New pixels for CMS

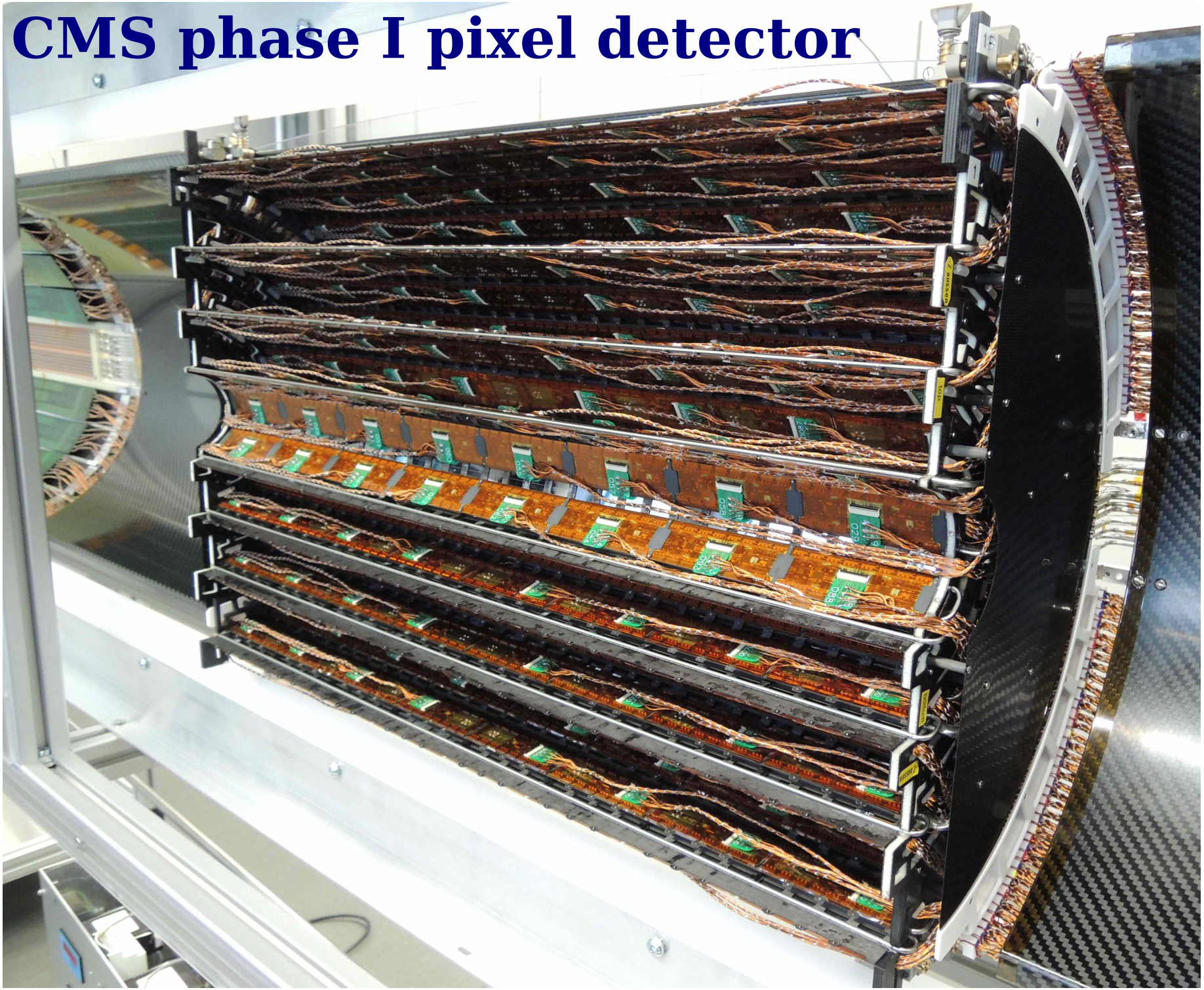
Daniel Pitzl, DESY

Hamburg Instrumentation Seminar, 10.11.2017

- Phase I upgrade
  - test beam studies
- Phase II sensor development
  - test beam studies

- not covered:
  - bump bonding
  - module production
  - commissioning
  - radiation effects

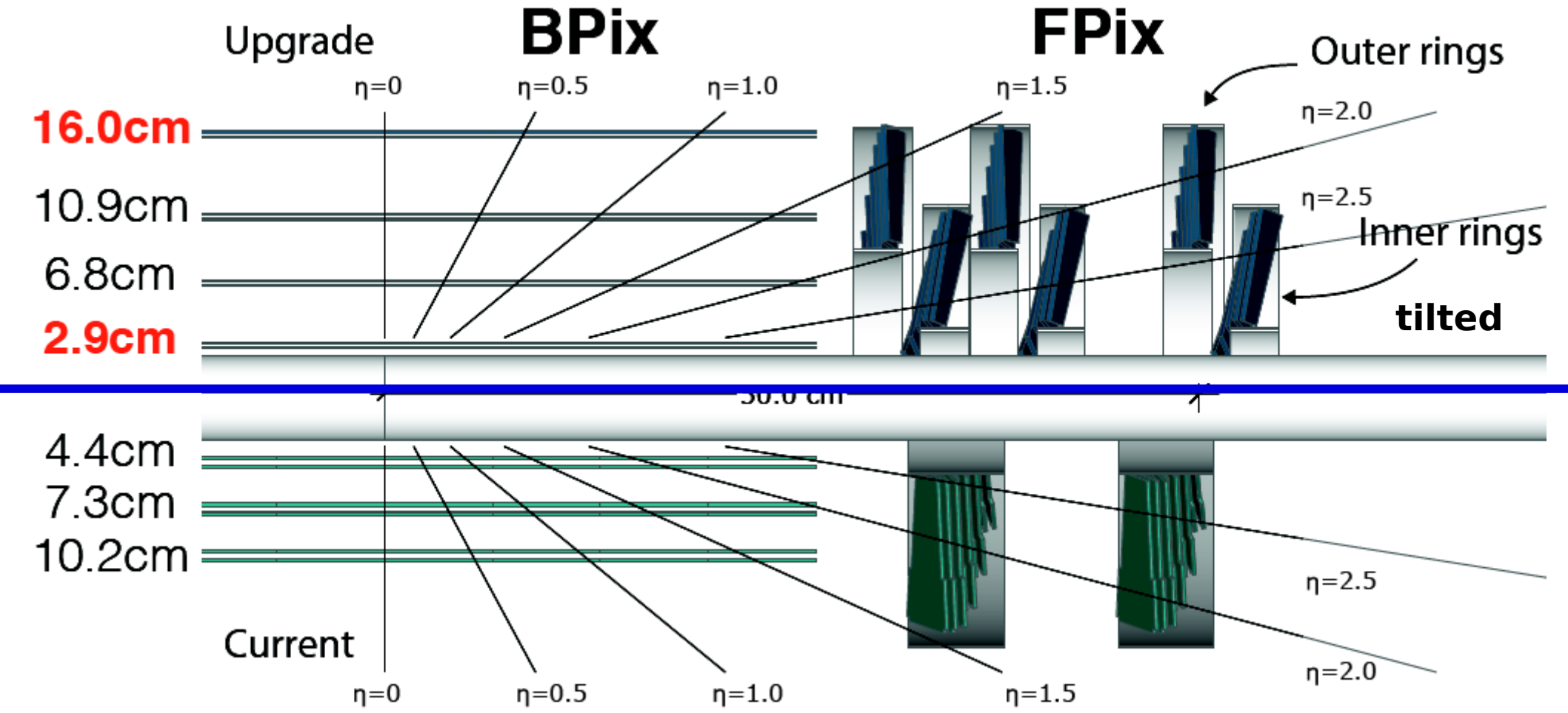
CMS phase I pixel detector



PSI
Jan
2017

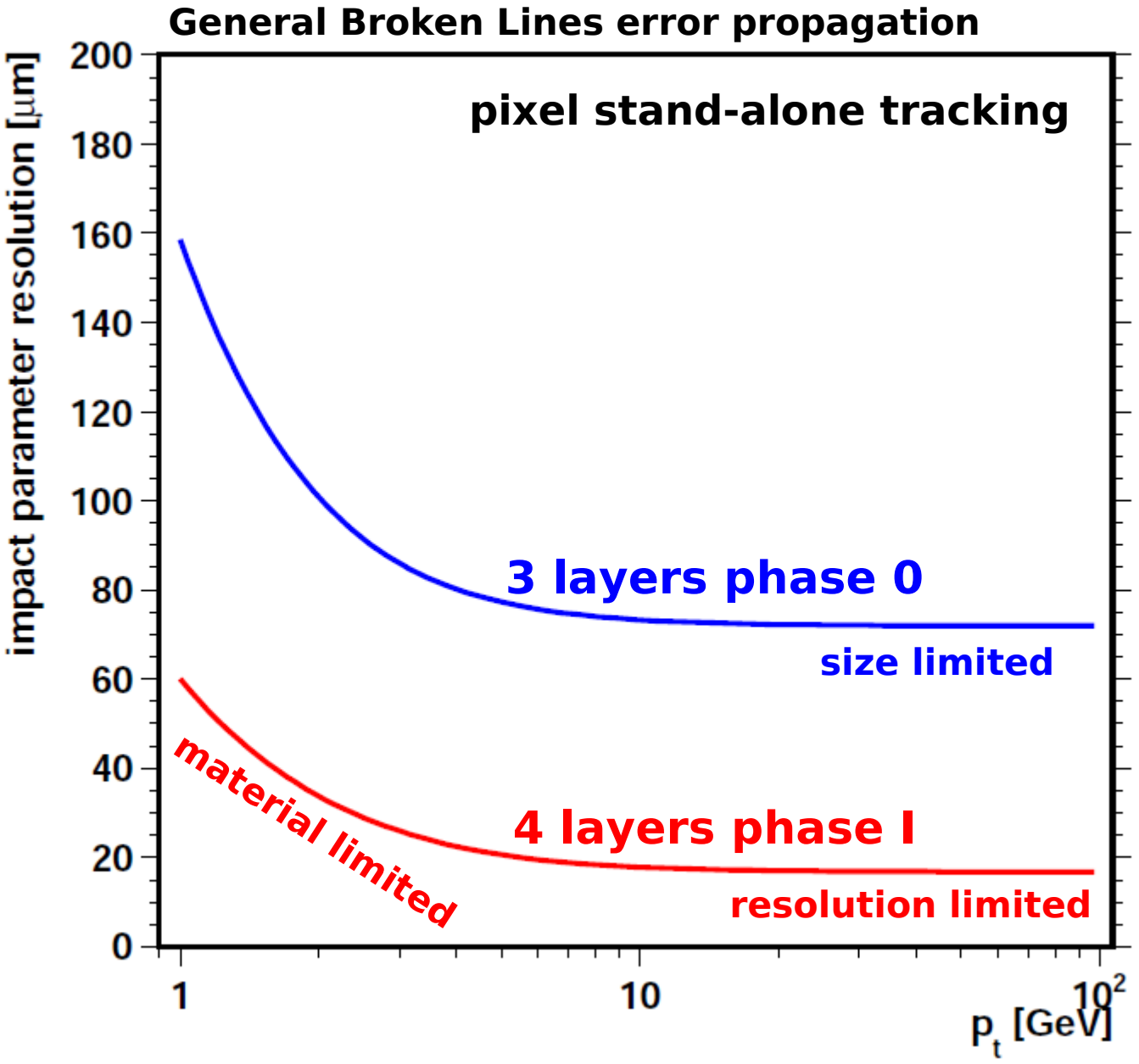
2017 phase I pixel upgrade

Phase I

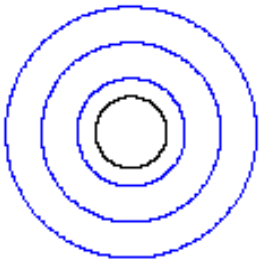


Phase 0

Pixel impact parameter resolution



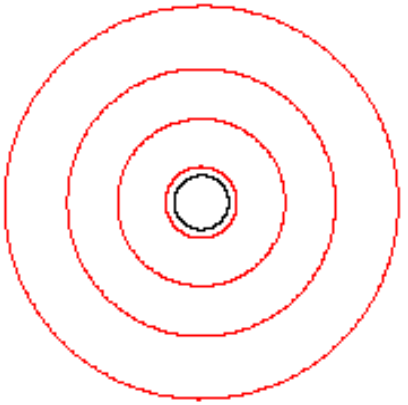
phase 0



R_{BP} 29 mm

$\sigma(d_{CA}) = 160\ \mu m / p_t \oplus 72\ \mu m$

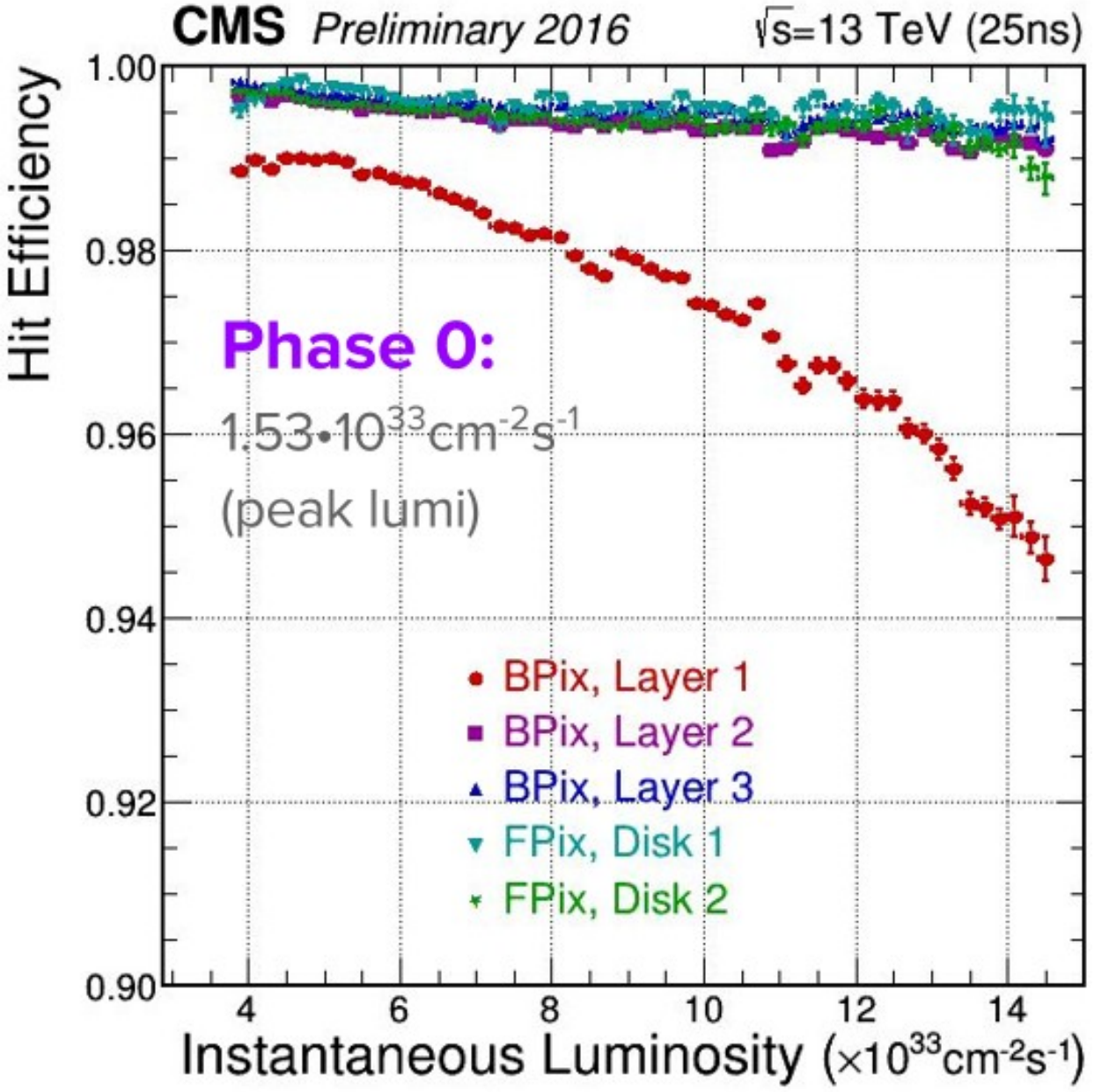
phase I



R_{BP} 22 mm

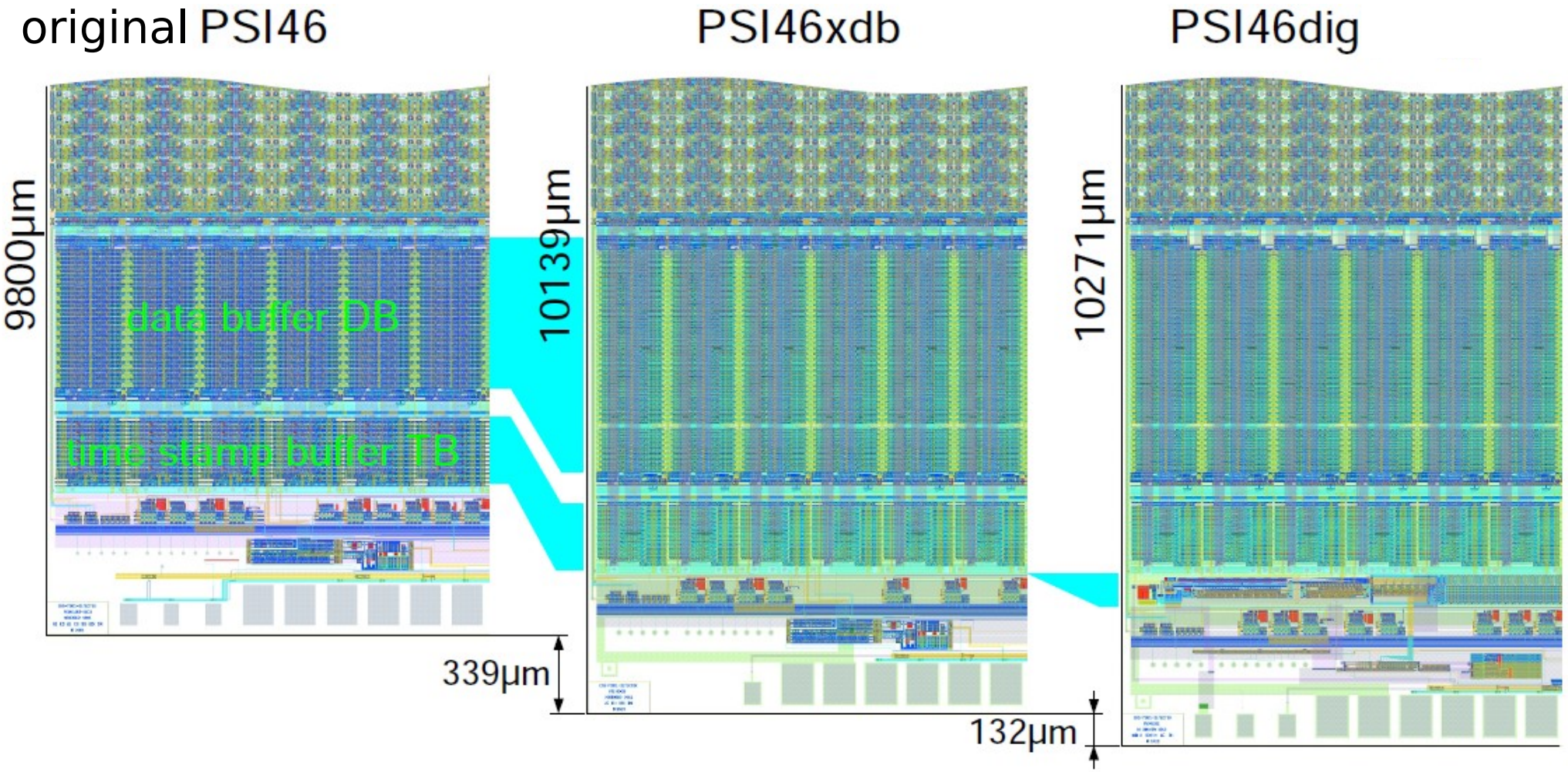
$\sigma(d_{CA}) = 60\ \mu m / p_t \oplus 17\ \mu m$

pixel hit finding efficiency in 2016



- LHC reached and exceeded design luminosity in 2016
- The increasing hit occupancy degraded the efficiency of the original pixel detector:
  - by -5% at $1.4 \cdot 10^{34}/cm^2/s$
  - was anticipated
- addressed by the phase I upgrade

pixel readout chip development



- DB 32
- TB 12
- 40 MHz

2007

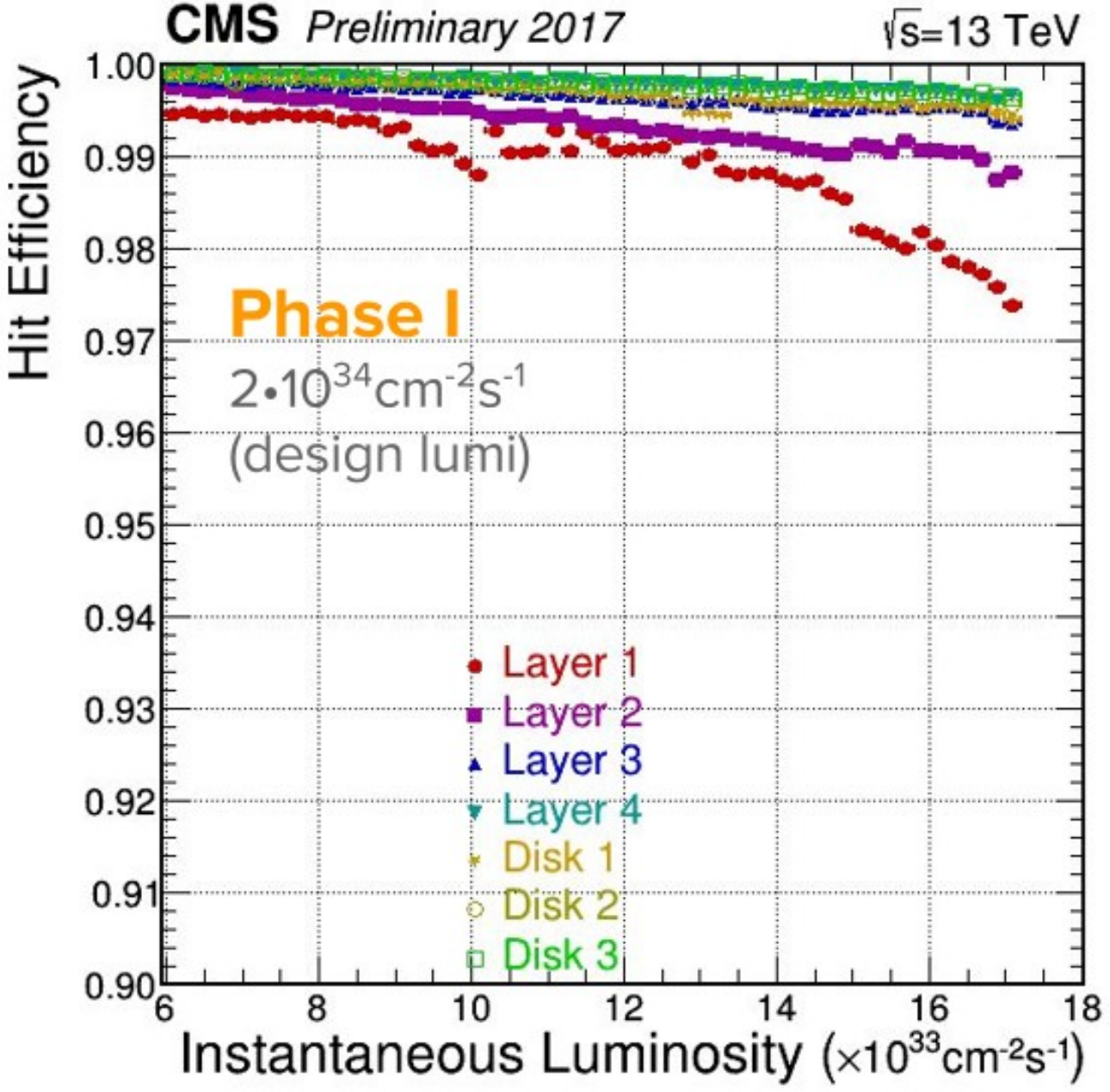
- DB 80
- TB 24
- 40 MHz

2012

- DB 80
- TB 24
- RB 64
- 8-bit ADC
- 160 MHz

2014

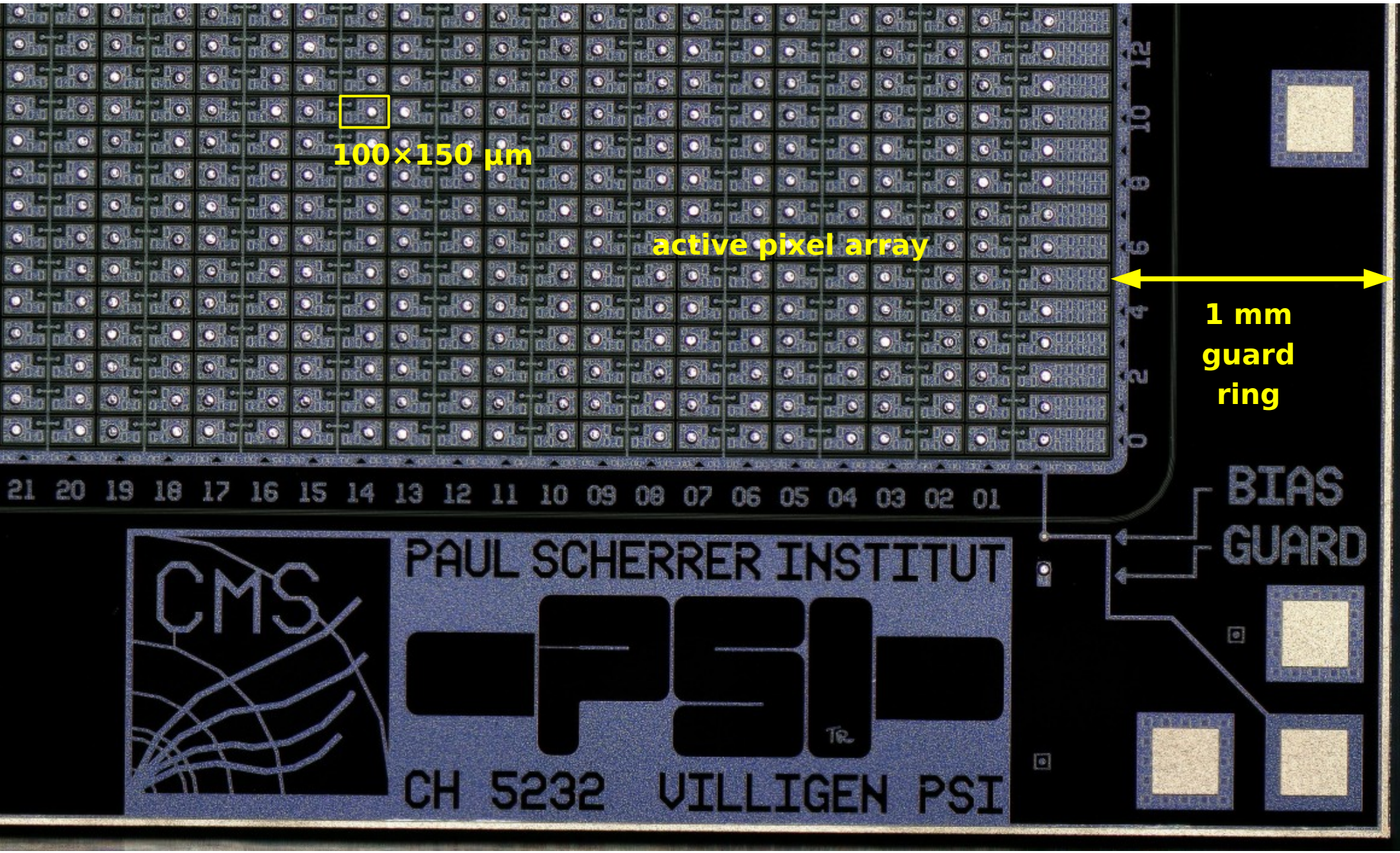
pixel hit finding efficiency in 2017



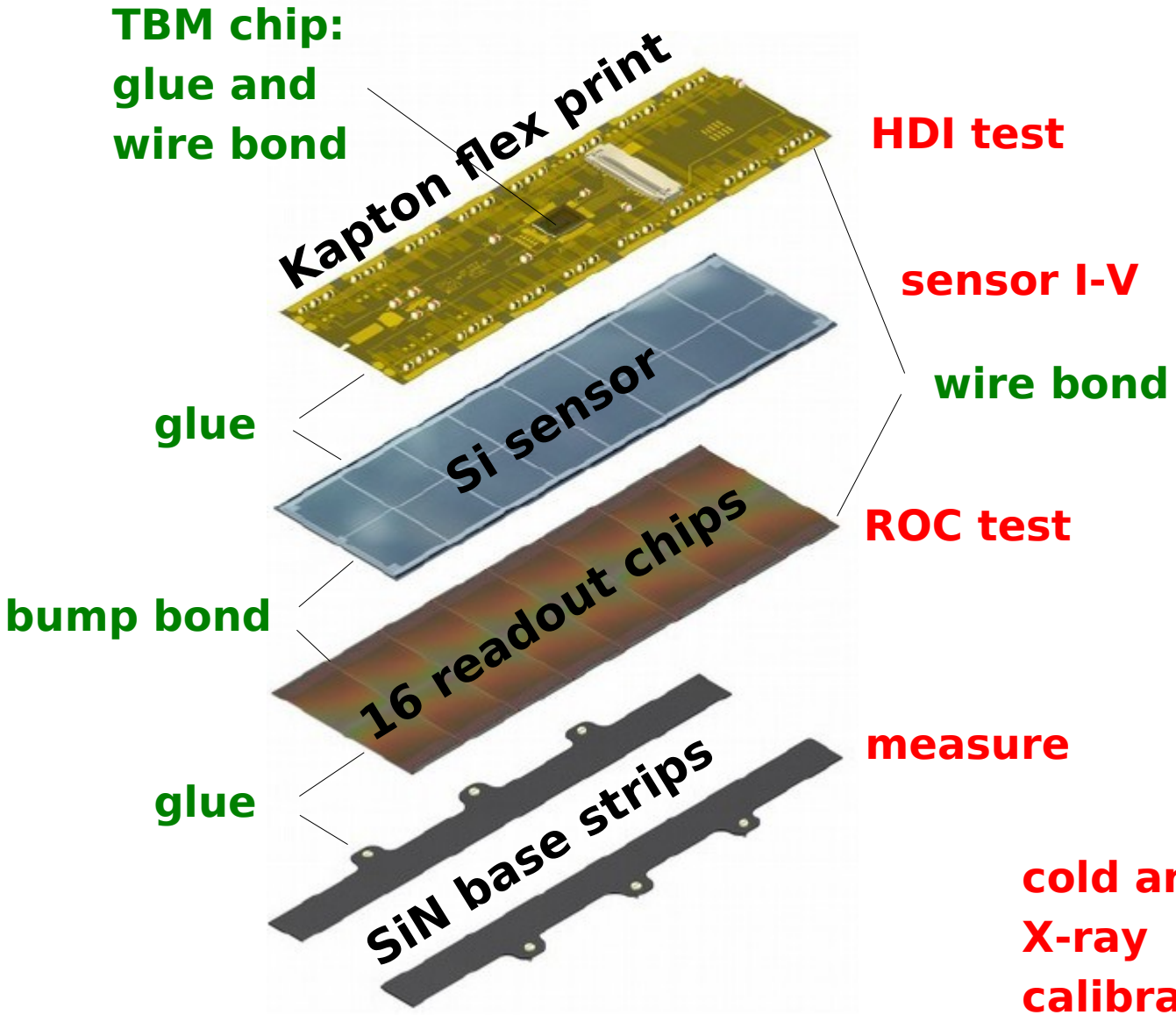
- Upgraded pixel detector 2017
- Layer 1:
  - smaller radius = higher hit density
  - higher luminosity than 2016
  - higher efficiency than 2016

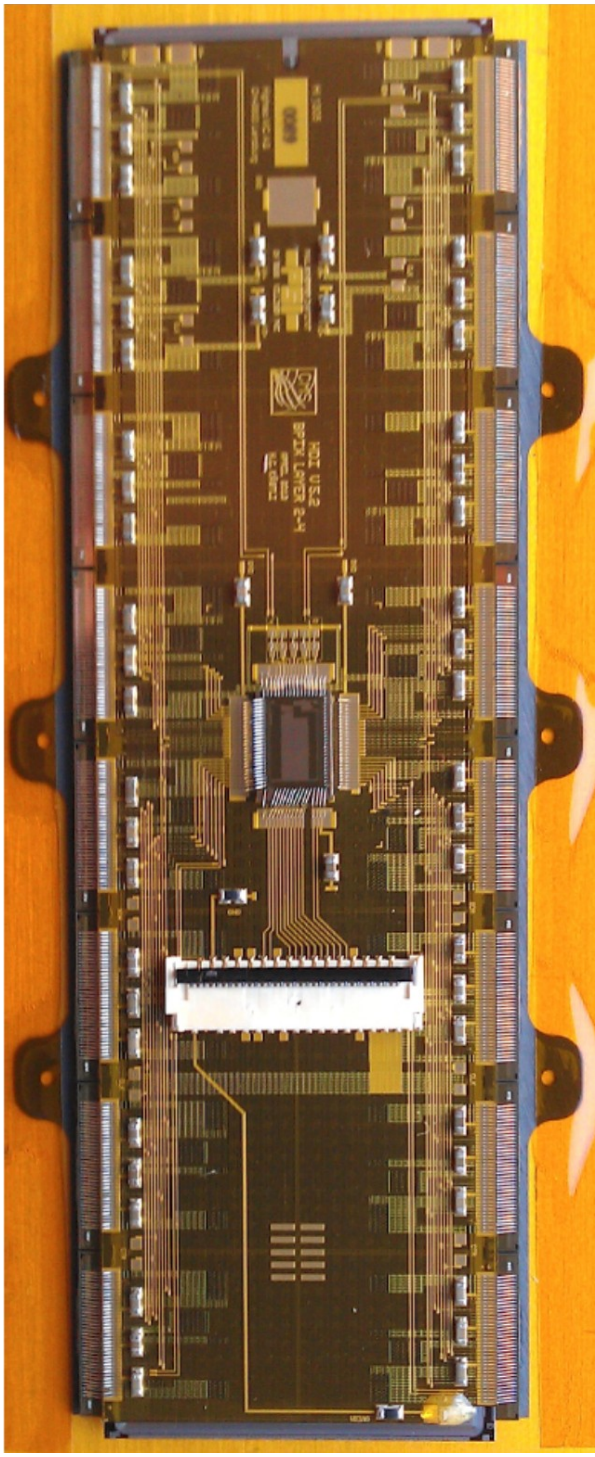
phase I sensor design unchanged

n-in-n (oxygenated) double sided processing at CiS (Erfurt)



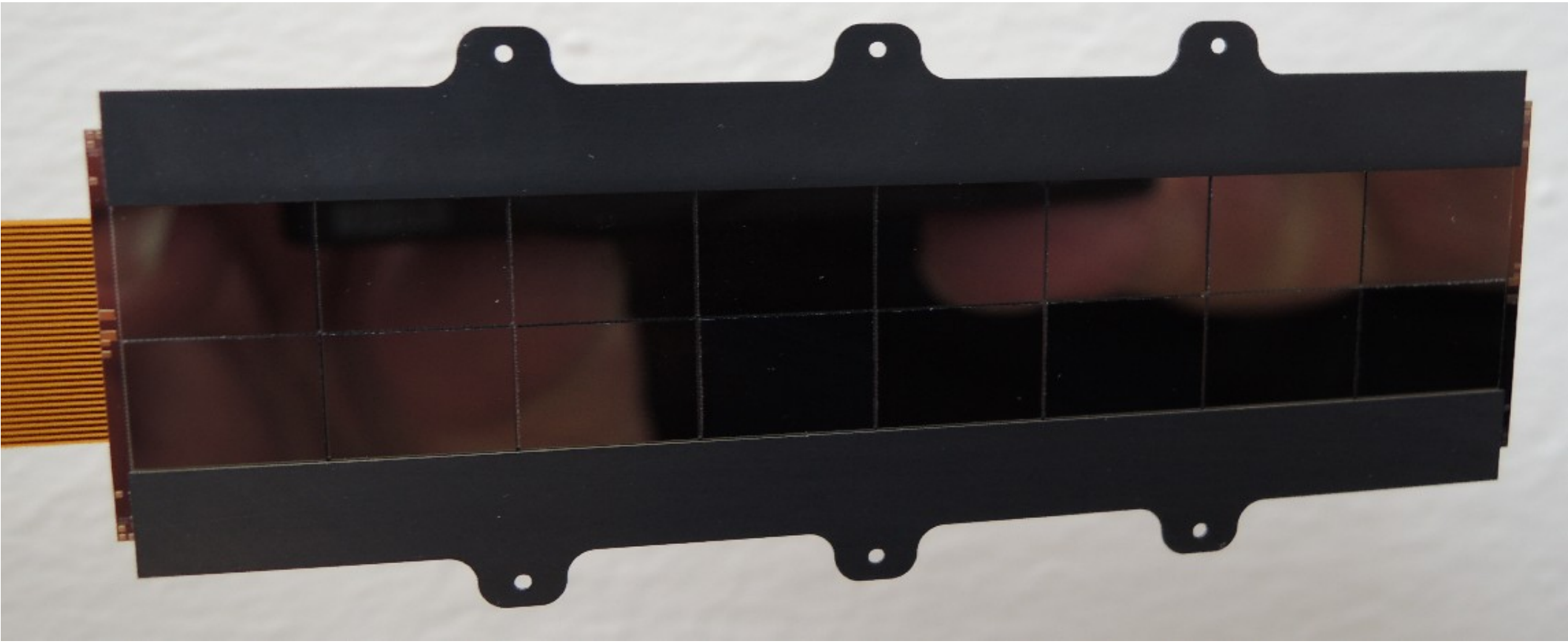
module production tasks





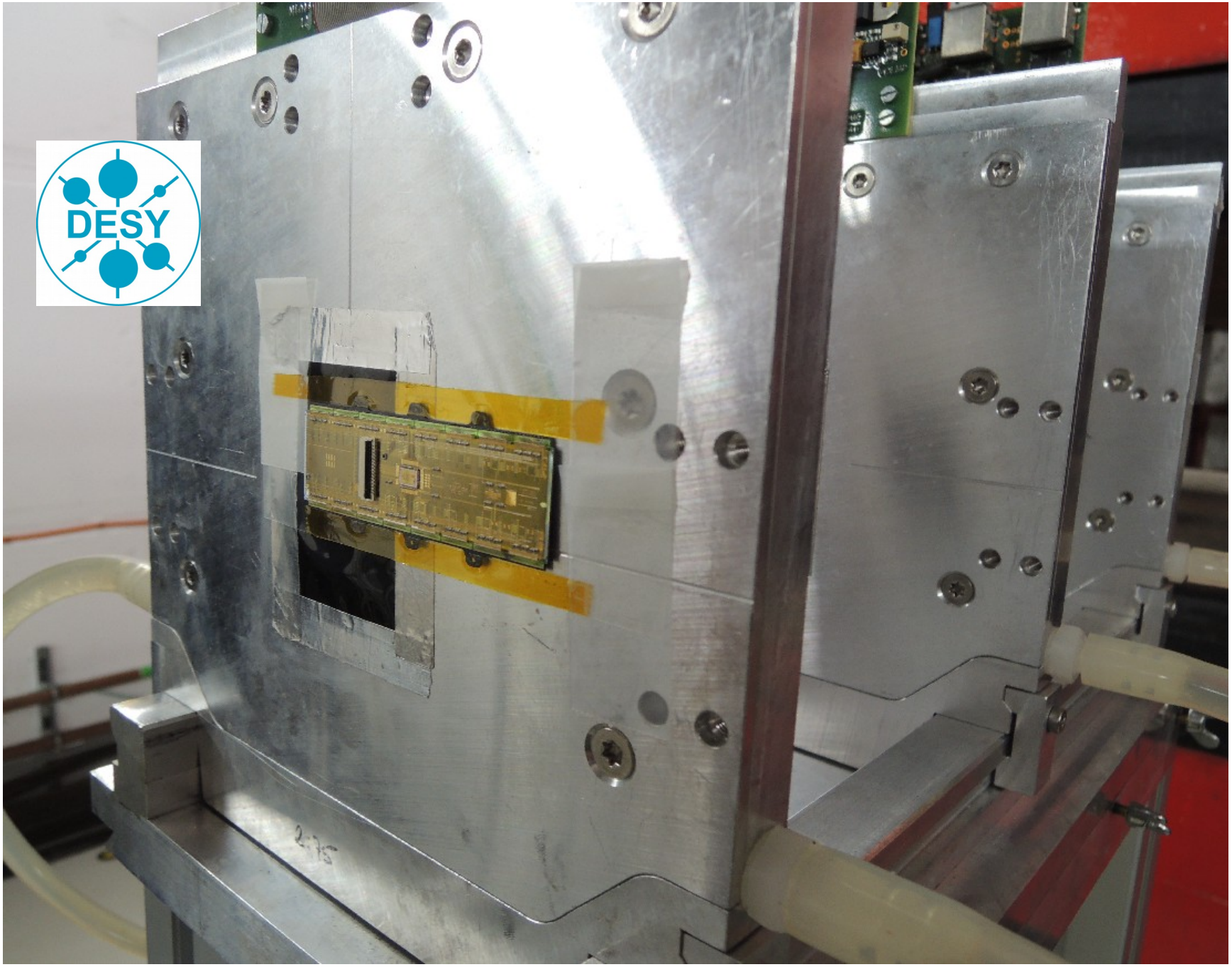
300+ modules produced in Hamburg
mid 2015 – mid 2016

phase I upgrade module

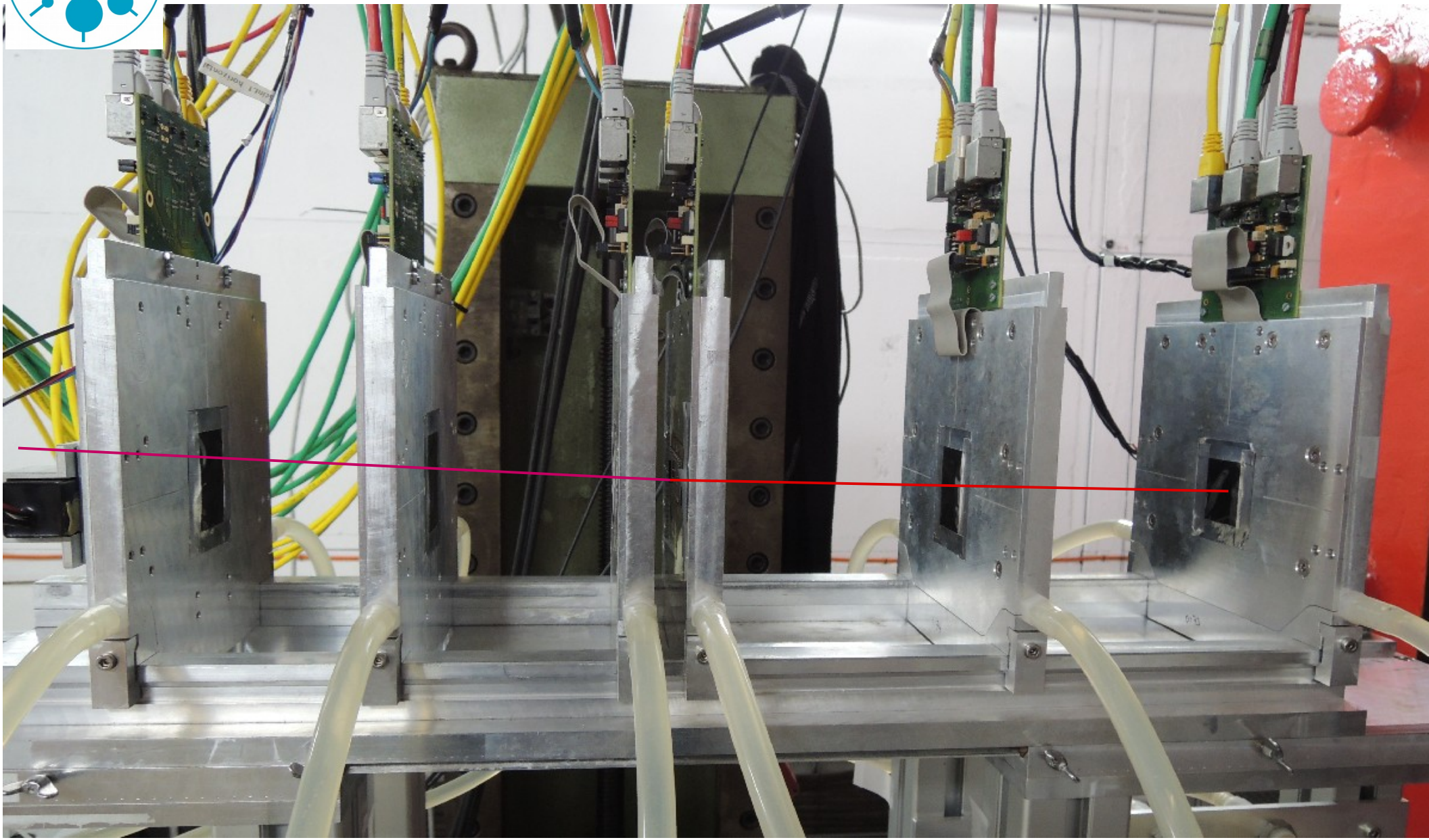


Material budget:
0.200 mm SiN base strips (0.25% X0, 5 mm width)
0.175 mm Si ROCs (0.2% X0)
0.285 mm Si sensor (0.3% X0)
0.050 mm Kapton flex print (0.15% X0) + SMD + connector + TBM

