Exploring the Intrinsic Time Resolution of the SiPM-on-Tile Technology

Fabian Hummer, Lorenz Emberger, Frank Simon

Contribution to the
DPG Spring Meeting, Heidelberg 22

Session T41.2: Calorimeters 1
2022-03-22

MAX-PLANCK-INSTITUT FÜR PHYSIK

CALICE SiPM-on-Tile Technology

Scintillator Tiles:

- 30x30x3 mm³ plastic scintillator tiles
- Wrapped in reflective foil

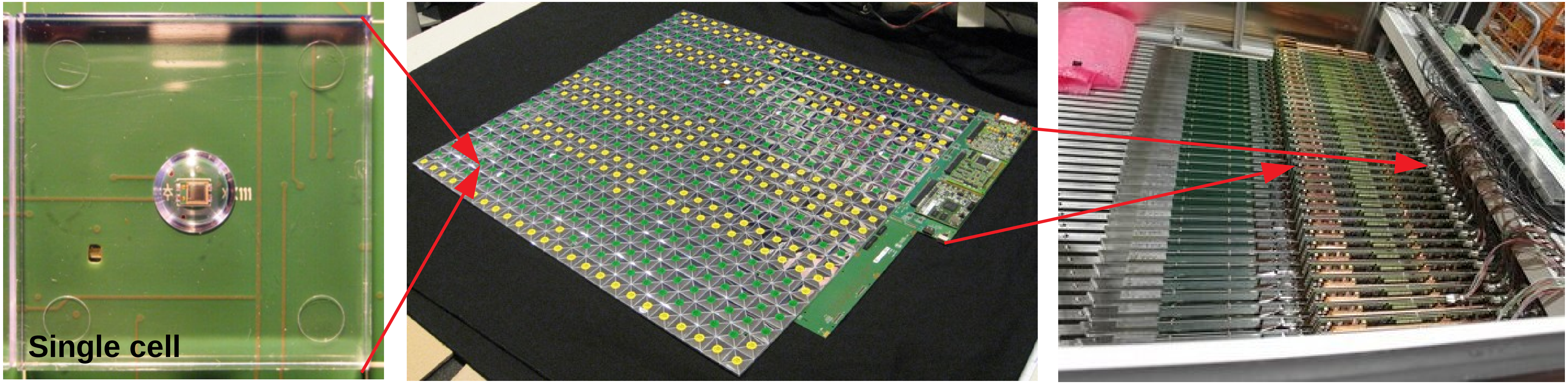
Active Layer:

- Tiles placed directly on PCB
- Individual SiPM readout for each channel

CALICE AHCAL Large Technological Prototype:

40 fully assembled layers

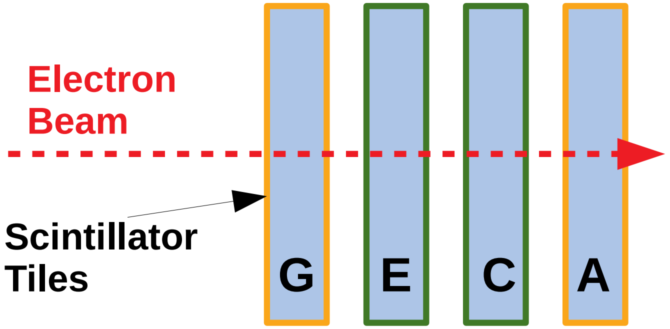
- 17 mm steel absorbers
- 3 mm scintillator tiles



Scintillator Timing Study

Concept of the Measurement:

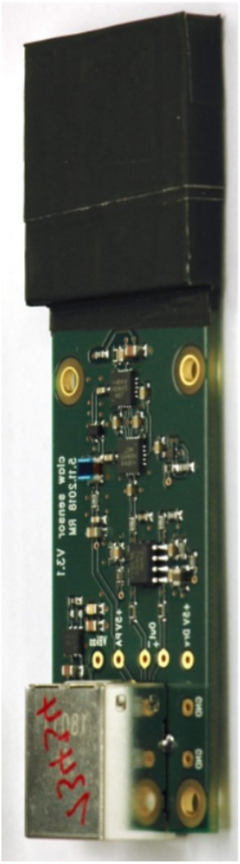
- Scintillator telescope with two coincidence triggers (**Ch A+G**)
- Two additional scintillator tiles (**Ch C+E**) to determine the time resolution as hit time difference of the channels



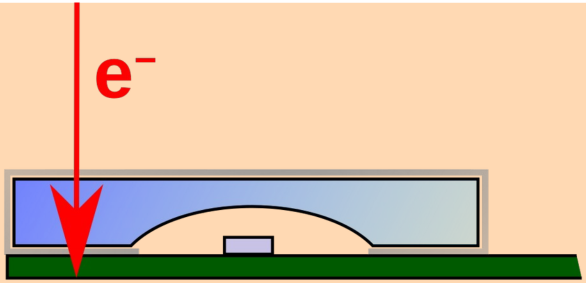
Channels A+G: Trigger
Channels C+E: Timing Measurement

Hardware

- CLAWS modules: flexible readout modules for a single SiPM-on-tile setup
- SiPM: Hamamatsu S13360-1325PE
- BC408 plastic scintillator
- ESR foil as reflective wrapping
- PicoScope 6804E for fast digitization of waveforms



Understanding the Signal Creation



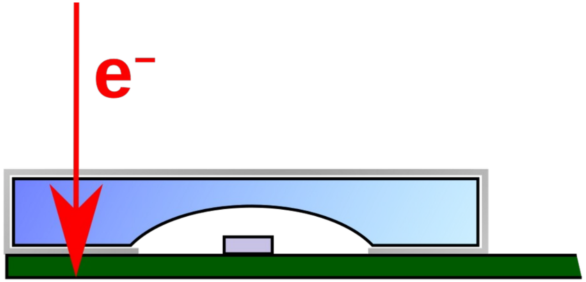
Full System Test Beam Measurements

1. Particle depoists energy in the scintillator, emission of light

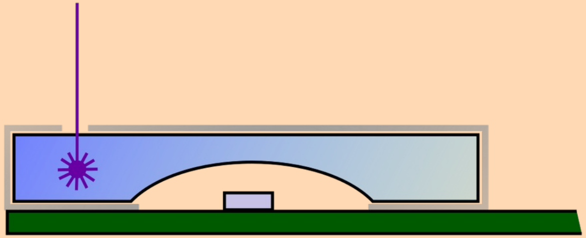
2. Light collection and transport to SiPM

3. SiPM creates electrical signal

Understanding the Signal Creation



Full System Test Beam Measurements

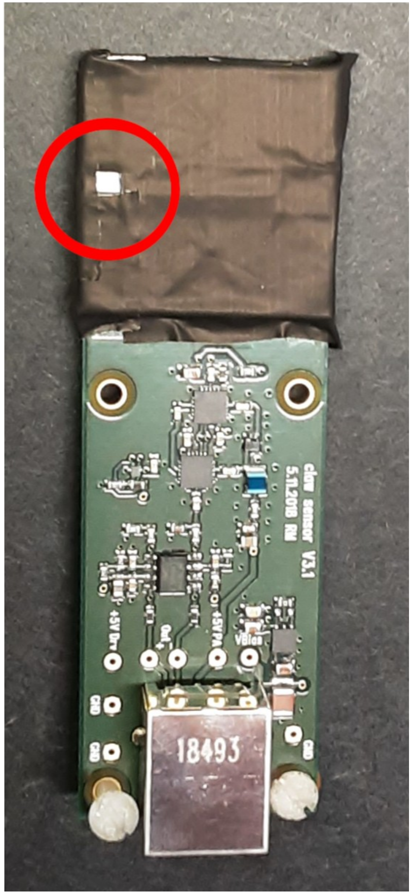


Inject pulsed laser beam into scintillator tile

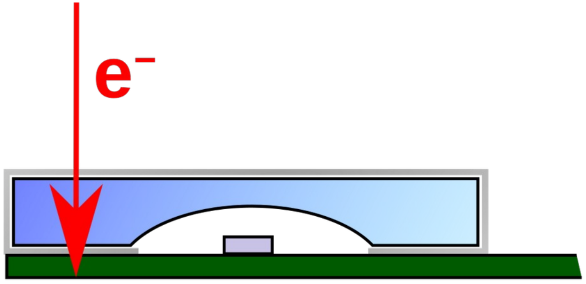
1. Particle depoists energy in the scintillator, emission of light

