CMS pixel resolution study in the DESY test beam telescope

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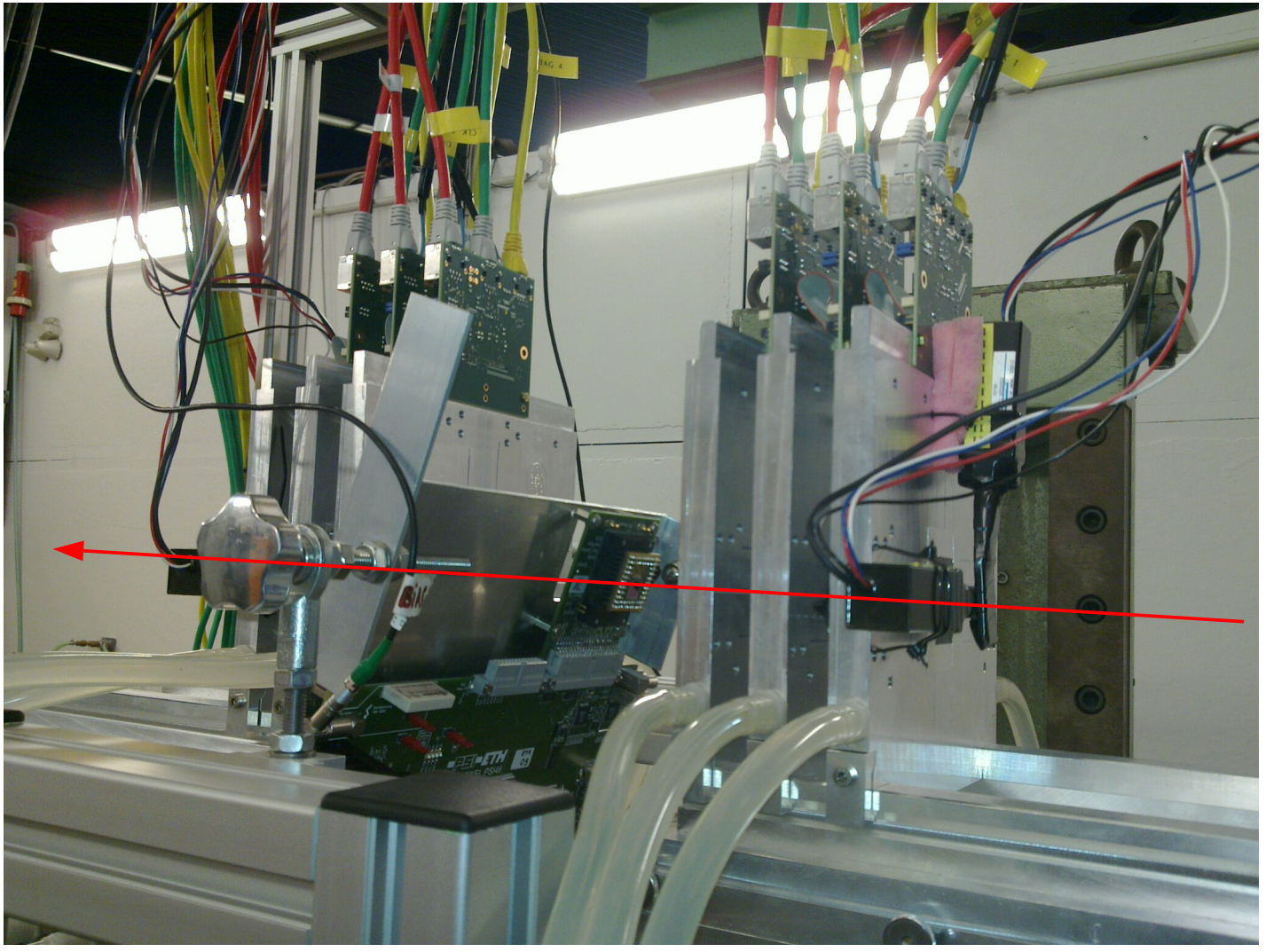
PSI visit, 25.1.2012