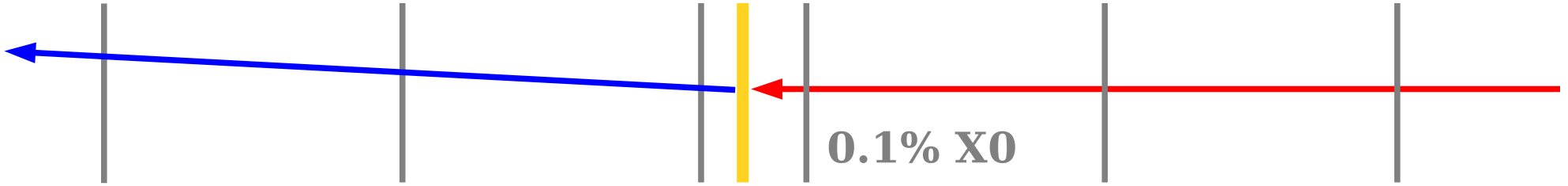
module as a target in the beam telescope



material imaging



scattering



downstream telescope track **module** **upstream telescope track**

measure kink angle θ between two track vectors:

$$\textbf{PDG: } rms(\theta) = \frac{13.6\,[mrad]}{p\,[GeV/c]}\sqrt{d/X_0}\left(1 + 0.038\,\ln(d/X_0)\right)$$

(PDG fit to Geant simulation, 98% Gaussian core)

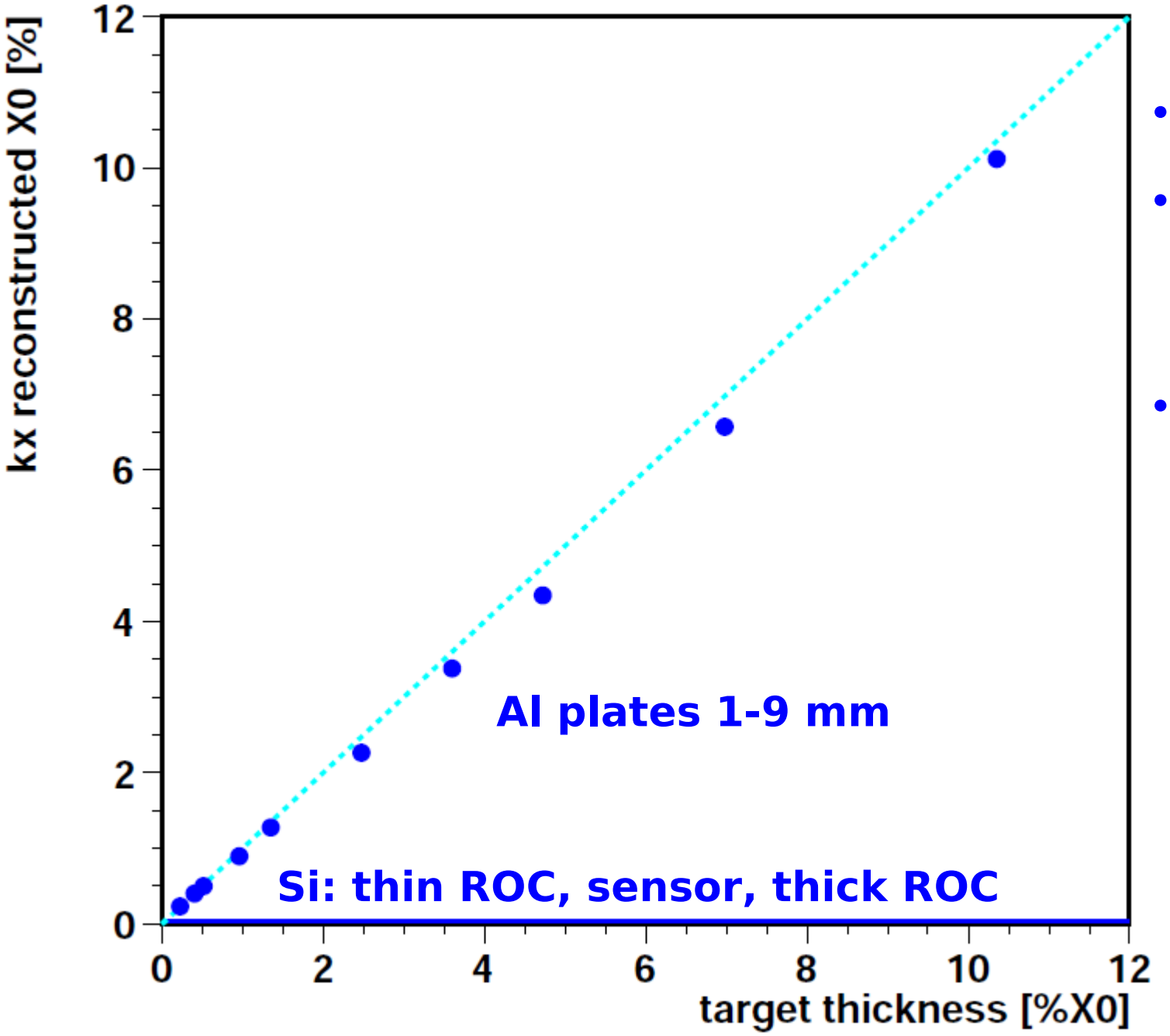
this is for a projected angle (θ_x or θ_y)

multiply by √2 for the 3-D scattering angle

data taken at p = 1.2 GeV/c

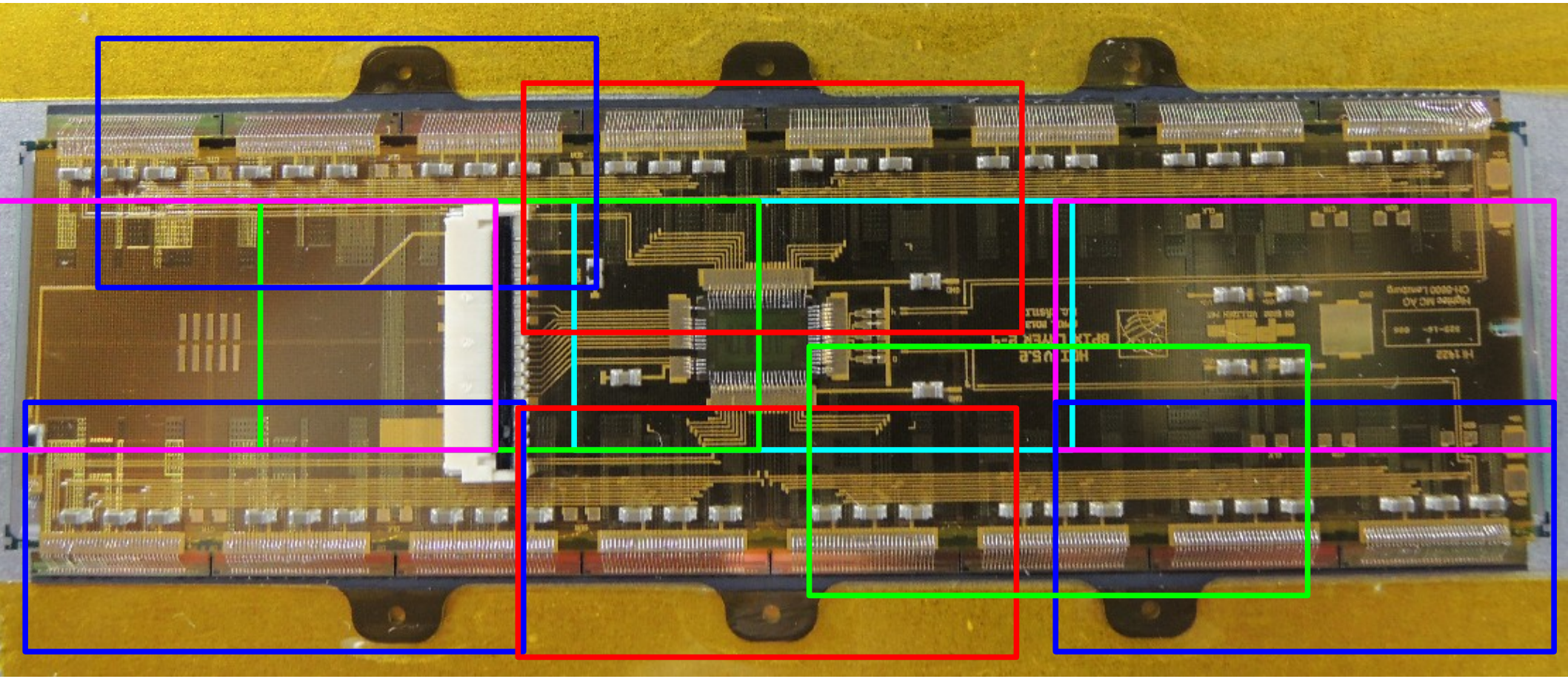
solve for d/X0 numerically (Newton-Raphson)

test with uniform materials



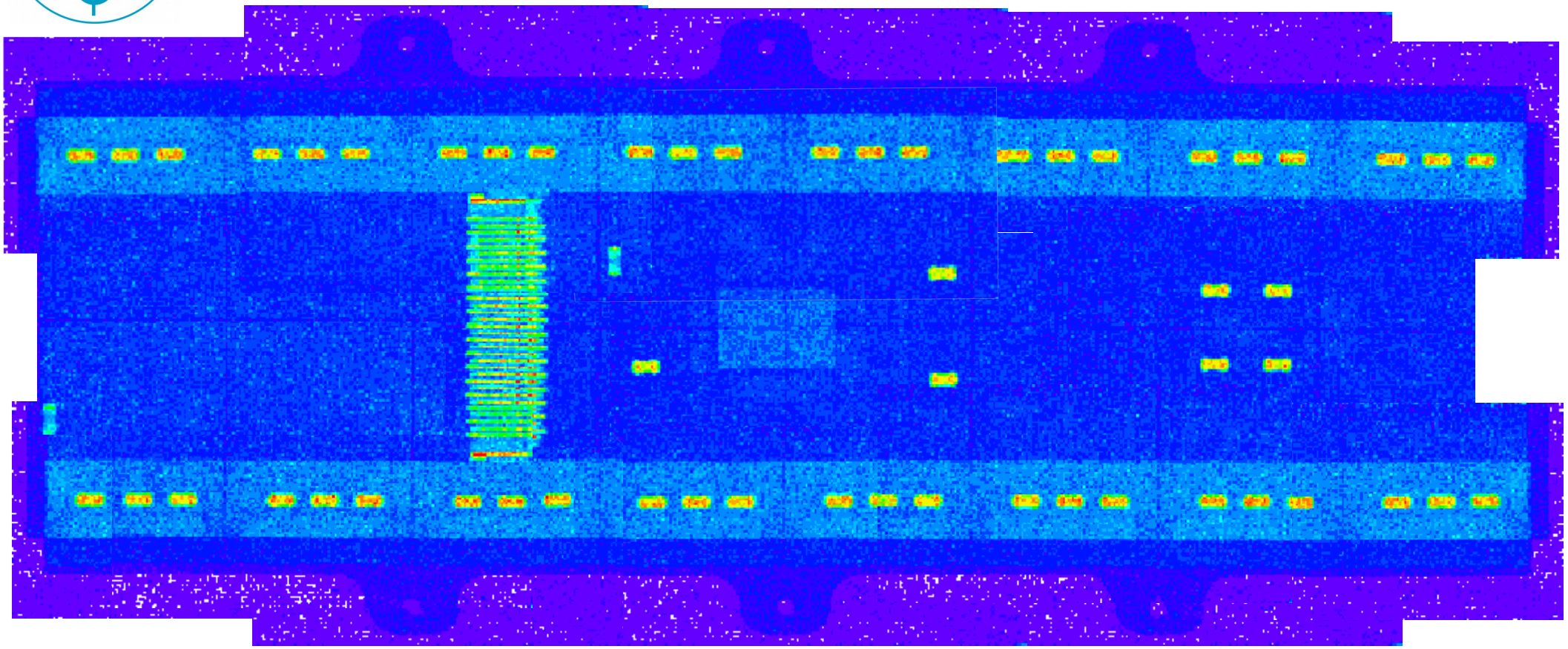
- 1.2 GeV data
- telescope with known materials in the center
- reconstructed vs expected X0:
  - OK within 5%
  - also for thin layers

Mimosa stitched imaging

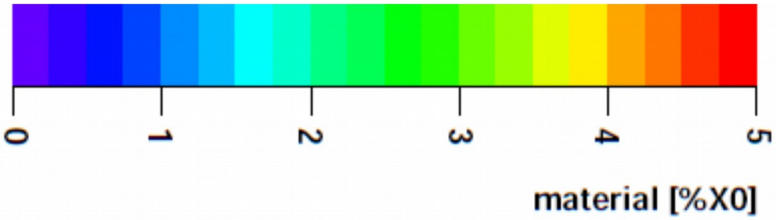


Mimosa:
21.2×10.6

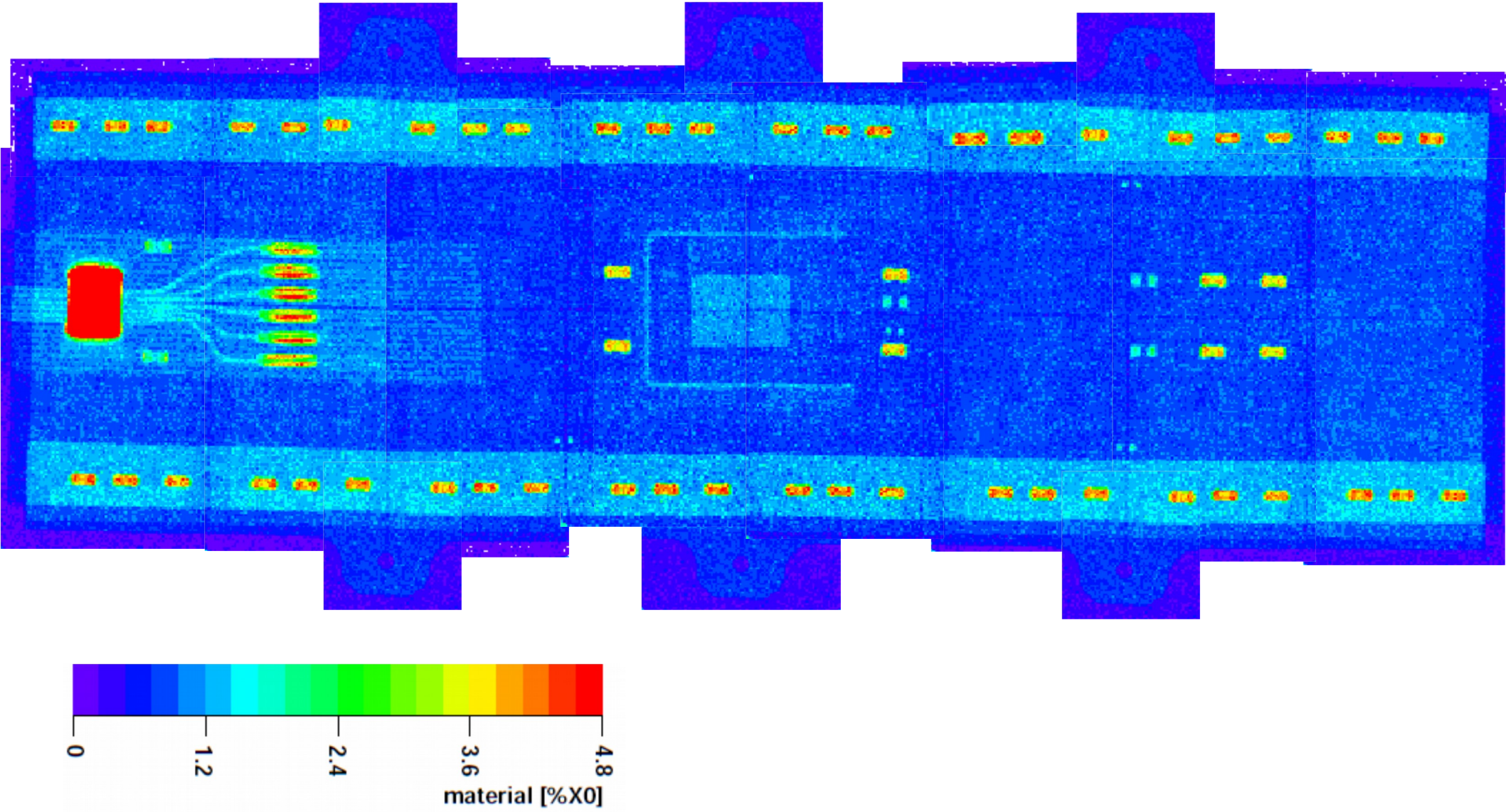
phase I module material map



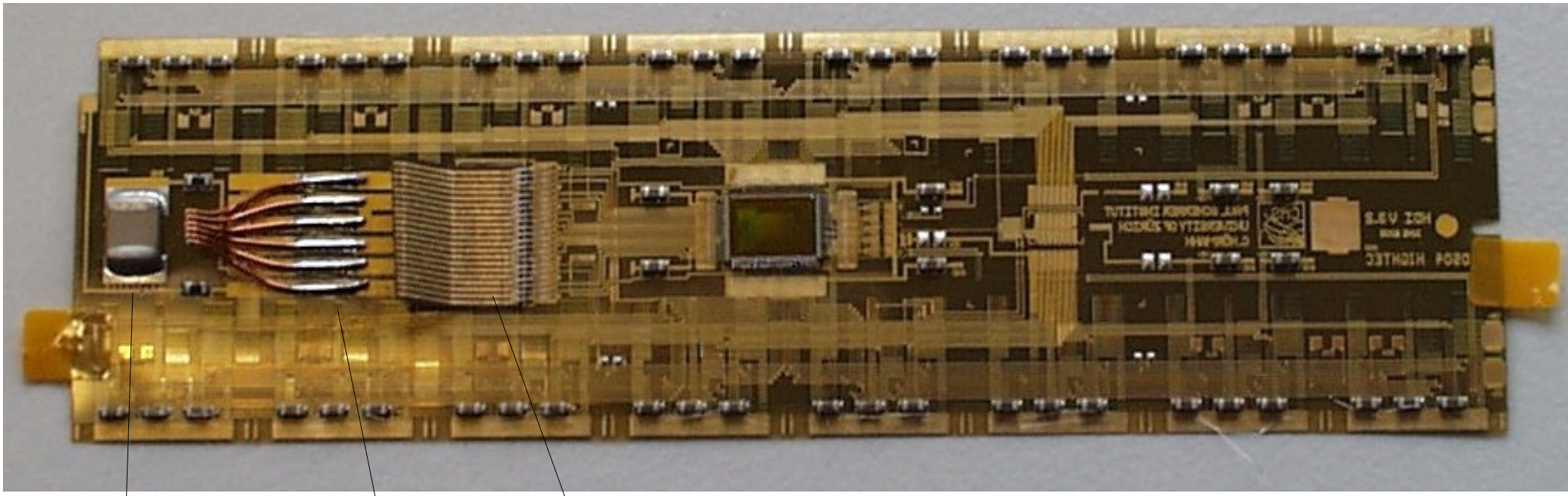
from scattering angle
at 1.2 GeV



phase 0 module X0 map



phase 0 HDI

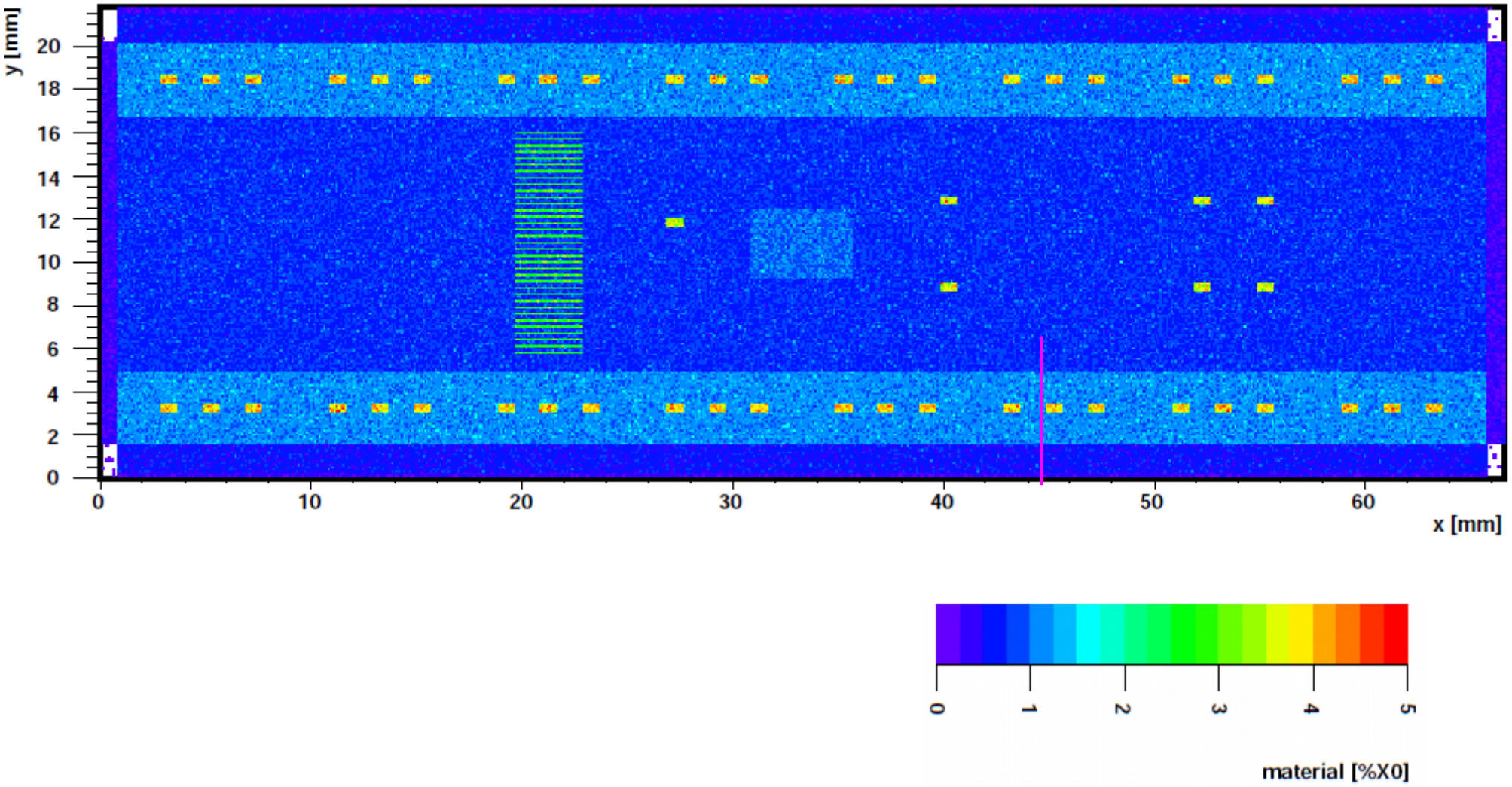


fat HV filter capacitor

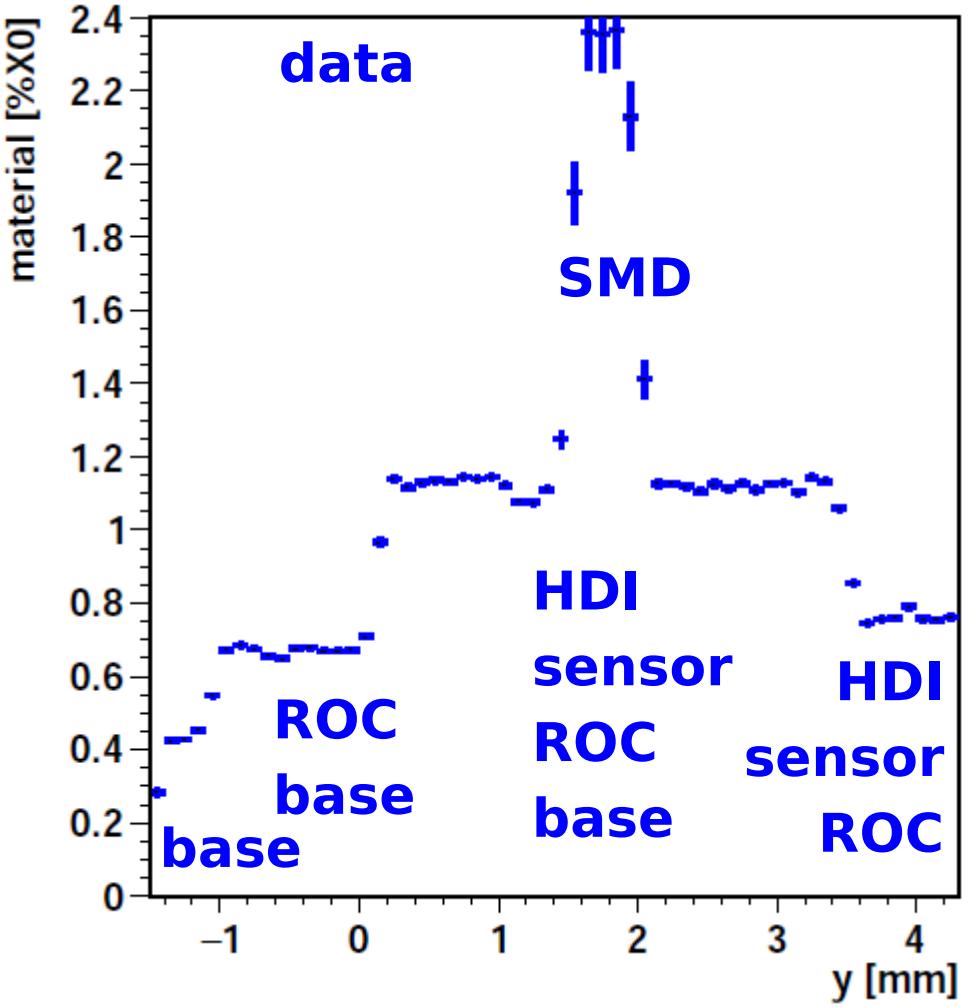
thick wires for power

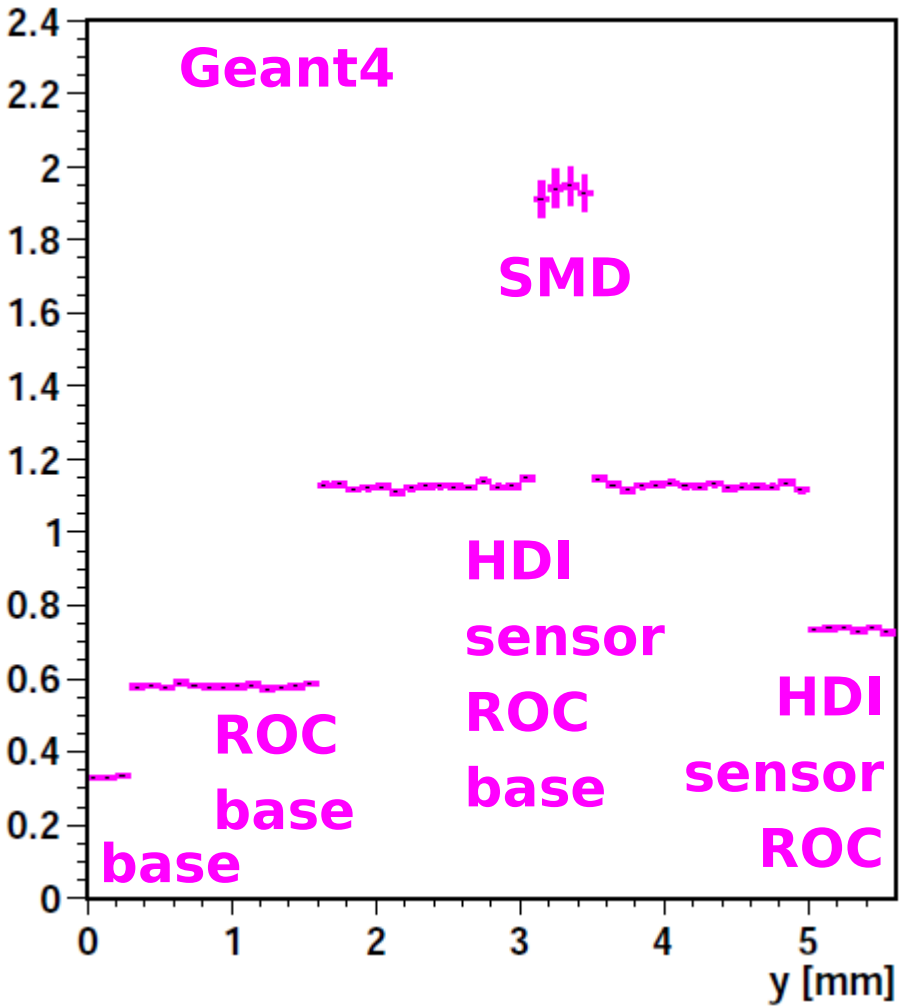
signal cable glued and wire bonded

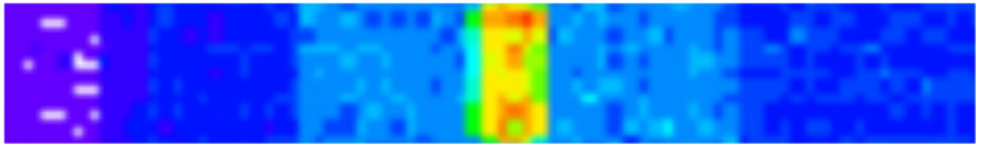
Geant4 simulation material map

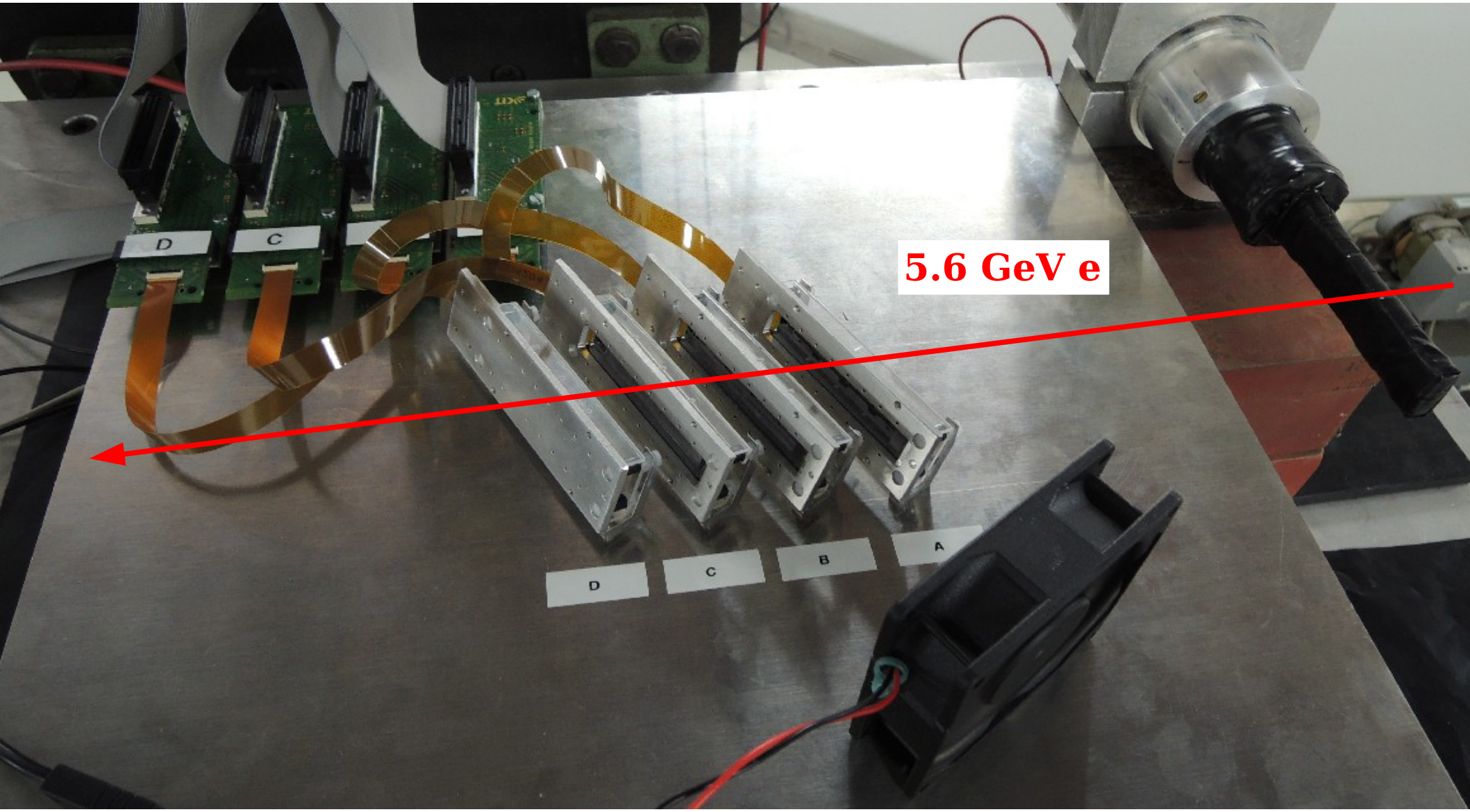


material profile









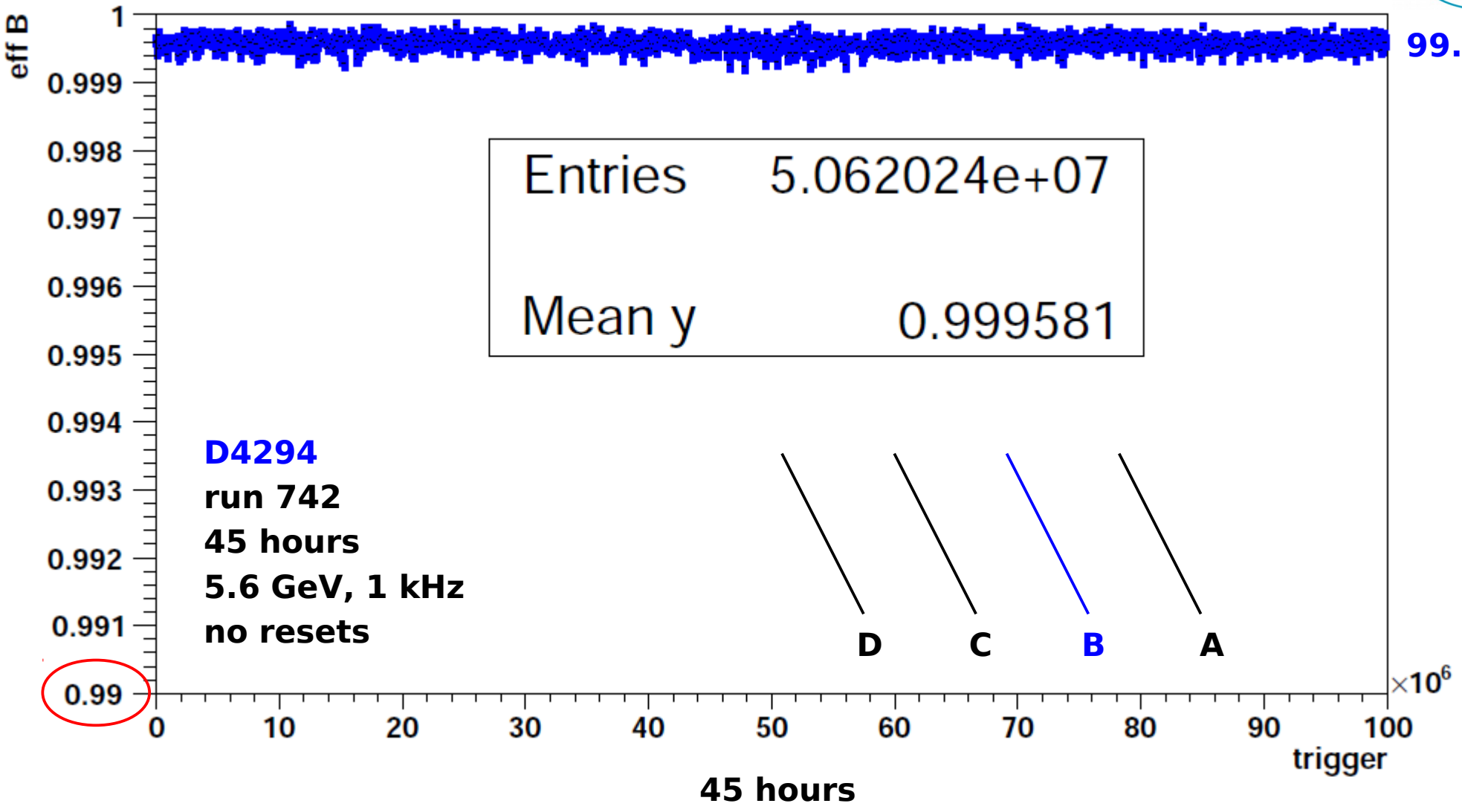
- 90 cm cables
- (4 DTBs to the left)

- 19° row tilt
- 28° column turn
  - η = 0.7
- 32 mm spacing

- air cooling
- (black cover not shown)

- trigger scintillator
  - BToF
  - -1500 V

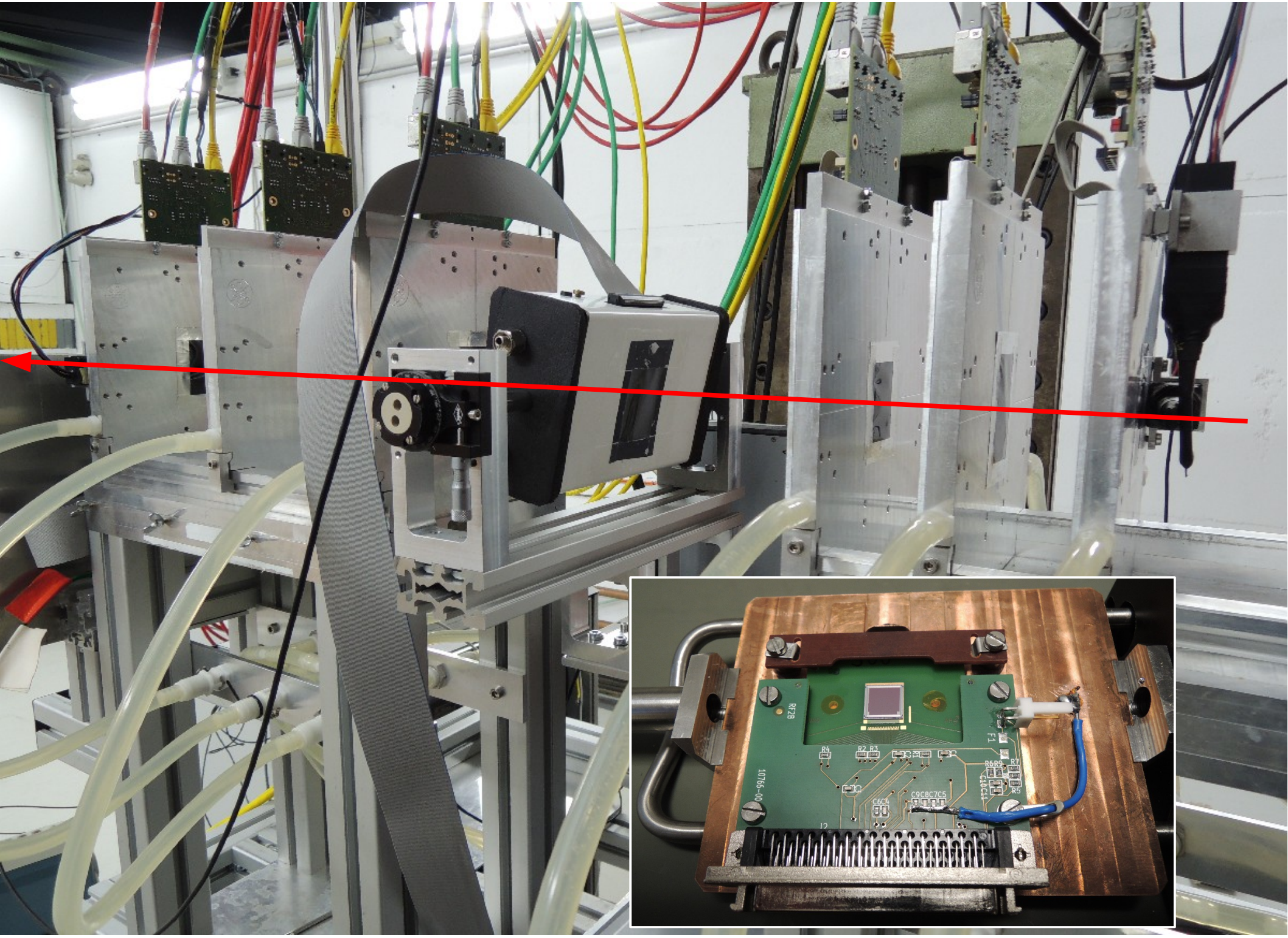
efficiency and stability



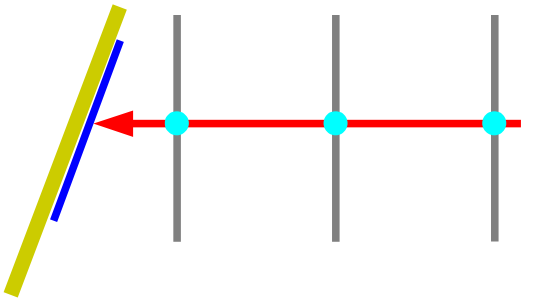
using narrow clock and trigger gate a la Gino Bolla

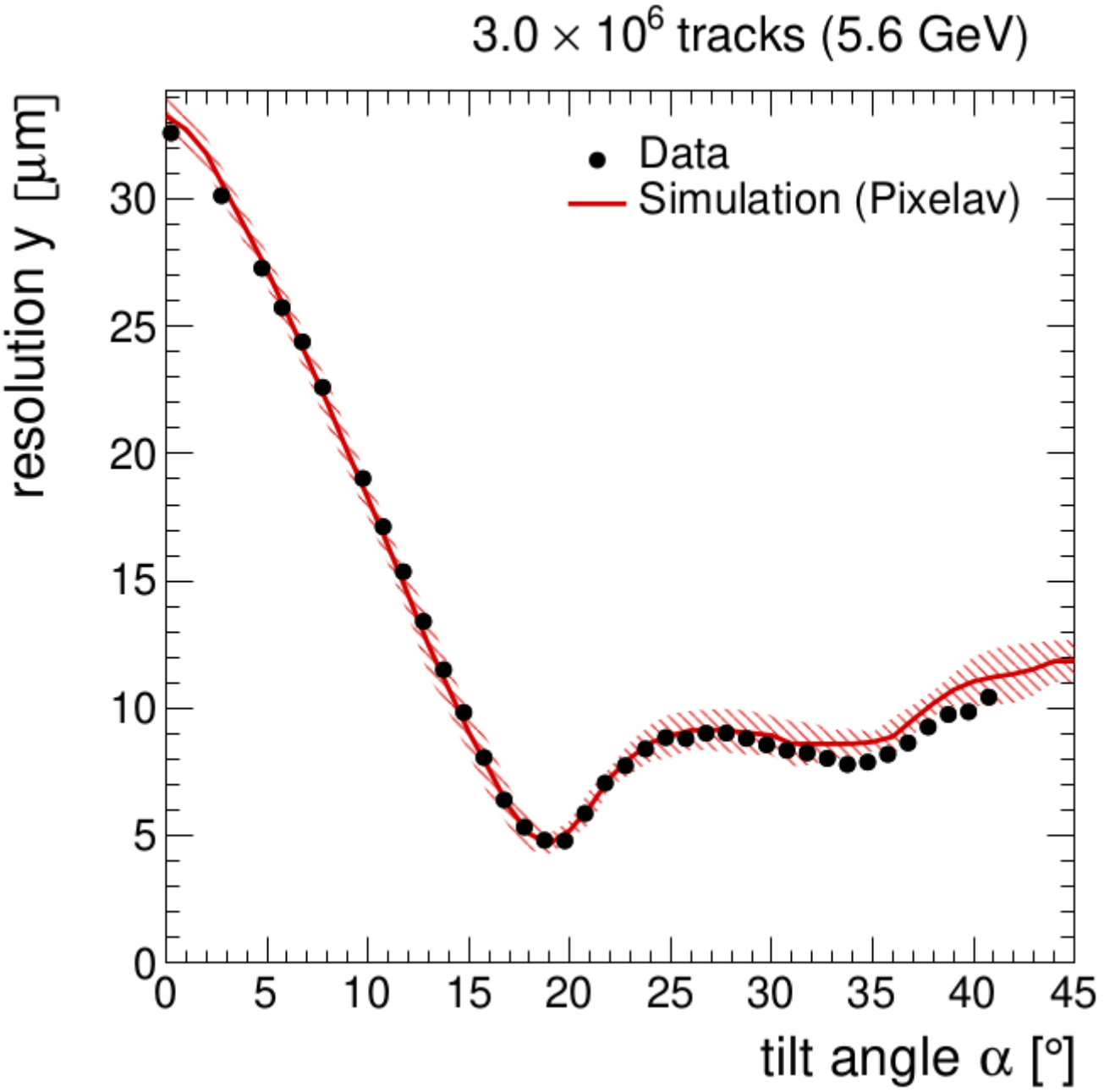
detector figures of merit and what is needed to measure them