2. Light collection and transport to SiPM

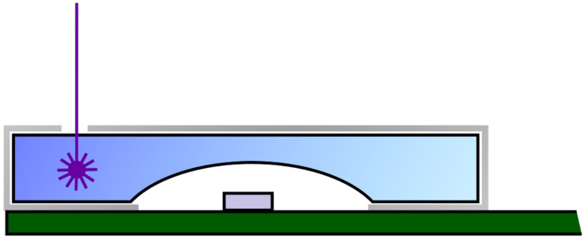
3. SiPM creates electrical signal



Understanding the Signal Creation



Full System Test Beam Measurements

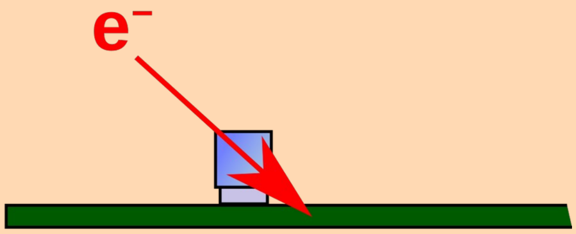


Inject pulsed laser beam into scintillator tile

1. Particle depoists energy in the scintillator, emission of light

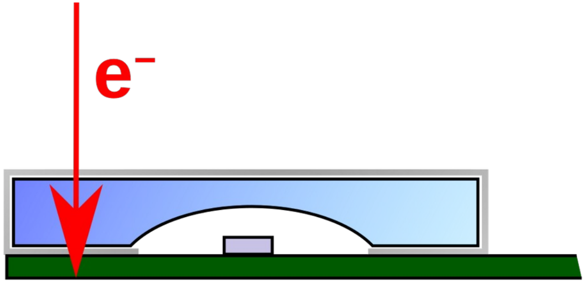
2. Light collection and transport to SiPM

3. SiPM creates electrical signal

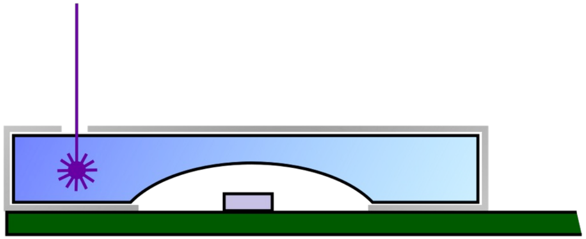


Emission measurements with small scintillators

Understanding the Signal Creation



Full System Test Beam Measurements

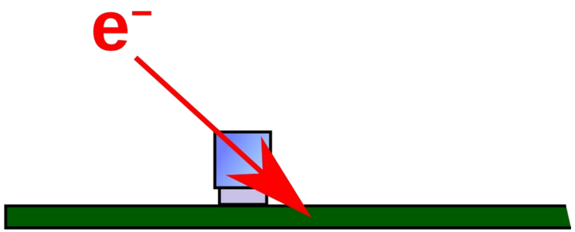


Inject pulsed laser beam into scintillator tile

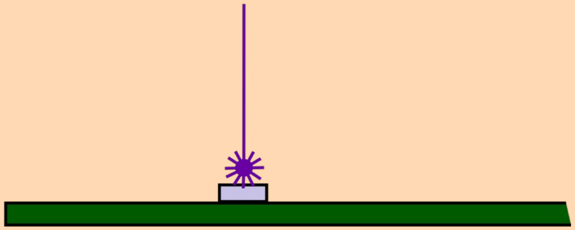
1. Particle depoists energy in the scintillator, emission of light

2. Light collection and transport to SiPM

3. SiPM creates electrical signal



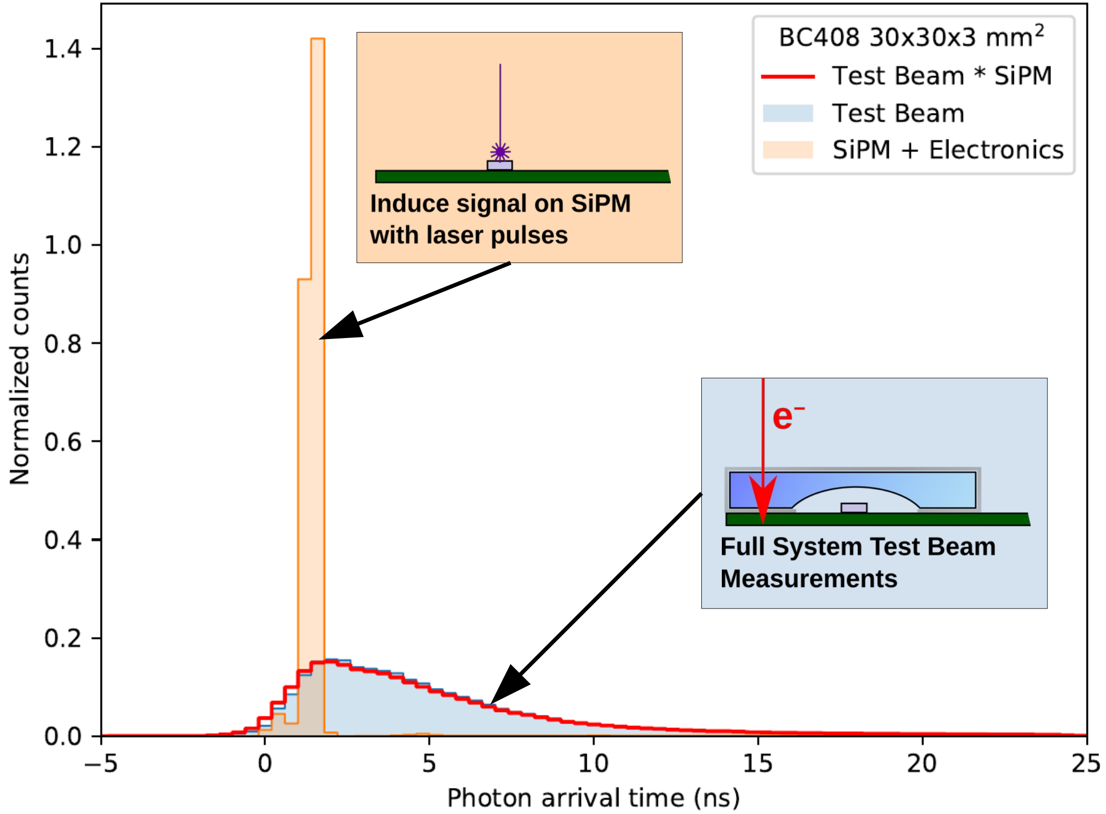
Emission measurements with small scintillators



