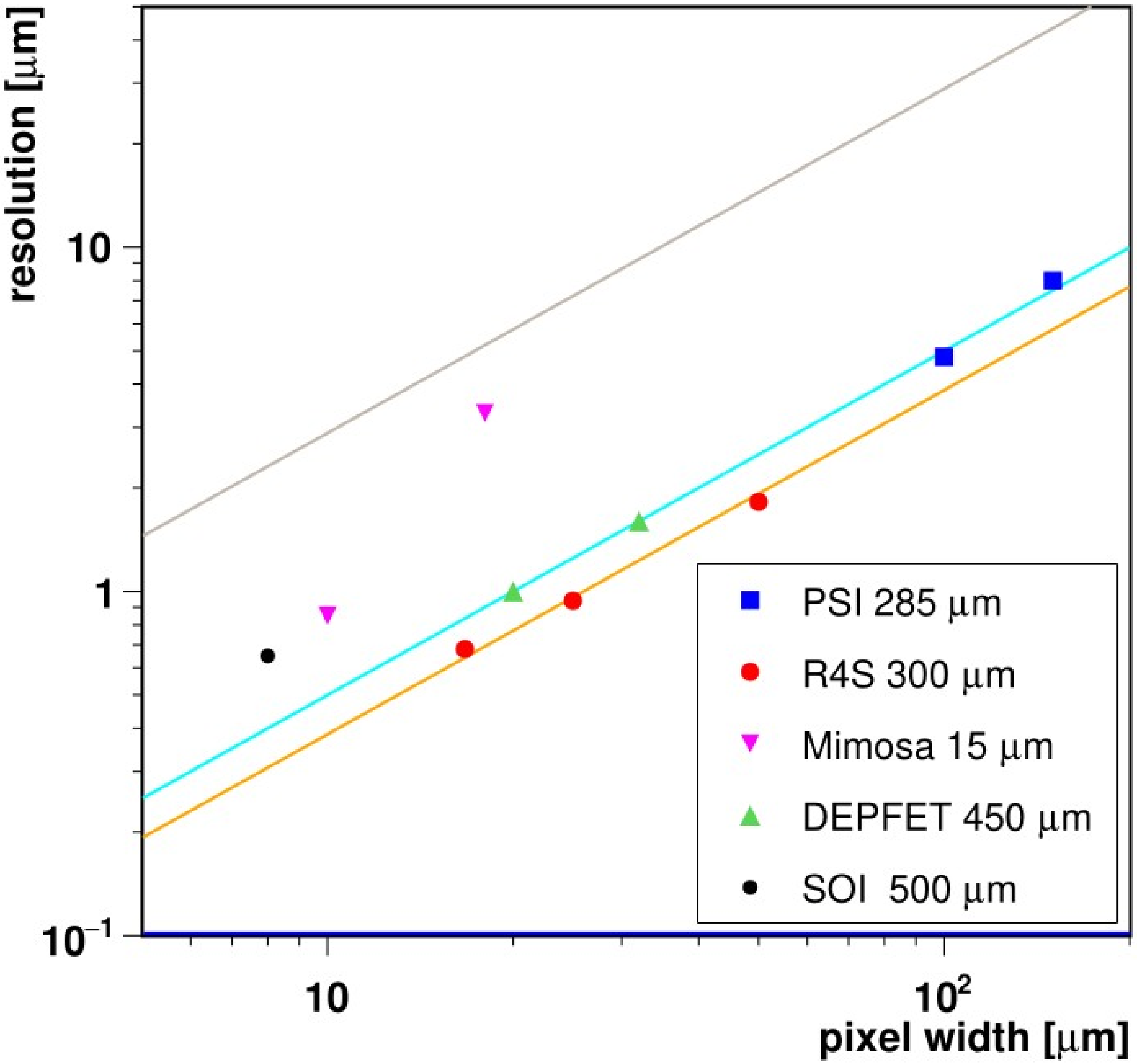
position resolution

Daniel Pitzl, DESY
DESY SiDet group, 13.1.2021



- position resolution effects
- small pixel designs
- telescope method
- three-plane method
- rotated edge-on method
- resolution summary

resolution issues

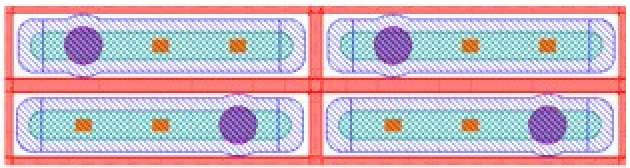
- **friends of resolution**
  - small pixels
  - optimal incidence angle
  - low threshold
  - thick sensors
  - diffusion (vertical)
  - uniform ionization
  - analog readout
  - 8-bit ADC or ToT
  - smart clustering

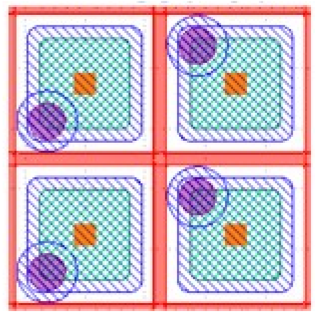
- **enemies of resolution**
  - large pixels
  - vertical incidence
  - high threshold
  - thin sensors
  - diffusion (inclined)
  - ionization fluctuations
  - binary readout
  - 4-bit ADC or ToT
  - cross-talk
  - delta rays
  - electronics noise
  - radiation damage

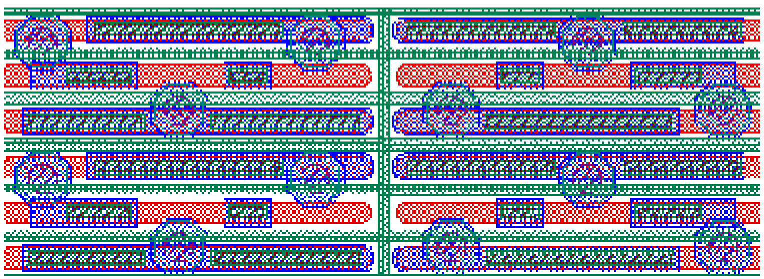
how to measure resolution

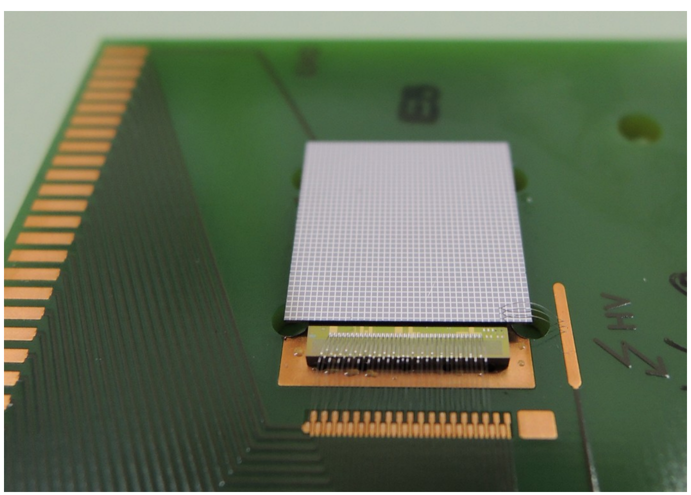
- classical:
  - reference telescope and one device under test (DUT)
  - telescope should have better resolution than DUT
- independent:
  - multiple DUT planes
  - simple error propagation to single plane
- telescope-on-a-chip:
  - edge-on
  - need only one DUT
  - low rate (few Hz)

sensor designs









8×8 mm active area

- 150 µm thickness (Uni HH):
  - 50×50 and 25×100 µm
- 285m thickness (PSI):
  - 50×50, 25×100, and **17×150** µm
- ROC4Sens readout chip (PSI):
  - 50×50 µm, 24’800 pixels
  - flip chip bump bonding (IZM)
  - analog readout, no zero suppression
  - USB 2 DAQ: 180 Hz

CMS Pixel test beam team

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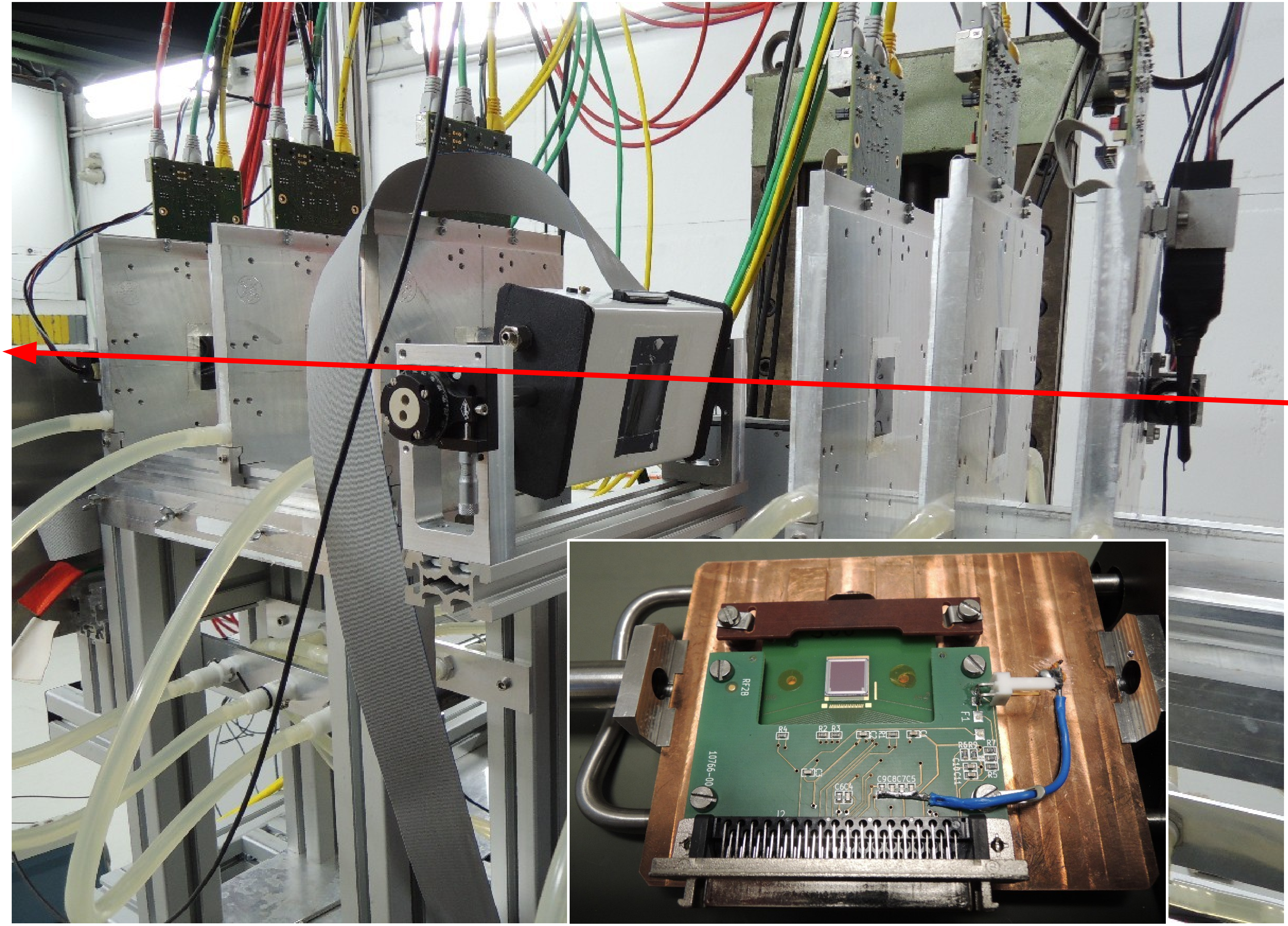
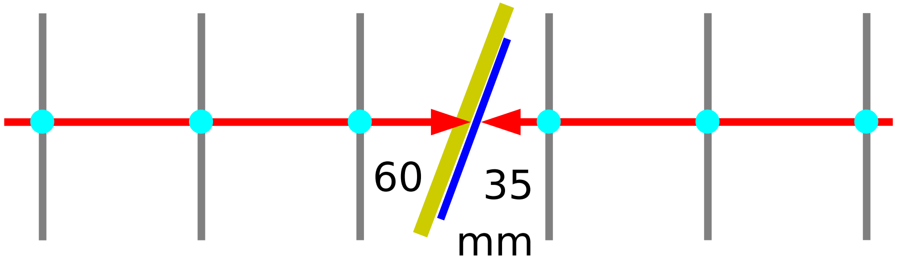
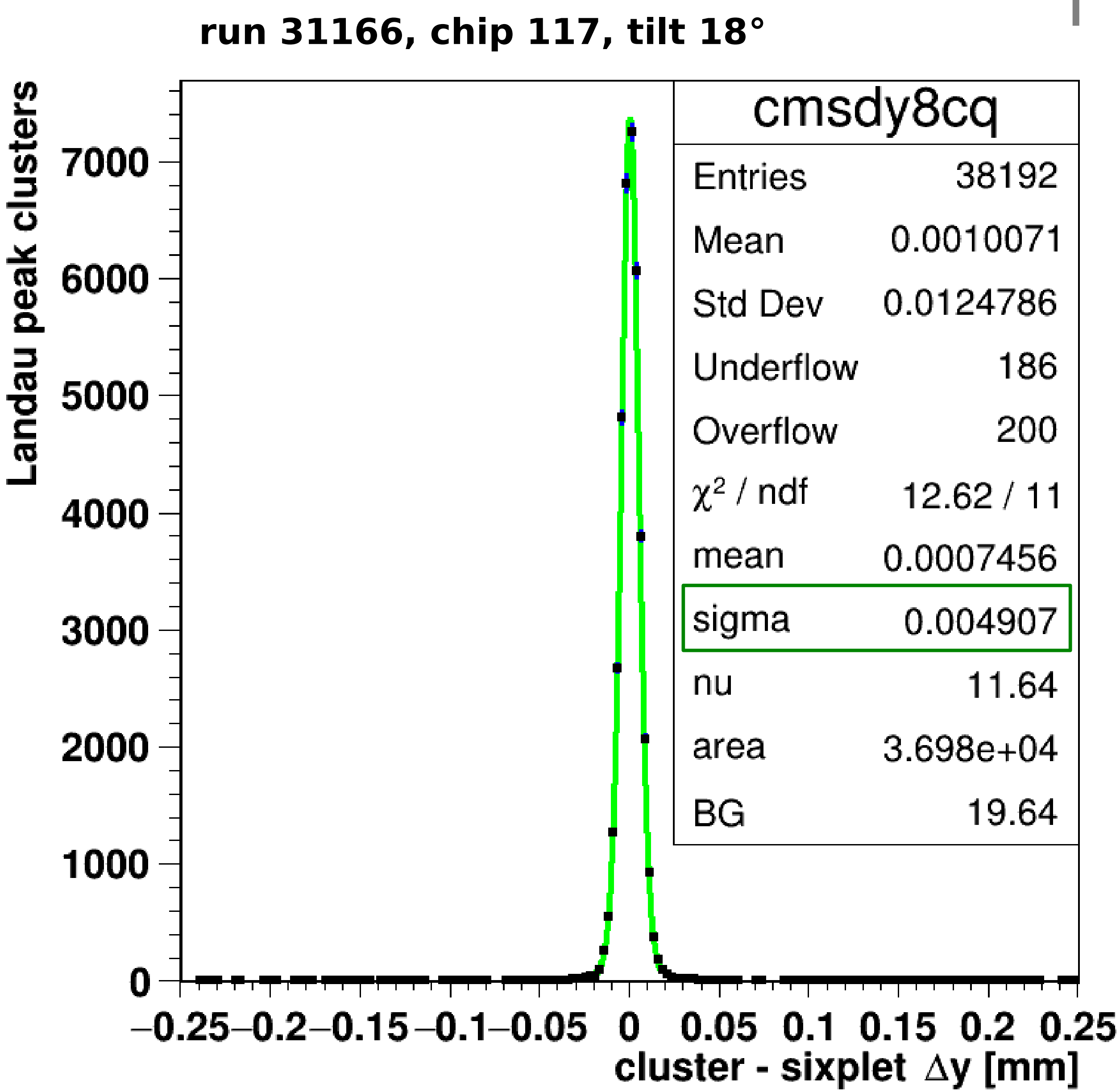
Mar 2019

