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

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Contribution to the

10th Beam Telescopes and Test Beam Workshop

2022-06-24

MAX-PLANCK-INSTITUT FÜR PHYSIK

CALICE

CALICE SiPM-on-Tile Technology

Scintillator Tiles:

- 30x30 mm² injection moulded polystyrene
- Wrapped in reflective foil

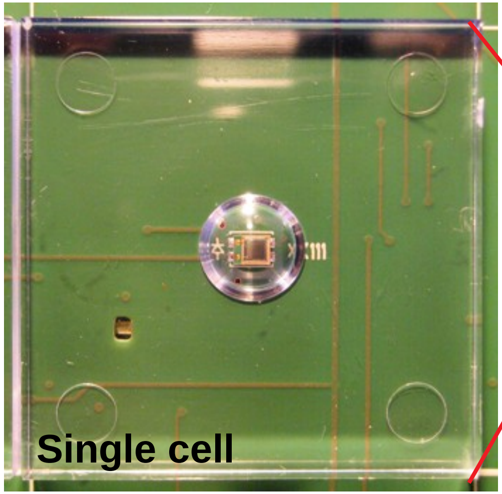
Active Layer:

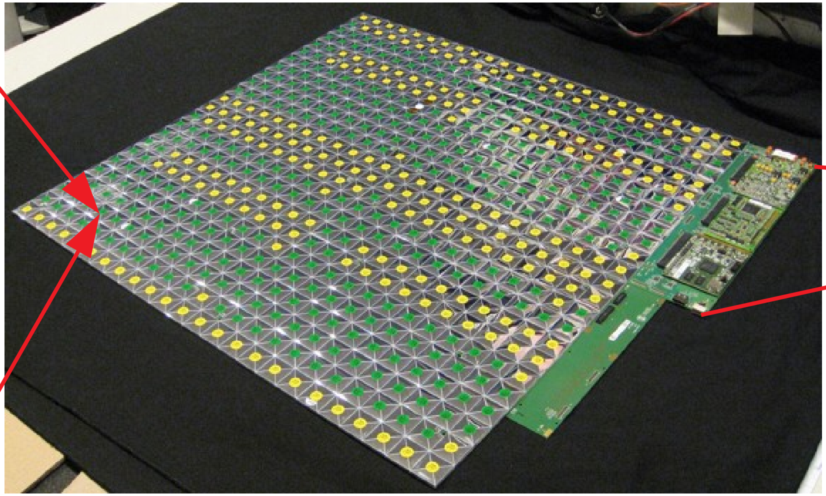
- Tiles placed directly on circuit board
- Individual SiPM readout for each channel

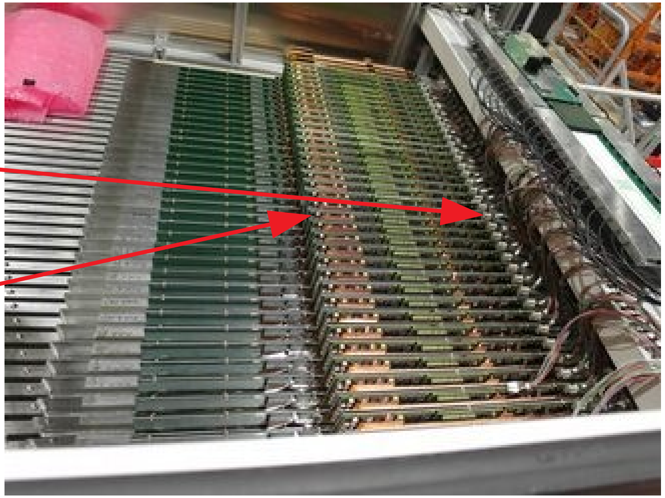
AHCAL Large Technological Prototype:

40 fully assembled layers

- 17 mm steel absorbers
- 3 mm scintillator tiles







Objectives of the Timing Study

First Test Beam: October 2020

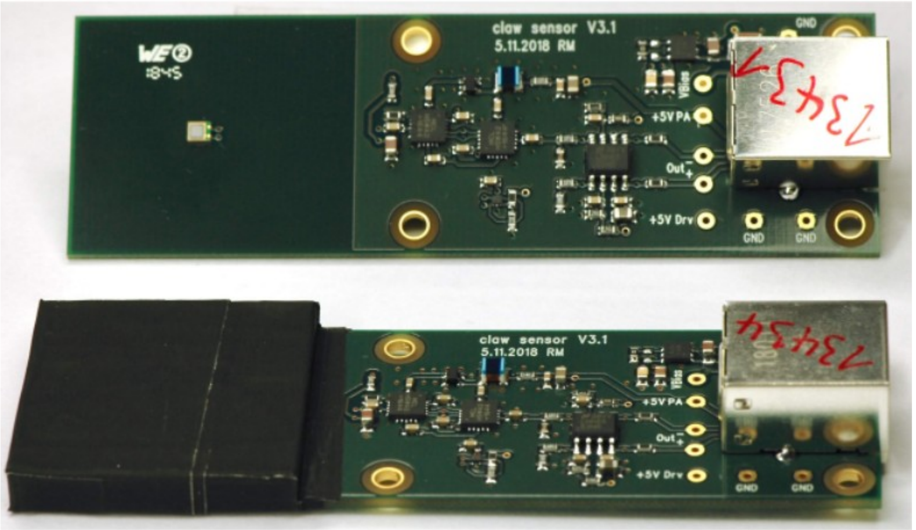
- Measure the time resolution of SiPM-on-tile independent of AHCAL electronics and DAQ
- Simple and modular setup
- Studied AHCAL PS tiles, and two sizes of BC408
- First indications of material and area depenence
- Simulations deliver first good results, but need more experimental data

Second Test Beam: October 2021

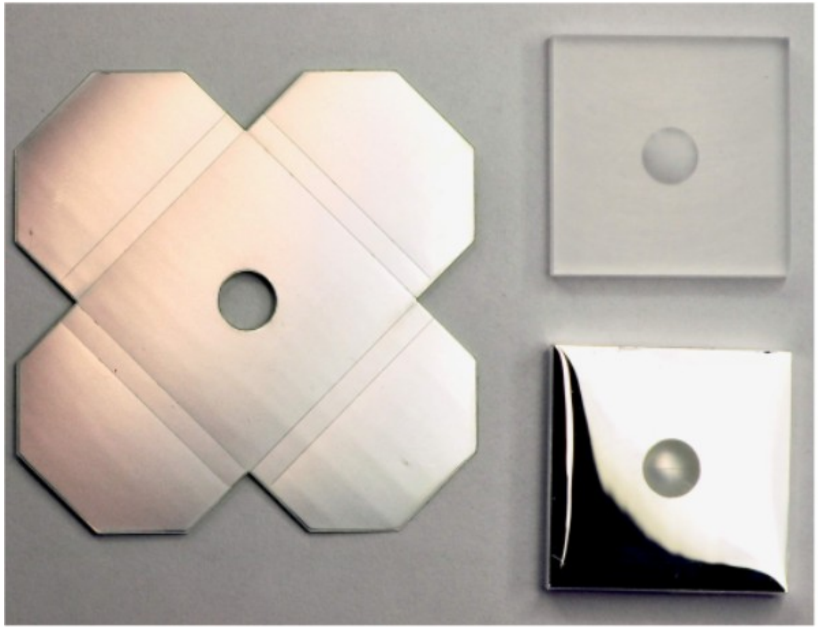
- Objective: Systematic study of how design choices impact light yield and time resolution
- Four different scintillator materials: BC404, BC408, BC418, BC422Q
- Three different tile sizes: 20x20 mm^2, 30x30 mm^2, 40x40 mm^2
- In this presentation: Results for BC408

SiPM-on-Tile Timing Study (STS)

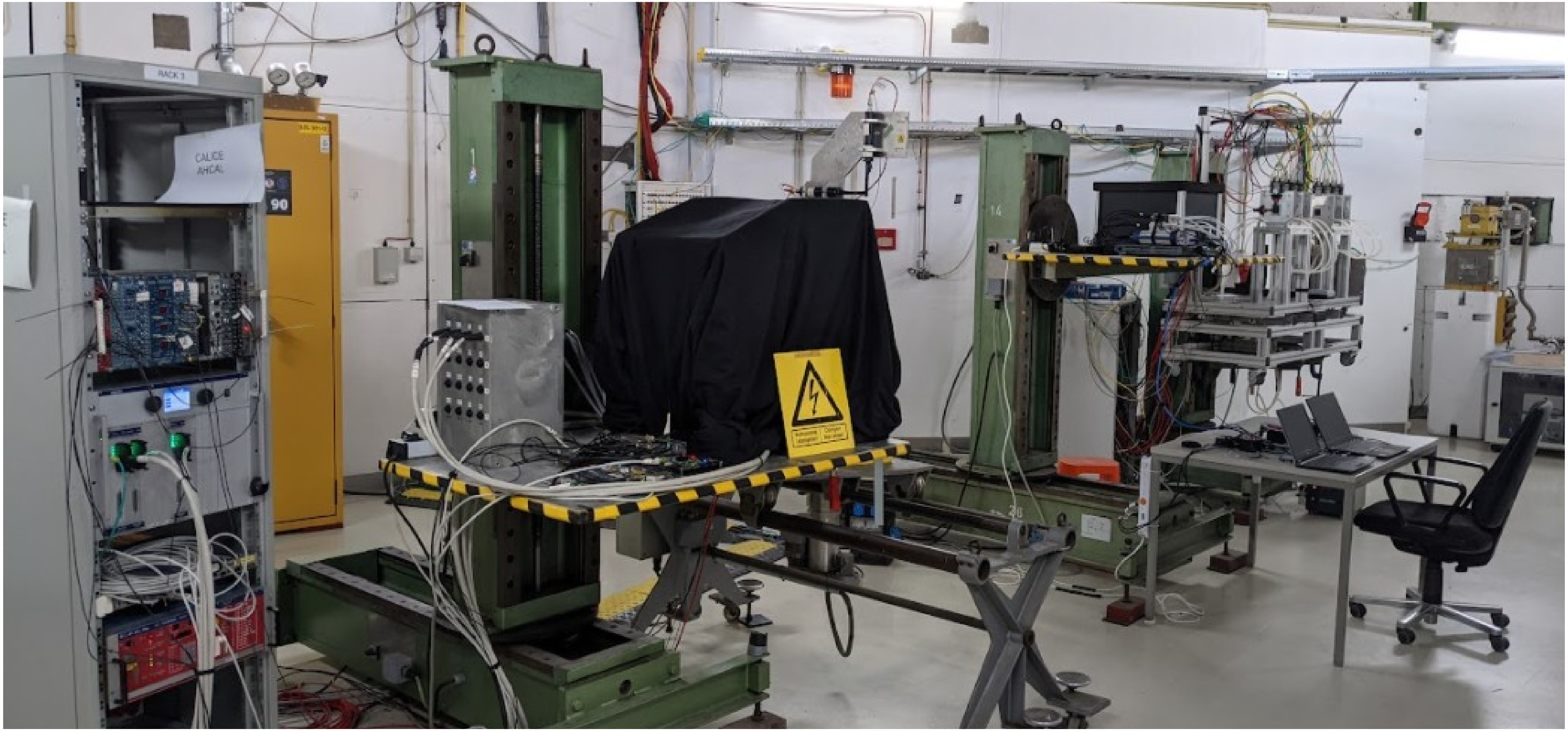
- Hardware for timing study: CLAWS boards
- SiPM: same as in AHCAL Prototype
- Record full analog waveforms



