Digital ROC beam test results

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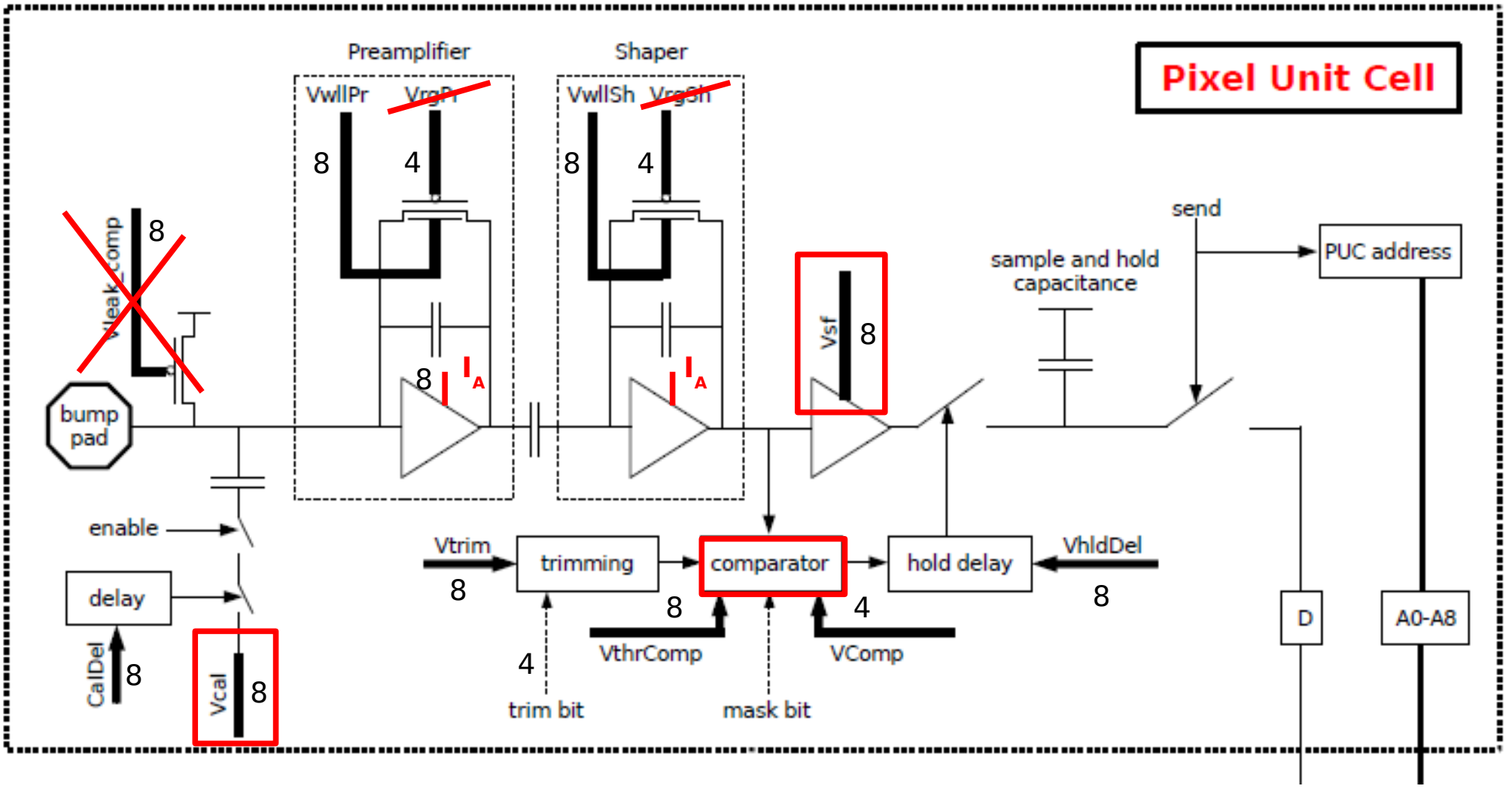
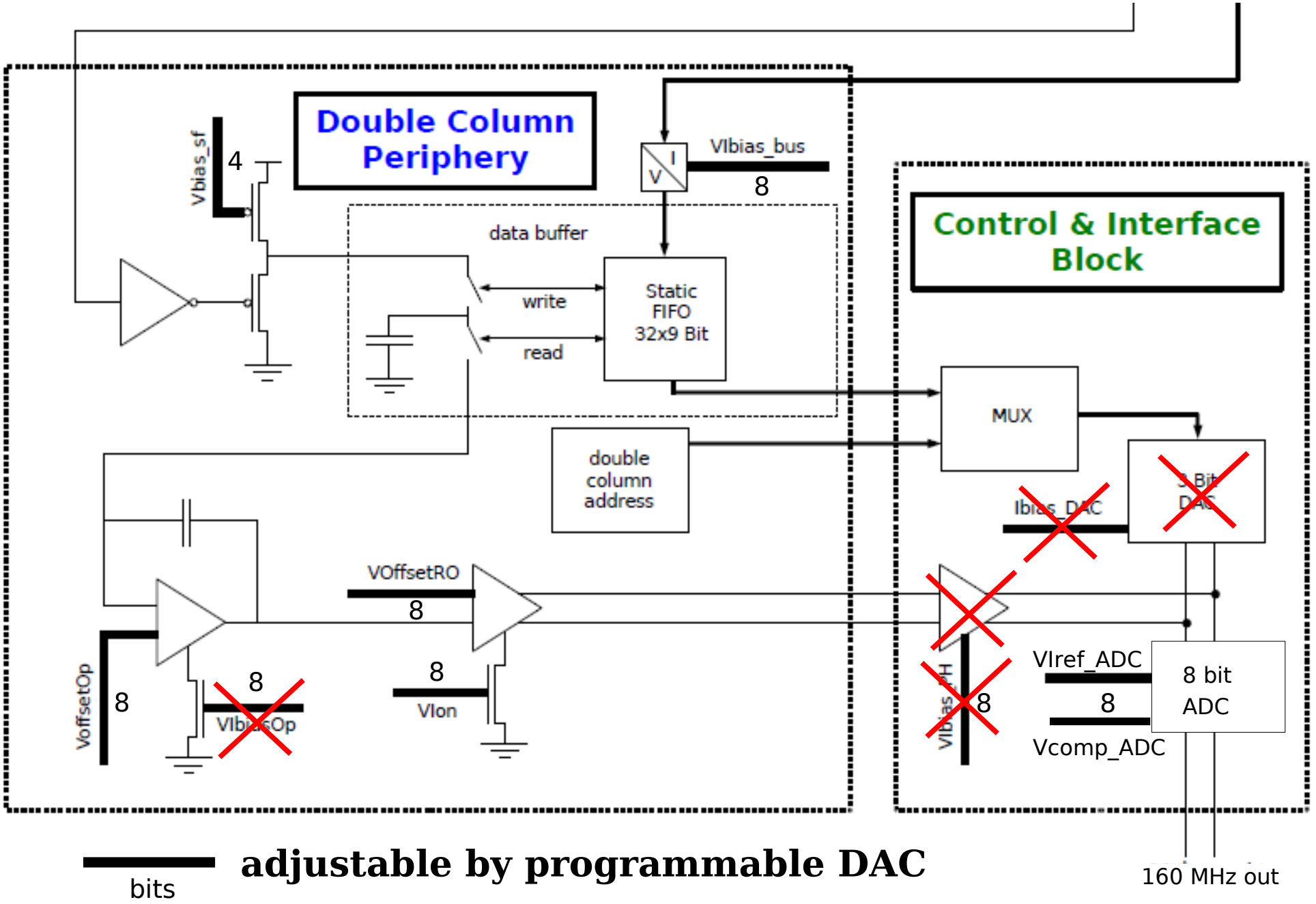
DESY CMS Phase I pixel upgrade, 24.8.2012

- digital ROC
- efficiency
- charge
- threshold scan

psi46dig pixel unit cell



psi46dig periphery

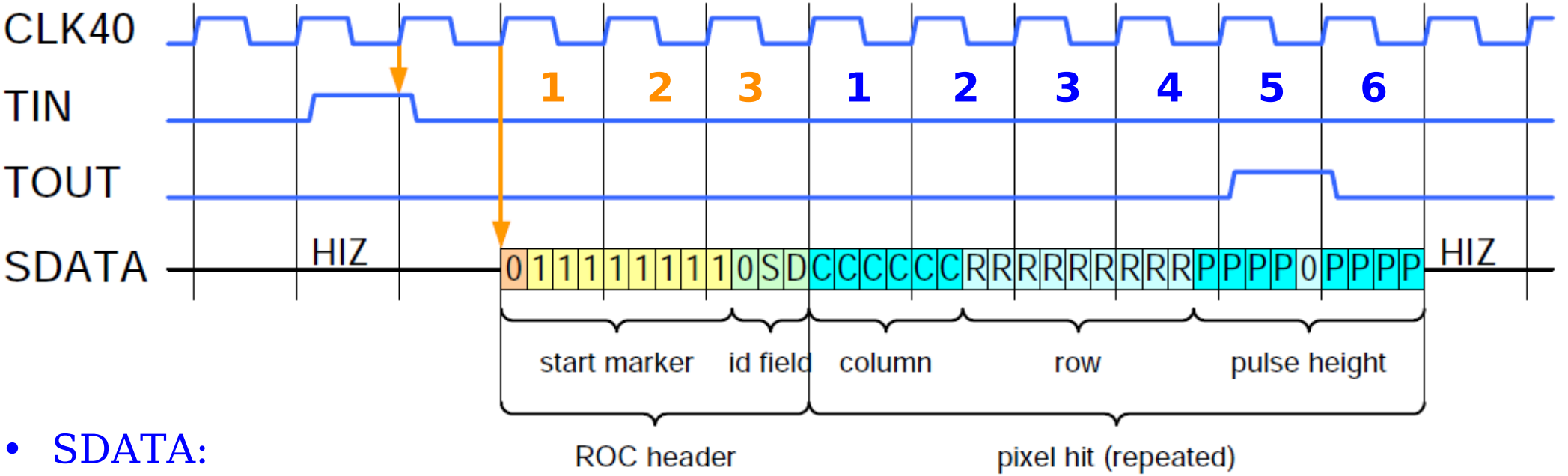


psi46dig DACs

1	Vdig	6
2	Vana	106
3	Vsf	30
4	Vcomp	12
7	VwllPr	60
9	VwllSh	60
10	VhldDel	250
11	Vtrim	97
12	VthrComp	81

13	VIBias_Bus	20
14	Vbias_sf	10
15	VoffsetOp	57
17	VOffsetR0	120
18	VIon	115
19	Vcomp_ADC	130
20	VIref_ADC	83
22	VIColOr	100
25	Vcal	200
26	CalDel	155
253	CtrlReg	0
254	WBC	100

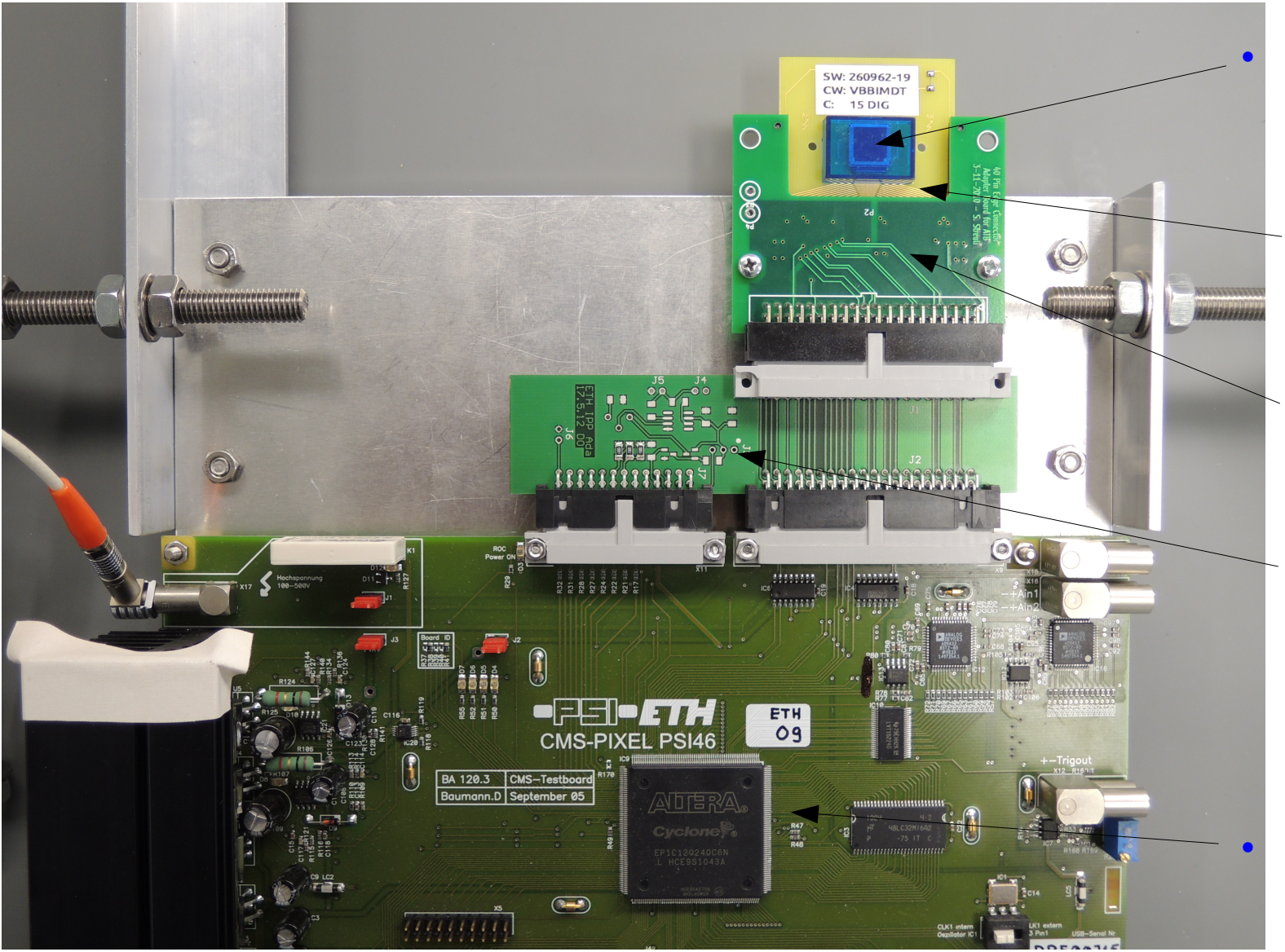
digital ROC data format



- SDATA:
  - 160 MHz
  - 4 bits per 40 MHz clock cycle
- FPGA FIFO:
  - 4 bits stored per data word (2 bytes)
  - (will be packed better on new digital tb)
- empty ROC:
  - 3 header words
- per pixel hit:
  - 6 data words

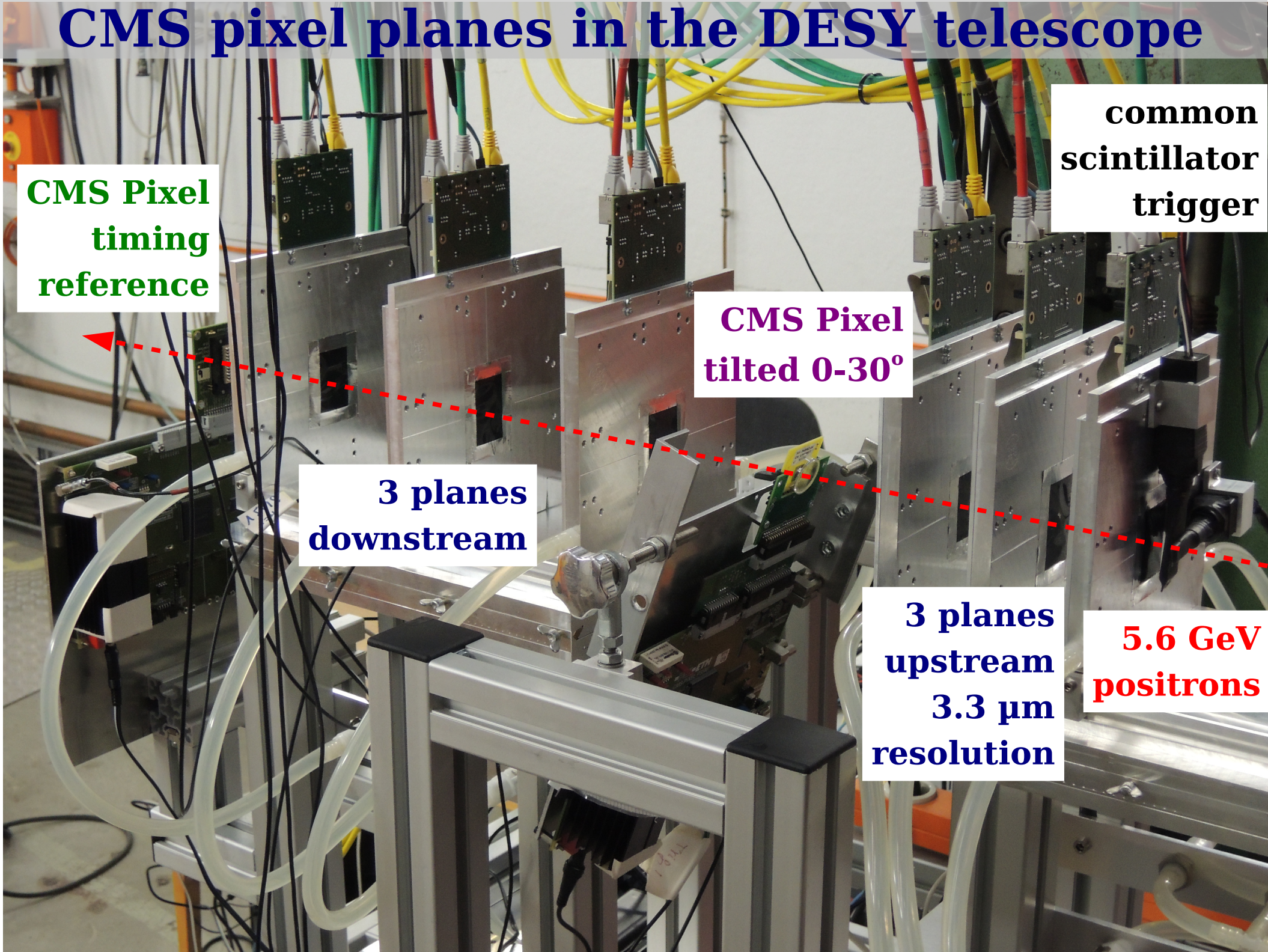
thanks to Simon Spannagel (KIT) for the digital decoder

Test setup at DESY

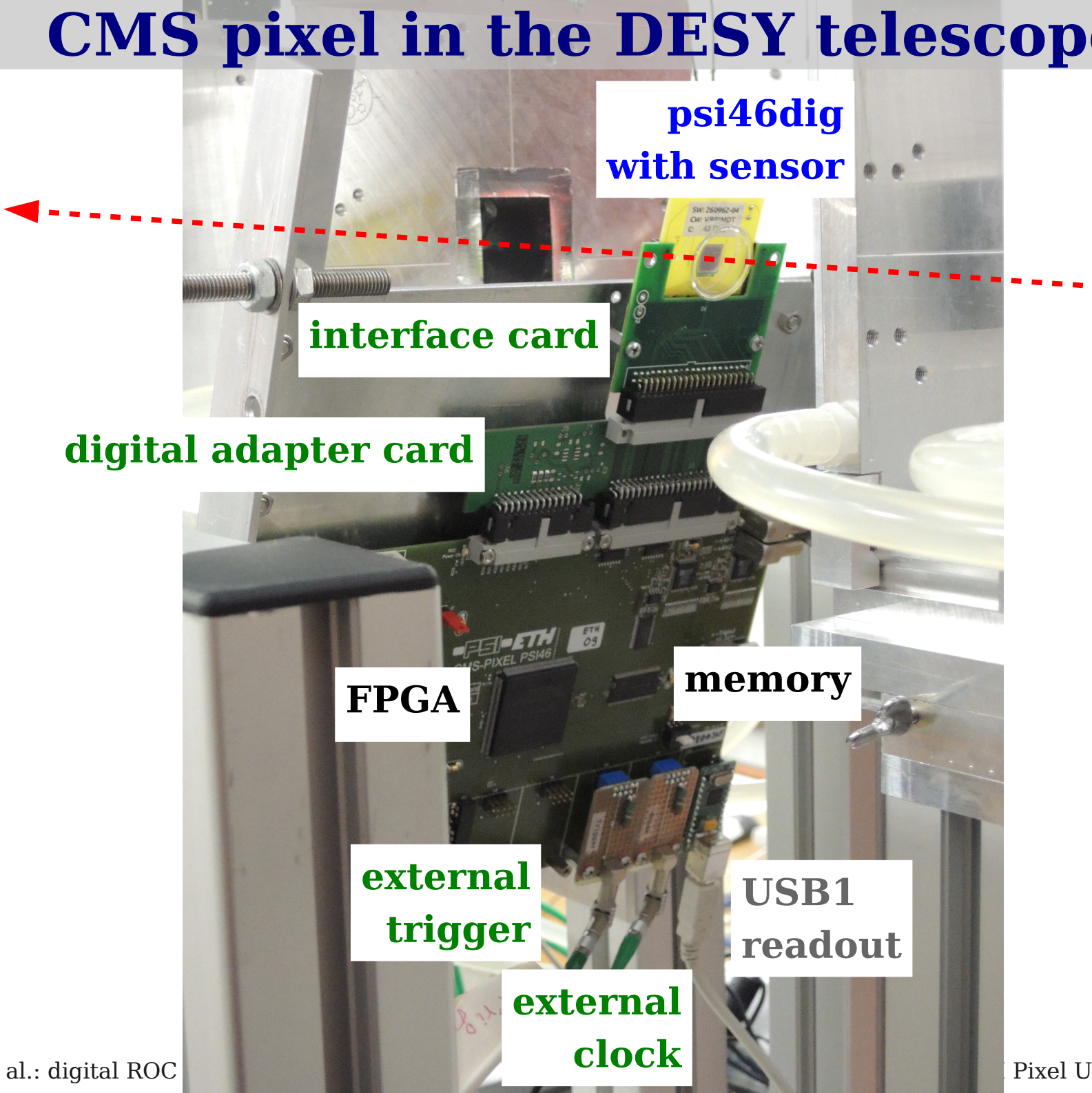


- Single chip module:
  - Indium bump bonded at PSI
  - Glued and wire bonded to carrier printed circuit board
  - Interface card to psi46 TB with edge connector
  - ETH adapter card for digital 160 MHz differential signal directly into FPGA (LCDS into LVDS)
- FPGA firmware update to select digital path as 'TBM channel 1'

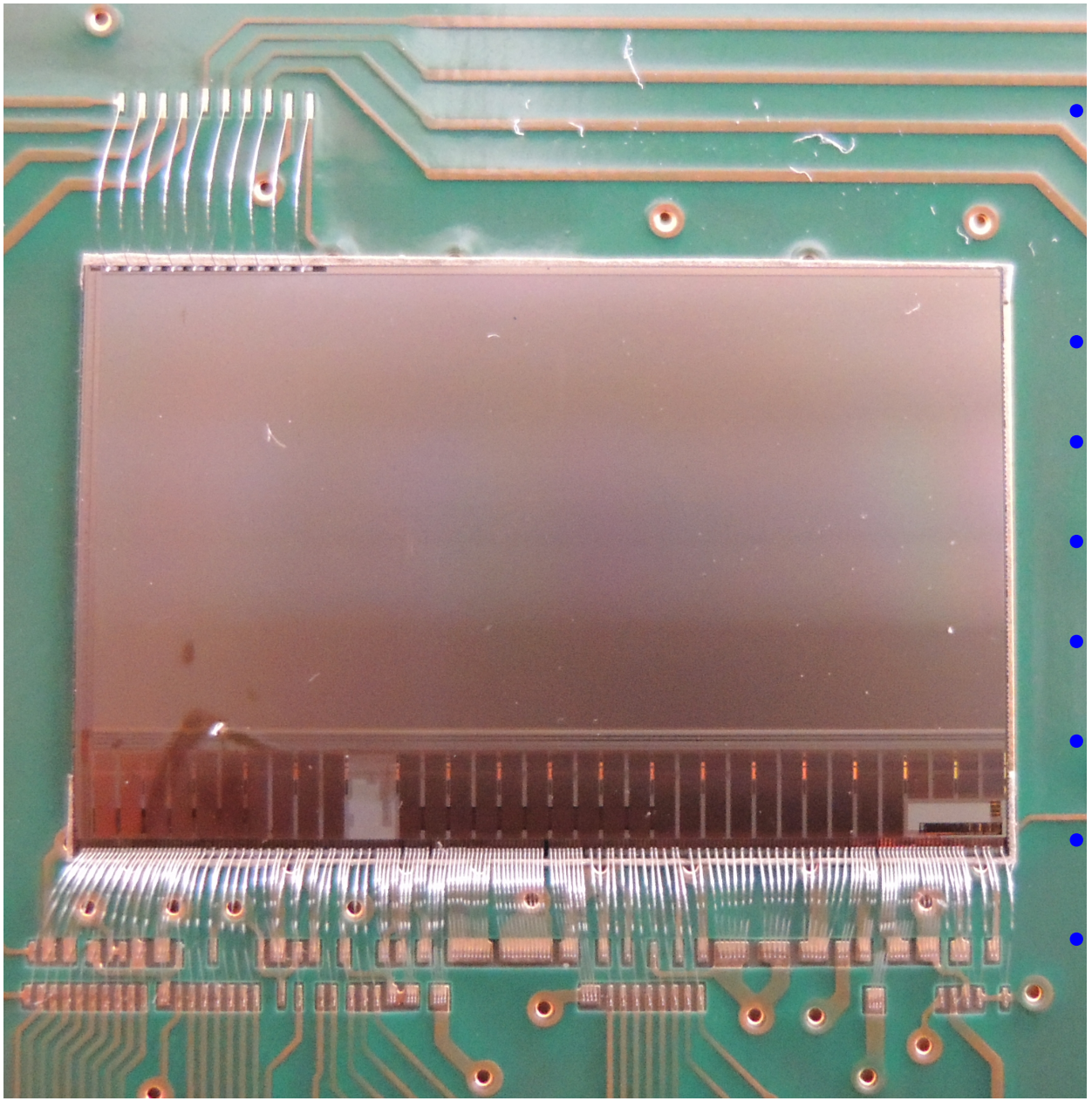
CMS pixel planes in the DESY telescope



CMS pixel in the DESY telescope

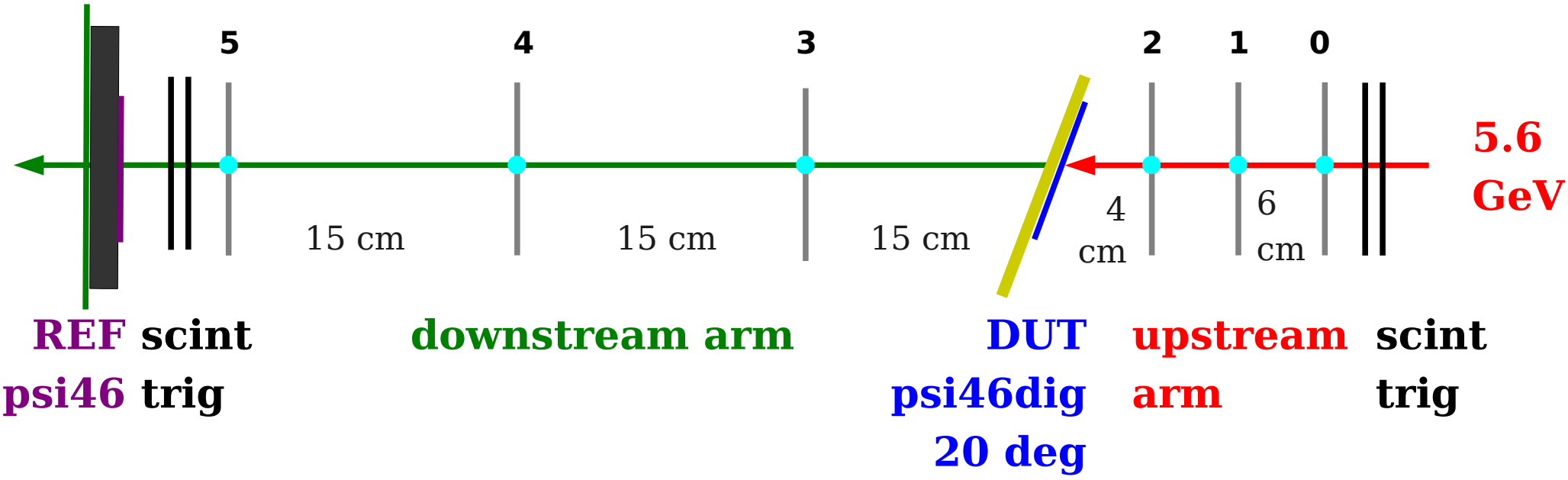


Mimosa26 pixel chip



- 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,
- developed for the ILC vertex detector

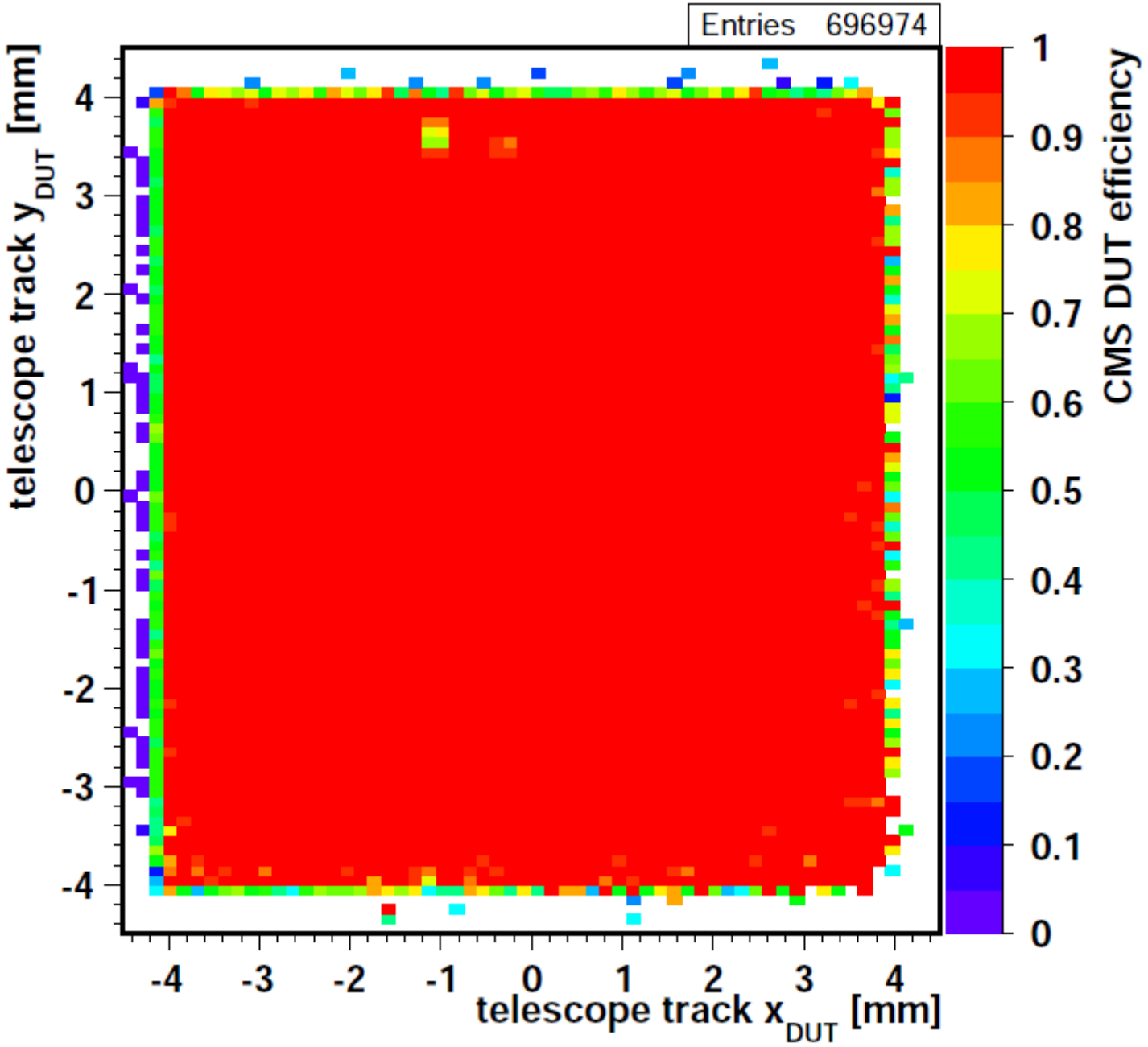
Default set up



- Upstream arm 0-1-2:
  - as close as possible to DUT, but allow for tilting
- DUT = single chip module, tilted by up to 30°,
- Downstream arm 3-4-5:
  - equally spaced between DUT and REF
- REF = single chip module for timing, as close as possible behind scint
- trigger: 4-fold scintillator coincidence, 1×1 cm^2 area

digital ROC efficiency map

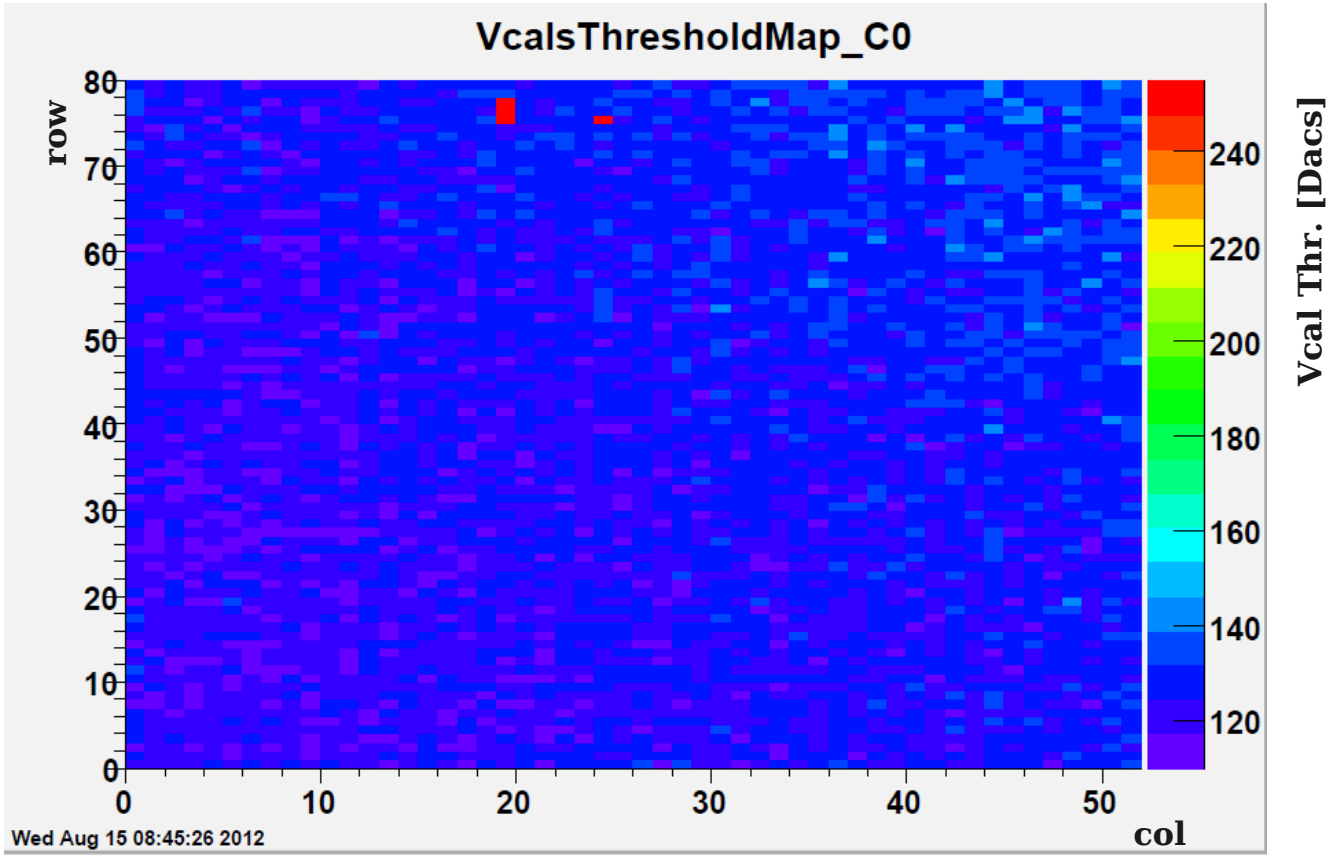
eff = (xdb linked clusters) / (telescope tracks with REF cluster)



- chip 202
  - I_A 350 mA
  - trim 40
- runs 4716-4726
- tilt 0^o
- **99.5% in fiducial volume**
- **6 dead pixels**

Bump bonding test

digital chip 202:
3 + 1 missing bumps, same location as in beam test



ETH procedure used:

The calibration signal injected to a pad on the ROC surface.

