A Novel Technique for the Measurement of Gas Gain Fluctuation of Gaseous Detectors

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Overview

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Introduction

Gas amplification of the electrons created by X-rays, UV photons, or charged particles plays an essential role in their detection with gaseous detectors. It acts as "preamplifier" with a sufficient gain. However, its gain fluctuates because of avalanche statistics, thereby degrading the energy resolution for monochromatic X-rays.
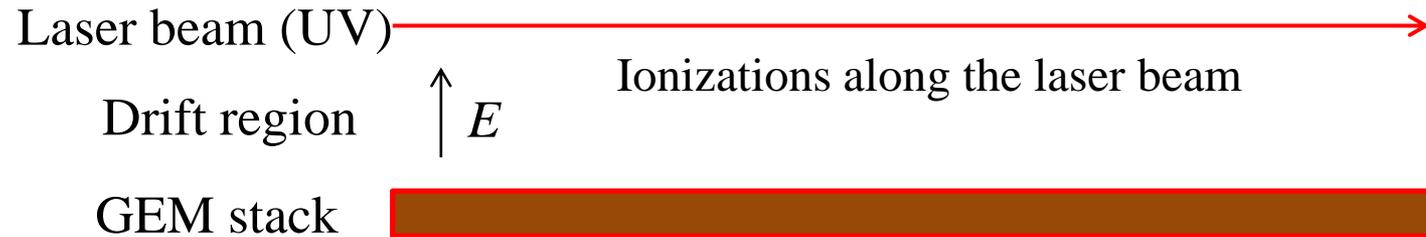
For large Time Projection Chambers (TPCs) the azimuthal spatial resolution at long drift distances is limited by the relative variance of the gas gain for single drift electrons (see NIM A 562 (2006) 136).

Conventionally, avalanche fluctuations are estimated from the gas-amplified charge spectrum for single electrons by a UV lamp or a laser.
This method is, however, not easy because of electronic noise interference.

We have developed a novel technique for the measurement of the relative variance of avalanche fluctuation (f) using laser-induced tracks, exploiting the fixed cluster size of one for each ionization act along the tracks.

Measurement Principle

Laser beam (UV)

Drift region $\quad\uparrow E \qquad$ Ionizations along the laser beam

GEM stack

Readout pad rows

Signal charges $\qquad\qquad Q1 \qquad\quad Q2$

$$1 + f \quad = \quad \frac{\langle n \rangle}{2} \cdot \langle R^2 \rangle$$

$$\equiv \quad \frac{\langle n \rangle}{2} \cdot \left\langle \left(\frac{Q_1 - Q_2}{\langle Q \rangle} \right)^2 \right\rangle$$

f : relative variance of the avalanche fluctuation

$< n >$: average number of electrons per pad row created by the laser, determined from the average charge ratio: laser signal / ^{55}Fe signal

Derivation of the formula

Let us define n to be the total number of electrons per pad row created by the laser beam, g_i to be the gas gain for the i-th liberated electron, and N be the total number of amplified electrons collected by a pad row. Then

$$N = \sum_{i=1}^{n} g_i \quad = \quad g_1 + g_2 + , \cdots , + g_n \tag{1}$$

$$\langle N \rangle \quad = \quad \langle n \rangle \cdot \langle g \rangle \tag{2}$$

$$\sigma_N^2 \quad \equiv \quad \left\langle (N - \langle N \rangle)^2 \right\rangle \tag{3}$$

$$= \quad \left\langle \left(((g_1 - \langle g \rangle) + (g_2 - \langle g \rangle) + , \cdots , + (g_n - \langle g \rangle)) + n \cdot \langle g \rangle - \langle n \rangle \cdot \langle g \rangle \right)^2 \right\rangle \tag{4}$$

$$= \quad \left\langle n \cdot (g - \langle g \rangle)^2 \right\rangle + \langle g \rangle^2 \cdot \left\langle (n - \langle n \rangle)^2 \right\rangle \tag{5}$$

$$= \quad \langle n \rangle \cdot \sigma_g^2 + \langle g \rangle^2 \cdot \sigma_n^2 \tag{6}$$

$$= \quad \langle n \rangle \cdot \langle g \rangle^2 \cdot (1 + f) , \tag{7}$$

with f being the relative variance of the gas gain for single drift electrons ($\equiv \sigma_g^2 / \langle g \rangle^2$). In Eq. (7) σ_n^2 is replaced by $\langle n \rangle$, assuming Poisson statistics for the number of initial ionizations.

In practice, $\langle n \rangle$ varies with time because of the laser intensity variation due to drift and/or shot-to-shot fluctuation:

$$\langle n \rangle = \langle \langle n \rangle \rangle + \delta \langle n \rangle \tag{8}$$

and

$$n = \langle \langle n \rangle \rangle + \delta \langle n \rangle + \delta n \tag{9}$$

where $\langle n \rangle$ is the average number of electrons per pad row created by a single laser shot and $\langle \langle n \rangle \rangle$, the average of $\langle n \rangle$ during a data taking period. Therefore

$$\langle \sigma_N^2 \rangle \quad \equiv \quad \left\langle (N - \langle \langle N \rangle \rangle)^2 \right\rangle \tag{10}$$

$$= \quad \left\langle (N - \langle N \rangle + \langle N \rangle - \langle \langle N \rangle \rangle)^2 \right\rangle \tag{11}$$

$$= \quad \left\langle (N - \langle N \rangle)^2 \right\rangle + \left\langle (\langle N \rangle - \langle \langle N \rangle \rangle)^2 \right\rangle \tag{12}$$

$$= \quad \langle \langle n \rangle \rangle \langle g \rangle^2 \cdot (1 + f) + \langle g \rangle^2 \cdot \left\langle (\langle n \rangle - \langle \langle n \rangle \rangle)^2 \right\rangle \tag{13}$$

$$= \quad \langle \langle n \rangle \rangle \langle g \rangle^2 \cdot (1 + f) + \langle g \rangle^2 \cdot \left\langle (\delta \langle n \rangle)^2 \right\rangle \tag{14}$$

where $\langle N \rangle$ is the average number of gas-amplified electrons per pad row for a single laser shot and $\langle \langle N \rangle \rangle$, the average of $\langle N \rangle$ during the data taking period. Obviously

$$\langle N \rangle \quad = \quad \langle g \rangle \cdot \langle n \rangle \tag{15}$$

$$\langle \langle N \rangle \rangle \quad = \quad \langle g \rangle \cdot \langle \langle n \rangle \rangle . \tag{16}$$