- **efficiency:**
  - target 99.9% — precise reference, stable timing
- **resolution:**
  - target 1 µm — precise reference, high momentum
  - incident angle dependency — rotating support
- **charge collection:**
  - after irradiation — cooling to -25°C, dry air
  - Lorentz angle — strong magnetic field
  - in-pixel imaging — high resolution tracking
- **readout chip:**
  - occupancy limit at Gpx/cm^2/s — very high rate


RF2B
10766-00
F1
R4
R2 R3
R6R9
R7
R5
C6C4
C9C8C7C5

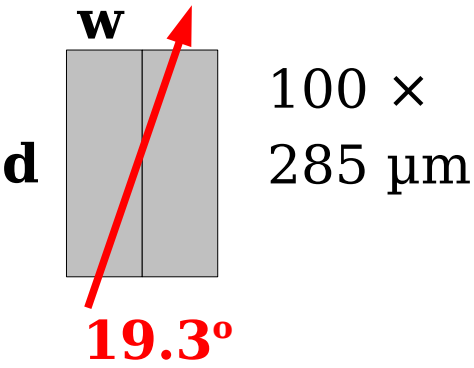
resolution vs tilt angle





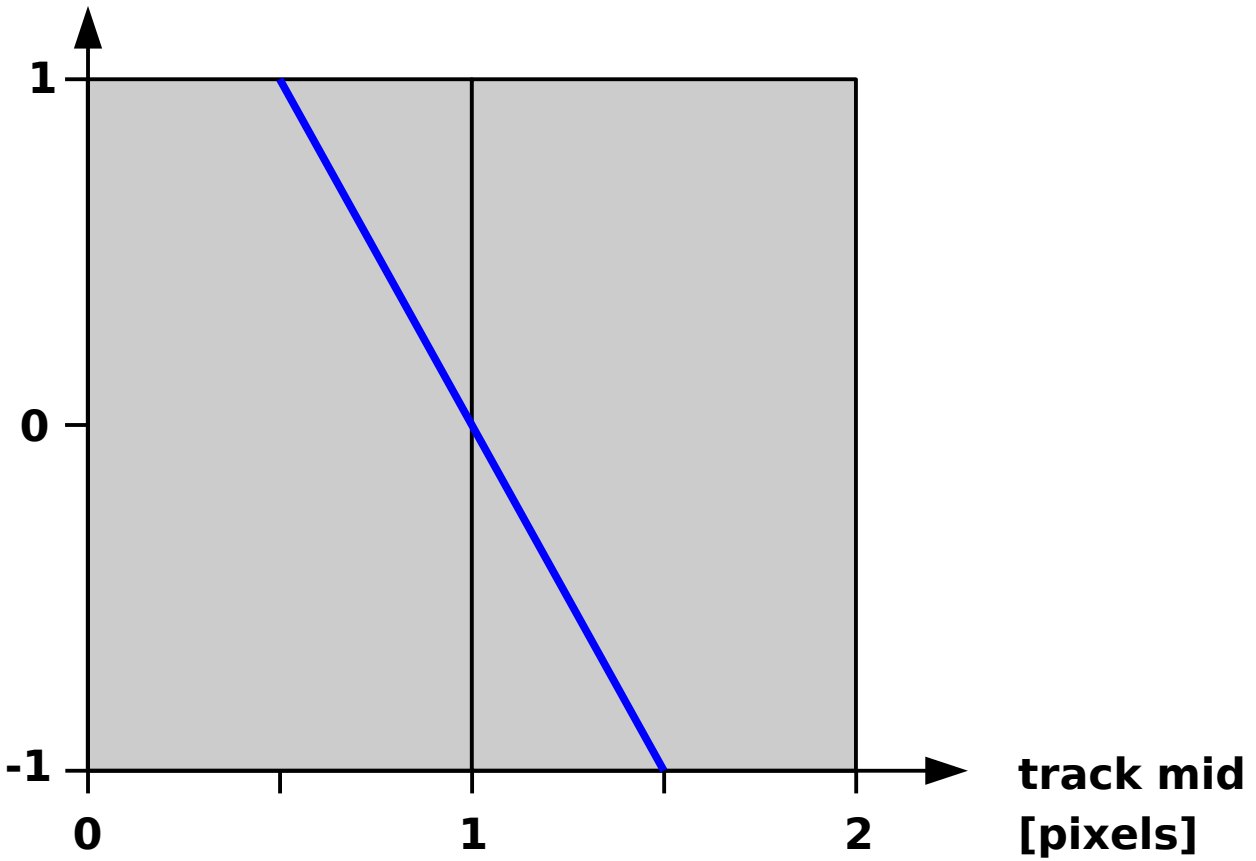
- **100 µm pixels**
  - thickness 285 µm
  - threshold 1.5 ke
- minimum:
  - **4.8 µm at 19.5°**
  - (at the Landau peak)

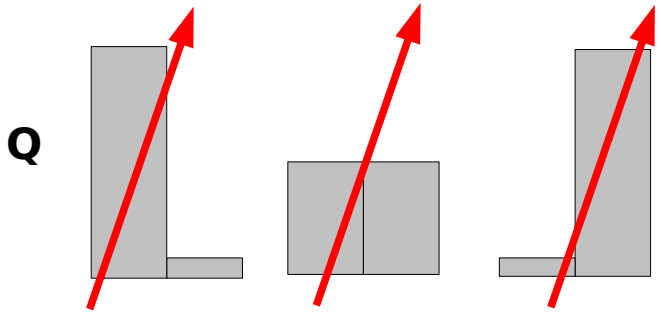
best tilt = atan(w/d)



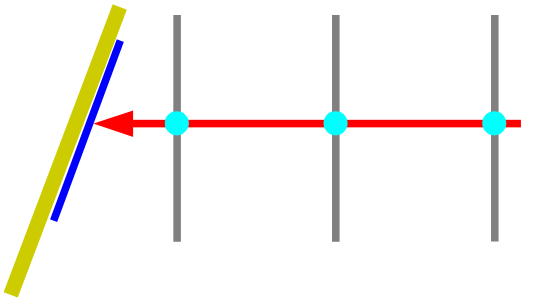
ideal charge sharing vs track position

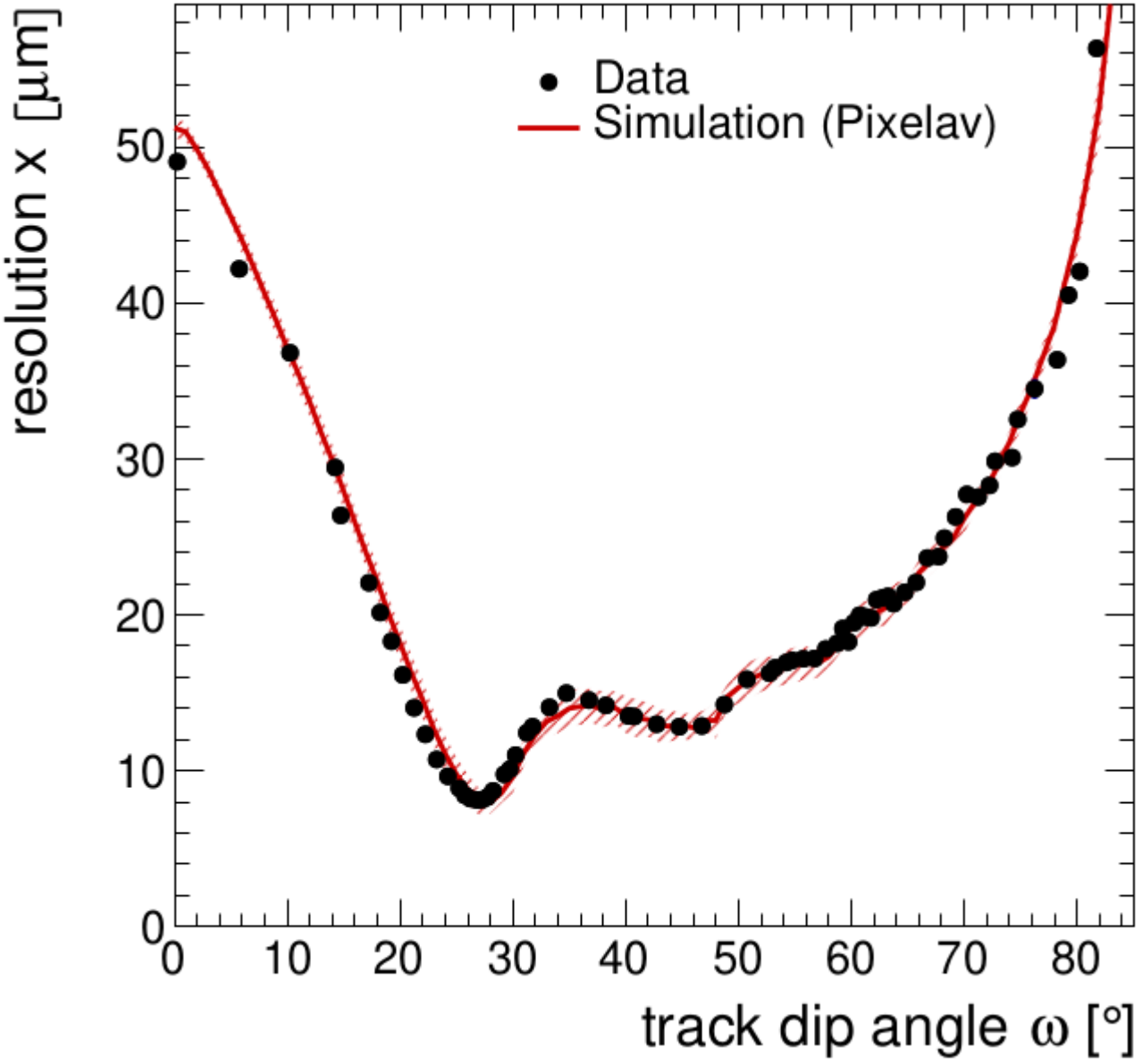
$$\eta = \frac{Q_1 - Q_2}{Q_1 + Q_2}$$





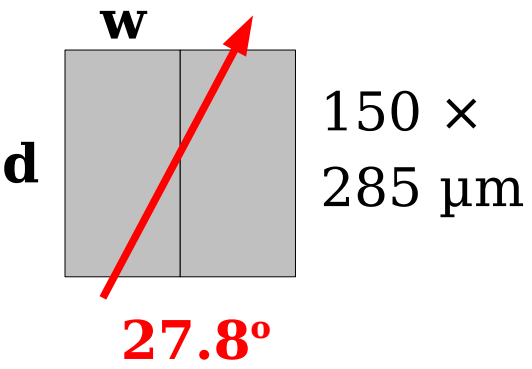
resolution vs incident angle



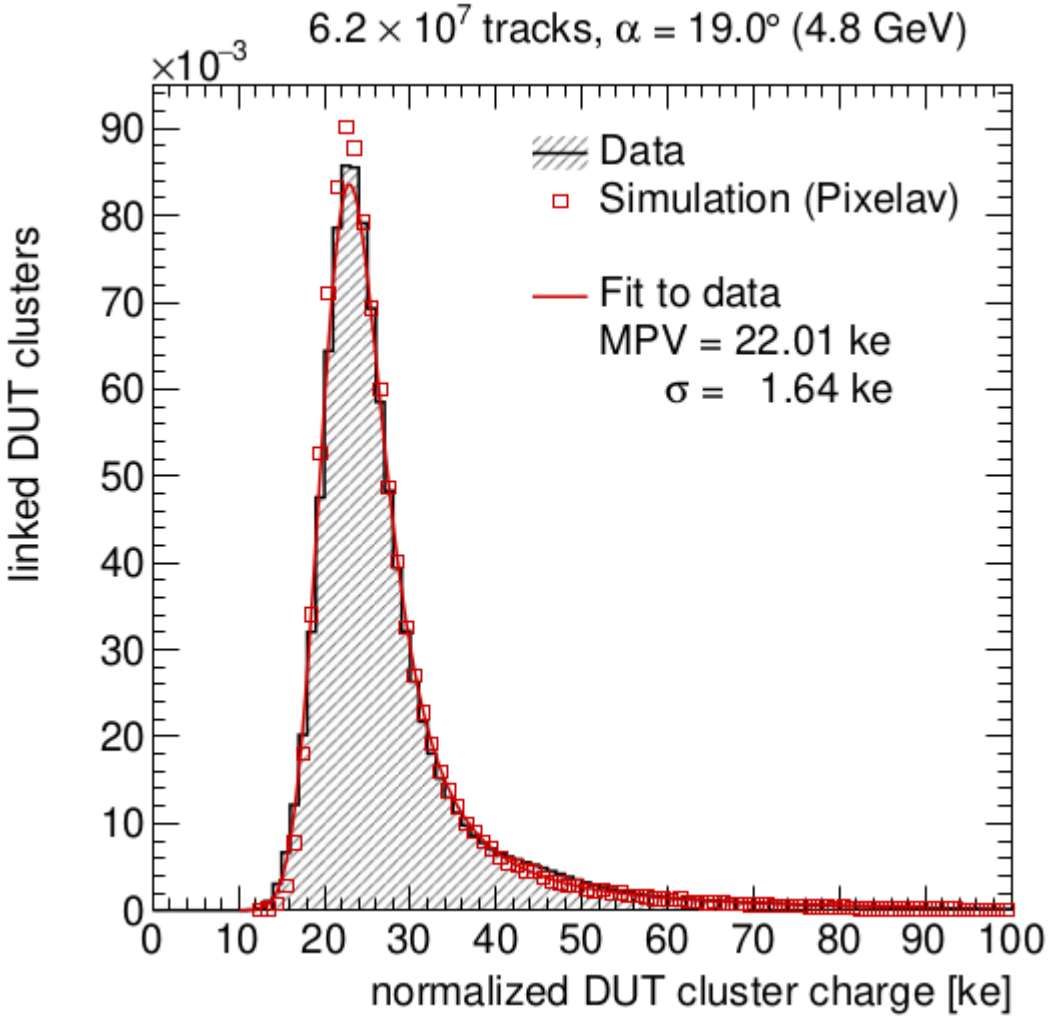


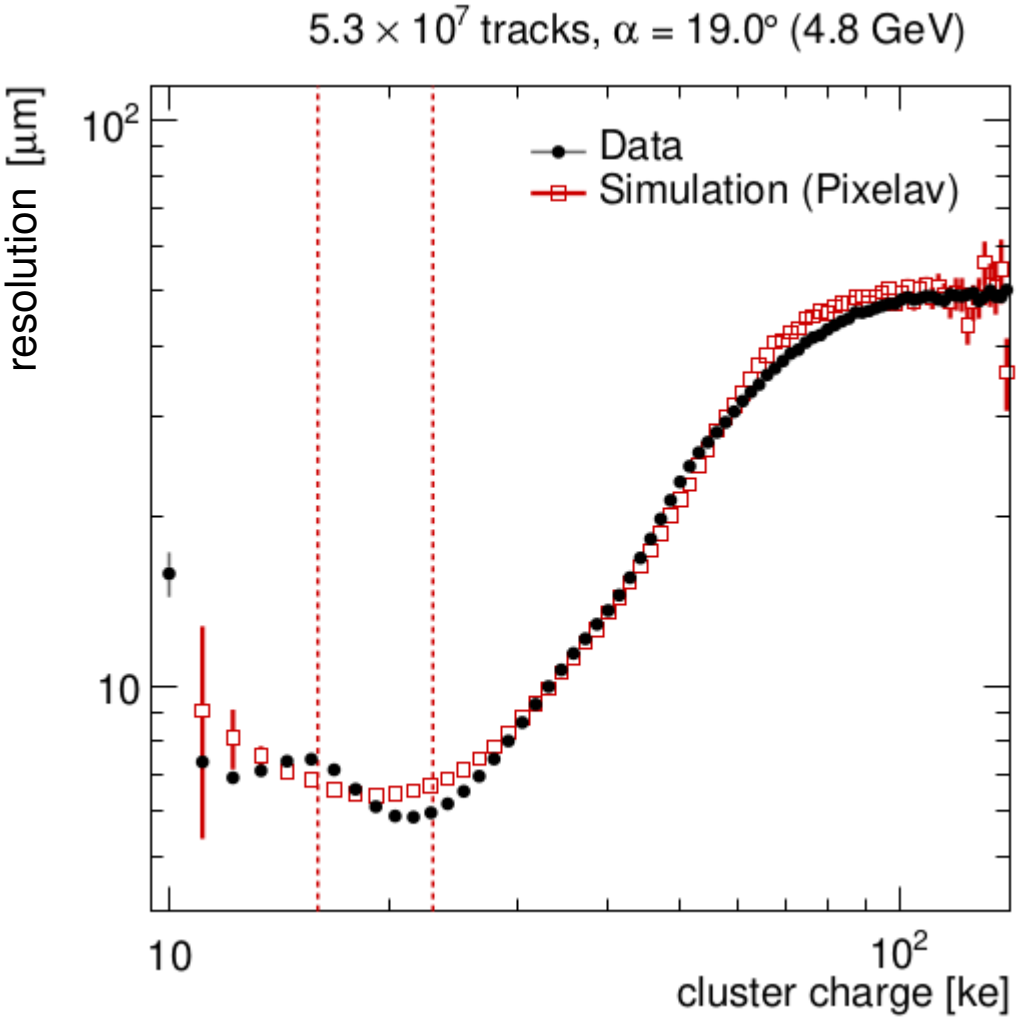
- **150 µm pixels**
  - thickness 285 µm
  - threshold 1.5 ke
- minimum:
  - **8.0 µm at 27.8°**
  - (at the Landau peak)

best dip = atan(w/d)



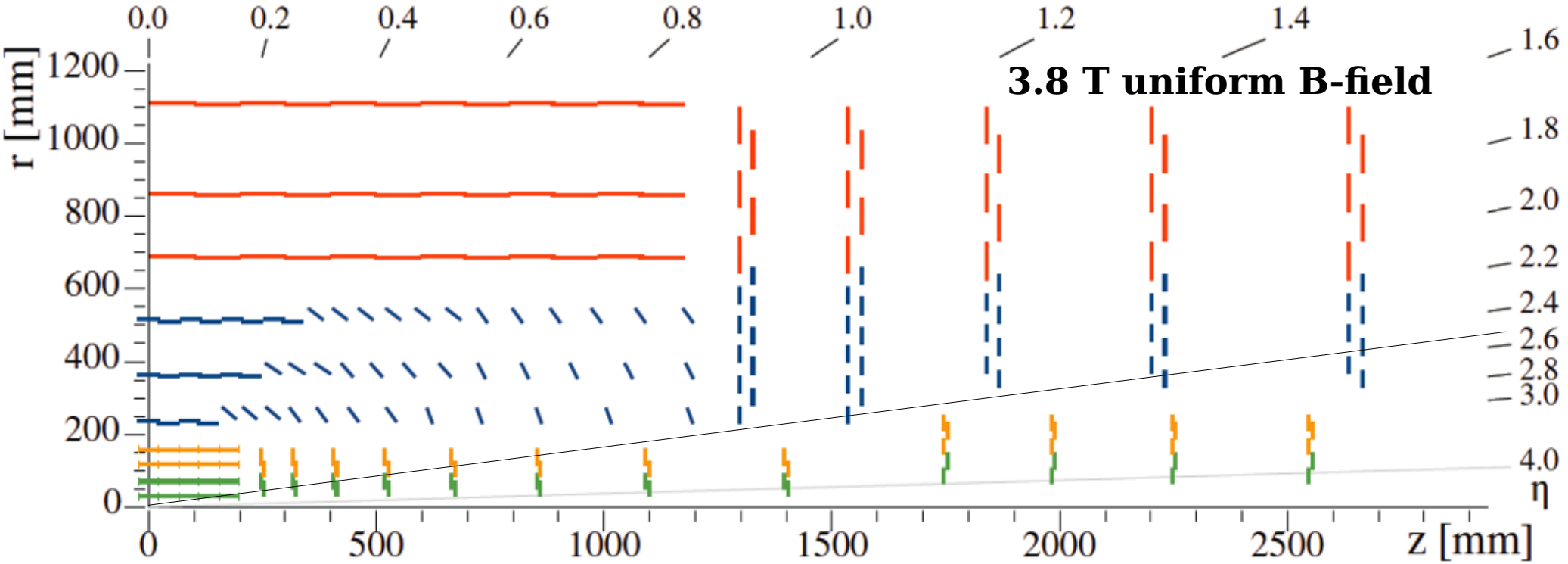
resolution vs energy loss





delta rays in the Landau tail spoil the resolution

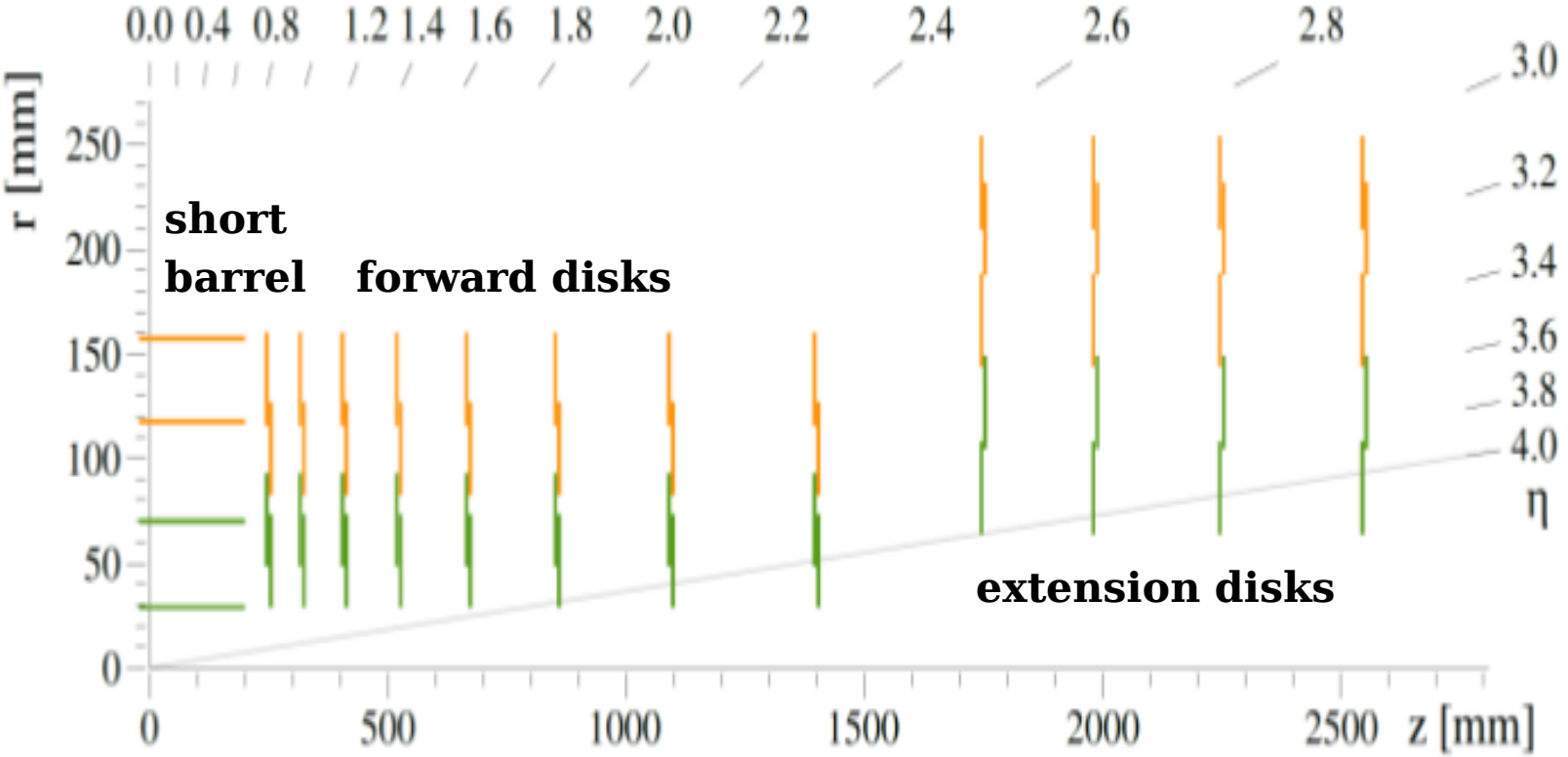
Phase II tracker design

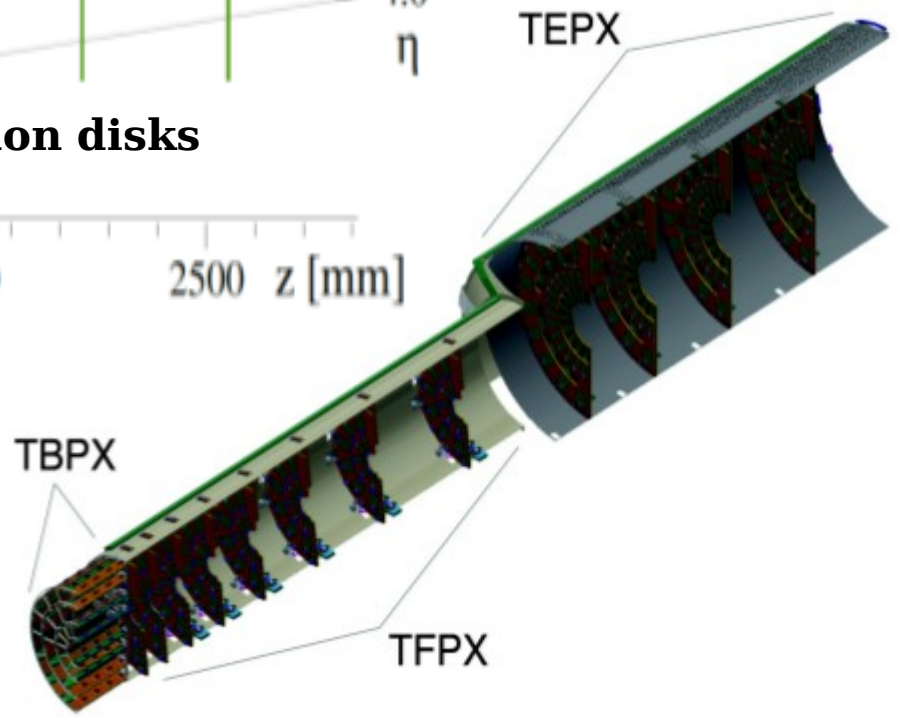


pixel stand-alone tracking
from 2.5 to 4 in pseudo-rapidity

CMS phase II pixel upgrade

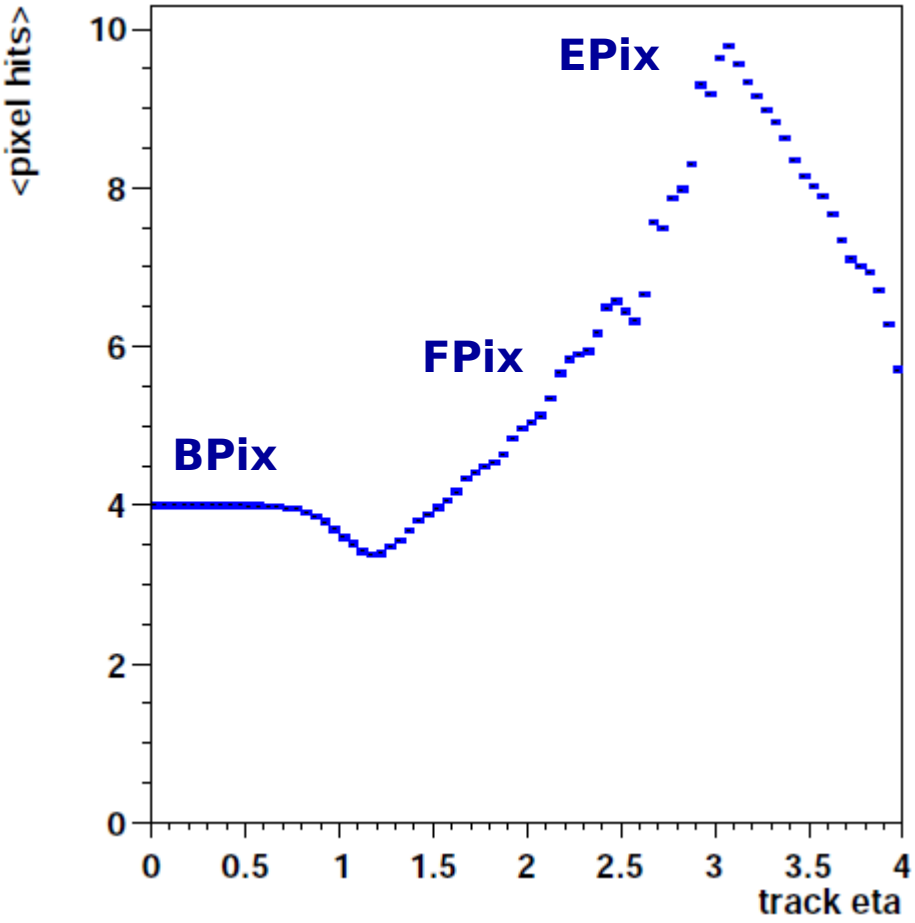
5 m^2 of pixel detectors by 2024: 2 G pixels



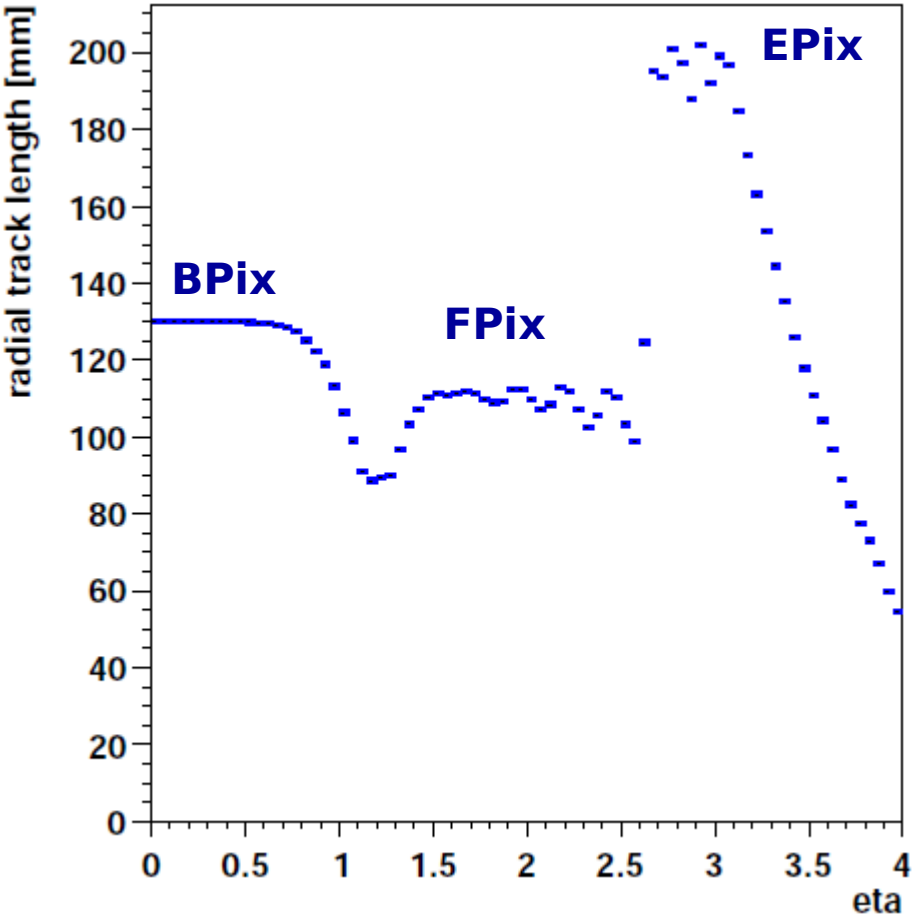


Phase II pixel tracks

pixel hits / track



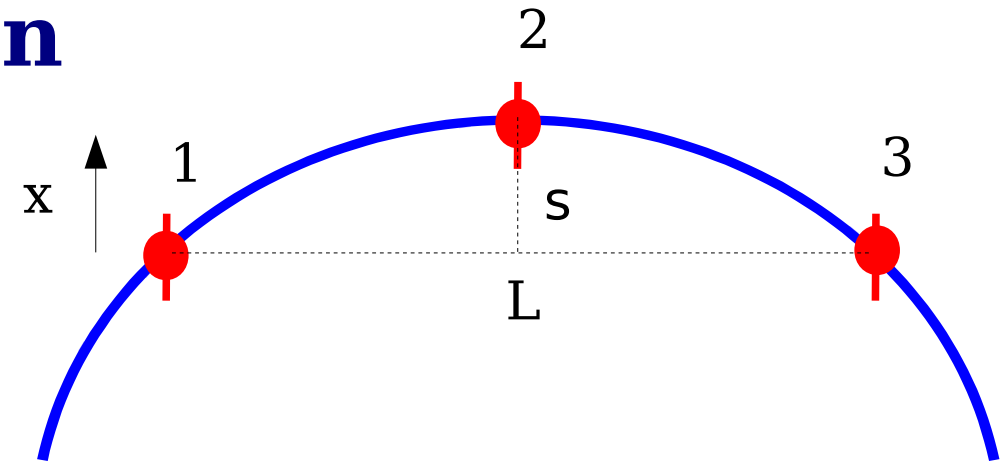
radial pixel track length



40 mm z-vertex smearing

without beam-spot constraint

Momentum resolution



Sagitta: $s = x_2 - \frac{x_1 + x_3}{2}$

Error propagation: $\sigma_s^2 = \sigma_2^2 + \sigma_1^2/4 + \sigma_3^2/4$ (usually Gaussian)

All σ equal: $\sigma_s = \sqrt{3/2}\,\sigma_x$, momentum: $p_t = qBL^2/8s$

$\Rightarrow \quad \sigma_{p_t}/p_t = \sigma_s/s = \sqrt{96}\,\sigma_x\, p_t/qBL^2$ (always non-Gaussian)

N equidistant measurements: $\boxed{\sigma_{p_t}/p_t = \sqrt{720/(N+4)}\,\sigma_x\, p_t/qBL^2}$

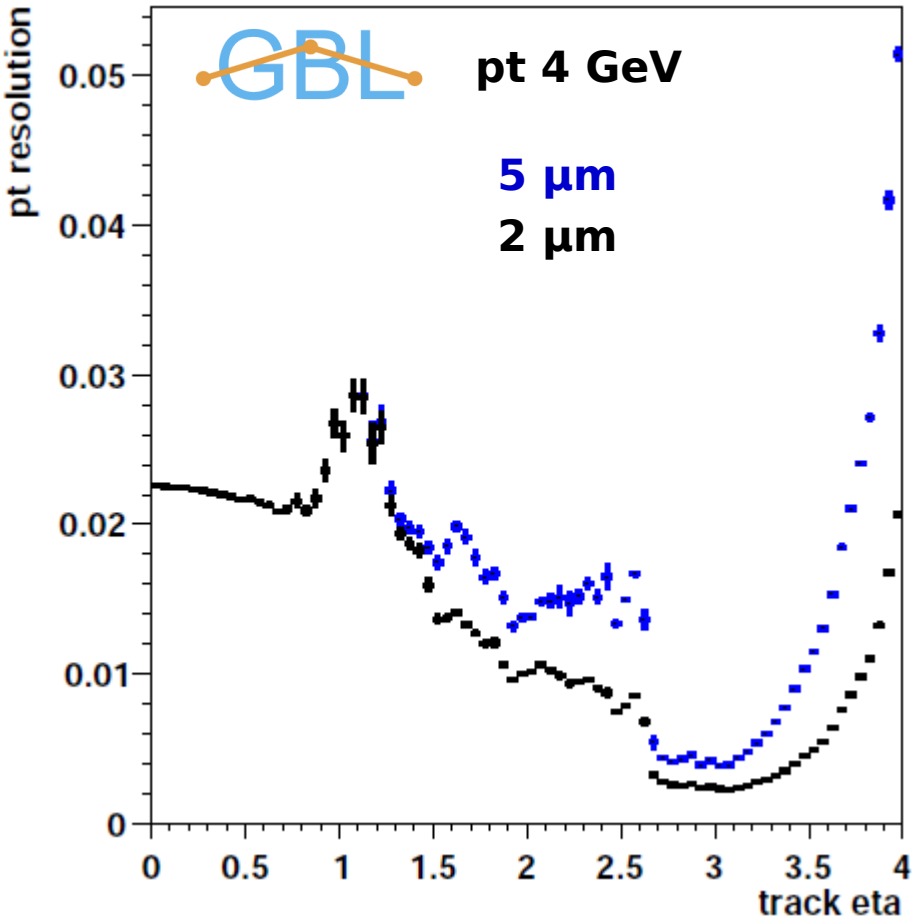
(Glückstern 1964)

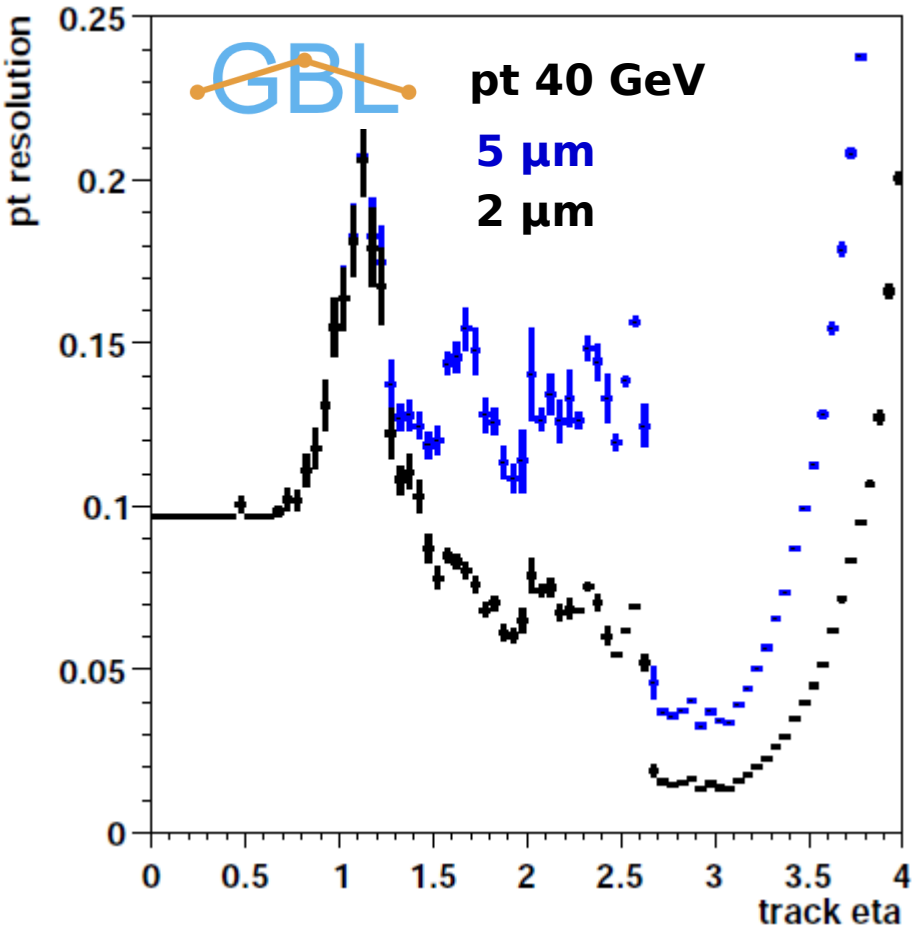
Note: $\sigma_{p_t}/p_t \sim p_t$ (worse resolution at high p_t)

$\sigma_{p_t}/p_t \sim \sigma_x/BL^2$ (want large, precise tracker, strong field)

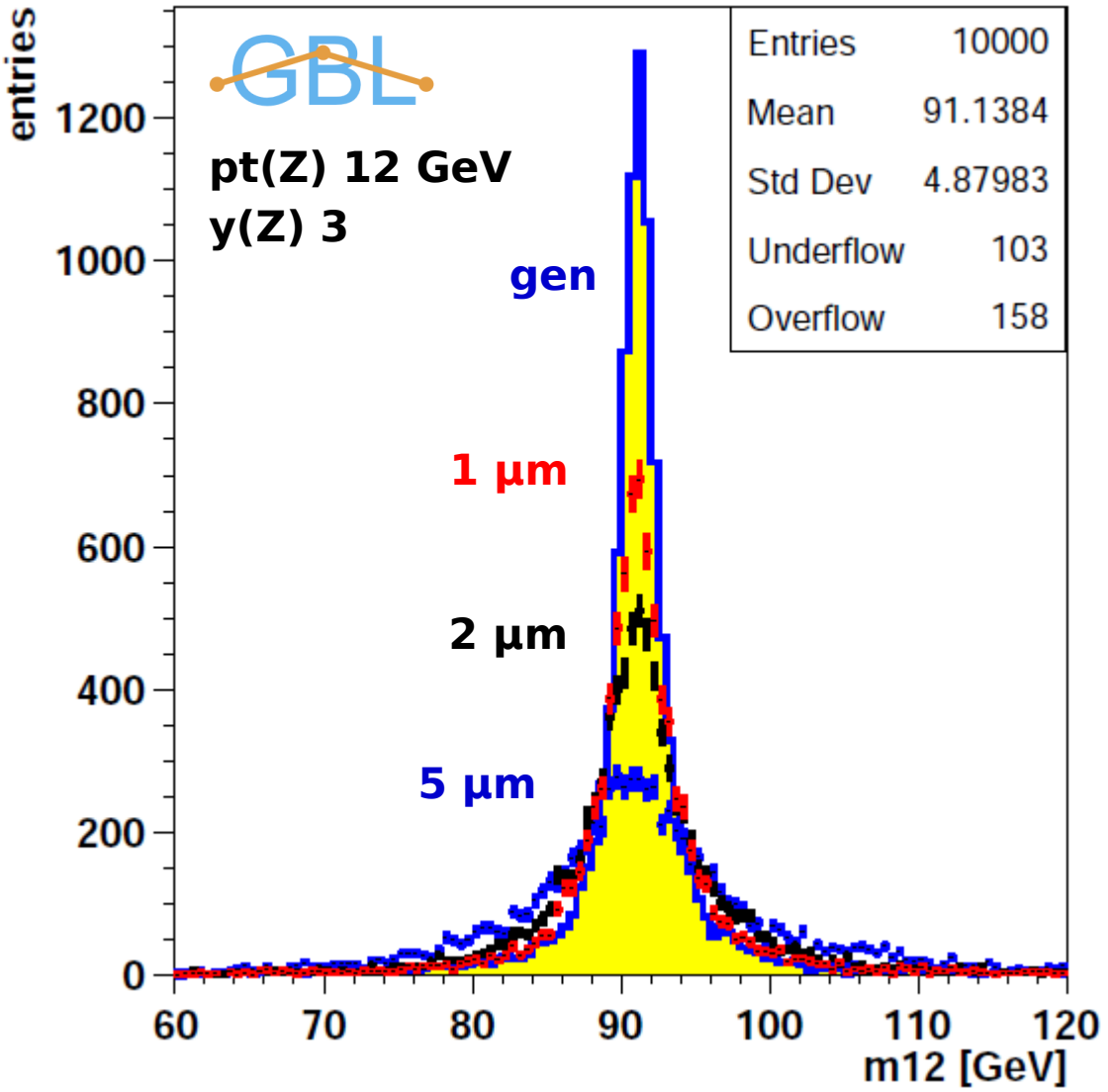
Phase II pixel momentum resolution

pixel stand-alone tracking, relative momentum resolution
General Broken Lines fit with multiple scattering
FPix/EPix hit resolution 5 µm or 2 µm (BPix fix at 5 µm)