It induces a charge in the sensor, which mimics a hit.

Hit is detected if bump bond is present.

Vcal – thresholds are measured in the high Vcal range.

CMS barrel pixel sensor

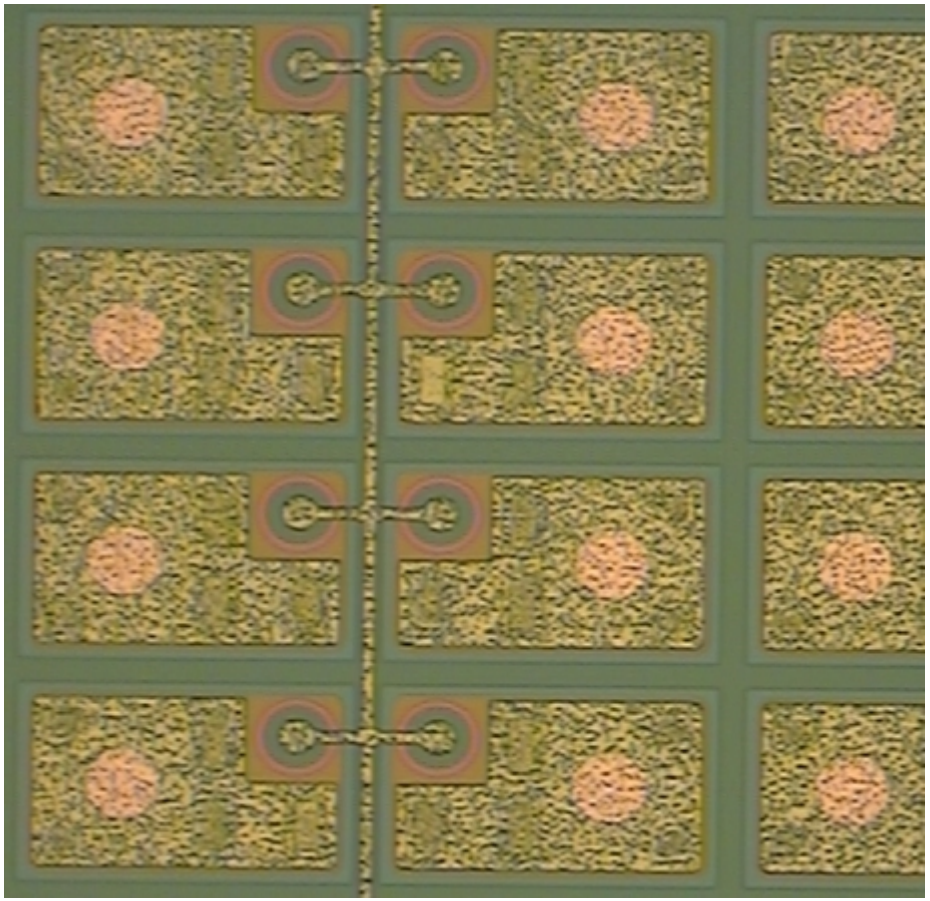
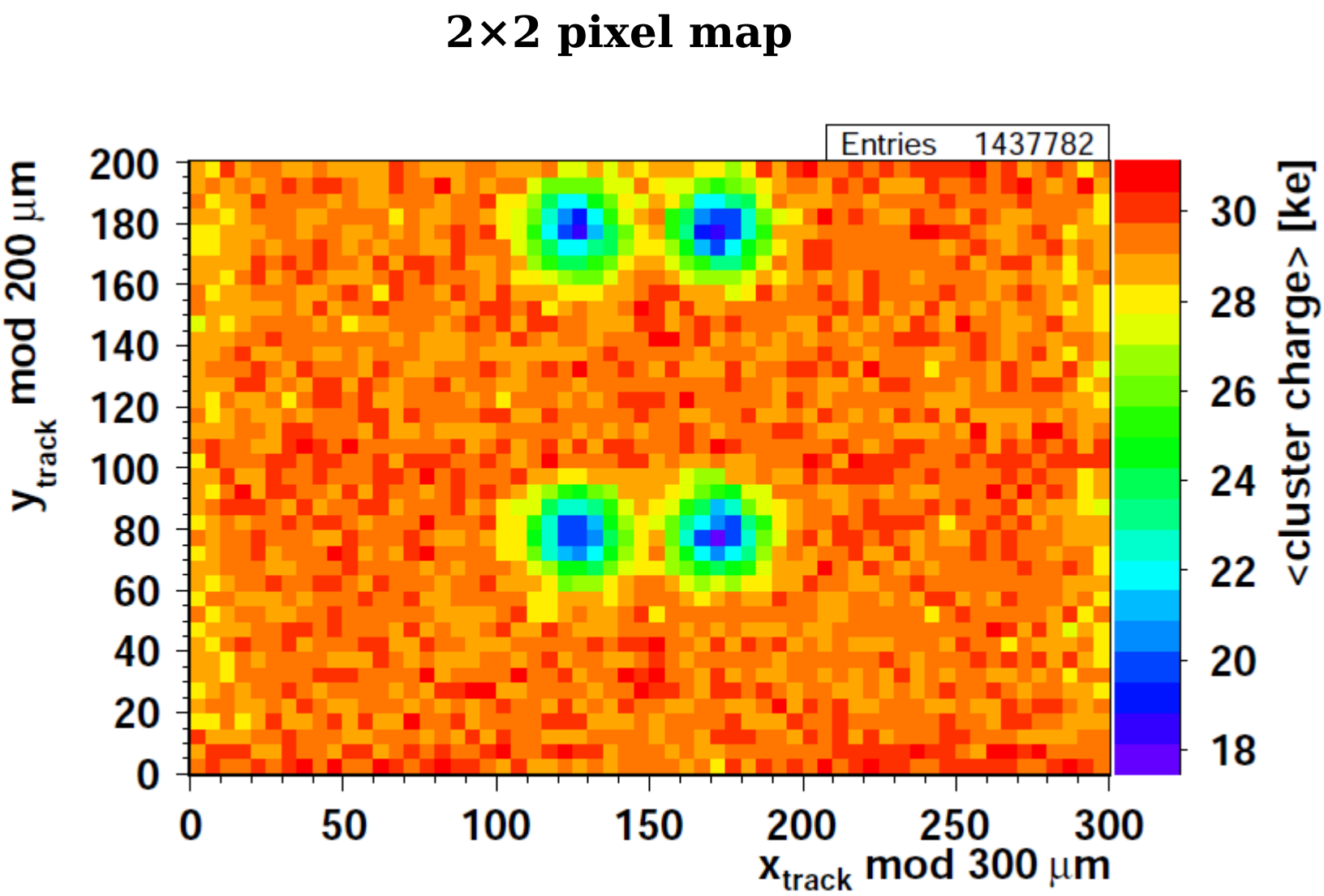


foto: Uni HH, 2012

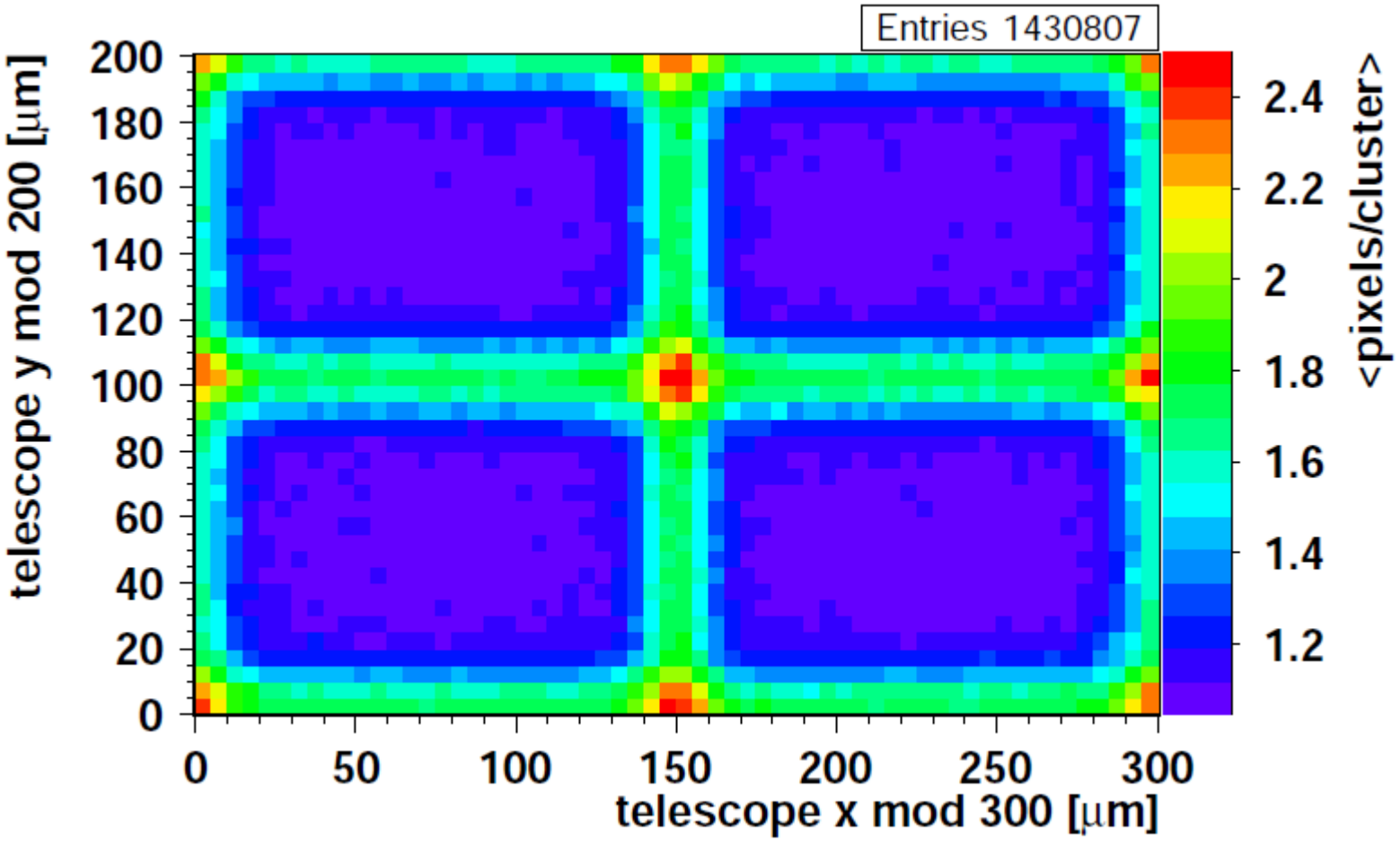
charge map with digital ROC



- c202, **0º tilt**
- 4.8 GeV runs 4716-4726
- Test pulse gain calibration applied (Weibull fit)
- Telescope track position
- **bias dots: charge deficit**

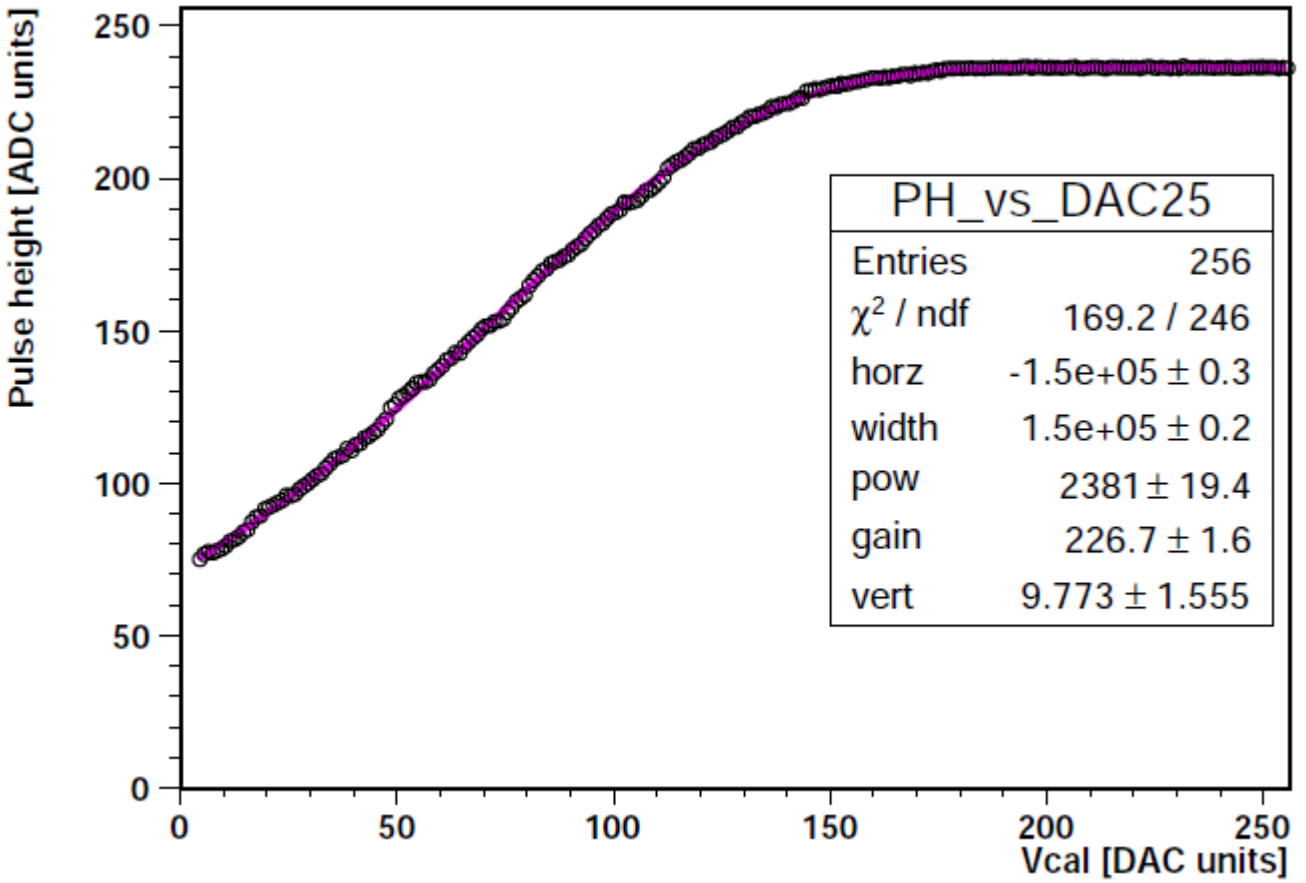
cluster size map with digital ROC

2×2 pixel map



- c202, **0º tilt**
- 4.8 GeV runs 4716-4726
- Telescope track has 6 µm precision
- **pixel core**
- **pixel edge**
- **pixel corner**
- **Charge diffusion radius is about 10 µm.**

gain calibration

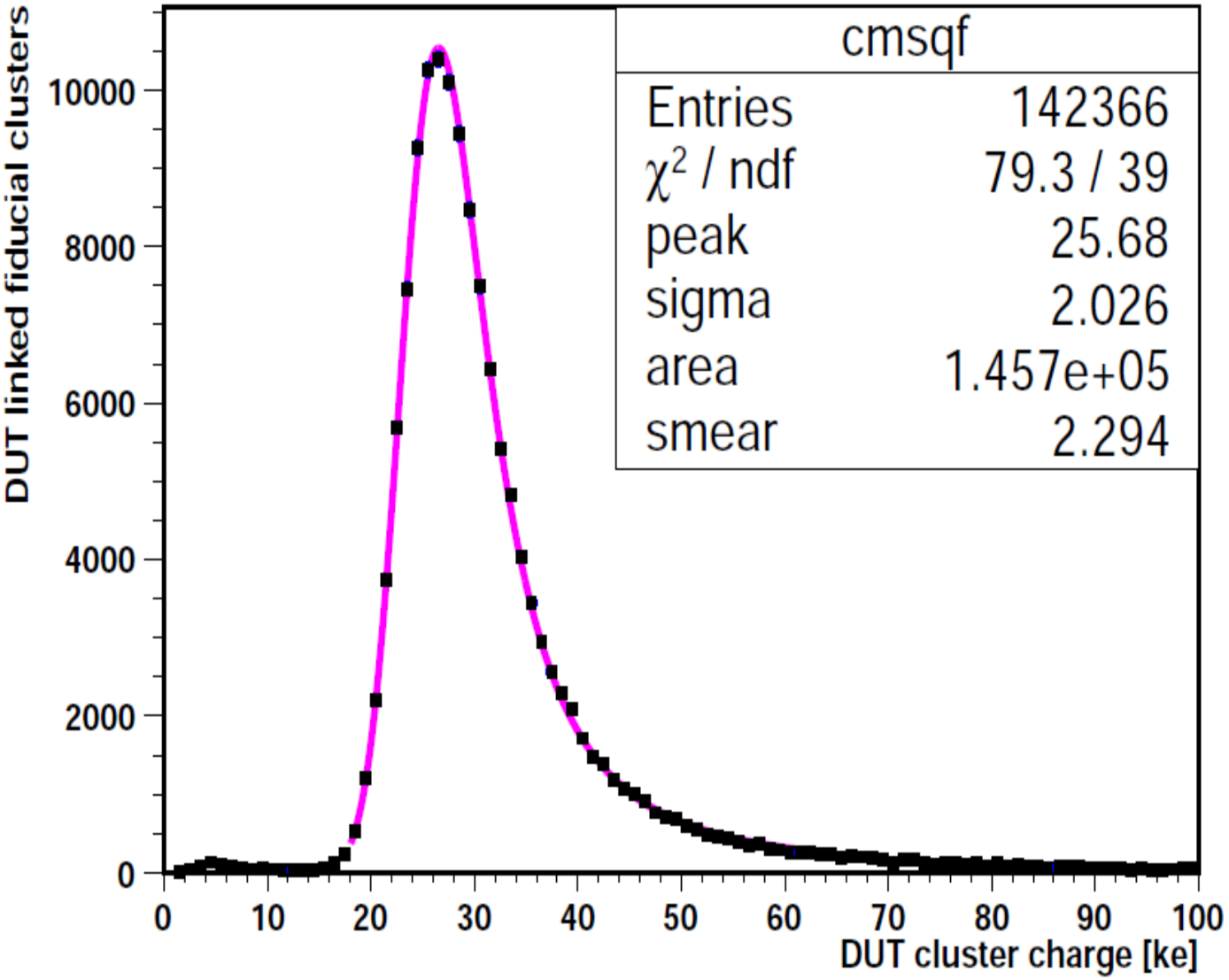


- Pulse height vs large Vcal
- Fit by Weibull function:
  - good fit from threshold to saturation
  - 5 parameters

Weibull: $PH = p_4 + p_3 \left(1 - \exp\left(-((V - p_0) / p_1)^{p_2}\right)\right)$

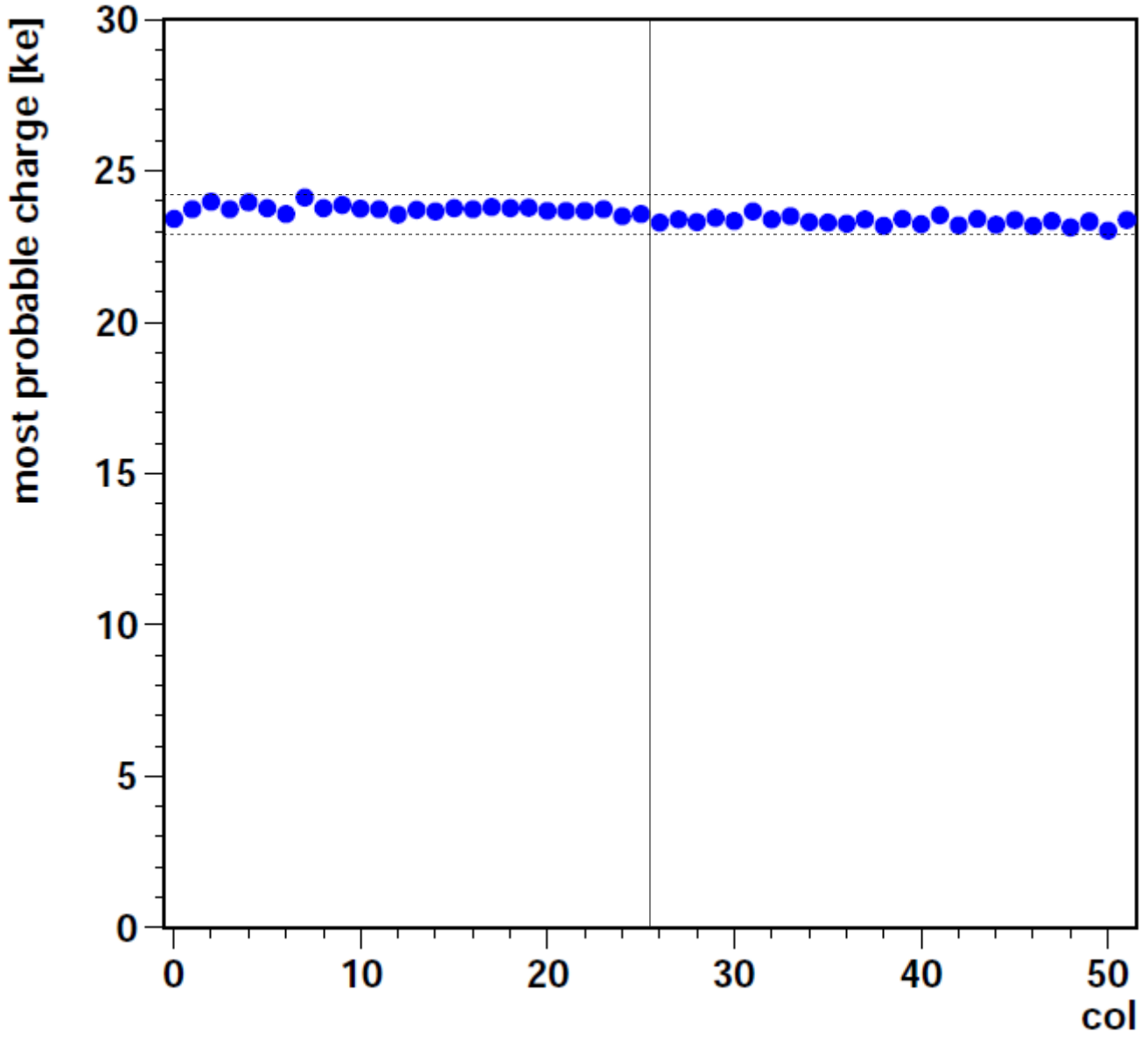
inverse: $V = p_1 \left(-\ln\left(1 - (PH - p_4)/p_3\right)\right)^{1/p_2} + p_0$

Landau distribution from digital ROC



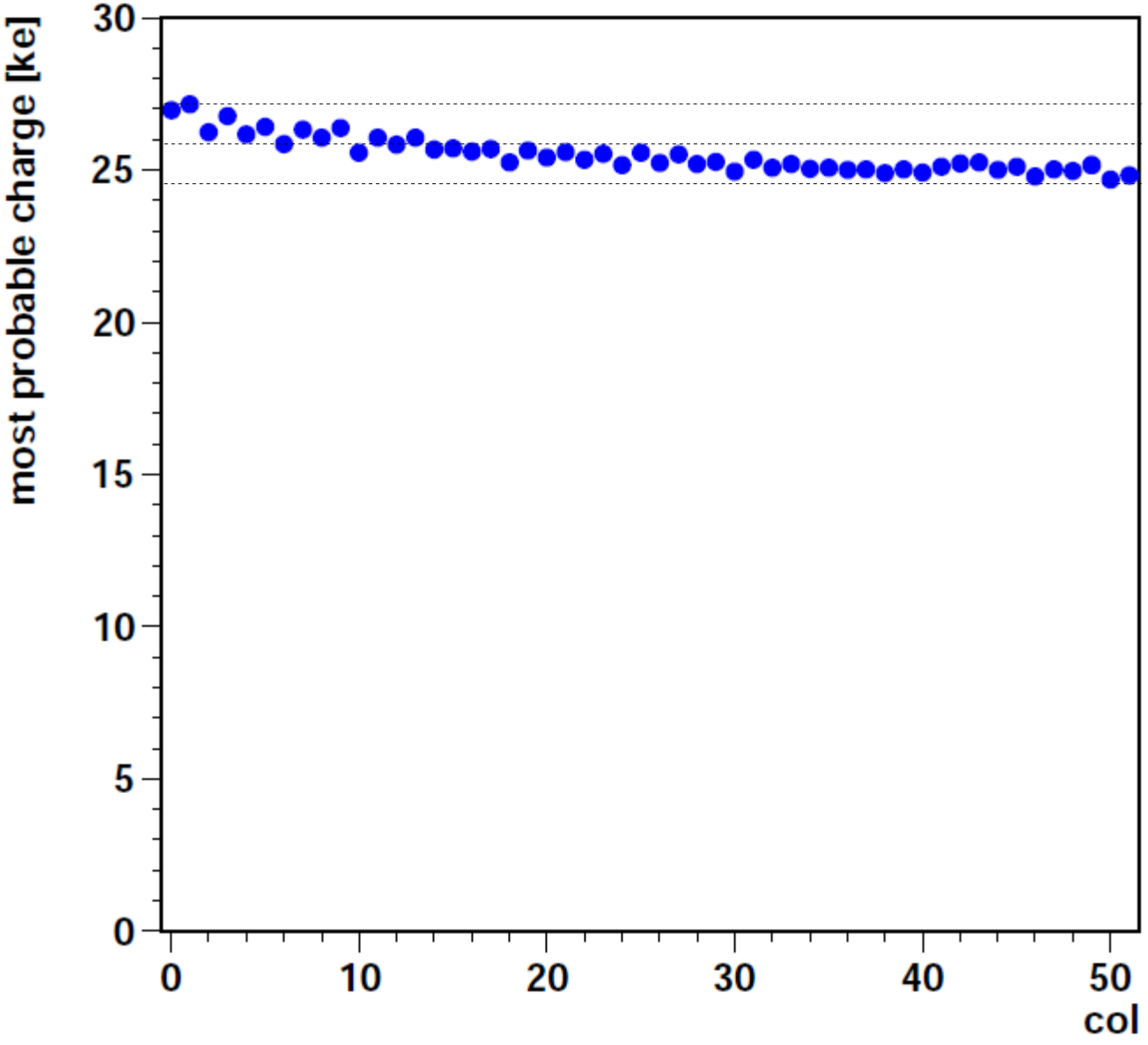
- digital chip 202
- run 4692:
  - bias -150V
  - threshold 2 ke
  - tilt 19°
- Weibull gain calibration applied
- Cluster charge distribution fit by Landau ⊗ Gauss
  - peak position adjusted, width OK
  - Gaussian smearing needed as usual

Cluster charge profile with psi46xdb



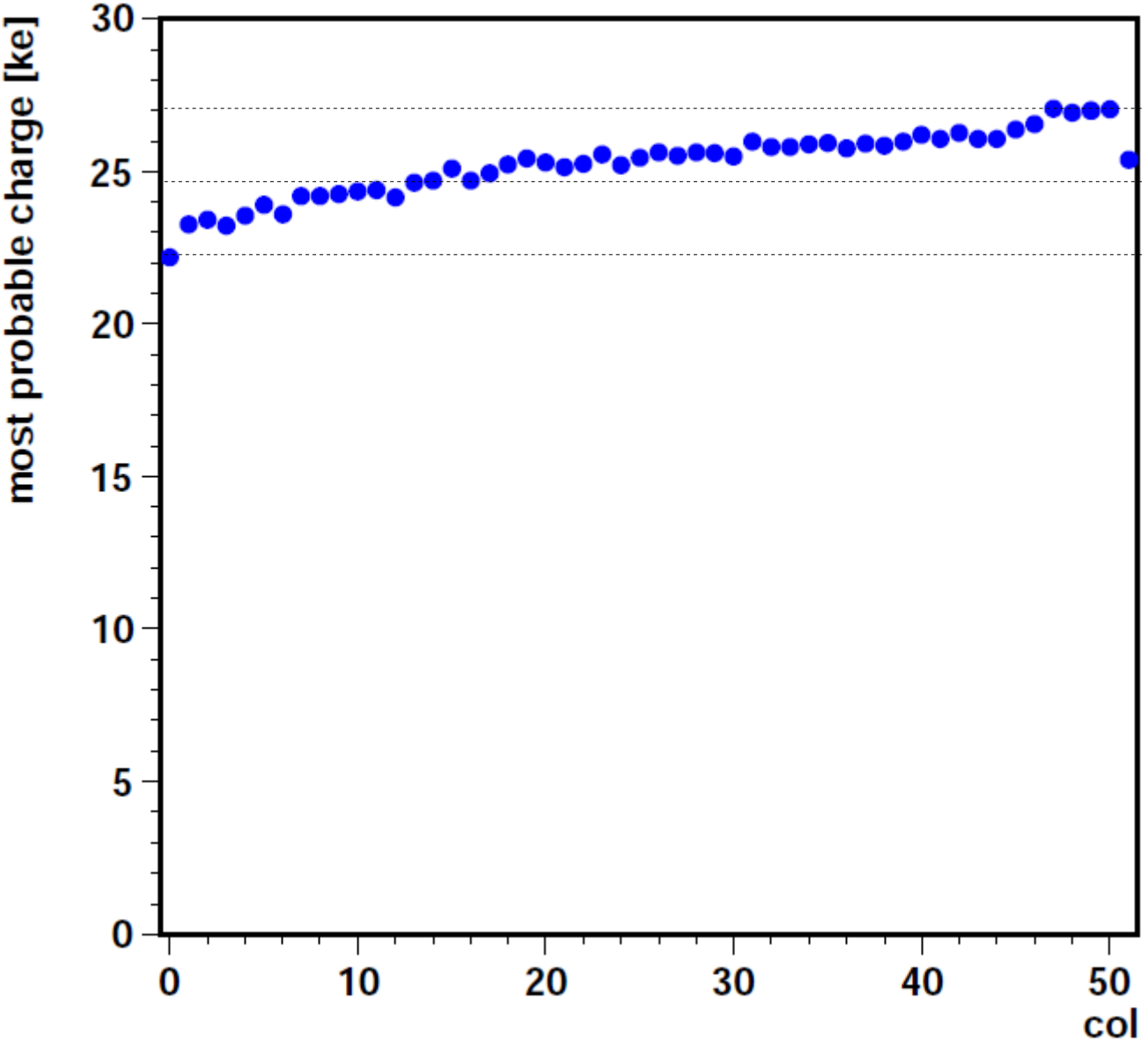
- xdb2, 0^{o} tilt
- 4.8 GeV, runs 3903-3947
- Test pulse gain calibration applied (Weibull fit)
- Landau peak per column
- **Flat within ±2%**
  - small difference between left and right half?
- Mean value is adjusted to 24 ke for e^{+} in 285 µm Si
  - 350 e / large Vcal DAC

Cluster charge profile with digital ROC



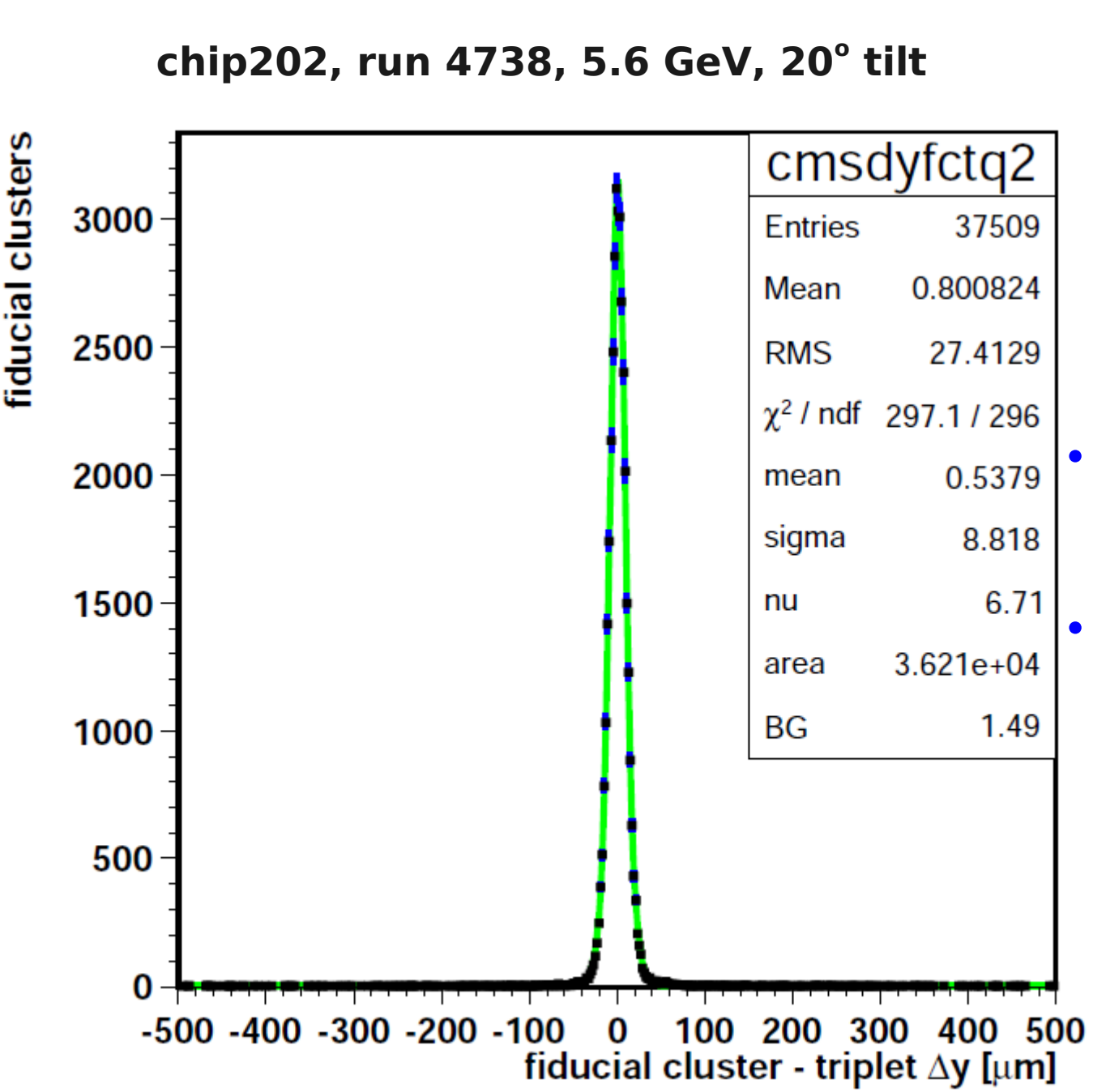
- chip202, 20° tilt
- 5.6 GeV, runs 5164-5180
- Test pulse gain calibration applied (Weibull fit)
- Landau peak per column
- **±4% trend across columns:**
  - better than psi46, worse than xdb?
- Mean value is adjusted to 24 ke for e^+ in 285 µm Si
  - 350 e / large Vcal DAC