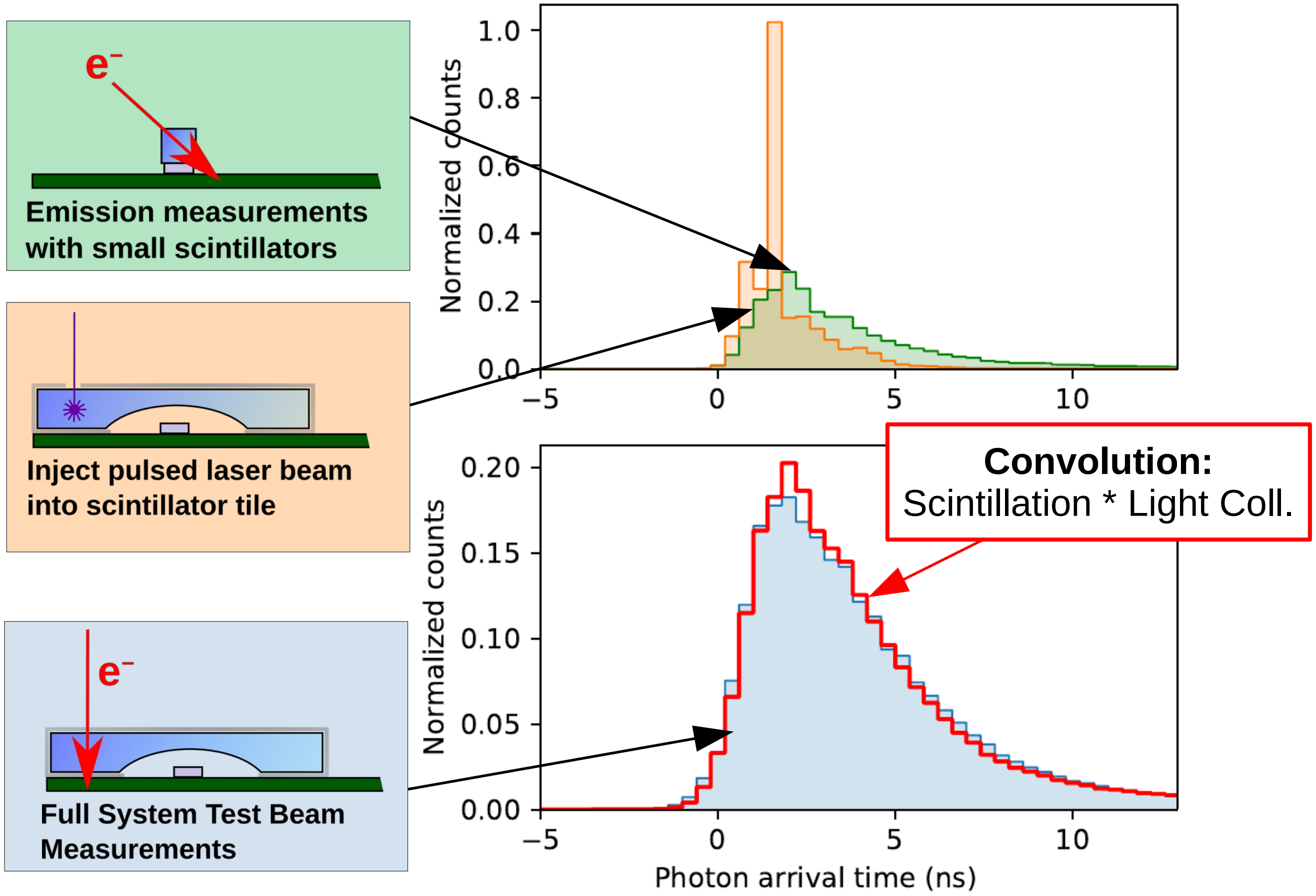
Induce signal on SiPM with laser pulses

Findings: Fast Hardware Response

- Laser measurement enables to study the response of CLAWS and SiPM to short laser pulses (σ_t < 80ps)
- Findings:
  - SiPM and electronics are significantly faster than other signal parts
  - Hardware does not contribute significantly to the time resolution



Findings: Scintillation + Light Collection

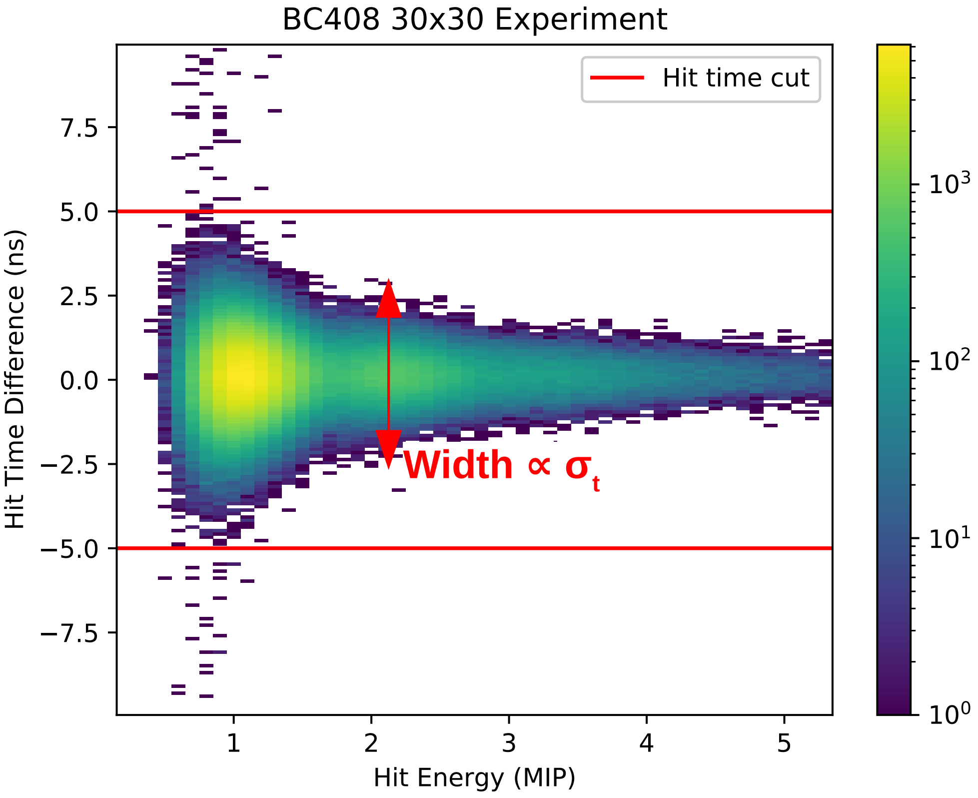


- The photon time distribution at the test beam can be fully described in terms of scintillation and light collection

Calculating the Time Resolution

- Hit time difference between channels C and E
  → eliminate trigger resolution effects
- Time resolution is the **width** of the hit time distribution, divided by √2
  → Assumption: hit times are uncorrelated random variables
- Time Resolution depends on energy deposition
- Mostly a „stochastic“ process of photon counting

$$\sigma_t = \frac{\sigma_1}{\sqrt{E}}$$



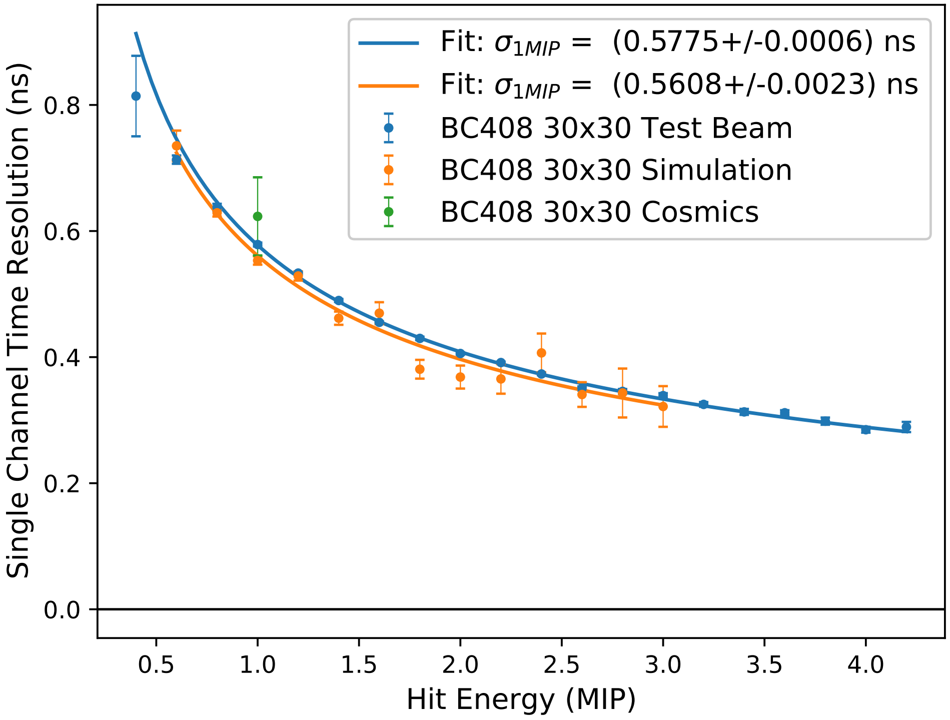
Energy-Dependent Time Resolution

- Time Resolution depends on energy deposition
- Mostly a „stochastic“ process:

$$\sigma_t = \frac{\sigma_1}{\sqrt{E}}$$

- Good agreement between experiment and simulation

Tile size	Experiment σ_1	Simulation σ_1
20x20	382.8 ± 0.3 ps	371.8 ± 0.8 ps
30x30	577.5 ± 0.6 ps	560.8 ± 2.3 ps
40x40	700.7 ± 0.8 ps	632.7 ± 3.4 ps



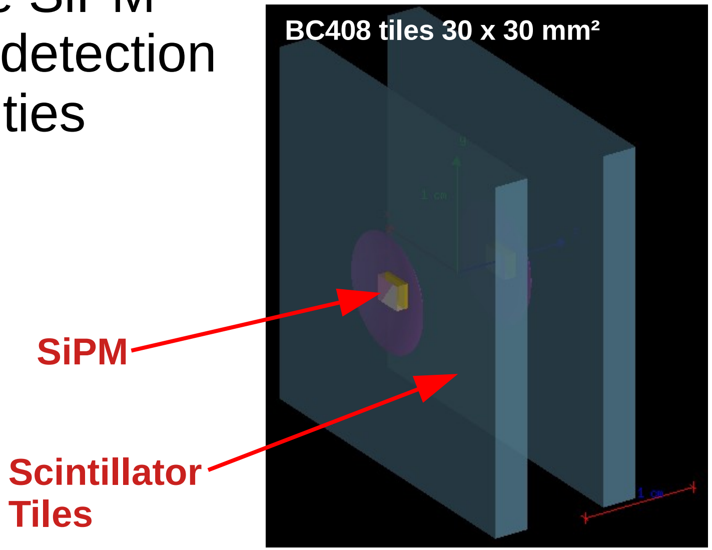
Geant4 Simulation

Concept of the Geant4 Simulation:

- Two scintillator tiles (**Ch C+E**) to determine the time resolution as hit time difference of the channels
- No trigger tiles since we know when the particle arrives
- Waveforms are generated from photon hit times and are analyzed in the same way as measurements
- Good agreement between simulation and experiment

→ This motivates to use the simulation as a tool for probing different SiPM-on-tile configurations:

- More different scintillator tile sizes
- Variable SiPM photon detection capabilities



SiPM-on-tile Model

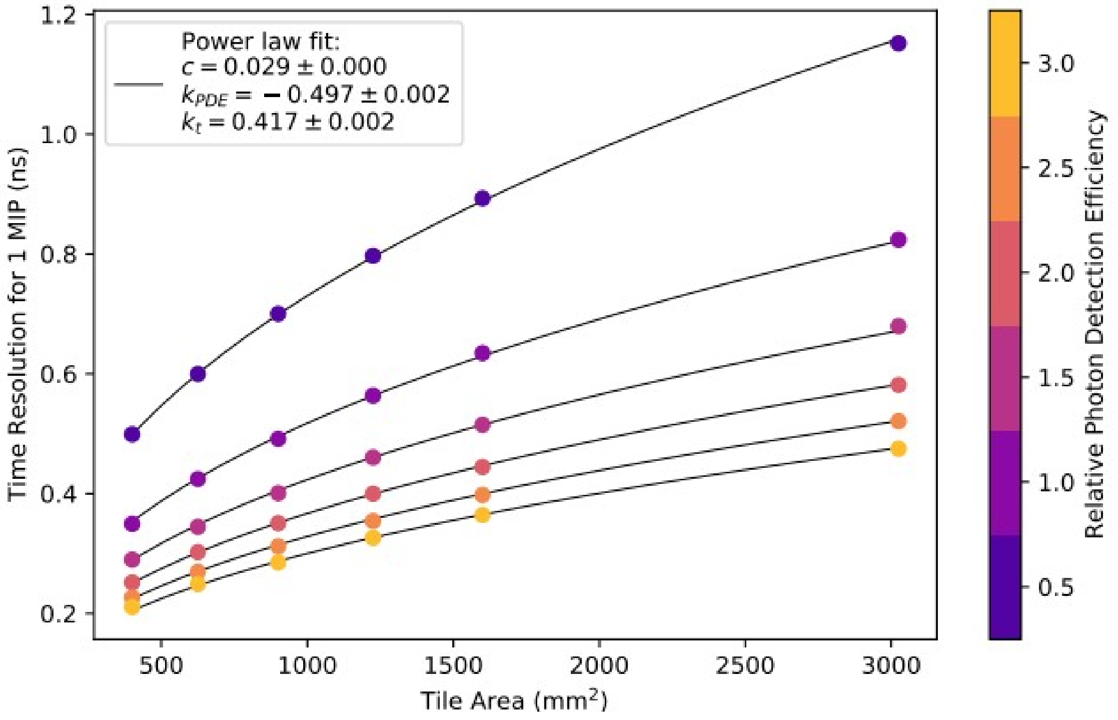
Set of two equations connects

- Design parameters: tile size A and relative rPDE
- Performance parameters: light yield LY and time resolution σ_t

$$LY = c_1 \cdot rPDE \cdot A^{k_1}$$

$$\sigma_t = c_2 \cdot rPDE^{k_2} \cdot A^{(k_1 \cdot k_2 + k_{LC})}$$

Exponents k	
k_1 (→ material)	-0.519 ± 0.004
k_2 (→ stochastic)	-0.495 ± 0.003
k_{LC} (→ light collection)	0.148 ± 0.004



Conclusion and Outlook

- Four different measurements to disentangle the different contributions to signal creation
- Developed a Geant4-based simulation framework and verified with various measurements
- Found a mathematical model for light yield and time resolution of SiPM-on-tile configurations

Potential for further studies:

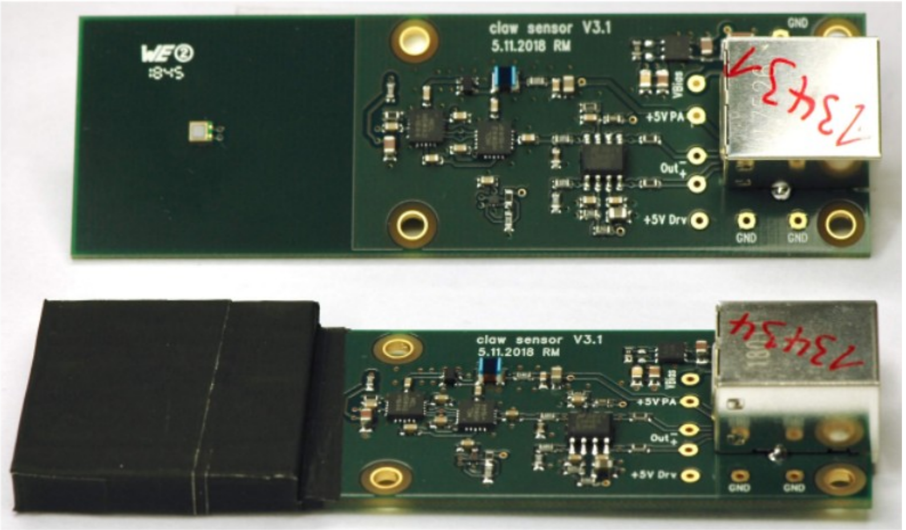
- So far only the pastic scintillator BC408 was studied in detail
- Extend analysis to different plastic scintillator materials to investigate
  - Different time constants of the scintillation process
  - Different light attenuation lengths → should change k_1

