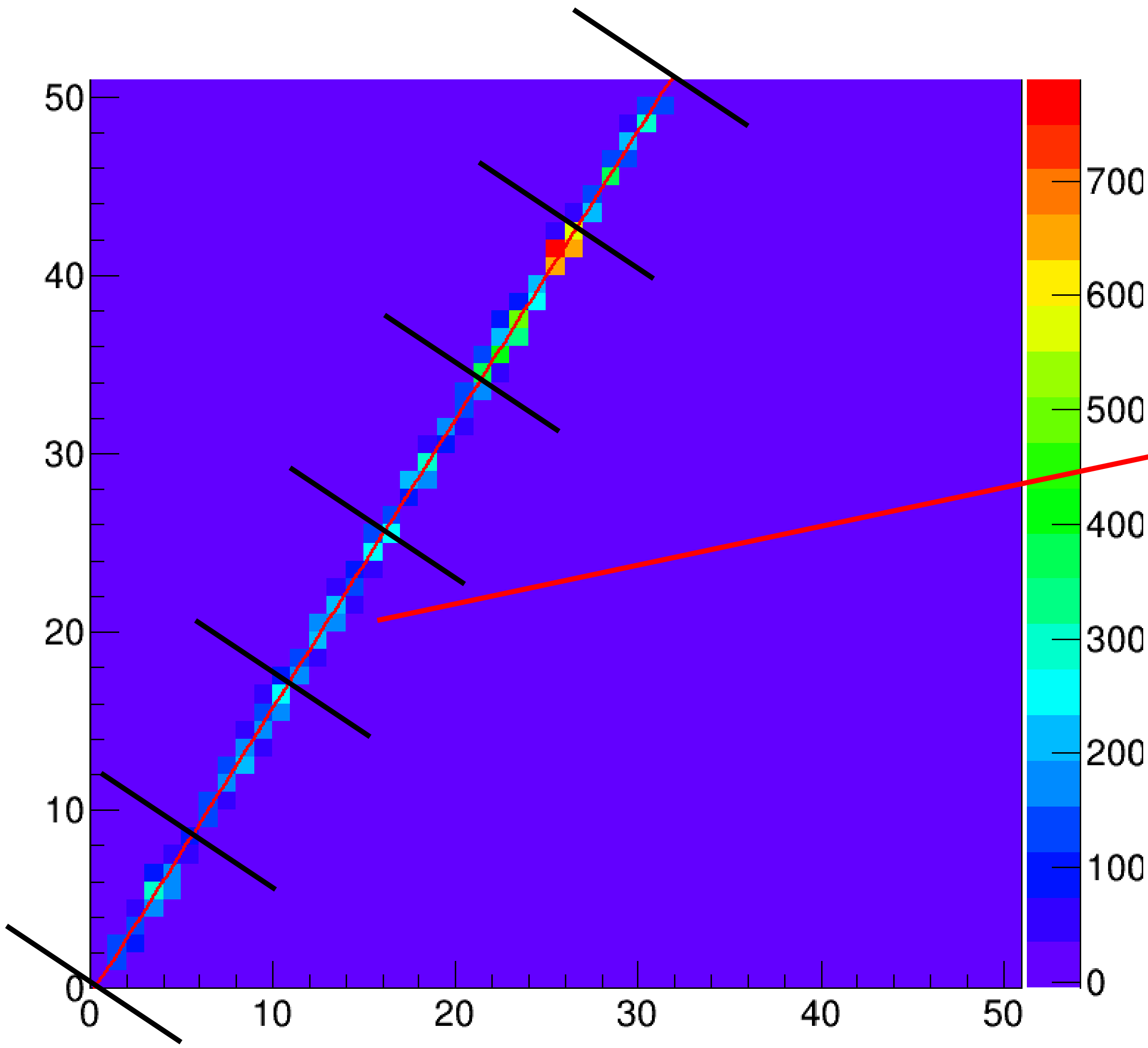


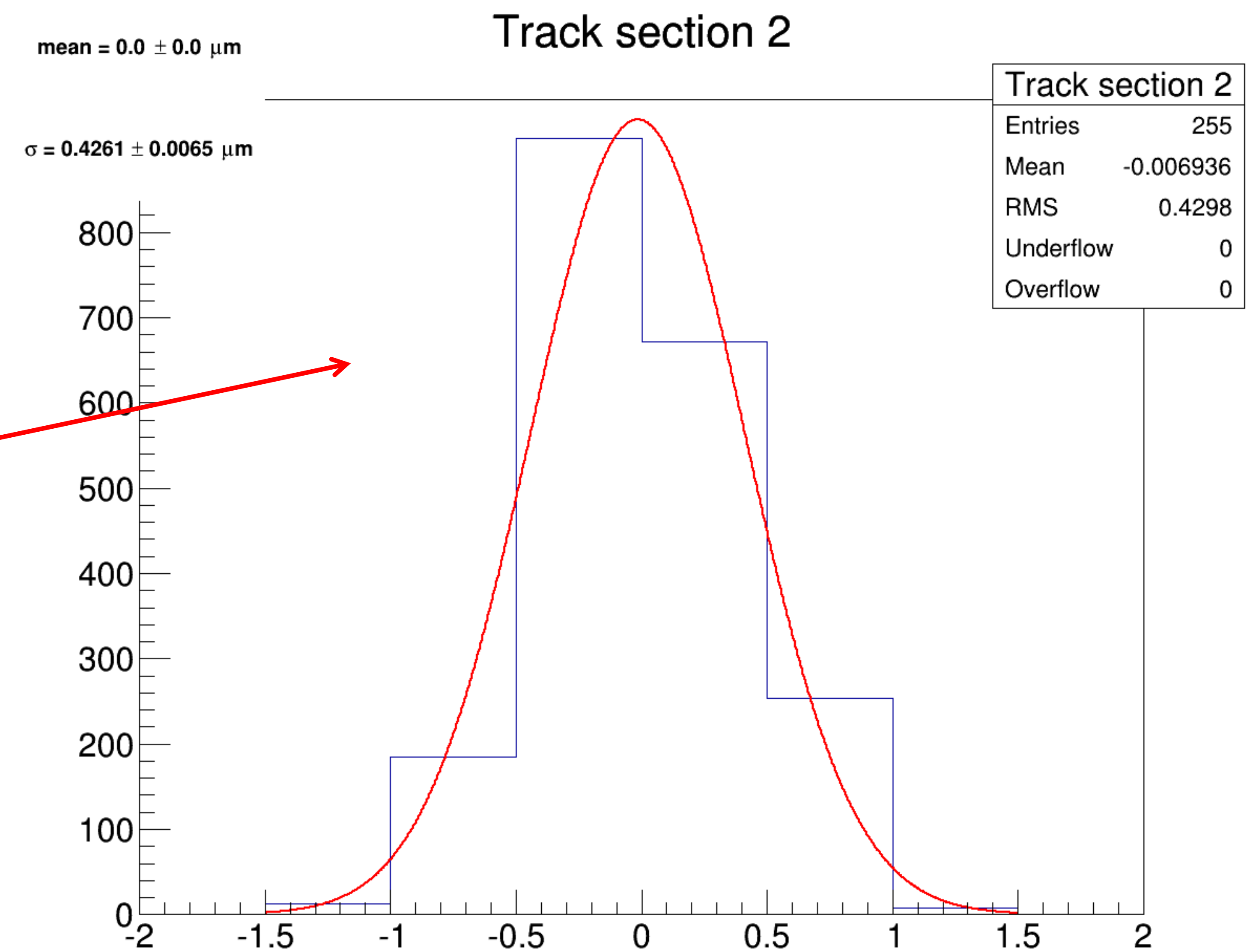

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