Studies of single-photoelectron response and of performance in magnetic field of a H8500C-03 photomultiplier tube

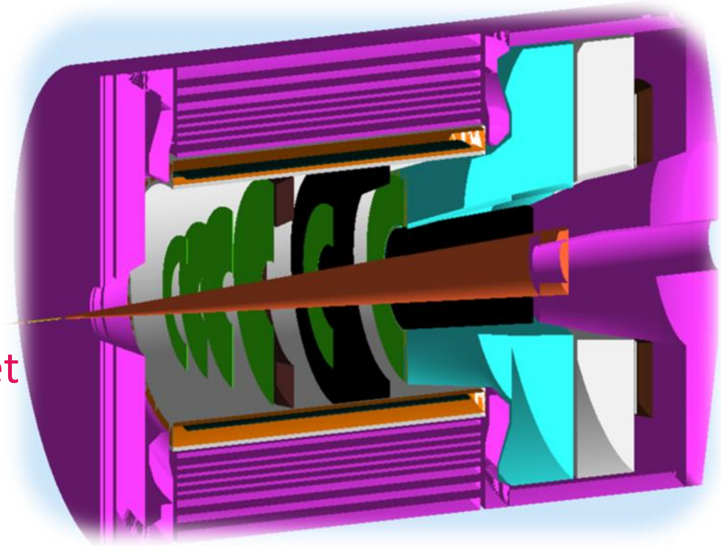
S.P. Malace (JLab)

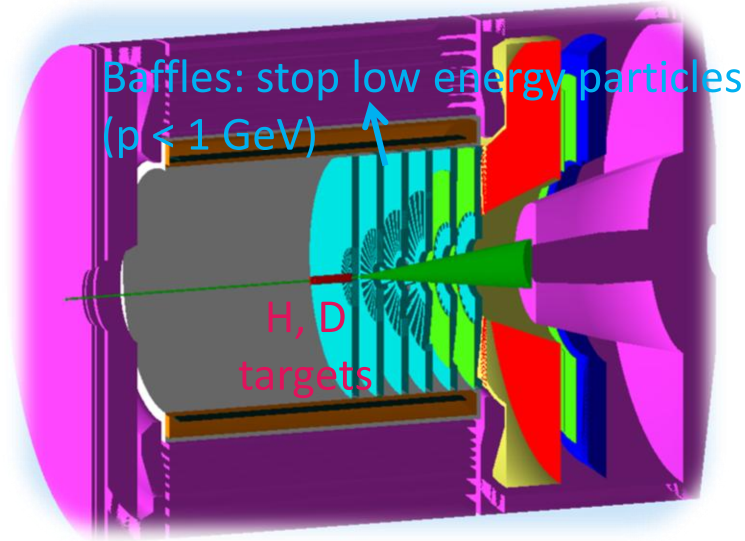
(reference *S.P. Malace, B.D. Sawatzky, H. Gao, to be submitted to NIM A*)

Acknowledgements: Drew Weisenberger, Jack Mckisson and the detector group, Chris Cuevas

Hall C Users Meeting, Jan. 24 – 25 2013, JLab

Motivation: SoLID … I suppose





SIDIS electron Cherenkov: 1.5 – 4.5 GeV

SIDIS pion Cherenkov: 2.5 – 7.5 GeV

PVDIS Cherenkov: 2 – 3 GeV

Threshold Cherenkov:
- electron-pion separation: SIDIS & PVDIS
- pion-kaon/proton separation: SIDIS

→ **2π** coverage

→ Perform in non-negligible magnetic field environment ~ 200 gauss

→ Perform in non-negligible electromagnetic and hadronic background environment

→ Simple design: cost effective, easy to install, operate

Why H8500C-03?

Possibly it could:

→ function in non-negligible magnetic field, ~200 gauss

→ be suitable for tiling: good packing density

→ have good resolution for single photoelectrons

→ work in an environment with non-negligible electromagnetic and hadronic background

H8500C-03

Parameter		H8500C	H8500D	H8500C-03	H8500D-0
Spectral Response		300 to 650		185 to 650	
Peak Wavelength		400			
Photocathode Material		Bialkali			
Window	Material	Borosilicate glass		UV glass	
	Thickness	1.5			
Dynode	Structure	Metal channel dynode			
	Number of Stages	12			
Number of Anode Pixels		64 (8 × 8 matrix)			
Pixel Size / Pitch at Center		5.8 × 5.8 / 6.08			
Effective Area		49 × 49			
Dimensional Outline (W × H × D)		52 × 52 × 27.4			
Packing Density (Effective Area / External Size)		89			

Outline

→ Since August 2012 we performed single-photoelectron (SPE) measurements and mapping of the multianode PMT H8500C-03 response to magnetic field -- more than 2000 runs taken, (too) many hours of data

→ We tested 3 individual pixels and 2 groups of 16 pixels (2 quads)

Single-photoelectron measurements

→ We clearly identified SPE signals on both individual pixels and sum of pixels (quads) – not a given, this PMT has fairly low gain ~10^6

→ We used an established PMT response function to extract the SPE resolution of the H8500C-03

→ We gain-matched pixels and shown that the resolution could be improved for sum of pixels

Outline

Magnetic field measurements

→ **We measured the effect of magnetic field on SPE distributions on both individual pixels and sum of pixels (quads)**

→ **We measured the effect of magnetic field on large signals (40 photoelectrons or larger) on both individual pixels and sum of pixels (quads)**

→ **We use magnetic fields as larger as 300 gauss (highest to date on this PMT to our knowledge)**

Experimental Setup

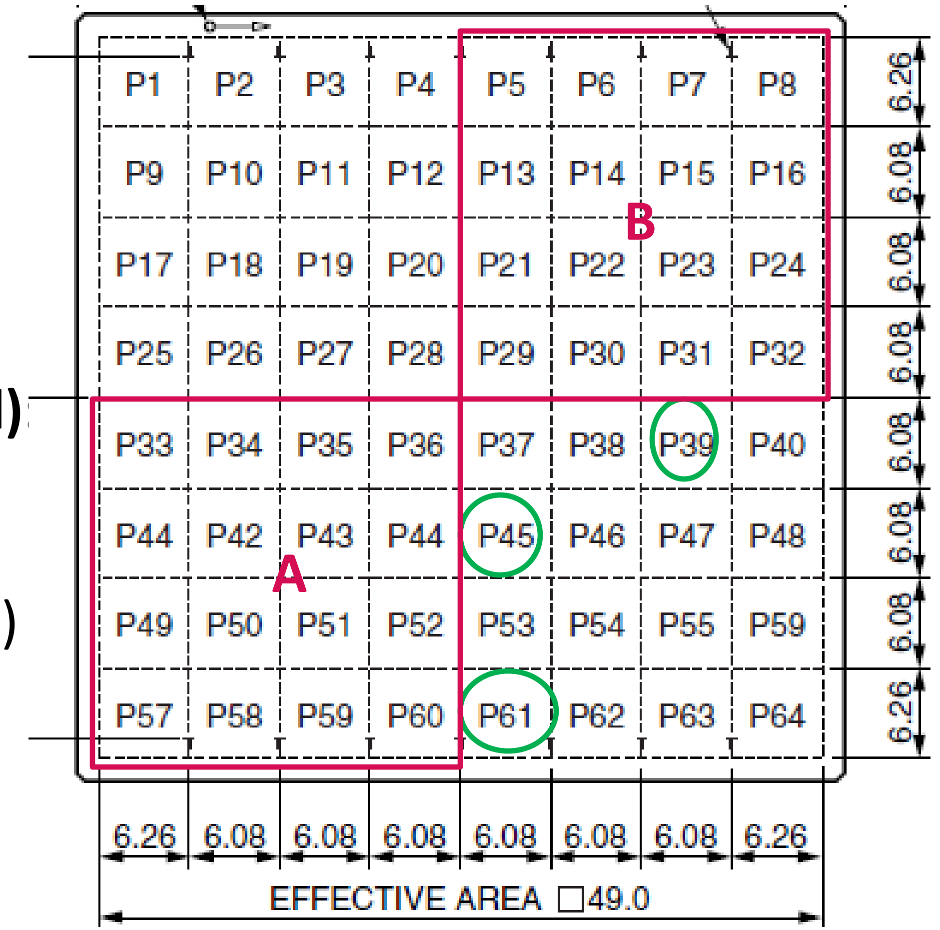
What is it that we measure?

→ We measure the output of 3 individual pixels:

Highest gain - pixel 61 (edge pixel): output = 100
Moderate gain - pixel 45 (central pixel): output = 79
Low gain - pixel 39: output = 51
(output as read from Hamamatsu map)

Edge pixels behave very differently in magnetic field than central pixels because their different dynode structure

→ We measure the output of 2 groups of 16 pixels (2 quads: A and B) – likely a configuration to be used for SoLID



Experimental Setup

→ **Tests were performed at JLab, EEL 126**

- We triggered on the pulse that powered the green LED used to illuminate the PMT

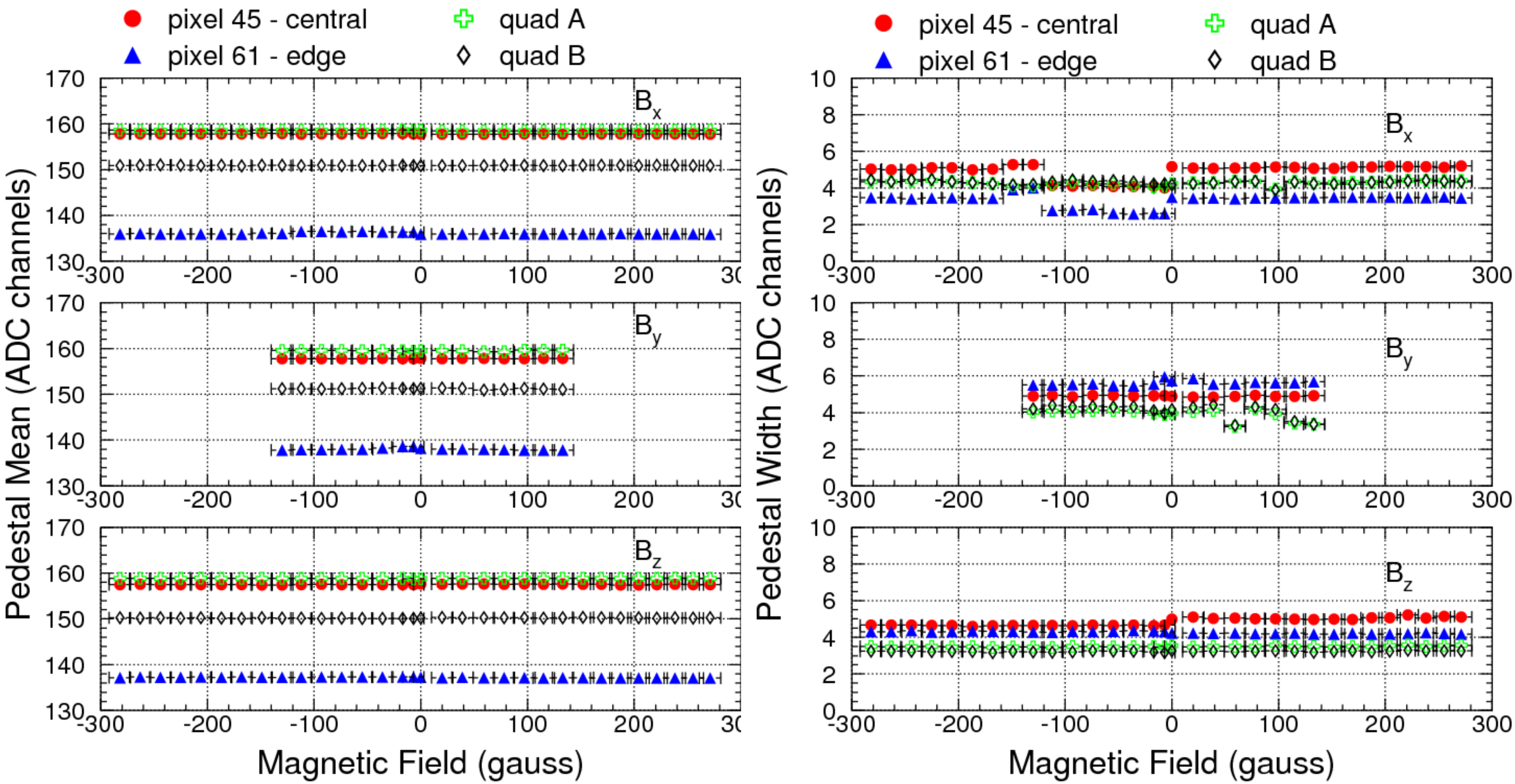
  - Characteristics of the LED pulse:
    → 20 ns wide
    → amplitude varied from 0.8 V to 4.5 V depending on the goal of the tests
    → rate: 2 kHz

- The PMT signal was passed through 10 X amplification

- For PMT signal detection we used a charge integrating ADC: 32-cannels V792 (we stayed away from the regions of nonlinearities this time:);
ADC gate = 200 ns
- For data acquisition we used CODA 2.5

Experimental Setup

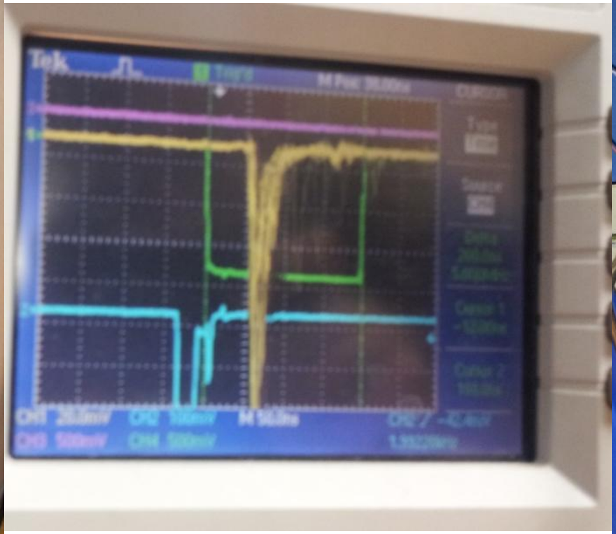
→ **The experimental setup has been very stable over the course of 3 months**

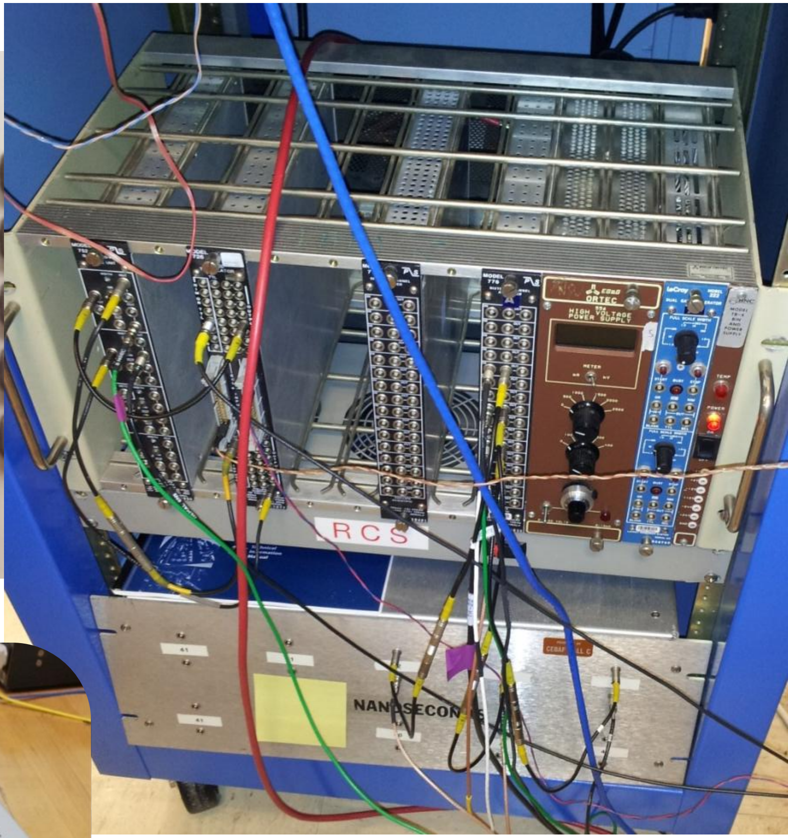


Example: mean and standard deviation of the pedestal runs taken during the magnetic field measurements over the course of ~2 months

Experimental Setup

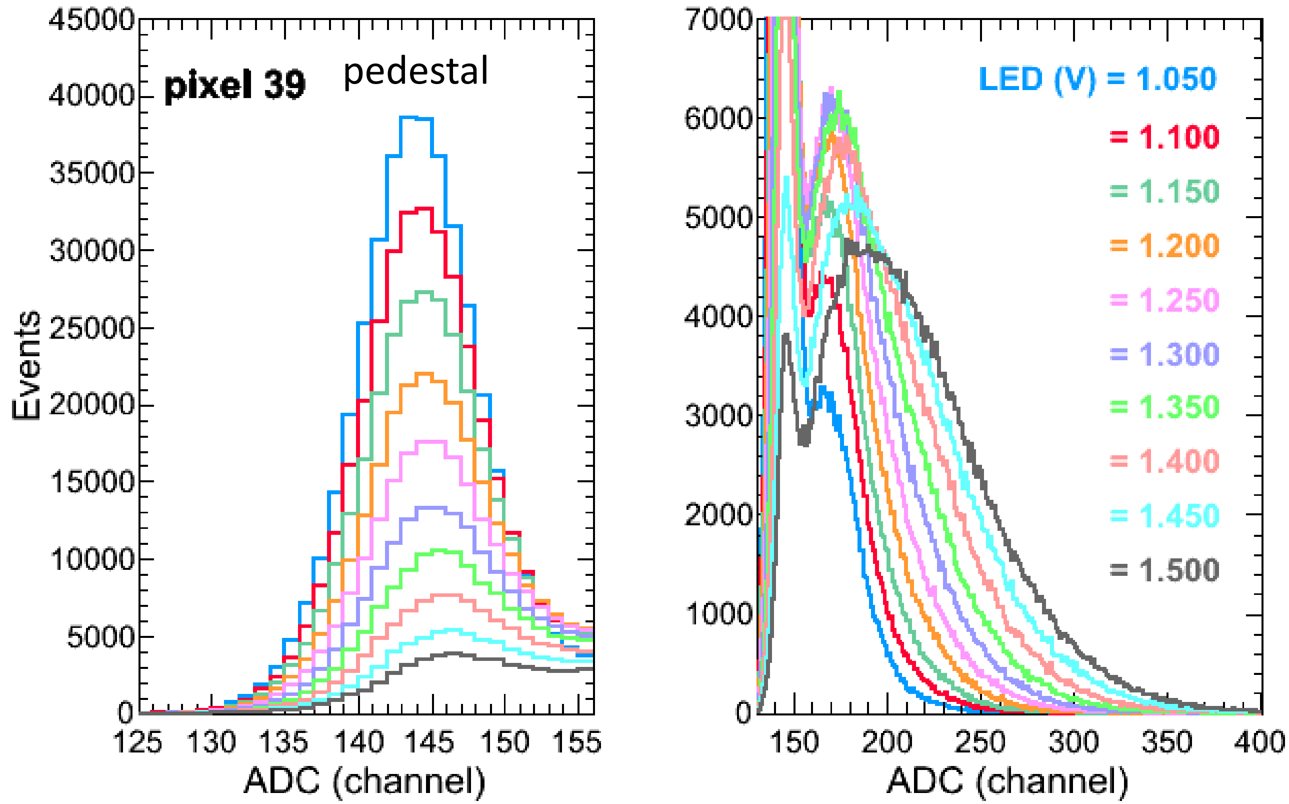
→ **The experimental setup in EEL 126 at JLab**





SPE Measurements: Pixel 39

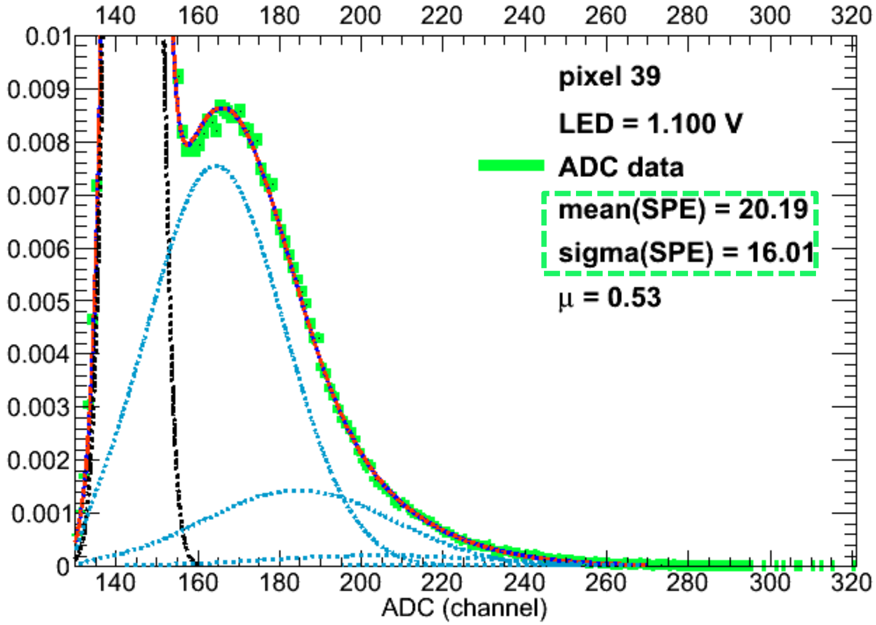
→ The yield of photons produced by the LED has been "chosen" such that the production of single photoelectrons from the PMT photocathode is favored; *by varying the LED voltage in small steps we reveal the quantum nature of the process*

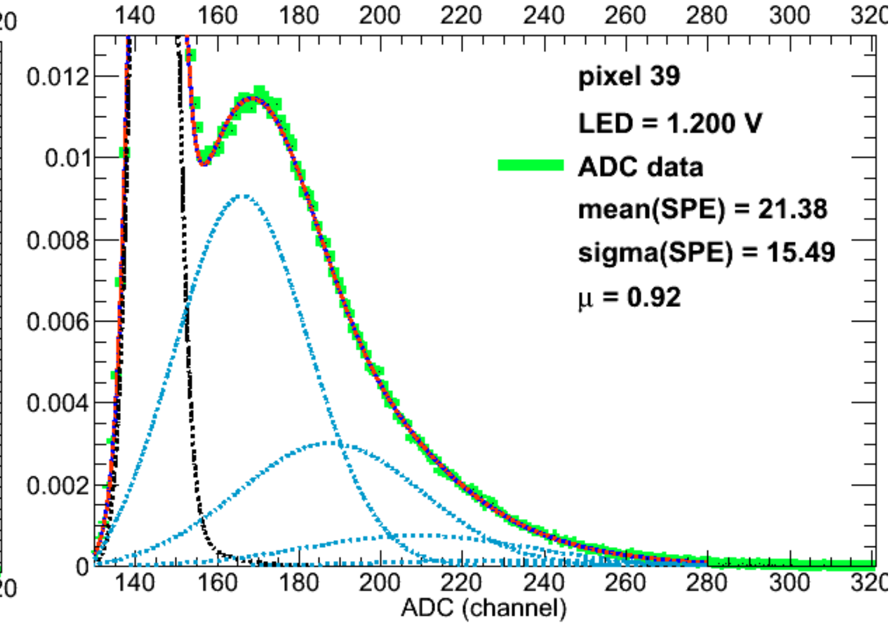


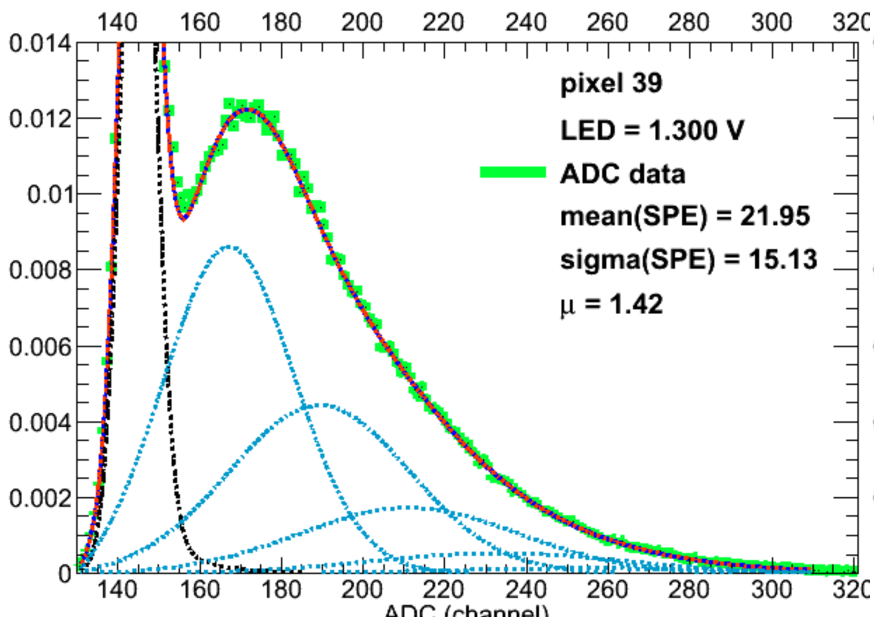
→ We use a well established PMT response function to extract the **mean** (above pedestal) and the **standard deviation** of the SPE distribution

