Calibrating the Cherenkov Detector

Some thoughts

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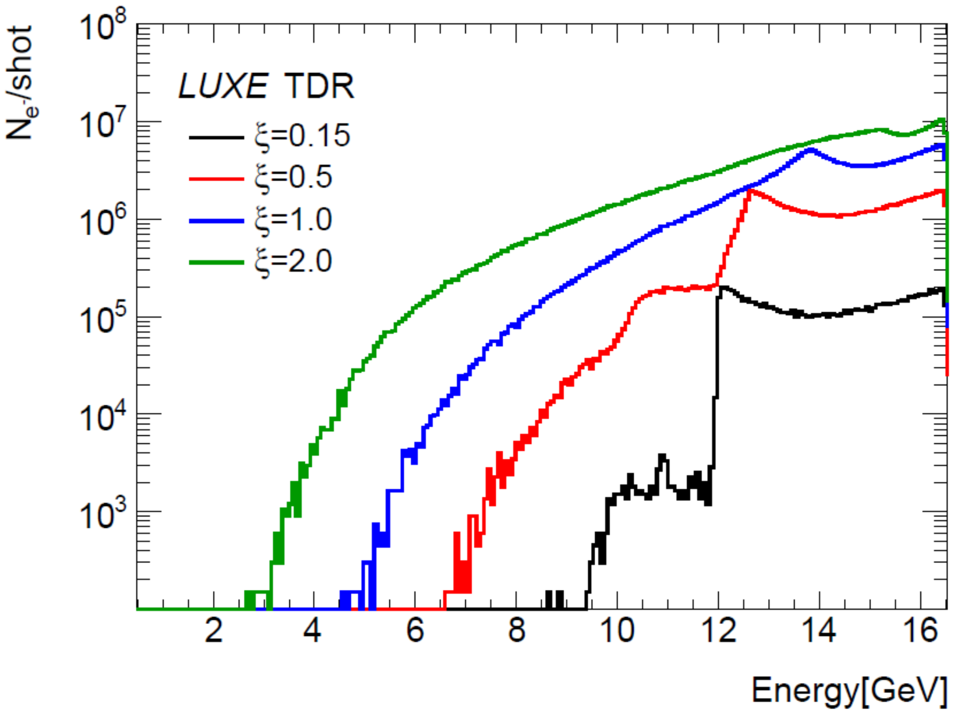
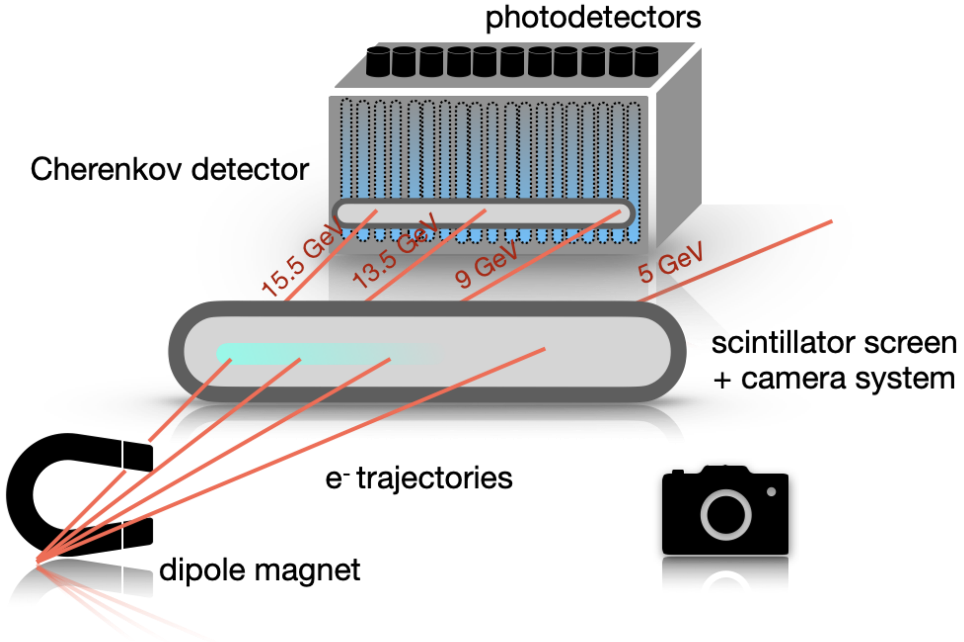
LUXE technical meeting 22.06.23

HELMHOLTZ

DESY.