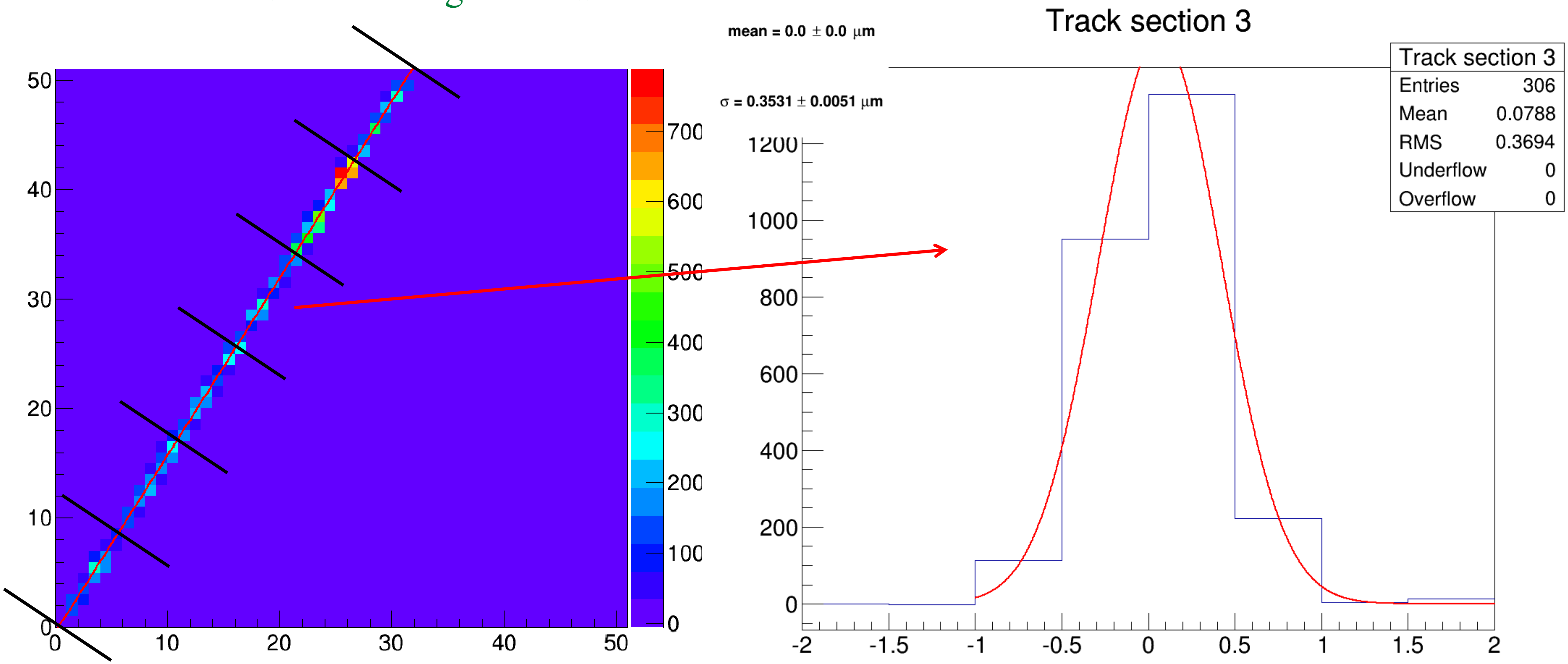

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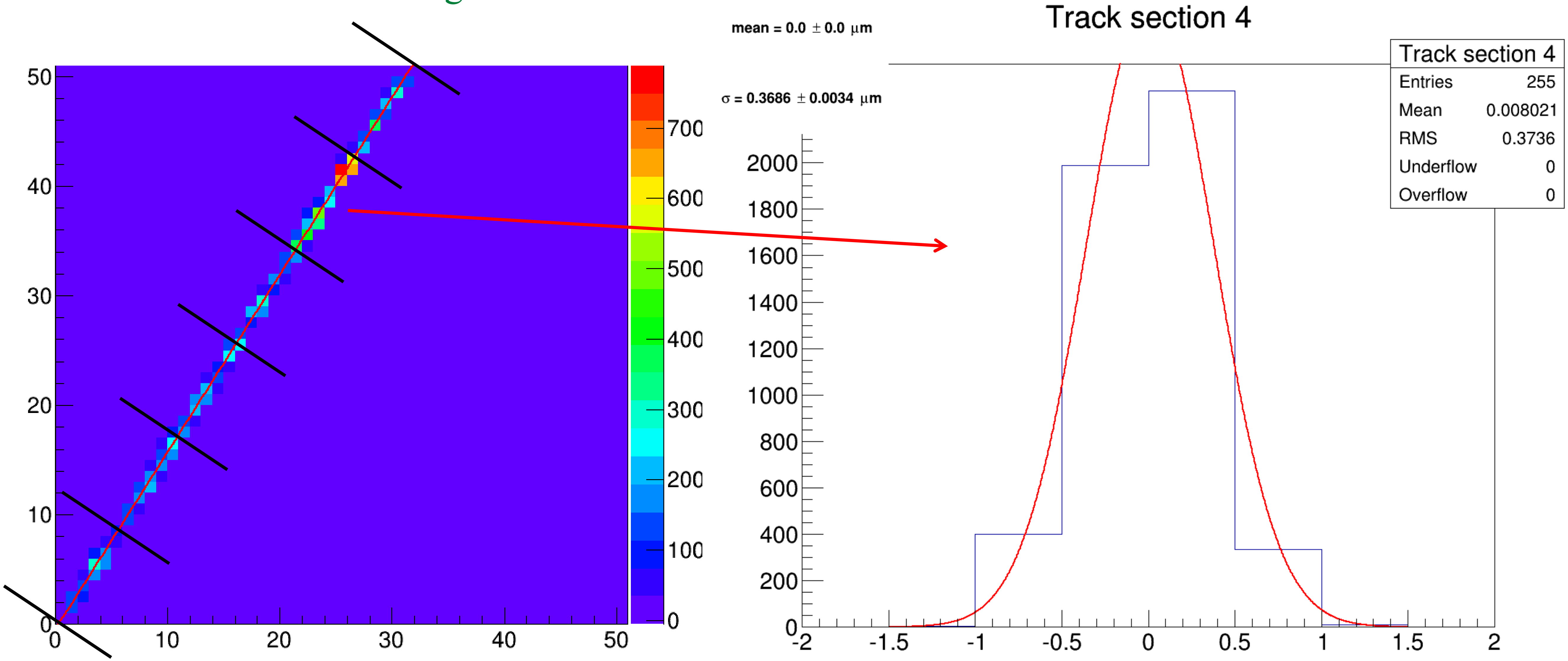