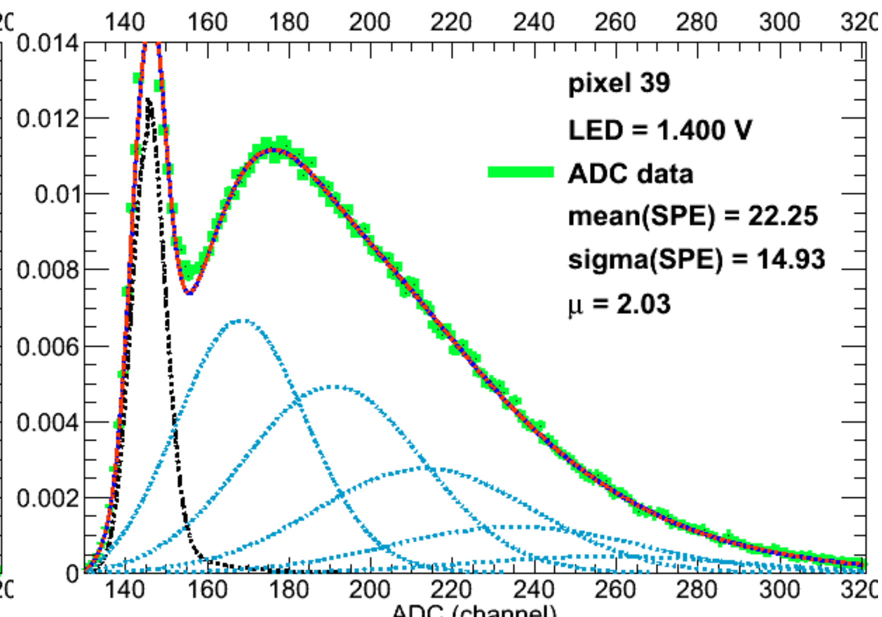
$$S_{\text{real}}(x) = \int S_{\text{ideal}}(x')B(x-x')\,\mathrm{d}x' = \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \times \left[(1-w)G_n(x-Q_0) + wI_{G_n \otimes E}(x-Q_0)\right]$$

SPE Measurements: Pixel 39



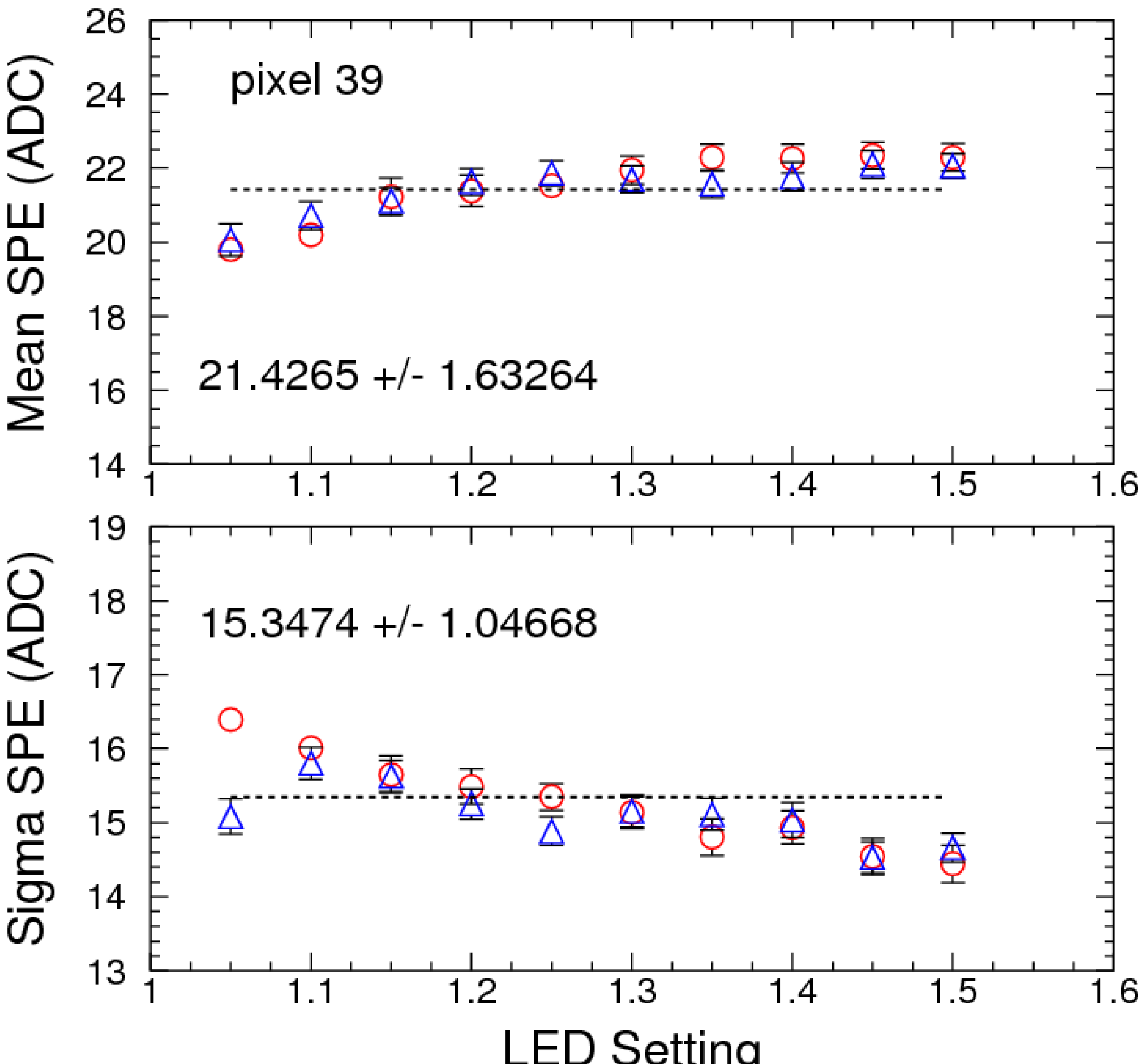






SPE Measurements: Pixel 39

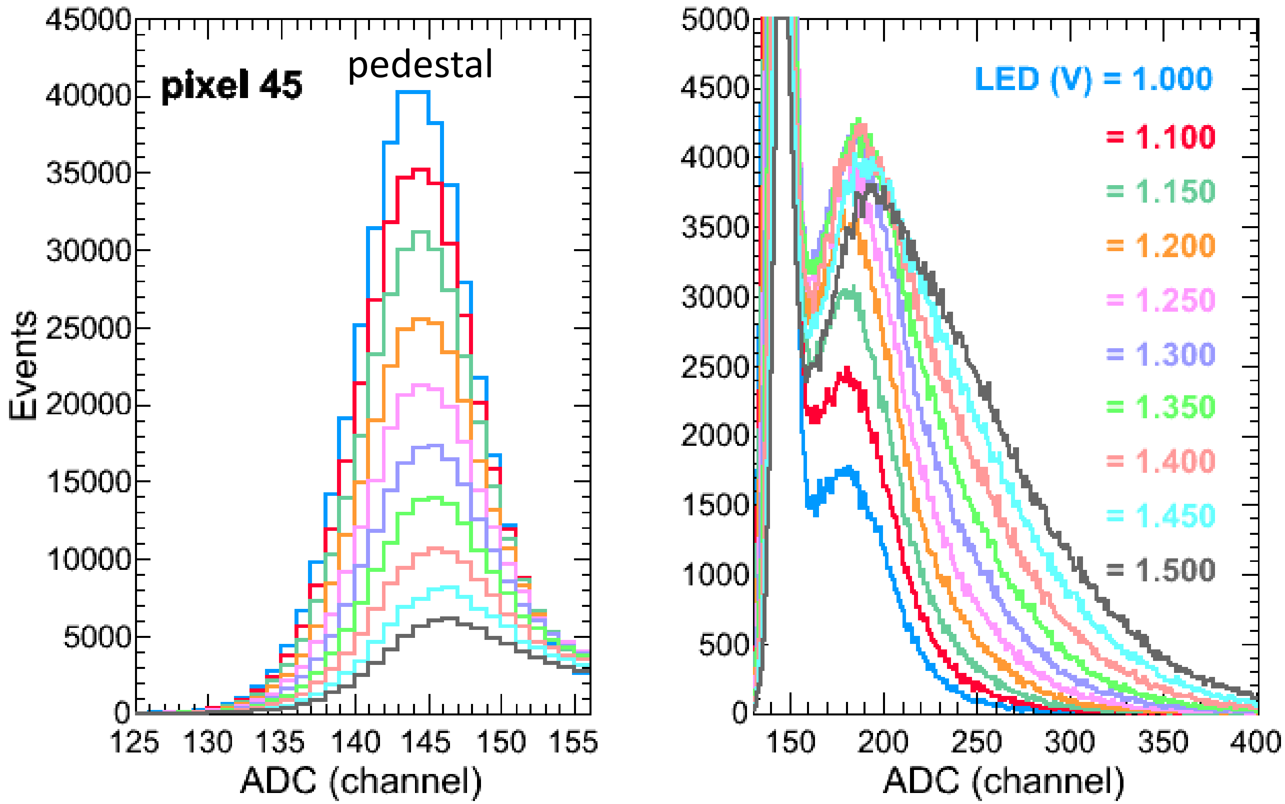
→ **Fit** extraction of the **mean** (measured from pedestal) and the **standard deviation** of the SPE distribution from ADC data corresponding to different LED settings is consistent



- *Different symbols correspond to different starting values for the fit parameters*
- *Mean: all data points within 1.6 channels from the average*
- *Standard deviation: all data points within 1 channel from the average*
- *Resolution of pixel 39: better than 1 photoelectron*

SPE Measurements: Pixel 45

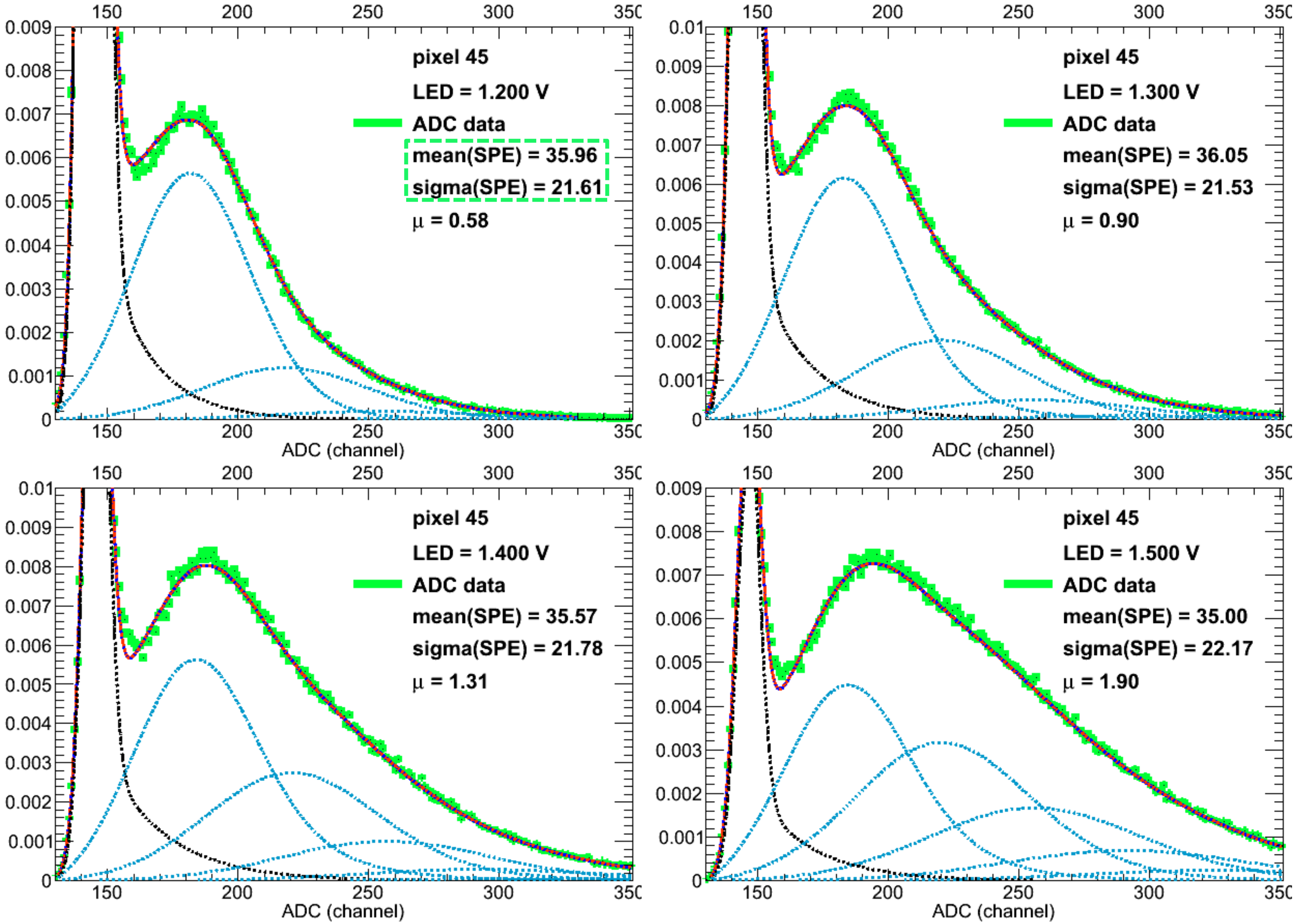
→ The yield of photons produced by the LED has been "chosen" such that the production of single photoelectrons from the PMT photocathode is favored; *by varying the LED voltage in small steps we reveal the quantum nature of the process*



→ We use a well established PMT response function to extract the **mean** (above pedestal) and the **standard deviation** of the SPE distribution

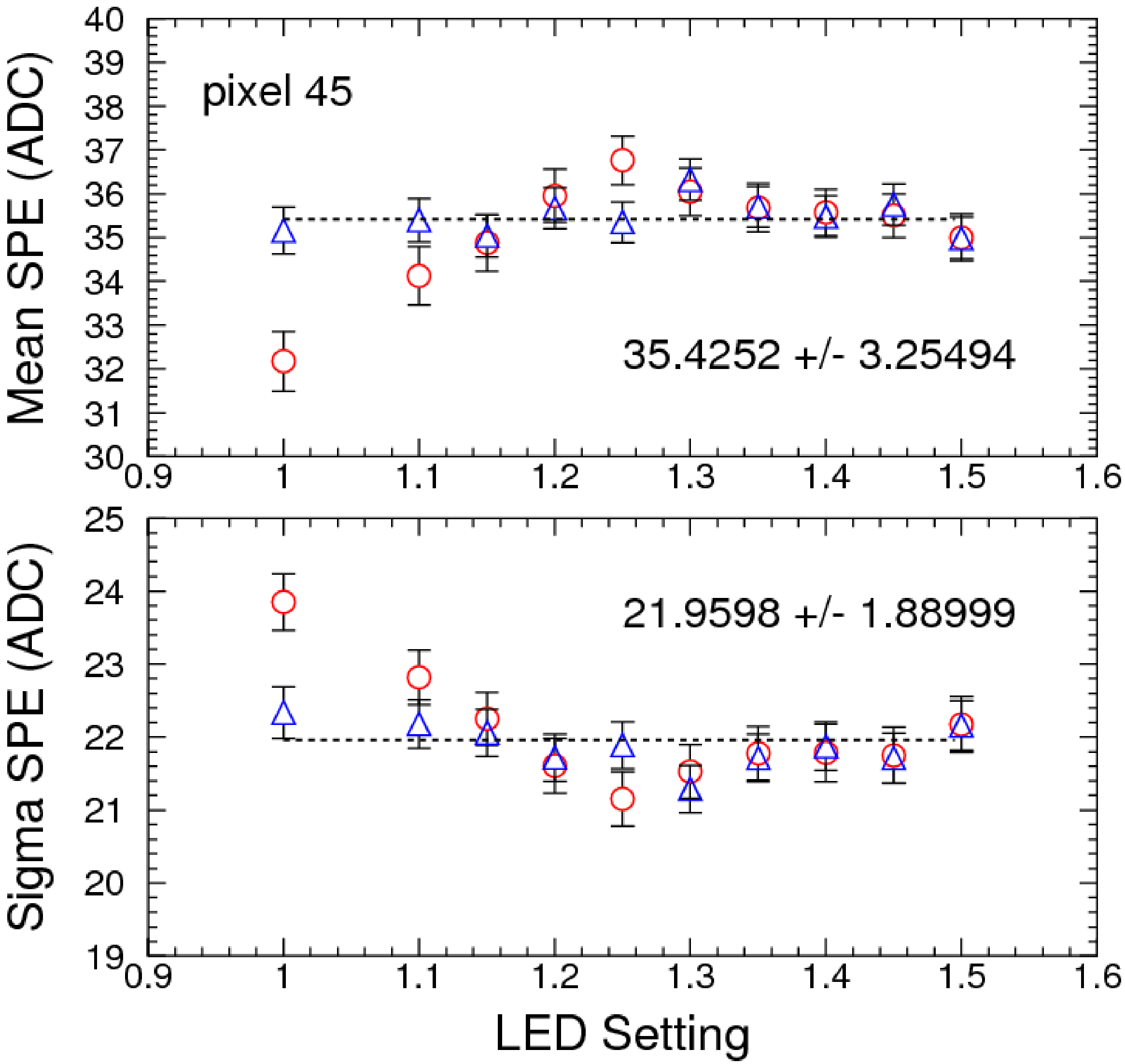
$$S_{\text{real}}(x) = \int S_{\text{ideal}}(x')B(x-x')\,\mathrm{d}x' = \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \times \left[(1-w)G_n(x-Q_0) + wI_{G_n \otimes E}(x-Q_0)\right]$$

SPE Measurements: Pixel 45



SPE Measurements: Pixel 45

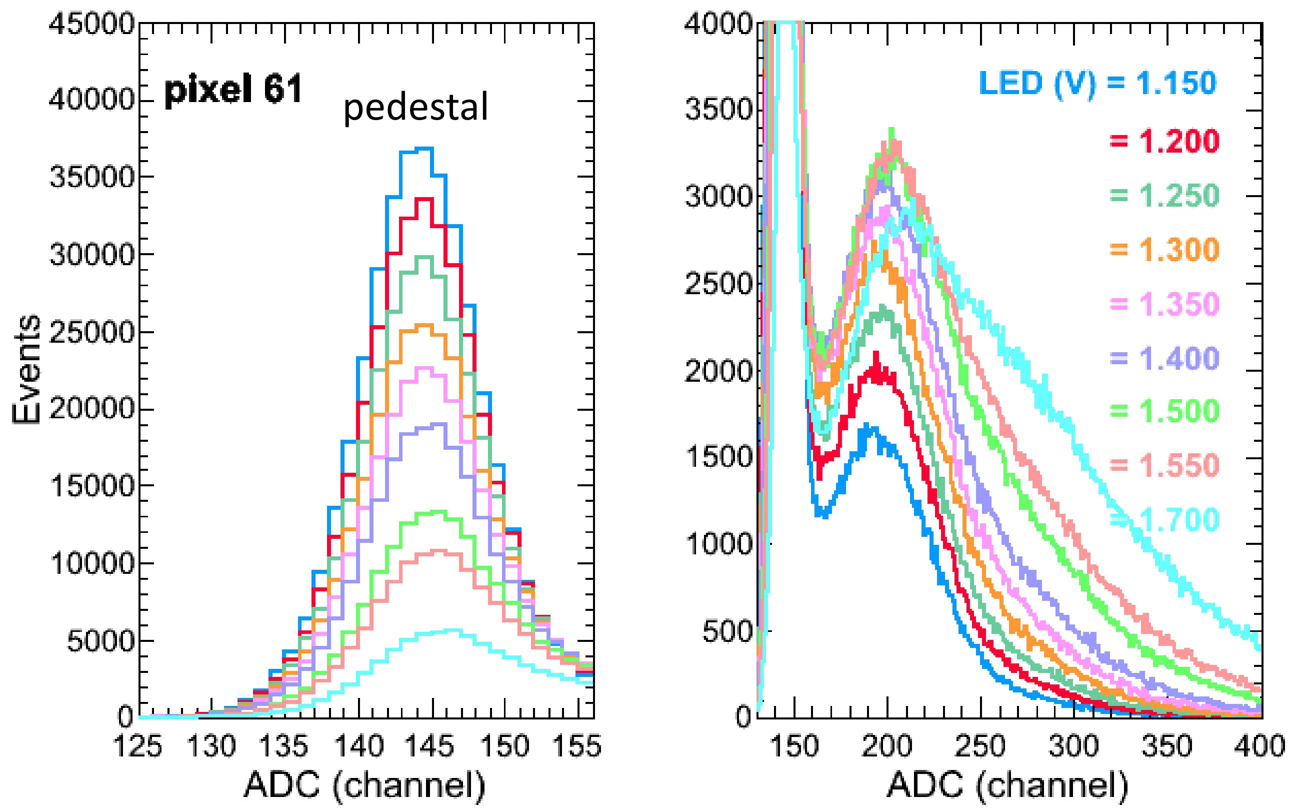
→ **Fit** extraction of the **mean** (measured from pedestal) and the **standard deviation** of the SPE distribution from ADC data corresponding to different LED settings is consistent



- *Different symbols correspond to different starting values for the fit parameters*
- *Mean: all data points within 3.3 channels from the average*
- *Standard deviation: all data points within 1.9 channels from the average*
- *Resolution of pixel 45: better than 1 photoelectron*

SPE Measurements: Pixel 61

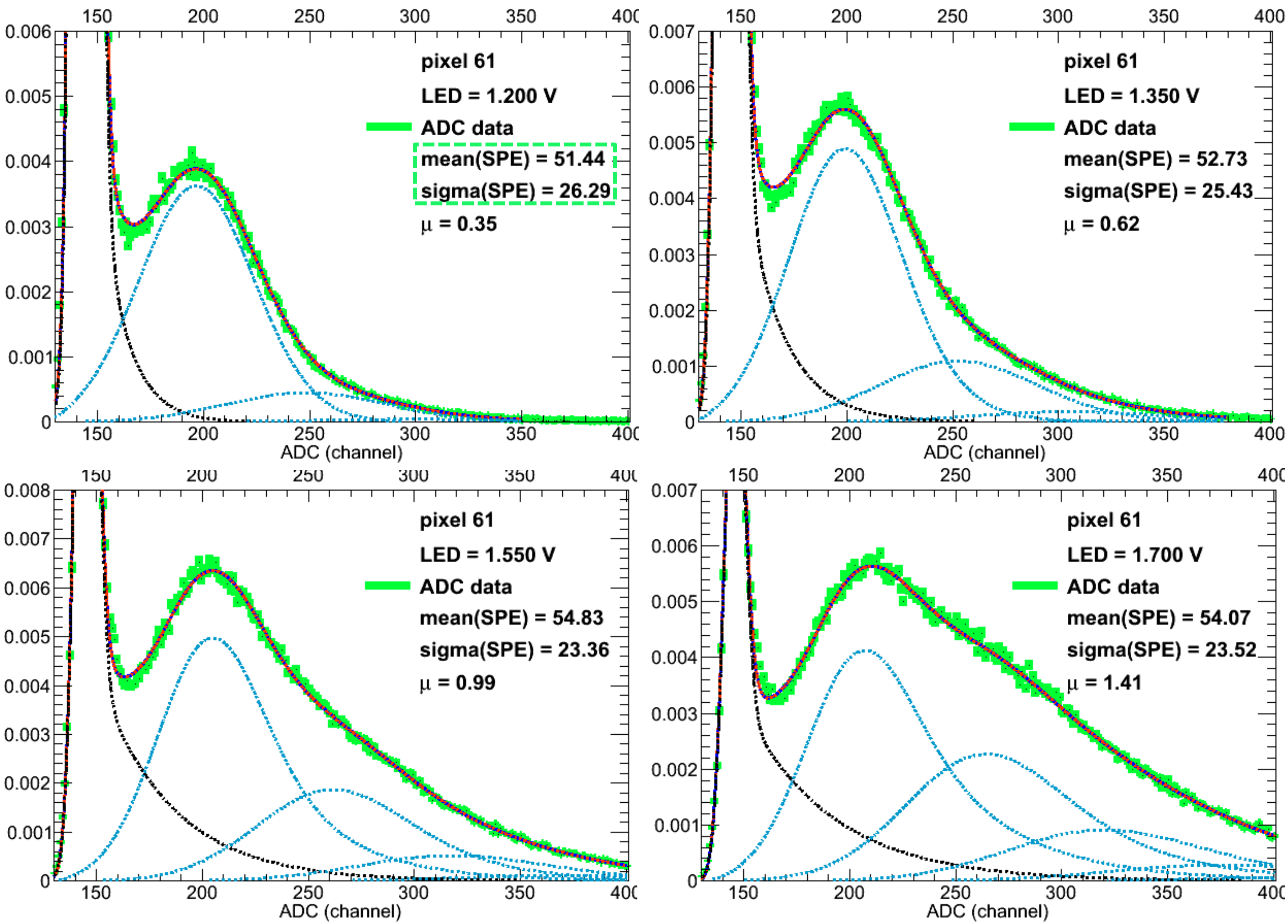
→ The yield of photons produced by the LED has been “chosen” such that the production of single photoelectrons from the PMT photocathode is favored; *by varying the LED voltage in small steps we reveal the quantum nature of the process*