The variance of the difference in the amplified number of electrons detected by two nearby pad rows, averaged over the data taking period, is given by

$$\left\langle\left\langle(N_1-N_2)^2\right\rangle\right\rangle = \left\langle\left\langle(N_1-\langle\langle N\rangle\rangle-(N_2-\langle\langle N\rangle\rangle))^2\right\rangle\right\rangle \tag{17}$$

$$= \left\langle\left\langle(N_1-\langle\langle N\rangle\rangle)^2\right\rangle\right\rangle+\left\langle\left\langle(N_2-\langle\langle N\rangle\rangle)^2\right\rangle\right\rangle-2\cdot\langle\langle(N_1-\langle\langle N\rangle\rangle)\cdot(N_2-\langle\langle N\rangle\rangle)\rangle\rangle \tag{18}$$

$$= 2\cdot\langle\langle n\rangle\rangle\cdot\langle g\rangle^2\cdot(1+f)+2\cdot\langle g\rangle^2\cdot\left\langle(\delta\langle n\rangle)^2\right\rangle-2\cdot\langle\langle(N_1-\langle\langle N\rangle\rangle)\cdot(N_2-\langle\langle N\rangle\rangle)\rangle\rangle \tag{19}$$

$$= 2\cdot\langle\langle n\rangle\rangle\cdot\langle g\rangle^2\cdot(1+f)+2\cdot\langle g\rangle^2\cdot\left\langle(\delta\langle n\rangle)^2\right\rangle$$
$$-2\cdot\langle\langle(N_1-\langle N\rangle+\langle N\rangle-\langle\langle N\rangle\rangle)\cdot(N_2-\langle N\rangle+\langle N\rangle-\langle\langle N\rangle\rangle)\rangle\rangle \tag{20}$$

$$= 2\cdot\langle\langle n\rangle\rangle\cdot\langle g\rangle^2\cdot(1+f)+2\cdot\langle g\rangle^2\cdot\left\langle(\delta\langle n\rangle)^2\right\rangle-2\cdot\left\langle(\langle N\rangle-\langle\langle N\rangle\rangle)^2\right\rangle \tag{21}$$

$$= 2\cdot\langle\langle n\rangle\rangle\cdot\langle g\rangle^2\cdot(1+f)+2\cdot\langle g\rangle^2\cdot\left\langle(\delta\langle n\rangle)^2\right\rangle-2\cdot\langle g\rangle^2\cdot\left\langle(\langle n\rangle-\langle\langle n\rangle\rangle)^2\right\rangle \tag{22}$$

$$= 2\cdot\langle\langle n\rangle\rangle\cdot\langle g\rangle^2\cdot(1+f) \tag{23}$$

assuming $\langle n_1\rangle=\langle n_2\rangle=\langle n\rangle$ and $\langle N_1\rangle=\langle N_2\rangle=\langle N\rangle$.

Accordingly

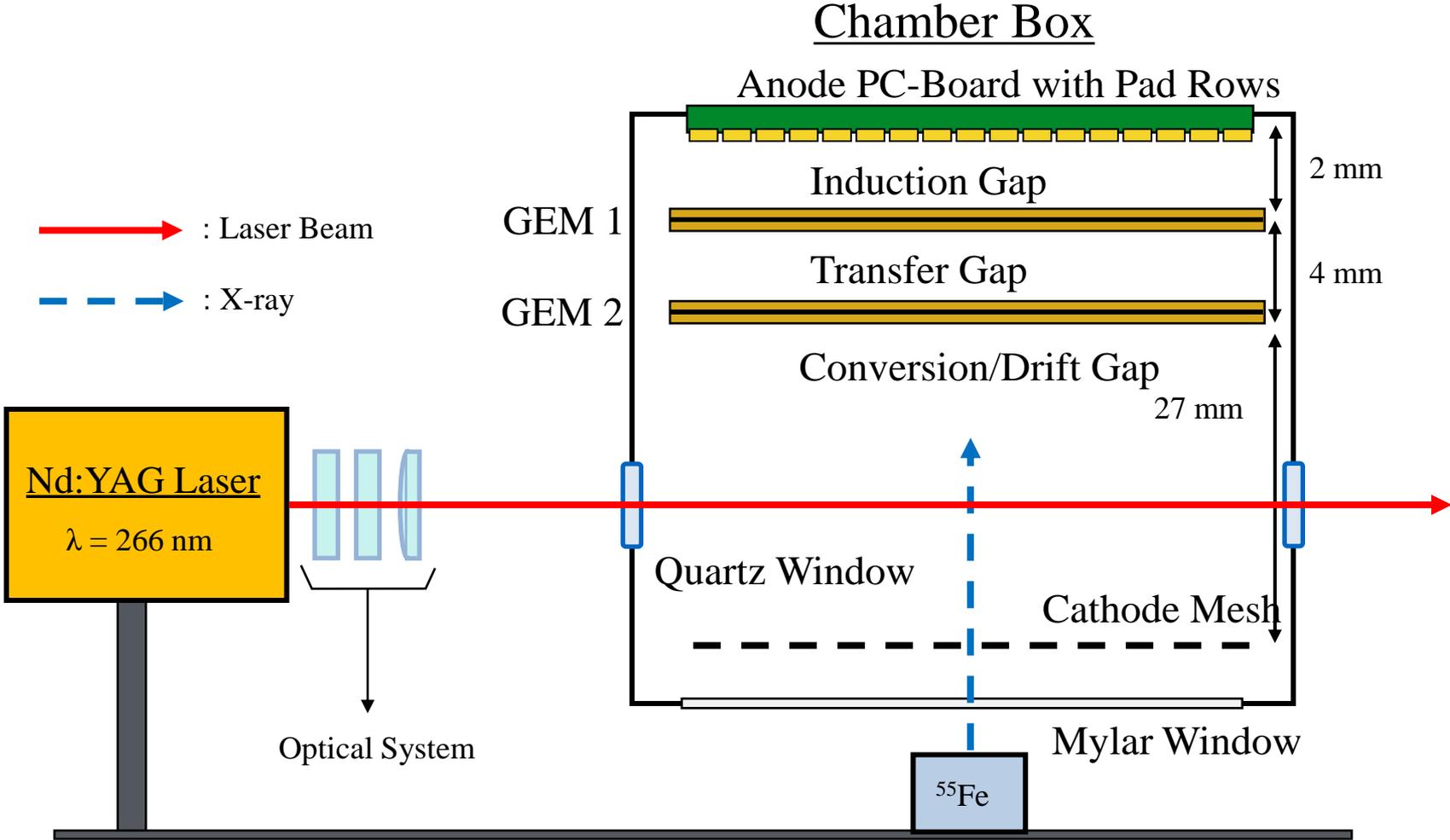$$1+f = \frac{1}{2}\cdot\frac{\left\langle\left\langle(N_1-N_2)^2\right\rangle\right\rangle}{\langle g\rangle^2\langle\langle n\rangle\rangle} \tag{24}$$