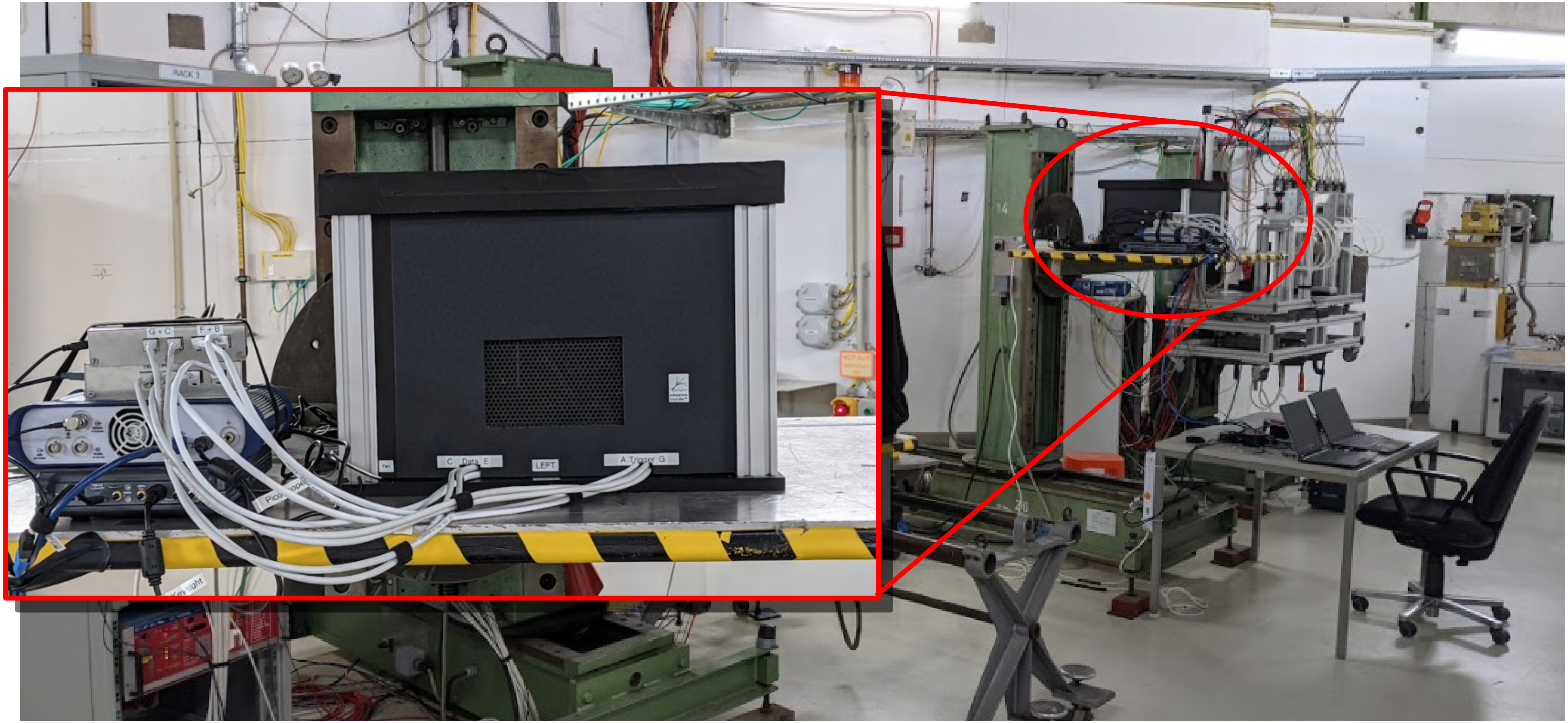
- Scintillator tiles: BC408, 3mm thick
- Different tile sizes (areas *A*) studied



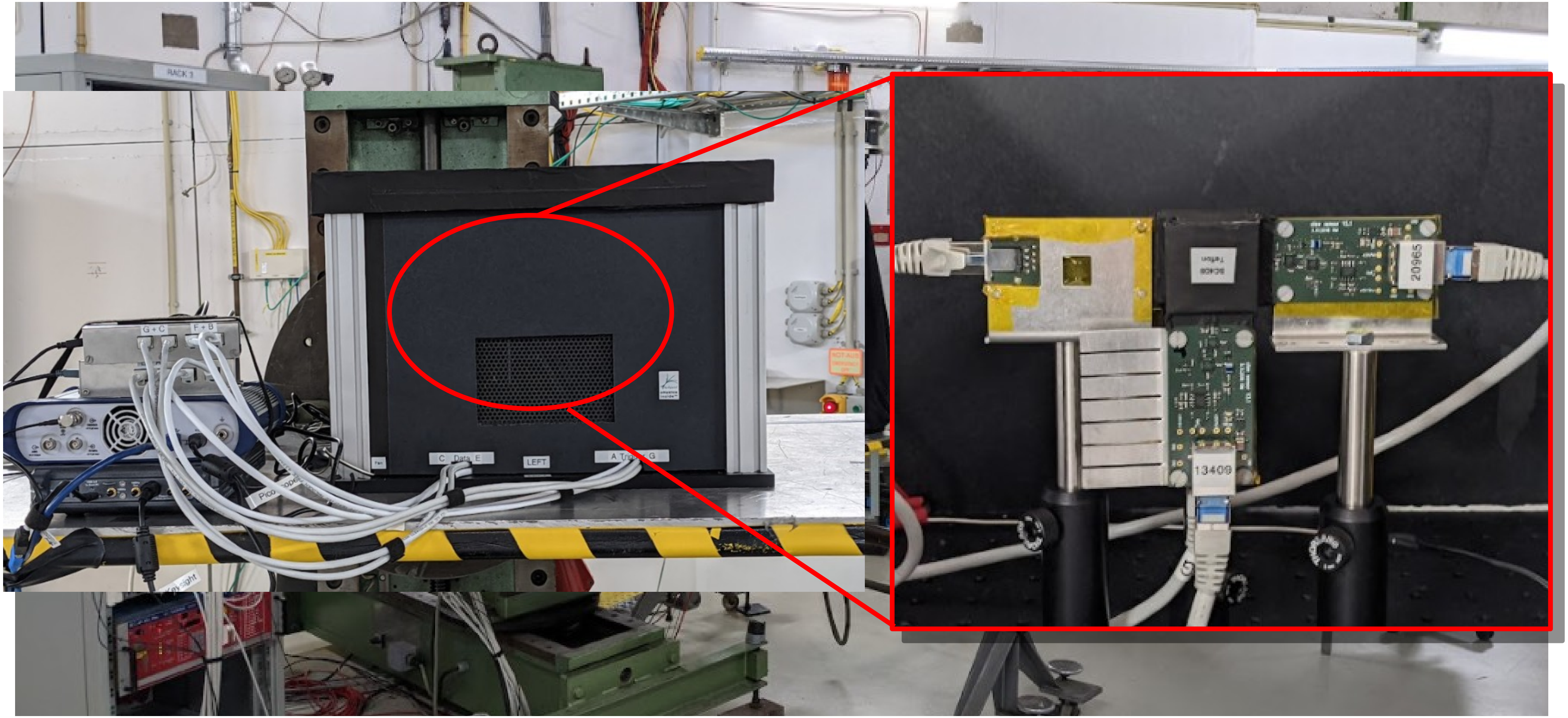
Timing Setup



Timing Setup



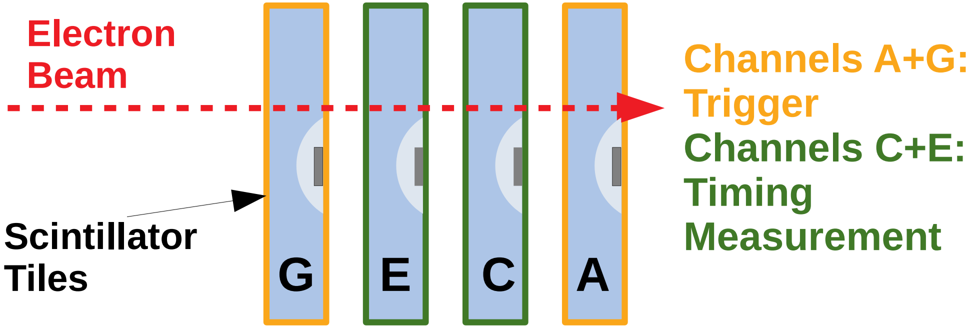
Timing Setup



Test Beam Setup

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



Setup at the Test Beam:

Test Beam Setup

Stack of 4 scintillator tiles:

- CLAWS board
- Hamamatsu S13360-1325PE

↓ **Cat 7 Ethernet cable**

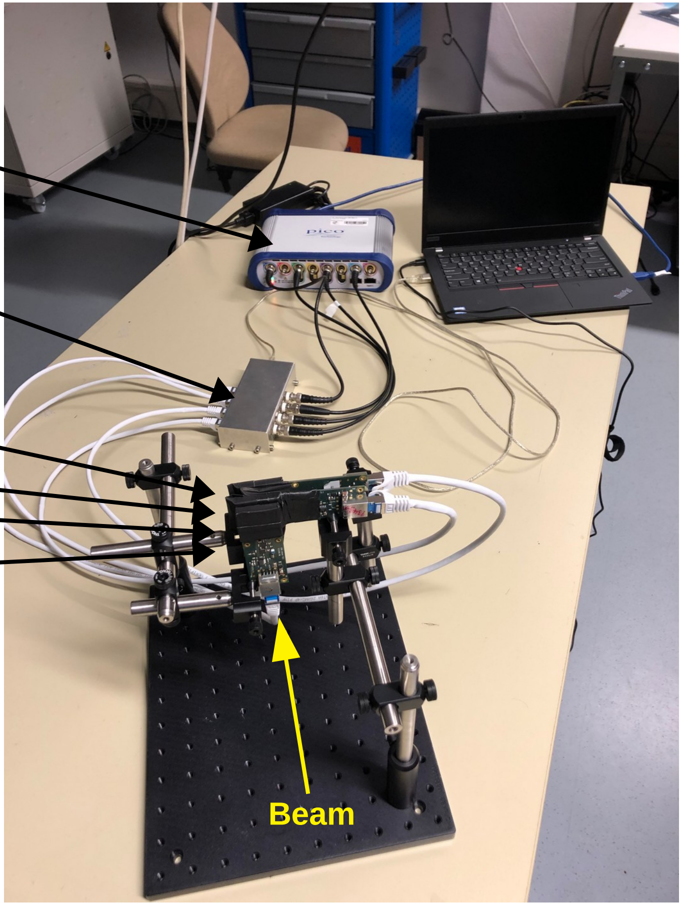
Receiver Box:

- USB controlled power supply
- Split signal and power lines

↓ **BNC**

Picoscope:

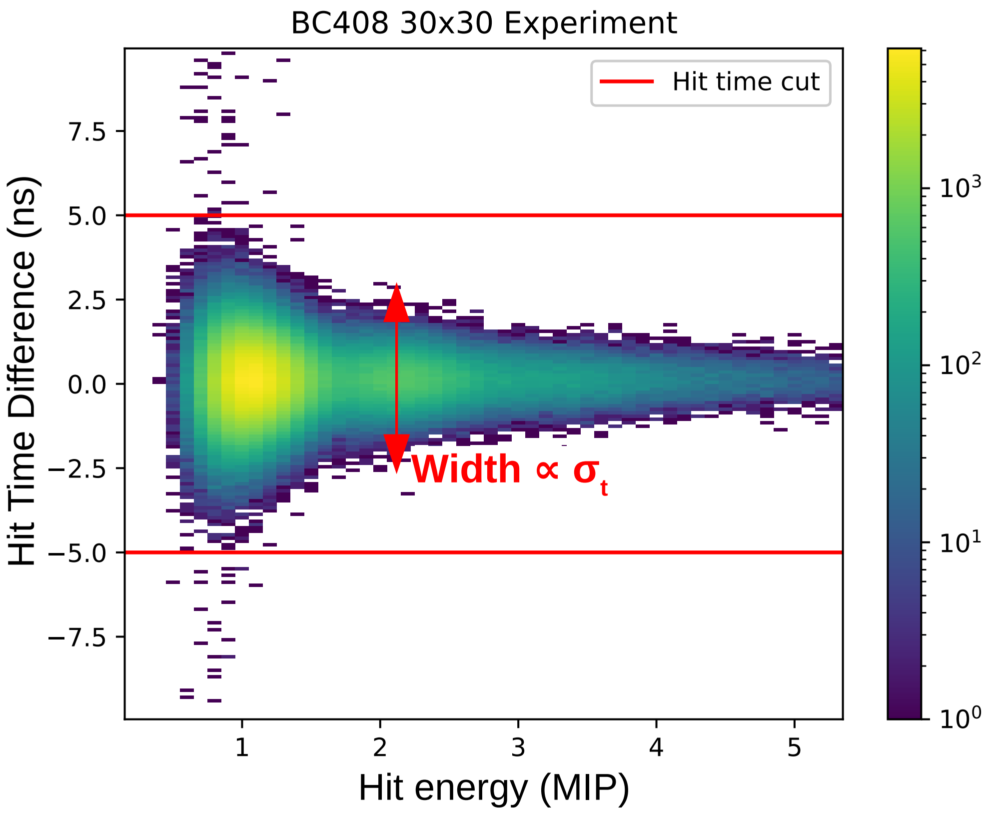
- Up to 2.5 GHz sampling rate on 4 channels
- 300 kHz peak trigger rate
- Save complete analog waveform
- Coincidence Trigger on Channels A and G



Calculating the Time Resolution

- Hit time difference
  → eliminate trigger effects
- Time resolution: **width** of the hit time distribution, divided by √2
- Time Resolution depends on energy deposition
- Mostly a „stochastic“ process

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



Energy-Dependent Time Resolution (1)

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

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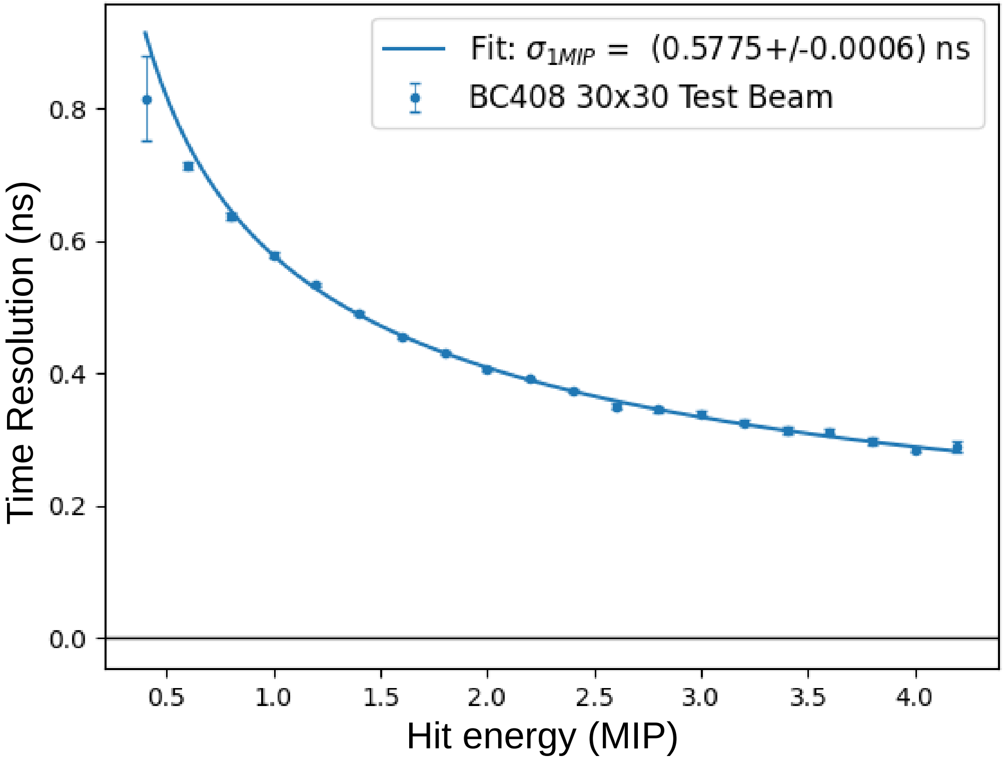
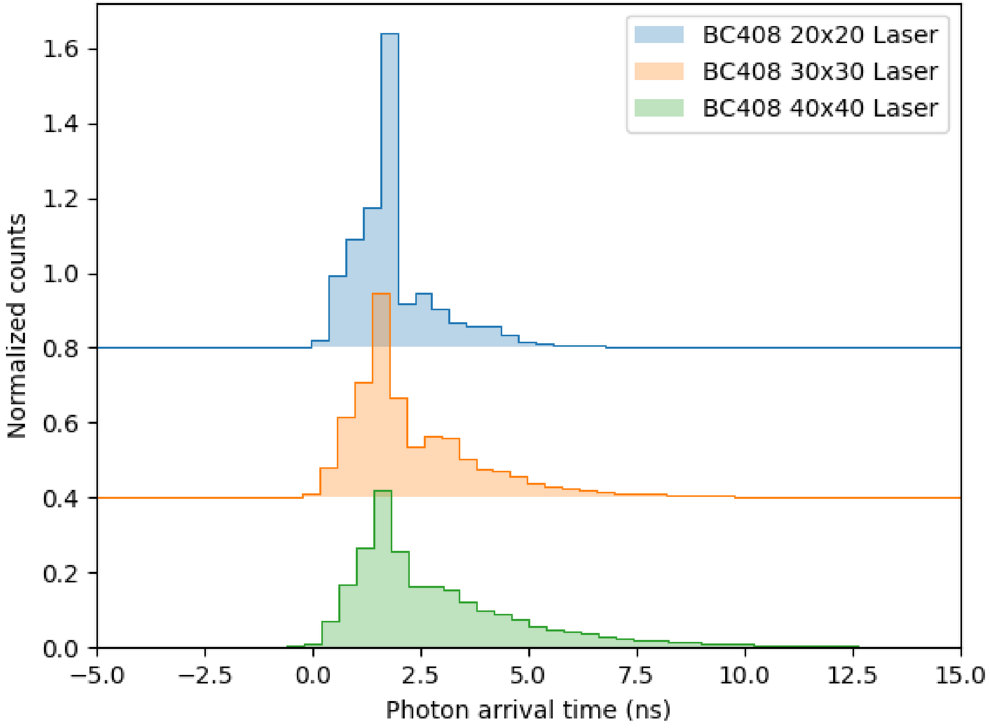


Tile size	Fit value for σ_1
20x20	(382.8 ± 0.3) ps
30x30	(577.5 ± 0.6) ps
40x40	(700.7 ± 0.8) ps

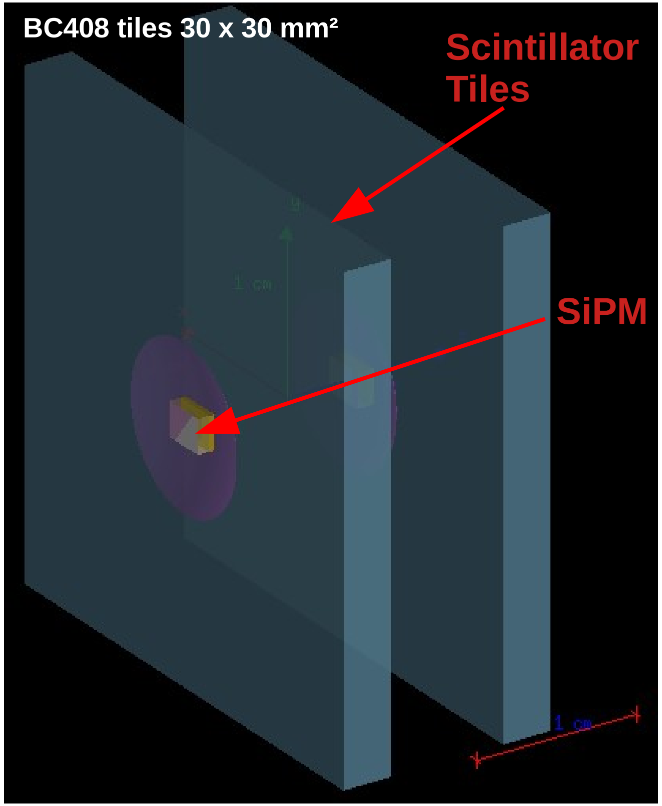
Additional Measurements

- Main experimental component: Laser system to probe light collection and hardware response
- Findings:
  - CLAWS hardware is significantly faster than other signal components
  - Test beam observations can be described in terms of scintillation and light collection
  - Time structure of the light collection depends on the scintillator tile size



Geant 4 Simulations

- Two scintillator tiles → hit time difference
- No trigger tiles since we know when the particle arrives
- Optical photons are tracked until they reach the SiPM
- Waveforms are generated from photon hit times and are analyzed in the same way as measurements
- Test beam as well as additional measurements delivered important inputs for the simulation



Energy-Dependent Time Resolution (1)