→ We use a well established PMT response function to extract the **mean** (above pedestal) and the **standard deviation** of the SPE distribution

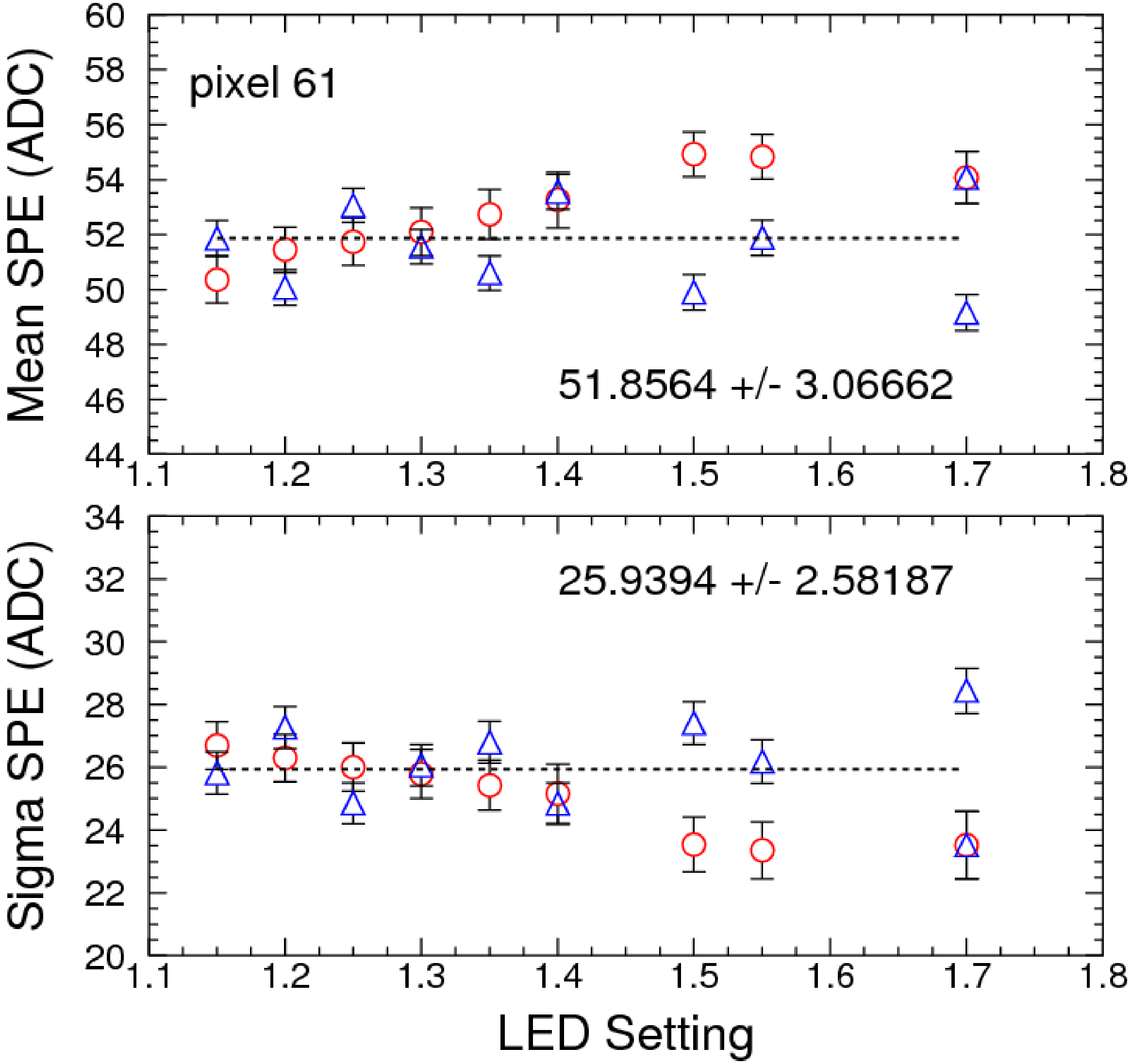
$$S_{\mathrm{real}}(x) = \int S_{\mathrm{ideal}}(x')B(x-x')\,\mathrm{d}x' = \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \times \left[(1-w)G_n(x-Q_0) + wI_{G_n \otimes E}(x-Q_0)\right]$$

SPE Measurements: Pixel 61



SPE Measurements: Pixel 61

→ **Fit** extraction of the **mean** (measured from pedestal) and the **standard deviation** of the SPE distribution from ADC data corresponding to different LED settings is consistent

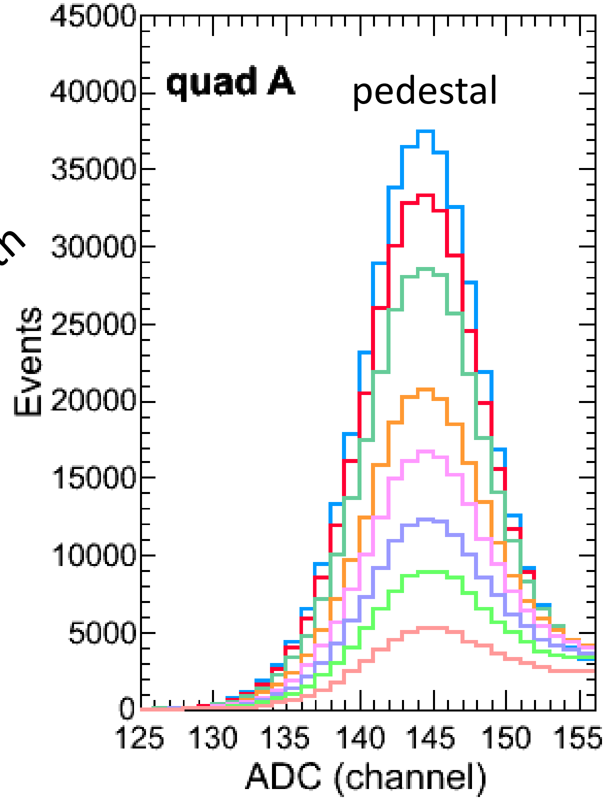


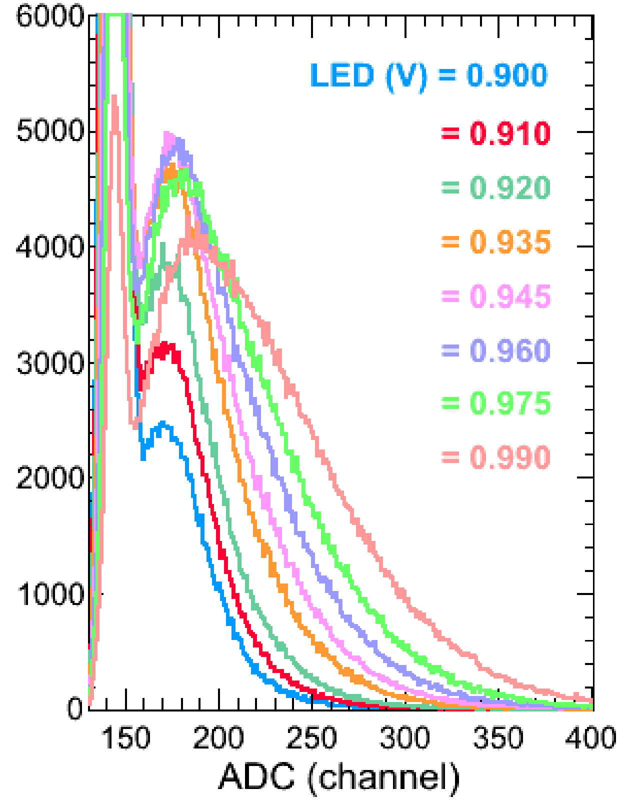
- *Different symbols correspond to different starting values for the fit parameters*
- *Mean: all data points within 3 channels from the average*
- *Standard deviation: all data points within 2.6 channels from the average*
- *Resolution of pixel 61: better than 1 photoelectron*

SPE Measurements: Quad A

→ The yield of photons produced by the LED has been "chosen" such that the production of single photoelectrons from the PMT photocathode is favored; *by varying the LED voltage in small steps we reveal the quantum nature of the process*

Sum over pixels with different gains

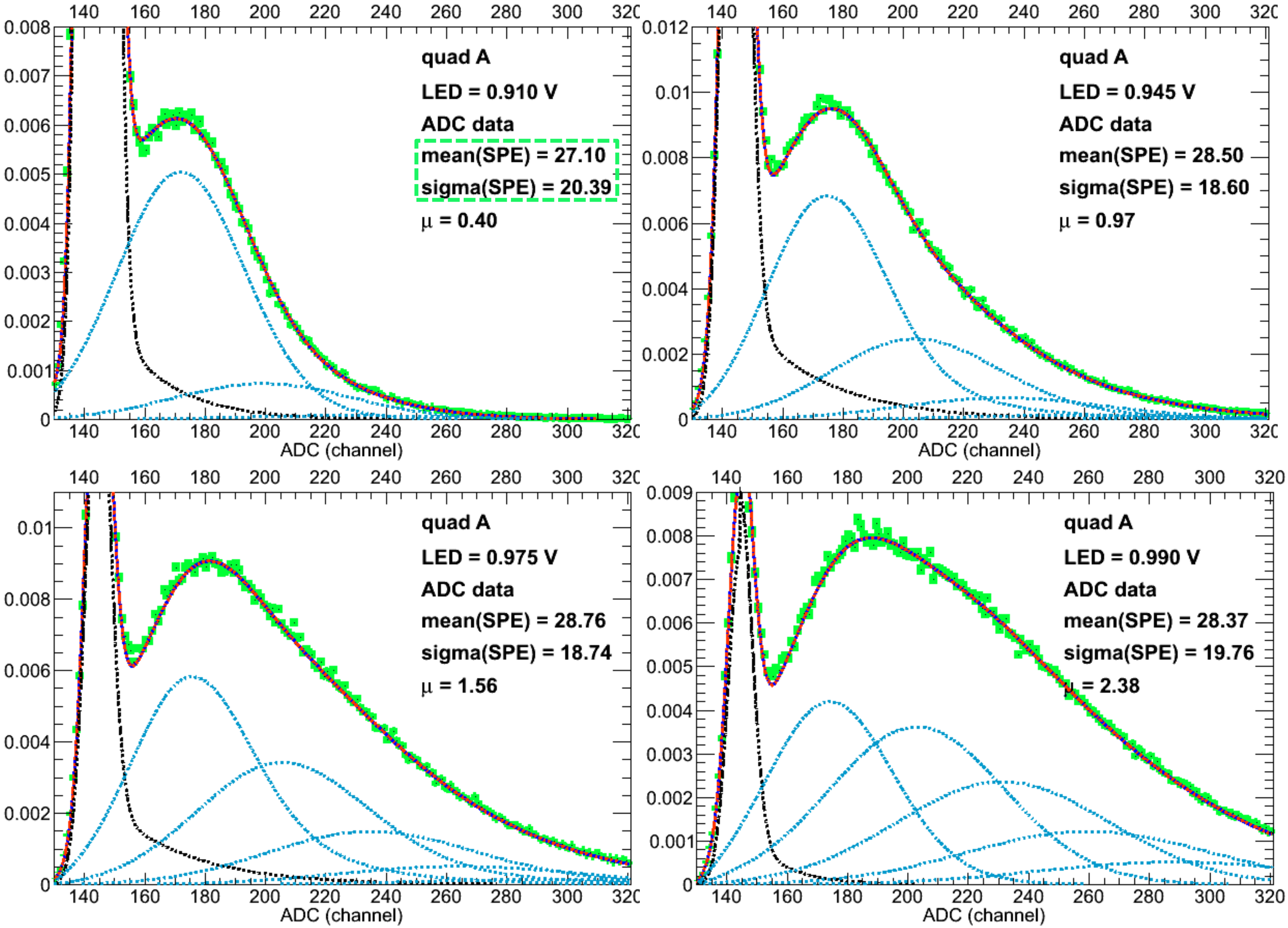




→ We use a well established PMT response function to extract the **mean** (above pedestal) and the **standard deviation** of the SPE distribution

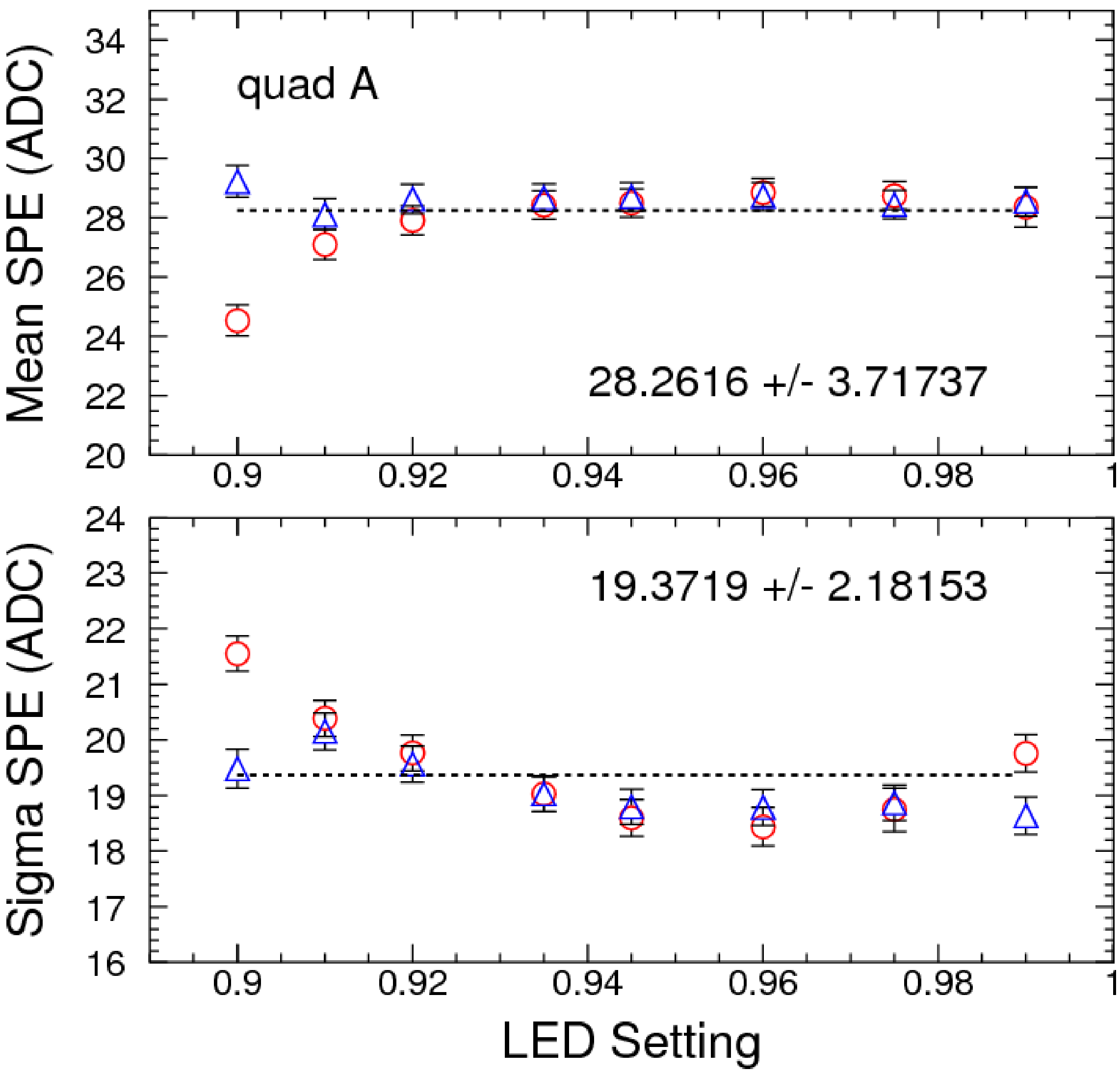
$$S_{\mathrm{real}}(x) = \int S_{\mathrm{ideal}}(x')B(x-x')\,\mathrm{d}x' = \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \times \left[(1-w)G_n(x-Q_0) + wI_{G_n \otimes E}(x-Q_0)\right]$$

SPE Measurements: Quad A



SPE Measurements: Quad A

→ **Fit** extraction of the **mean** (measured from pedestal) and the **standard deviation** of the SPE distribution from ADC data corresponding to different LED settings is consistent



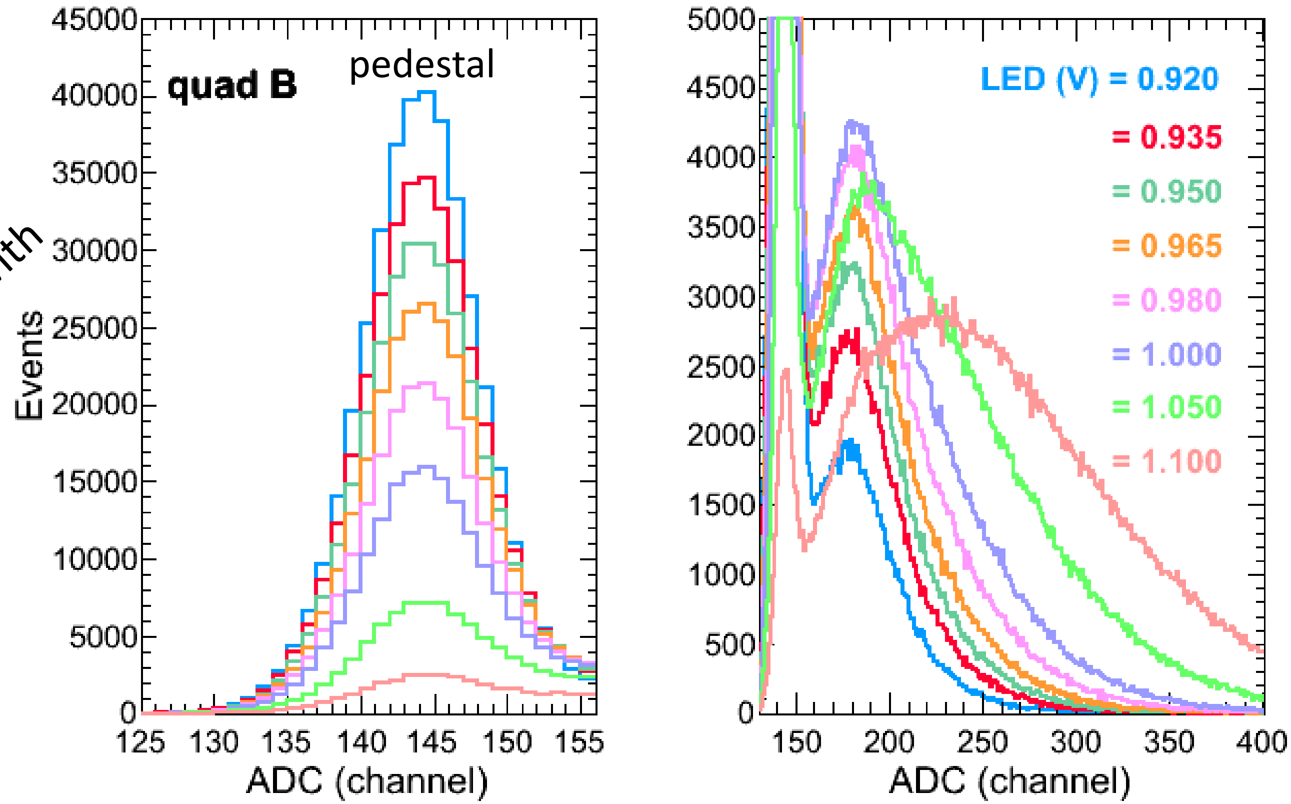
- *Different symbols correspond to different starting values for the fit parameters*
- *Mean: all data points within 3.7 channels from the average*
- *Standard deviation: all data points within 2.2 channels from the average*
- *Resolution of quad A: better than 1 photoelectron*

Quads (sum of pixels) behave just like individual pixels

SPE Measurements: Quad B

→ The yield of photons produced by the LED has been “chosen” such that the production of single photoelectrons from the PMT photocathode is favored; *by varying the LED voltage in small steps we reveal the quantum nature of the process*

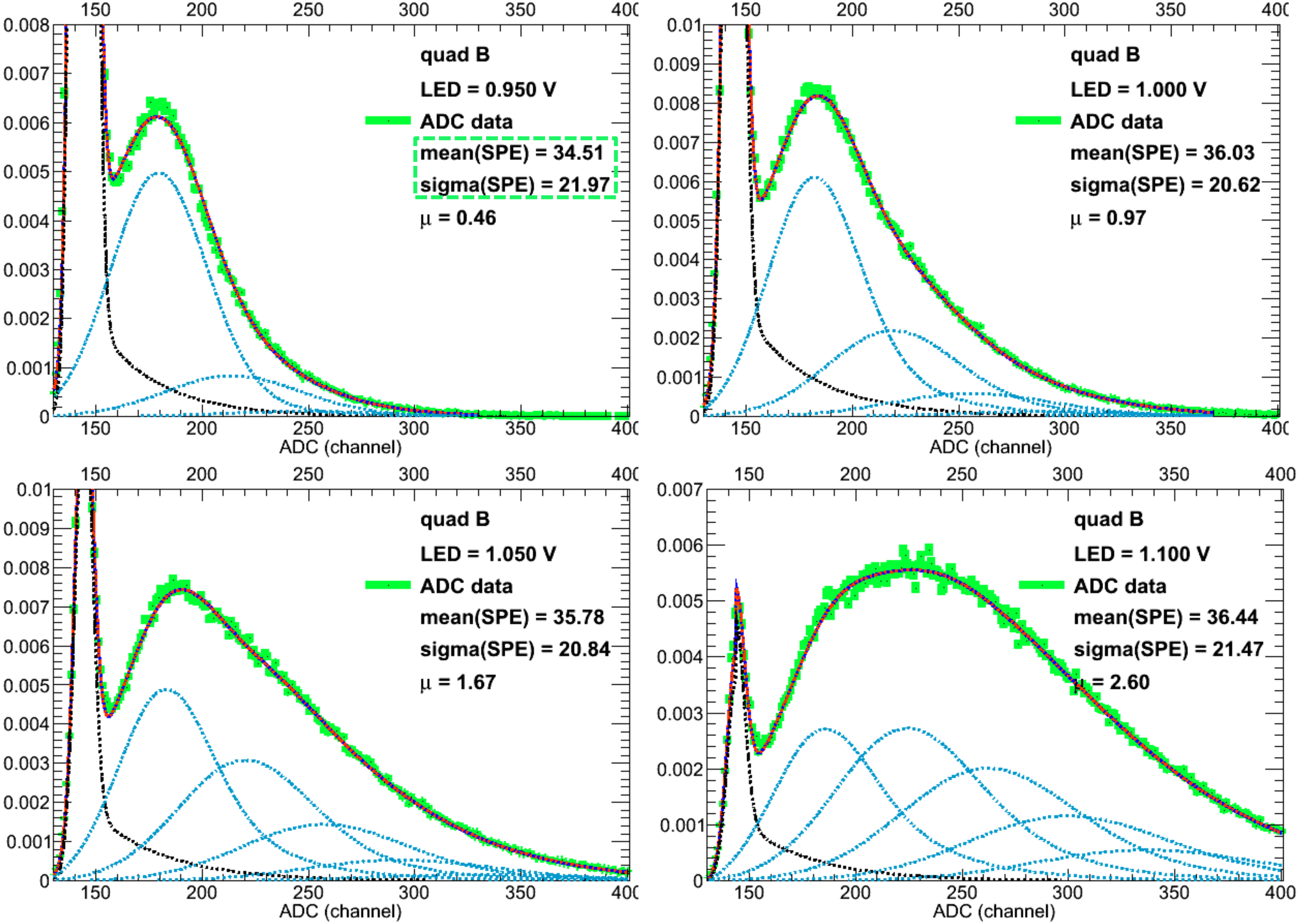
Sum over pixels with different gains



→ We use a well established PMT response function to extract the **mean** (above pedestal) and the **standard deviation** of the SPE distribution