$$= \frac{\langle\langle n\rangle\rangle}{2}\cdot\frac{\left\langle\left\langle(N_1-N_2)^2\right\rangle\right\rangle}{\langle\langle N\rangle\rangle^2} \tag{25}$$
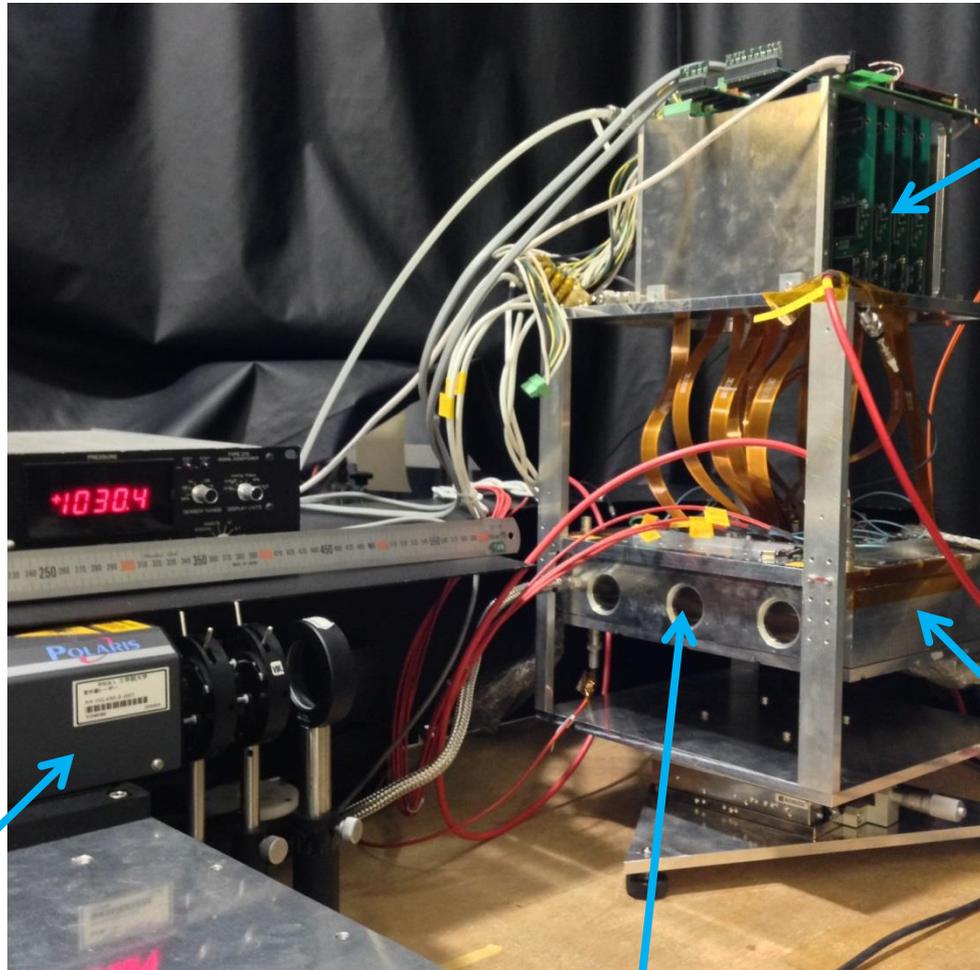
$$= \frac{\langle\langle n\rangle\rangle}{2}\cdot\frac{\left\langle\left\langle(Q_1-Q_2)^2\right\rangle\right\rangle}{\langle\langle Q\rangle\rangle^2} \tag{26}$$

where Q represents the charge, proportional to N, recorded by the readout electronics.

Schematic view of the experimental setup

Chamber Box

Picture of the experimental setup

Readout electronics (ALTRO)

Laser (NewWave Polaris II)

Quartz window

Chamber box

GEM foils and Readout plane (originally for LC-TPC test module)

GEM foil (× 2)
   Laser-etched LCP (100 μm thick)
            with copper electrodes
   Hole diameter/pitch: 70 μm/140 μm
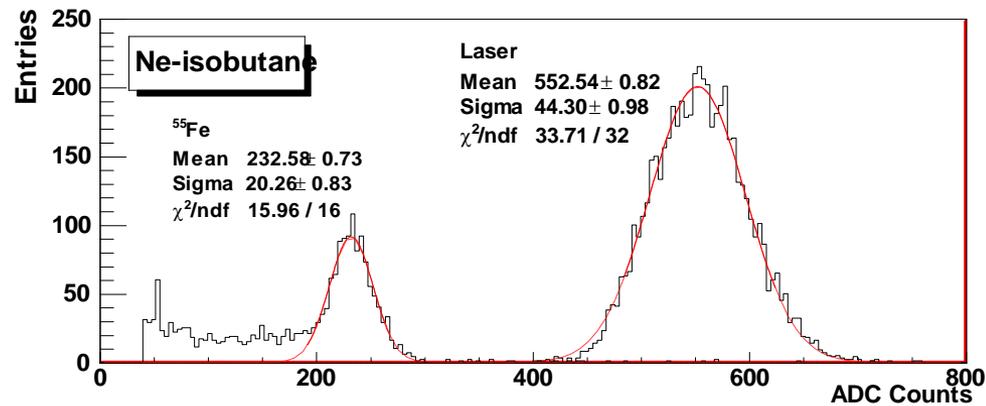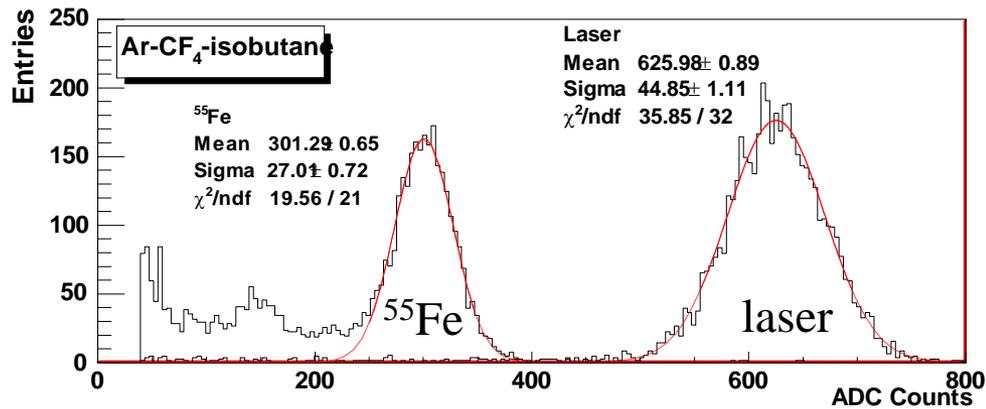   Segmentation: 2

Readout plane
  28 pad rows
  Average pad width: 1.25 mm
           height: 5.26 mm

10-12 pad rows are equipped with readout electronics (ALTRO).

Determination of $< n >$ using ^{55}Fe source

The average number of electrons created by the laser beam is estimated from the ratio of the signals: Q_{laser} / Q_{55Fe}.