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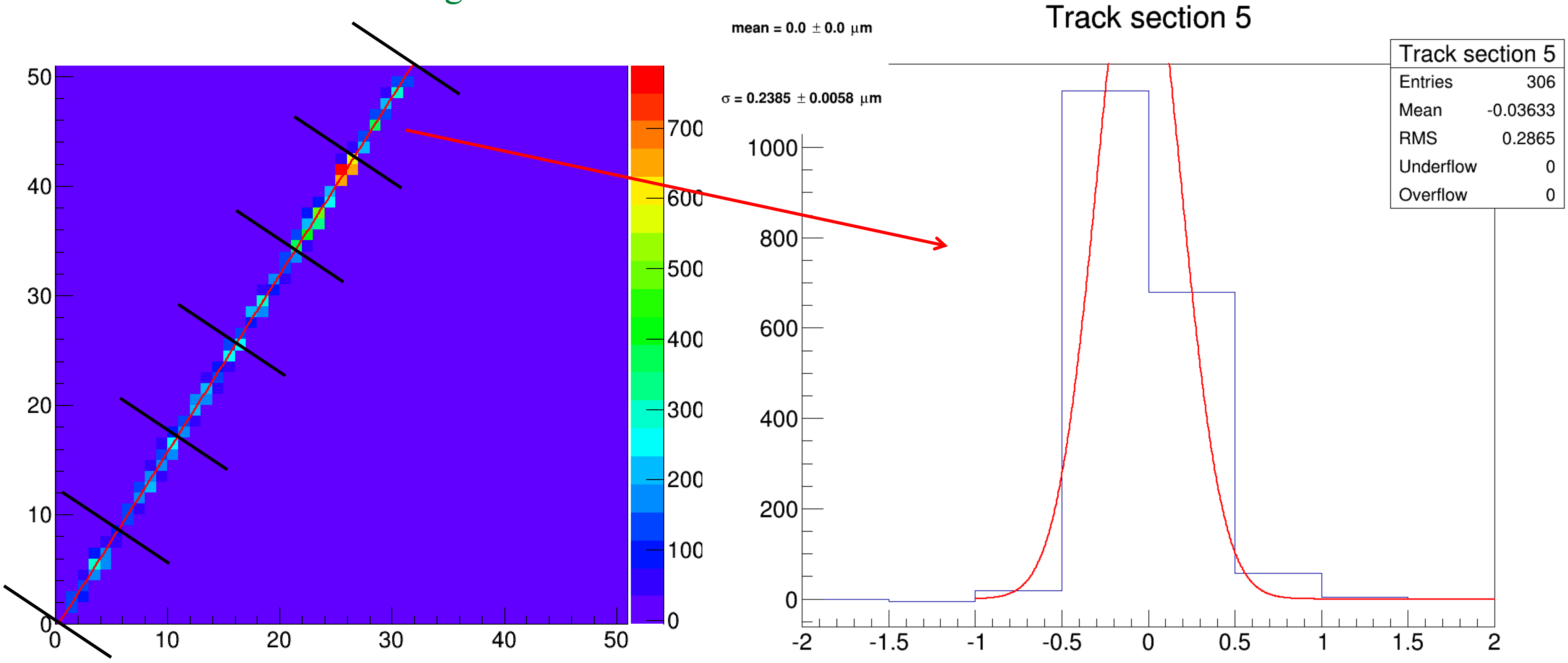
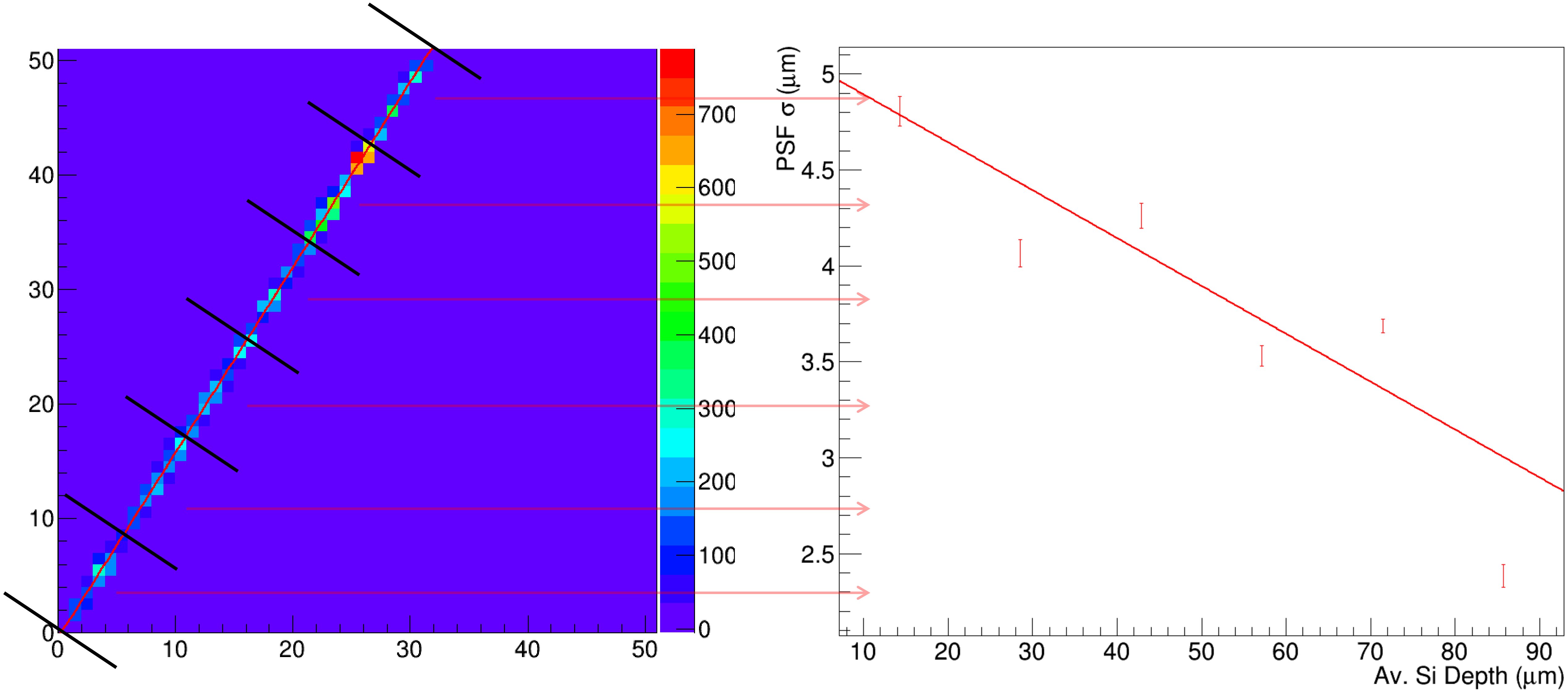


# Segment Measurement

- Plot the widths of these Gaussians w.r.t. track segment number
- Fit a straight line to determine the orientation of the track with respect to the silicon
- If gradient is positive – leave as is
- If gradient is negative – reverse order
  - Tracks are now aligned w.r.t sensor surface