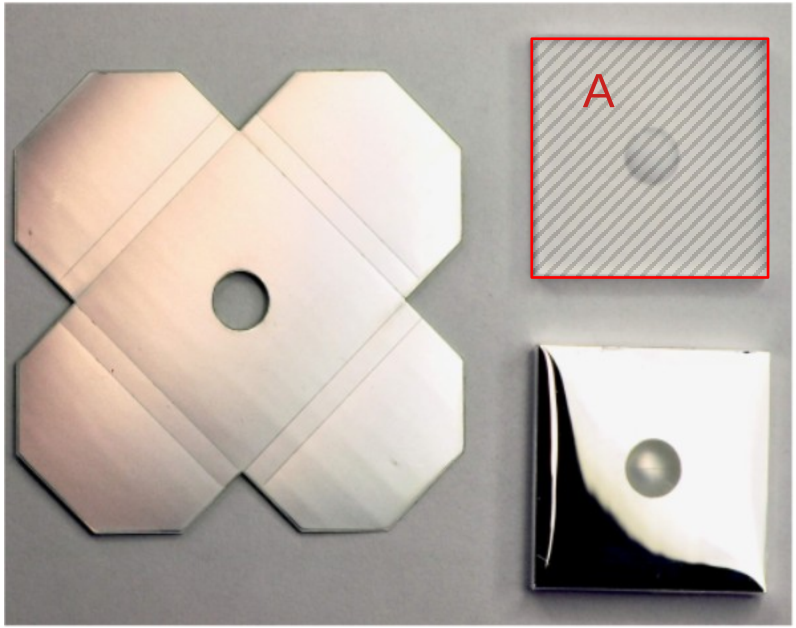
Backup Slides

SiPM-on-Tile Timing Study (STS)

- Hardware for timing study: CLAWS boards
- SiPM: Hamamatsu S13360-1325PE
- PicoScope 6804E

- Scintillator tiles: BC408, 3mm thick
- Different tile sizes (areas *A*) studied





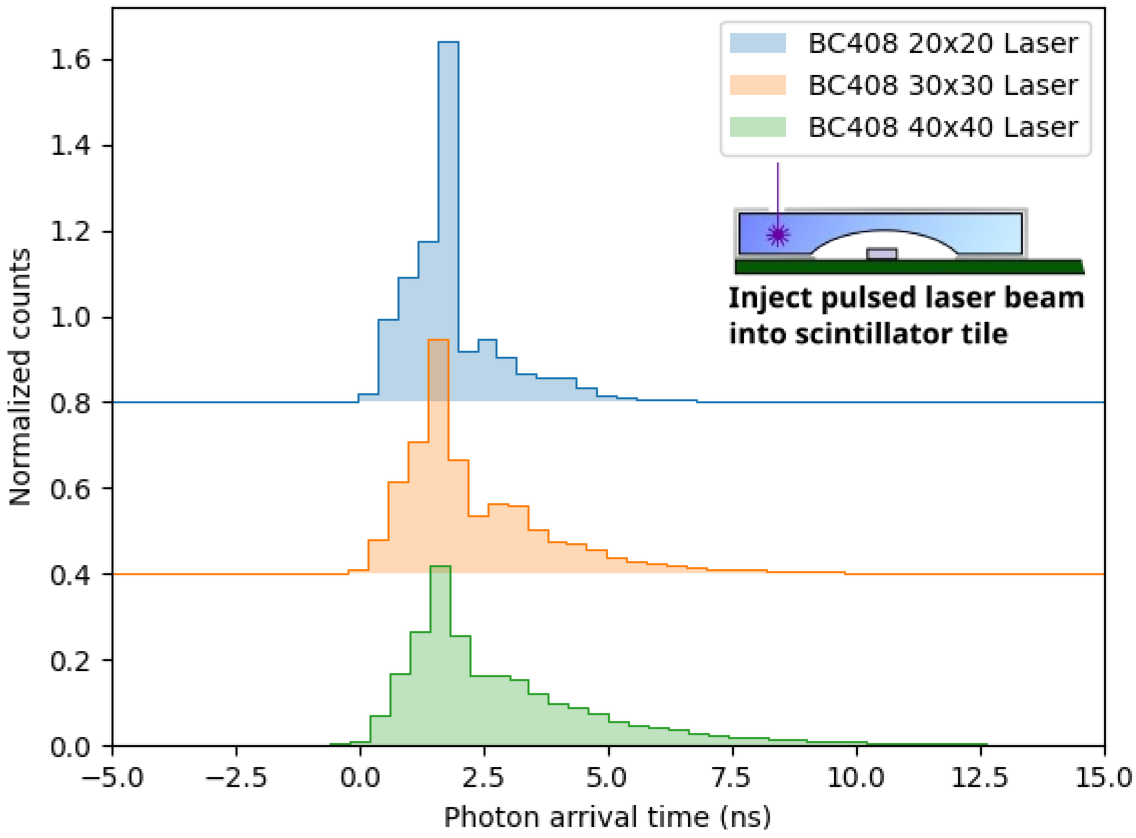
SiPM: Hamamatsu S13360-1325PE

Number of channels	1 channel
Effective photosensitive area	1.3 x 1.3 mm²
Number of pixels per channel	2668
Pixel size	25 µm
Spectral response range	320 … 900 nm
Gain (typical)	$7.0 \cdot 10^5$

Information taken from: https://www.hamamatsu.com/eu/en/product/type/S13360-1325PE/index.html

Time Dependence of Light Collection

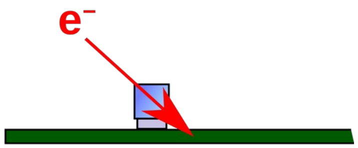
- The **width** of the photon arrival time distribution **increases** for bigger tiles
- In bigger scintillator tiles the photons travel longer paths
  - Light collection „takes longer“
- In the thesis I verified that the broadening of the photon time distribution is modeled correctly in Geant4



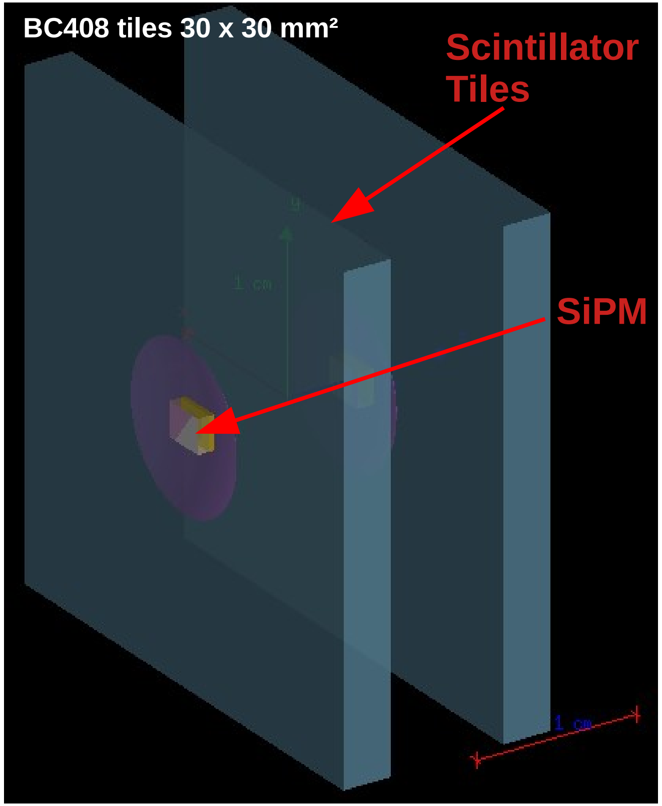
Geant 4 Simulations

- Two scintillator tiles in detector geometry
  → hit time difference
- 3 GeV electrons as primary particles
- Optical photons are tracked until they reach the SiPM → signal creation in a later step
- Scintillator emission modeled as double-exponential function
- Time constants are determined with a measurement using small scintillator cubes