Typical $< n >$ is 250 and the measurement is much easier than observing the gas-amplified charge spectrum for single electrons, even at low gas gain.
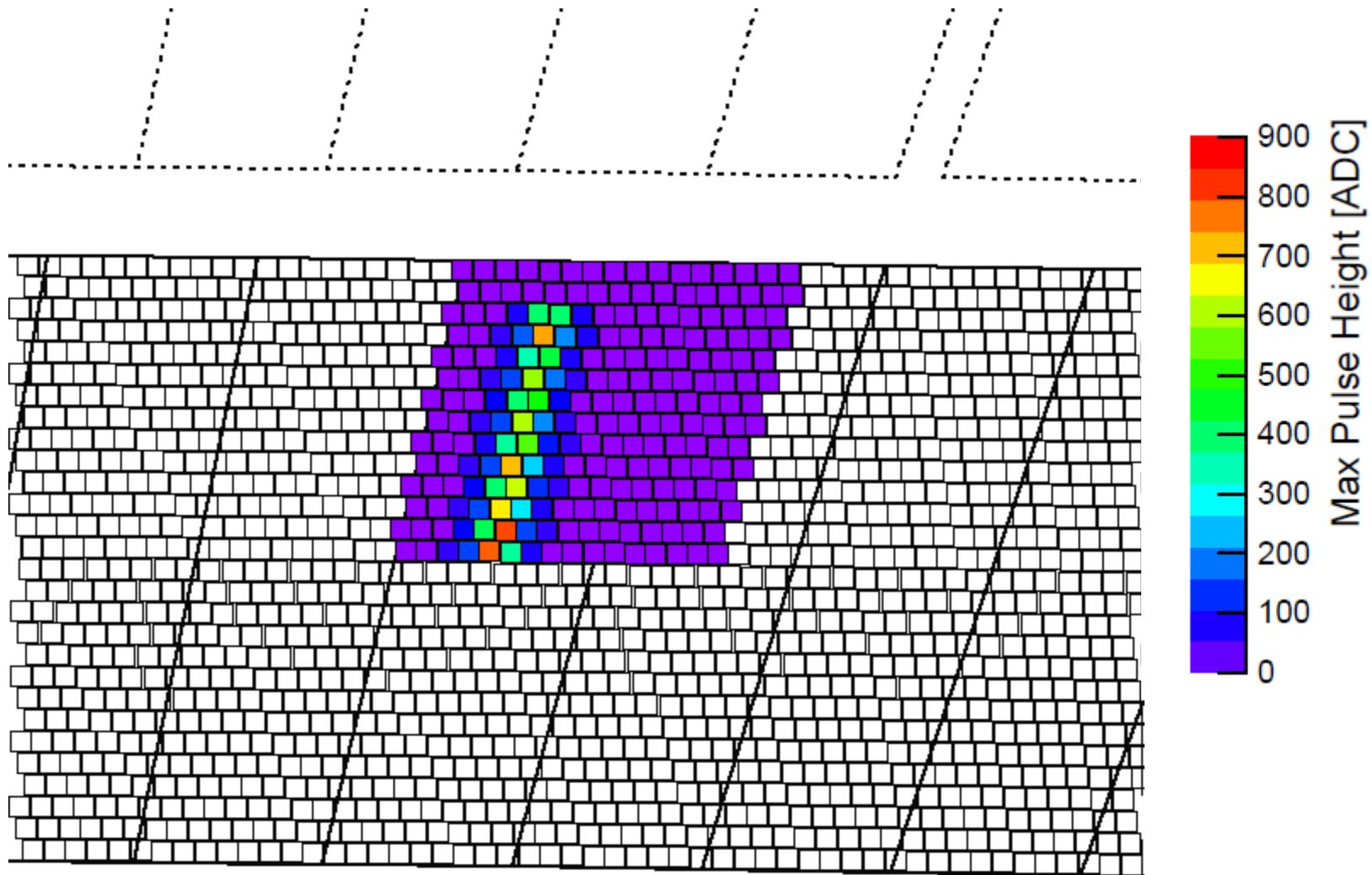
Signal Charge vs. Laser Power
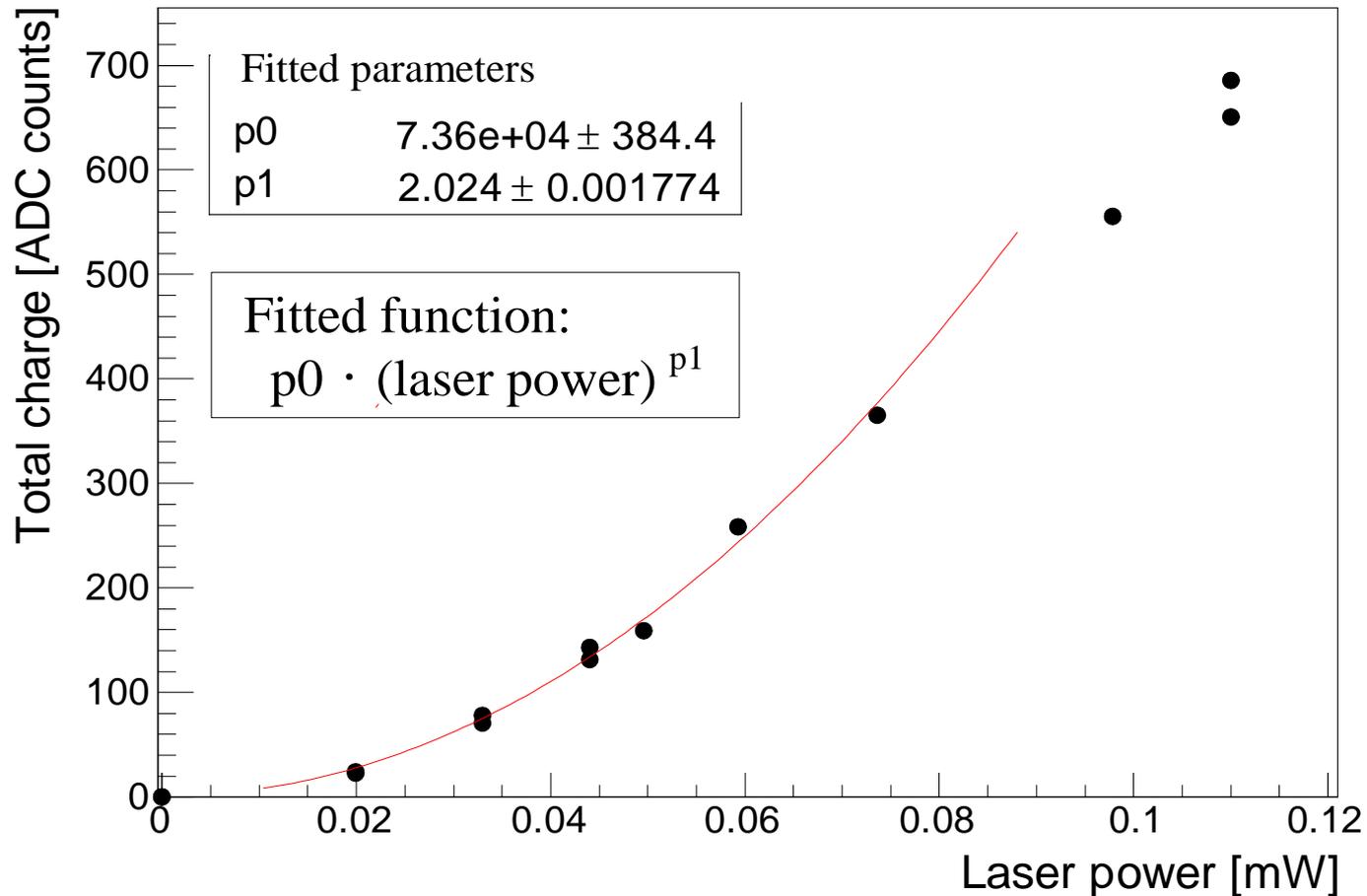
The signal charge created by the laser is proportional to the laser power squared when the power is low, suggesting a two-photon ionization process.