DUT in the telescope



DUT-telescope residual

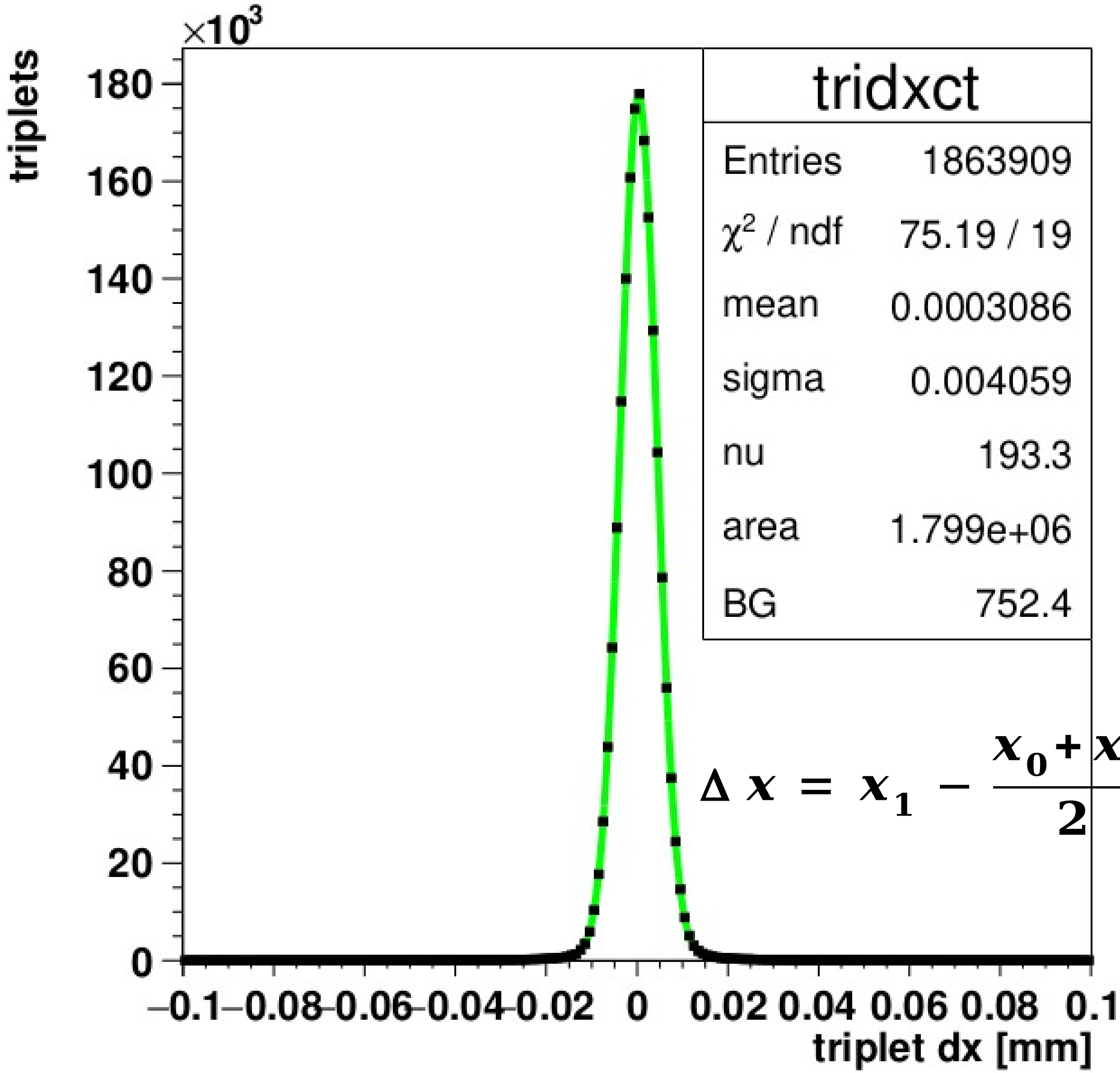




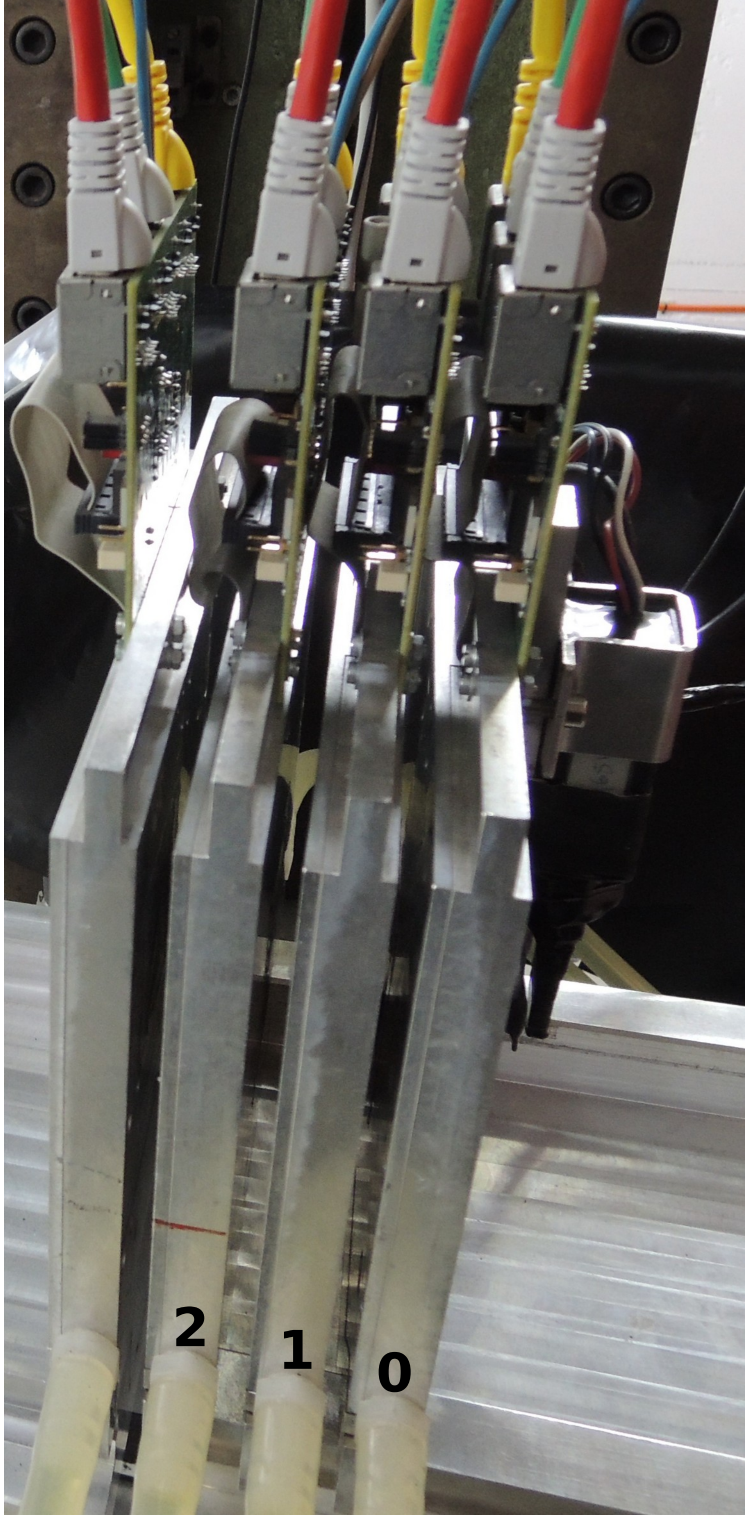
- thickness 150 μm:
  - 50×50 μm pixels
  - tilt 18°, 5.6 GeV
  - ×2 overdepletion
  - Landau peak
- residual width:
  - **4.9 μm**
- subtract track (3.4 μm):
  - **DUT 3.5 μm**

telescope resolution

Datura, threshold 5, 5.6 GeV, 21 mm spacing

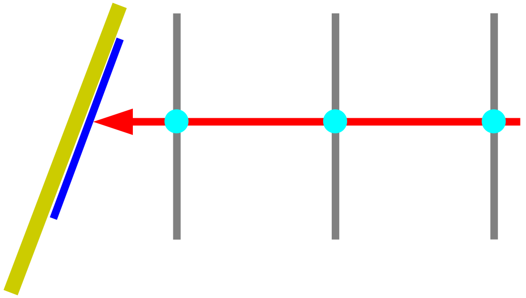


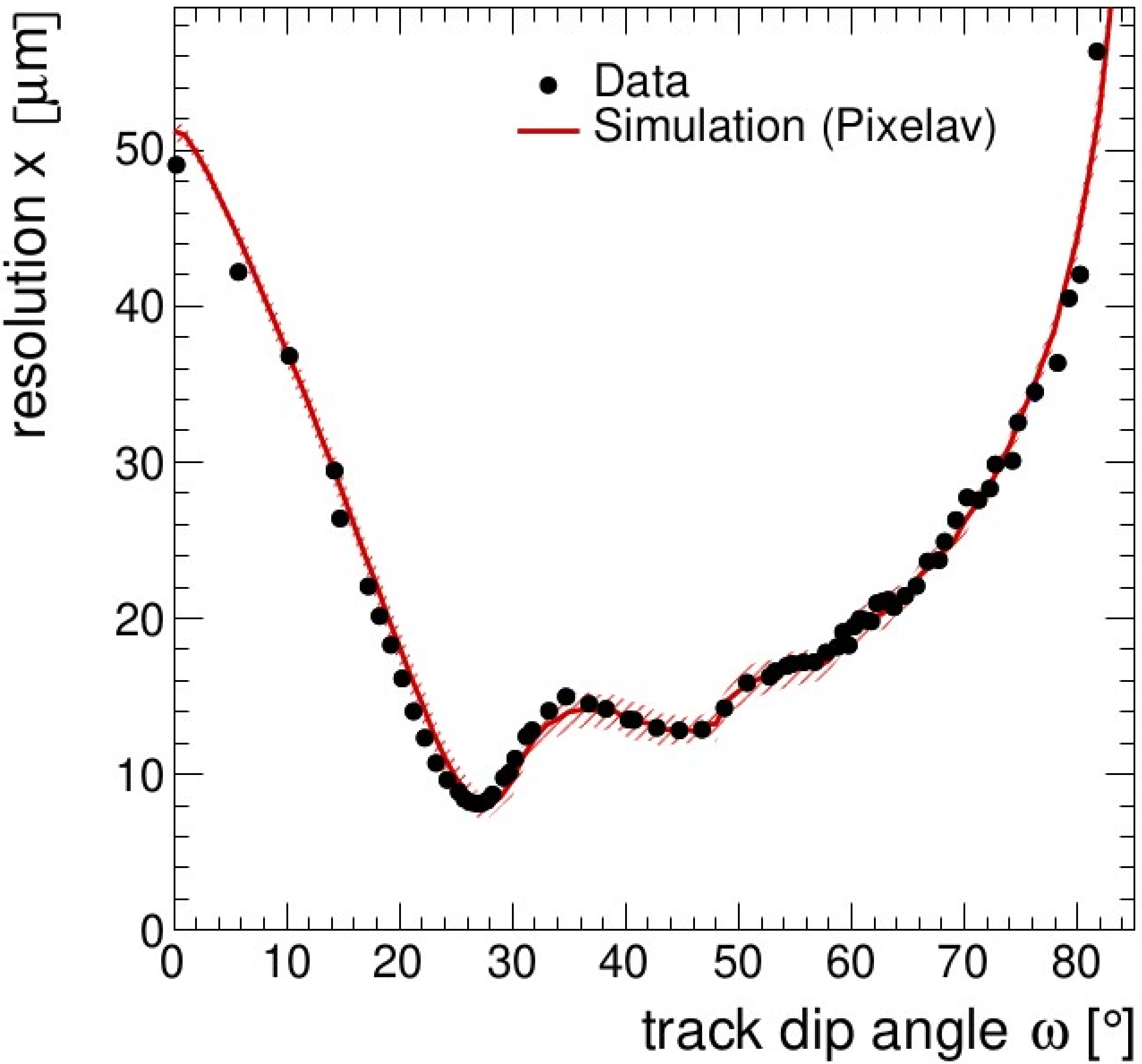
$$\Delta x = x_1 - \frac{x_0 + x_2}{2}$$