Phase II pixel mass resolution



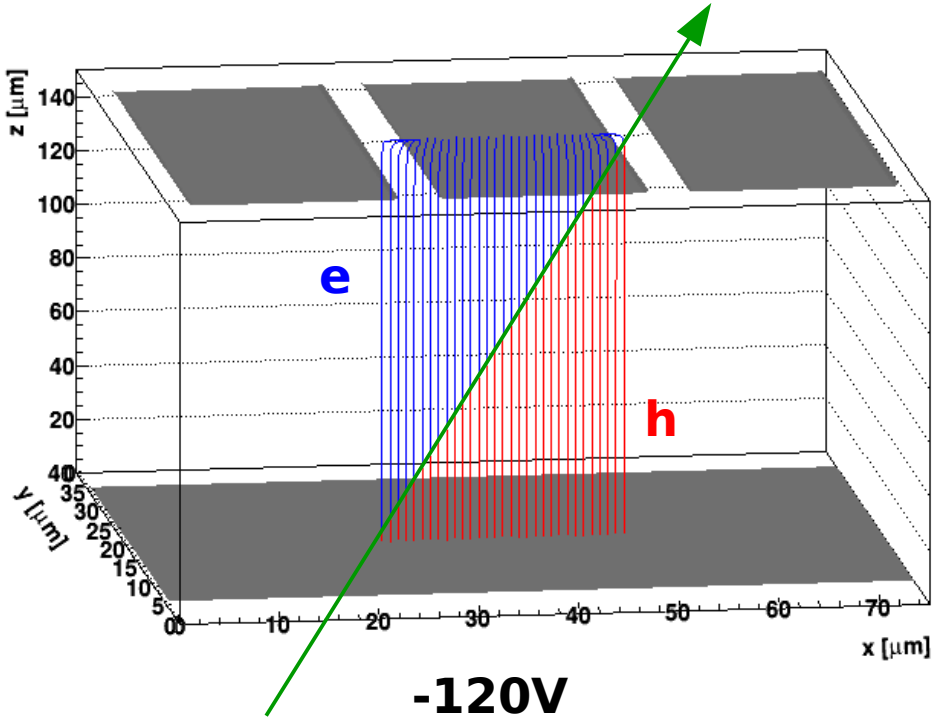
- $Z \rightarrow \mu\,\mu$ simulation:
  - fixed Z p_t and $y = 3$
  - isotropic decay in the Z rest frame, boost to lab frame
  - follow muons through pixel disks, generate hits with different resolutions
  - GBL track fit
  - mass reconstruction

resolution issues

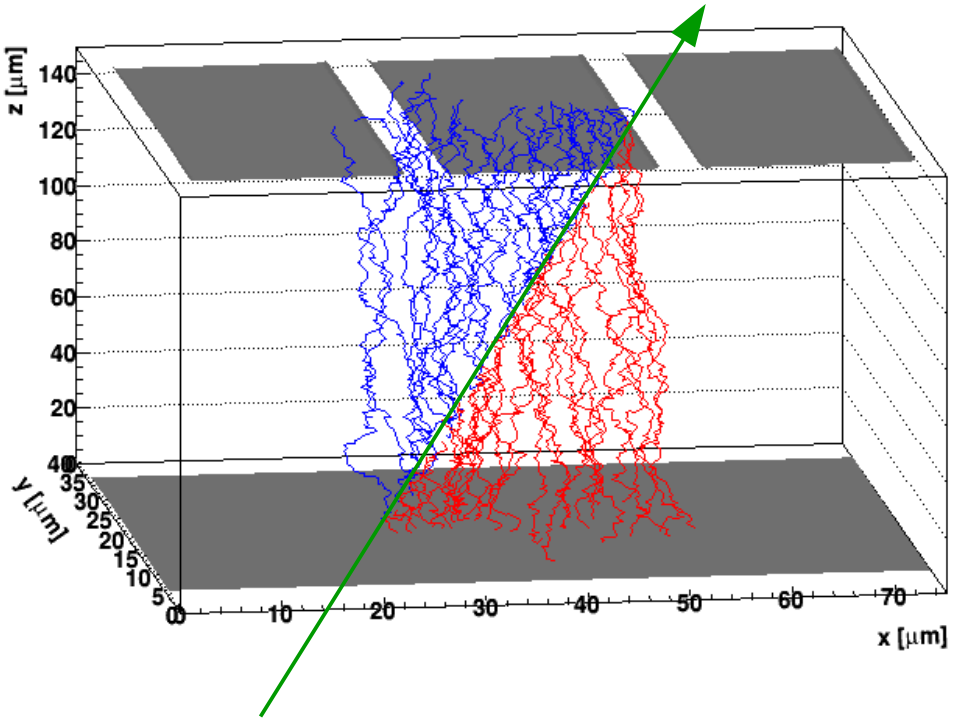
- **friends of resolution**
  - small pixels
  - optimal incidence angle
  - diffusion
  - low threshold
  - uniform ionization
  - smart clustering
  - analog readout
  - 8-bit ADC or ToT
- **enemies of resolution**
  - large pixels
  - vertical incidence
  - cross-talk
  - high threshold
  - ionization fluctuations
  - delta rays
  - binary readout
  - 4-bit ADC or ToT
  - radiation damage
  - electronics noise

drift and diffusion

drift only



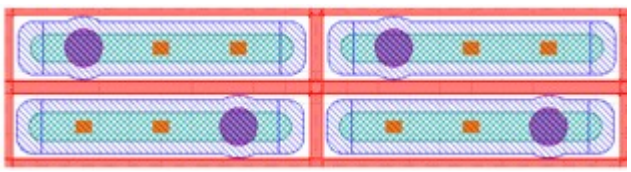
drift and diffusion

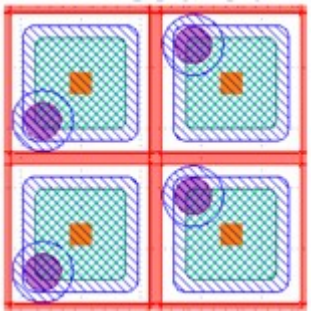


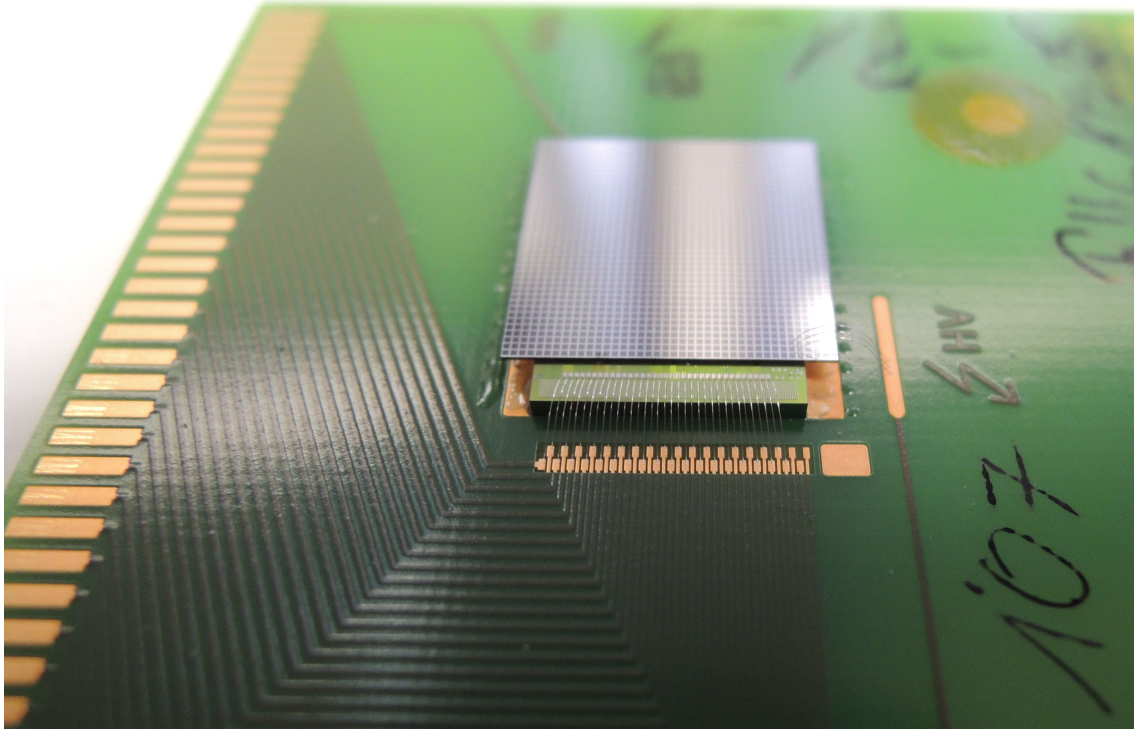
in addition:
ionization fluctuations

using KDetSim by Gregor Kramberger (Ljubljana)

sensor design studies





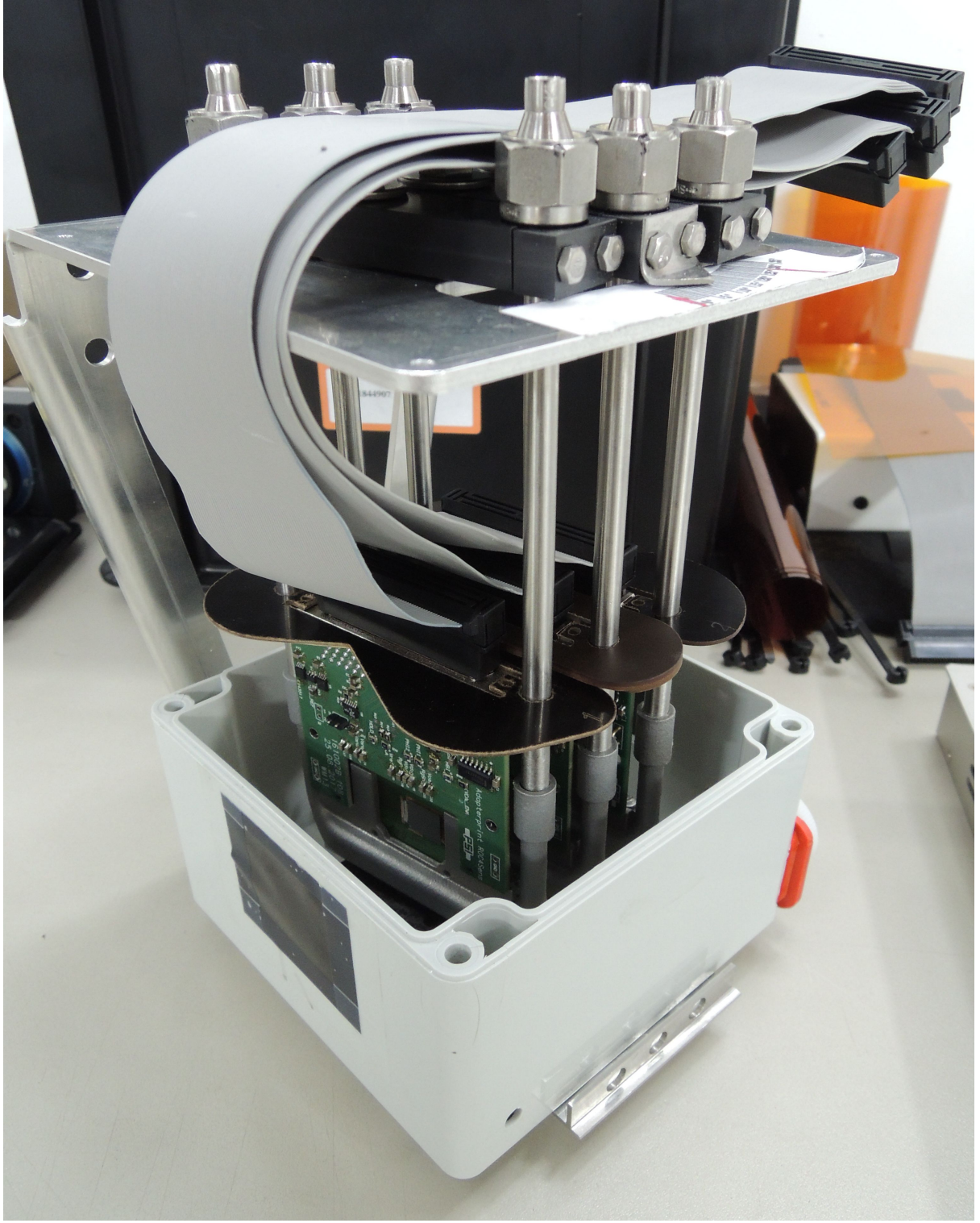


8×8 mm active area

- development of smaller pixels sensors:
  - 150 µm thickness
  - 50×50 and 25×100 µm
  - n-in-p with p-stop or p-spray insulation
  - plain, punch-through, and polysilicon biased
- ROC4Sens readout chip from PSI:
  - 50×50 µm, 24’800 pixels
  - analog readout, no zero suppression

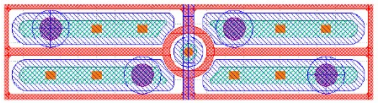
Dreimaster

- Support frame for three single chip modules:
  - 20 mm spacing
  - common turn angle from 0 to 30°
  - without parallax shearing: maintain geometrical overlap
  - with cooling and housing
- Changing sensors takes ~30 min

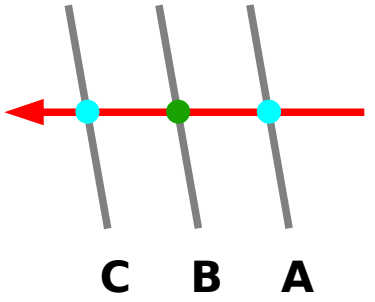


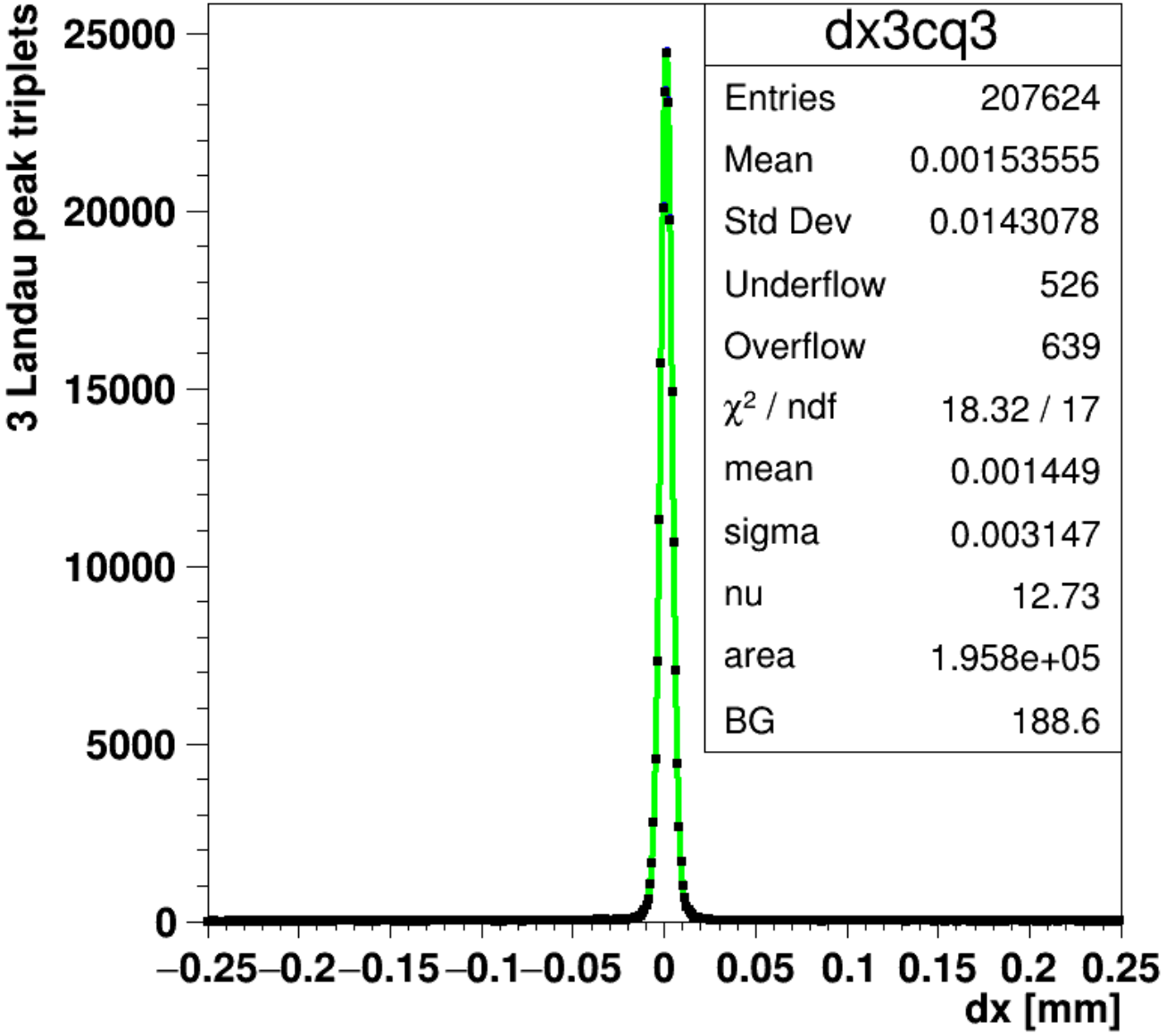
triplet residuals

run 884, chip 148, turn 8°



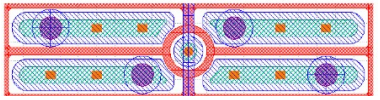
track

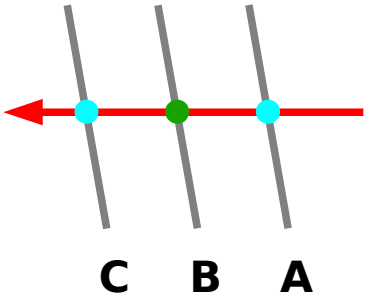




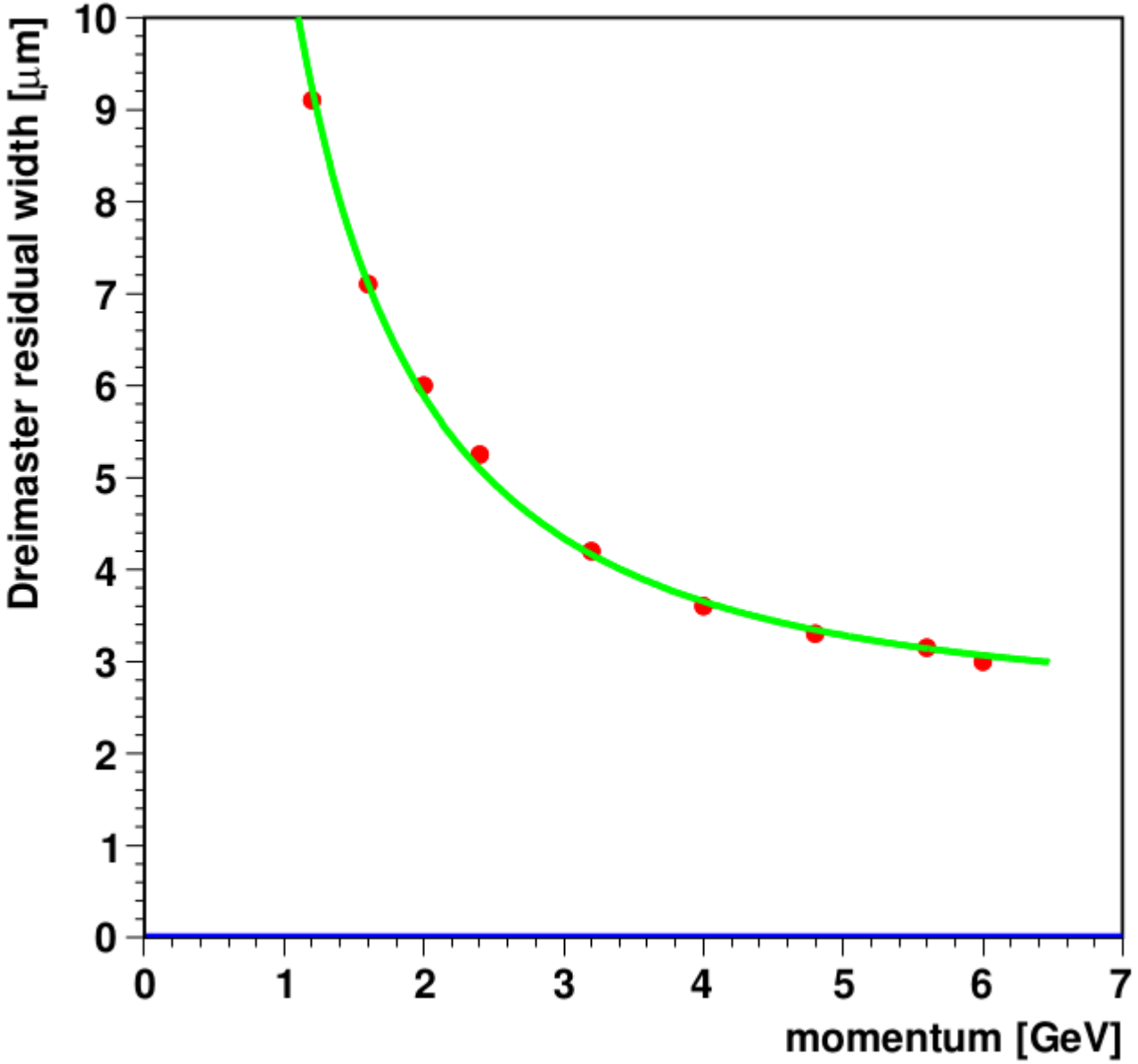
- sensor 150 µm thick
- turn 8°
- Landau peak clusters
- 5.6 GeV
- Triplet residuals:
  - $\Delta x = x_B - \frac{x_A + x_C}{2}$
  - **fit: 3.15 µm**
  - **unfolding tracking and scattering: 2.0 µm hit resolution**

momentum scan



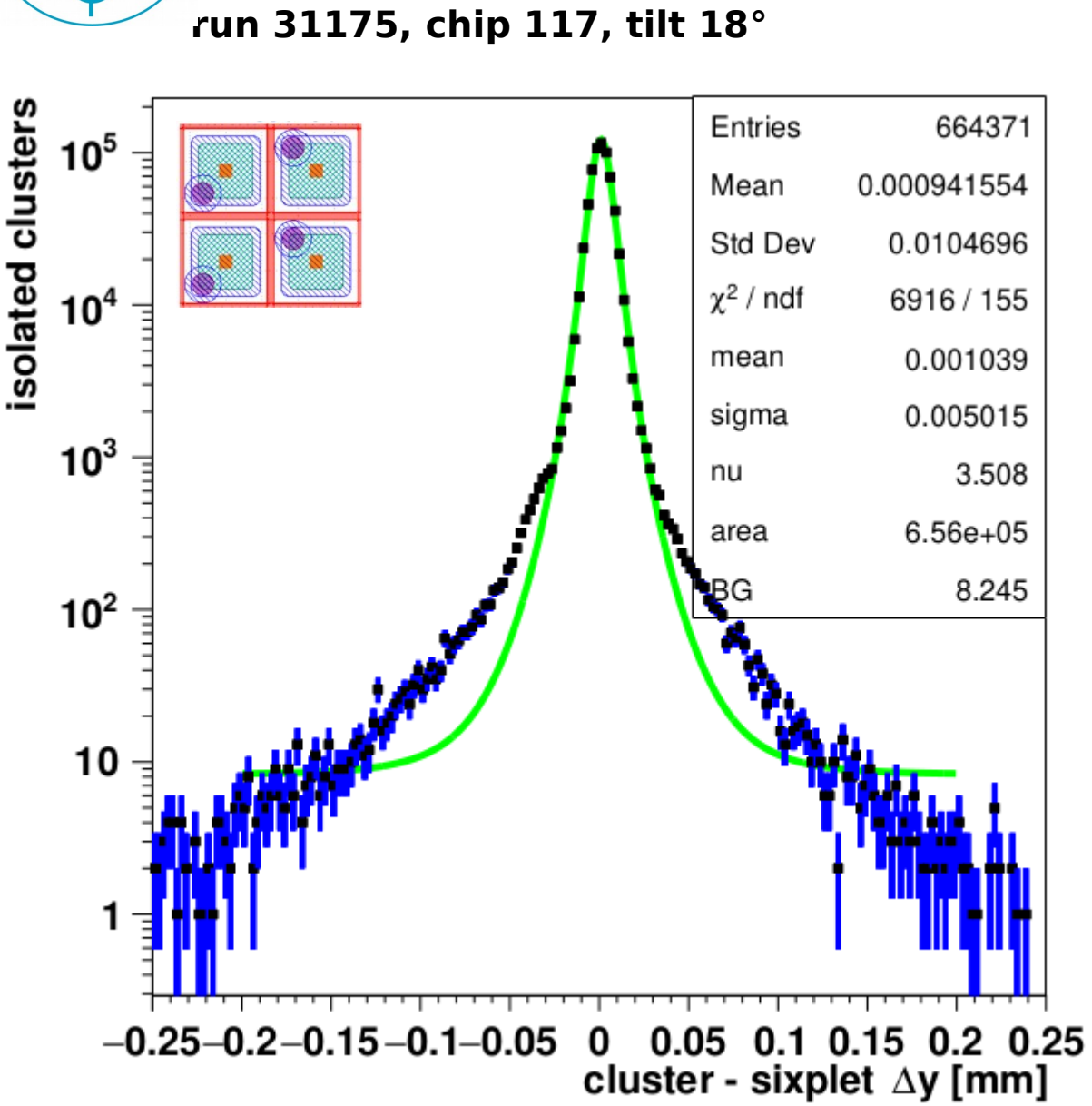


runs 876-885, chip 148, turn 8°



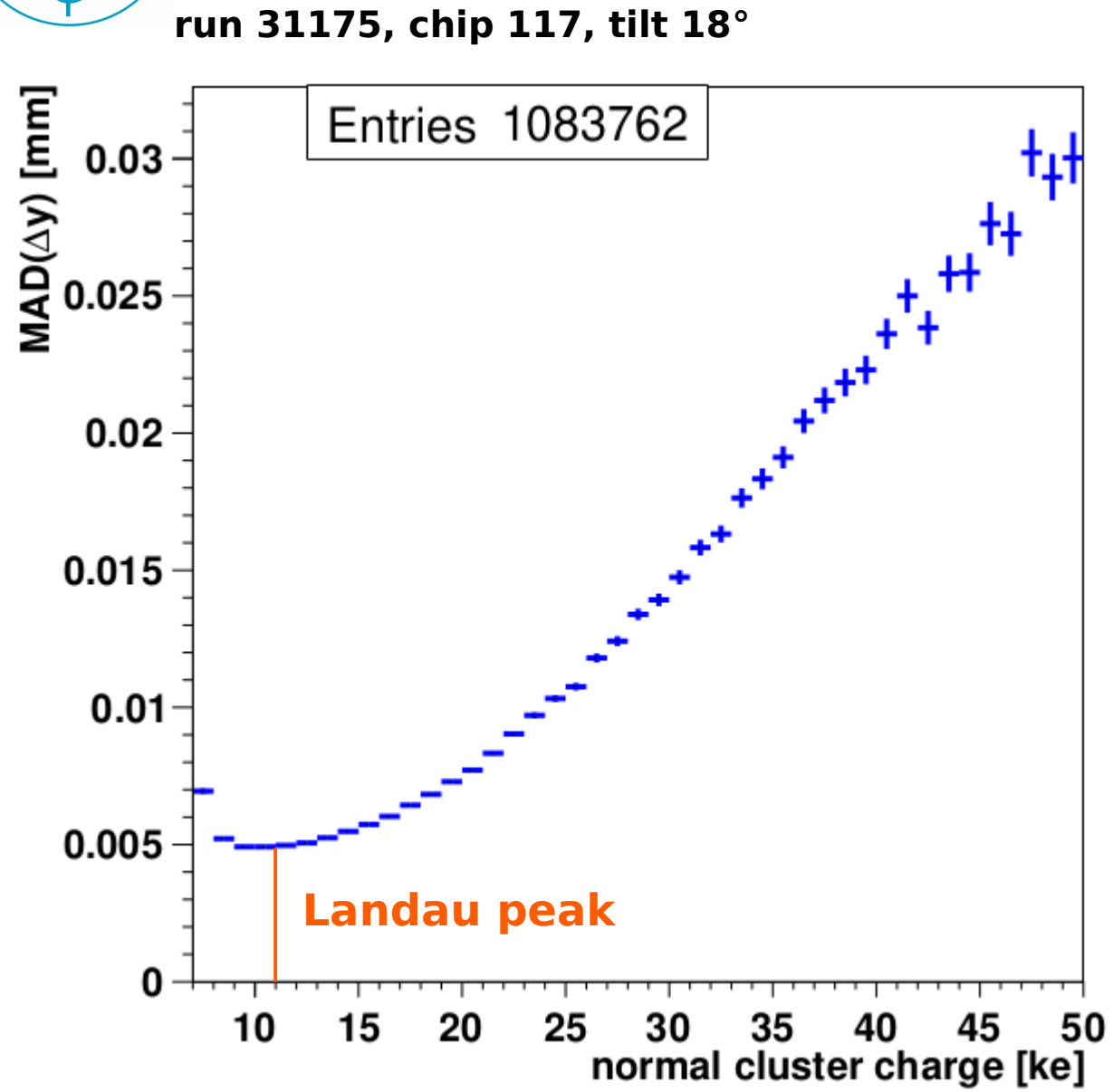
- unfold resolution and multiple scattering:
  - momentum scan
- **fit:**
  - **residual^2 = (scattering / p)^2 + resolution^2**
  - **triplet resolution: 2.5 µm**
  - **single hit resolution: 2.0 µm**

residual tails



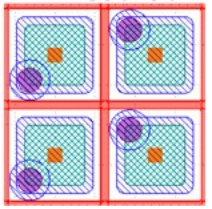
- chip 117:
  - 50×50 µm pixels
  - tilt 18°, 5.6 GeV
  - bias 120 V
  - dph > 12 ADC
  - isolated clusters
- wide tails:
  - 2% outside ±5 σ

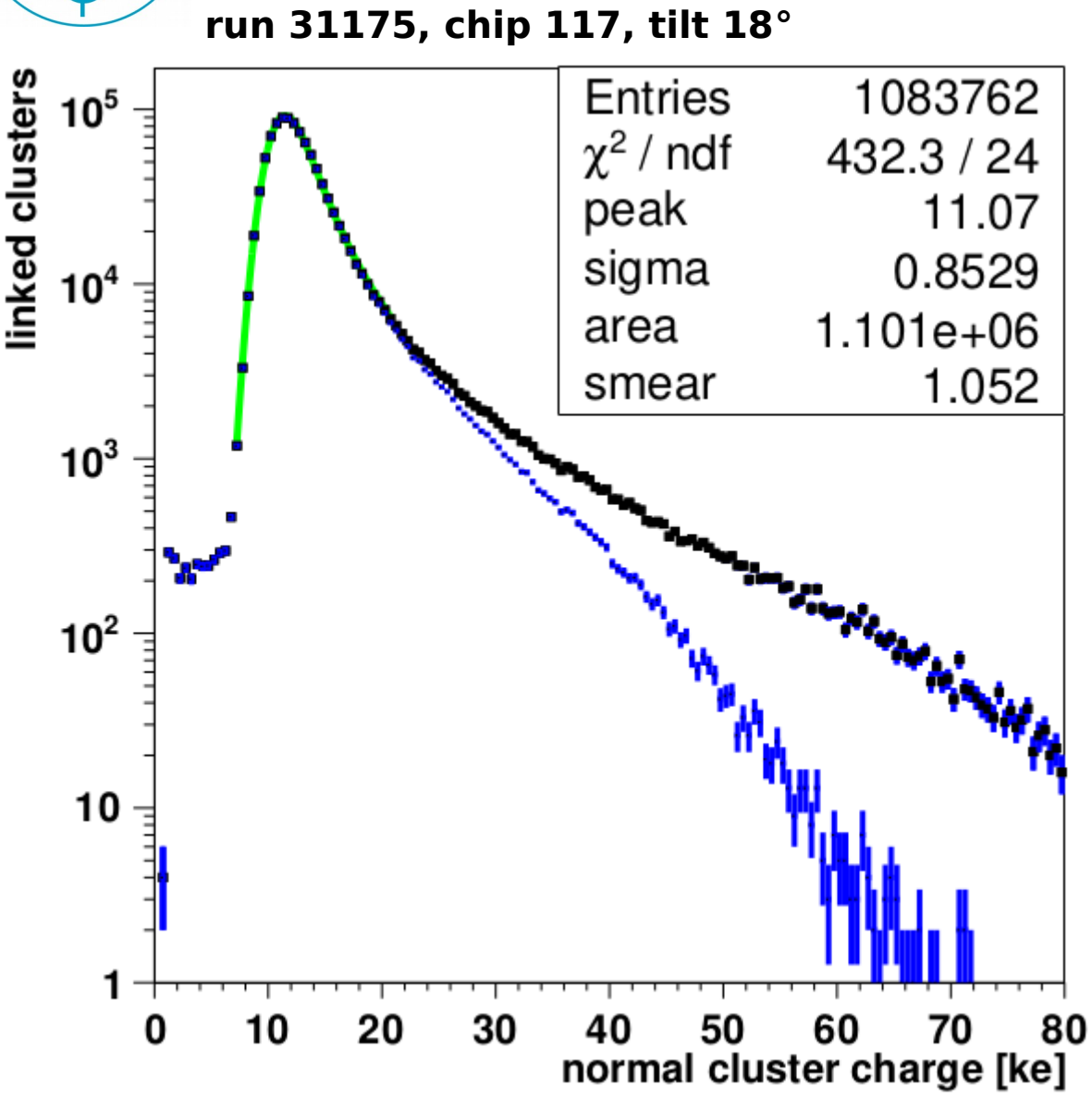
resolution vs cluster charge



- chip 117:
  - 50×50 µm pixels
  - tilt 18°, 5.6 GeV
  - isolated clusters
- MAD:
  - mean absolute deviation
  - MAD = RMS/sqrt(pi/2)
- delta rays:
  - large charge
  - shifted cluster
  - poor resolution

Landau tail



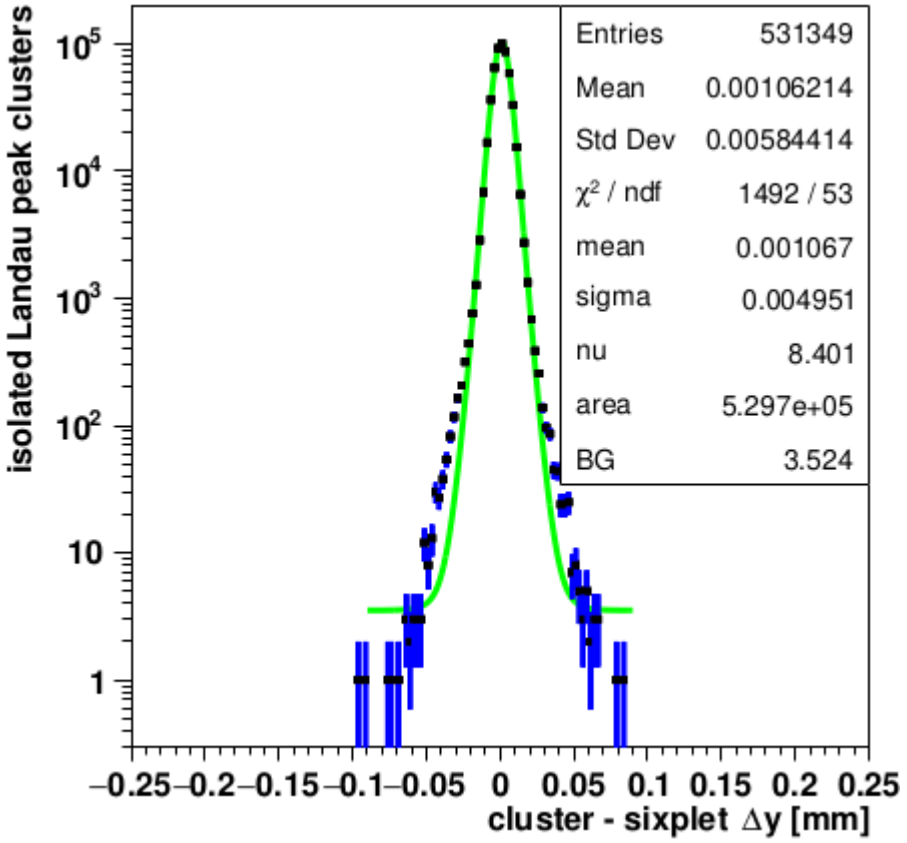


- chip 117:
  - 50×50 µm pixels
  - tilt 18°, 5.6 GeV
  - bias 120 V
  - isolated clusters
- cluster size ≤ 2 columns and rows:
  - suppresses high charge tail
  - keeps 97%

suppressing delta rays

by cluster charge

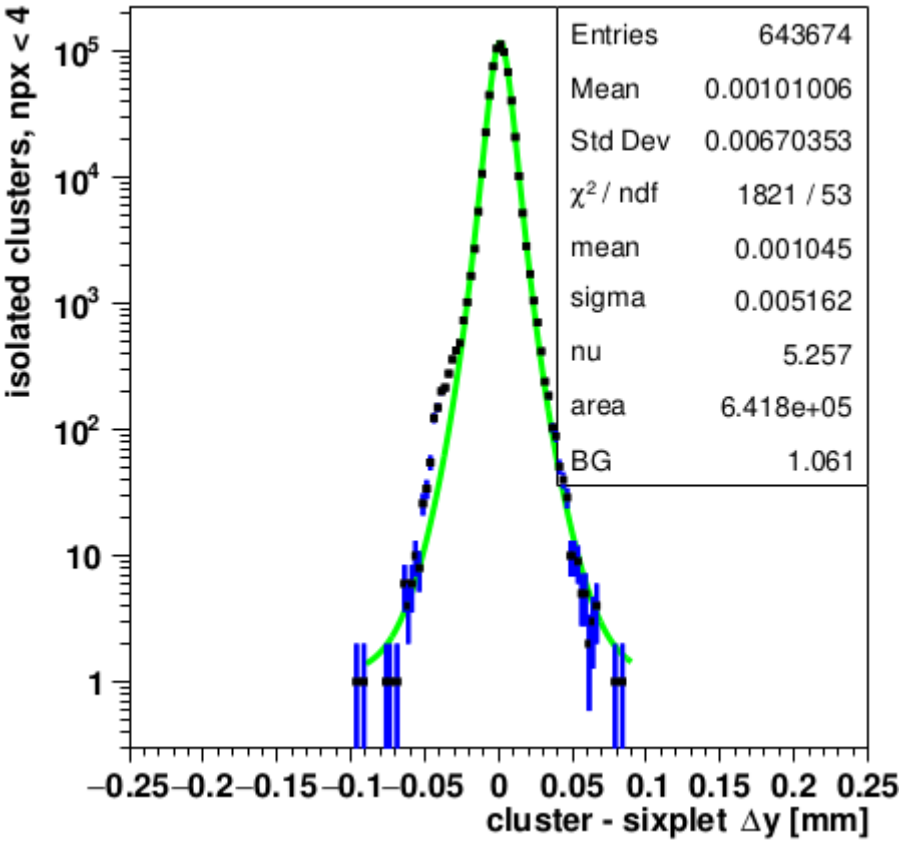
8 ke < Q_0 < 16 ke (80%)



0.3% outside ±5 σ

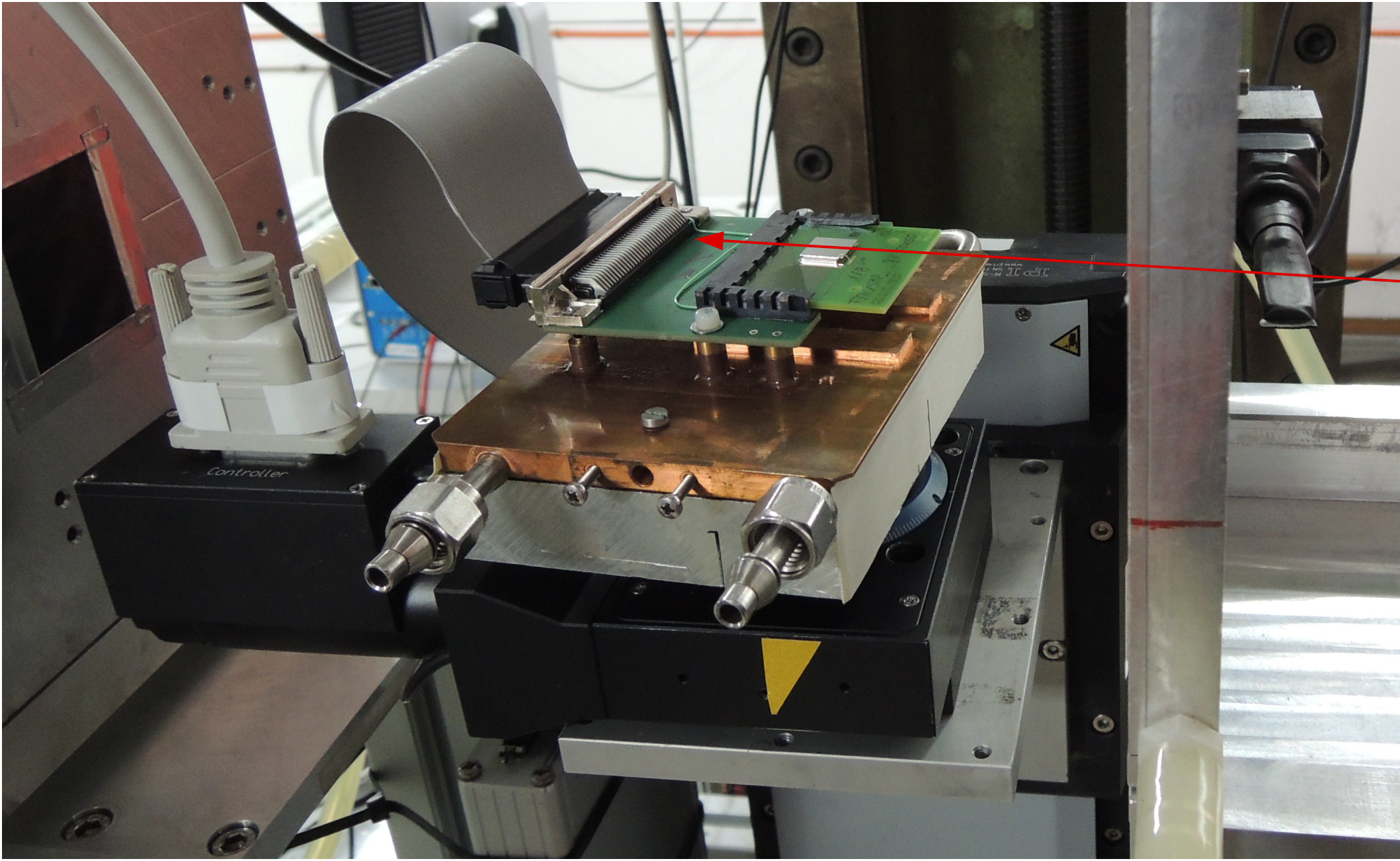
by cluster size

cluster size < 4 pixels (97%)