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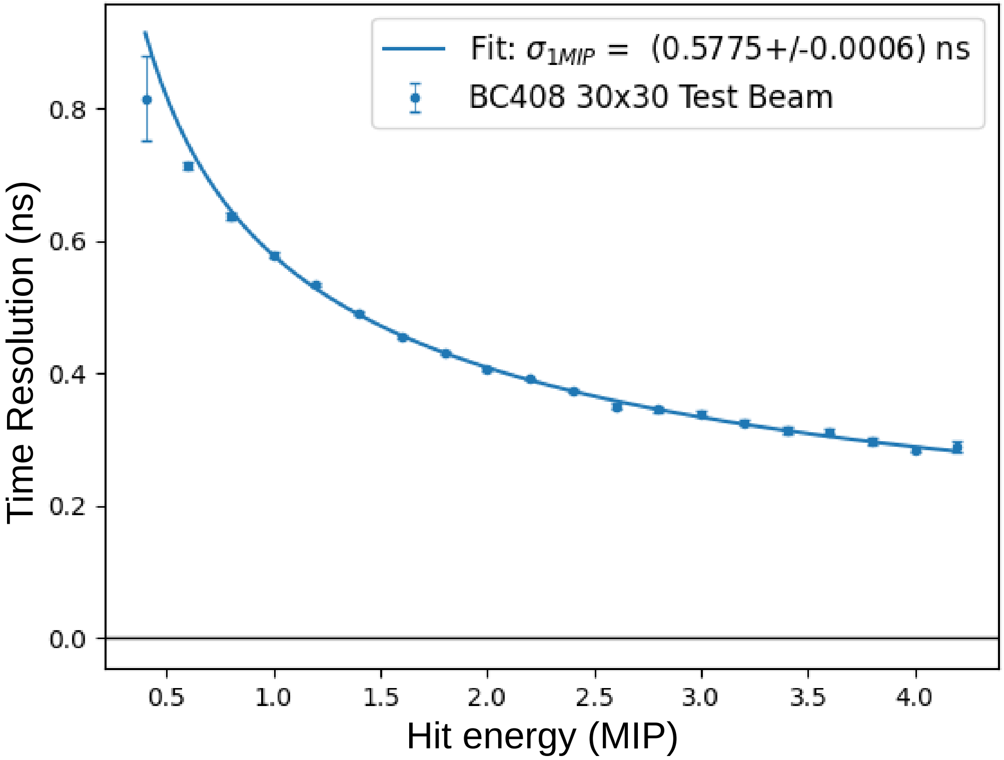


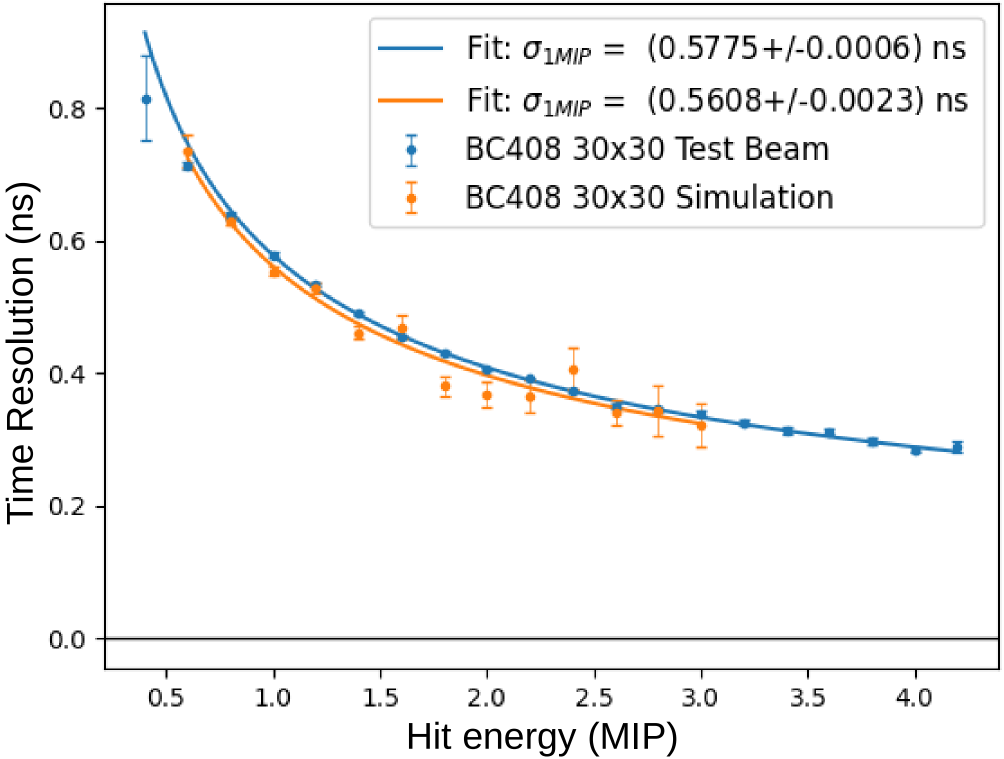
Energy-Dependent Time Resolution (2)

- 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	Measured 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

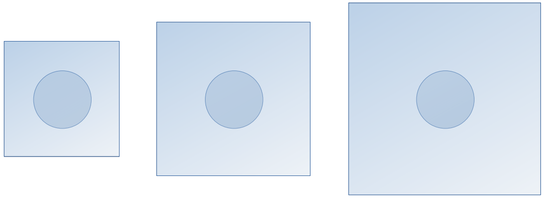


→ Let‘s use the simulations to study more different SiPM-on-tile configurations

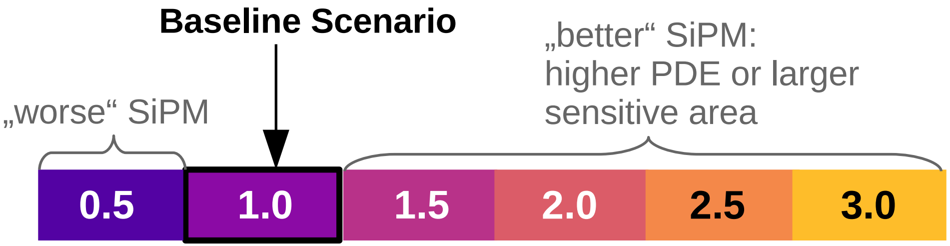
Simulation Study of SiPM-on-tile

Input Parameters:

- Scintillator tile size *A*:

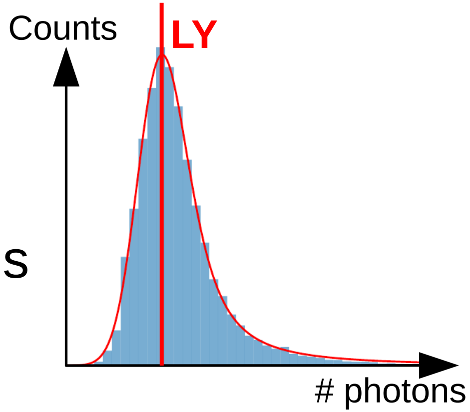


- SiPM photon detection capabilities:
  rPDE = detection efficiency relative to measured case



Output Variables:

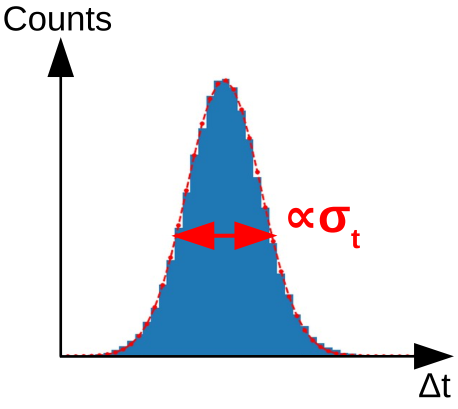
- Light Yield:
  Most probable number of photons for a MIP



- Time Resolution:
  ~ width of hit time difference Δt:

$$\sigma_t = \frac{\sigma(\Delta t)}{\sqrt{2}}$$

(in this study, σ_t is given for the MIP spectrum)

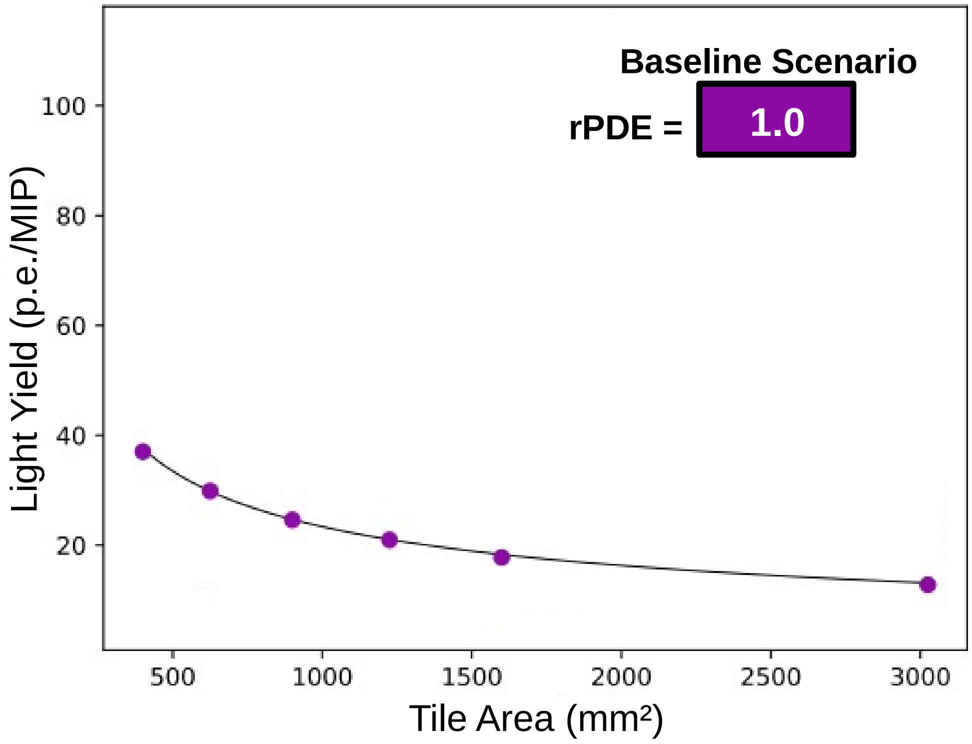


Light Yield

- Finding: $LY \propto A^{k_1}$

Exponents k	
k_1	-0.519 ± 0.004

- Exponent agrees with other experimental studies of BC408
- Exponent k_1 should depend on the light attenuation length of the scintillator.