residual 4.1 µm ⇒ hit 3.3 µm

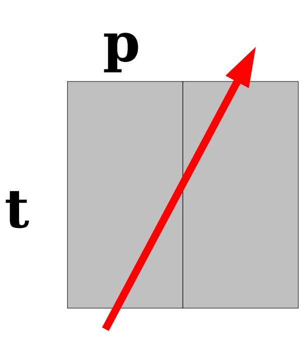
resolution vs incident angle



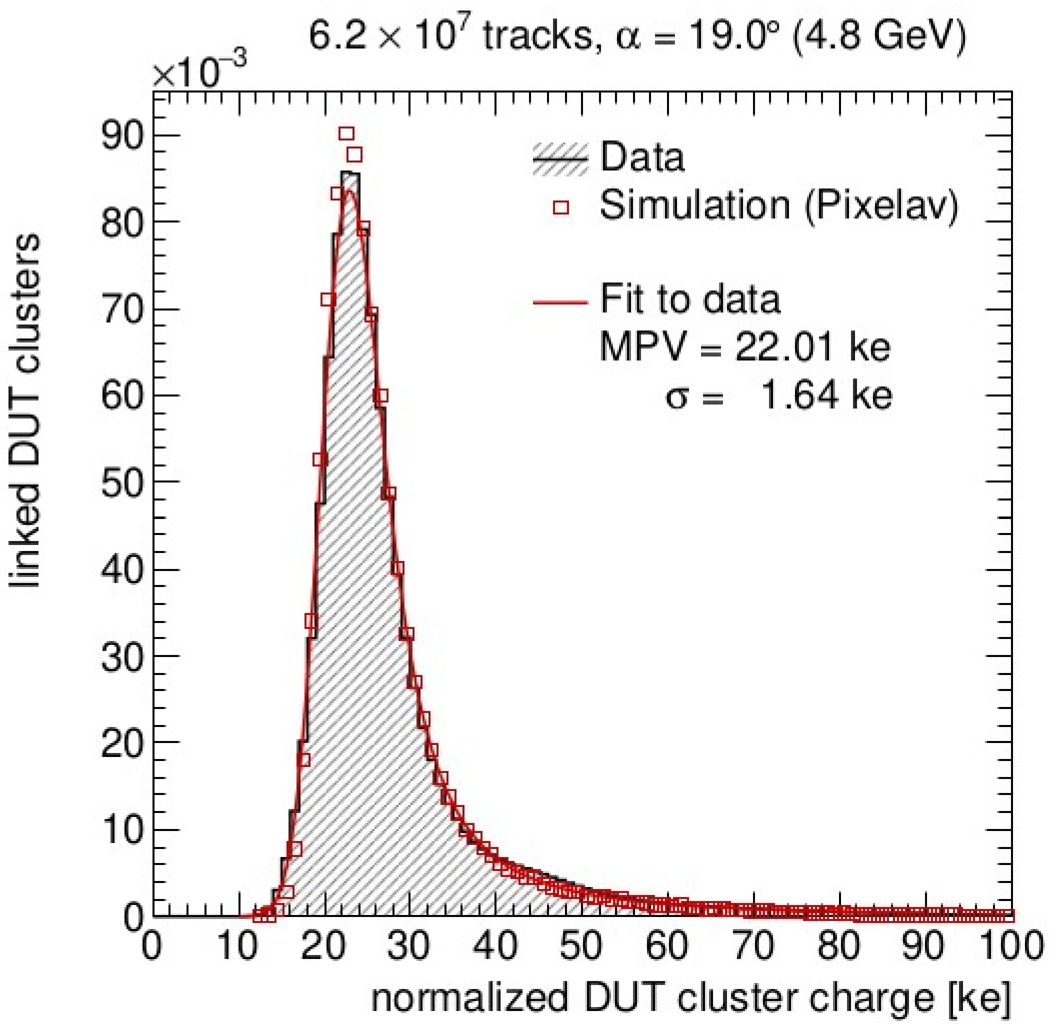


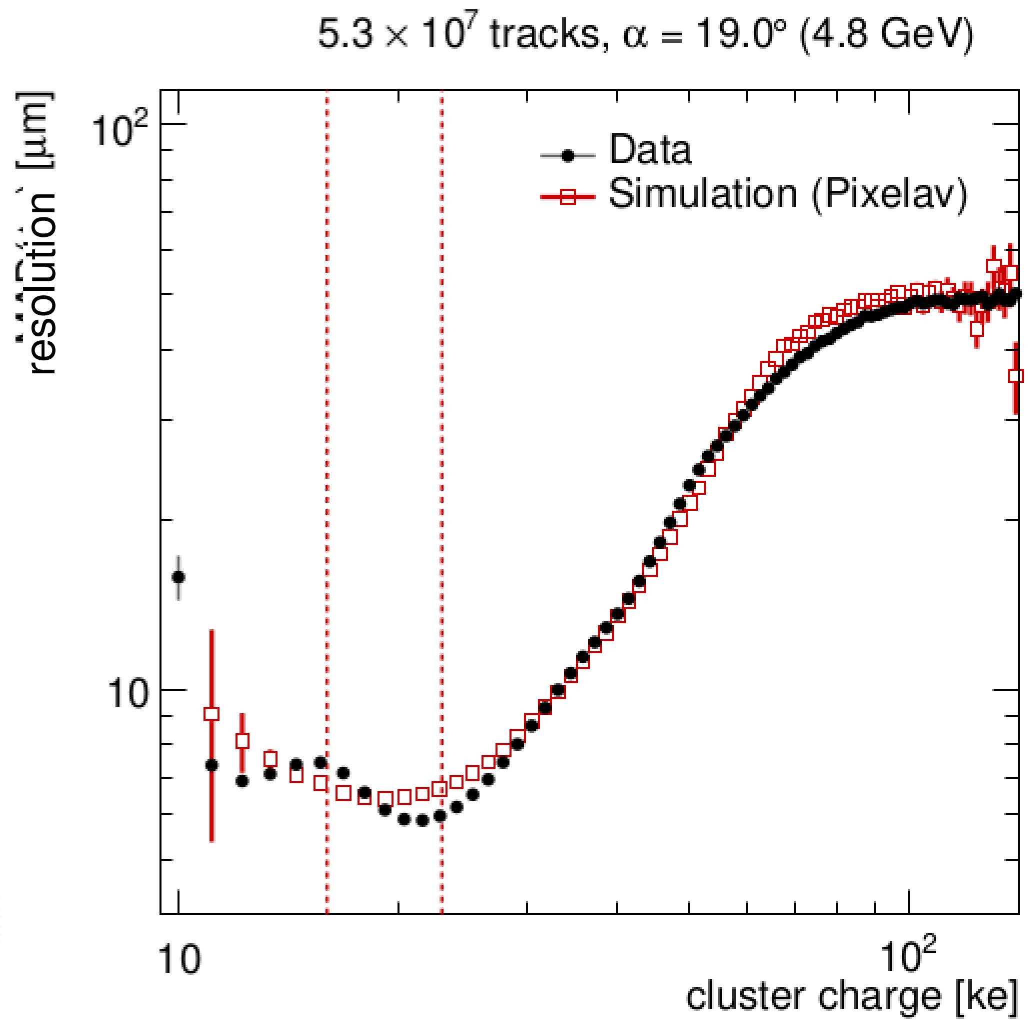
- **150 µm pixels**
  - thickness 285 µm
  - threshold 1.5 ke
- minimum:
  - **8.0 µm at 27.8°**
  - (at the Landau peak)

best dip = atan(p/t)



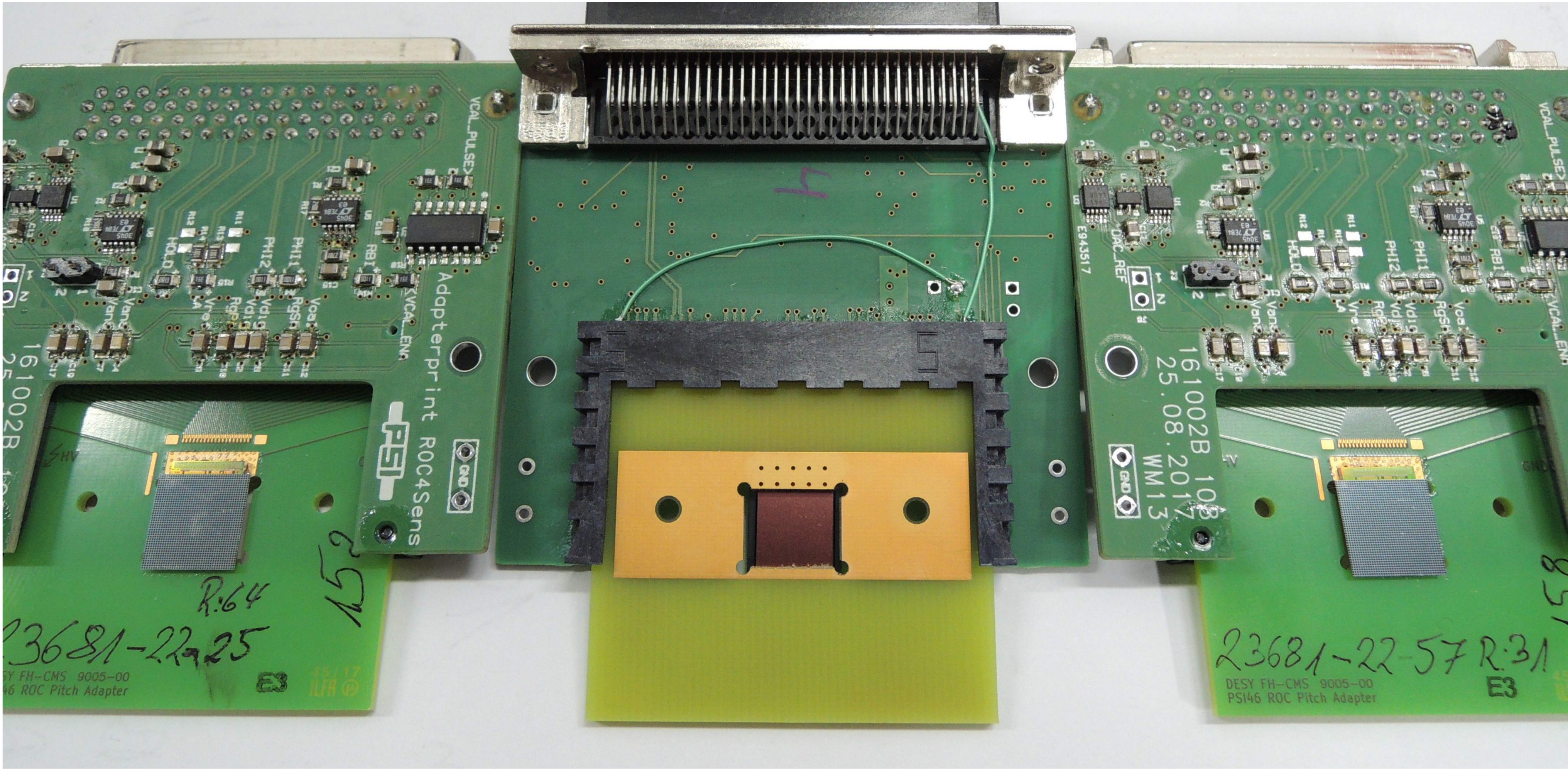
resolution vs energy loss





delta rays in the Landau tail spoil the resolution

multiple DUTs

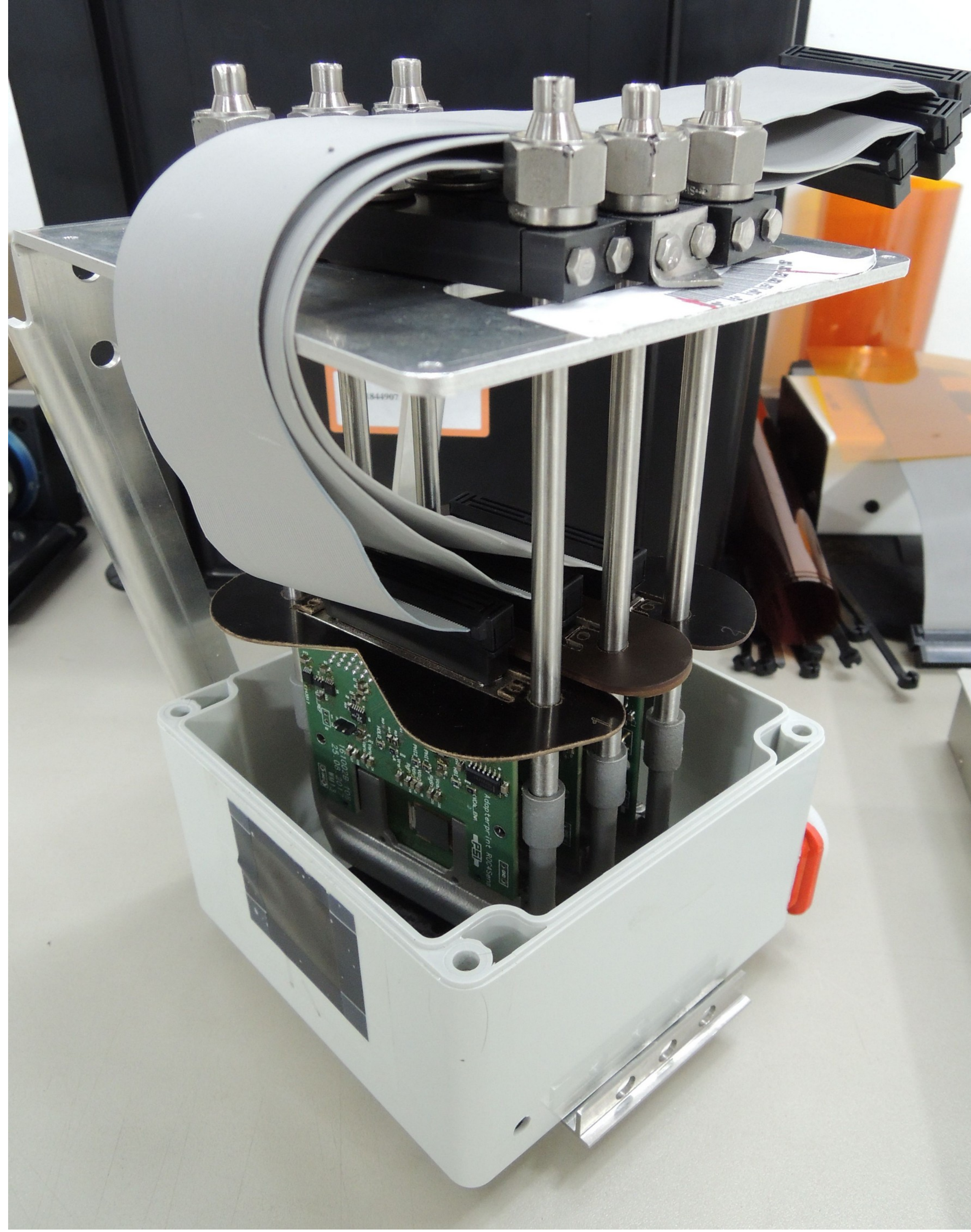


PCB with cutout: less material in the beam

(poor cooling: not possible for irradiated samples)