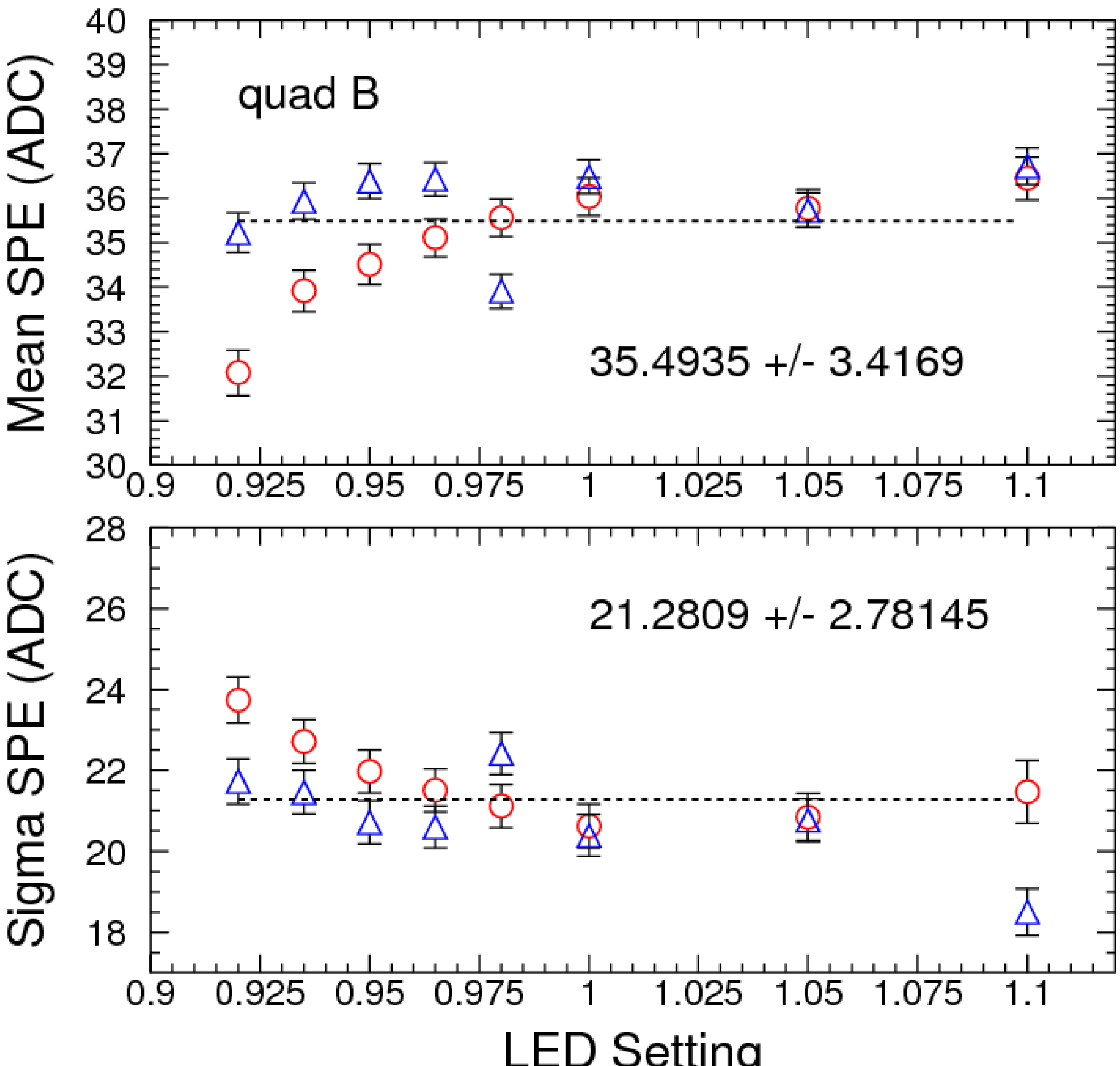
$$S_{\mathrm{real}}(x) = \int S_{\mathrm{ideal}}(x')B(x-x')\,\mathrm{d}x' = \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \times \left[(1-w)G_n(x-Q_0) + wI_{G_n \otimes E}(x-Q_0)\right]$$

SPE Measurements: Quad B



SPE Measurements: Quad B

→ **Fit** extraction of the **mean** (measured from pedestal) and the **standard deviation** of the SPE distribution from ADC data corresponding to different LED settings is consistent



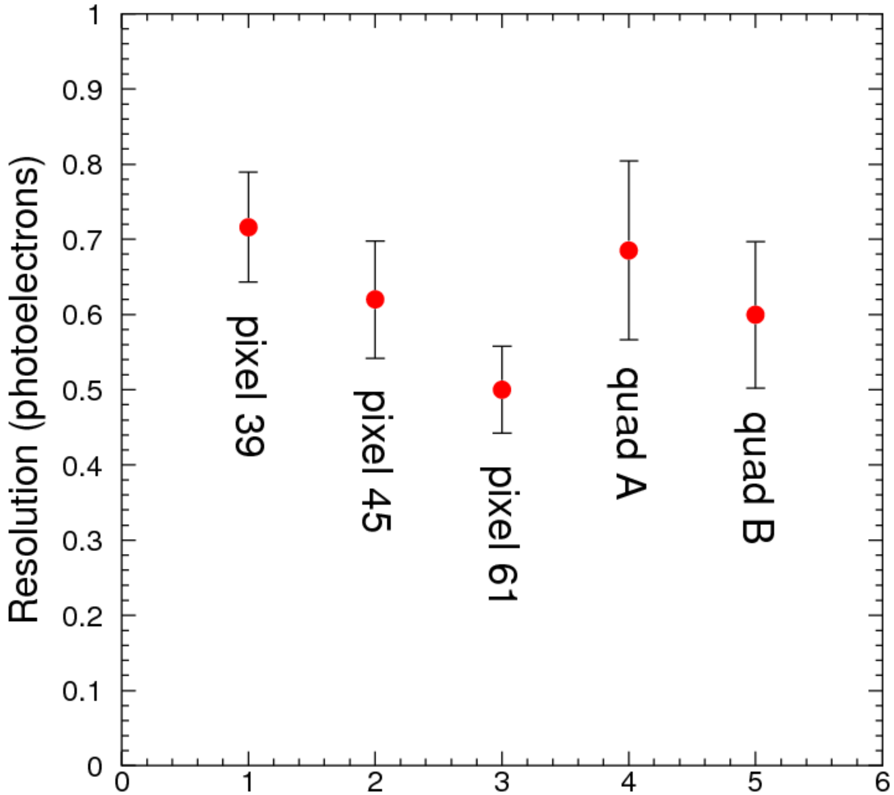
- *Different symbols correspond to different starting values for the fit parameters*
- *Mean: all data points within 3.4 channels from the average*
- *Standard deviation: all data points within 2.8 channels from the average*
- *Resolution of quad B: better than 1 photoelectron*

Quads (sum of pixels) behave just like individual pixels

SPE Measurements: Summary

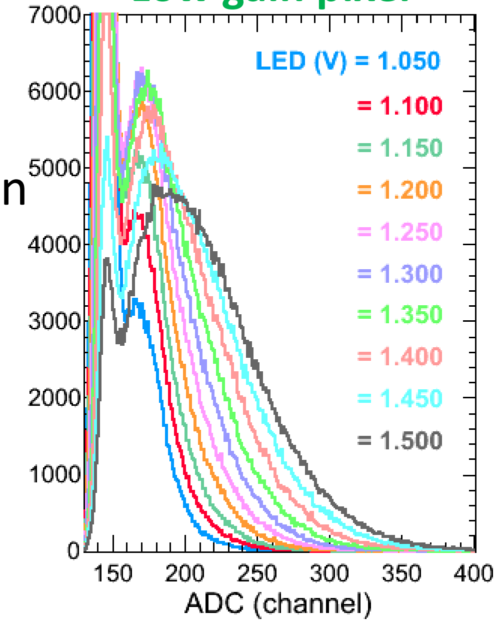
→ H8500C-03: good SPE resolution, better than 1 photoelectron

→ Our measurements follow the trend shown in the Hamamatsu map of pixels gain

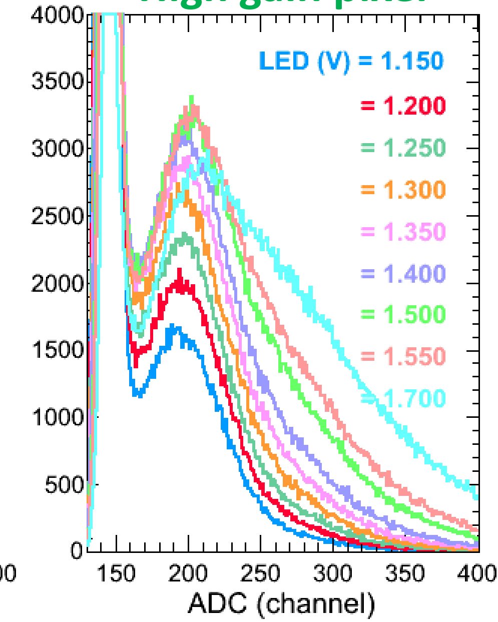


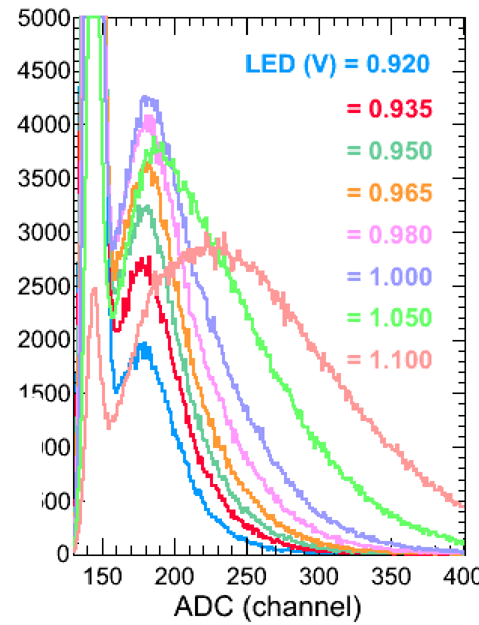
→ Though the quads are superpositions of 16 pixels with possibly different gains, the SPE is still clearly identifiable

Low gain pixel



High gain pixel



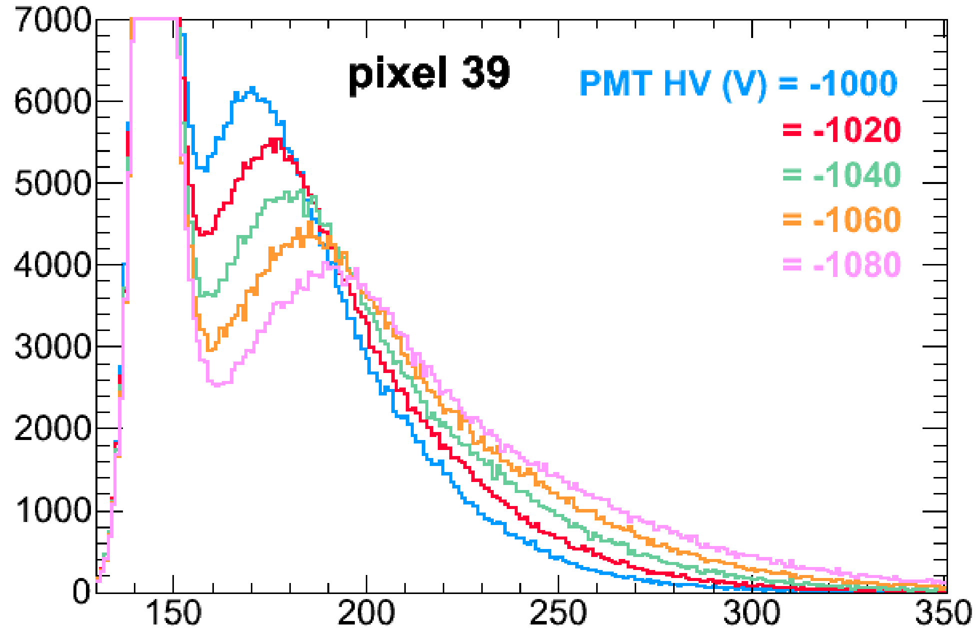


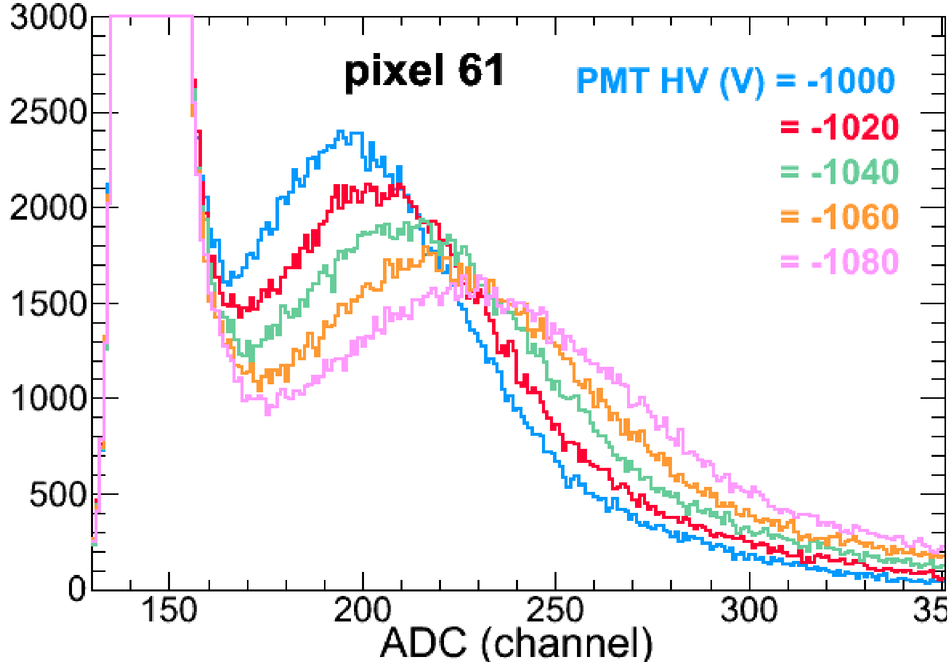
Quad: sum of 16 pixels
SPE clearly identified

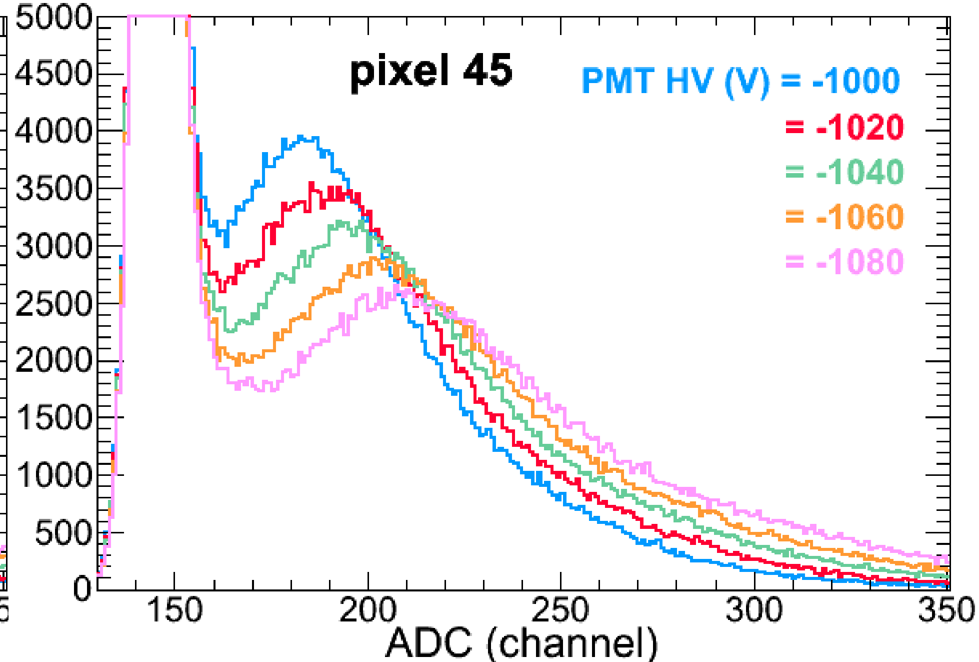
Gain Measurements: PMT High Voltage Scan

→ Keeping constant the yield of photons on pixel (i.e. the LED setting is fixed) we increase the PMT HV – this will boost up the pixels gain

→ The boost in gain with increasing PMT HV is clearly seen in our data for all 3 pixels tested

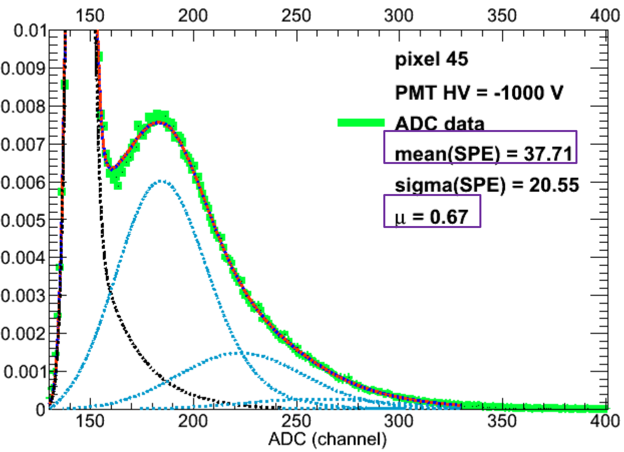


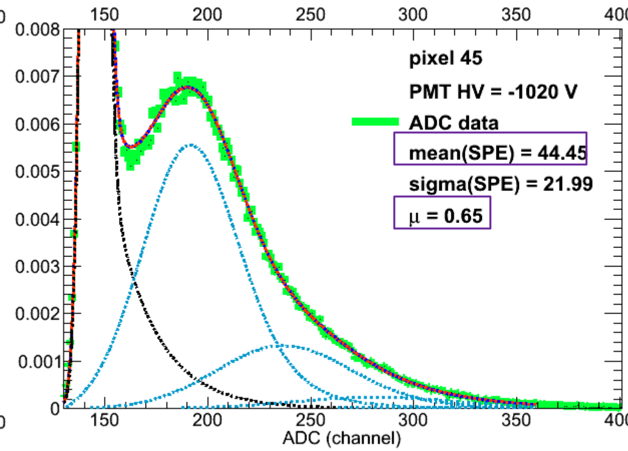


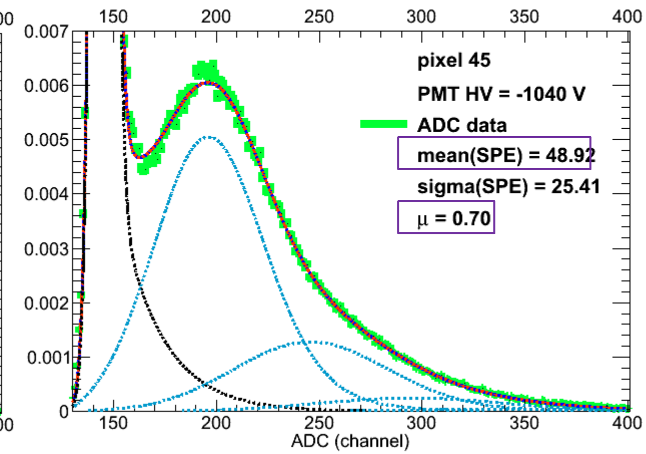


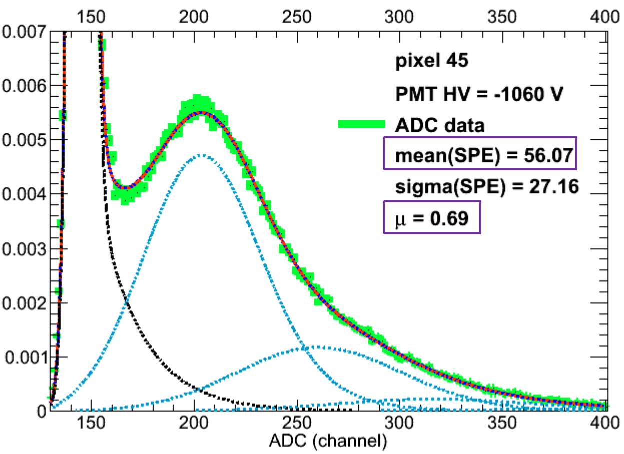
Gain Measurements: PMT High Voltage Scan

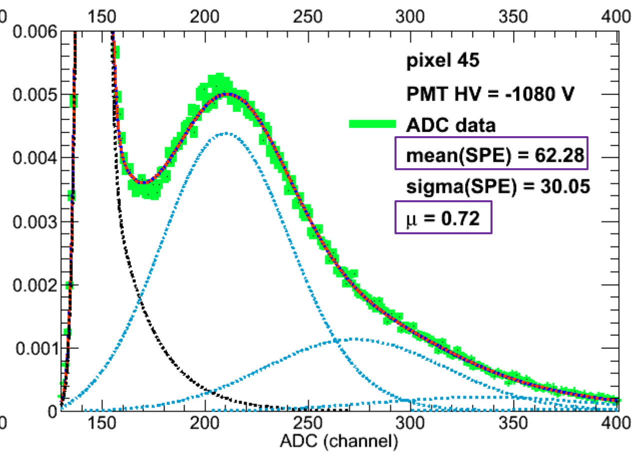
Example: Pixel 45











SPE resolution at -1000 V = 0.52

SPE resolution at -1080 V = 0.48

Fit is stable

→ The mean of the Poisson distribution, μ, stays the same with increasing PMT HV (as expected given that the yield of photons illuminating the pixel stays the same)

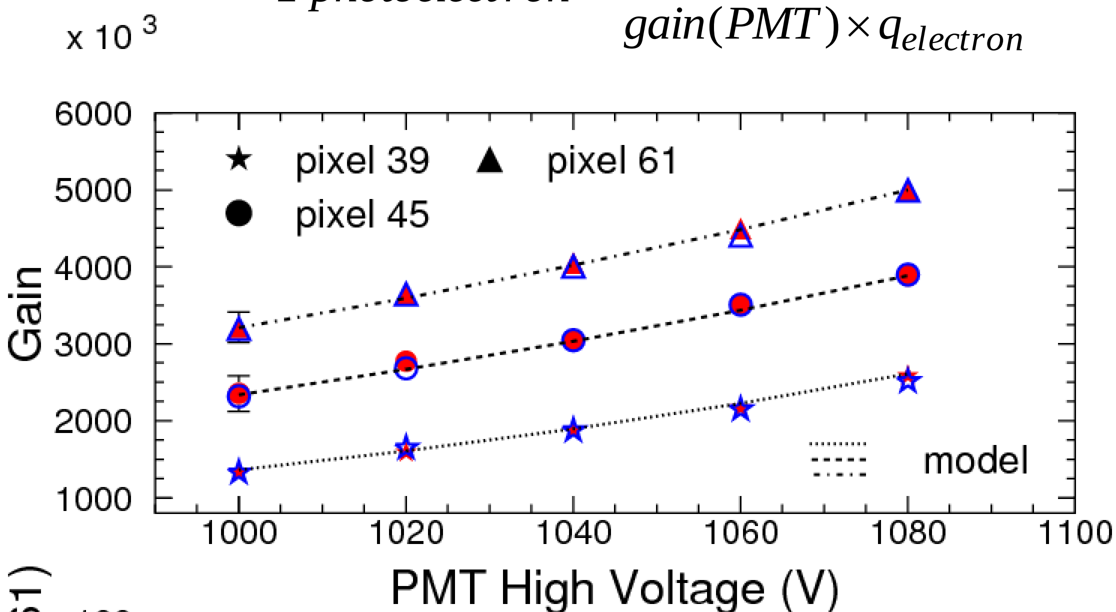
→ The number of channels above the PED corresponding to the SPE signal, **mean(SPE)**, increases with increasing PMT HV, i.e. the pixel gain increases and the SPE resolution gets better