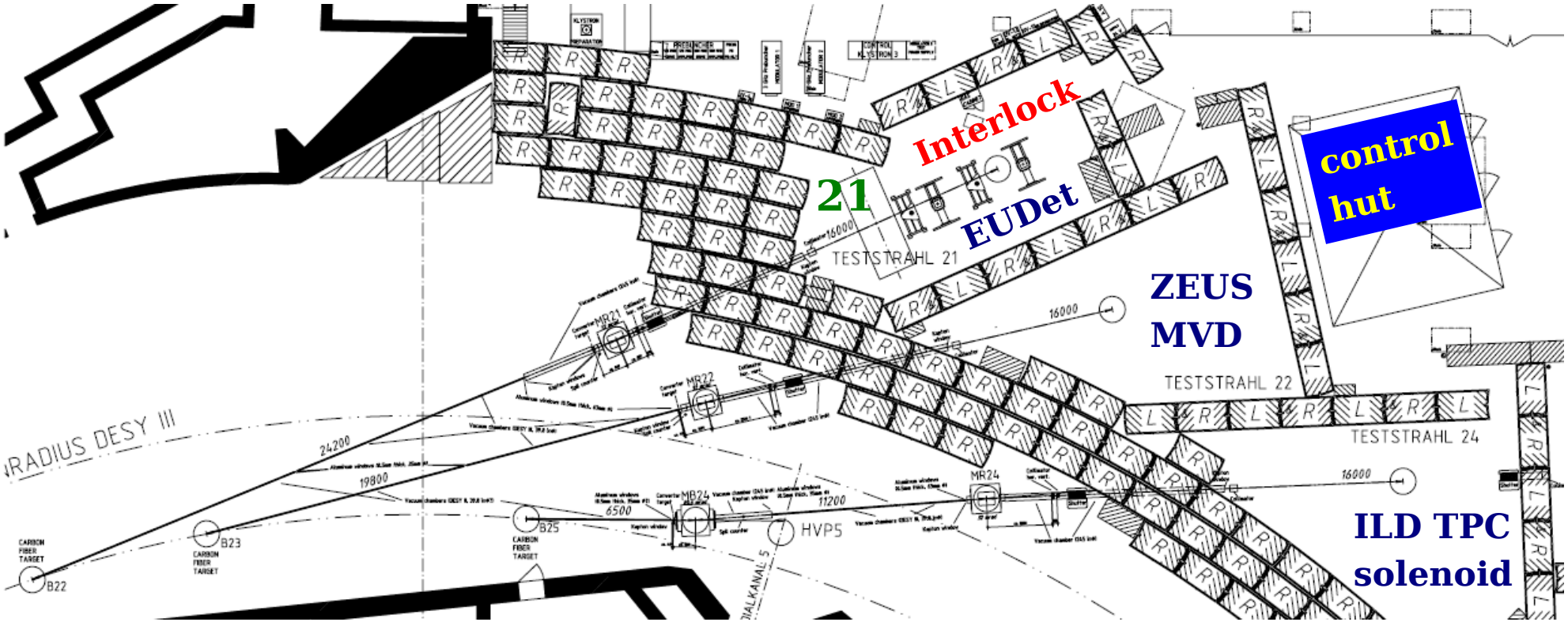


- DESY test beam
- scans
- tilted pixel
- charge sharing
- resolution

DESY II

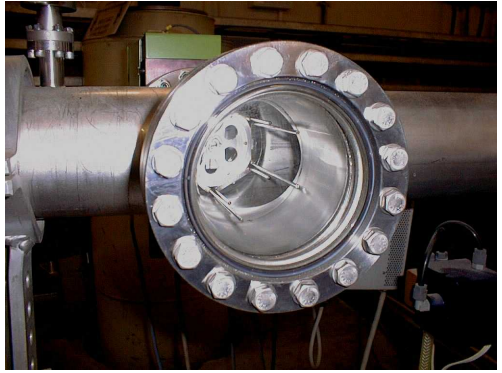

http://adweb.desy.de/~testbeam
24
DESY II
(positrons)
22
DESY III
(protons)
21

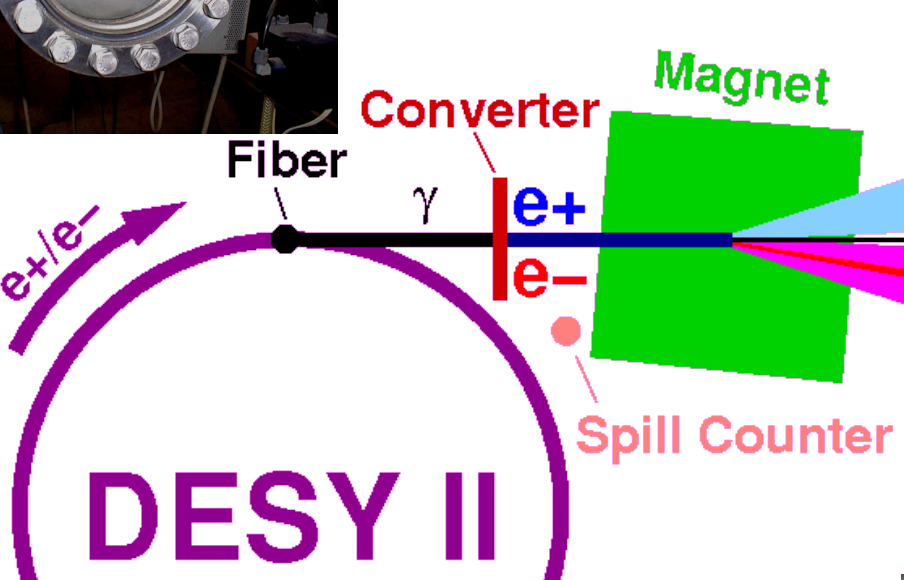
DESY II test beams

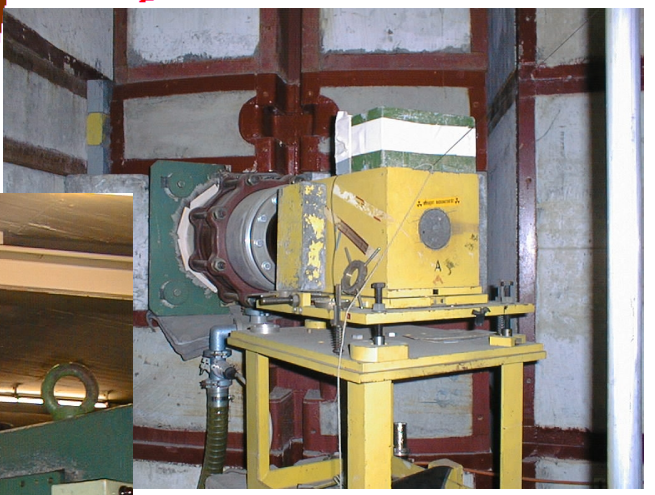


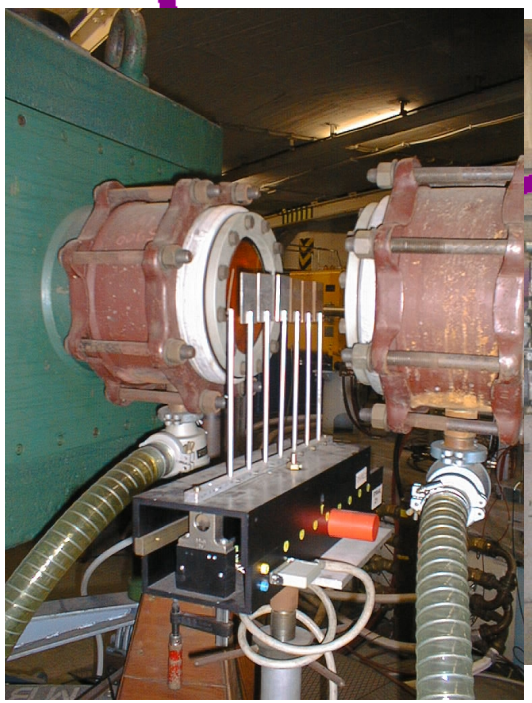
http://adweb.desy.de/~testbeam/

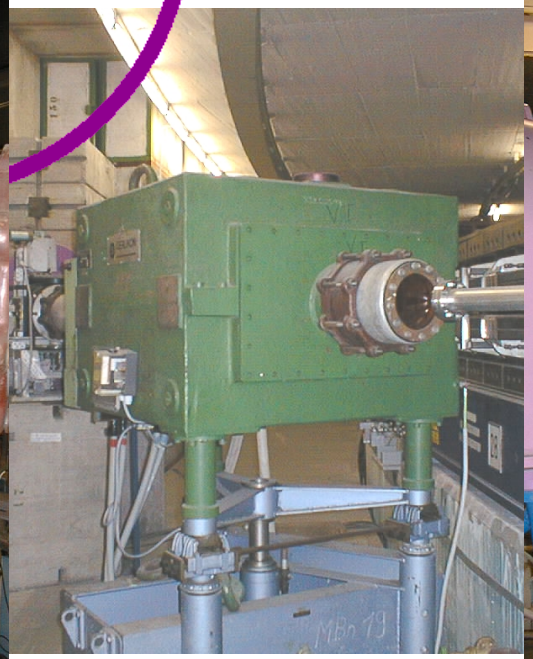
test beam extraction

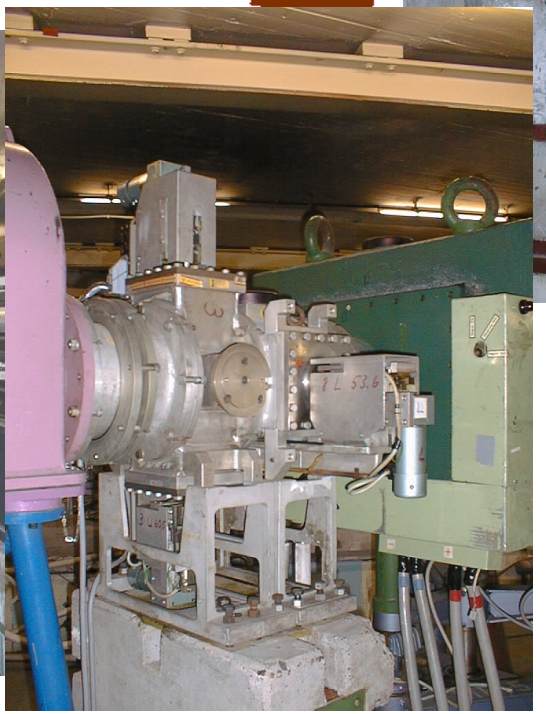




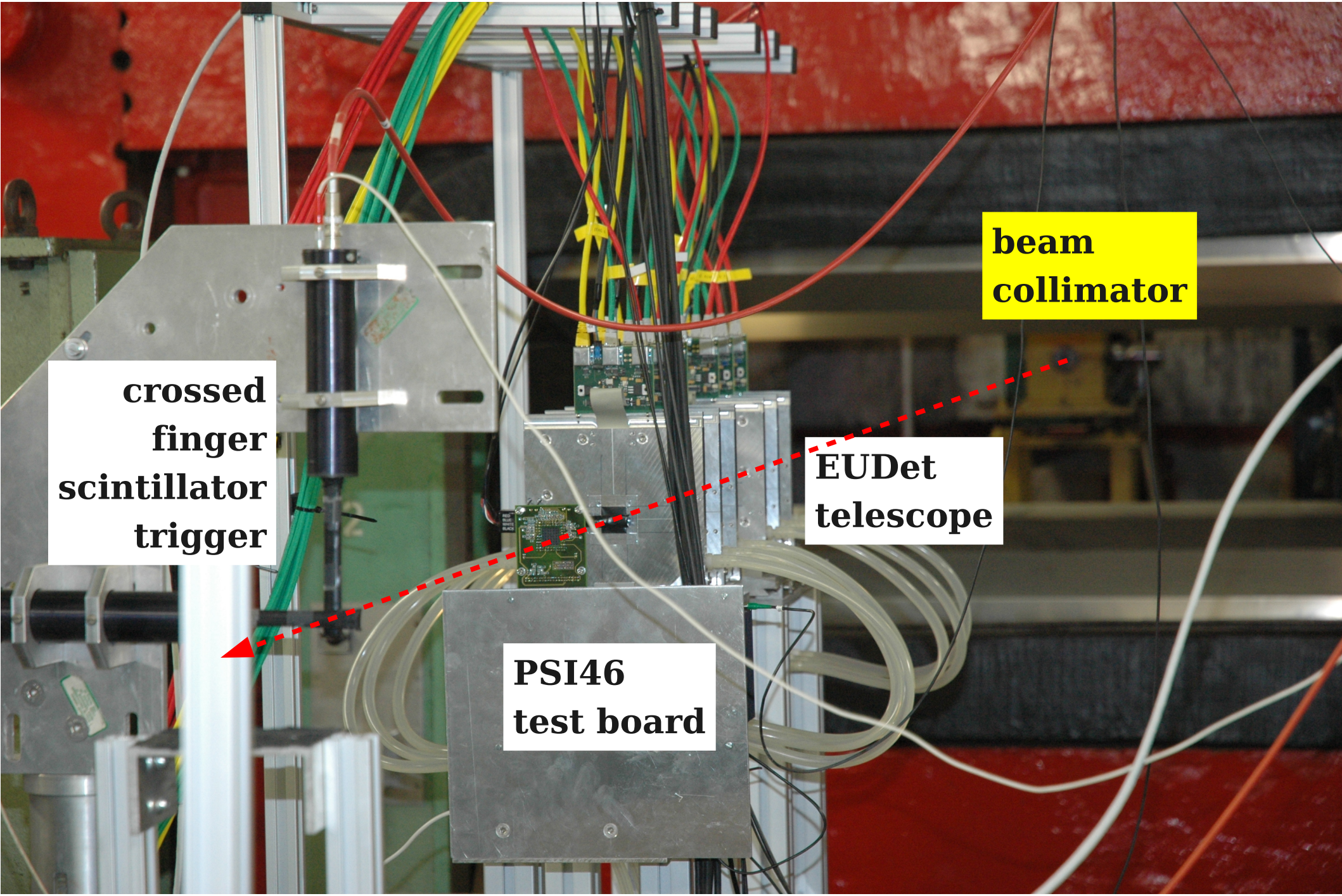




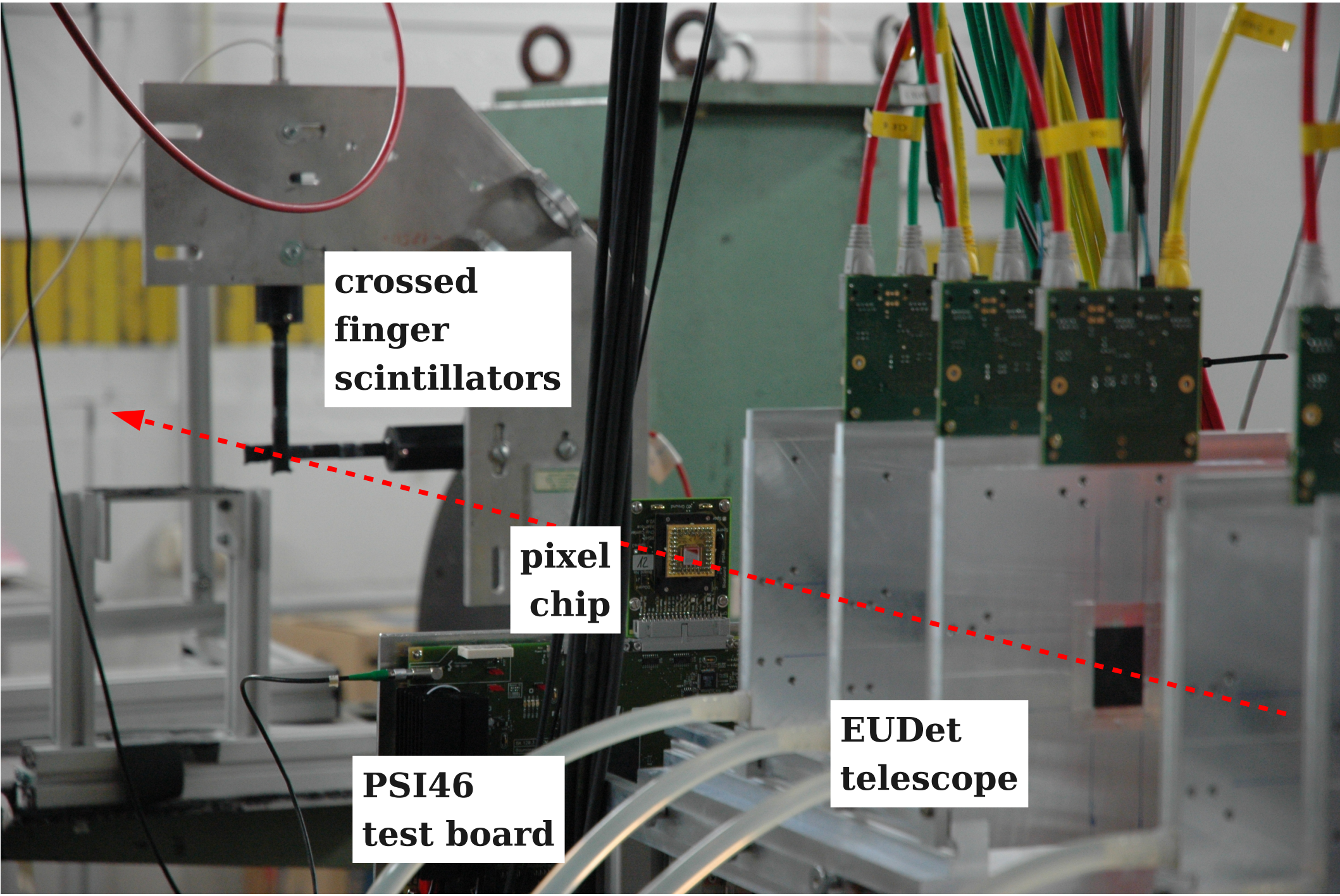




Beam test setup



Beam test setup

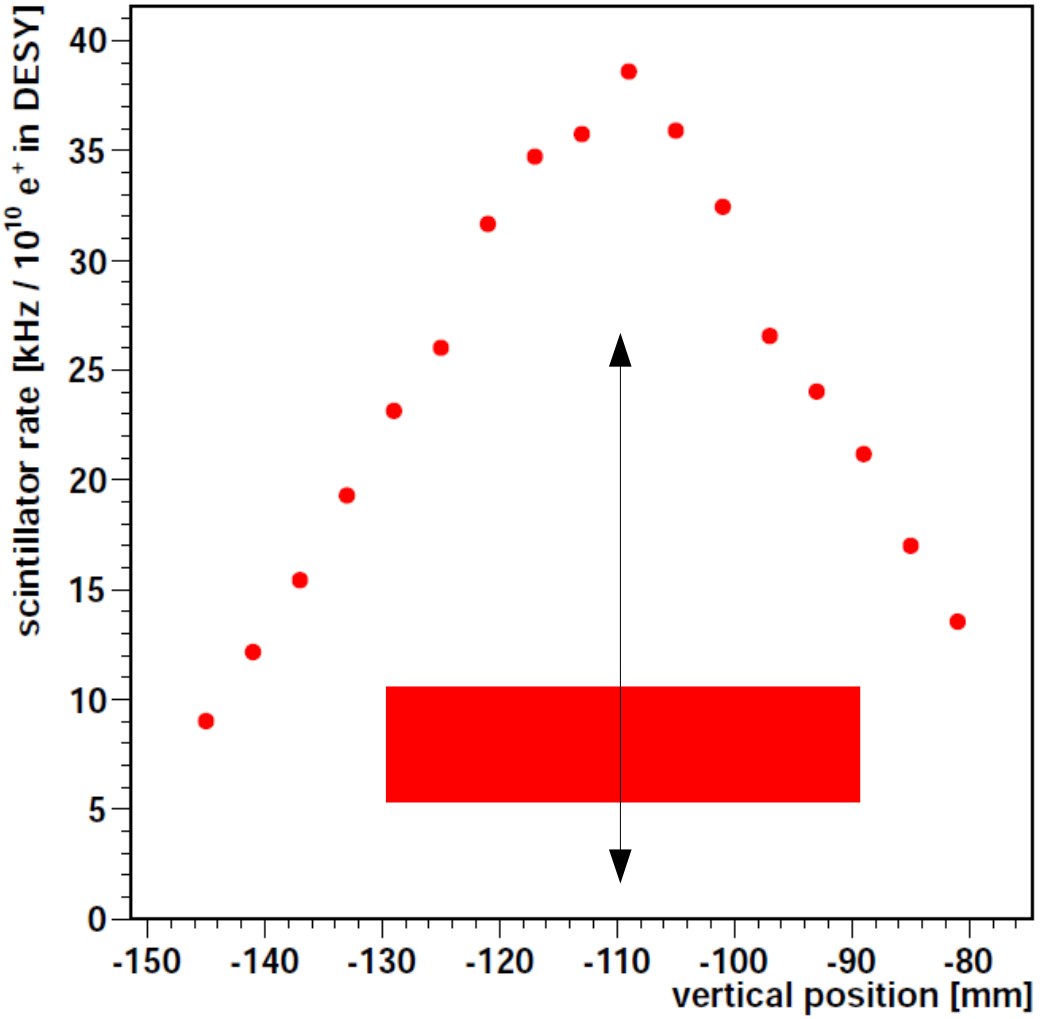


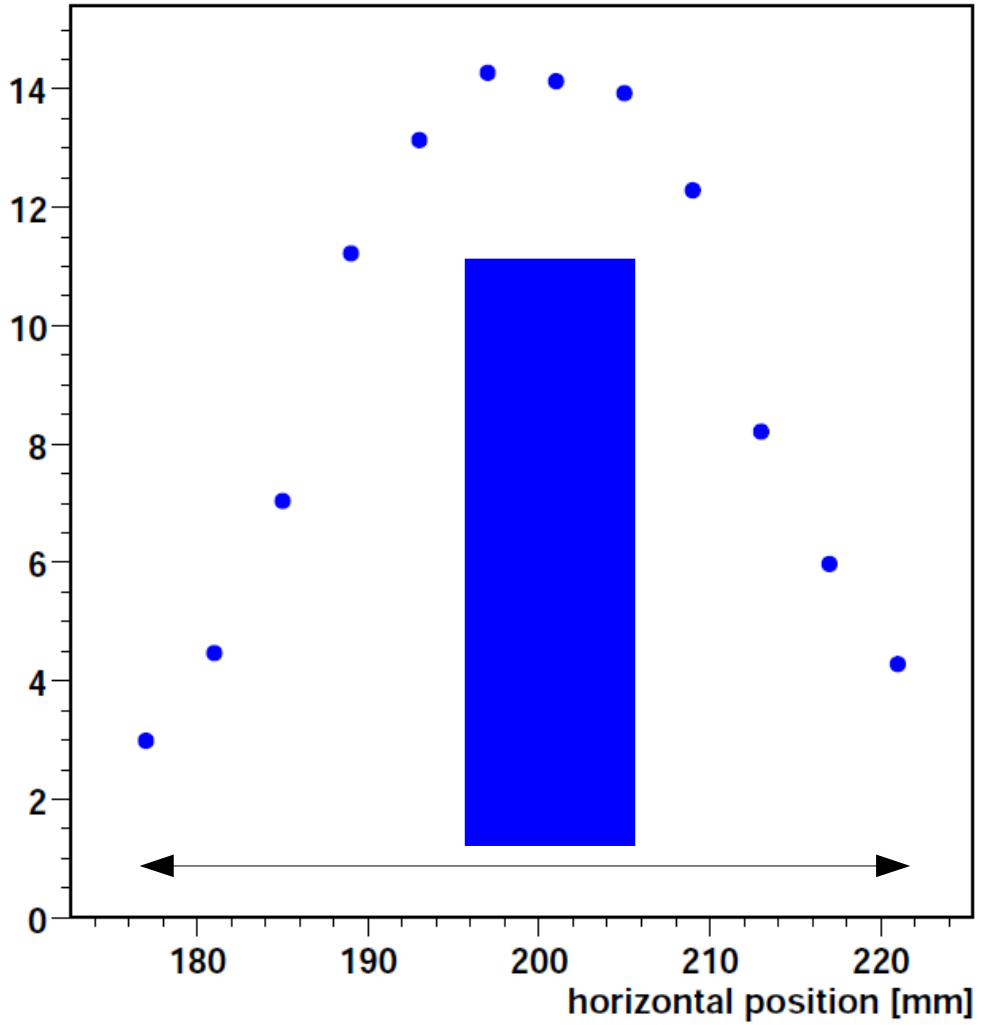
beam setup

- Crossed finger scintillators (~1 cm^2 overlap area) as trigger:
  - Mounted on movable support (x-y stage with step motors, remote)
  - CAEN HV supply (-1700 V) outside in the control hut.
  - NIM trigger logic inside interlock, and mirrored in the control hut.
  - HP trigger delay and level adapter (NIM → TTL) in control hut.
  - Up to 7 kHz scintillator coincidence rate (at 2 GeV e^+).
- PSI46 test board with single-chip sensor:
  - Mounted after EUDet telescope.
  - Keithley bias voltage supply outside in the control hut.
  - Board control and readout via USB from computer inside interlock.
  - LAN connection to a computer outside in the control hut.
- All worked well...

Scintillator position scan

Scintillators on movable support, remote control, ~0.2 mm precision

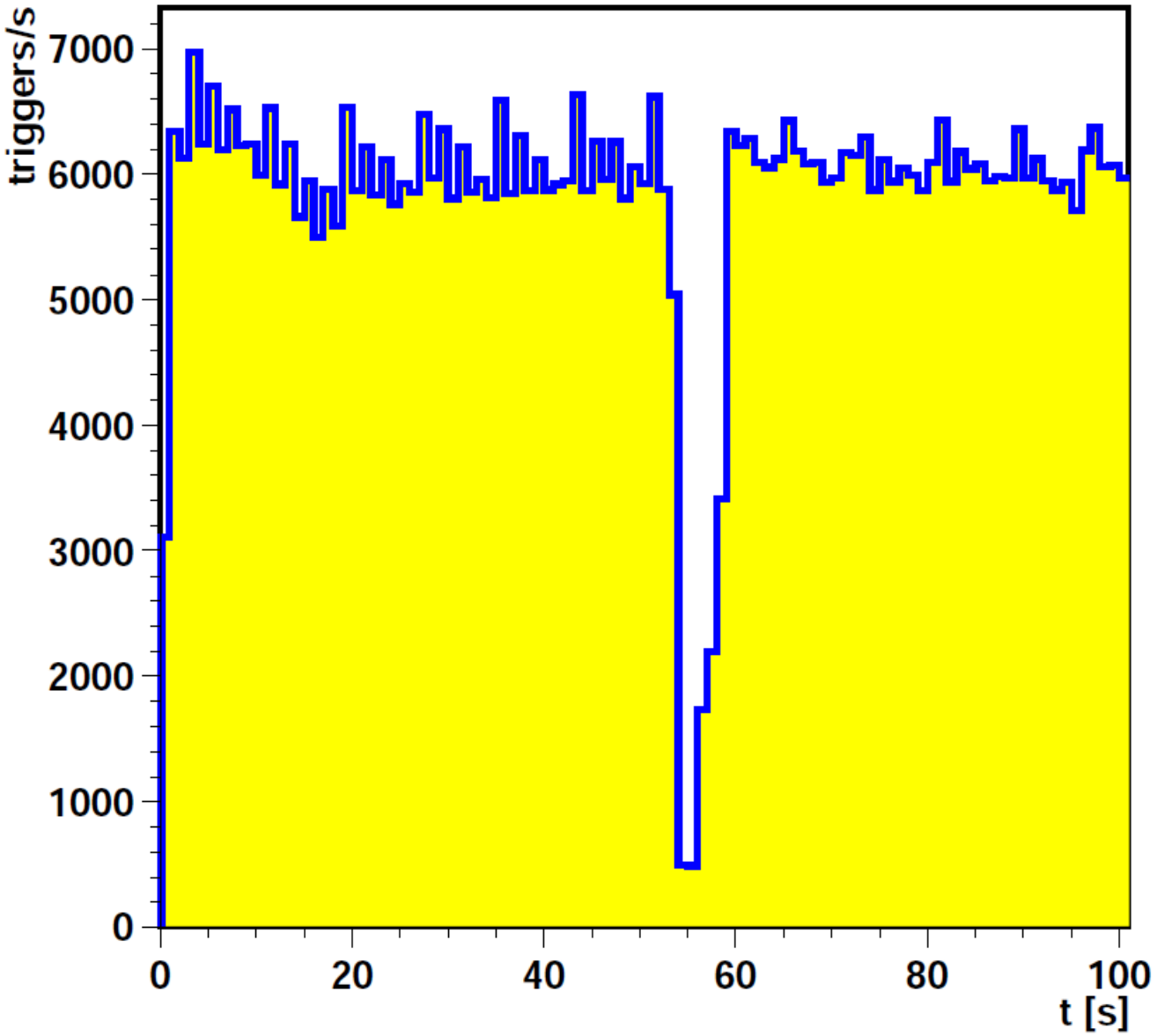




vertical FWHM ≈ 45 mm

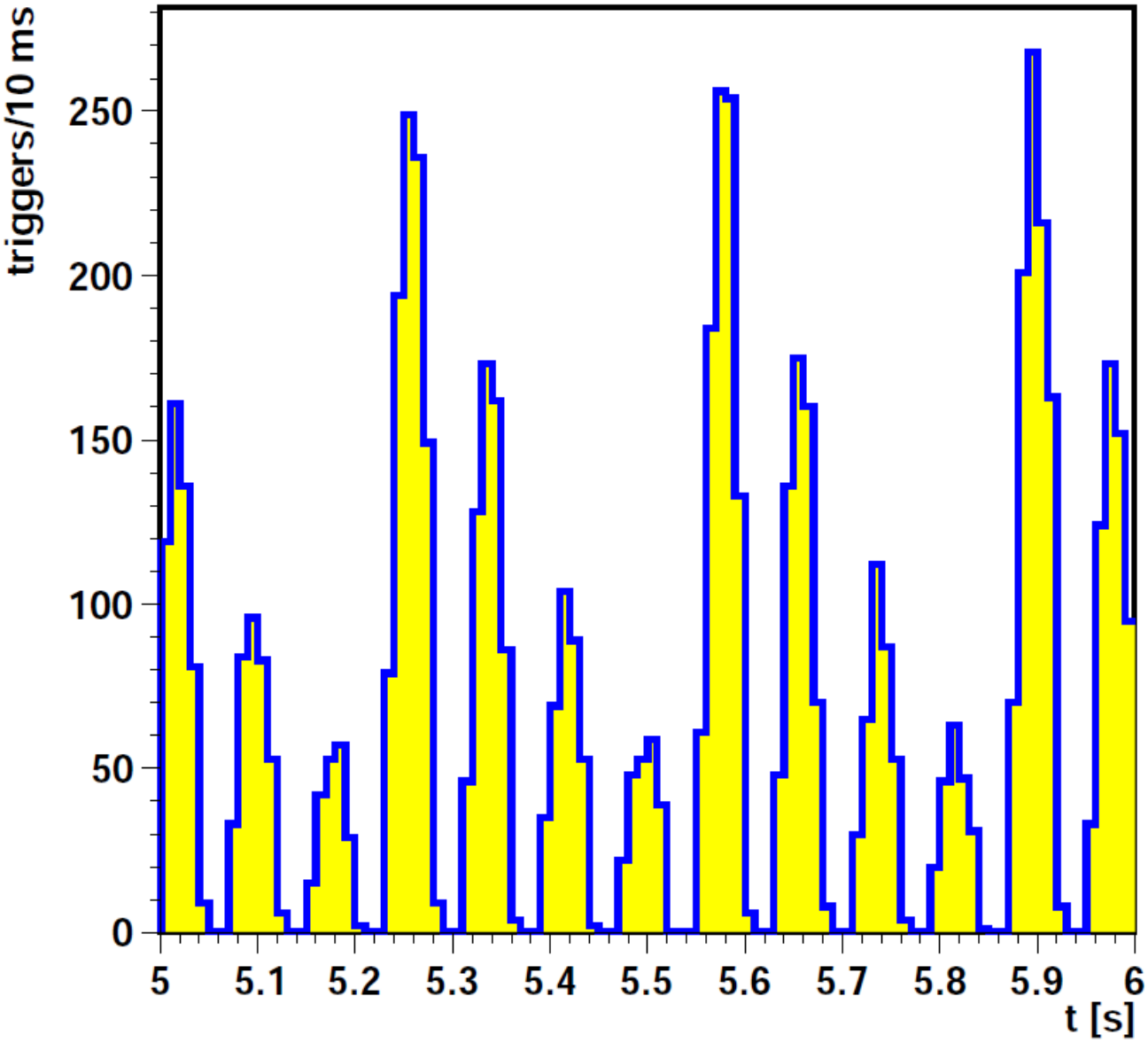
horizontal FWHM ≈ 30 mm

Data taking



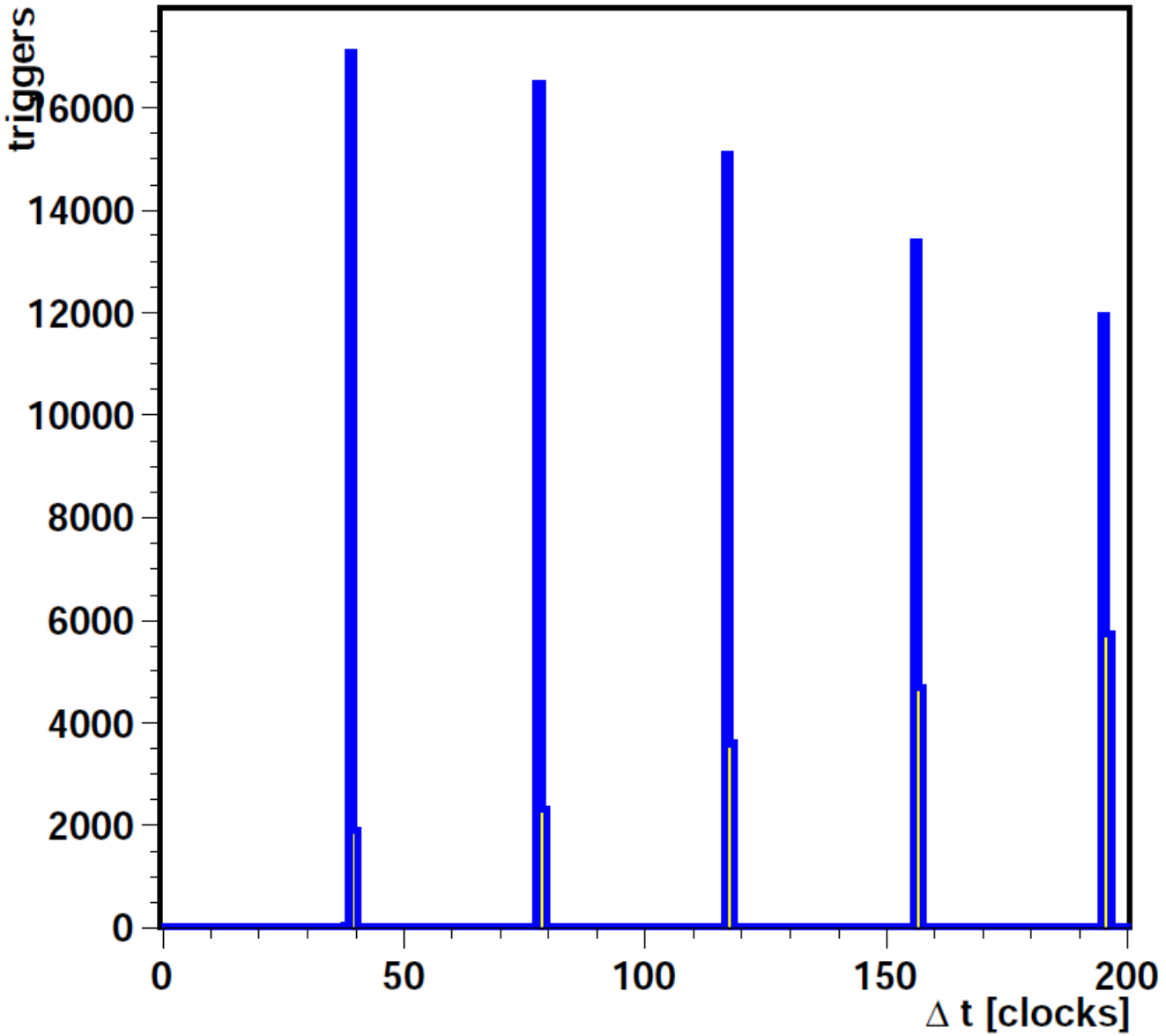
- FPGA provides a time stamp for each event by counting 40 MHz clock cycles.
- Typical scintillator coincidence trigger rate:
  - ~6.4 kHz.
- Dips:
  - DESY filling DORIS or PETRA.

DESY II time structure



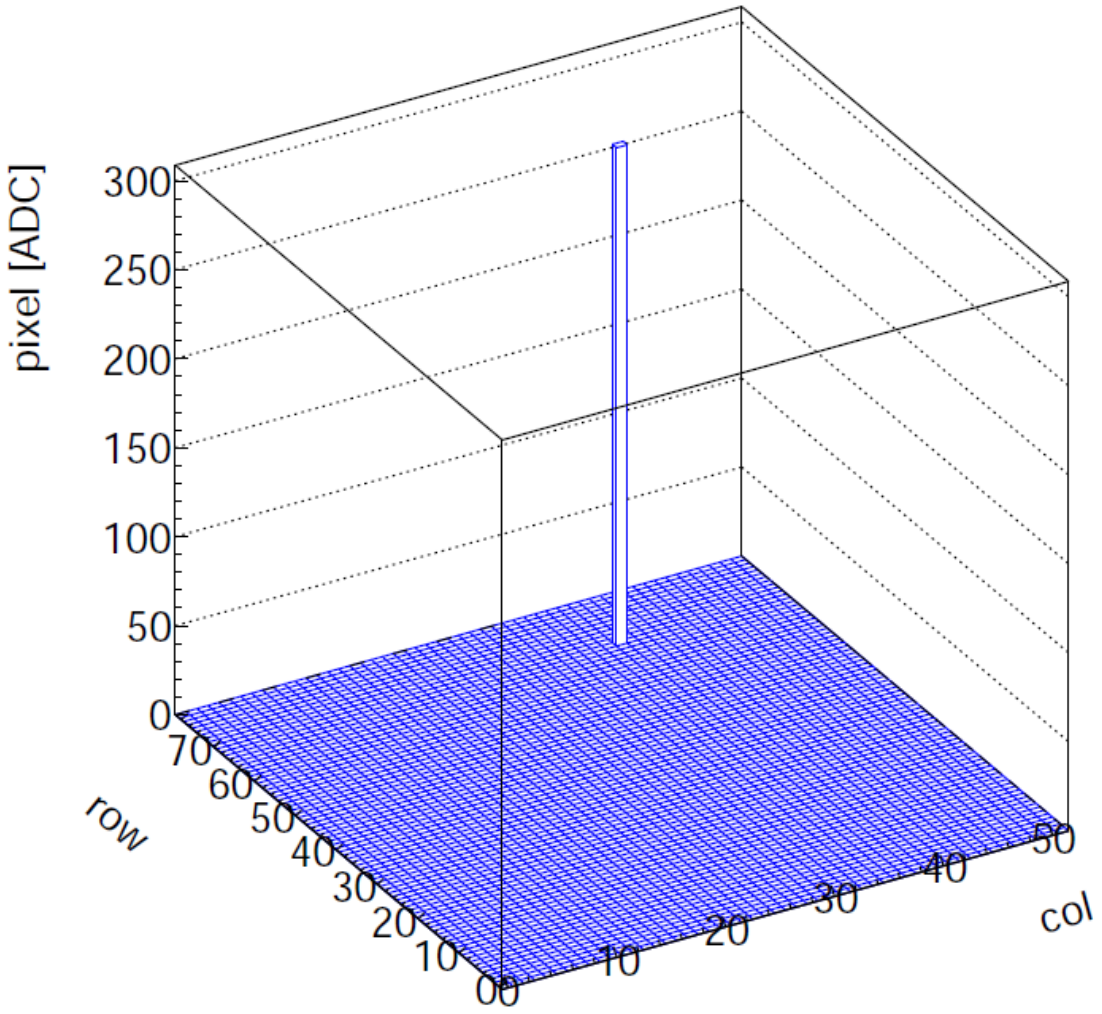
- DESY II has 80 ms cycle (12.5 Hz):
  - ramp down
  - fill one bunch from Linac II (e^-) or PIA (e^+).
  - ramp up
  - eject to DORIS or PETRA
  - or ramp down and dump
  - wire target is always in
  - test beam gets rate as long as DESY energy is above magnet setting.

one bunch in DESY II



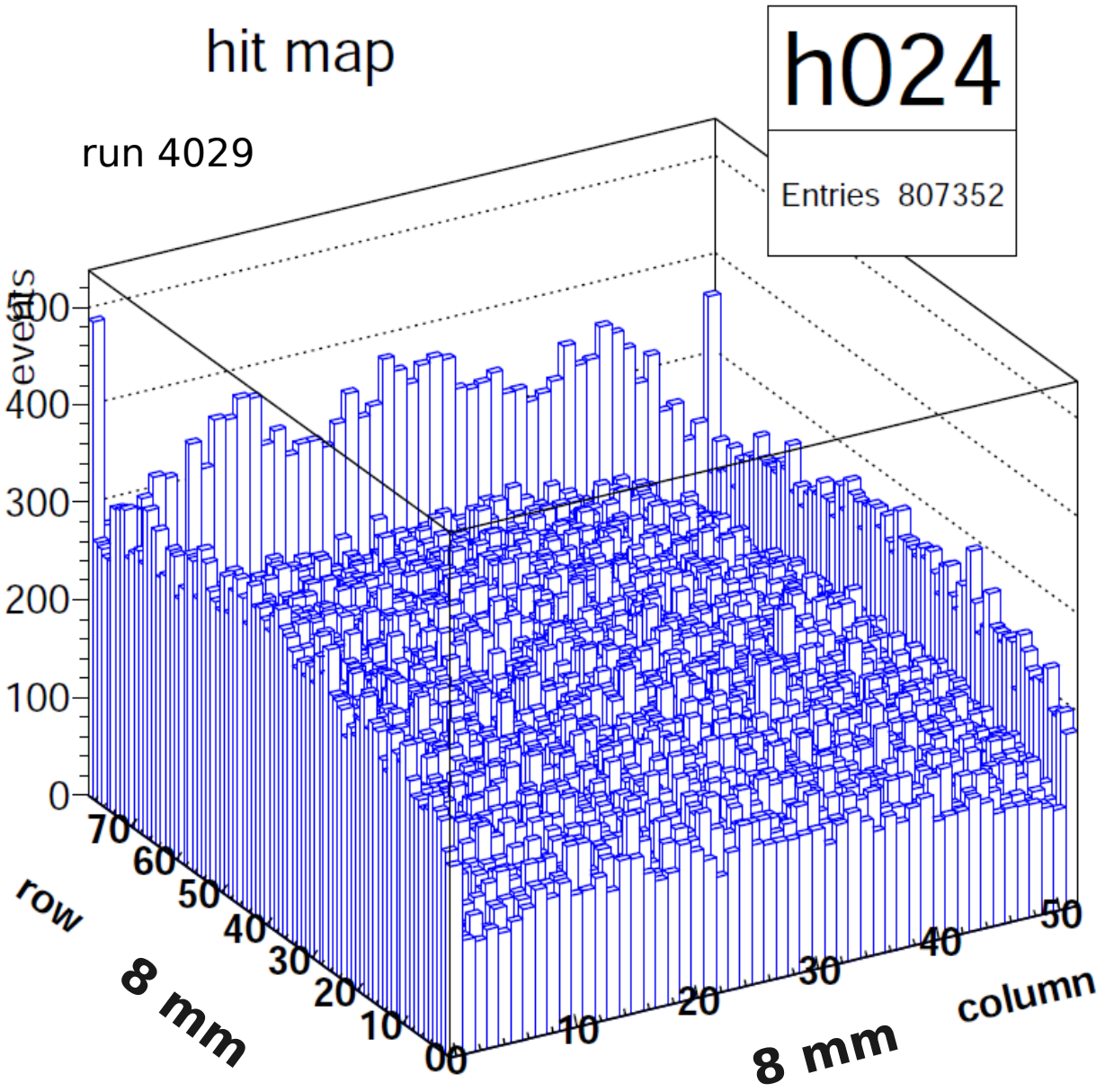
- FPGA counts 40 MHz clock cycles.
- DESY II circumference is 292.8 m
- DESY II has one bunch:
  - repeats every 0.977 µs (1.024 MHz)
  - 1 turn = 39.067 clocks.
- Problem:
  - FPGA clock was not synchronized to DESY
  - Phase of beam to clock was not fixed.