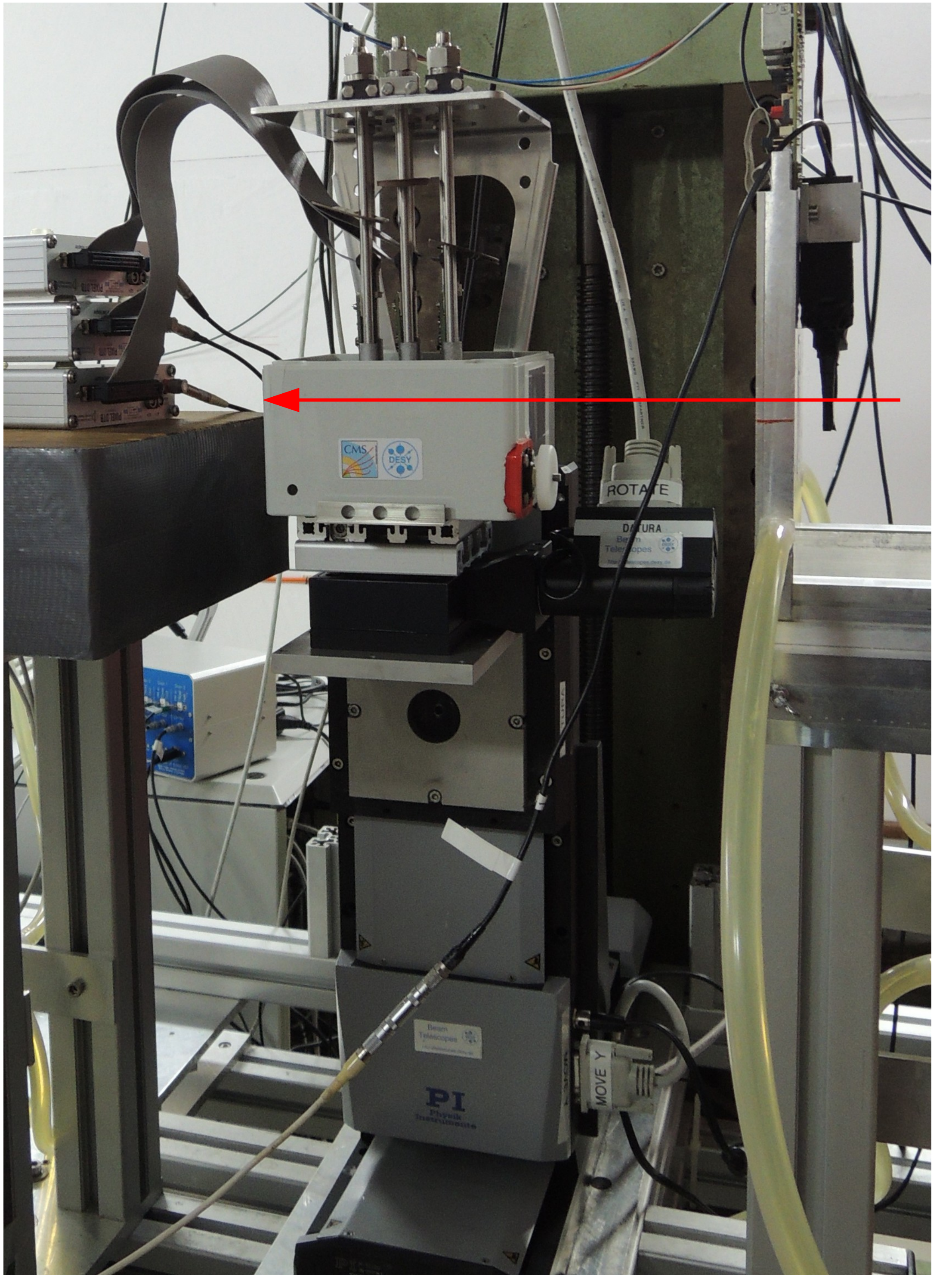
Dreimaster

- Resolution measurement by the triplet method
- three single chip modules:
  - 20 mm spacing
  - common turn angle from 0 to 30°
  - with cooling and housing
- change of modules takes ~20 min

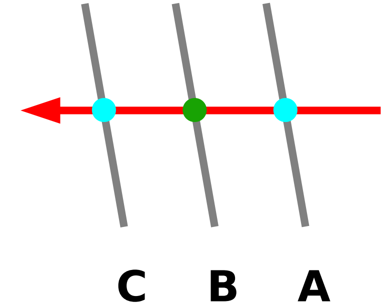


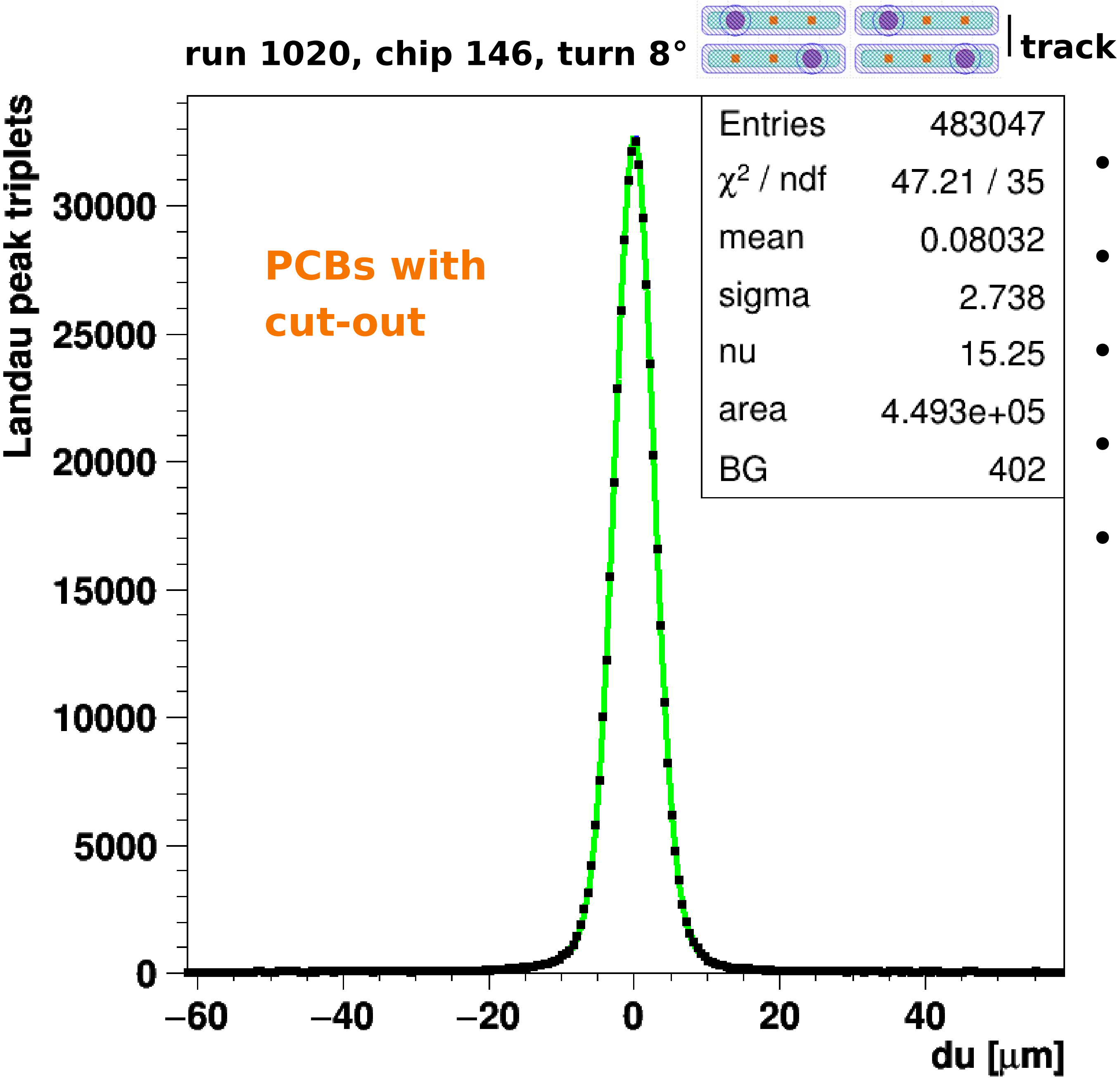
Dreimaster test beam

- Dreimaster mounted on PI stage:
  - x and y movement
  - θ rotation
- (telescope not used)
  - trigger scintillator



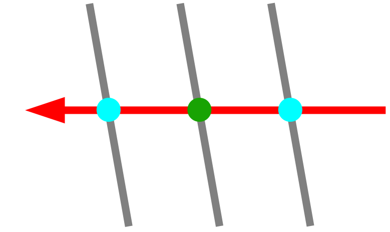
Dreimaster residuals

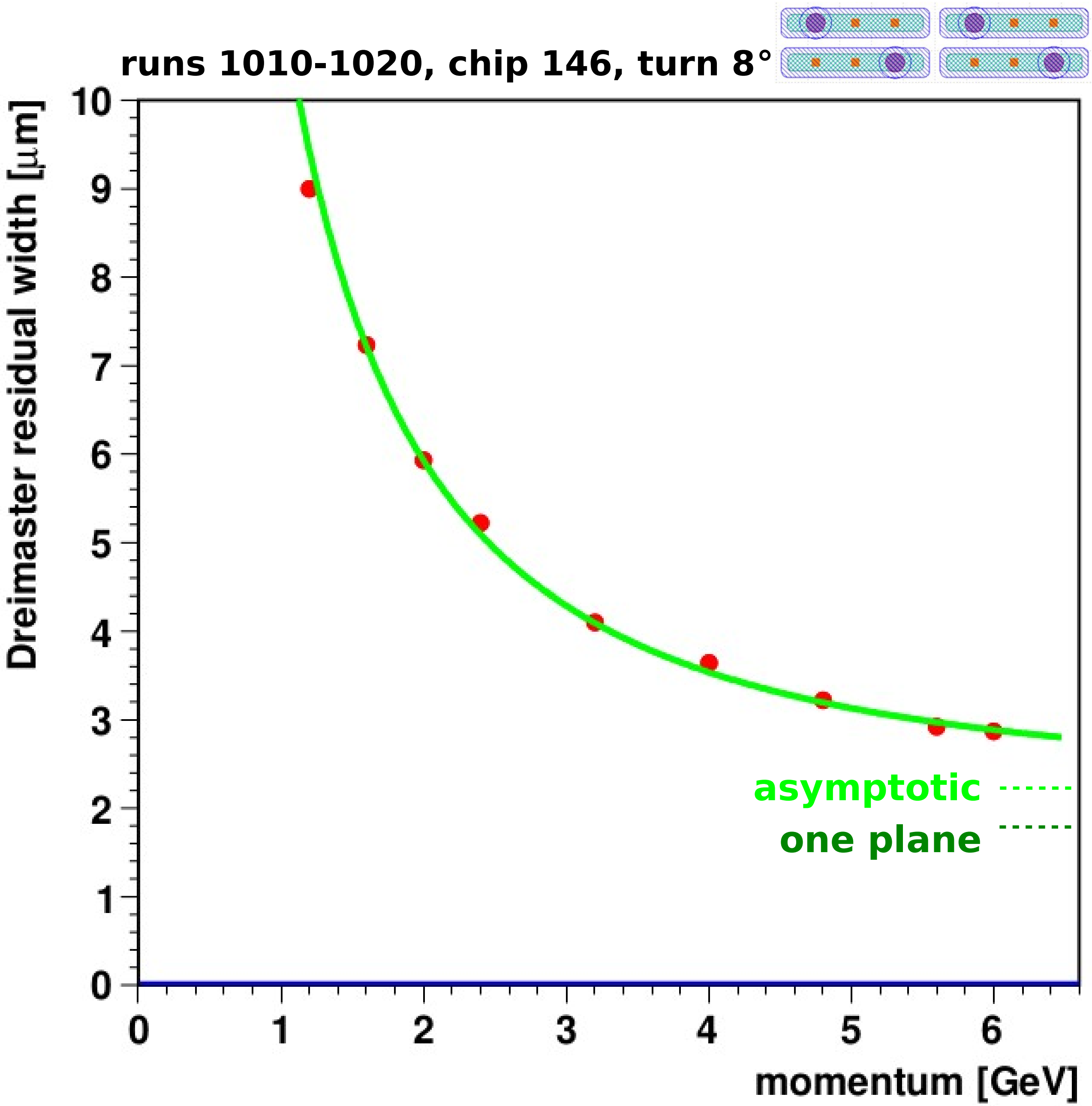




- pixel pitch 25 μm
- turn 8° (150 μm thick)
- Landau peak clusters
- 6 GeV
- Triplet residuals:
  - $\Delta x = x_B - \frac{x_A + x_C}{2}$
  - **fit: 2.74 μm**
  - **unfolding tracking and scattering: 1.8 μm hit resolution**

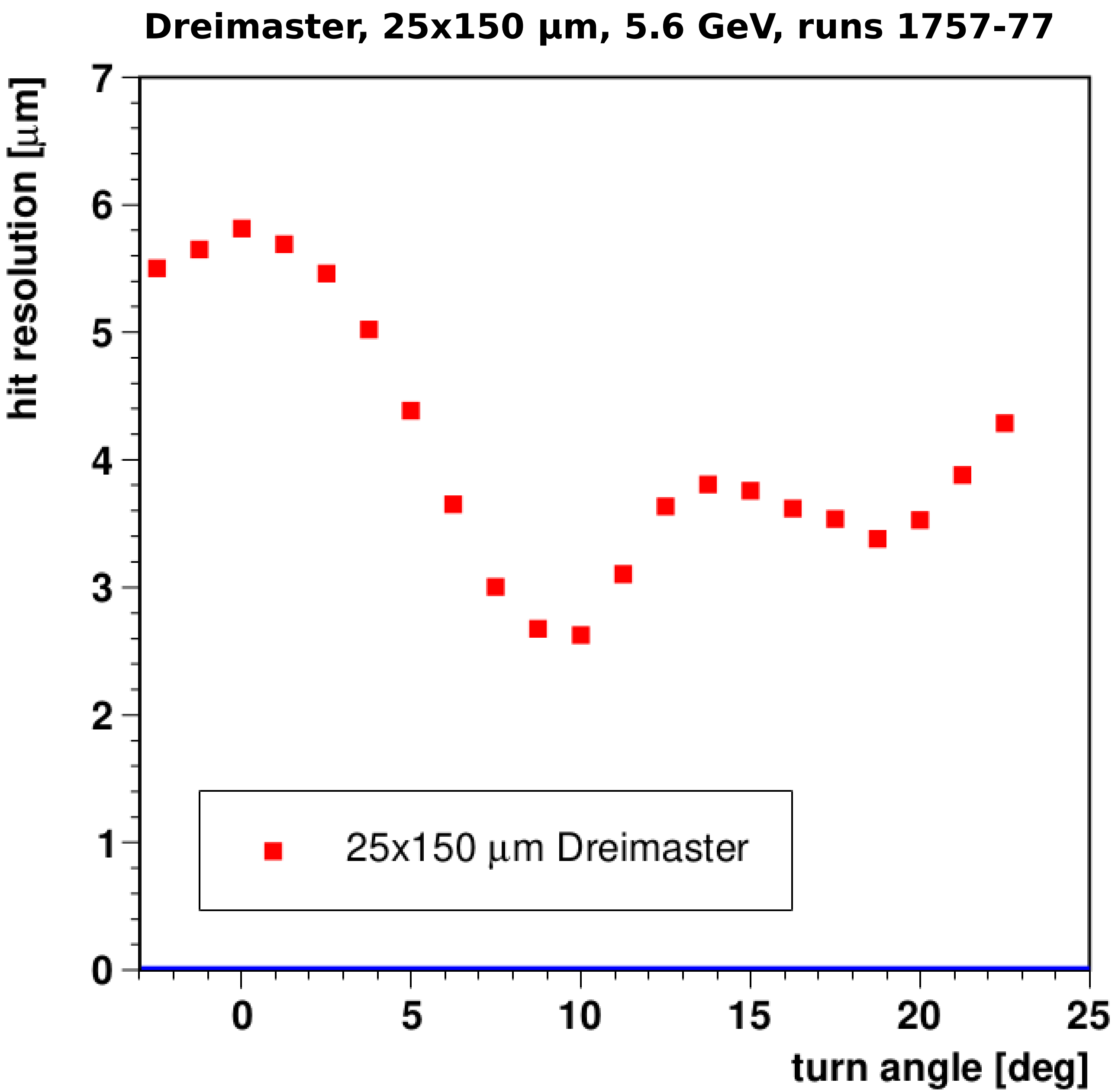
momentum scan



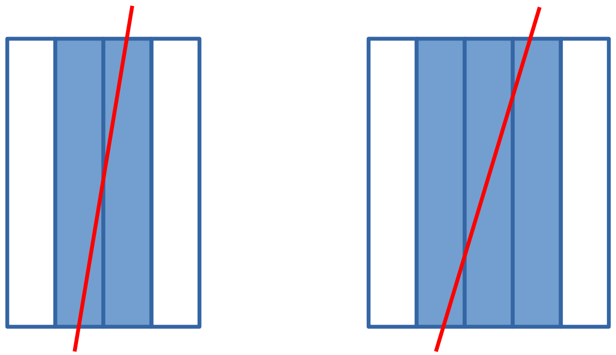


- unfold resolution and multiple scattering:
  - momentum scan
- **fit:**
  - **residual² = (scattering / p)² + resolution²**
  - **triplet resolution: 2.2 μm**
  - **single plane resolution: 1.8 μm**