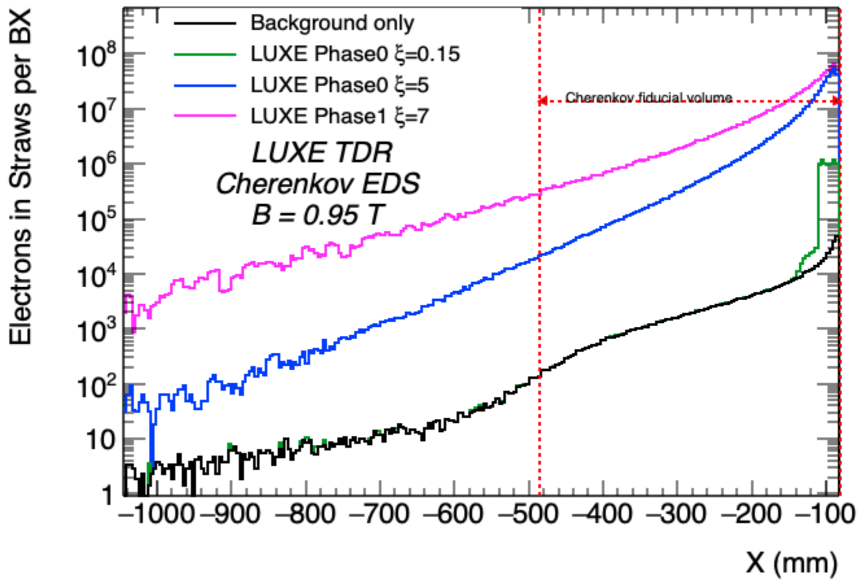
High-rate electron detection in LUXE

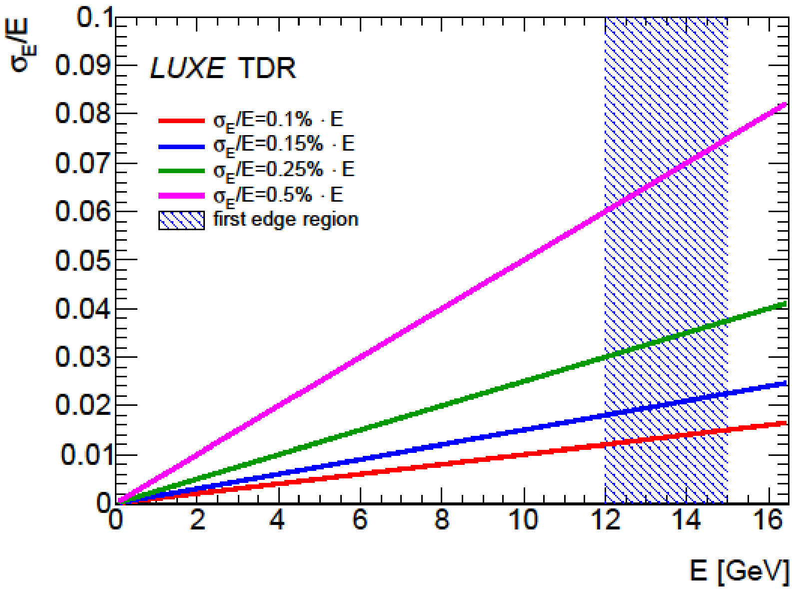


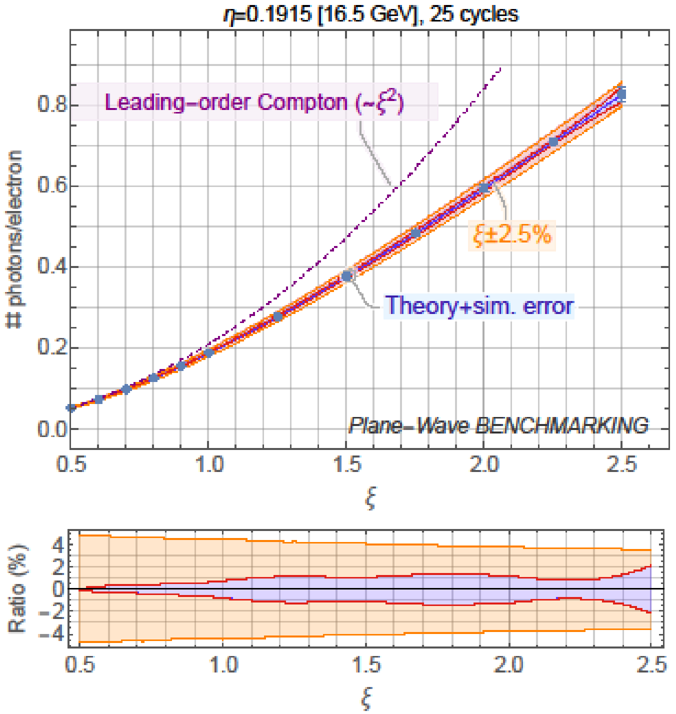


- challenge of electron side (in e+LASER): enormous electron rate from Compton scattering (Signal/Background ~100)
- Goal: Measure non-linear Compton spectrum
  → Compton edges shift as function of the Laser intensity
- Dipole spectrometer + combined detector: Scintillator screens and segmented gaseous Cerenkov detector
- same detector technologies used to monitor electrons from Bremsstrahlung in photon + LASER

Challenges & Requirements







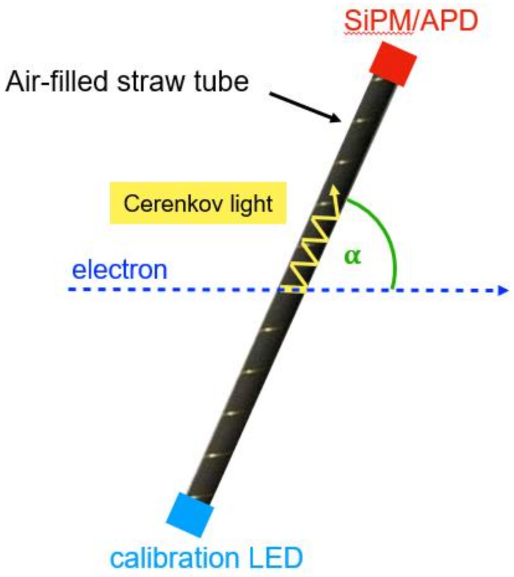
- **Dynamic Range:** per-channel signal electron rates between 10^3-10^8
  → detector dynamic range must cover 5 orders of magnitude

- **Background rejection (built-in):** - Cherenkov: threshold in air (20MeV), photon rejection
  - S/B between 25 (ξ=0.15) and 1000 (ξ=7)

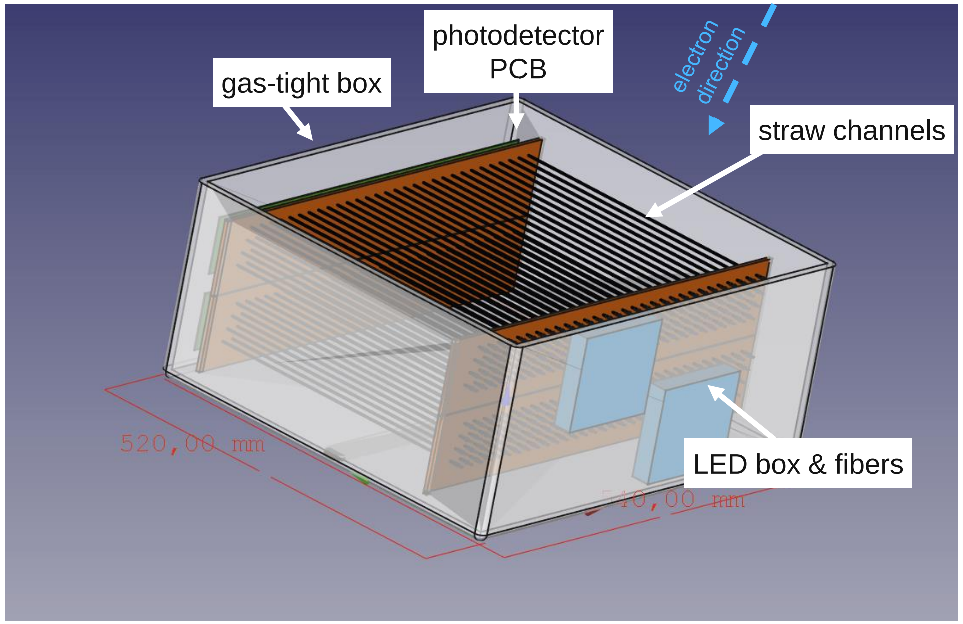
- **Energy Resolution:** - ~2% energy resolution in first edge region

