A Triggerless Readout System for Mimosa26 based Telescopes and A Python based test-beam analysis software

Y. Dieter, C. Bespin, T. Hemperek, T. Hirono, F. Hügging, J. Janssen, H. Krüger, D.-L. Pohl, N. Wermes, P. Wolf and J. Dingfelder

Physikalisches Institut der Universität Bonn

Outline

- Part I: Trigger-less readout system for Mimosa26 based telescopes
  - Motivation
  - Original triggered readout
  - New trigger-less readout with pymosa
  - Track reconstruction

- Part II: Python based test-beam analysis software
  - Basic structure
  - Analysis flow overview
  - Performance results

Part I
A Trigger-less Readout System for Mimosa26 based Telescopes

Motivation

- Beam time is expensive and rare
- Need high statistics

  → High event rate

→ Fast readout

- No endless space for all hardware components
- As few components as possible

→ Compact and easy to use setup

- Goals:

  → Mimosa26 telescope: high track resolution

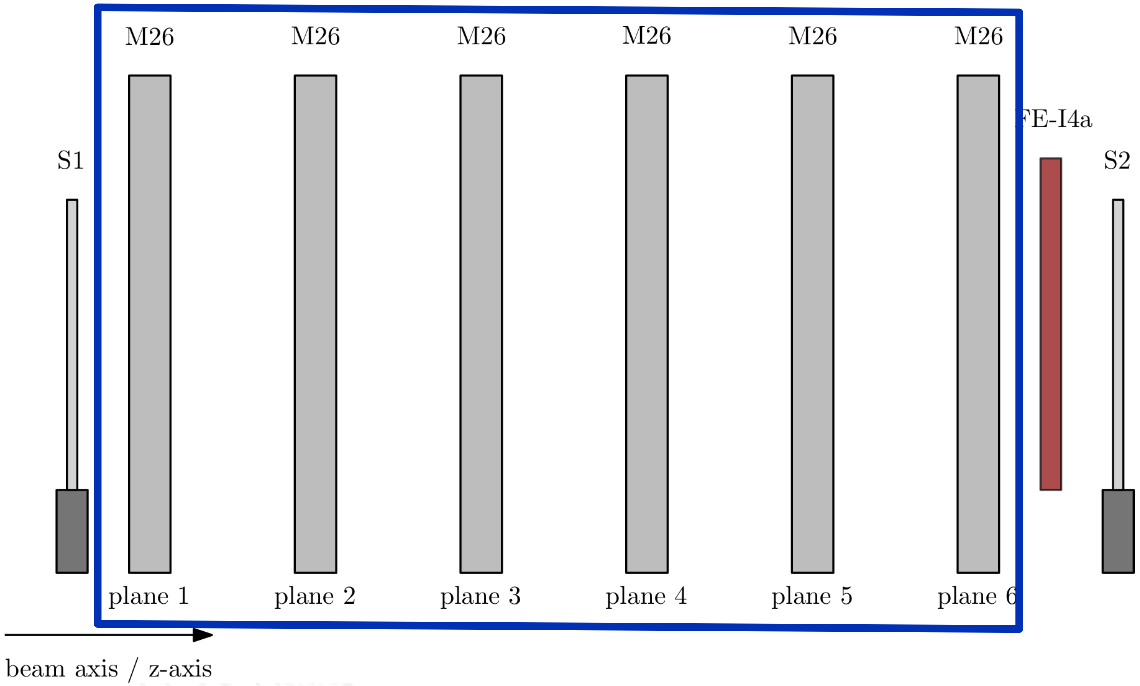
  → ATLAS FE-I4: high time resolution

  → Use of existing hardware from EUDET/AIDA

A Nice Eudet Mimosa Bonn Telescope

ANEMONE: **A Ni**ce **E**udet **M**imosa b**ON**n t**E**lescope

Pymosa (python based Mimosa26 readout software) https://github.com/SiLab-Bonn/pymosa



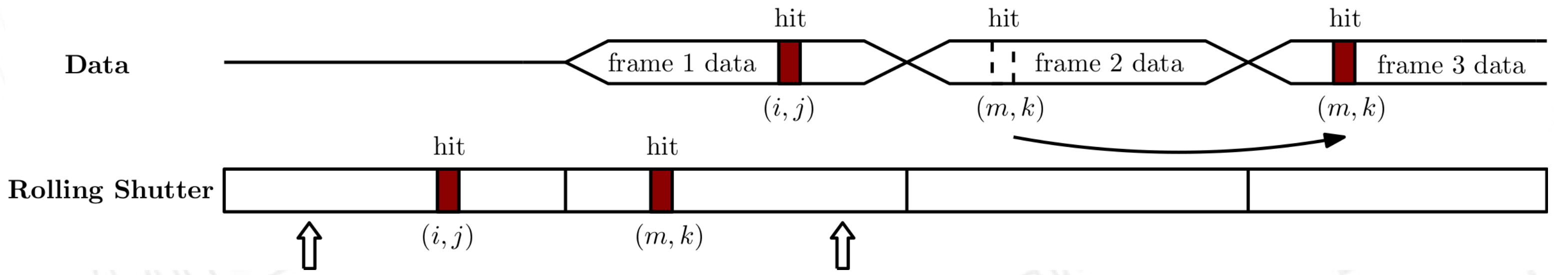
[P. Wolf, Testing and extending a Python-based readout system for a high-resolution pixel detector telescope]

- 6 Mimosa26 planes: high resolution tracking
- ATLAS FE-I4 plane: high time resolution reference plane
- 2 scintillators for triggering FE-I4 (using TLU)
- New readout system for Mimosa26 sensors (pymosa + readout board)

Original triggered readout of M26

- Trigger: Rolling shutter readout of Mimosa26 sensors
- One frame: 115 µs
- Merge data of frame n and n + 1
- Limited rate: 1 trigger / 2 frames

  → Does not allow to operate on high rate (~ 4.3 kHz)