Single event display



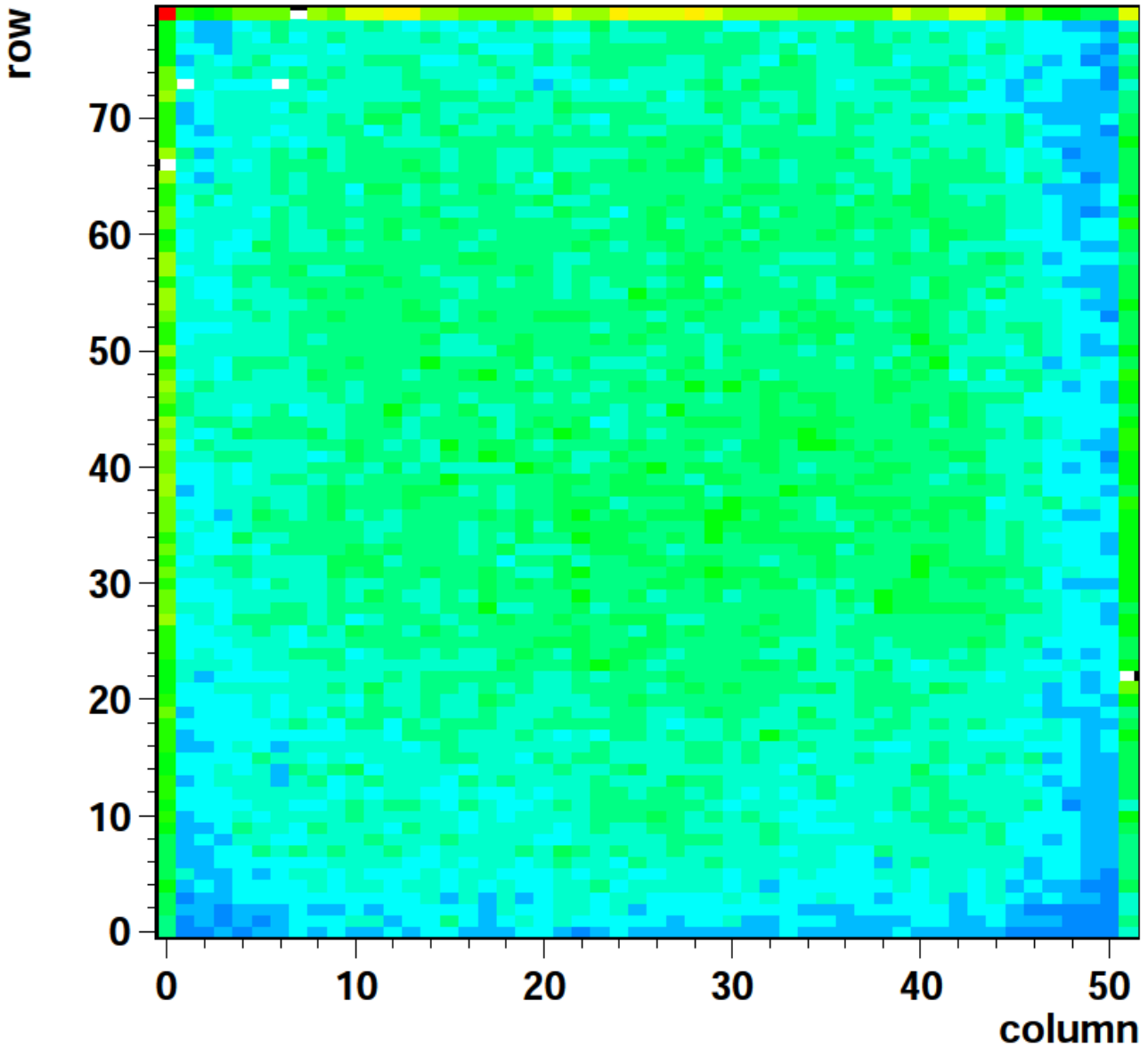
- Sample event:
  - 2 GeV tertiary e^+ beam
  - Scintillator trigger
  - Pixel chip 8
  - -90 V bias
  - optimal clock cycle

Pixel hit map



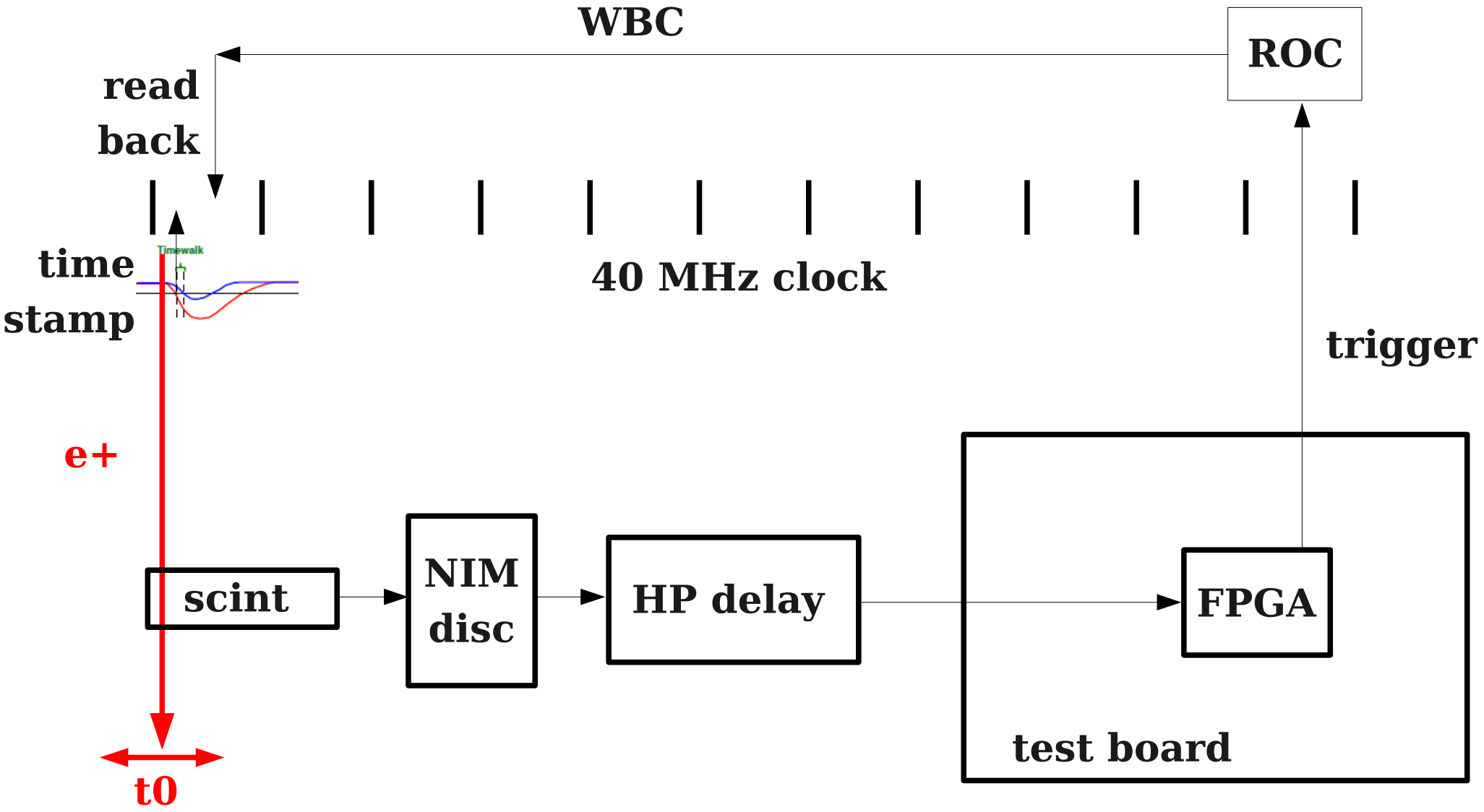
- 2 GeV e^+ beam.
- After space and time alignment:
  - 4 kHz coincidence rate
  - Fill test board memory: 60MB in 3.5 min.
  - USB transfer takes another ~2 min.
- One chip fully illuminated.
- Border pixels have double size and rate
- Corner pixels have quadruple size and rate

Pixel hit map



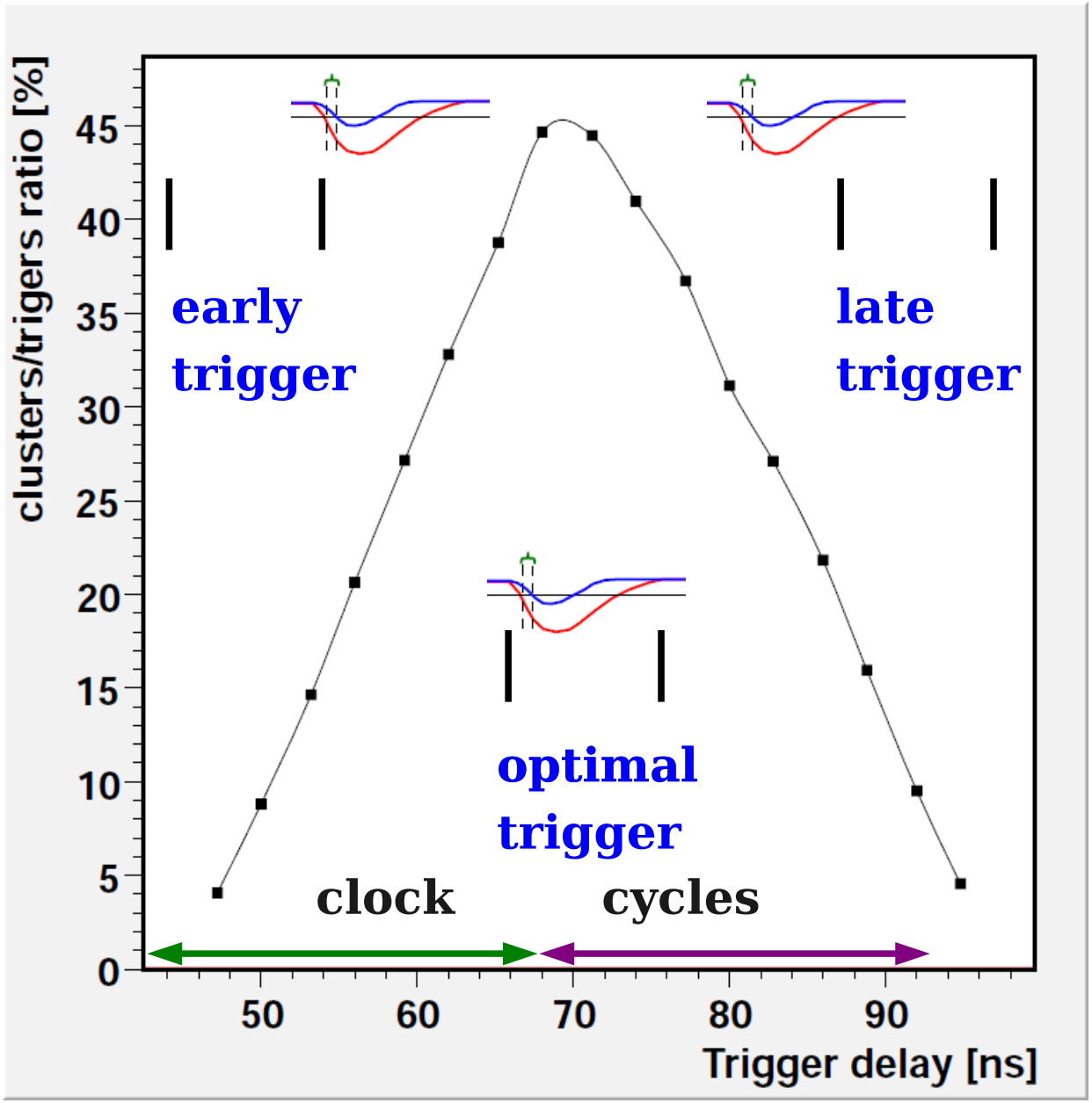
- the same run
- a few dead pixels
- non-uniformity:
  - beam profile,
  - misalignment between sensor and scintillator,
  - limited trigger region (~1 cm^2) just enough to cover 0.8×0.8 cm^2 chip.

Timing



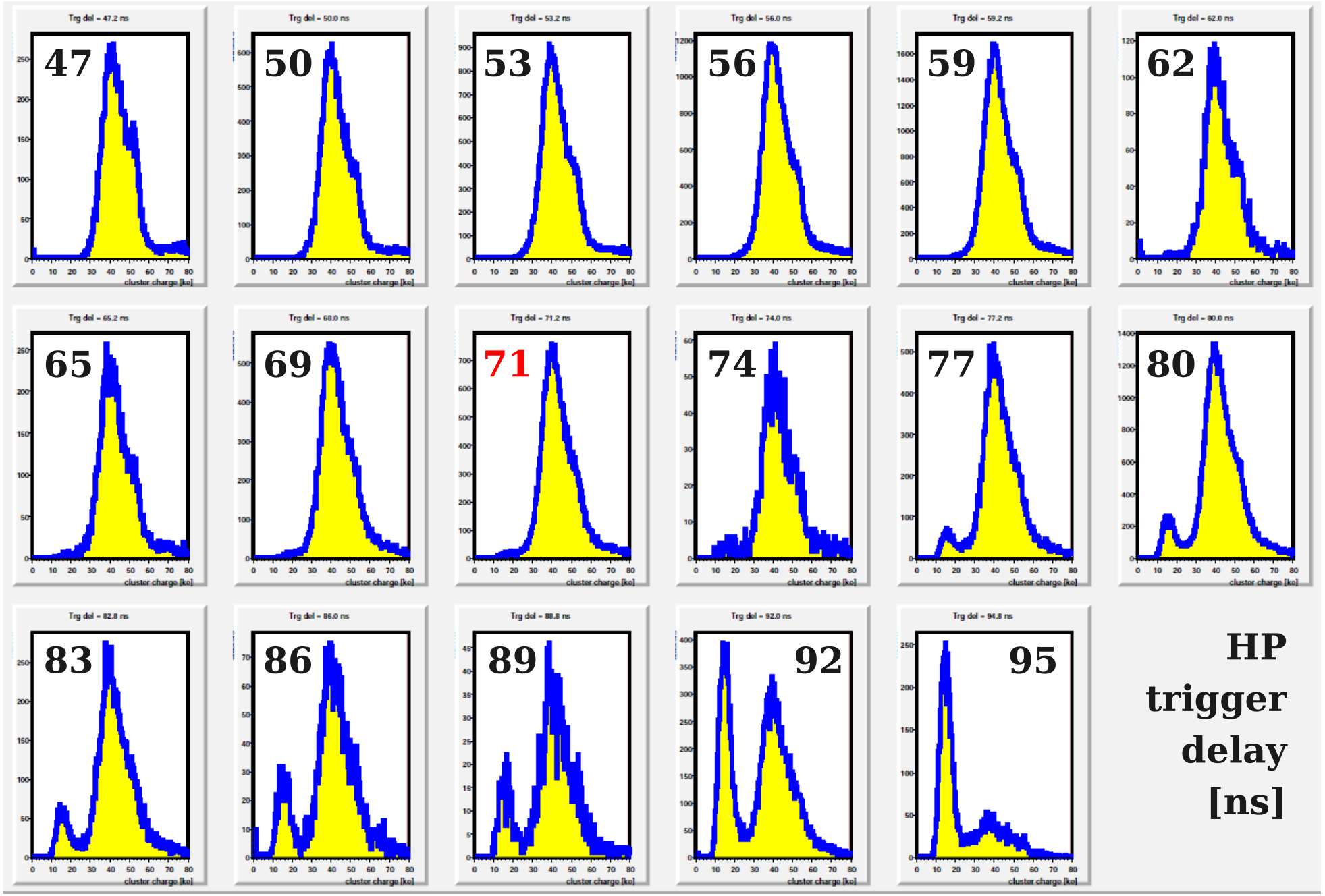
beam not synchronized to clock

Trigger fine delay scan

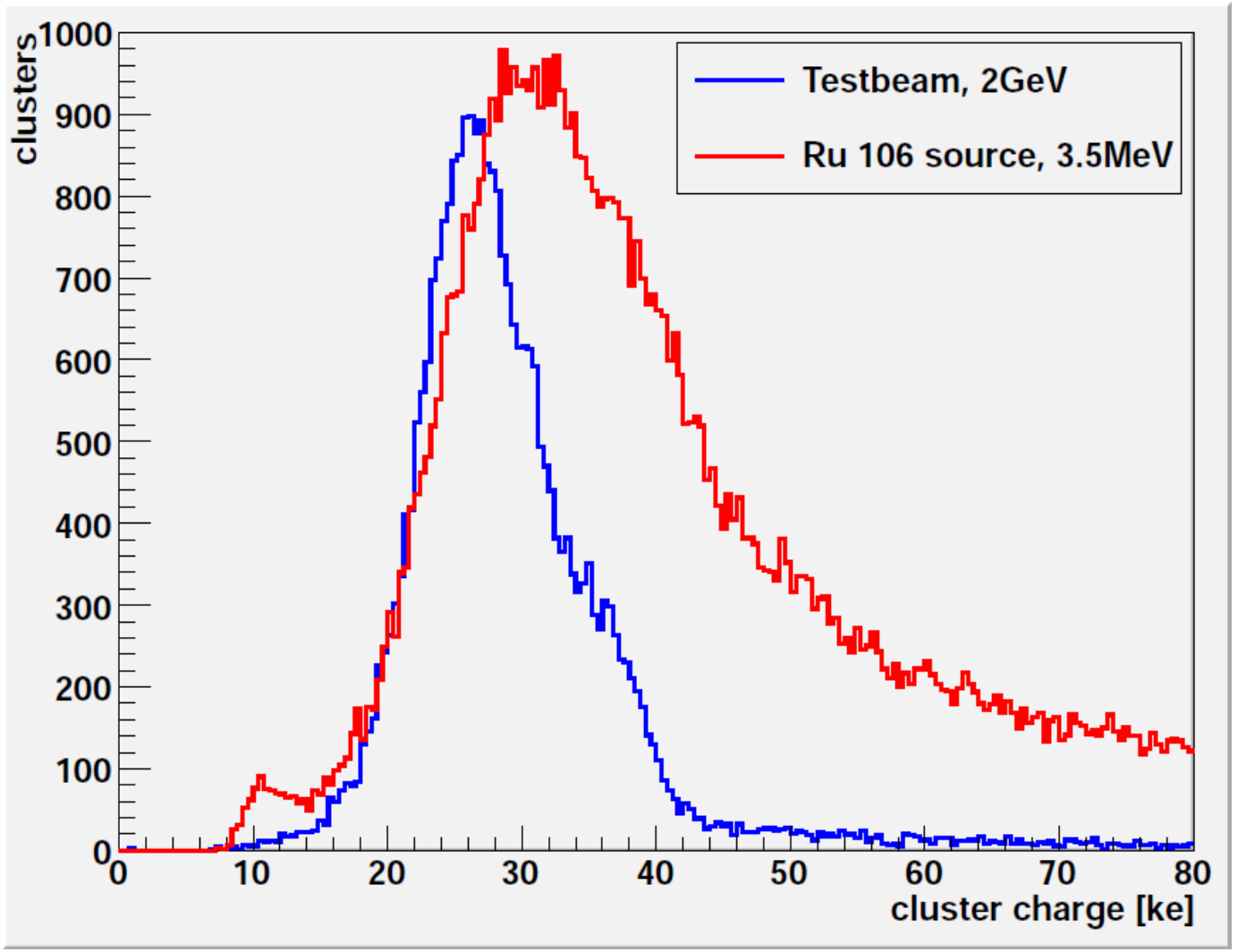


- DESY test beam:
  - 2 GeV e+
  - Scintillator trigger
- delay scintillator trigger going to the PSI46test board
- 25 ns clock cycle
- Triangular efficiency curve:
  - flat arrival time distribution (clock not synchronized to beam)
- Chose 70 ns as working point.

Trigger delay scan: pulse height spectrum

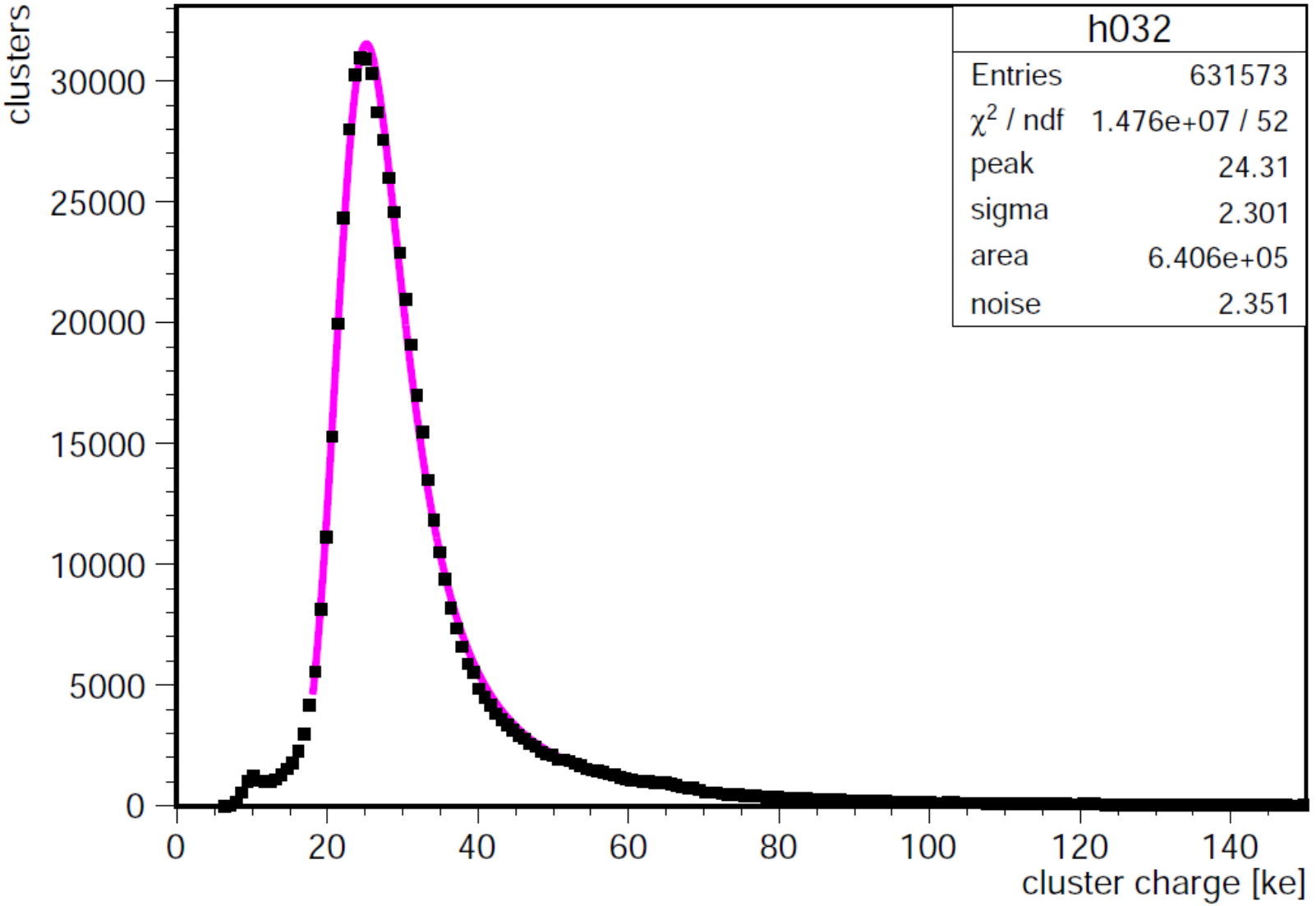


Cluster charge: Ru source vs beam



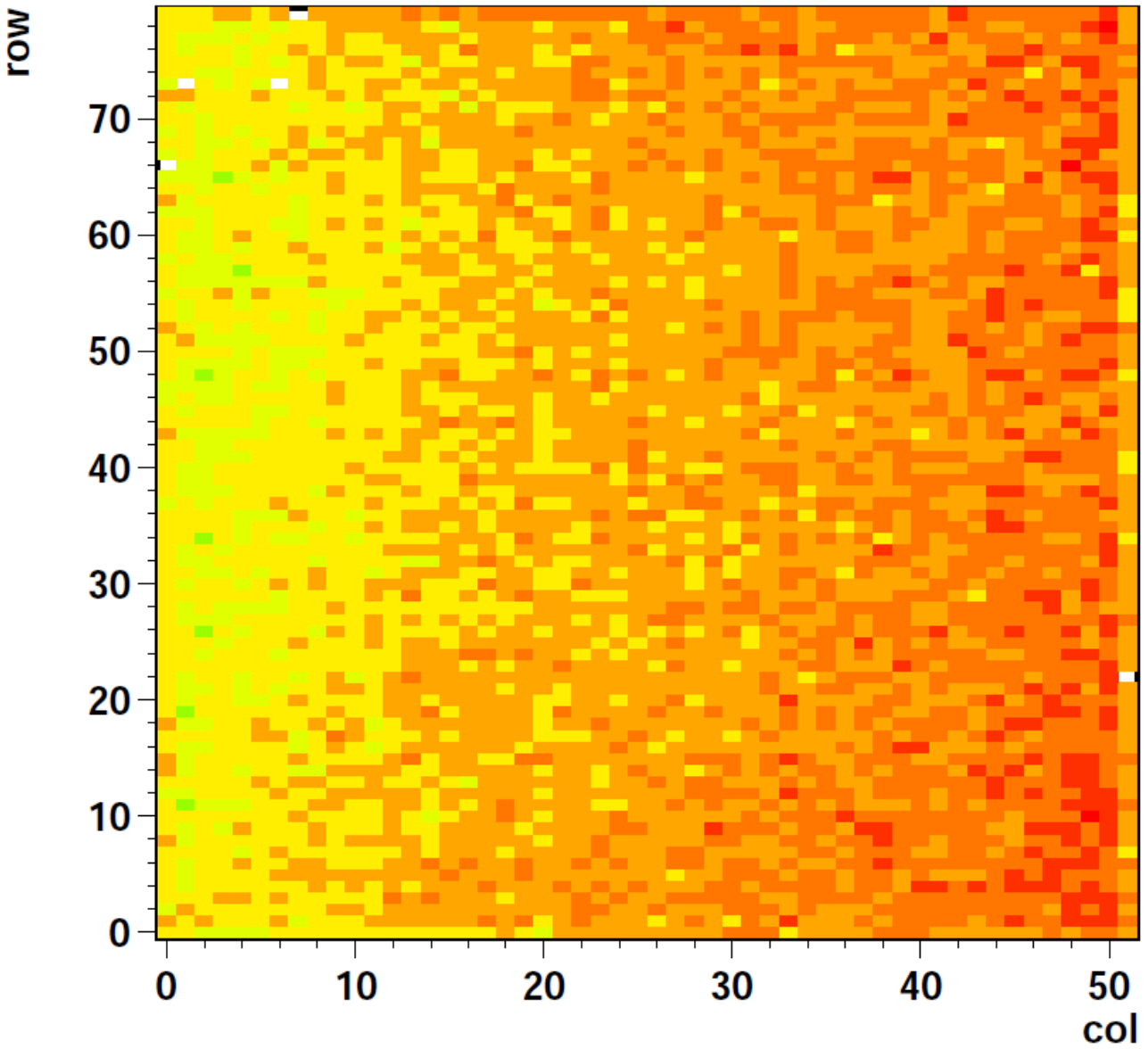
- Chip 8, -90V bias, Vthr 100
- 2 GeV e+ test beam:
  - Minimum ionizing particles
- Ru 106 source:
  - long tail of stronger ionizing electrons (not fully relativistic).