- **Linearity:** - <4% uncertainty on Compton photon/electron ratio
  → <2.8% uncertainty on electron rate detector response

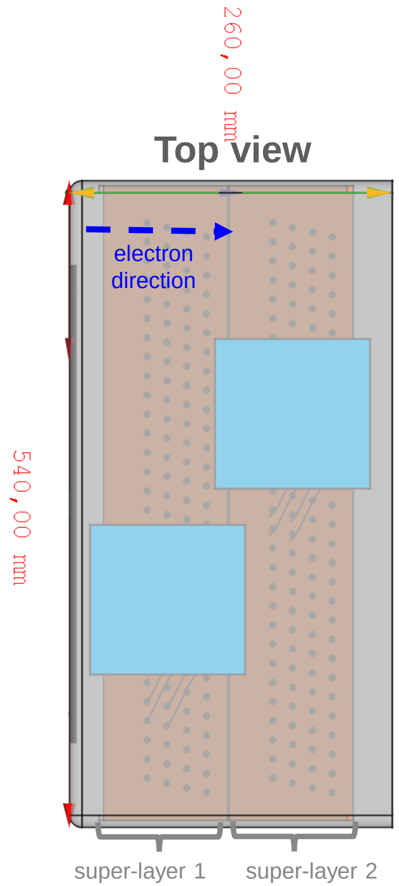
Cherenkov detector



Perspective view (rotated)

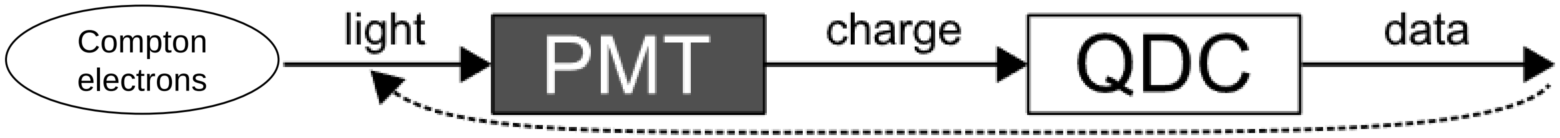


Top view



- straw tube light guides: Cherenkov light in air reflected towards photodetector
- spatially segmented detector: 2x 100 parallel straw channels (3mm diameter)
- extend dynamic range: dual photodetector readout (SiPM and APD)
  - → one straw super-layer (à 100 channels) for each photodetector
  - → overlapping channel staggering for higher effective resolution
- How to calibrate?

Non-linearities

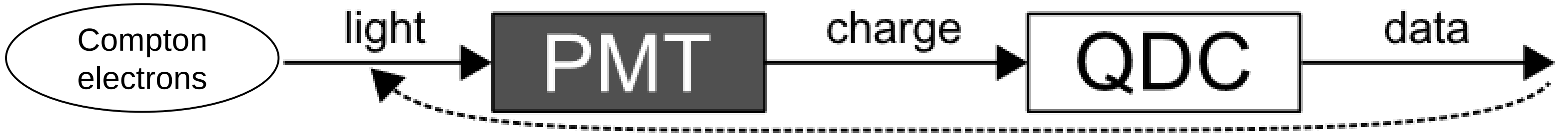


- Want to know the Number of Compton electrons in each detector channel but we actually get a digital electronic signal
- In an ideal world the relation between them is perfectly linear

  → would need only one measurement of Number of electrons and corresponding signal output to calibrate
- In real world measurement devices are not linear!

In addition to non-linearity there are also other effects (calibration differences between channels, time-dependent variations) etc., will discuss those later

Sources of Non-linearities



Sources of non-linearities for our detector:

1) SiPM response

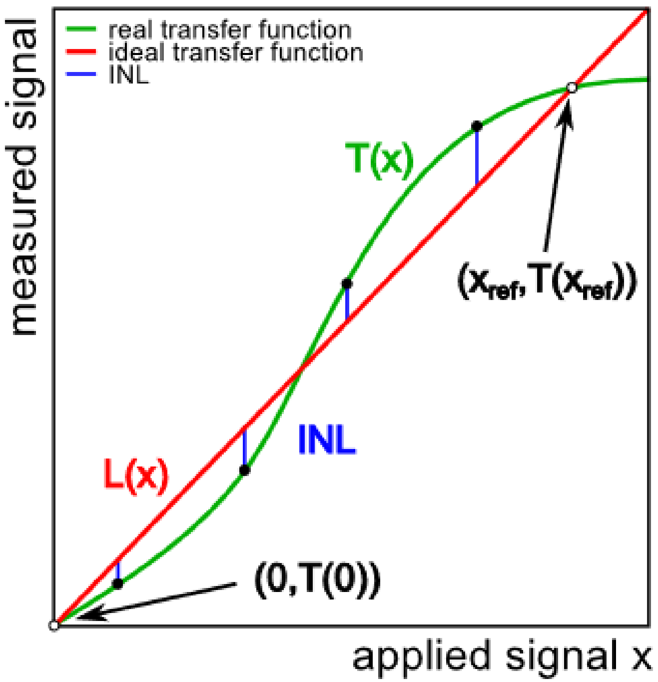
- at high photon densities, finite pixel number causes non-linearities
  (pixels have to recharge O(10ns) after each breakdown avalanche)
- thermal noise, afterpulses, cross-talk