Laser beam size
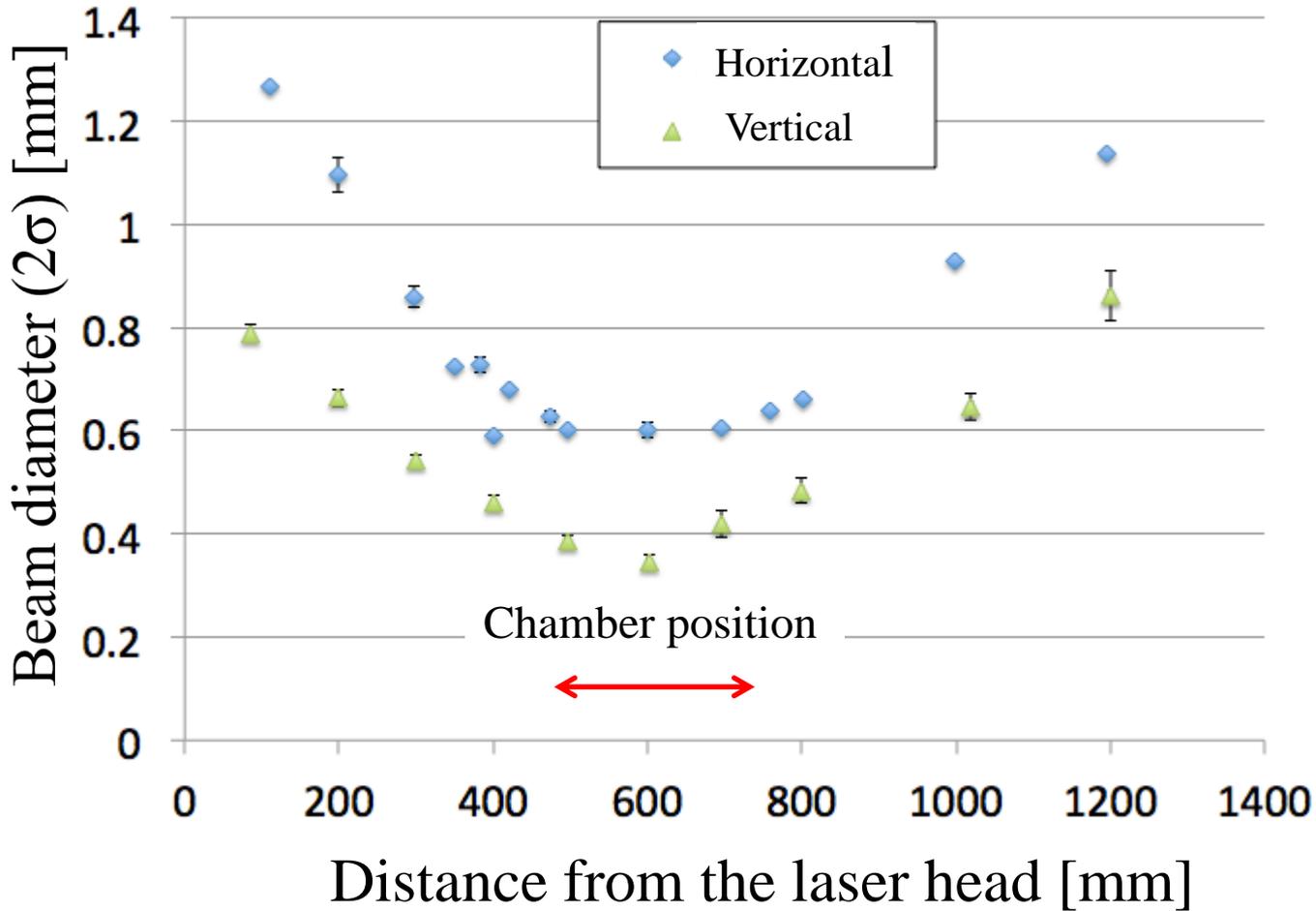
In the case of charged particle tracks (cosmic rays)

Pad row #4

Pad row #6
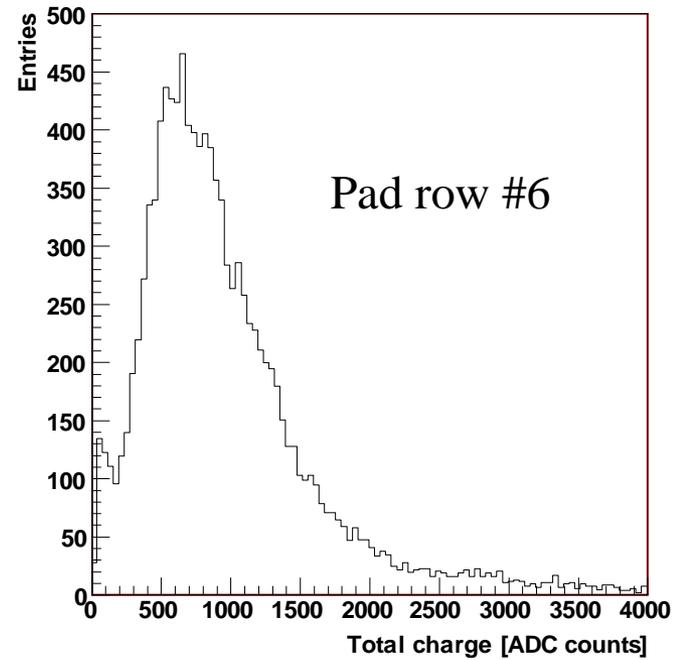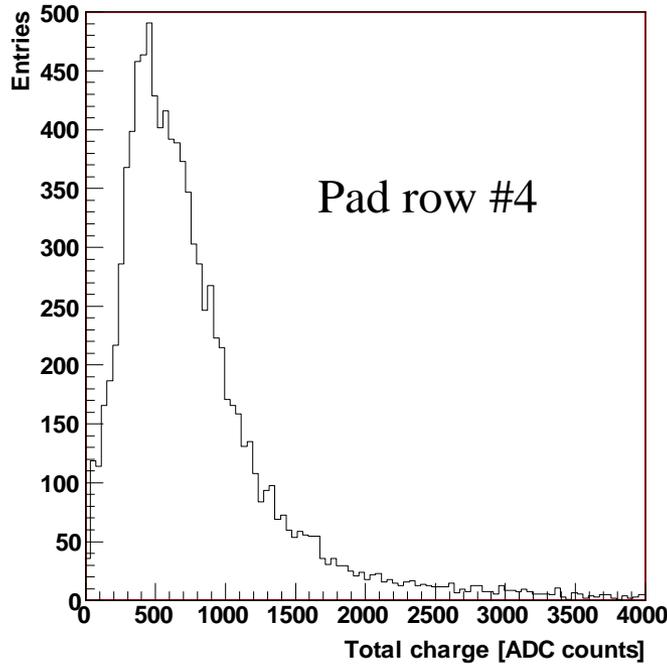
It is difficult to estimate the variance of the distribution because of Landau tails

