CMS pixel resolution and efficiency in the DESY test beam telescope

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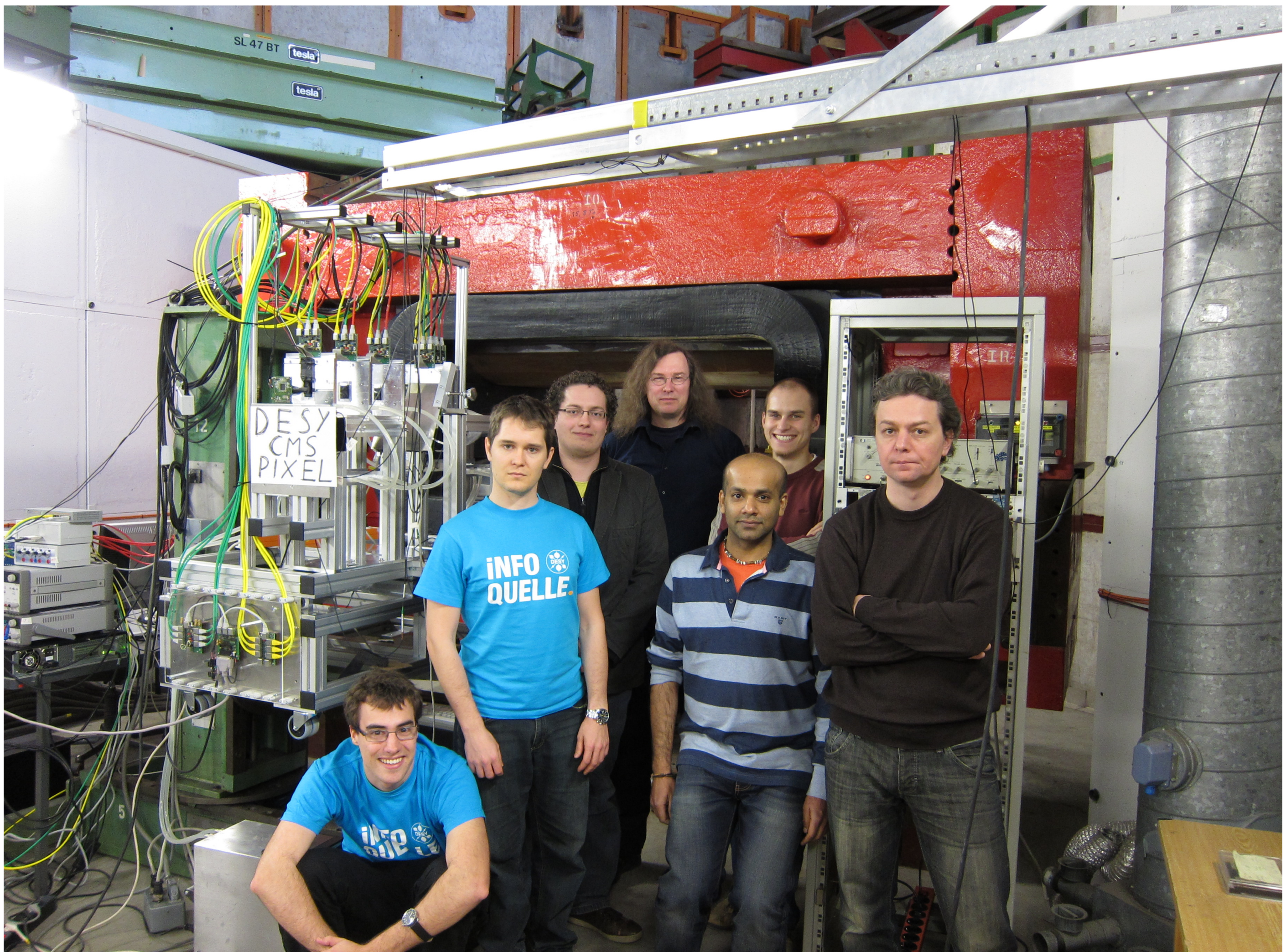
DESY CMS Phase I pixel upgrade, 18.5.2012

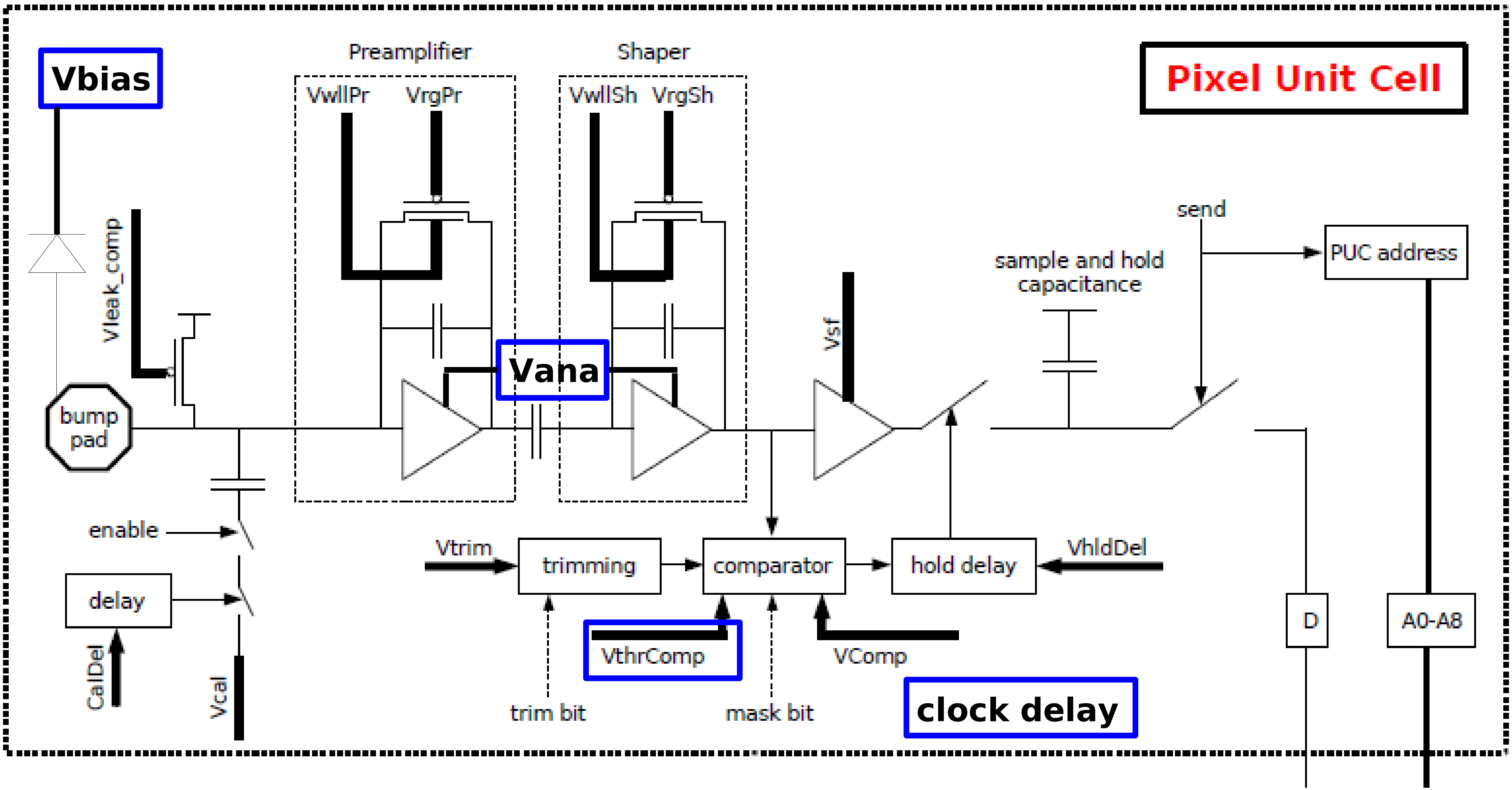


- setup
- partial analysis:
  - threshold scan
  - tilt scan
  - bias scan

Goals for the April 2012 beam test

- Take reference data with the present Pixel ROC PSI46 v2.3
  - large statistics
- measure efficiency and resolution:
  - vs clock delay (0..25 ns) **not done, clock jumping**
  - vs bias voltage (up to 150 V) **done**
  - vs threshold (soft to hard, cutting small pulses) **done**
  - vs tilt angle (0 to 30 deg, mimic Lorentz angle) **done**
- Procedure established:
  - operate 2 single chip modules
  - clock synchronized with the DESY II beam
  - parallel DAQ with 2 PSI46 test boards and the EUDET telescope
  - analyze with modified/extended EUTelescope software
- 2^{nd} beam test with new PSI46xdb in summer

PSI46 pixel ROC



vary in beam test

planned programme

- Defaults: DUT at 20°, bias -150 V, softest threshold, optimal delays
- Optimize rate in test beam by adjusting position ½ day
- Clock delay scan: 0..24 ns, 4 ns steps, finer at edges (~10 runs) ½ day
- Bias voltage scan: -150 to -10 V, 20 V steps (8 runs) ½ day
- DUT tilt scan: 0°, 5°, 10°, 15°, 18°, 20°, 22°, 25°, 30° (9 long runs) 1.5 day
- Threshold scan: `VthrComp` 97 to 7 step 10 (10 long runs) 1.5 day
- gain calibrations each day
- scan Vana (less power), always re-optimize other DACs 2 days
  - possibly repeat delay and threshold scans
- another chip as DUT 1 day
- repeat problematic runs 1 day
- reserve 1 day + weekends + extension week

EuTelescope software in Marlin

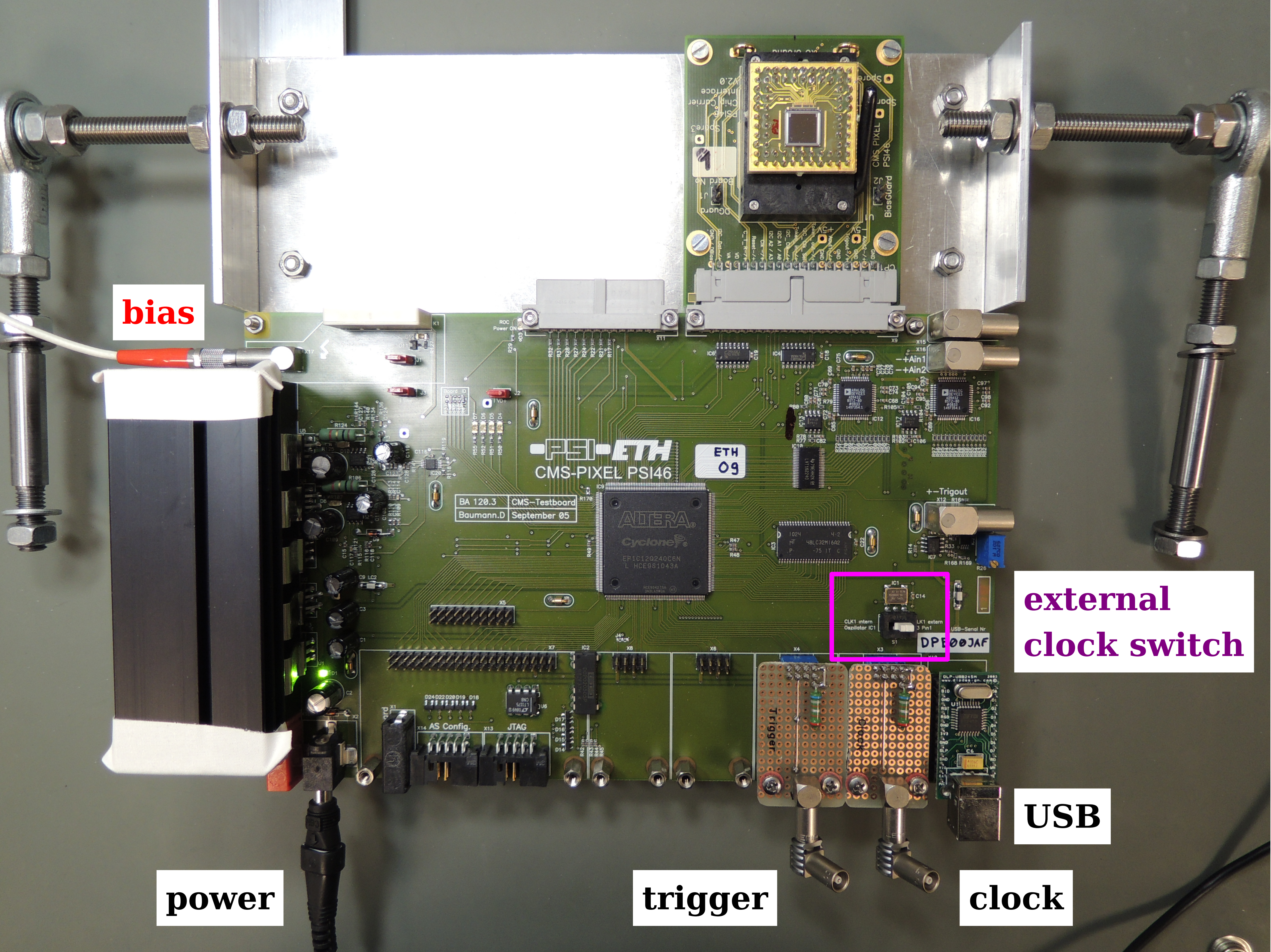
step	output.format	constants
0. EUDAQ data taking	native.bin	
1. convert, find hot pixels	raw.lcio	hotpixel.db
2. clustering	clusters.lcio	offset.db
3. hits, coarse align	hits.lcio	pre-align.db
4. Millepede alignment with GBL	pede.bin	align.db
5a. read CMS, GBL tracks Millepede align	tracks.lcio	DUTal.txt
5b. re-run GBL track fit	final plots	

All steps produce ROOT histograms for monitoring

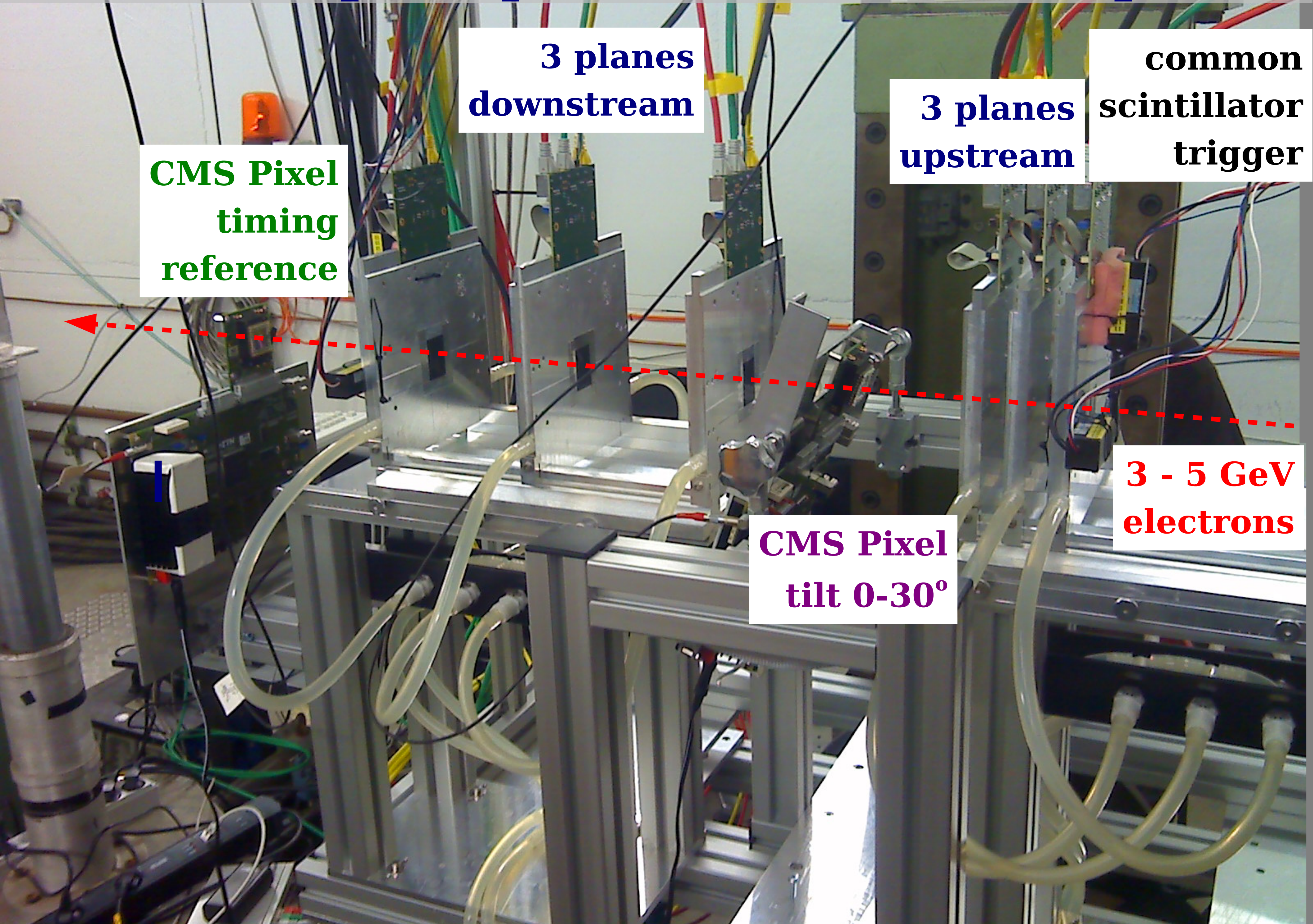
alignment of DUT and REF not yet fully automated **DP**

code: `desy-cms010:/data/group/pixel/software` **HP, AB**

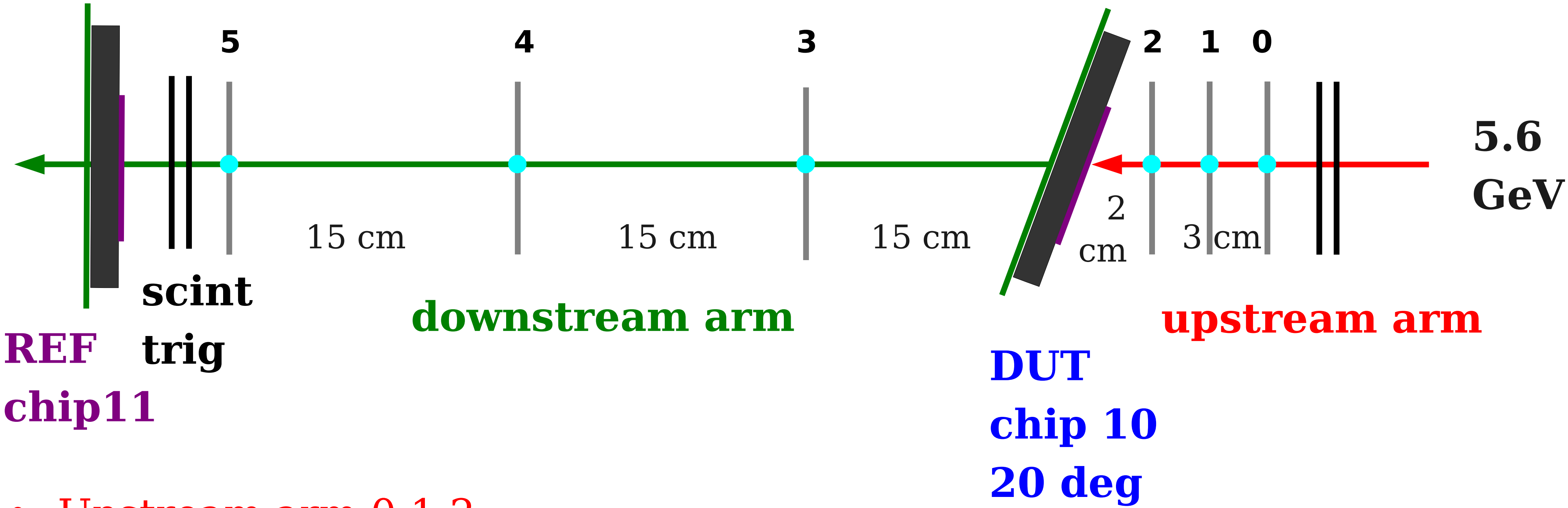
data: `desy-cms010:/data/group/pixel/testbeam`


bias
external
clock switch
USB
power
trigger
clock
CMS-PIXEL PSI46
ETH 09
BA 120.3 CMS–Testboard
Baumann.D September 05
ALTERA
Cyclone
AS Config.
JTAG
+–Trigout
–+Ain1
–+Ain2
Trigger