# Diffusion Measurement

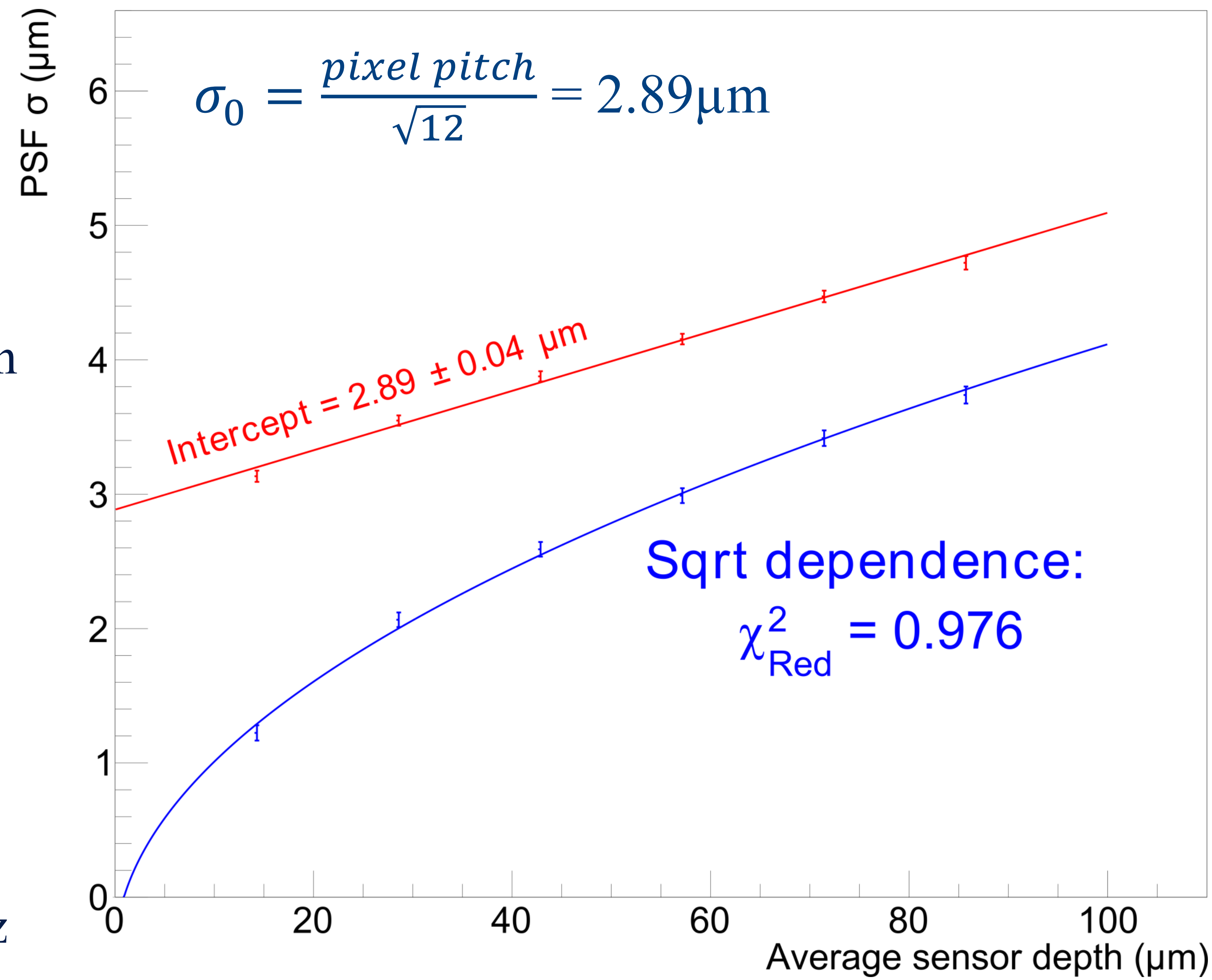
- Average all tracks segment PSFs together
- Plot these average PSFs as a function of (averaged) depth in silicon
  - → Get diffusion as a function of depth in silicon

$$\sigma = \sqrt{\sigma_0^2 + \sigma_{diff}^2}$$

- Where:
- $\sigma$ is the total PSF
- $\sigma_0$ is the intrinsic resolution of the pixel detector
- $\sigma_{diff}$ is the contribution from diffusion

$$\sigma_{diff}(\Delta z) = \sqrt{2\frac{kT}{e}\frac{D\Delta z}{V}}$$

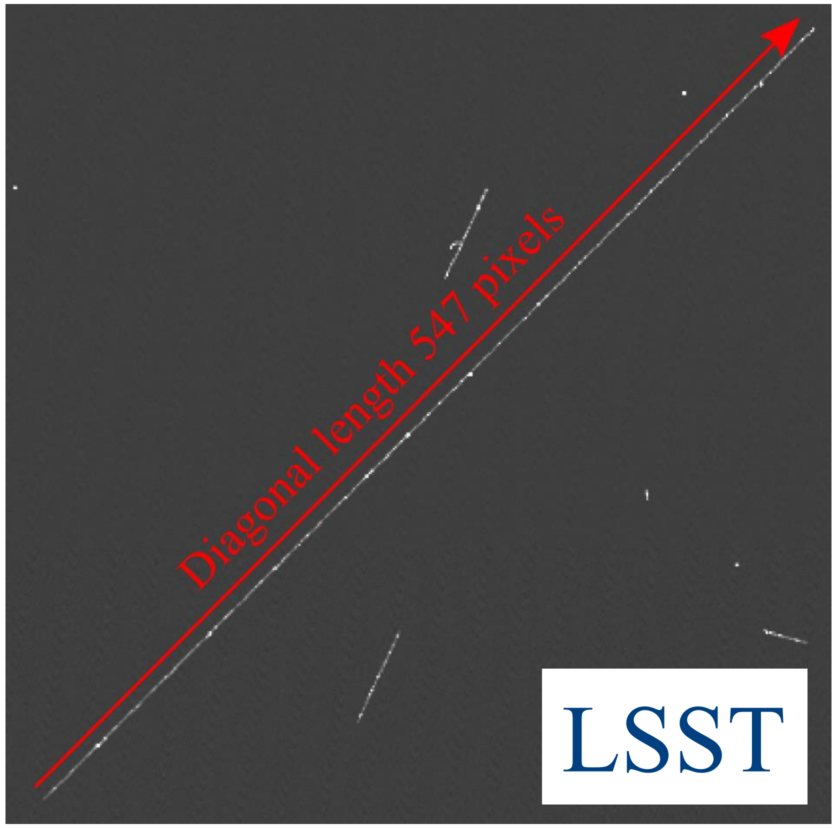
- For sensor of thickness D, at bias voltage V, at depth z