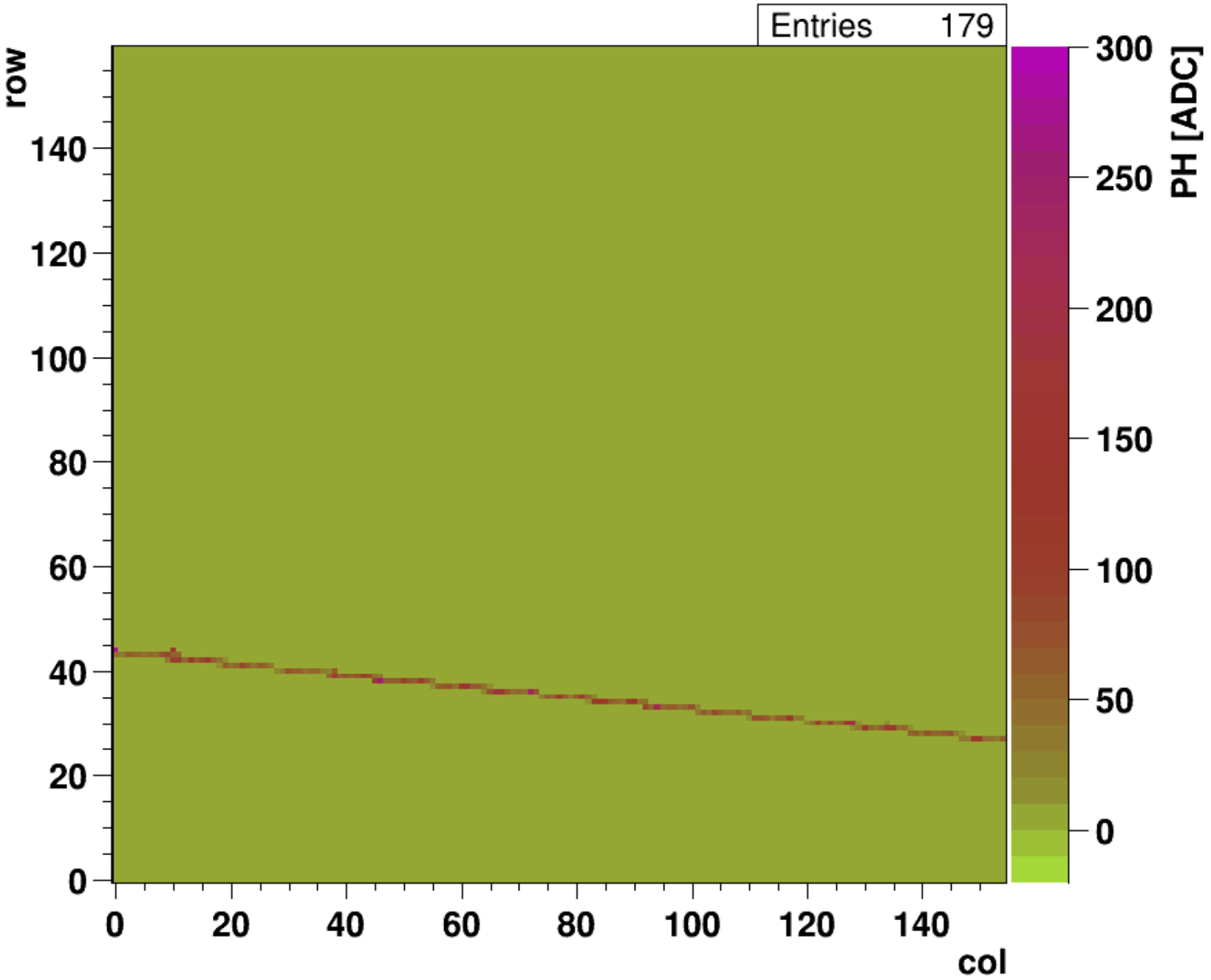


0.7% outside ±5 σ

rotated edge-on tracking



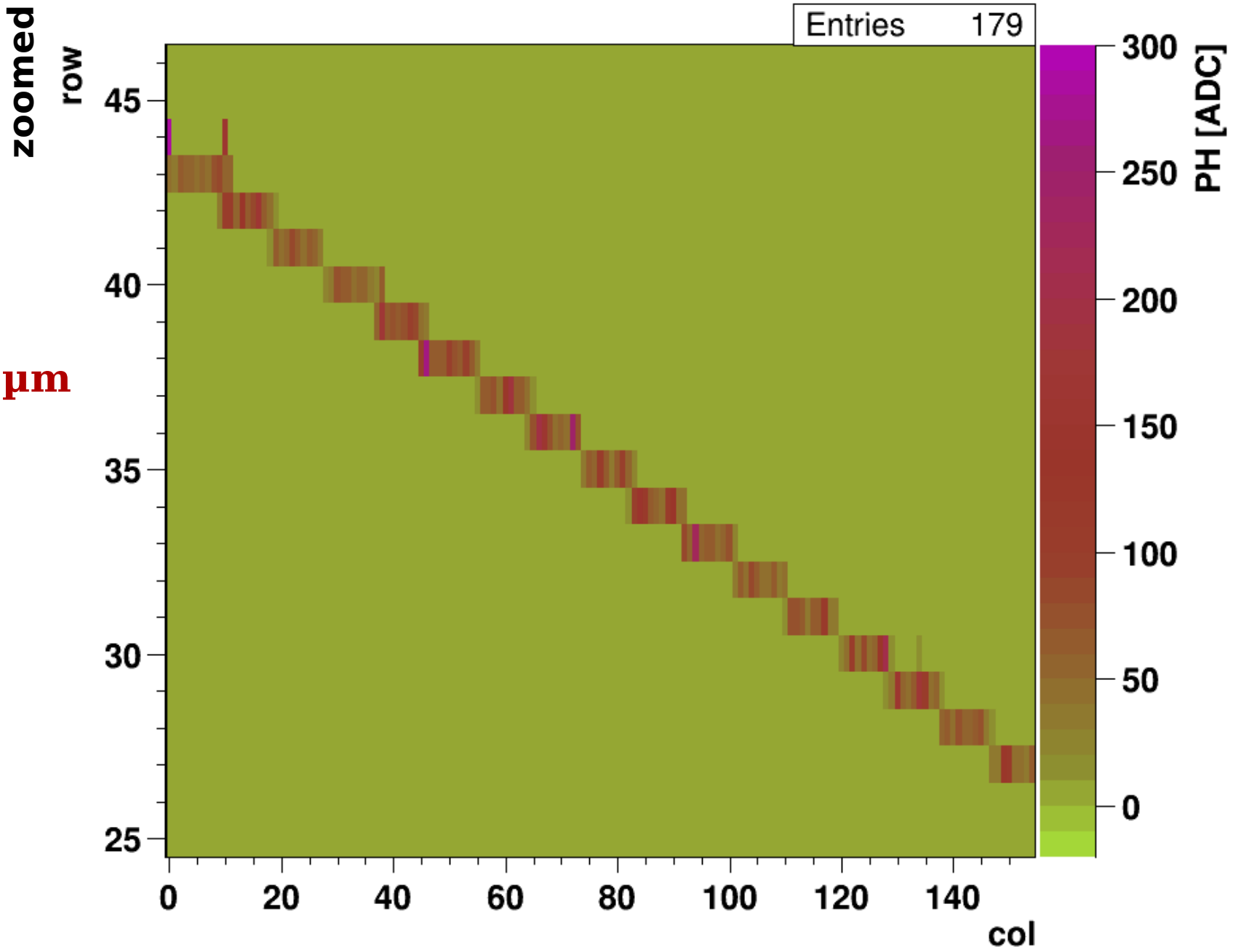
edge-on track



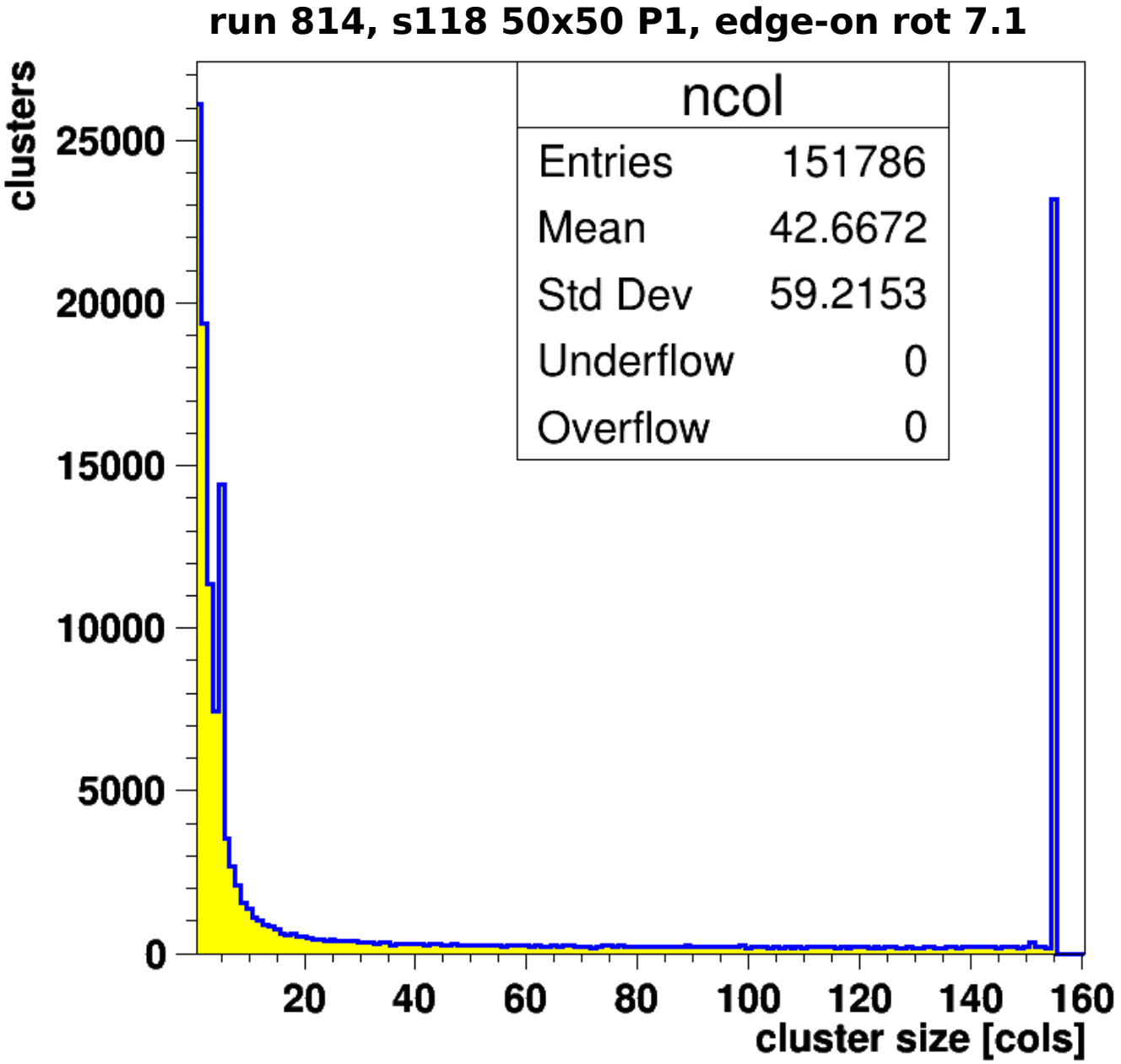
50×50 µm pixels

edge-on track

rotation angle: 7.1°
50 µm / 400 µm



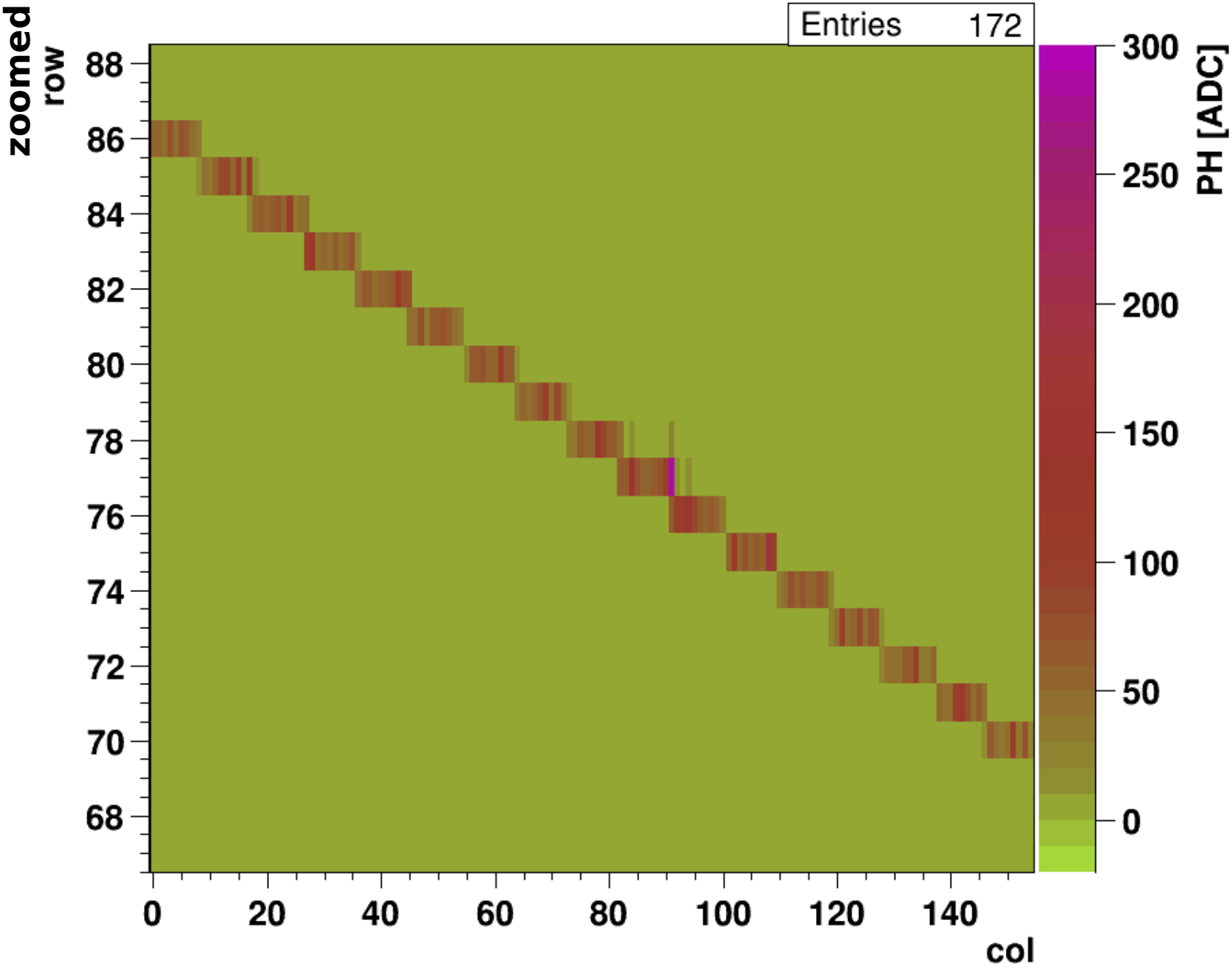
track length



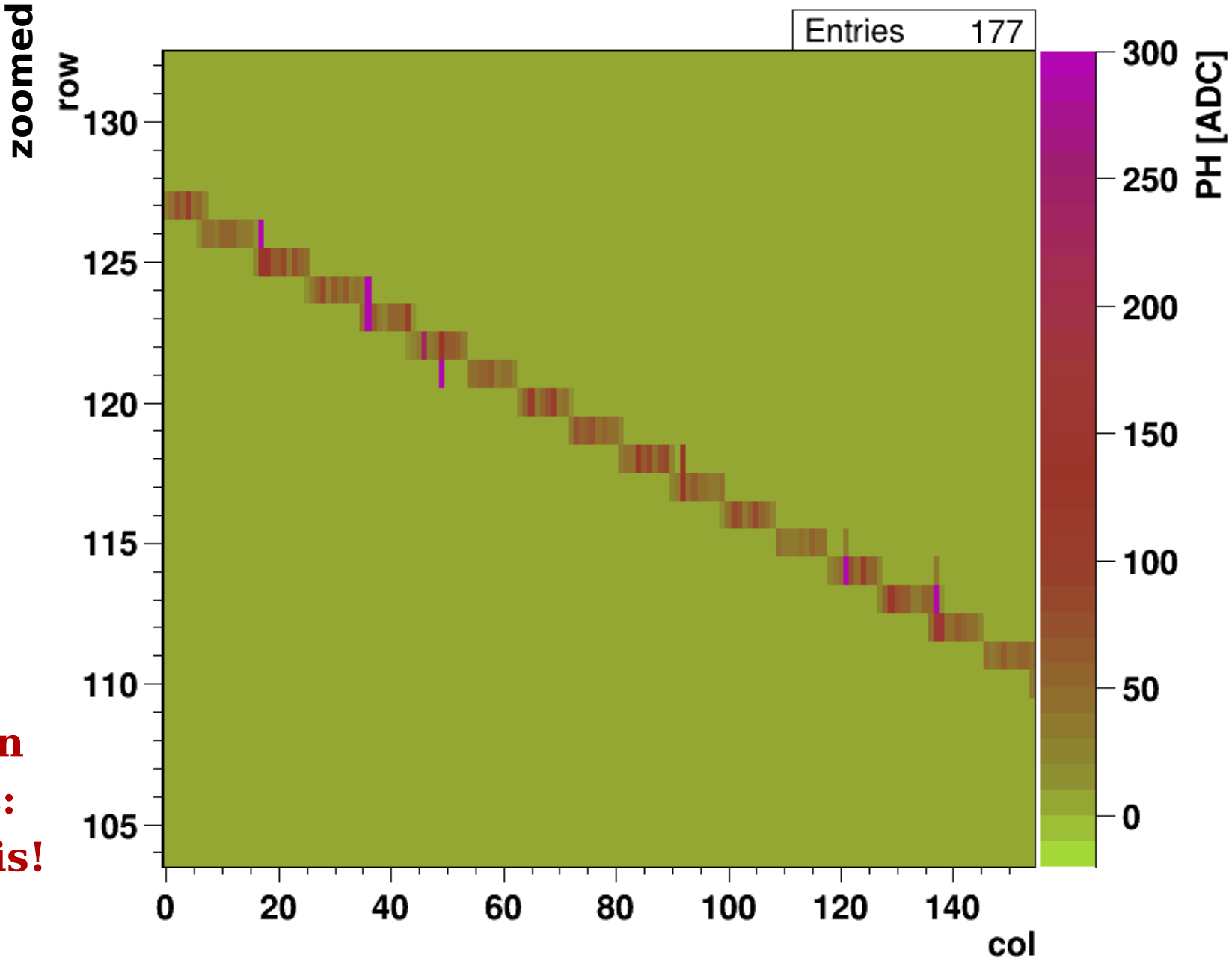
- over-night run
  - 2.6 M triggers
  - 152 k non-empty events
  - 23 k full-length tracks
  - 7.9 M pixel hits

edge-on track

short
delta rays



edge-on track

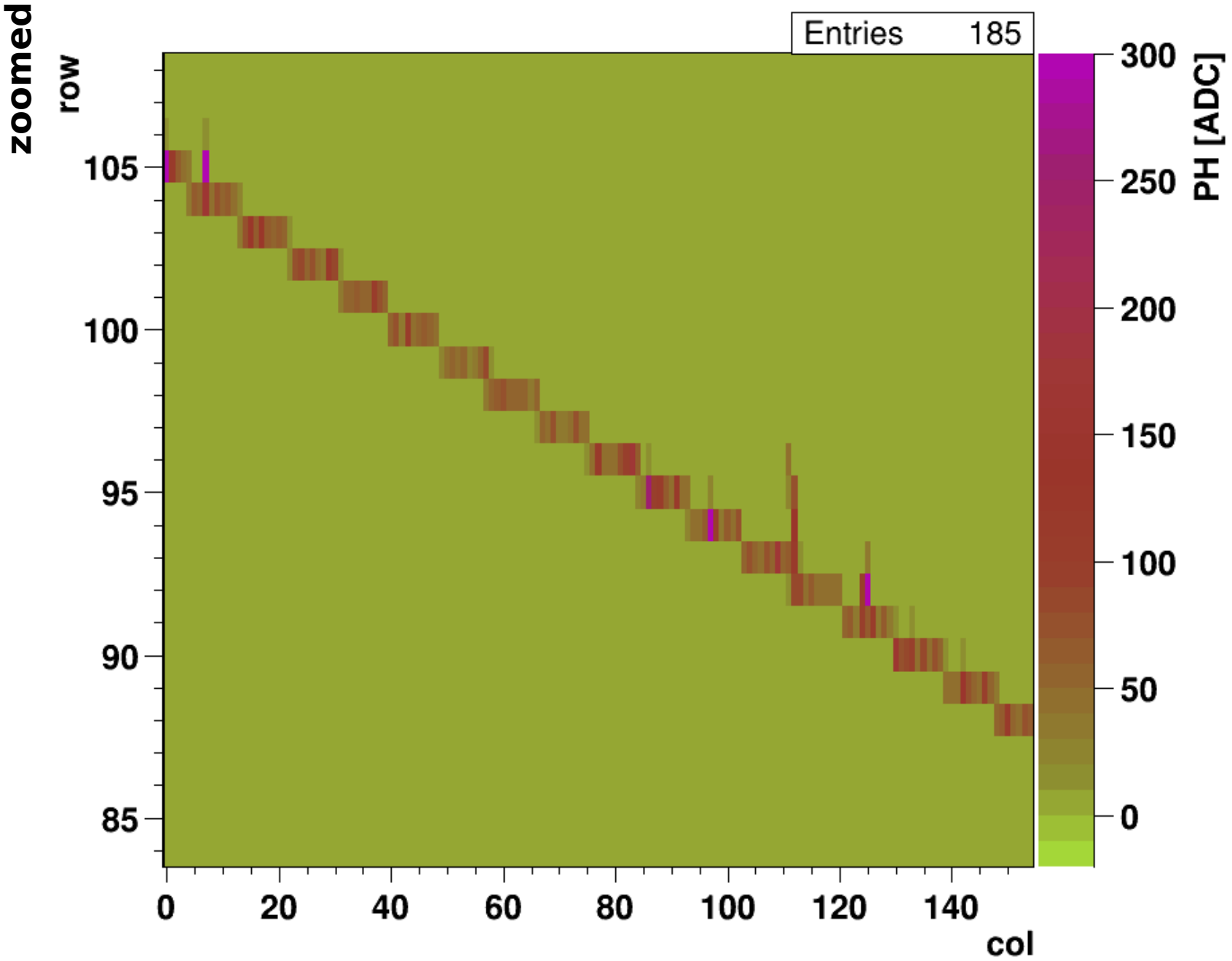


short delta rays

small pixels allow topological identification of delta rays: Master thesis!

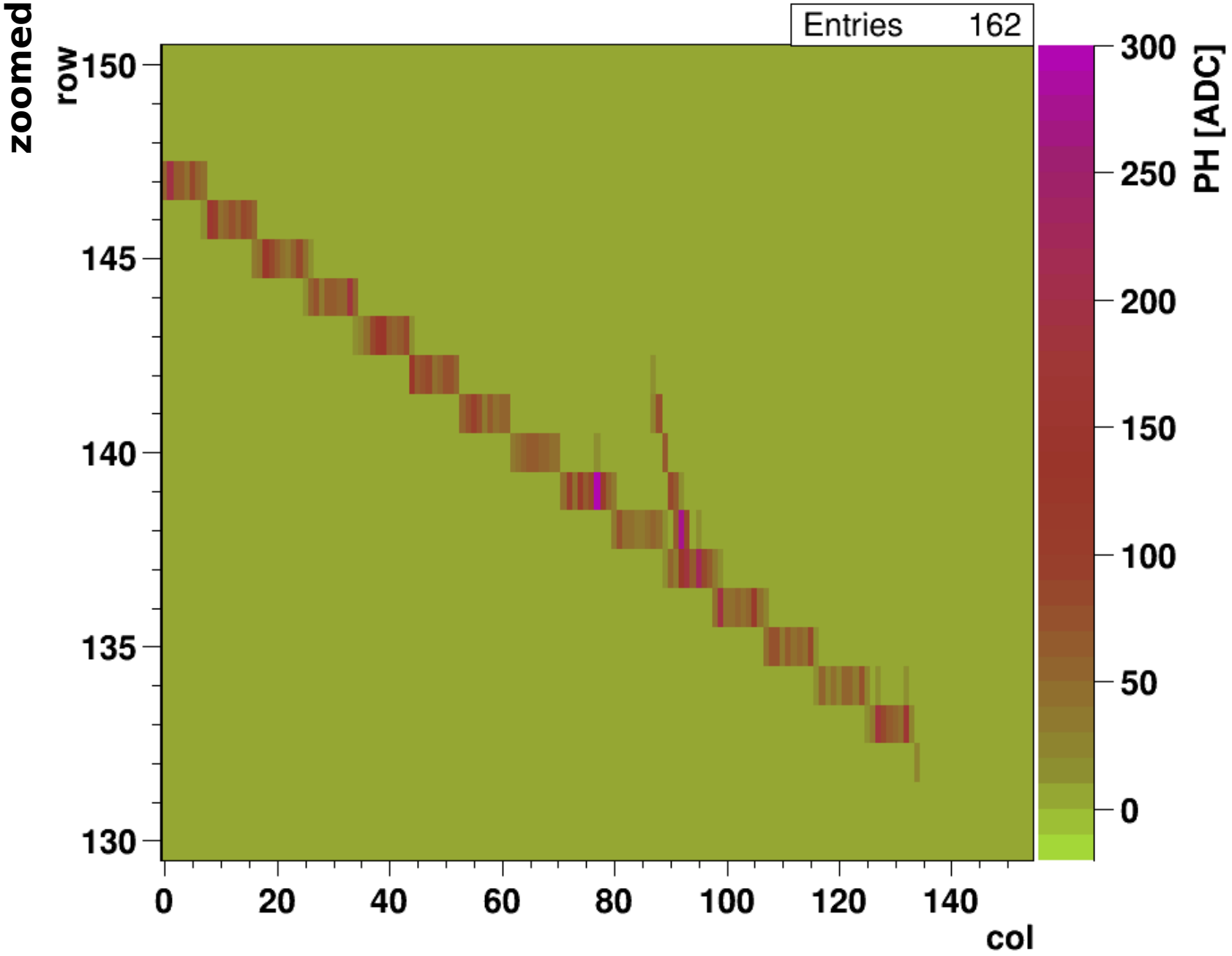
edge-on track

longer delta rays



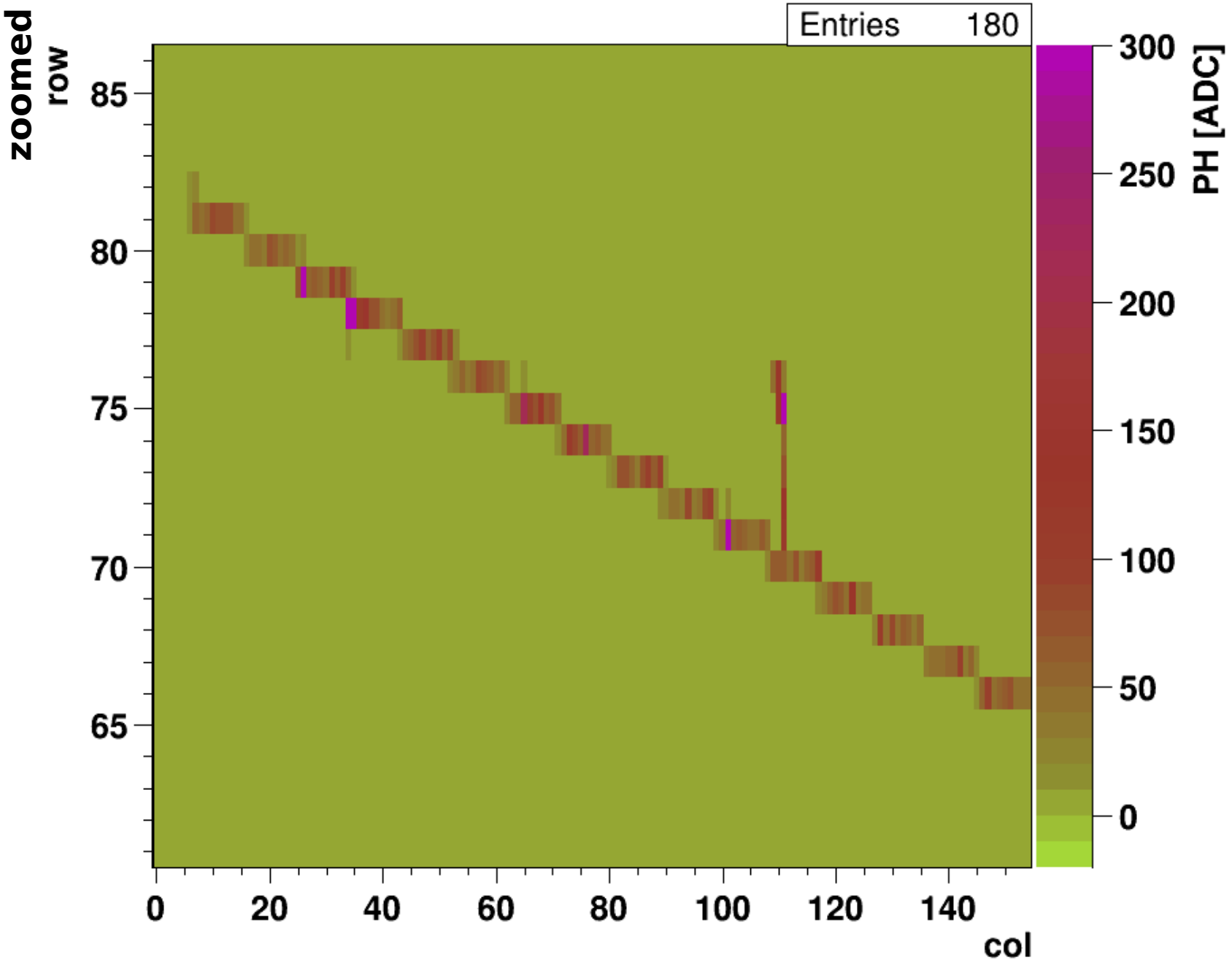
edge-on track

longer delta rays

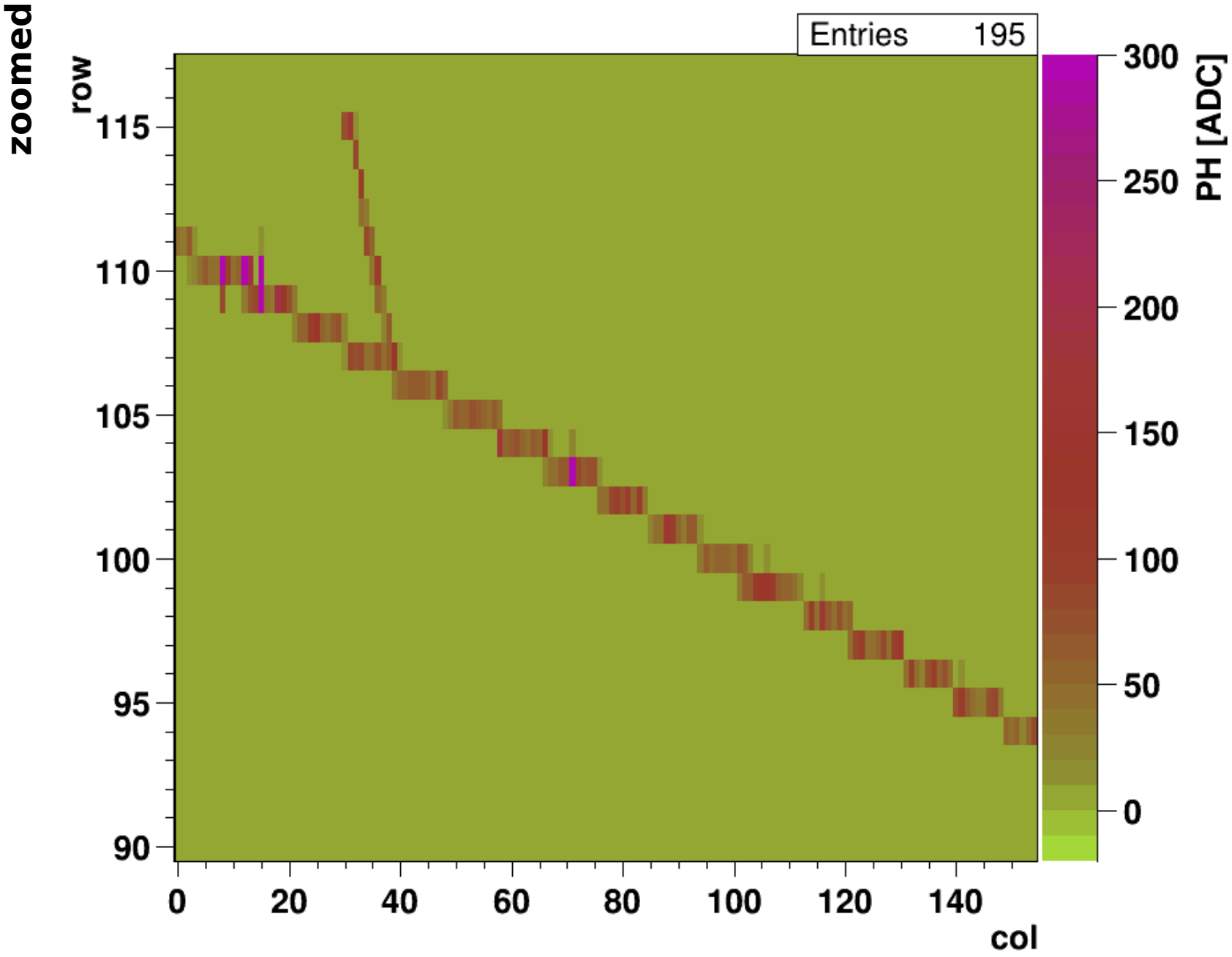


edge-on track

longer delta ray stopping ?



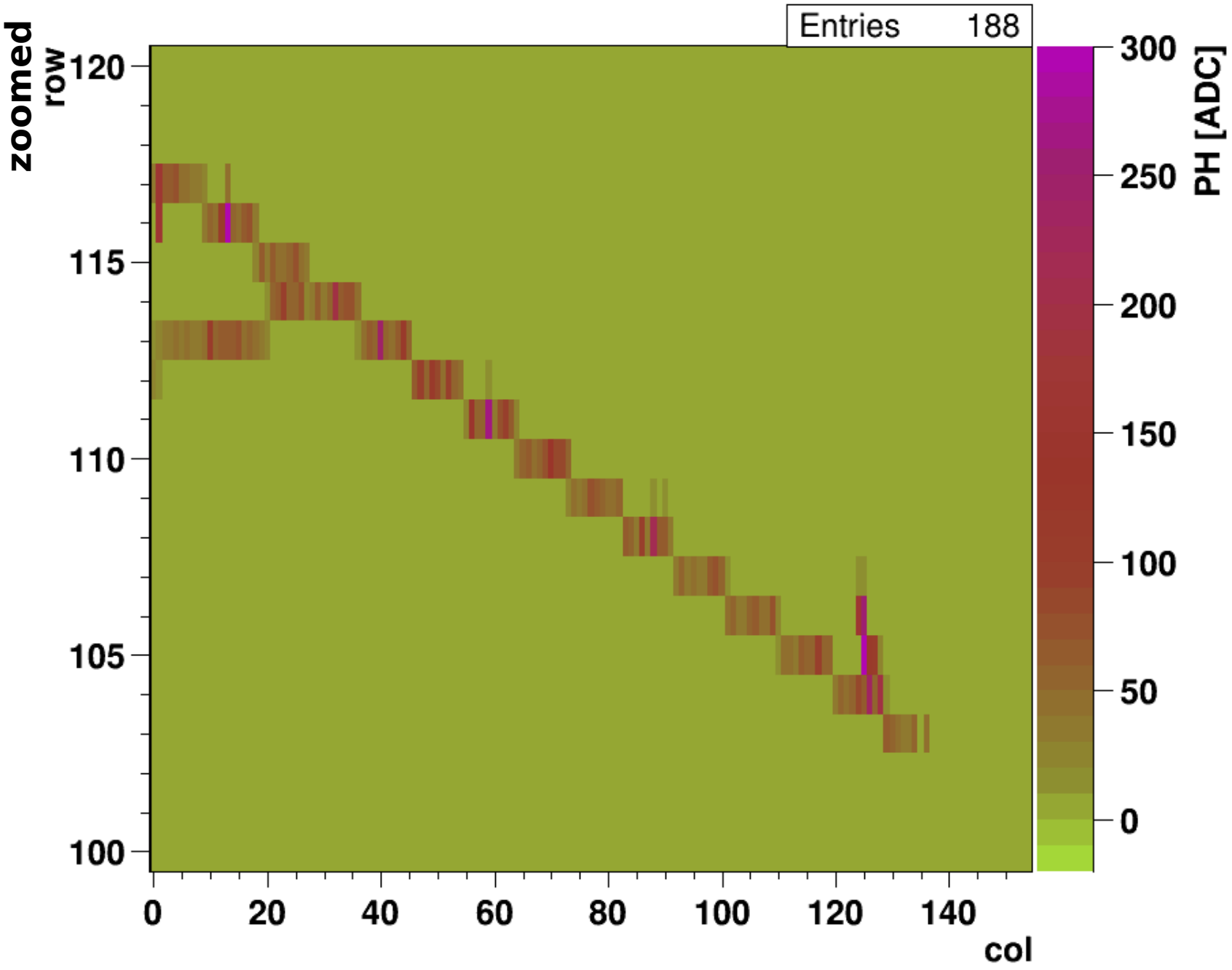
edge-on track



longer delta ray stopping ?