2 CMS pixel planes in the telescope

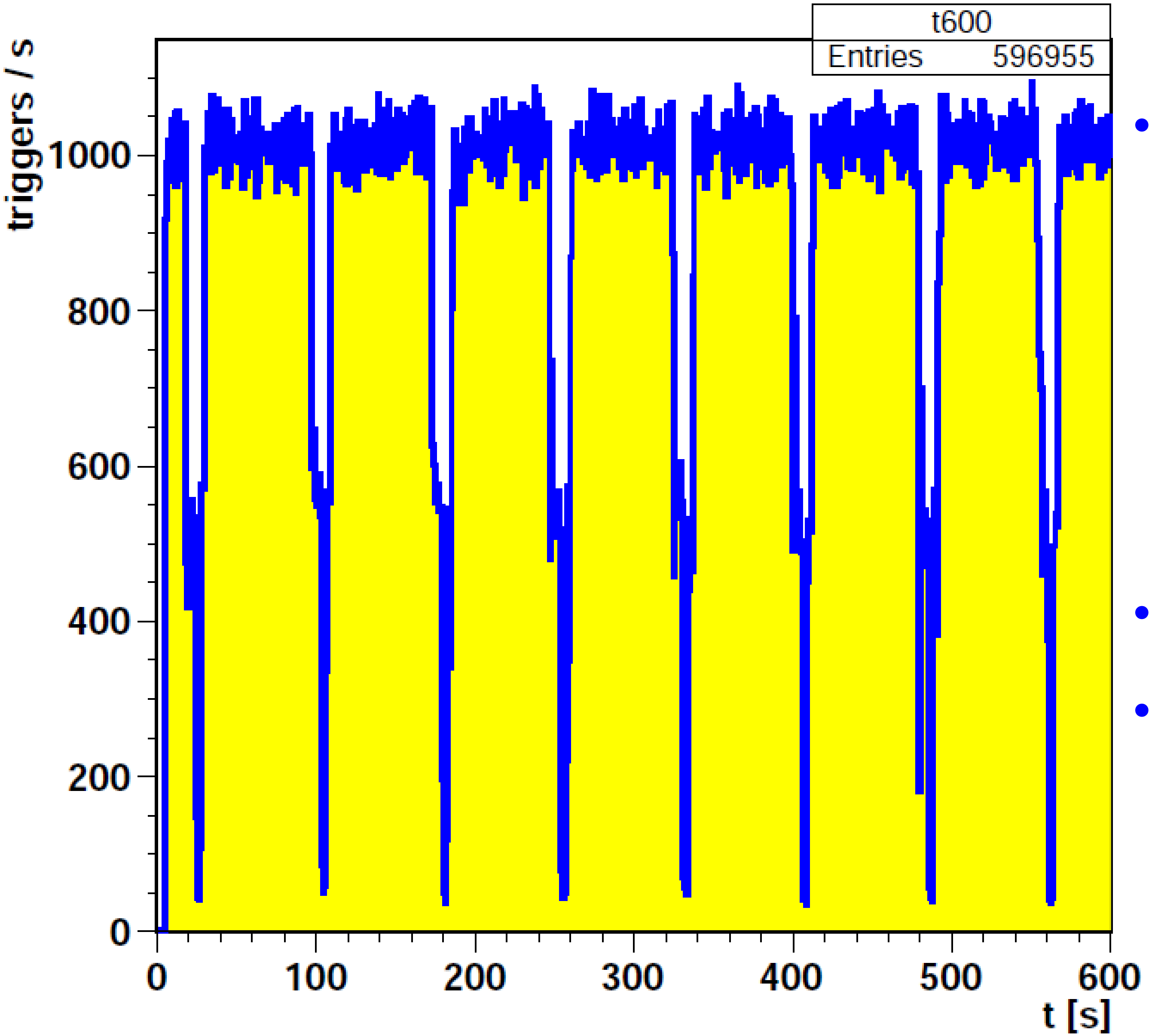


Default set up



- Upstream arm 0-1-2:
  - as close as possible to DUT, but allow for tilting (open for insertion)
- DUT = single chip module, tilted by up to 30°,
- Downstream arm 3-4-5:
  - equally spaced between DUT and REF, allow for DUT tilting
- REF = single chip module for timing, as close as possible behind scint
- trigger: 2-fold coincidence (config: TLU AndMask 12)

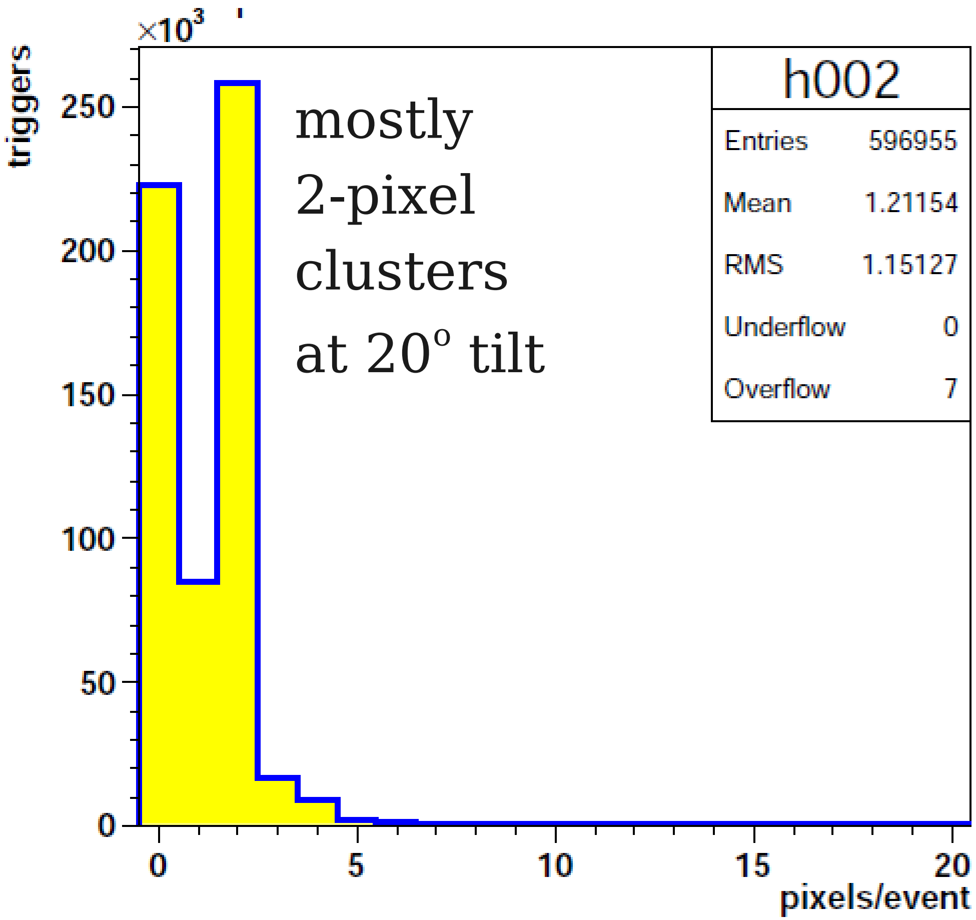
Data taking



- Telescope trigger:
  - back pair (2&3) in coincidence,
  - 1 kHz at 5.2 GeV with 10^{10} e in DESY,
  - 650 Hz at 5.6 GeV
- Most runs: 600 s.
- Dips:
  - DESY filling PETRA every 75 s.