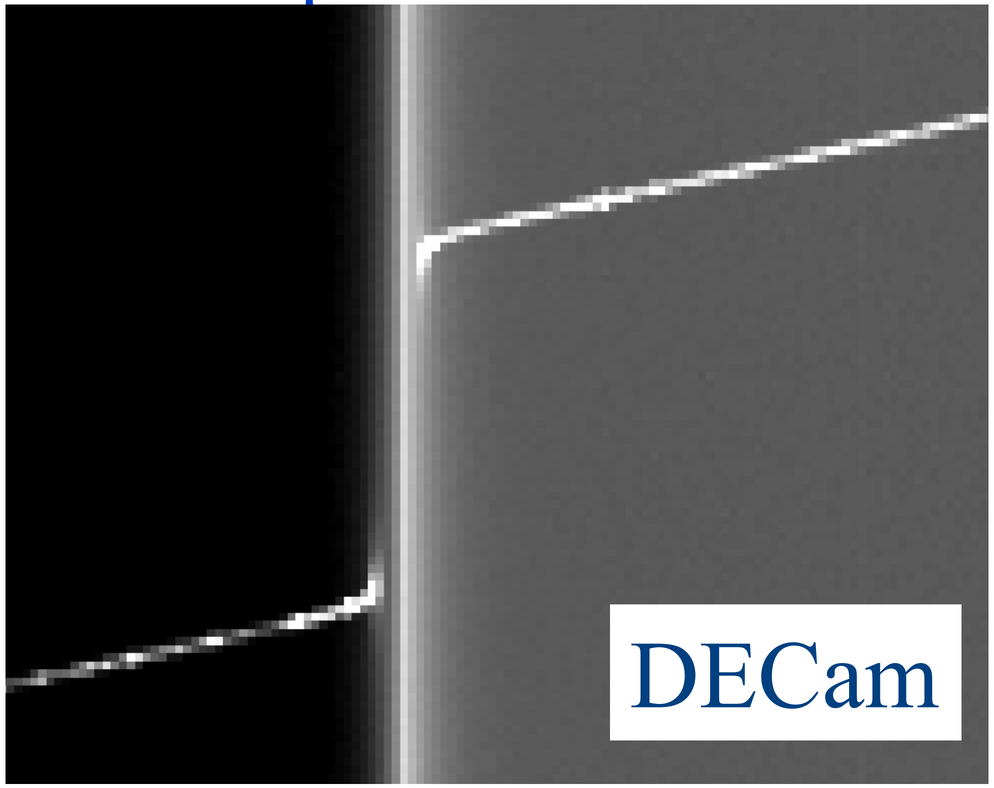


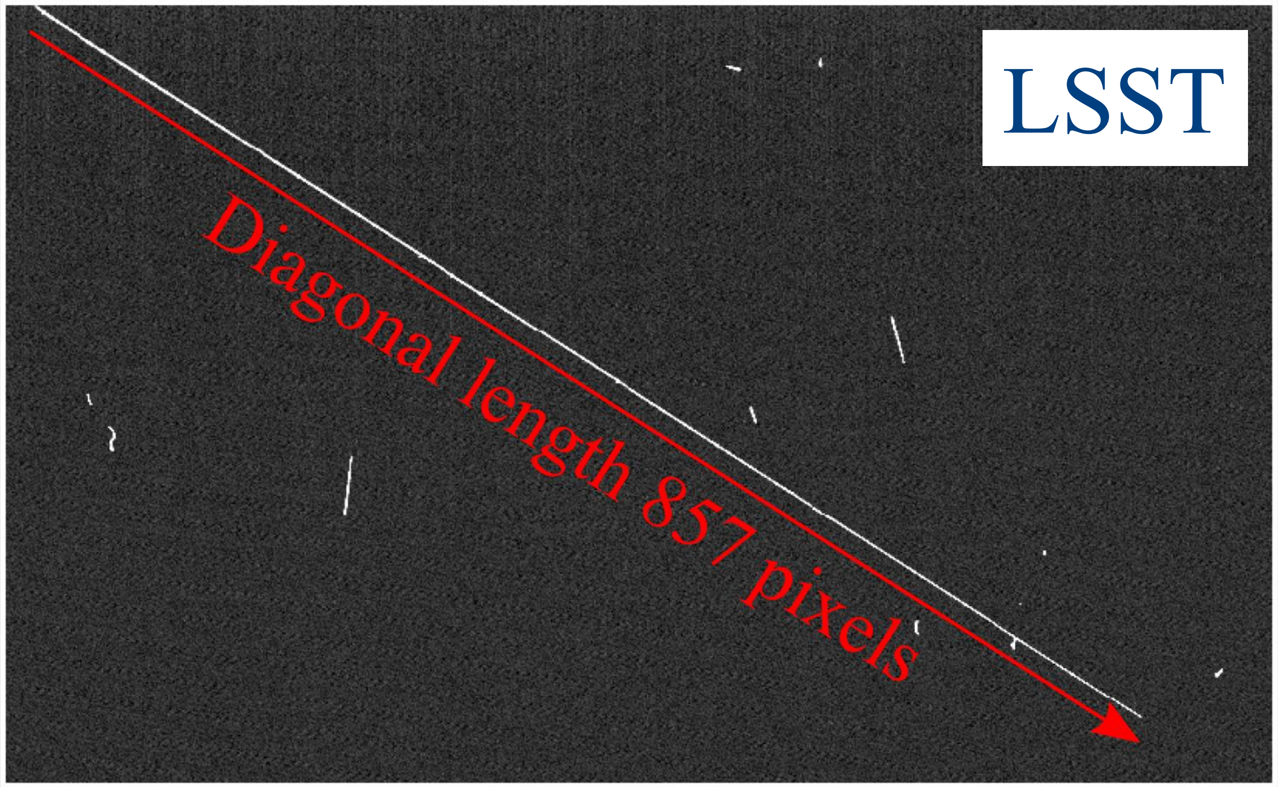
# Edge Effects

# Measuring straightness

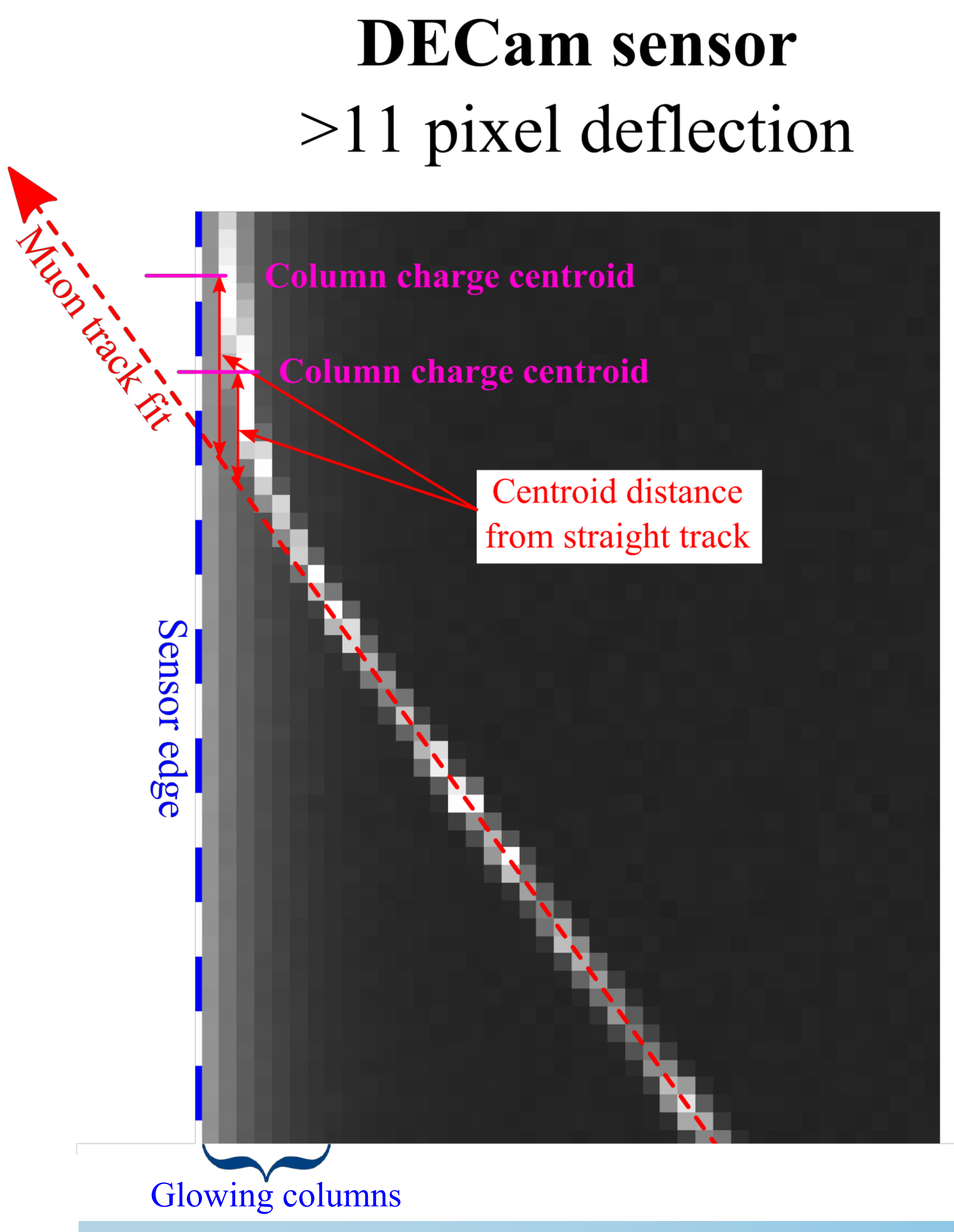
- Cosmic ray tracks are very straight
- This straightness can be exploited to measure distortion at the edges caused by lateral electric fields arising from guard rings etc
- DECam sensors are known to suffer badly from these distortions – how do LSST sensors perform?