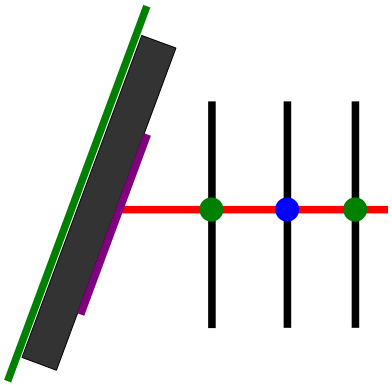
Cluster charge profile with psi46



- 4 GeV e^-
- chip 10, 20° tilt
- Test pulse gain calibration applied (tanh fit)
- peak charge
- **Observe ±8% gain variation across the chip**

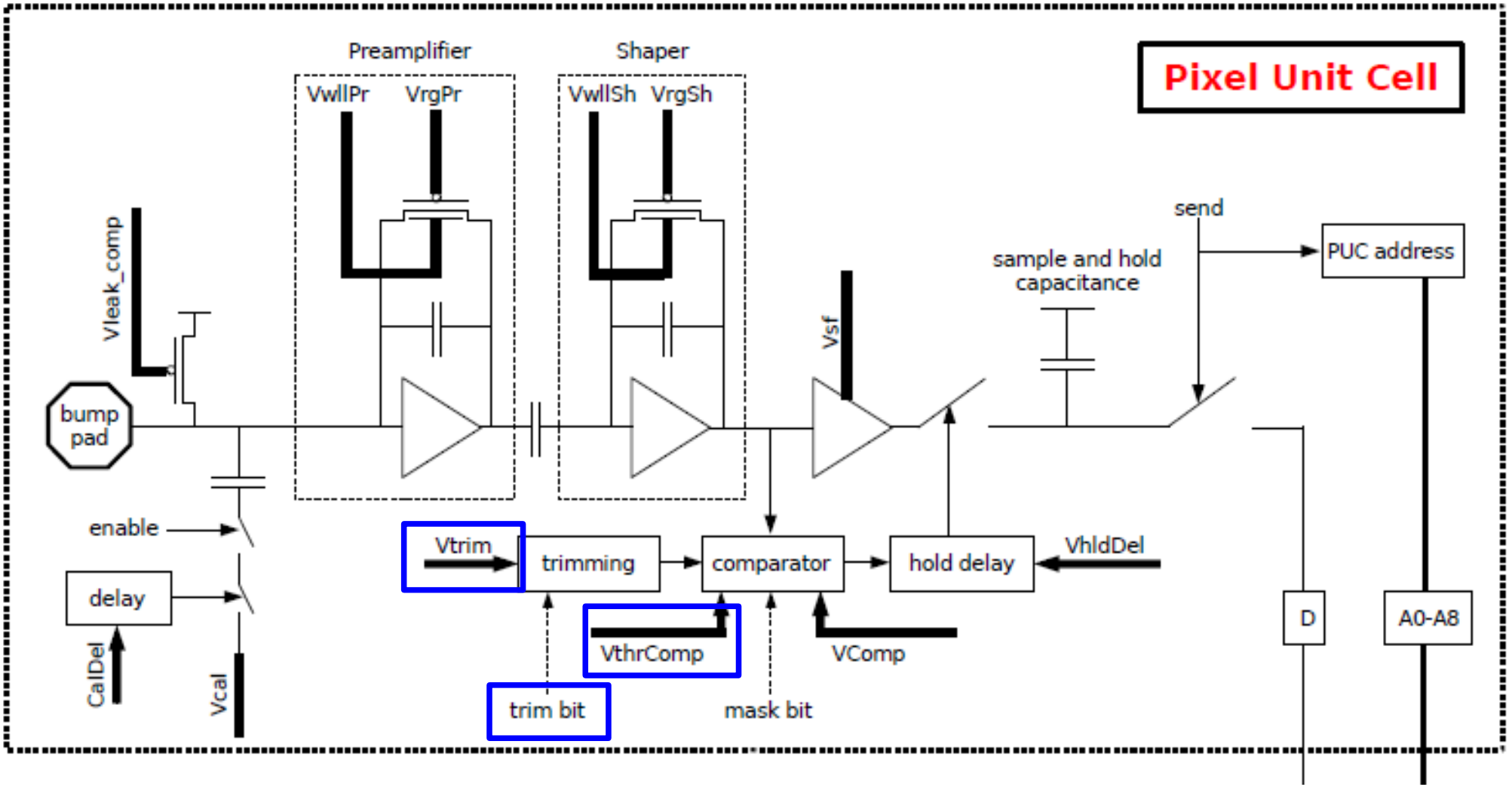
row resolution with digital ROC





- Vertical = rows
  - CMS pixel = 100 µm.
- Residual:
  - σ = 8.8 µm,
  - telescope extrapolation: 5.7 µm,
  - **dig resolution: 7 µm**
  - **similar to psi46**

Threshold scan

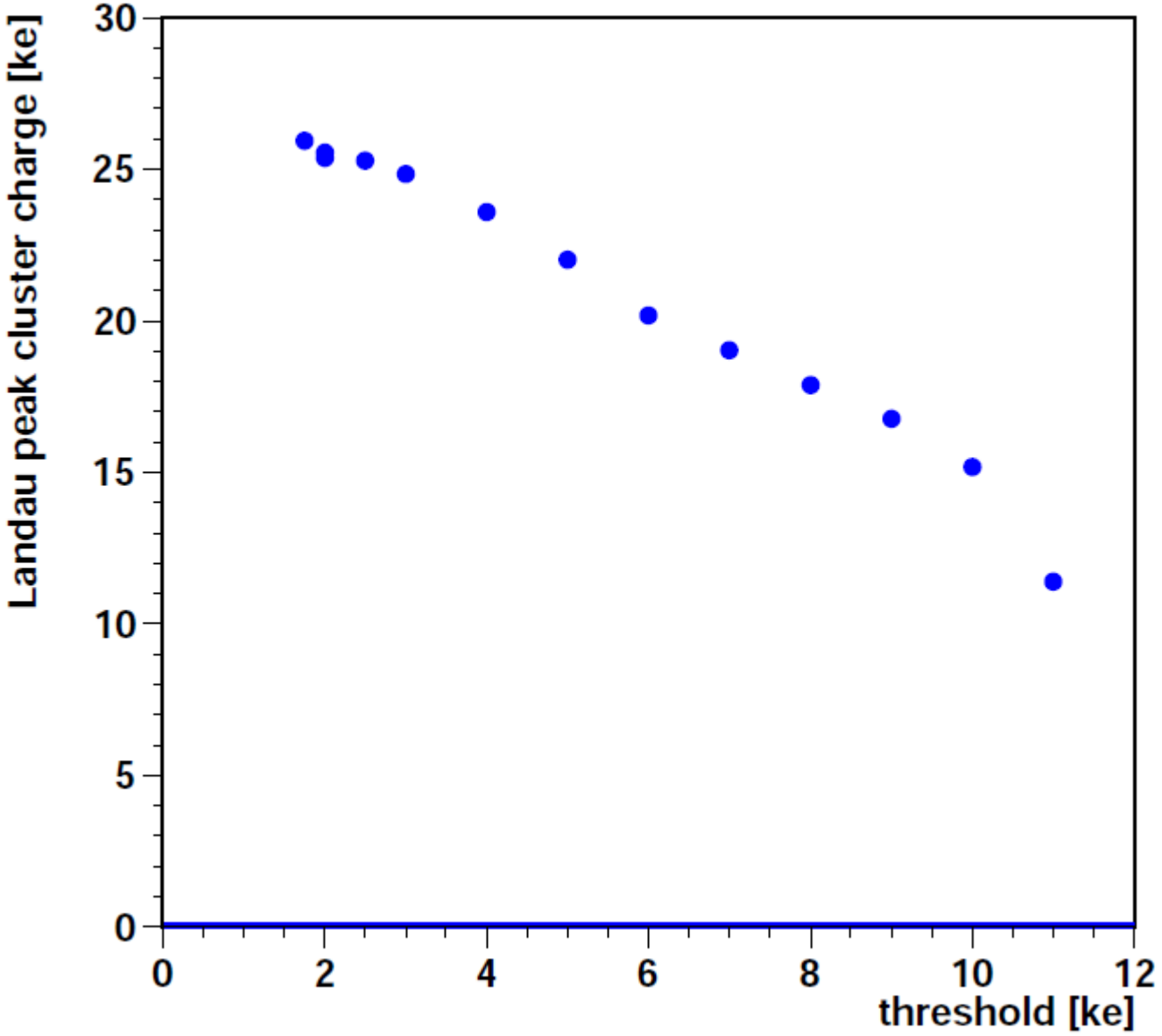


Threshold = VthrComp – Vtrim · trimbits

Harder threshold: loose small pulses

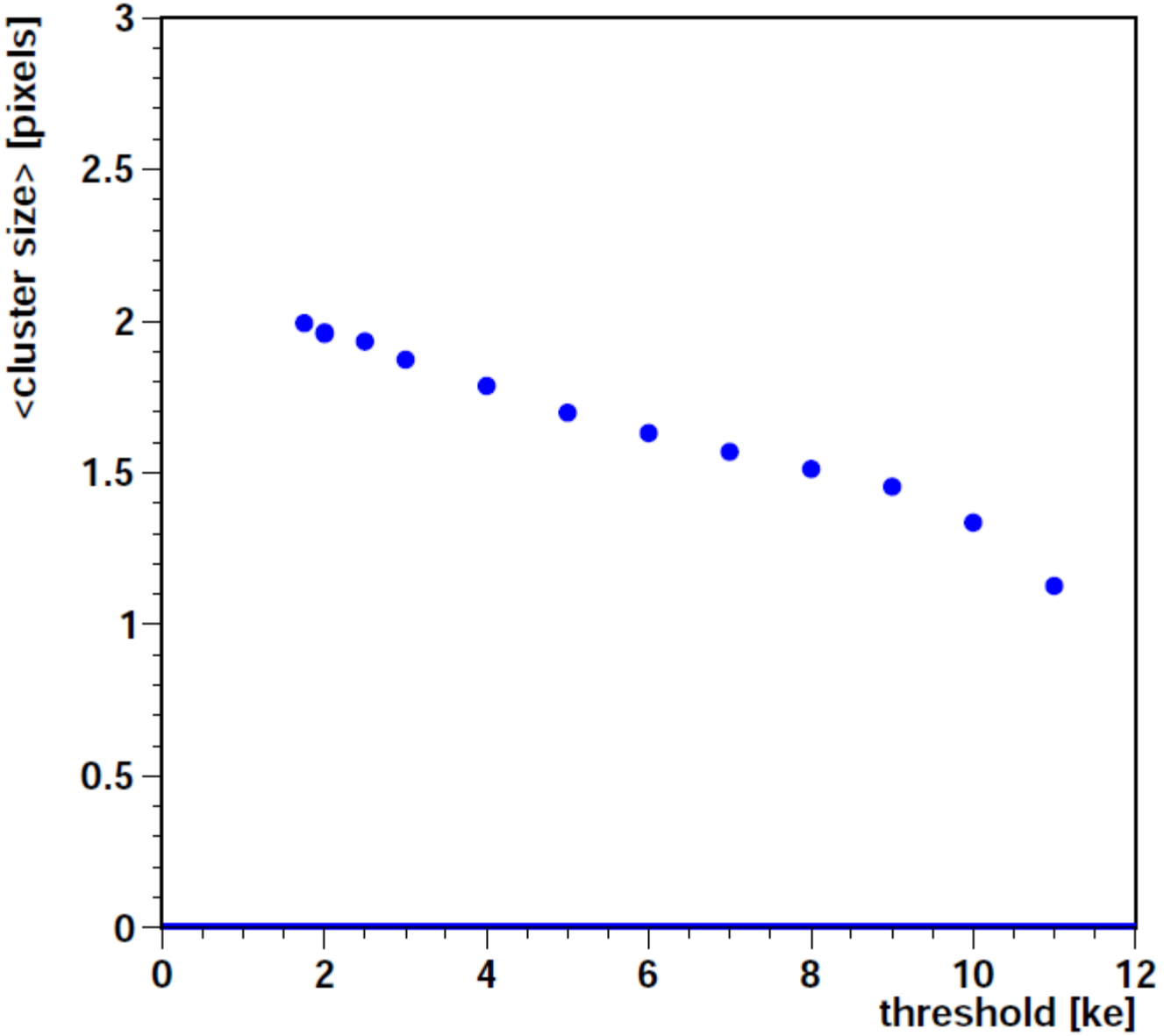
Simulates reduced charge collection (radiation damage)

Cluster charge vs threshold with psi46dig



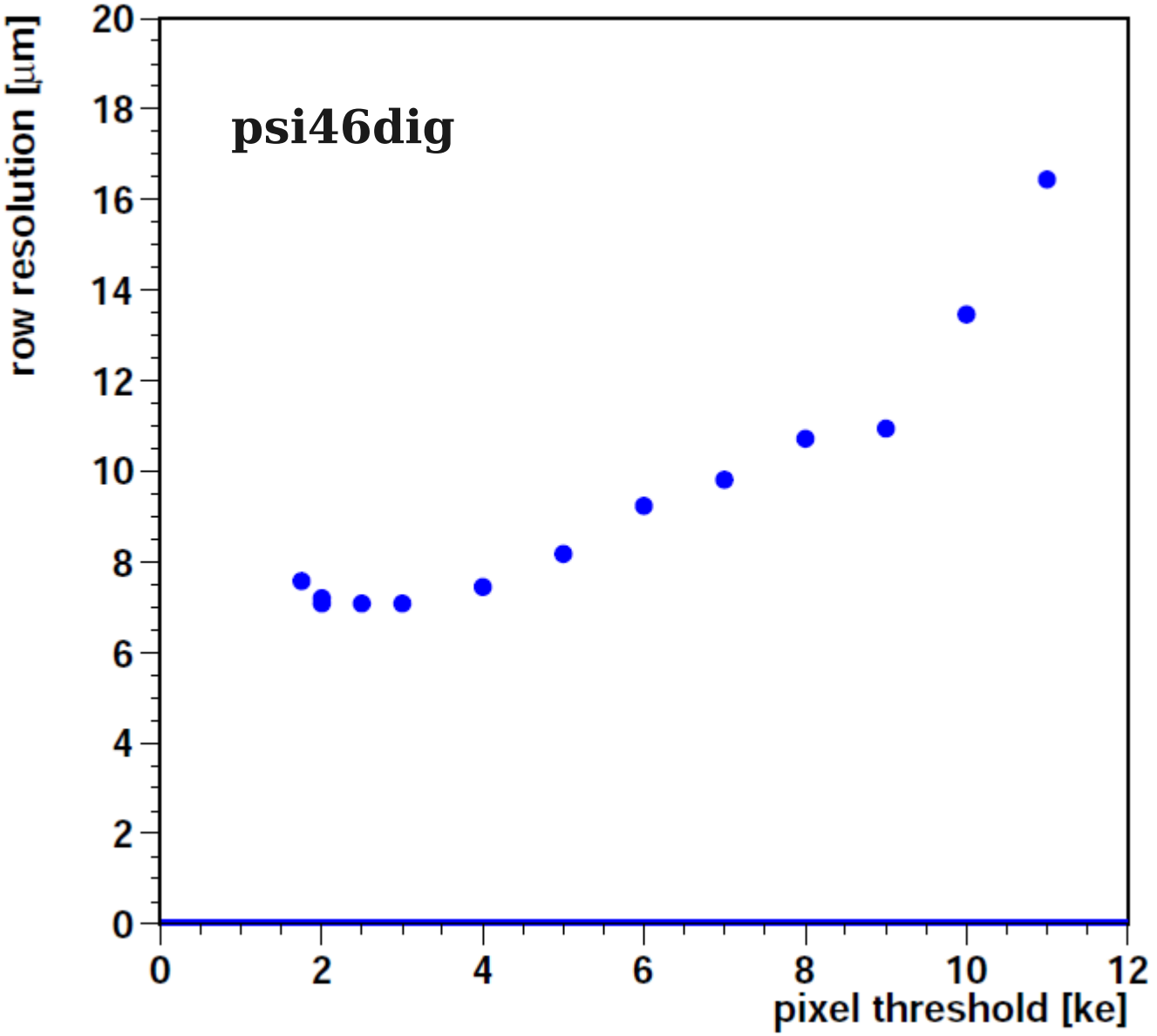
- Digital Chip 202, -150V, 20° tilt, Ia 30 mA
  - runs 5310-5384
- Threshold and delay adjusted together
- Position of Landau peak
  - decreases with harder threshold

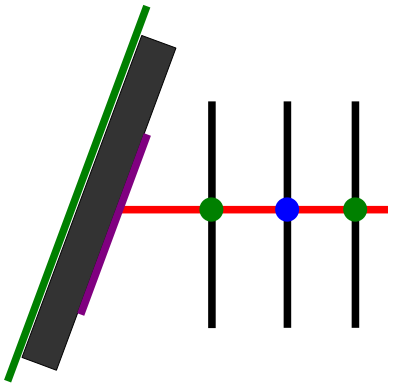
Cluster size vs threshold with psi46dig



- Digital Chip 202, -150V, 20° tilt, Ia 30 mA
  - runs 5310-5384
- Threshold and delay adjusted together
- rows per cluster:
  - decreases with harder threshold

Resolution vs psi46dig threshold





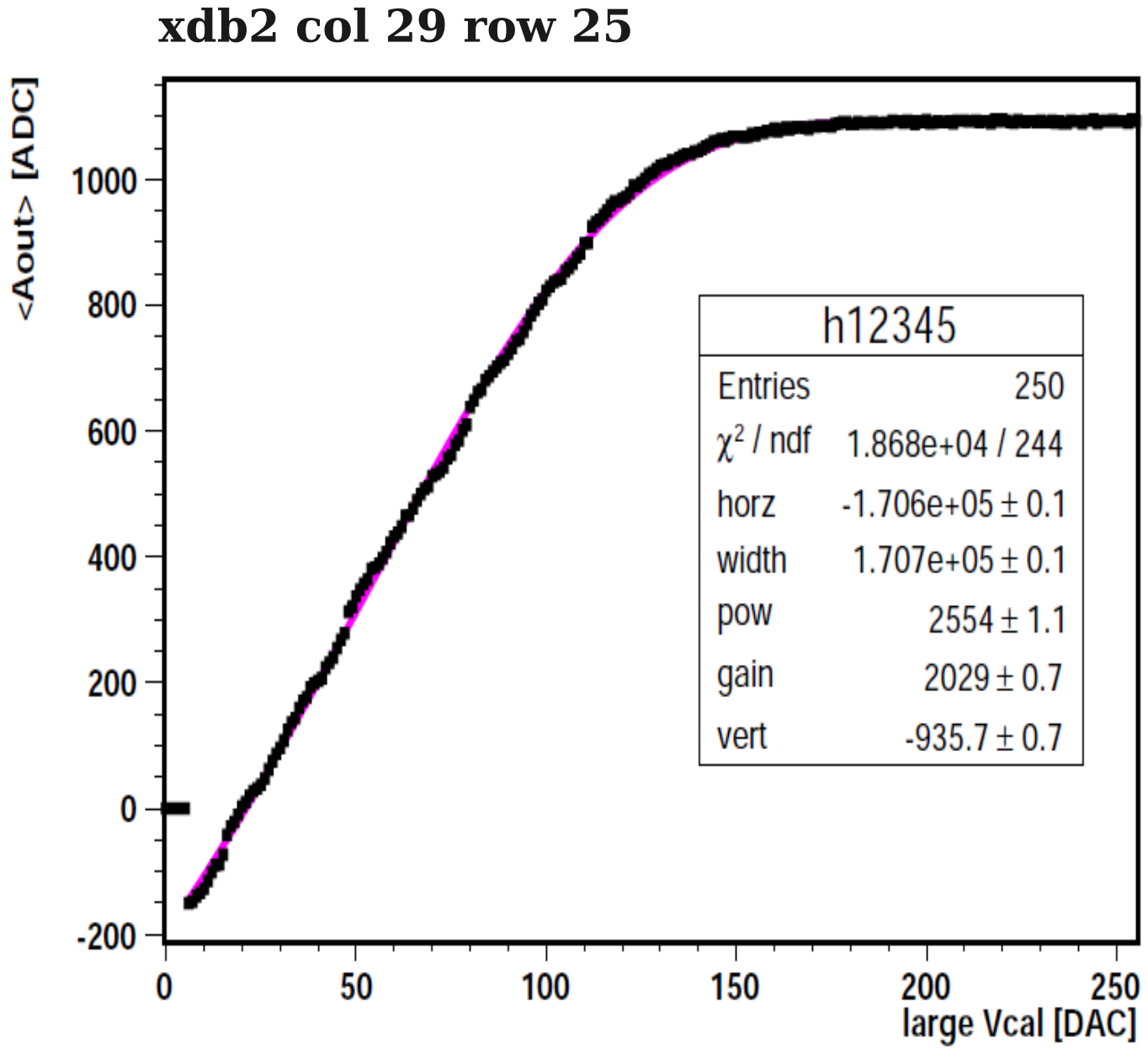
- Chip 202, 20.5° tilt
- 5.6 GeV, telescope extrapolation uncertainty subtracted.
- lower threshold:
  - resolution seems to saturate at 7 µm below 3 ke.

Summary

- PSI46dig single chip pixel sensor operated at the DESY test beam:
  - efficiency up to 99.8%
  - better gain uniformity than psi46
  - lower thresholds reached (1.8 ke), less time walk than psi46
  - resolution 7 µm at 19°, similar to psi46, despite lower thresholds

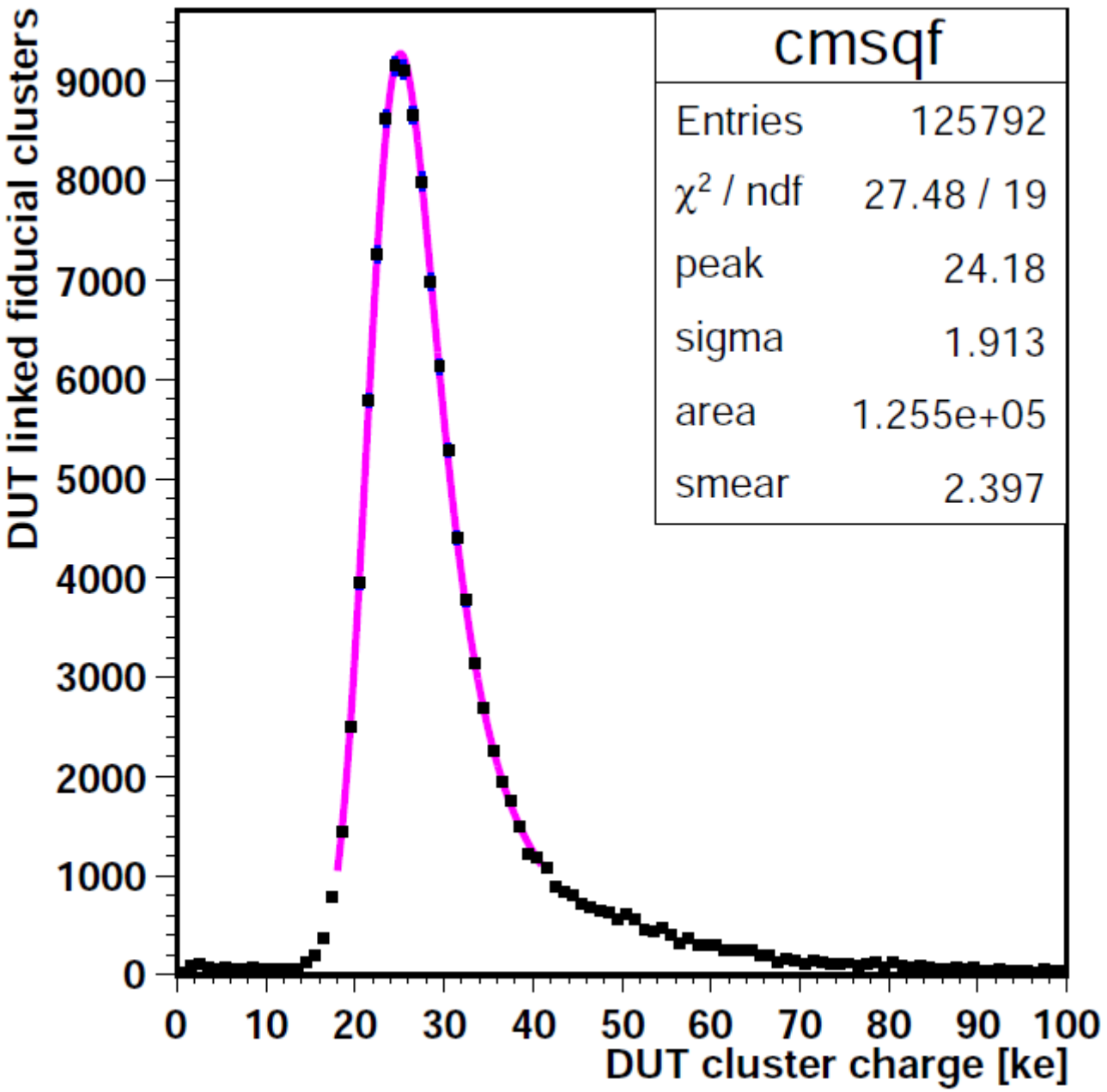
xdb plots

xdb2 Aout vs Vcal gain curve



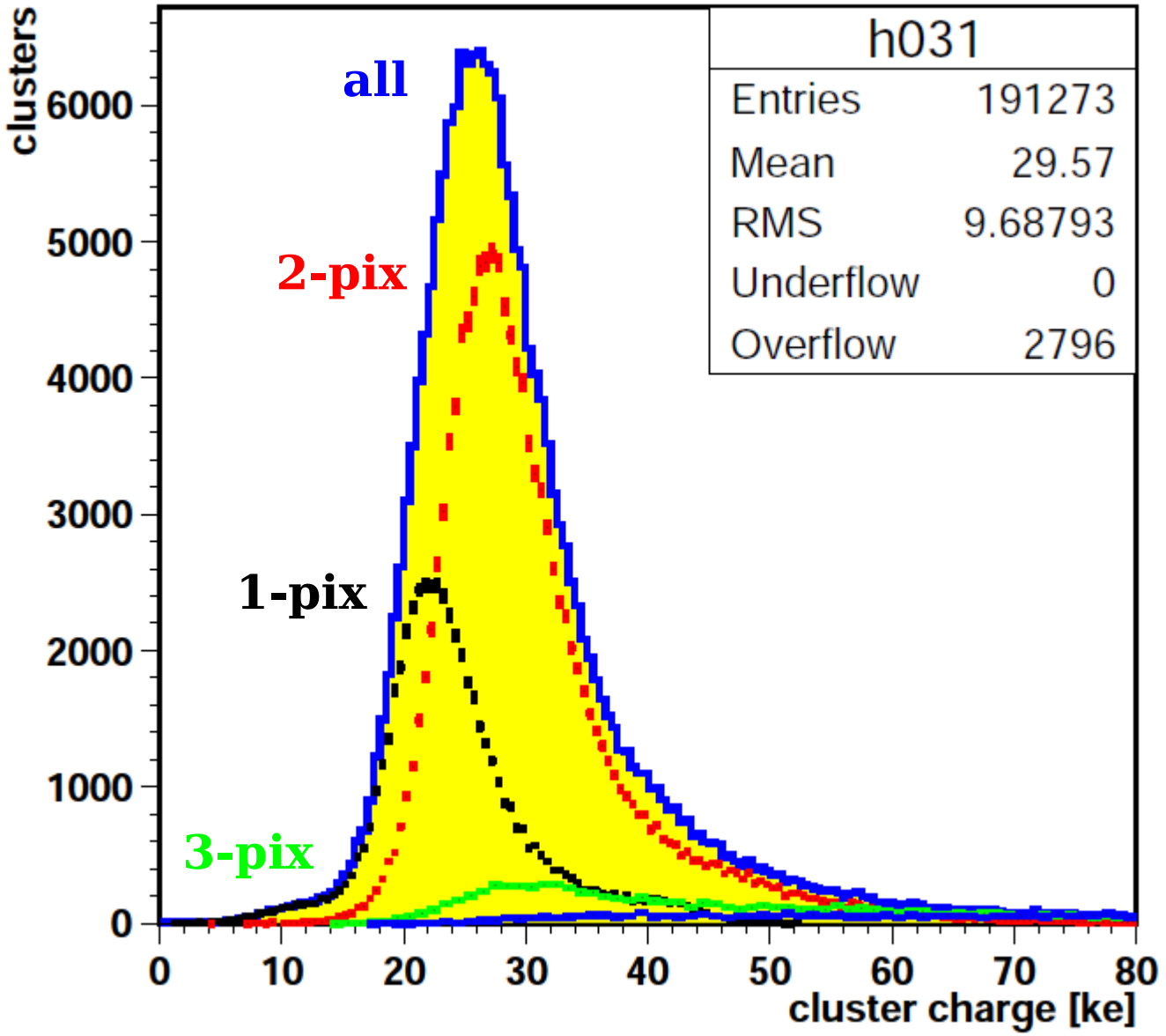
- xdb2
- for each pixel
- gainmap with disarm instead disable
- large Vcal:
  - 380 e / DAC (Landau calibration)
- Fit by Weibull function

xdb2 Landau distribution



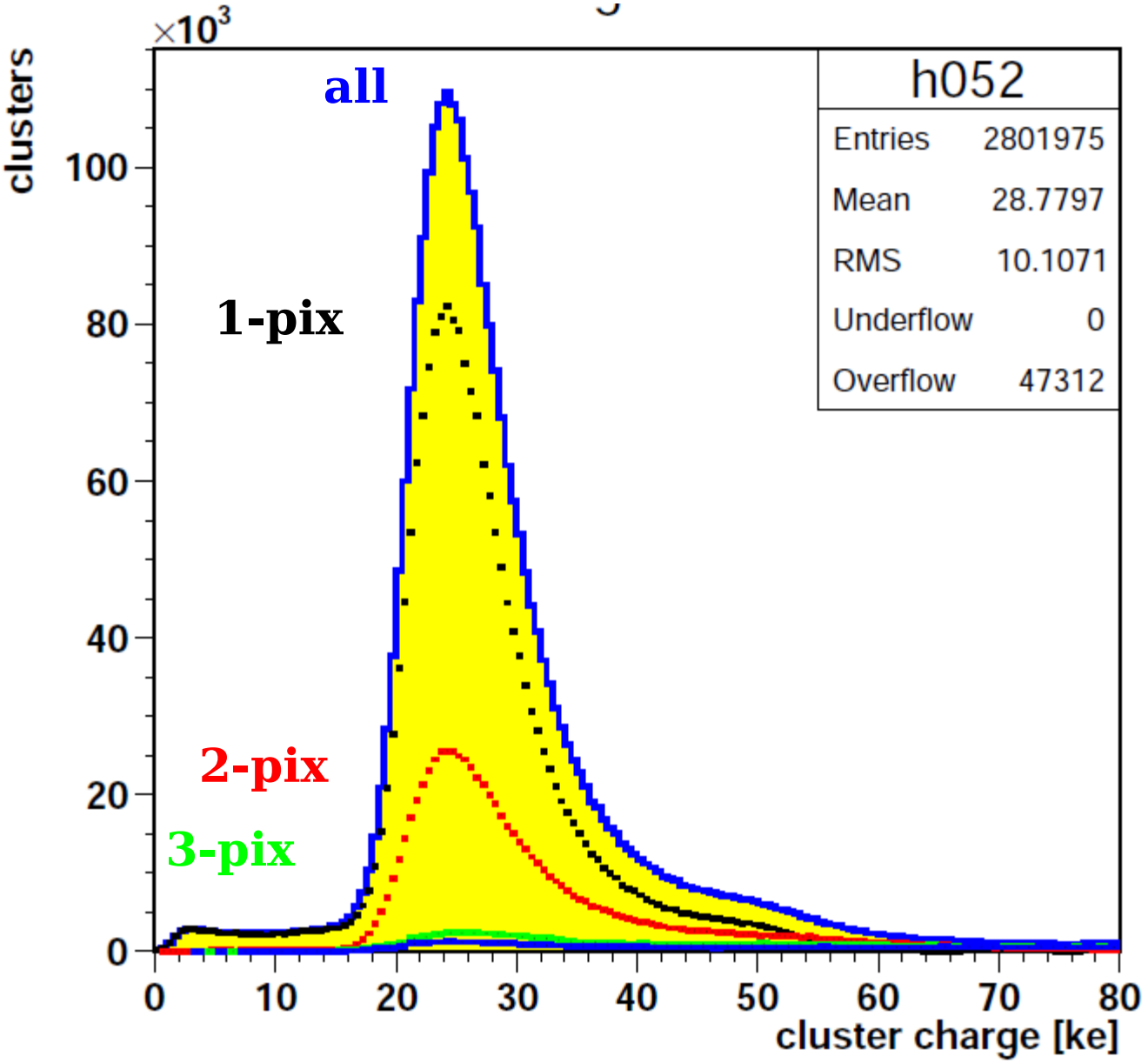
- xdb2
- run 4211:
  - bias -150V
  - threshold 1.8 ke
  - tilt 19°
- Weibull gain calibration applied
- Cluster charge distribution fit by Landau ⊗ Gauss
  - peak position and width OK
  - Gaussian smearing needed

Cluster charge vs size for psi46



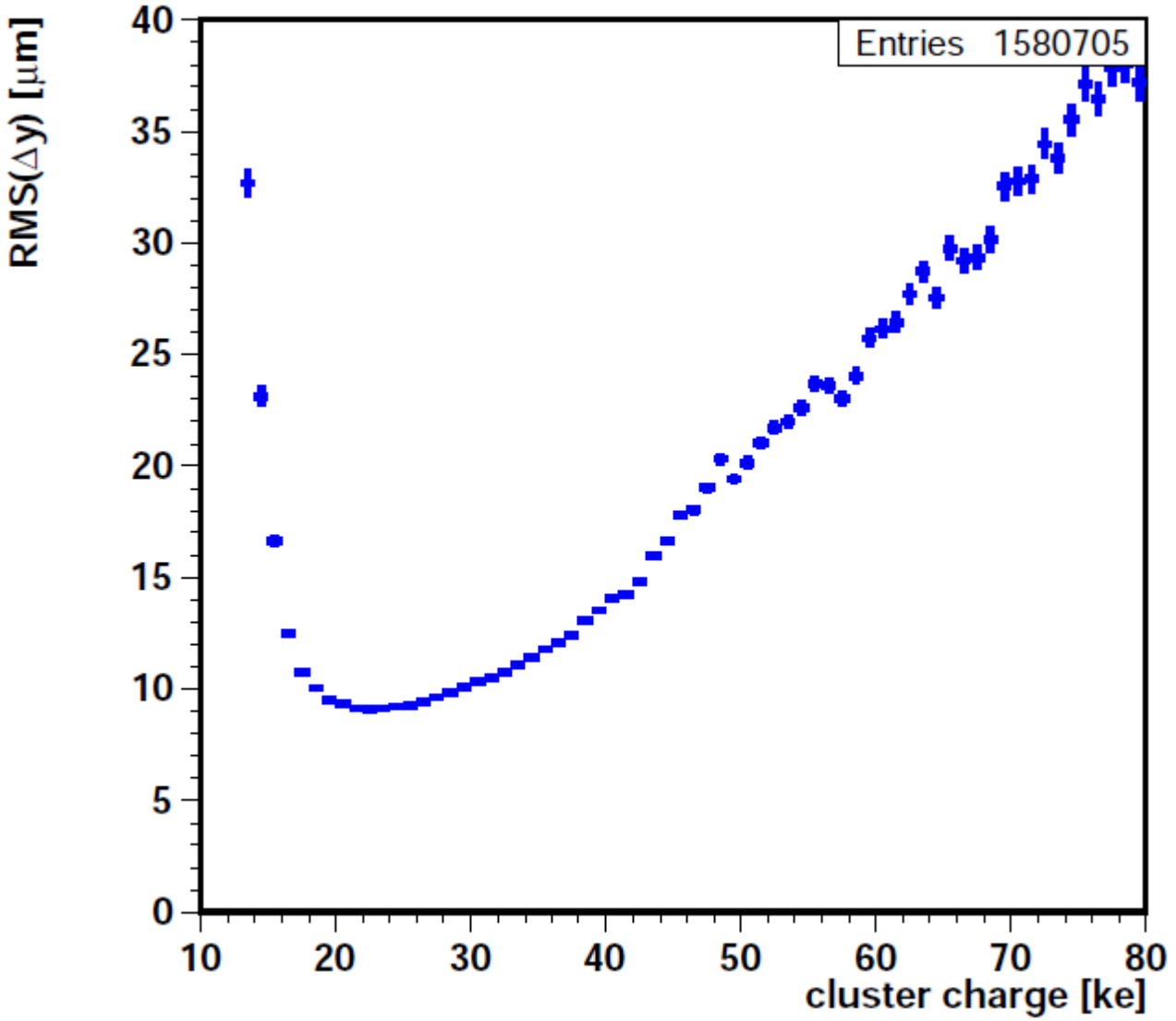
- 4 GeV e-, run 2880, chip 10, 20° tilt
- Test pulse gain calibration applied (tanh fit)
- 1-pixel clusters have lower Landau peak:
  - charge loss due to threshold?