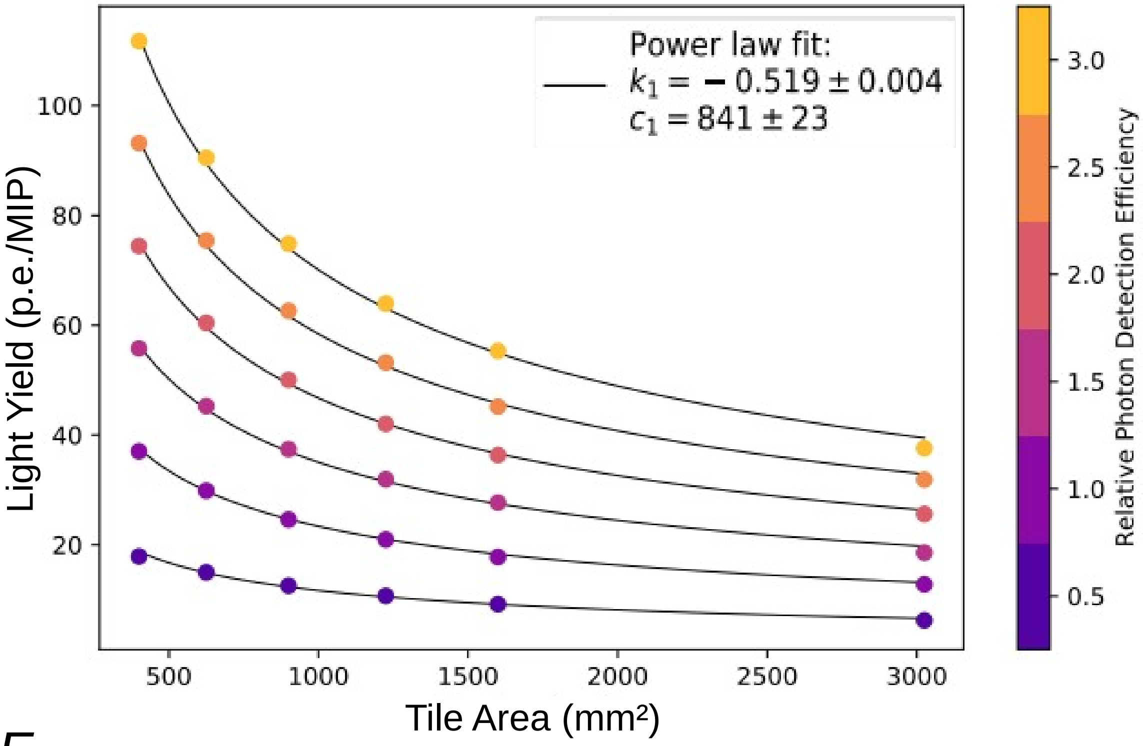


Light Yield

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

Exponents k	
k_1	-0.519 ± 0.004

- Exponent agrees with other experimental studies of BC408
- Exponent k_1 should depend on the light attenuation length of the scintillator.
- Light yield scales linear with *rPDE*

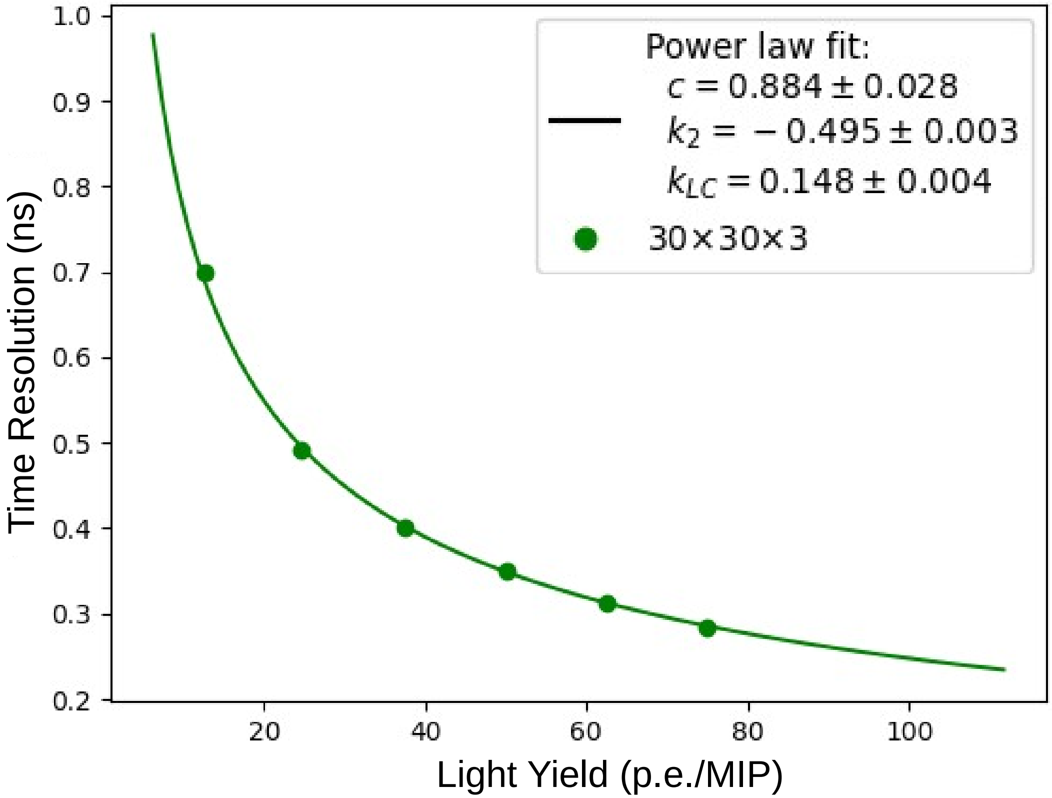


Time Resolution

- Finding: $\sigma_t \propto LY^{k_2}$

Exponents k	
k_2	-0.495 ± 0.003

- Exponent k_2 corresponds to $1/\sqrt{n_\gamma}$
  → photon counting

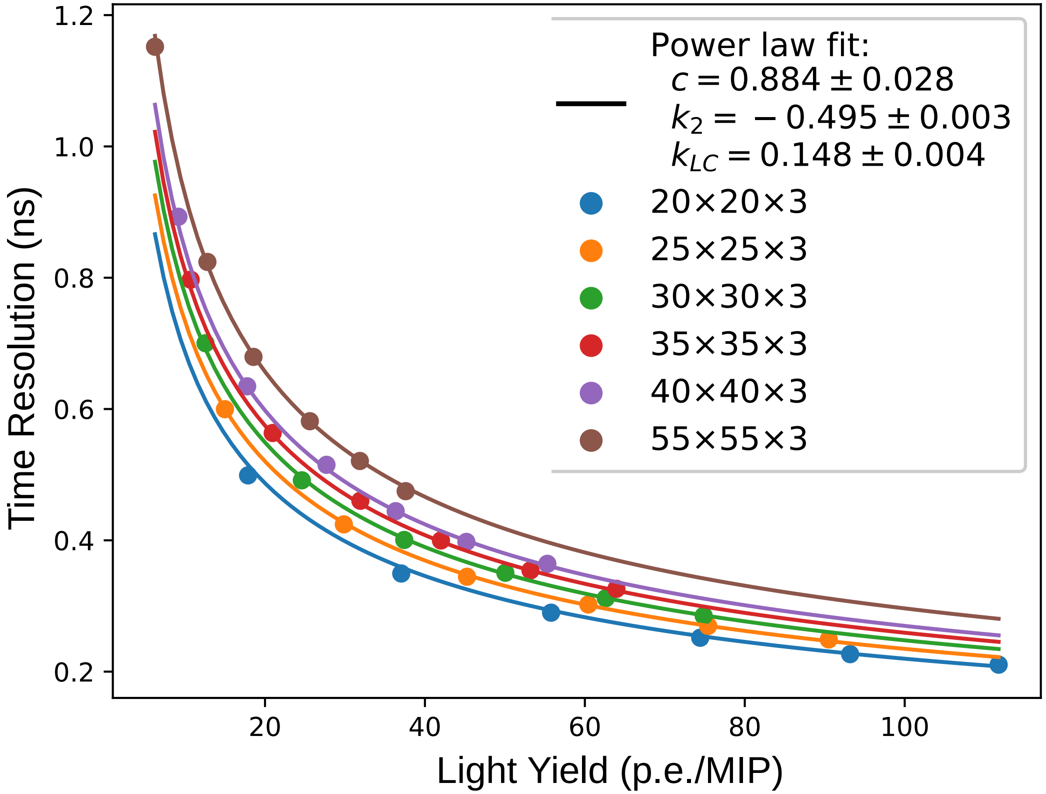


Time Resolution

- 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 structure of light collection
  → smaller tiles respond faster



SiPM-on-Tile Model

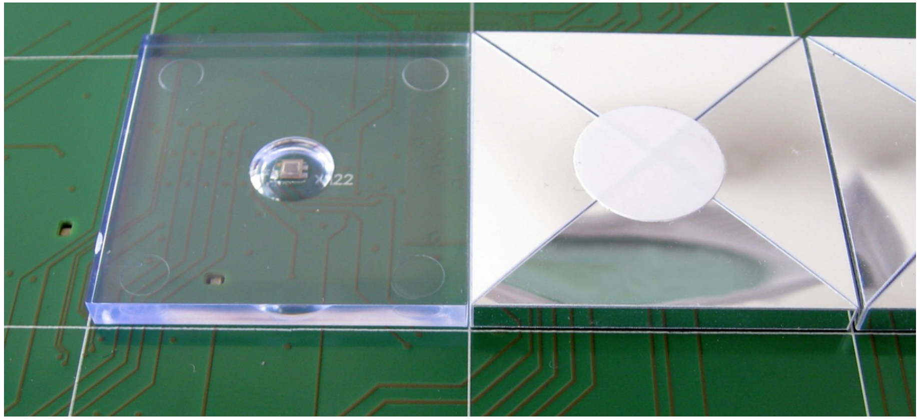
Set of two equations connects

- 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



→ Input for calorimeter design

SiPM-on-Tile Model

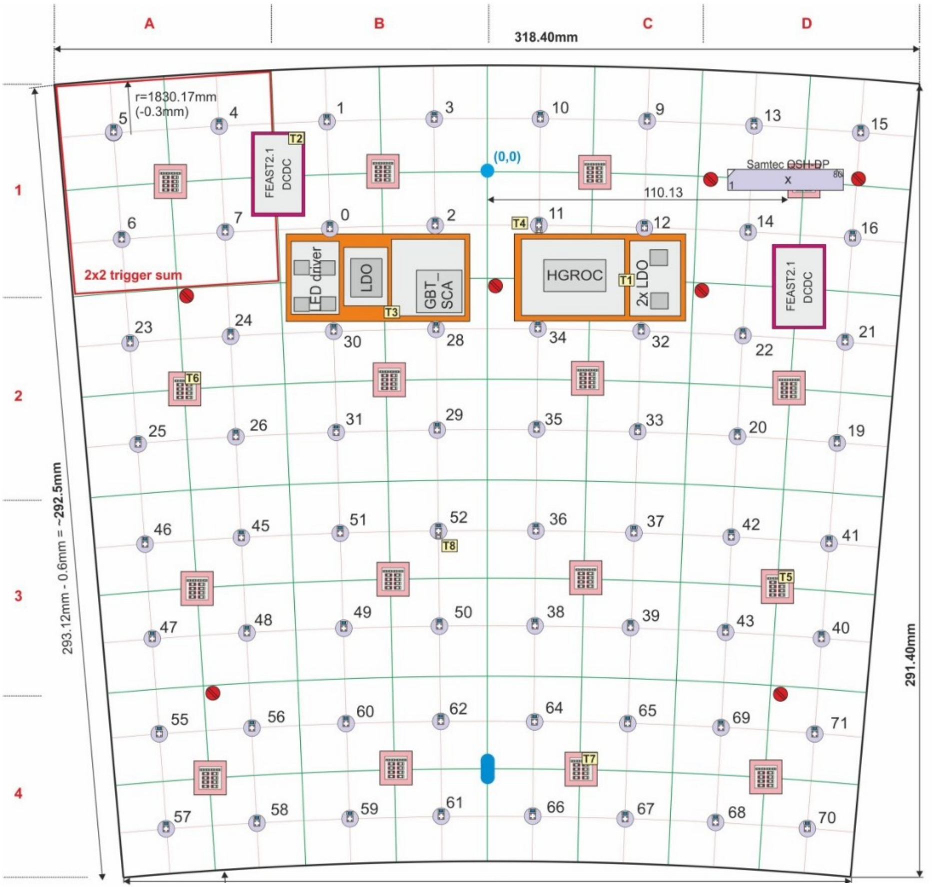
Set of two equations connects

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

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

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

Application example: CMS HGCAL endcap
→ many different scintillator tile sizes



[M. Reinecke, AHCAL main meeting December 2019]