Difference

In the case of laser induced tracks, the distribution is almost normal and Gaussian fitting is justified.
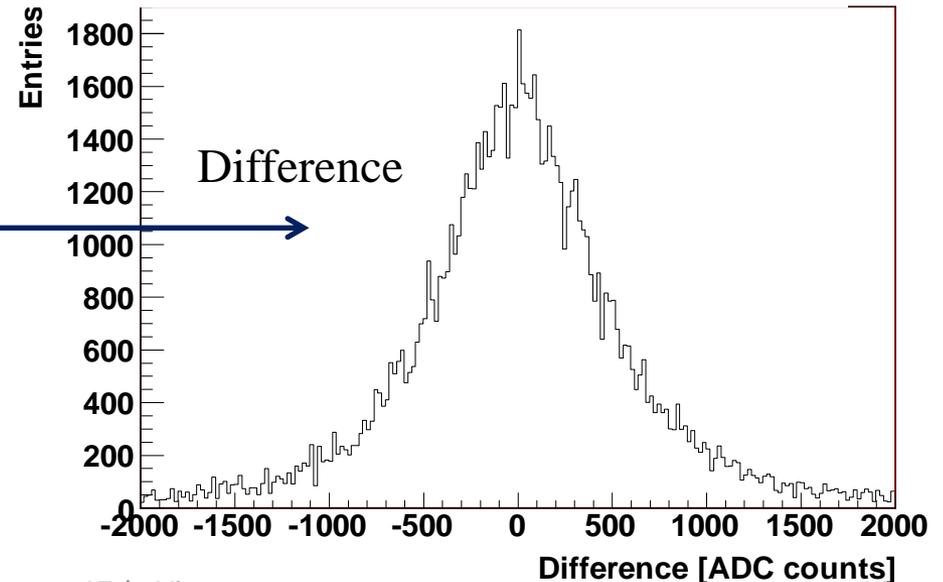
Correlation of the laser signal charges measured by two pad rows

- The two charges are correlated mainly due to the variation of the laser intensity: drift and/or shot-to-shot fluctuations.
- The contribution of gas-gain drift is small because of short data taking time of 10 minutes.
- The electronic noises are correlated: common-mode dominant.

Projection to the Y' axis

h1f

Entries	5000
Mean	-0.3288
RMS	7.495
χ^2 / ndf	57.71 / 11
Constant	1035 ± 18.3
Mean	-0.304 ± 0.109
Sigma	7.624 ± 0.081

h1f

Entries	9999
Mean	-0.08187
RMS	116.6
χ^2 / ndf	21.17 / 25
Constant	1094 ± 13.5
Mean	-0.4297 ± 1.1674
Sigma	116.4 ± 0.8

h1f

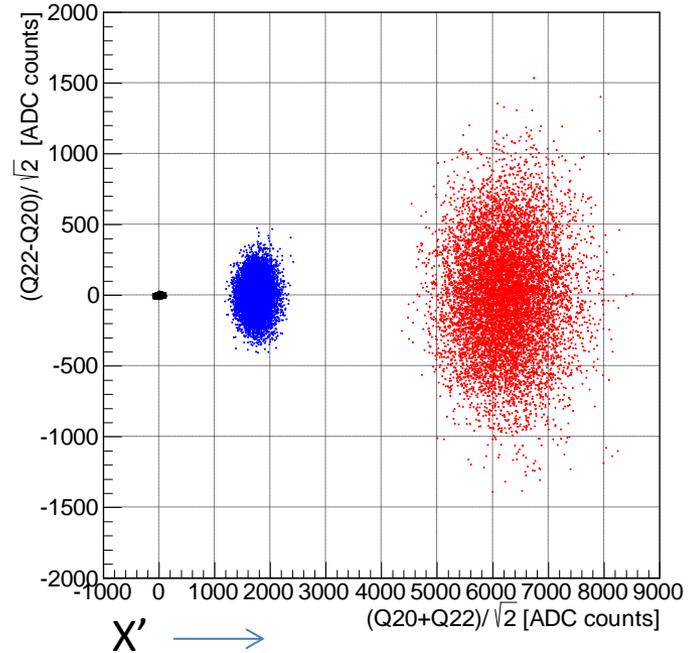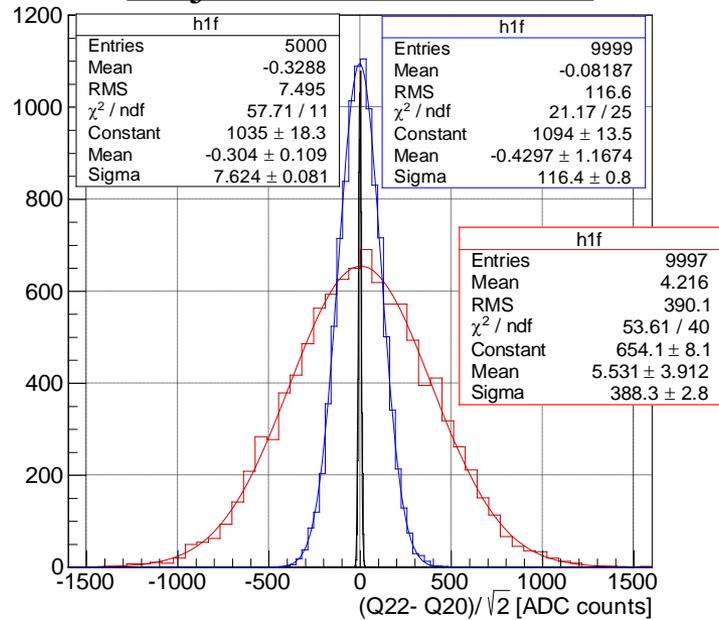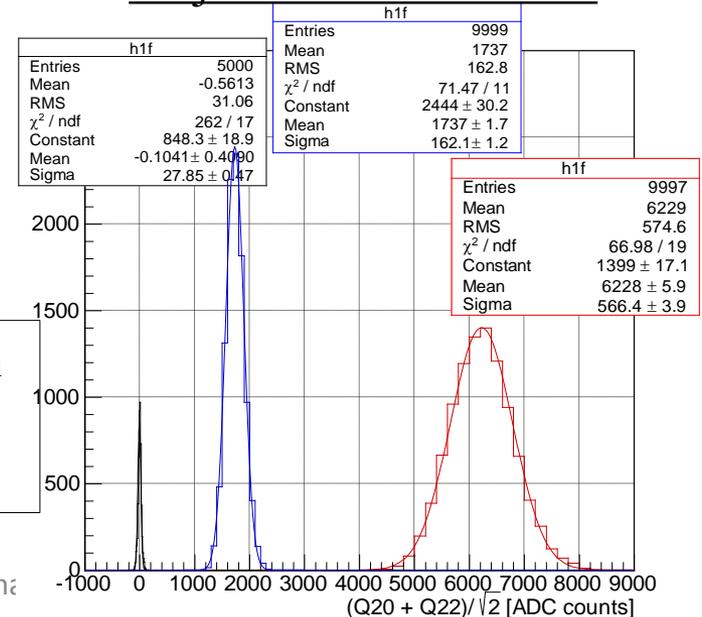|	
Entries	9997
Mean	4.216
RMS	390.1
χ^2 / ndf	53.61 / 40
Constant	654.1 ± 8.1
Mean	5.531 ± 3.912
Sigma	388.3 ± 2.8

X-axis: $(Q22 - Q20)/\sqrt{2}$ [ADC counts]