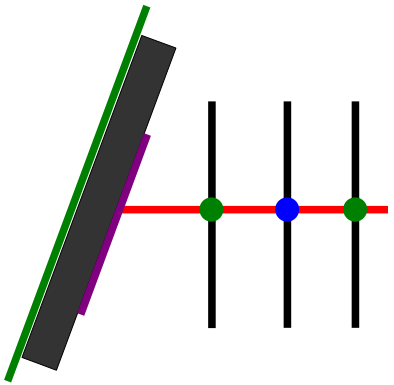
Cluster charge vs size for xdb



- xdb2
- 0^{o} tilt
- 4.8 GeV, runs 4249-4269
- Test pulse gain calibration (Weibull fit): gainweib.dat
- 1-pixel and 2-pixel clusters have same Landau peak:
  - no large loss due to threshold

row resolution vs cluster charge

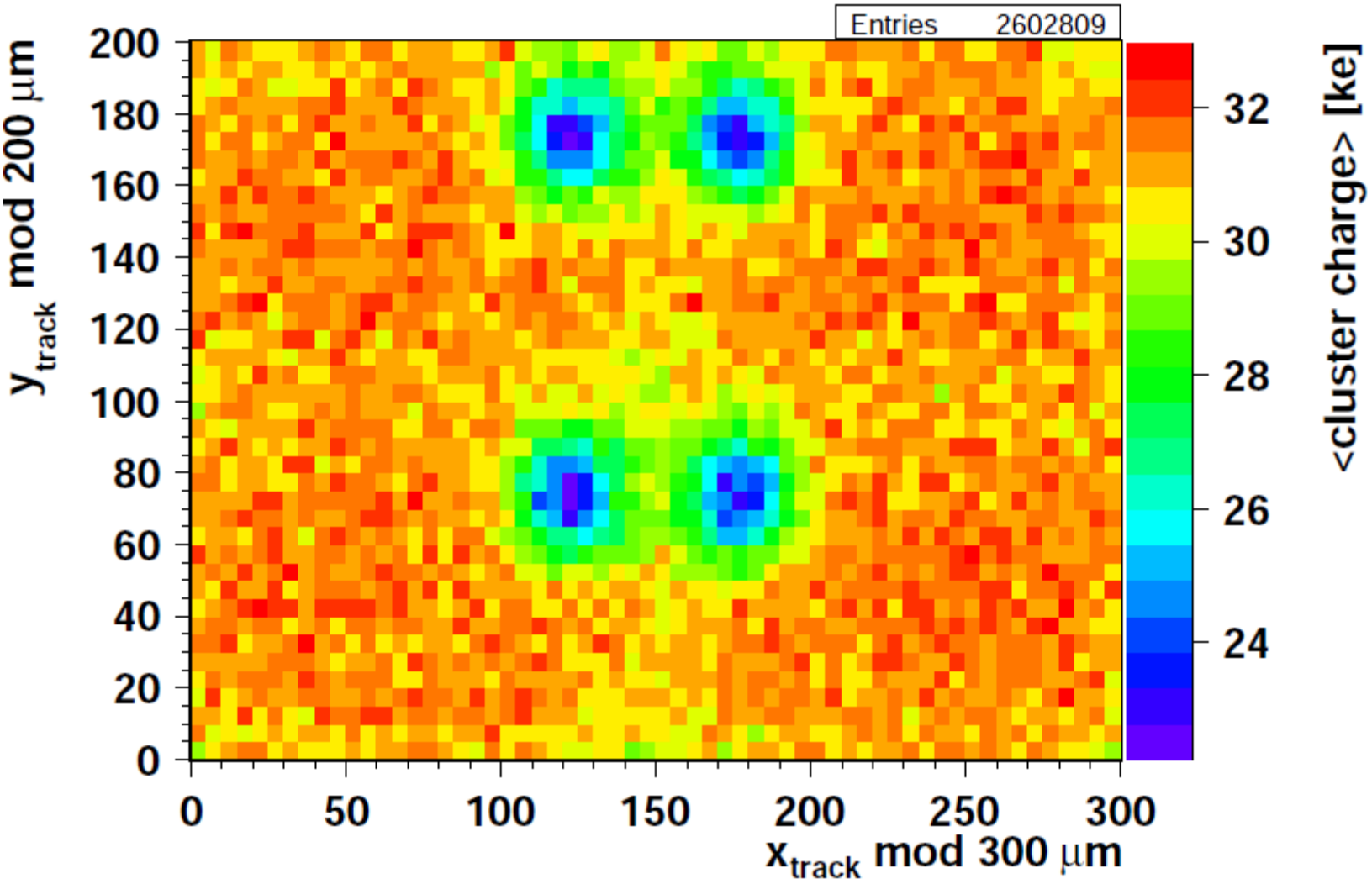




- Best resolution for mips at the Landau peak around 24 ke
- Poor resolution below 18 ke:
  - broken clusters
- Poor resolution in Landau tail above 40 ke:
  - delta rays

charge map with xdb

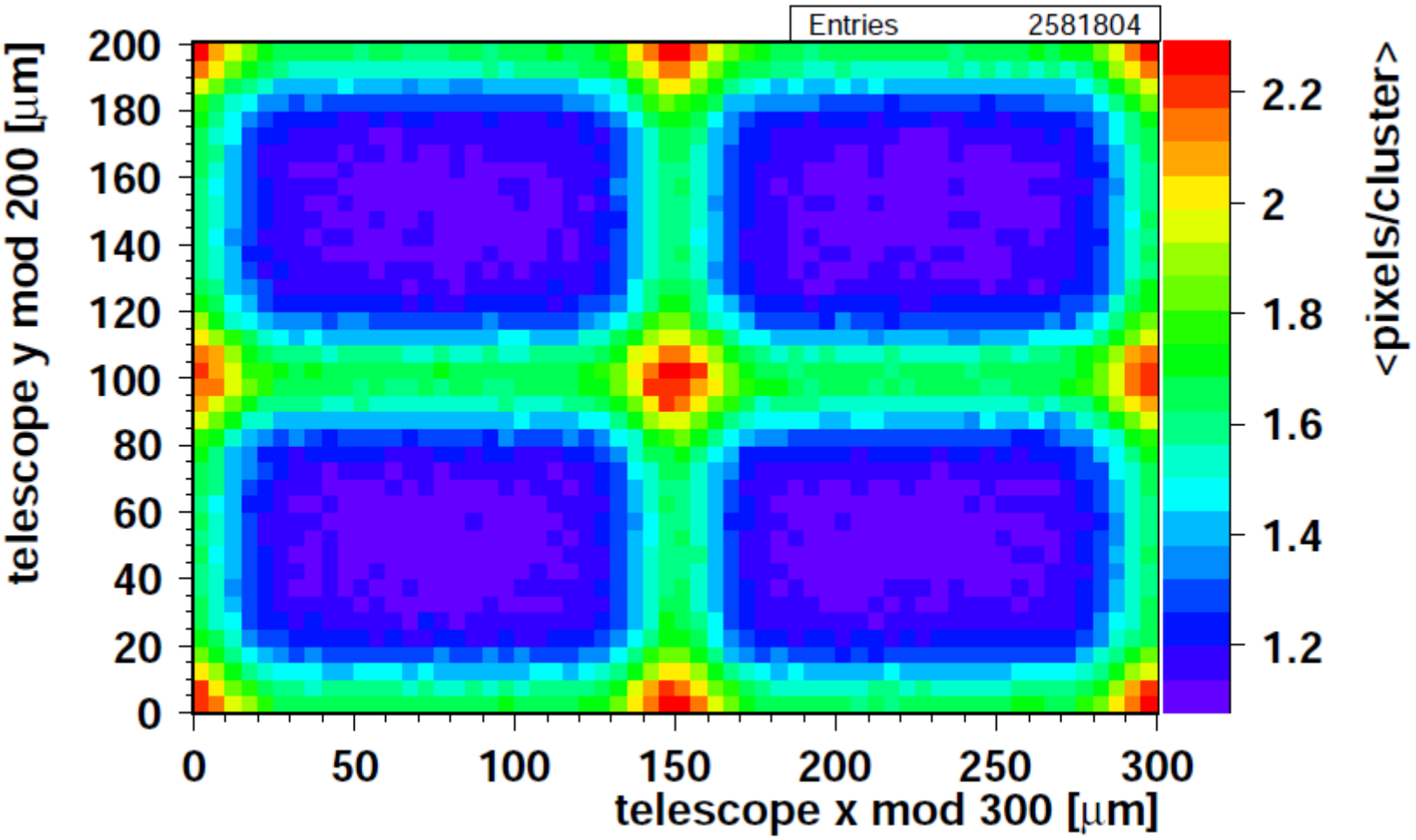
2×2 pixel map



- xdb2, 0° tilt
- 4.8 GeV runs 4249-4269
- Test pulse gain calibration applied (Weibull fit)
- Telescope track position
- **bias dots: charge deficit**

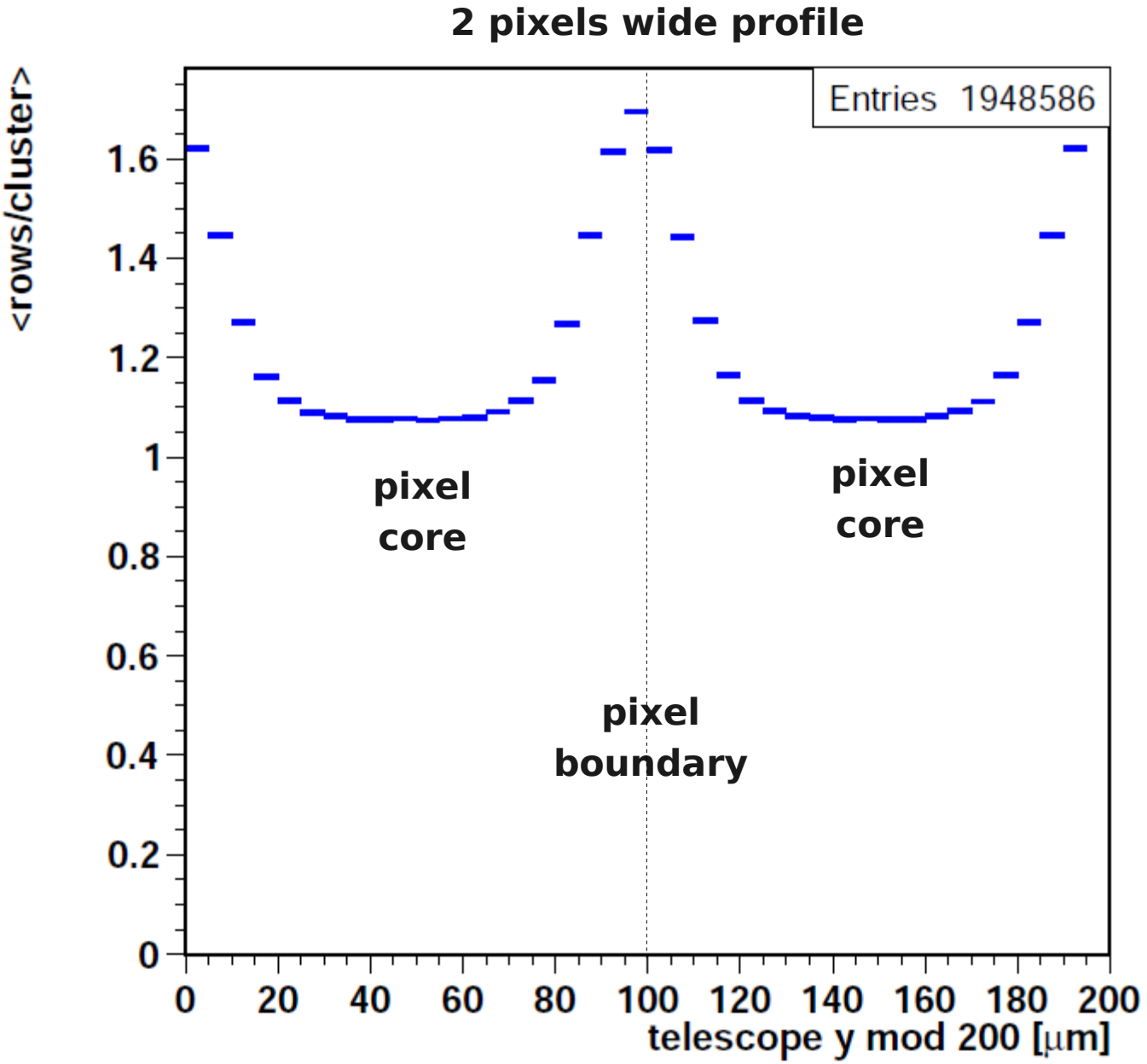
cluster size map with xdb

2×2 pixel map



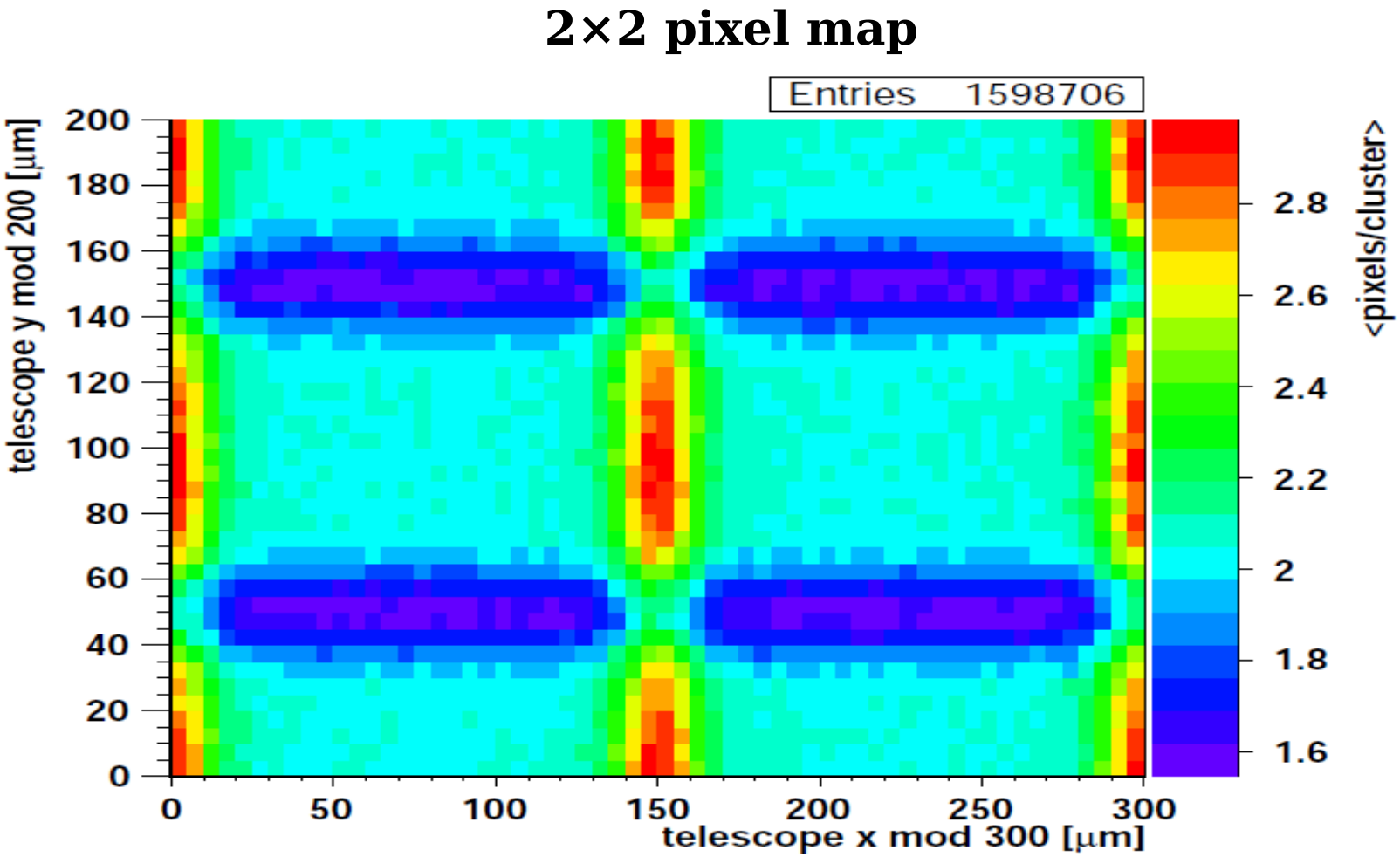
- xdb2, **0º tilt**
- 4.8 GeV runs 4249-4269
- Telescope track has 6 μm precision
- **pixel core**
- **pixel edge**
- **pixel corner**
- **Charge diffusion radius is about 10 μm.**

vertical cluster size profile with xdb



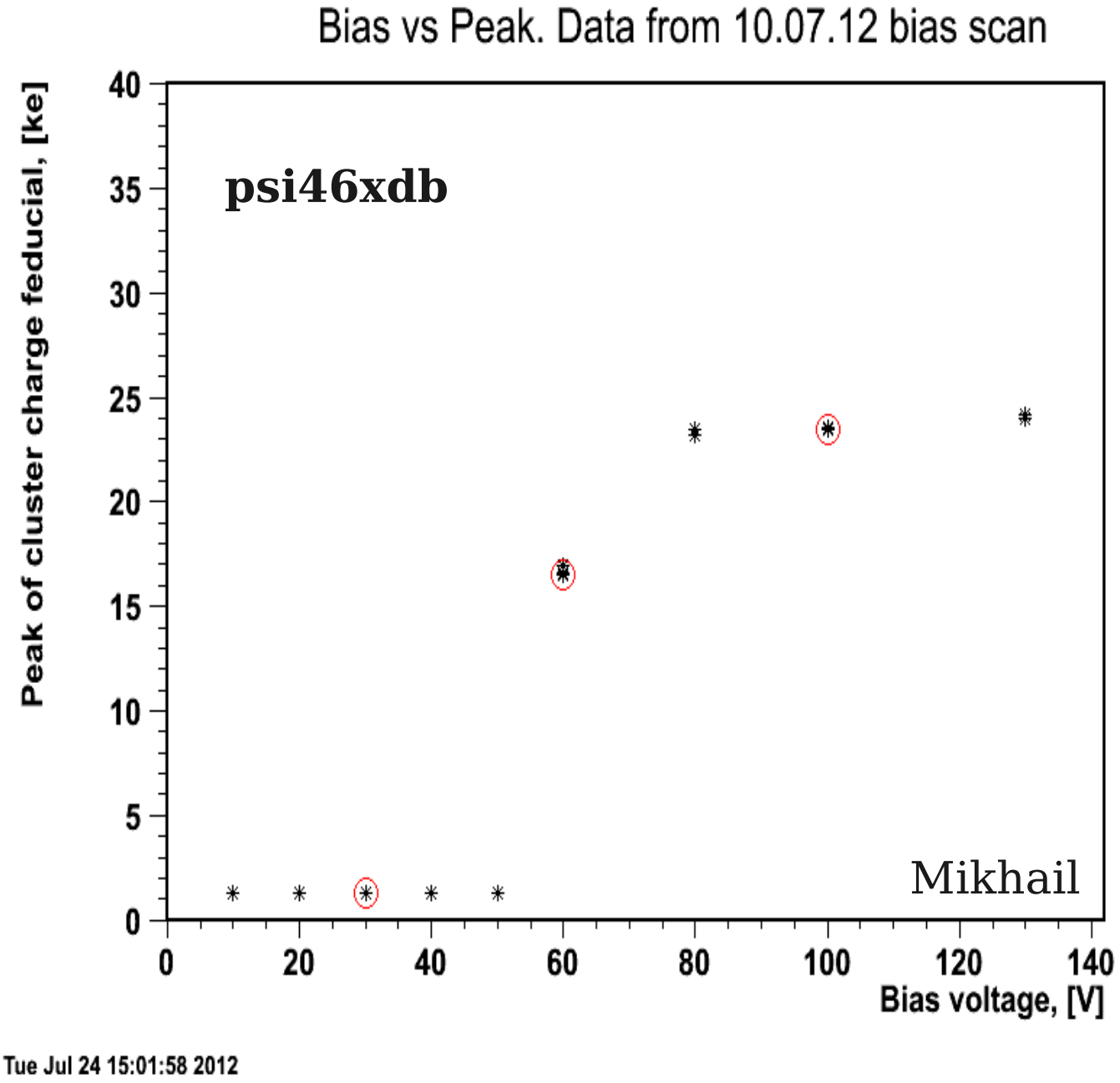
- xdb2, **0° tilt**
- 4.8 GeV runs 4249-4269
- Telescope track has 6 µm precision
- **pixel core:**
  - **minimal cluster size**
- **pixel boundary:**
  - **larger clusters due to charge diffusion**
  - **diffusion radius about 10 µm**

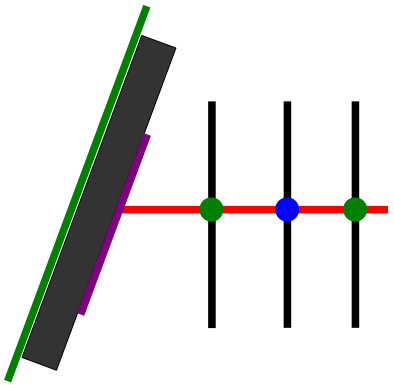
cluster size map with xdb



- xdb2, **18° tilt**
- 4.8 GeV runs 4211-4231
- **pixel core:**
  - **2-pix clus**
  - **tilt**
- **row edge:**
  - **1-pix clus**
  - **threshold**
- **col edge:**
  - **diffusion**

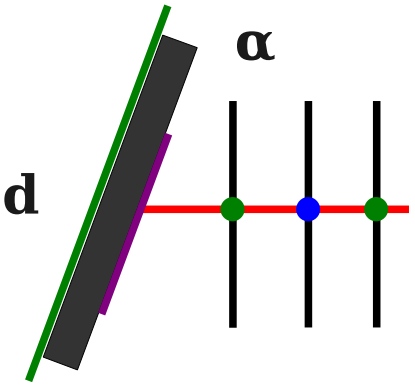
charge vs bias voltage

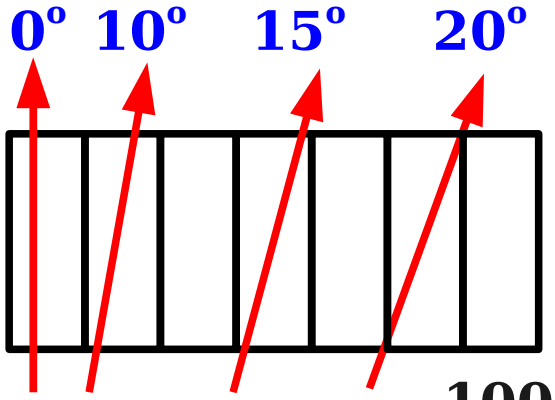




- Chip xdb2, 19° tilt
- bias voltage scan
  - need >70 V for full depletion

tilt angle





sensor thickness

285 µm

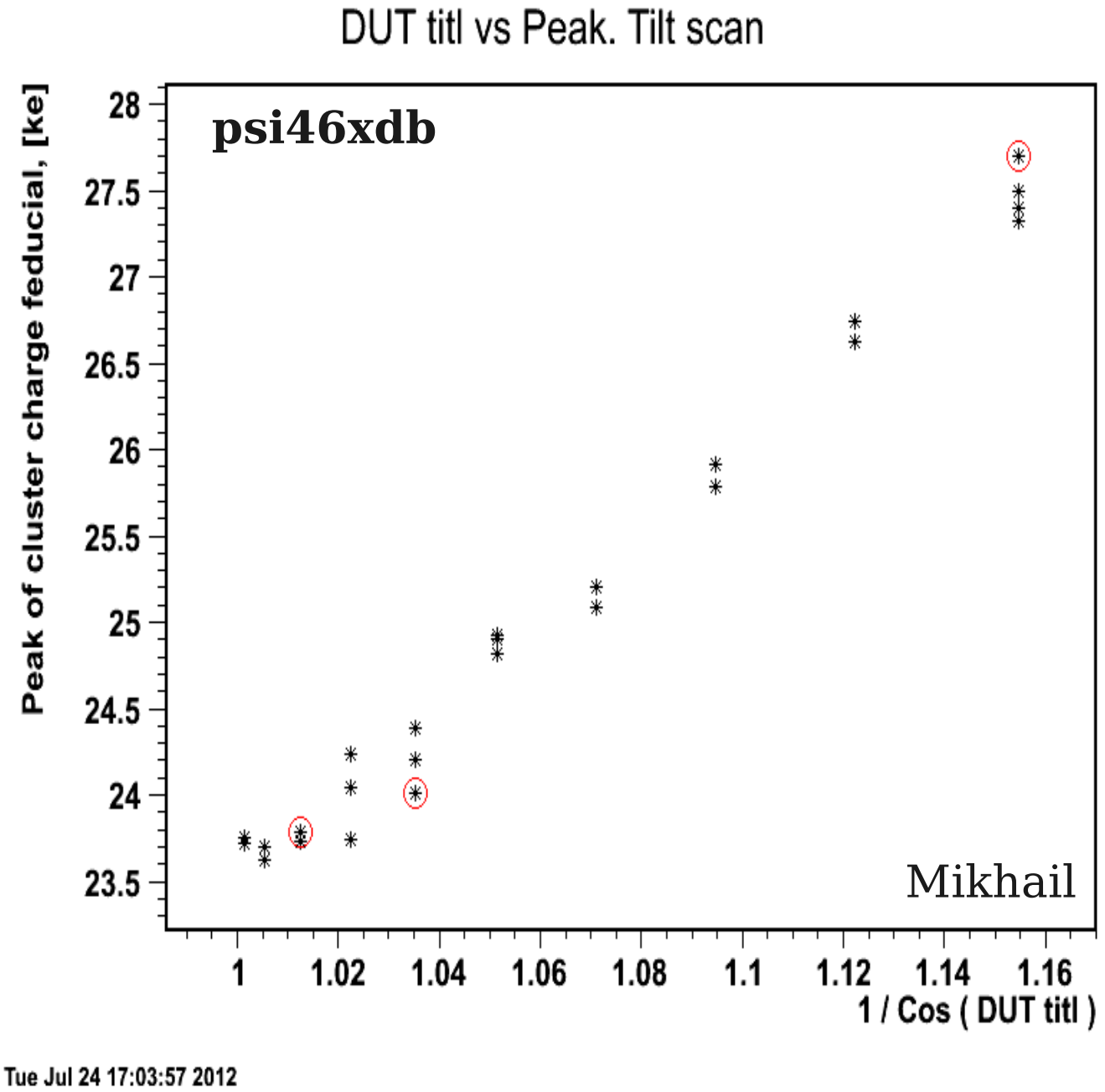
100 µm

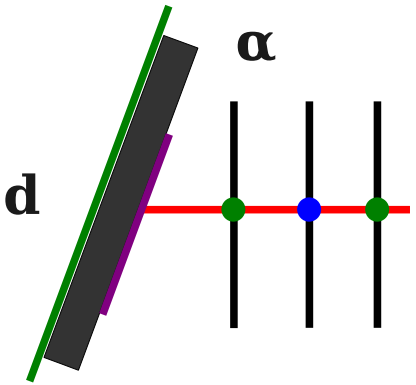
pixel size

optimal angle:

atan(100/285) = 19.3°

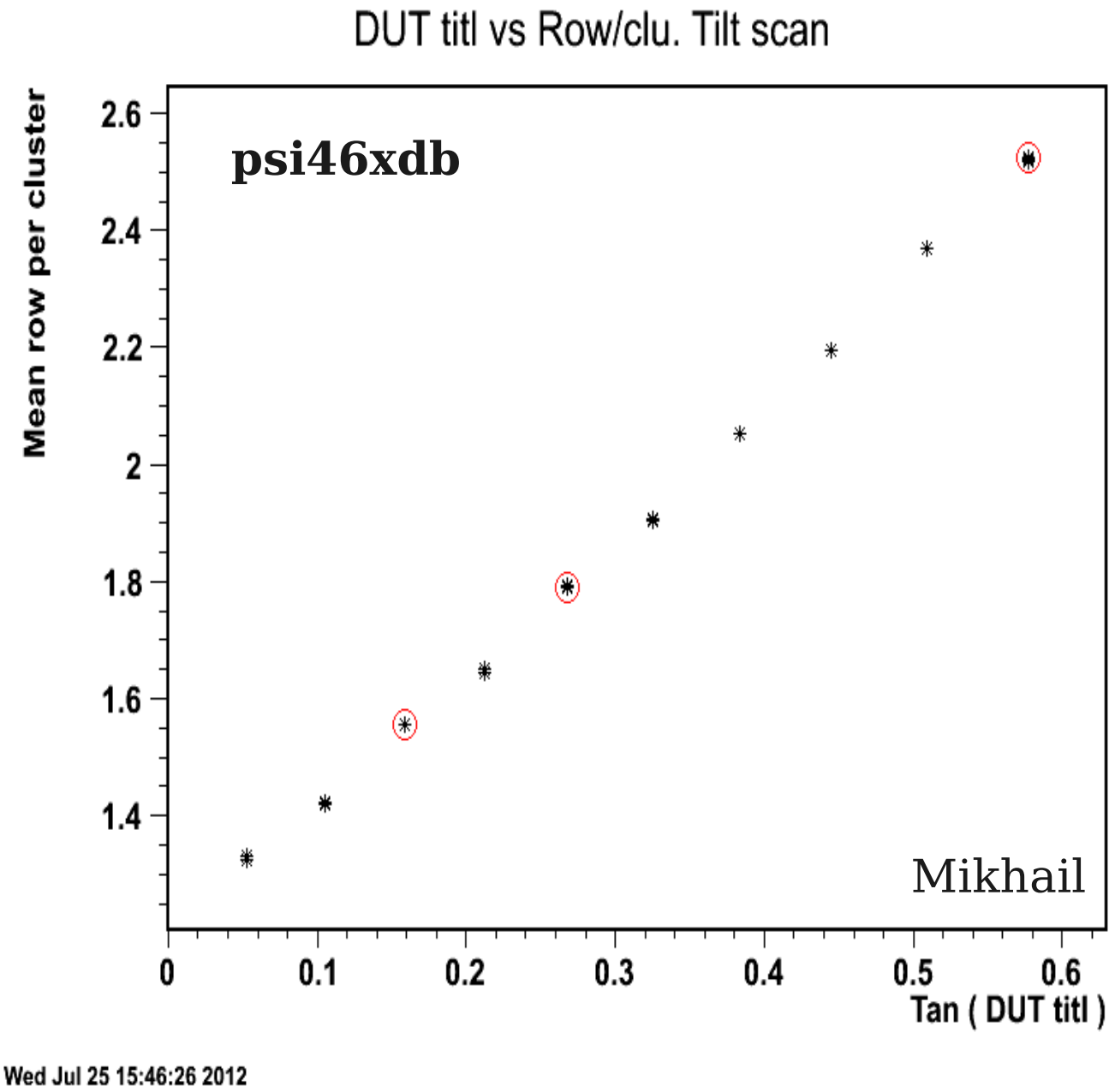
Cluster charge vs tilt angle

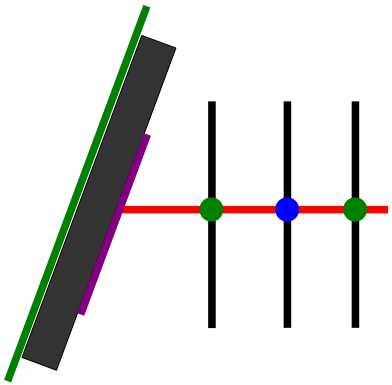




- Chip xdb2, -150V
- effective sensor thickness:
  - $d = 285\ \mu m / \cos \alpha$
- position of the Landau peak should be linear in d