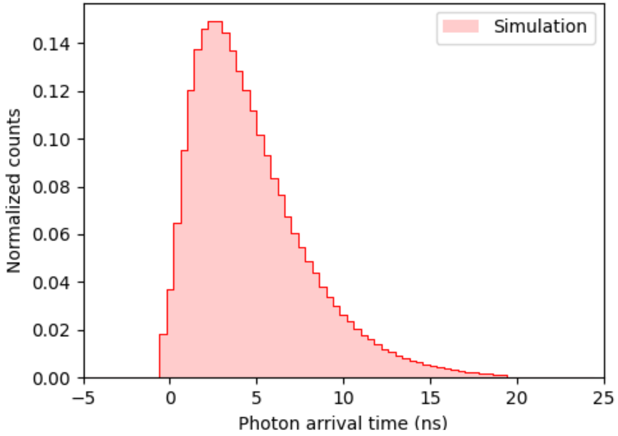
	Measured	Datasheet
Rise time	0.73 ± 0.15 ns	0.9 ns
Fall time	2.56 ± 0.13 ns	2.1 ns



Emission measurements with small scintillators

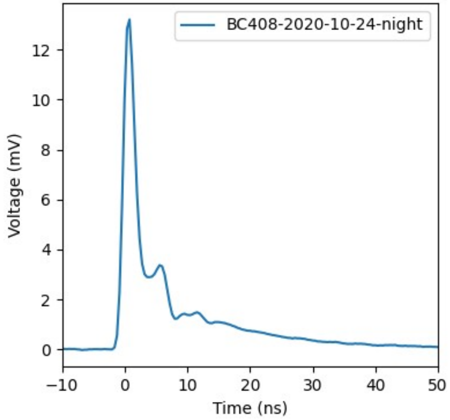


Simulation: Waveform Generation



Photon arrival times from Geant4 simulations

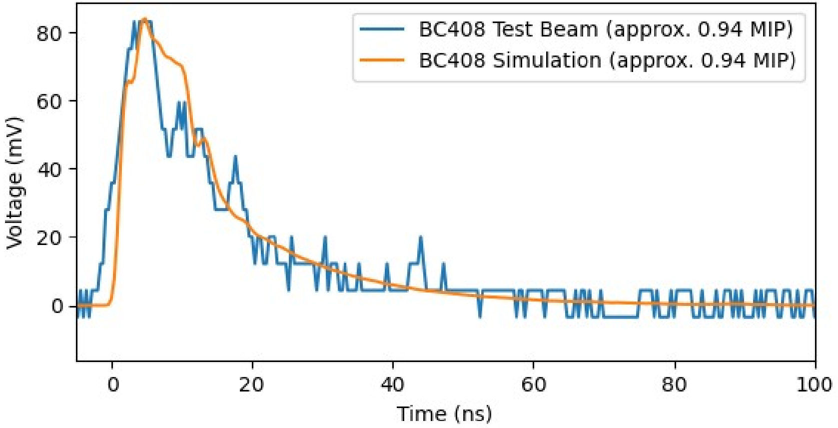
plus



Average 1 p.e. waveform from a measurement

Stack 1p.e. waveforms

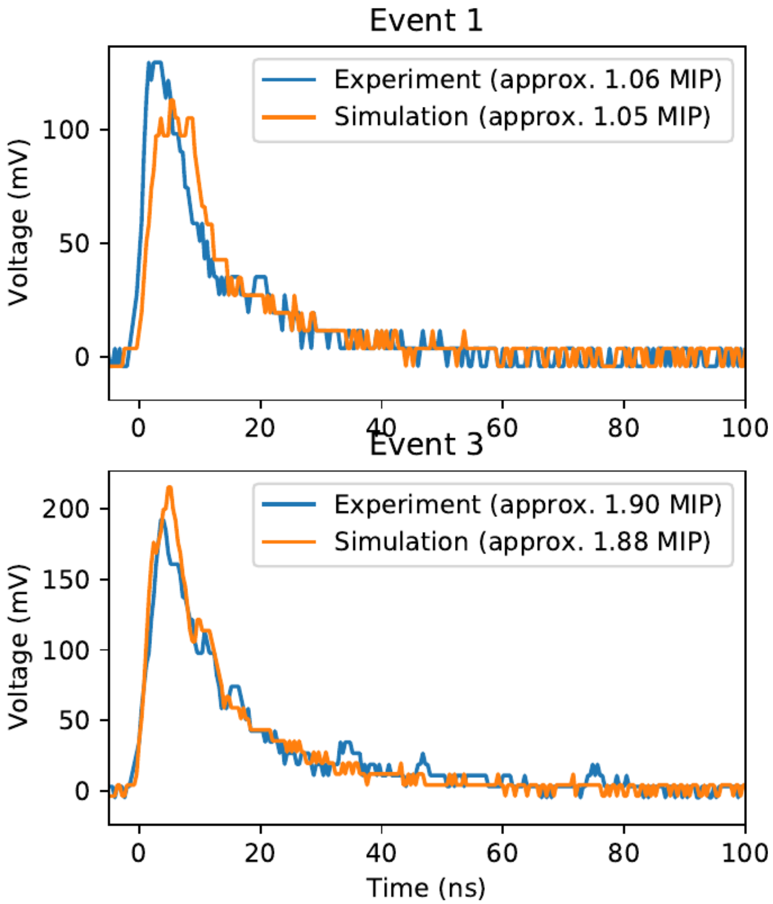
SiPM response for each simulated event.



Caveat: „Light collection term“ needs to be adjusted so that amplitudes agree (once for all measurements)

Some Generated Waveforms

- Generated waveforms are stored in same data format as measurements
  - Also add noise to generated signals and digitize to 8 bit
- Simulation and experiment are analyzed with the same software
- In test beam conditions, there are events with more than one particles
  - This changes the energy distribution of the signals
  - Emulated by „stacking" the waveforms of independent simulated events



Calculating the Time Resolution (1)