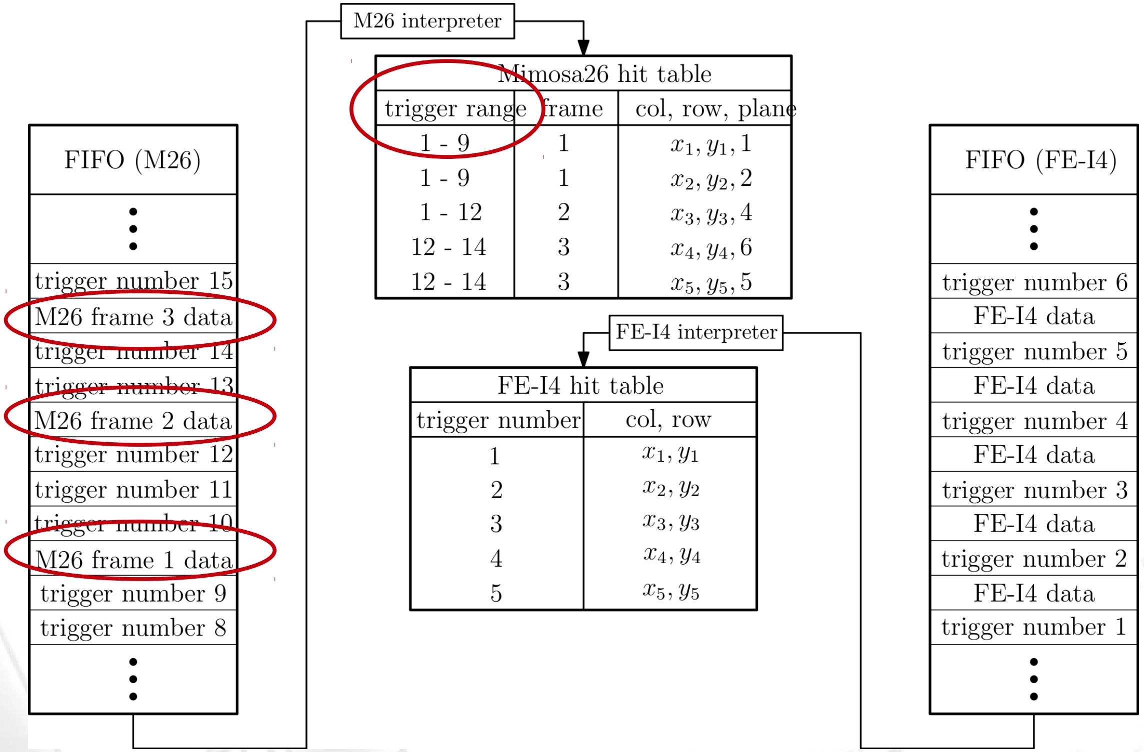


New trigger-less readout of M26

- Continuous rolling shutter readout of Mimosa26 sensors (record all data)
- Obtain distinct time information by using time reference plane (e.g. FE-I4)

  → Correlate Mimosa26 data to FE-I4 data (time reference)

→ Allows to operate at high event rates



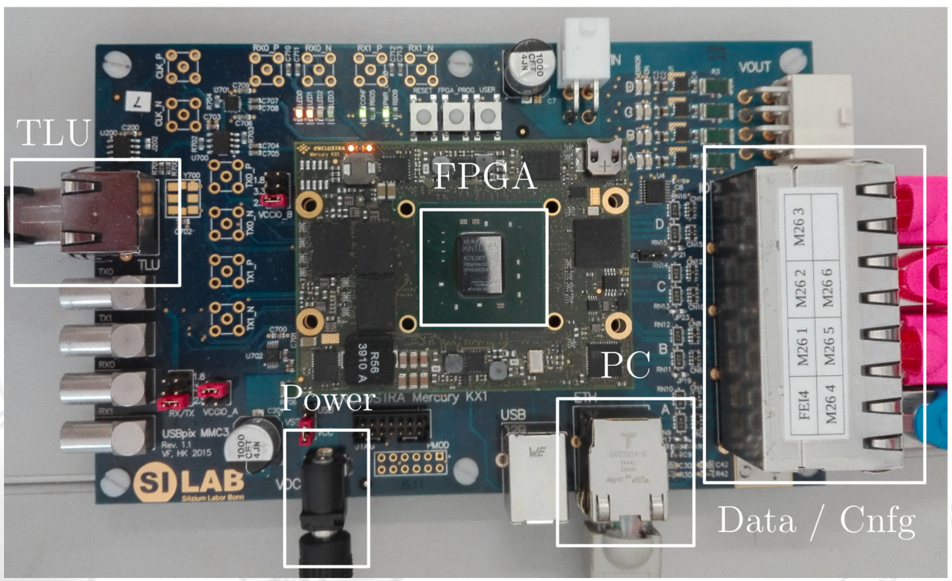
Disadvantage: bandwidth limited due trigger-less readout