Pixel detector in DESY test beam



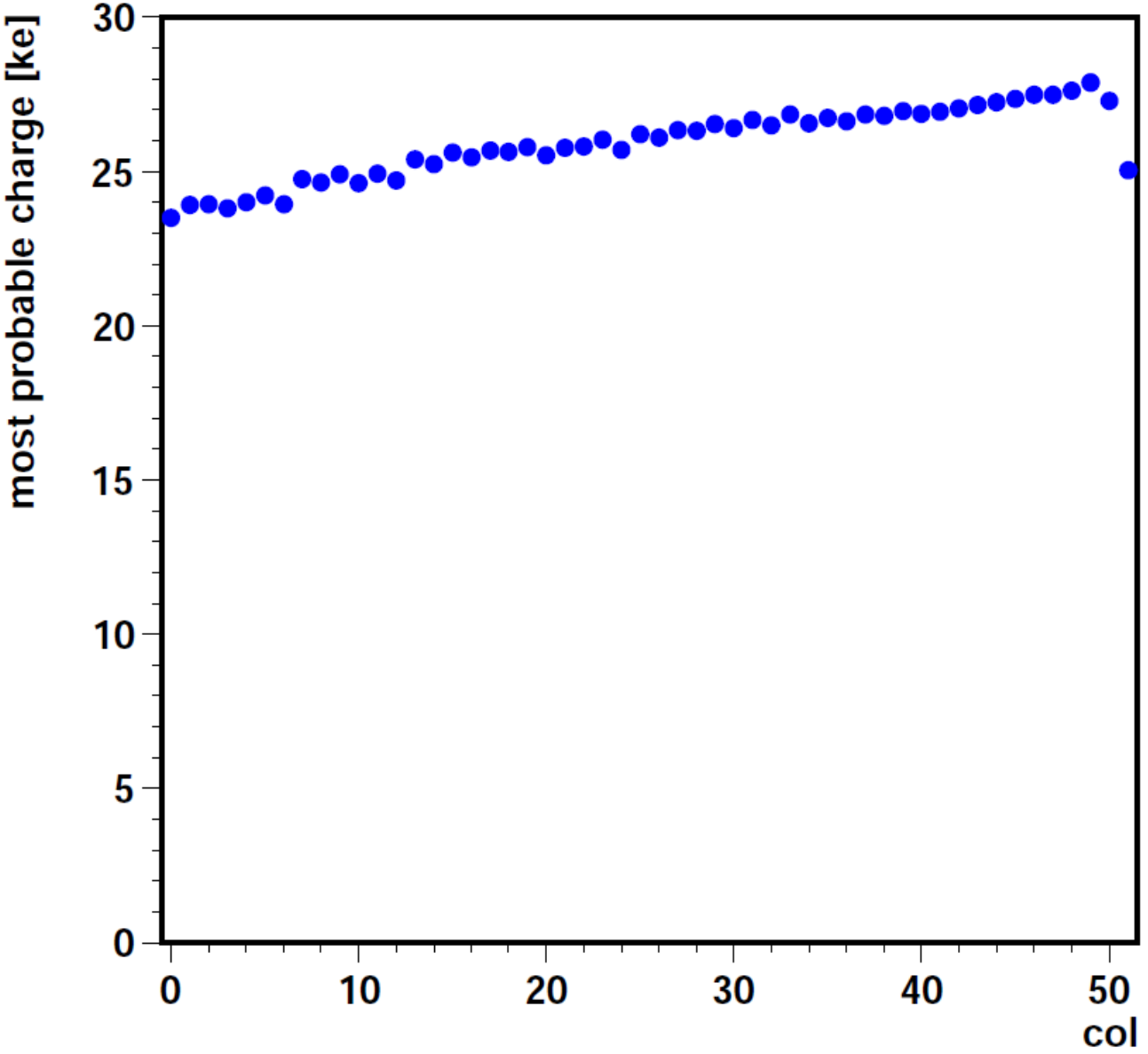
- 2 GeV e^+ beam.
- Landau ⊗ Gauss:
  - Peak position and width OK for 285 um silicon,
  - Folded noise too large.

Cluster charge map



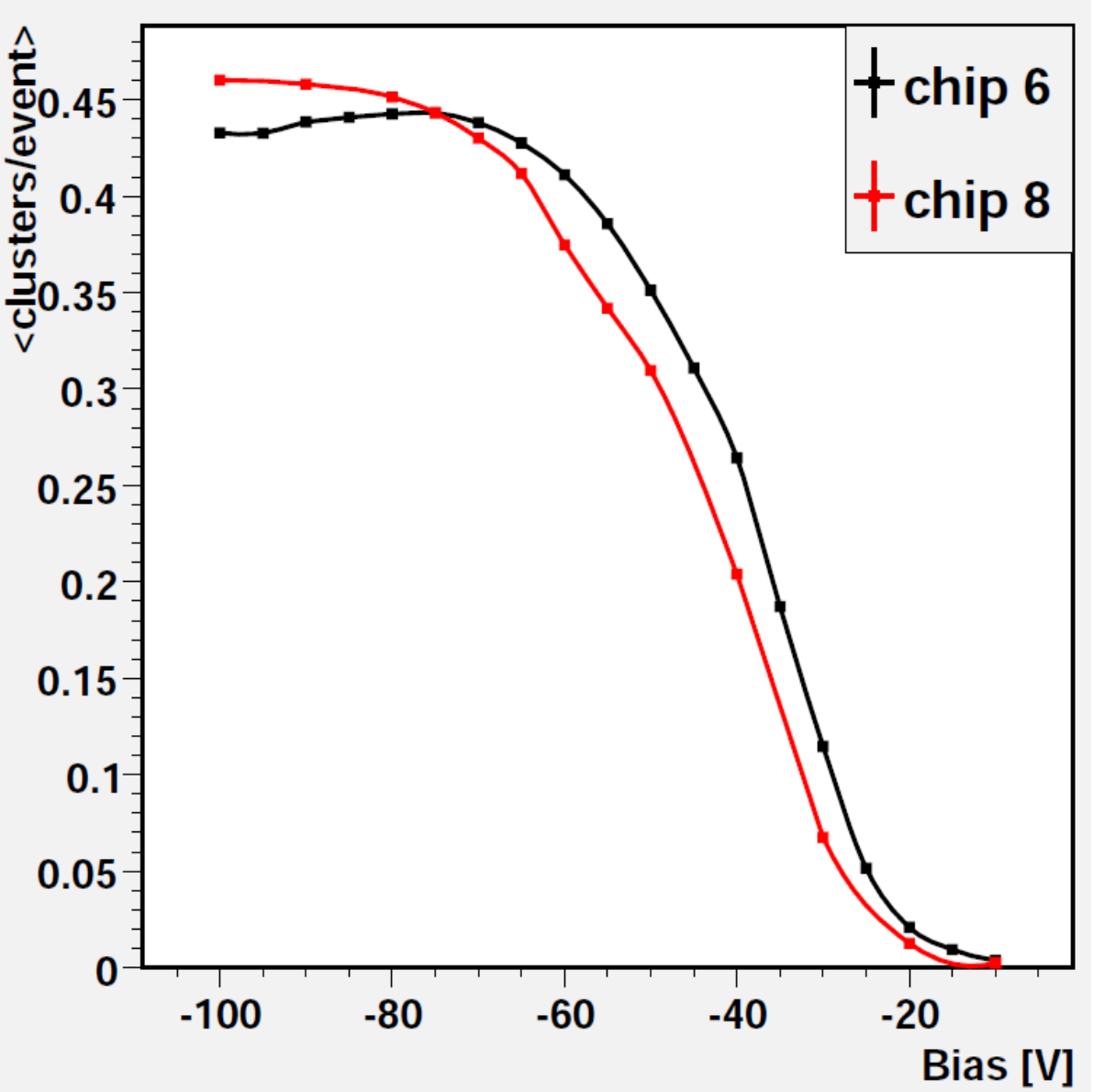
- 2 GeV e+ test beam.
- Pixel detector at vertical incidence, fully depleted (-90V bias).
- No magnetic field.
- Test pulse gain calibration applied.
- Trend across the chip
  - test pulse problem?
- Quite uniform along one column.

T



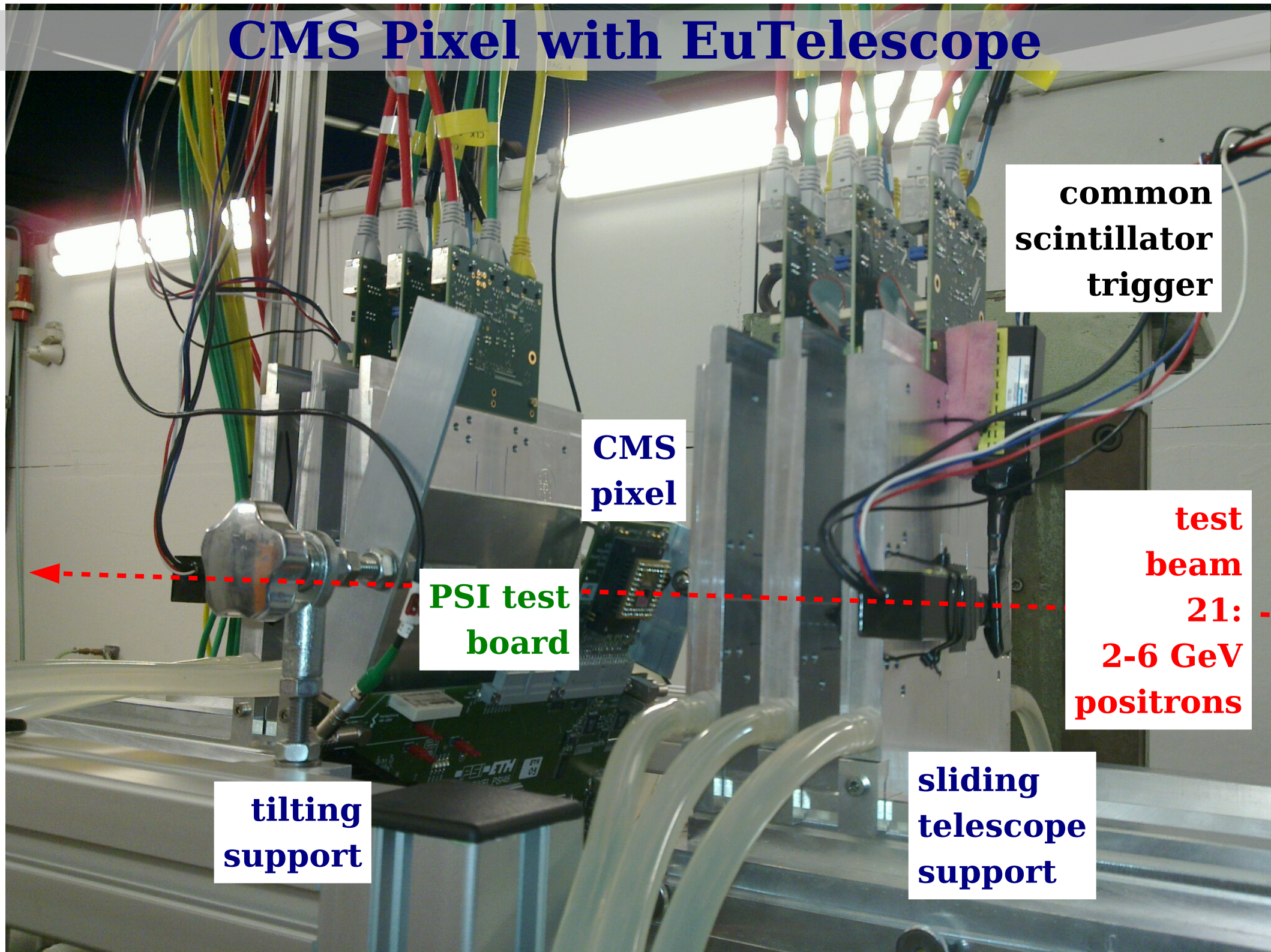
- 2 GeV e+ test beam.
- Pixel detector at vertical incidence, fully depleted.
- Test pulse gain calibration applied.
- Moyal fit to each column.
- Expect ~25 ke from 285 µm silicon.
- Observe ~8% gain variation across the chip:
  - test pulse problem?
  - check with X-ray source!

Cluster multiplicity vs. bias voltage

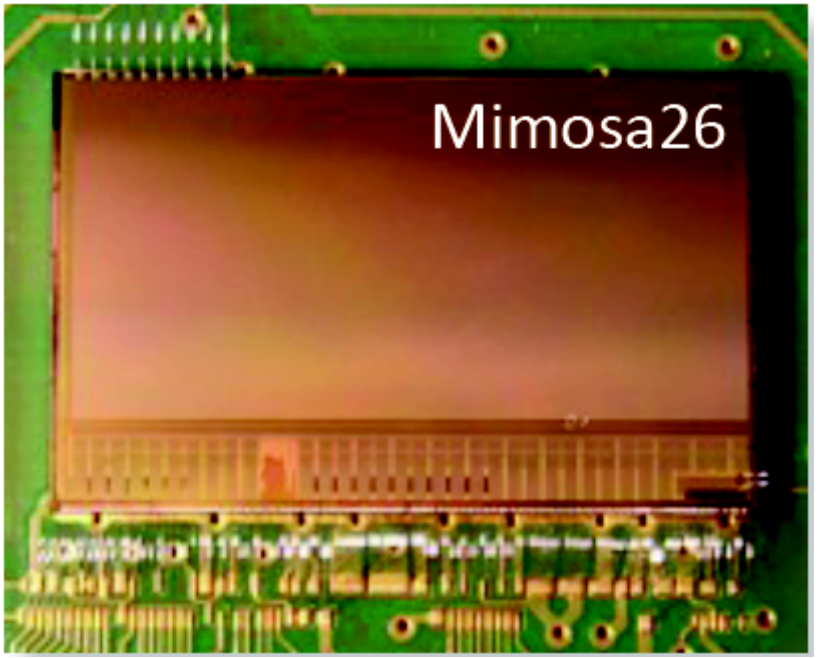


- 2 GeV e^+ beam.
- Cluster efficiency saturates below -80 V:
  - choose -90 V as operating point (Keithley 917)
- Keithley 237 will allow higher bias voltage.

CMS Pixel with EuTelescope

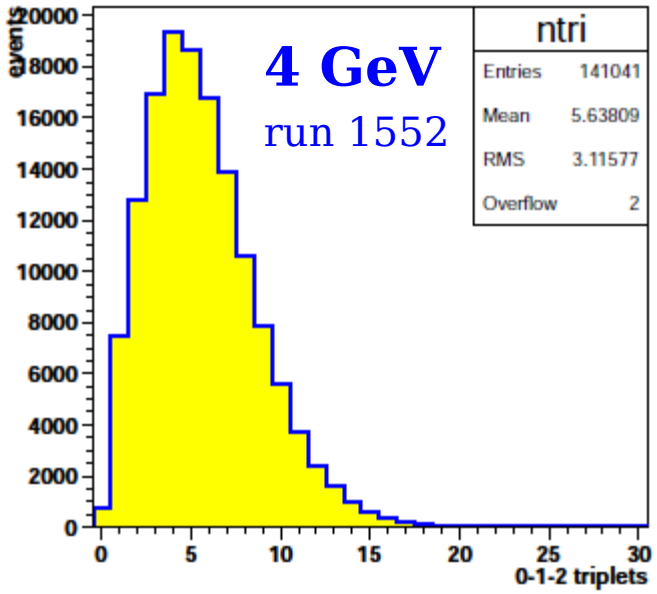


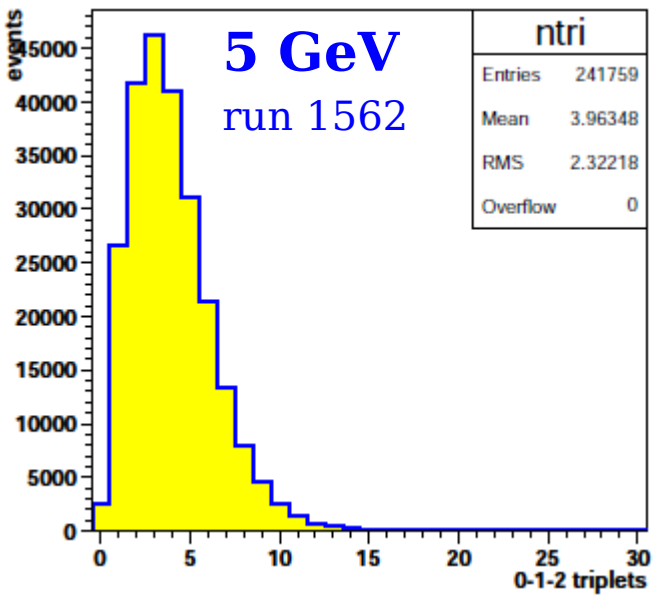
Mimosa26 ILC pixel chip



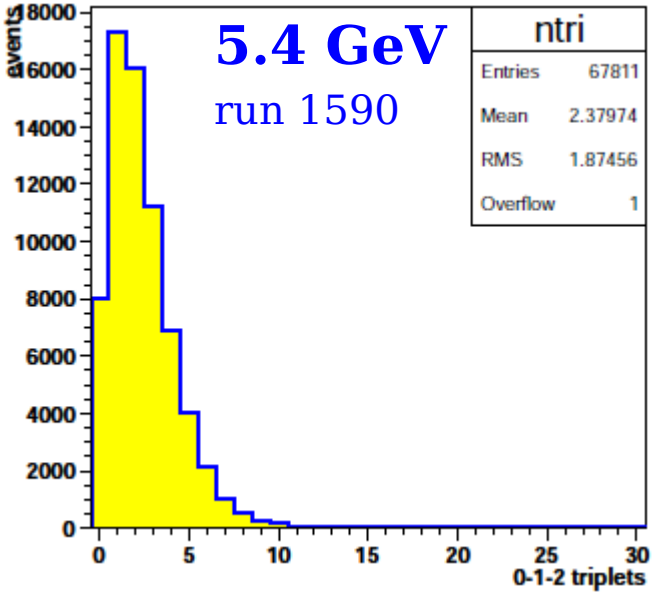
- Mimosa26 monolithic active pixel sensors (Strasburg, 2009):
- thinned to 50 µm,
- 18.4 × 18.4 µm^2 pixel size,
- 1152 × 576 = 663k pixels,
- 10.6 × 21.2 mm^2 active area,
- binary readout,
- integration time 115 µs.
  - 0.5 – 5 pile-up tracks, depending on beam rate.

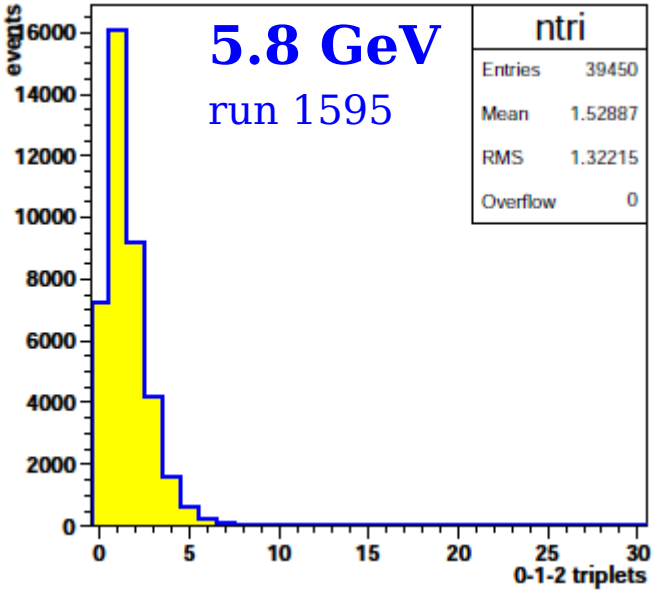
telescope pile up

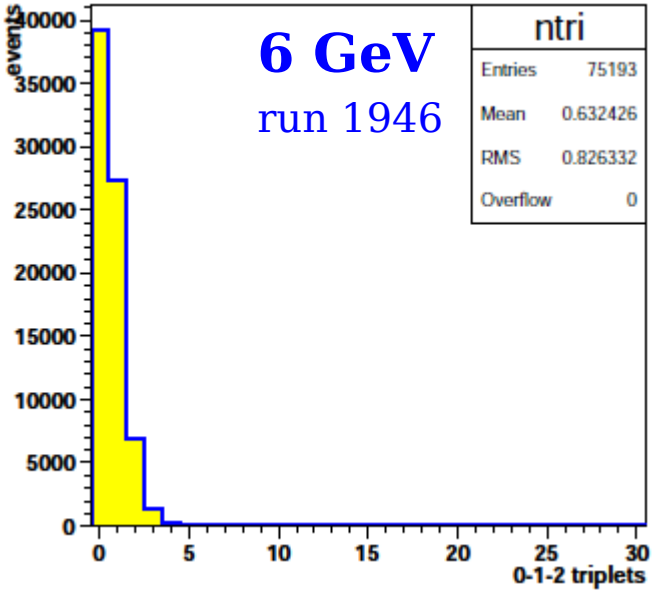




- Mimosa chips integrate over 115 µs = 115 DESY turns.
- We observe pile up
  - depending on DESY current, beam energy, and collimator opening.