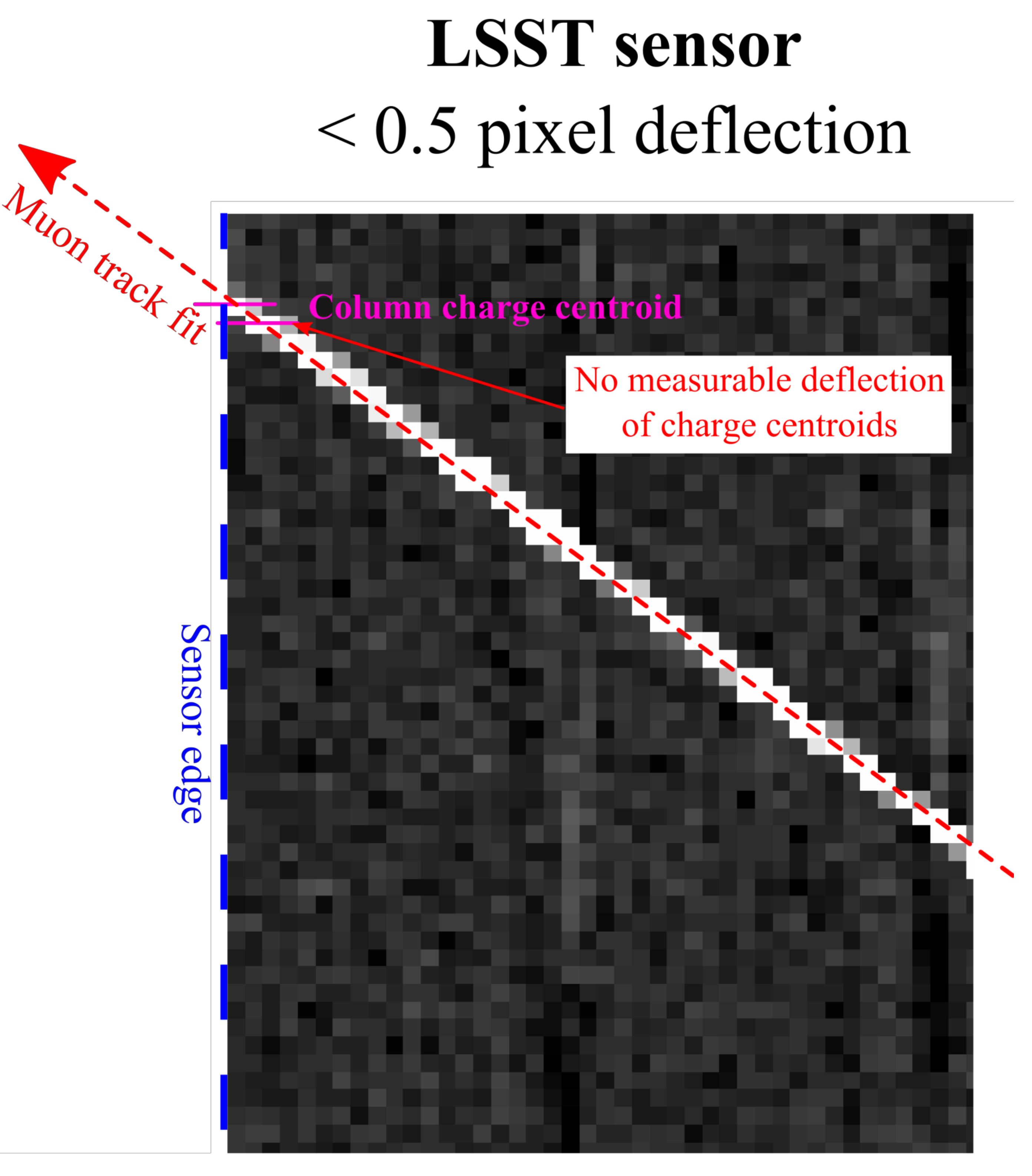


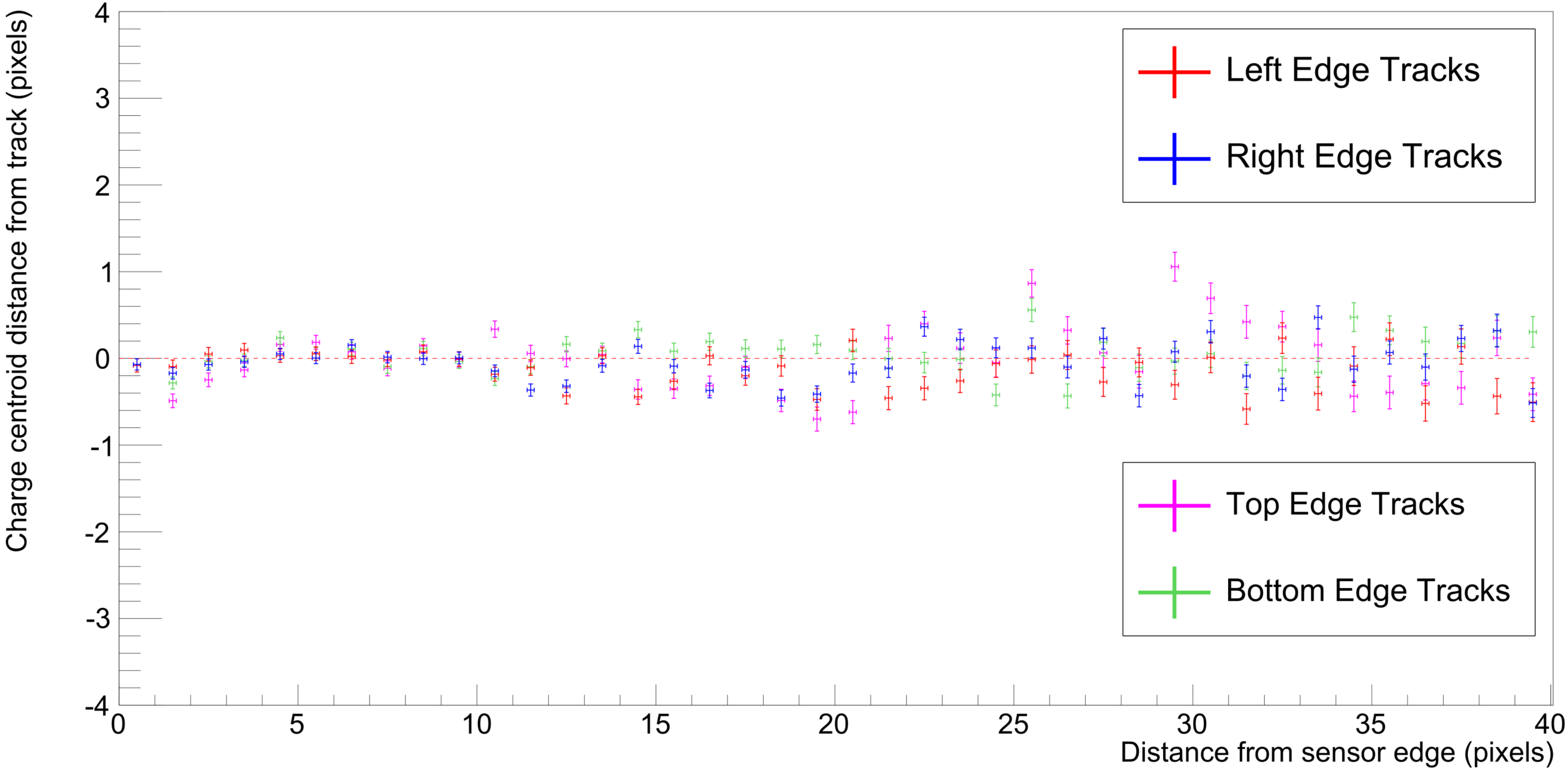



# Track Bending



# Quantitative Straightness Analysis

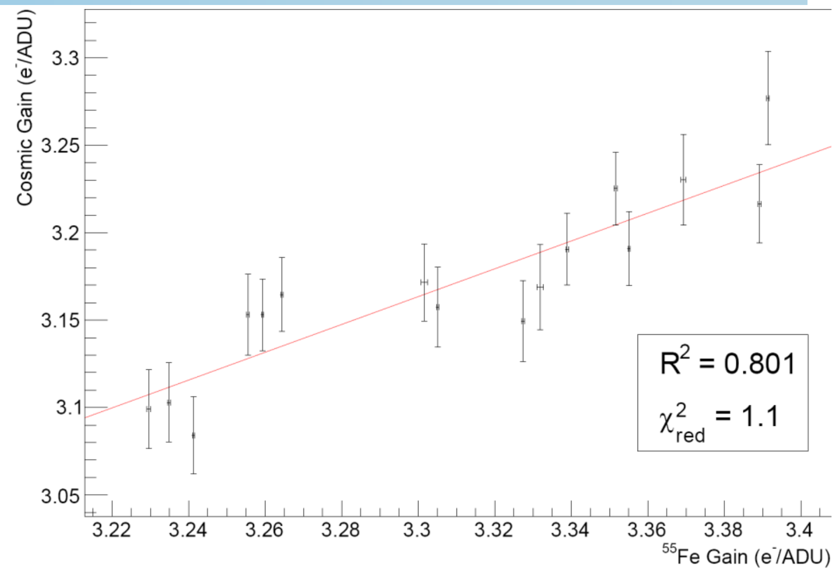



Distance of charge centroid from track

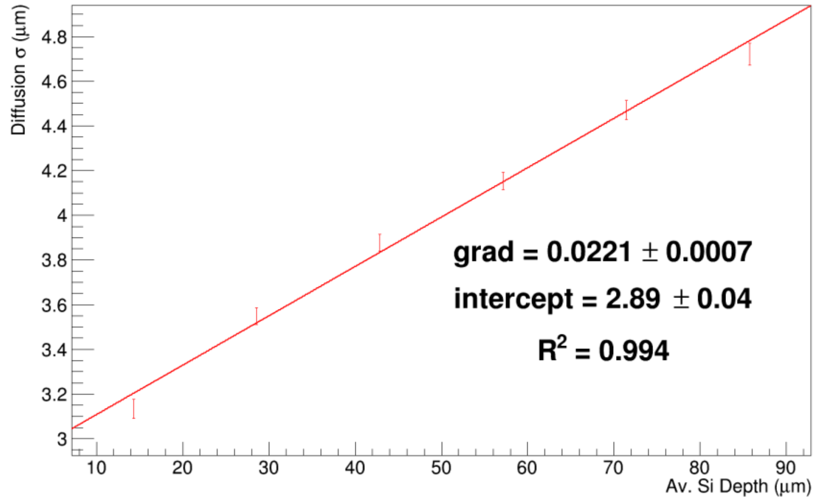
plotted vs distance from sensor edge