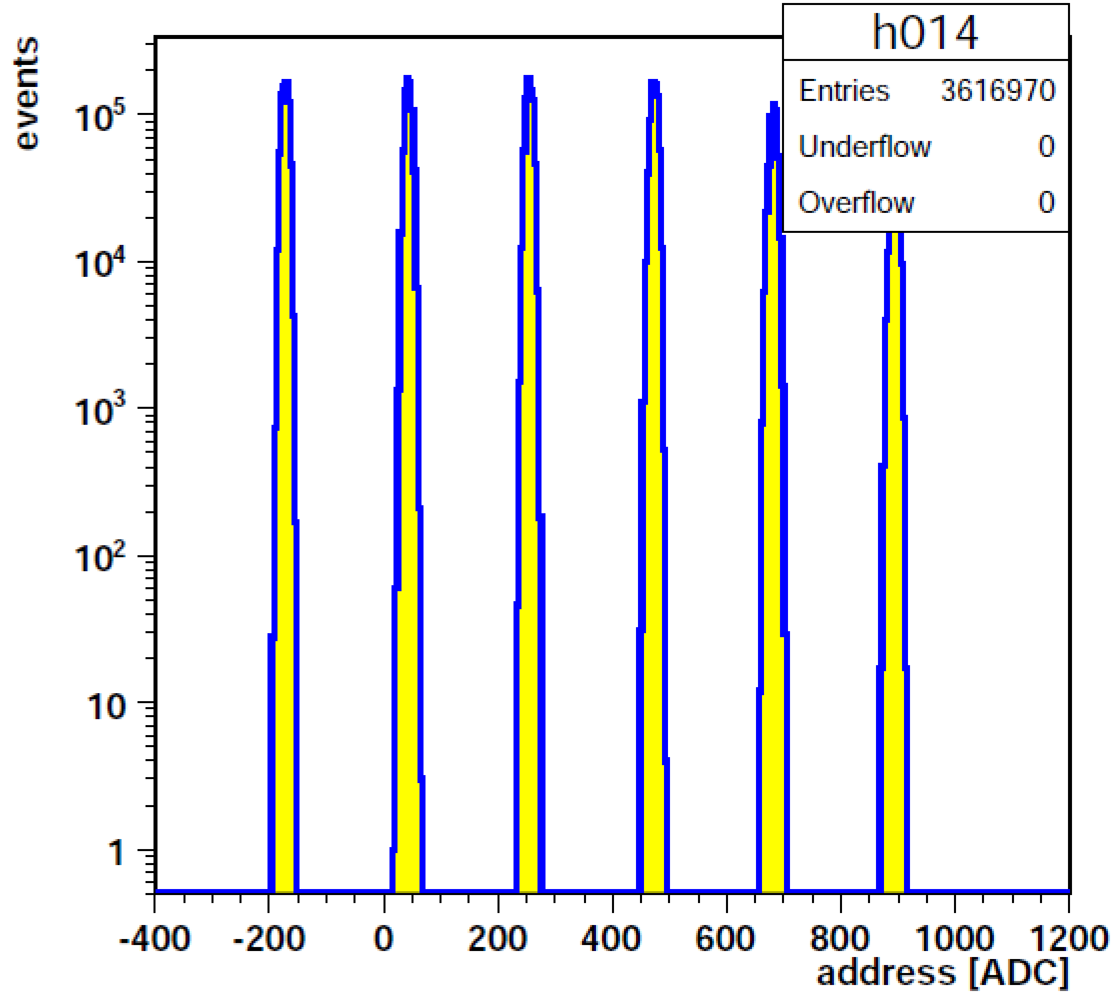
CMS pixel raw data monitoring

pixels / event



empty triggers by design:
CMS sensor is smaller than trigger

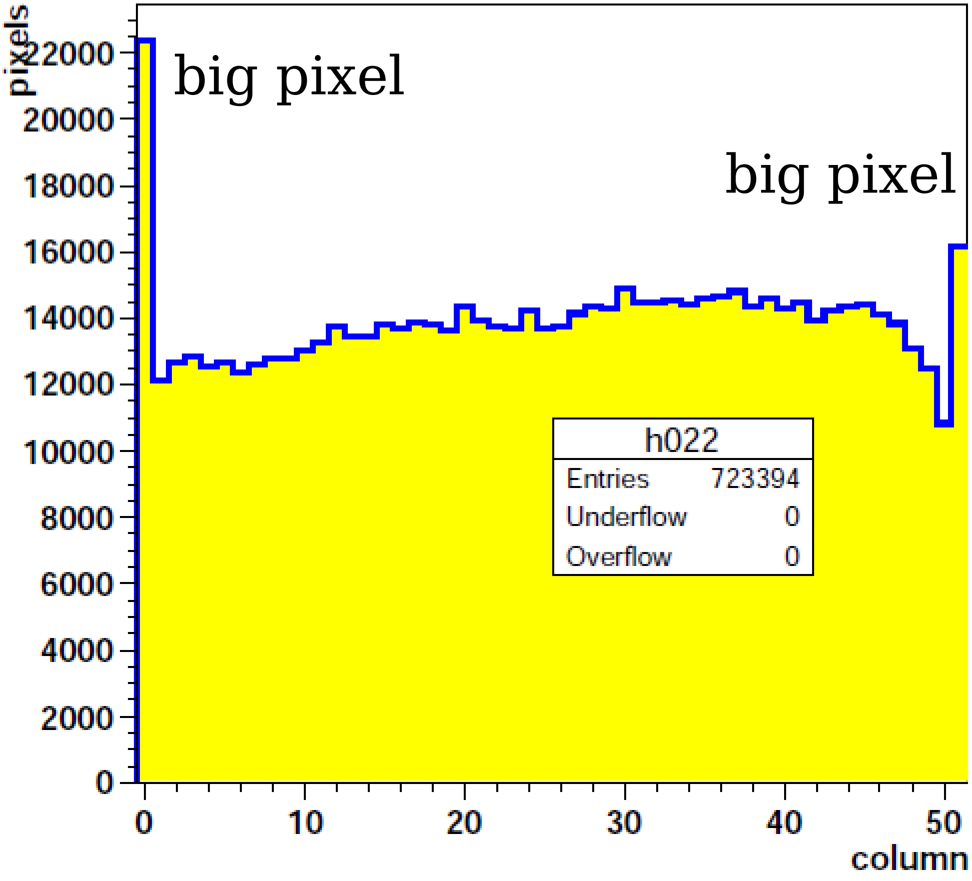
hexal address encoding



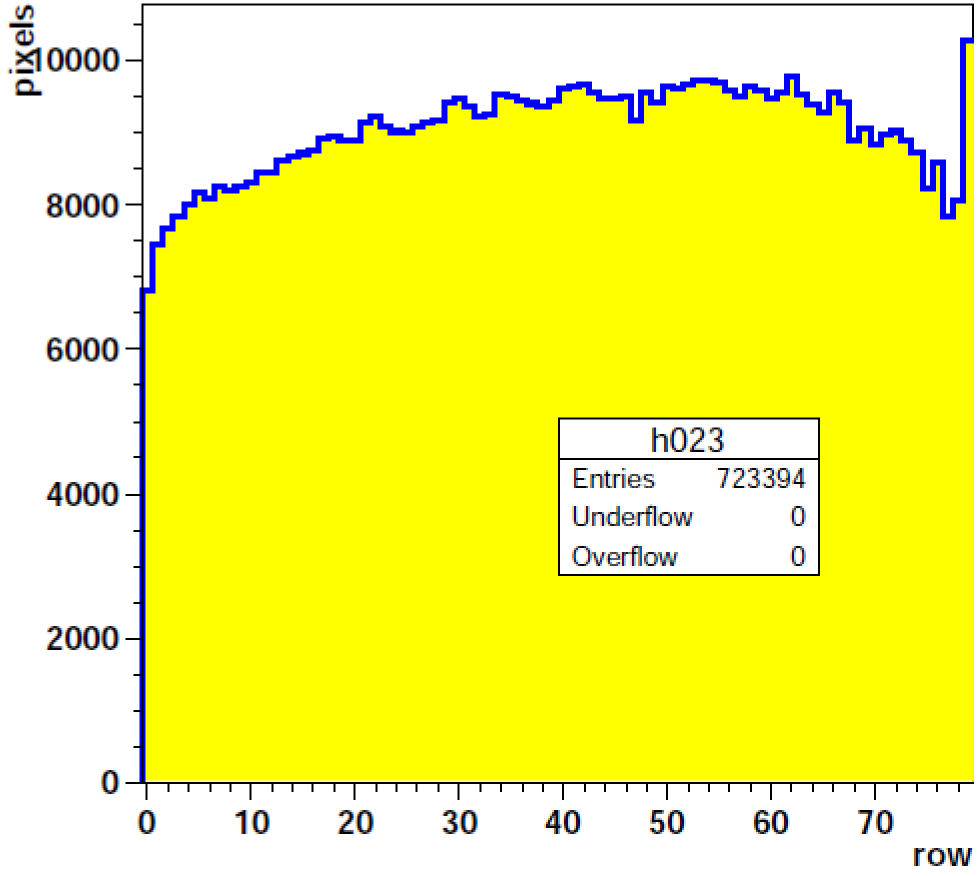
6 levels perfectly separated

CMS pixel occupancy

columns = horizontal



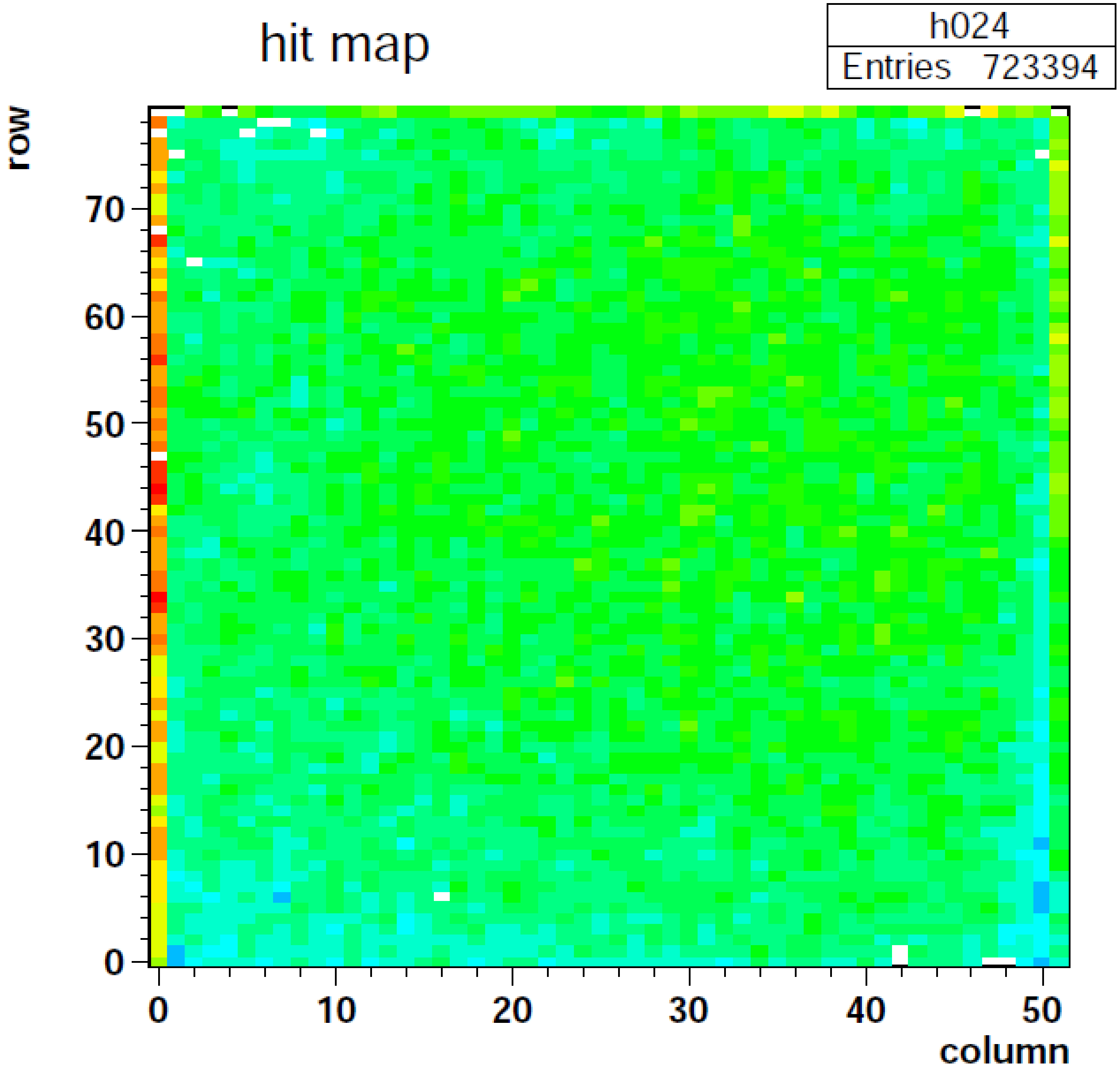
rows = vertical



CMS pixel nicely illuminated

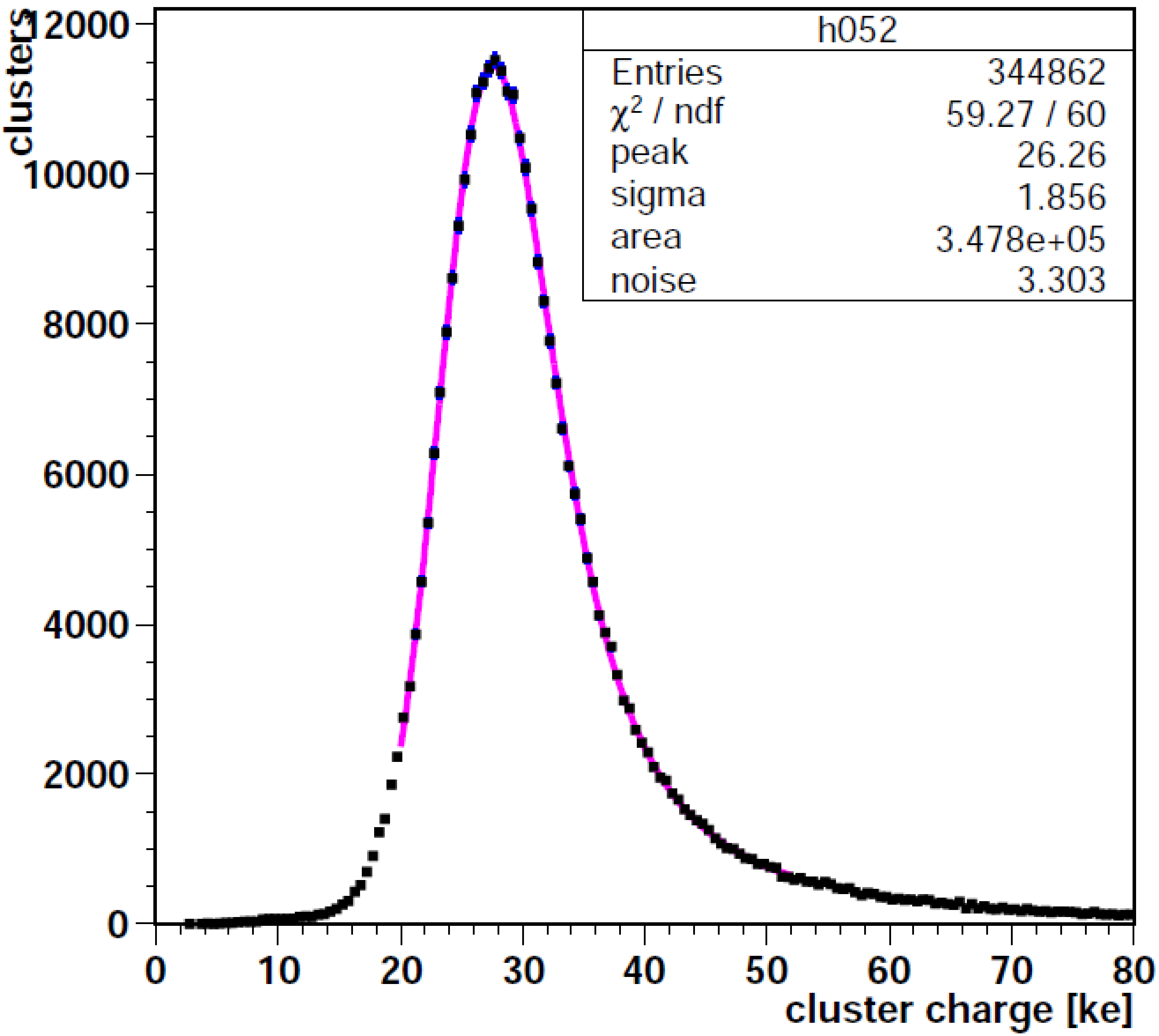
Chip 10: all columns functional

CMS pixel hit map



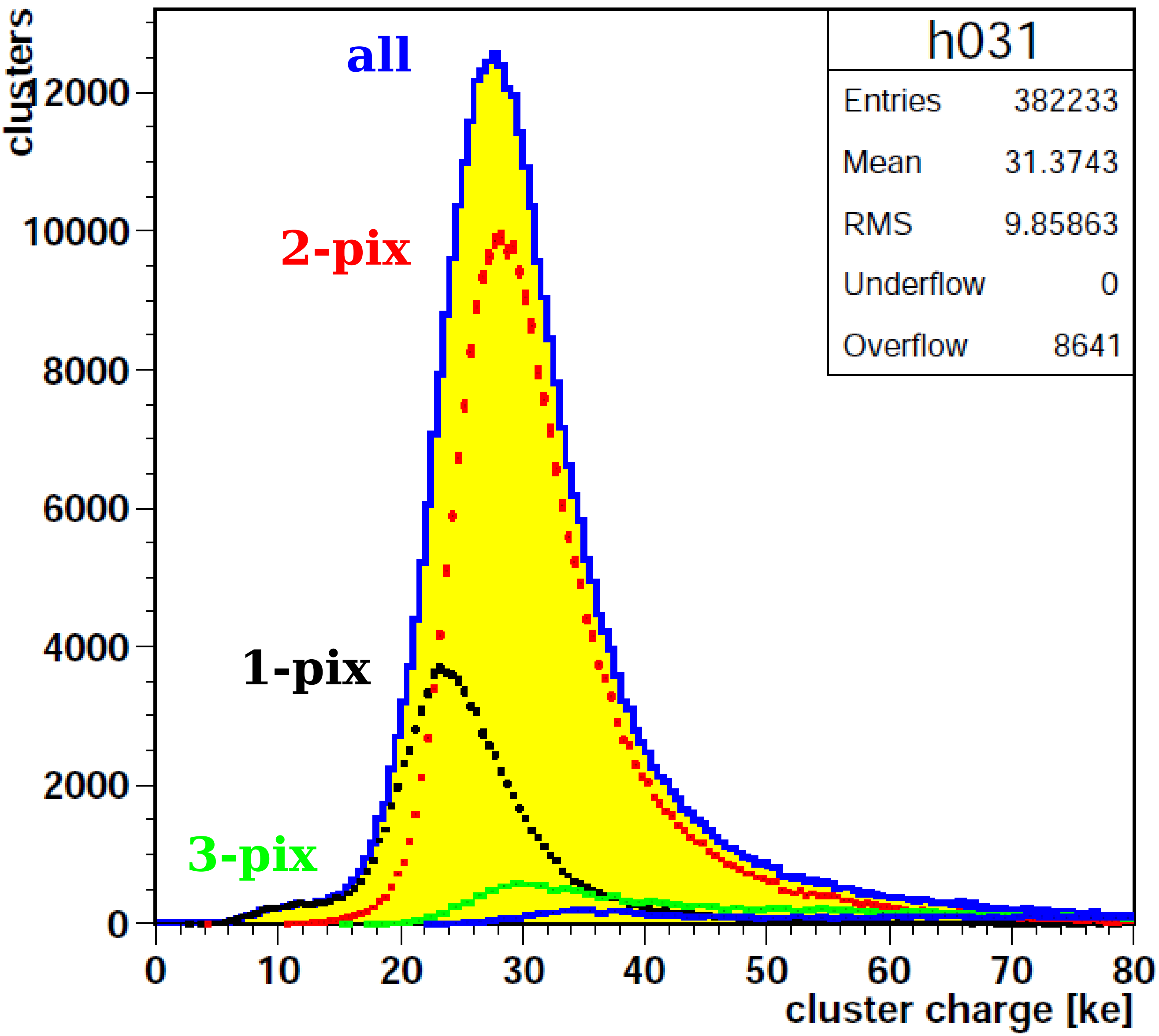
- Chip 10:
  - a few dead pixels, mostly at the edges
- Run 1778:
  - 174 entries/pixel on average in 600 s

Pulse height distribution



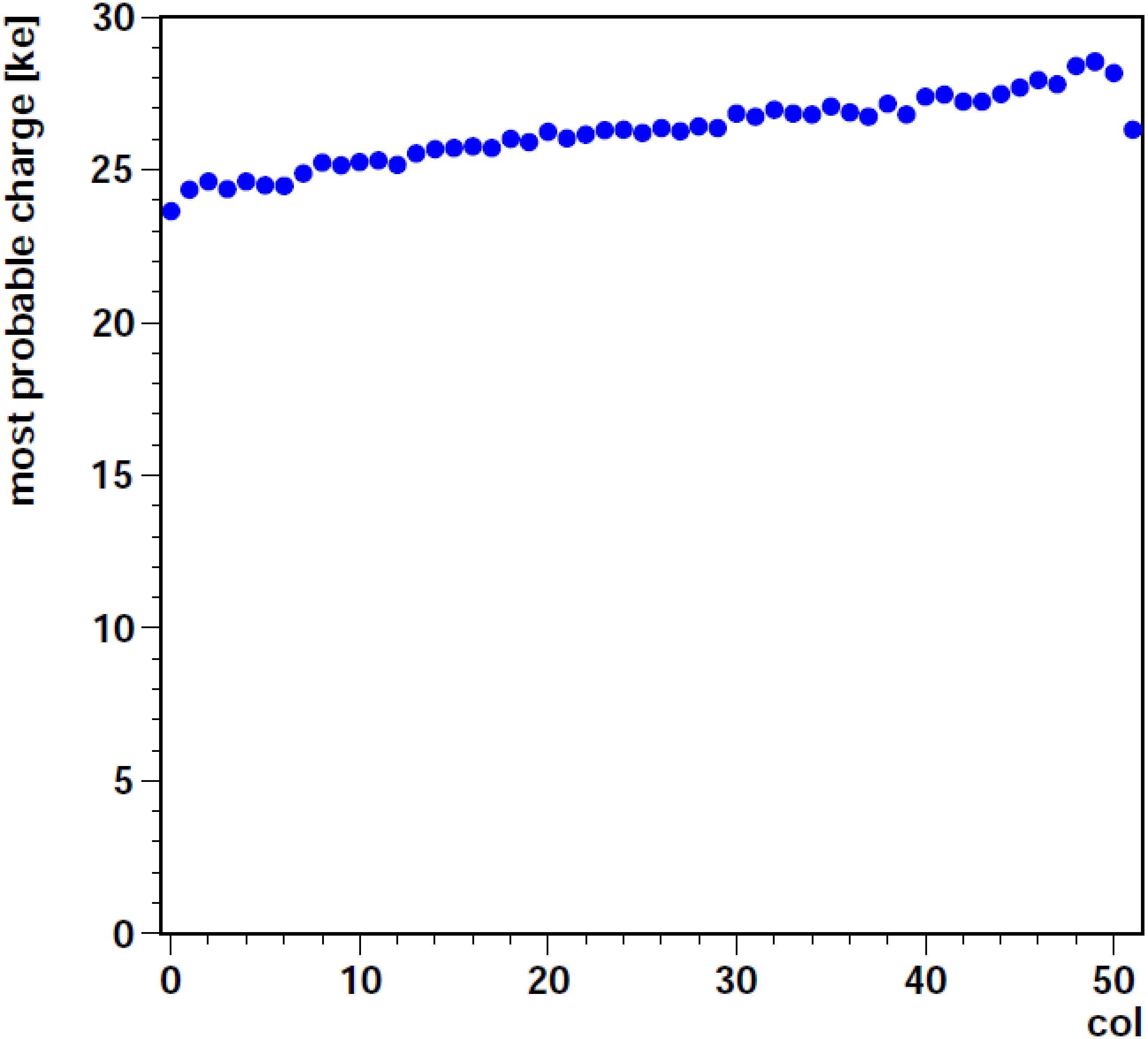
- Chip 10 at 20° tilt.
- Gain calibration from Shiraz.
- fiducial cuts:
  - edge pixels avoided.
- Landau ⊗ Gauss:
  - perfect fit,
  - peak position and width OK for 285 μm silicon,
  - Gaussian smearing too large: non-uniformities?

Cluster charge



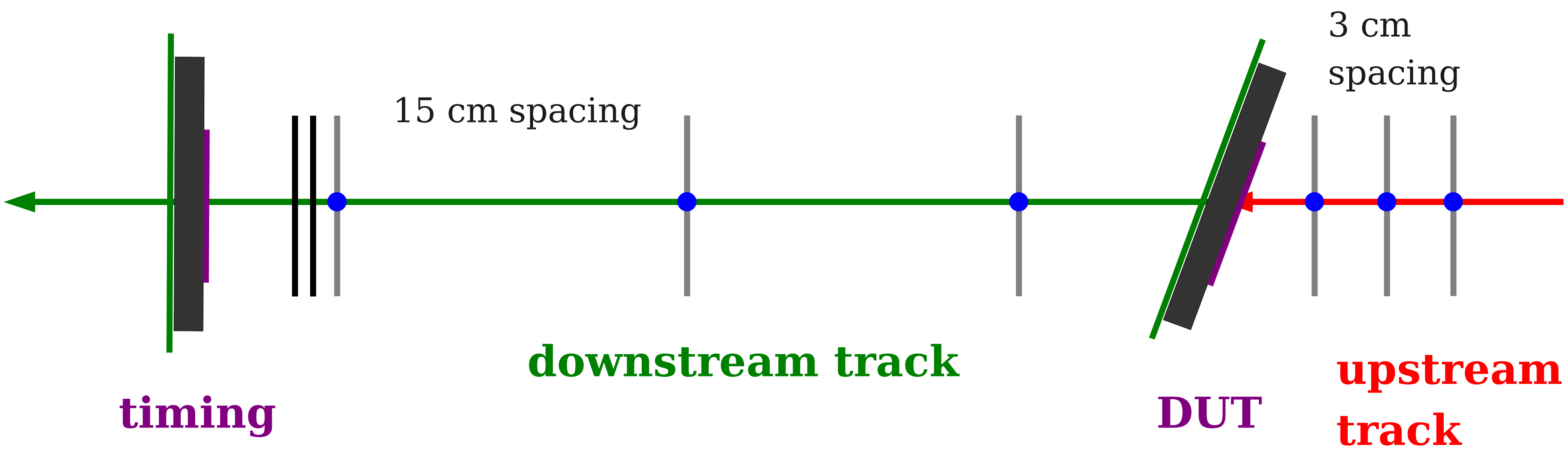
- Chip 10, run 1778, 20° tilt.
- Gain calibration from Shiraz applied
- 1-pixel clusters have less charge:
  - threshold losses

Cluster charge per column



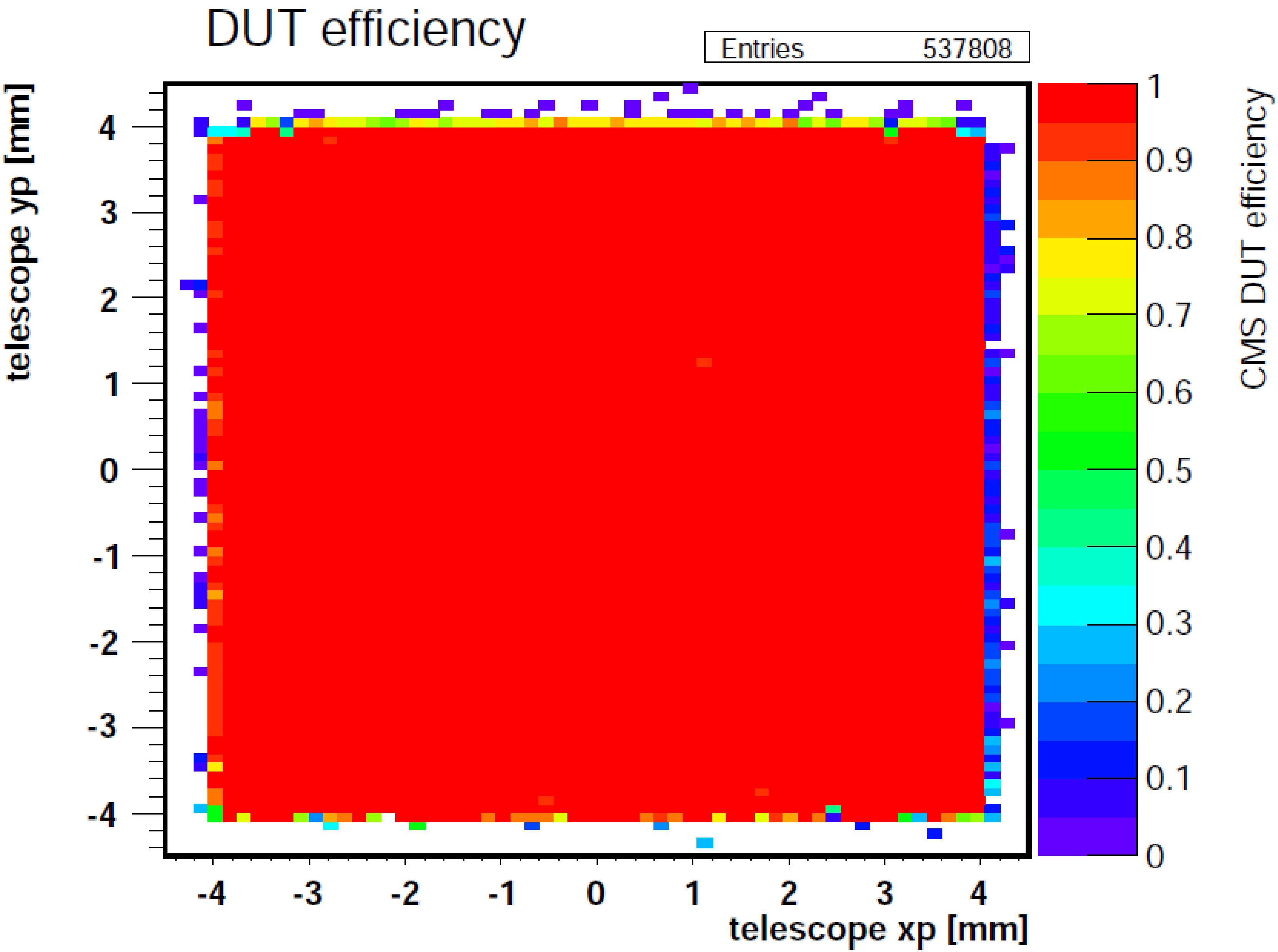
- Chip 10, 20° tilt
- Gain calibration from Shiraz applied
- Landau fit to each column.
- Observe ±8% gain variation across the chip:
  - calibration problem?

efficiency measurement



- Downstream track = telescope planes 3+4+5
  - link to hit in timing reference plane (CMS pixel)
- Upstream track = telescope planes 0+1+2
  - link to hit in device under test (another CMS pixel single chip module)
- match downstream and upstream track at DUT (scattering material)
- **efficiency = (linked hit in DUT) / (telescope track with timing)**
  - **within fiducial region cuts**

Efficiency map

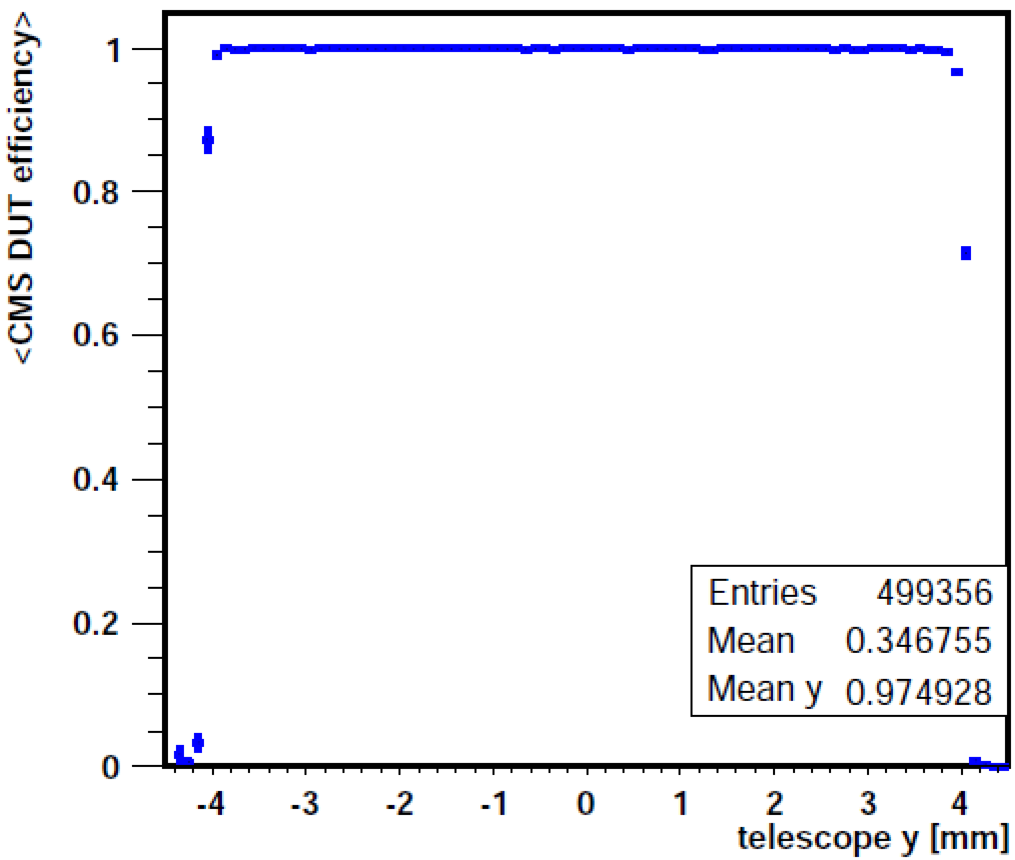


- run 3096
  - 2800 s
- 5.6 GeV
- chip 10
- tilt 20°

Efficiency profiles

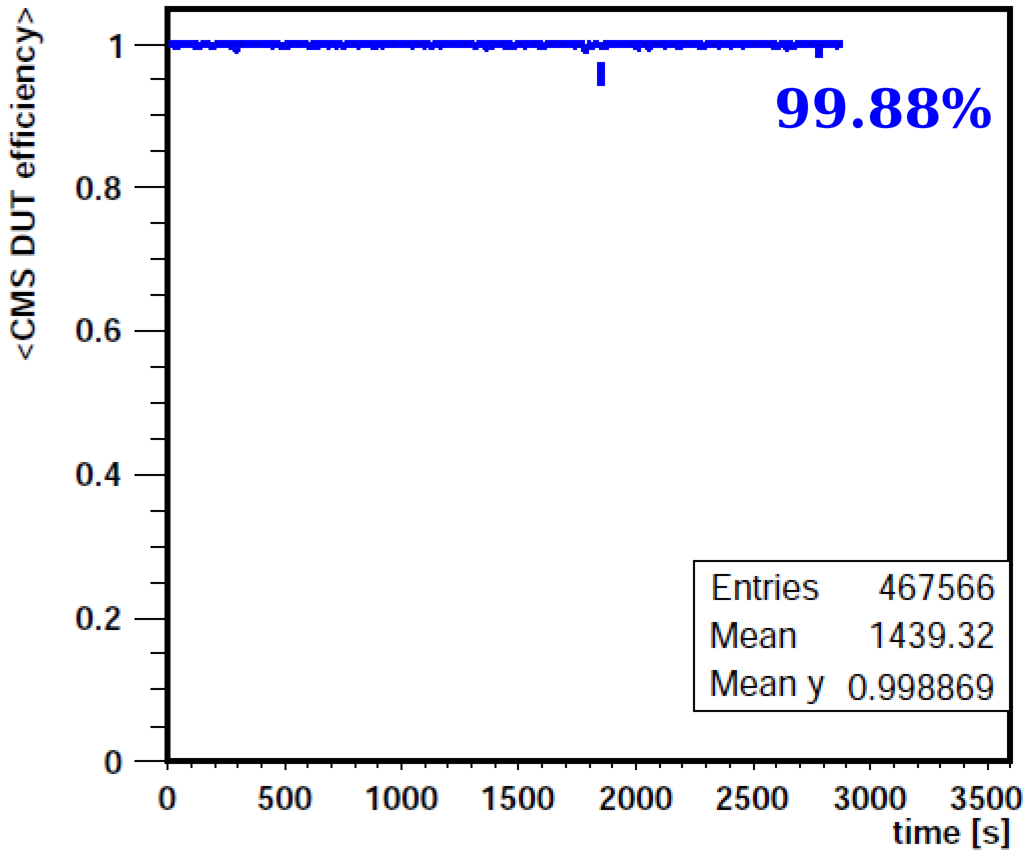
Chip 10, 20°, run 3096

efficiency vs *y* after fiducial cuts in *x*



80 rows

Efficiency vs time after fiducial cuts in *x* and *y*



2800 s

EuTelescope software in Marlin

step	output.format	constants
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1. convert, find hot pixels	raw.lcio	hotpixel.db
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5a. read CMS, GBL tracks Millepede align	tracks.lcio	DUTal.txt
5b. re-run GBL track fit	final plots.pdf	