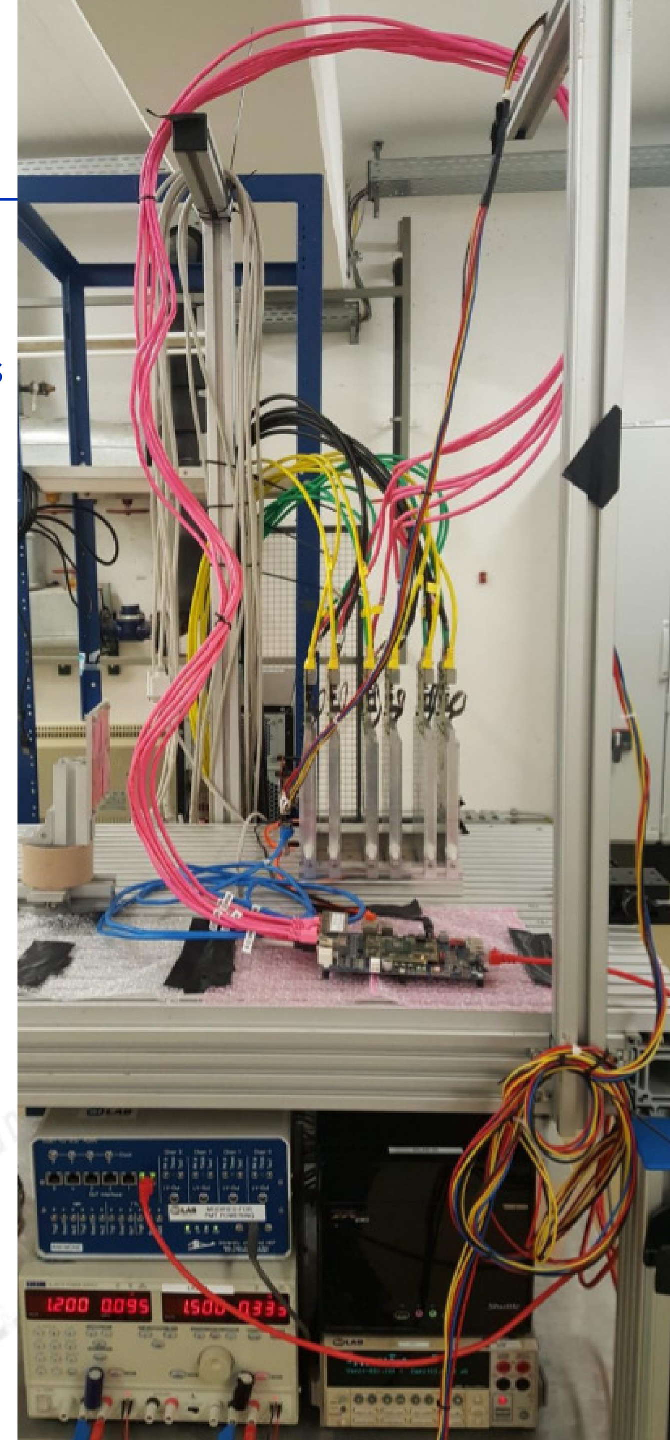
Pymosa + MMC3

- Pymosa + MMC3 (https://github.com/SiLab-Bonn/pymosa):
  - Python based readout system for M26 based telescopes
    → Triggerless and continuous readout of up to 6 M26 planes
  - Supports configuration of M26 sensors
  - Based on single FPGA-readout board (MMC3)

→ Compact setup

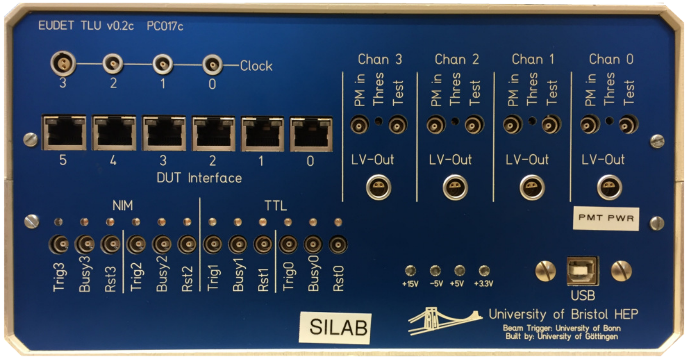
→ Operation at high particle rates is possible (20 kHz)

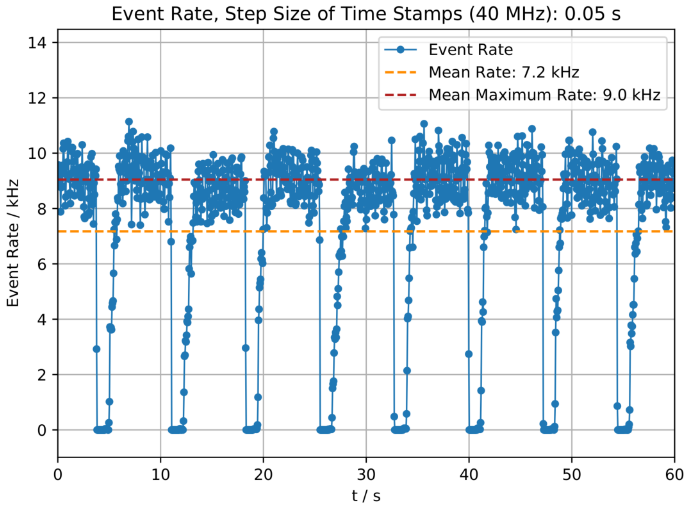




TLU – Trigger Logic Unit

- TLU: EUDET JRA1 Trigger Logic Unit (TLU v0.2c)
  - 4 Trigger inputs via LEMO
  - PMT powering possible
  - 6 DUT interfaces (RJ45)





Rate measurements with TLU

- Developed new DAQ software and TLU firmware
  - Easy to use software (stand-alone)
    → See pytlu: https://github.com/SiLab-Bonn/pytlu
  - Continuous data storage of triggers in output file
    → Timestamp (64 bit)
    → Trigger number (32 bit)
    → Rel. distance of input trigger signals and generation of trigger
  - Protocol (Trigger mode) is compatible with original firmware

Track Reconstruction of ANEMONE

- Challenge: correct matching of Mimosa26 tracks with FE-I4 (time reference)
  → Track reconstruction
- Track reconstruction efficiency: Percentage of correctly assigned FE-I4 hits to Mimosa26 tracks
  → Need high (~ 99 %) efficiency in order to keep high statistics
  → Defines systematic error on all track based analyses

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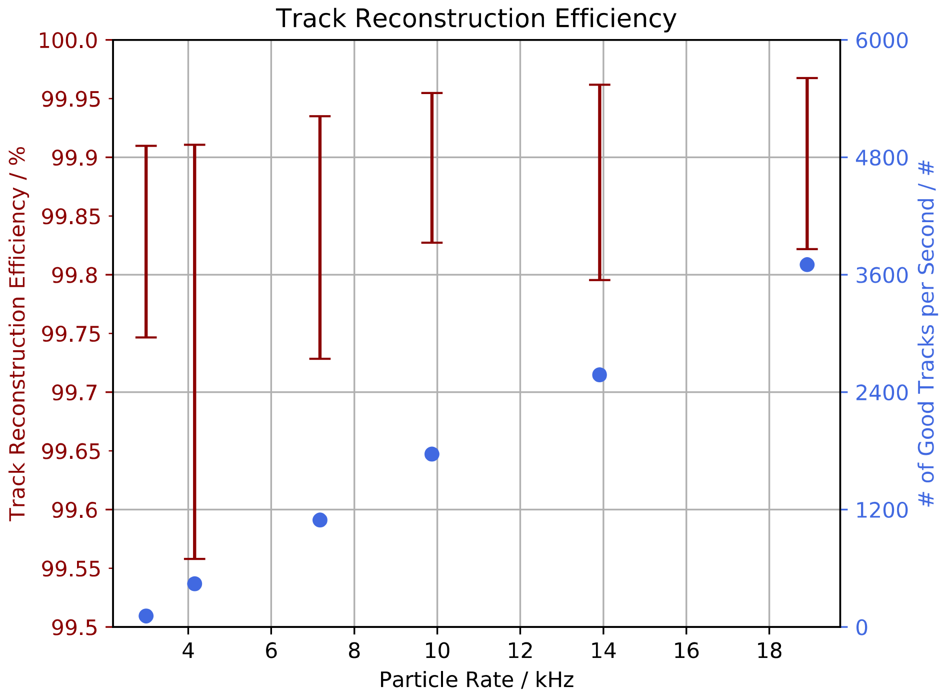