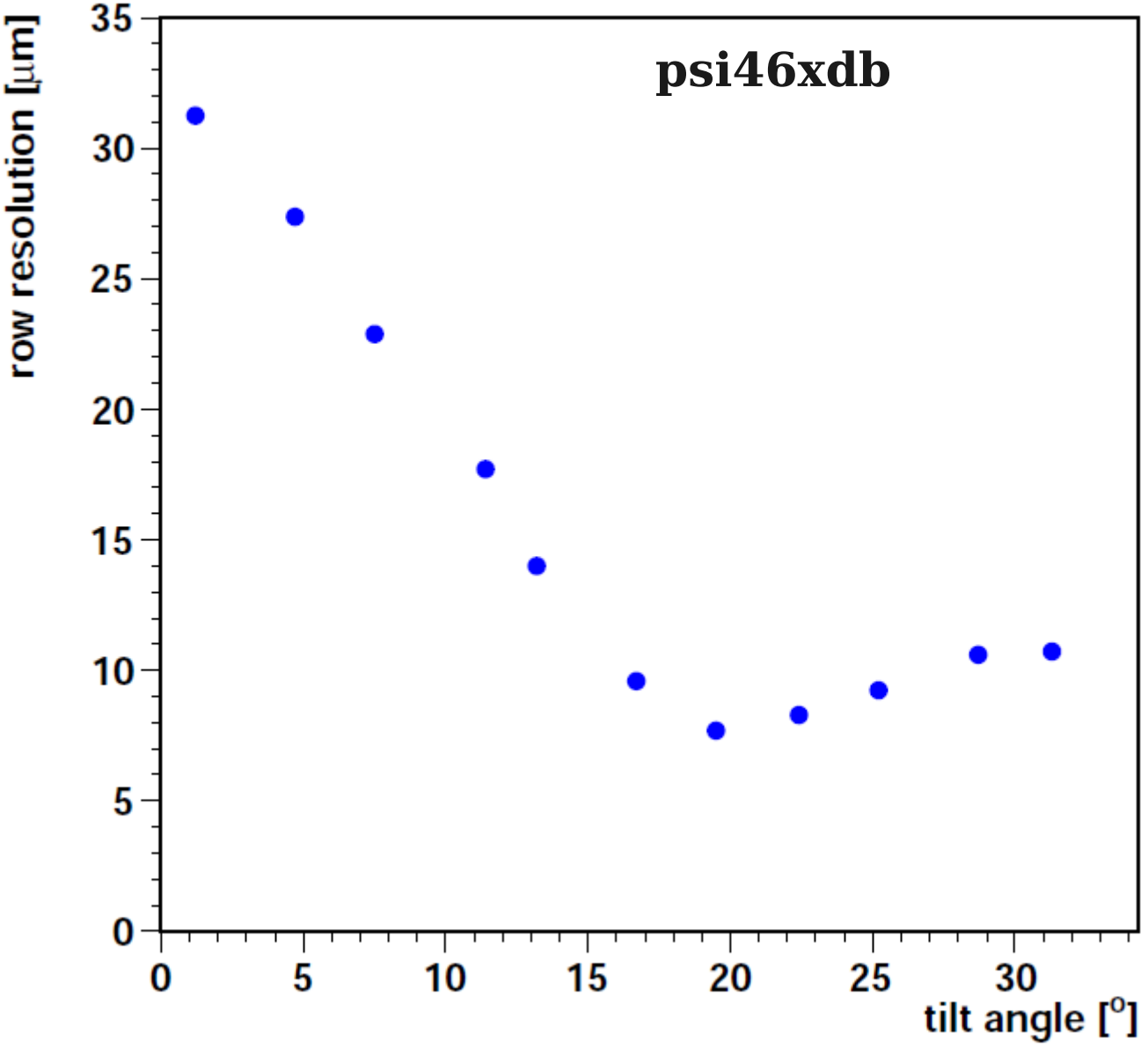
xdb cluster size vs tilt angle

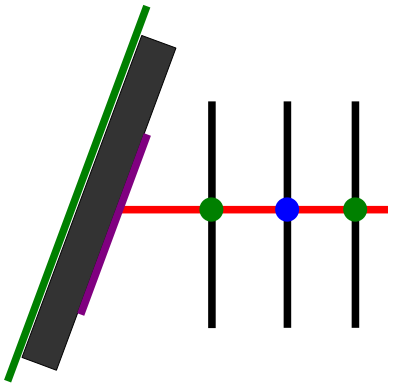




- Chip xdb2, -150V
- rows per cluster:
  - scales with tan(tilt)

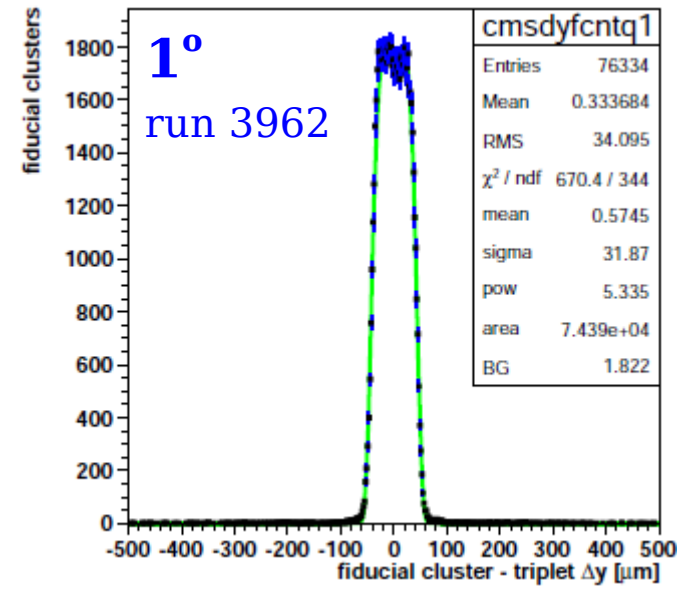
xdb row resolution vs tilt angle

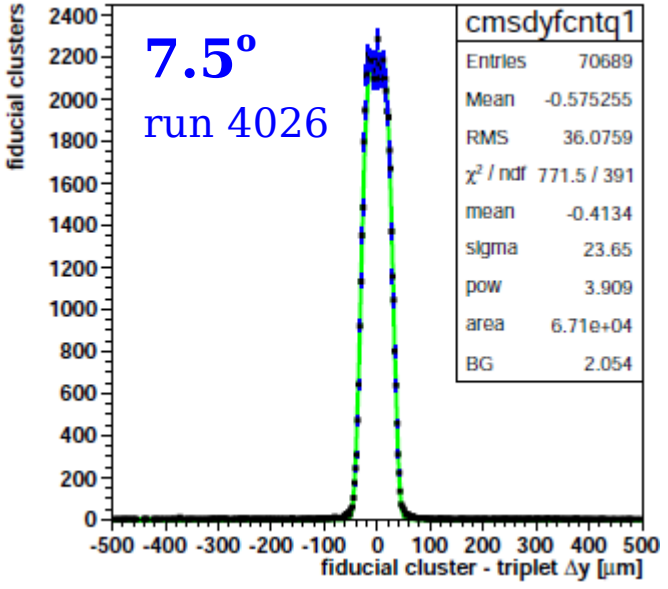


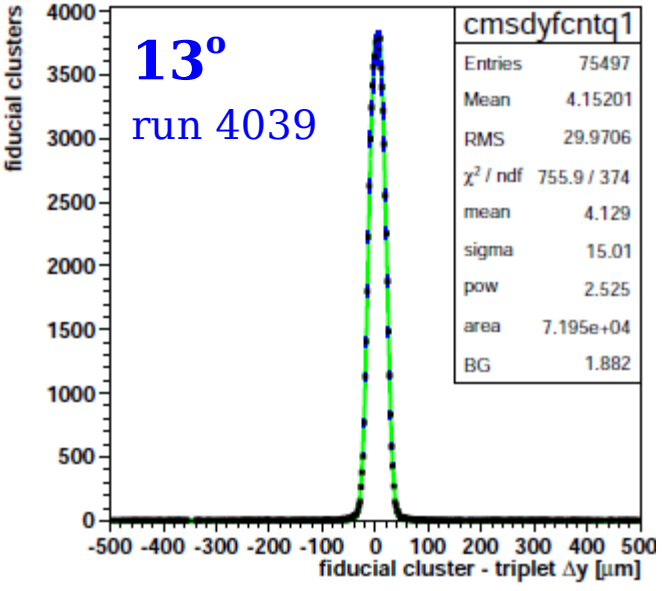


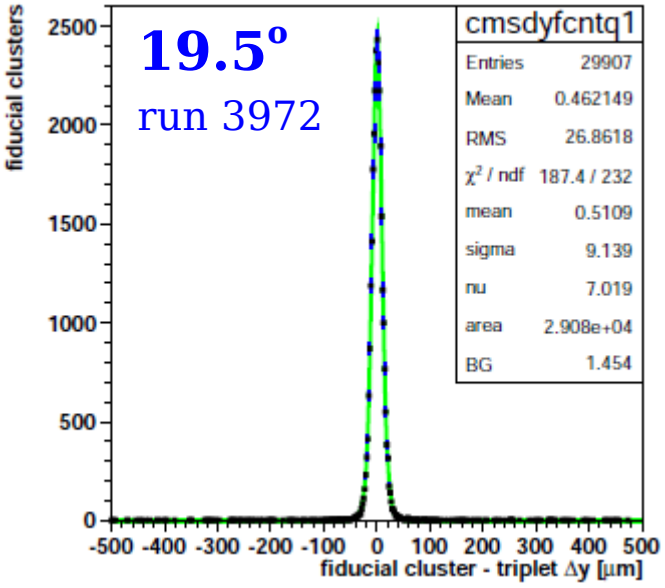
- Chip xdb2, 5.6 GeV, telescope extrapolation uncertainty subtracted.
- row pixels = 100 μm.
- At 0°:
  - σ = 100 / √12 = 29 μm
- Optimal angle 19.5°:
  - σ = 7 μm.
- Similar to psi46

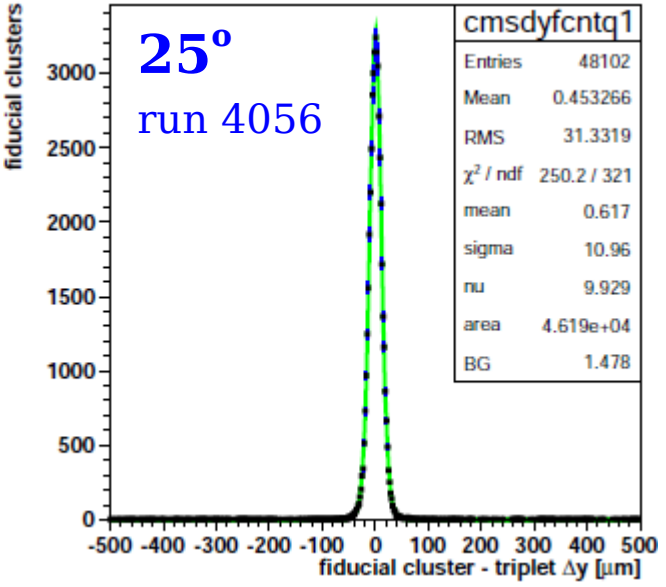
xdb row resolution vs tilt angle

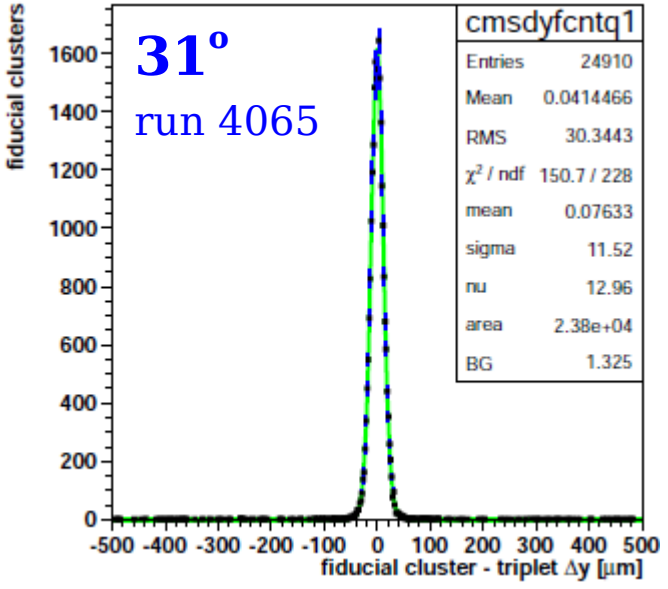




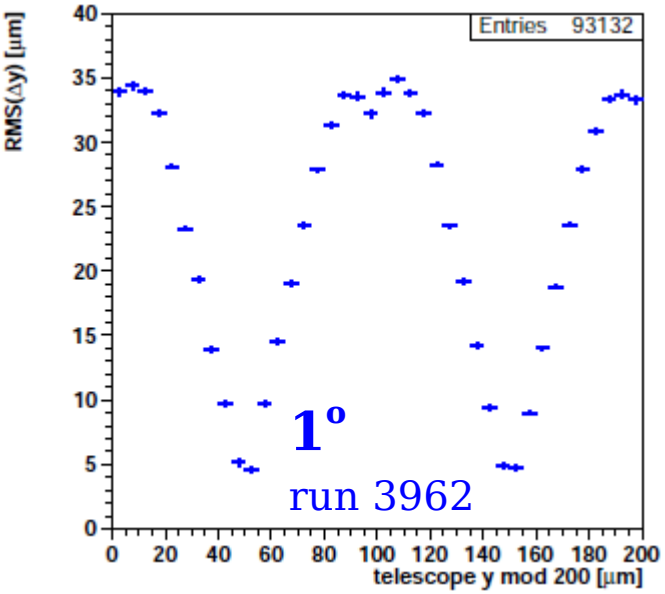


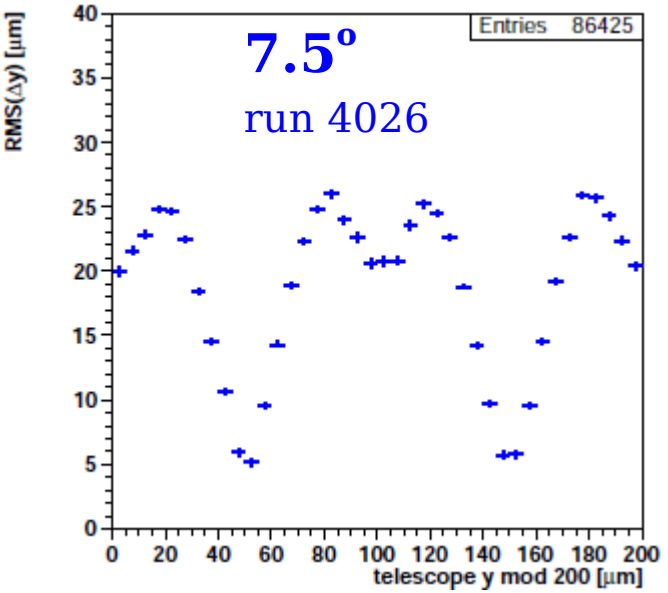


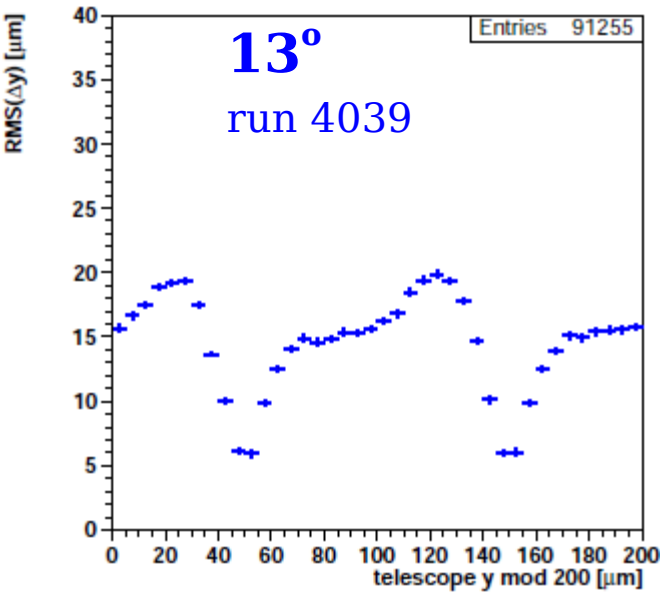




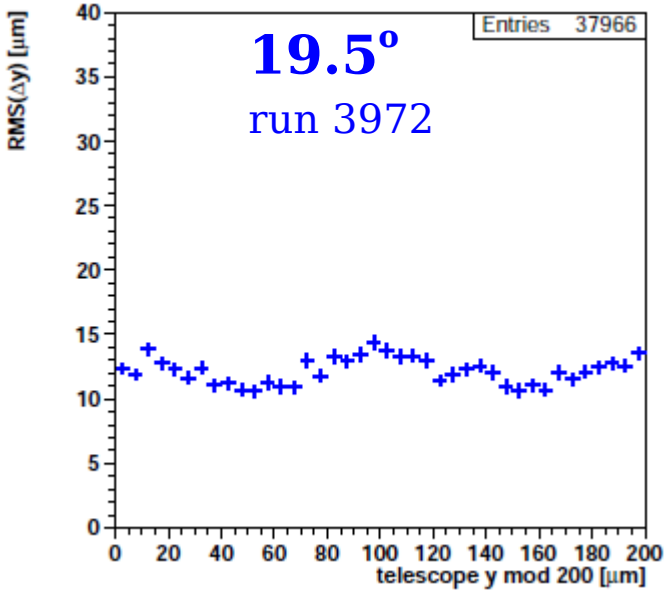
xdb resolution vs impact point & tilt angle

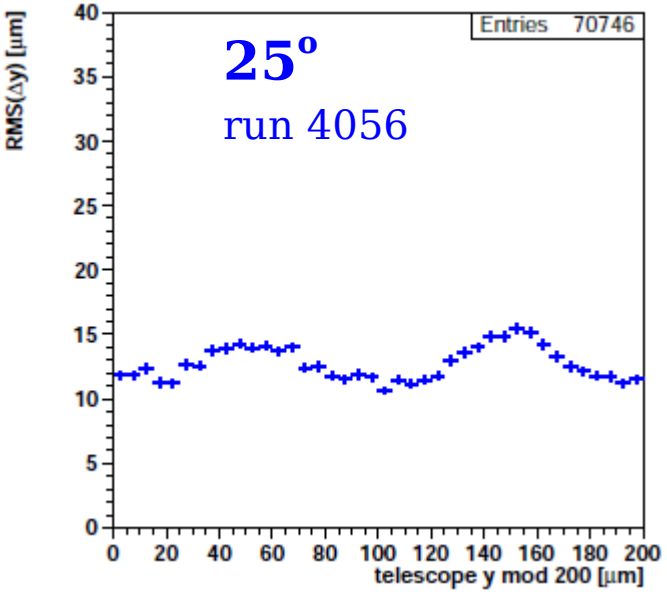


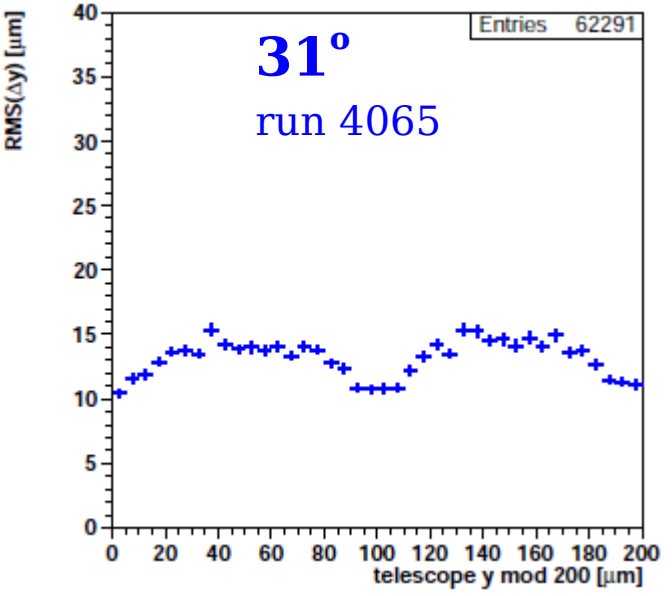




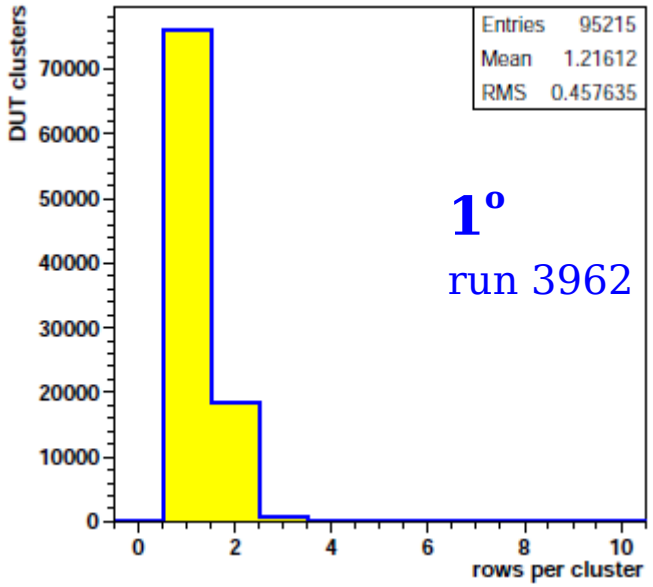
y_{impact} mod 200 μm: 2 pixels wide

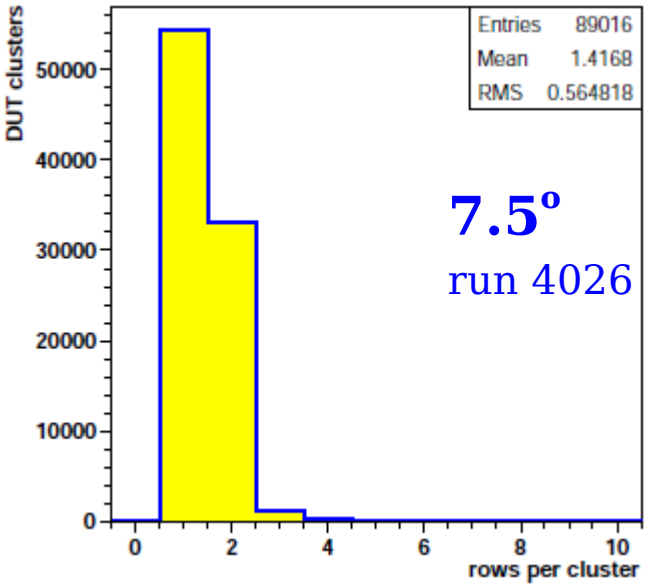


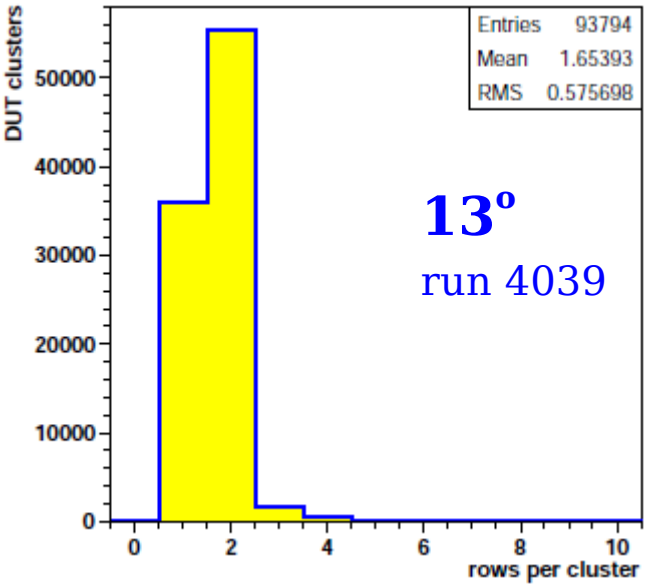


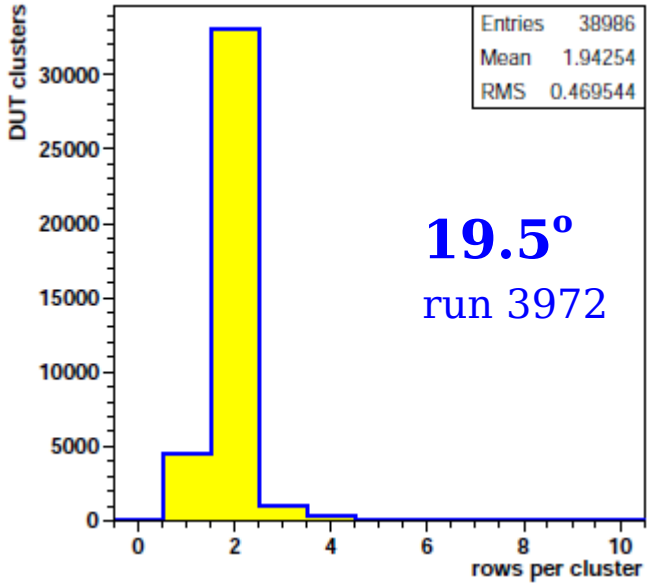


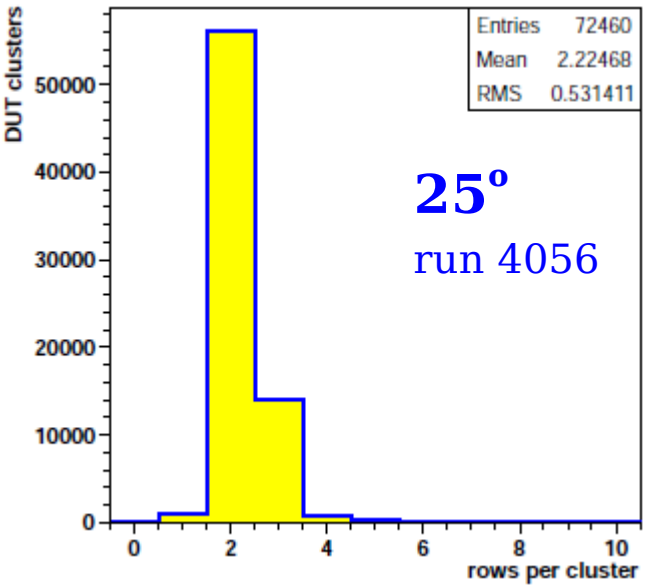
xdb rows per cluster vs tilt angle

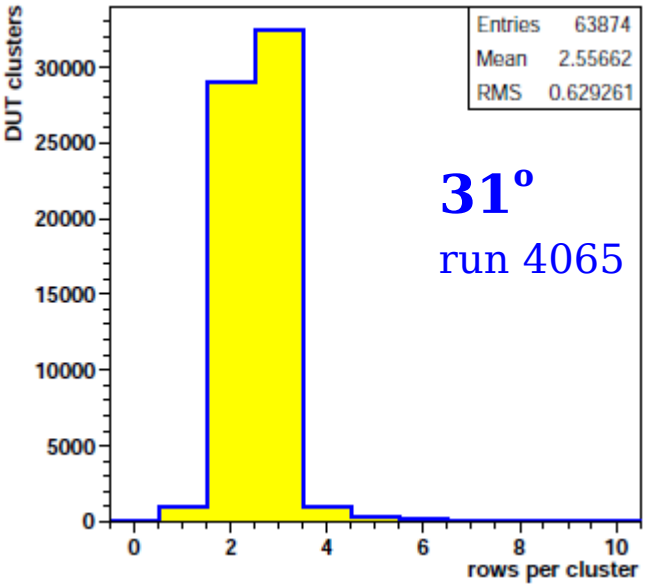




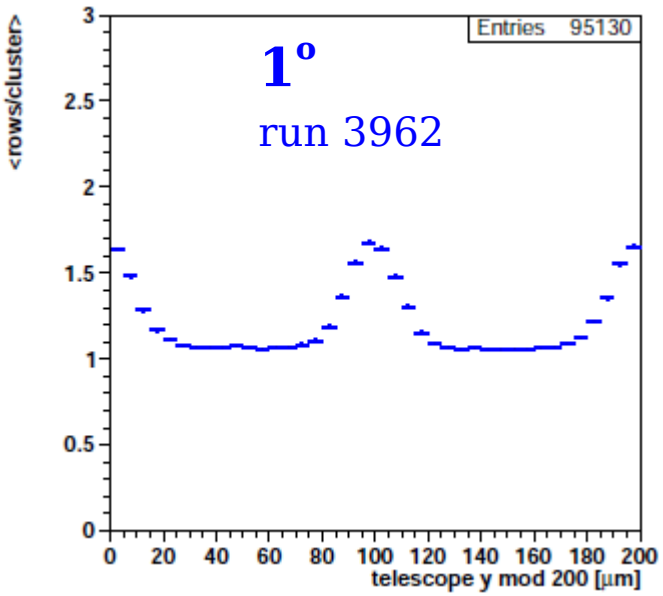


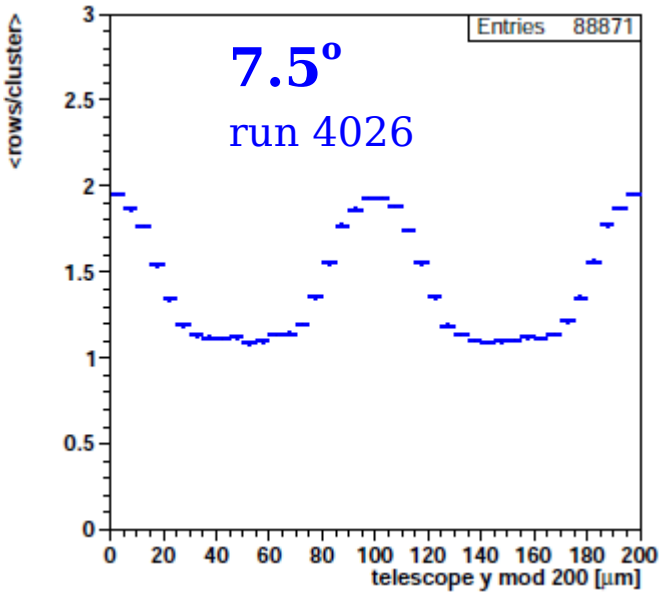


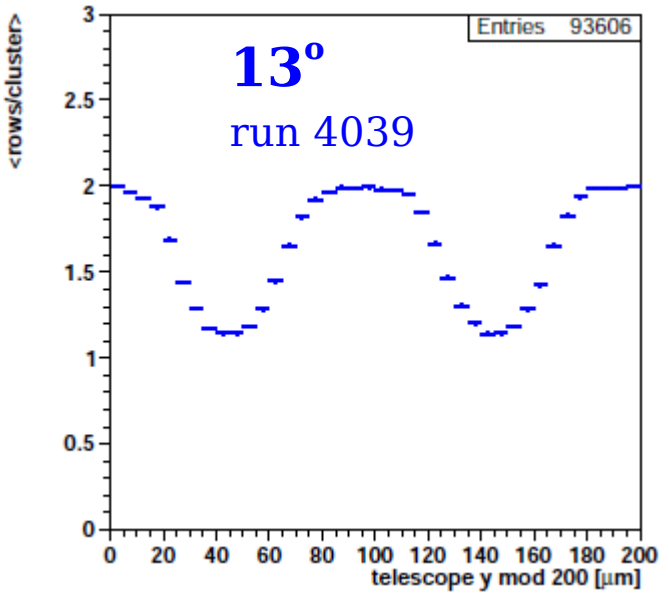




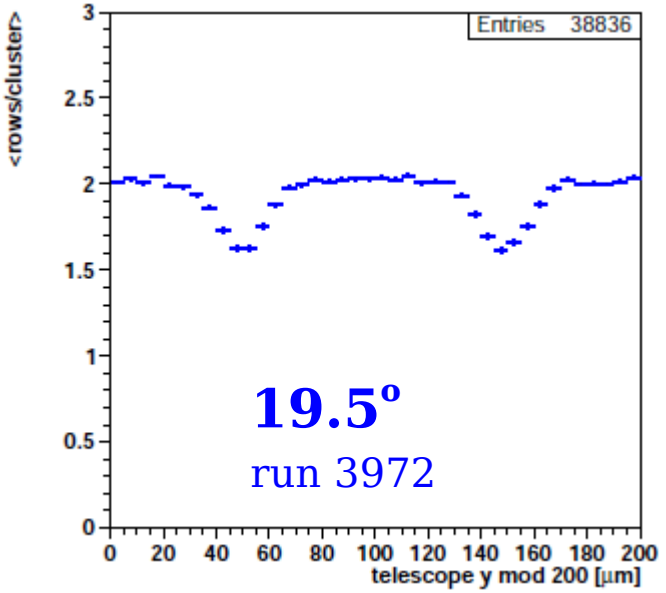
cluster size vs impact point and tilt angle