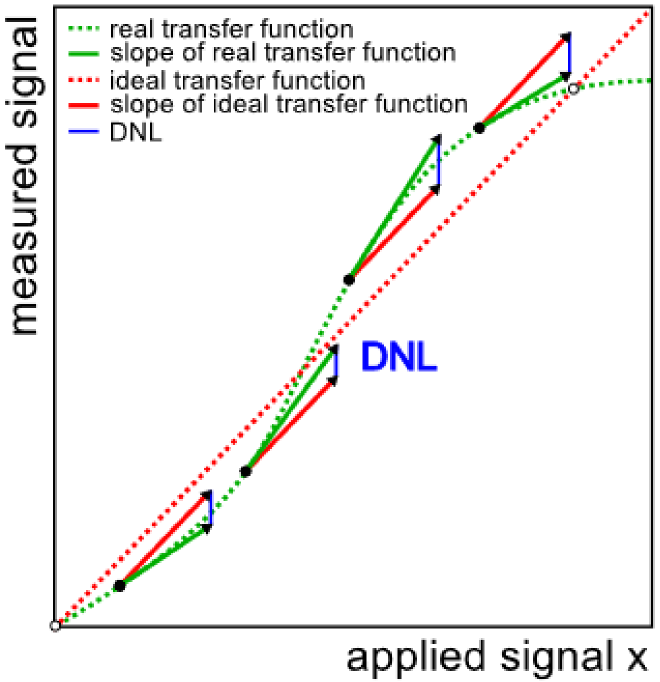
2) Readout non-linearities:

- unstable pedestal currents
- non-linearity in digitization step → depends on ADC implementation

Correct these by measuring non-linearity!

Non-linearities





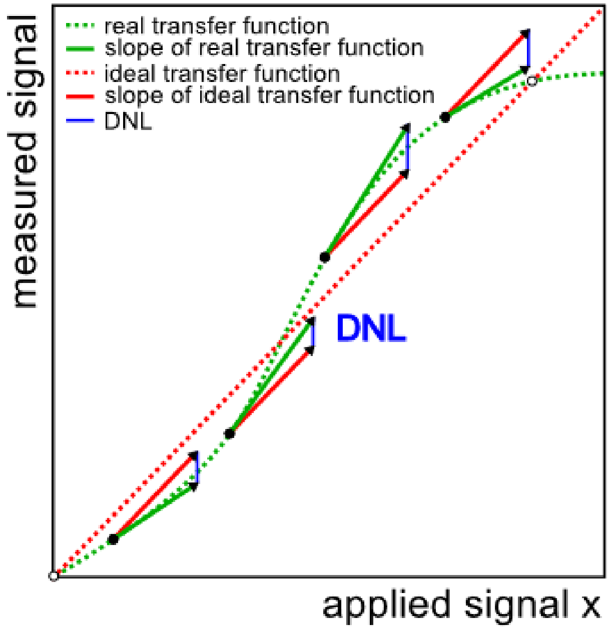
- Detector response: measured signal (e.g. ADC) versus applied signal (e.g. incoming electrons per channel
  → ideally: linear function $L(x) = A_0 + B_{x_{ref}} \cdot x$
  → in reality: non-linear function $T(x)$

- Two anchor points: $A_0 = \mathrm{T}(0)$ (Null measurement), $B_{x_{ref}} = \frac{T(x_{ref})-T(0)}{x_{ref}}$ (reference measurement at x_{ref})

- Two ways to express non-linearity:
  - integrated (difference between ideal and real) $\mathrm{INL(x)} = T(x) - L(x)$
  - differential (difference in slope between ideal and real) $\mathrm{DNL(x)} = \frac{d}{dx}\big(T(x) - L(x)\big) = \frac{dT(x)}{dx} - B_{x_{ref}}$

INL: Getting a high-light-yield stable short UV LED pulse is complicated! (exect O(40%) intensity variation)

Differential non-linearity measurement



- Measuring DNL means measuring $\frac{dT(x)}{dx}$
- Approximate : $\frac{dT(x)}{dx} = \frac{T(x+\Delta x)-T(x)}{\Delta x}$

Technical meaning:

x: variable base signal (e.g. a variable LED pulse)
Δx: constant differential signal (e.g. second, constant low-intensity LED pulse)

$T(x+\Delta x)$: detector response with both signal at the same time
$T(x)$: detector response with just base signal

- Consequence of constant differential signal: $\frac{dT(x)}{dx} = \frac{\Delta T(x)}{c} \propto \Delta T(x)$, where c is constant
- Now measuring DNL(x) means measuring $\left(x_i, \frac{dT(x_i)}{dx}\right) \propto (x_i, \Delta T(x_i))$
- For small integrated non-linearities, assume: $x_i \propto T(x_i)$
- Extract information about non-linearity from $(T(x_i), \Delta T(x_i))$
  $\rightarrow$ no more dependence on absolute signal x!