H8500C-03 Gain Extraction from SPE Data

→ We extract the H8500C-03 gain from our SPE measurements

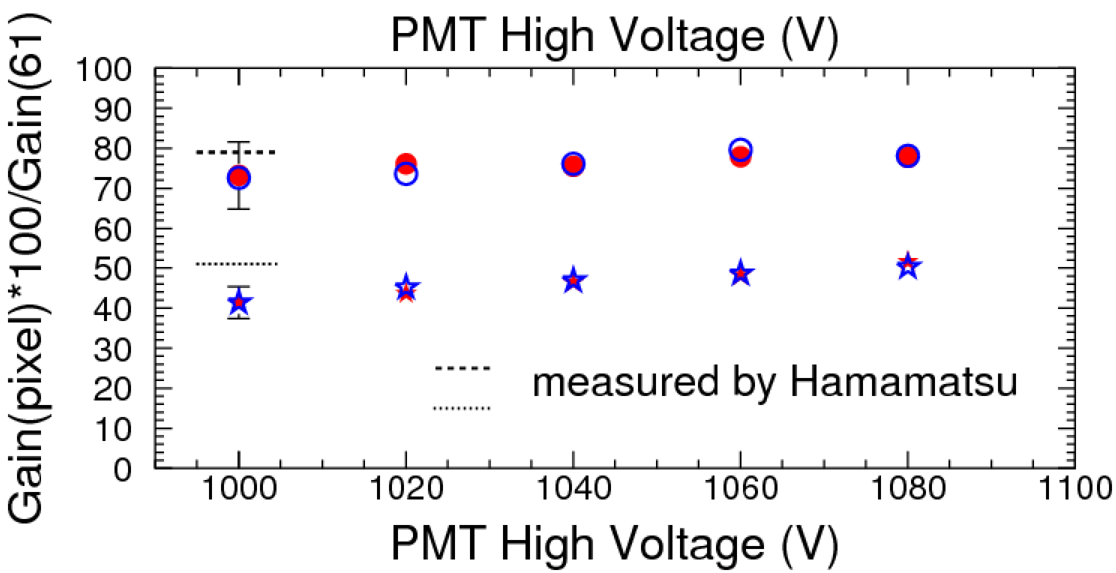
$$1\ photoelectron = \frac{Q_{ADC}}{gain(PMT) \times q_{electron}}$$

$$Q_{ADC} = \frac{Q_{ADC}^{per\_channel} \times mean(SPE)}{amplification}$$



$$\text{gain (model)} = \frac{a^{12}}{13^{k*12}} \times V^{k*12}$$

*We extract coefficients **a** and **k** from data at -1000 and -1080 V*

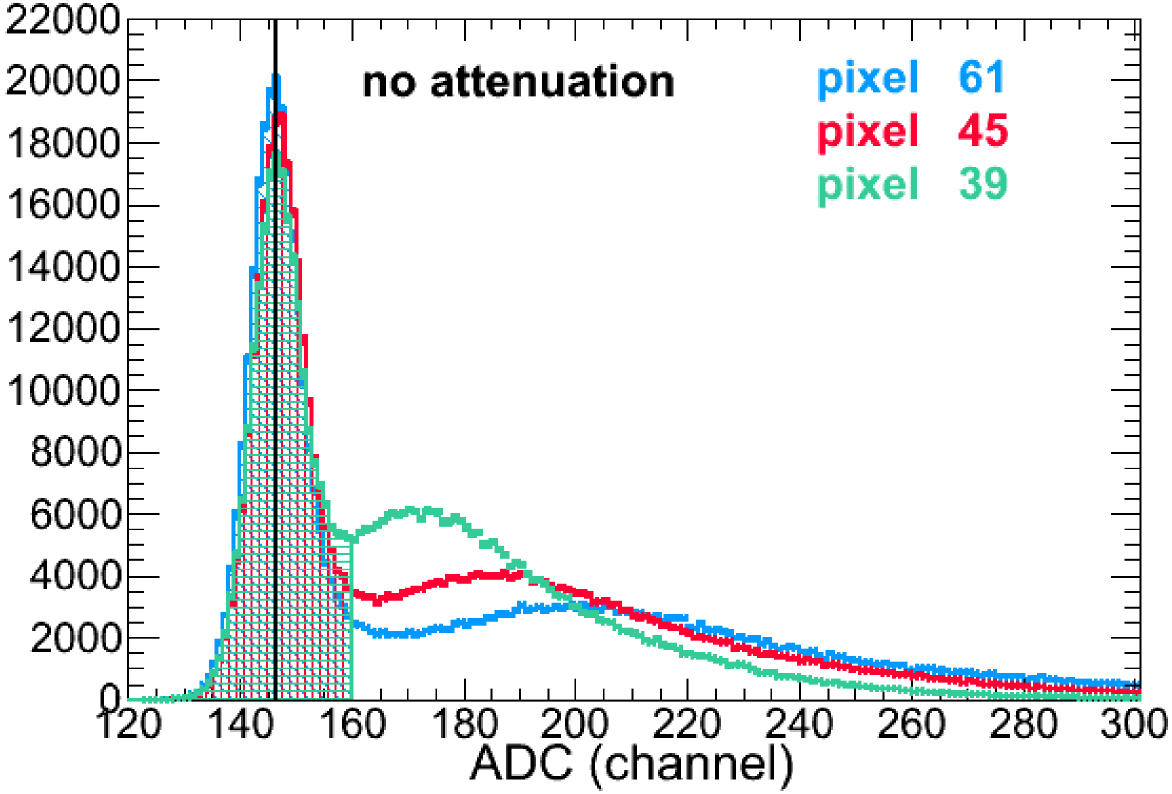


Our measurements of pixel gain variation agree reasonably well with data provided by Hamamatsu (their measurements were done using large yields of photoelectrons)

Pixel Gain Matching

→ It is well established that the gain of pixels within the same PMT can vary by factor of 2 or more

→ Hamamatsu provides a map with pixel to pixel gain variation

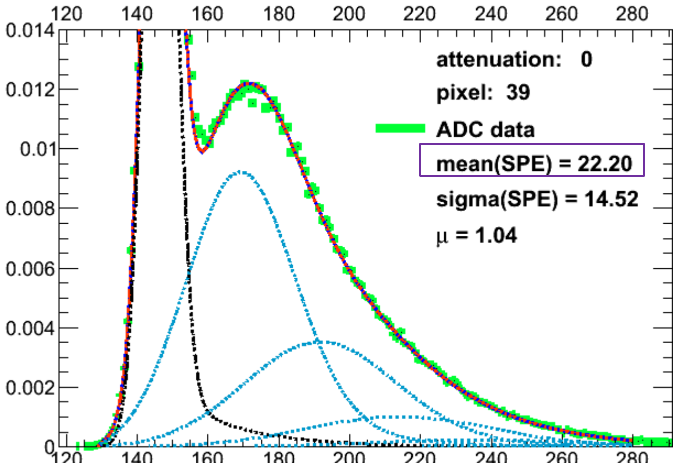


→ We have shown that even for sum of pixels (quads) reasonable SPE resolution can be achieved

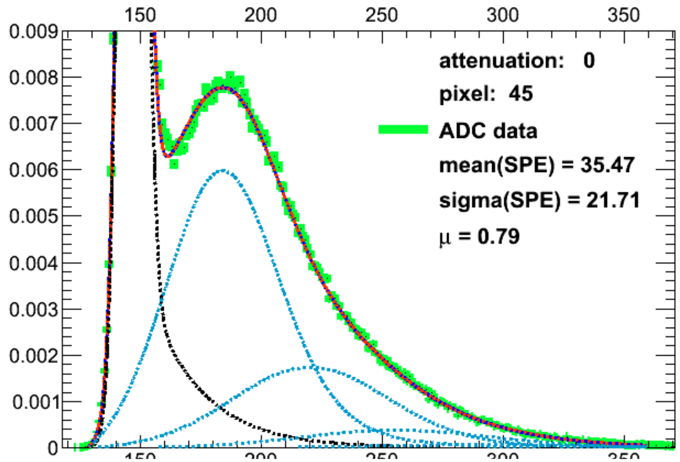
→ However, if better resolution would be needed matching the gain of all pixels to the lowest output pixel could be the solution

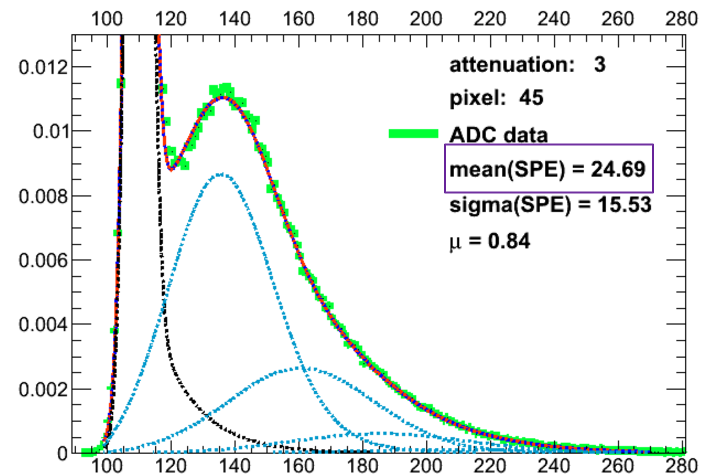
Pixel Gain Matching

→ We used a rotary attenuator to normalize the output of the pixels with higher gains, 45 and 61, to the pixel with lowest gain, pixel 39

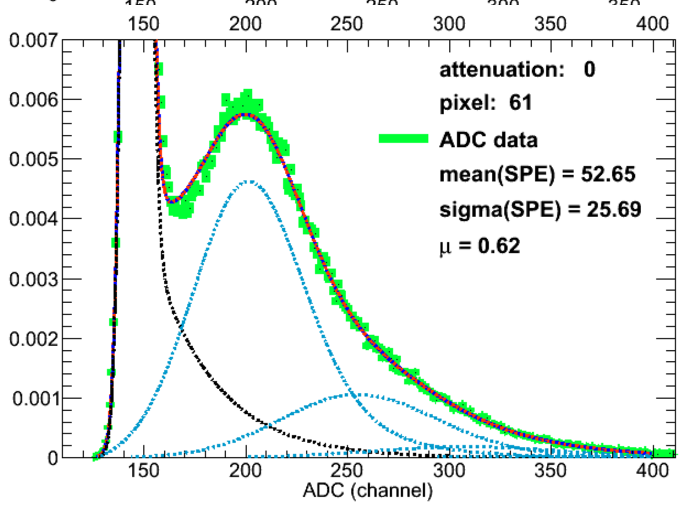


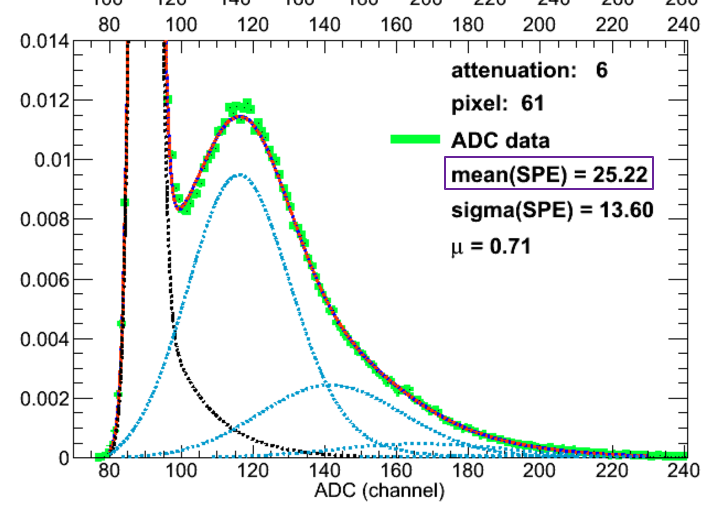
Output from pixel 45 is attenuated by 3 dB



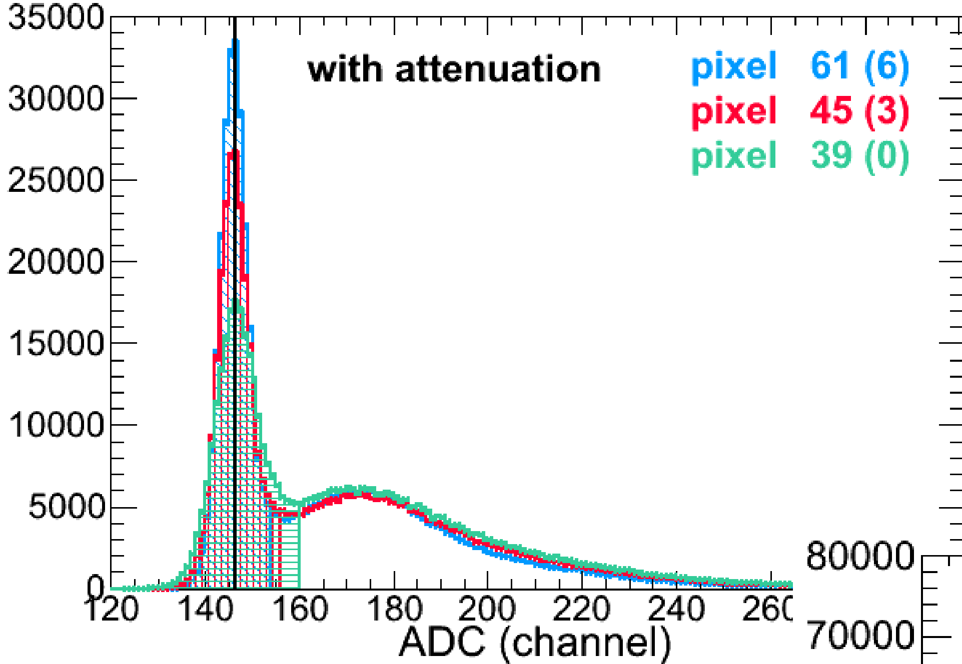


Output from pixel 61 is attenuated by 6 dB



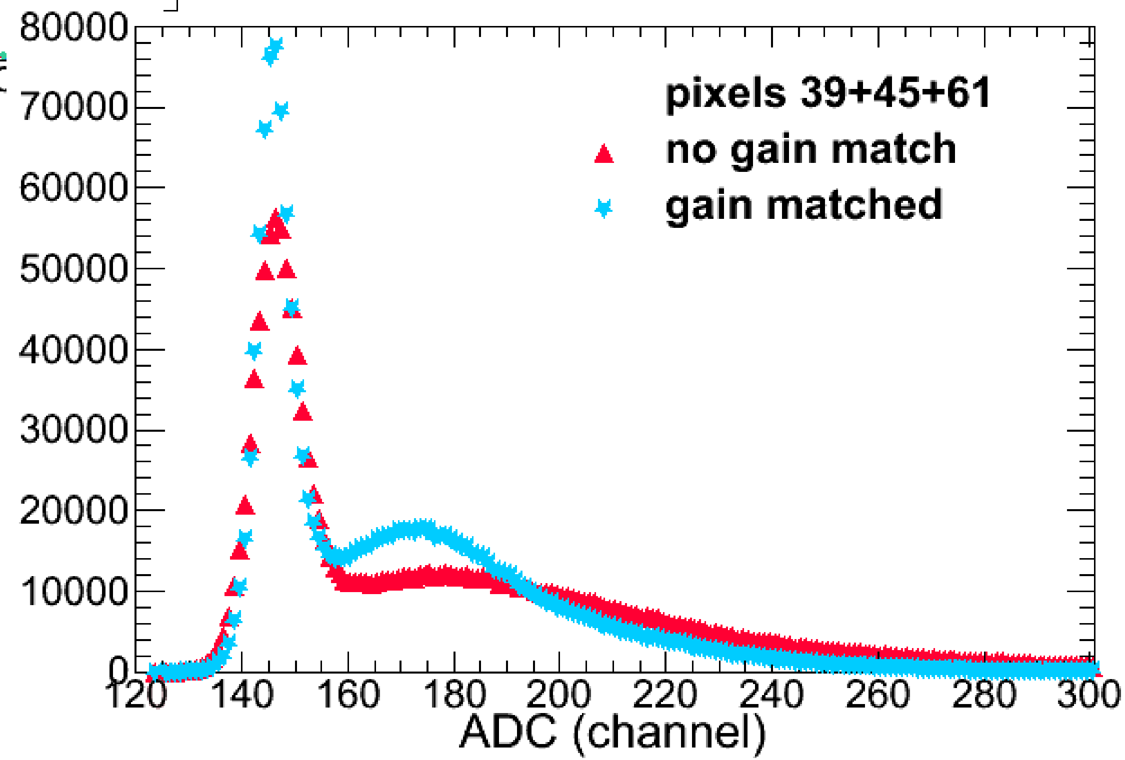


Pixel Gain Matching



→ After signal attenuation of higher gain pixels, the charge corresponding to the SPE as recorded by the ADC is ~ the same for all 3 pixels (clearly seen in the ADC distributions)

→ The effect of gain matching is a more pronounced SPE peak in the ADC distribution



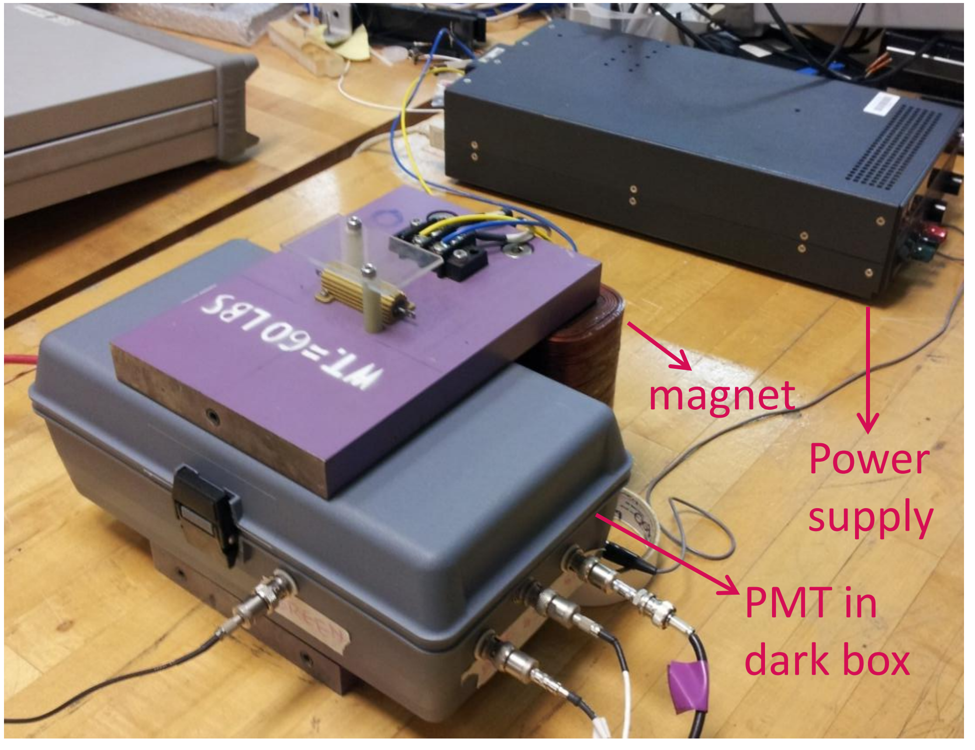
Magnetic Field Measurements

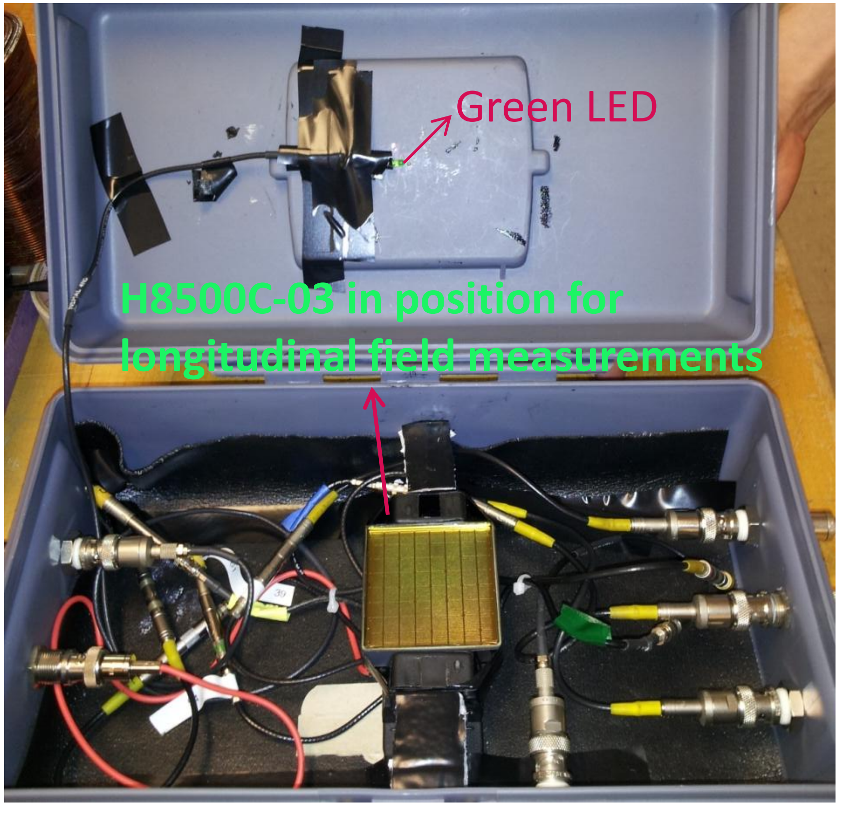
→Field on SPE signals

→ Field on large signals: 30-50 photoelectrons

Experimental Setup

→ **We quantified the response to magnetic field of 1 central pixel (45), 1 edge pixel (61) and 2 groups of 16 pixels (2 quads)**





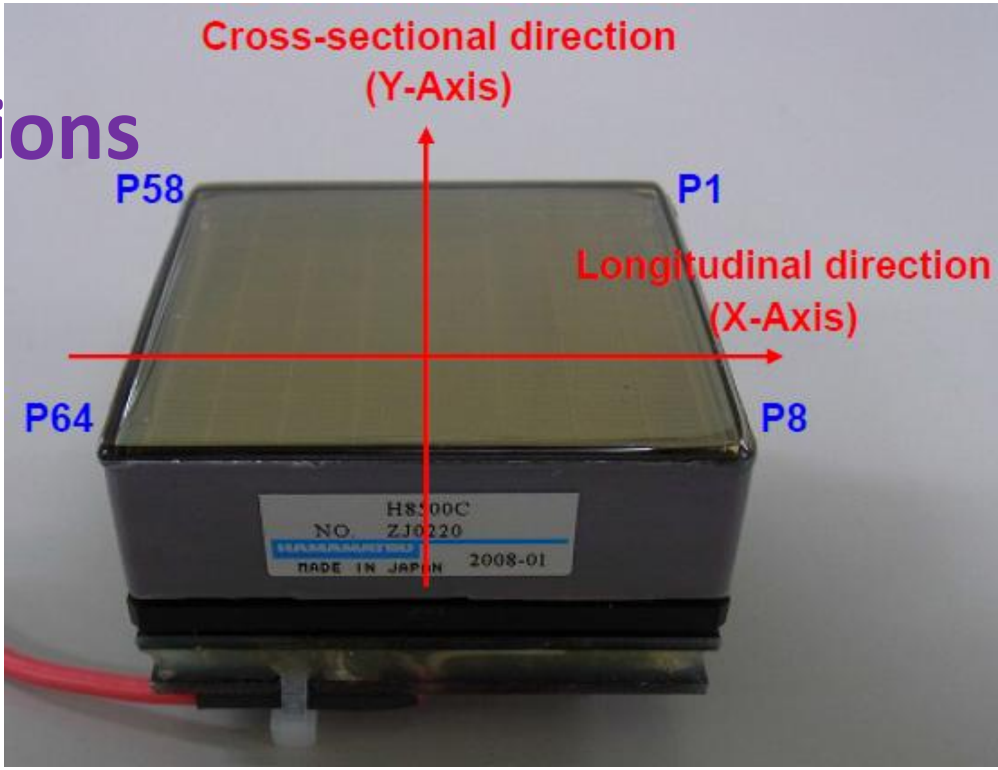
→ **We paid special attention to the PMT orientation w.r.t. the direction of the magnetic field: we surveyed the PMT tilt angle w.r.t. the longitudinal and transverse field orientations and ensured that we measure the PMT response to purely transverse/longitudinal fields**

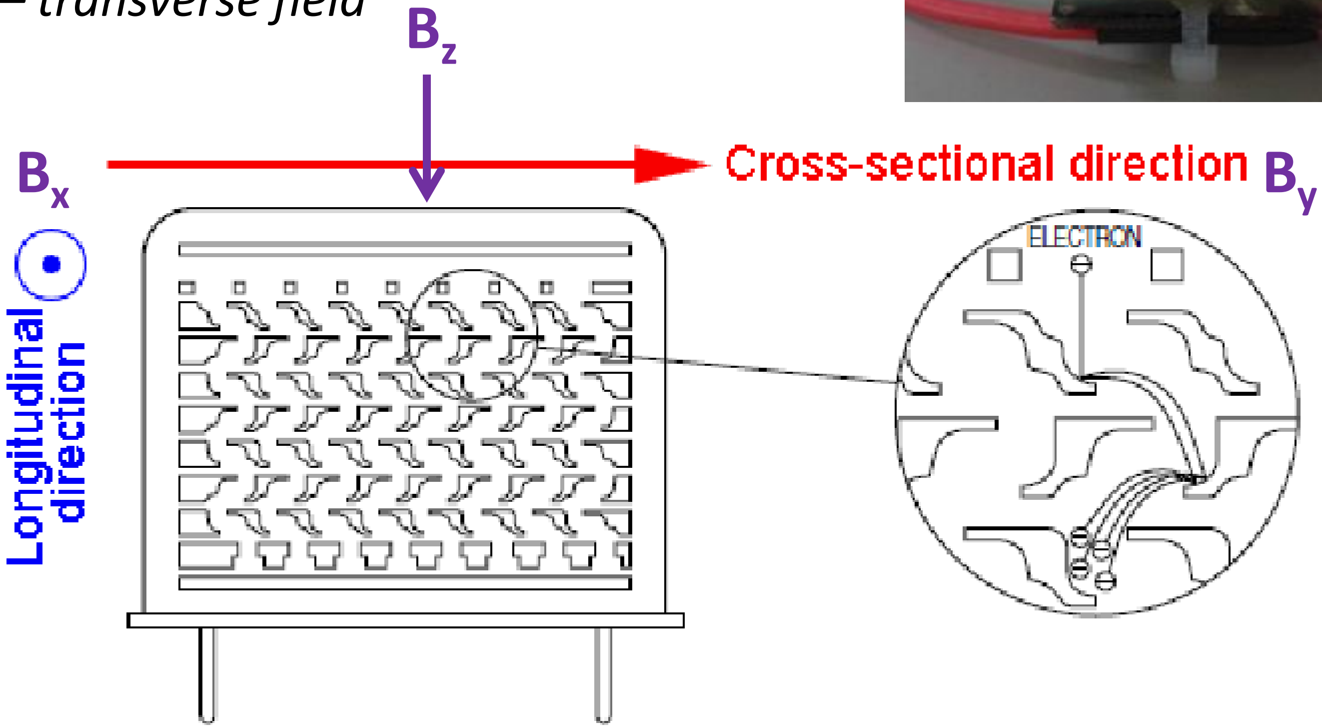
Experimental Setup: Magnetic Field Orientations

→We use the same convention as Hamamatsu to label different field orientations:

B_z – perpendicular to the face of the PMT – longitudinal field

B_x and By – perpendicular to the sides – transverse field



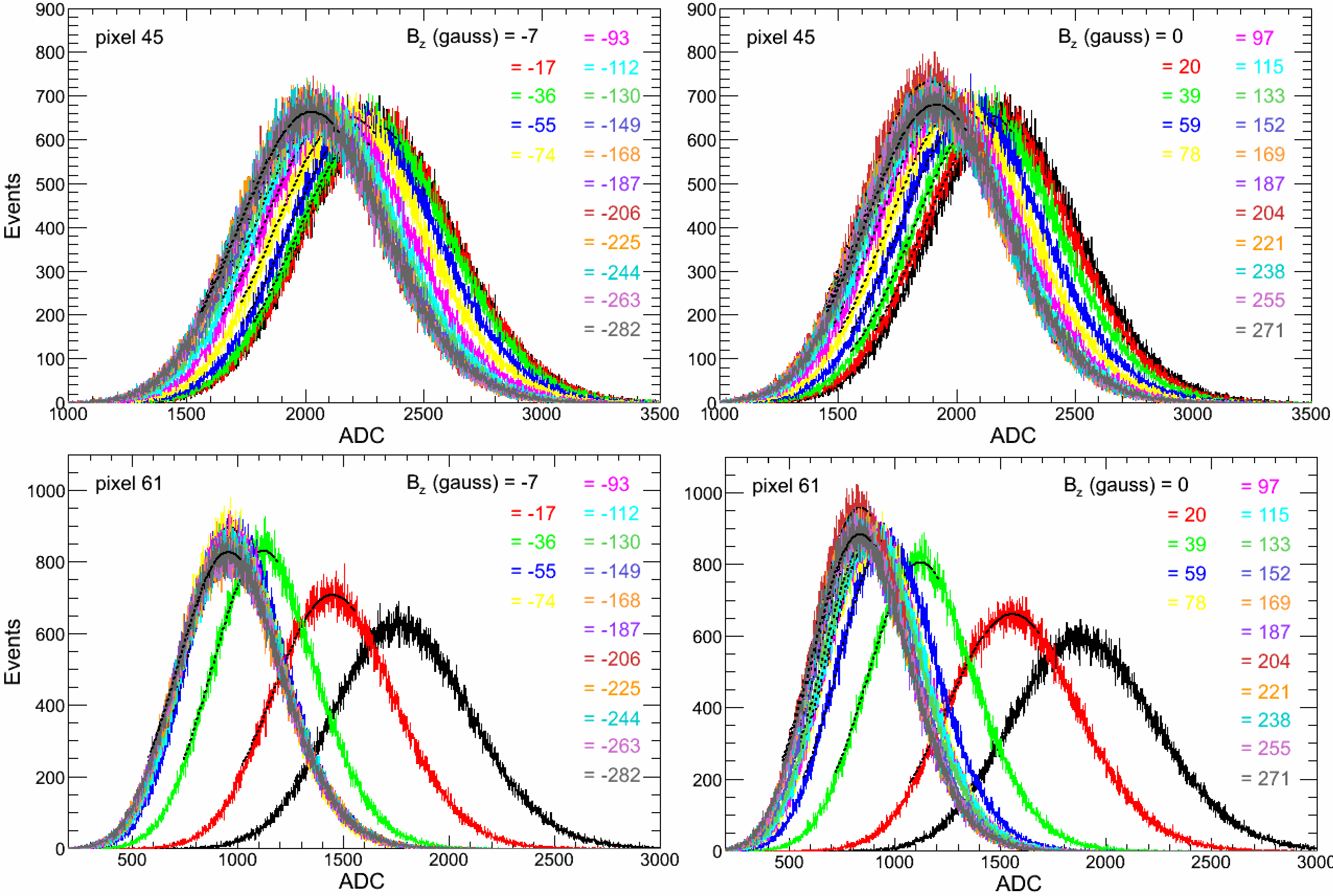


Pictures from Hamamatsu: thanks to Ardavan Ghassemi

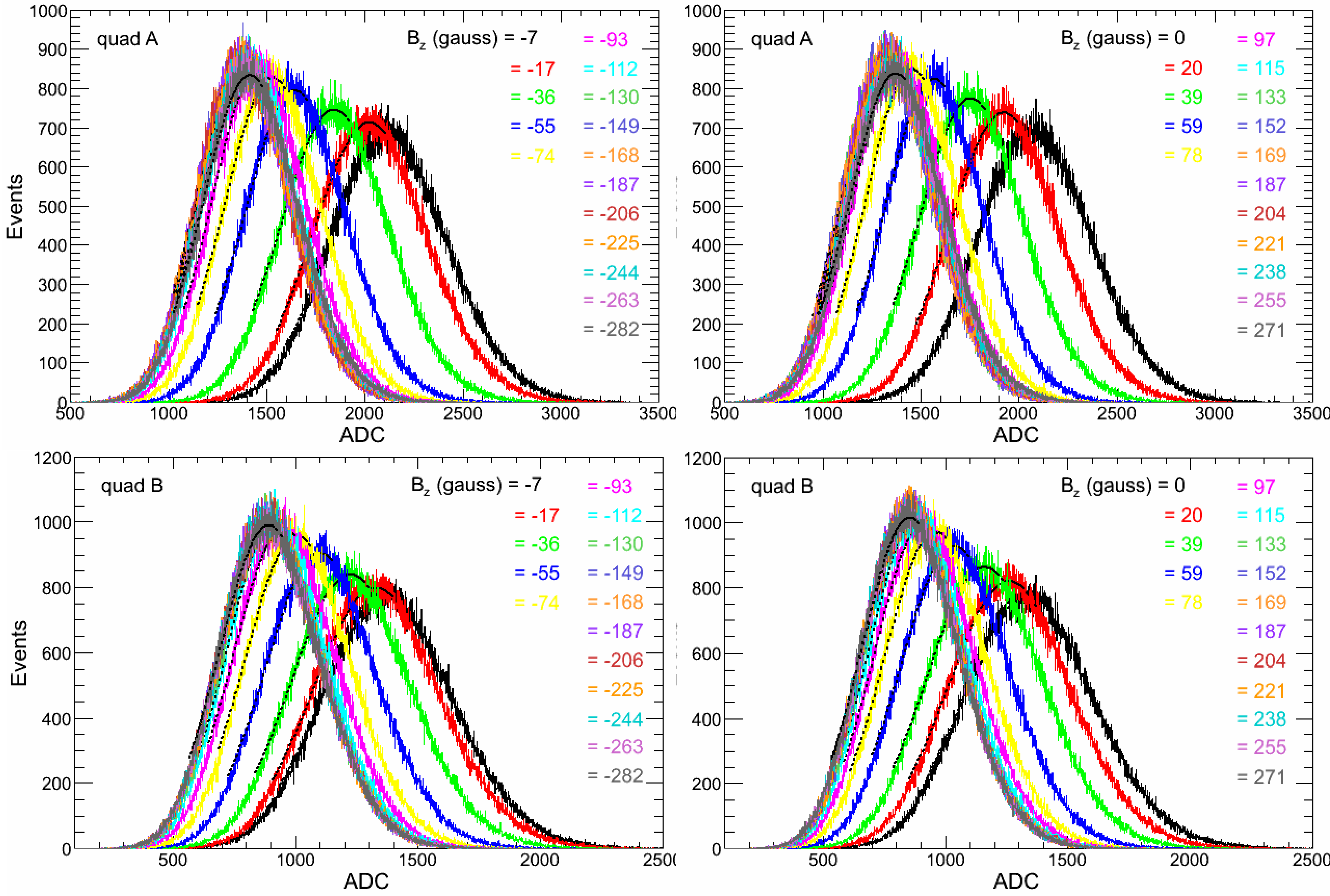
Magnetic Field Measurements
→ Field on SPE signals
→ Field on large signals: 30-50 photoelectrons

Methodology:
→ Start with a large signal, possibly the number of photoelectrons expected during the experiment
→ Take ADC data at zero field: this will become the baseline
→ Run a scan by changing the magnetic field in reasonable steps

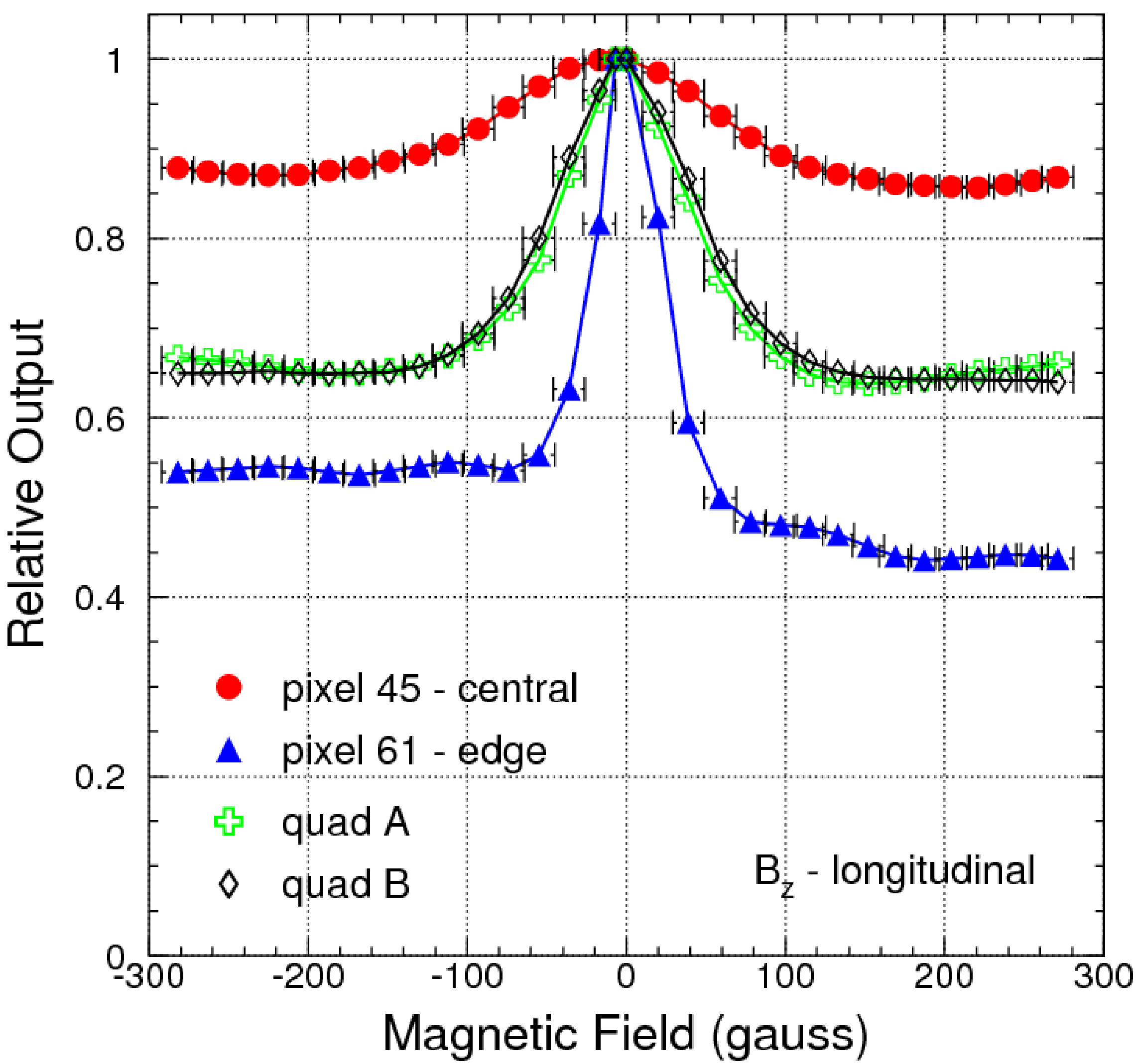
H8500C-03 response to longitudinal B_z field: Pixels



H8500C-03 response to longitudinal B_z field: Quads



H8500C-03 response to longitudinal B_z field: Summary



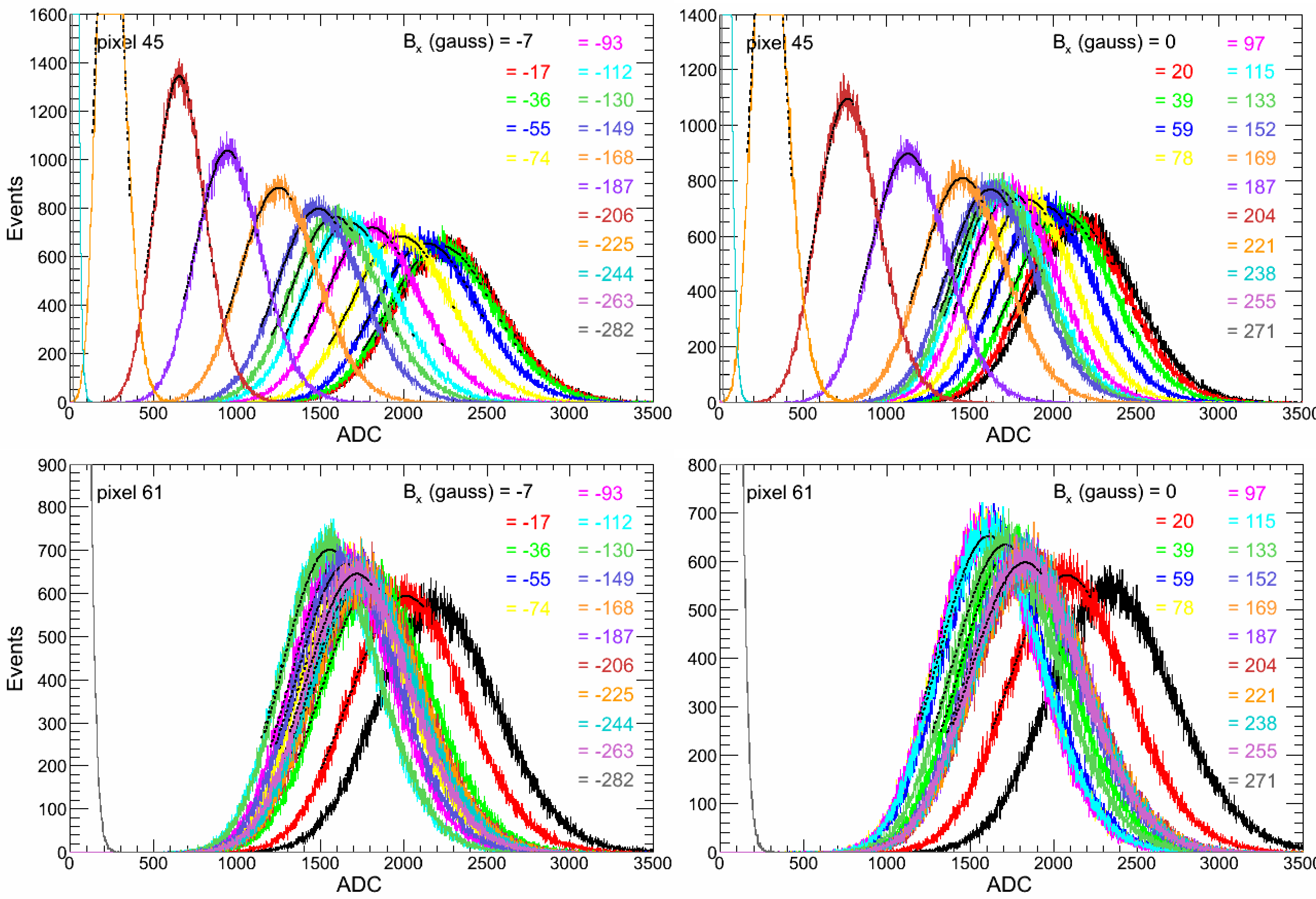
→ "Relative output" represents the mean of the ADC distribution at a given field value normalized to the mean of the ADC distribution at "zero" field value

→ The yield of photoelectrons at "zero" field value is ~ 40-50

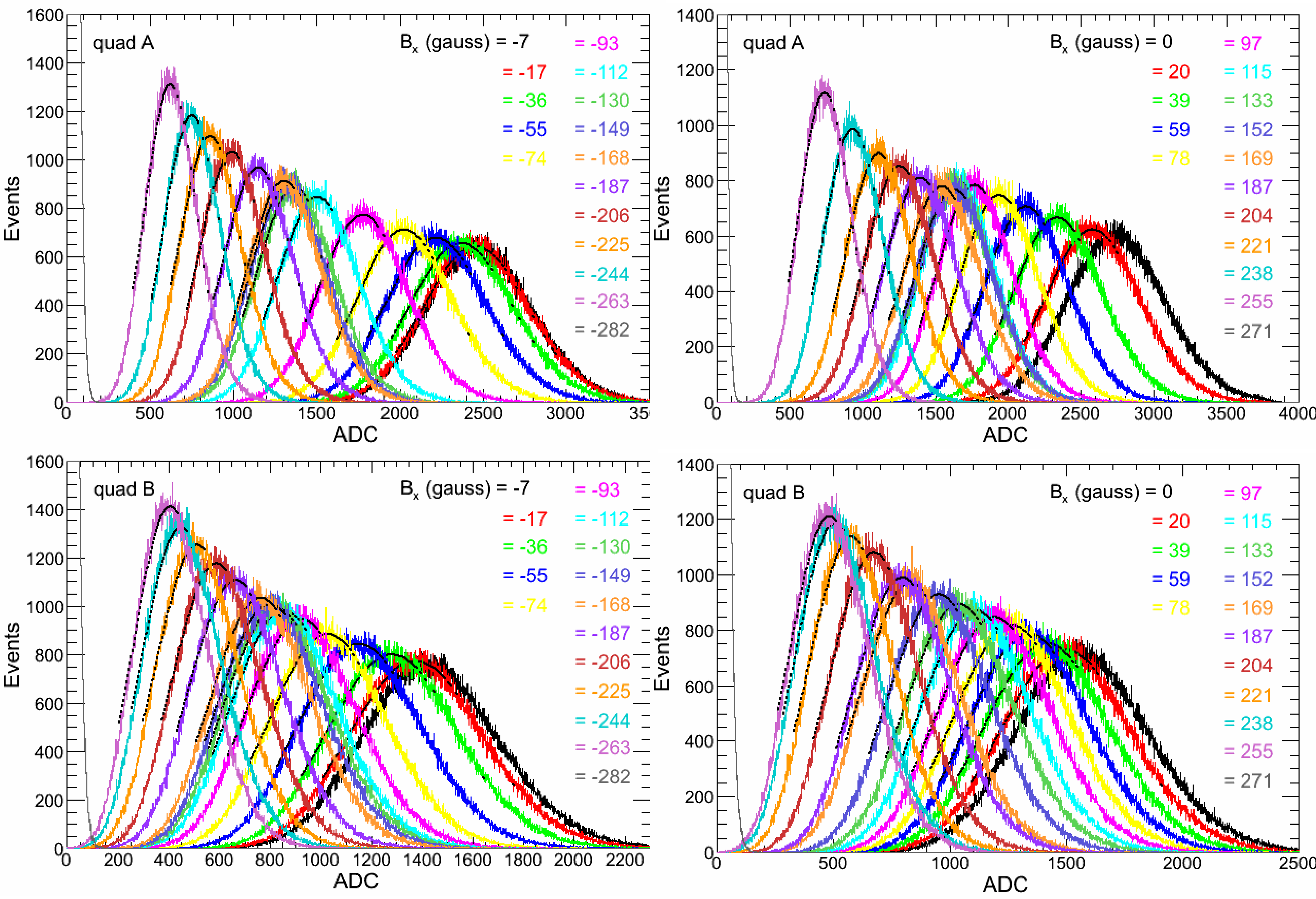
→ Edge pixel experience a greater loss in field than central pixel while quads (sum of pixels) are somewhere in between

→ There is a pronounced drop with field of the relative output up to ~80 gauss; beyond that loss of signal remains constant up to 300 gauss

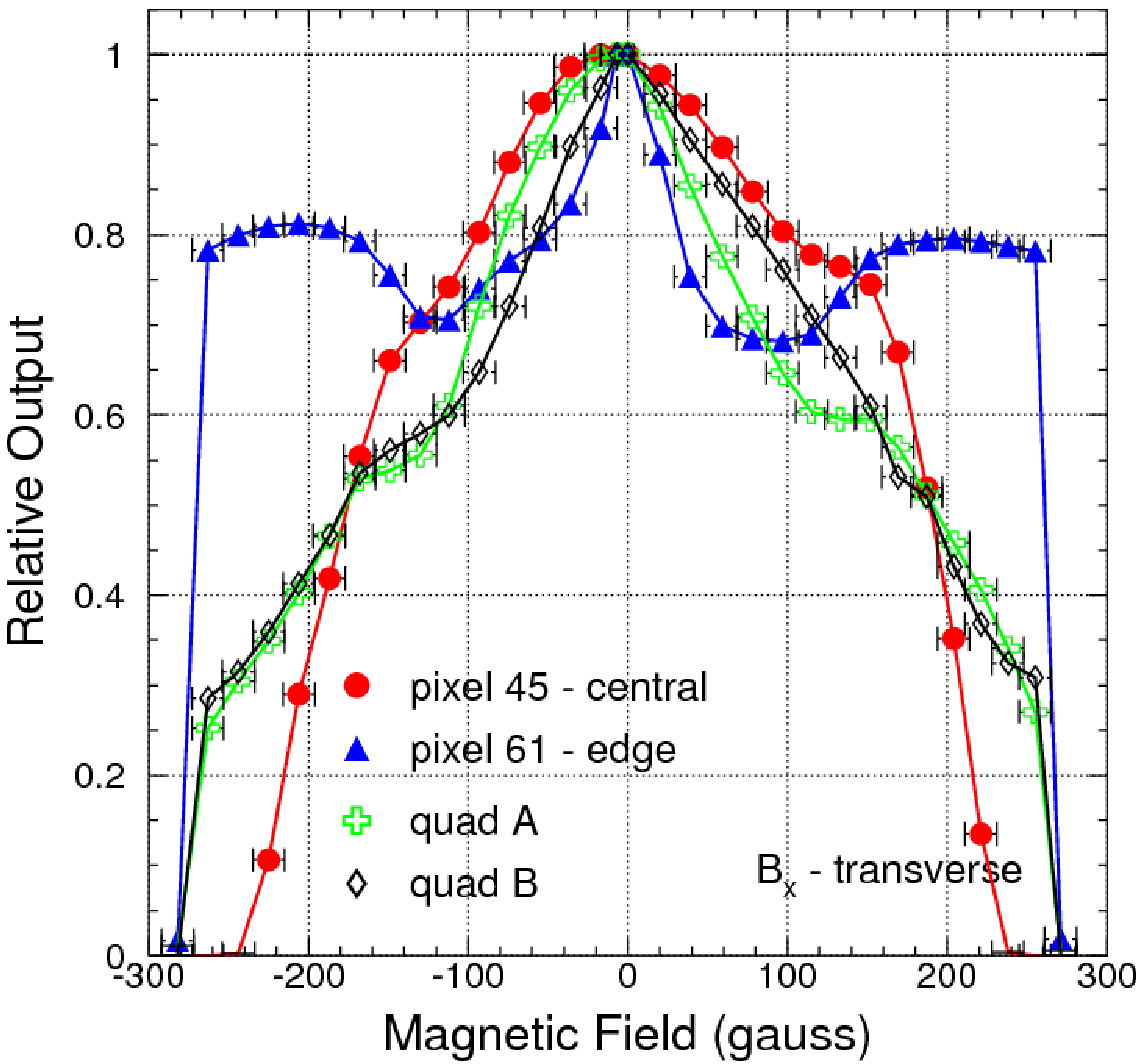
H8500C-03 response to transverse B_x field: Pixels



H8500C-03 response to transverse B_x field: Quads



H8500C-03 response to transverse B_x field: Summary



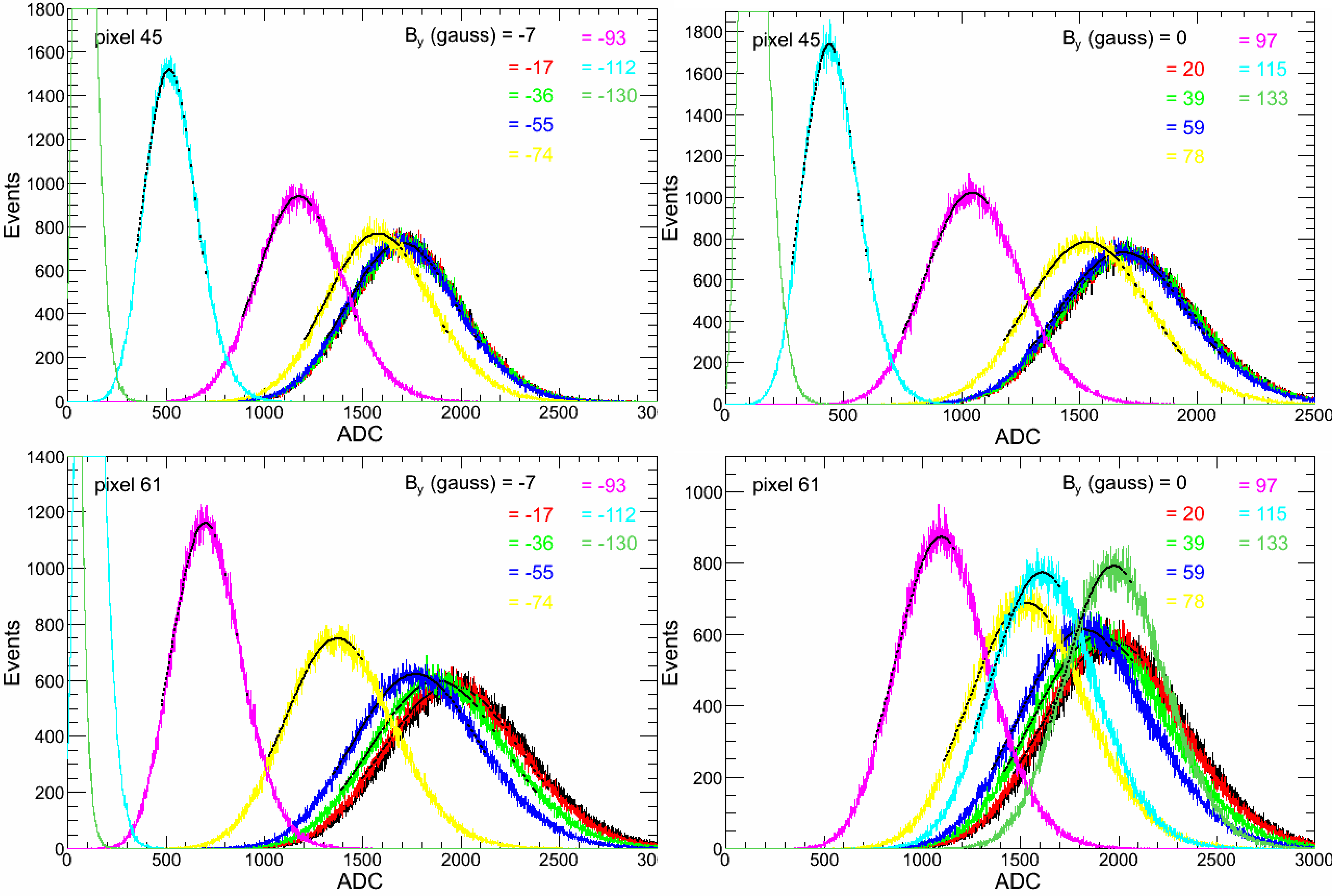
→ "Relative output" represents the mean of the ADC distribution at a given field value normalized to the mean of the ADC distribution at "zero" field value