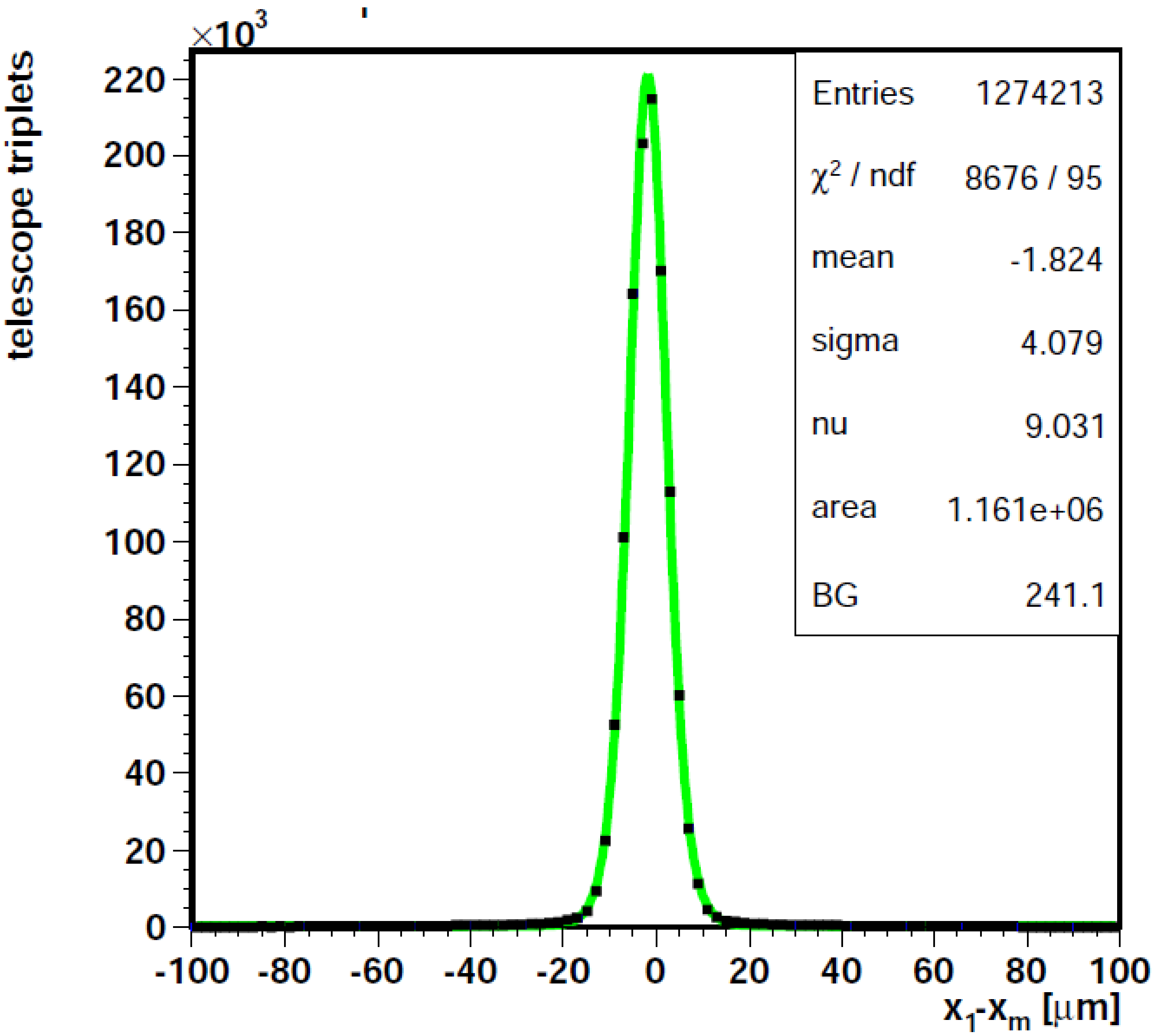
All steps produce ROOT histograms for monitoring

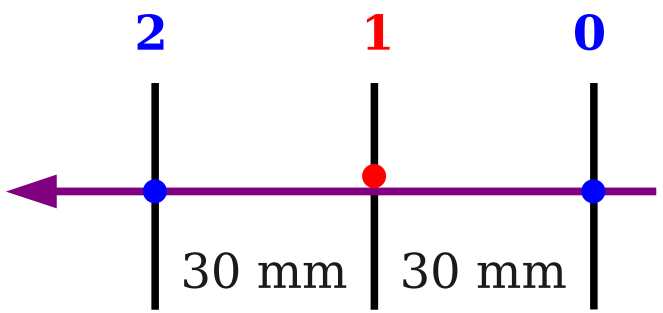
alignment of DUT and REF not yet fully automated

code: `desy-cms010:/data/group/pixel/software`

data: `desy-cms010:/data/group/pixel/testbeam`

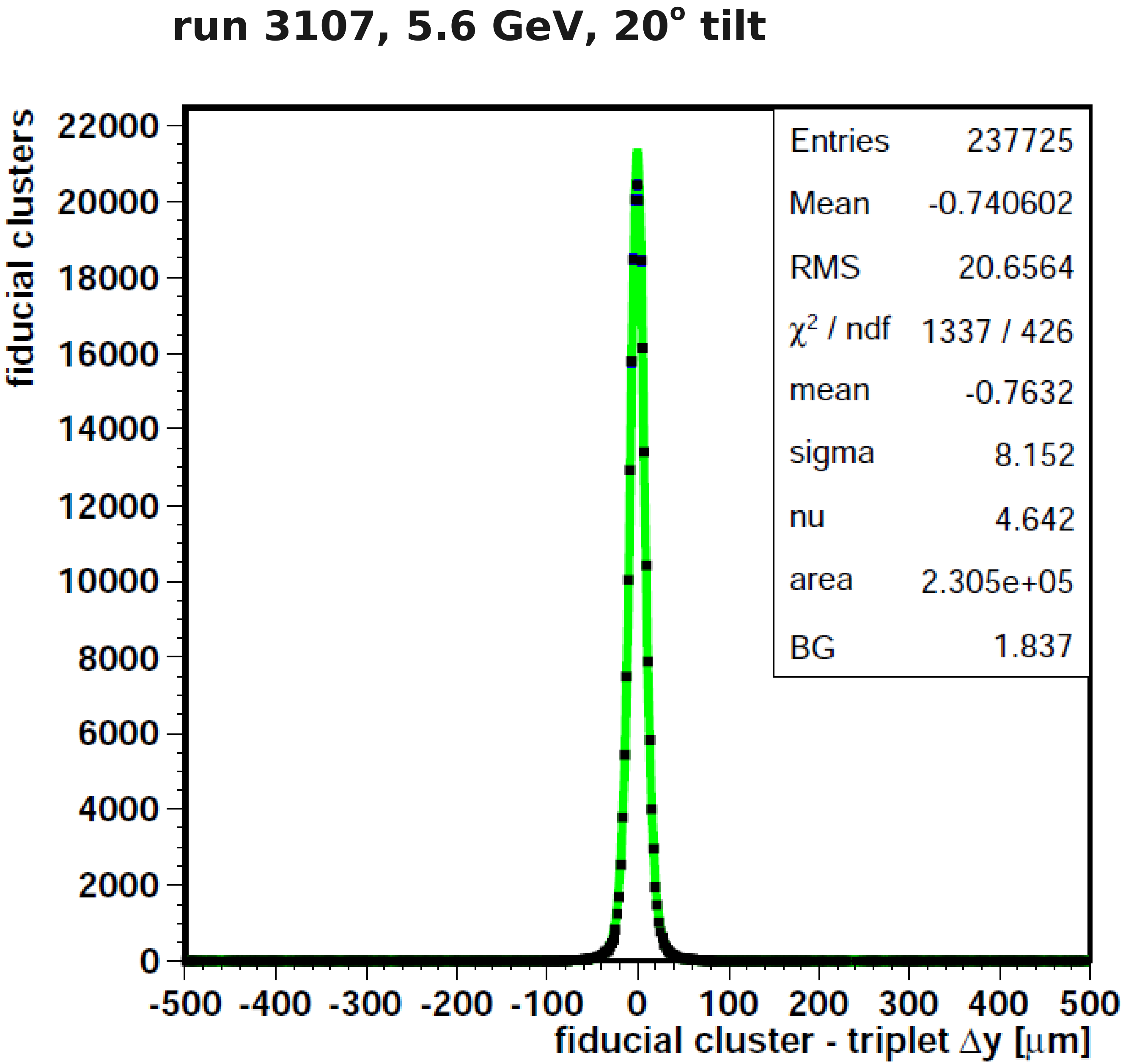
Datura telescope hit resolution

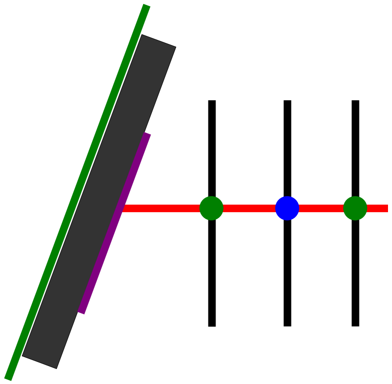




- 5.6 GeV e^+ beam.
- Triplet residuals:
  - 3 upstream planes,
  - hits in plane 0 and 2 form vector,
  - residual to hit in middle plane 1,
  - $\sigma_r = 4.1\ \mu m = \sqrt{(3/2)}\ \sigma_i$
  - **$\sigma_i = 3.3\ \mu m$.**

CMS pixel row resolution





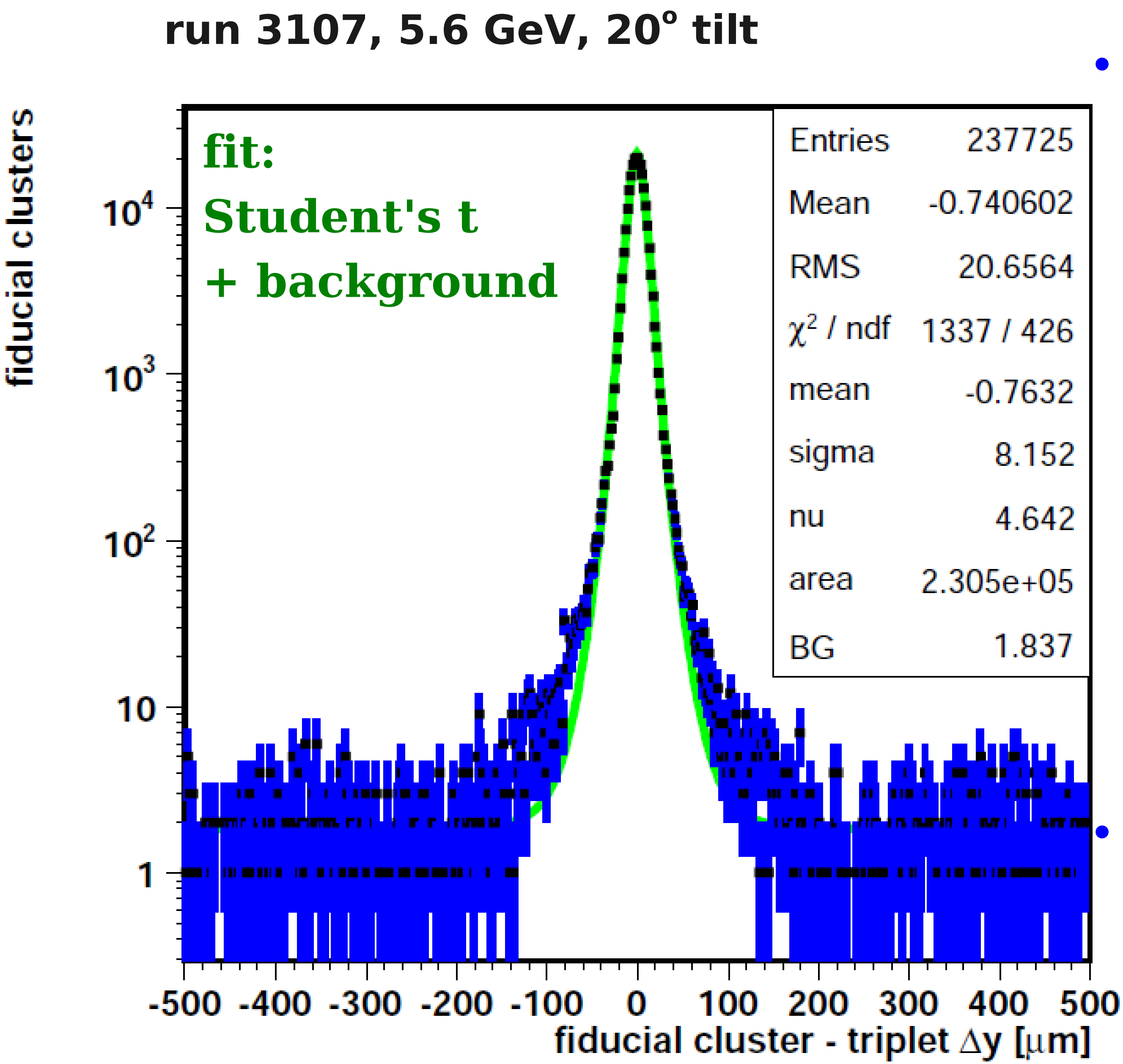
Vertical = rows

- CMS pixel = 100 μm.

Residual:

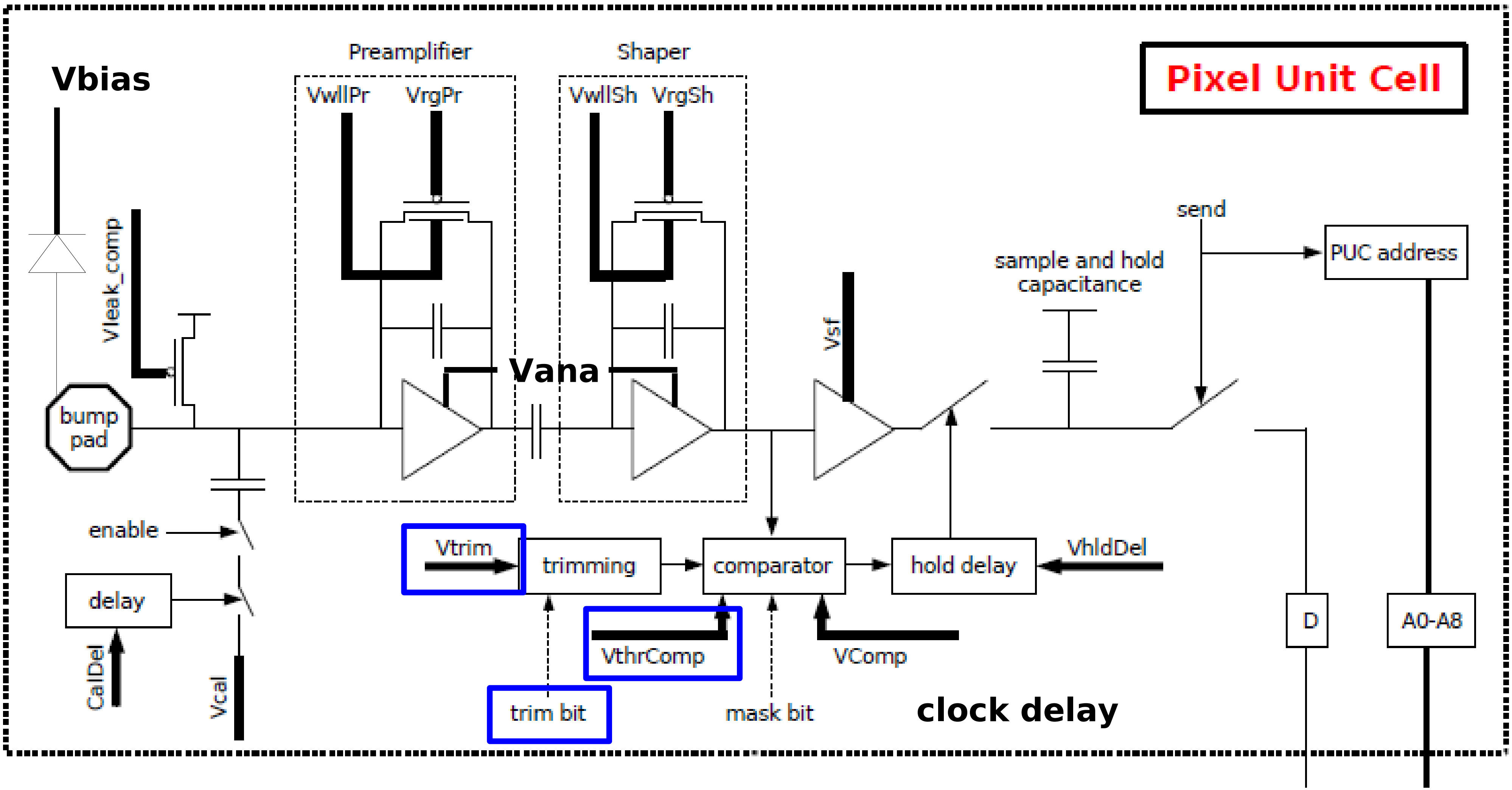
- σ = 8.2 μm,
- telescope extrapolation: 4.5 μm,
- **CMS resolution: 7 μm.**

CMS pixel residual distribution



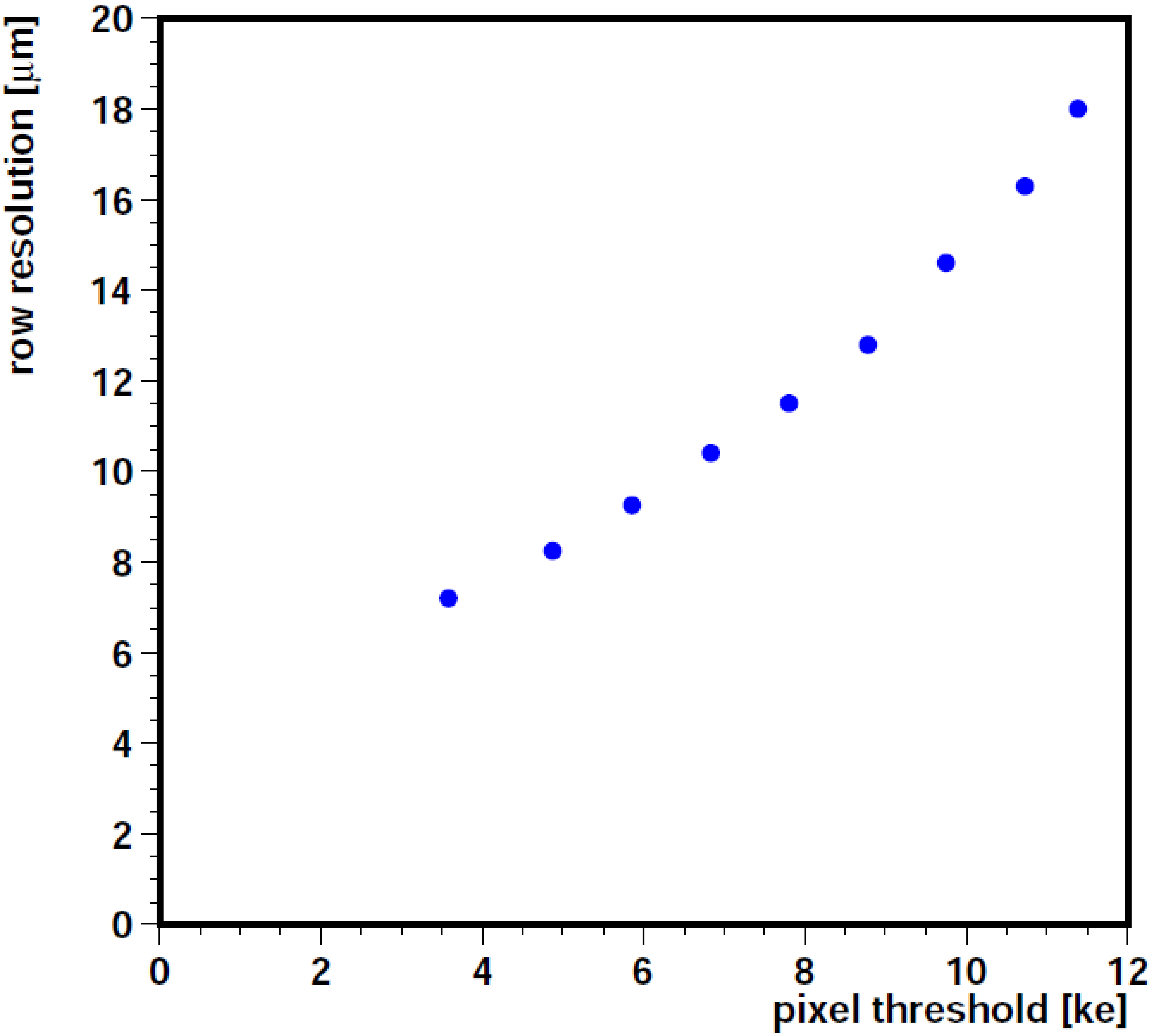
- cleaning cuts:
  - cluster one pixel away from edges,
  - | Δx | < 0.15 mm,
  - only 1- and 2-row clusters (against δ-rays)
  - cluster charge > 18 ke (against wrong timing),
  - | track angle | < 2 mrad (against scattering).
- Result:
  - less tails, more Gaussian

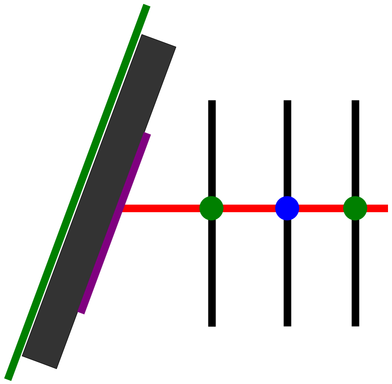
Threshold scan



Threshold from soft to hard: loose small pulses
Simulates reduced charge collection
Study cluster size, resolution, efficiency