Max rate limited by buffer size of readout system (2 Mb)

Matching of FE-I4 hits with Mimosa26 tracks works reliably and gives high efficiency

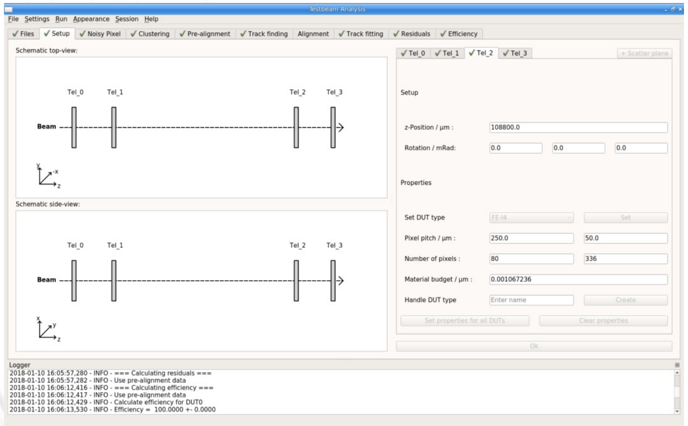
Part II
A Python based test-beam analysis software

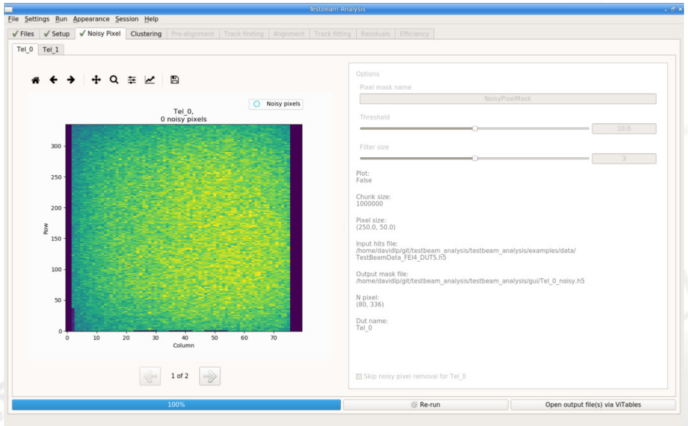
Test Beam Analysis Software

- Goal: Simple to use test beam analysis software
- Software written in Python

https://github.com/SiLab-Bonn/testbeam_analysis

- State-of-the-art scientific modules (scipy, numpy, numba, …)
- Multiprocessing on all cores
- All steps of test beam analysis implemented
  → Each step has own function
- Results of each step are summarized in output file and plots
- Code is documented, examples are available
- Graphical User Interface for Test Beam Analysis
- Simulation of data is possible





Test Beam Analysis Flow

Convert data
↓
Noisy pixel removal
↓
Clustering
↓
Correlation
↓
Pre-Alignment
↓
Alignment
↓
Track finding
↓
Track fitting
↓
Result analysis

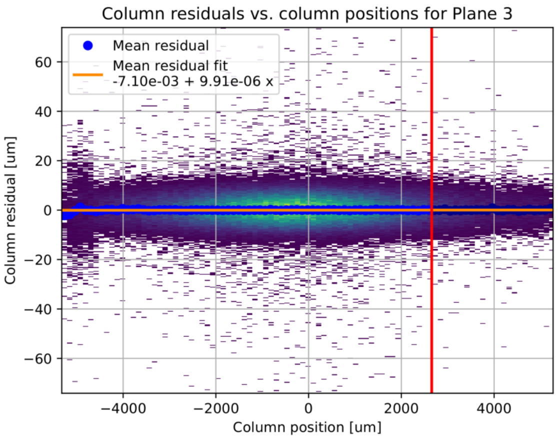
Data type for hit table: event number, frame number, charge, column, row

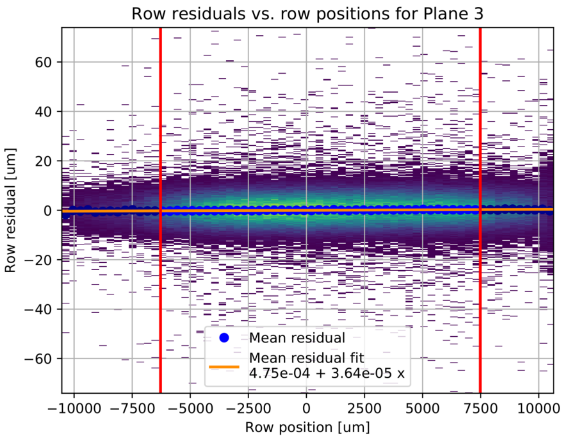
- Noisy pixel removal:
  - Check for noisy pixels and remove them
- Clustering:
  - Cluster hits for given row/column cluster distance
- Correlation:
  - Correlate clusters of reference DUT with all other DUTs on event number basis
- Pre-Alignment:
  - Correct displacement in x and y between DUTs (reference DUT is origin of coord. System)
- (Fine) Alignment:
  - Correct translations and rotations (in all dimensions) between DUTs
- Track finding:
  - Search for matching cluster in subsequent DUTs
- Track fitting:
  - → Kalman Filter
  - → Straight line fit
- Result Analysis:
  - Residual calculation
  - Efficiency calculation
  - ...

Performance of Test Beam Analysis

Results based on 2.5 GeV at ELSA (new external beam line for detector tests)
→ More information about beam line: Talk of D. Proft

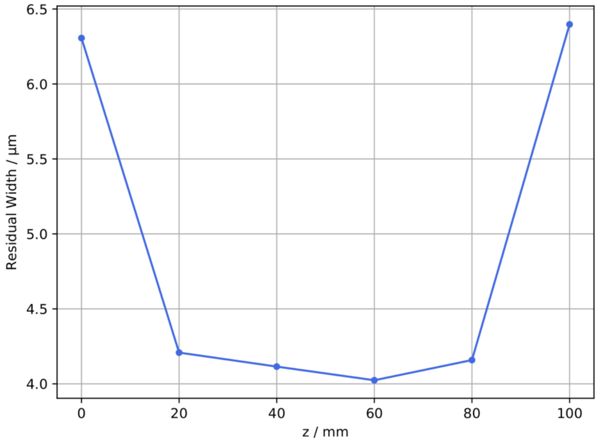
- Alignment example:





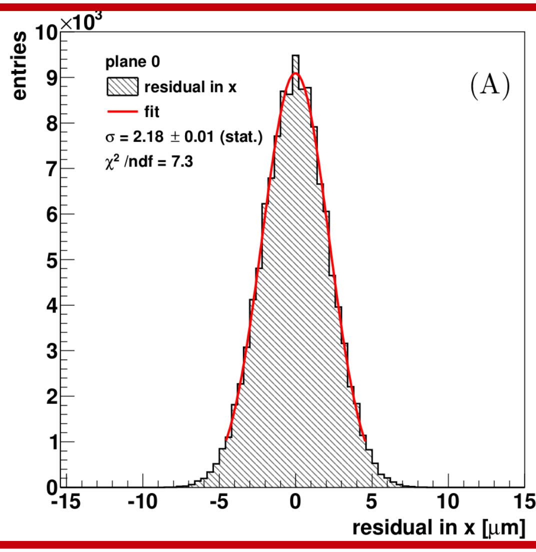
→ 0.1 µm residual deviation on 1 cm achievable

- Unbiased residual width vs z-position (@ M26 threshold of 7, 20 mm spacing)



→ 4 µm residual width for innermost telescope planes

Performance - Residuals



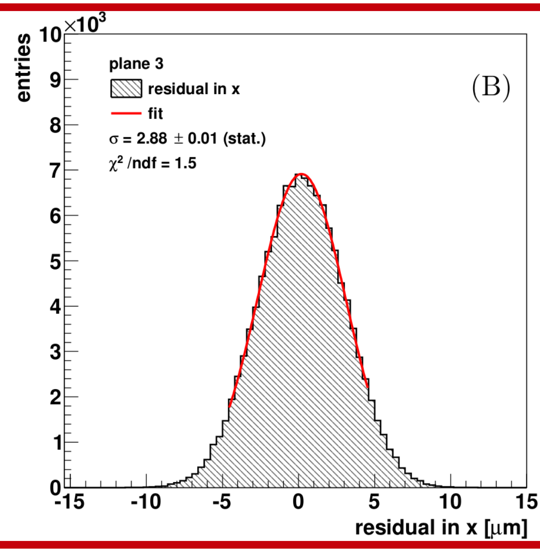
Residuals based on 6 GeV at DESY

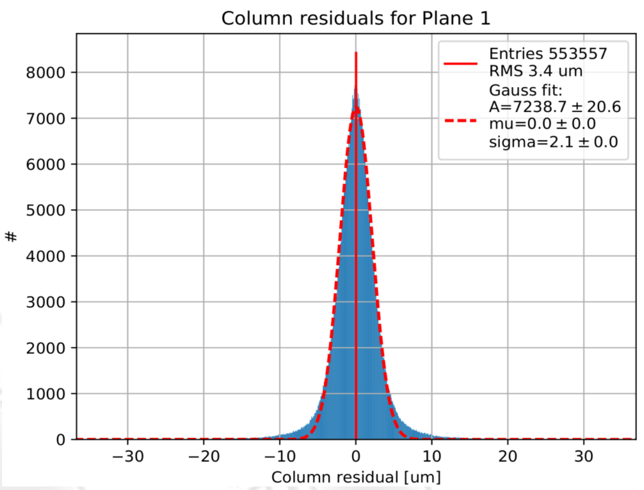
EuTel software

Plane 1: 2.2 µm

Plane 4: 2.9 µm

[H. Jansen et al., Performance of the EUDET-type beam telescopes, EPJ Techniques and Instrumentation 3 (2016) 7]

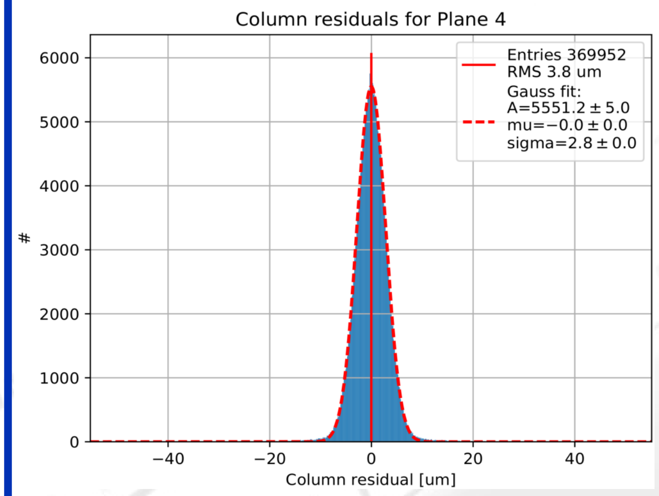




Test Beam Analysis SiLab

Plane 1: 2.1 µm

Plane 4: 2.8 µm



Performance - Resolution

Comparison of intrinsic resolution using iterative pull method

$$\sigma_{\mathrm{res}}^2 = \sigma_{\mathrm{int}}^2 \pm \sigma_{\mathrm{point}}^2 \quad \rightarrow \text{Pull quantity:} \quad p_b = \frac{\sigma_{\mathrm{res}}}{\sqrt{\sigma_{\mathrm{int}}^2 \pm \sigma_{\mathrm{point}}^2}}$$