# Summary

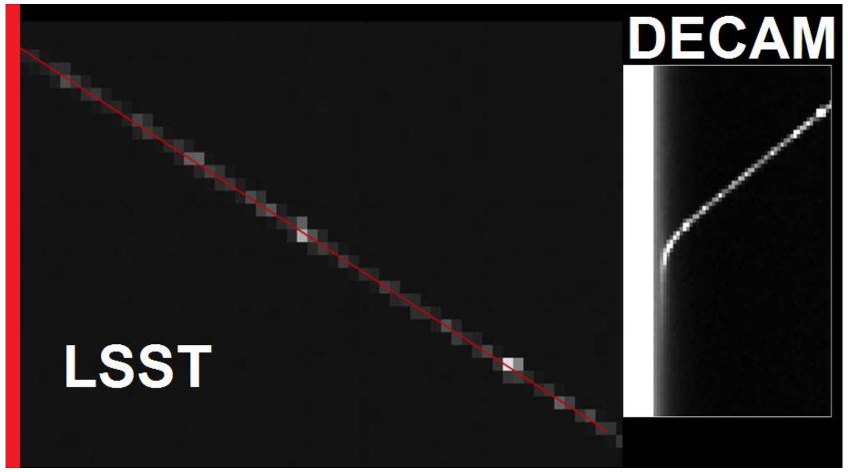
- Gain measurement with cosmics
  - No radioisotopes required
  - Good correlation with $^{55}$Fe gain measurement




- Diffusion measurement
  - PSF found to increase with distance to collection electrode
  - Will be compared with DECam sensors