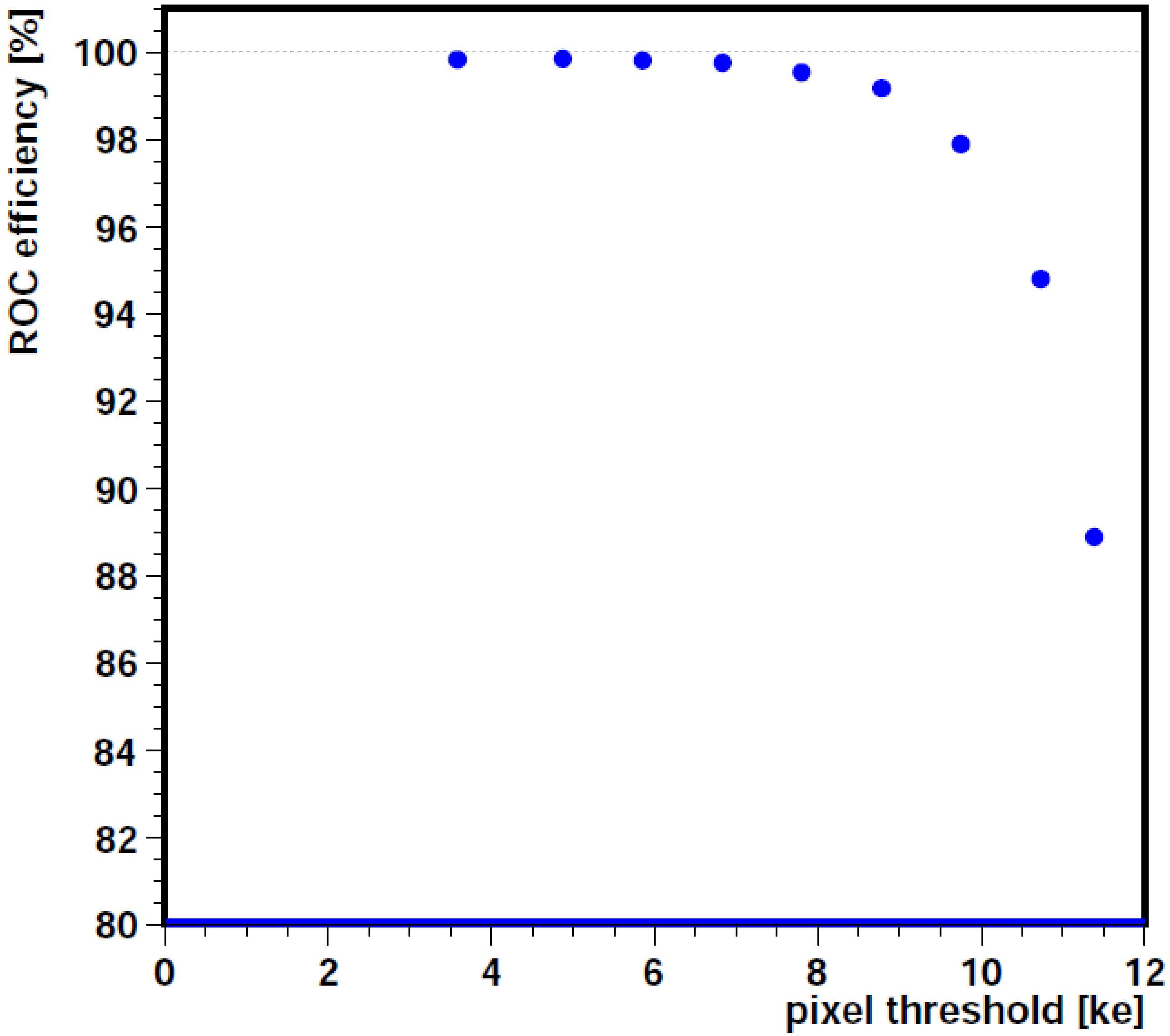
CMS pixel row resolution vs threshold

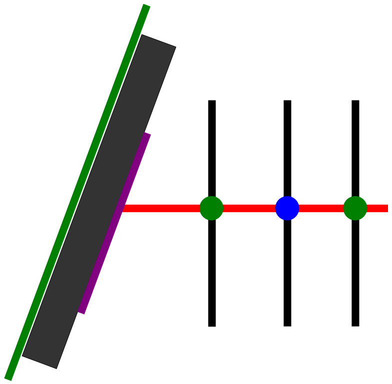




- Chip 10, 20° tilt
- 5.6 GeV, telescope extrapolation uncertainty subtracted.
- lower threshold:
  - charge sharing better exploited
  - better resolution

CMS pixel ROC efficiency vs threshold



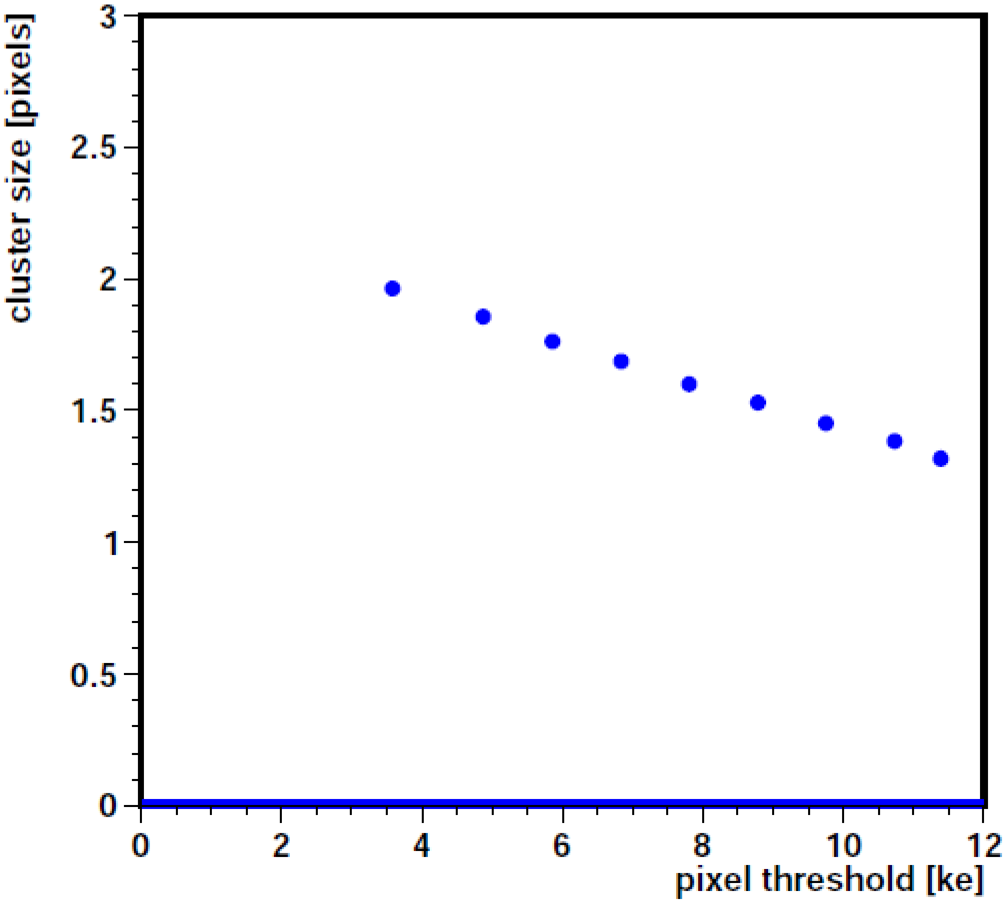


- Chip 10, 20° tilt
- top efficiency 99.85%
- efficiency stays above 99% for thresholds below 9 ke,
  - rapid drop above 9 ke.

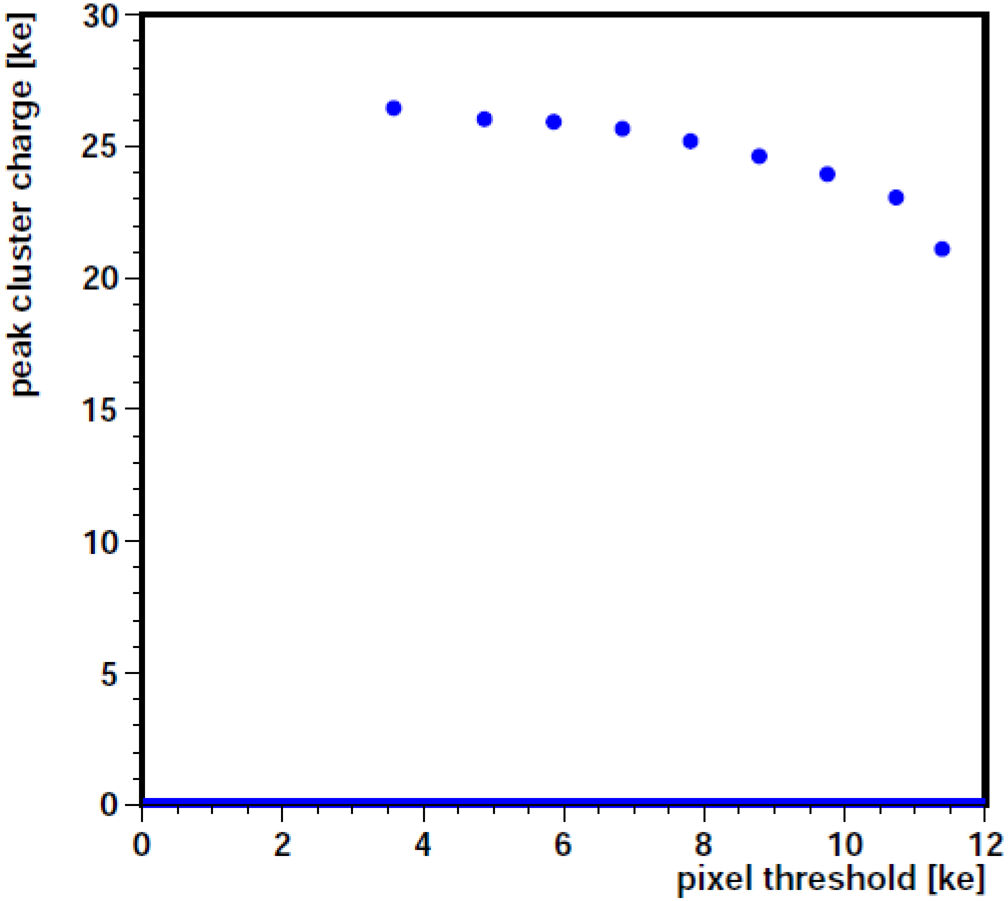
Cluster size and charge vs. threshold

Chip 10, 20° tilt

pixel / cluster



position of Landau peak



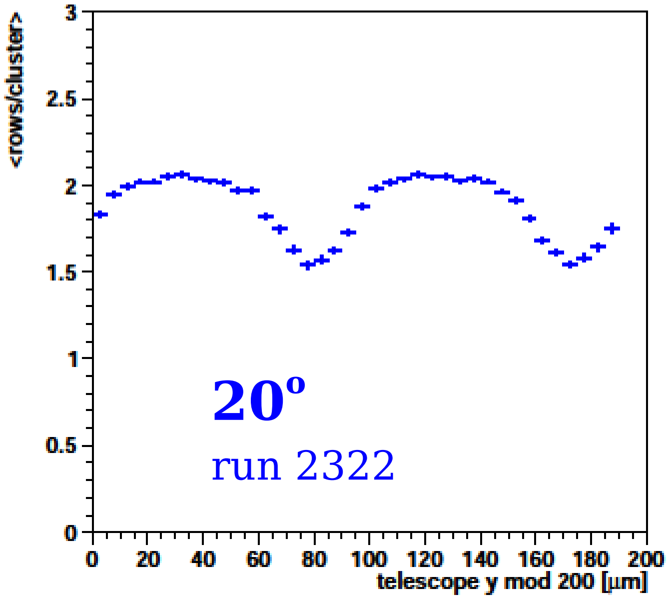
cluster size vs impact point and threshold

0°
run 2331

10°
run 2330

15°
run 2328

y_{impact} mod 200 µm: 2 pixels



20°
run 2322

25°
run 2325

30°
run 2326

charge sharing vs threshold

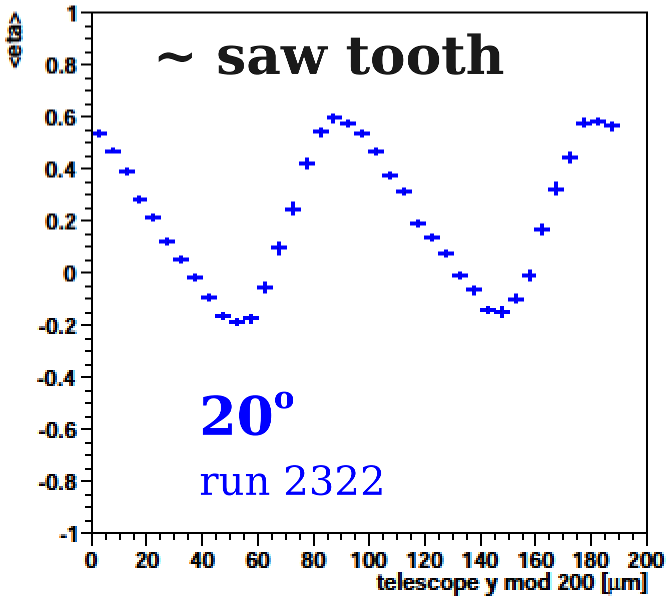
1-row: $\eta = 1$

0°
run 2331

10°
run 2330

15°
run 2328

y_{impact} mod 200 μm: 2 pixels



20°
run 2322

25°
run 2325

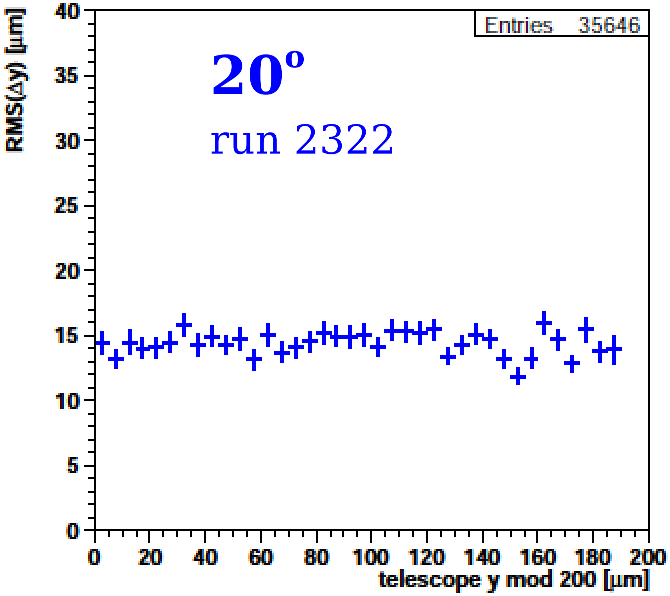
30°
run 2326

resolution profile vs threshold

10°
run 2330

15°
run 2328

0°
run 2331

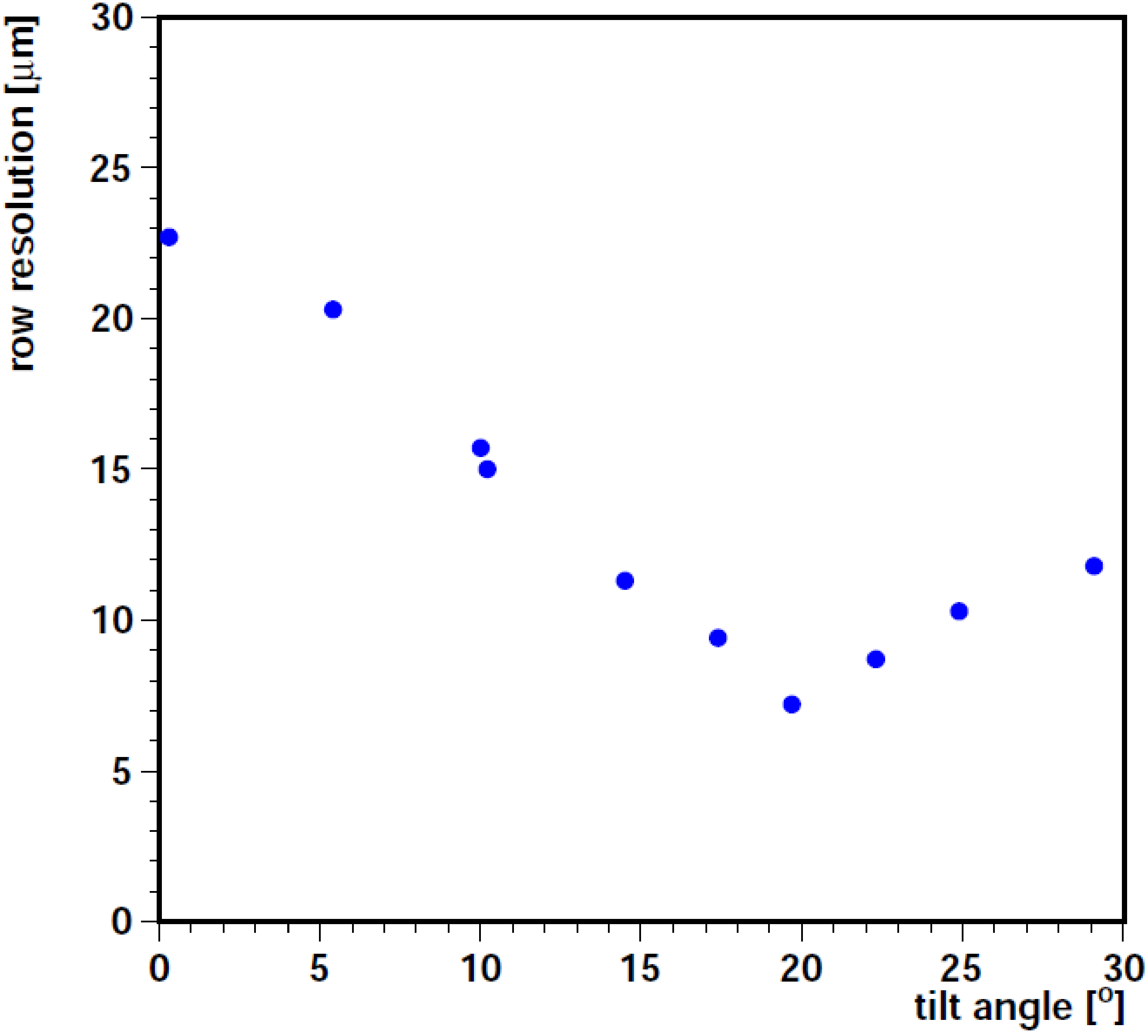


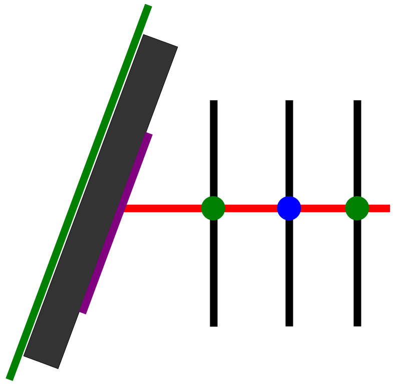
20°
run 2322

25°
run 2325

30°
run 2326

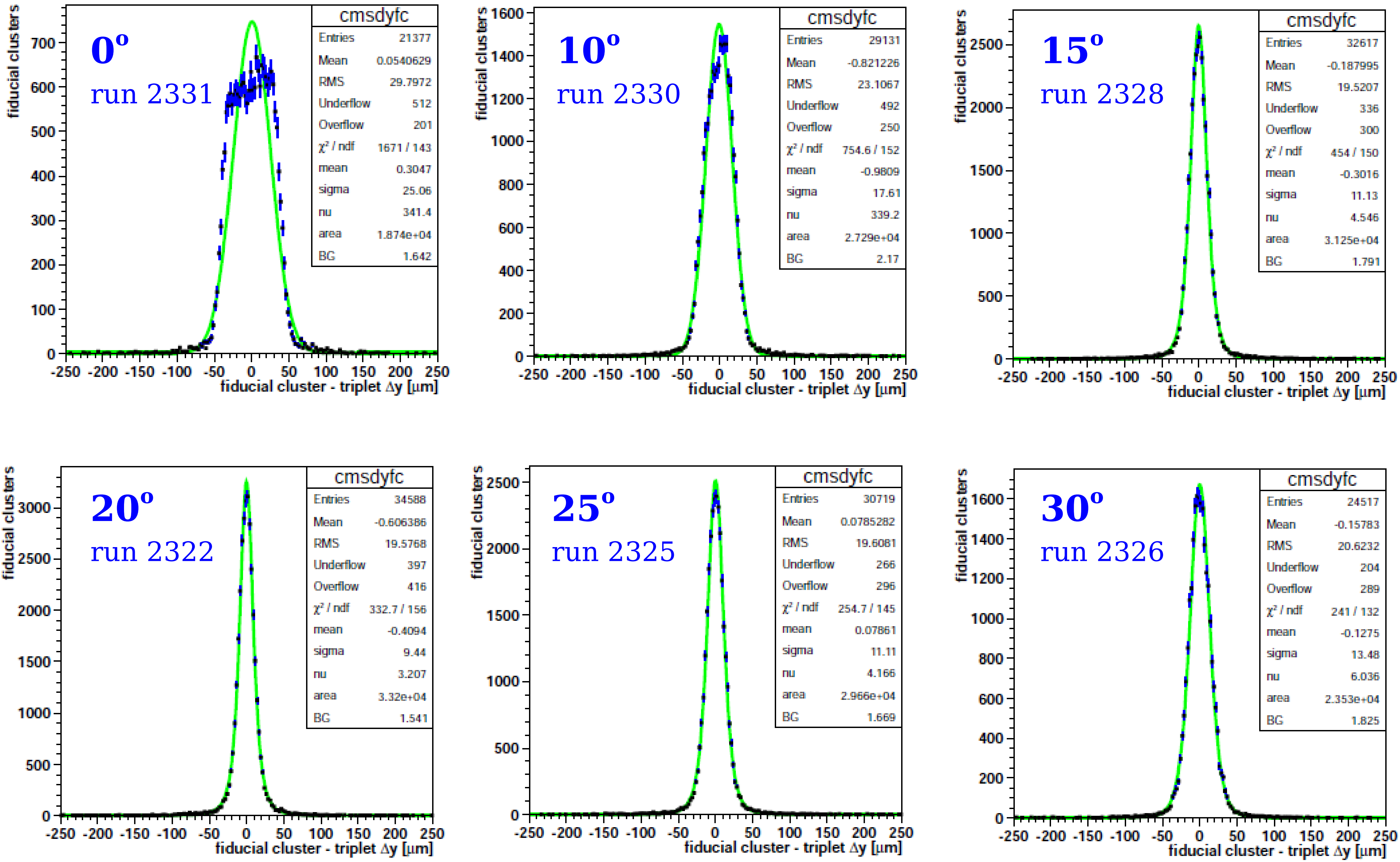
CMS pixel row resolution vs tilt angle



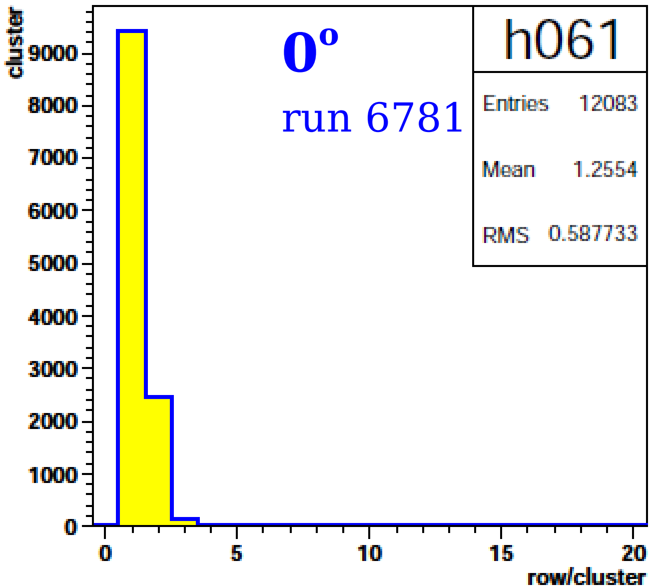


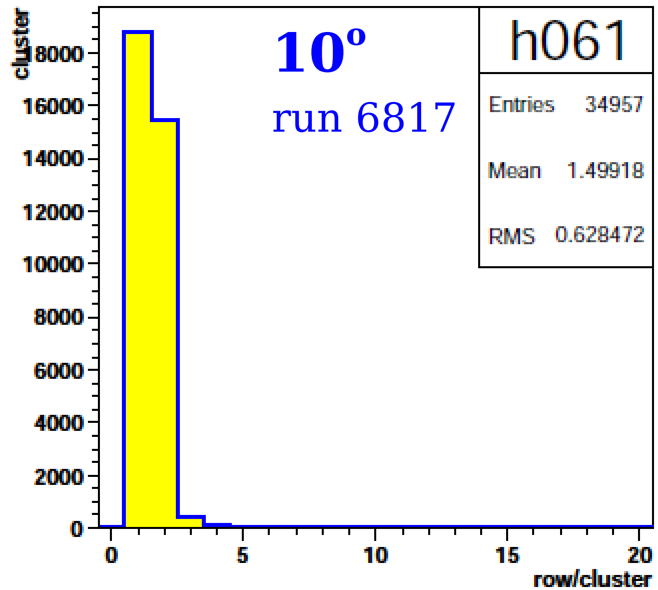
- Chip 10, 5.6 GeV, telescope extrapolation uncertainty subtracted.
- row pixels = 100 μm.
- Binary:
  - $\sigma = 100 / \sqrt{12} = 29$ μm
- Optimal angle 19.5°:
  - $\sigma = 7$ μm.