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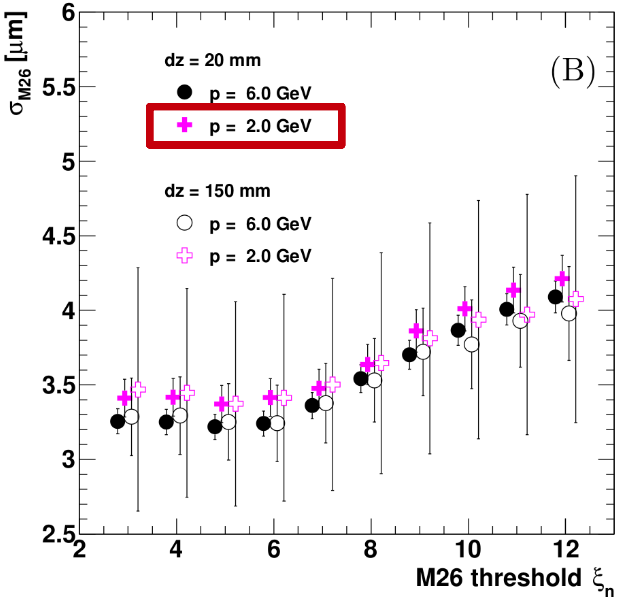
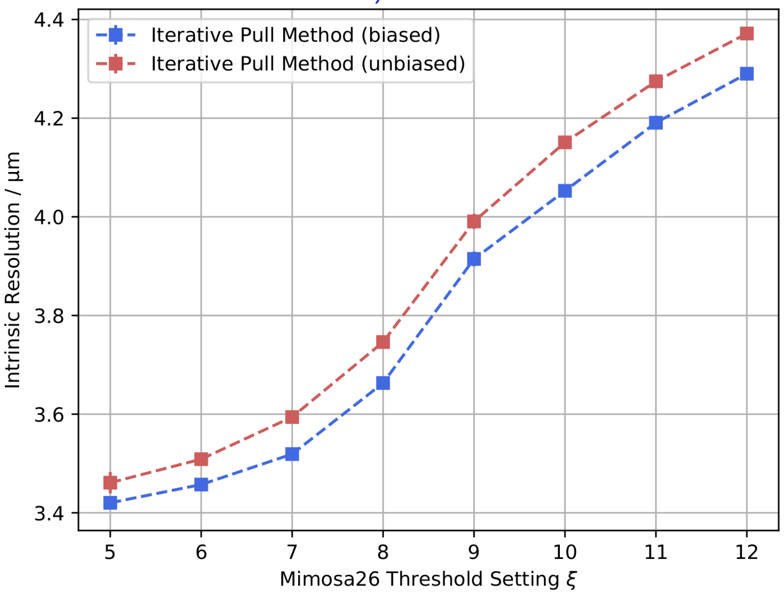


2 GeV, dz = 20 mm



- Obtained values for intrinsic resolution reproduce results from EuTel analysis:

  → EuTel: $\sigma_{\mathrm{int}}^{\mathrm{M26}} = 3.4\,\mu\mathrm{m}$ @ $\xi = 6$ TBA: $\sigma_{\mathrm{int}}^{\mathrm{M26}} = 3.5\,\mu\mathrm{m}$ @ $\xi = 6$

- Pointing resolution: comparison not possible since different methods used

  → EuTel: $\sigma_{\mathrm{point}}^{\mathrm{M26}} = 1.8\,\mu\mathrm{m}(1.5\,\mu\mathrm{m})$ @ $\xi = 6$ TBA: $\sigma_{\mathrm{point}}^{\mathrm{M26}} = 2.5\,\mu\mathrm{m}(2.0\,\mu\mathrm{m})$ @ $\xi = 6$

Conclusion / Outlook

- New readout system for M26 based telescopes was developed
  → Based on single FPGA readout board
- Features continuous and trigger-less data taking of M26 sensors
- Time information: correlating M26 data to time reference plane (e.g. ATLAS FE-I4)

  → Fast readout: particle rates up to 20 kHz (in future: increase buffer size to 2 Gb)
  → Compact and easy to use setup

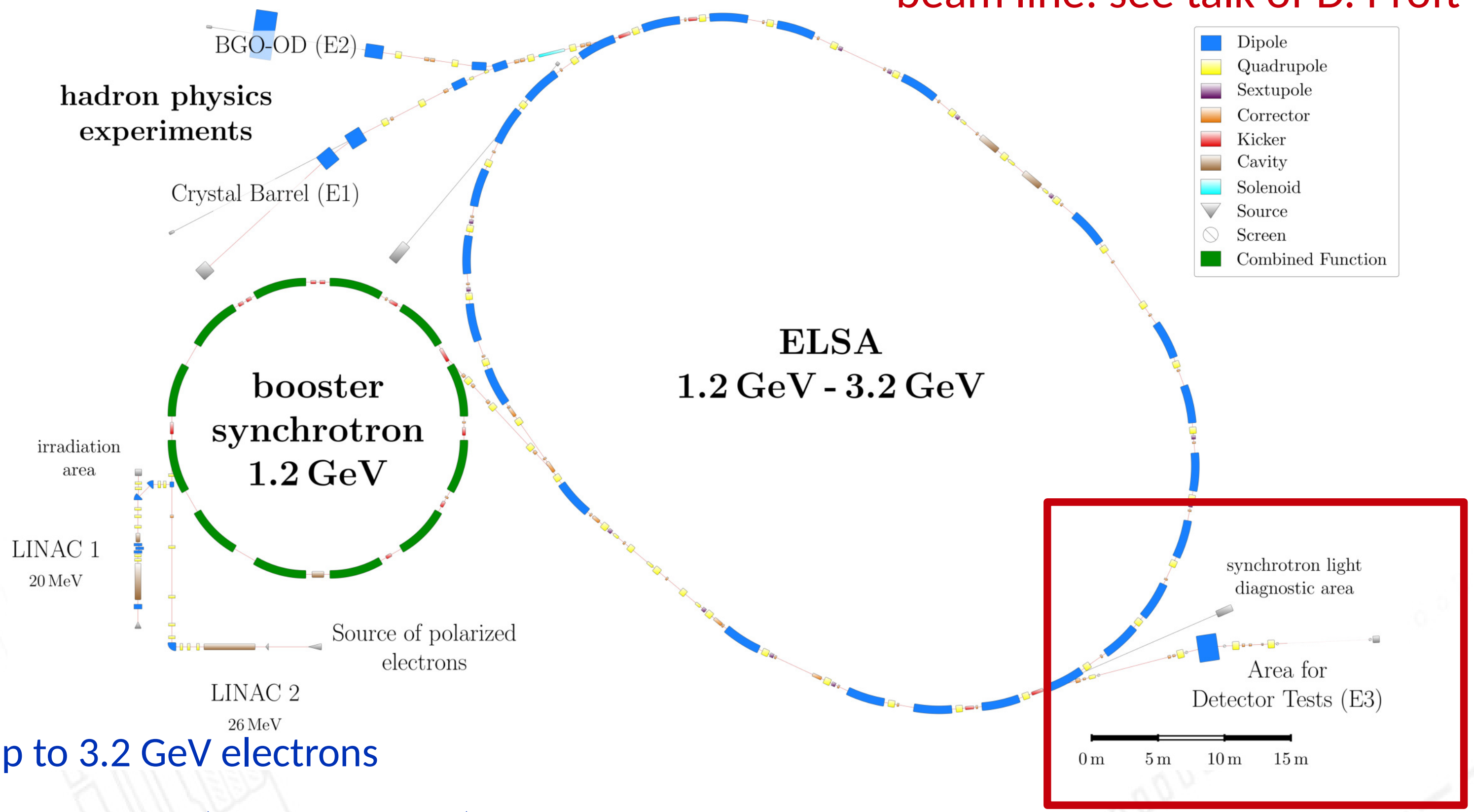
- Simple to use test beam analysis software was developed
- GUI is available
- To do: extend documentation and examples
- Performance comparable to commonly used analysis software (EuTel)
- Achievable pointing resolution: ~3.5 µm @ 2.5 GeV (ELSA)

THANK YOU!