Conclusion and Outlook

Conclusion and Outlook

Achievements:

- Simple and modular measurement setup
- Two successful test beam weeks
- 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:

- Follow-up project: Test beam and simulation study with scintillator strips
- Extend analysis to different plastic scintillator materials
  - Study different time constants
  - Light attenuation length should change k_1
- Study optical properties of scintillator tiles → account for manufacturing imperfections

Backup Slides

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

Calculating the Time Resolution (1)

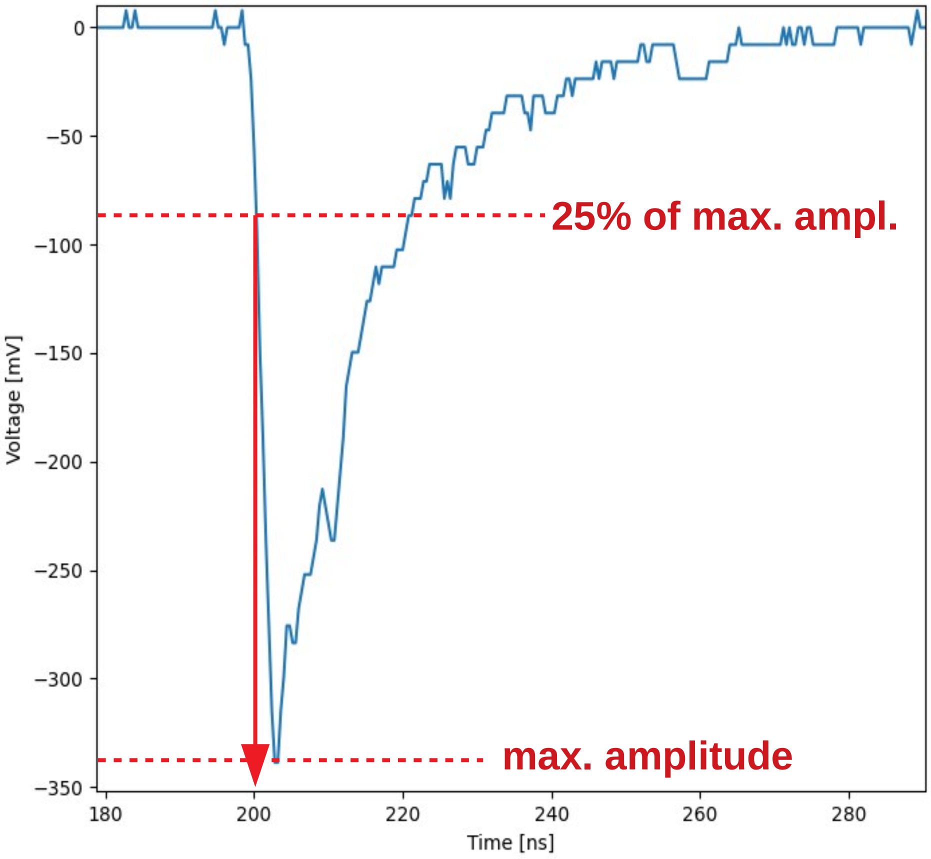
Constant Fraction Discrimination:

- 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

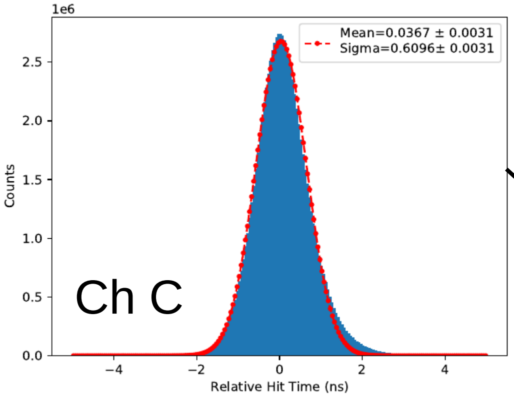
Leading Edge Method:

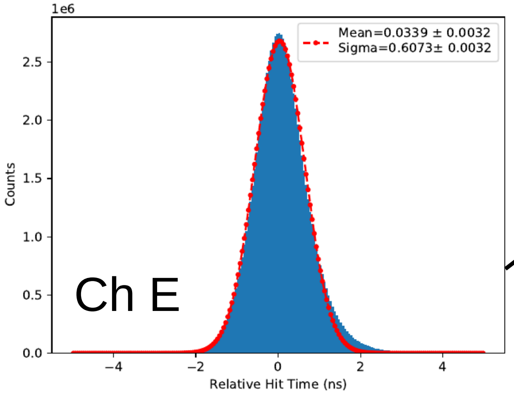
- Set threshold to fixed voltage

Typical SiPM response

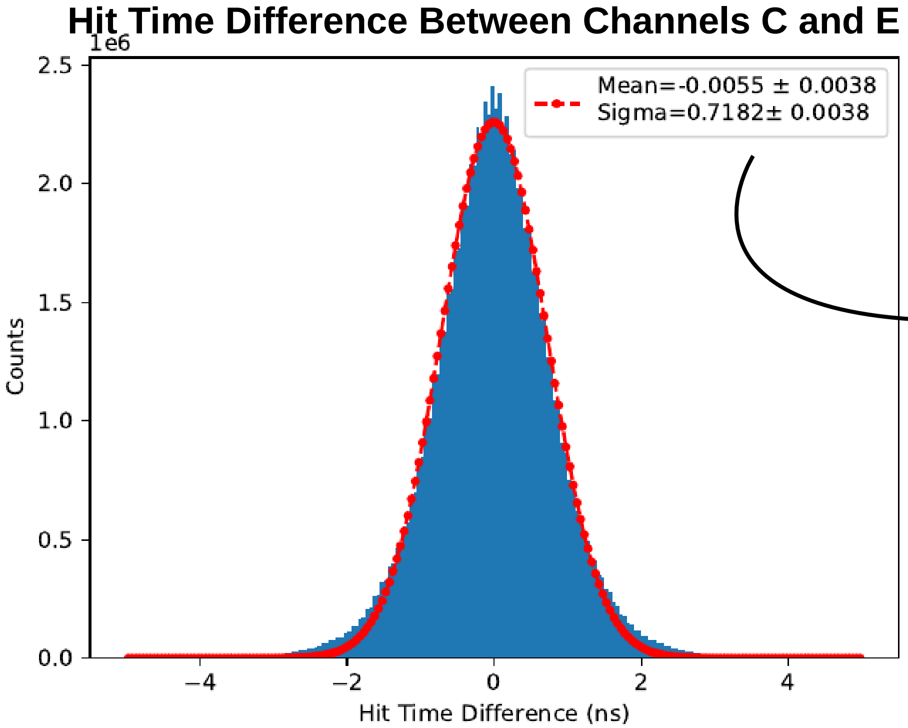


Calculating the Hit Time Difference





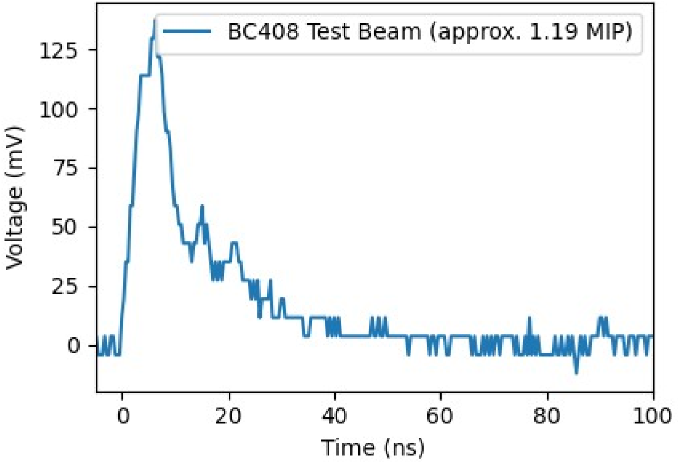
Channels C and E give two independent hit times
→ subtract to eliminate trigger resolution effects



Single Channel
Time Resolution:

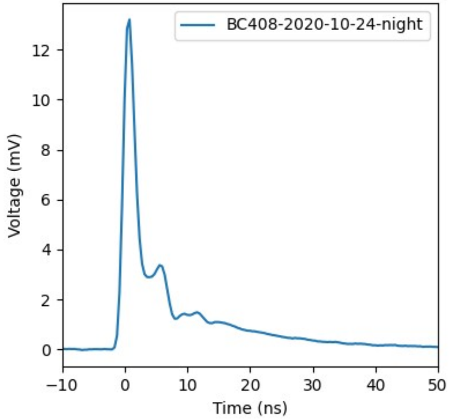
0.718/√2 = 0.507 ns
for AHCAL tiles
(30x30 mm²)

Waveform Decomposition



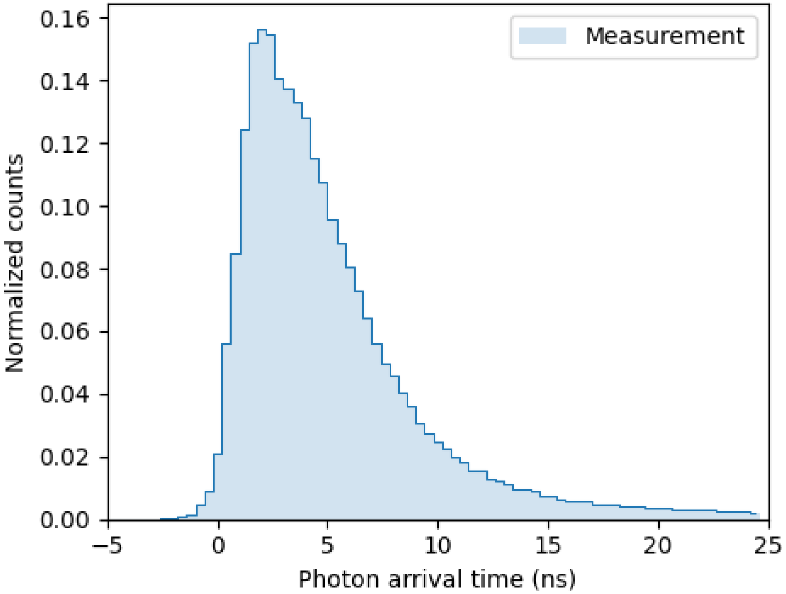
SiPM response for each measured event.