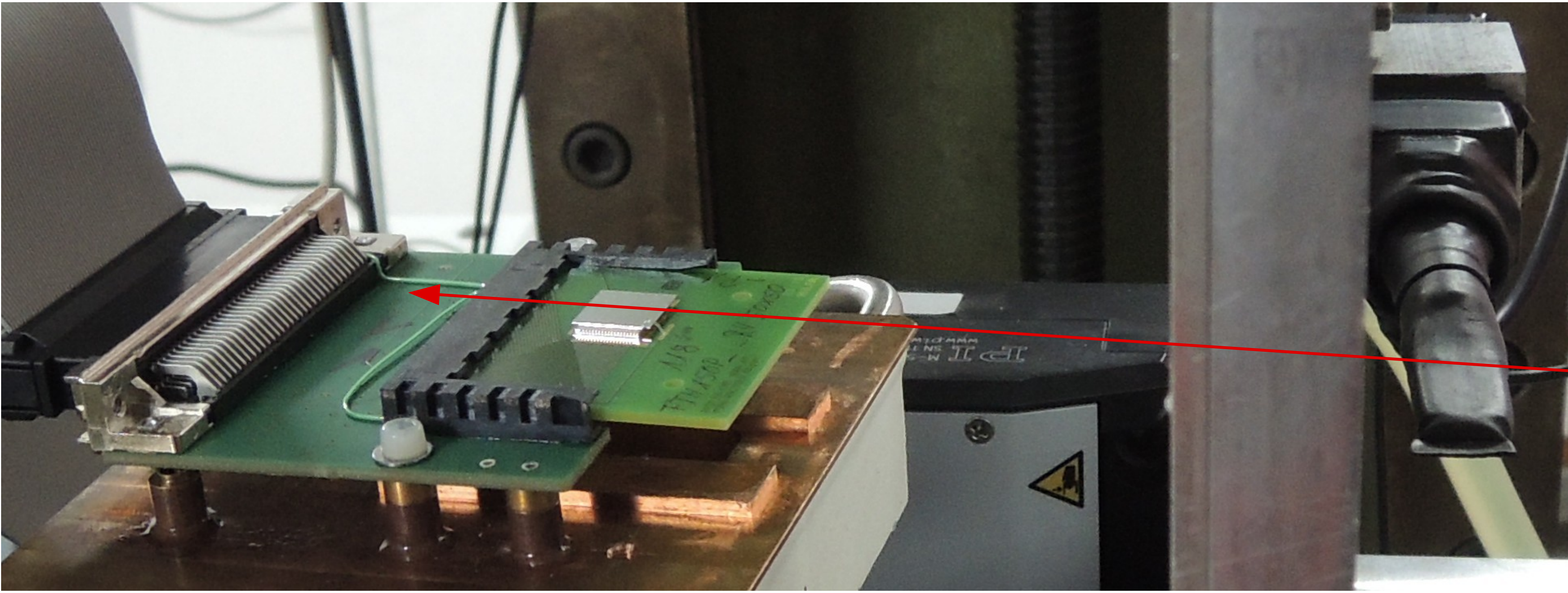
Dreimaster: turn scan



- **25×150 µm sensors:**
  - Dreimaster triplet
- fresh
- optimal resolution at:
  - atan(25/150) = 9.5°
- 2nd minimum:
  - atan(50/150) = 18.4°



rotated edge-on tracking

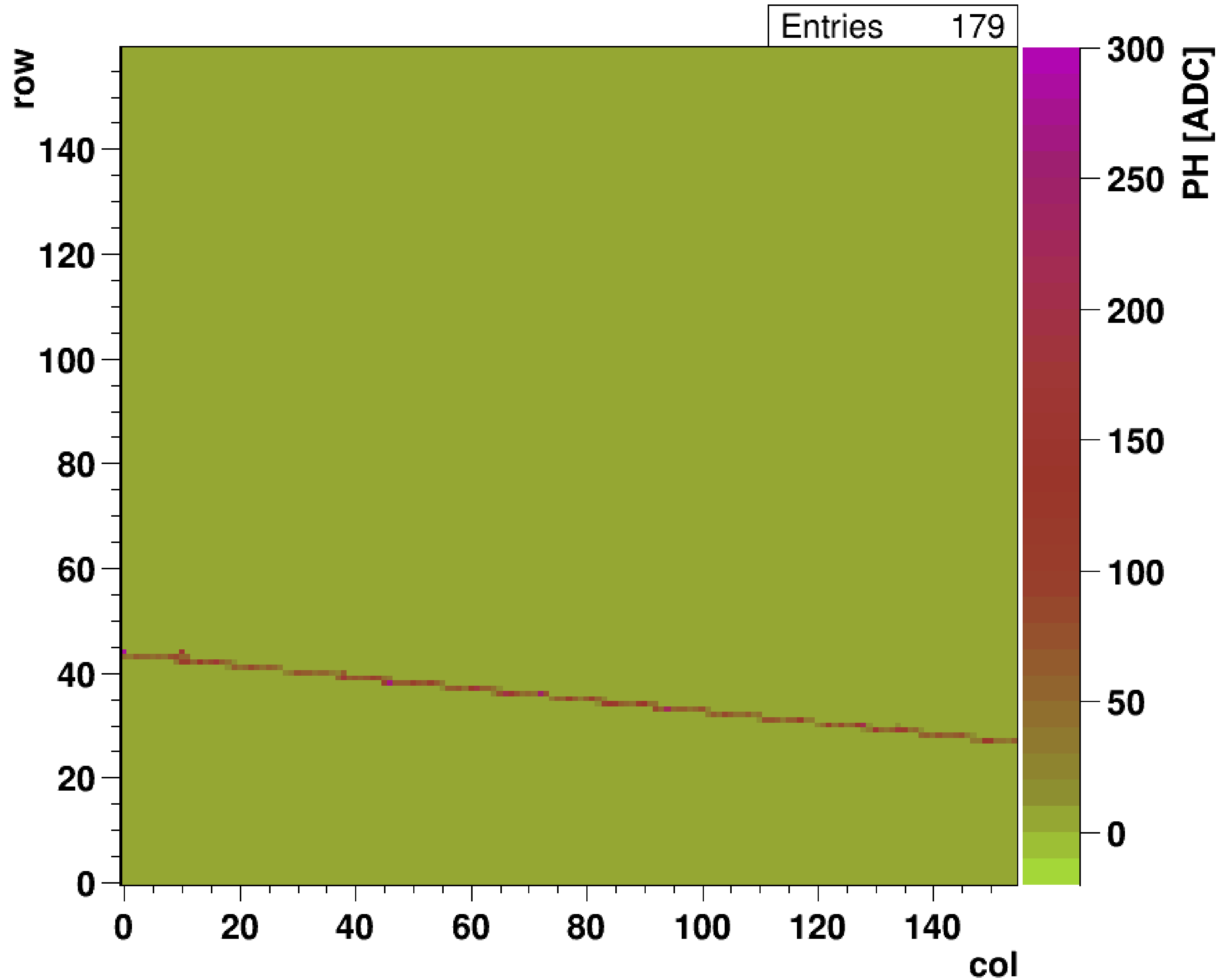


Planar pixel sensor with ROC4Sens readout

mounted on a rotation stage

beam: edge-on

edge-on track



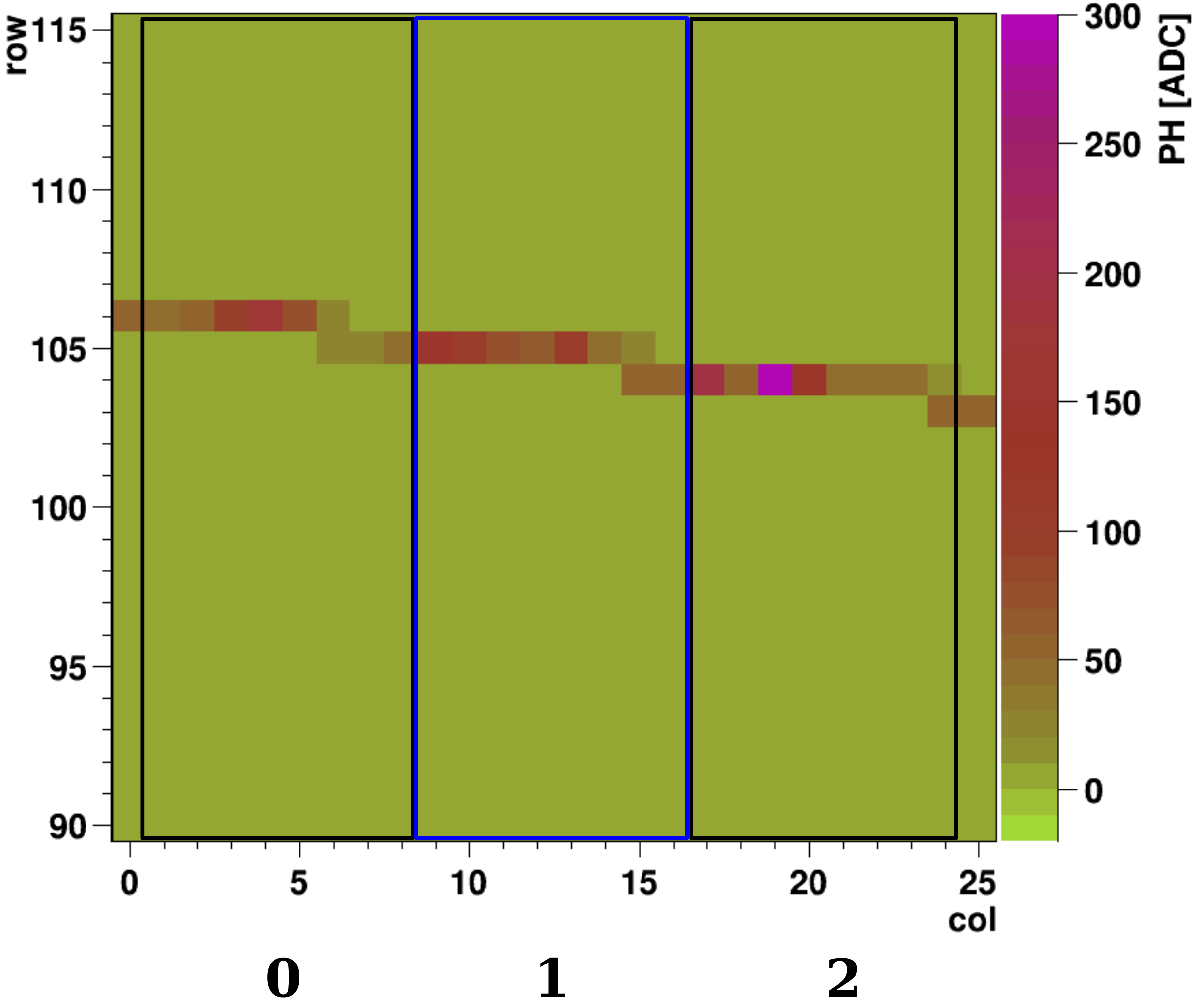
50×50 μm pixels

rotated edge-on combined tracking

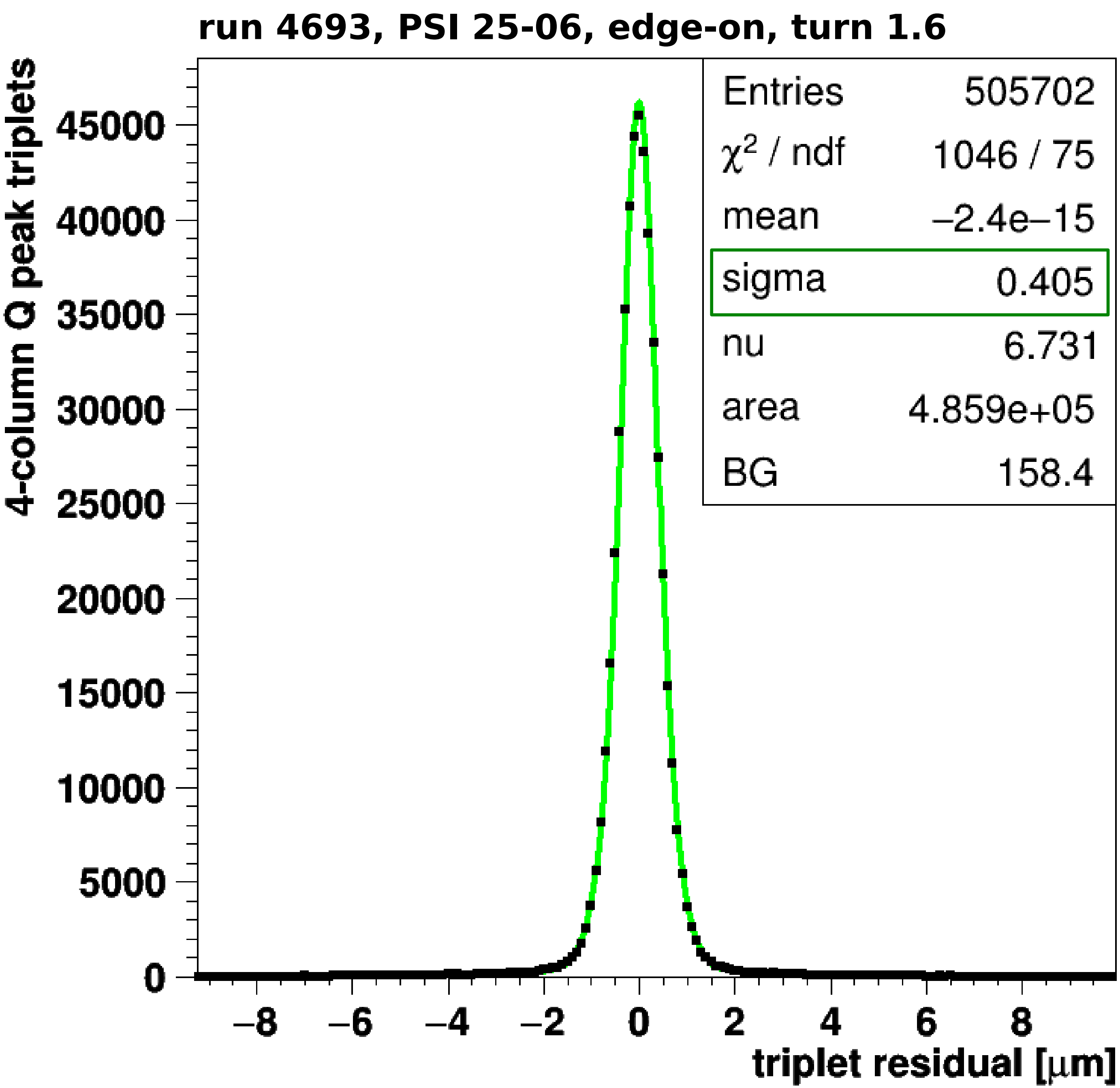
- small turn angle
- combine neighbouring columns into one measurement:
  - effective thicker sensor
- triplet tracking:

$$\Delta y = y_1 - \frac{y_0 + y_2}{2}$$

$$\sigma(\Delta y) = \sigma(y) \cdot \sqrt{3/2}$$

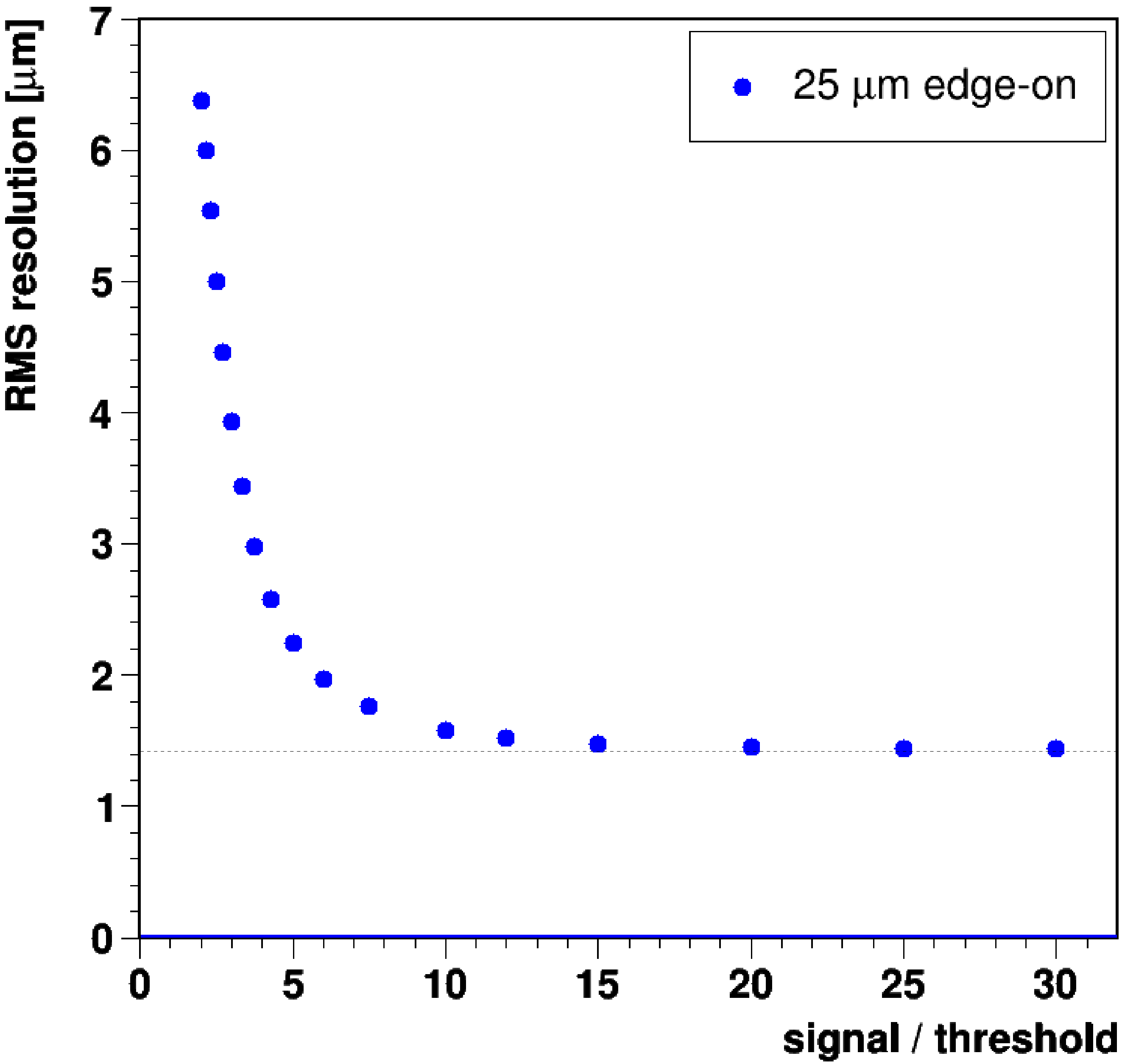


edge-on residuals



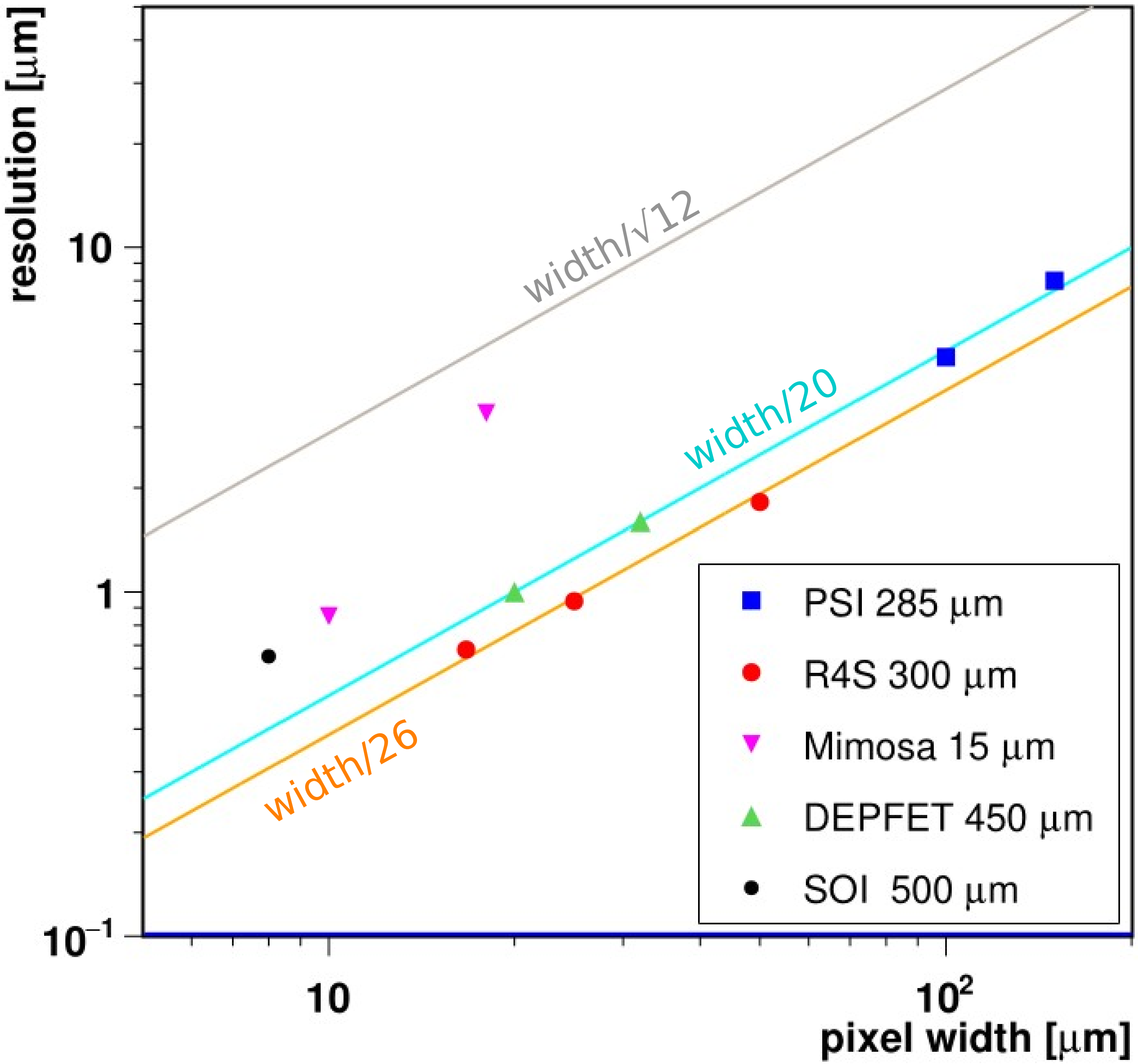
- **150×17 μm pixels**
  - edge-on with 1.6° turn angle
  - combine 4 columns
  - Landau peak
- triplet residual:
  - **width 0.4 μm**
- ⇒ single hit:
  - **0.33 μm**
  - **the best ever?**

resolution vs threshold



- **25 µm pixels**
  - edge-on
  - optimal turn angle
- threshold applied offline
- need:
  - threshold < 0.1 signal
  - for best resolution

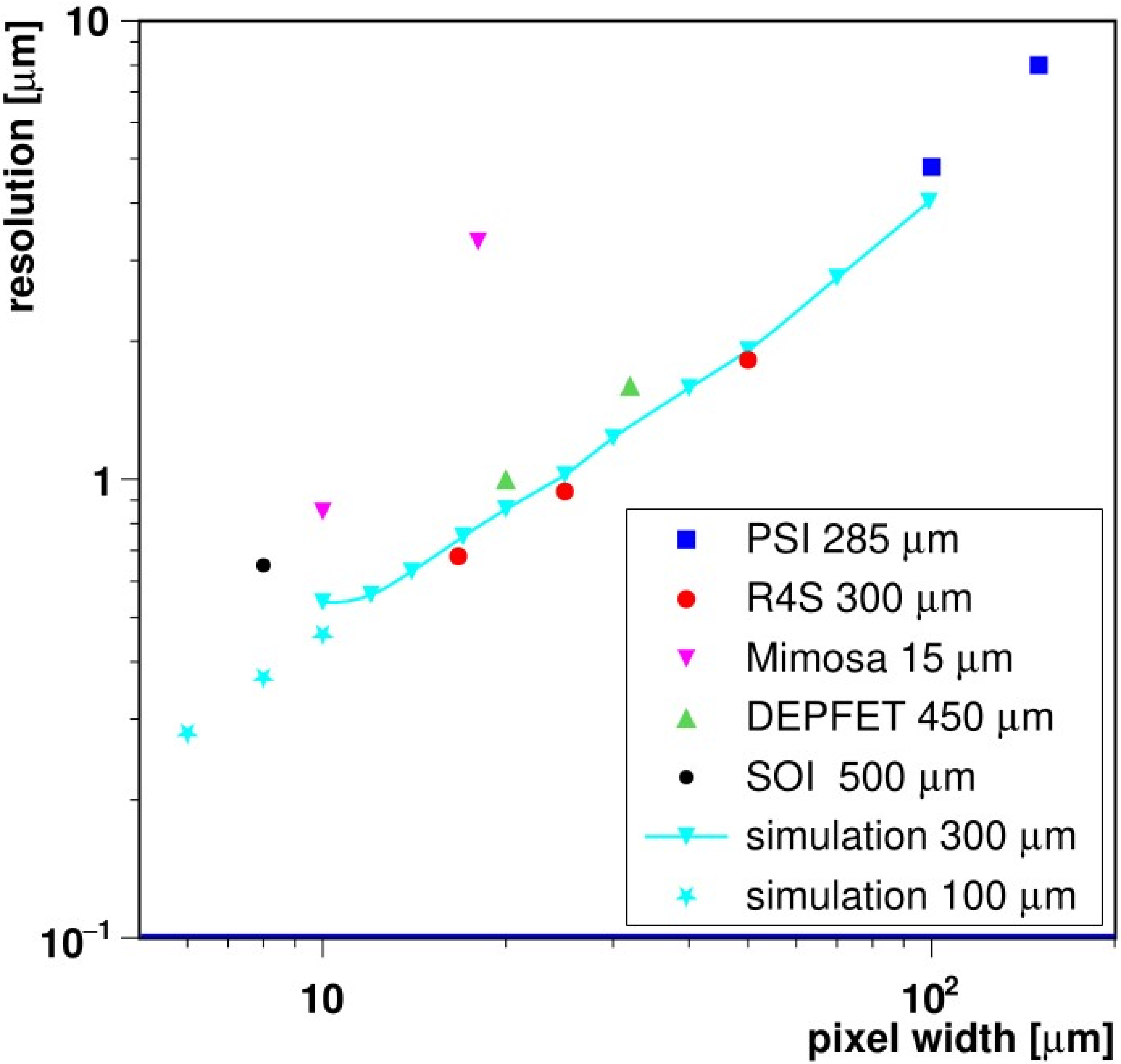
resolution vs pixel geometry



- a composition of measurements
  - with lines to guide the eye
- most at optimal incidence angle