→ The yield of photoelectrons at "zero" field value is ~ 40-50

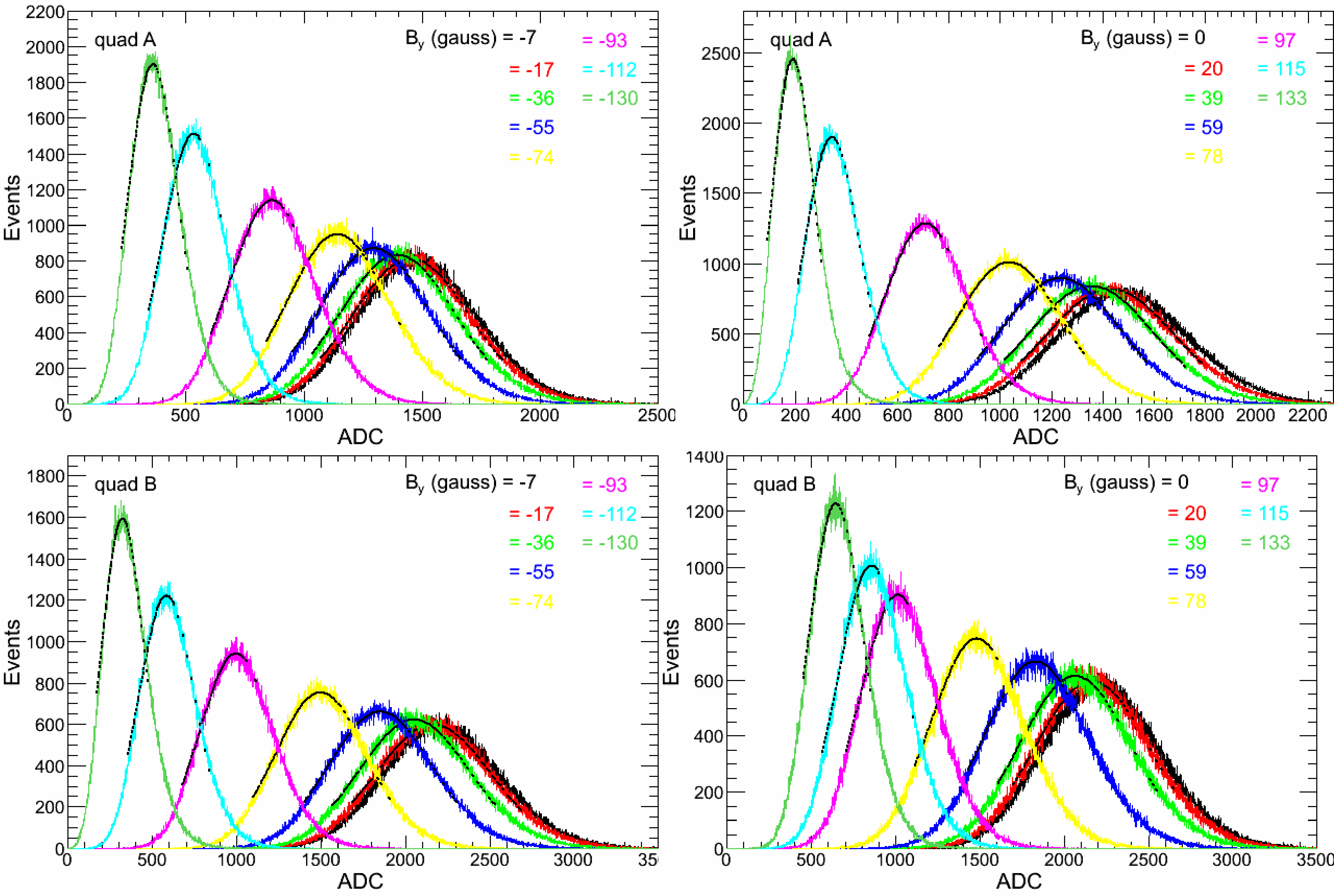
→ Edge pixel behave … strange

→ There is a pronounced drop with field of the relative output all the way up to 300 gauss

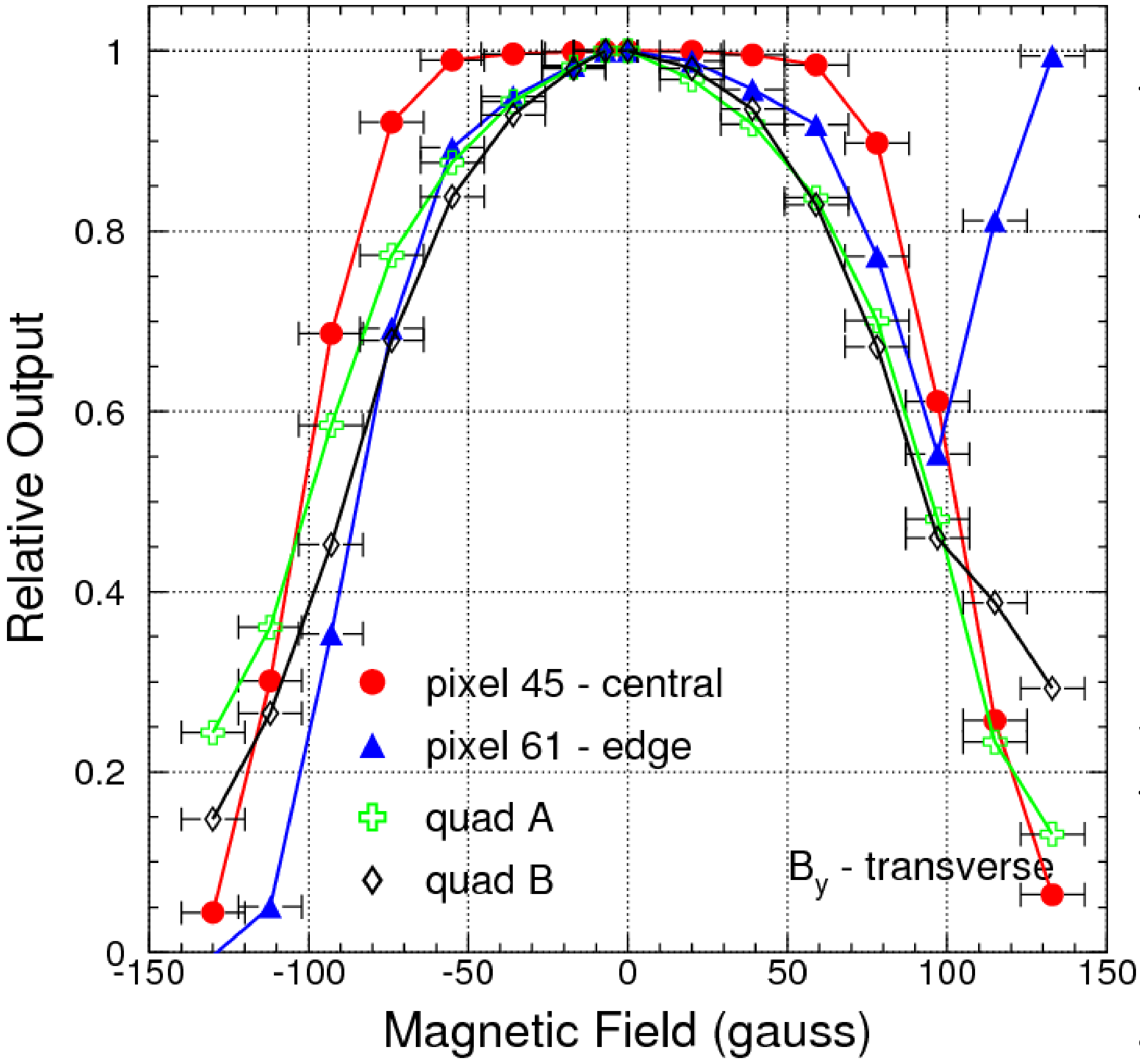
H8500C-03 response to transverse B_y field: Pixels



H8500C-03 response to transverse B_y field: Quads



H8500C-03 response to transverse B_y field: Summary



→ "Relative output" represents the mean of the ADC distribution at a given field value normalized to the mean of the ADC distribution at "zero" field value

→ The yield of photoelectrons at "zero" field value is ~ 40-50

→ Edge pixel behave … strange

→ There is a pronounced drop with field of the relative output all the way up to 300 gauss

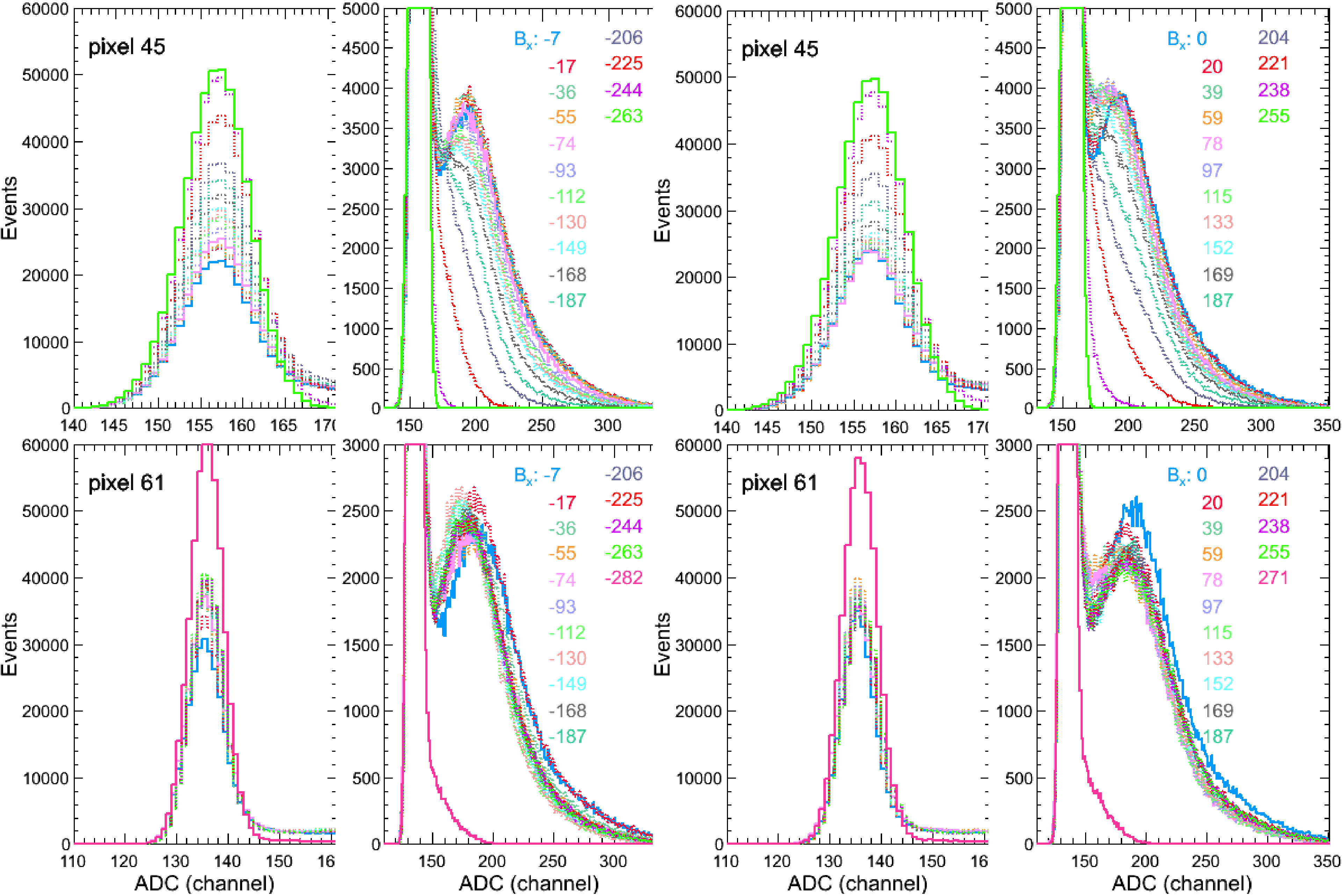
→ The output from the central pixel insensitive to field up to 50 gauss

Magnetic Field Measurements

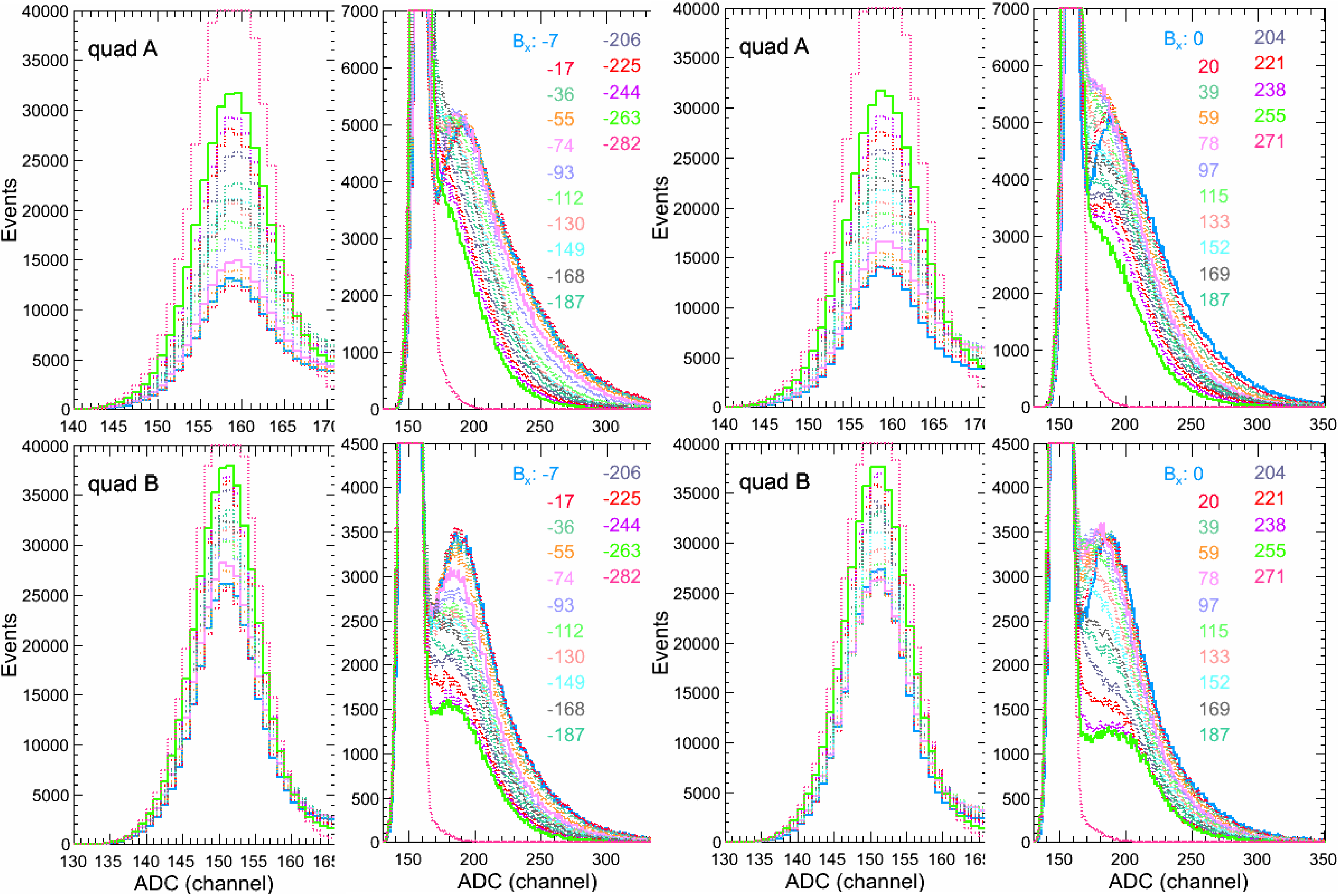
→Field on SPE signals

→ Field on large signals: 30-50 photoelectrons

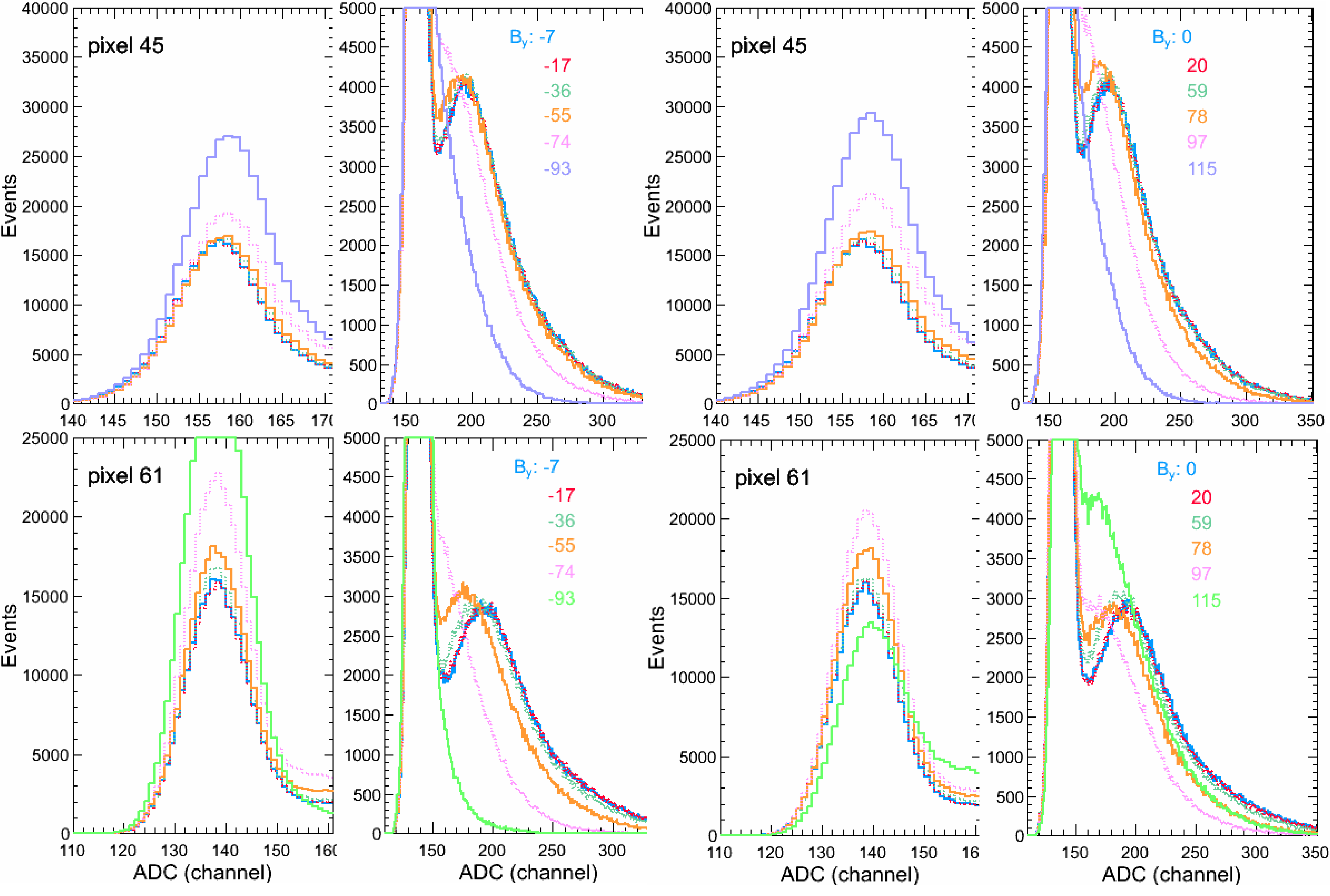
H8500C-03 response to transverse B_x field: Pixels



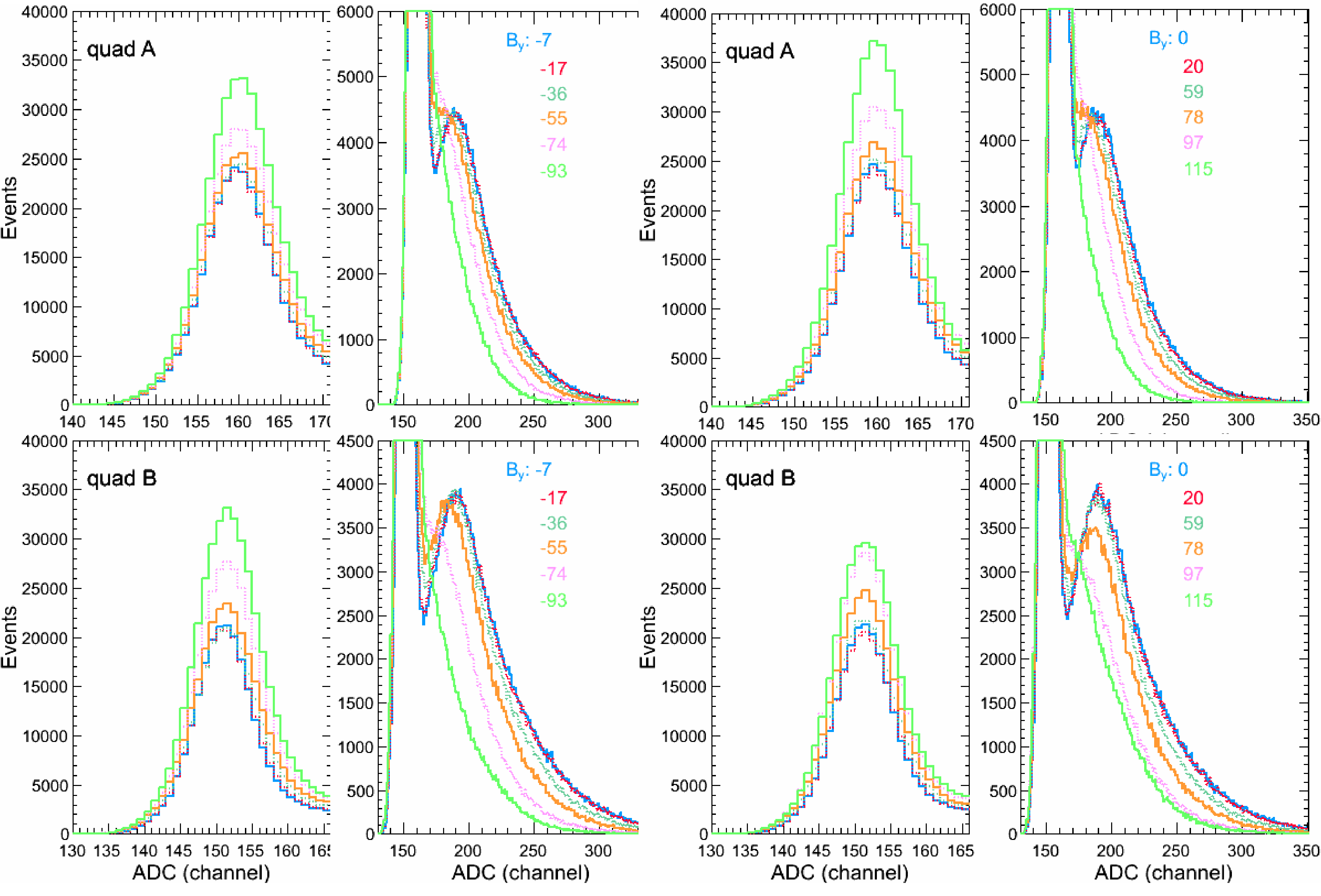
H8500C-03 response to transverse B_x field: Quads



