Analysis of Timing and Position Resolution of Plastic Scintillator Bars with Dual SiPM Readout

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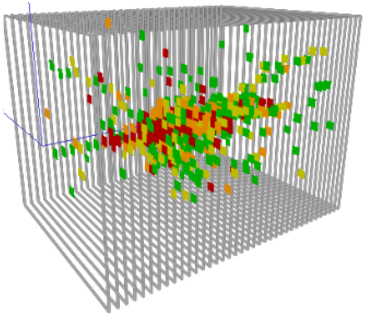
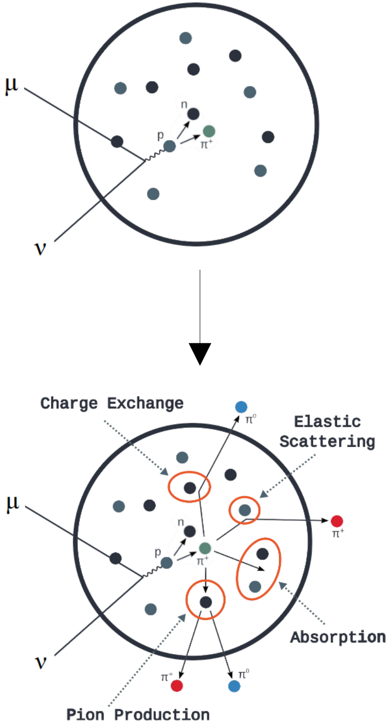
Motivation

- Open questions in physics motivate large scale projects such as an e+e- Higgs Factory, and long baseline neutrino experiments such as DUNE
- Processes of interest like $e^+e^- \rightarrow HZ \rightarrow$ Jets rely on energy resolution and particle separation to reconstruct bosons with highest possible accuracy
- Neutrino final states require the reconstruction and identification of out going leptons, charged and neutral hadrons

$\rightarrow$ Calorimeters with good spatial and time resolutions are needed





Neutrino-Nucleus Scattering (DUNE)
[Dune Collaboration]

Motivation

- Search for new physics demands more precise measurements, resulting in large volumes and active area for detectors

  → immense number of readout channels necessary, e.g. DUNE ND with over 2 million channels

  → enormous complexity

- Practical challenges in detector design arise, such as:
  - Spatial concerns, tight packing necessary
  - Maintainability
  - Power consumption and cooling
  - Cost

Sampling Calorimeter

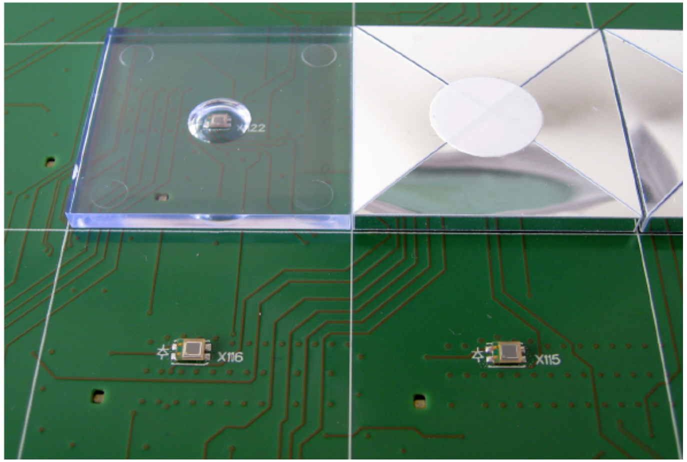
- Shower production and energy measurement take place in seperate materials
- Components:
  - Absorber structures, e.g. tungsten plates
  - Active Material, e.g. plastic scintillators (+ photosensors)
  - Electronics

→ High granularity goes along with an increase of the number of seperate calorimeters components

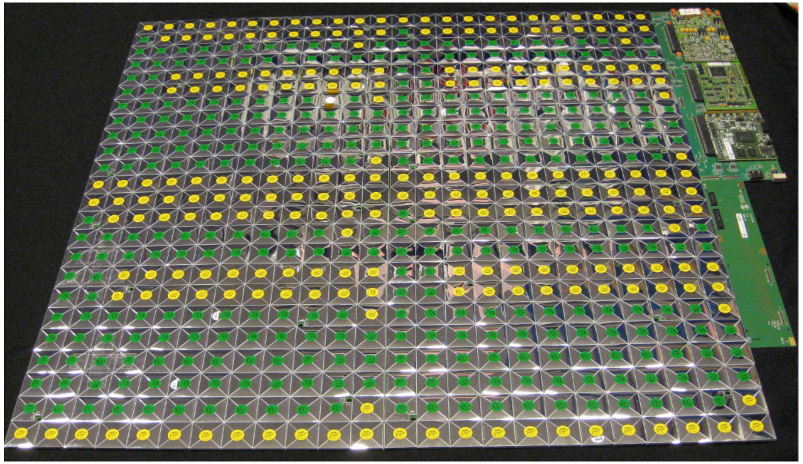
CALICE SiPM-on-Tile Technology

- State of the art technology, developed for the CALICE AHCAL, now adapted for parts of CMS HGCAL
- SiPM directly mounted on PCB, scintillator with dimple placed on top

  → Prototype of a highly granular calorimeter



Two tiles, wrapped/unwrapped

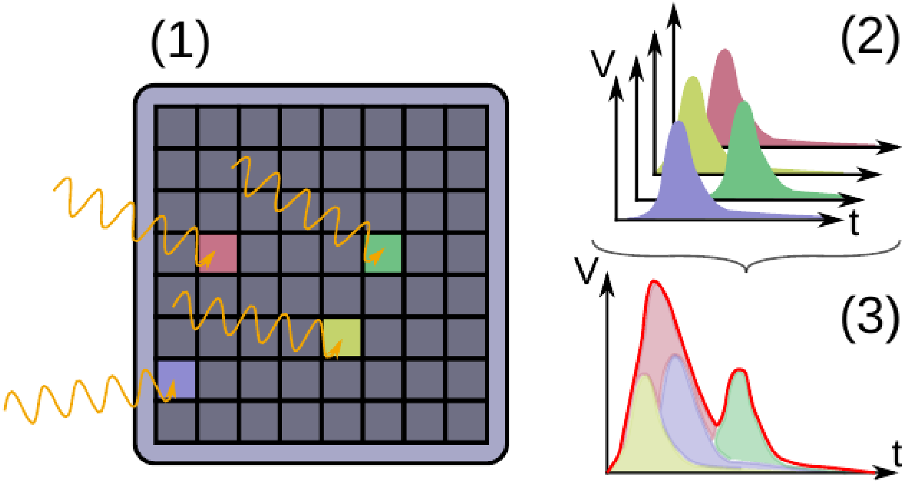


Full layer

Silicon Photomultiplier (SiPM)

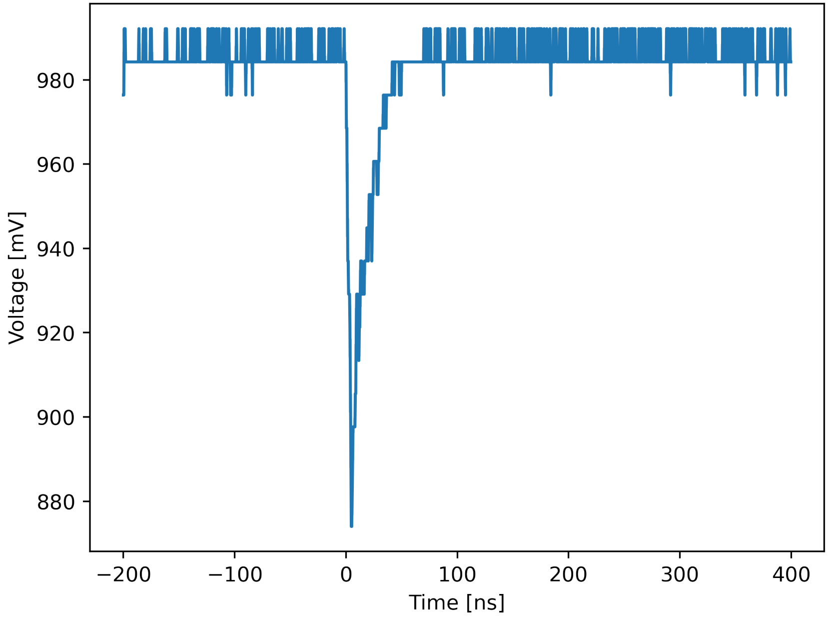
- Array of APDs operated in Geiger mode, each triggering on impact by a photon
- Each pixel capable of detecting a single photon in the timeframe of a signal