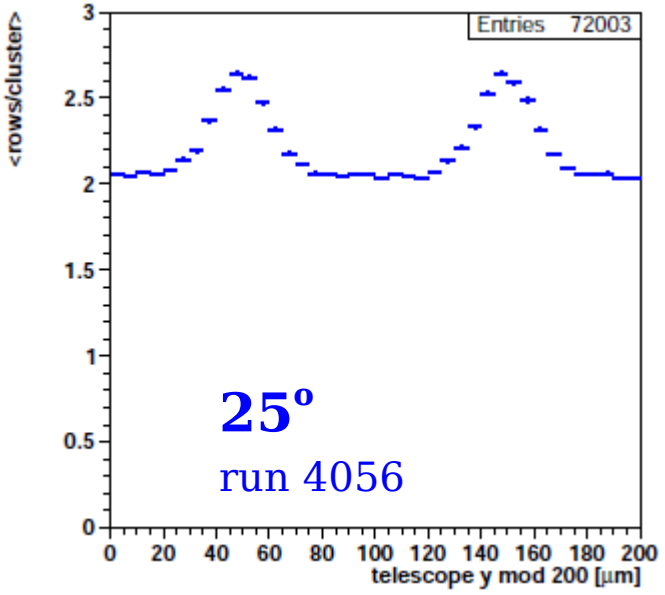


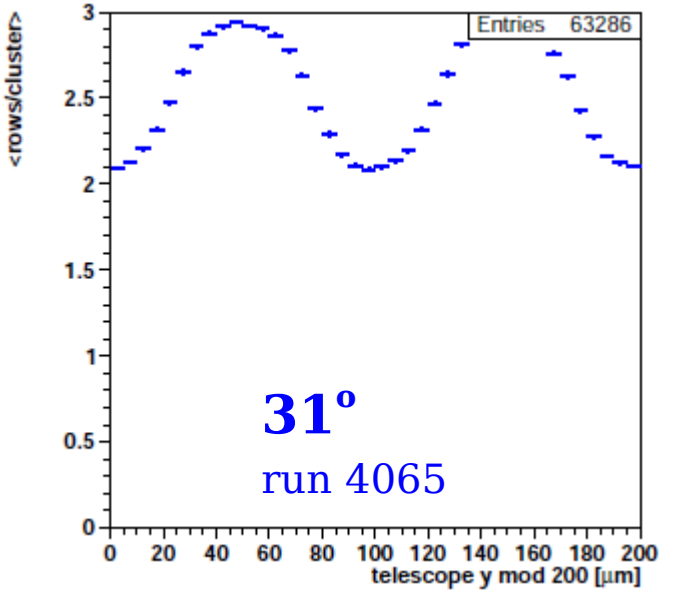




y_{impact} mod 200 µm: 2 pixels wide

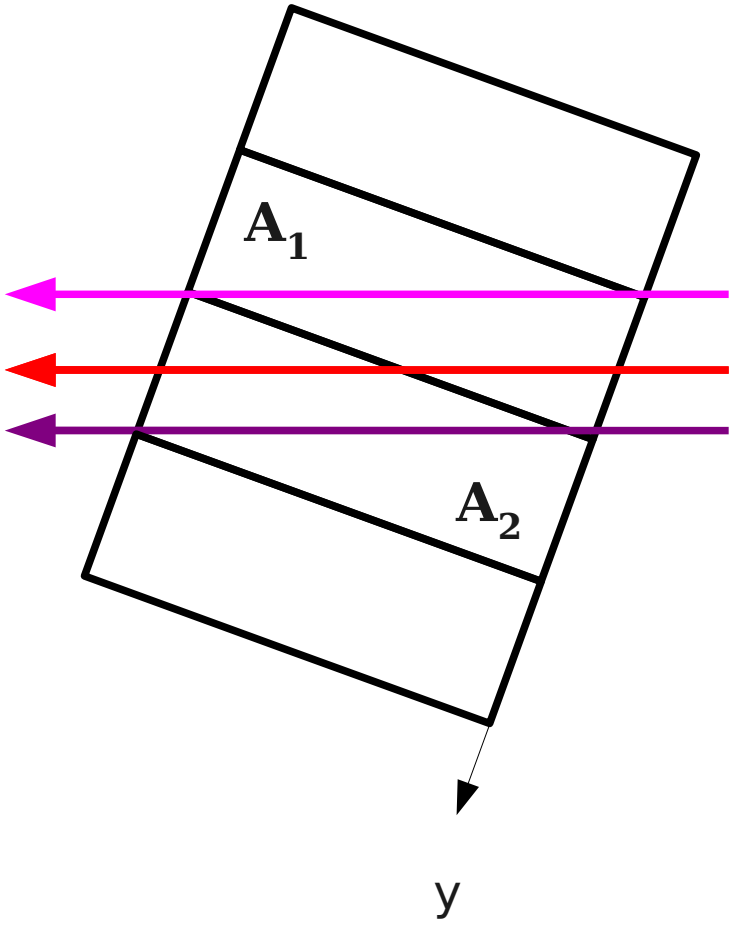






charge sharing: η

at 20°:



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

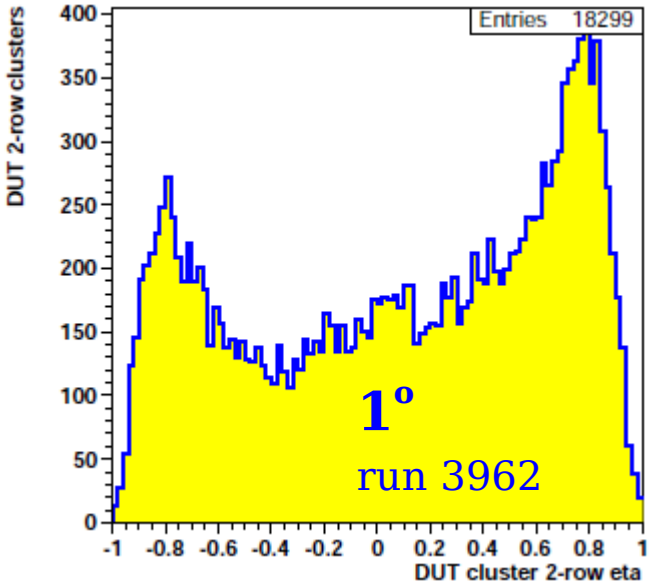
1.0
0.0
(-1.0)

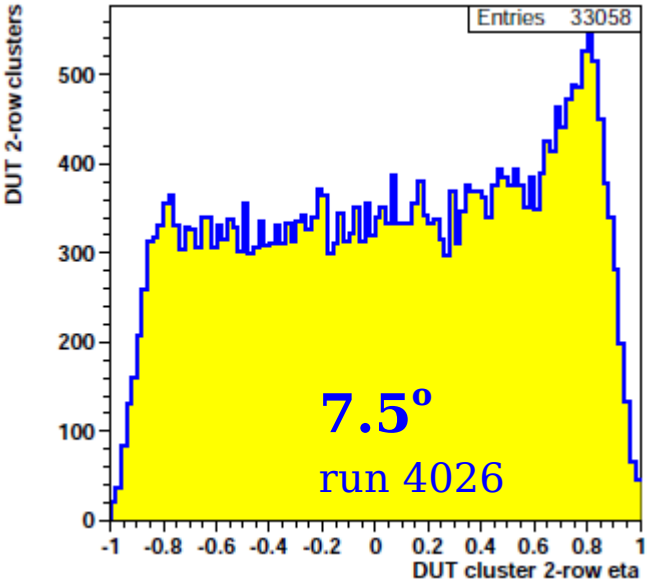
1-row clusters have η = 1.

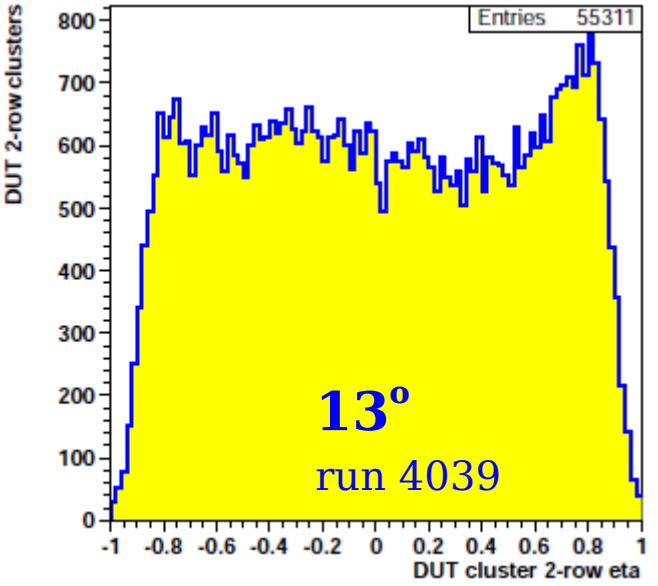
ideal:
linear η vs y
(saw tooth)

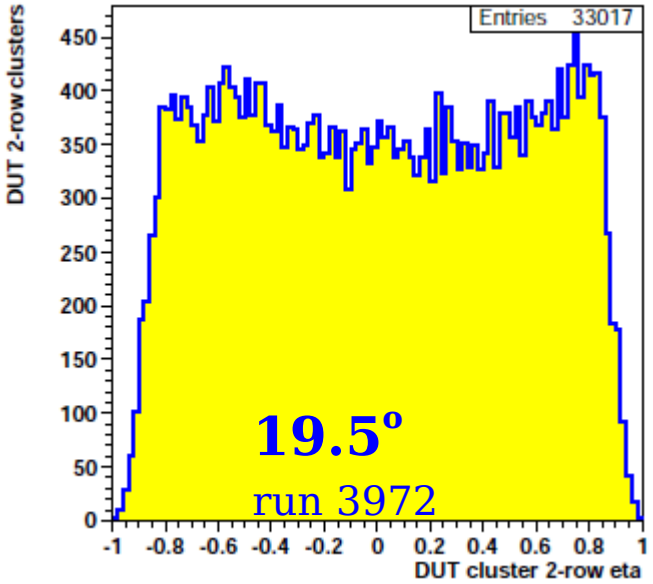
deviations:
- **diffusion**
- **thresholds**
- **trapping**
- **delta-rays**

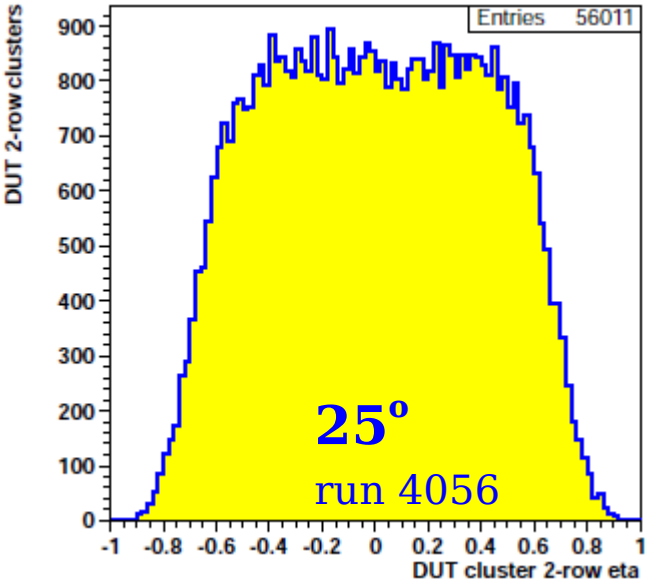
xdb charge sharing vs tilt angle

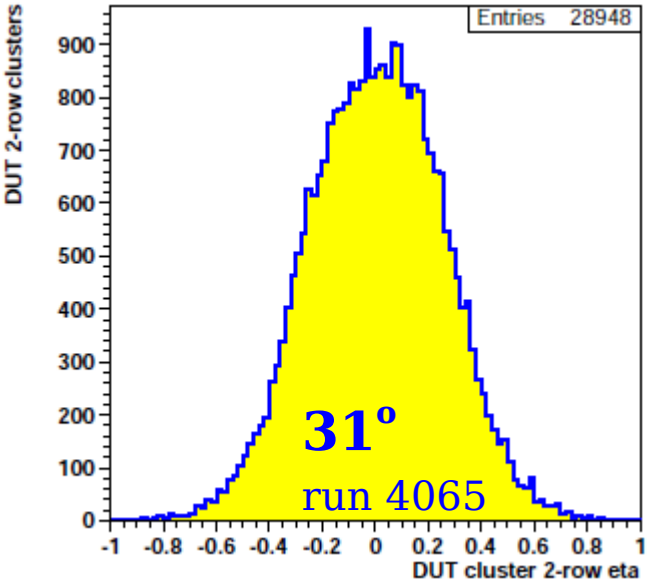




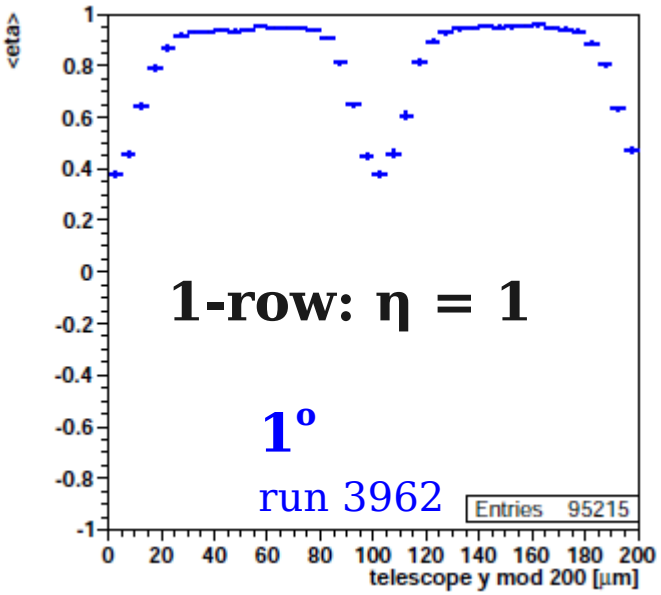


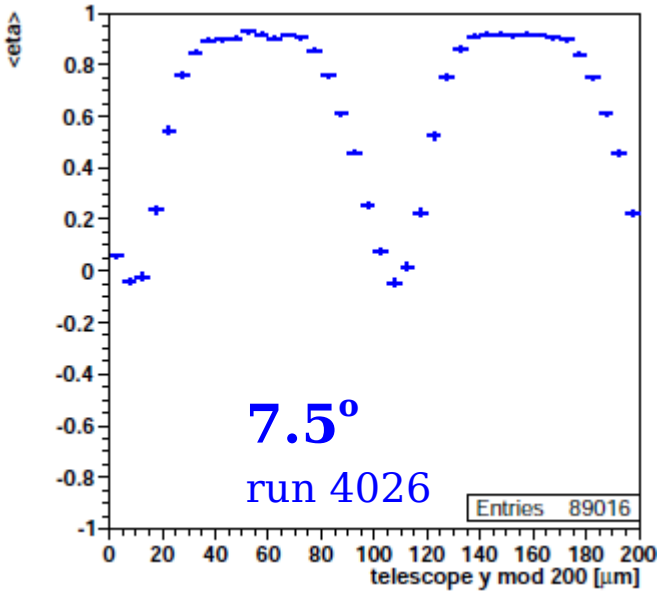


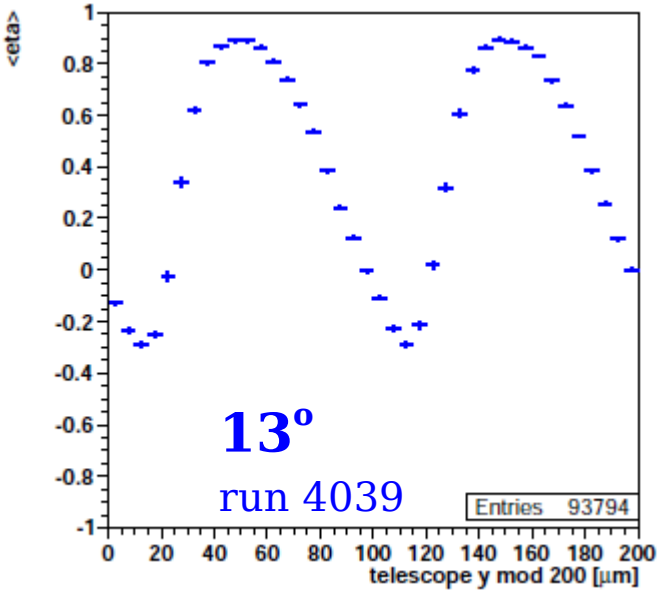




xdb charge sharing vs impact point

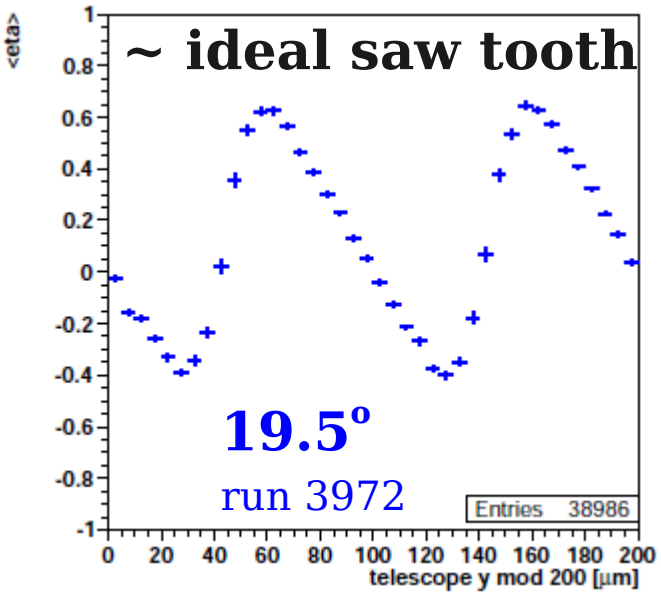


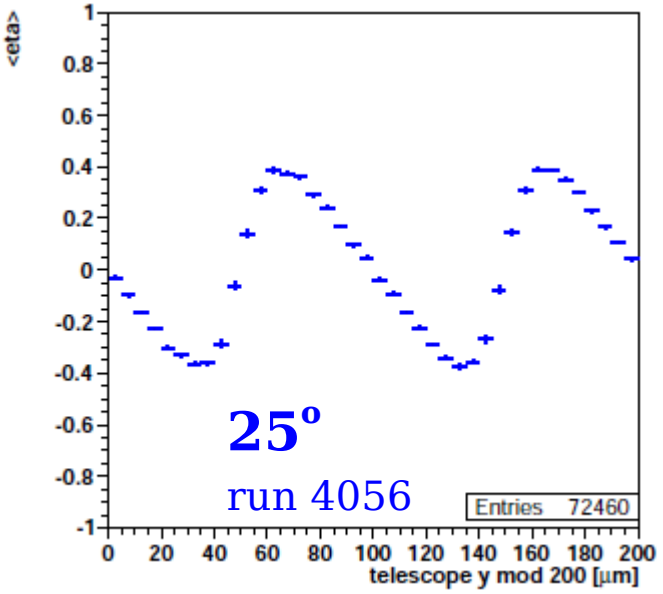


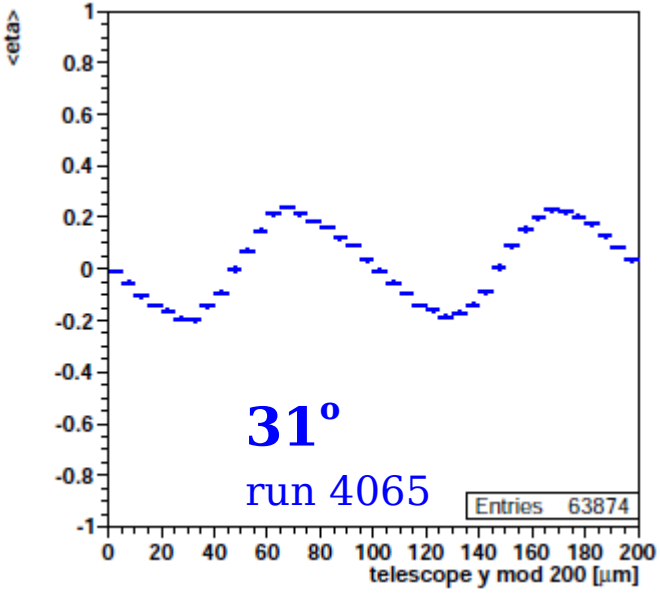


1- and 2-row clusters

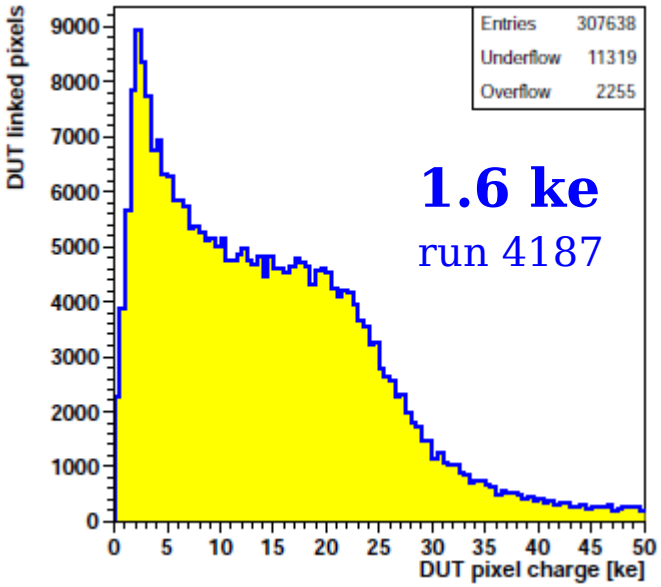
y_{impact} mod 200 µm: 2 pixels wide

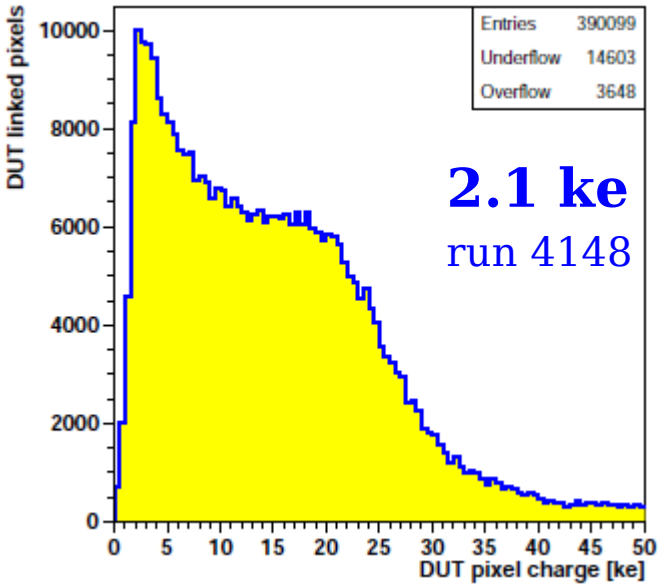


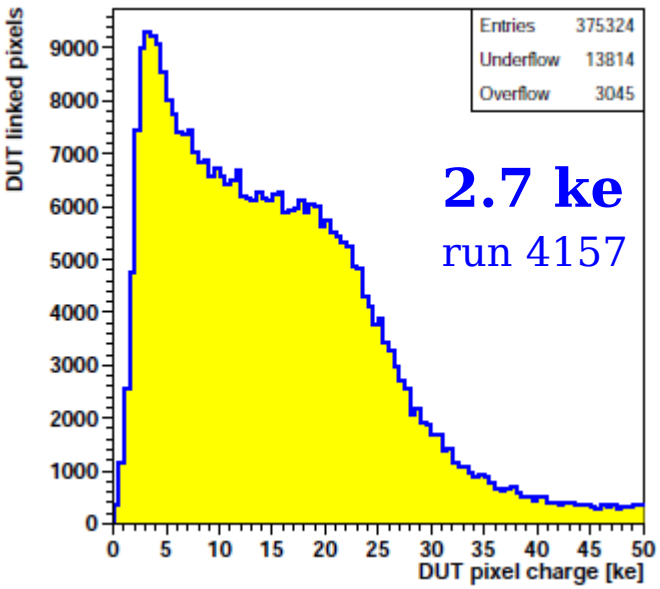


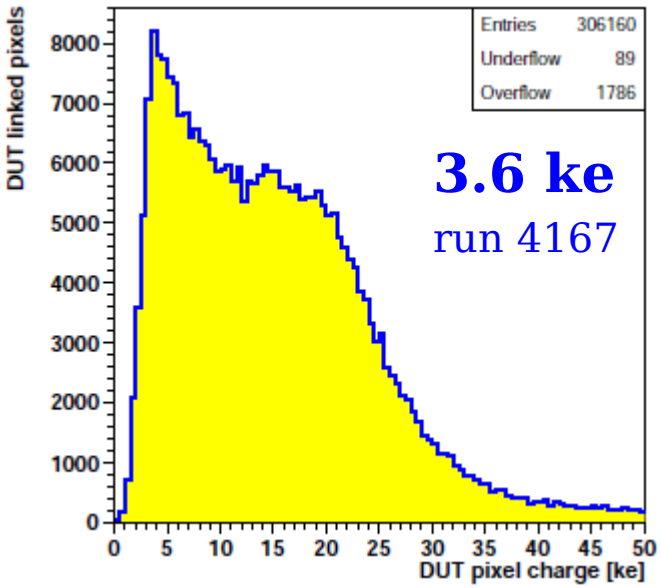


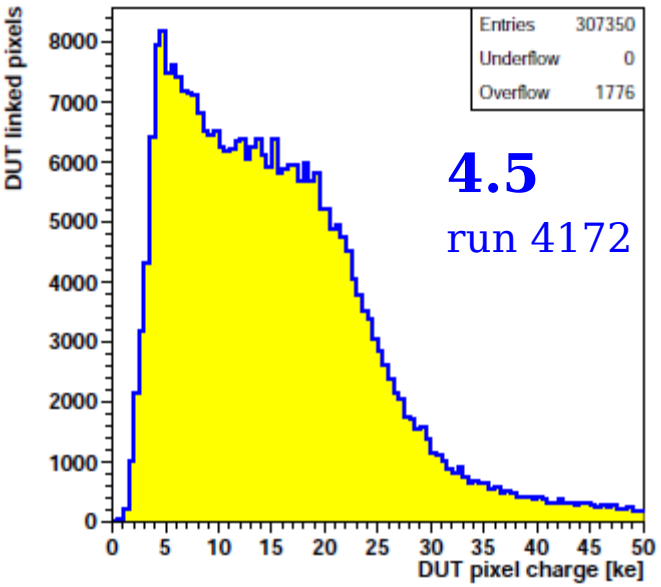
xdb pixel charge vs threshold

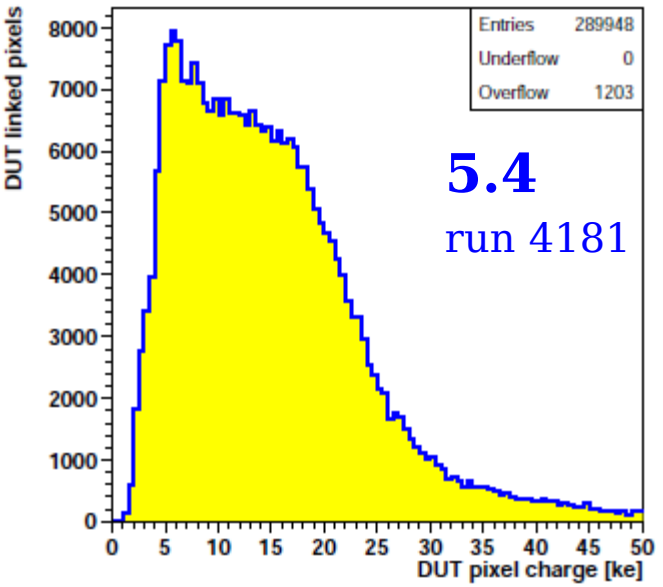




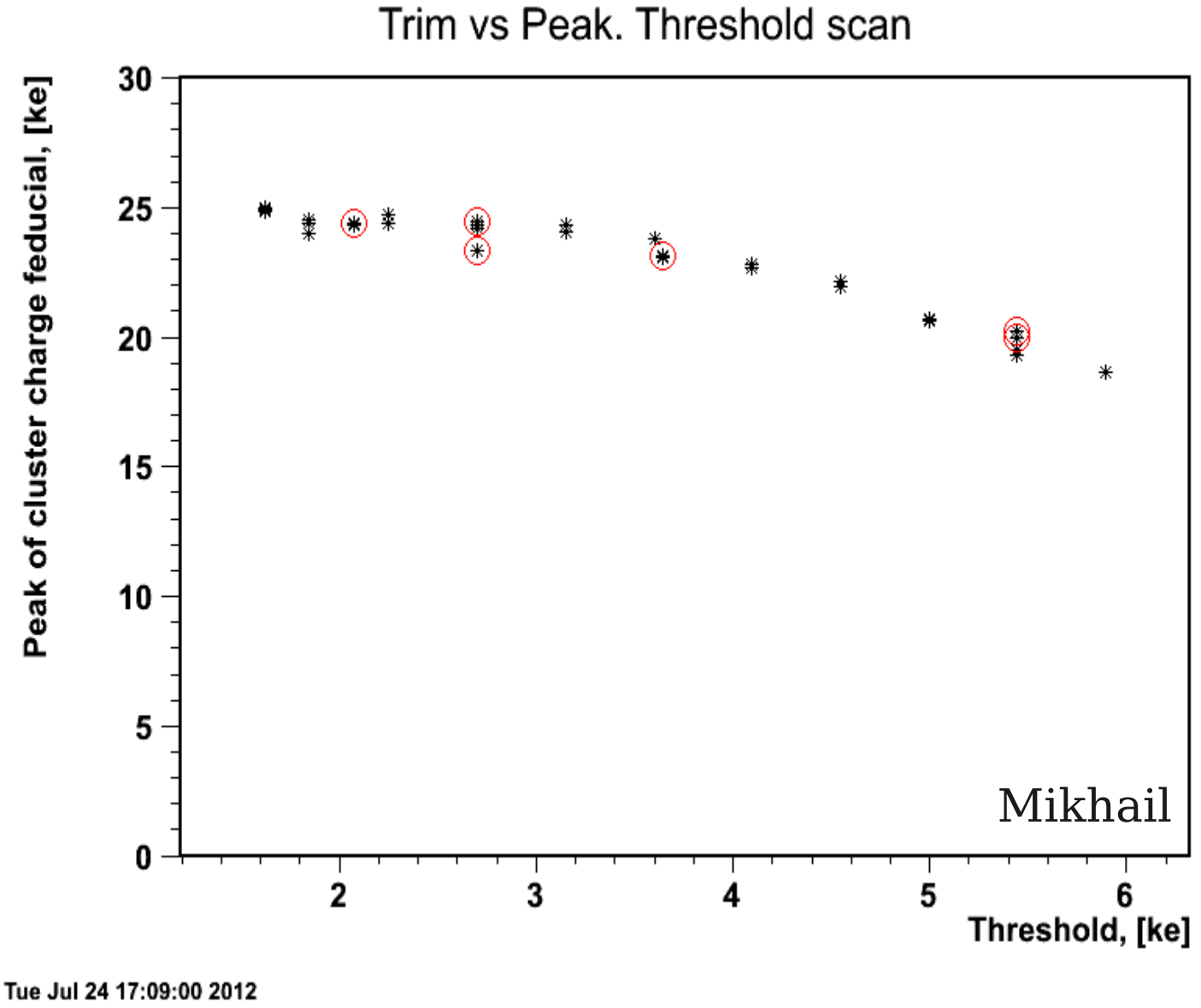






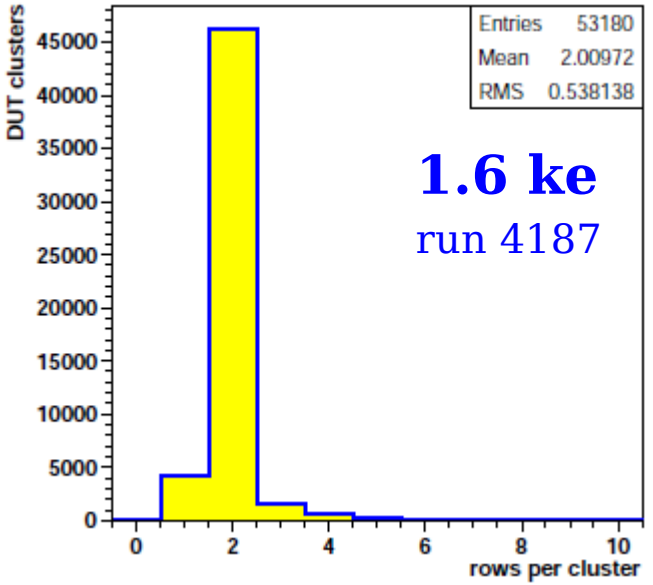


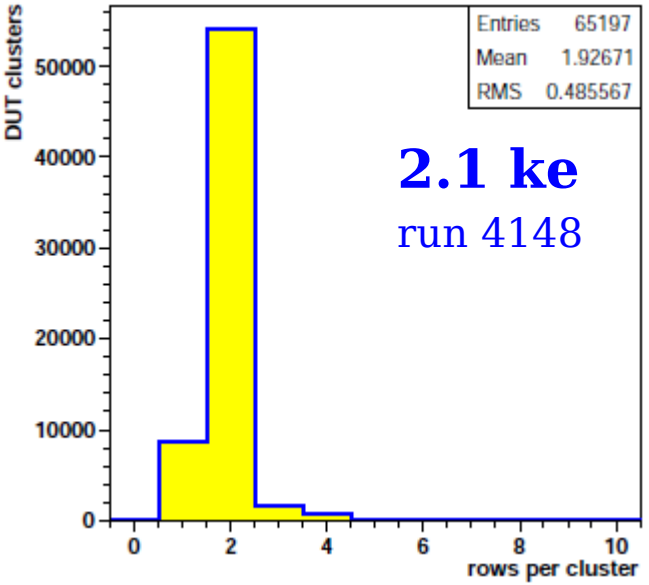
xdb cluster charge vs threshold

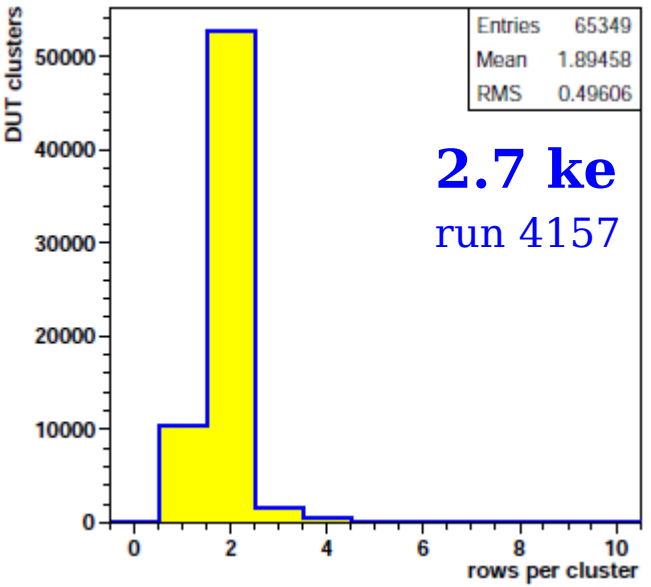


- Chip xdb2, -150V, 19° tilt
- Position of Landau peak
  - decreases with harder threshold