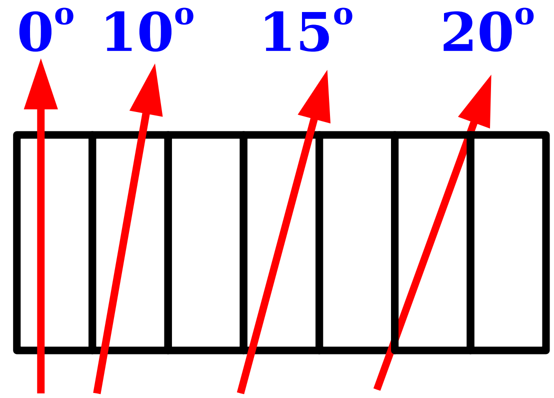
CMS pixel resolution vs tilt angle



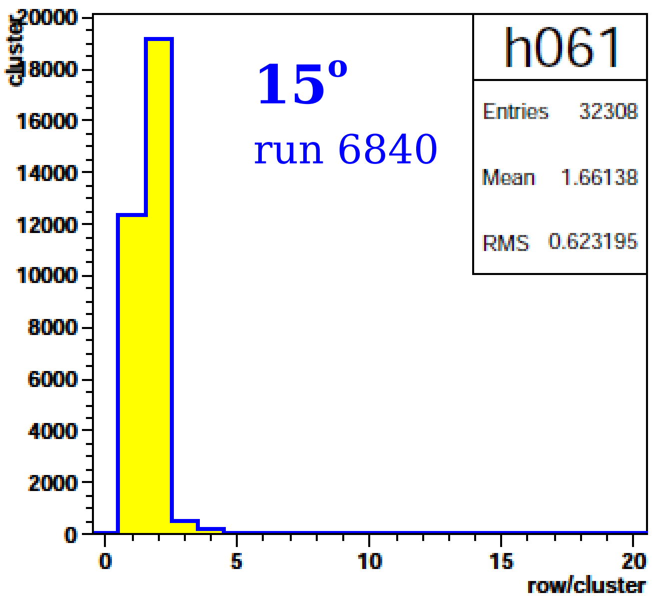
cluster size vs tilt angle

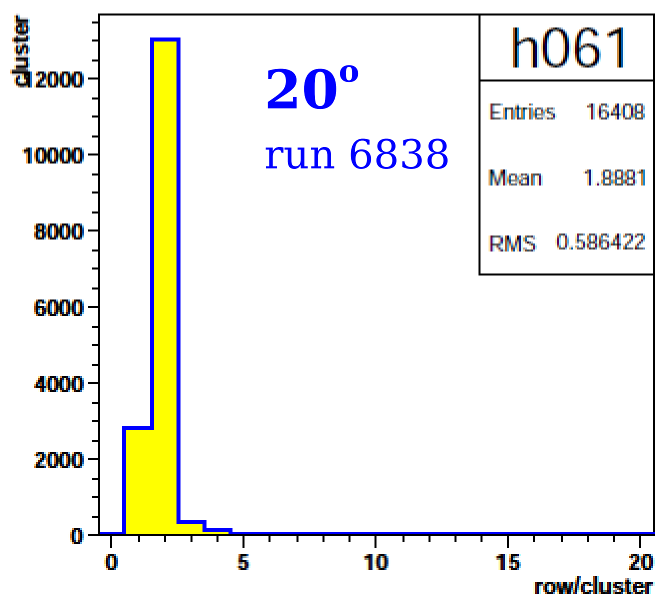


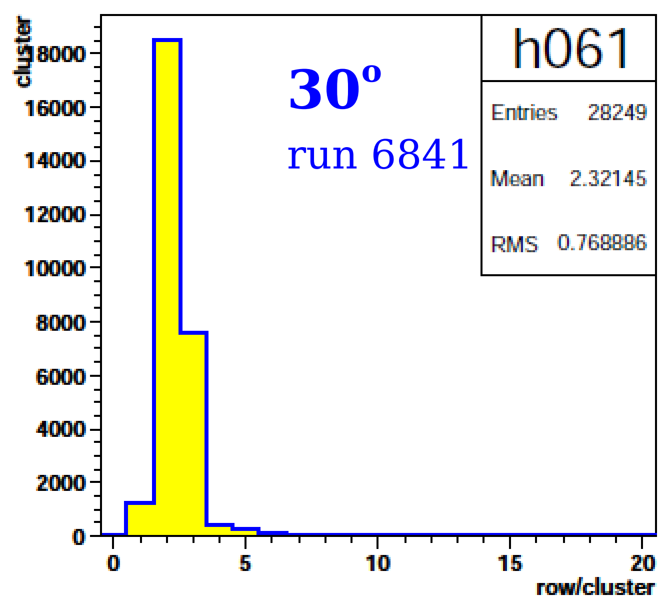




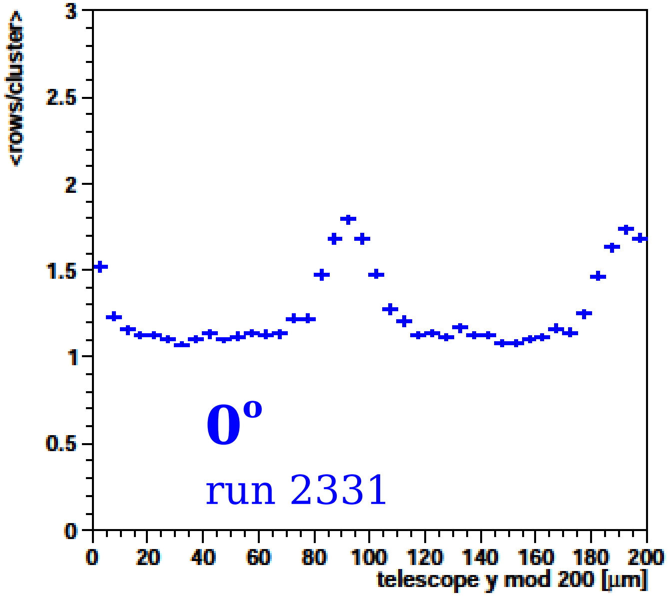
atan(100/285) = 19.3°

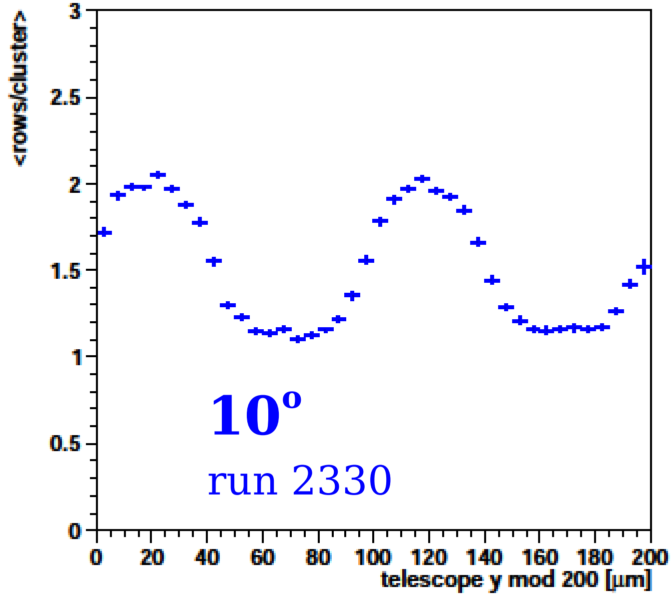


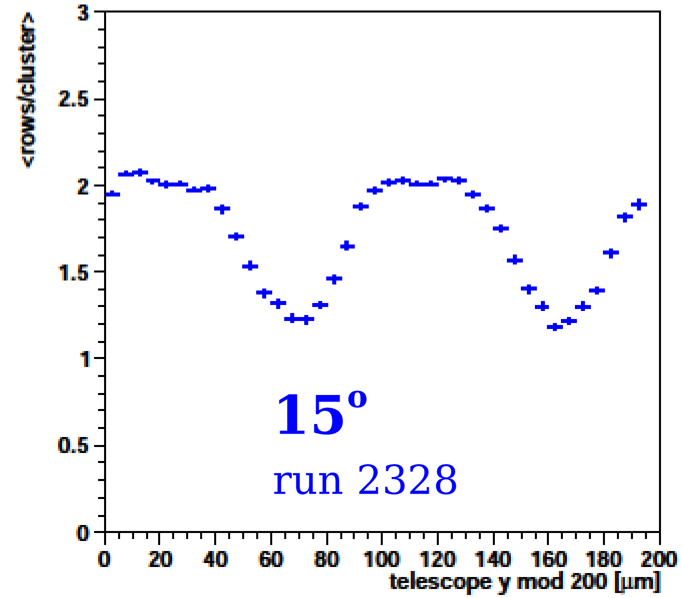




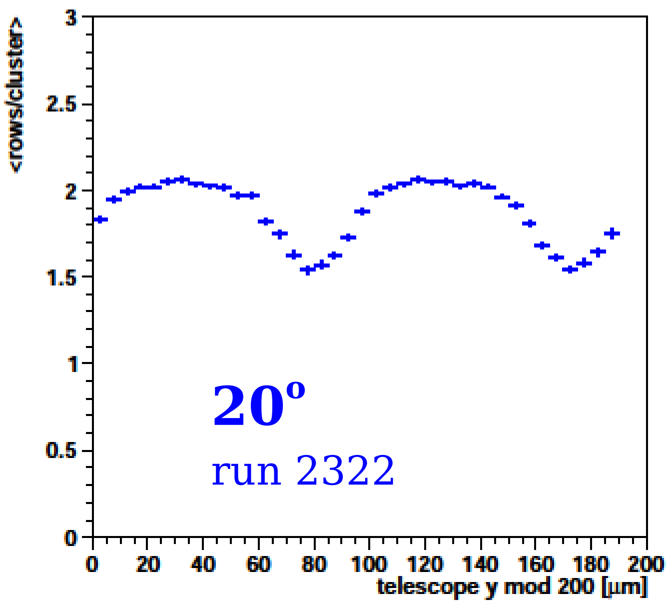
cluster size vs impact point and tilt angle

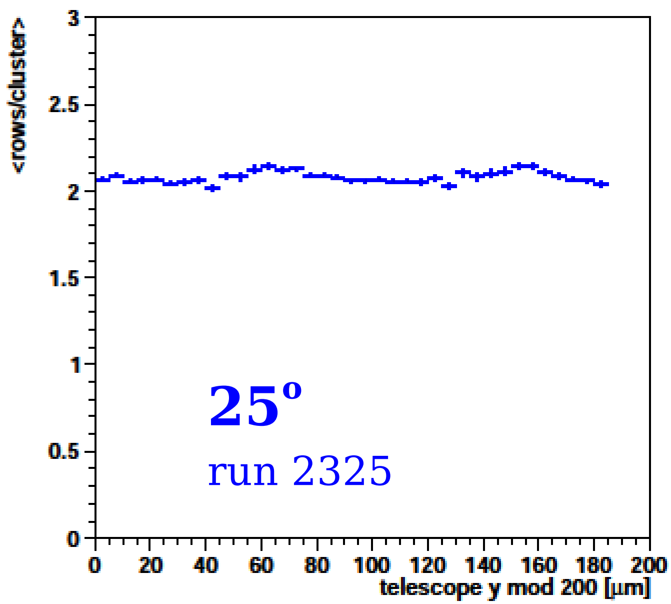


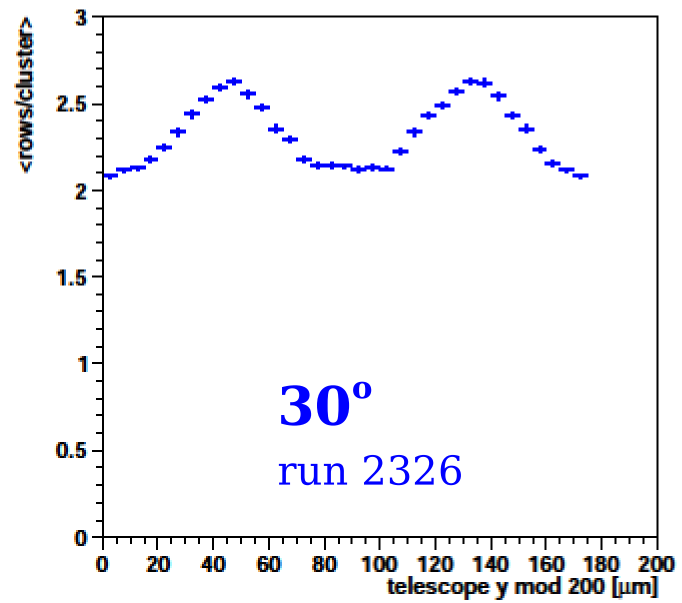




y_{impact} mod 200 µm: 2 pixels

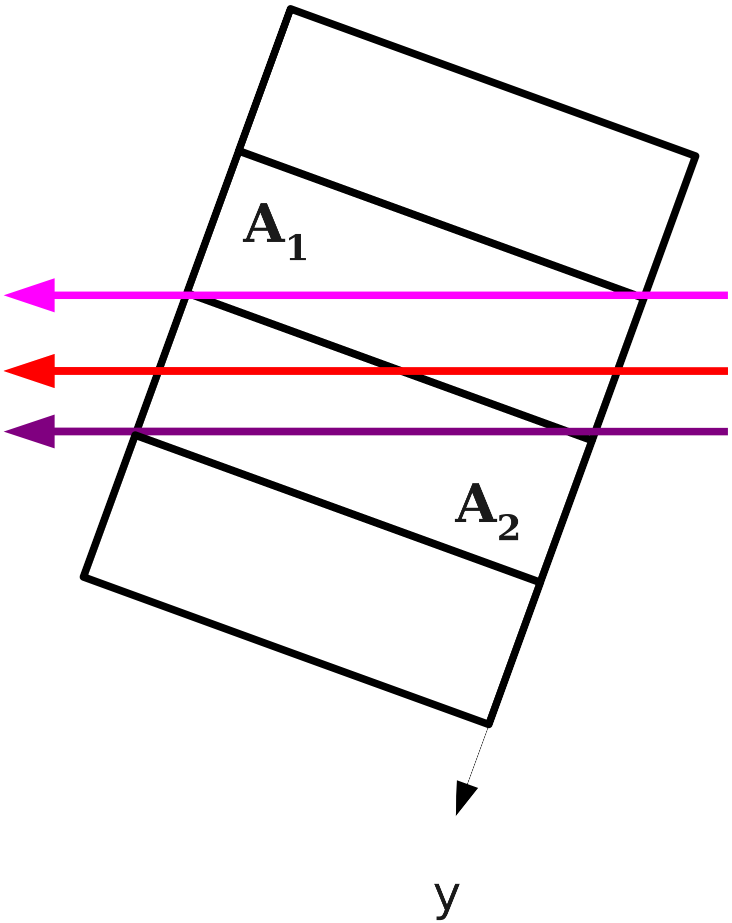






charge sharing: η

at 20°:



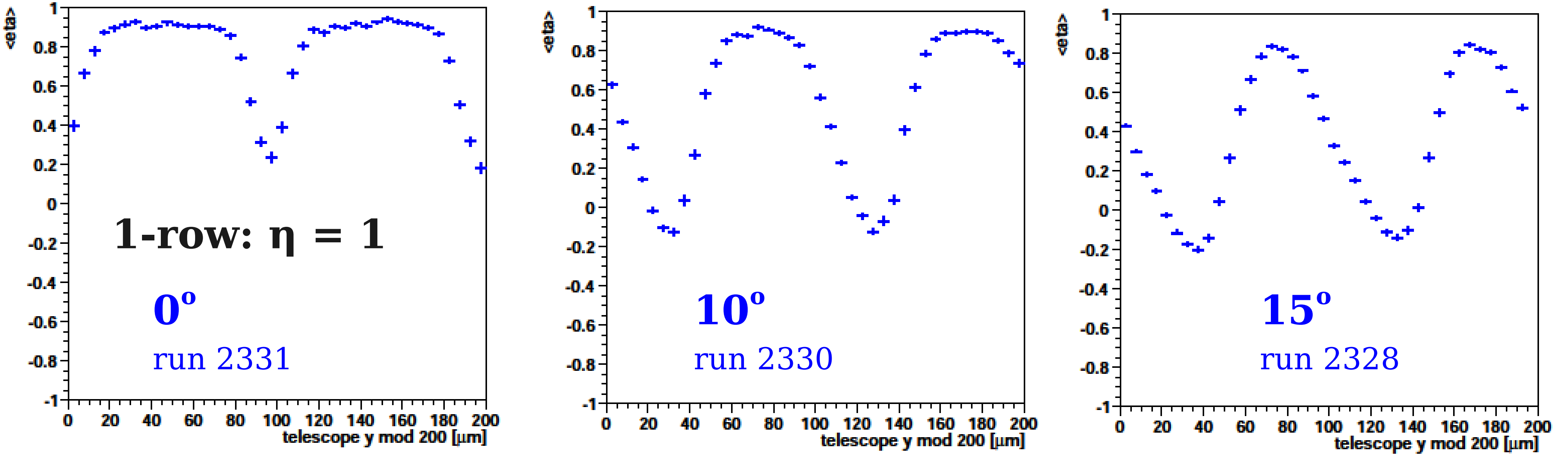
$$\eta = (A_1 - A_2) / (A_1 + A_2)$$

1-row clusters have η = 1.