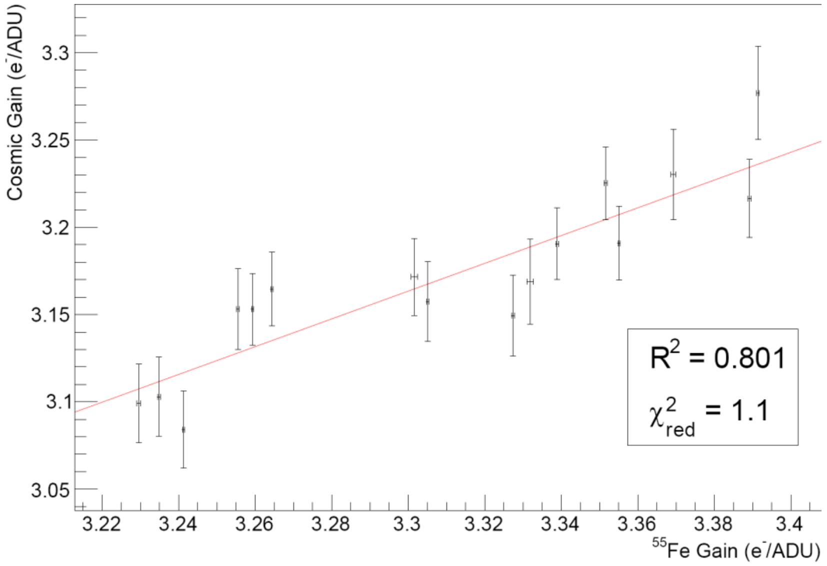


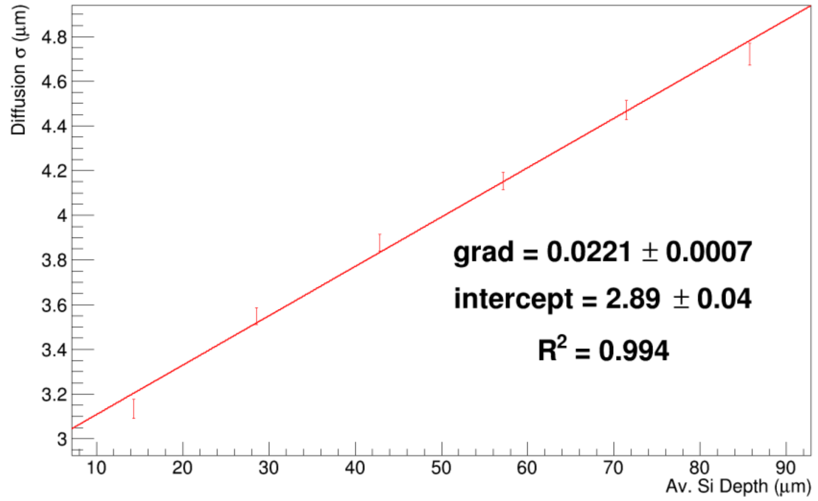

- Measurement of edge straightness
  - LSST sensors distort much less than DECam (if at all)
  - Comparative quantitative analysis to follow

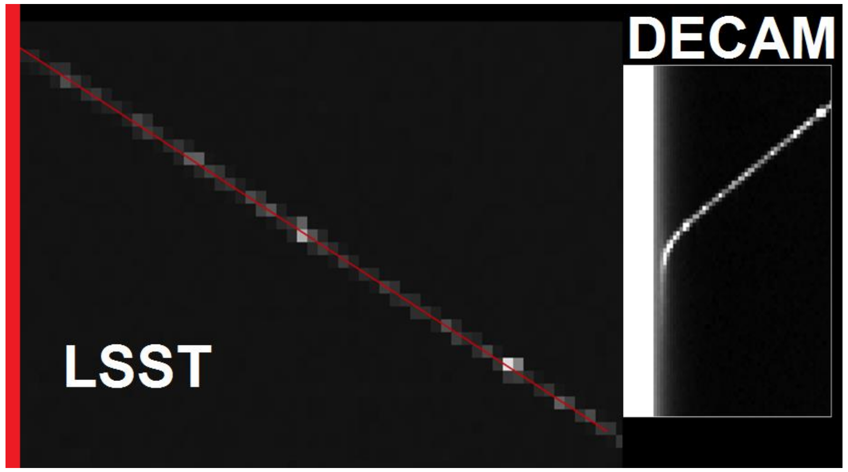


# Summary

- Many thanks to:
  - Paul O’Connor & Ivan Kotov for the data
  - Robert Lupton & Paul Price for their help with DMStack



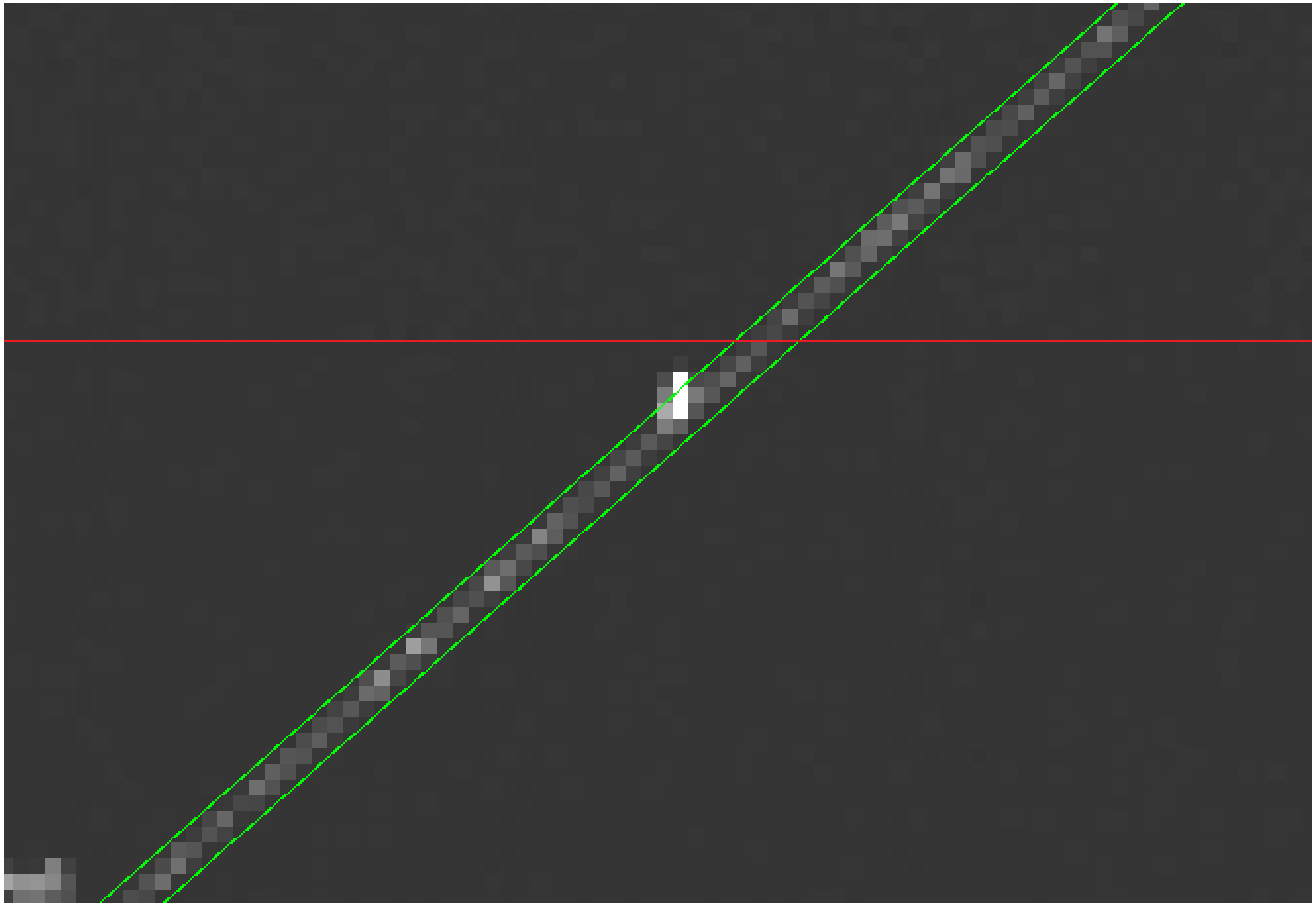



# Backup slides

# Midline bending

- Midline doesn't appear to bend either
  - No quantitative analysis yet



Midline