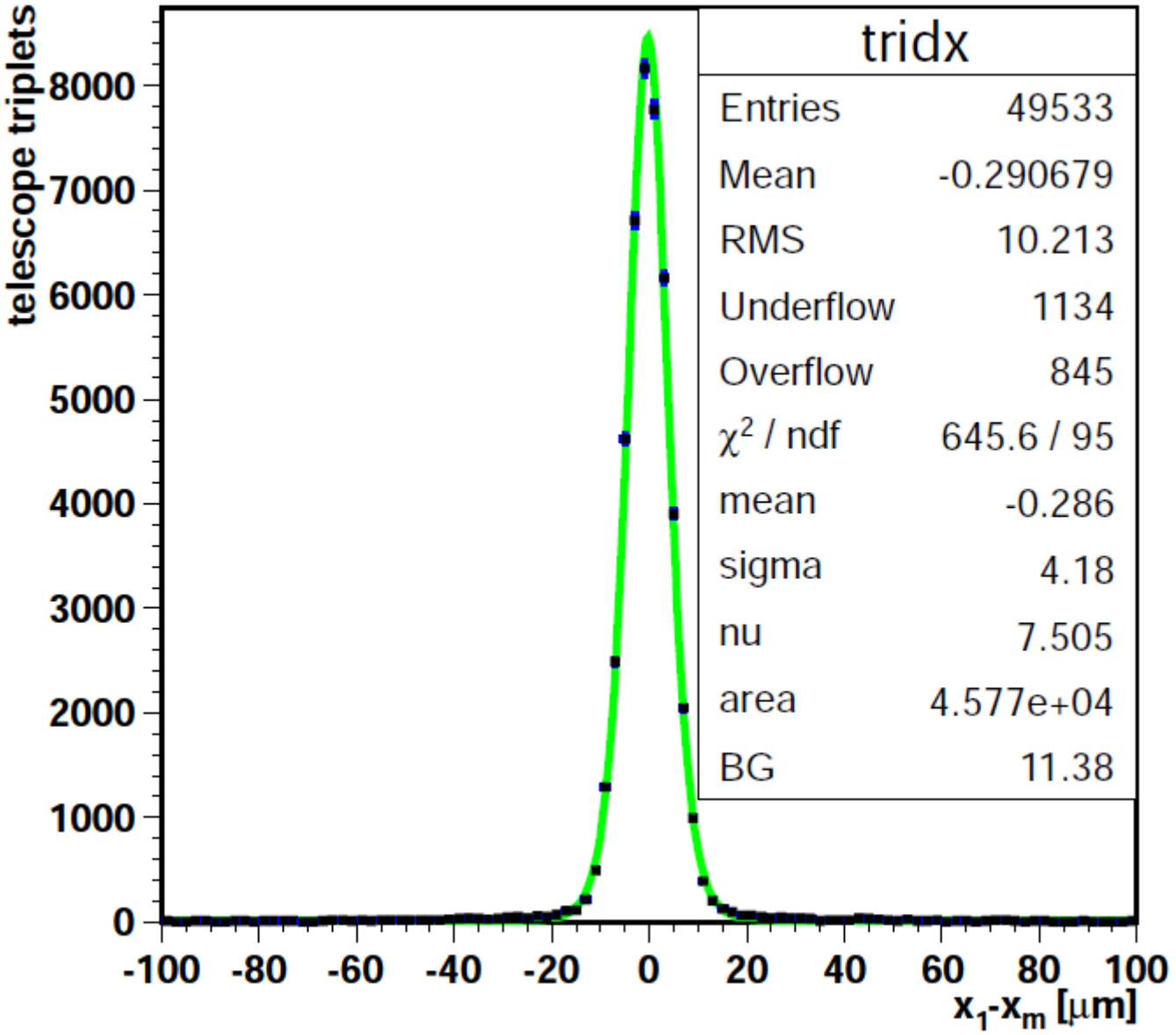
EuTelescope software

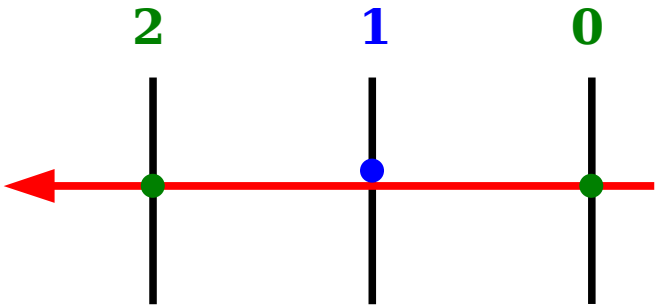
step	data.format	constants
0. EUDAQ data taking: 900s	**native.bin,** e.g. 200 MB 500k triggers	
1. convert, find hot pixels: 70s	**raw.lcio,** e.g. 200 MB	**hotpixel.db**
2. clustering: 240s	**clusters.lcio,** e.g. 400 MB	**offset.db**
3. hits, coarse align: 250s	**hits.lcio,** e.g. 600 MB	**pre-align.db**
4. Millepede alignment: 12s	**pede.bin,** e.g. 120 MB	**align.db**
5. track fitting: 270s	**tracks.lcio,** e.g. 25 MB	

All steps produce ROOT histograms for monitoring.

CMS pixel data are merged by reading from a 2nd input stream:
requires strict synchronicity between the DAQ systems
achieved with common trigger, except for initial event offset (0 - 109).

Telescope point resolution

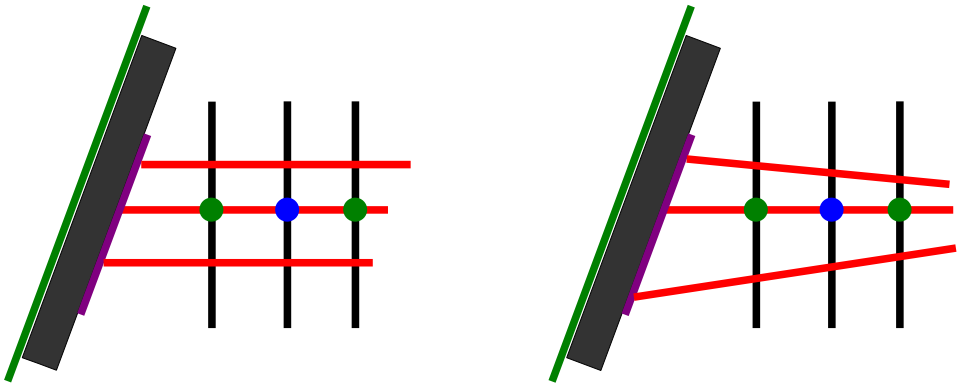




- 6 GeV e^+ beam.
- Triplet residuals:
  - 3 upstream planes,
  - hits in plane 0 and 2 form vector,
  - residual to hit in middle plane 1,
  - $\sigma_r = 4.2\ \mu m = \sqrt{(3/2)}\ \sigma_i$
  - **σ_i = 3.4 um**

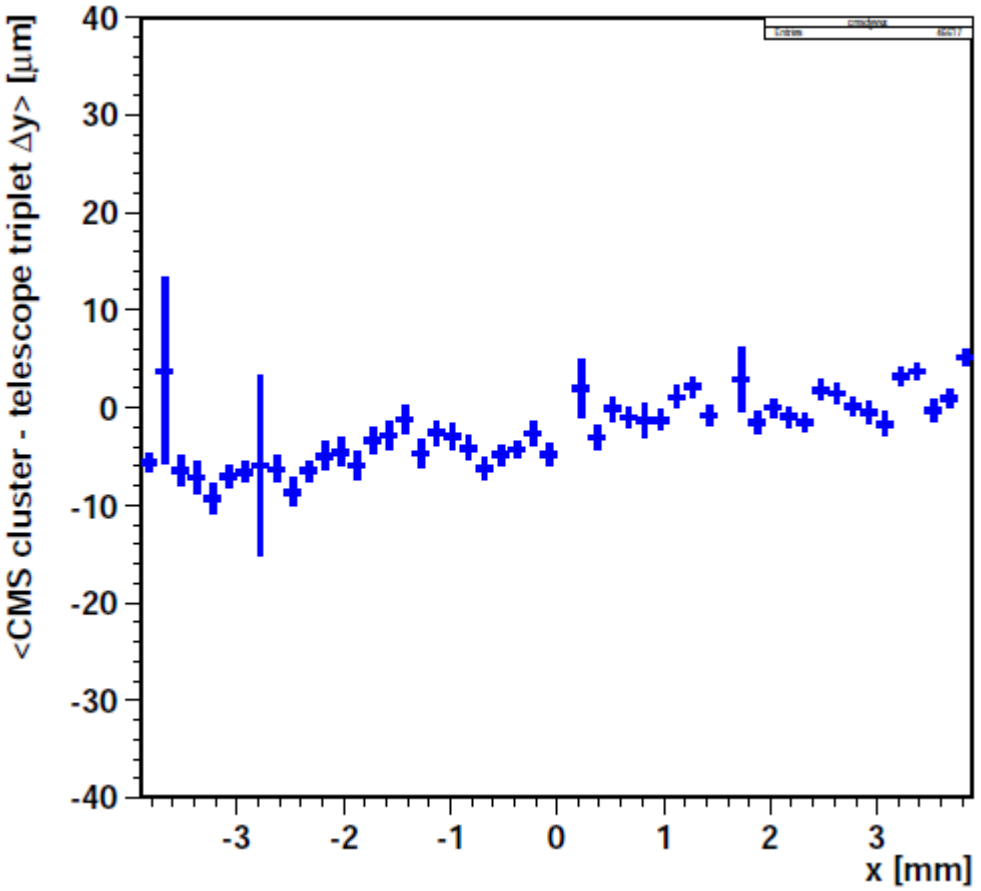
CMS pixel alignment w.r.t. telescope

- shift in x and y based on peak of residuals: `cmssxa`, `cmsdya`
- rotate by ϕ around z based on Δy vs x: `cmsdyvsx`
- adjust tilt angle α based on Δy vs y: `cmsdyvsy`
- adjust z shift based on Δy vs θ_y: `cmsdyvsty`
- to be automated:
  - include into telescope MillePede alignment, or
  - part of the general broken line track refit

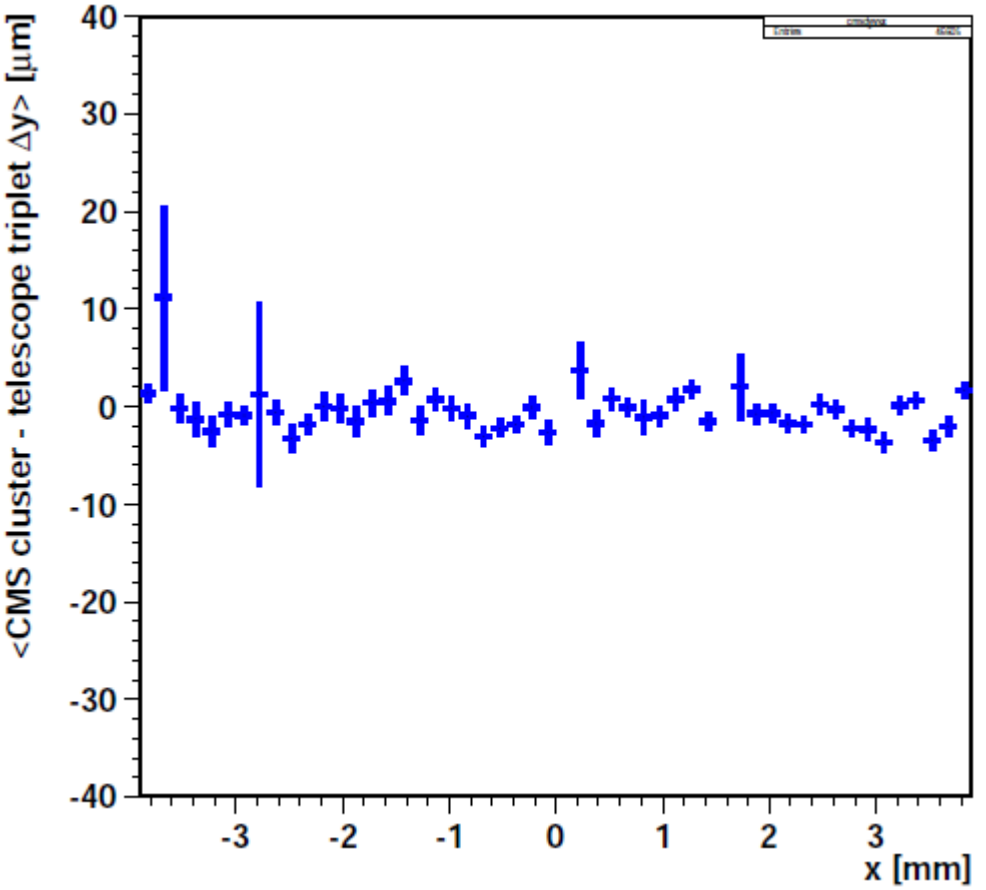


rotate pixel around z

ϕ = 20 mrad

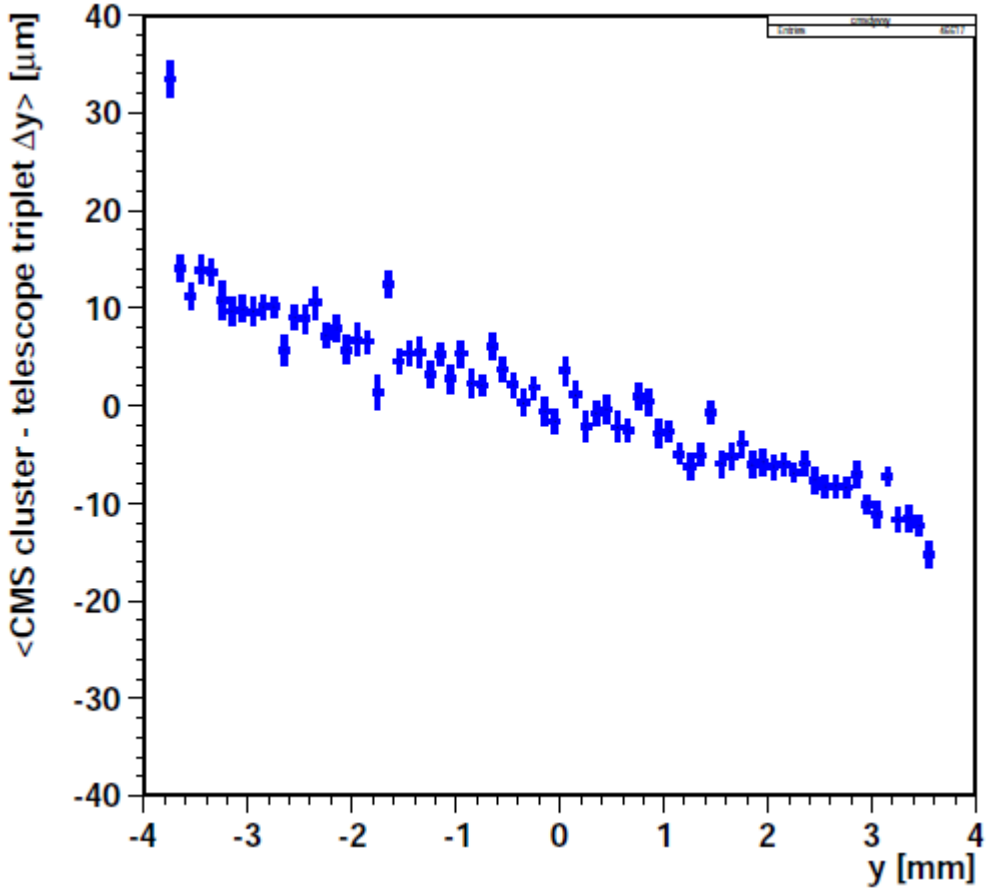


ϕ = 30 mrad

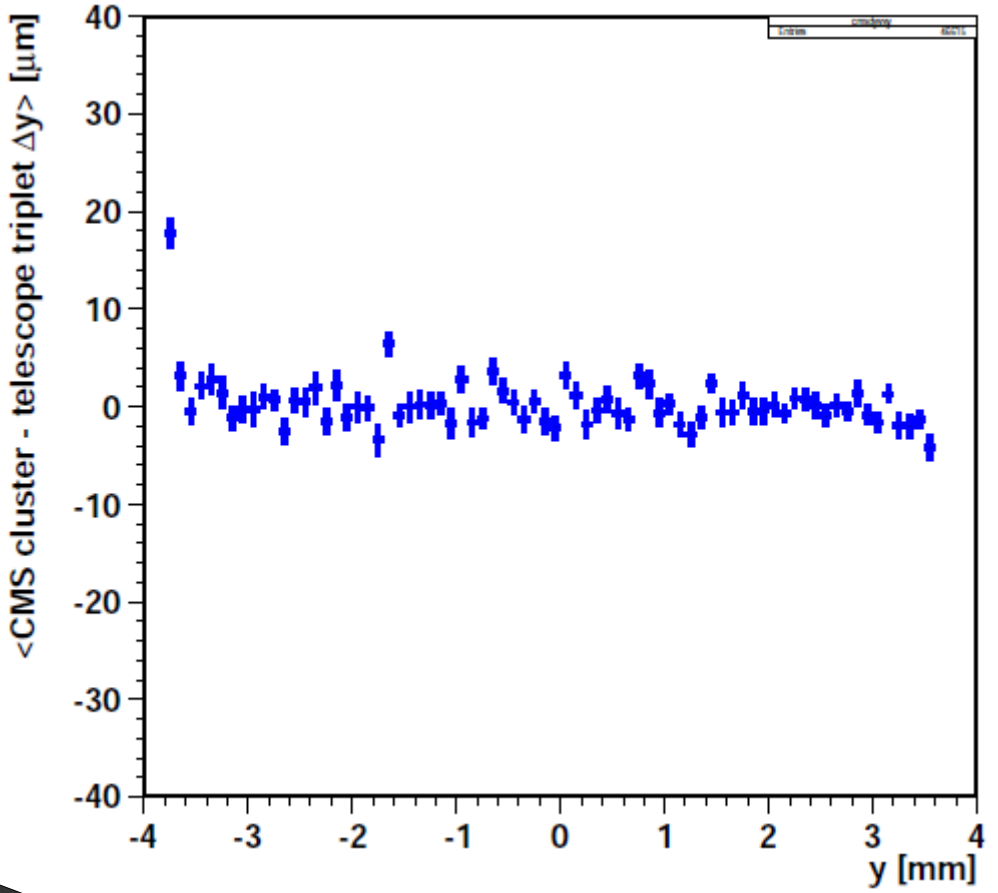


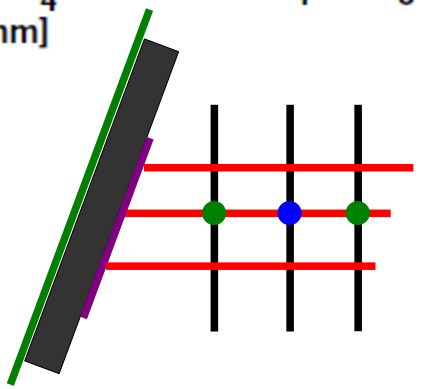
adjust tilt angle

α = 20.5°



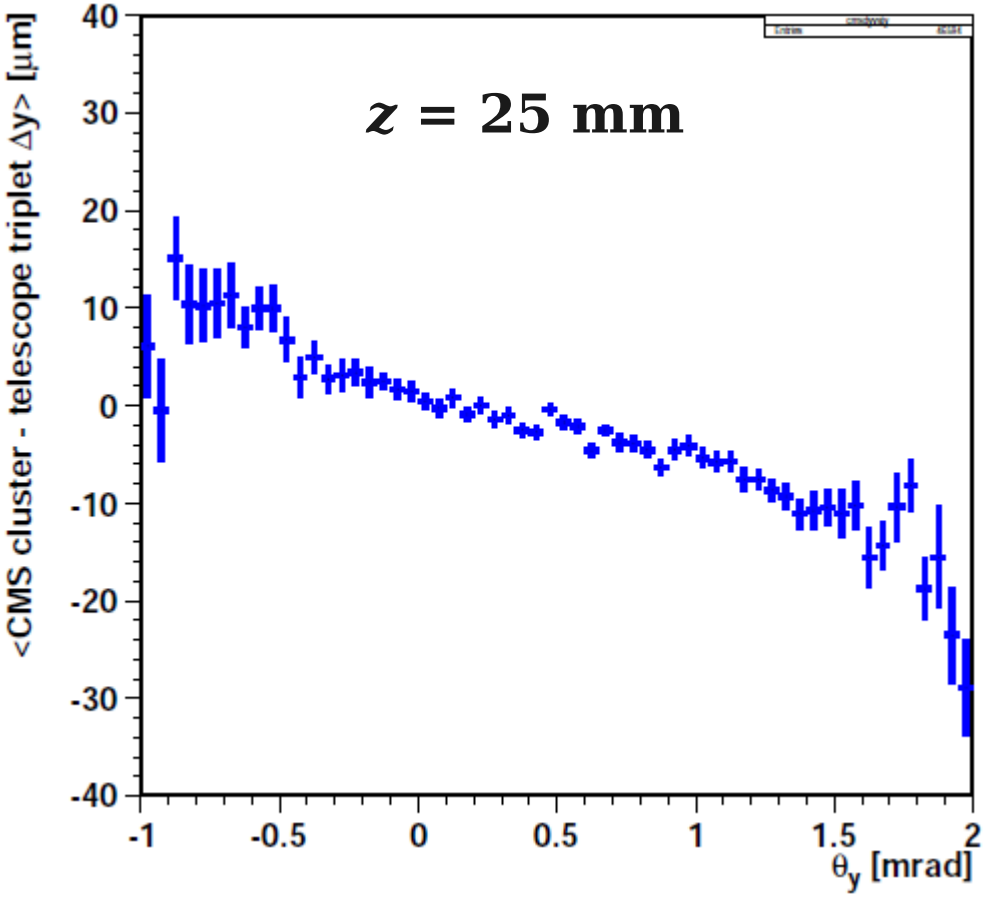
α = 20.0°

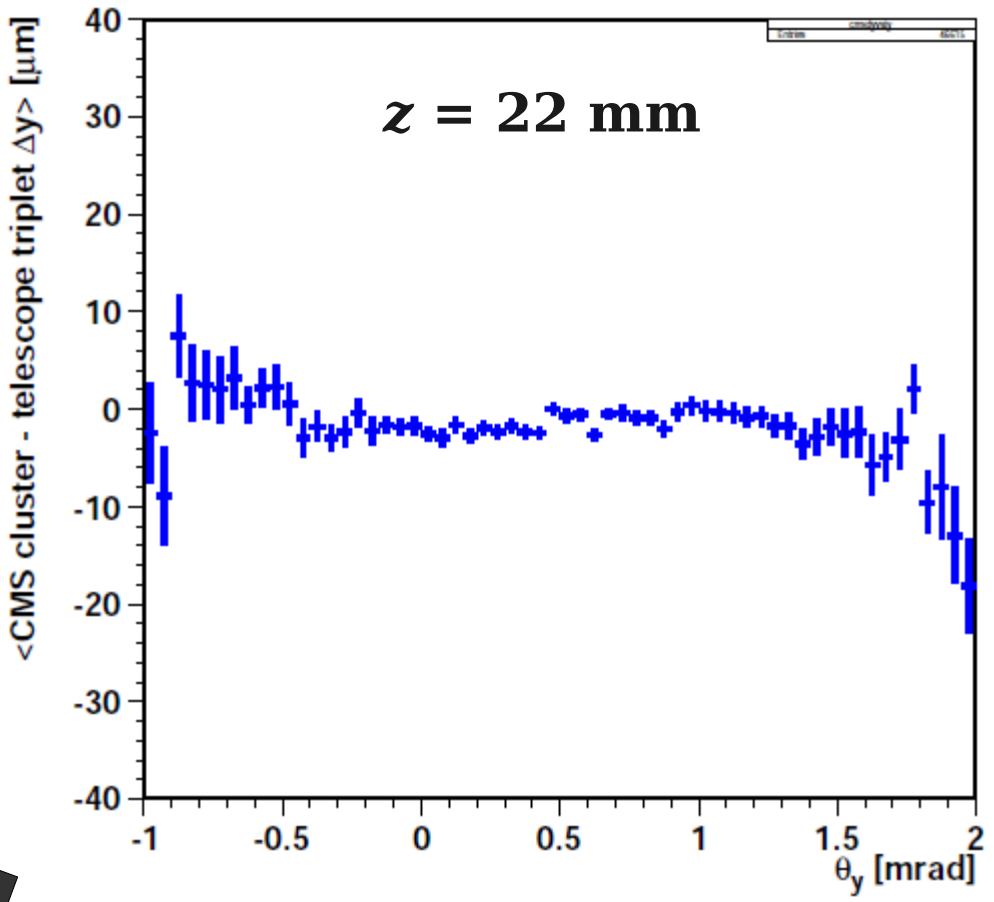


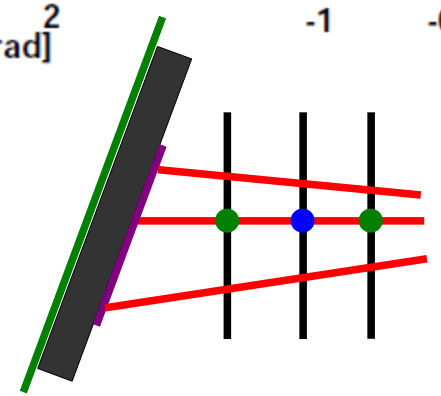


adjust z shift

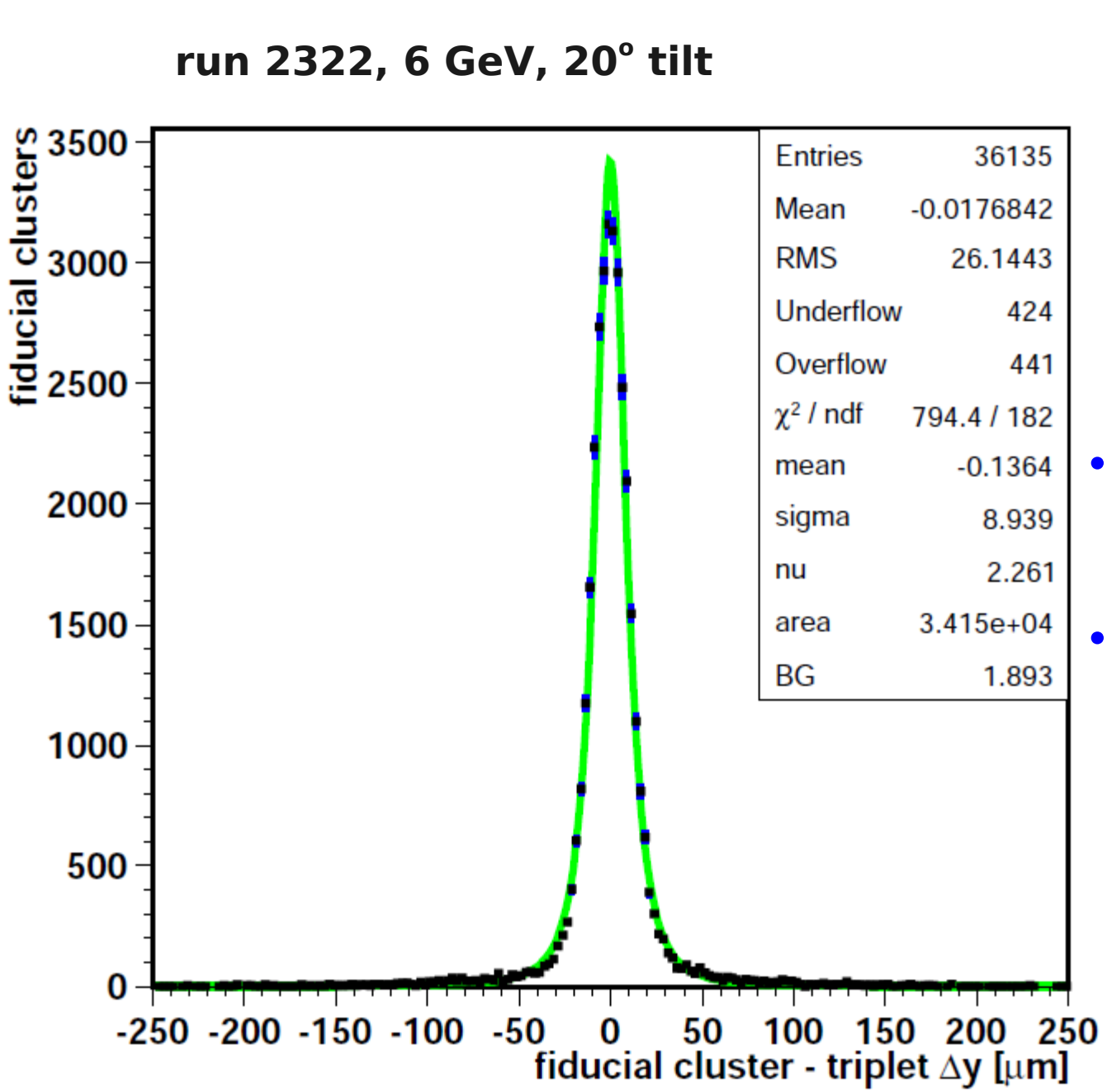
z position of CMS pixel w.r.t. telescope plane 2