Addition of individual signals



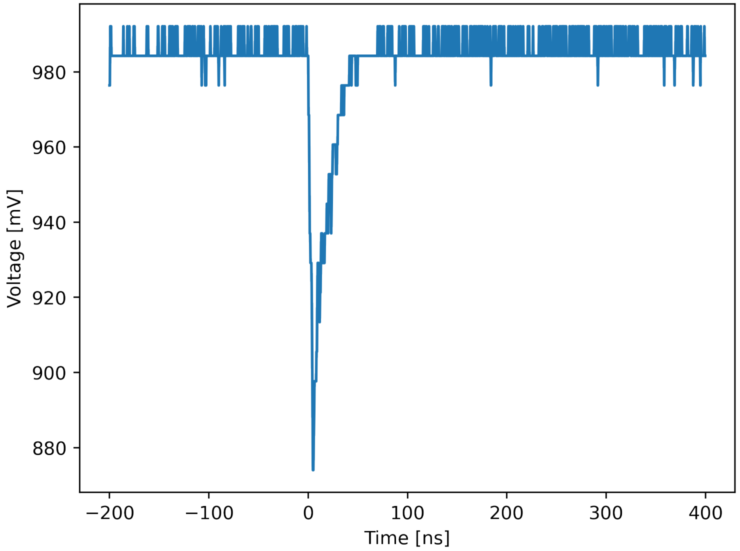
[F. Hummer, 2022]

SiPM signal, *Waveform*



Silicon Photomultiplier (SiPM)

- Each waveform contains information about energy of the incident particle, as well as timing information



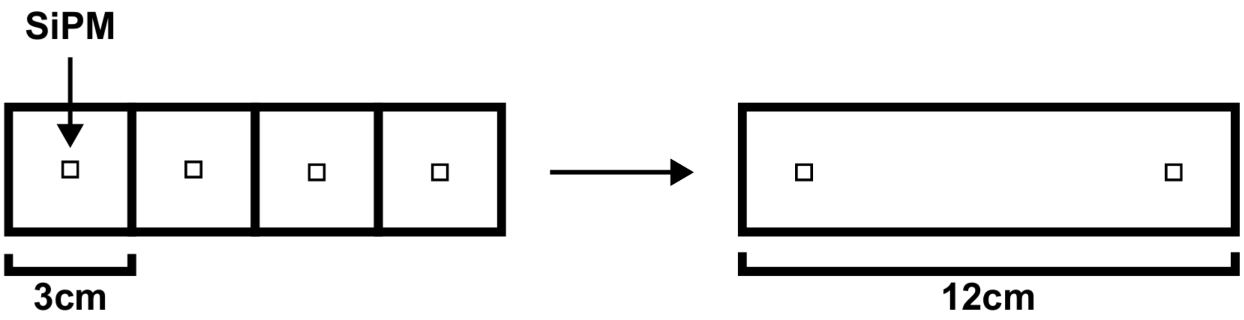
Energy: Area under the waveform

Time: Time when the waveform crosses 40 percent of its maximum height

Design Concept: From Tiles to Bars

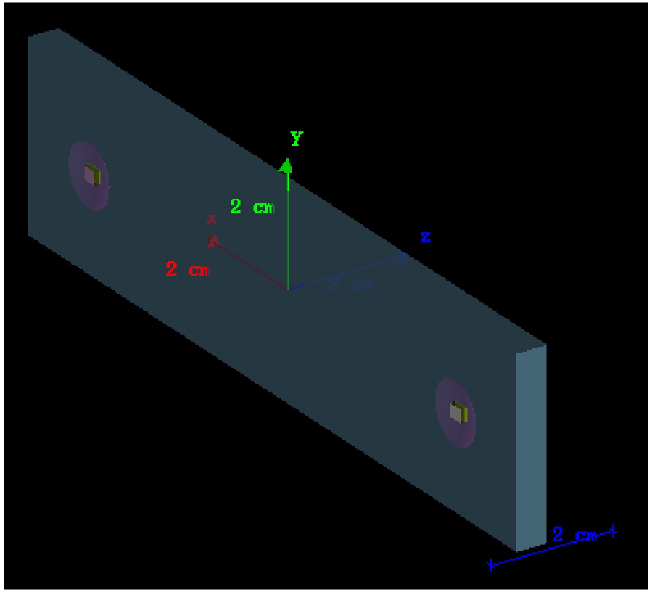
- It is desirable to look for an optimised solution, such that
  - the number of SiPMs scales *better* with the size of a layer
  - the electronics can be placed conveniently, to allow for a tightly packed setup
  - the spatial resolution is conserved to a reasonable degree

→ Scintillator bars, as a way to cover the same area, utilising less SiPMs



Scintillator Bars

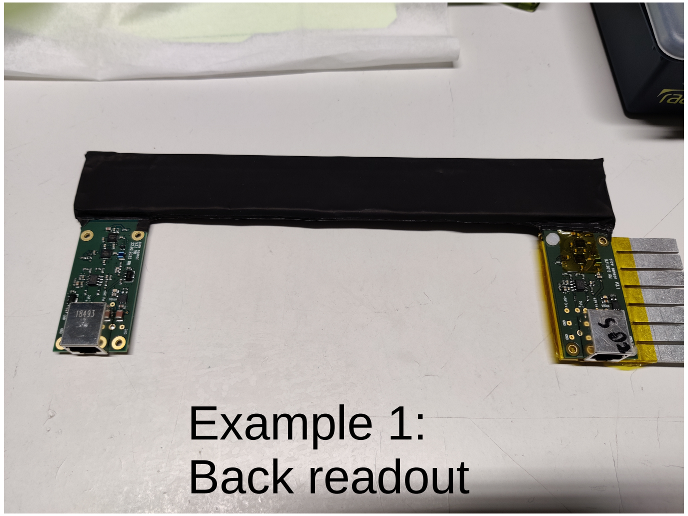
- Differences in geometry:
  - Bar shaped instead of square shaped with width = 30 mm, height = 5 mm and varying length between 120 and 500 mm
  - 2 dimples, located 15 mm from the edge of the bar
  - 2 SiPMs corresponding to each dimple
- Similarities:
  - Same materials used
  - Dimples of same size, despite thicker tile



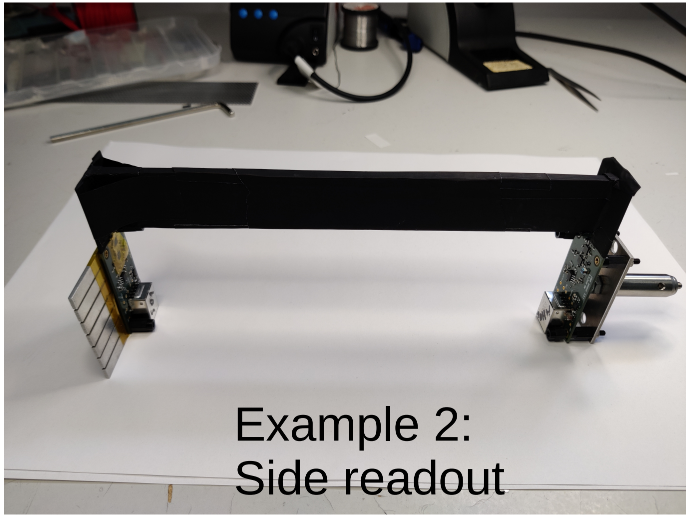
Roadmap

Three Parts:

- 1. Simulation study: Investigation of different bar geometries and dimple positions
- 2. Test beam campaign: Build scintillator bar and try it at the DESY test beam
- 3. Hit position reconstruction: Construct an alogrithm that predicts the hit position of a particle on the bar



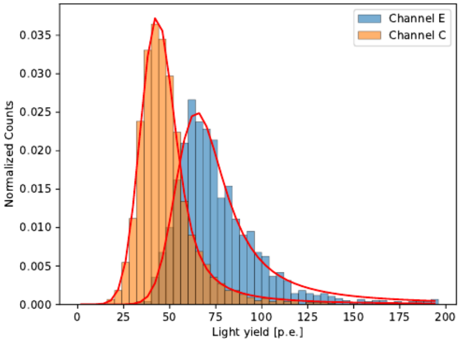
Example 1:
Back readout



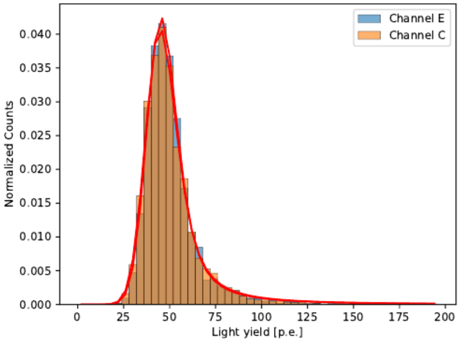
Example 2:
Side readout

1. Simulation: Light yield

- High enough light yields for lengths < 500 mm
- e.g. 240 mm bar:

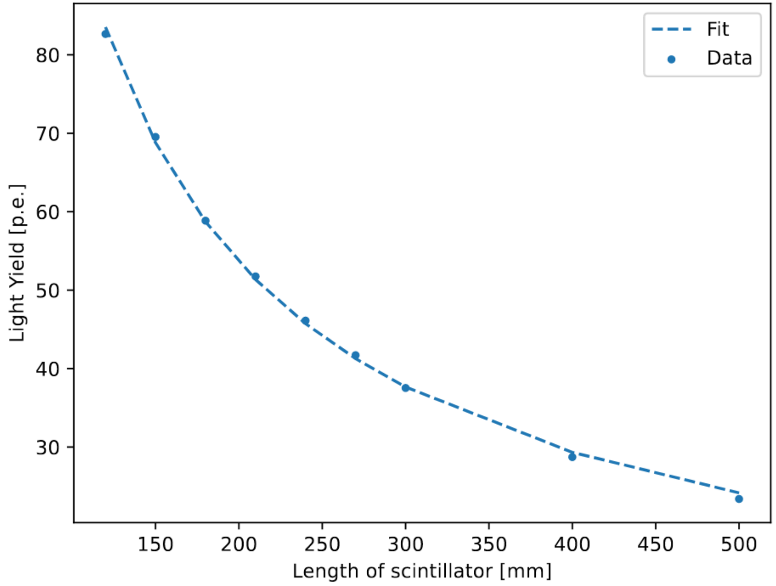


(a) Beam position at x = 105 mm



(b) Beam position at x = 0

$$\text{Light Yield}(x) = 5354\ \text{p.e.} \cdot \left(\frac{x}{[\text{mm}]}\right)^{-0.87}$$



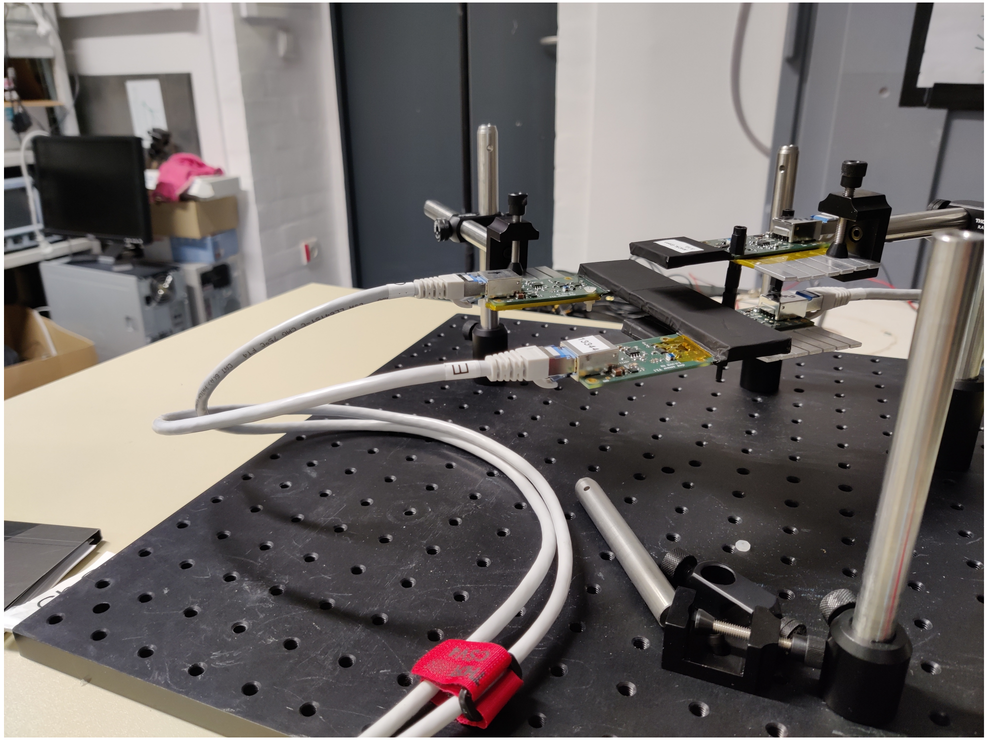
→ Promising results for a test beam campaign!

Remark:

In beam direction

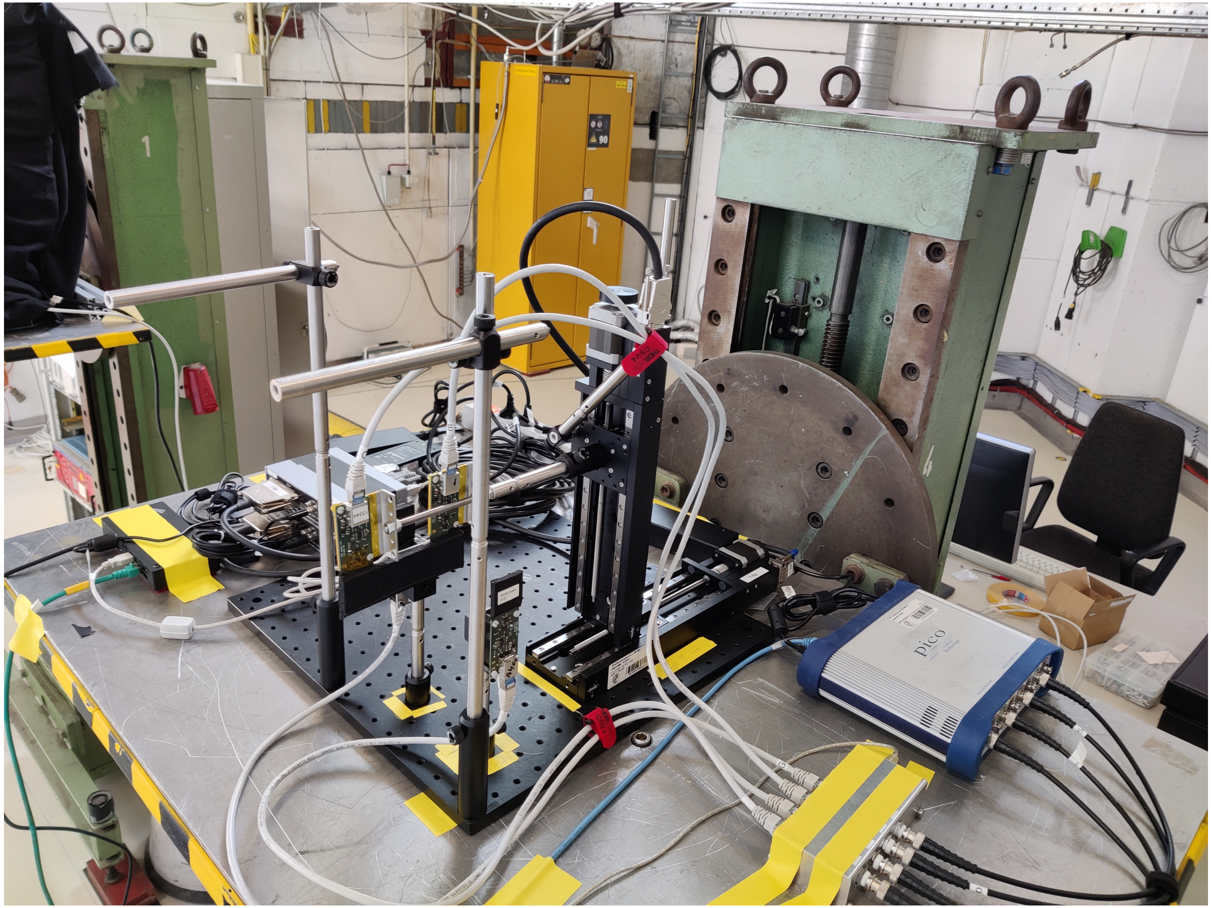
2. Experimental Setup

- 2 Bars:
  - 120 x 30 x 5 mm
  - 240 x 30 x 5 mm
- 2 trigger with different geometries dependings on the measurement
- Moveable stage for easier operation