minus



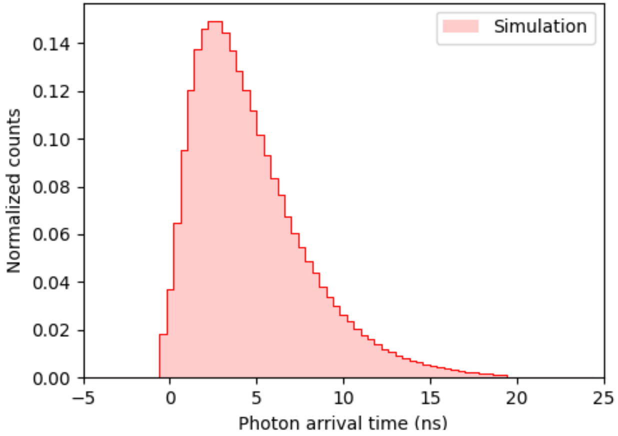
Average 1 p.e. waveform from a measurement

Subtract 1p.e. waveforms



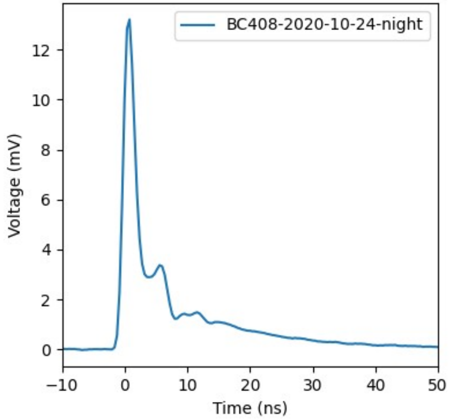
Extrapolate photon arrival times at the SiPM

Simulation: Waveform Generation



Photon arrival times from Geant4 simulations

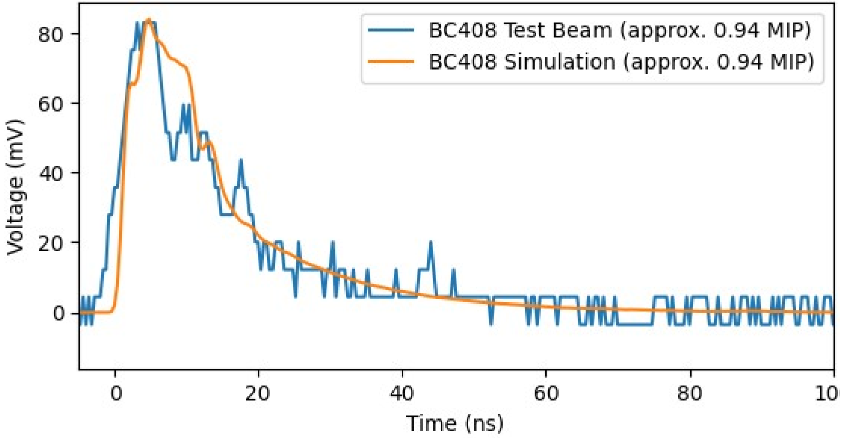
plus



Average 1 p.e. waveform from a measurement

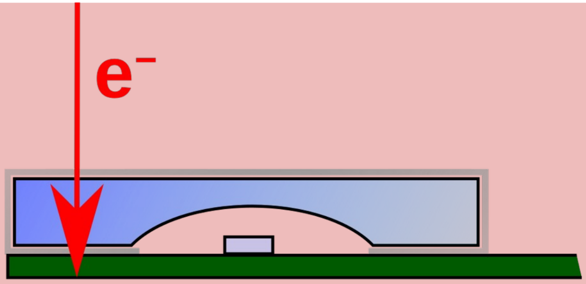
Stack 1p.e. waveforms

SiPM response for each simulated event.



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

Additional Measurements (1)



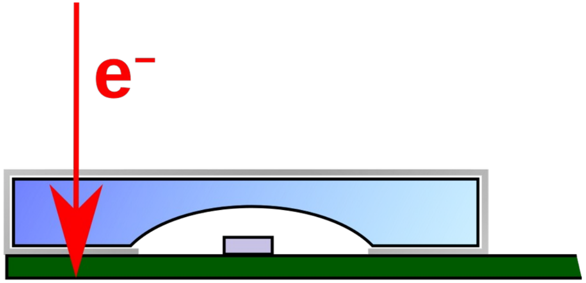
Full System Test Beam Measurements

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

2. Light collection and transport to SiPM

3. SiPM creates electrical signal

Additional Measurements (1)



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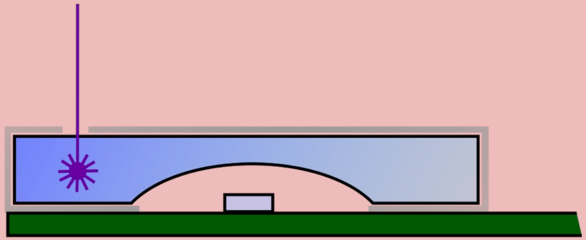

Inject pulsed laser beam into scintillator tile

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

2. Light collection and transport to SiPM

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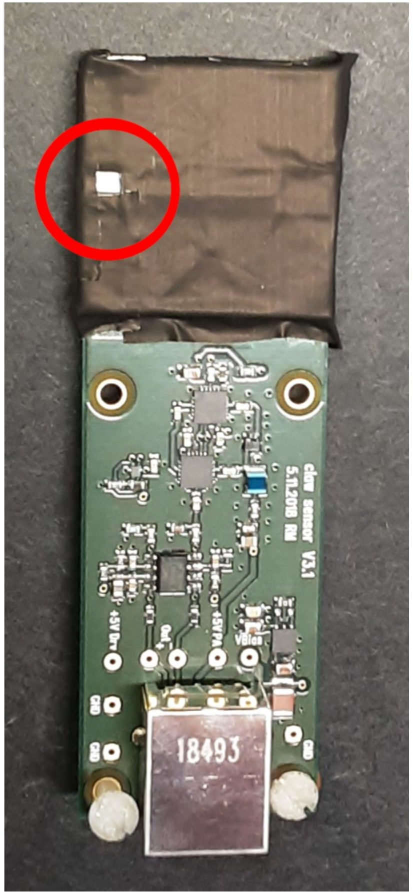

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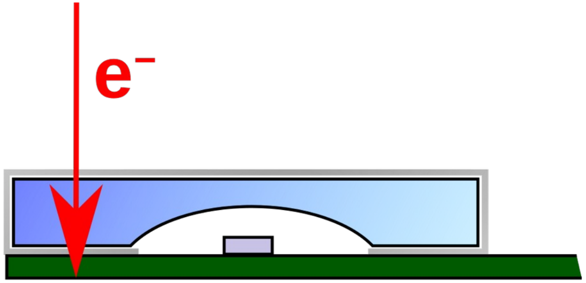

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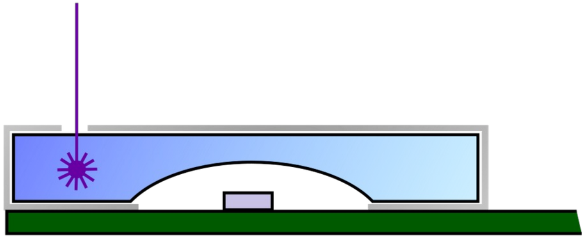

Inject pulsed laser beam into scintillator tile

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

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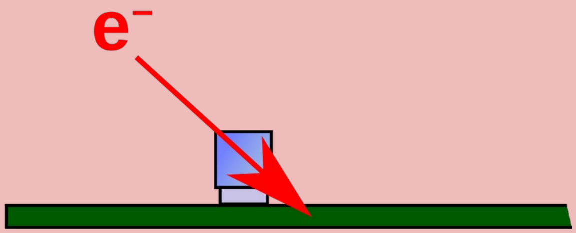
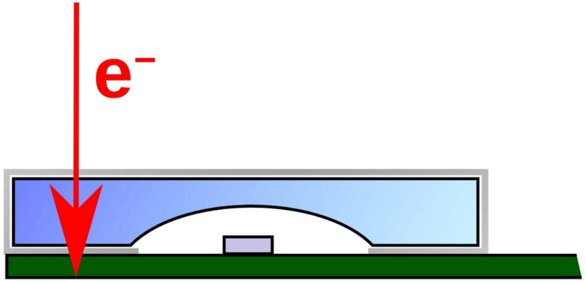
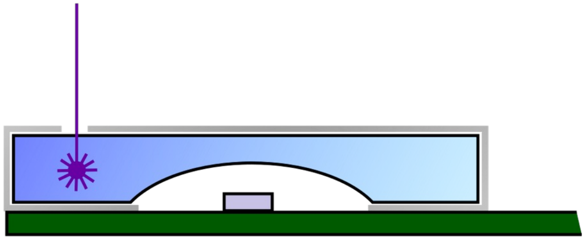


Emission measurements with small scintillators

Additional Measurements (1)



Full System Test Beam Measurements

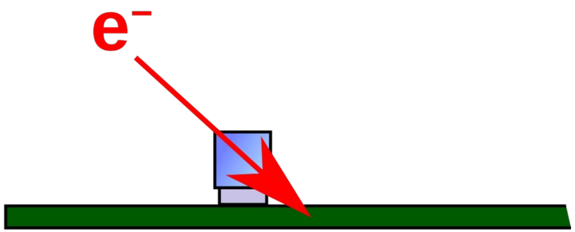


Inject pulsed laser beam into scintillator tile

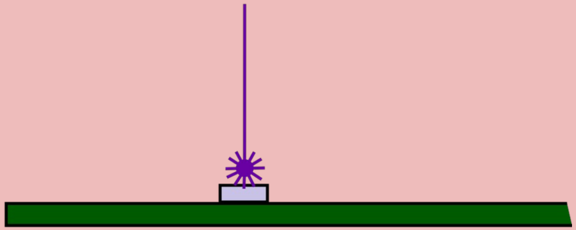
1. Particle deposits energy in the scintillator, emission of light

2. Light collection and transport to SiPM

3. SiPM creates electrical signal



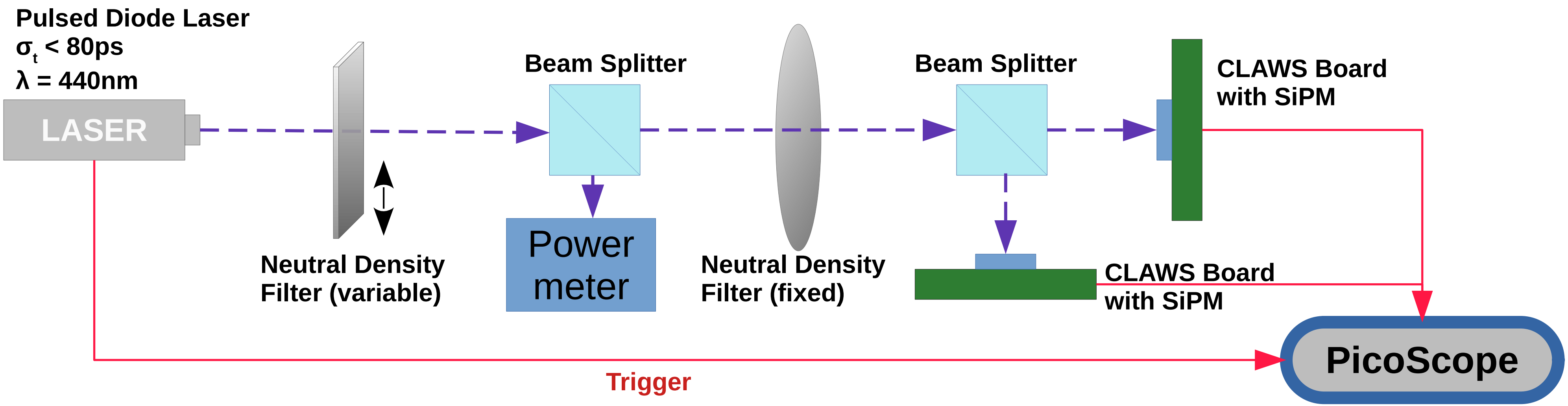
Emission measurements with small scintillators