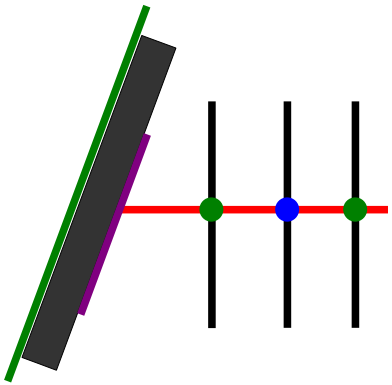






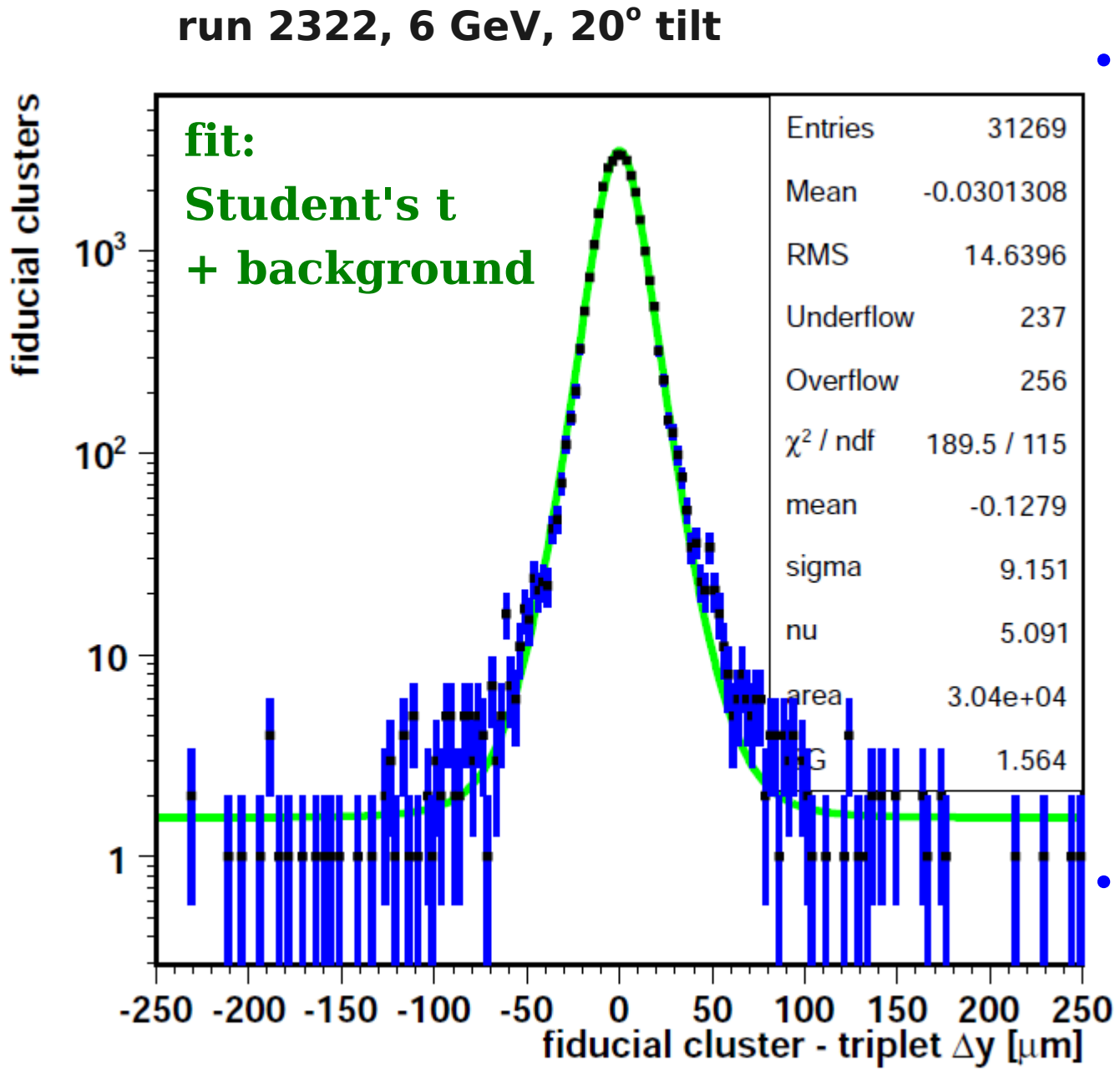
CMS pixel row resolution





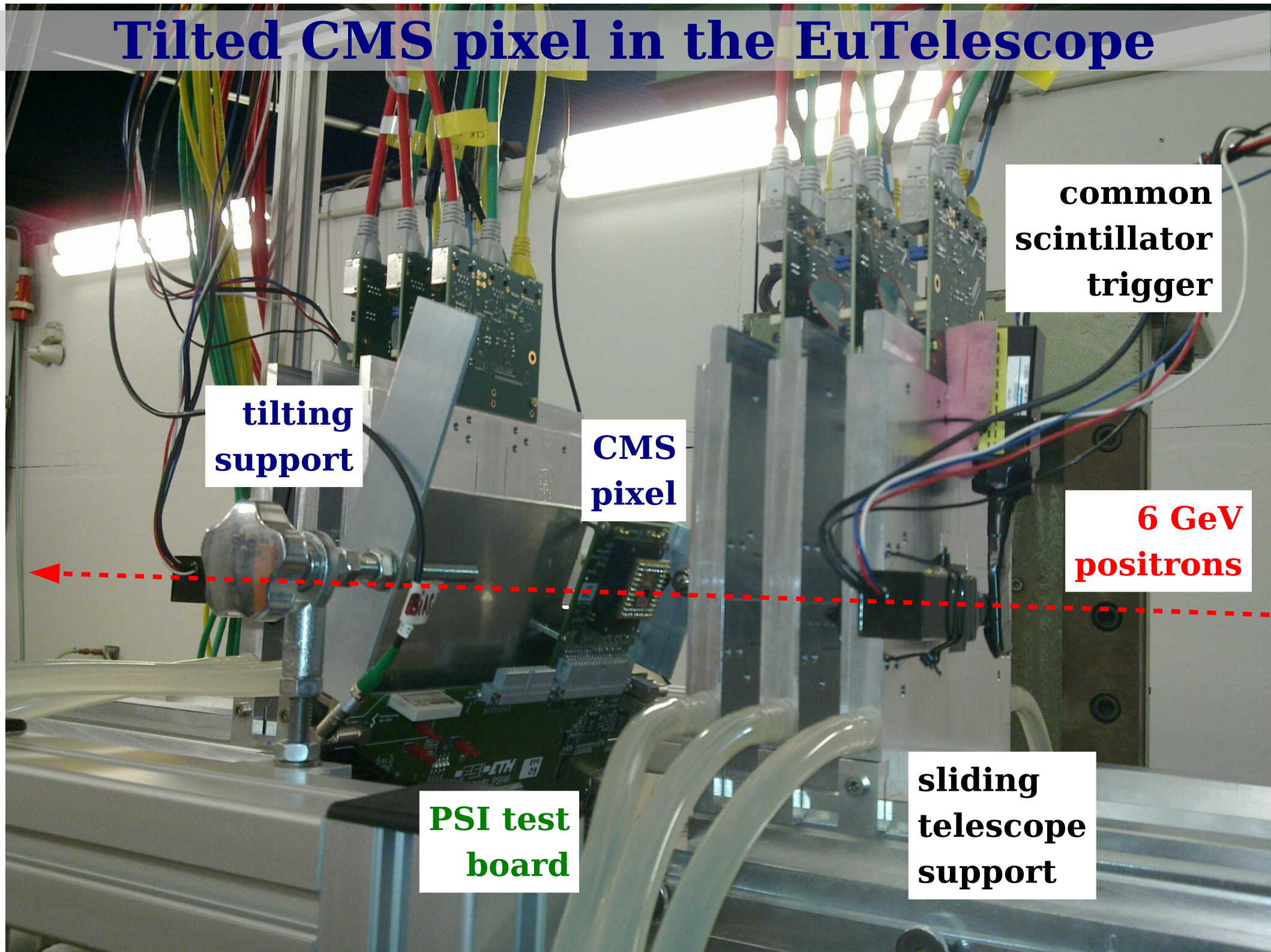
- Vertical = rows
  - CMS pixel = 100 µm.
- Residual:
  - σ = 9 µm,
  - telescope extrapolation: 4.5 µm,
  - **CMS resolution: 8 µm.**

CMS pixel residual distribution

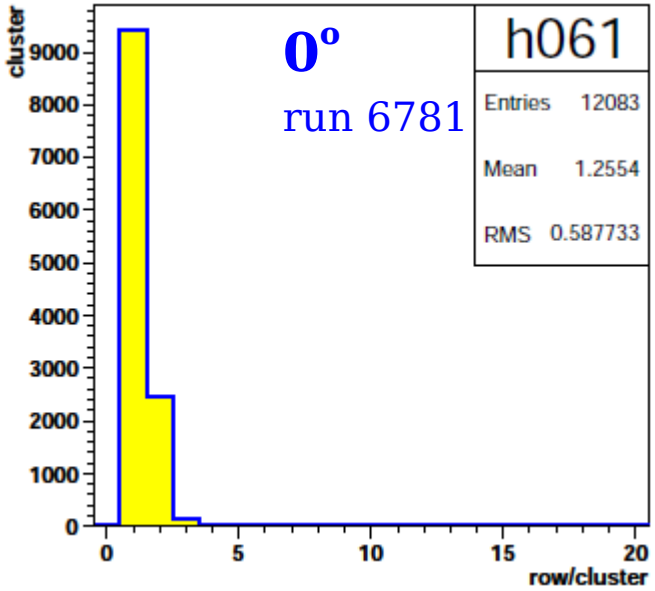


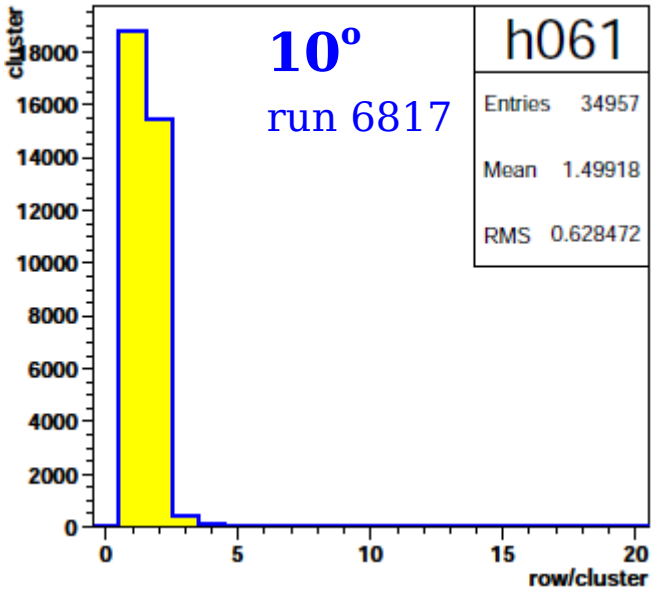
- cleaning cuts:
  - cluster one pixel away from edges and dead columns,
  - $|\Delta x| < 0.15$ mm,
  - only 1- and 2-row clusters (against δ-rays)
  - cluster charge > 18 ke (against wrong timing),
  - | track angle | < 2 mrad (against scattering).
- Result:
  - less tails, more Gaussian

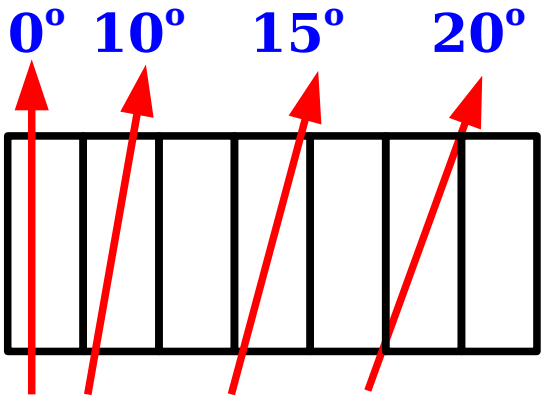
Tilted CMS pixel in the EuTelescope



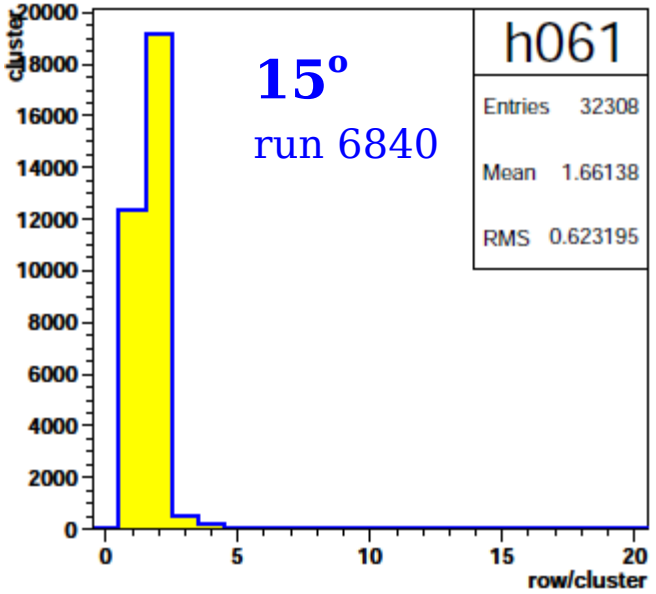
cluster size vs tilt angle

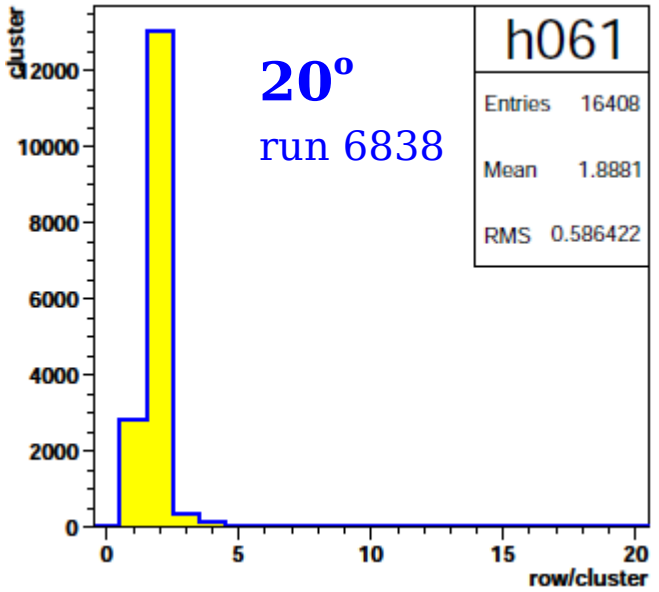


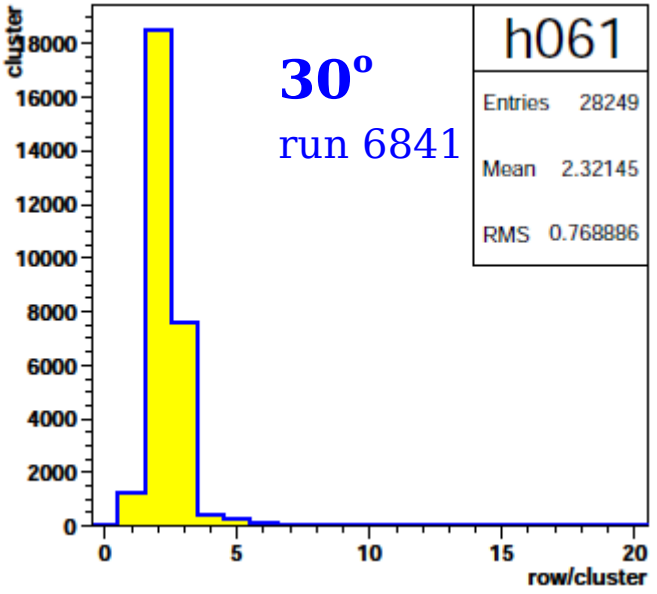




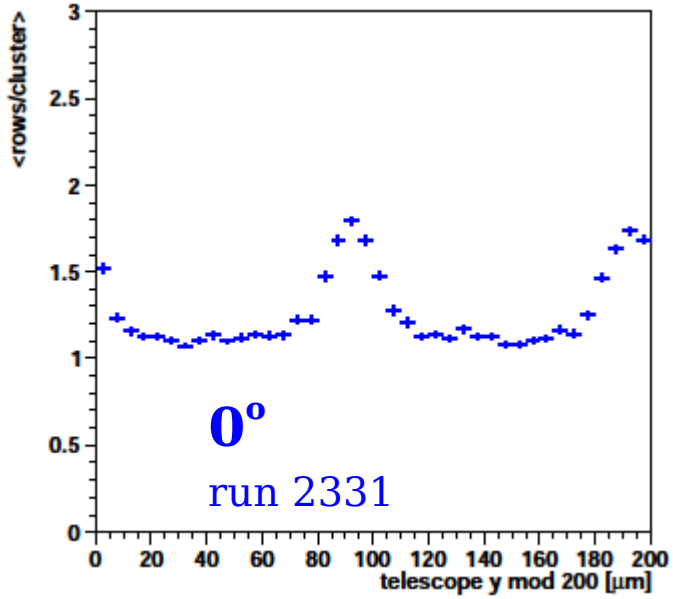
atan(100/285) = 19.3°

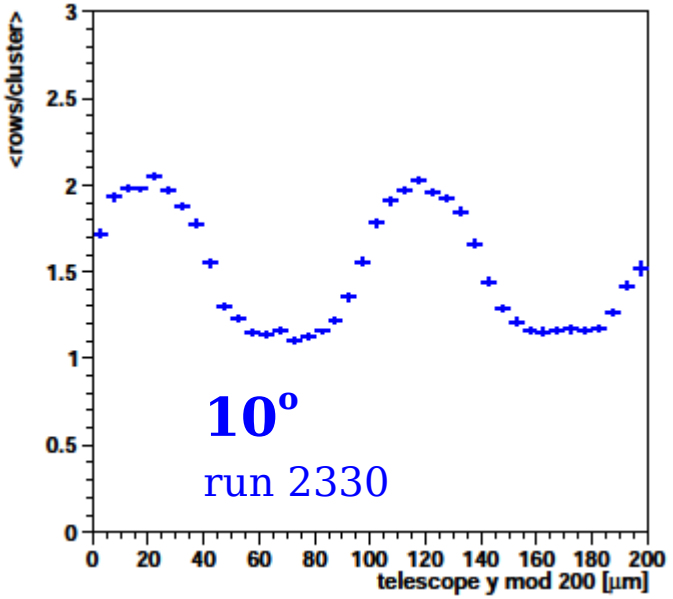


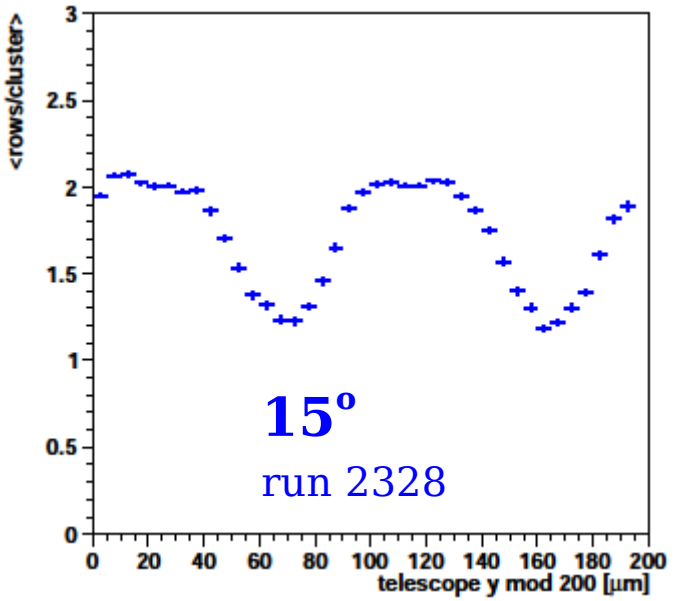




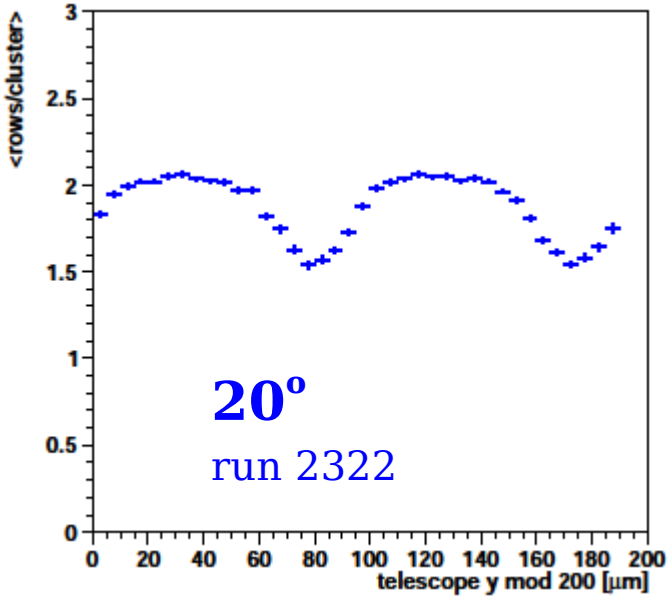
cluster size vs impact point and tilt angle