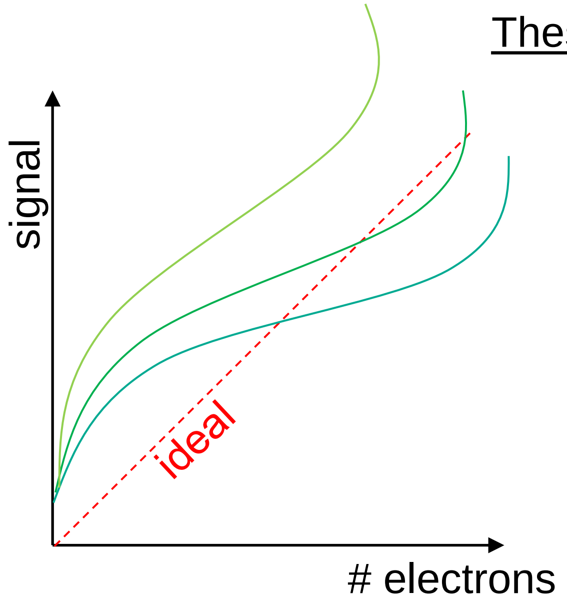
Linearisation

Thesis B. Vormwald

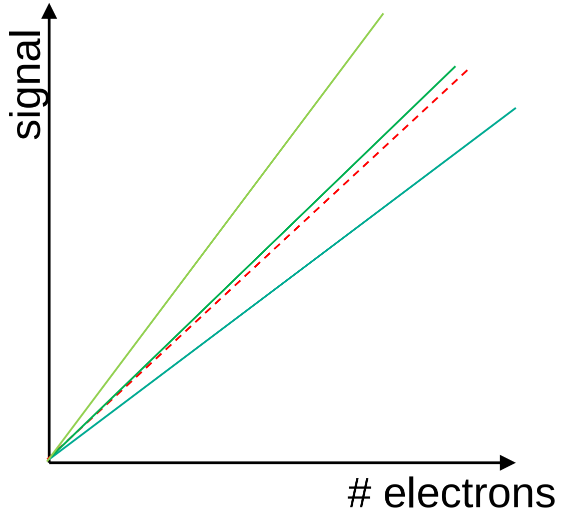
- Parametrize non-linearities in response: $T(x) = (B_{x_{ref}} + nl(x)) \cdot x$
- Express $\Delta T(x) = c \cdot \frac{dT(x)}{dx} = c \cdot (B_{x_{ref}} + nl(x) + nl'(x) \cdot x)$
- Solve for the non-linearity: $c \cdot nl(x) = \frac{1}{x} \int (\Delta T(x) - c \cdot B_{x_{ref}})\,\mathrm{dx}$
- Can show that: $\langle \Delta T(x) \rangle = c \cdot B_{x_{ref}}$
- And: $c \cdot nl(x) = \frac{1}{x} \int \Delta T(x)\,\mathrm{dx} - \langle \Delta T(x) \rangle$
- Linearisation correction factor: $Corr(x) = \frac{B_{x_{ref}}}{B_{x_{ref}} + nl(x)} = \frac{x \cdot \langle \Delta T(x) \rangle}{\int \Delta T(x)\mathrm{dx}}$

  → **Completely independent from absolute calibration scale!**

- Prescription:
  - take measurements of $(T(x_i), \Delta T(x_i))$
  - fit a polynomial function $\Delta T(x)$
  - calculate the correction factor using the integral and the average



BEFORE



AFTER

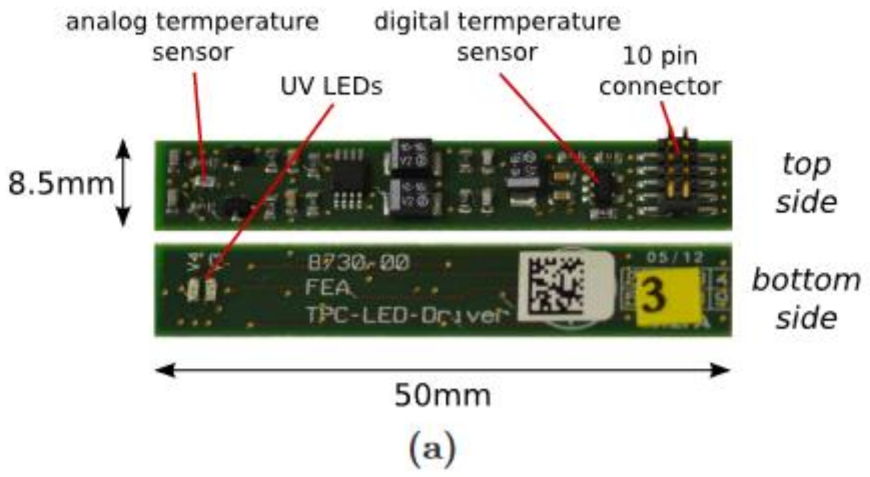
After this procedure, we know our detector response is linear, but we know the slope only to factor c!
→ Can correct using a complementary measurement (e.g. TB or in-situ calibration)

How to practically do the linearization?

- There is already a LED board from the Polarimetry setup (based on CALICE) that can produce the base and differential signals
- Requirement: - choose Δx such that it is small compared to the calibration range of the photodetector and to the full-scale range of the readout ADC (e.g. comparable to LSB)
  - could be matching our requirements already?

<u>Practical Procedure:</u>

- Measure QDC spectra with and without the differential signal for varying base LED signals
- Get the mean of the QDC, and difference between means for base only vs. base+ differential
- Fit polynomial function and proceed with linearization



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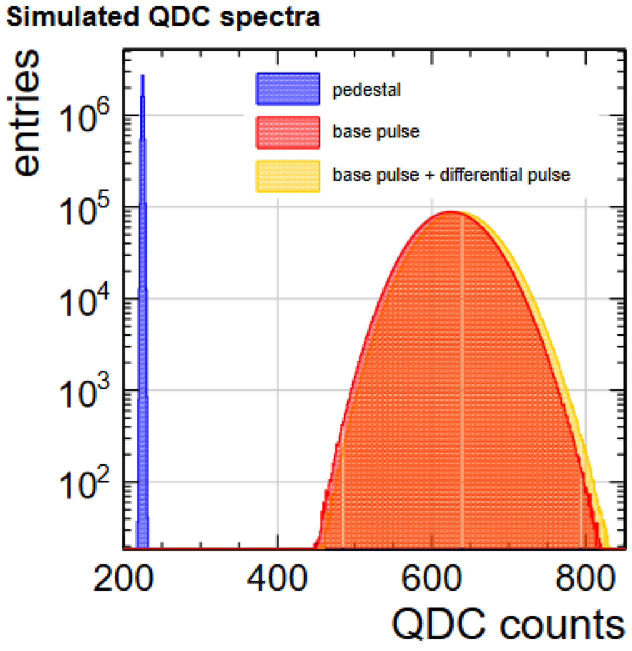
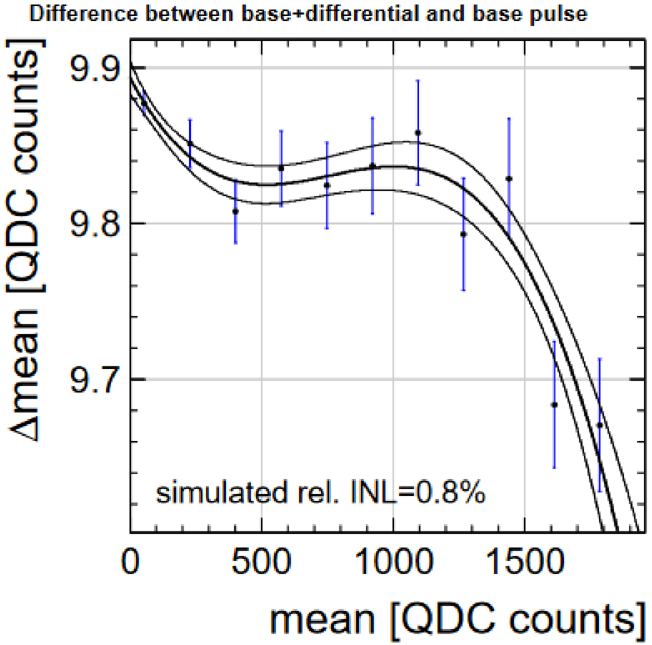