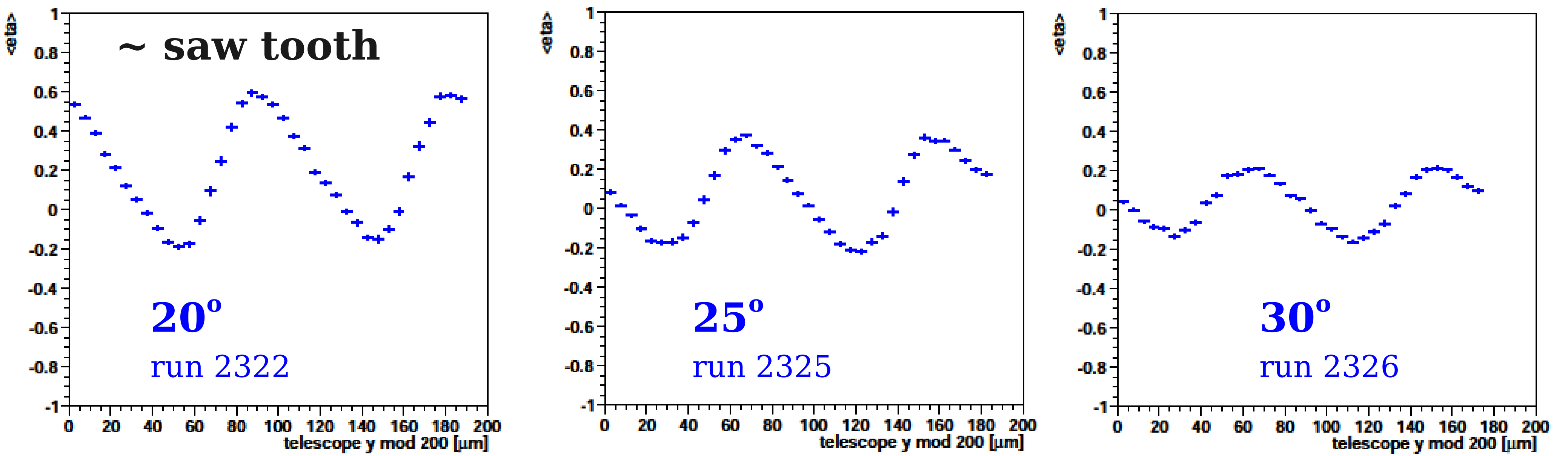
ideal:
linear η vs y
(saw tooth)

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

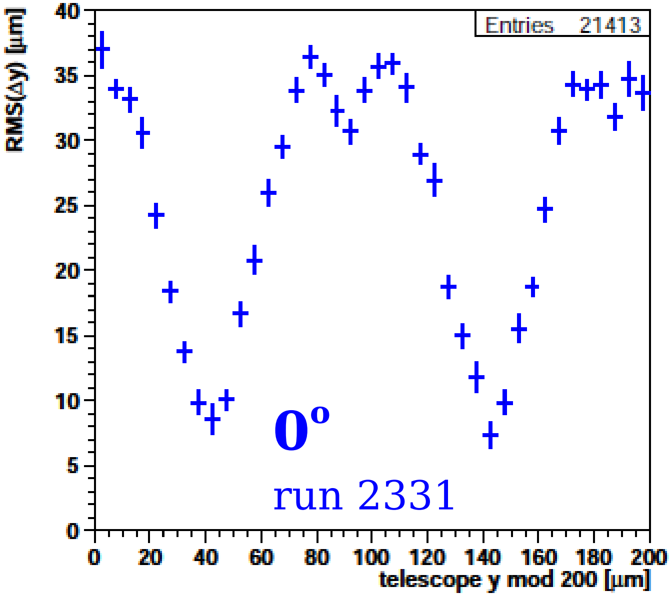
charge sharing vs tilt angle

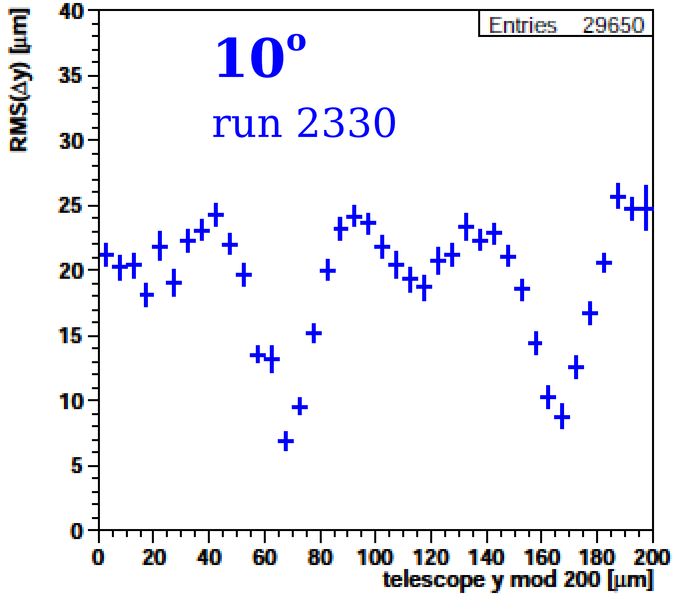


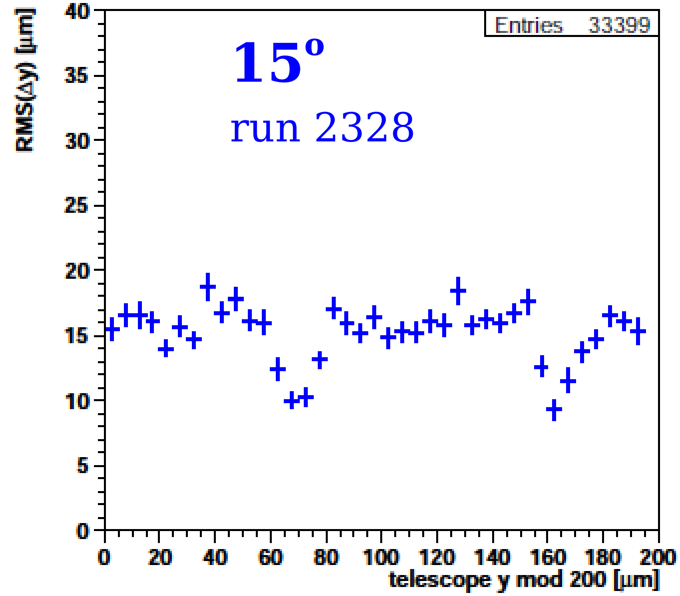
y_{impact} **mod 200 µm: 2 pixels**

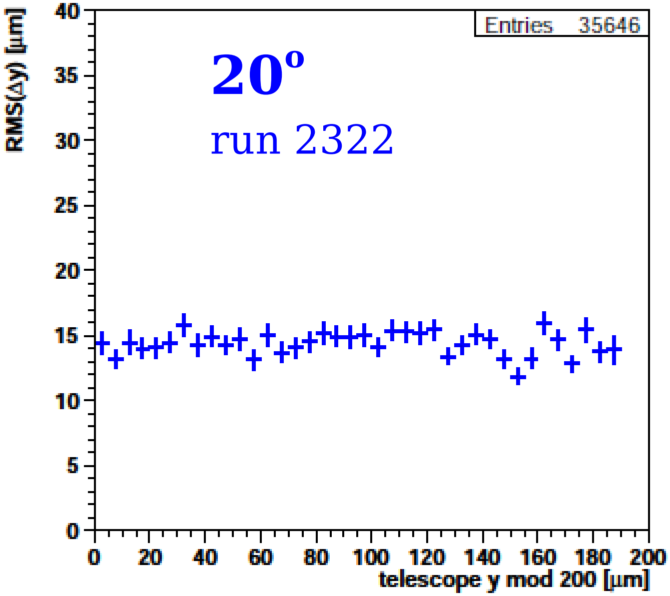


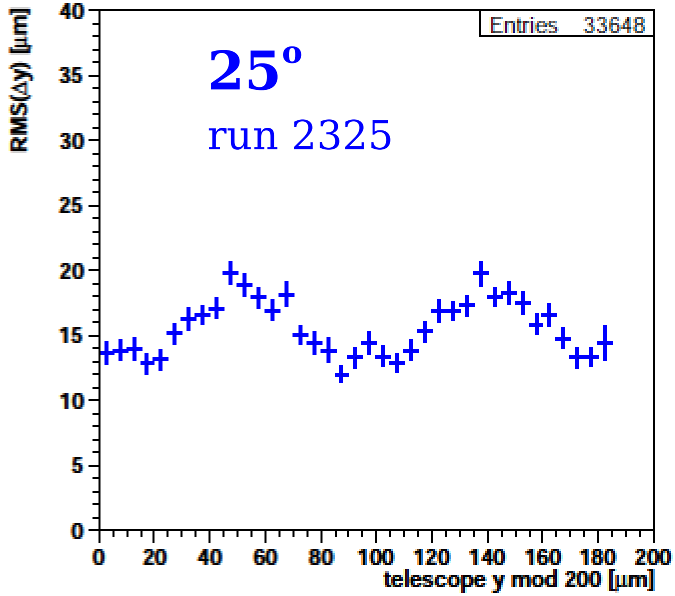
resolution profile vs tilt angle

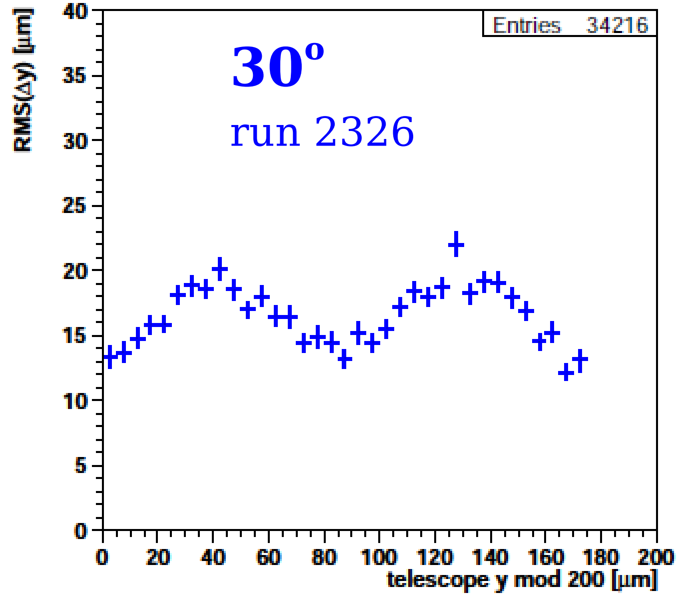




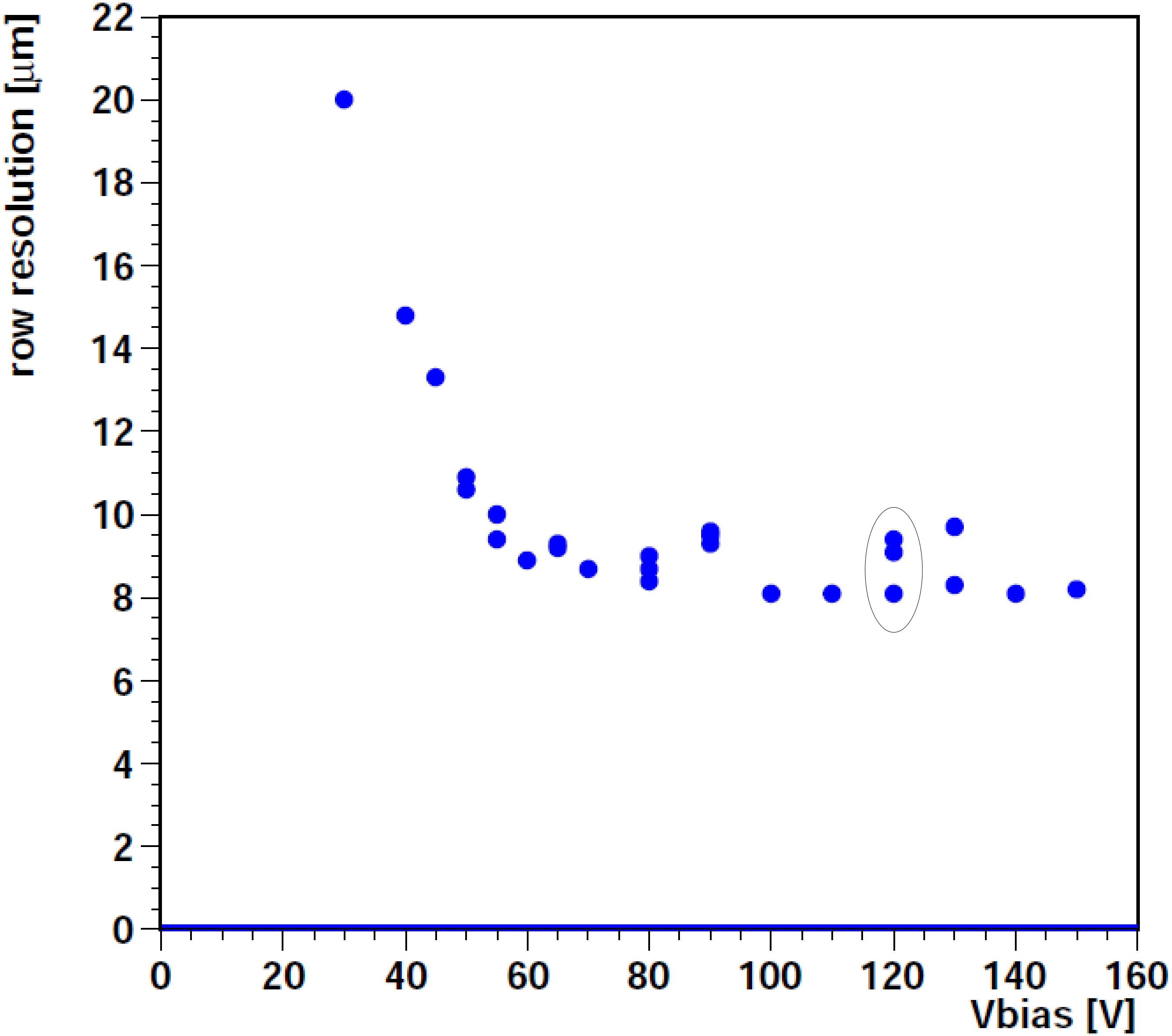


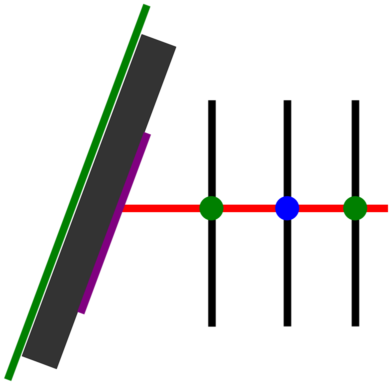






CMS pixel row resolution vs bias voltage



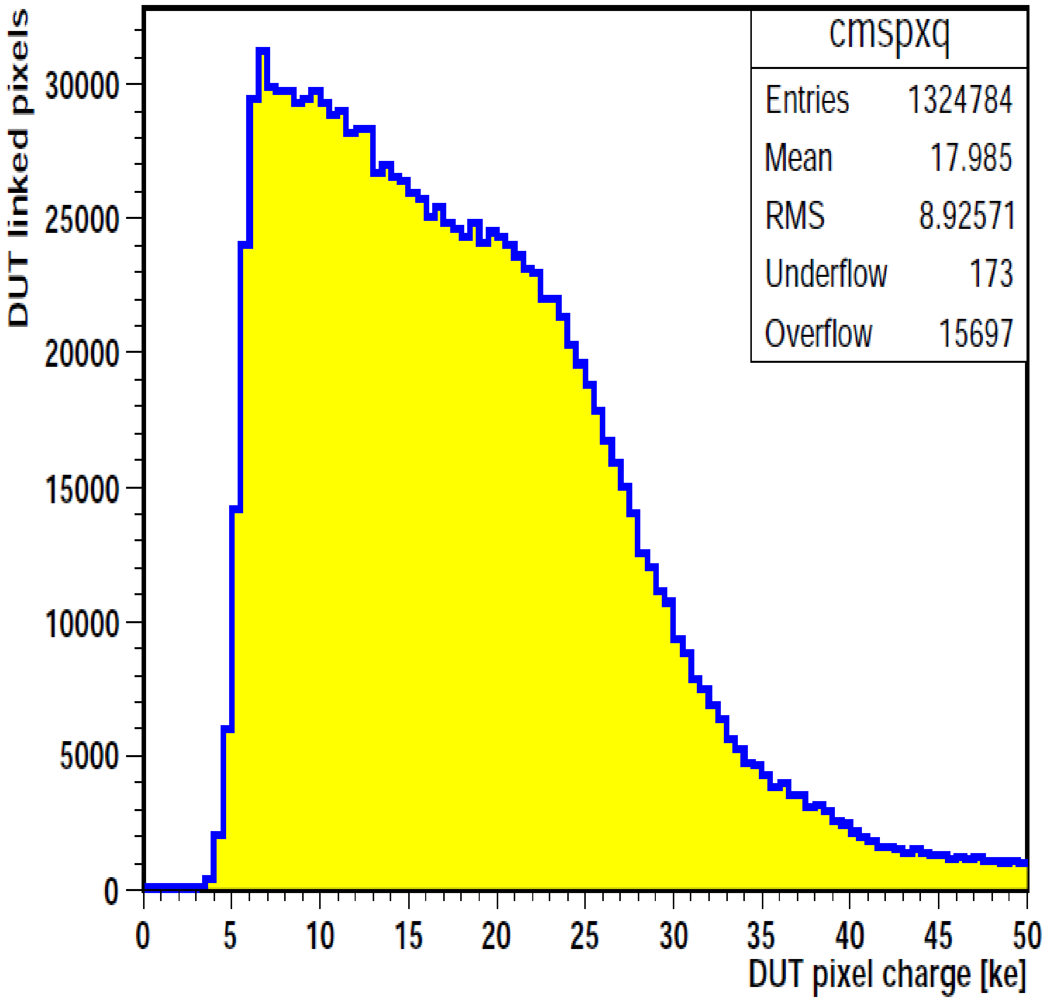


- Chip 10, 5.6 GeV, 20^{o} telescope extrapolation uncertainty NOT subtracted.
- best: 8 um above 100V
- reproducible?
- kink at ~60V: depletion?
- why does the n-in-n pixel sensor work below full depletion?