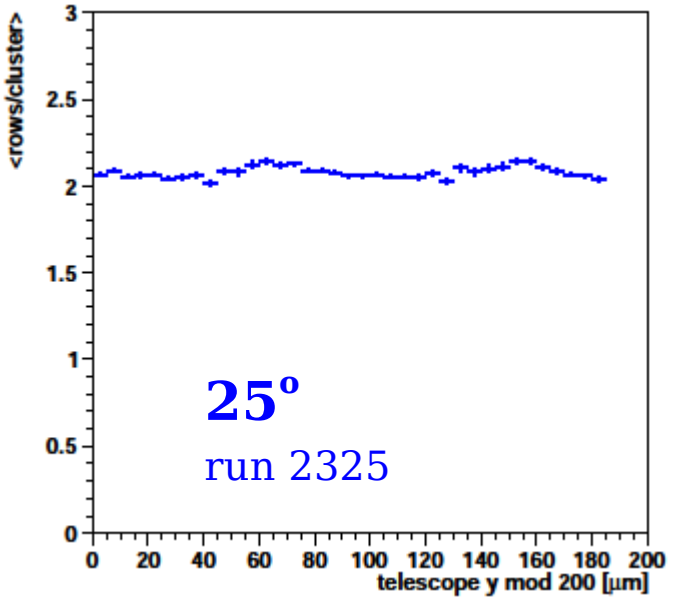


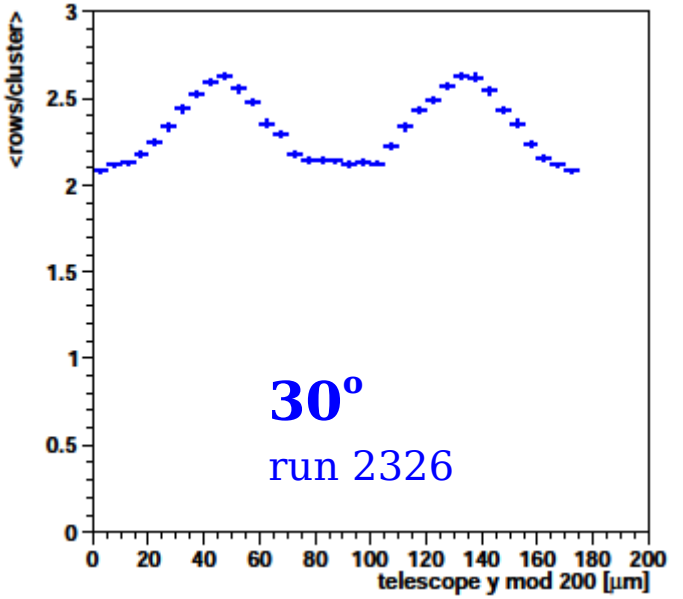




y_{impact} mod 200 µm: 2 pixels

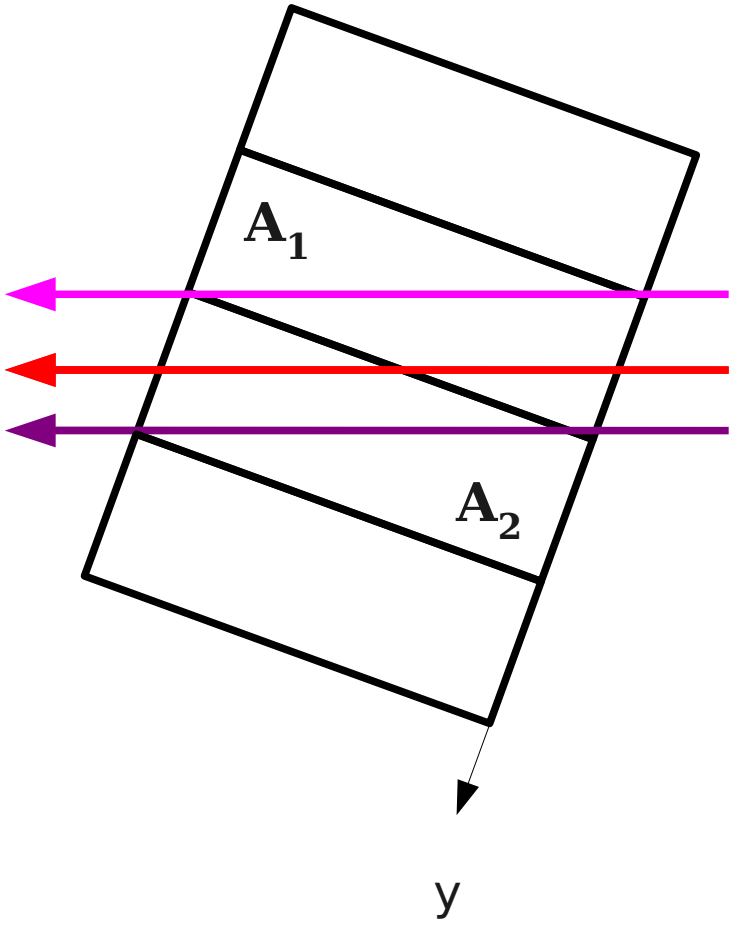






charge sharing: η

at 20°:



$\eta = (A_1 - A_2) / (A_1 + A_2)$

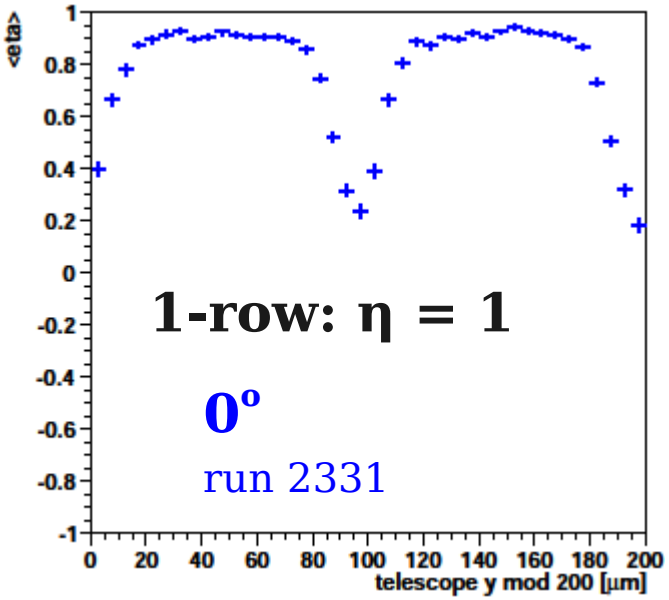
1.0
0.0
(-1.0)

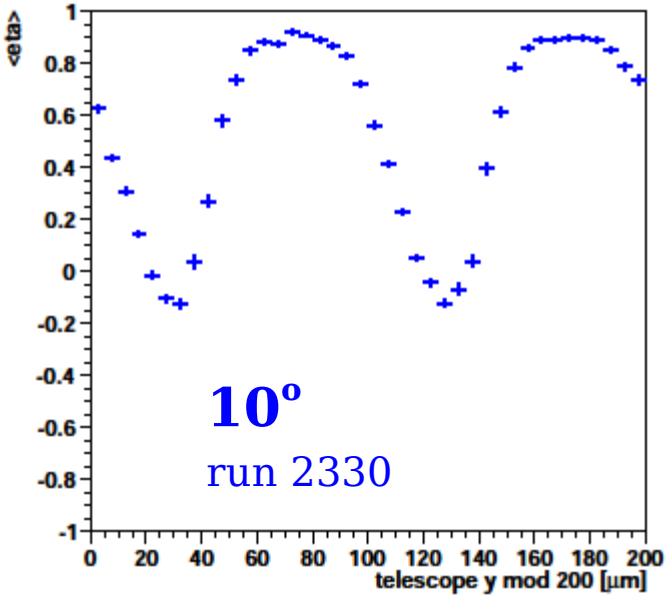
1-row clusters have η = 1.

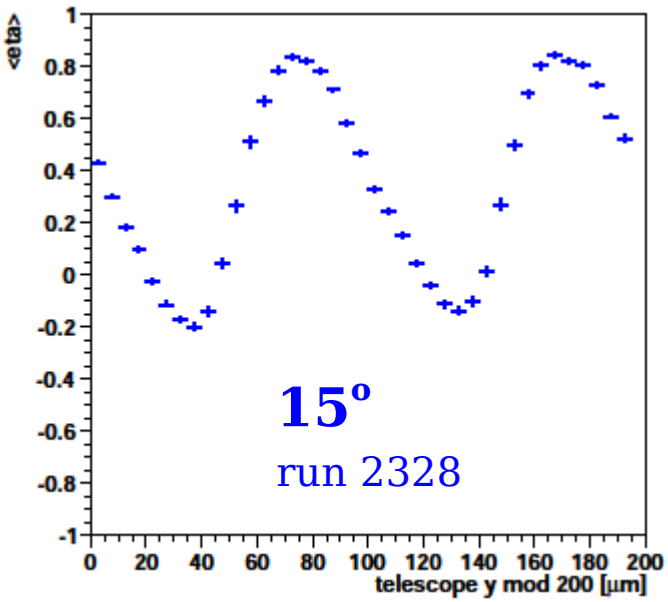
ideal:
linear η vs y
(saw tooth)