New External Beam Line at ELSA

ELectron **S**tretcher **A**ccelerator (ELSA)

Detailed information for new external beam line: see talk of D. Proft

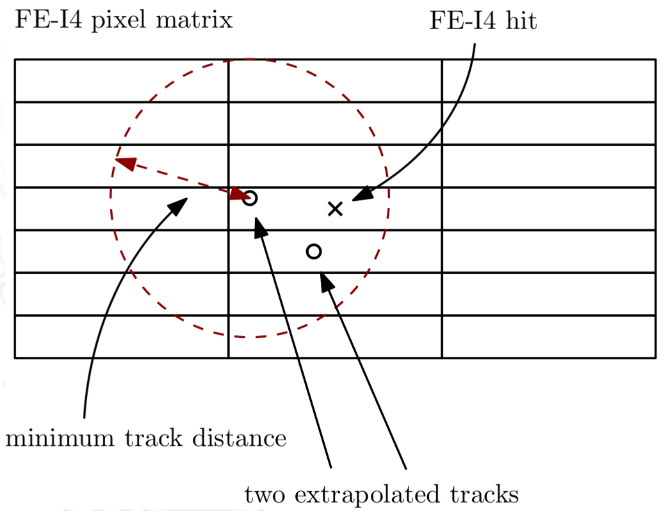


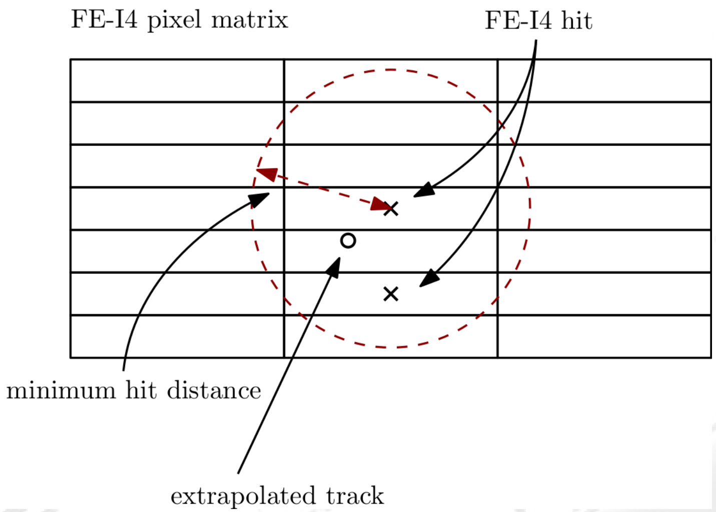
Area for detector tests

- Up to 3.2 GeV electrons
- Variable rate (up to 625 MHz)
- Variable beam width at extraction (1 – 10 mm)
- Large experimental area (~ 30 m²)

Track Reconstruction of ANEMONE

- Challenge: correct matching of Mimosa26 tracks with FE-I4 (time reference)
  → Track reconstruction
- Track reconstruction efficiency: Percentage of correctly assigned FE-I4 hits to Mimosa26 tracks
  → Need high (~ 99 %) efficiency in order to keep high statistics
  → Defines systematic error on all track based analyses
- Complete telescope track:
  - Hit in all M26 planes
  - Distinct hit in FE-I4 (time reference)
- Minimum track and hit distance (FE-I4): Ensure correct and distinct time reference matching





Track Reconstruction Efficiency of FE-I4

Track reconstruction Efficiency: Percentage of correctly assigned FE-I4 hits to M26 tracks

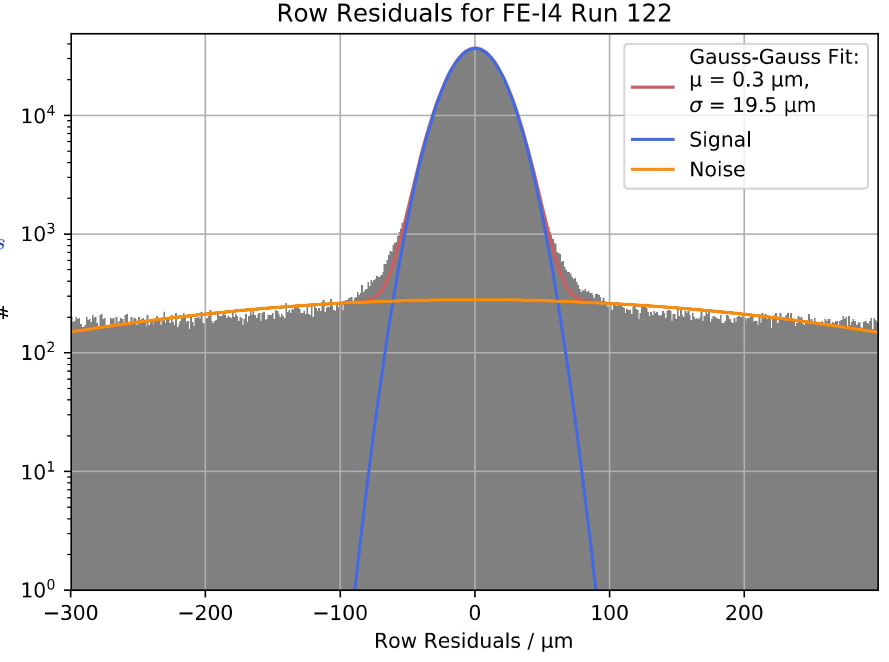
- Use residuals of FE-I4 plane
- Estimate track reconstruction efficiency from amount of wrongly reconstructed tracks
- Assumption: wrongly reconstructed tracks have large residual in FE-I4 (track not correlated to hit)
- Approach:
  - Take FE-I4 row residuals
  - Cut row residuals:

    $$\Gamma_{\pm}^{\text{row}} = \mu_s \pm (\tfrac{\text{FWHM}}{2} + \sigma_s),\ \text{FWHM} = 2\sqrt{2\ln(2)}\sigma_s$$

  - Cut column residuals with row cut → row cut column residuals
  - Cut row cut column residuals:

    $$\Gamma_{\pm}^{\text{column}} = \mu_{\text{box}} \pm (d_{\text{box}} + \sigma_{\text{box}})$$