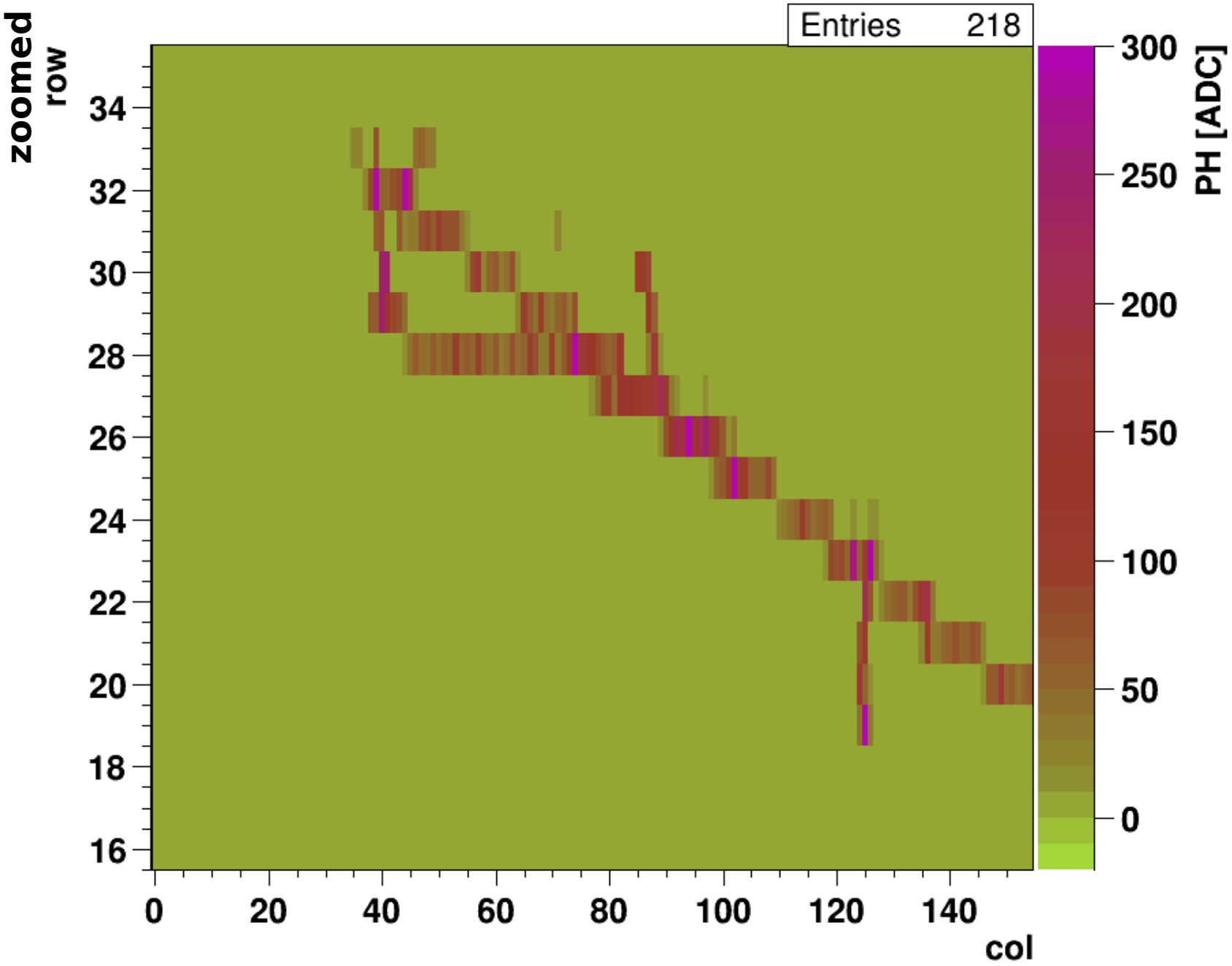
edge-on track

forward delta ray



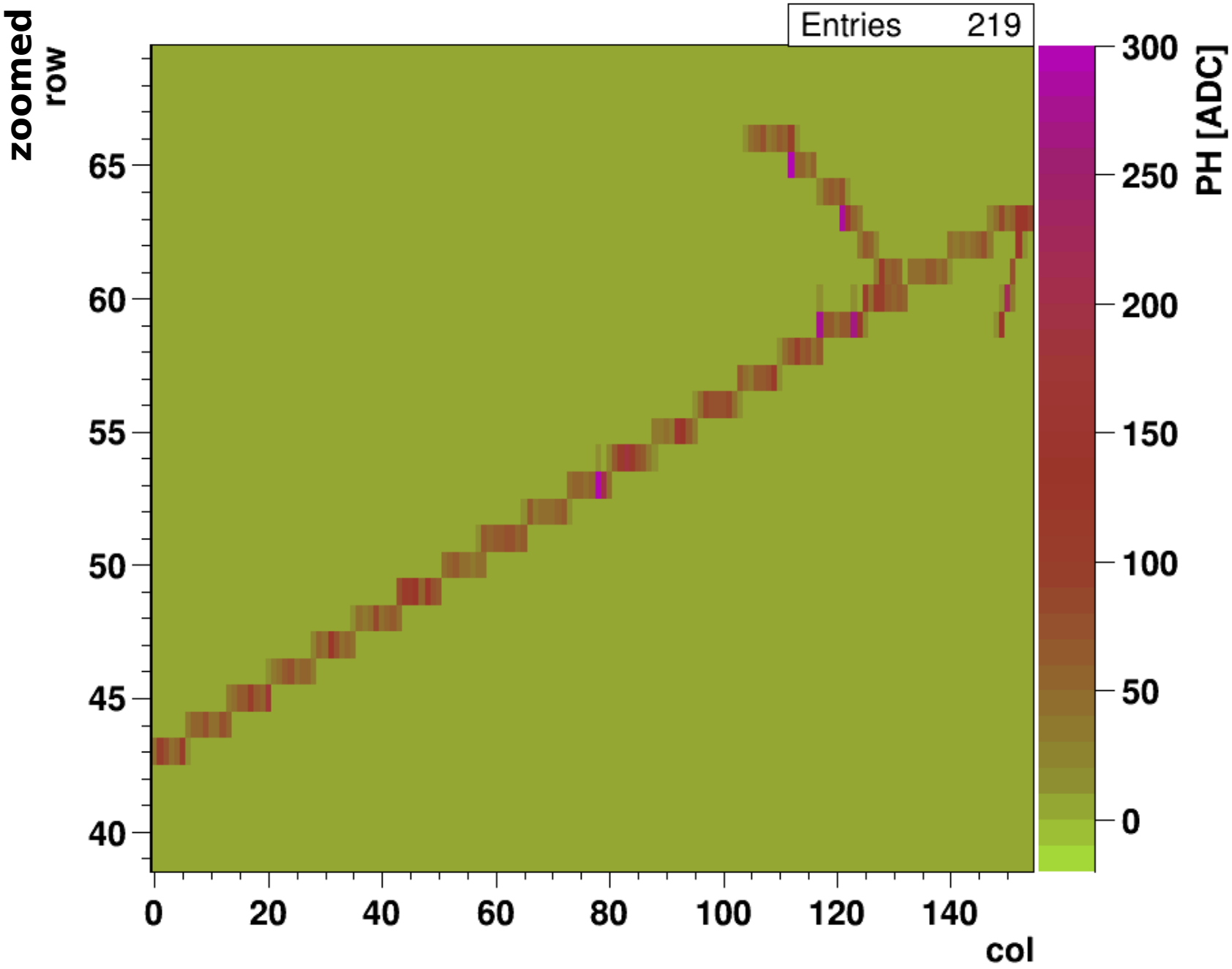
edge-on track

delta ray cocktail



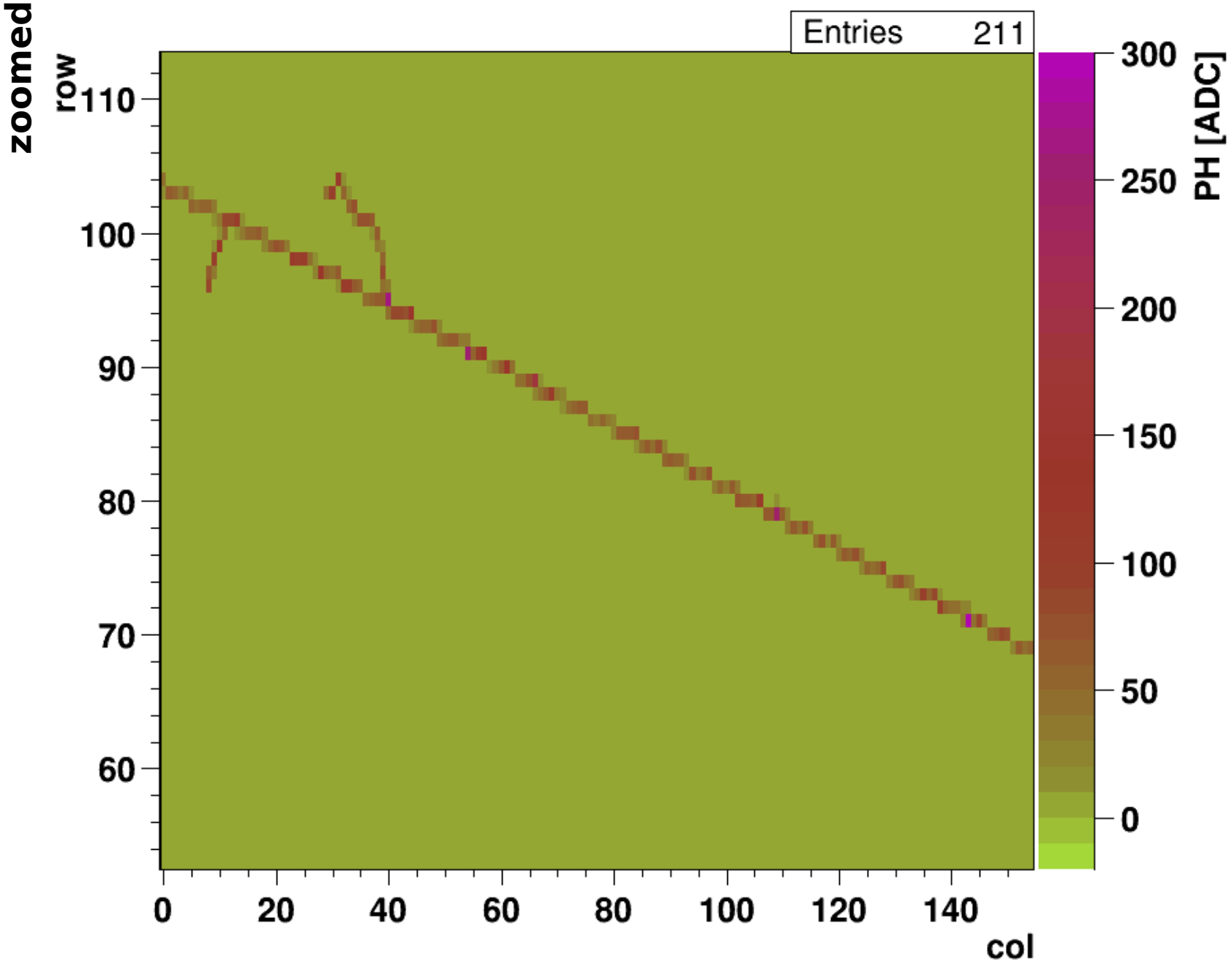
edge-on track

delta ray cocktail

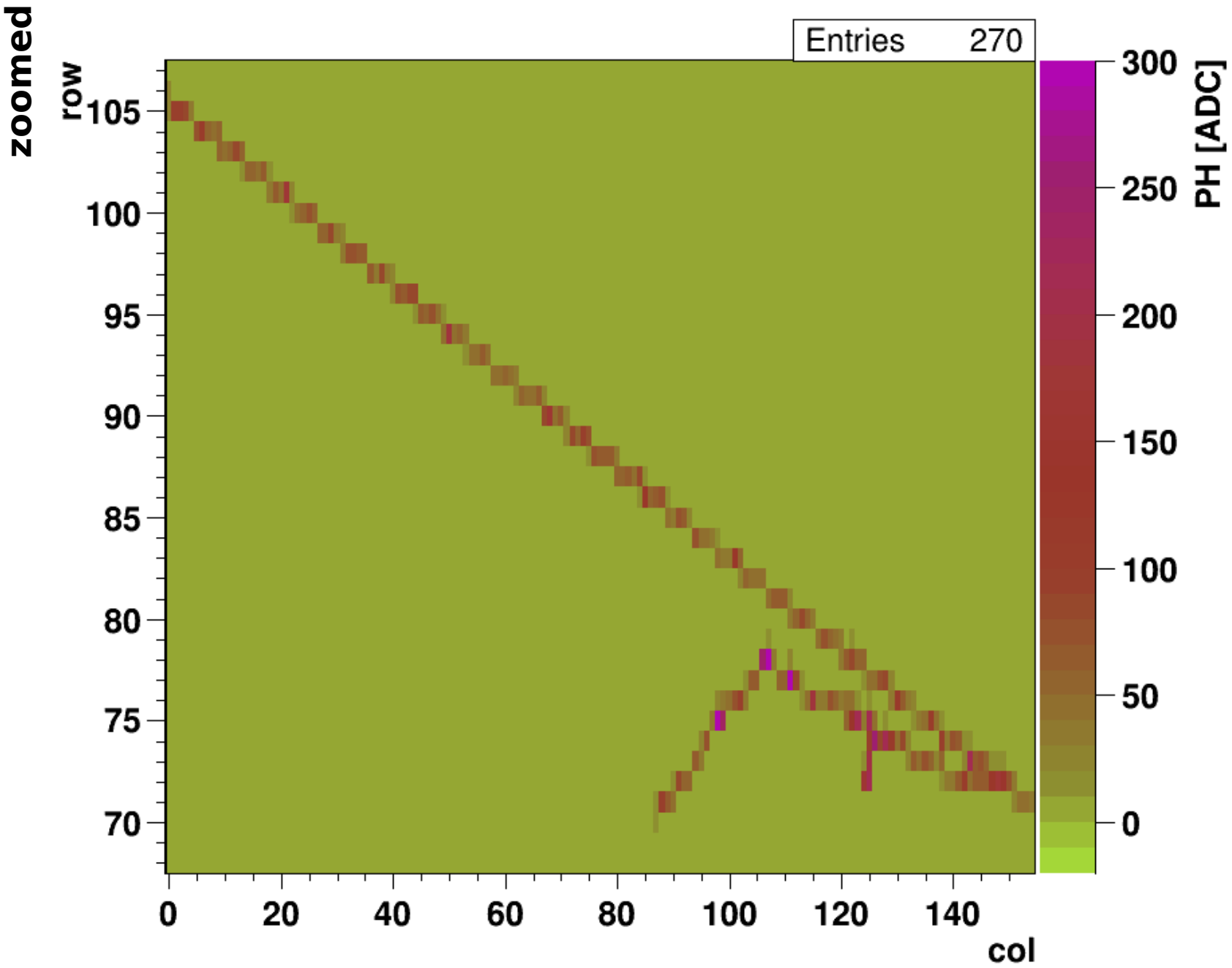


edge-on track

delta ray cocktail



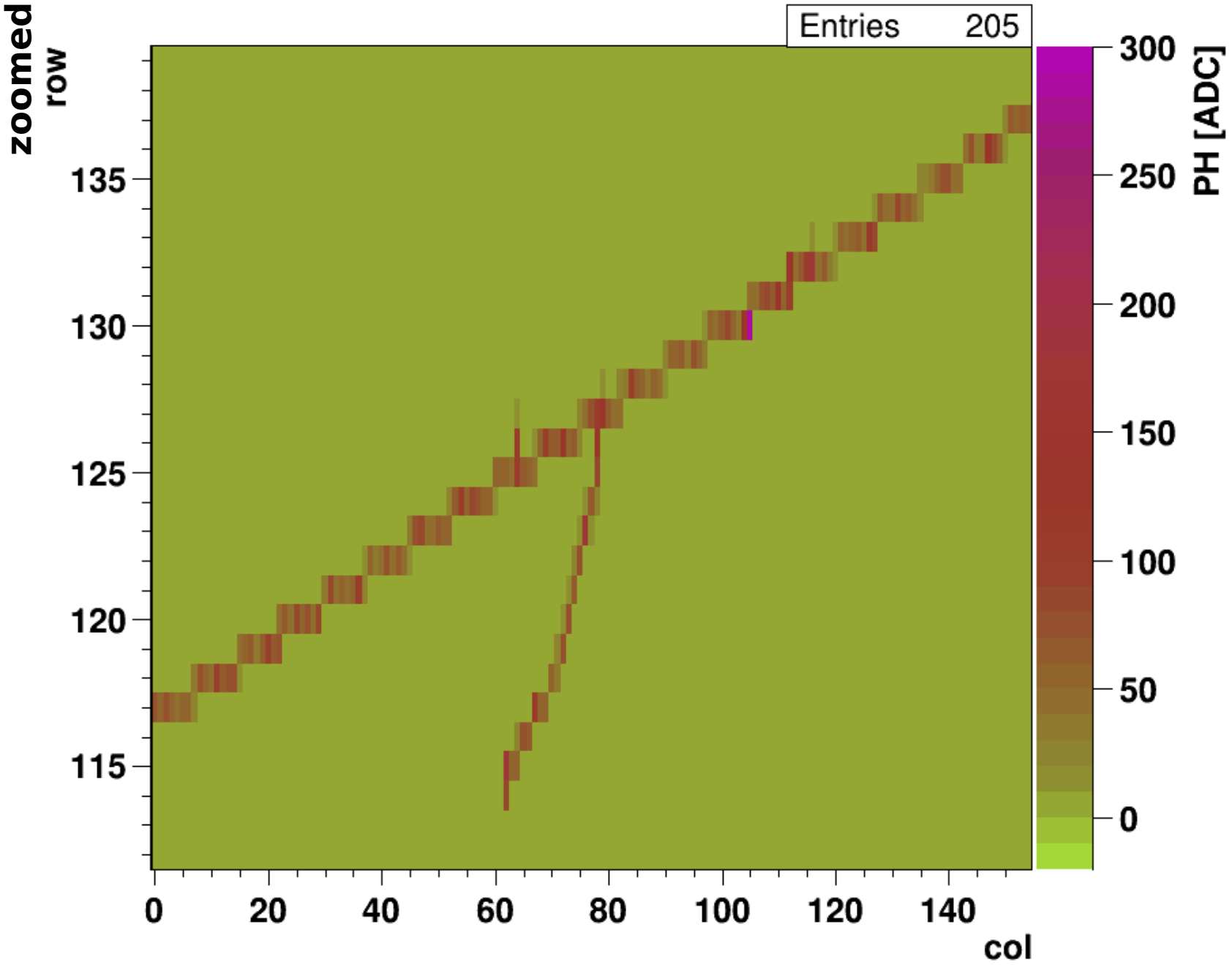
edge-on track



secondary delta ray

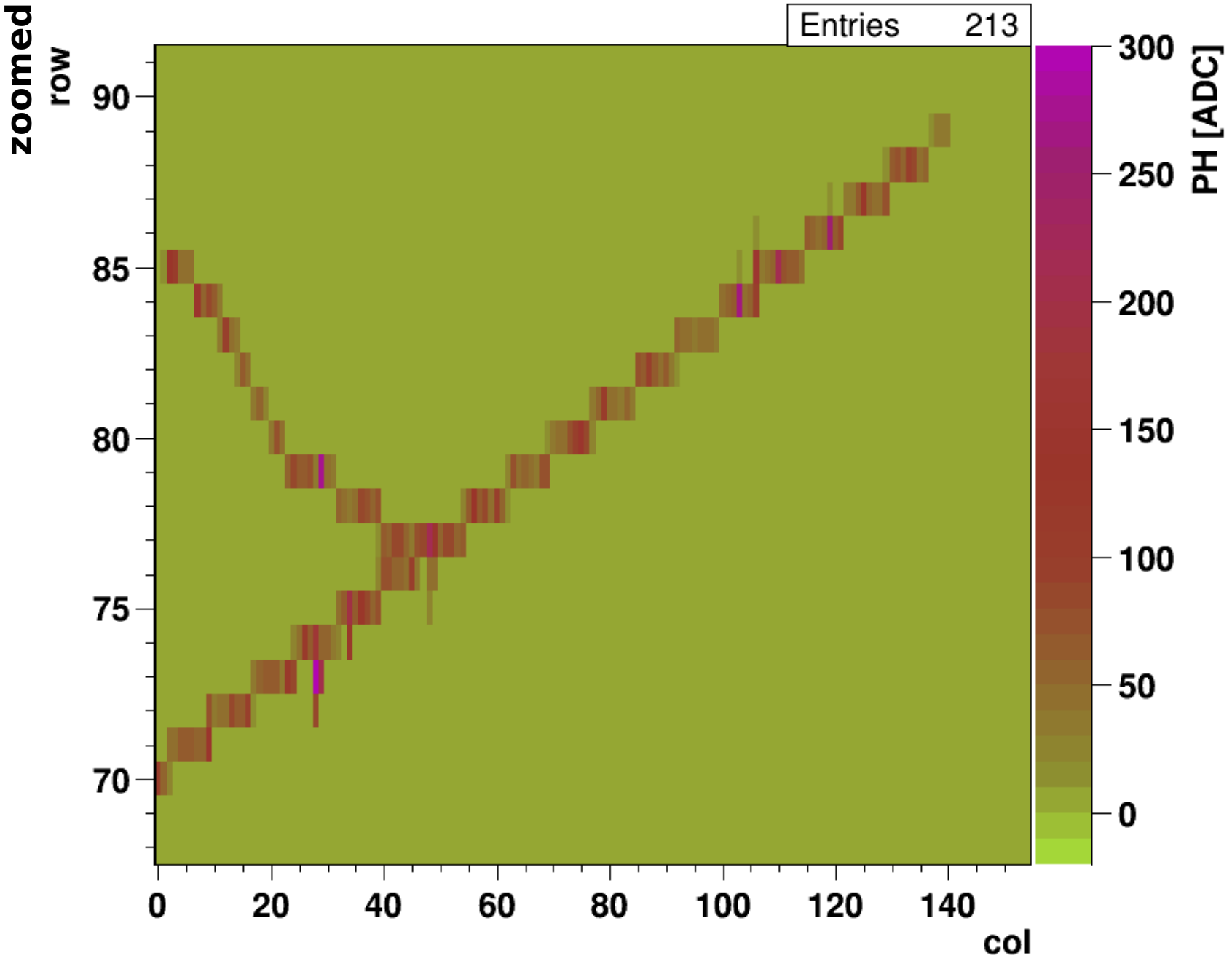
edge-on track

long delta ray



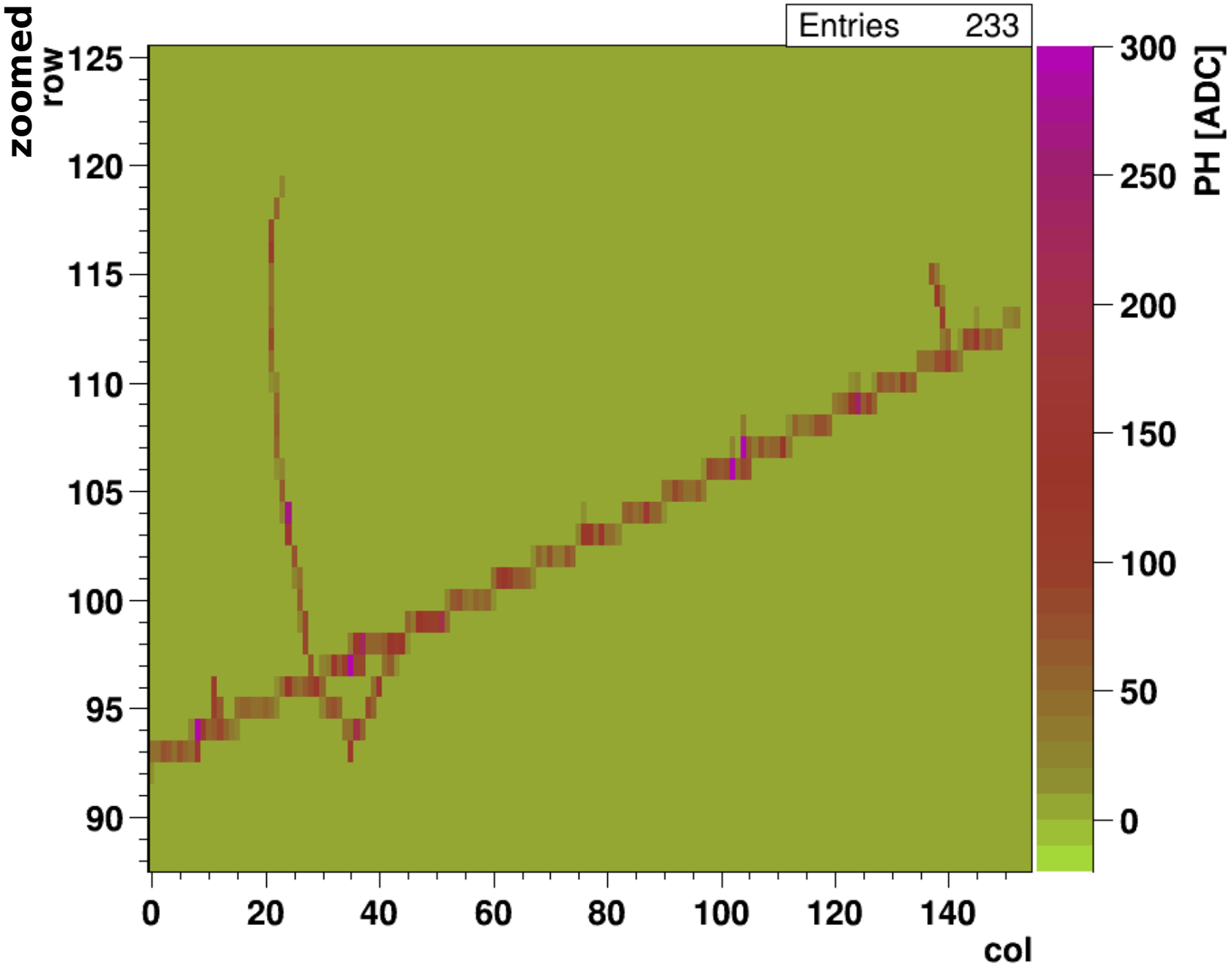
edge-on track

long delta ray



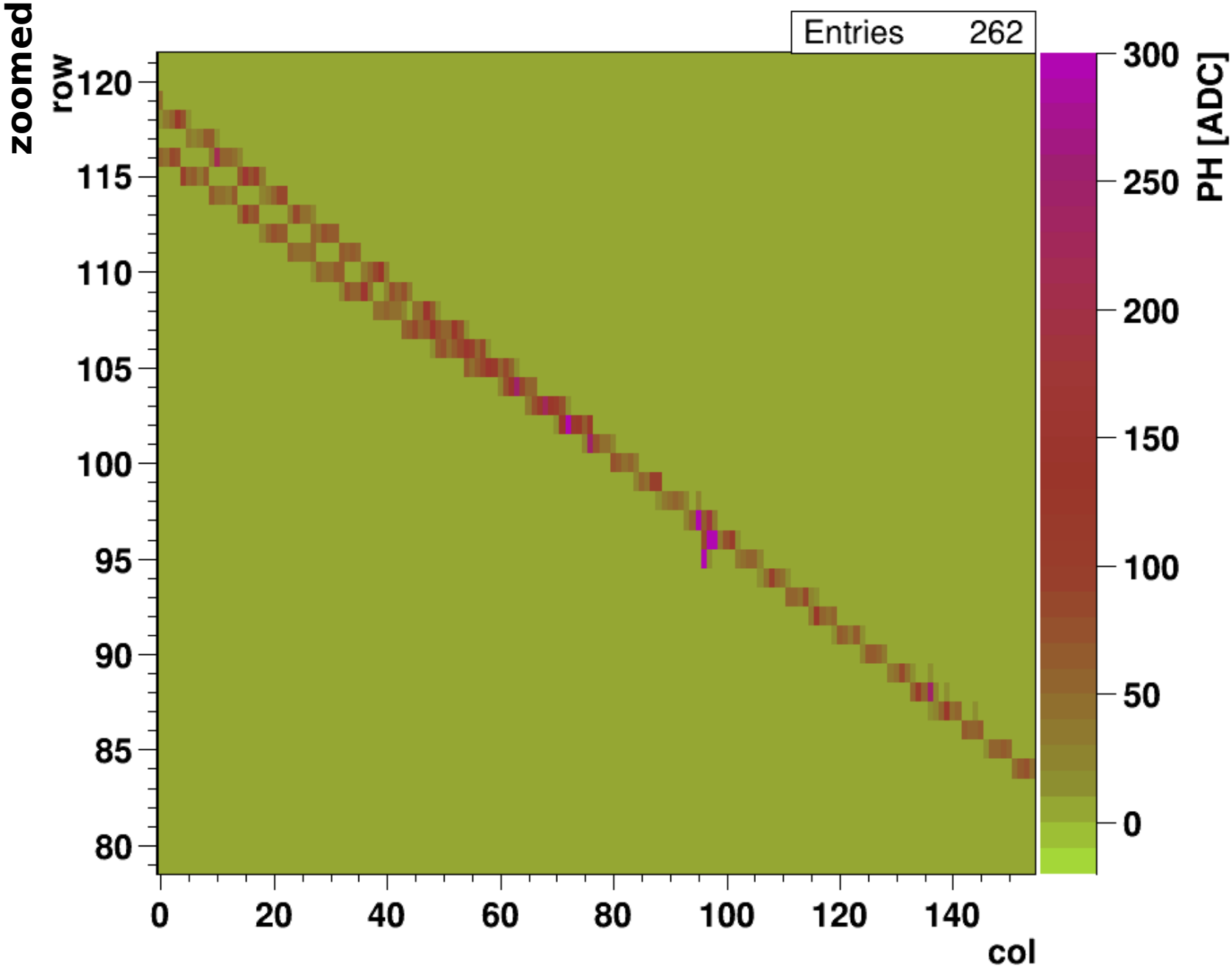
edge-on track

long delta ray



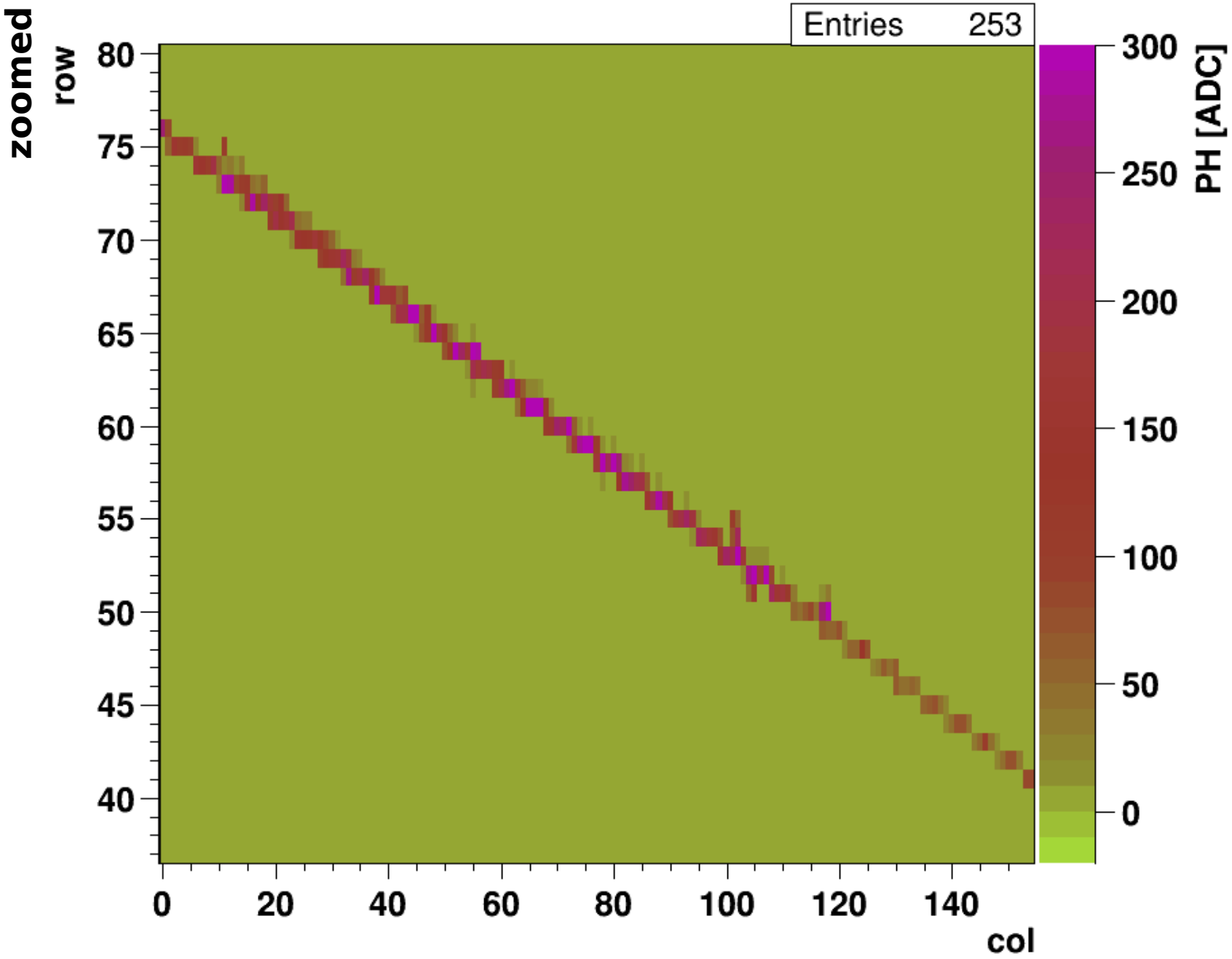
edge-on track

forward delta ray



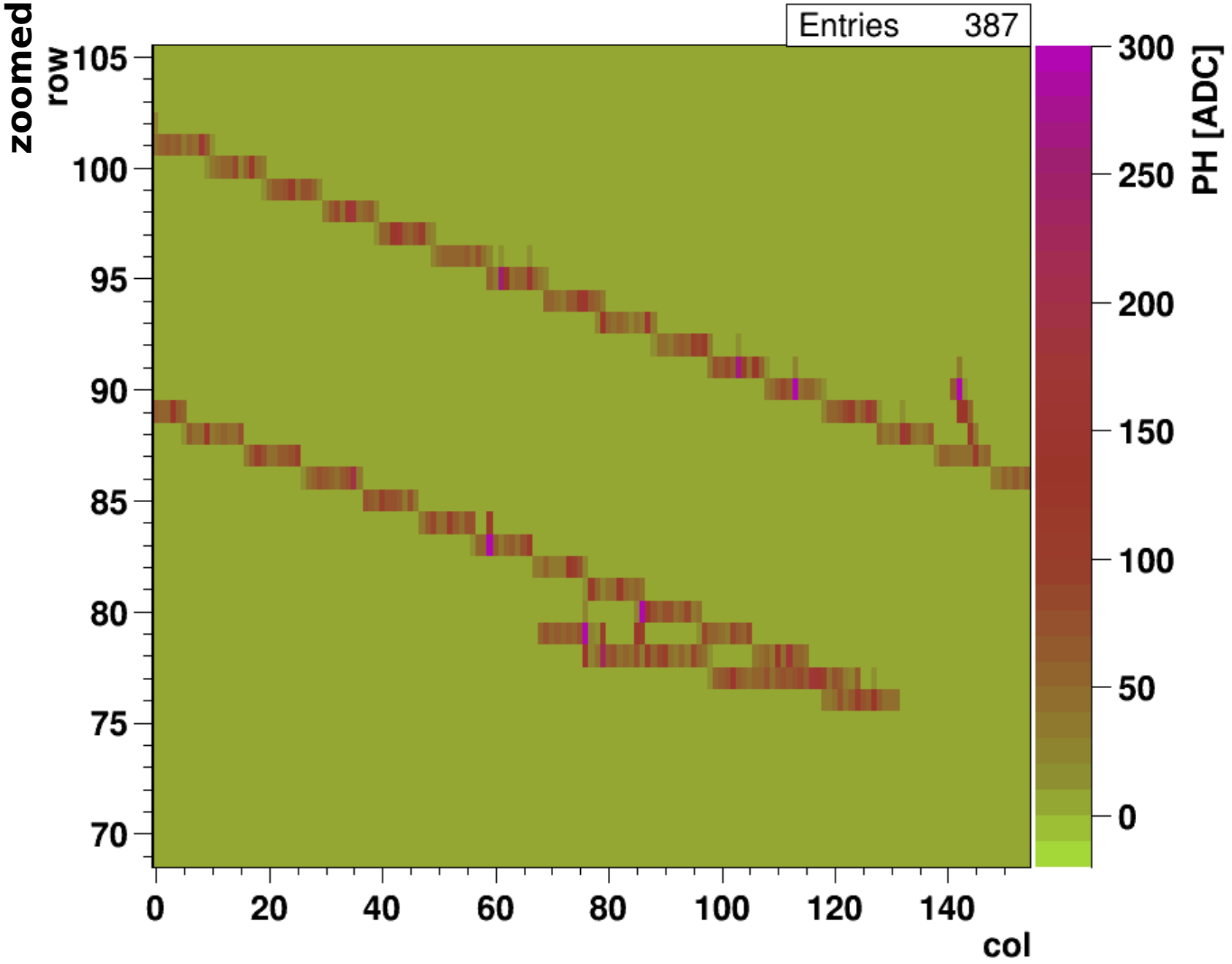
edge-on track

forward delta ray overlay



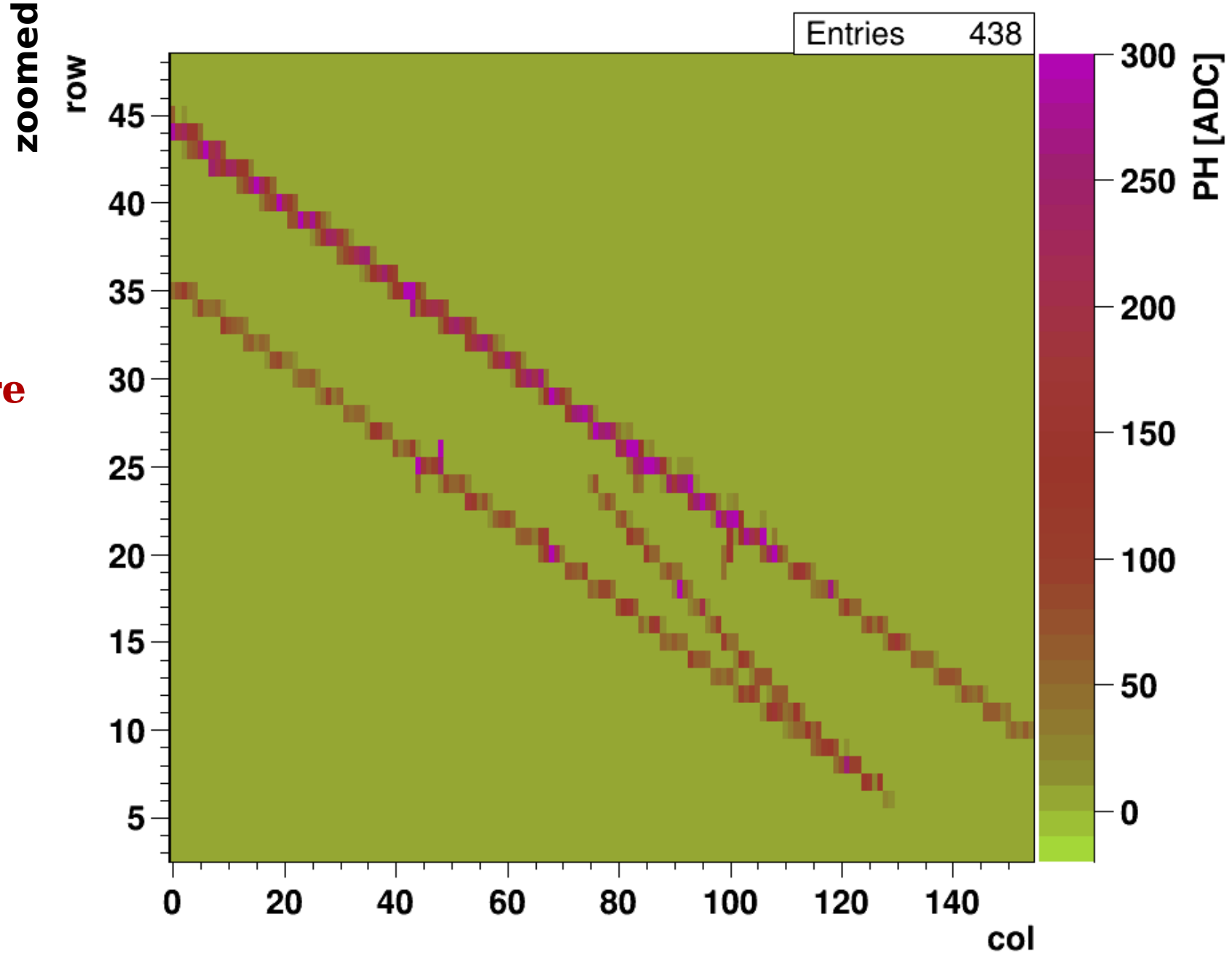
edge-on tracks

pile up!



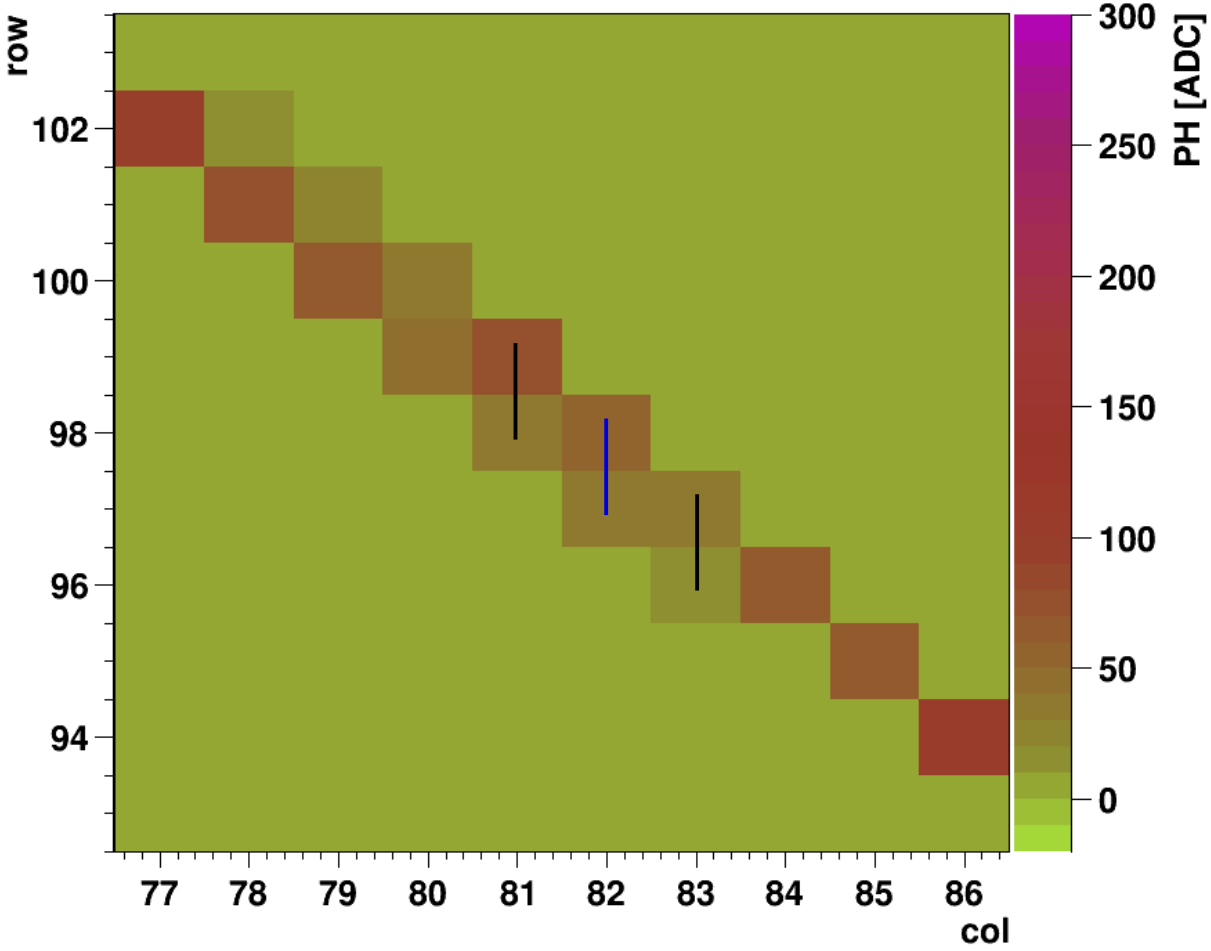
edge-on tracks

one picture to sum it all up



rotated edge-on tracking

- 50×50 µm pixels
  - angle 42° for charge sharing
- triplet tracking:
  - column = plane
  - shortest possible lever arm
  - minimal multiple scattering
  - self-aligned
  - no external tracking required



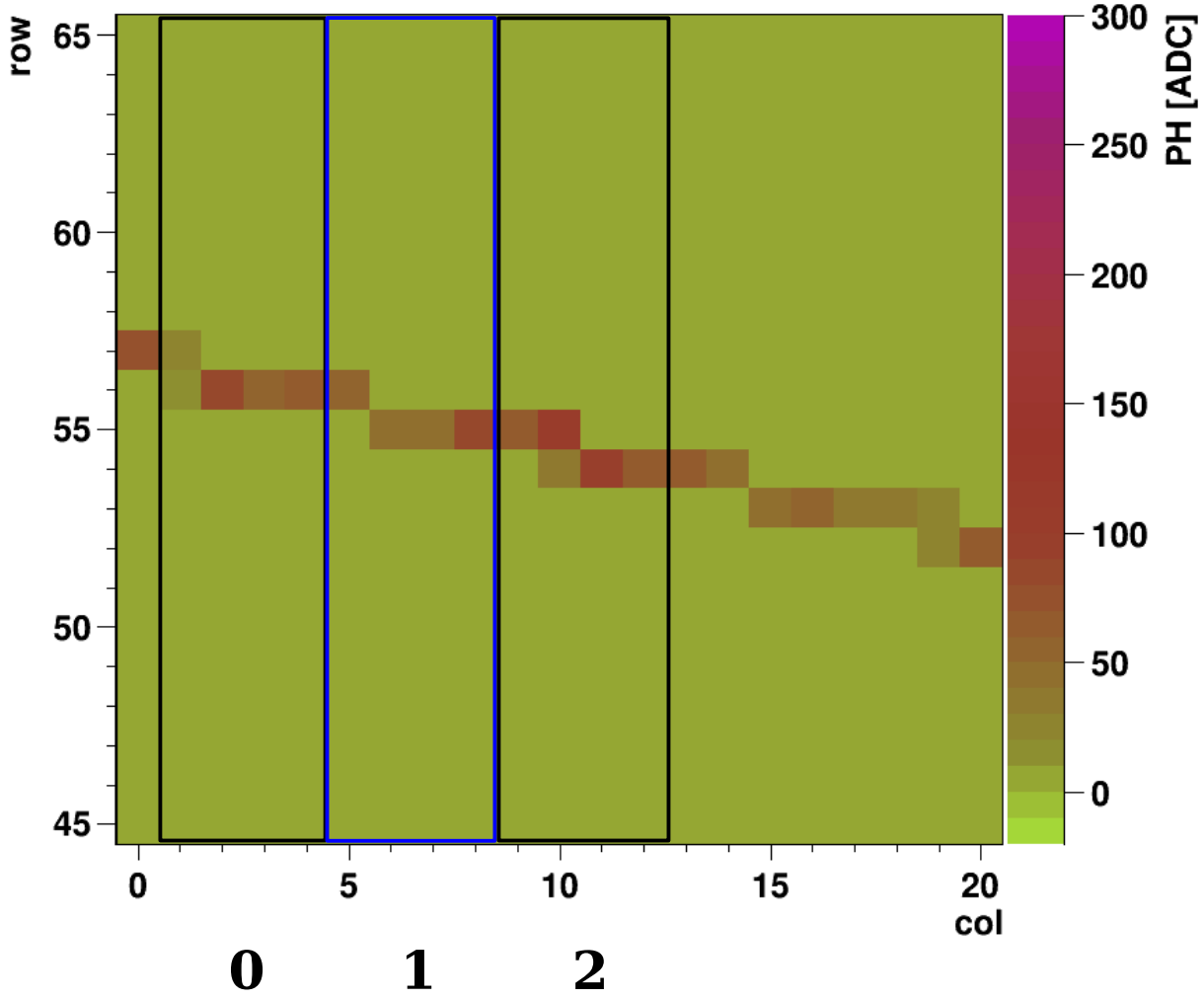
3.8 ke in 50 µm

rotated edge-on combined tracking

- 50×50 µm pixels
  - angle 14° for charge sharing every 4 columns
- combine 4 neighbouring columns into one ‘plane’
  - simulates thicker sensor
- triplet tracking on 4-column planes

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

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



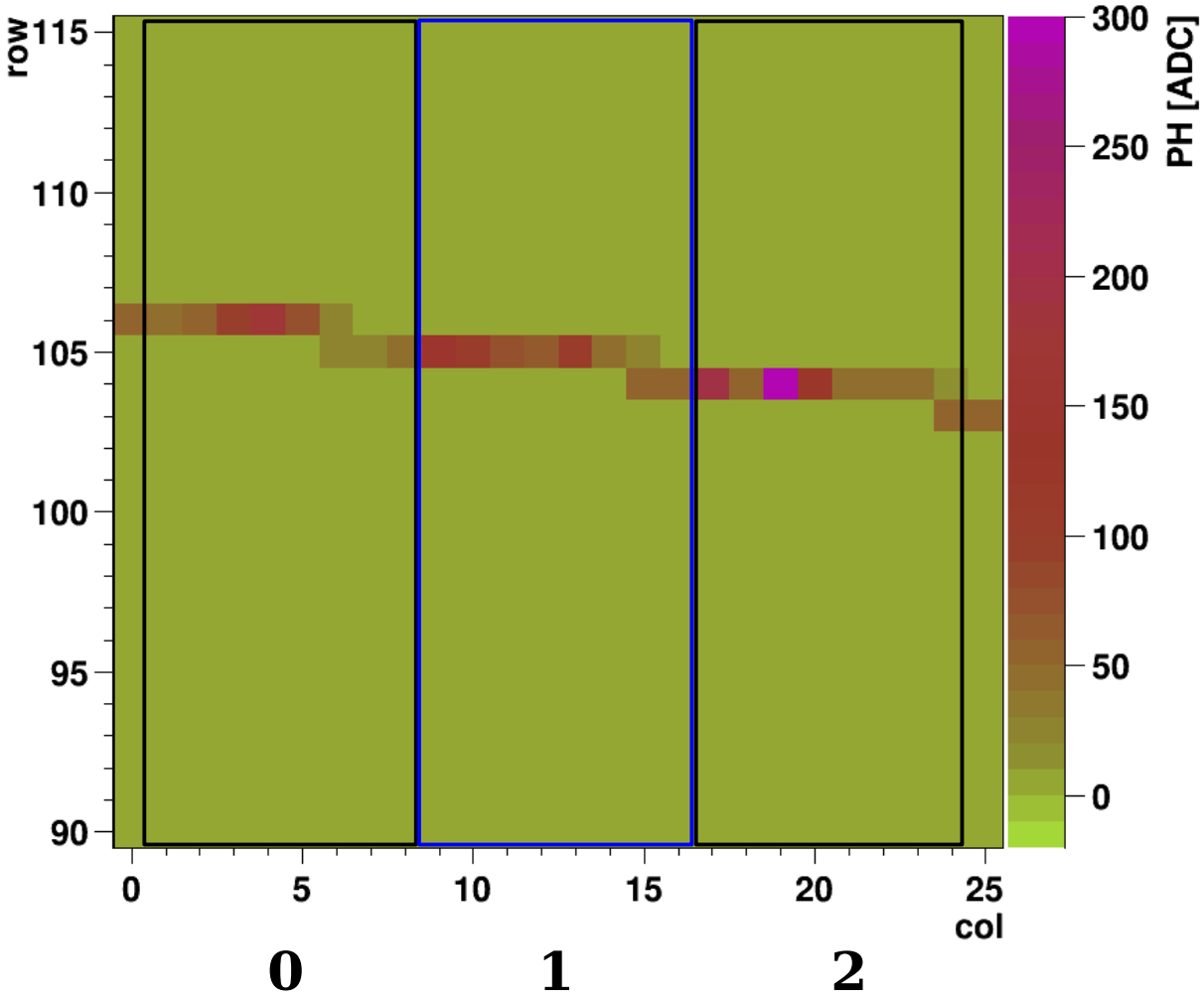
summed 15 ke in 200 µm

rotated edge-on combined tracking

- 50×50 µm pixels
  - angle 7.1° for charge sharing every 8 columns
- combine 8 neighbouring columns into one ‘plane’
  - simulates thicker sensor
- triplet tracking on 8-column planes

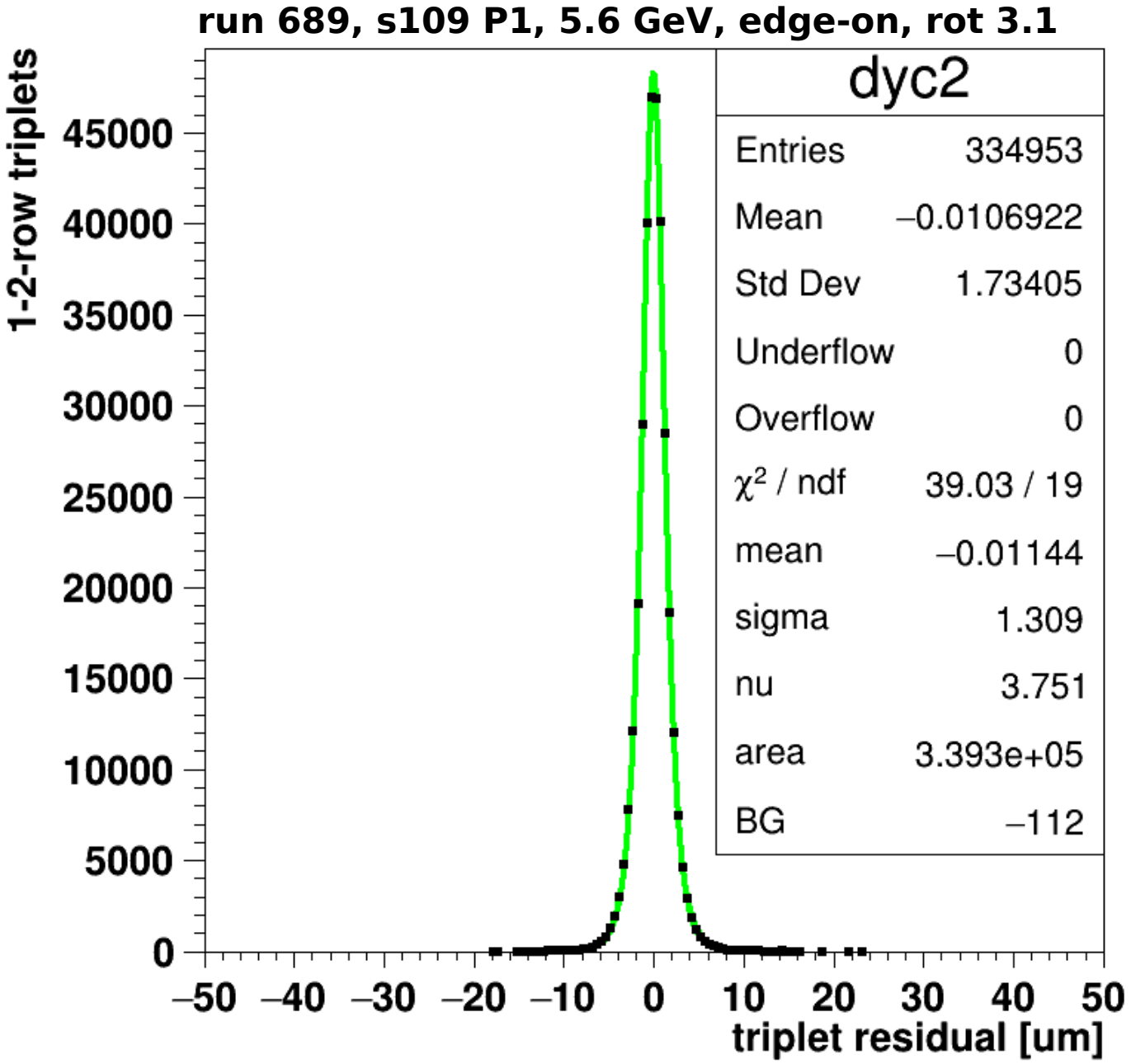
$$\Delta y = y_1 - \frac{y_0 + y_2}{2}$$