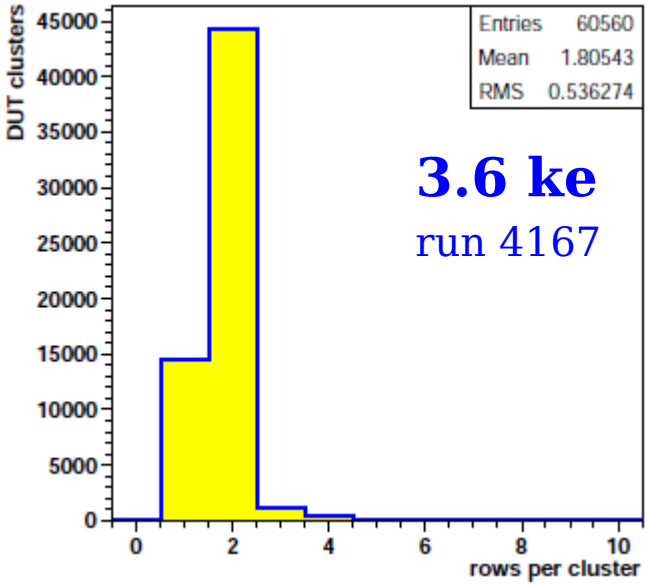
xdb cluster size vs threshold

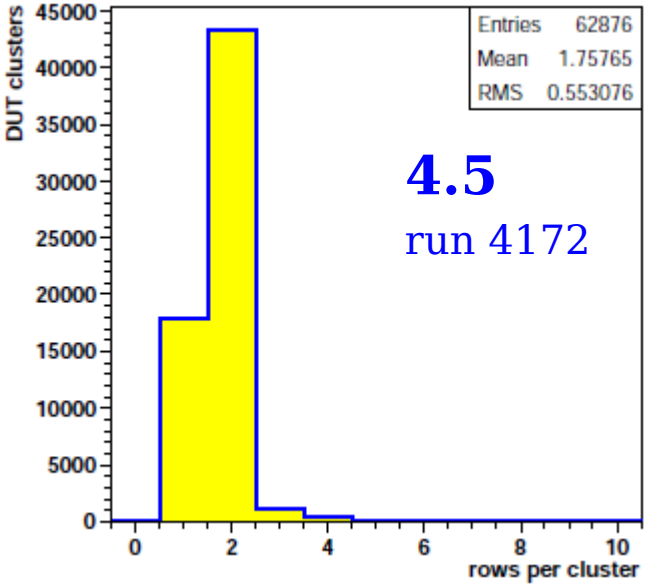


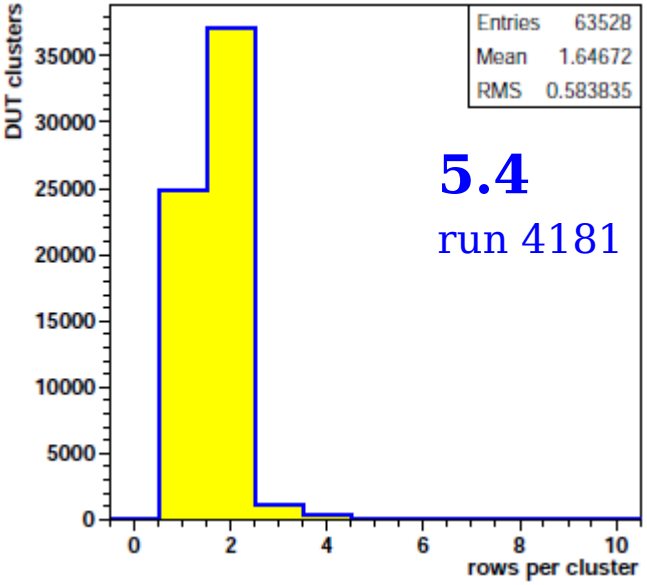




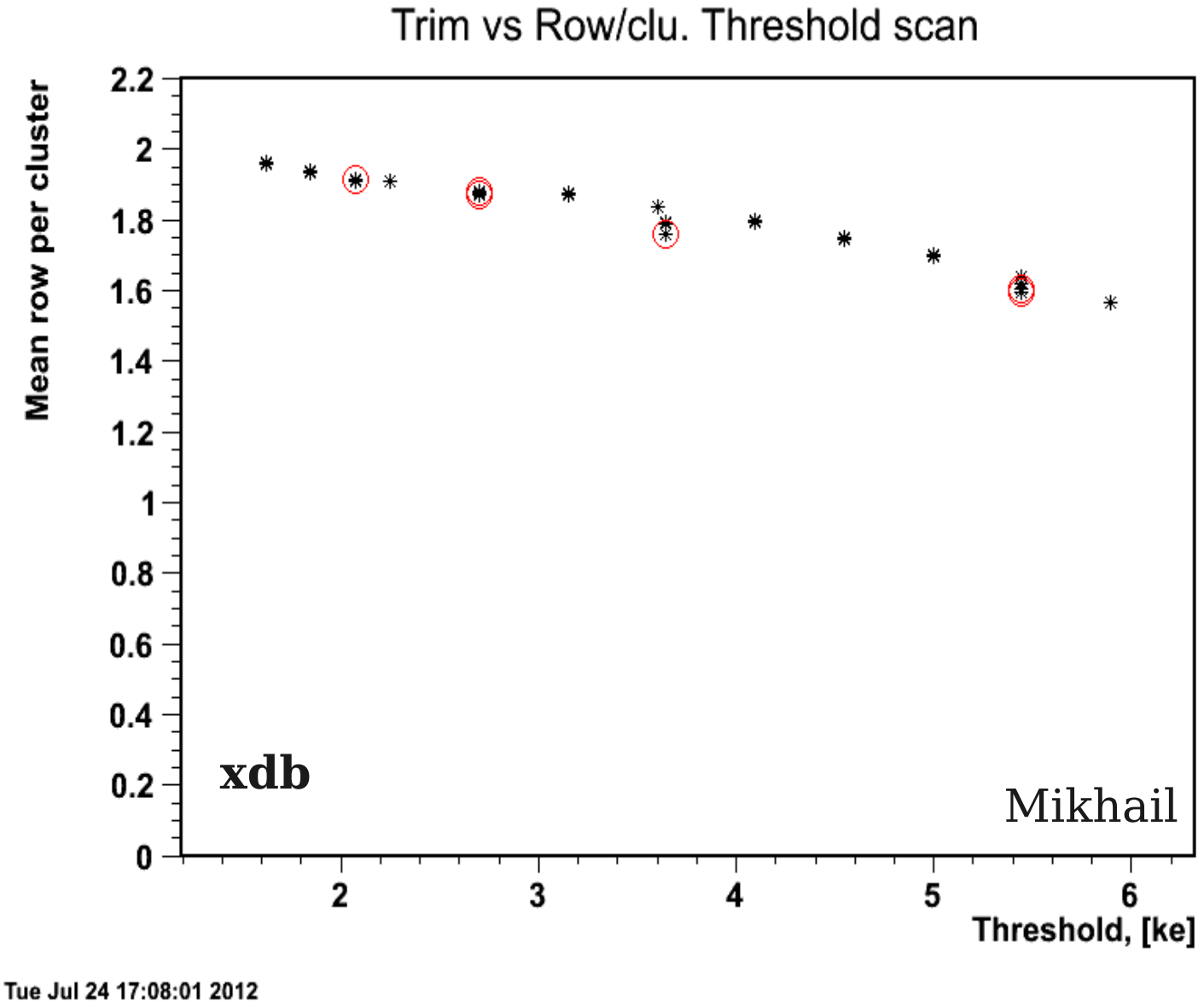
tilt 19.5°





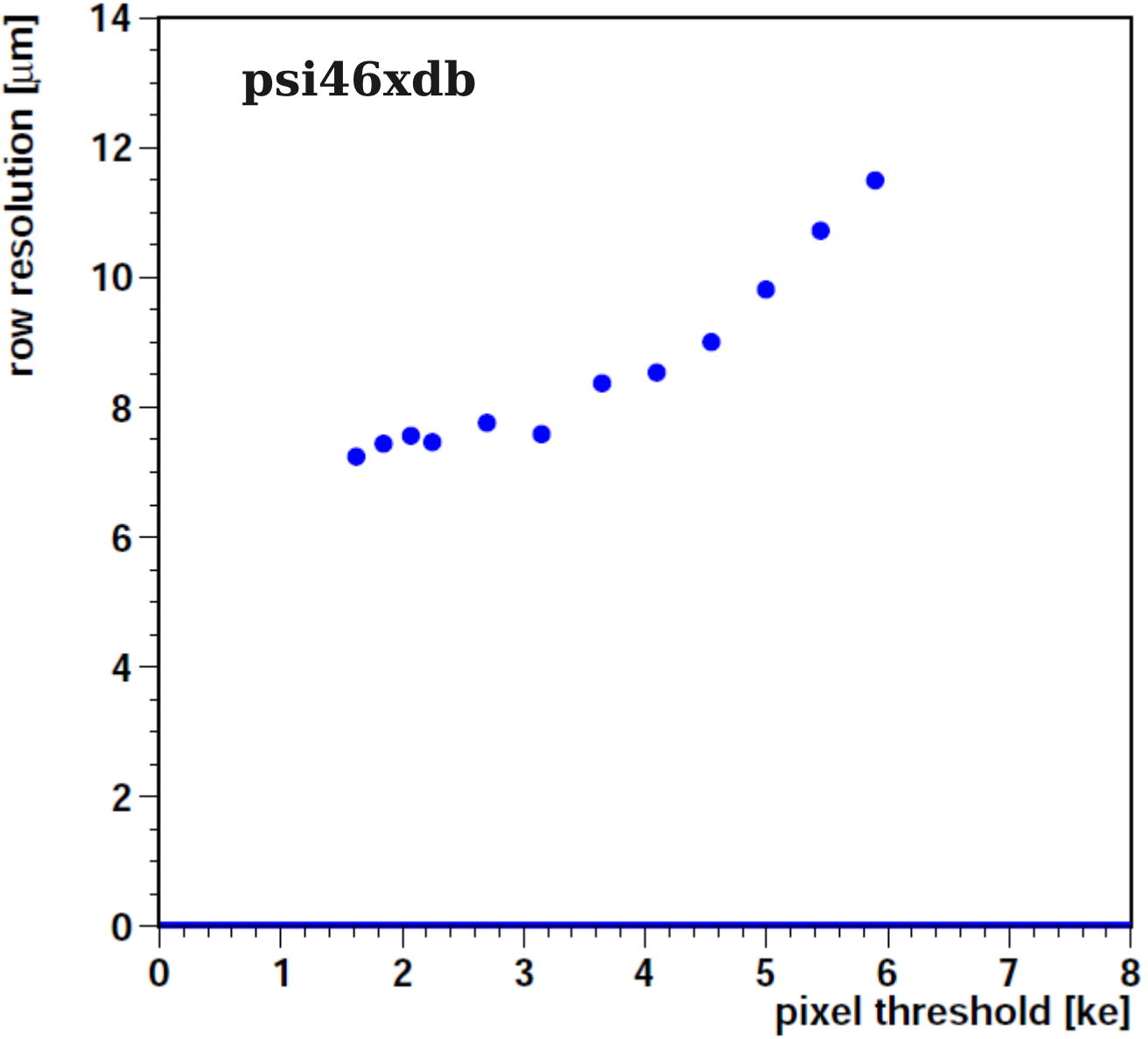


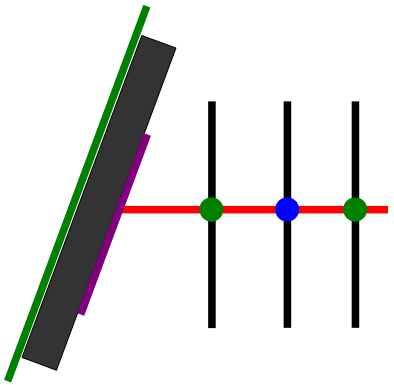
xdb cluster size vs threshold



- Chip xdb2, -150V, 19^{o} tilt
- rows per cluster:
  - decreases with harder threshold

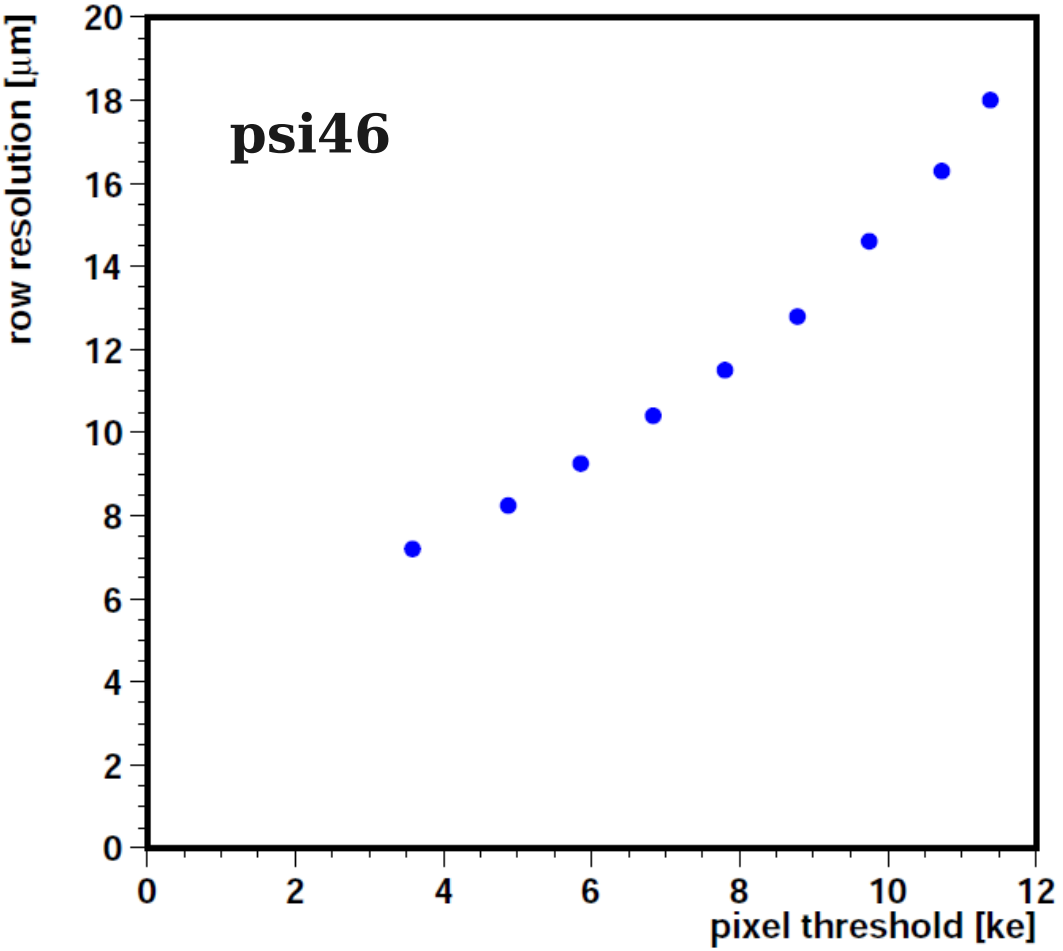
xdb row resolution vs threshold

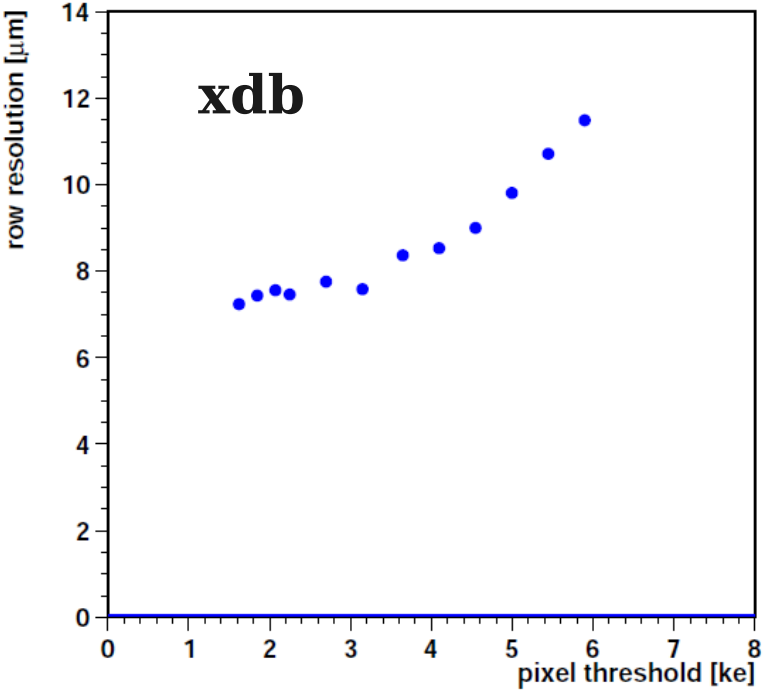




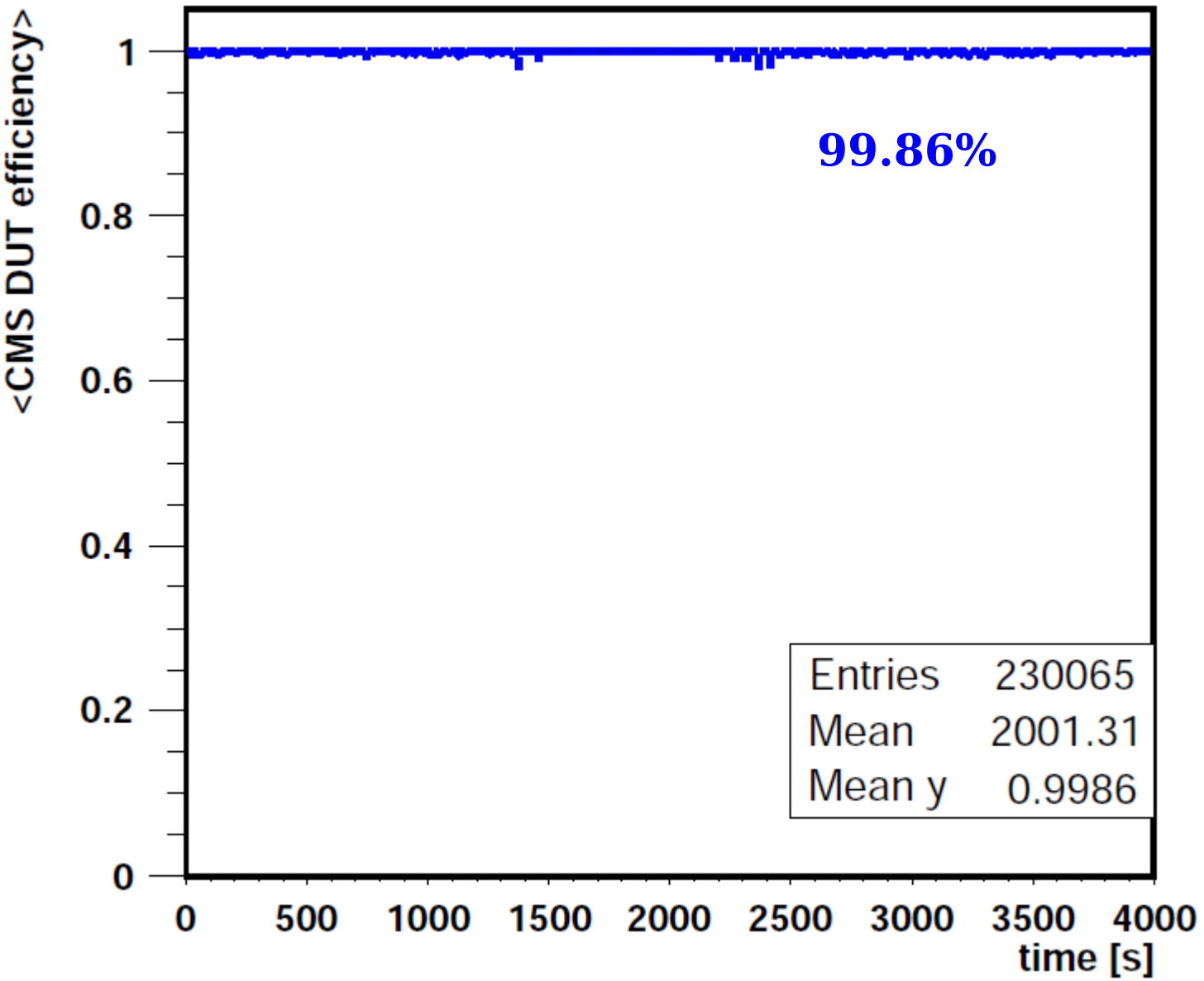
- Chip xdb2, 19.5° tilt
- 5.6 GeV, telescope extrapolation uncertainty subtracted.
- lower threshold:
  - resolution seems to saturate at 7 µm below 3 ke.

psi46 row resolution vs threshold





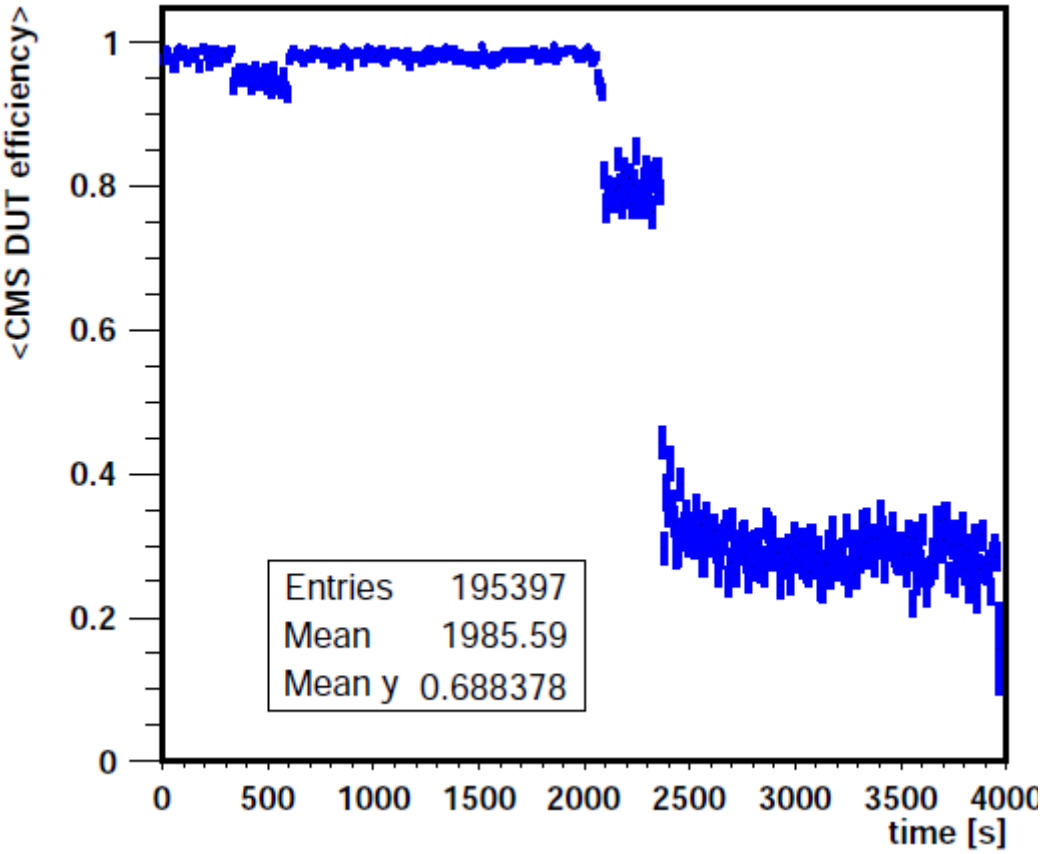
xdb efficiency stability



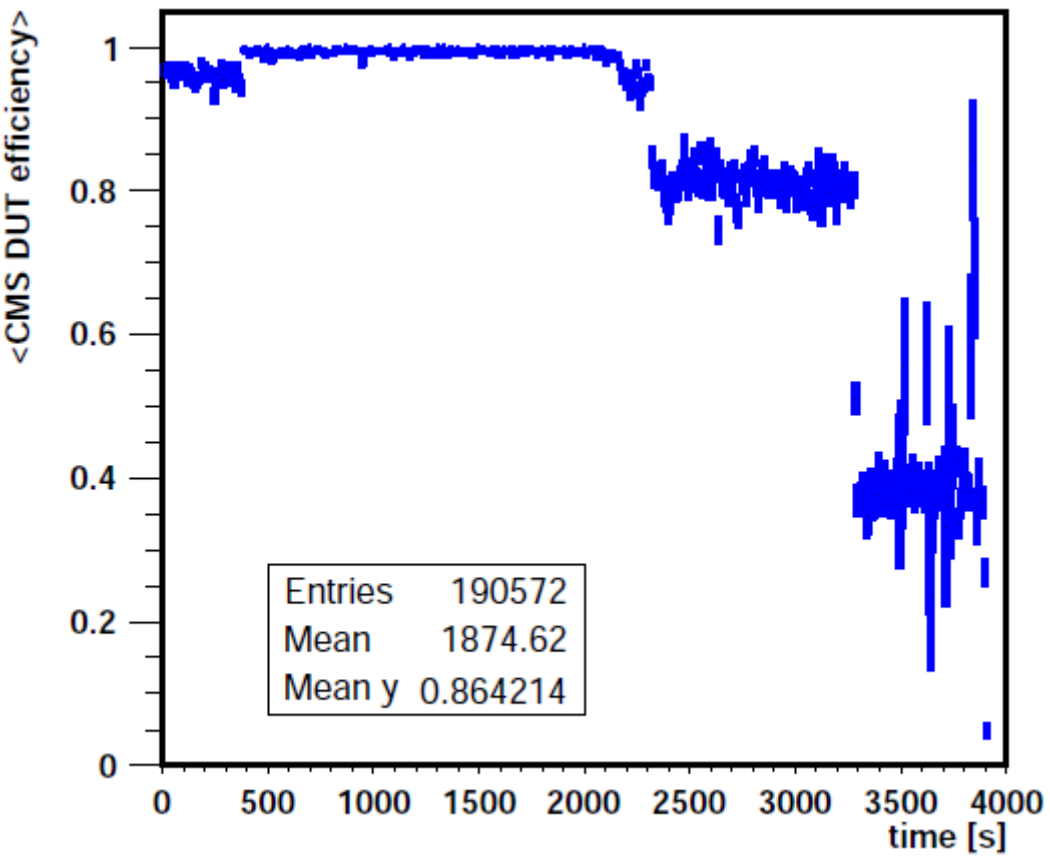
- Chip xdb2
  - 19.5° tilt
  - trim 80
  - run 3899
- fiducial region:
  - track 0.1 mm from edge
- 99.86% stable over 1 hour.

xdb efficiency instability

xdb 2, run 3958



xdb 2, run 3960

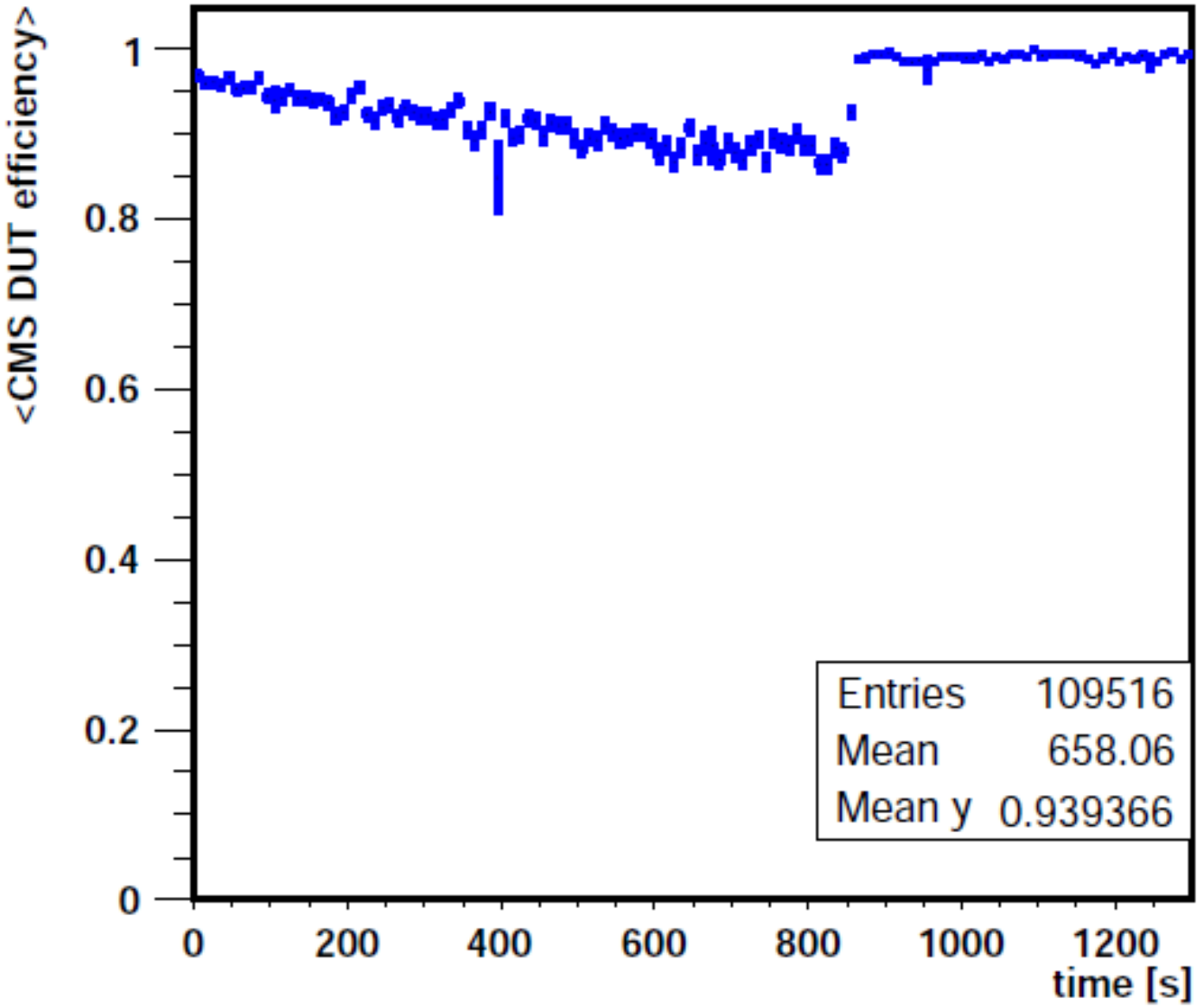


such runs are not used for analysis

most analysis runs are only 600 s long

xdb efficiency recovery

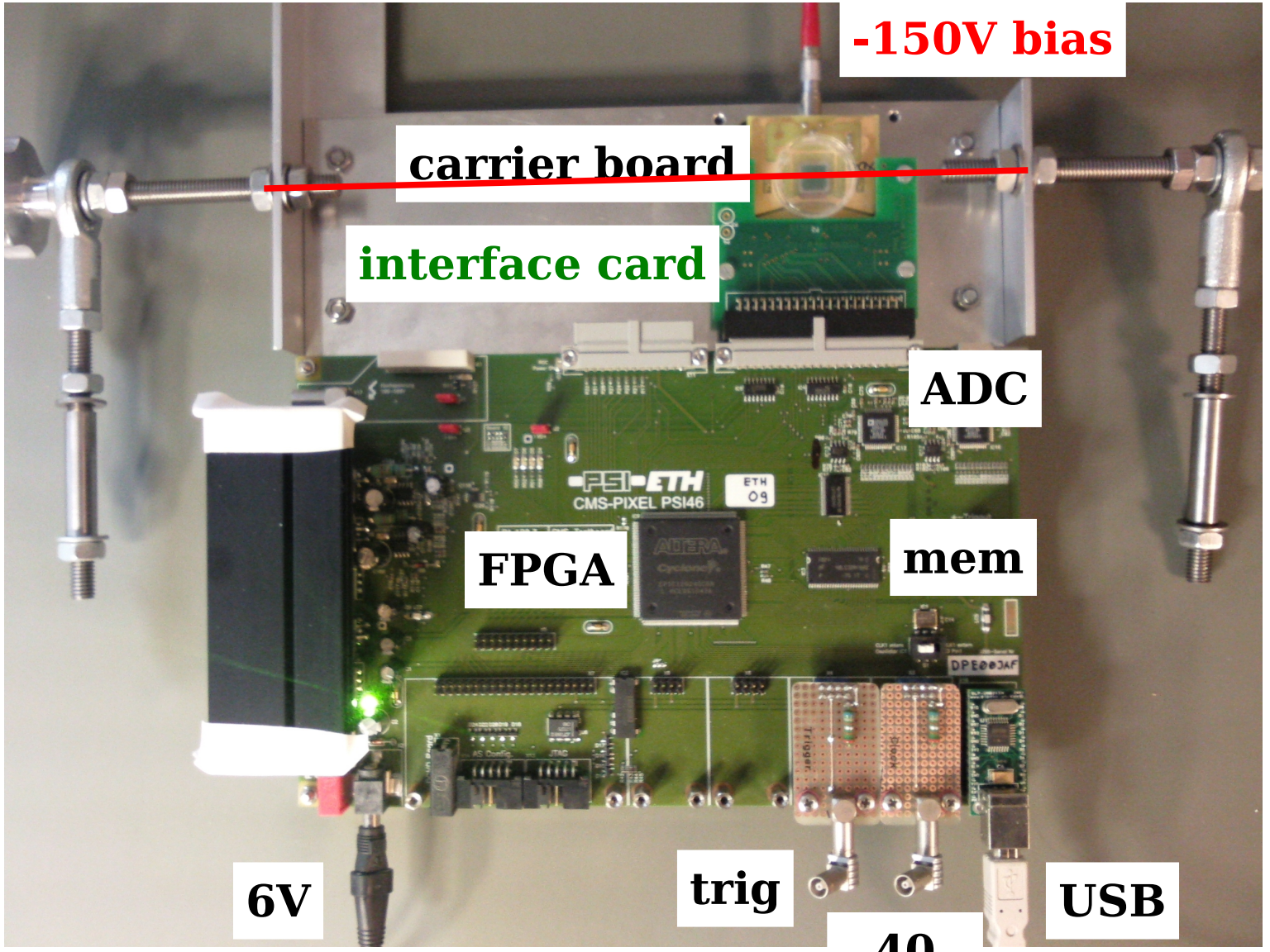
xdb 2, run 3898



Configuration at DESY

- Second digital ROC with sensor arrived from PSI on Thu 9.8.2012
- Adapter and interface cards from PSI and ETH, soldered at DESY ZE.
- old PSI46 test board, with new FPGA firmware (binary file from Beat Meier downloaded using ALTERA USB Blaster via JTAG connector)
- run in 40 MHz mode
- Dell laptop running Scientific Linux 6.1.
- psi46expert software digital branch from ETH compiled using gcc-4-5-2 in AMD 64 bit.
- libftd2xx.0.4 for USB interface from FTDI: http://www.ftdichip.com/Drivers/D2XX.htm

psi46xdb and test board at DESY



- Single chip module:
  - Indium bump bonded at PSI
  - Glued and wire bonded to carrier printed circuit board
  - Interface card to test board
  - xdb 2 arrived 25.6.
- Use the same board, firmware, software as for psi46

PSI46xdb

Data Rate, Efficiency:

- Extended data buffer 32 → 80 cells
- Extended time stamp buffer 16 → 24

Crosstalk, threshold uniformity:

- 6 metal layer (process option)
- Thick top metal (LM instead of MZ process option, +37%)
  → better power and ground distribution (lower resistance)
  → better threshold uniformity
- New routing for calibrate signal → less crosstalk of calibrate signal
- Better decoupling of comparator and digital voltage → less crosstalk
- Different other minor layout changes to reduce crosstalk

PSI46xdb

DAC:

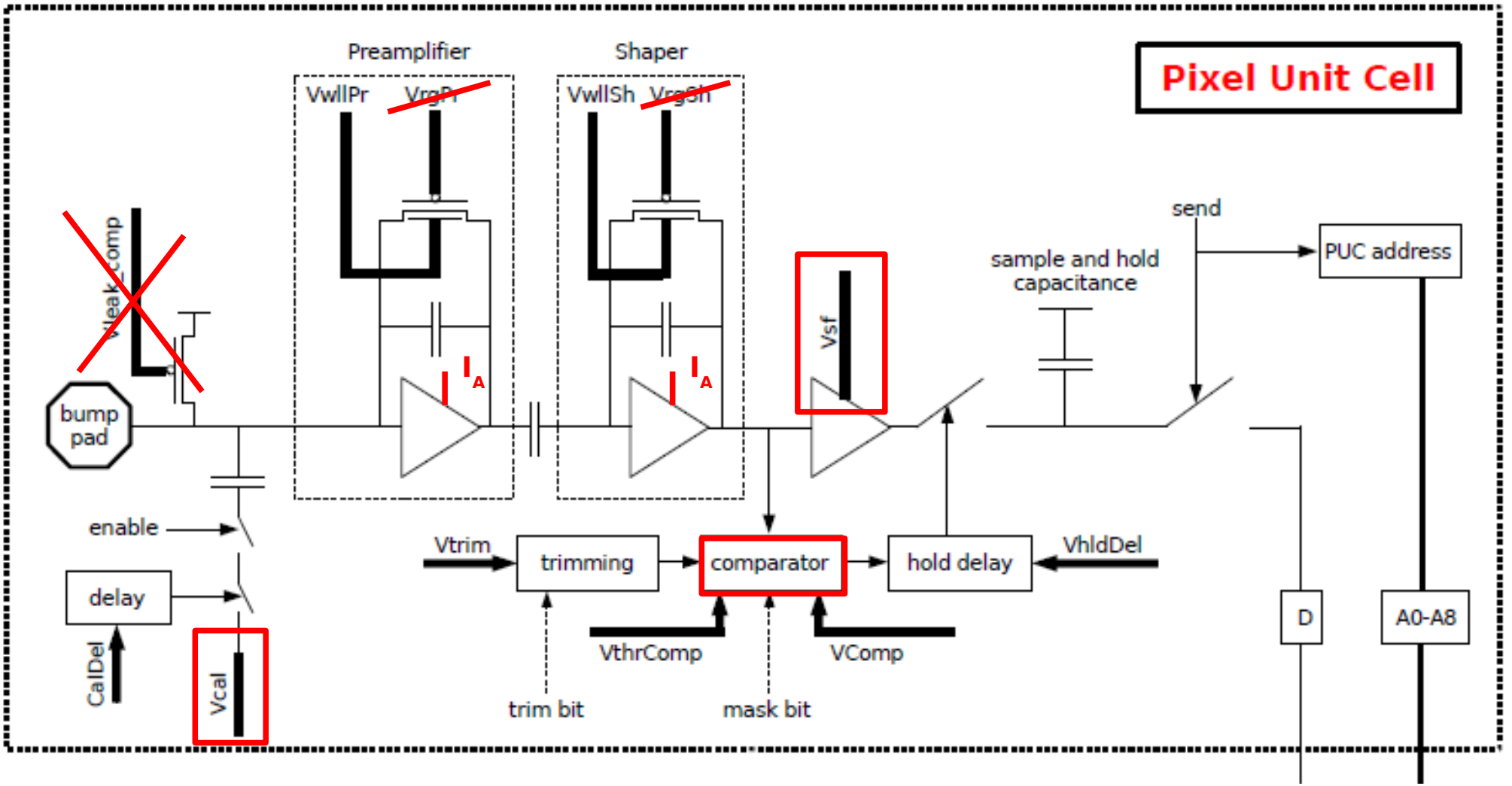
- 3 DACs removed: VRGPR, VRGSH and Vleakage
- All DAC's with power on reset for low power ROC configuration
- Current control instead of voltage control for S&H and analog power supply → easier and independent setup

Timing:

- Small performance optimization in column drain mechanism (timing)
- Modified comparator with reduced timewalk

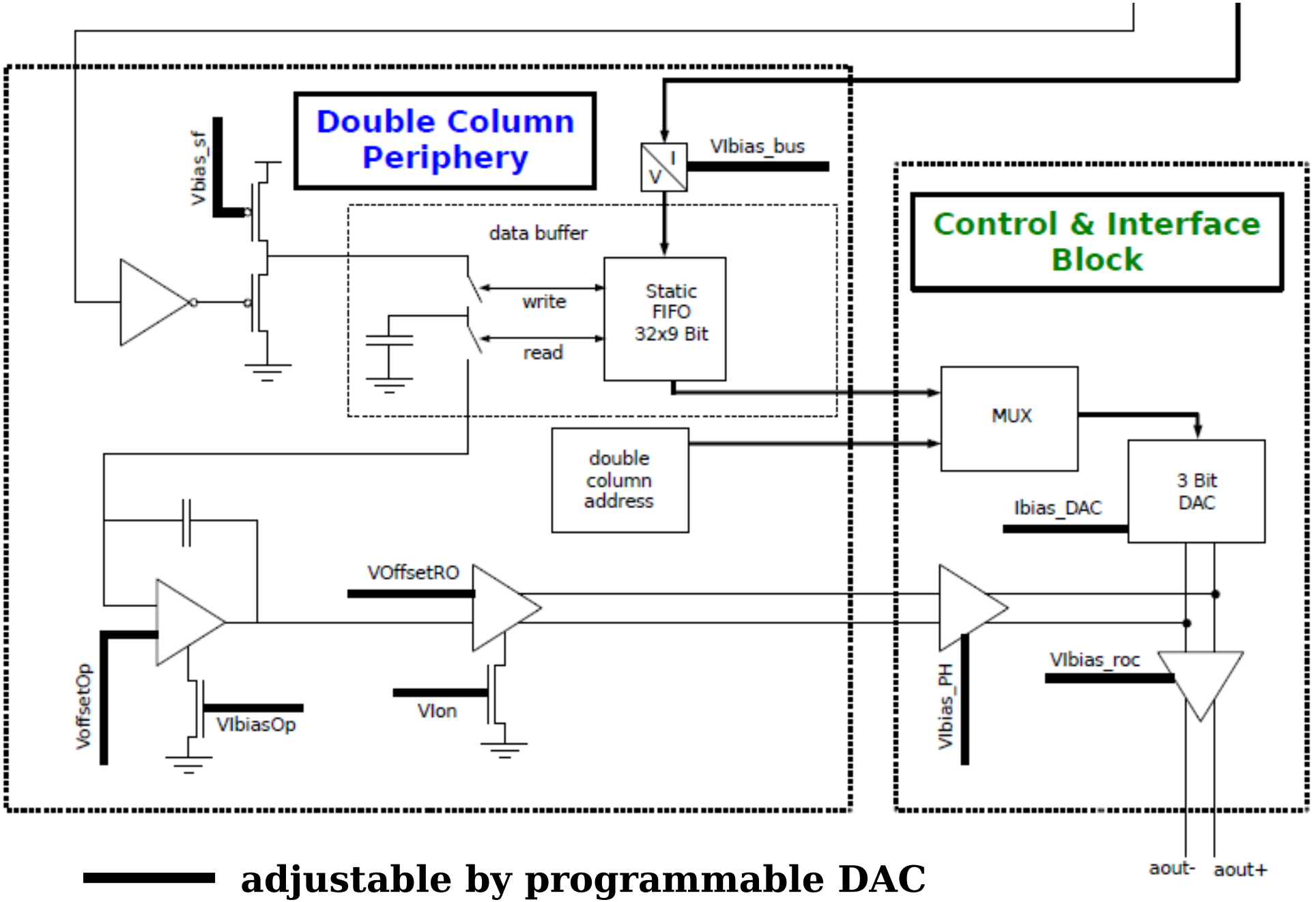
- Same analog read out as PSI46 → same test board
- Comparison possible between PSI46 and PSI46xdb

PSI46xdb pixel unit cell



modified in PSI46xdb

psi46 pixel readout chip



adjustable by programmable DAC

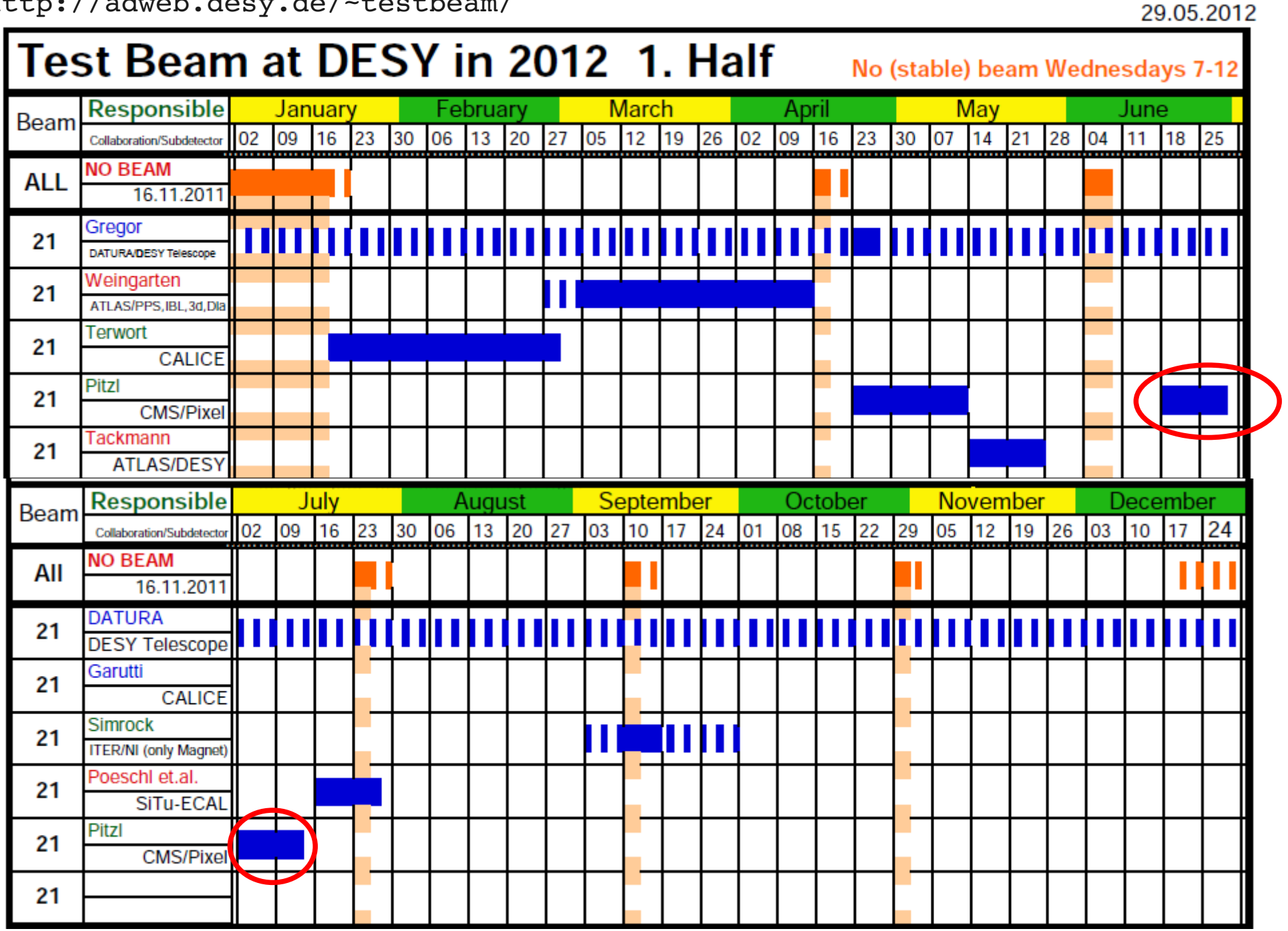
psi46xdb DACs

1	Vdig	6
2	Vana	166
3	Vsf	30
4	Vcomp	10
7	VwllPr	60
9	VwllSh	60
10	VhldDel	250
11	Vtrim	130
12	VthrComp	74
253	CtrlReg	0
254	WBC	20

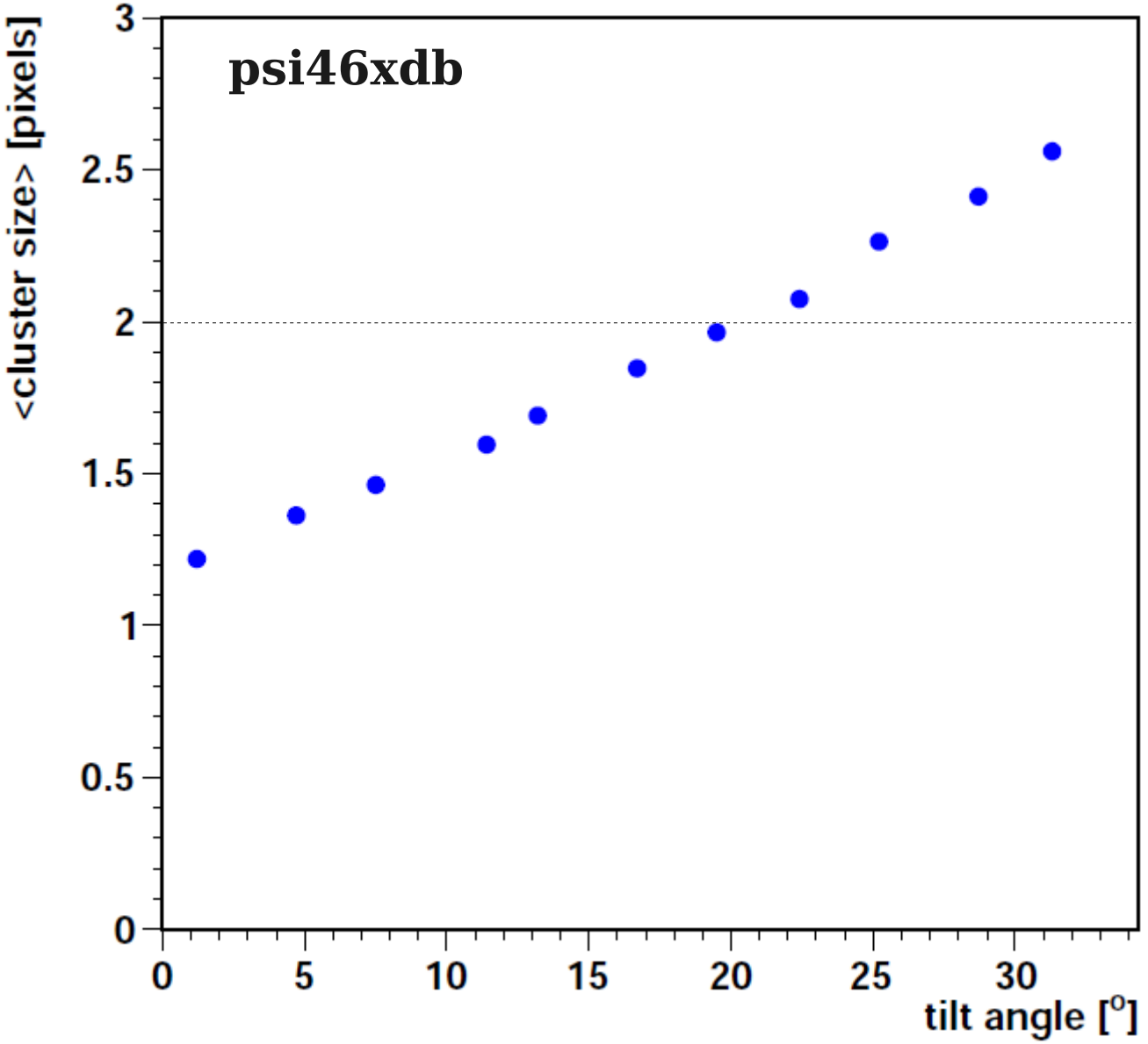
13	VIBias_Bus	30
14	Vbias_sf	10
15	VoffsetOp	57
16	VIbiasOp	115
17	VOffsetR0	120
18	VIon	115
19	VIbias_PH	130
20	Ibias_DAC	83
21	VIbias_roc	190
25	Vcal	200
26	CalDel	155
27	RangeTemp	0

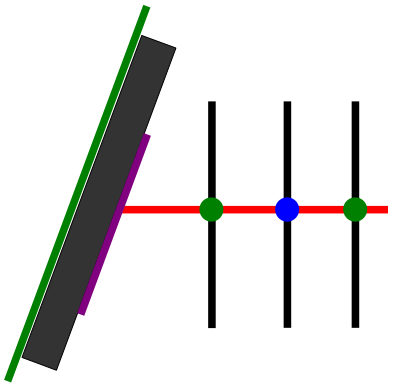
CMS Pixel in the DESY test beam

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



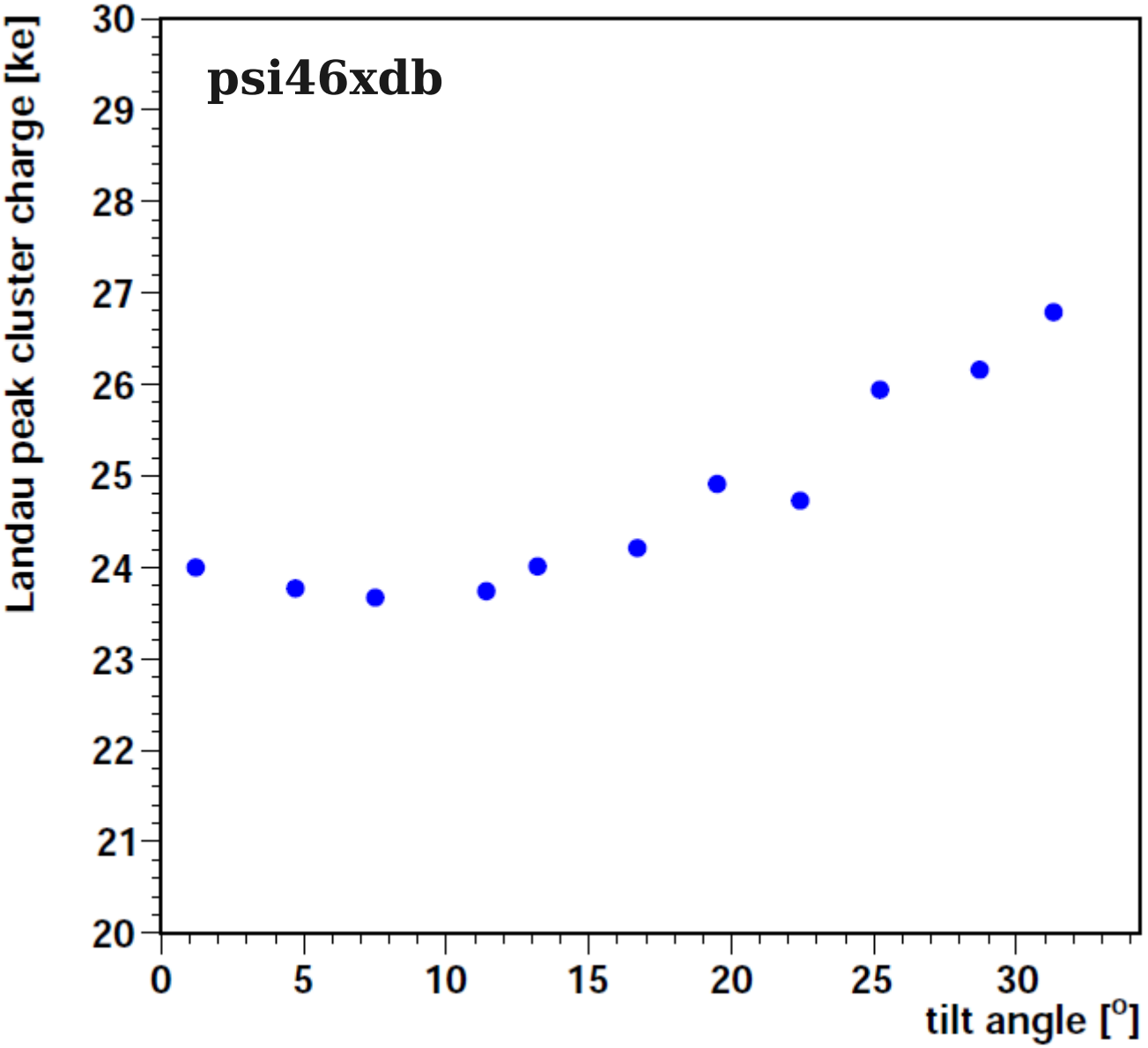
CMS pixel cluster size vs tilt angle

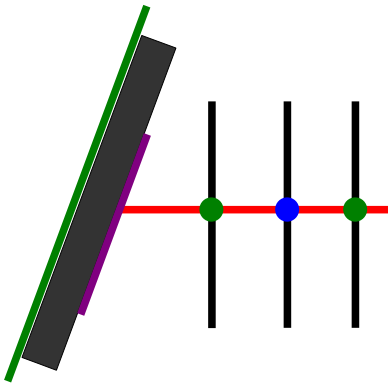




- Chip xdb2, -150V
- row pixels = 100 µm.
- sensor thickness 285 µm
- optimal:
  - size 2 at 20°.

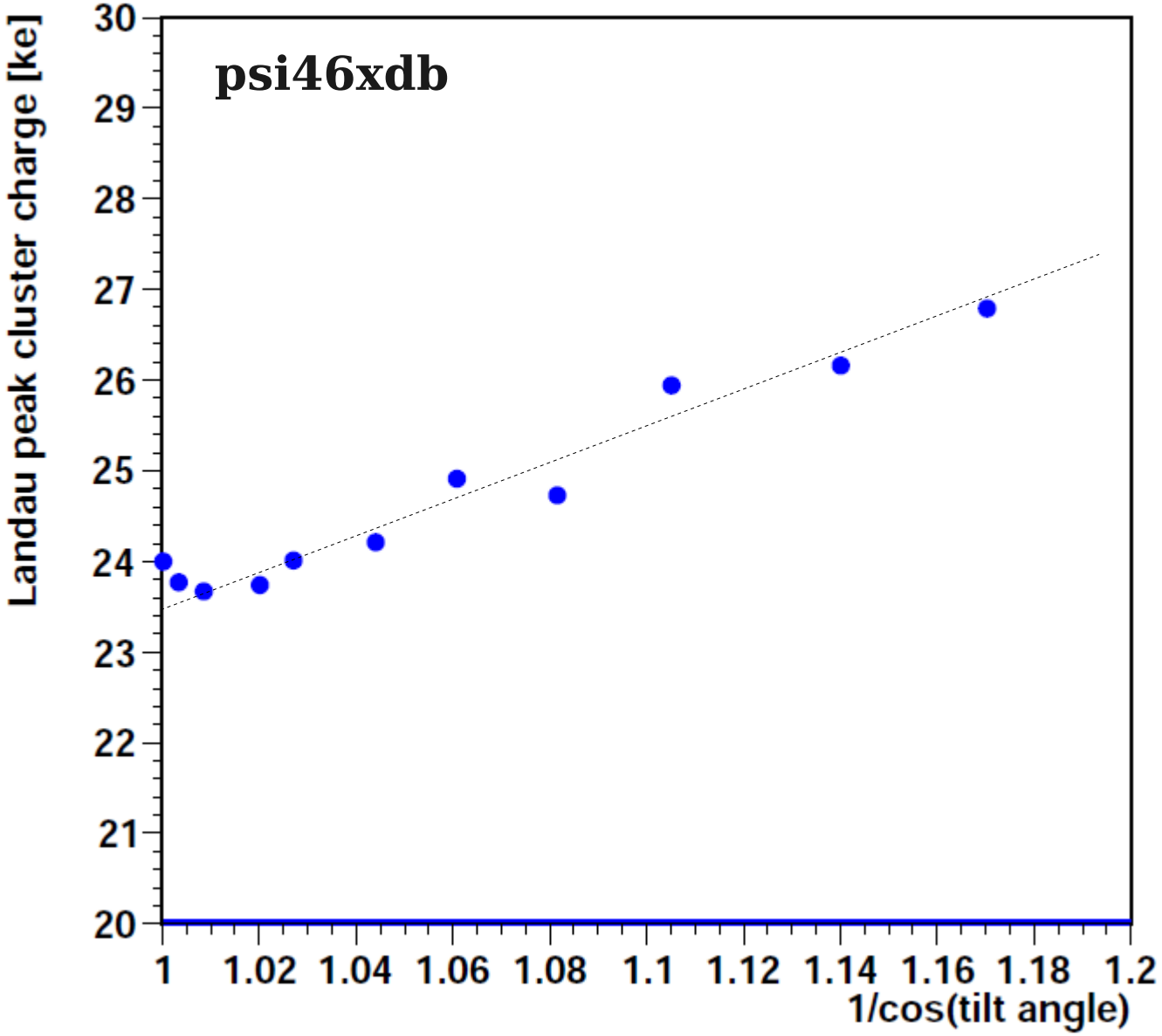
Cluster charge vs tilt angle

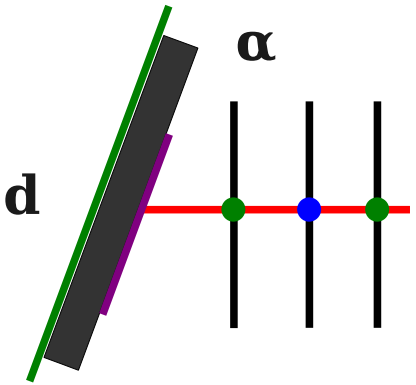




- Chip xdb2, -150V
- sensor thickness 285 µm
- position of the Landau peak
  - should increase with path length in silicon

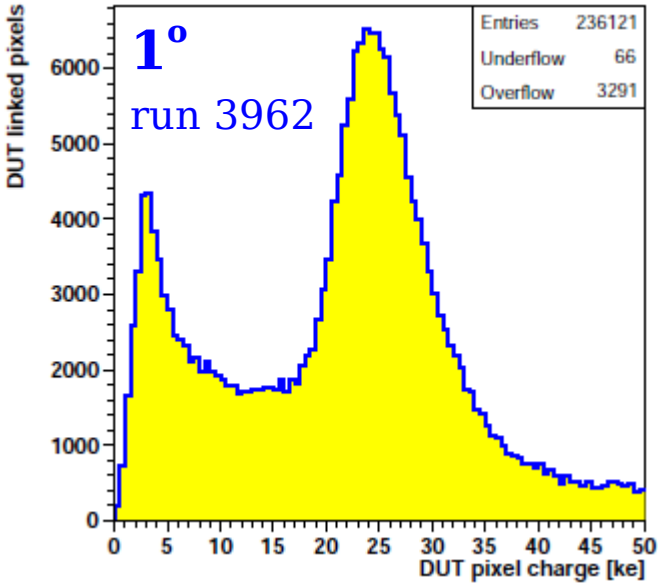
Cluster charge vs tilt angle

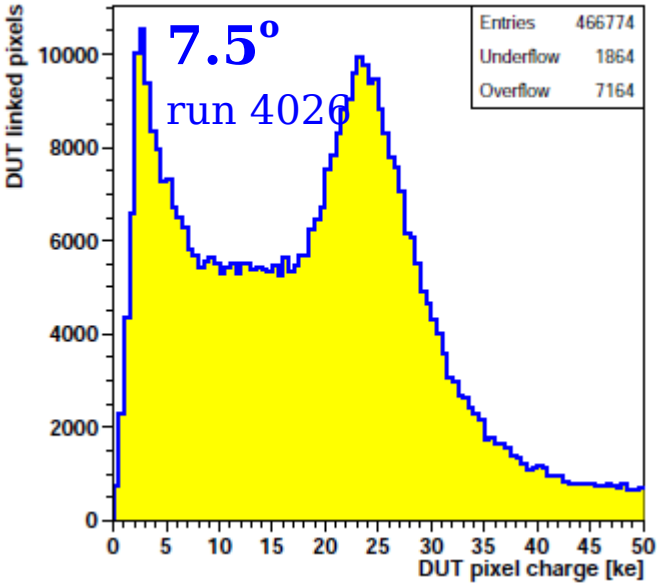


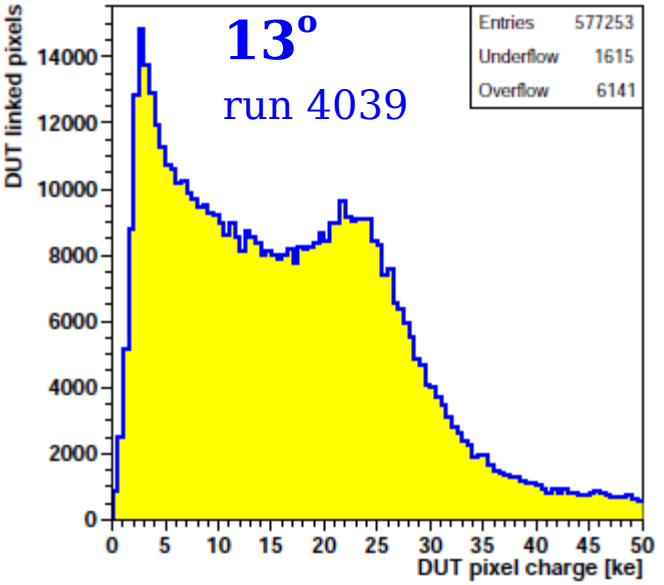


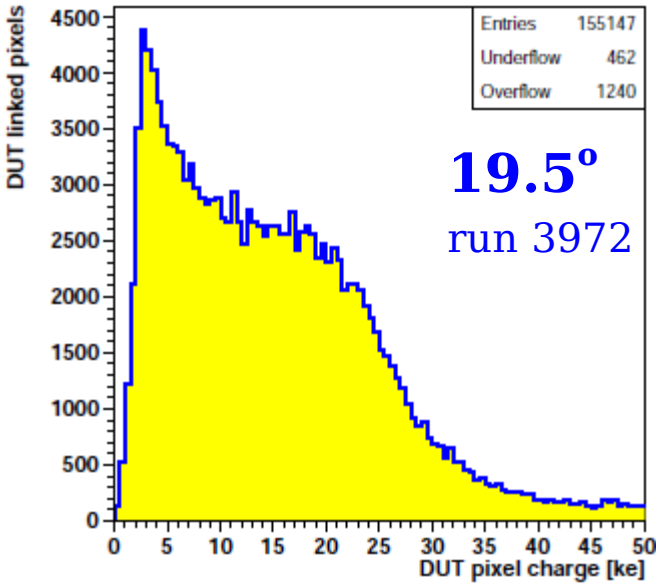
- Chip xdb2, 150V
- effective sensor thickness:
  - d = 285 µm / cos α
- position of the Landau peak should be linear in d
  - timing problems?
  - threshold effects?

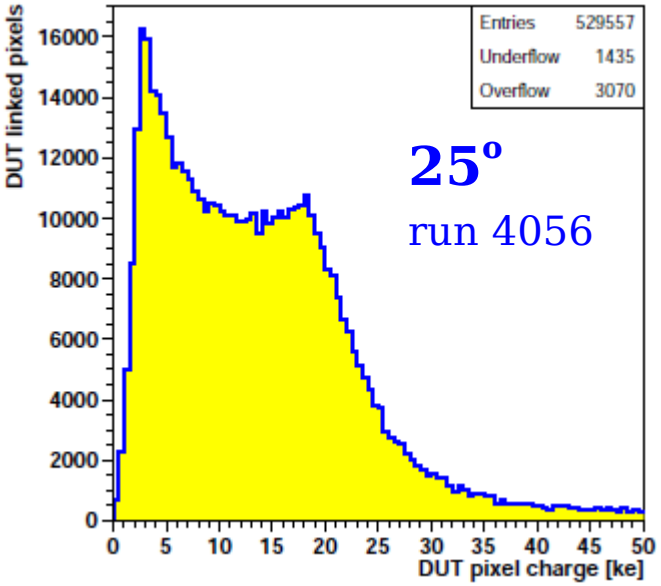
xdb pixel charge vs tilt angle

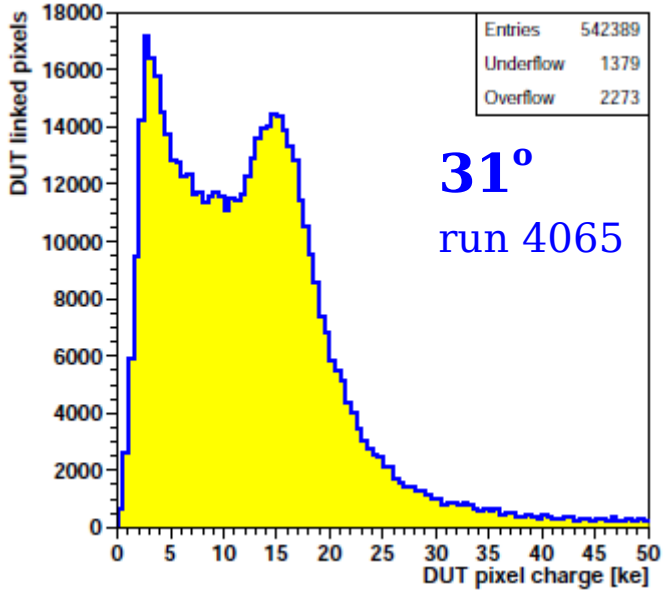








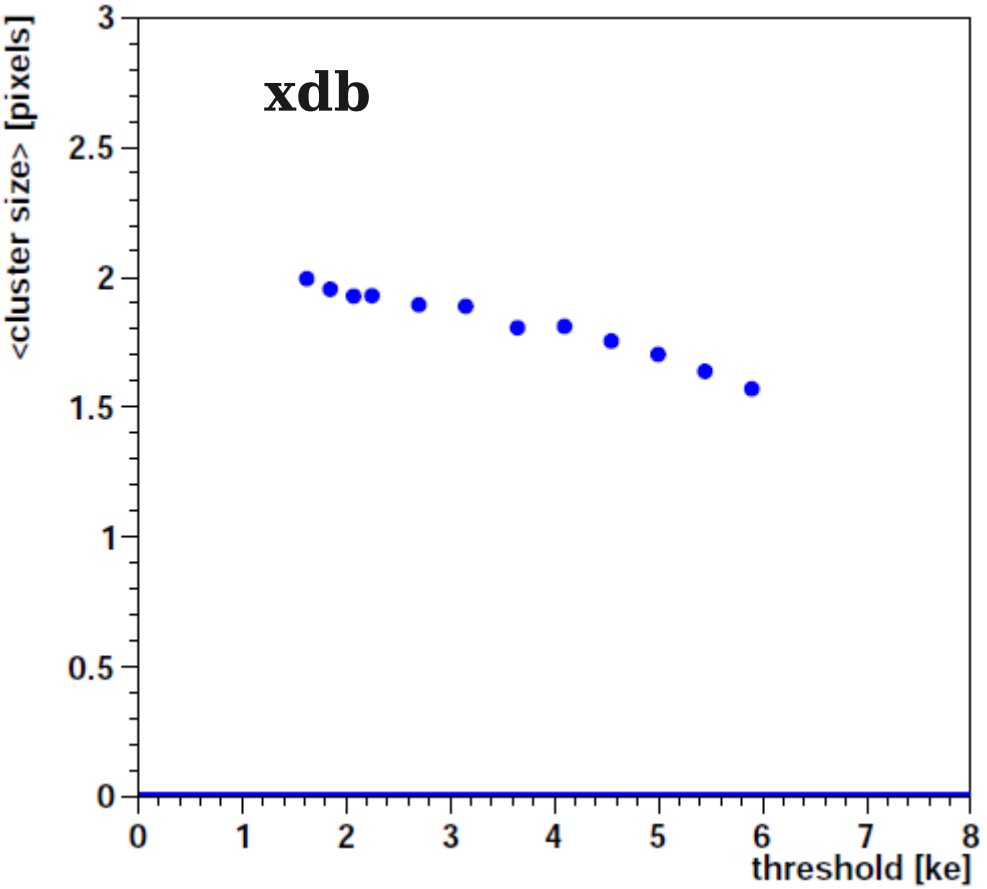




xdb cluster size and charge vs threshold

Chip xdb2, 19° tilt

pixel / cluster



position of Landau peak