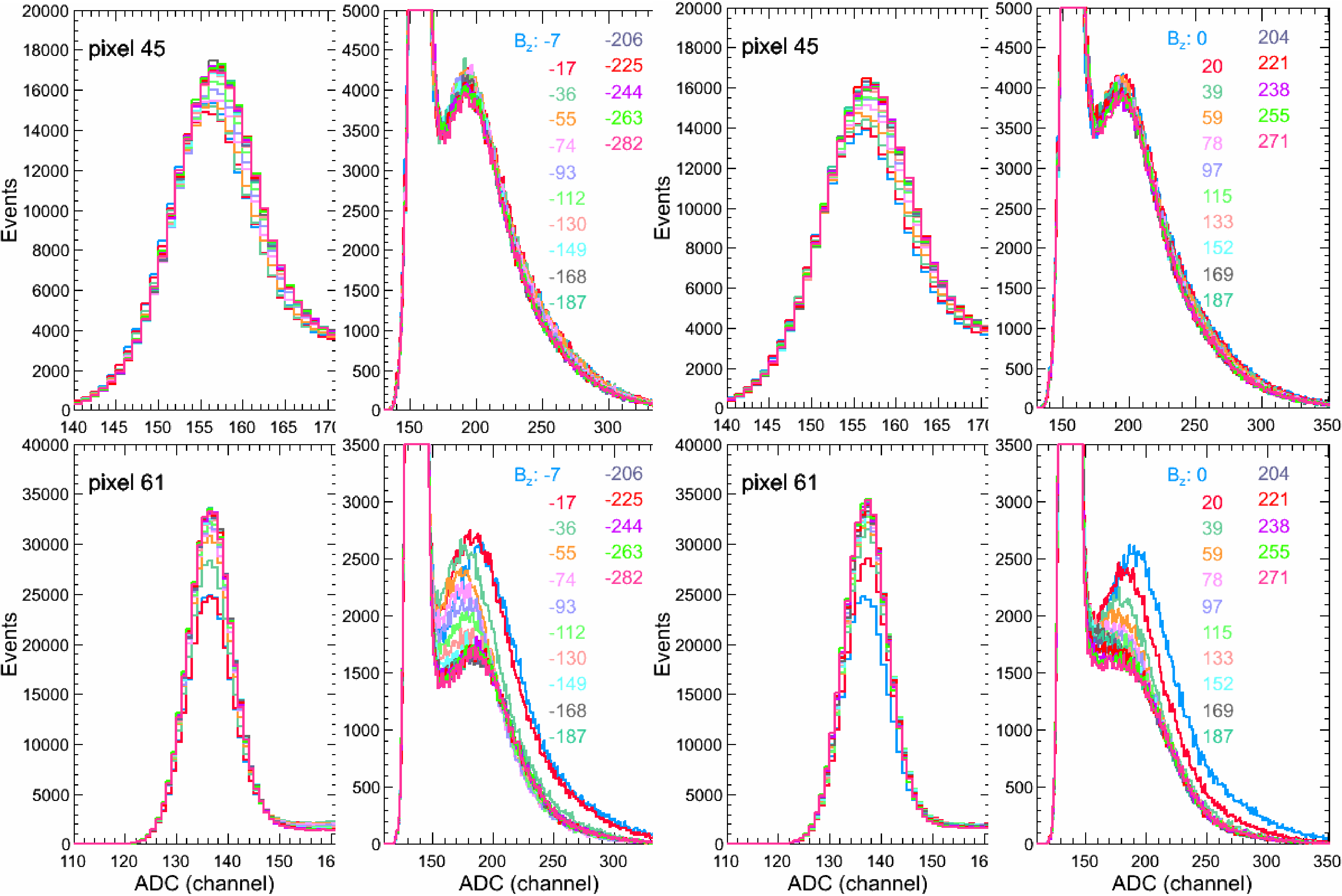
H8500C-03 response to transverse B_y field: Pixels



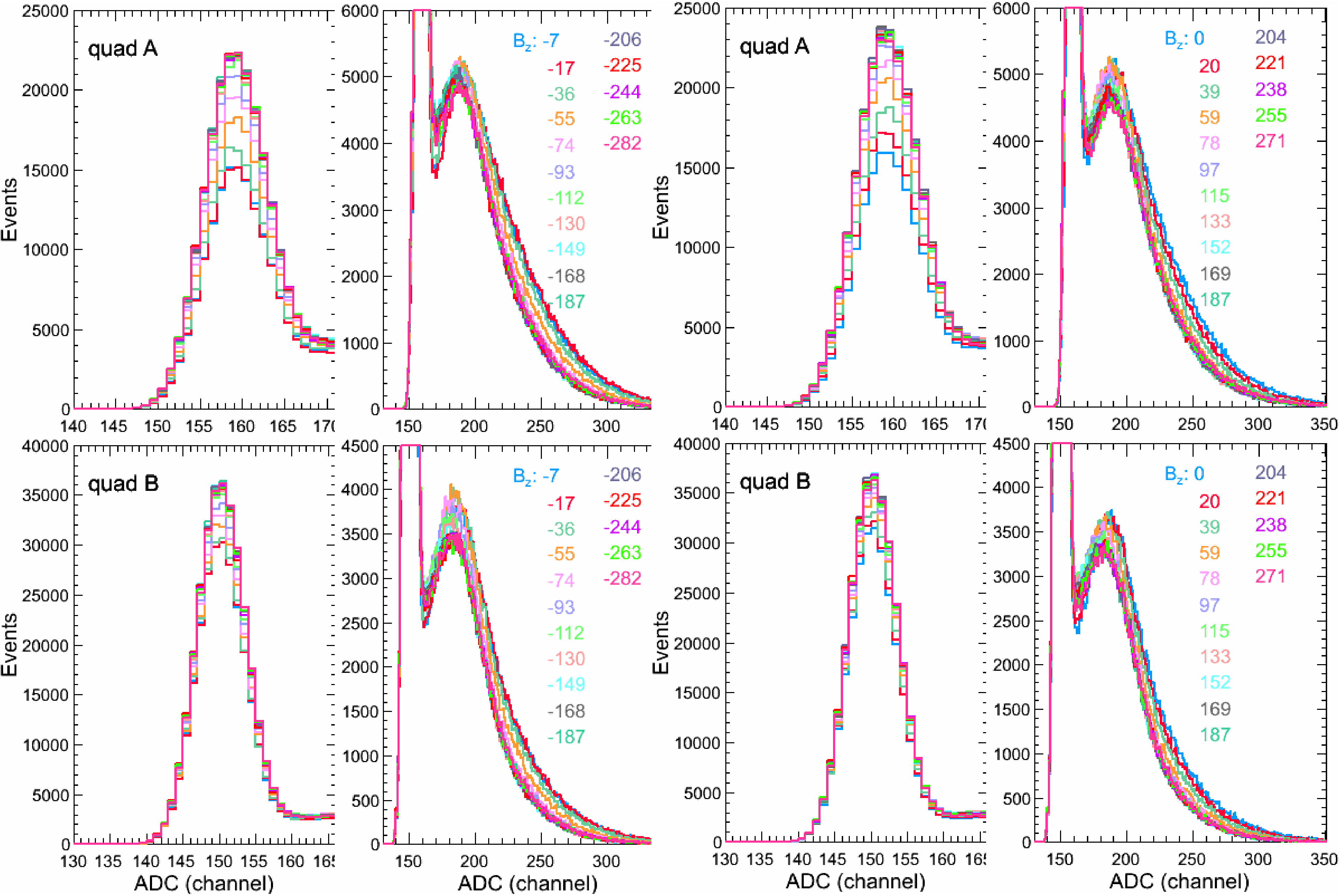
H8500C-03 response to transverse B_y field: Quads



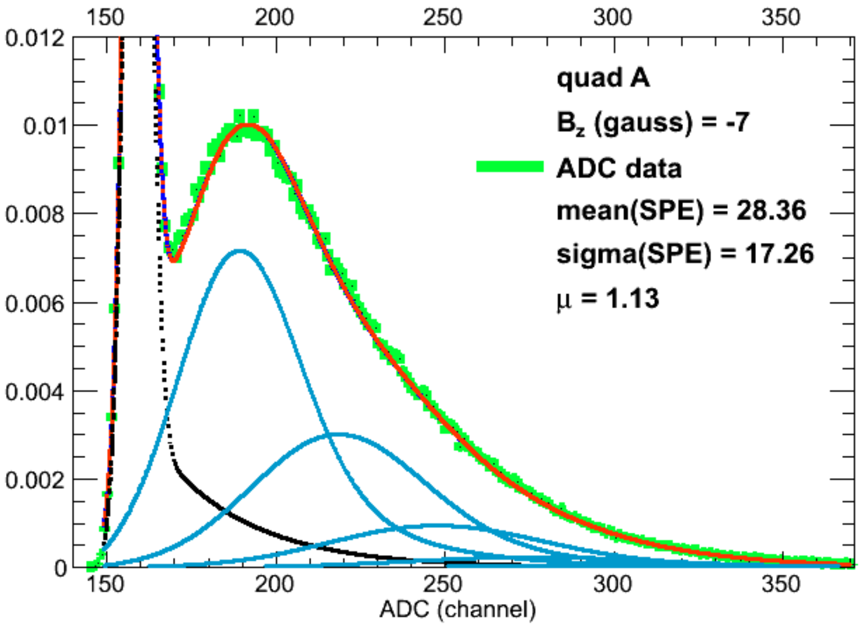
H8500C-03 response to longitudinal B_z field: Pixels

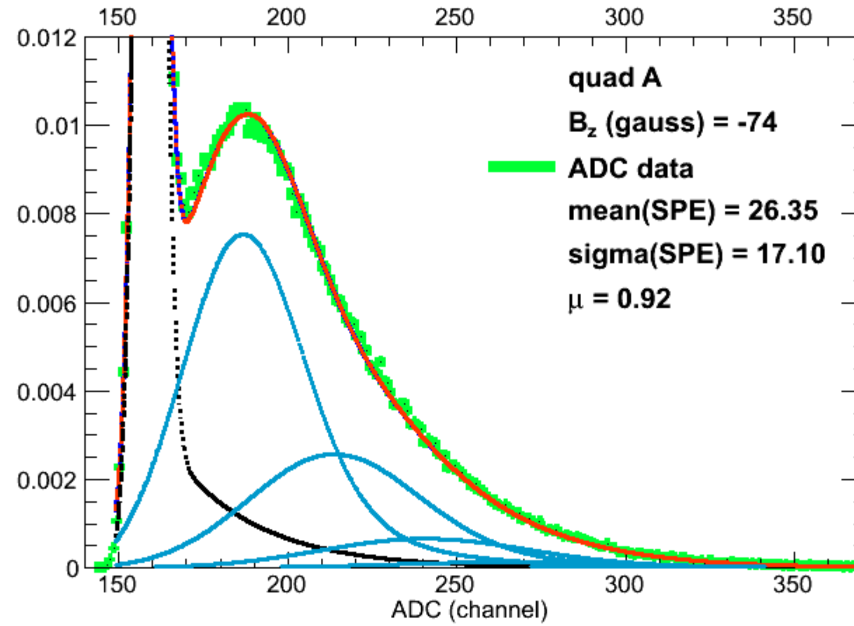


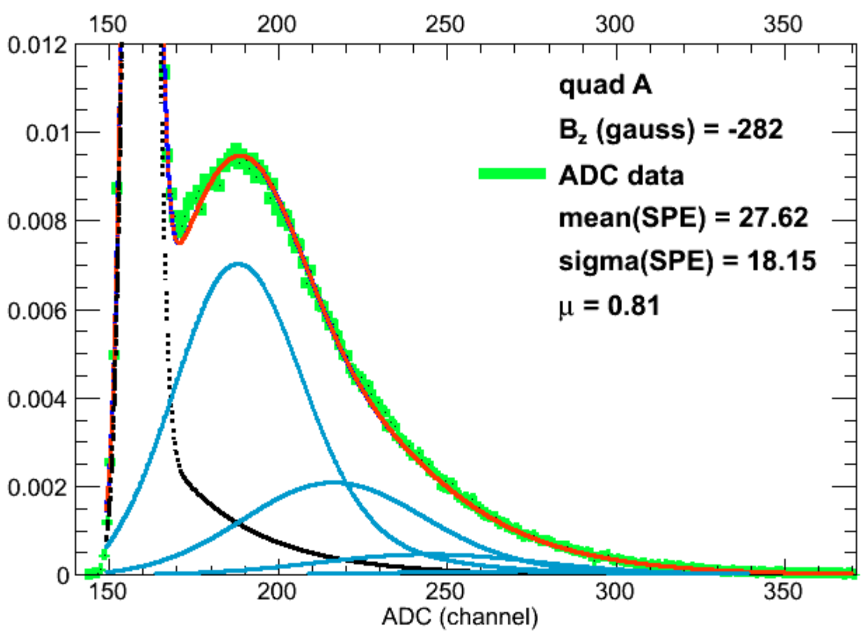
H8500C-03 response to longitudinal B_z field: Quads



Quantifying the response to longitudinal B_z field







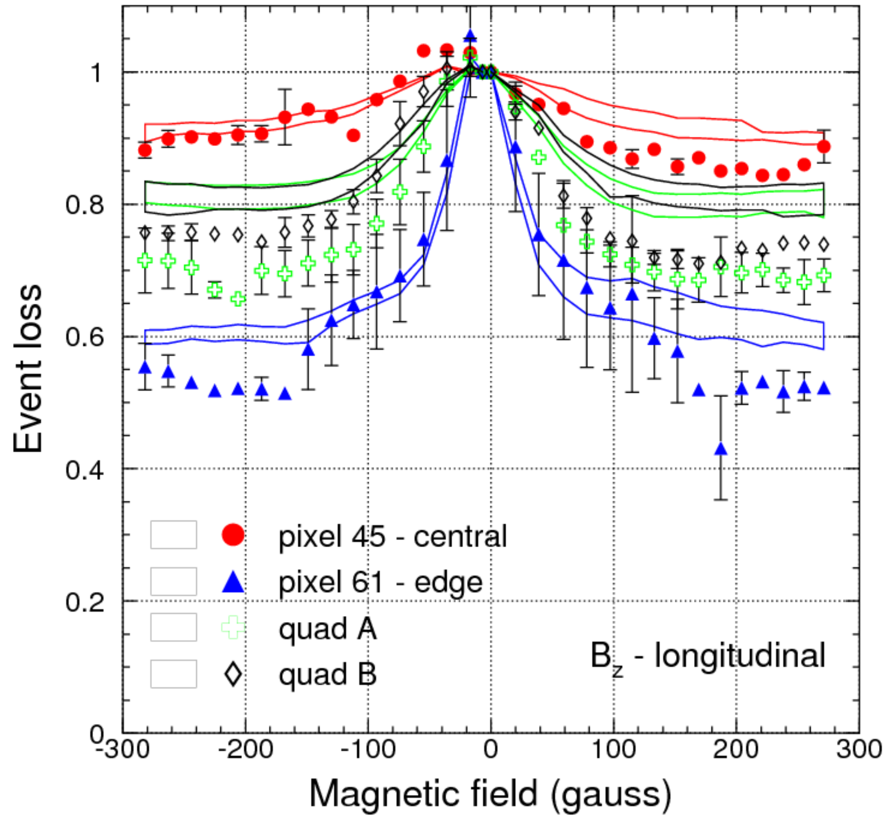
→ Parameter **mean(SPE)** connected to the **gain**

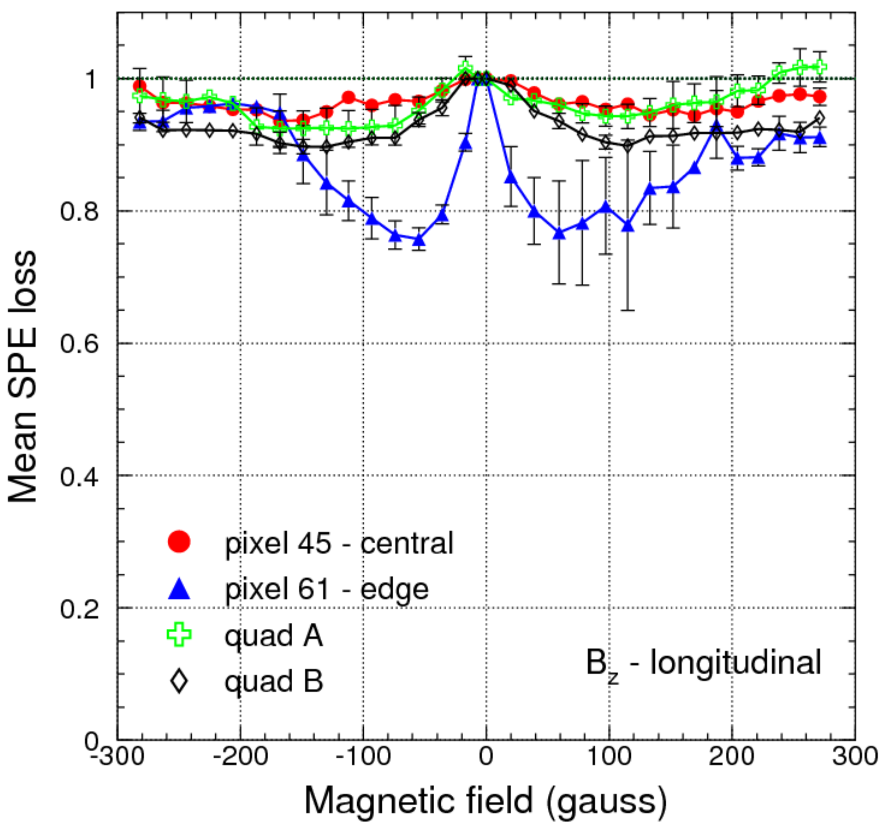
→ Parameter μ connected to the **average number of photoelectrons**

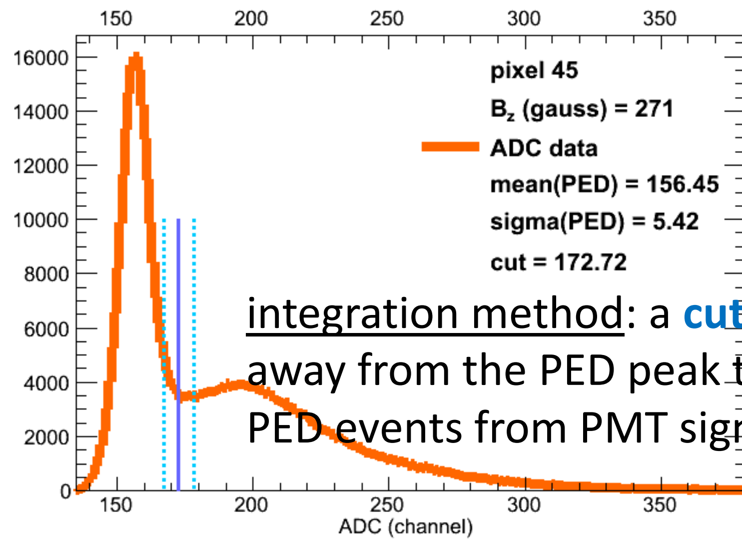
Monitoring the change of the 2 parameters with field could give indication about the mechanism through which the signal is lost

H8500C-03 response to longitudinal B_z field: Summary

→ The event loss is estimated using the μ parameter from the fit (points) and an integration method (bands)



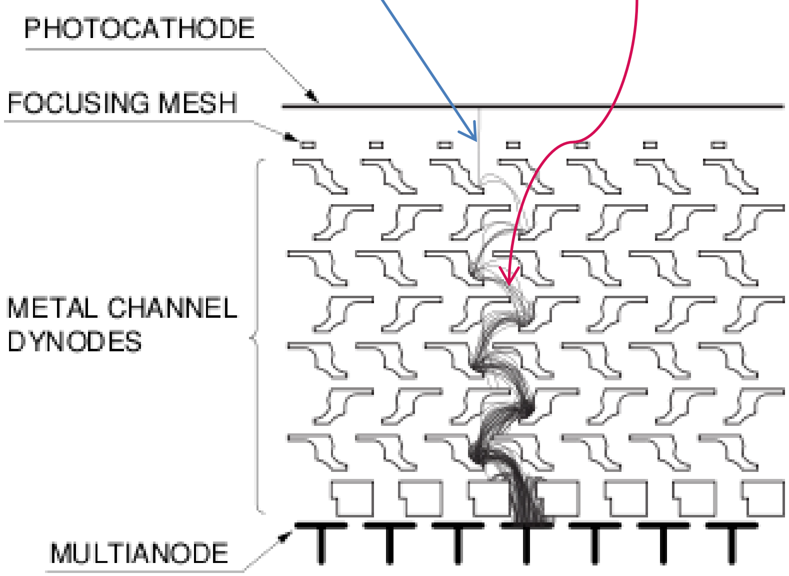




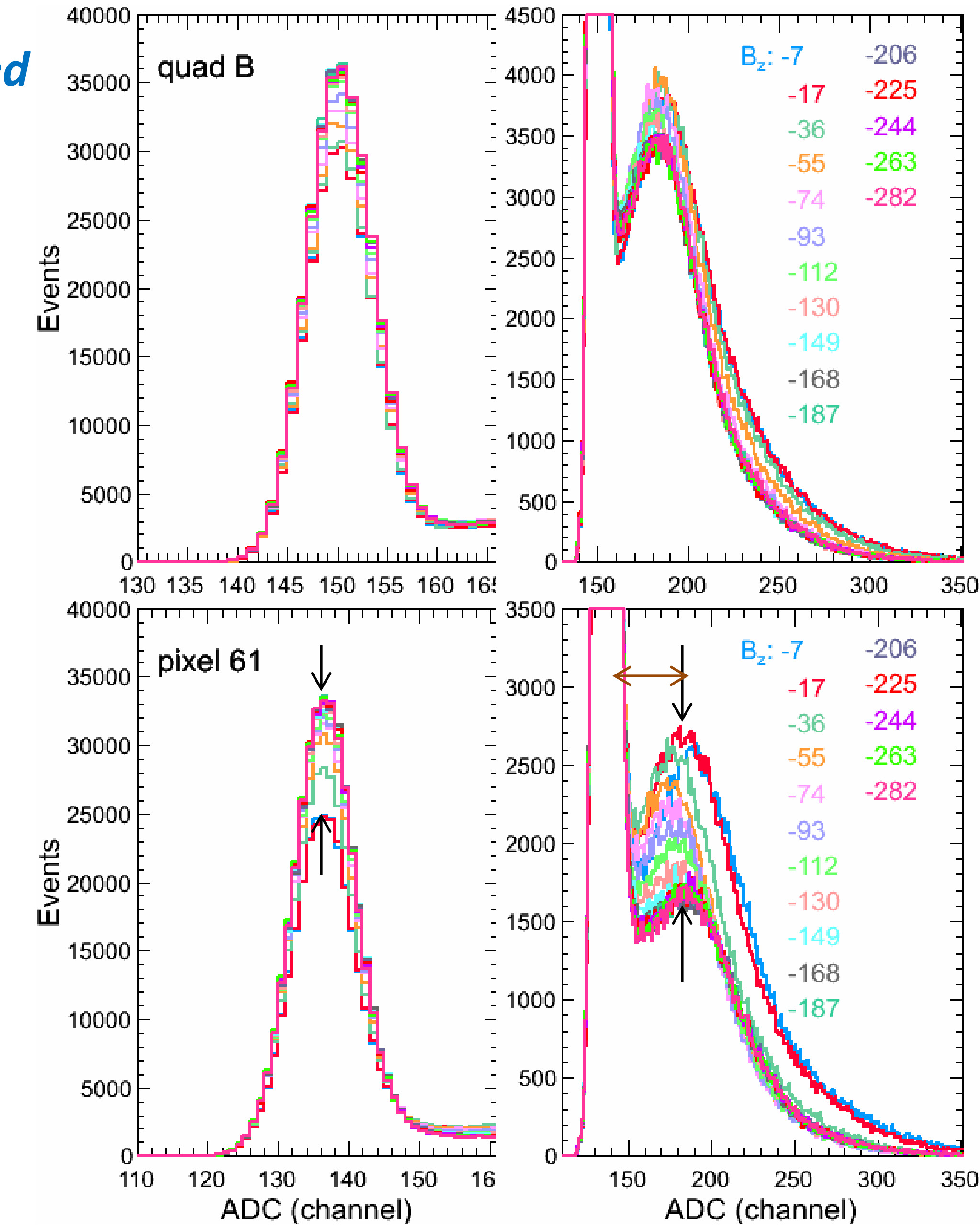
<u>integration method</u>: a **cut** is placed 3 σ away from the PED peak to separate PED events from PMT signal events

Signal Loss Mechanism in longitudinal B_z field

*Do we lose the **photoelectron extracted from the photocathode** or **gain**?*



→ It's a combination of both but ***the dominant effect it appears to be the loss of photoelectron extracted from the photocathode, in most cases***



Conclusions

Single photoelectron measurements

→ H8500C-03: good SPE resolution, better than 1 photoelectron

→ Though the quads are superpositions of 16 pixels with different gains, the SPE is still clearly identifiable

→ If needed, the SPE resolution could be improved for groups of pixels by gain matching

Though it has a fairly low gain, H8500C-03 could be used – individual pixels or groups of pixels -- for applications where identification of SPE is important

Magnetic field measurements

→ For groups of pixels reduction of ~10-15% at 40 gauss for all field orientations; for central pixels <5%; for edge pixels ~20% at most

→ The mechanism of signal loss appears to be dominated by the loss of the photoelectron extracted from the photocathode

With appropriate shielding this PMT could be used in high magnetic field environments