Setup with two 3 cm^2 trigger scintillators

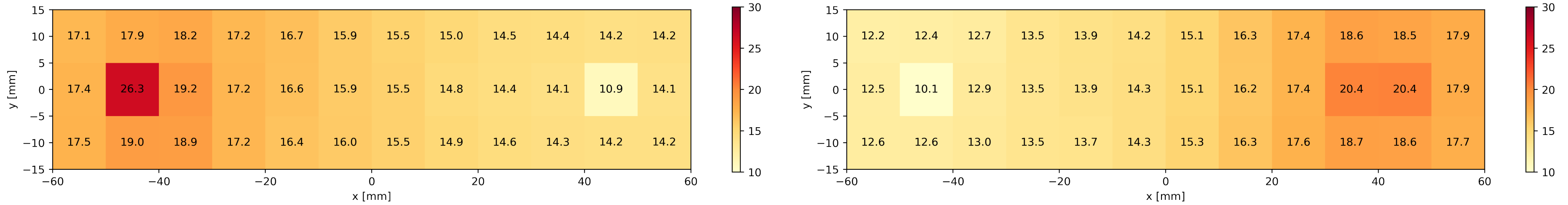
2. Experimental Setup: Testbeam



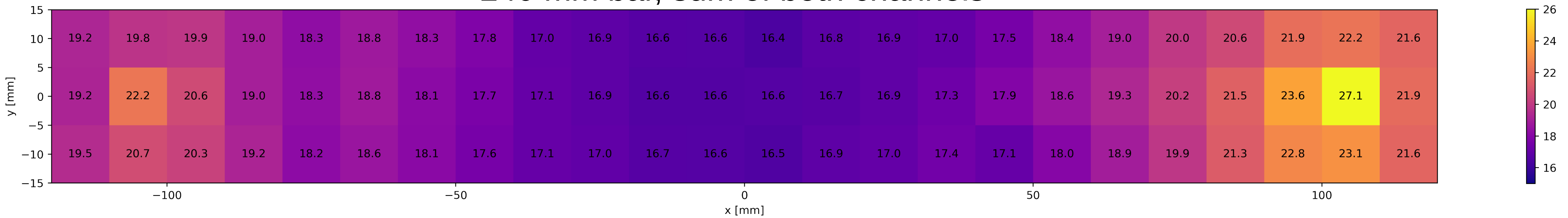
2. Testbeam Data: Light Yields

- Light yields overall considerably lower than expected from the simulations
  → persisting problem, that light yields are hard to judge from the simulations
- Still: Overall the light yields are high enough to separate from the noise

120 mm bar, channels individually

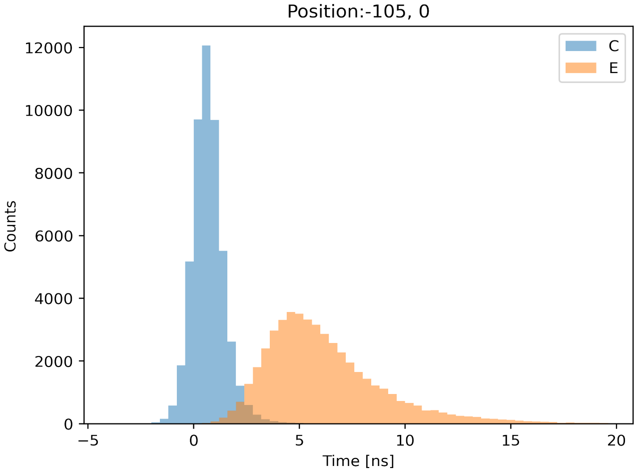


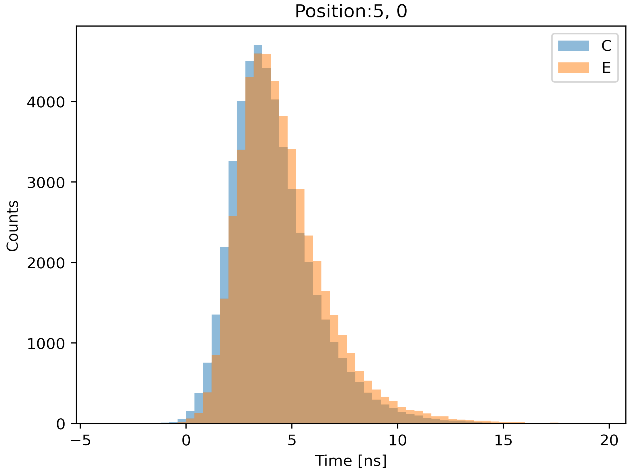
240 mm bar, sum of both channels

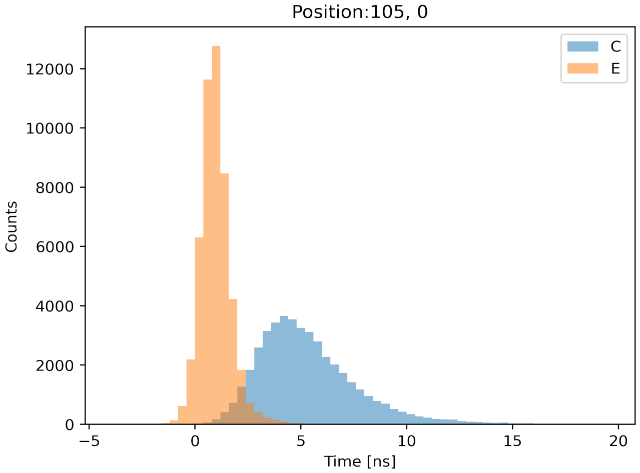


2. Testbeam Data: Timing

- Distinct time distributions depending on position
- In general the distributions get:
  - Broader with greater distance between impact position and SiPM
  - Further from 0 (towards bigger times) with greater distance between hit and SiPM





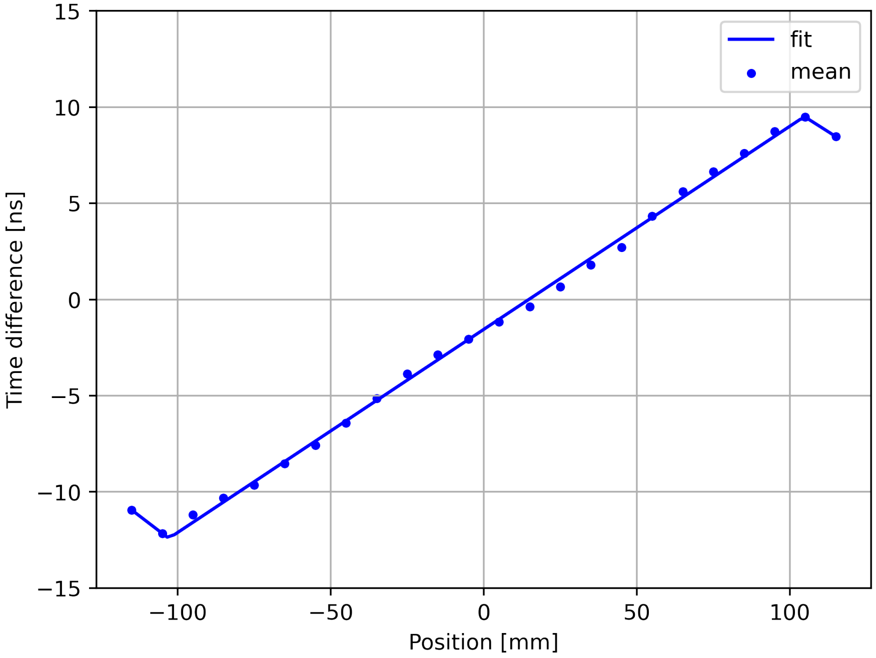


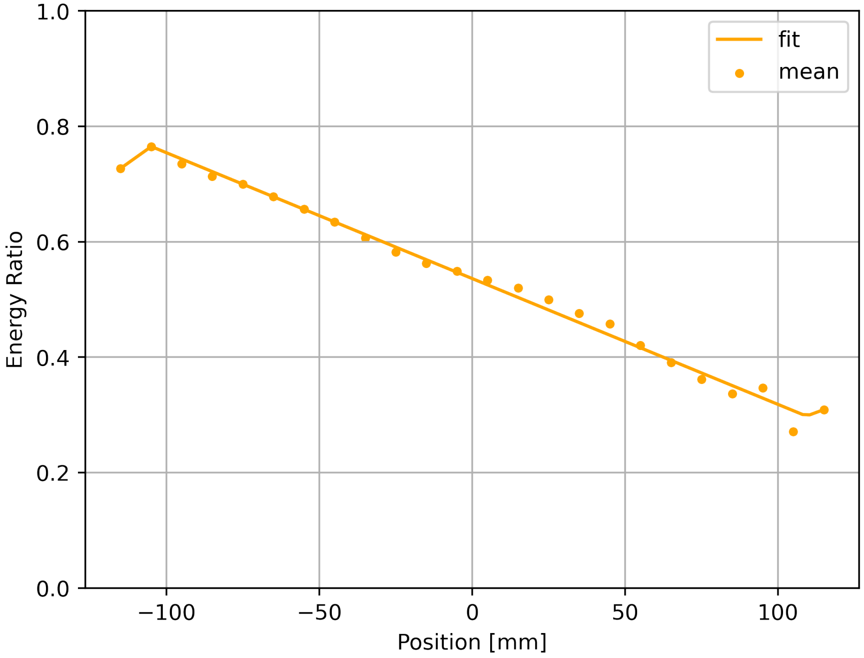
All time measurements are done with 0.4 constant fraction