thickness

data vs simulation

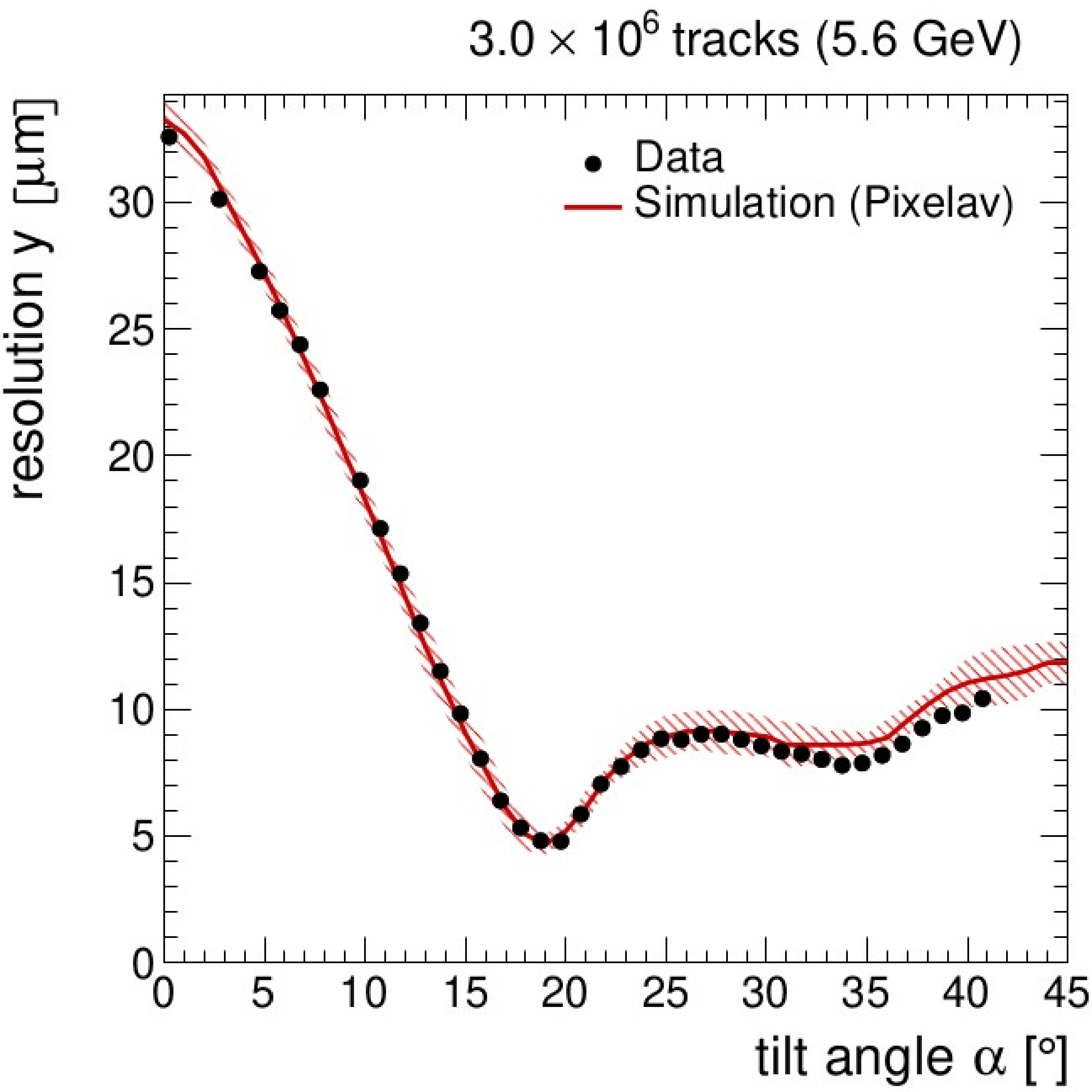


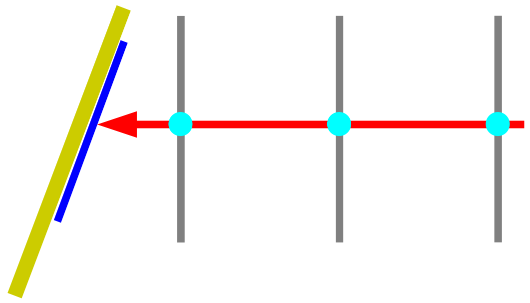
- Bichsel simulation:
  - incident angle
  - ionization fluctuations
  - diffusion
- **need thinner sensors to avoid diffusion limit**
- **edge-on data:**
  - **better than simulation?**

summary

- position resolution scales with pixel size:
  - from 150 to 17 µm
- with signal / threshold ≈ 10:
  - resolution ≈ pitch / 20 (at optimal incidence angle)
- edge-on telescope-on-a-chip:
  - resolution 0.4 µm for 17 µm pixels at 600 µm thickness
  - (better than simulation? correlation?)
- to do:
  - Dreimaster with 17 µm pixels
- another talk:
  - sensor simulation details

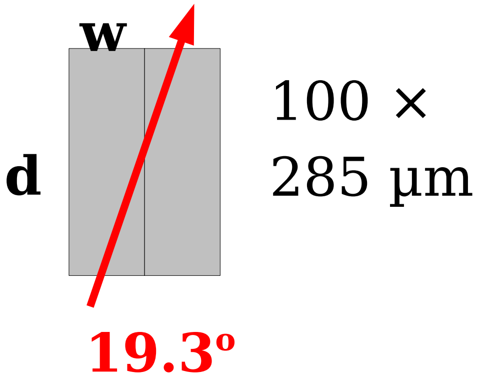
resolution vs tilt angle



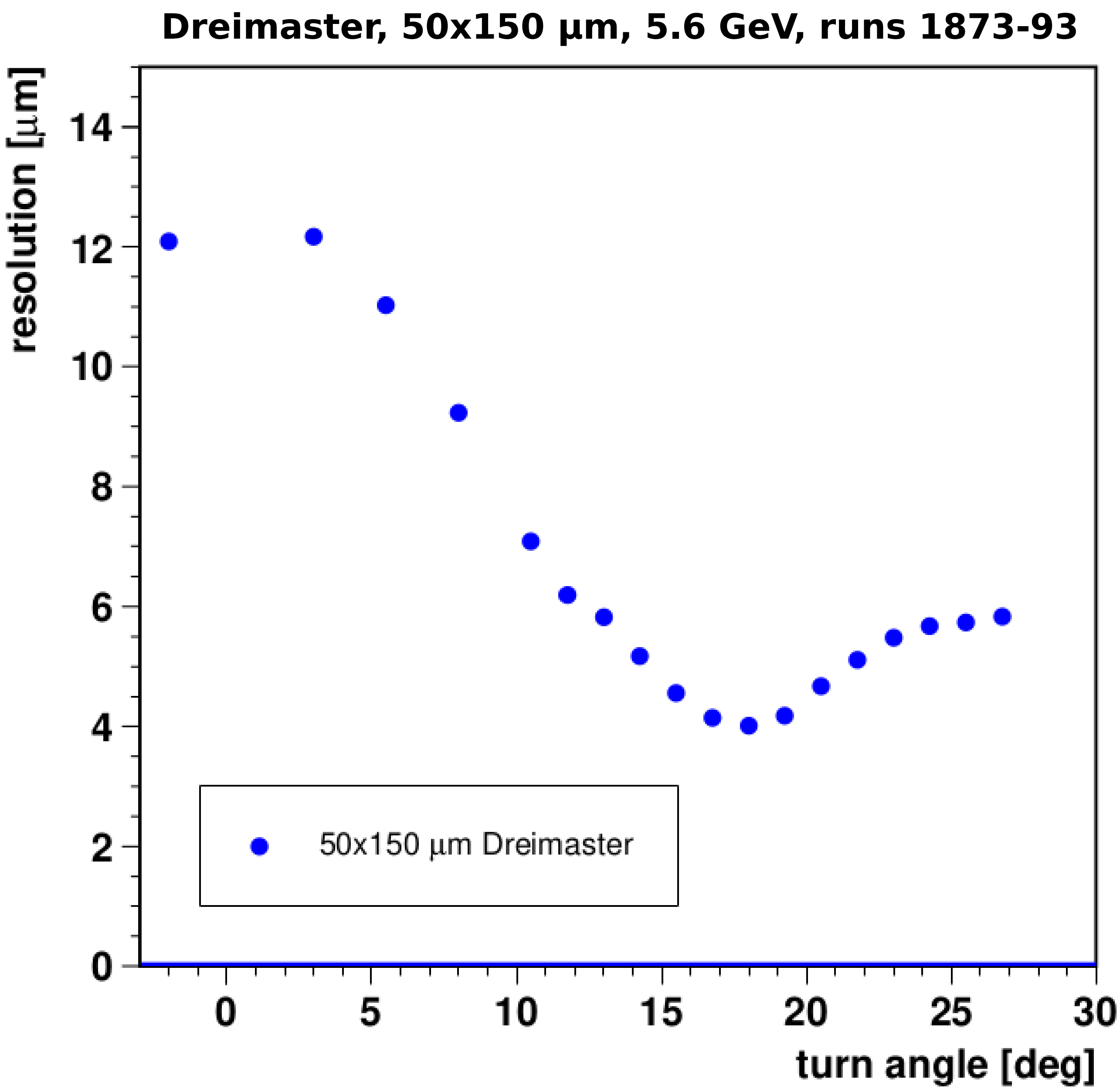


- **100 μm pixels**
  - thickness 285 μm
  - threshold 1.5 ke
- minimum:
  - **4.8 μm at 19.5°**
  - (at the Landau peak)

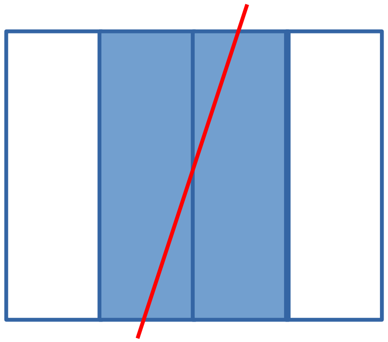
best tilt = atan(w/d)



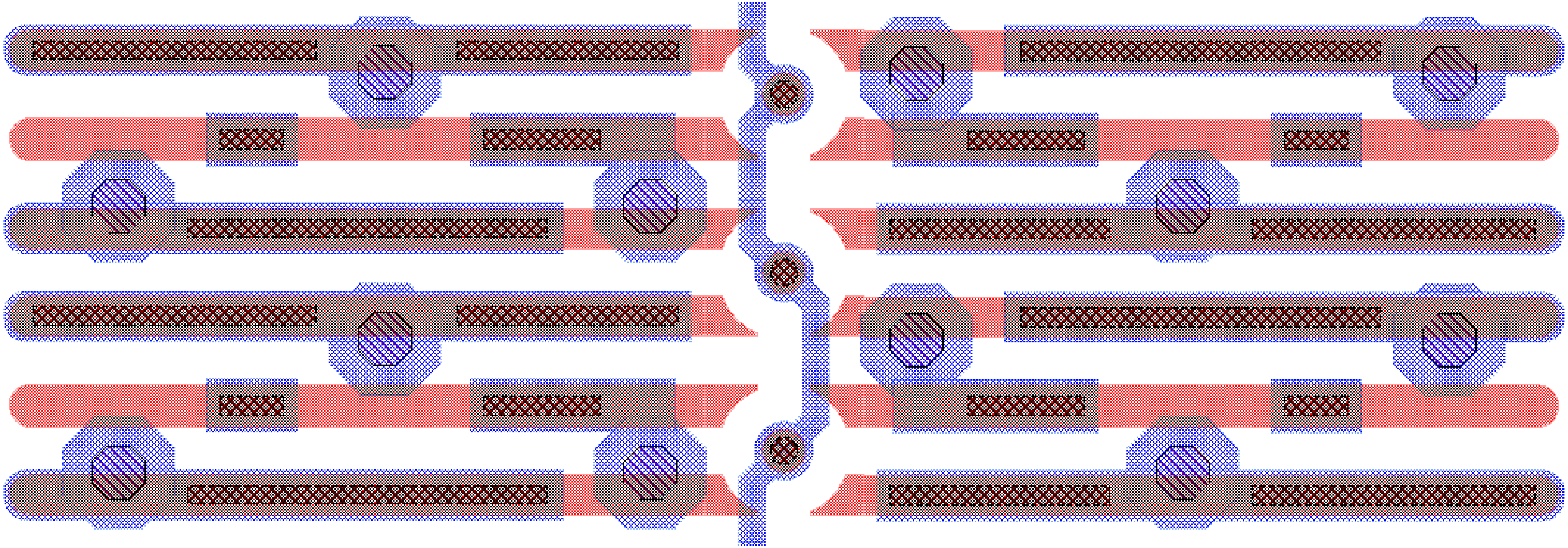
Dreimaster: turn scan



- **50×150 µm pixel sensors:**
  - Dreimaster triplet residuals
- fresh
- optimal resolution at:
  - atan(50/150) = 18.4°