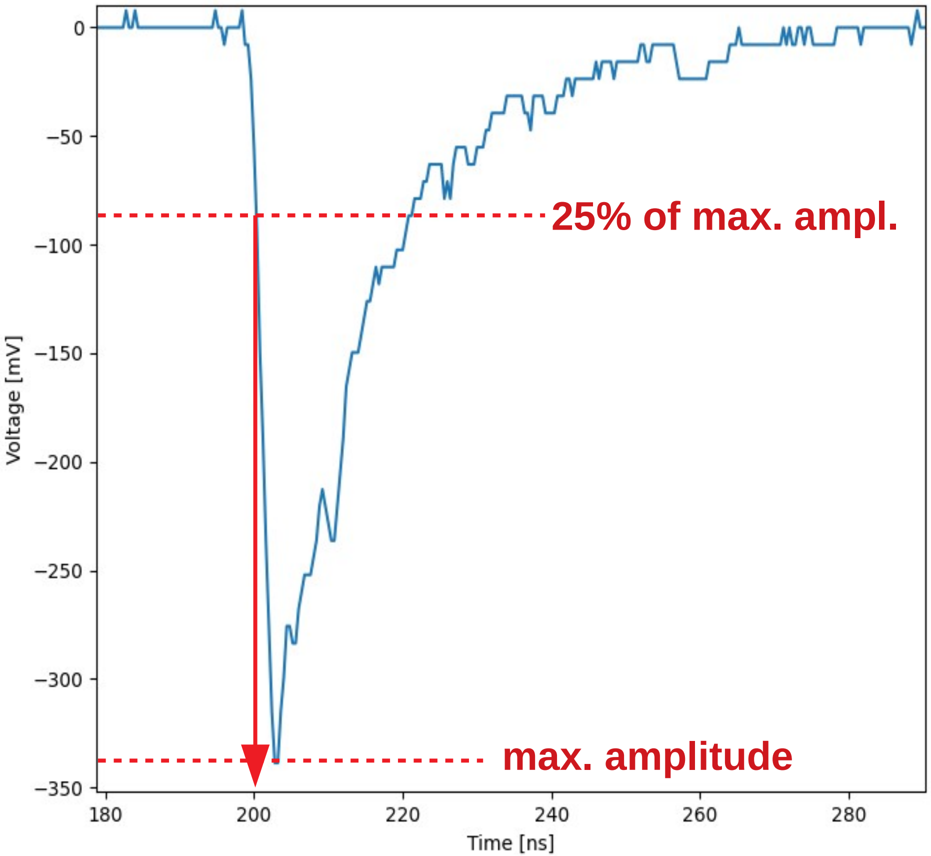
Constant Fraction Discrimination:

- Get maximum amplitude of the event
- Search for the first time that the signal crosses 25%
- If the crossing is between two bins, interpolate linearly

Leading Edge Method:

- Set threshold to fixed voltage

Typical SiPM response

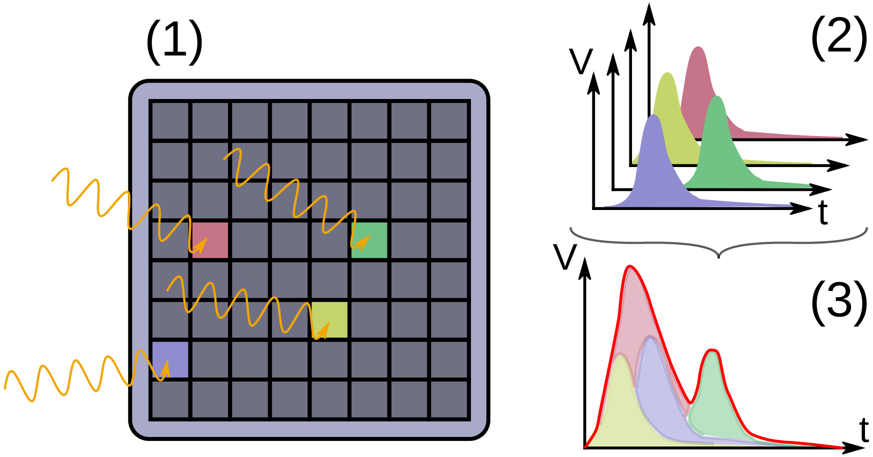


Photon Detection Scheme: SiPM

(1) Photons arrive at different pixels and excite an electron (photoelectric eff.)

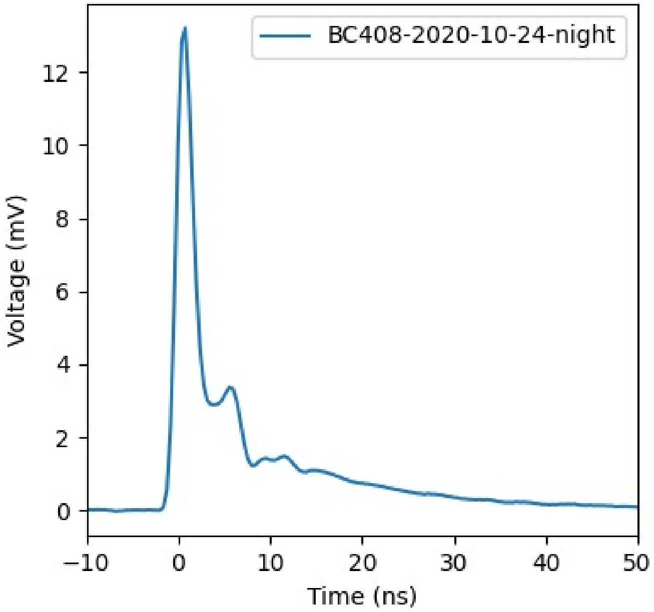
(2) High bias voltage → avalanche of charge carriers → short current spike

(3) SiPM has only one channel → signals of all pixels added together

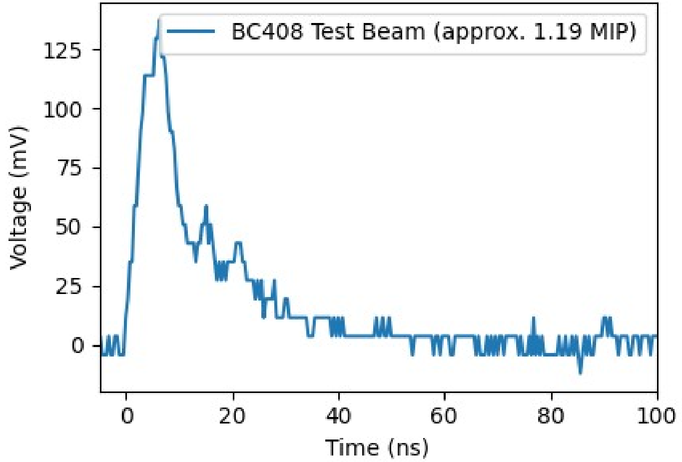


Important property: All pixels cause the same signal response

→ let's use this property in data analysis

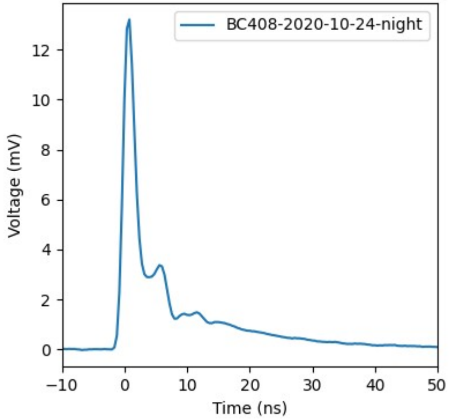


Waveform Decomposition



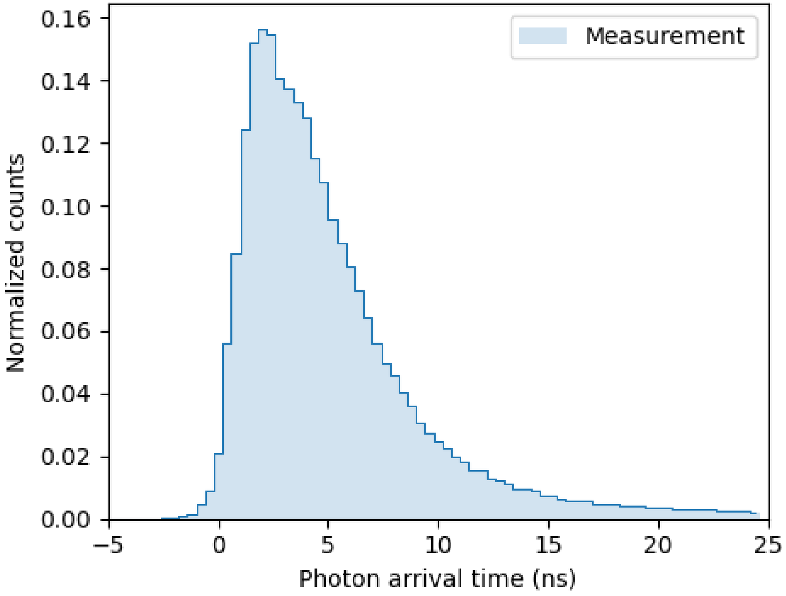
SiPM response for each measured event.