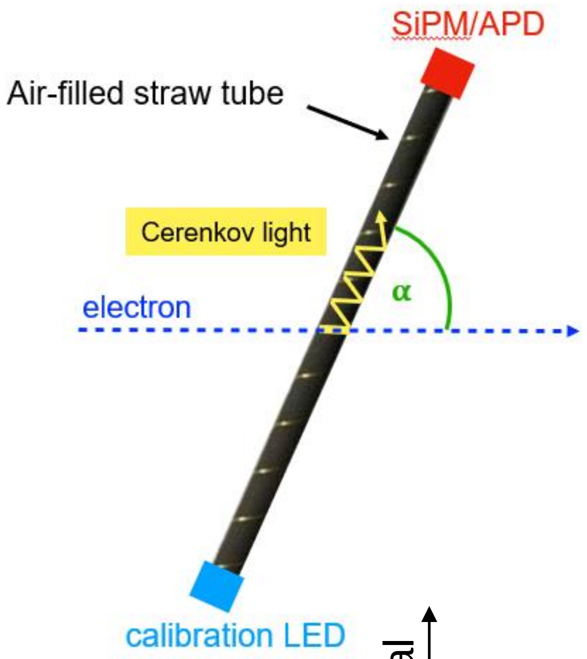
Absolute charge calibration

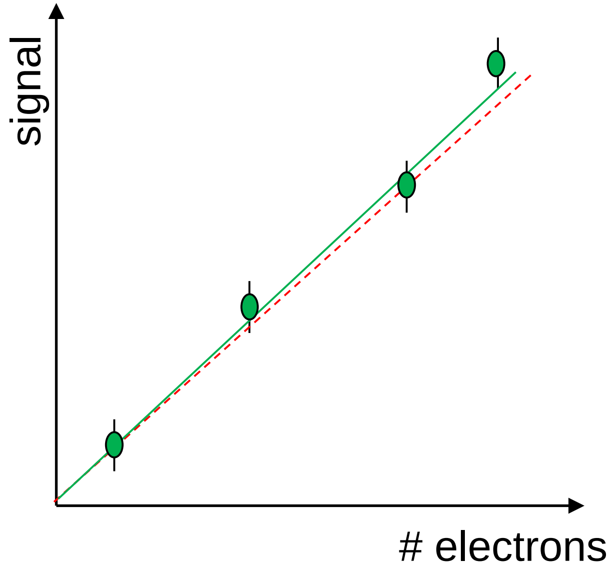
- After the linearization, we know we have a linear detector response, but we only know the slope of the linear response up to a factor → How to determine this factor?

- **Method 1: Beam-based response measurement**
  - test-beam with variable bunch charge (such as ARES) with an independent charge measurement)
  - absolute calibration of the whole detector chain (straw+SiPM+readou
  - limited statistics, limited number of charge points
  - scattering effects

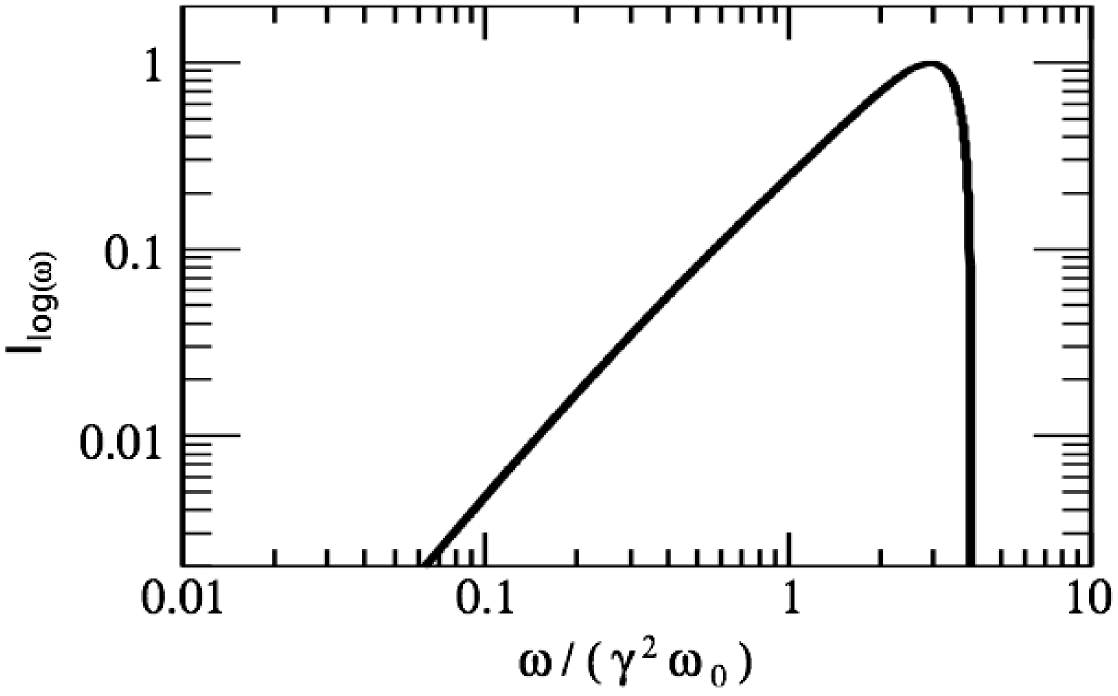
- Measure calibration range (range of Cherenkov photons expected) for different bunch charges