3. Reconstruction: Linear

- Goal: Reconstruct the position of the hit from characteristics of the waveform, mostly hit times and energies at both SiPMs

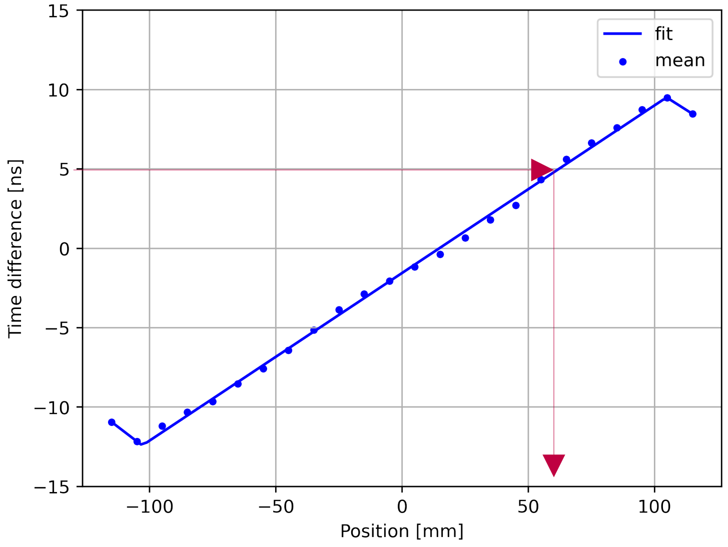
1. Approach: Linear Interpolation





3. Reconstruction: Linear

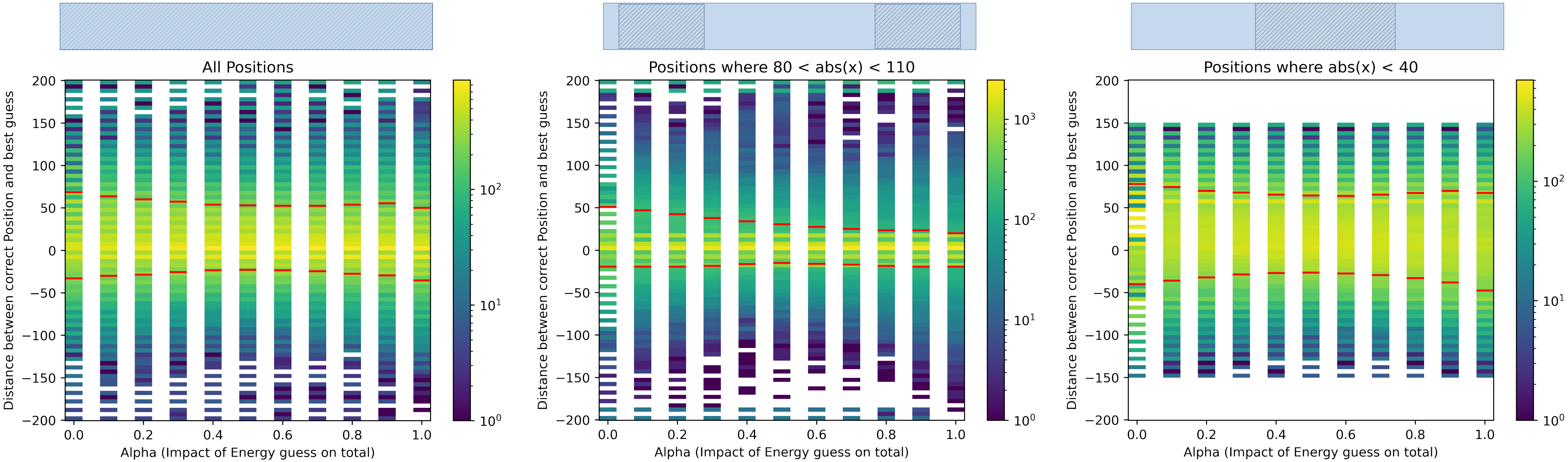
- E.g. time difference measured 5 ns would result in a prediction of ≈ +60 mm
- Combining both functions for time and energy and minimize for the best prediction
- Problems:
  - Only can predict between SiPMs
  - Limited range for input values
  - Assumes bijective fit function
- Overall: Good results, but only for very limited cases



3. Reconstruction: Linear

- Accuracy of hit position strongly depends on position of hit within the bar

Minimize: $$\alpha\left(E_{exp}(x)-\frac{E_C}{E_C+E_E}\right)^2+(1-\alpha)\left(\Delta t_{exp}(x)-\Delta t\right)^2$$

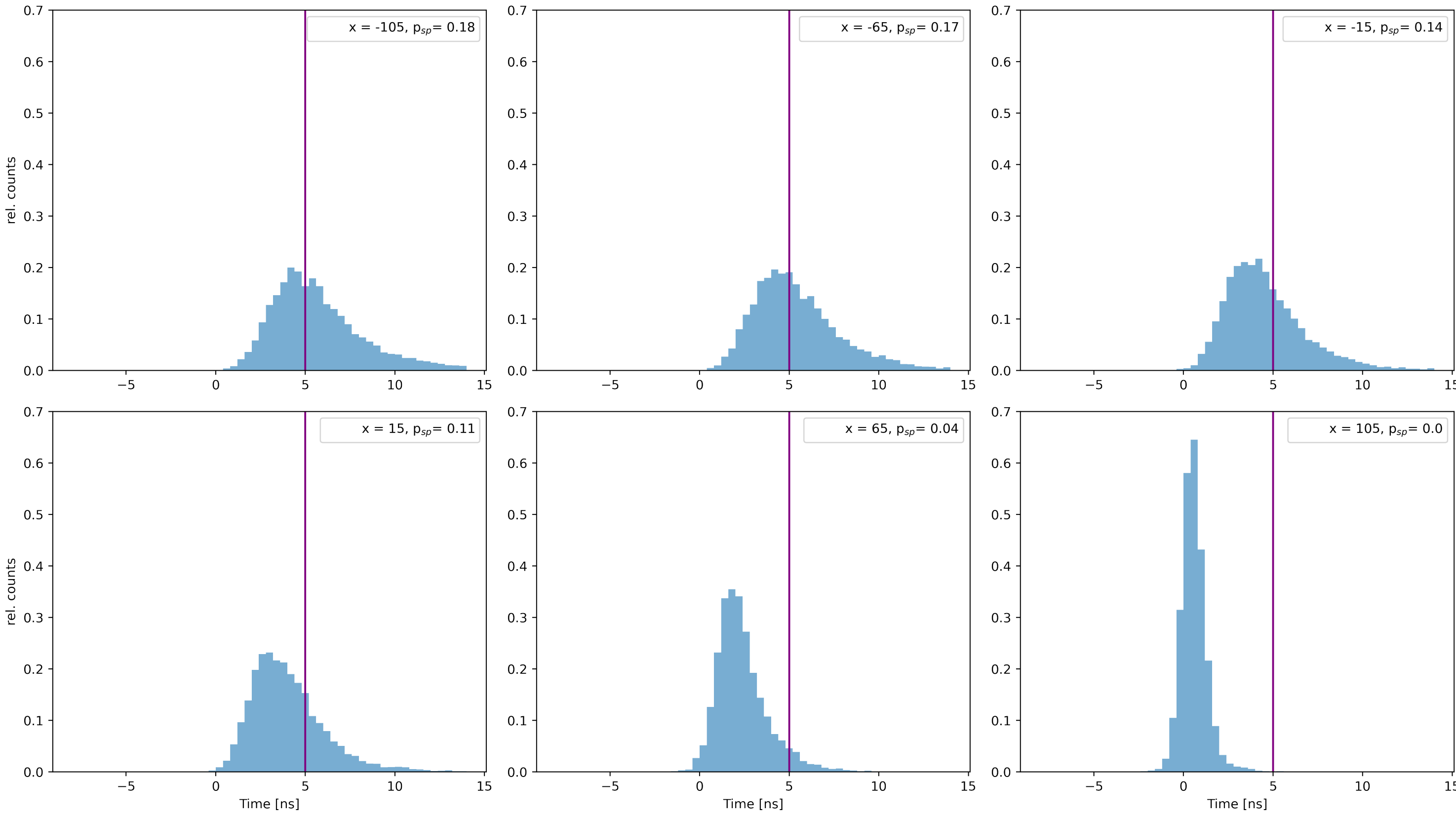


3. Reconsturction: Lookup Table

E.g. $t_E = 5$ ns

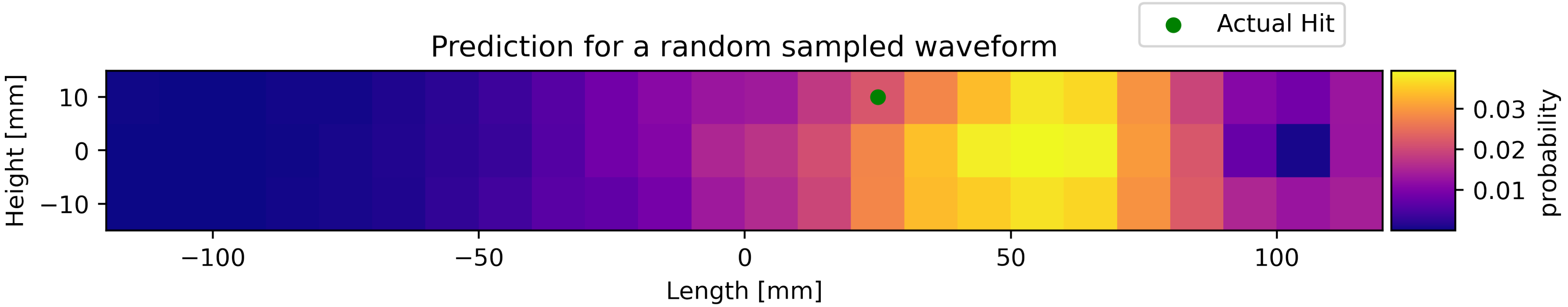
→ Search for distribution with highest magnitude at t = 5