Y' axis / X' axis scatter plot:
Y-axis: $(Q22-Q20)/\sqrt{2}$ [ADC counts]
X-axis: $(Q20+Q22)/\sqrt{2}$ [ADC counts]

Projection to the X' axis

h1f

Entries	9999
Mean	1737
RMS	162.8
χ^2 / ndf	71.47 / 11
Constant	2444 ± 30.2
Mean	1737 ± 1.7
Sigma	162.1 ± 1.2

h1f

Entries	5000
Mean	-0.5613
RMS	31.06
χ^2 / ndf	262 / 17
Constant	848.3 ± 18.9
Mean	-0.1041 ± 0.4090
Sigma	27.85 ± 0.47

h1f

Entries	9997
Mean	6229
RMS	574.6
χ^2 / ndf	66.98 / 19
Constant	1399 ± 17.1
Mean	6228 ± 5.9
Sigma	566.4 ± 3.9

X-axis: $(Q20 + Q22)/\sqrt{2}$ [ADC counts]

By comparing the two signal charges on an event-by-event (shot-by-shot) basis, the measurement can be insensitive to the laser intensity variation, as well as to the dominant common-mode electronic noise.

It is practically impossible to estimate the contribution of the avalanche fluctuation from the width of the single signal charge distribution.
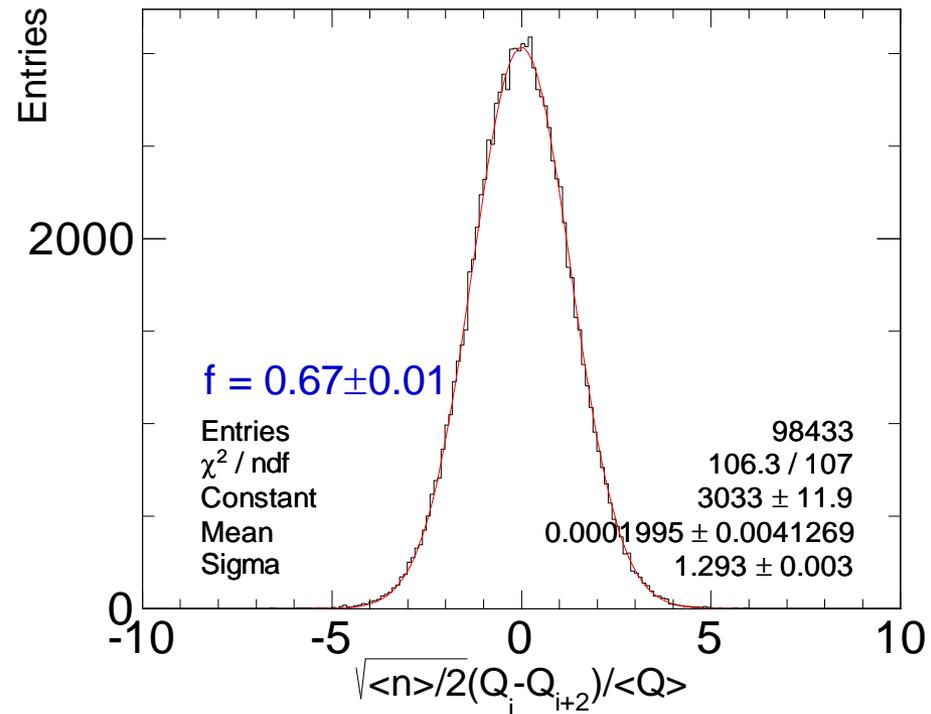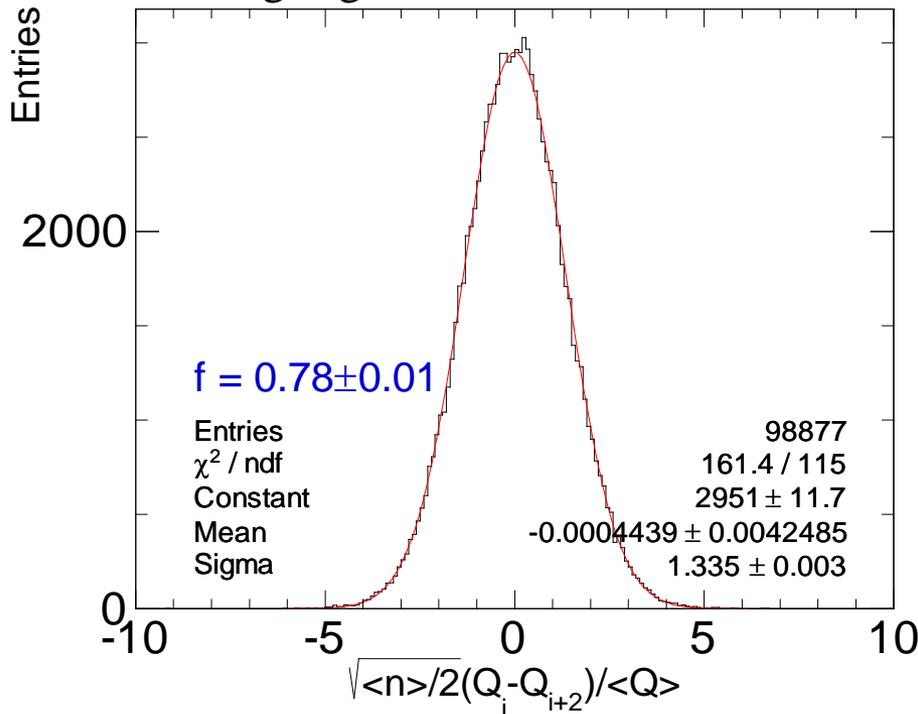
Preliminary results (the errors are statistical only)

argon - methane (5%)   The variance of the distribution gives the value of $1 + f$.

gas gain = 1400

gas gain = 2400

Left plot (gas gain = 1400):

f = 0.78±0.01

Entries	98877
χ^2 / ndf	161.4 / 115
Constant	2951 ± 11.7
Mean	-0.0004439 ± 0.0042485
Sigma	1.335 ± 0.003

x-axis: $\sqrt{<n>/2}(Q_i-Q_{i+2})/<Q>$
y-axis: Entries

Right plot (gas gain = 2400):

f = 0.67±0.01

Entries	98433
χ^2 / ndf	106.3 / 107
Constant	3033 ± 11.9
Mean	0.0001995 ± 0.0041269
Sigma	1.293 ± 0.003