minus



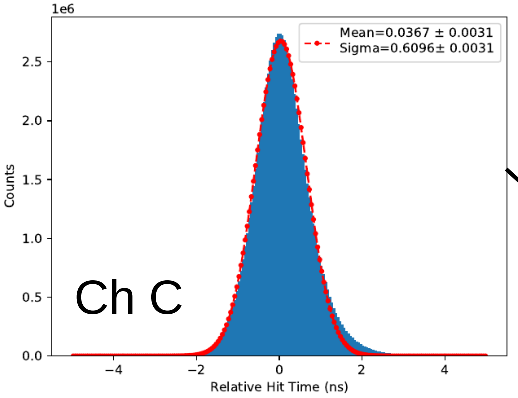
Average 1 p.e. waveform from a measurement

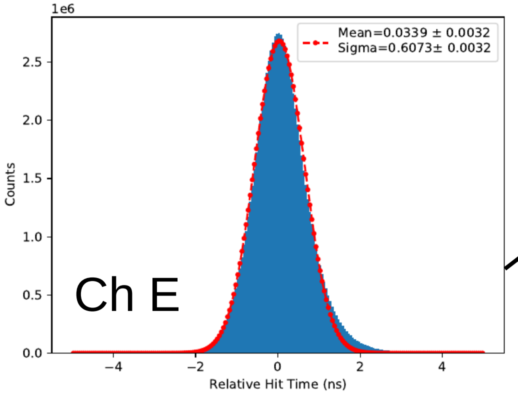
Subtract 1p.e. waveforms



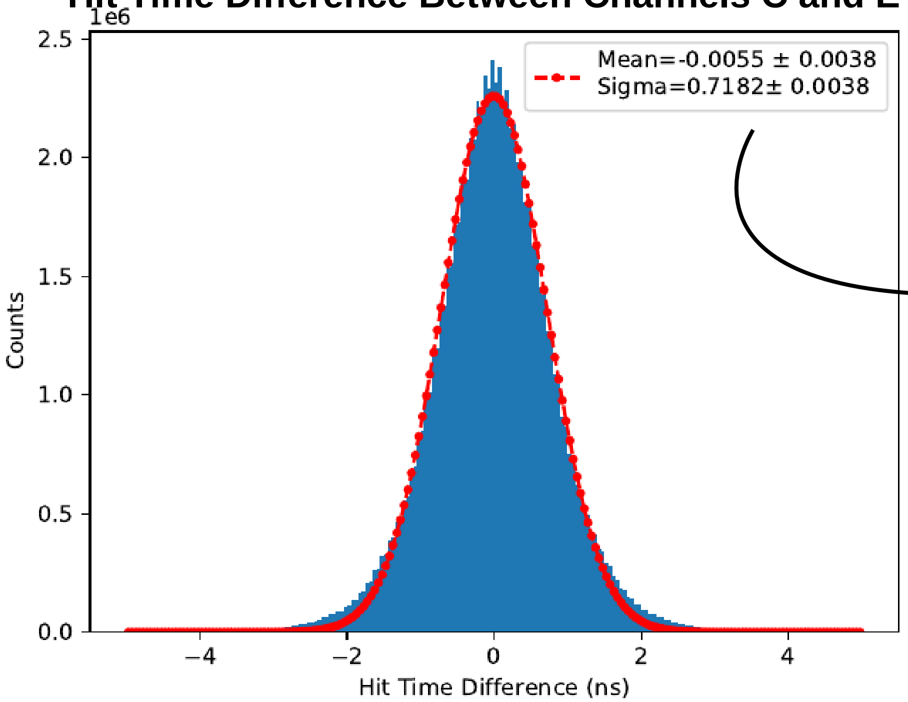
Extrapolate photon arrival times at the SiPM

Calculating the Hit Time Difference





Channels C and E give two independent hit times
→ subtract to eliminate trigger resolution effects



Single Channel Time Resolution:

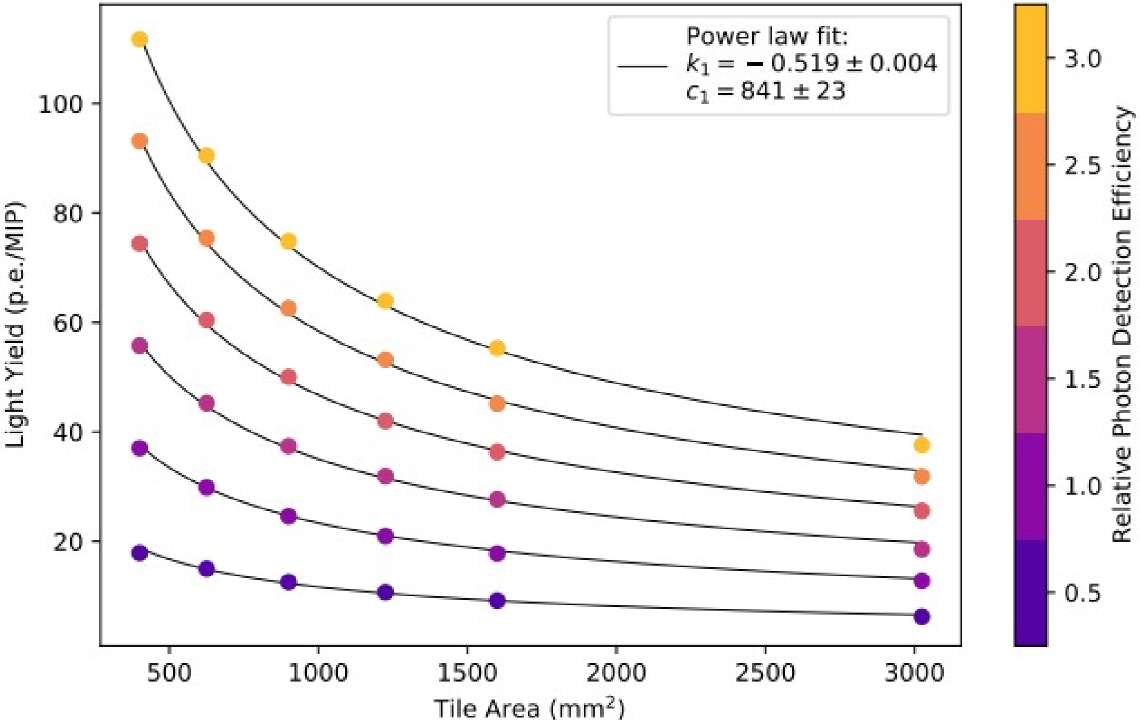
0.718/√2 = 0.507 ns
for AHCAL tiles (30x30 mm²)

Light Yield

- Finding: $LY = c_1 \cdot rPDE \cdot A^{k_1}$

Exponents k	
k_1	-0.519 ± 0.004

- Instead of adjusting the PDE to experimental results, use different values
- Exponent agrees with other experimental studies of BC408



Time Resolution

- Finding: $\sigma_t = c_2 \cdot LY^{k_2} \cdot A^{k_{LC}}$

Exponents k	
k_2	-0.495 ± 0.003
k_{LC}	0.148 ± 0.004

- Exponent k_2 corresponds to $1/\sqrt{n_\gamma}$
  → photon counting
- Exponent k_{LC} accounts for time dependence of light collection
  → smaller tiles respond faster