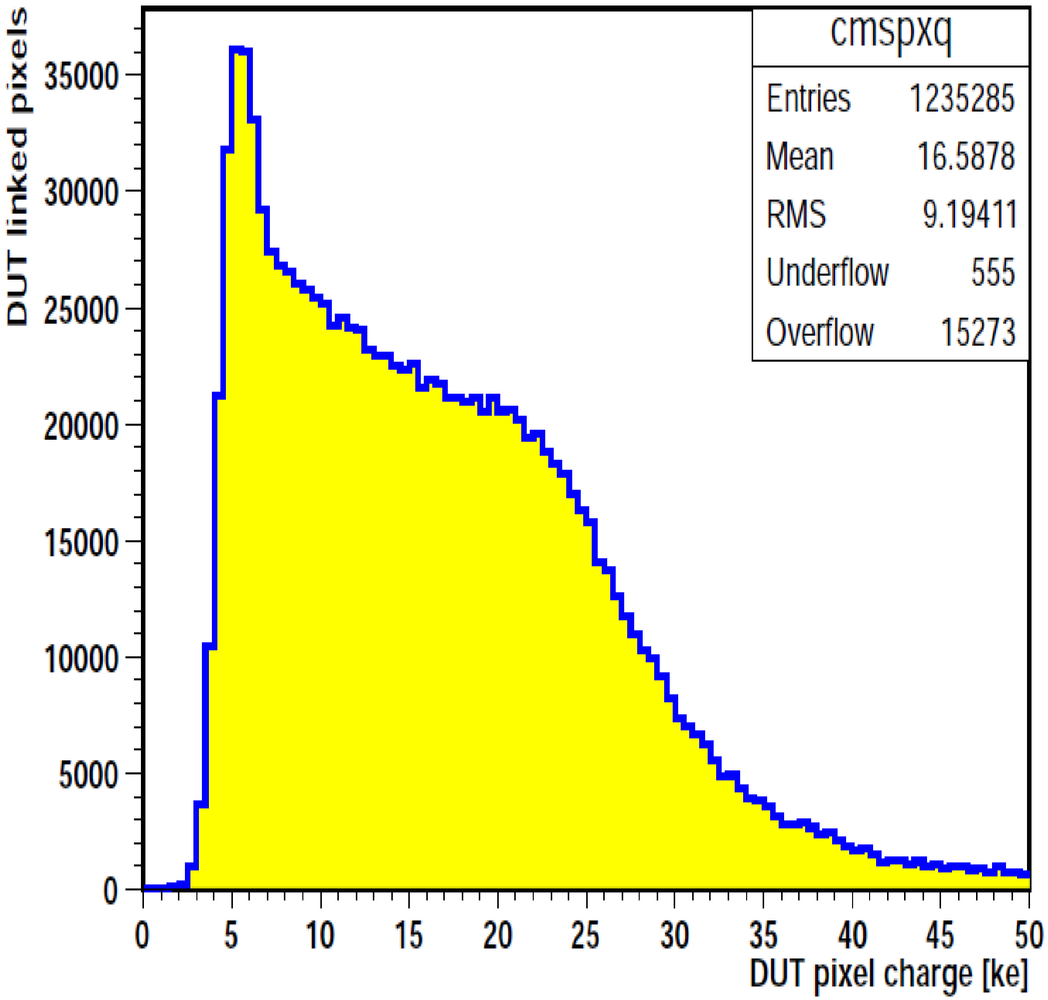
pixel charge

Chip 10, 120 V, 20°, Ia 24 mA, trim Vcal 55

Run 3113, σ 9.1 μm

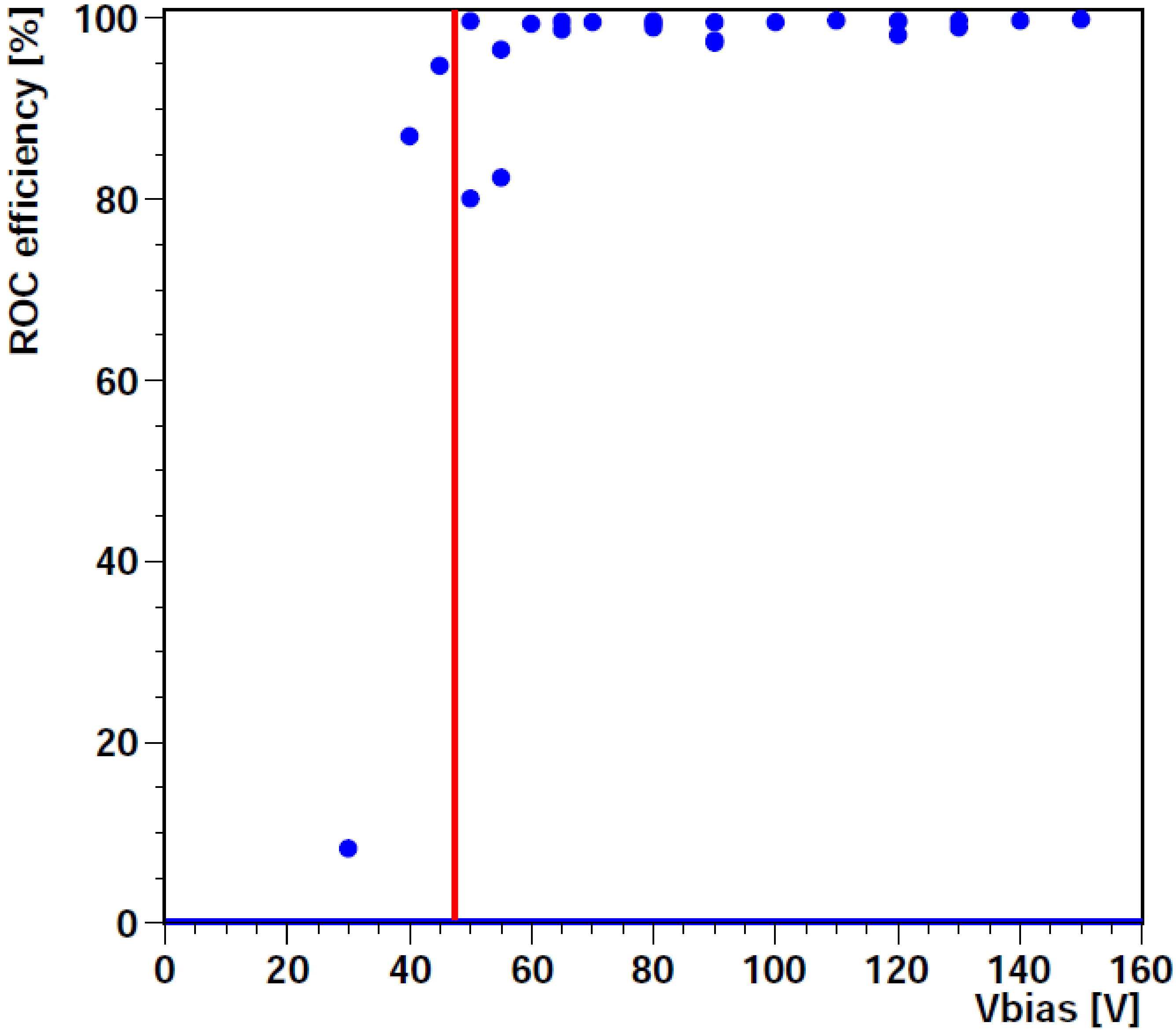


Run 3211, σ 8.1 μm



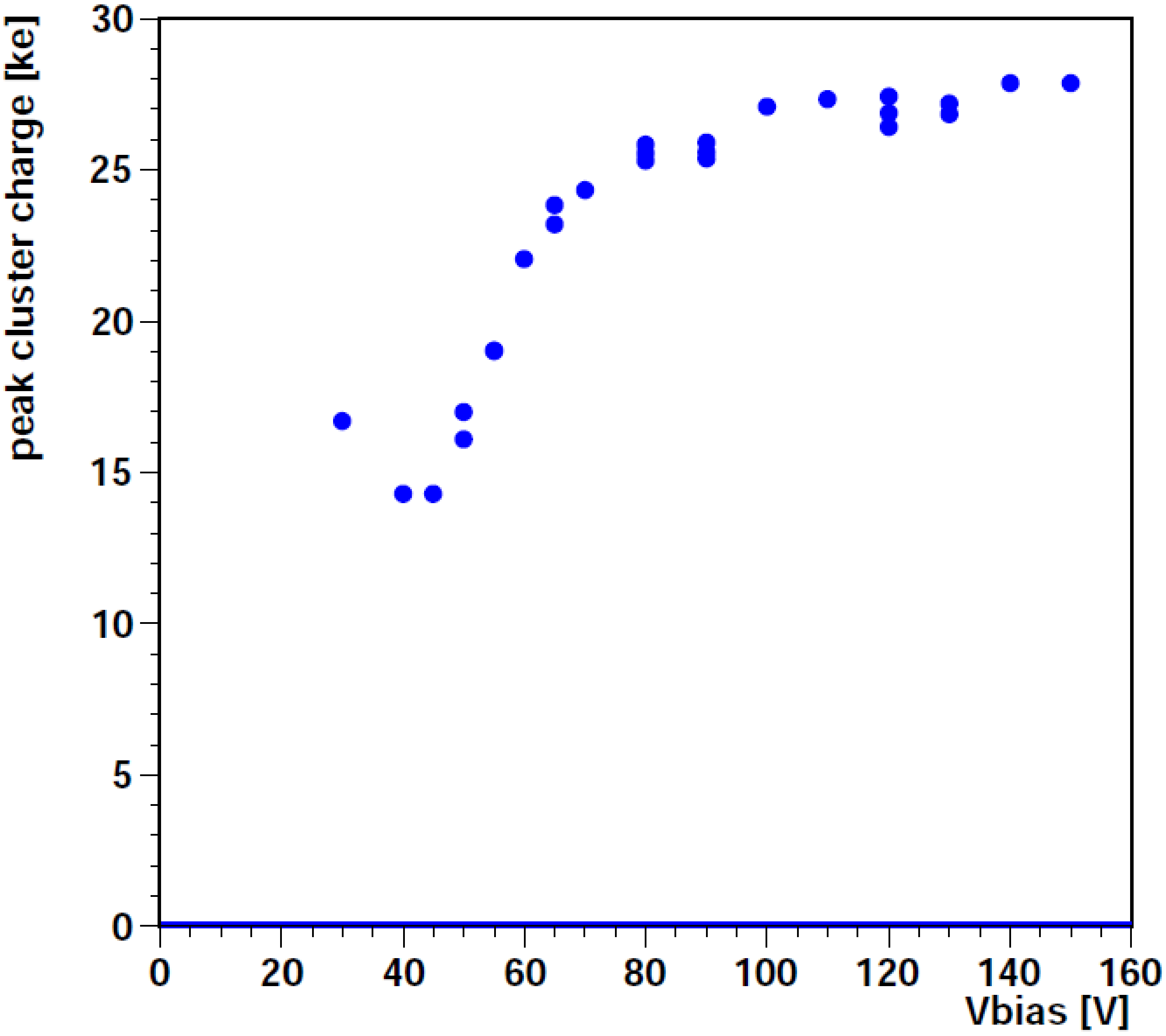
lower 'effective' threshold: better timing?

Efficiency vs bias voltage



- Chip 10, 5.6 GeV, 20°
- fully efficient at 50 V: full depletion?
- reproducible?

Cluster charge vs bias voltage

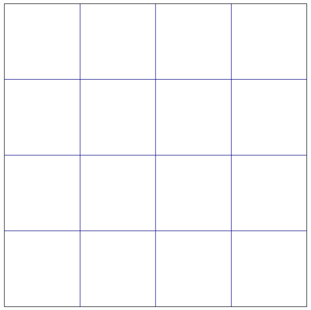


- Chip 10, 5.6 GeV, 20°
- Position of the Landau peak.
- slowly reaching plateau:
  - not a good indicator of full depletion?

Summary

- Beam test of a CMS pixel sensor with the DESY telescope.
- threshold scan:
  - efficiency above 99% for thresholds below 9 ke
  - best resolution 7 μm at 3.3 ke (with 20^{o} tilt)
- drive towards lowest threshold:
  - only reached 3.3 ke (from 3.9)
  - increasing analog current from 24 to 30 mA does not help
- bias voltage scan:
  - sensor can be operated below full depletion
  - why? (it is n-in-n)
- tilt angle scan:
  - Optimal resolution 7 μm at 20^{o} (with 3.3 ke threshold),
  - charge sharing appears almost linear at 20^{o}.

Further studies?



- Subdivide chip into regions:
- or study per double-column
- or check for even/odd column effect:
  - resolution
  - Landau
  - cluster size
- Simulation:
  - detailed pixel simulation available in CMS
  - port to test beam?

Outlook

- Expect improvements from the new ROC:
  - lower threshold
  - less 1-row clusters
  - even better resolution
  - better efficiency when sensor charge collection degrades
- Single-chip modules with the new ROC will be prepared at PSI:
  - analog PSI46xdb and/or digital PSI46dig
- Followed to testing in the lab, DAC parameter determination
- New ROC beam test scheduled for mid June – mid July

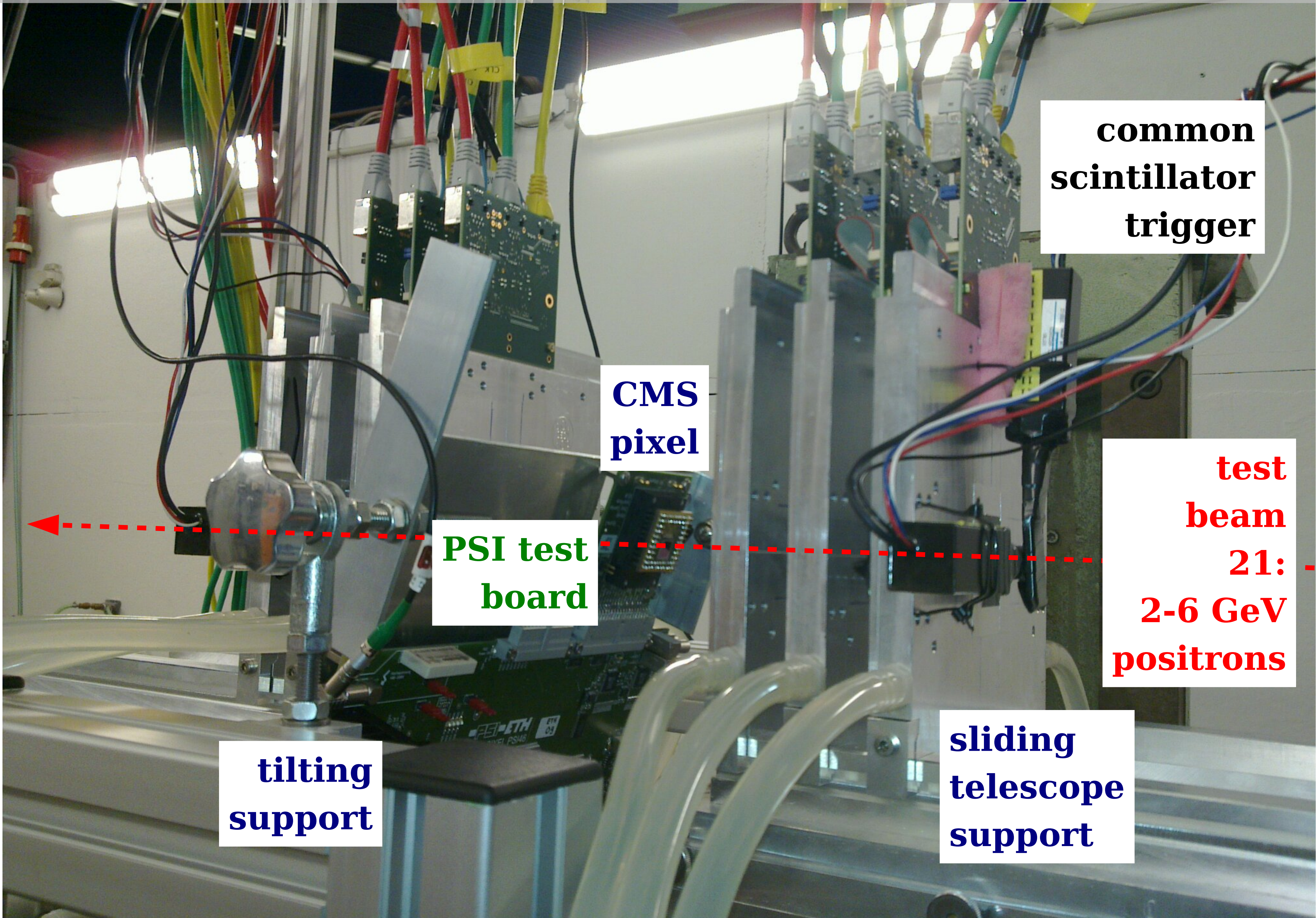
Things to improve

- Fix clock jumps (how?)
- Common run start/stop: EUDAQ and takeData
- Include REF plane into GBL track fit and Millepede alignment.
- Include DUT and REF into EUTel GEAR file
- Would be nice to have:
  - motor controlled tilting, along 2 axes,
  - active cooling of the ROC: would reduce gain drift,
  - TDC in data stream for beam time and clock monitoring.

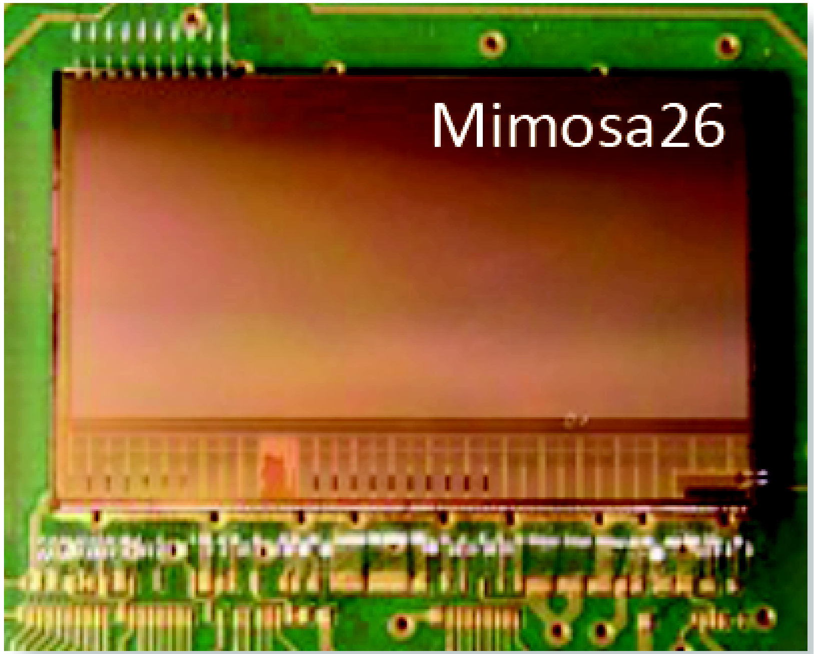
Acknowledgements

- Ingrid Gregor, Artem Kravchenko, Igor Rubinskiy (all DESY ATLAS):
  - building the Datura telescope for TB21
- Adam Zuber, Holger Maser (DESY CMS):
  - improved the support frames for the test boards
- Torsten Külper (FH electronics lab):
  - made the trigger and clock adapters for the test board
- Beat Meier (PSI):
  - new test board firmware with external trigger input
- Ulrich Hurdelbrink (machine group):
  - developed the clock generation setup
- Claus Kleinwort (DESY CMS):
  - General Broken Lines code, advice on alignment

CMS Pixel with EuTelescope



Mimosa26 ILC pixel chip



- Mimosa26 monolithic active pixel sensors (Strasburg, 2009):
- thinned to 50 µm,
- $18.4 \times 18.4\ \mu m^2$ pixel size,
- $1152 \times 576 = 663k$ pixels,
- $10.6 \times 21.2\ mm^2$ active area,
- binary readout,
- integration time 115 µs.

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	

script `submit-all.sh run energy` by Armin Burgmeier

All steps produce ROOT histograms for monitoring.

Steps 1-5 require a geometry file defining the telescope.

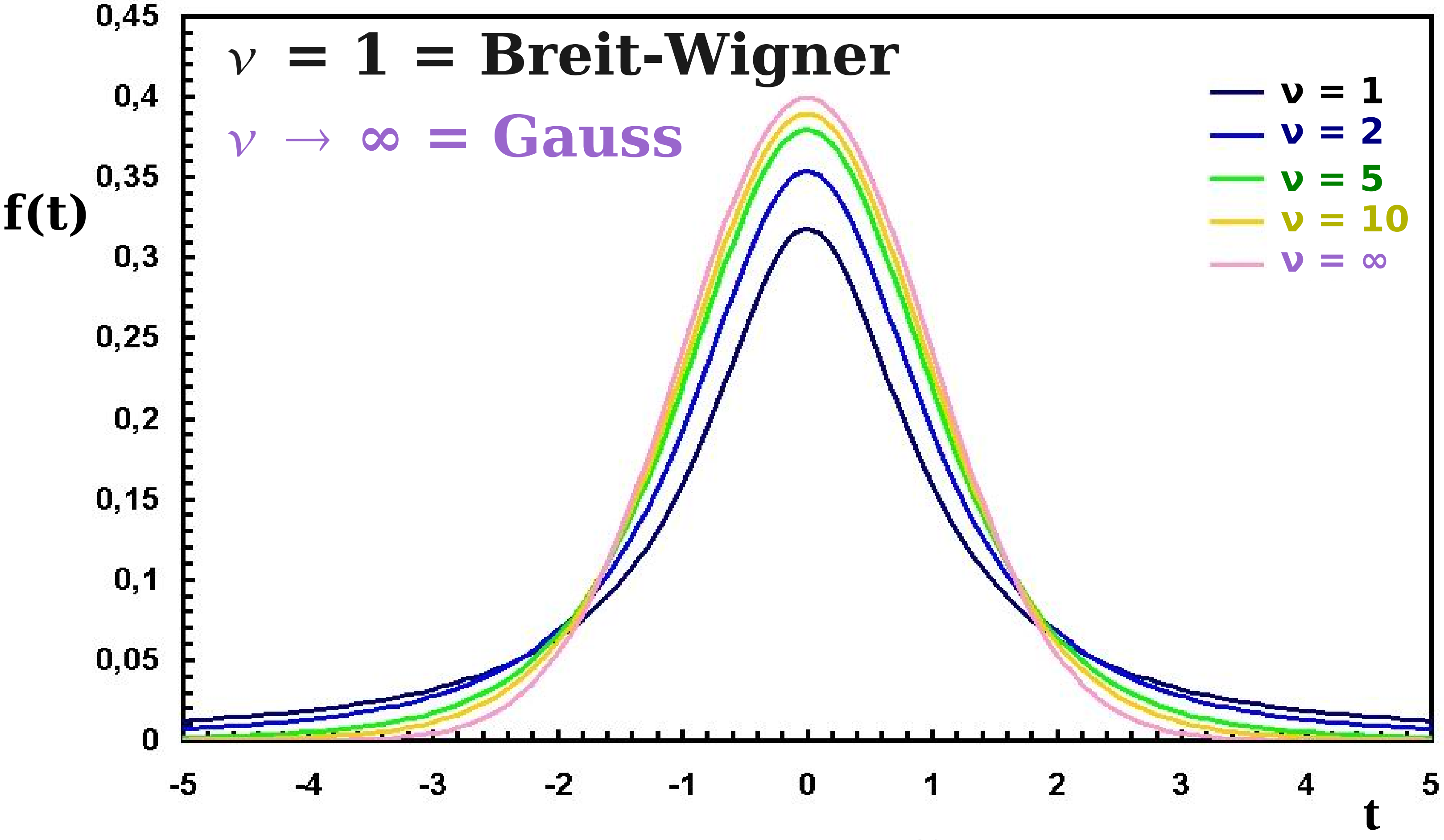
Parameters are passed from xml files. Code in svnsrv cmspixelupgrade.

Fitting peaks with Student's t

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

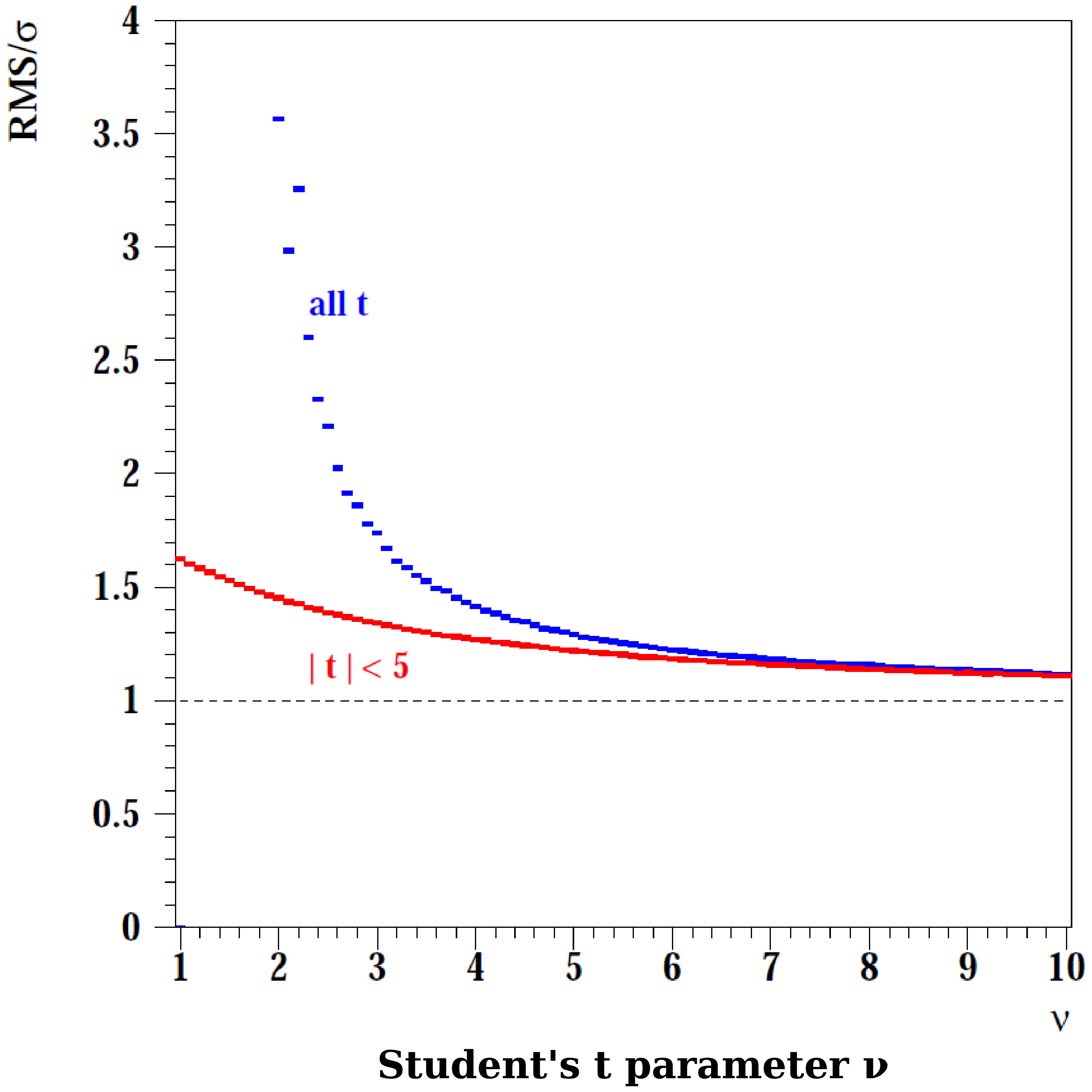
$$f(t) = \frac{\Gamma((\nu+1)/2)}{\sqrt{\nu\pi}\,\Gamma(\nu/2)}(1+t^2/\nu)^{-(\nu+1)/2}$$

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 $\nu = 1$).
  - for $| t | < 5$. (rms stays below 1.62 for all $\nu \geq 1$).
- Asymptotic value (rms/σ = 1) slowly approached.