deviations:
- **diffusion**
- **thresholds**
- **trapping**
- **delta-rays**

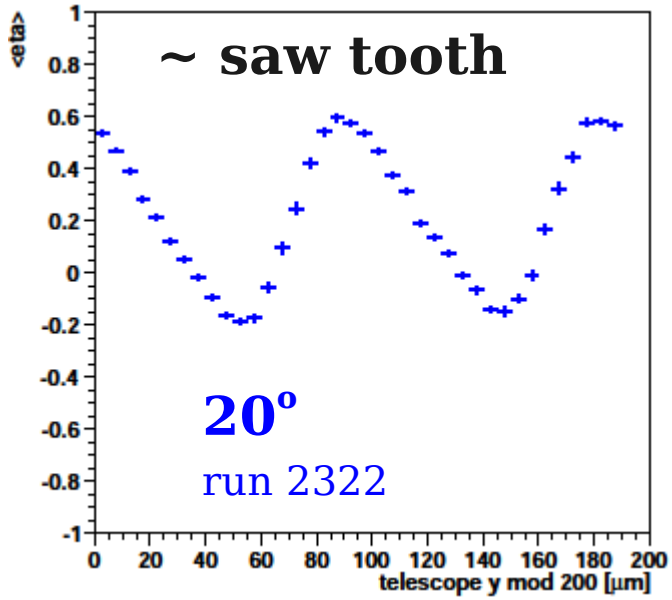
charge sharing vs tilt angle

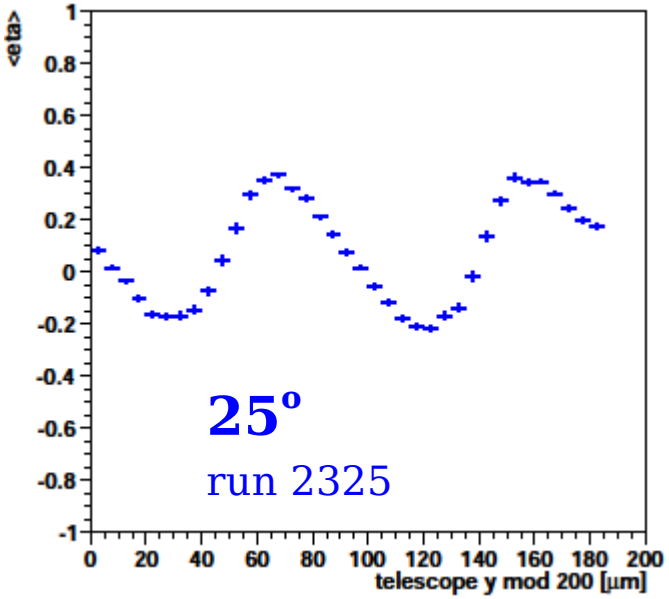


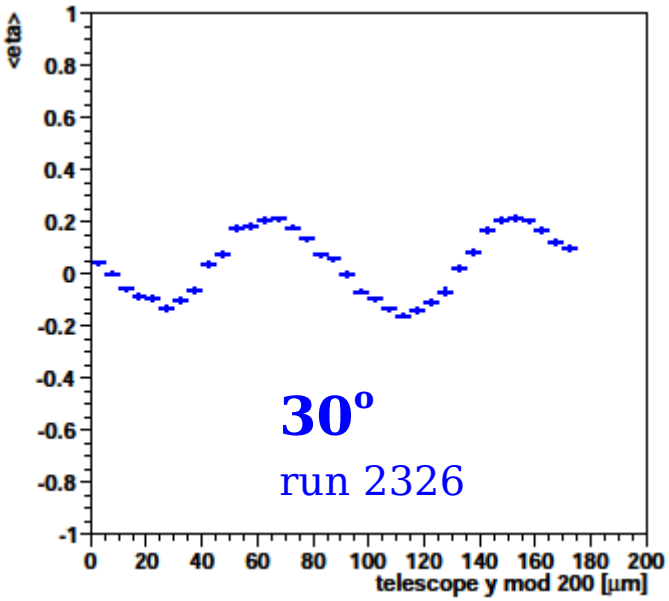




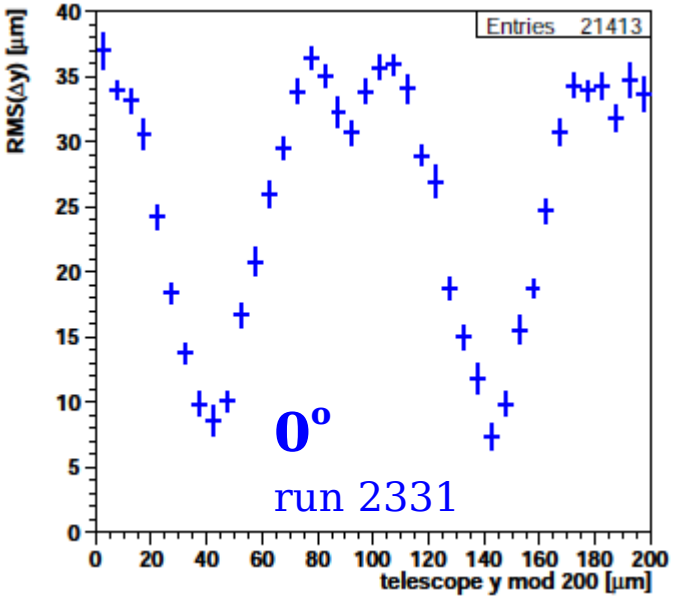
y_{impact} mod 200 μm: 2 pixels

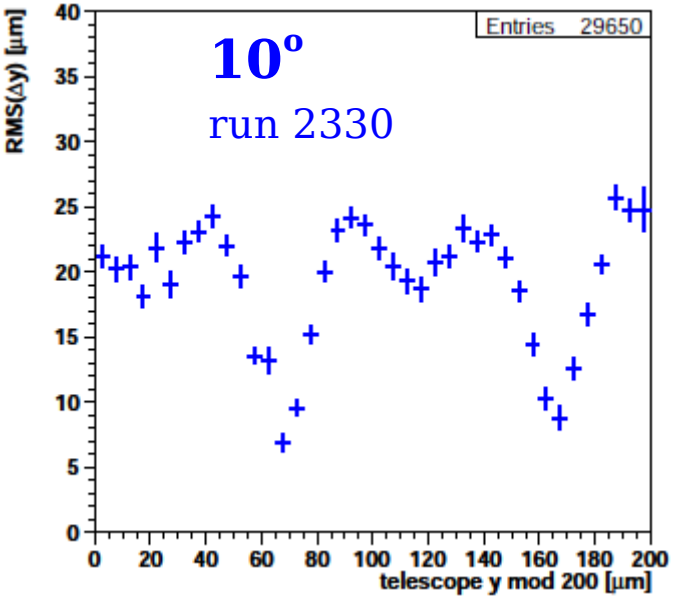


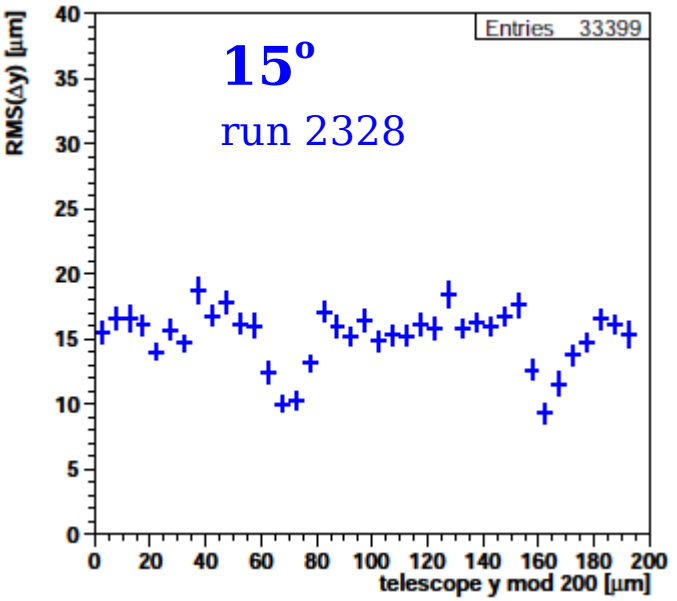


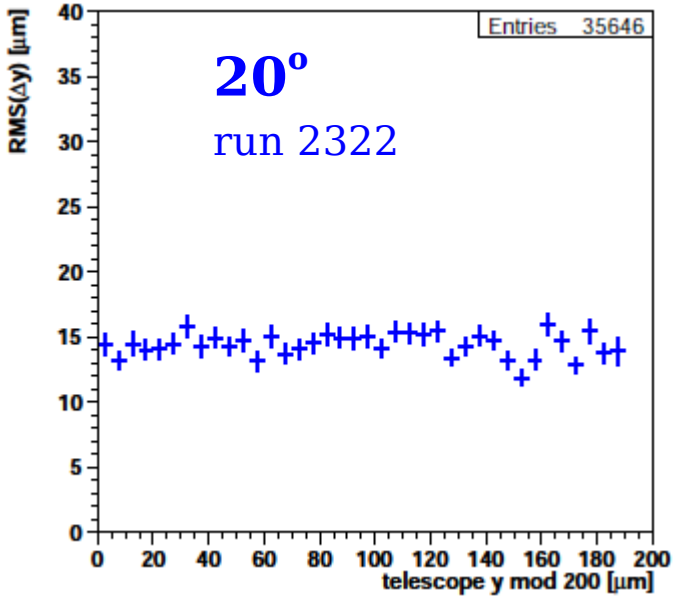


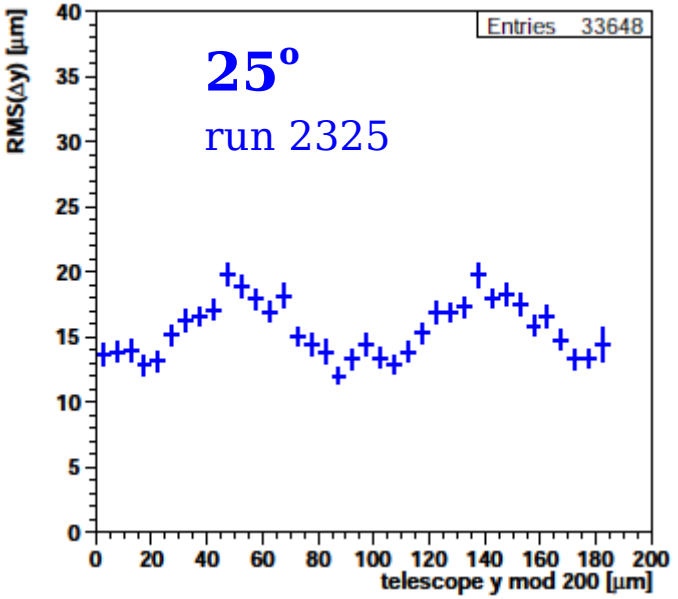
resolution profile vs tilt angle

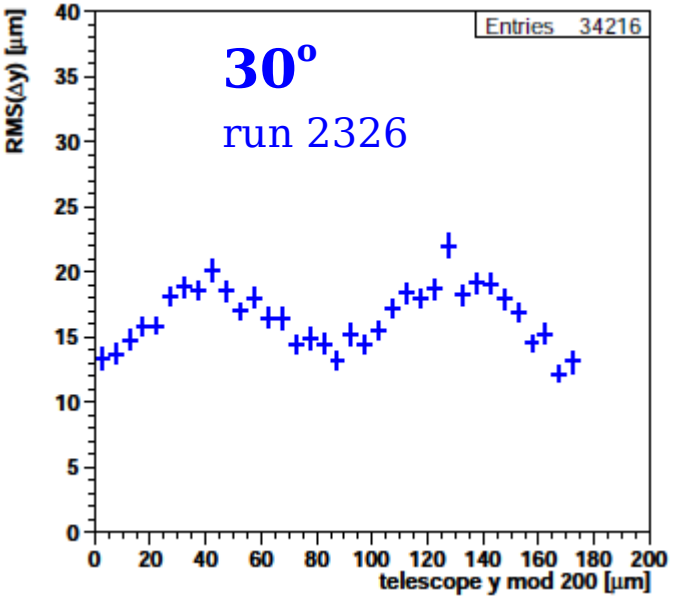




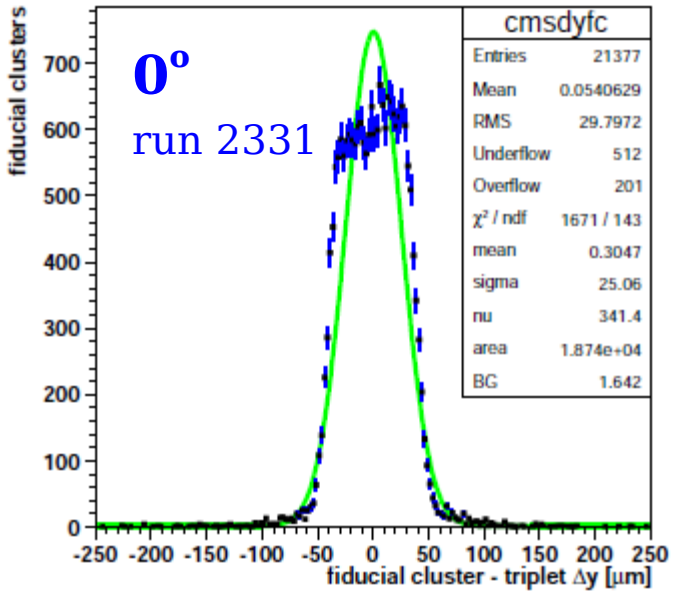


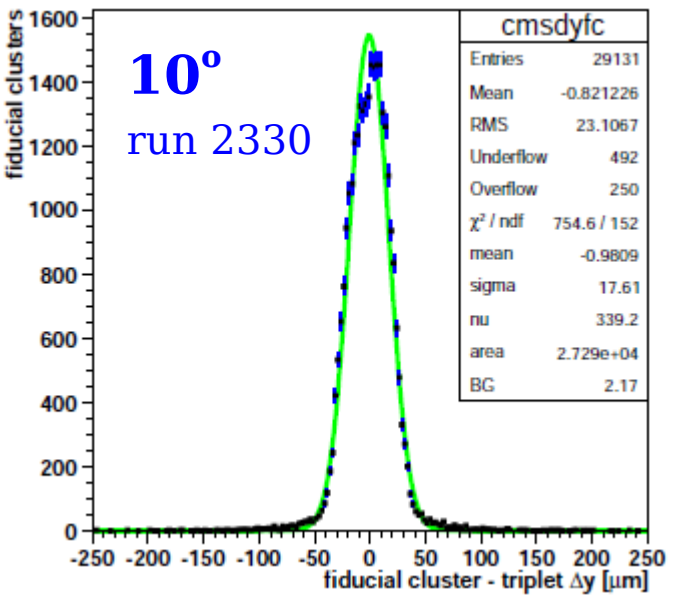


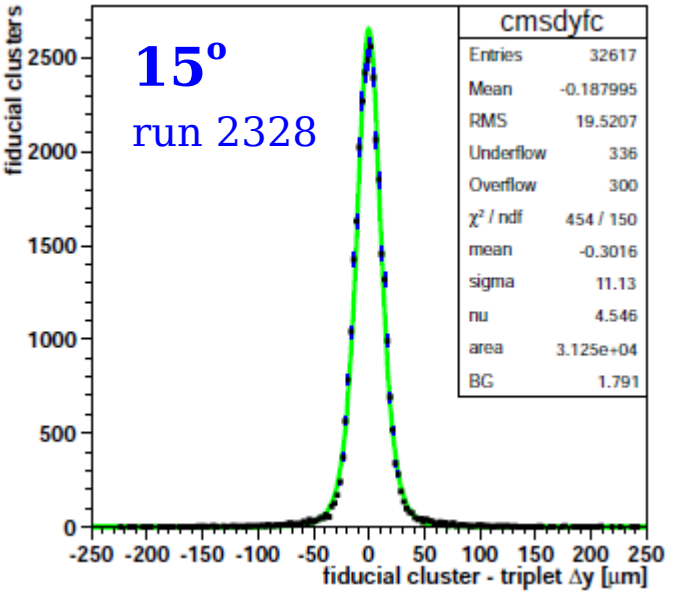


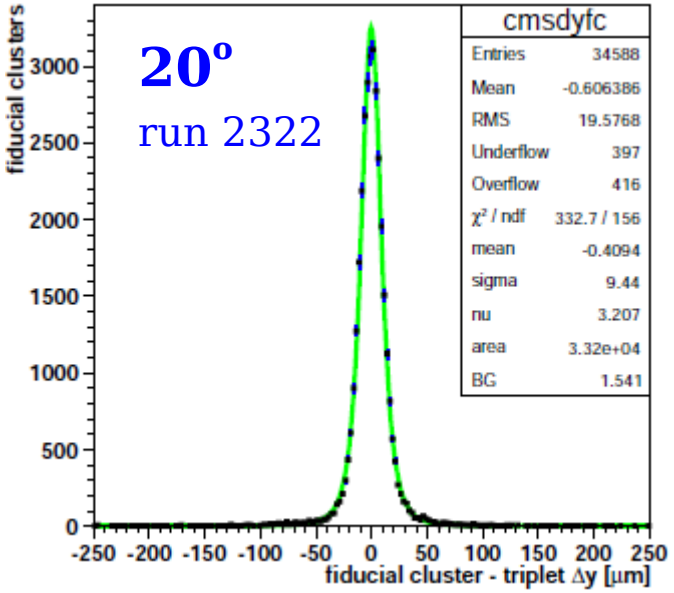


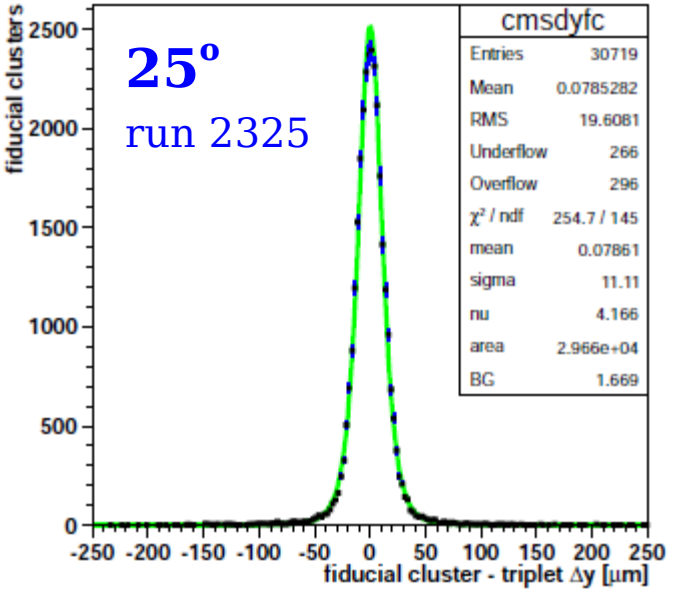
CMS pixel resolution vs tilt angle

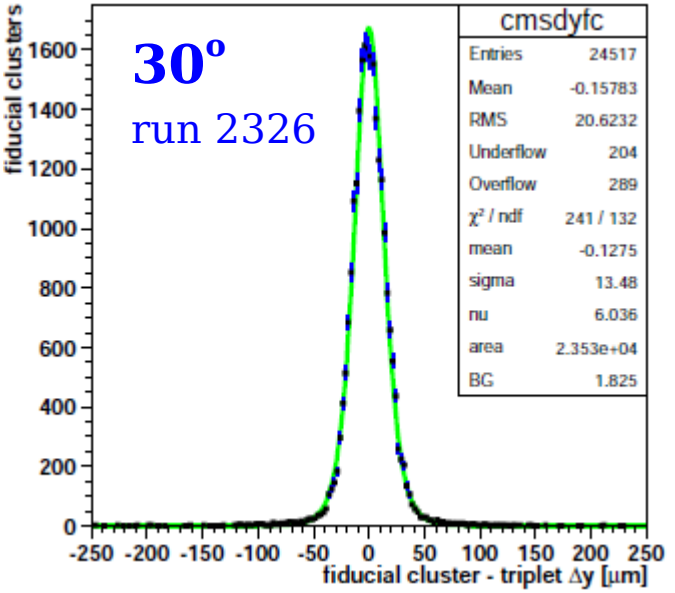




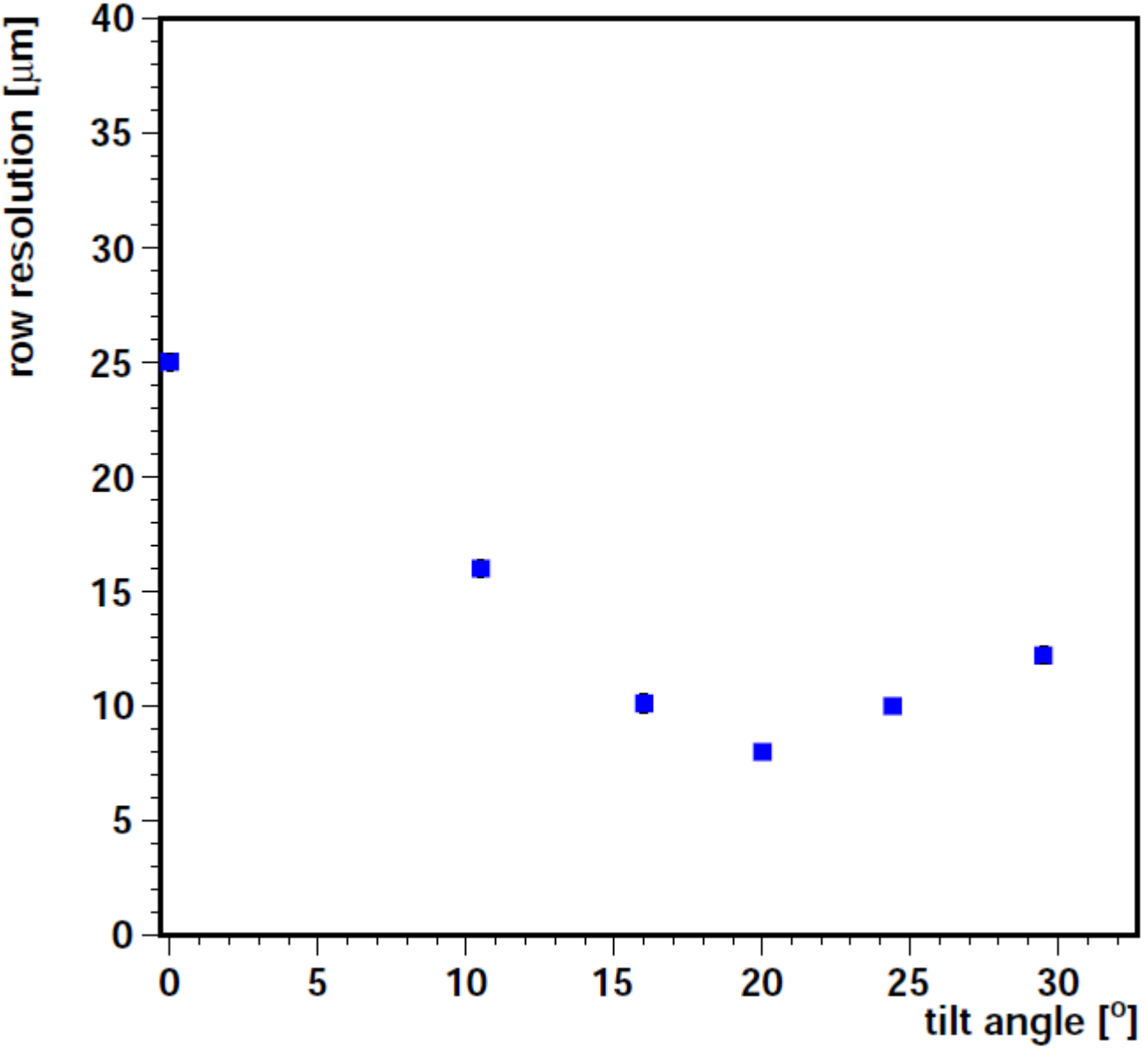


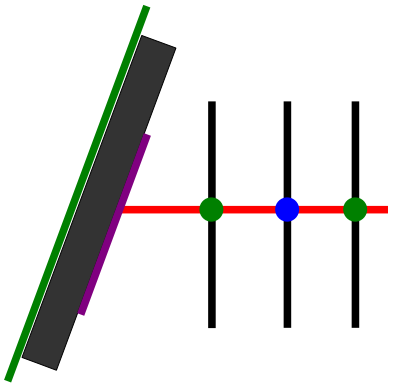






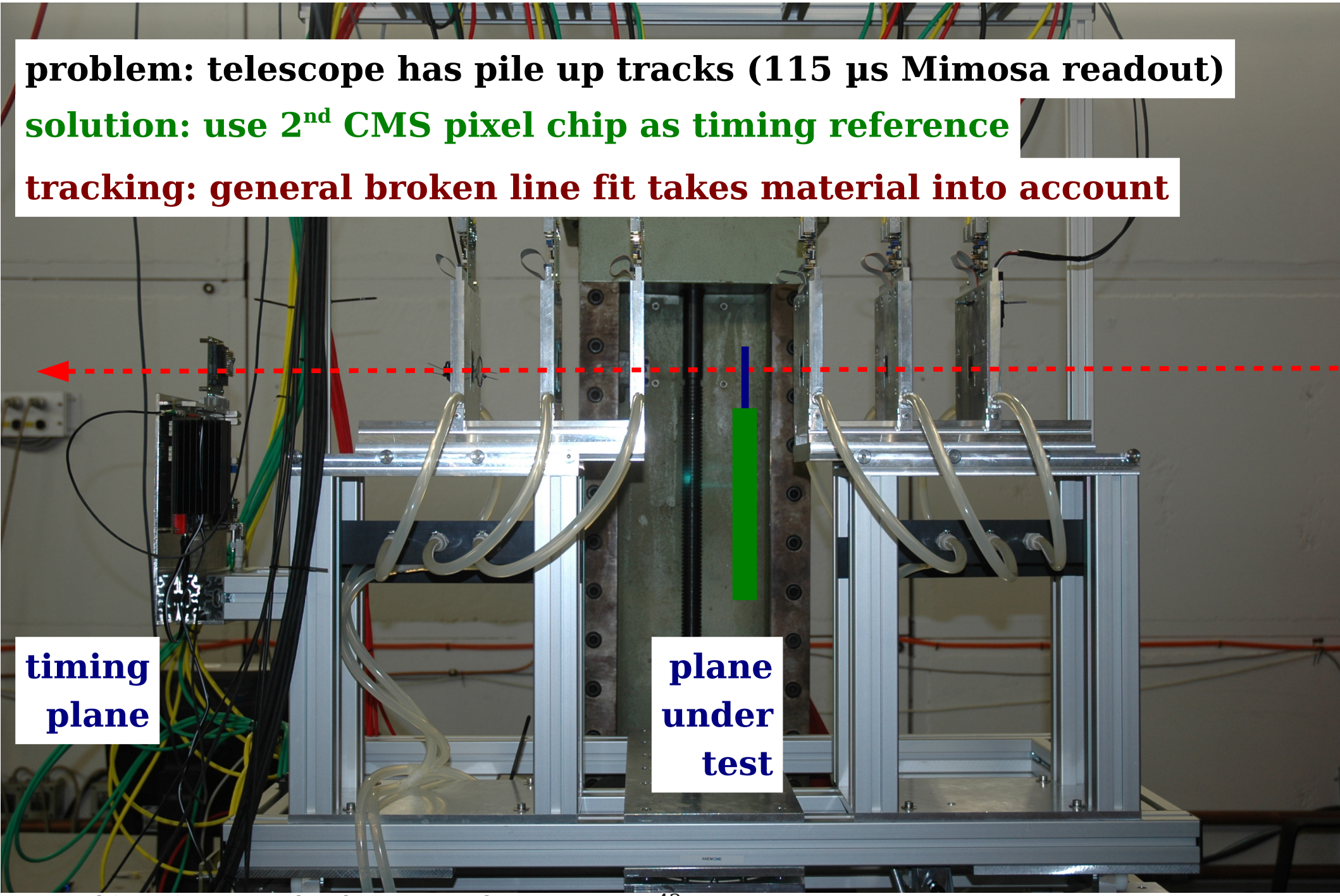
CMS pixel row resolution vs tilt angle





- 6 GeV, telescope extrapolation uncertainty subtracted.
- row pixels = 100 μm.
- Binary:
  - σ = 100 / √12 = 29 μm
- Optimal angle 19°:
  - σ = 8 μm.

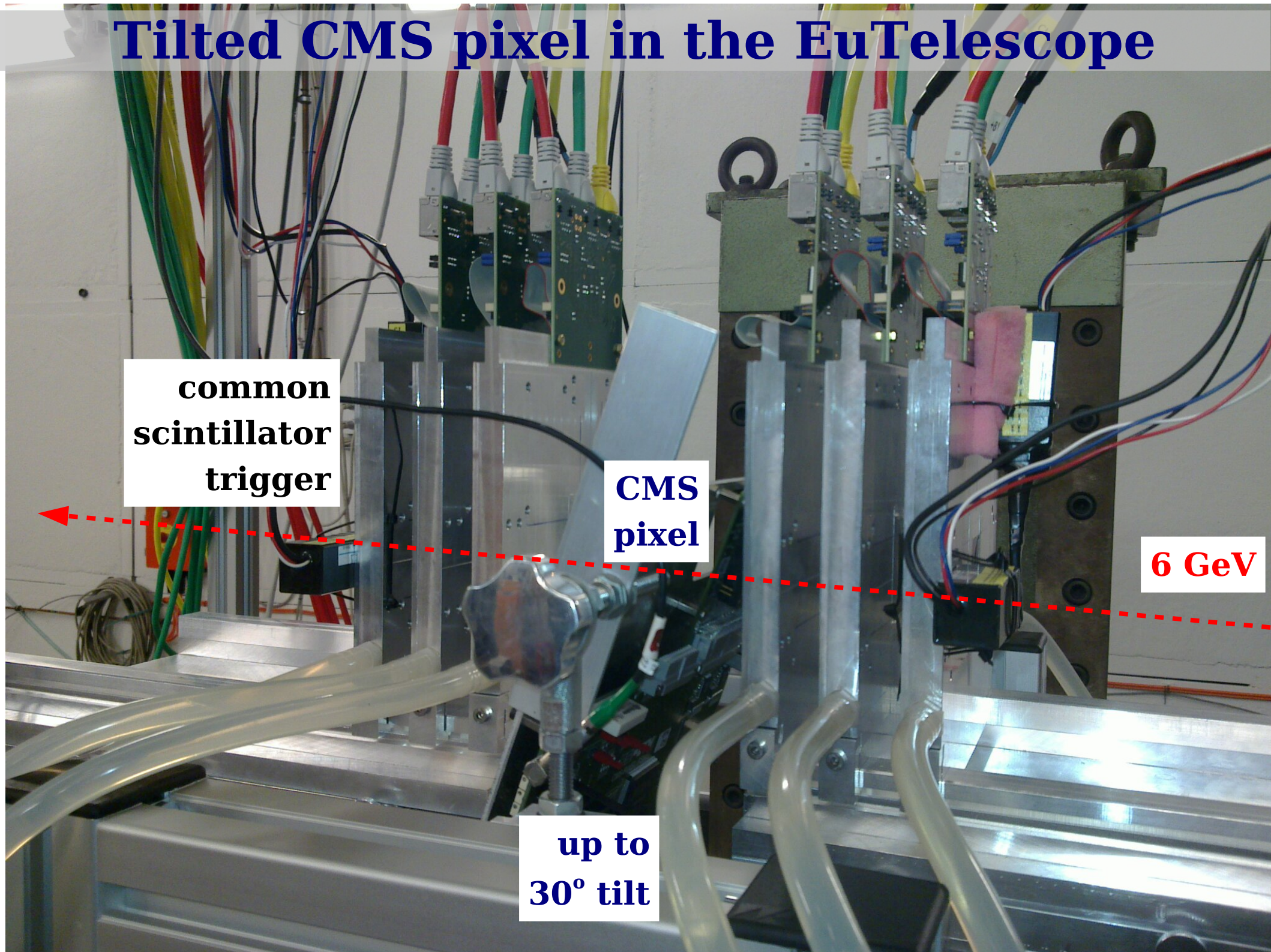
Efficiency measurement in the test beam



Summary

- CMS pixel sensor operated in the DESY test beam
- CMS pixel resolution measured as function of tilt angle:
  - Optimal resolution 8 µm at 20°,
  - charge sharing appears almost linear at 20°,
  - can we improve on the simple center-of-gravity cluster algorithm?
  - CMS uses template matching.
- Expect further improvements from the new ROC:
  - lower threshold
  - less 1-row clusters
  - even better resolution
- Next: efficiency measurement
  - needs 2nd CMS pixel as timing reference
- We are ready to test the PSI46xdb on single chip modules!

Tilted CMS pixel in the EuTelescope

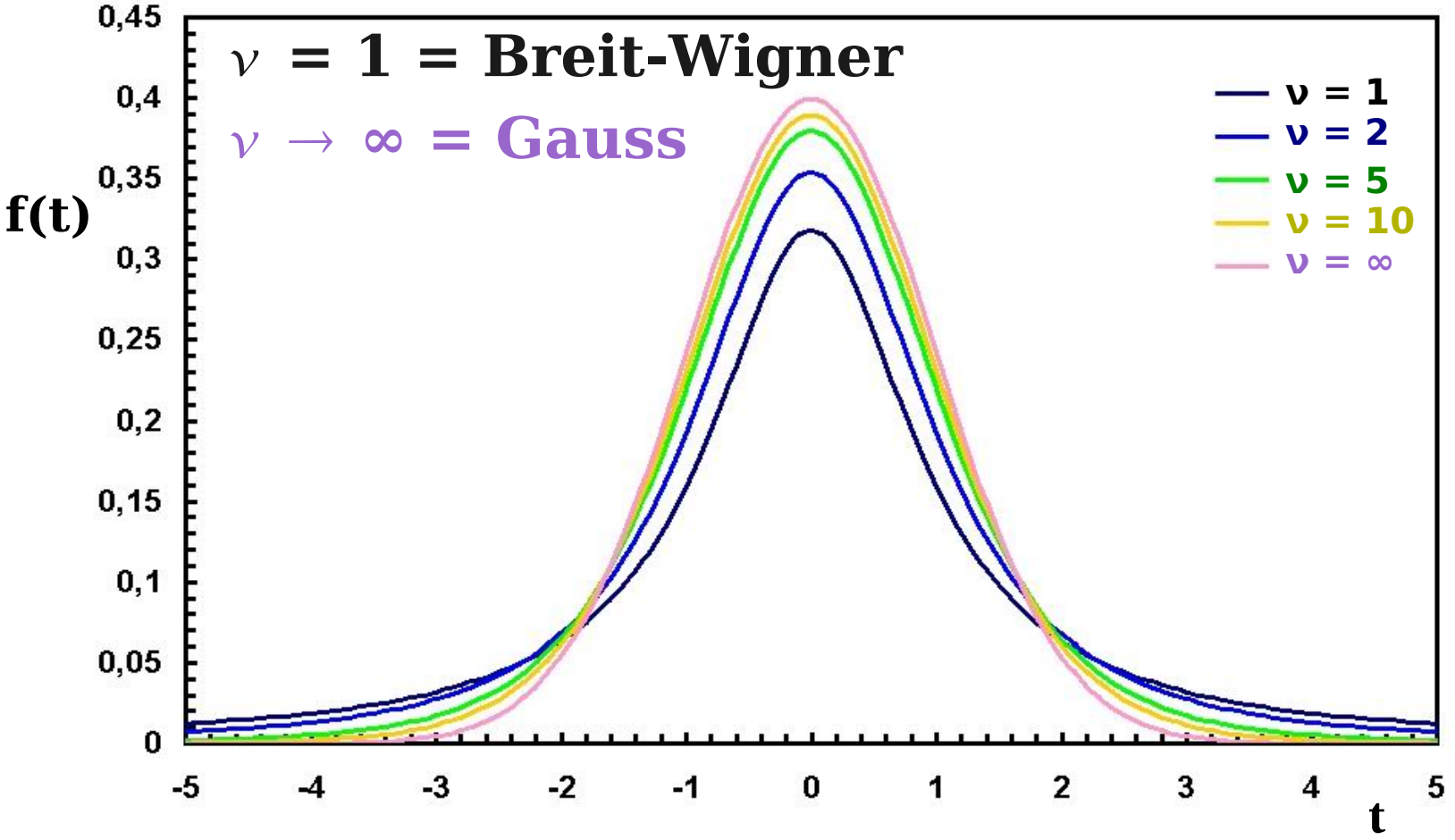


Fitting peaks with Student's *t*

$t = (x\text{-}x_0)/\sigma$ = normalized residual.

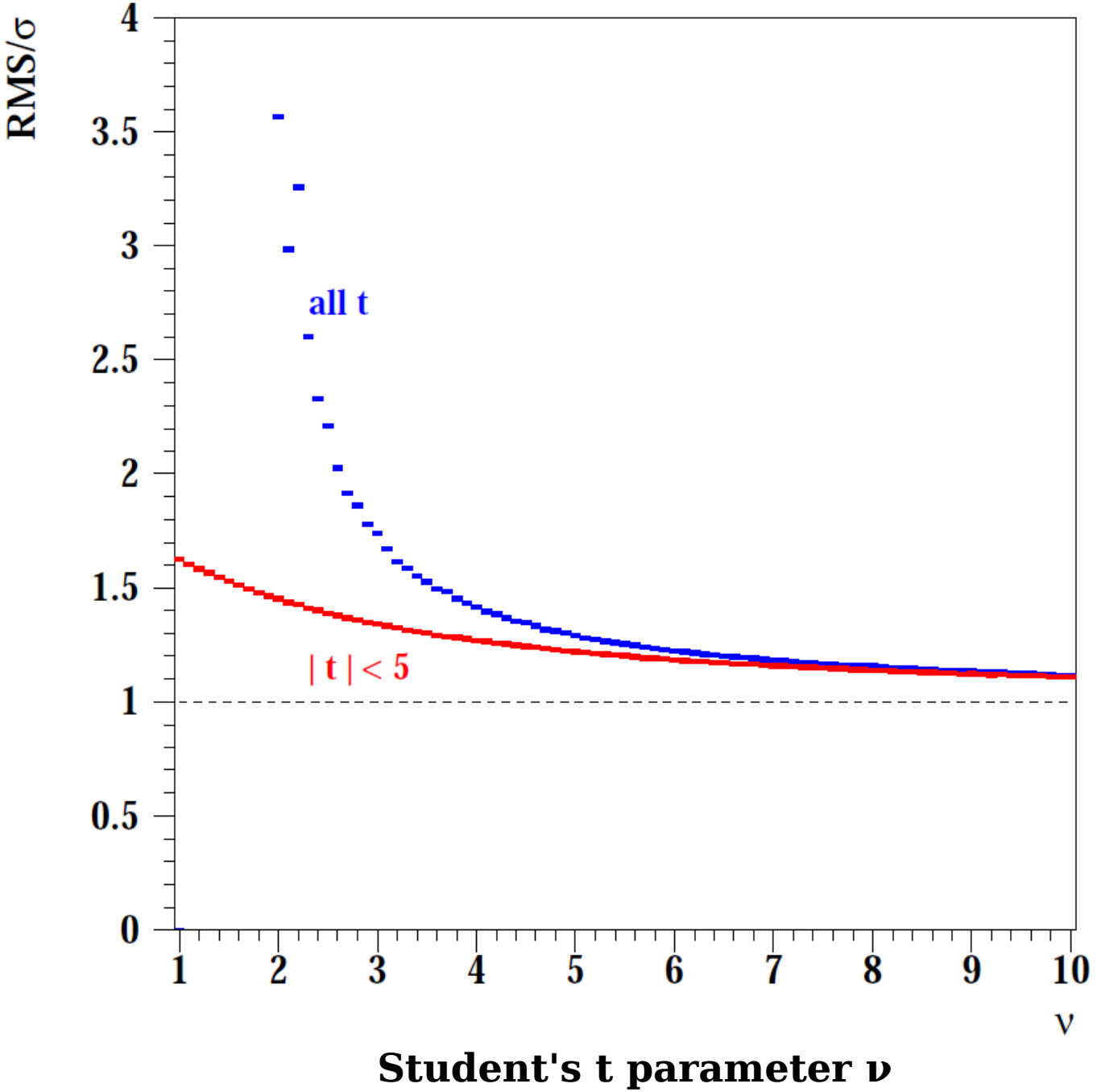
$$f(t) = \frac{\Gamma((\nu+1)/2)}{\sqrt{\nu\pi}\,\Gamma(\nu/2)}(1+t^2/\nu)^{-(\nu+1)/2}$$

f(t) is a normalized probability density.
Γ function is in PAW, ROOT.



Parameter ν interpolates between Gaussian and Breit-Wigner.

rms/σ for Student's t



- Generate random numbers according to Student's t for different ν (see W. Hoermann, Computing 81 (2007) 317).
- calculate rms:
  - for all t. (rms diverges for ν = 1).
  - for | t | < 5. (rms stays below 1.62 for all ν ≥ 1).
- Asymptotic value (rms/σ = 1) slowly approached.