→ Proposed position would be x = -105



3. Reconstruction: Lookup Table

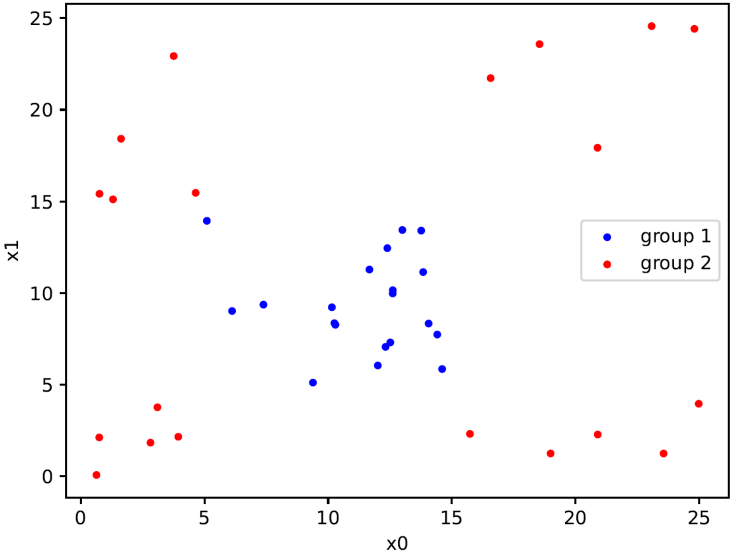
- Challenge: Best possible combination of all four measurements (t_C, t_E, E_C and E_E) to generate a score for each position.
- Advantages:
  - Clean representation of best predictions
  - No limitations to input and only viable locations as output



3. Reconstruction: Gradient Boosting

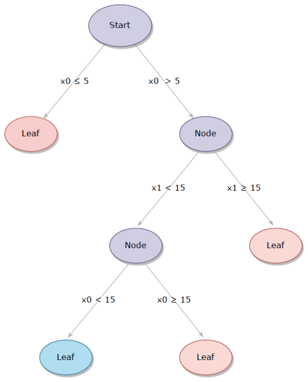
- Idea: Provide a data set with the waveforms most interesting characteristics e.g. times, energies, shape of waveform… to a ML classifying algorithm

  → Gradient Boosting Decision Tree



Example: Two groups to be classified based on two features

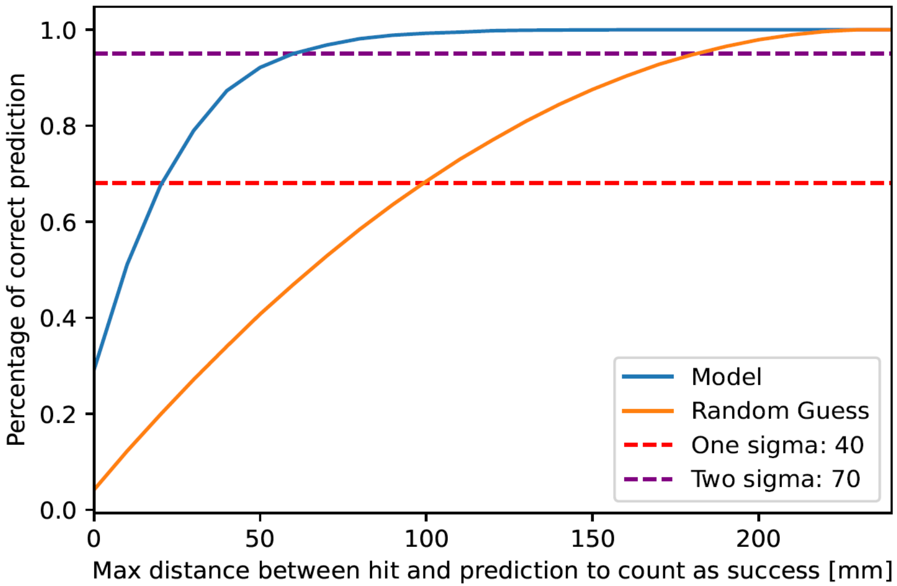
Decision Tree (Classifier):
Ruleset based of a training dataset, that assigns new inputs to a class

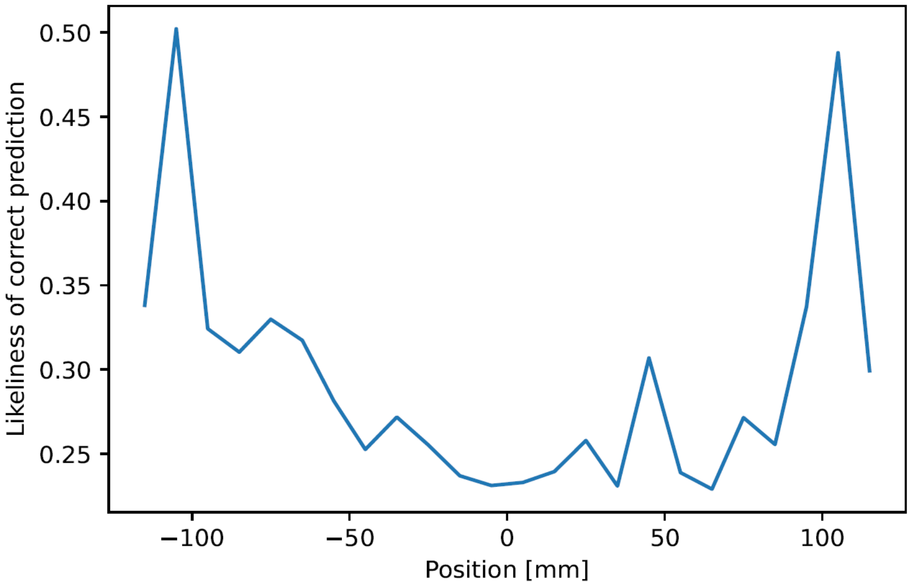


Gradient Boosting:
Way of combining weak learners into a strong ensemble model

3. Reconstruction: Gradient Boosting

After training with scikit's HistGradientBoostingClassifier:



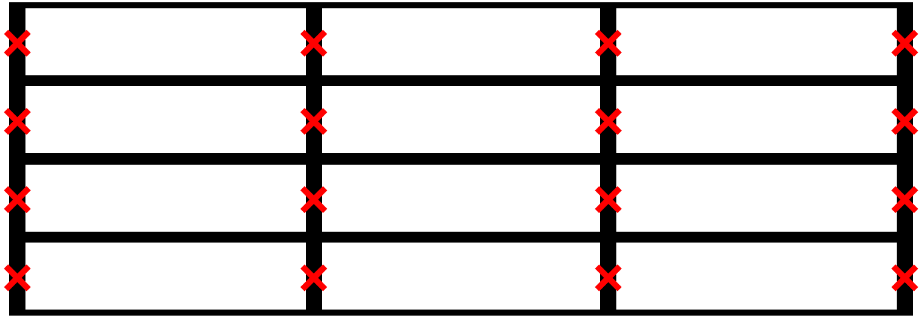


3. Reconstruction: Comparison

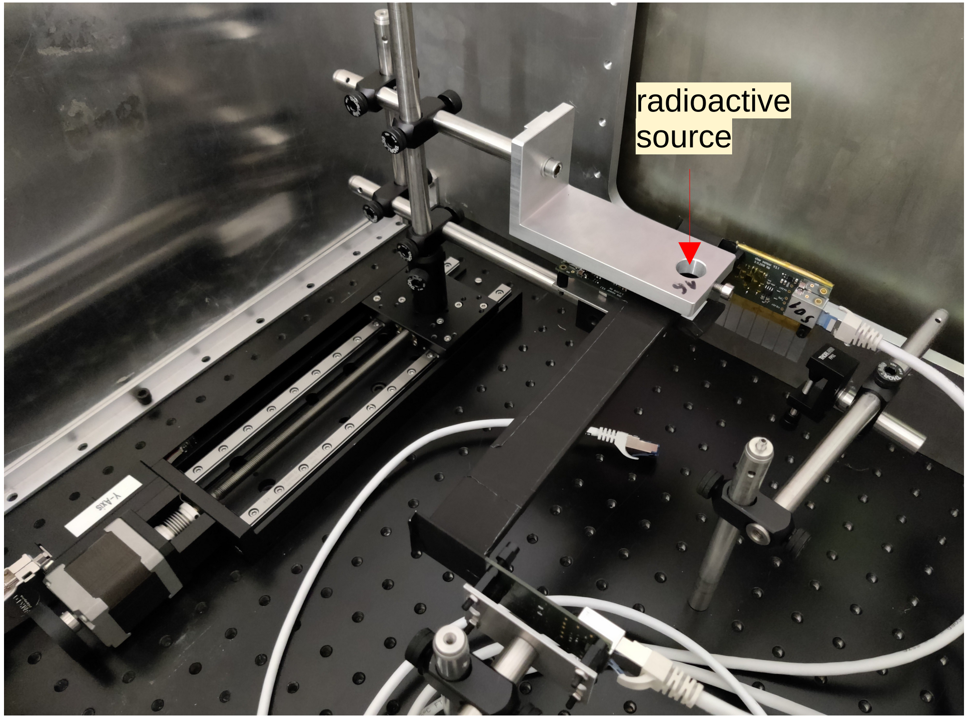
- **Linear:** Only suitable for geometries with large distances between the SiPMs, overall mediocre performance
- **Lookup Table:** Best results (70%+ correct) in the vicinity of the SiPMs, mediocre results for the middle of the bar.
  Is driven by the design of the lookup table so doesn't work as nicely out of the box
- **Gradient Boosting:** Best overall performance. Only algorithm that can reasonably distinguish in the middle of the bar. No easy visualization of results + less physical insights. Possibly a lot of room for improvement with different ML algorithms or better training

Side Readout

- Modified setup for side readout with a Strontium-90 source in the MPI laboratory
- Each SiPM located at the side of the bar in a small dimple
- PCBs perpendicular to bar
  → Dead area between bars

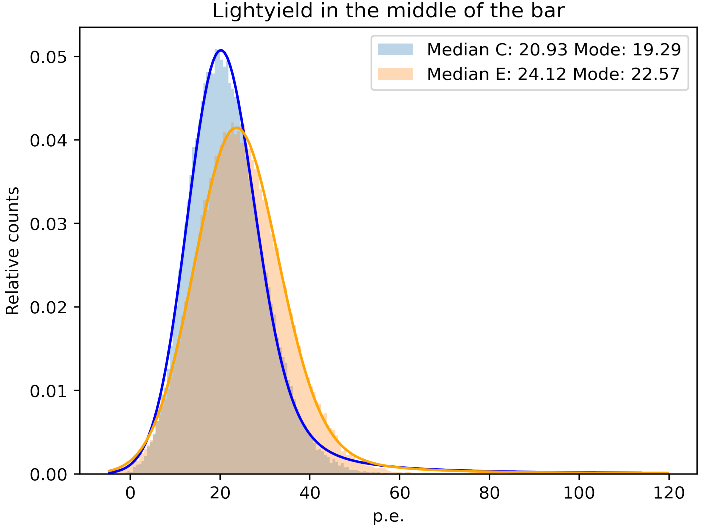


Possible arrangement in a detector layer,
x denotes the SiPMs

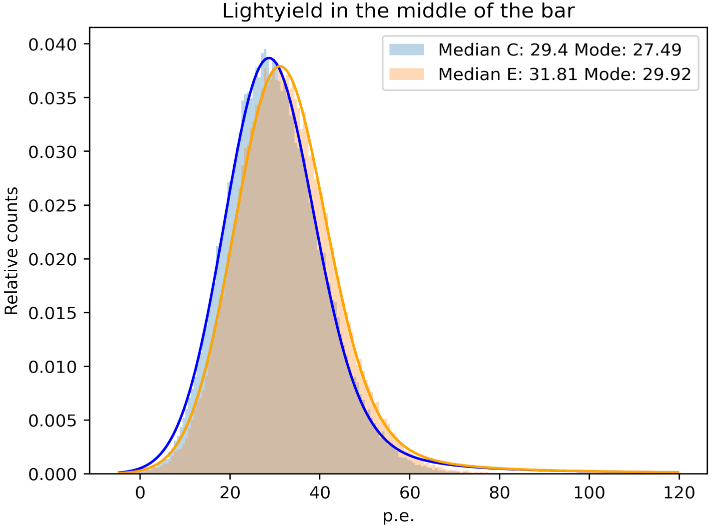


Side Readout

- Scintillator bar with SiPMs on the side of the bar shows almost 50% improvement in lightyield compared to SiPMs at ±15 mm from side



SiPMs at ±15 mm from side



SiPMs at the side

→ Improved light yields, but not without challenges

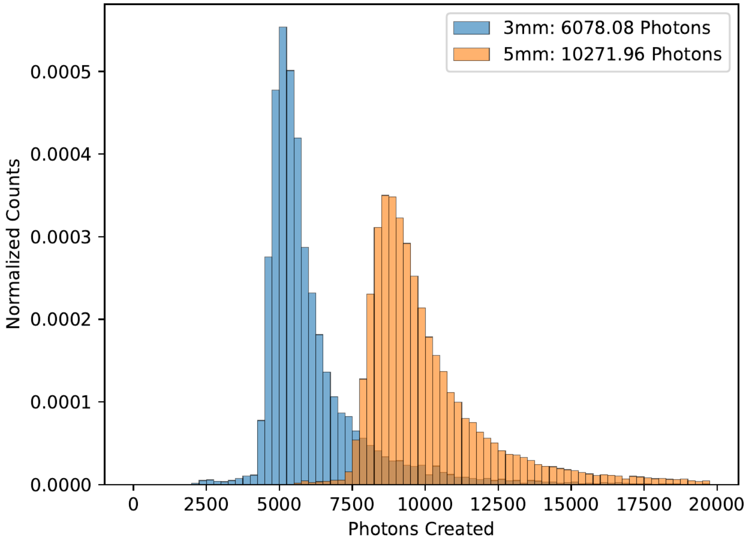
Results

- Scintillator bar approach viable design option for detectors where pile-up isn't a problem to reduce complexity
- Two SiPM readout, one on each side of the bar, to enable position reconstruction
- Light yield depends on the length of the bar according to a power law (only based on simulations)
- 240 mm seems to be a good bar length
  - We can expect to be within ±4 cm for 68%, and ±7 cm for 95% of the actual hit positions
  - Improvements can be expected with side readout instead of back readout

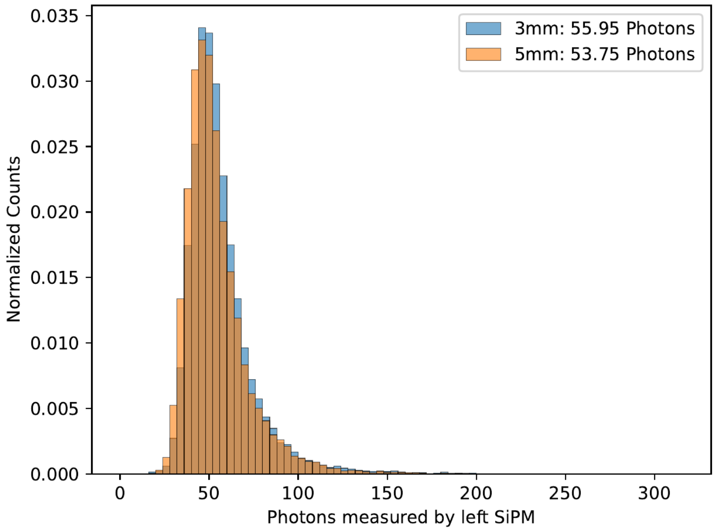
Backup

Backup: Thickness and Light Yields

- Initial idea: Increase thickness from 3mm → 5mm
- Simulation indicates that more photons get produced
- **But** similar numbers measured at the SiPM for a 240mm bar