    → row and column cut residuals



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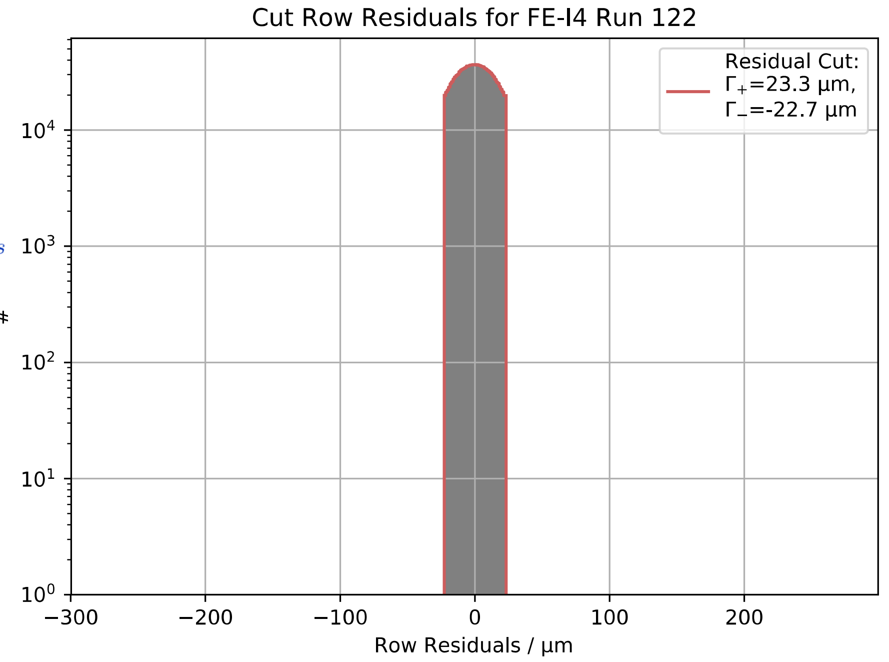

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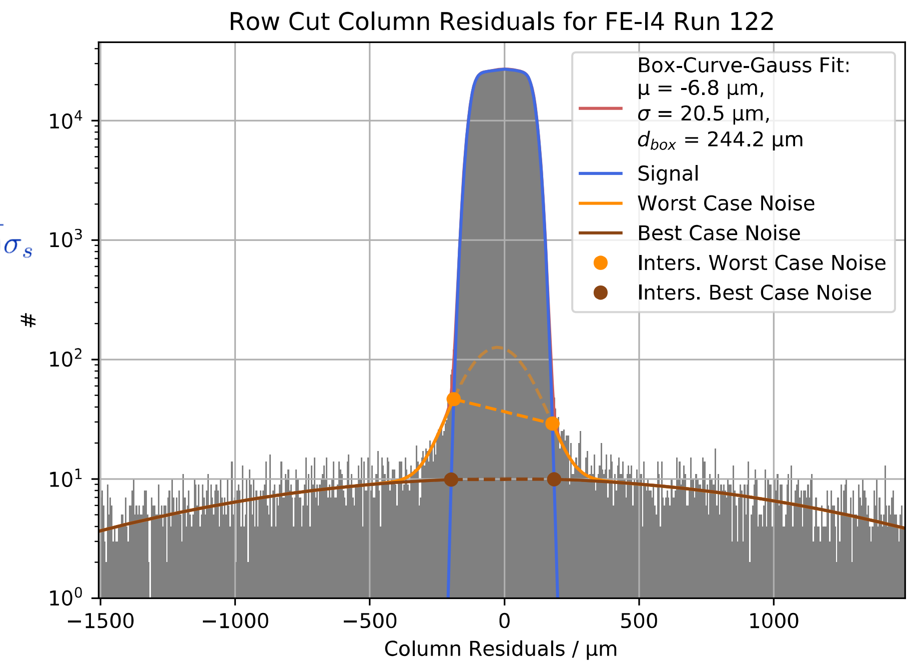

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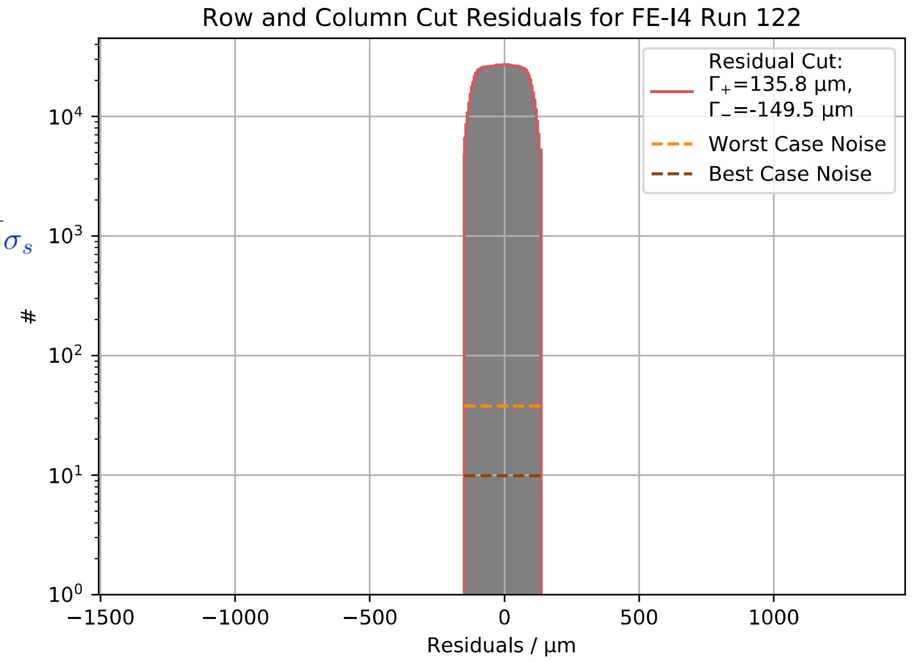

$$\epsilon_{\text{reco}} = \frac{\text{signal - background}}{\text{signal}}$$

Correctly reconstructed tracks in FE-I4

Analysis Cuts

- Cuts (Tracks):
  - Hit requirement: hits in all M26 planes + FE-I4 (~ 40 %)
  - Min track/hit distance (~ 10 %)
  - Track quality (distance between hit and track intersection): 2σ of correlation (~ 5 %)