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



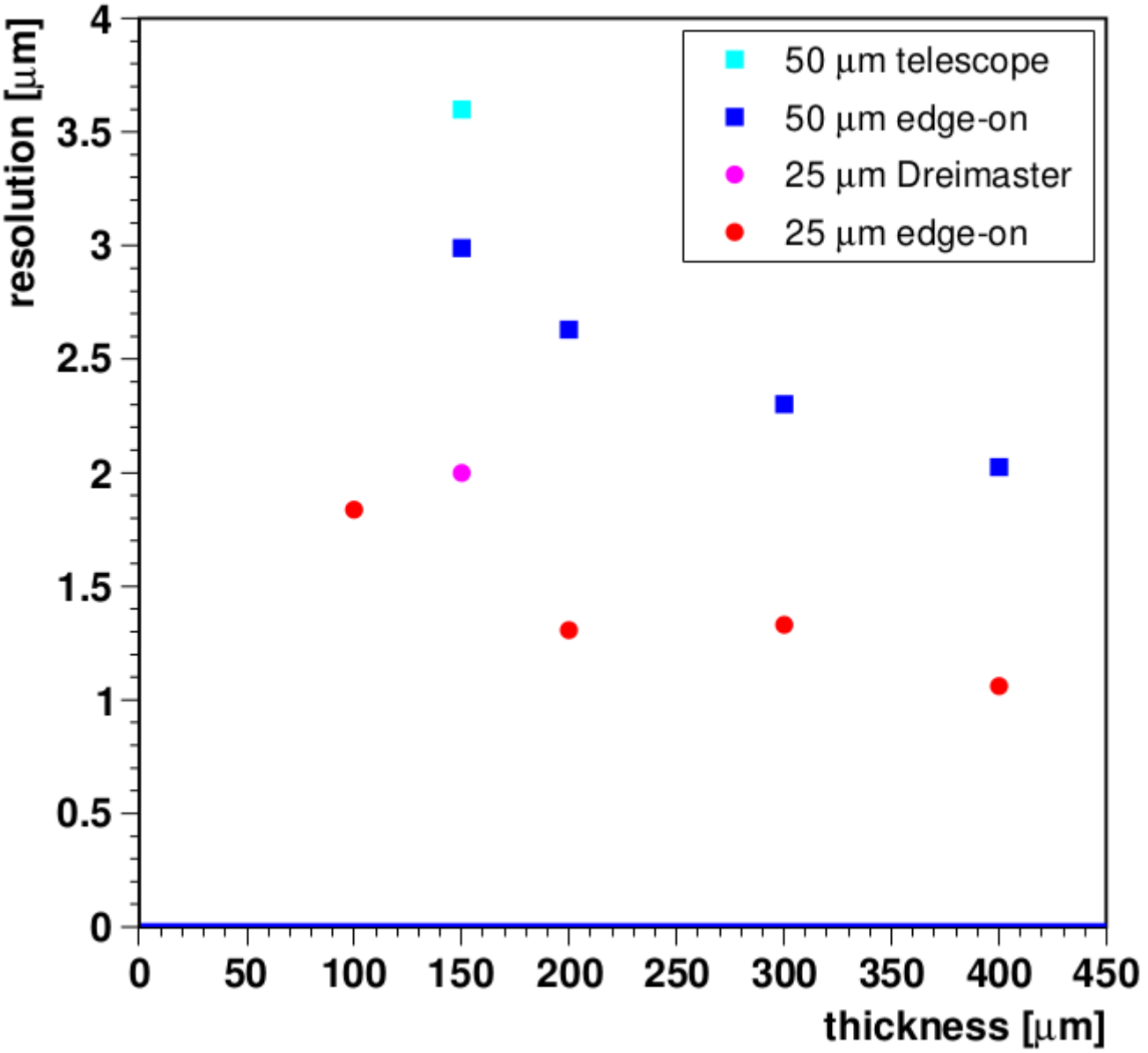
summed 30 ke in 400 µm

resolution



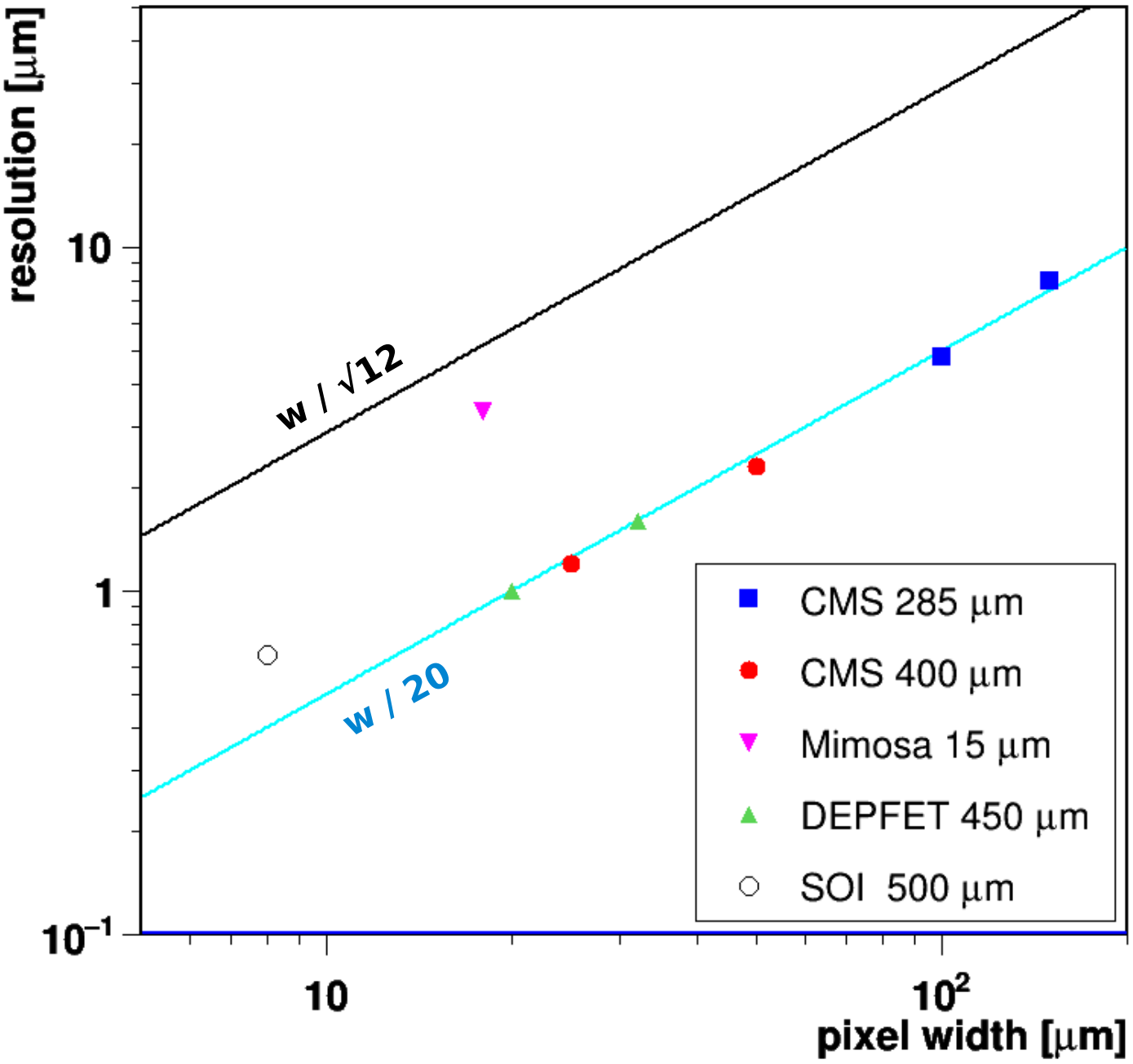
- 25×100 µm
  - default design P1
  - edge-on with 3.1° rotation
- combine 4 neighbouring columns:
  - 400 µm ‘thickness’
- delta ray suppression:
  - ≤ 2 rows
- residual 1.3 µm
  - **resolution 1.1 um**

resolution vs track length



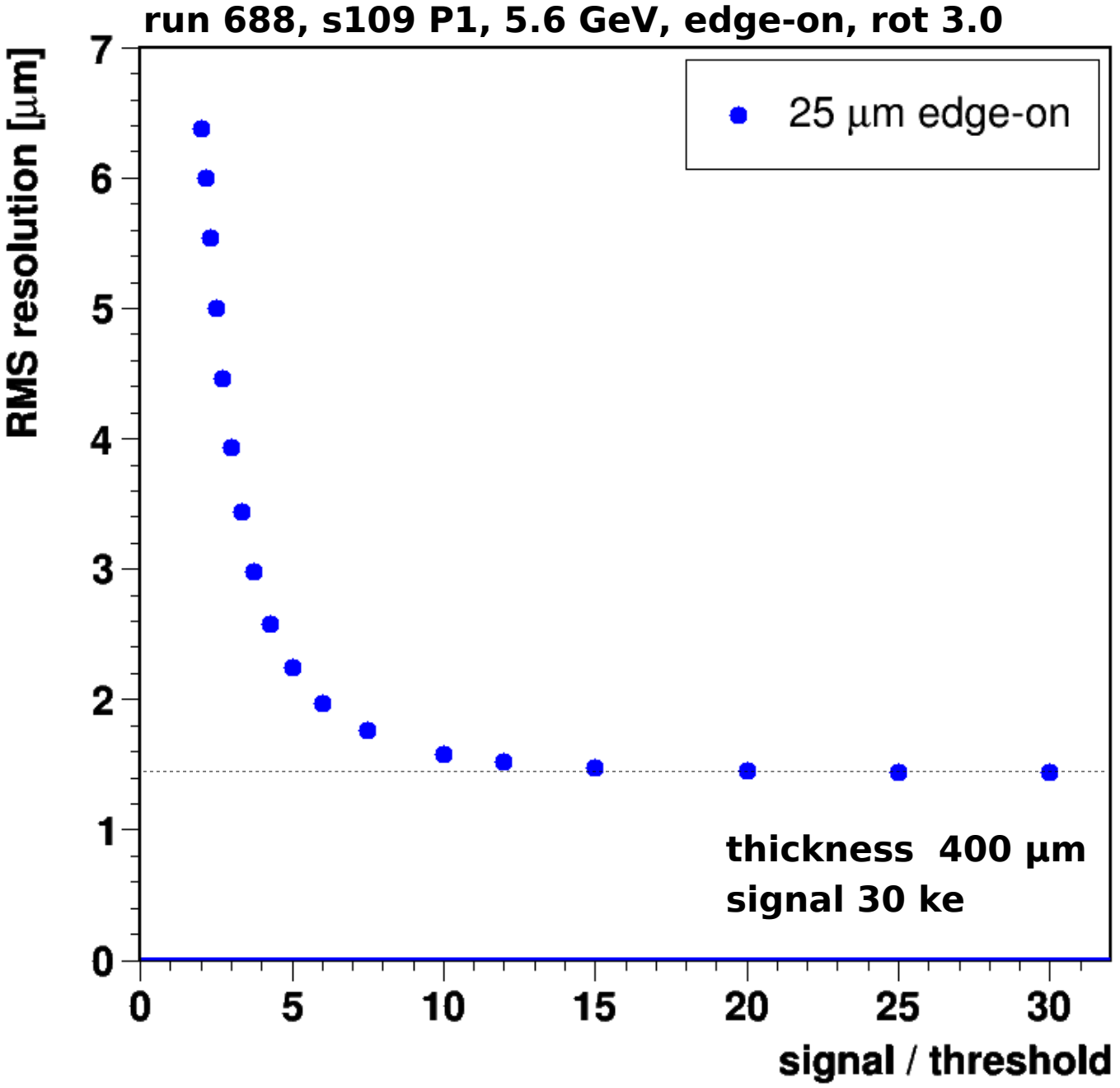
- default designs P1
- 5.6 GeV
- edge-on:
  - optimal angle for each ‘thickness’
  - internal triplet residuals
- telescope or Dreimaster:
  - external residuals
  - track contribution subtracted
  - difference to be understood

resolution vs pitch



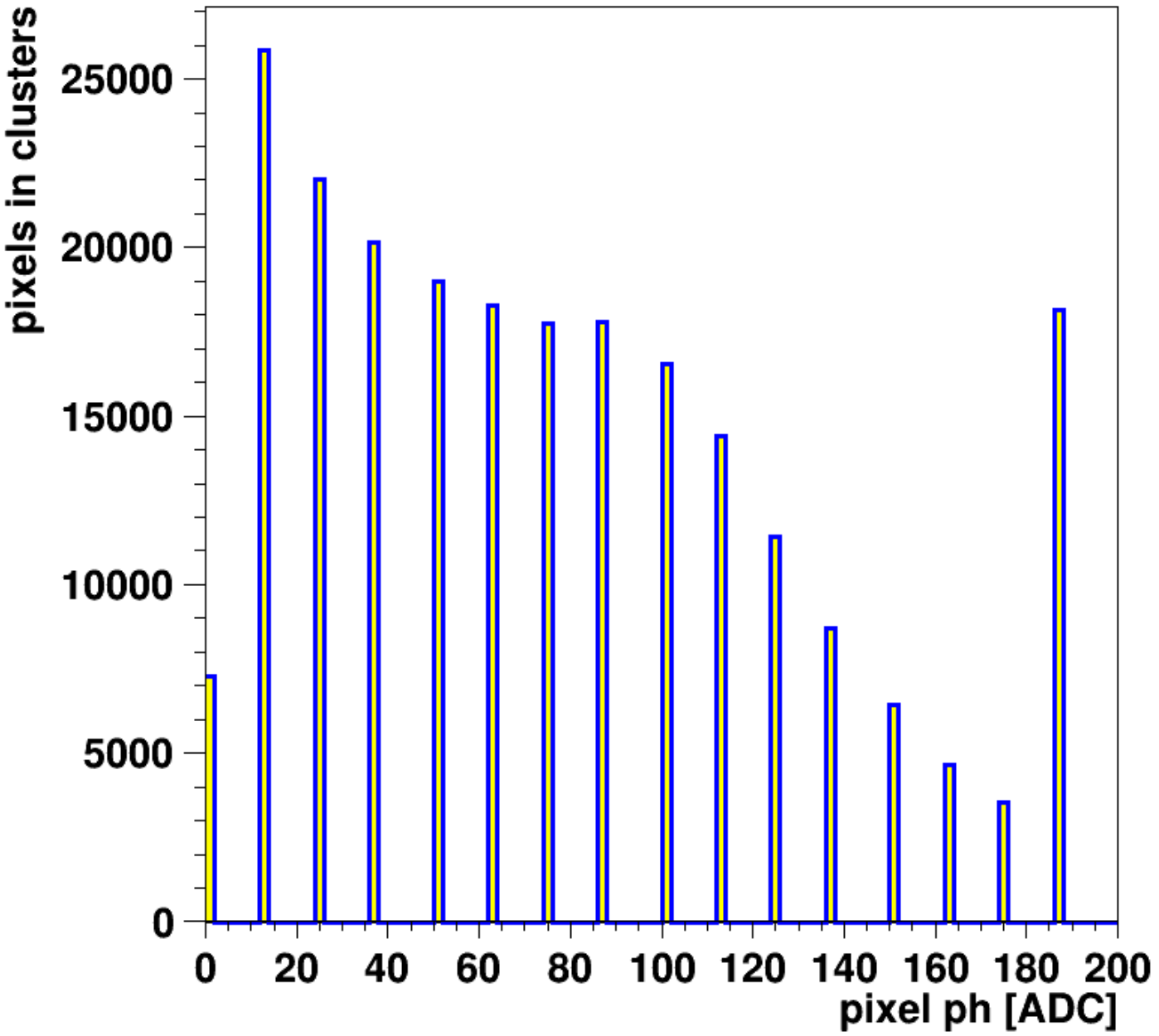
- vertical incidence, binary readout:
  - $\sigma = w / \sqrt{12}$
- optimal tilt angle, charge interpolation:
  - **$\sigma = w / 20$**
  - (empirical)
- physical resolution limit:
  - ionization fluctuations

resolution vs signal over threshold



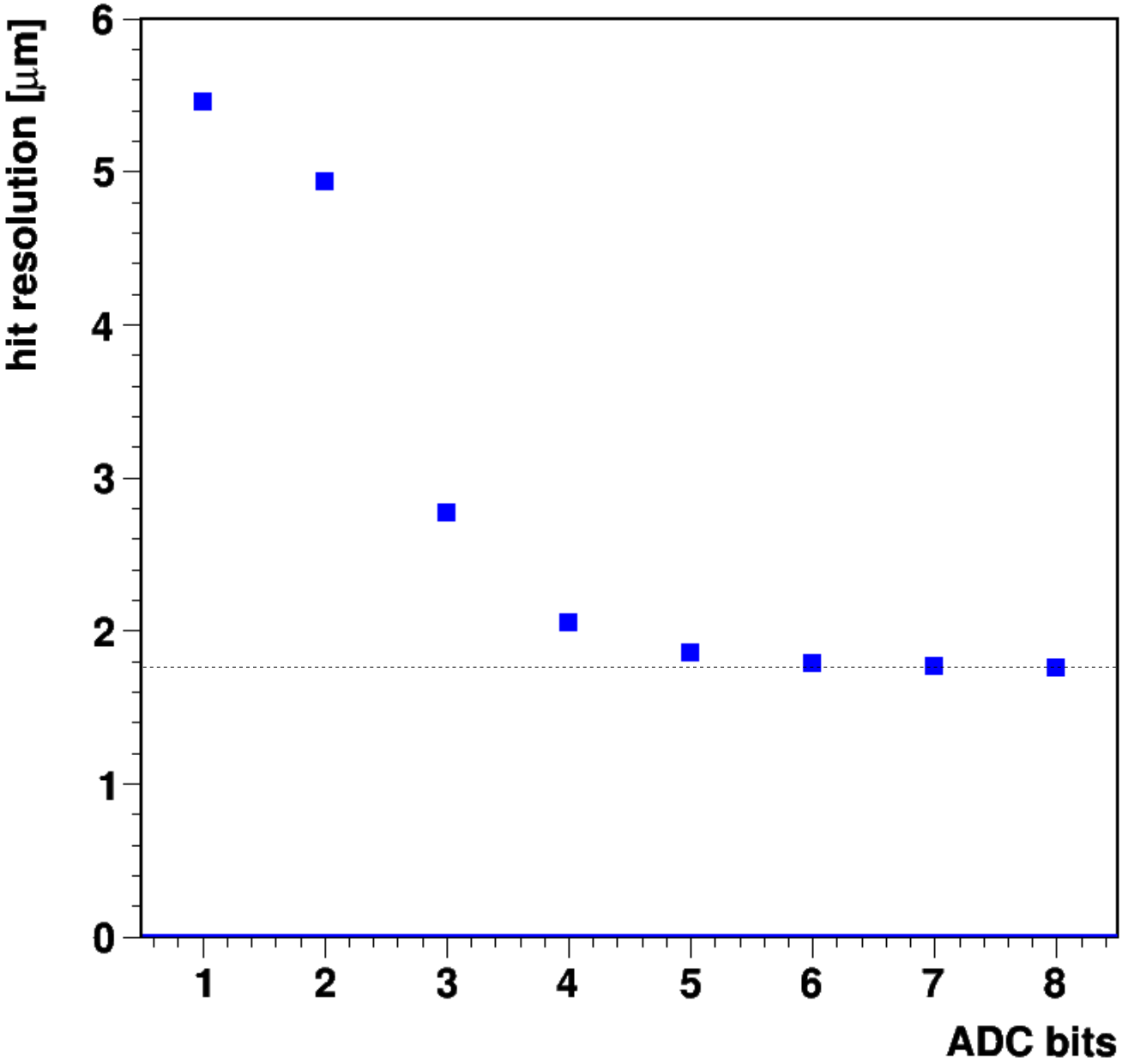
- edge-on
  - 25 µm pixels
  - default design P1
  - 5.6 GeV
  - angle 3° for 400 µm track length
  - 30 ke signal
  - threshold applied offline
- RMS single hit resolution
  - from triplet residuals
  - best above 15:1

4-bit pixel ADC spectrum



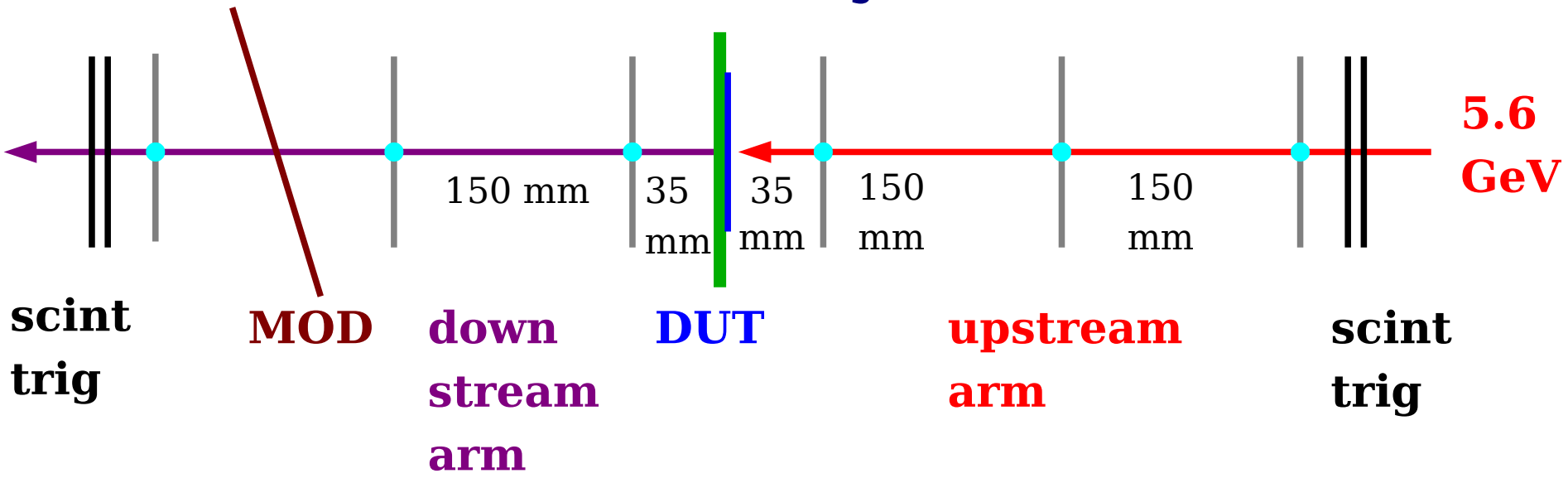
- the phase II pixel readout chip from CERN RD53 will have a 4-bit ADC per pixel:
  - 16 values
  - limited dynamic range: 1.5 MiP
- applied (offline) to test beam data with cluster Landau peak at 130 ADC counts

resolution vs ADC bits



- test beam data:
  - edge-on
  - 25 μm pixels
  - optimal tilt angle
  - 100 μm segments
- ADC digitization in range 0 to 1.5 MIPs
  - applied offline
- resolution degrades below 6 bits:
  - 4 bits is 16% worse than 8 bits

DUT efficiency definition



$$\text{eff} = \frac{\text{DUT hit linked to isolated telescope track with link to MOD hit}}{\text{isolated telescope track with link to MOD hit}}$$

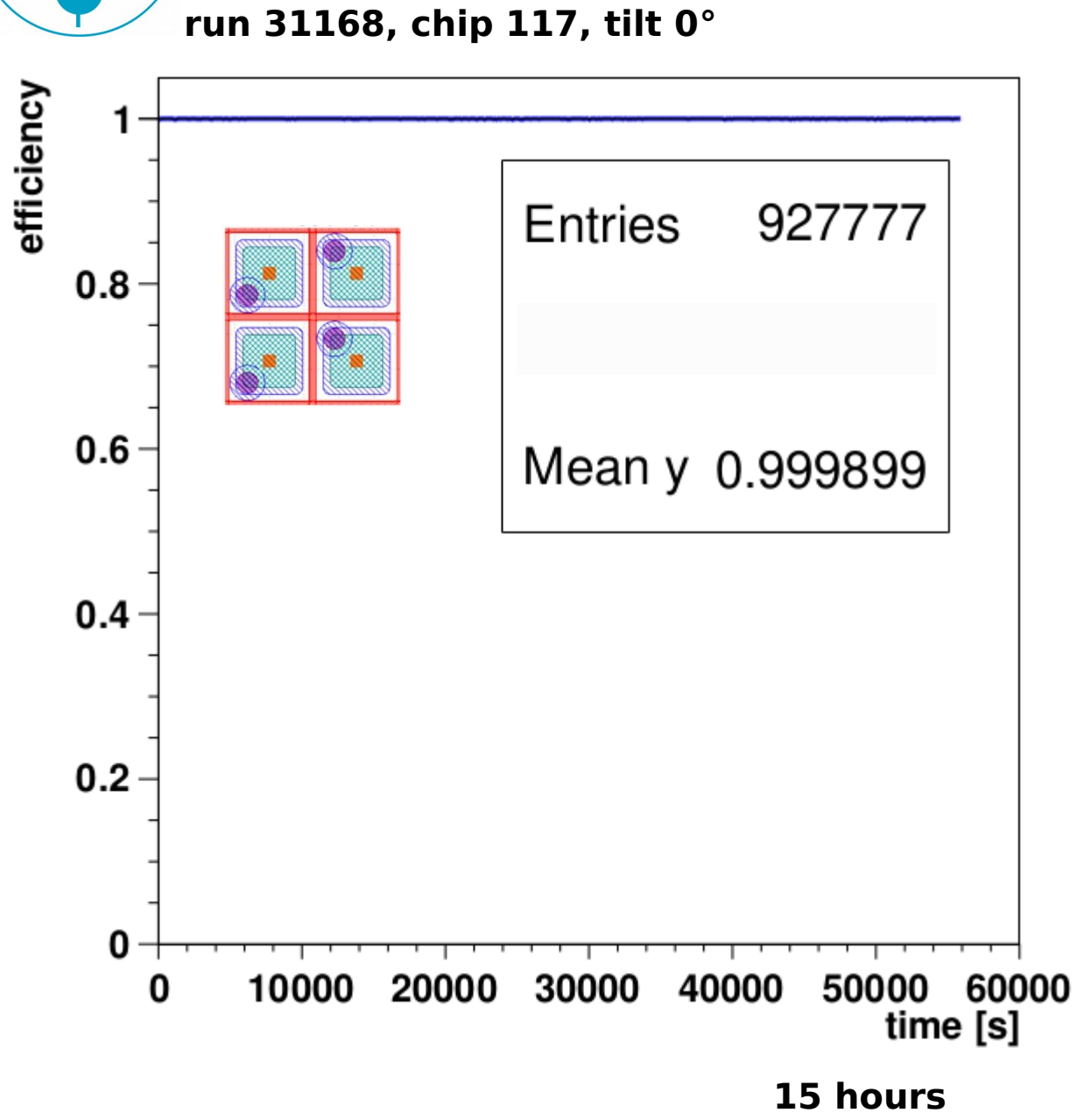
telescope track: tight matching cut 0.1 mm in *x* and *y*

isolation: no other telescope track within 0.6 mm at MOD

MOD link: tight cut 0.1 mm in *x* and *y*

DUT link: loose cut 0.3 mm in *x* and *y*

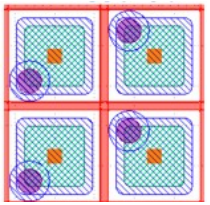
efficiency vs time

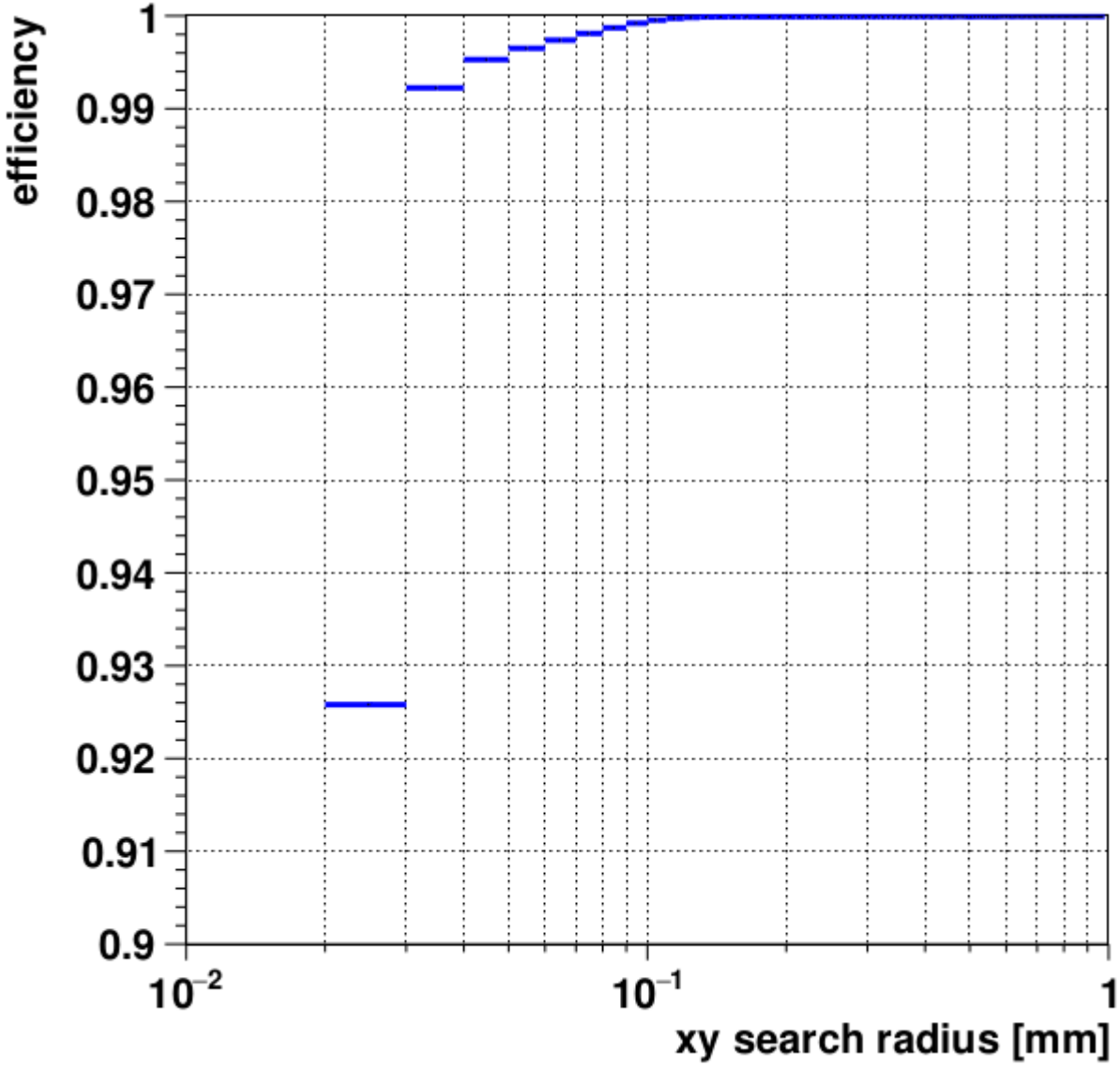


15 hours

- Efficiency:
  - nearest pixel
  - 0.3 mm window
- fiducial region:
  - 0.2 mm from sensor edges
- **flat at 99.99%**
  - thanks to ROC4Sens

efficiency vs window radius





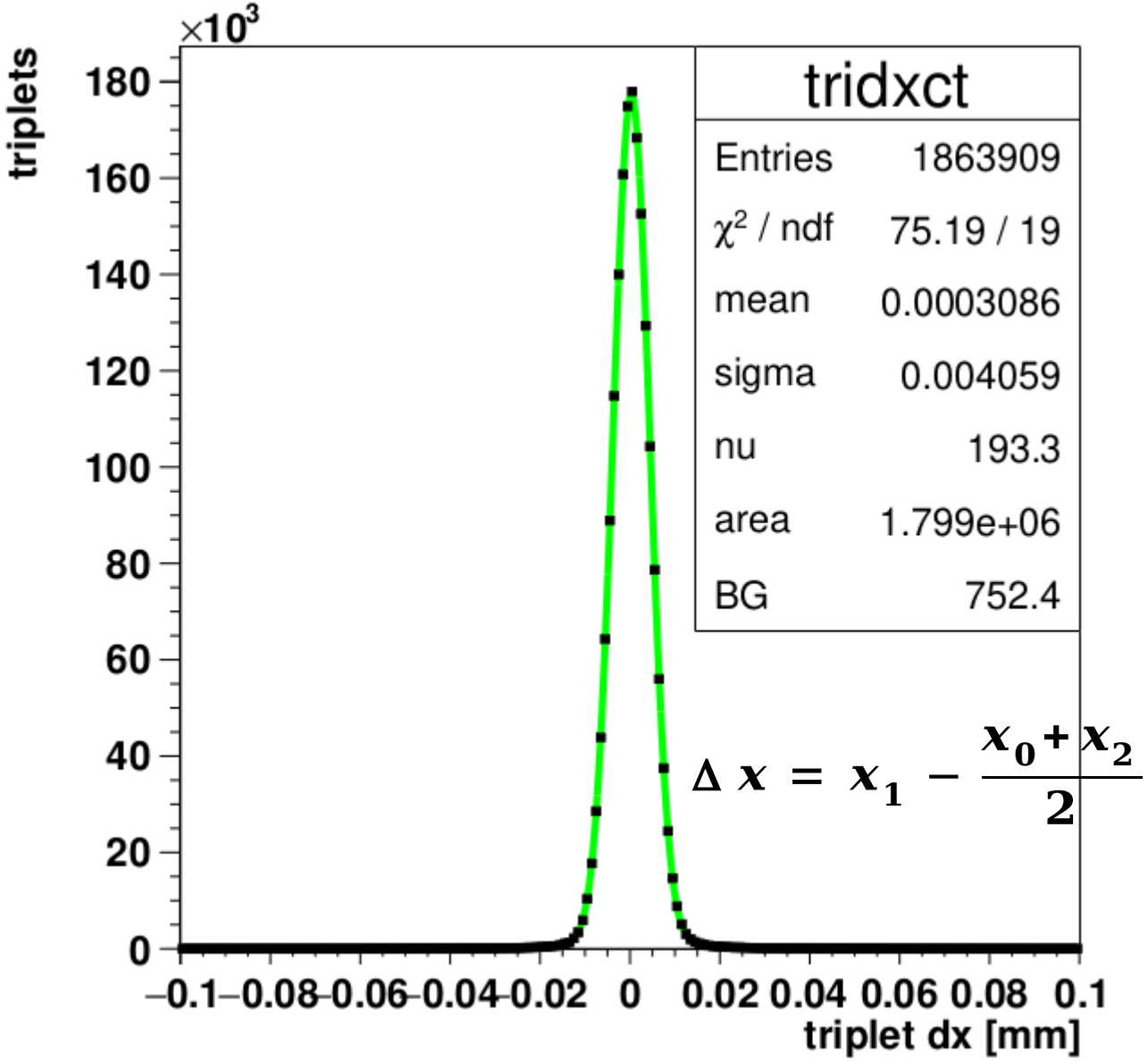
- Chip 117:
  - 50×50 µm pixels
- Efficiency:
  - nearest pixel
  - fiducial region
- *xy* search window:
  - sqrt($\Delta x^2 + \Delta y^2$)
  - 0.03 mm for 92%
  - 0.04 mm for 99%
  - 0.09 mm for 99.9%
  - 0.14 mm for 99.99%

Summary

- phase I upgrade of the CMS pixel detector completed in Hamburg:
  - module production
  - characterization in the test beam
- phase II smaller pixel sensor development ongoing at Uni HH:
  - extensive test beam program underway
  - will cover irradiated devices soon
- resolution studies:
  - need precise reference below 3 µm
  - or use self-reference with Dreimaster or edge-on technique
  - empirical scaling $\sigma = w / 20$

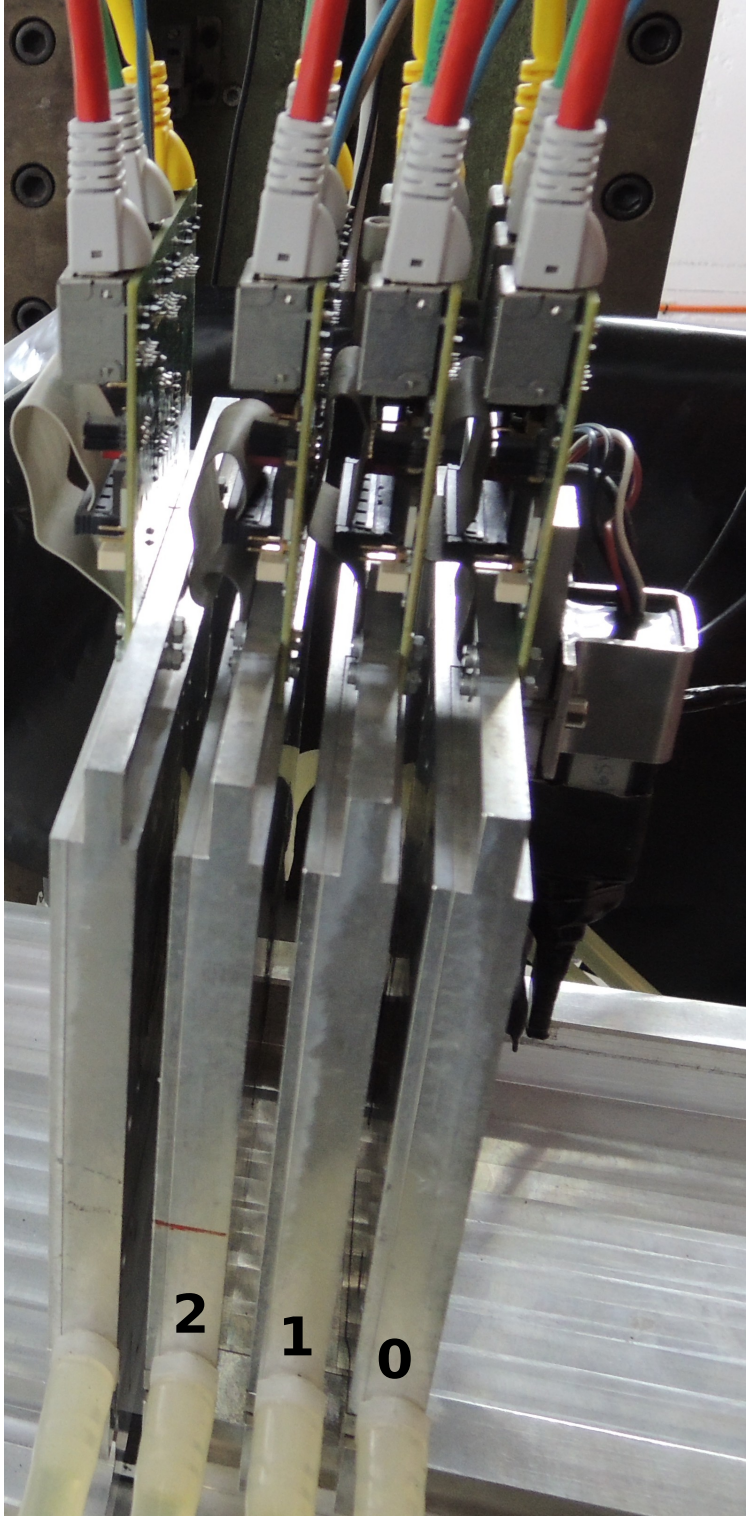
telescope resolution

Datura, threshold 5, 5.6 GeV, 21 mm spacing

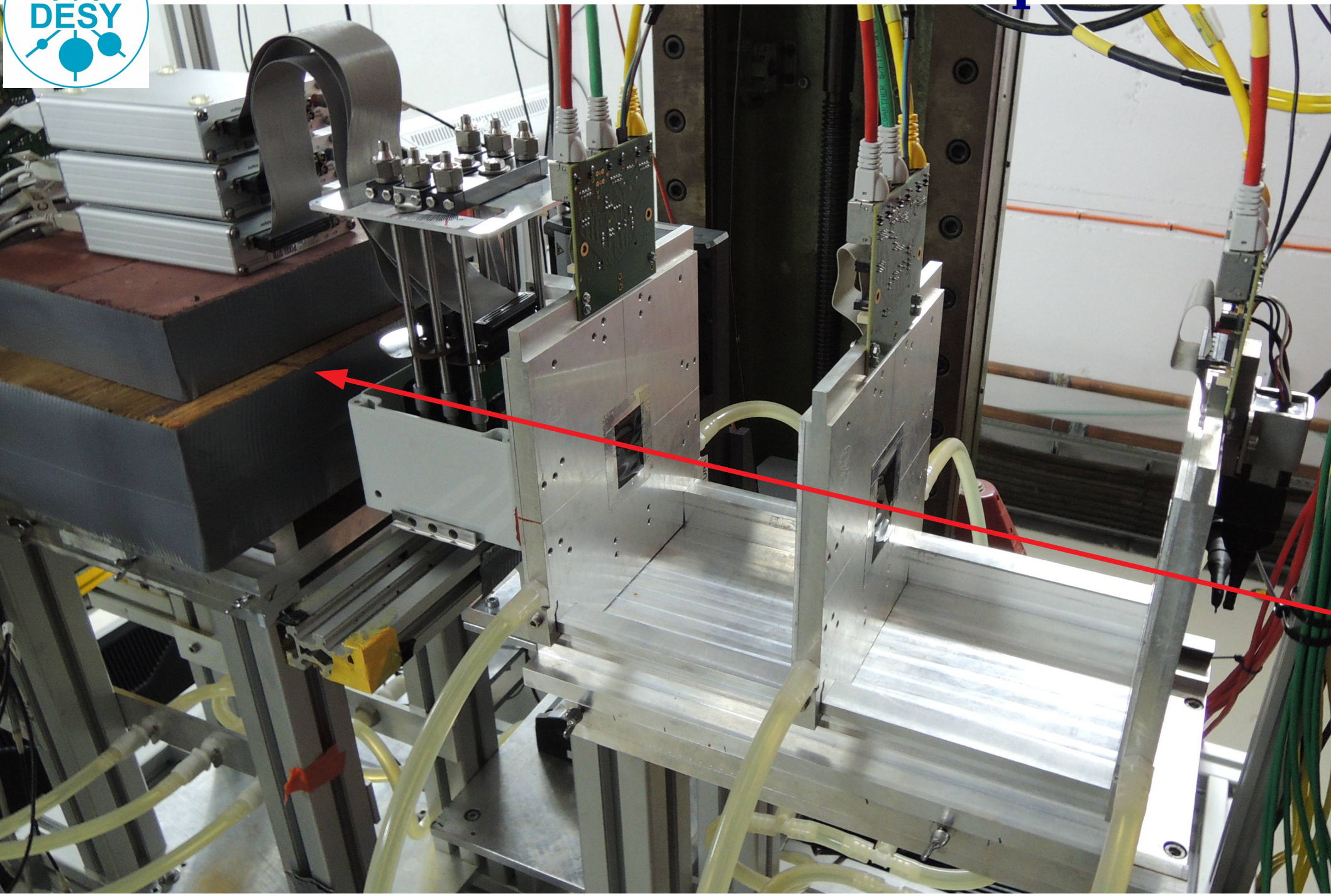


$$\Delta x = x_1 - \frac{x_0 + x_2}{2}$$

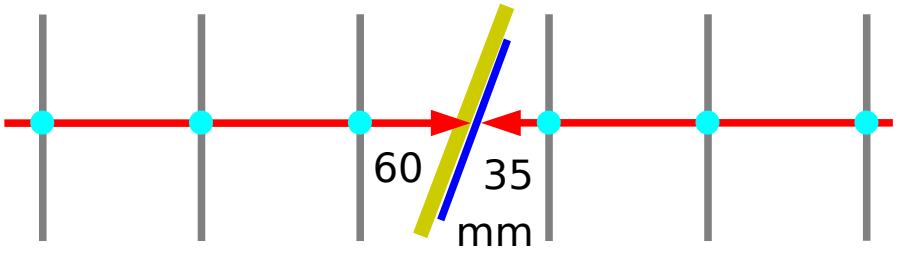
residual 4.1 µm ⇒ hit 3.3 µm



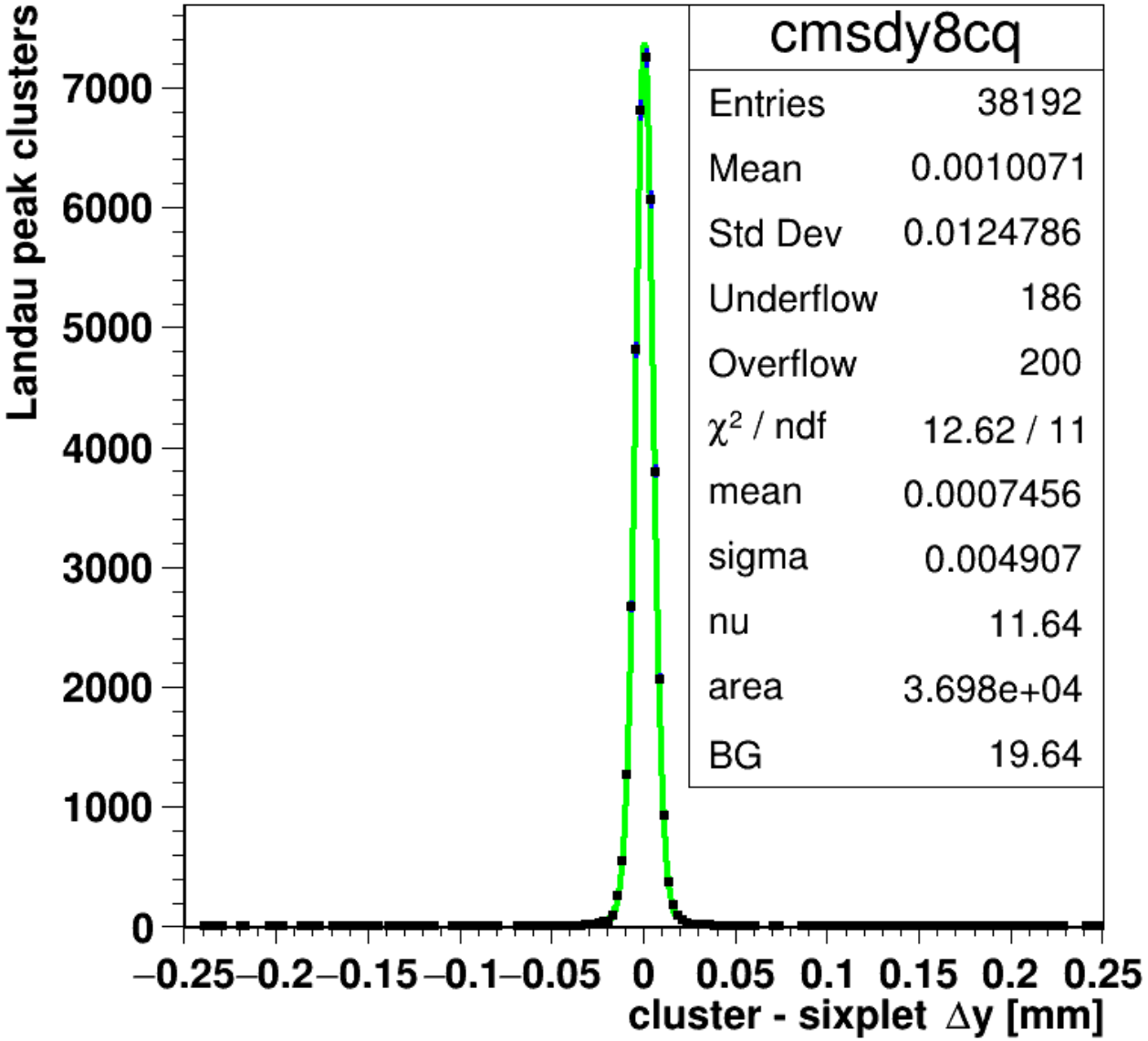
Dreimaster in the telescope



DUT residual vs six

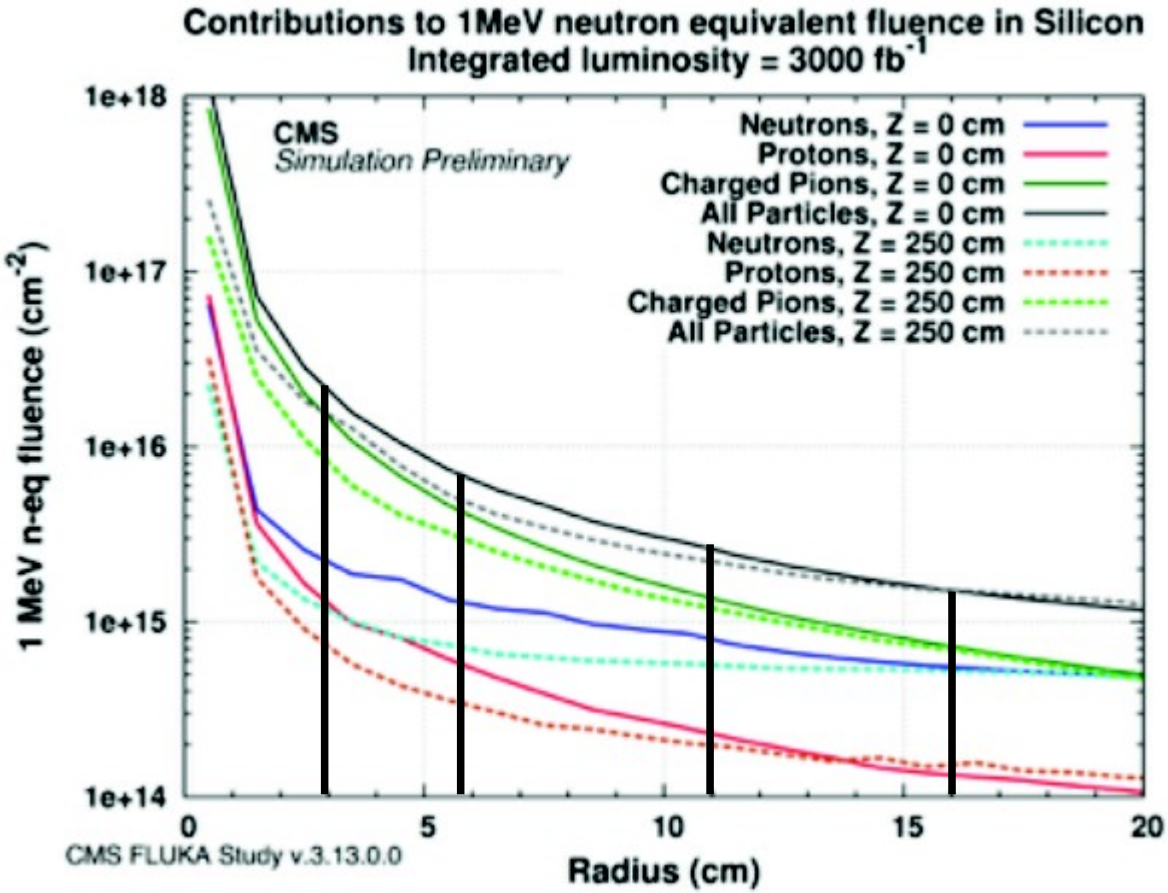


run 31166, chip 117, tilt 18°



- chip 117:
  - 50×50 µm pixels
  - tilt 18°, 5.6 GeV
  - bias 120 V
  - dph > 12 ADC
  - isolated clusters
  - Landau peak
- residual vs six:
  - **4.9 µm**
- subtract track 3.4 um:
  - **DUT 3.5 µm**
  - (like with triplet)