- Anchor point for the calibration curve after linearization

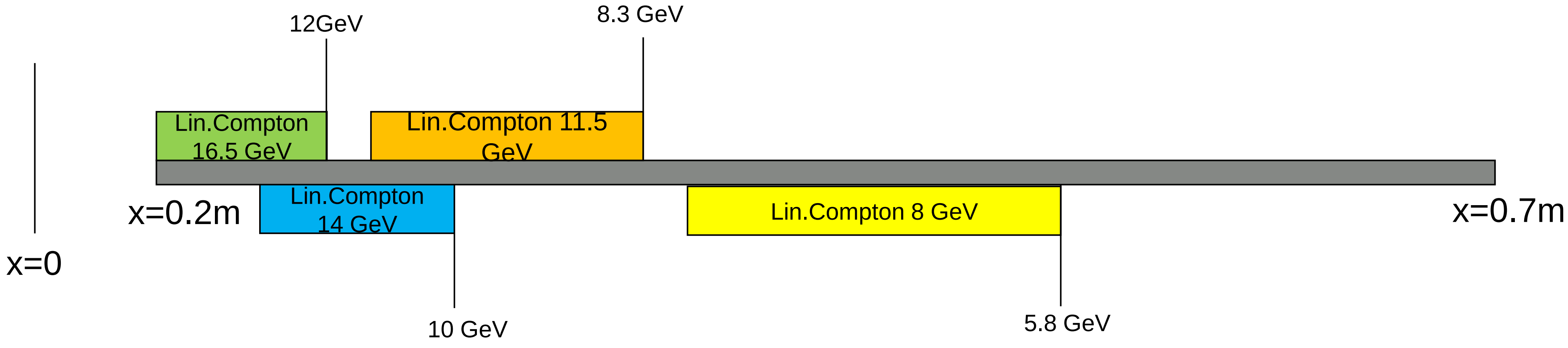




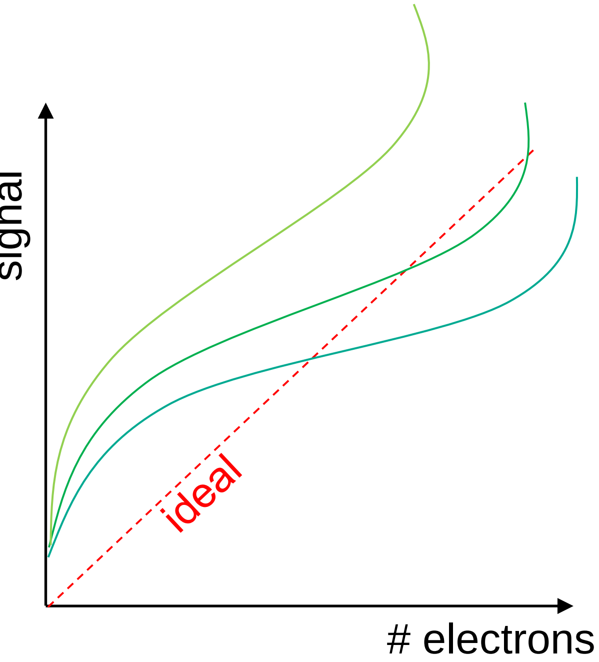
Absolute charge calibration



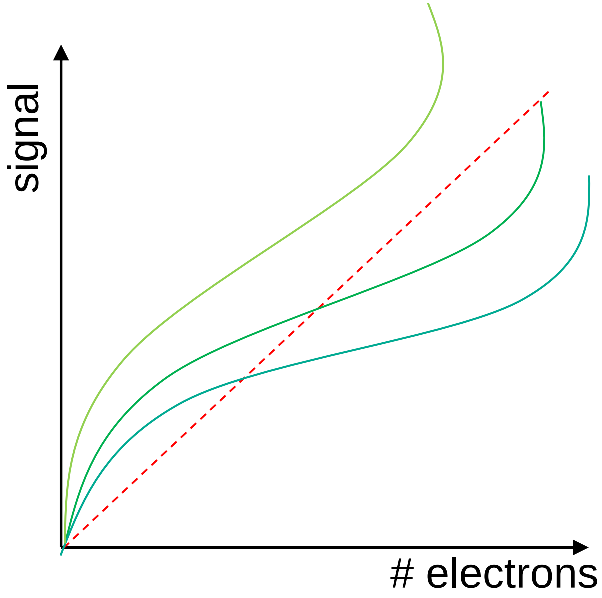
- **Method 2: In-situ physics-based calibration**
  - use well-known inverse linear Compton scattering to calibrate the full detector
  - eg.g by comparing detector simulation to measured data
  - XFEL runs at 8,11.5,14,16.5 GeV energies covered energy range shifts
  - to reach all channels of a 50cm detector (z_m=1.2m, z_d=3.2m), need a 1.5T magnet or make the detector moveable (~10 cm)
  - covers full detector chain including channel-by channel correction



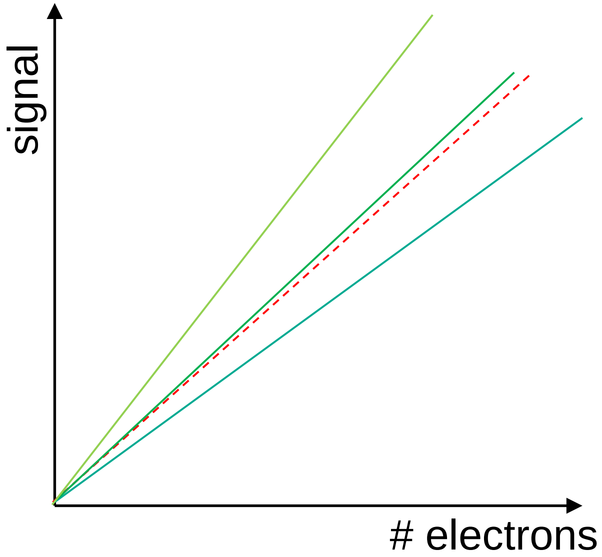
Calibration chain



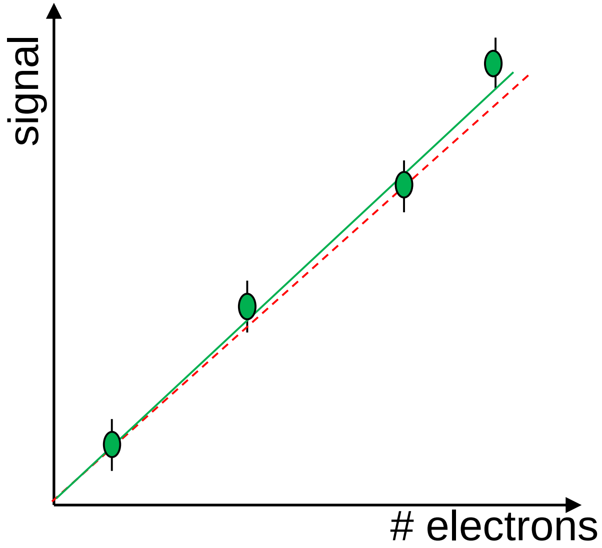
Before calibration



After null measurement (empty triggers)



After linearisation (Differential LED)