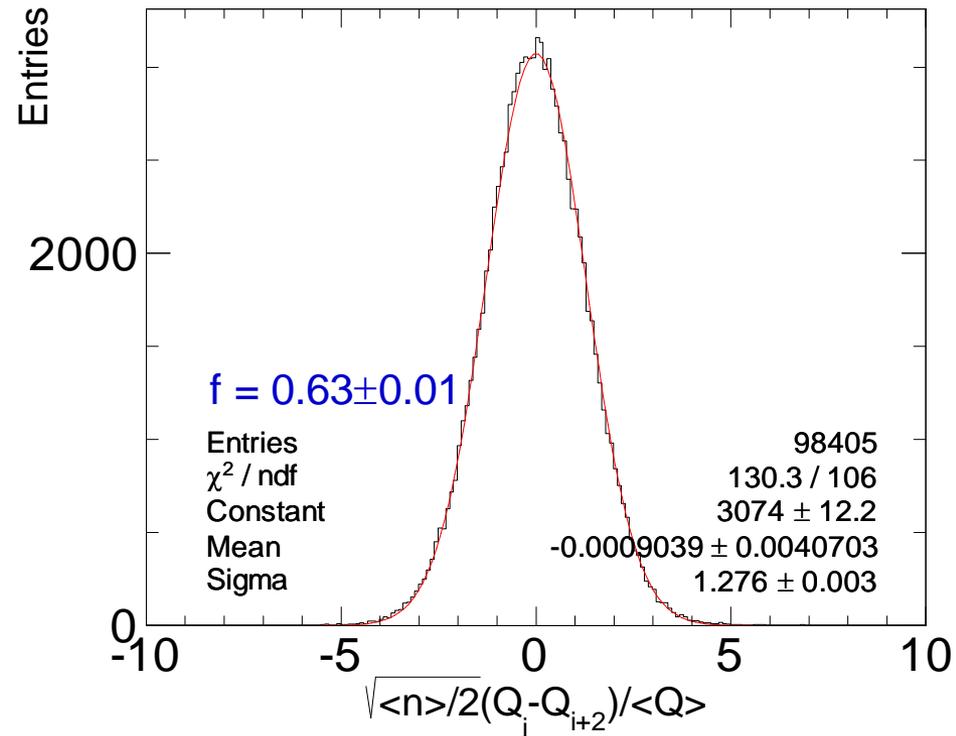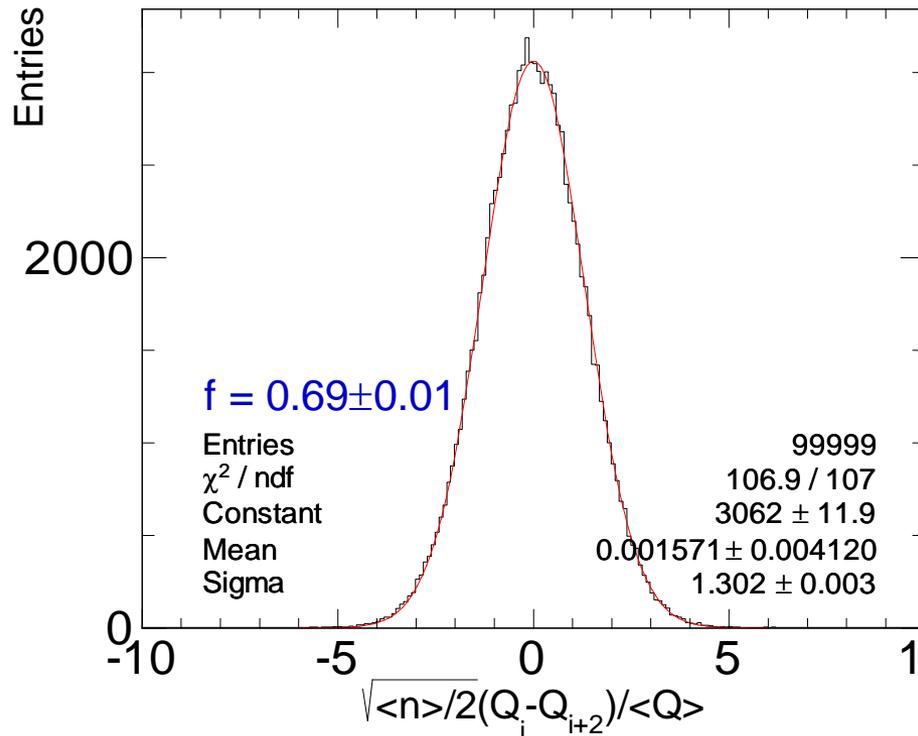x-axis: $\sqrt{<n>/2}(Q_i-Q_{i+2})/<Q>$
y-axis: Entries

We used the charges on pairs of every other pad rows instead of neighboring ones because of the charge sharing caused by the diffusion of amplified electrons in the transfer/induction gaps, and electronic crosstalk, in the latter case.

argon - CF$_4$ (3%) – isobutane (2%)   a candidate gas for the linear collider TPC

gas gain = 1900

f = 0.69±0.01

Entries	99999
χ² / ndf	106.9 / 107
Constant	3062 ± 11.9
Mean	0.001571 ± 0.004120
Sigma	1.302 ± 0.003

$\sqrt{<n>/2}(Q_i - Q_{i+2})/<Q>$

gas gain = 5800

f = 0.63±0.01

Entries	98405
χ² / ndf	130.3 / 106
Constant	3074 ± 12.2
Mean	-0.0009039 ± 0.0040703
Sigma	1.276 ± 0.003

$\sqrt{<n>/2}(Q_i - Q_{i+2})/<Q>$

neon - isobutane (5%)

gas gain = 2200

Entries

f = 0.33±0.01

Entries	99986
χ^2 / ndf	81.03 / 96
Constant	3462 ± 13.4
Mean	0.003413 ± 0.003644
Sigma	1.151 ± 0.003

2000

0
-10   -5   0   5   10

$\sqrt{\langle n \rangle / 2}(Q_i - Q_{i+2})/\langle Q \rangle$

gas gain = 6500

Entries

f = 0.35±0.01

Entries	99963
χ^2 / ndf	93.25 / 96
Constant	3426 ± 13.3
Mean	0.004107 ± 0.003682
Sigma	1.163 ± 0.003

2000

0
-10   -5   0   5   10

$\sqrt{\langle n \rangle / 2}(Q_i - Q_{i+2})/\langle Q \rangle$

Conclusion

1. The value of f measured with the argon-based gas is close to the indirect estimation from the resolution degradation with increasing drift distance observed with a prototype TPC for the linear collider experiment:
    M. Kobayashi et al., NIM A 641 (2011) 37.

2. The measurement with the neon-based mixture is consistent with that obtained with Micromegas using the charge spectrum for single electrons:
    T. Zerguerras et al., NIM A 772 (2015) 76.

3. Our technique using laser-induced tracks for the measurement of avalanche fluctuation is relatively simple and easier than observing the charge spectrum for single electrons, and requires no assumption for the functional form of the charge spectrum.
    The typical data-taking time is about 10 minutes, corresponding to 10 000 laser shots.

4. It is worth mentioning that this technique relies on the absence of secondary ionizations, i.e. cluster size = 1, in the 2-photon ionization process by the laser photons. It is, therefore, not applicable for charged particle tracks because of large Landau fluctuations.

Future plan

The present experiment was carried out using a readout module of a prototype TPC for the linear collider experiment, for the proof of principle of our technique.
This is a byproduct of the TPC performance test: a kind of serendipity.

In fact, many pad rows, each consisting of small pads equipped with individual readout, are not necessary for the measurement.

We are now preparing a smaller dedicated chamber with a couple of moderate-size readout pads or strips, in order to measure the gas gain fluctuations for different gas amplification devices and counting gases.

Thank you for your attention.

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Backup Slide

Pad row dependence of the value of f

argon - CF_4 (3%) – isobutane (2%)

neon - isobutane (5%)

gas gain = 1900

gas gain = 2200