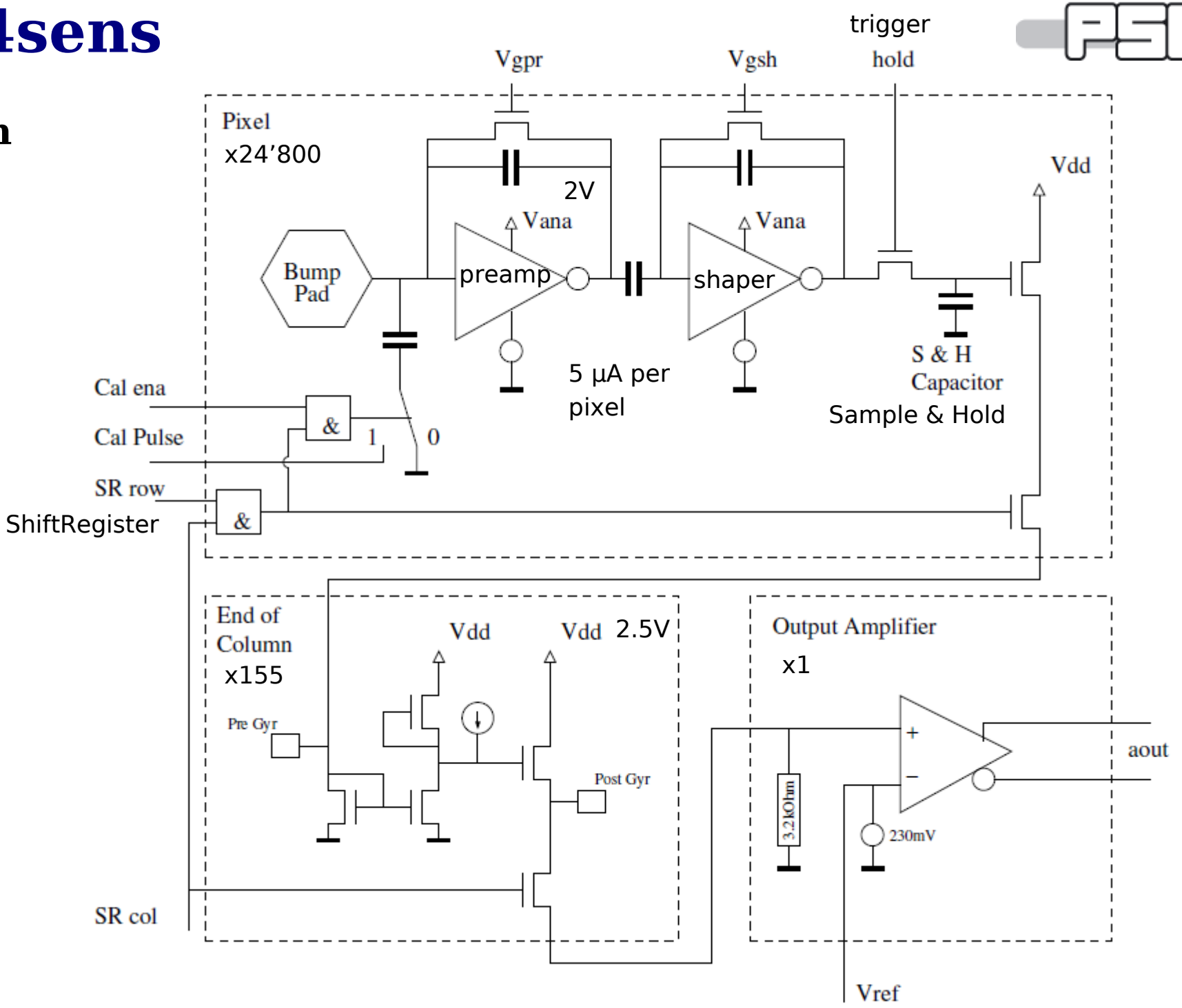
radiation



		300 fb^{-1}		500 fb^{-1}		
Layer	R, cm	Fluence, 10E15 1MeVneq/cm²	Dose, Mrad	Fluence, 10E15 1MeVneq/cm²	Dose, Mrad	Rate, MHz/cm²
1	3	2.1	**102**	3.5	**170**	**420-600***
2	6.8	0.54	29	0.9	48	120
3	10.9	0.27	14.4	0.45	24	58
4	16	0.15	7.8	0.25	13	32

ROC4sens

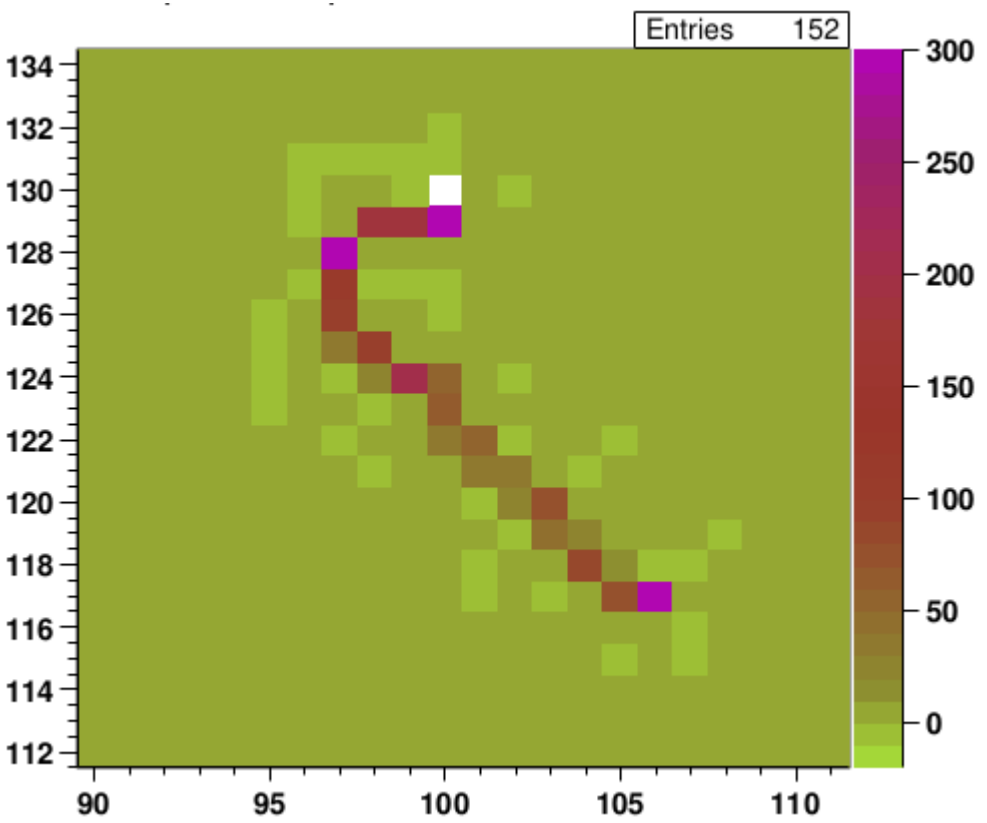
0.25 µm
IBM
CMOS

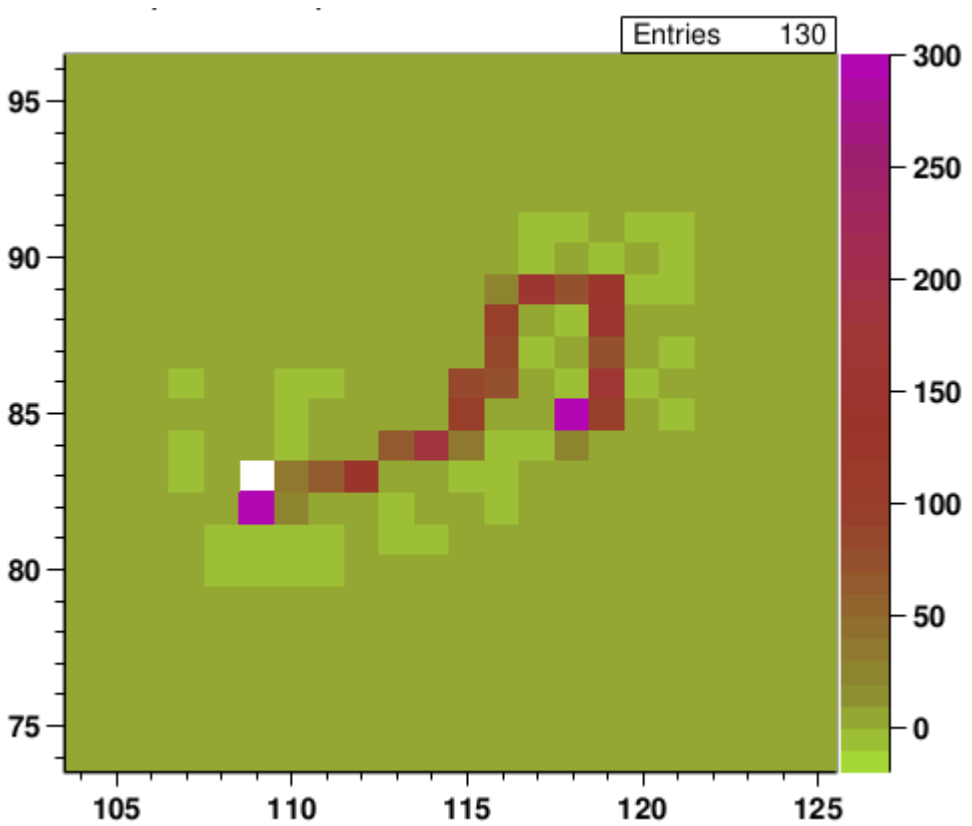


delta rays

vertical track incidence

run 540, chip 117, 50×50, 0°

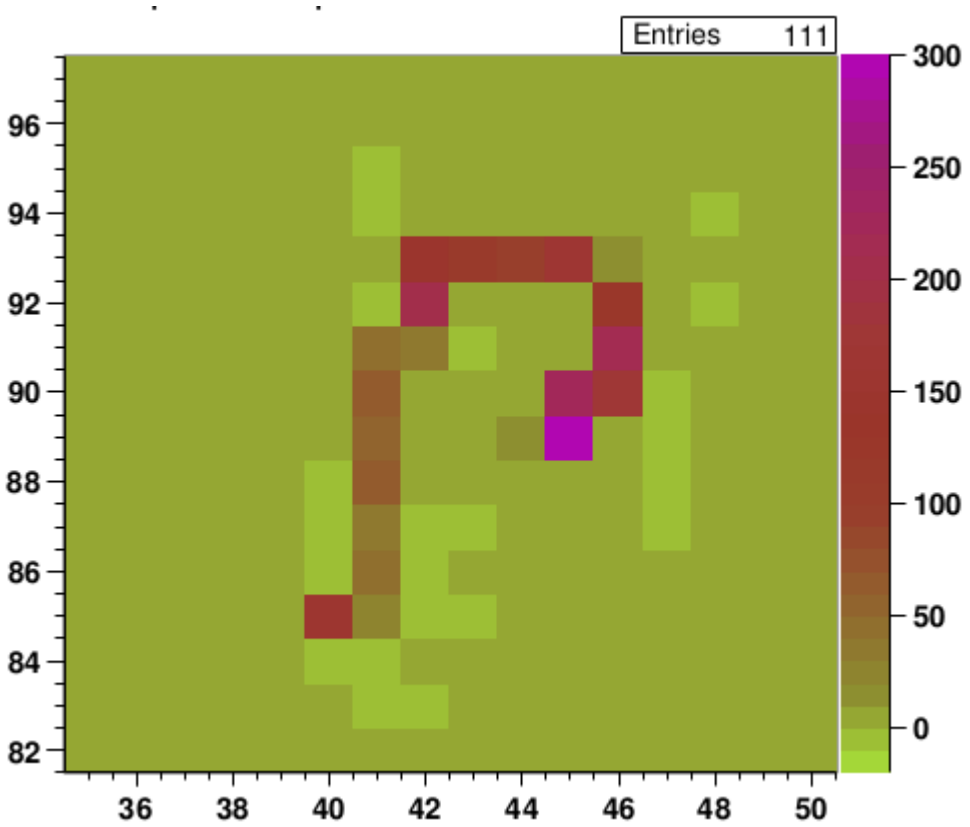


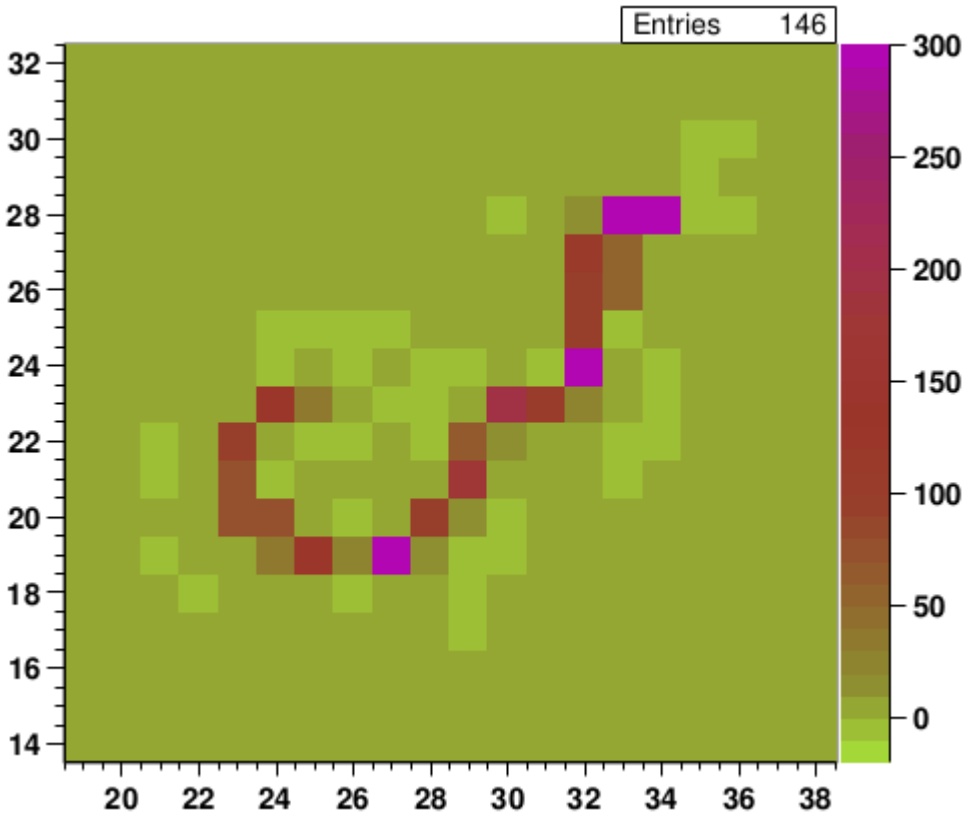


stopping delta rays: Bragg peak

vertical track incidence

run 540, chip 117, 50×50, 0°

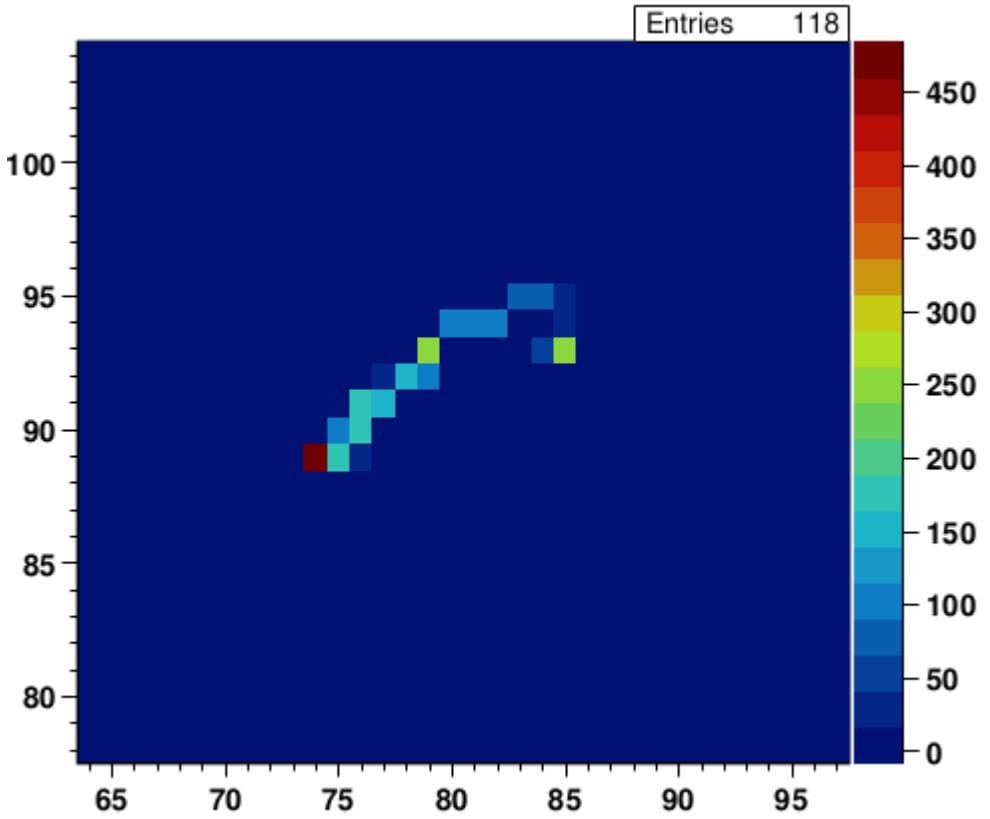


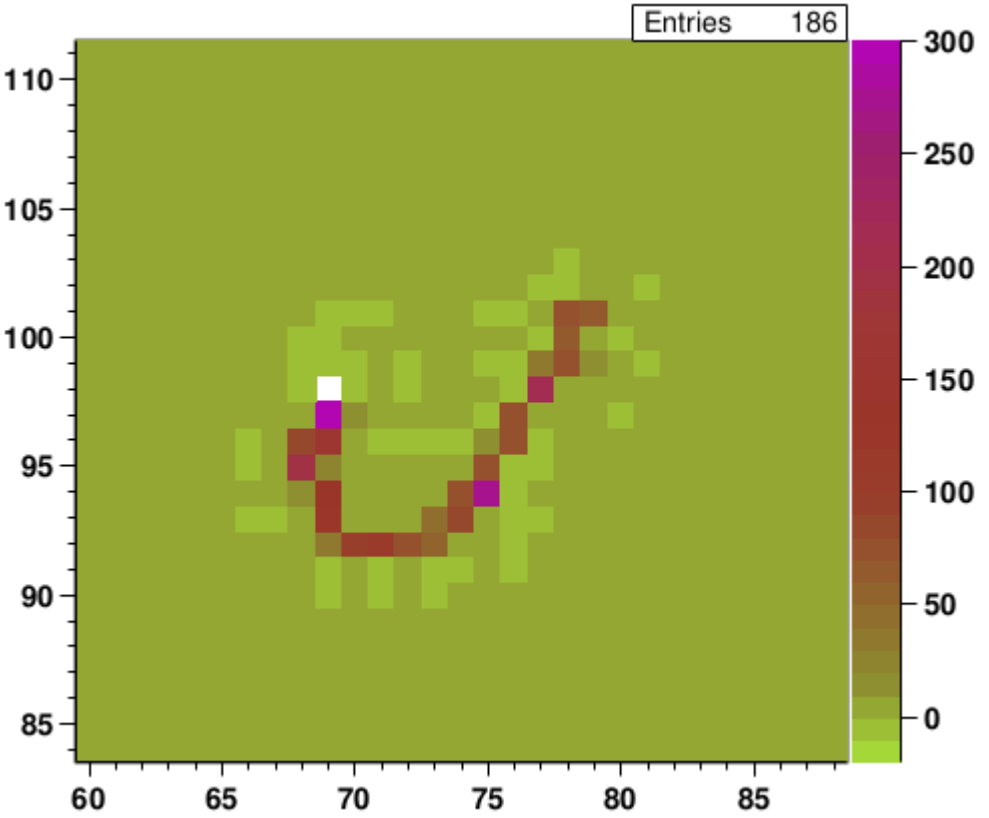


stopping delta rays: Bragg peak

vertical track incidence

run 540, chip 117, 50×50, 0°

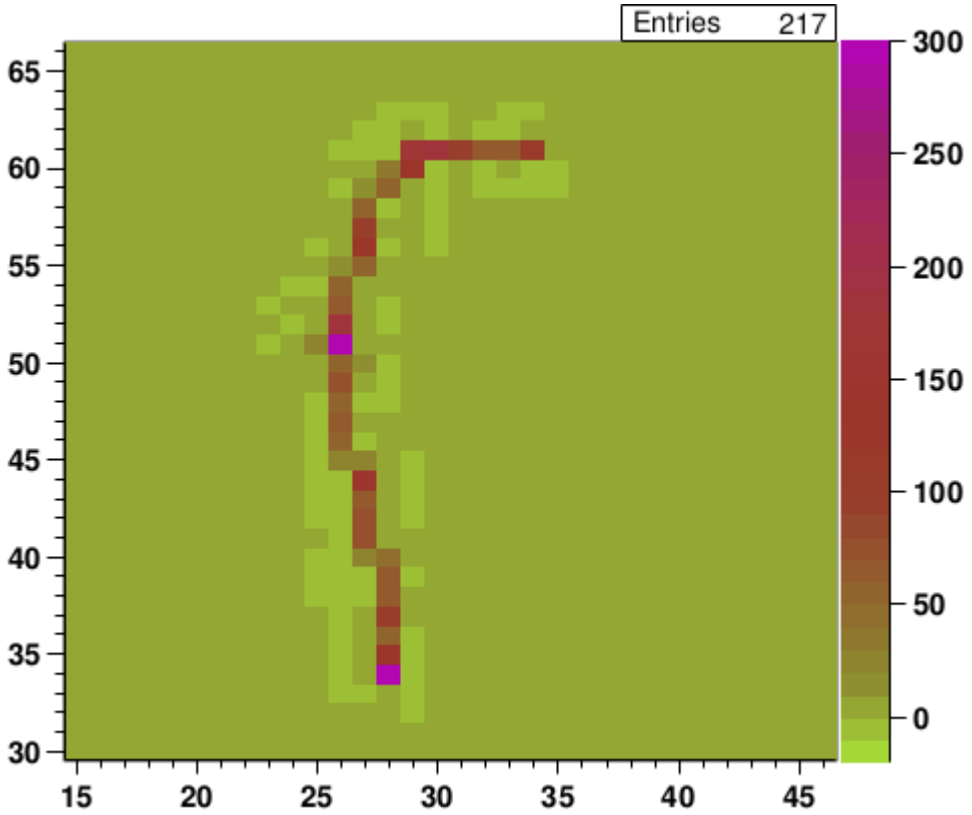


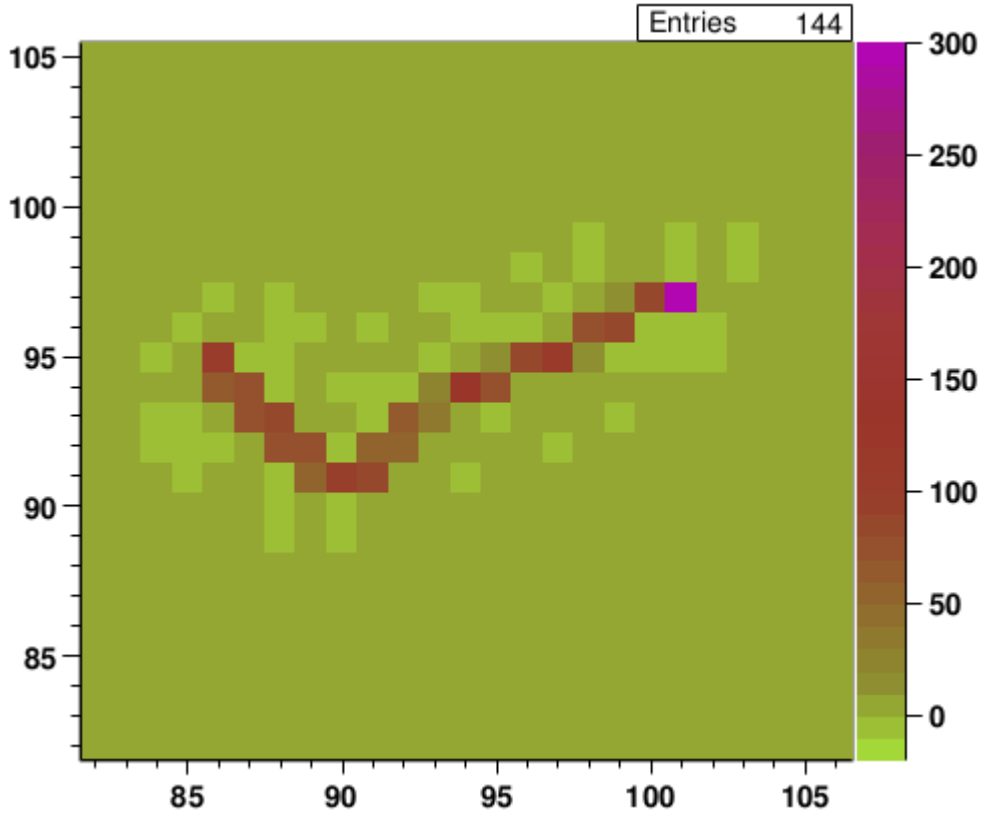


delta rays: 1 mm range

vertical track incidence

run 540, chip 117, 50×50, 0°

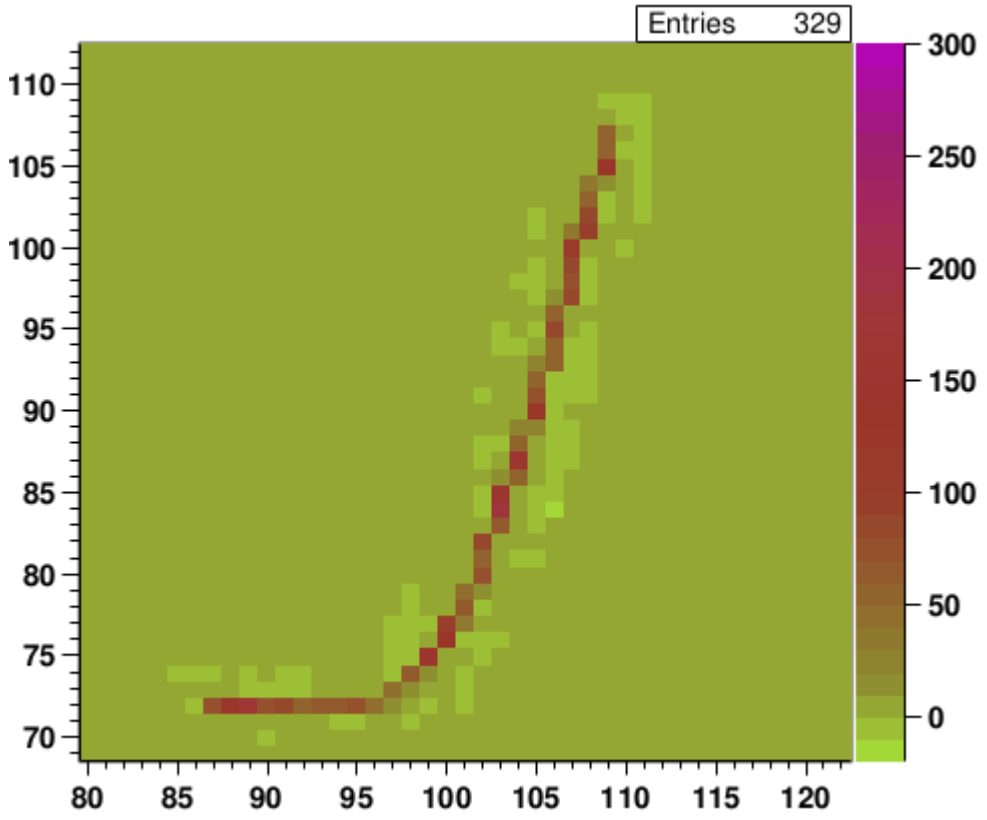


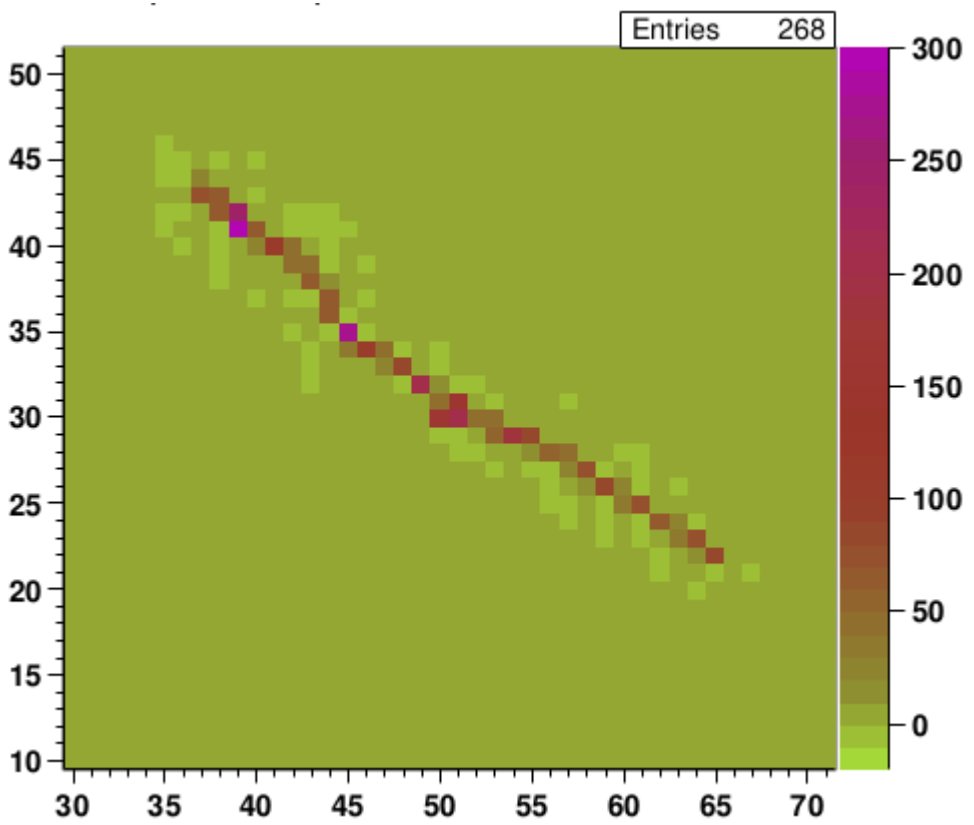


delta rays: 1.5 mm range

vertical track incidence

run 540, chip 117, 50×50, 0°

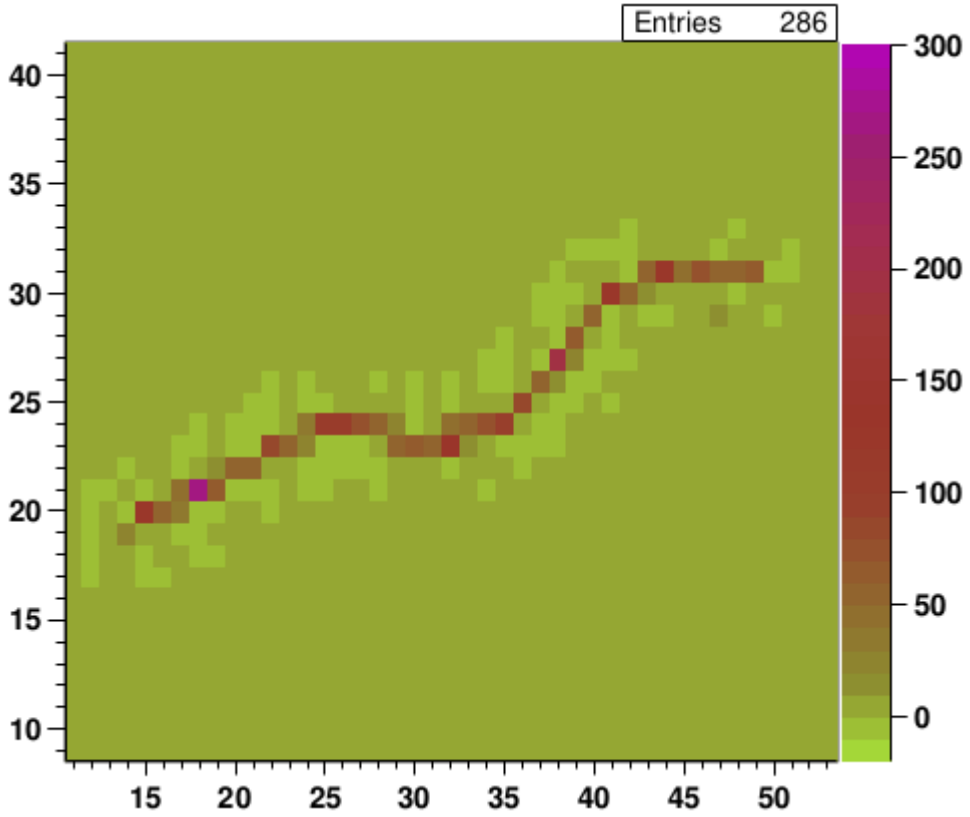


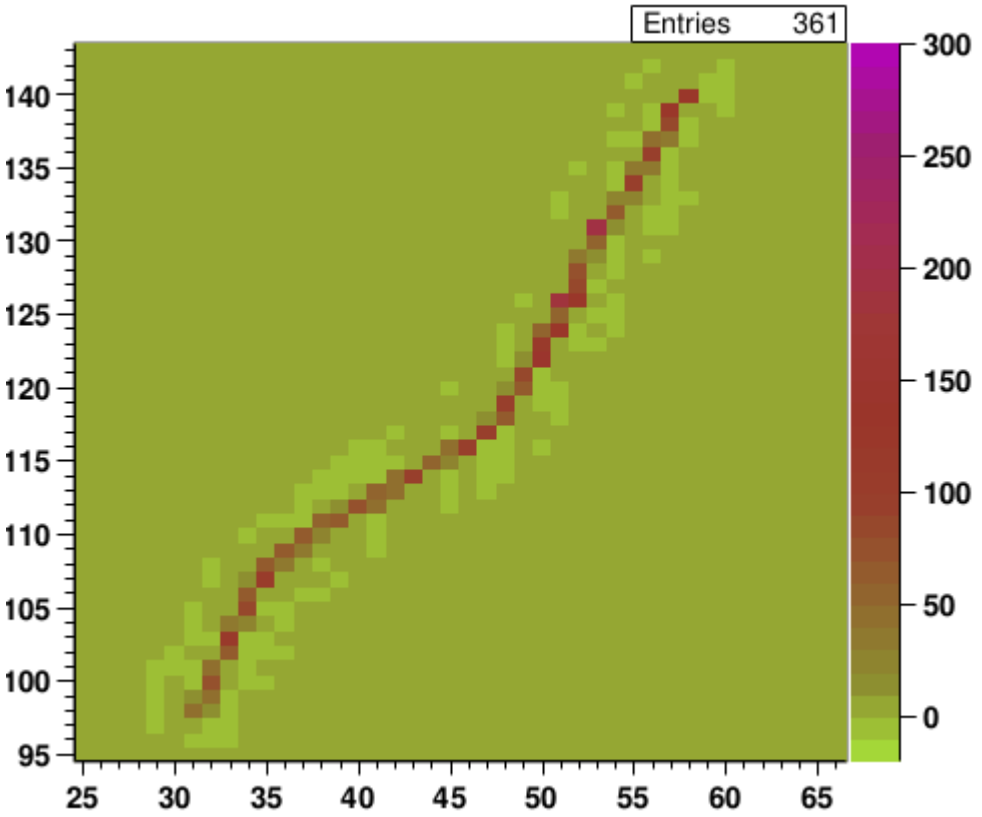


delta rays: 2 mm range

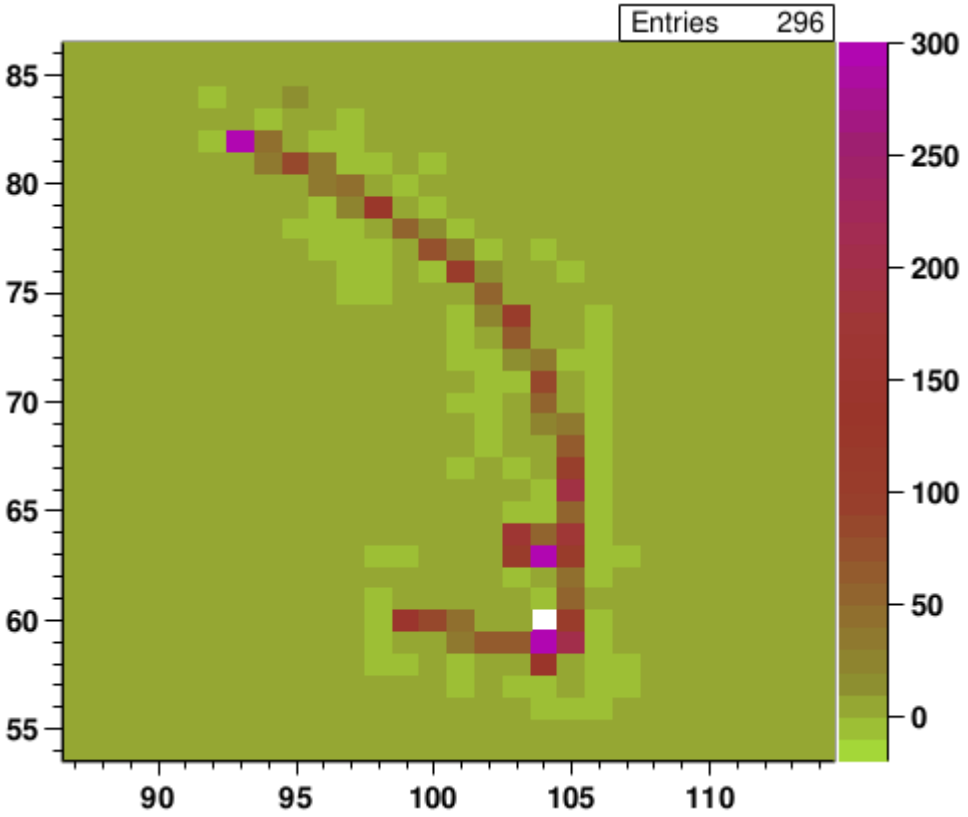
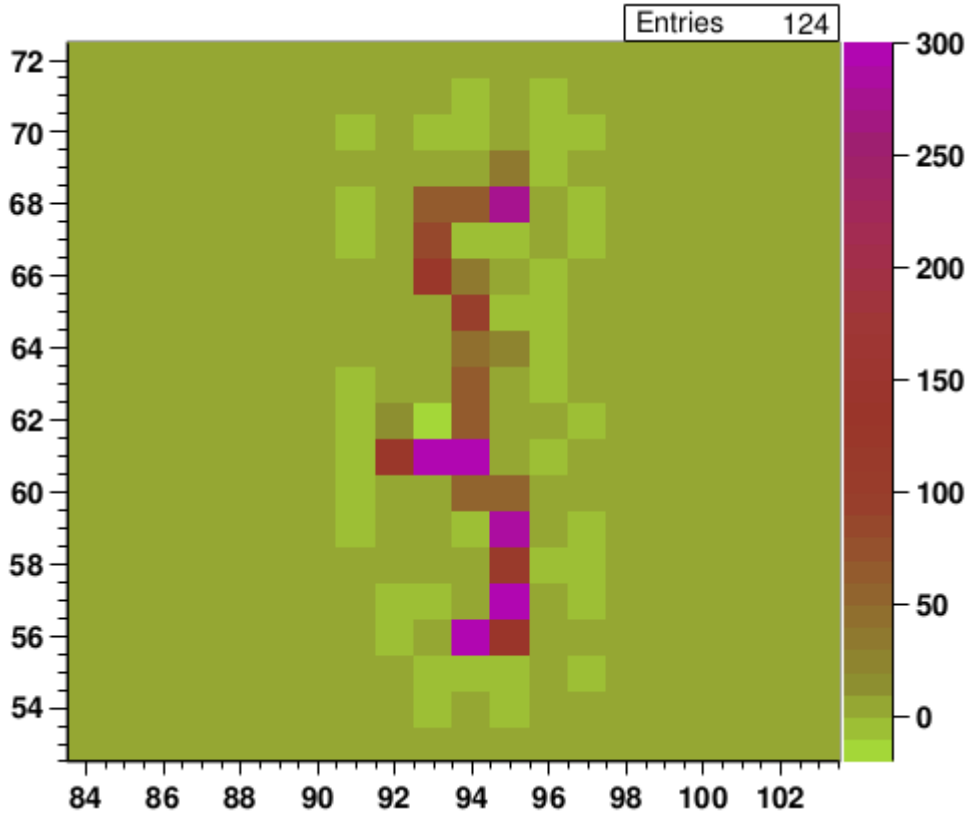
vertical track incidence

run 540, chip 117, 50×50, 0°





delta rays make delta rays

vertical track incidence

run 540, chip 117, 50×50, 0°