Number of photons created



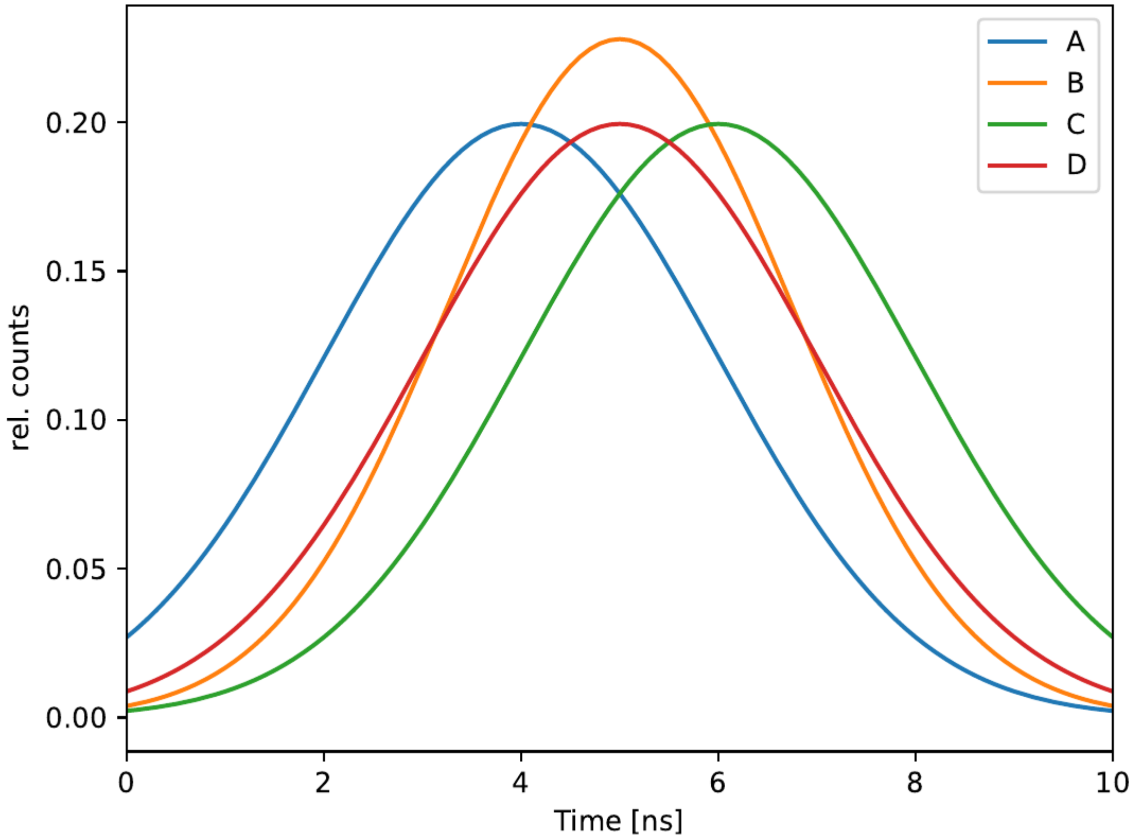
Number of photons detected

Backup: Overlap for Lookup Table

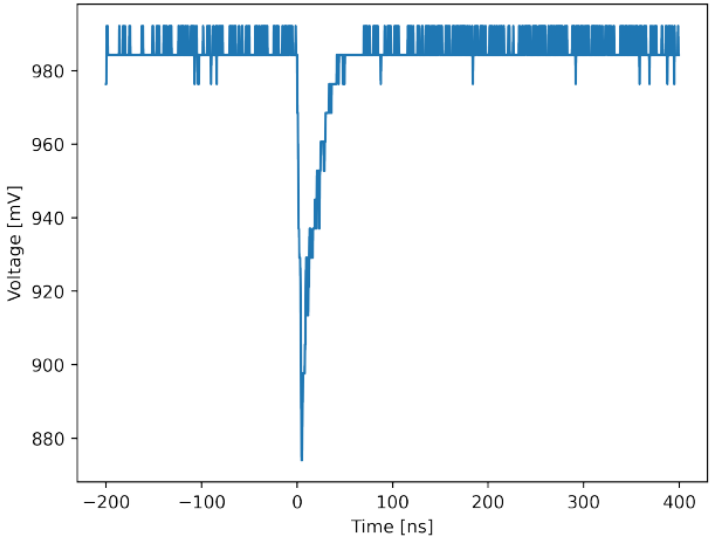
For the lookup table algorithm, Positions whose distributions are fully covered cannot be guessed

e.g. D is fully covered by A,B and C and therefore the corresponding position would be unavailable.

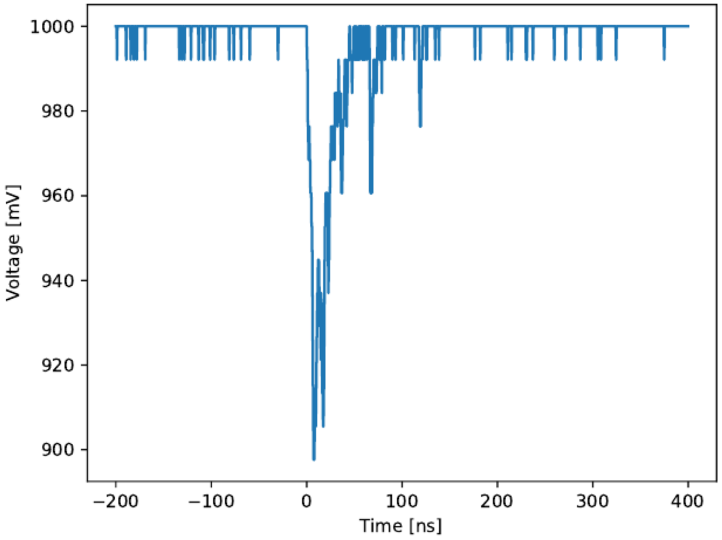
The effect is in the spirit of the algorithm. If the selected value is more likely to be from another position, than that one should always be preferred.



Backup: ADC Cut-off



(a) Normal recorded waveform

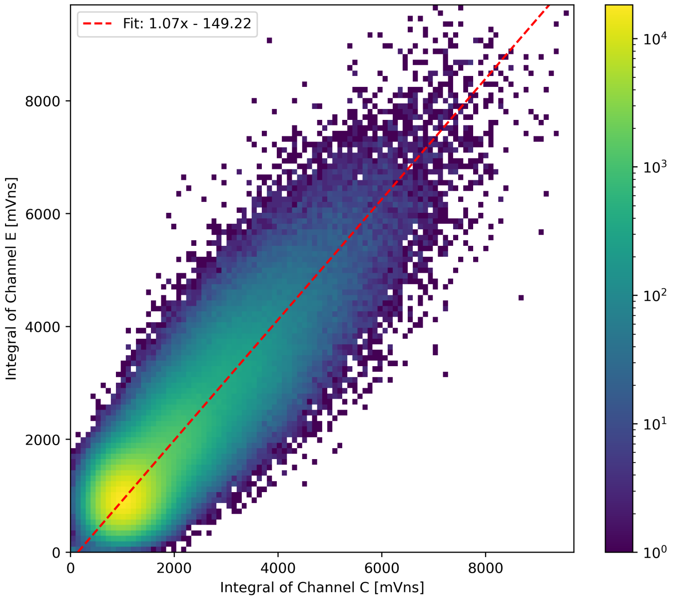


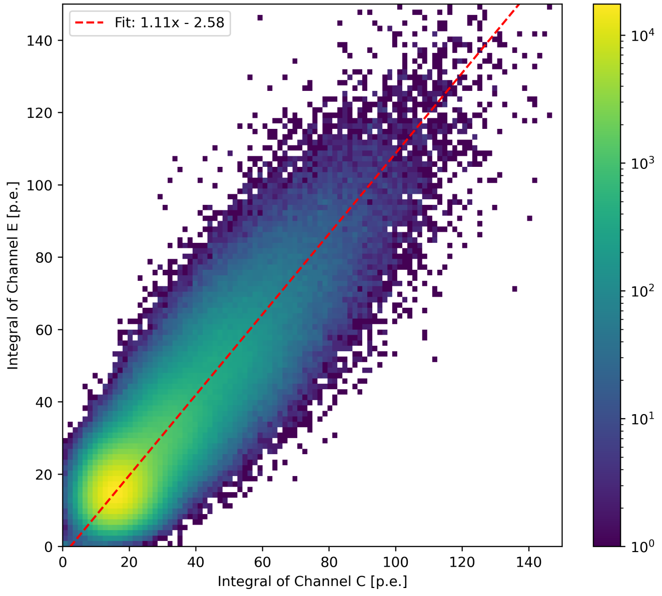
(b) Problematic channel E

Backup: ADC Cut-off

- Since the Cut-off also affects the 1 p.e. waveforms the histogram before and after p.e. calibration offers insights about the size of the error induced

  → If the Cut-off is big, it should result in **bigger** values after p.e. calibration





Conclusion: *Cut-off is negligible, and most likely small in comparison to other assymetries expected*