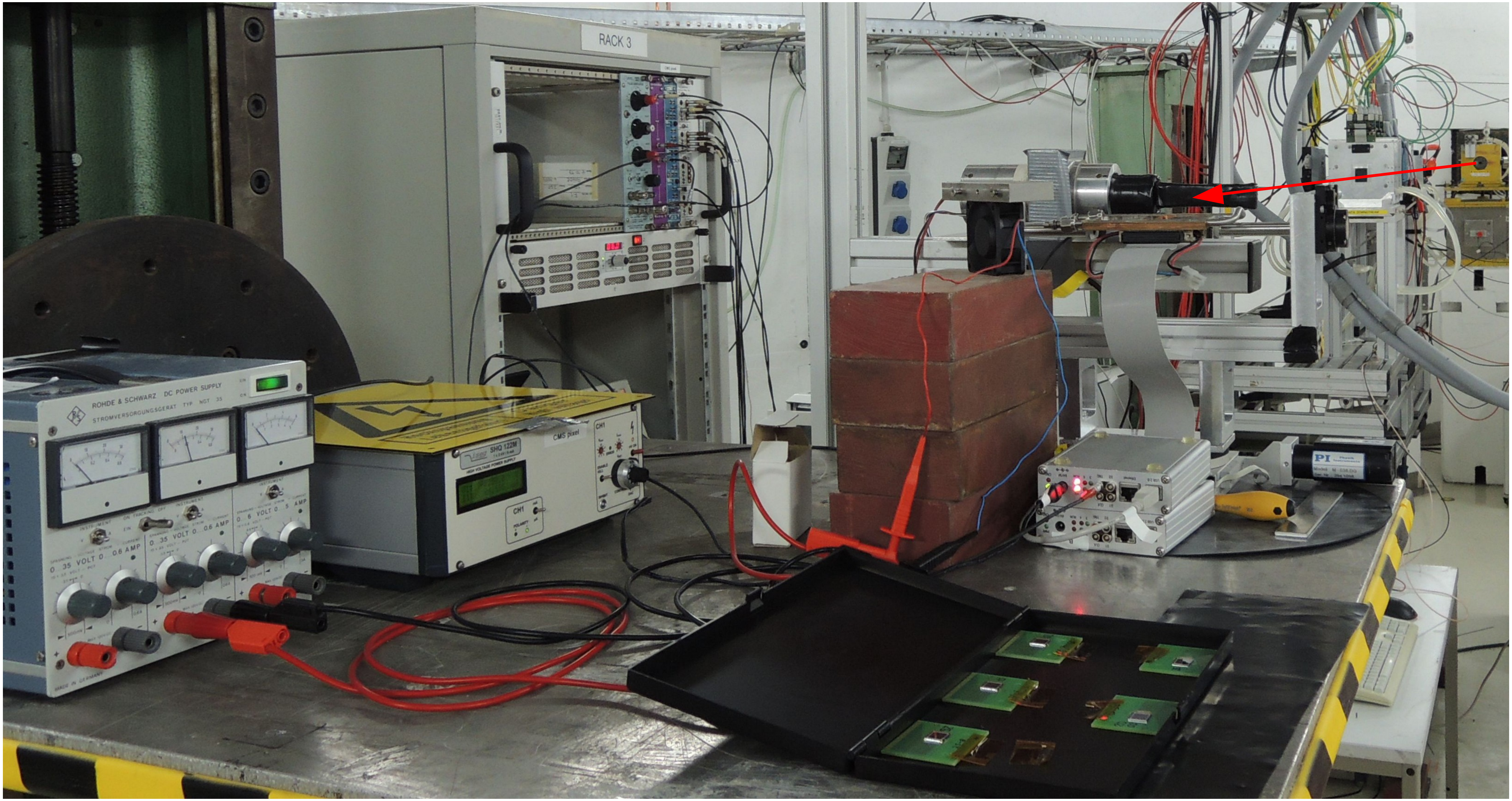


narrow pixel design



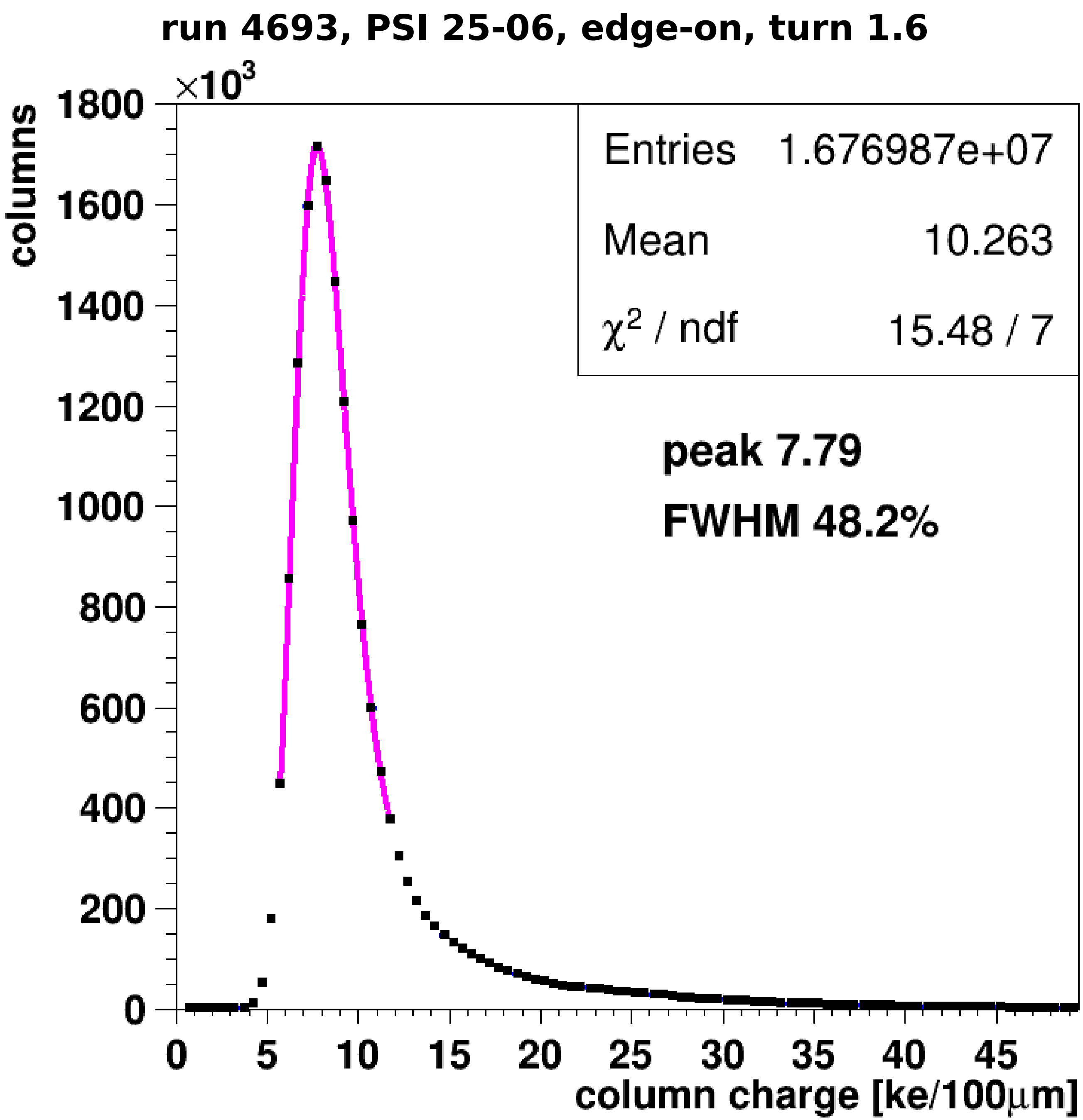
- 150×16.7 µm pixels
  - design by T. Rohe, PSI
  - with bias dots
  - mapped to 50×50 ROC4Sens
  - bump bond pad overlap induces cross talk

edge-on setup



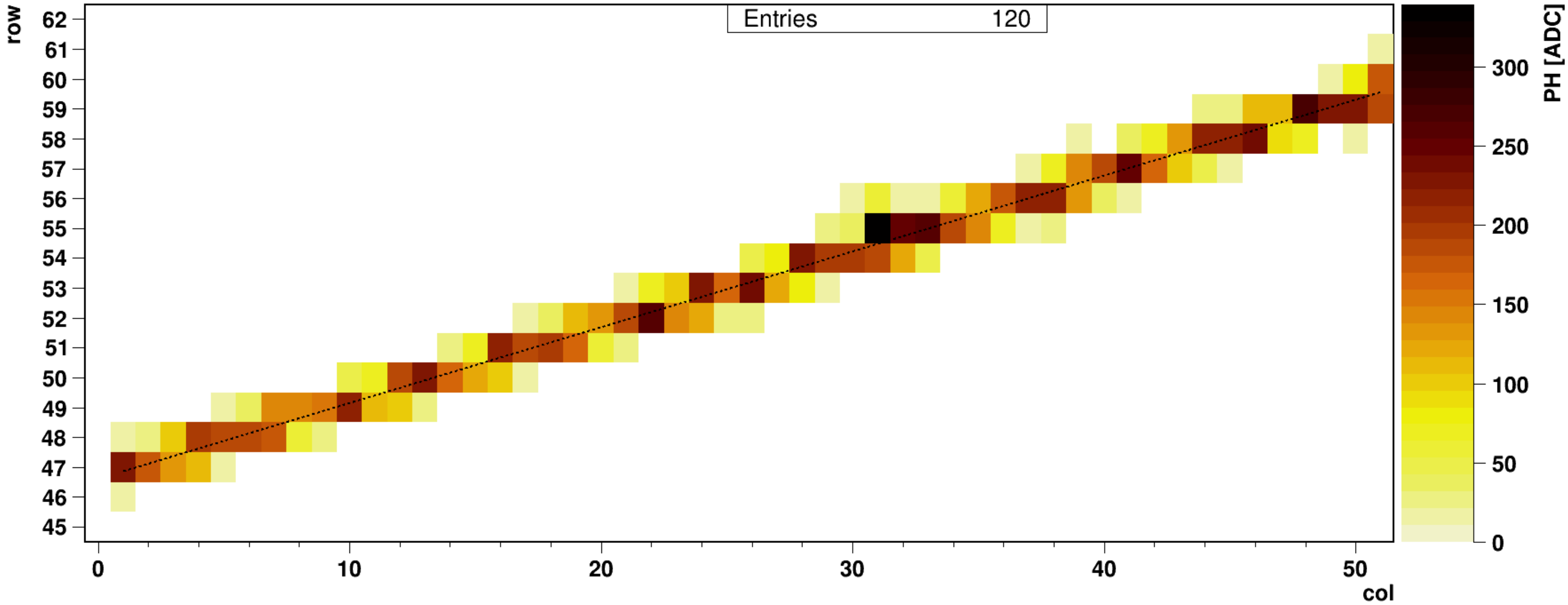
parasitic downstream setup in TB22, without telescope

edge-on charge distribution



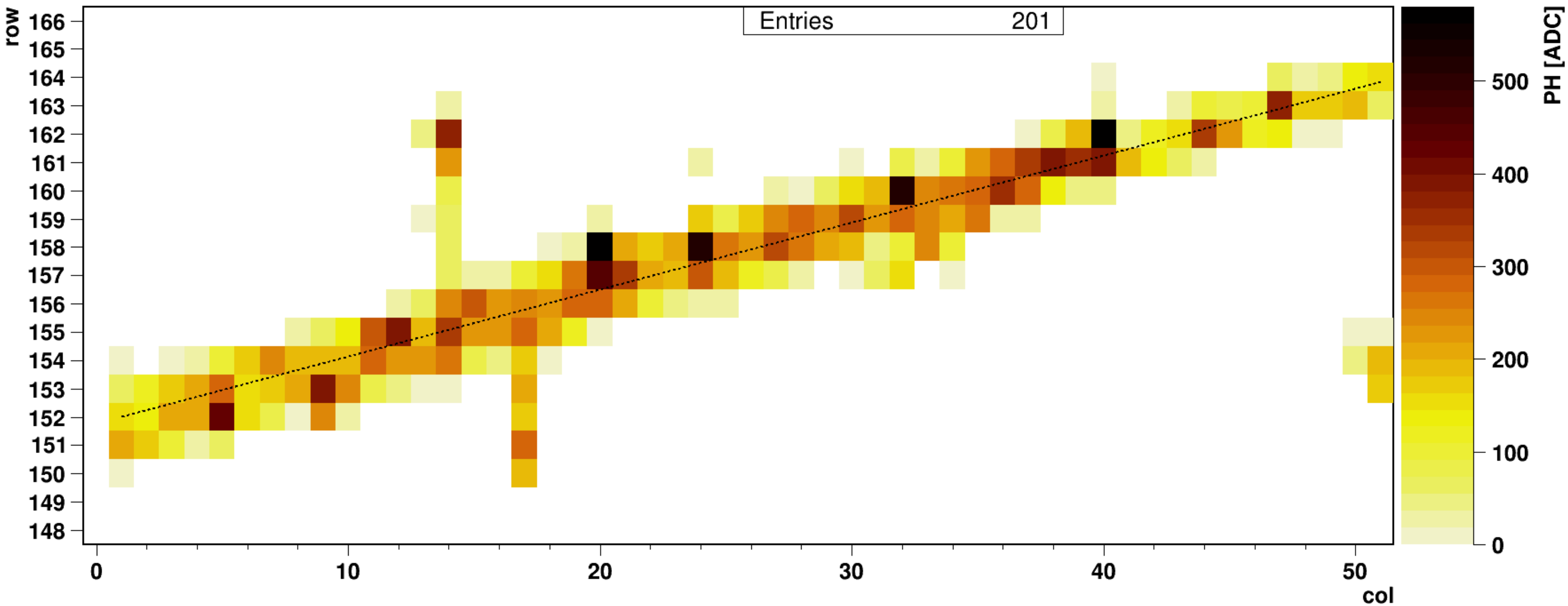
- **charge distribution**
  - **normalized to 100 μm**
- **tail = delta rays**

edge-on track



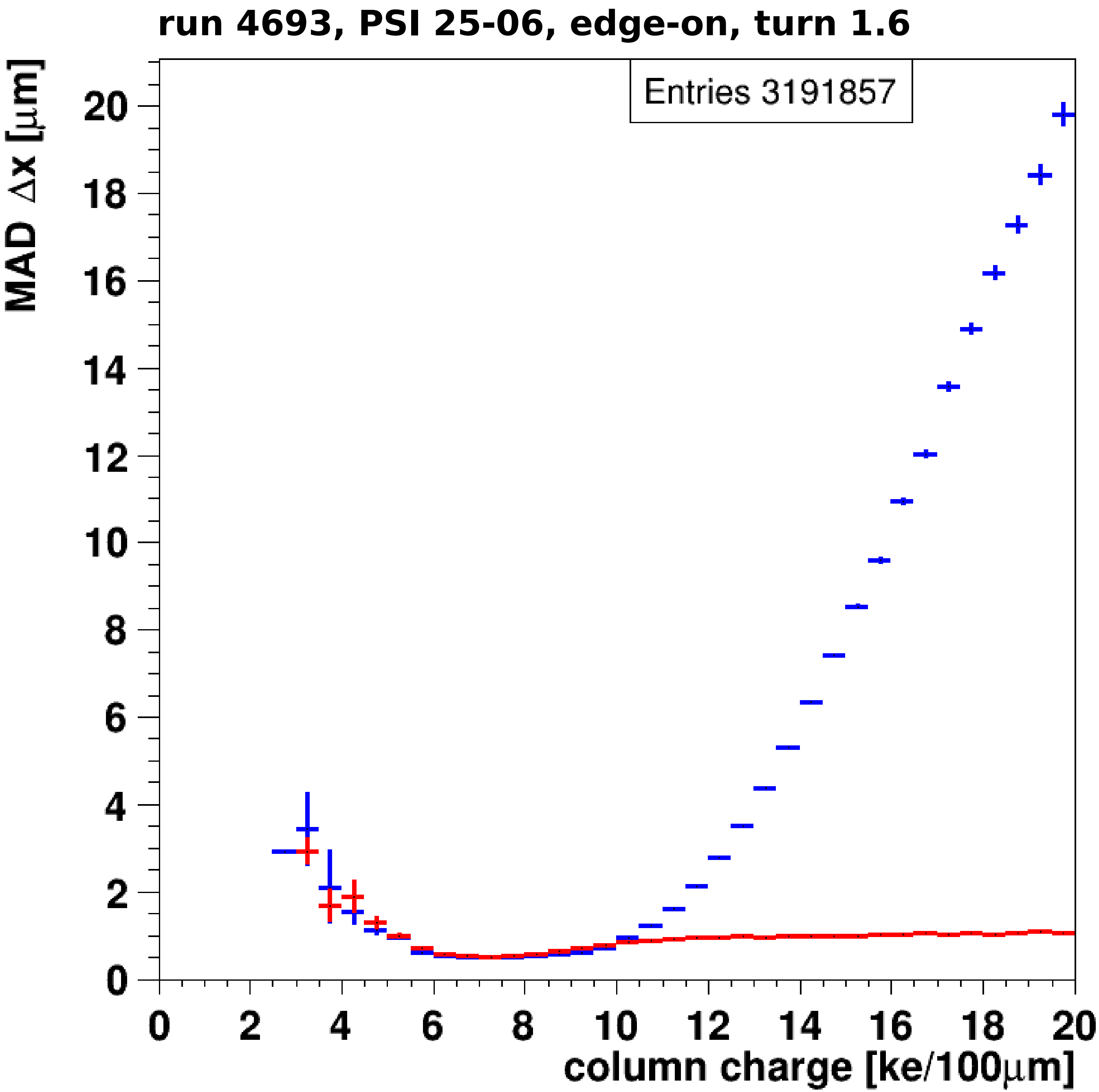
- 150×17 µm pixels
- turn angle 1.6°
  - track changes row every 4th pixel
  - ‘telescope-on-a-chip’

edge-on track



- most delta rays are emitted near 90°
  - omit columns with large charge
  - remaining pixel group has good resolution

position resolution



- **MAD = mean absolute deviation**
  - measures width of a distribution
- suppresion of delta rays stabilizes resolution

ROC4sens

0.25 µm
IBM
CMOS