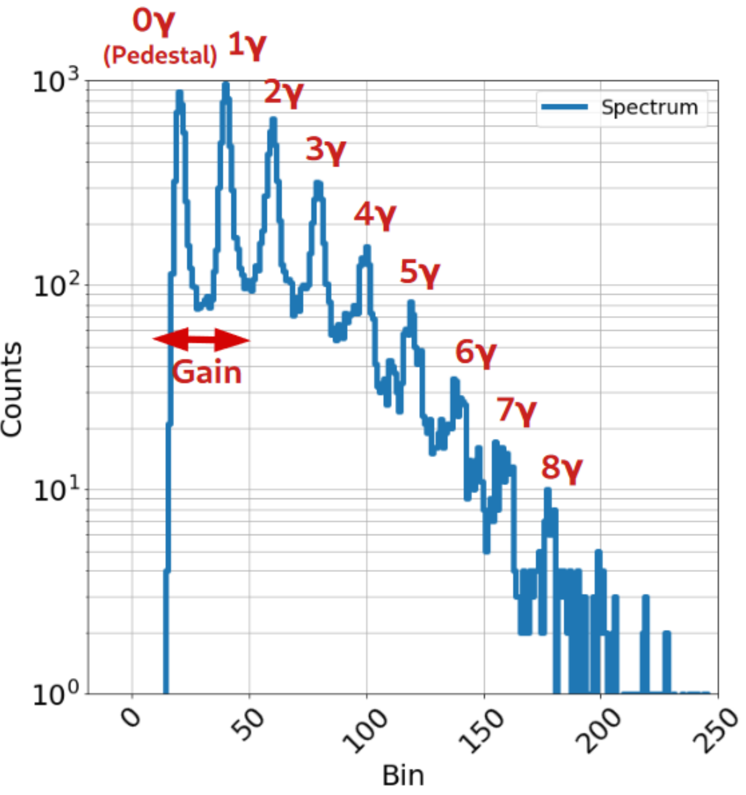


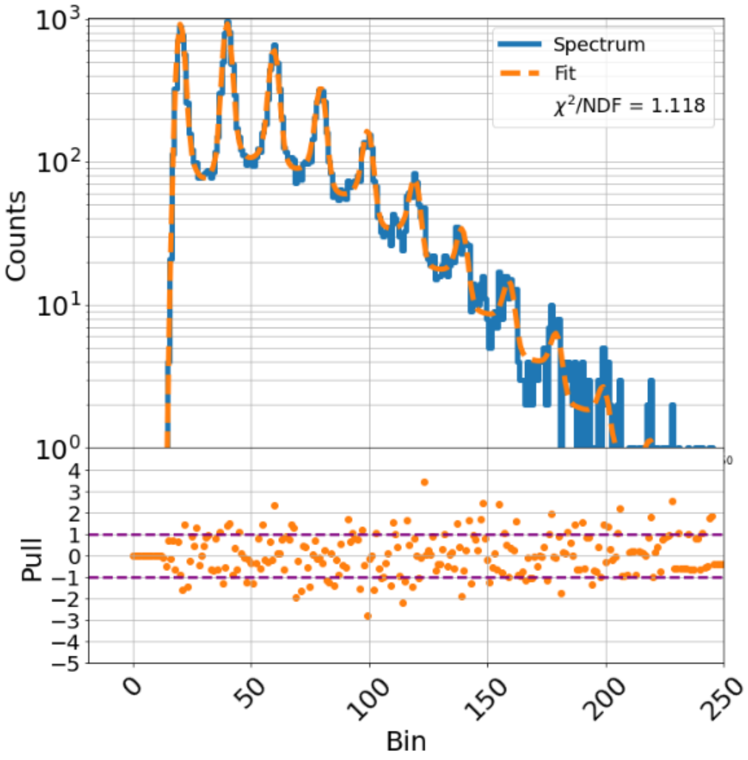
After absolute calibration (Beam-based or in-situ)

- Propose to use Linearization + Absolute Calibration sequentially
- Technically, could do full calibration beam-based only, but LED linearization will be possible to do more often and with finer granularity

Aside: SIPM Pre-calibration/Monitoring with single-photon spectra

- To characterize the SiPM performance, typically look at single-photon peak spectrum using low-intensity LED
- Tool developed by group of E. Garutti (UHH) to fit SiPM spectra - **PeakOTron: https://gitlab.desy.de/jack.rolph/peakotron**
- Can extract many SiPM performance quantities (gain, dark count rate, afterpulse probability etc.)





Thesis/Talk by Jack Rolph (UHH)

Parameter	Definition	Range
μ	Mean Number of Primary Geiger Discharges from Photons	10^{-10} to ∞
λ	GP-Branching Parameter	10^{-10} to $1-10^{-10}$
G^*	Effective Gain	1 Bin to ∞
Q_0	Pedestal Position	$-\infty$ to $+\infty$
σ_0	Pedestal Width	0.1Bin to ∞
σ_1	Gain Spread	0.1Bin to ∞
DCR	Dark Count Rate	1 Hz to ∞
p_{Ap}	After-pulse Probability	10^{-10} to $1-10^{-10}$
τ_{Ap}	After-pulse Time Constant	3 ns to $t_{\mathrm{gate}}/2$
A_{sc}	Scale Factor	$N_{\mathrm{events}} \pm 3 \cdot \sqrt{N_{\mathrm{events}}}$

Ideally adjust operating parameters of SiPMs such that performance is as uniform as possible!
Use for quality control/time-dependent monitoring!

Summary

- Need to calibrate our detector over a huge dynamic range!

- Propose to do linearization and calibration of the detector in two sequential steps

- Linearization: - measure response of SiPM and readout to a differential LED signal
  →prototype board & knowledge from Polarimetry available
  - can determine the non-linear response up to a constant factor
  - not dependent on the absolute light yield of the LED
  - not dependent on the reflective properties of straw light guide
  - can be done regularly during data-taking

- Absolute Charge-to-Signal calibration:
  - based on variable-bunch-charge test beam (ARES!)
  → can only do before installation
  - in-situ measurement of linear Compton spectrum (requires variable B-field or moveable stage)
  → propose regular linear Compton calibration run!
  - takes into account effects from in-straw reflection, per-channel differences etc.

Would be interesting to test diffrential linearization in the lab (+ simulation)!