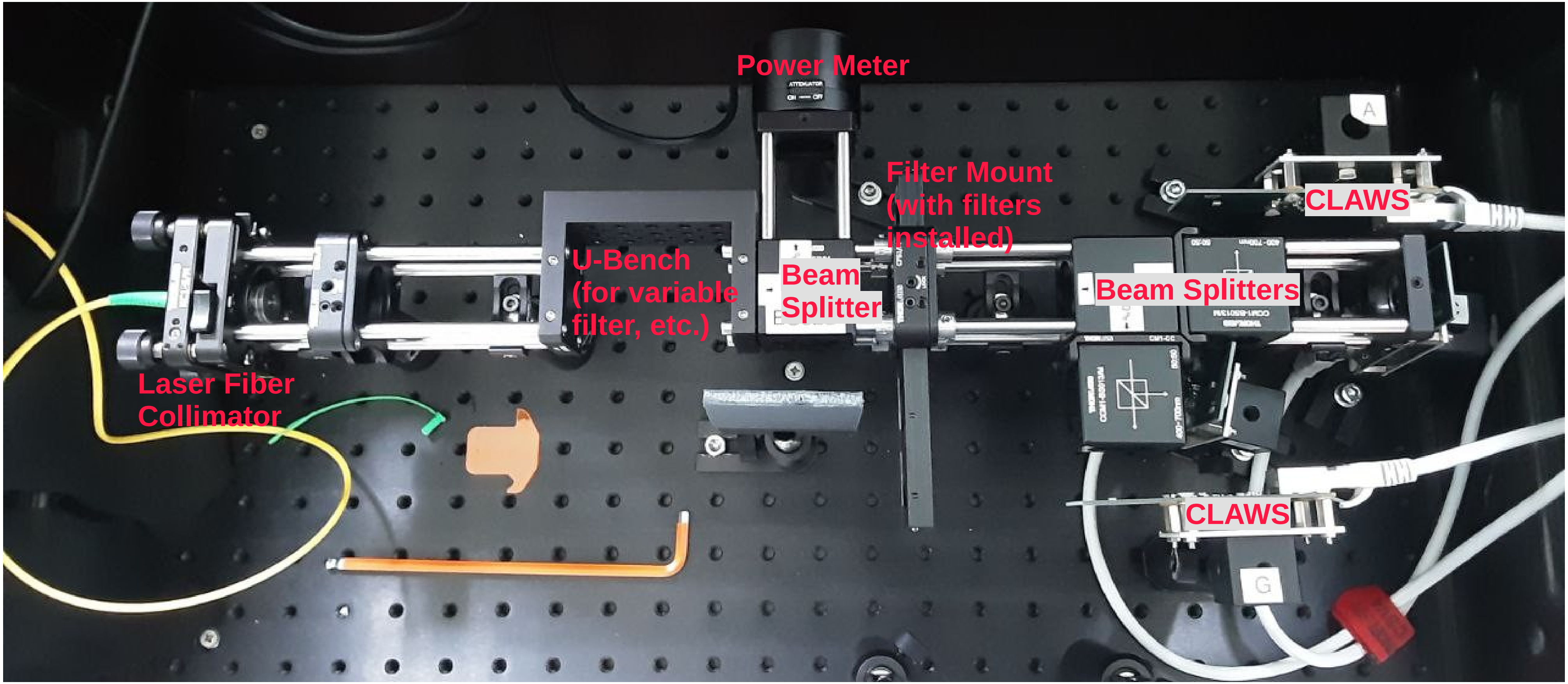
Induce signal on SiPM with laser pulses

Laser Setup

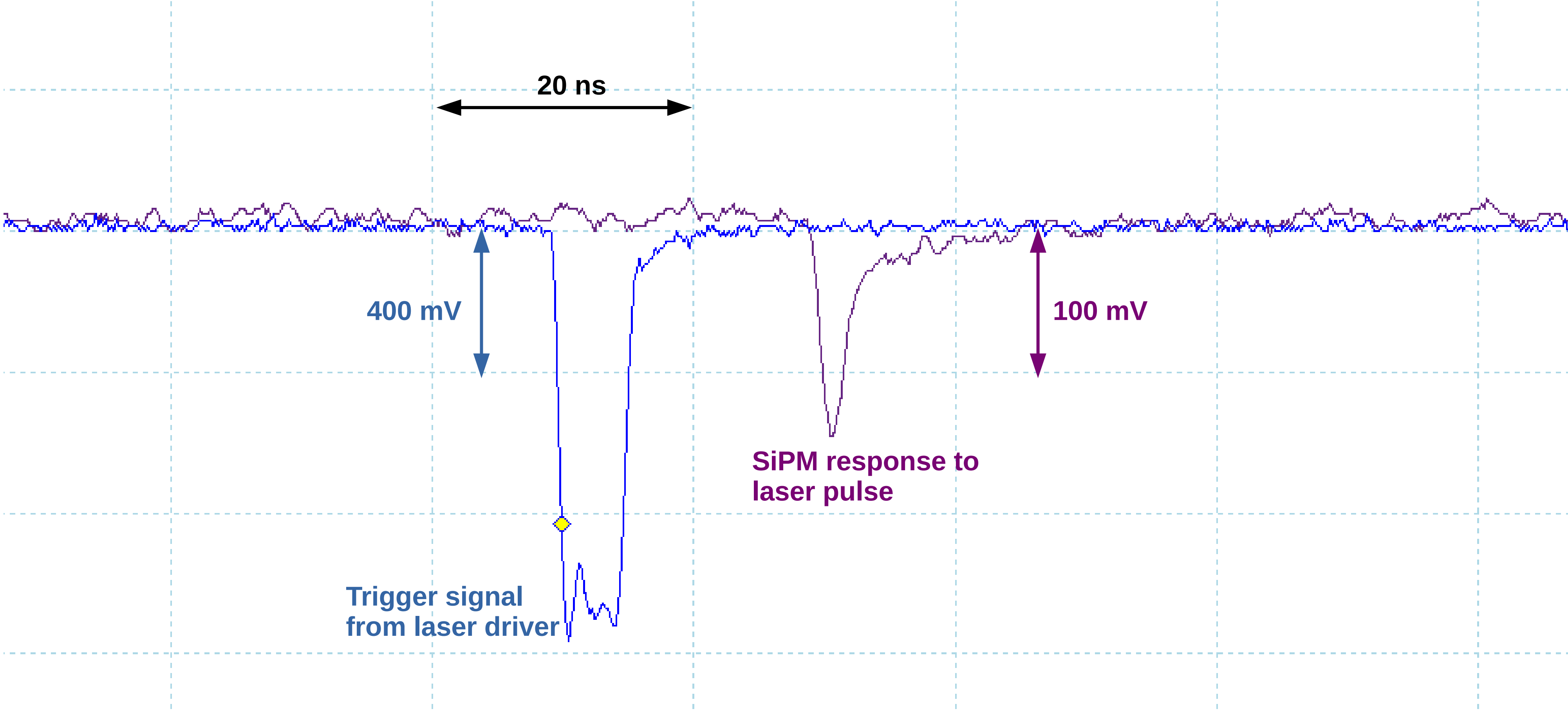
- Idea: Use laser pulses as alternative light source
  - Probe the light collection without effects from the scintillators
  - Measure the SiPM response to short light pulses → probe hardware effects



Laser Setup: Inside the Dark Box

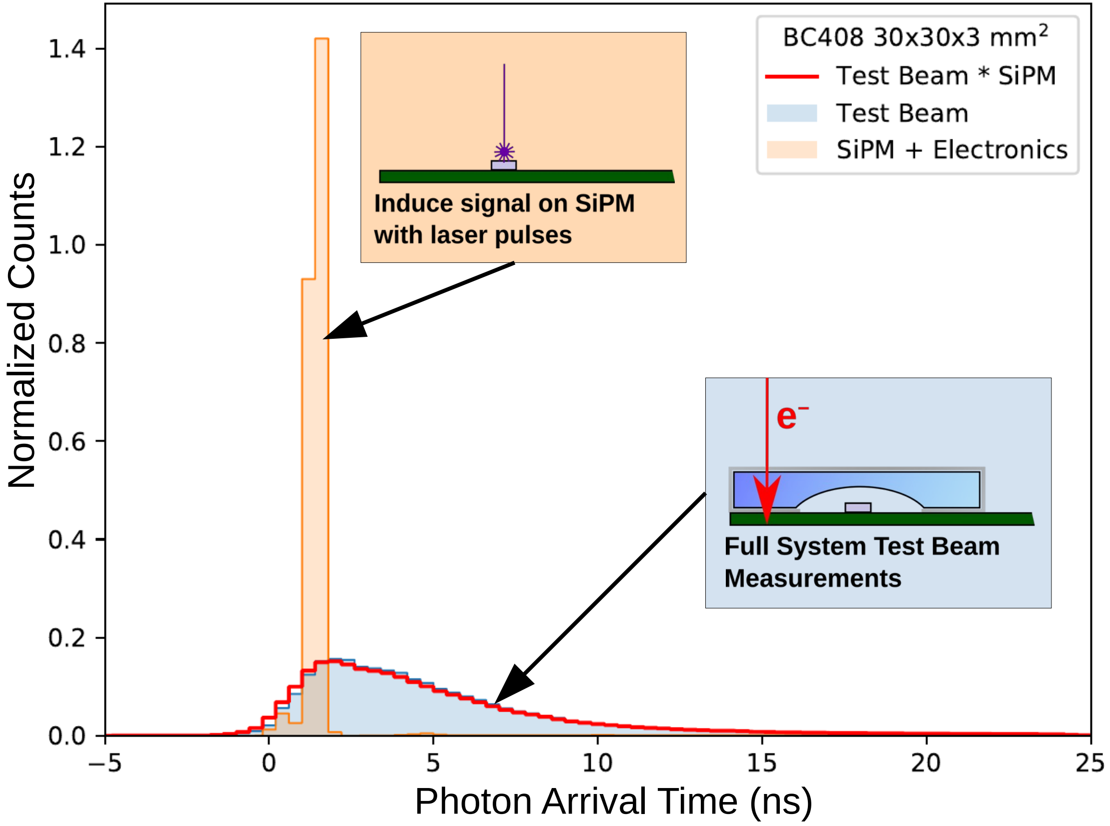


First Laser Event

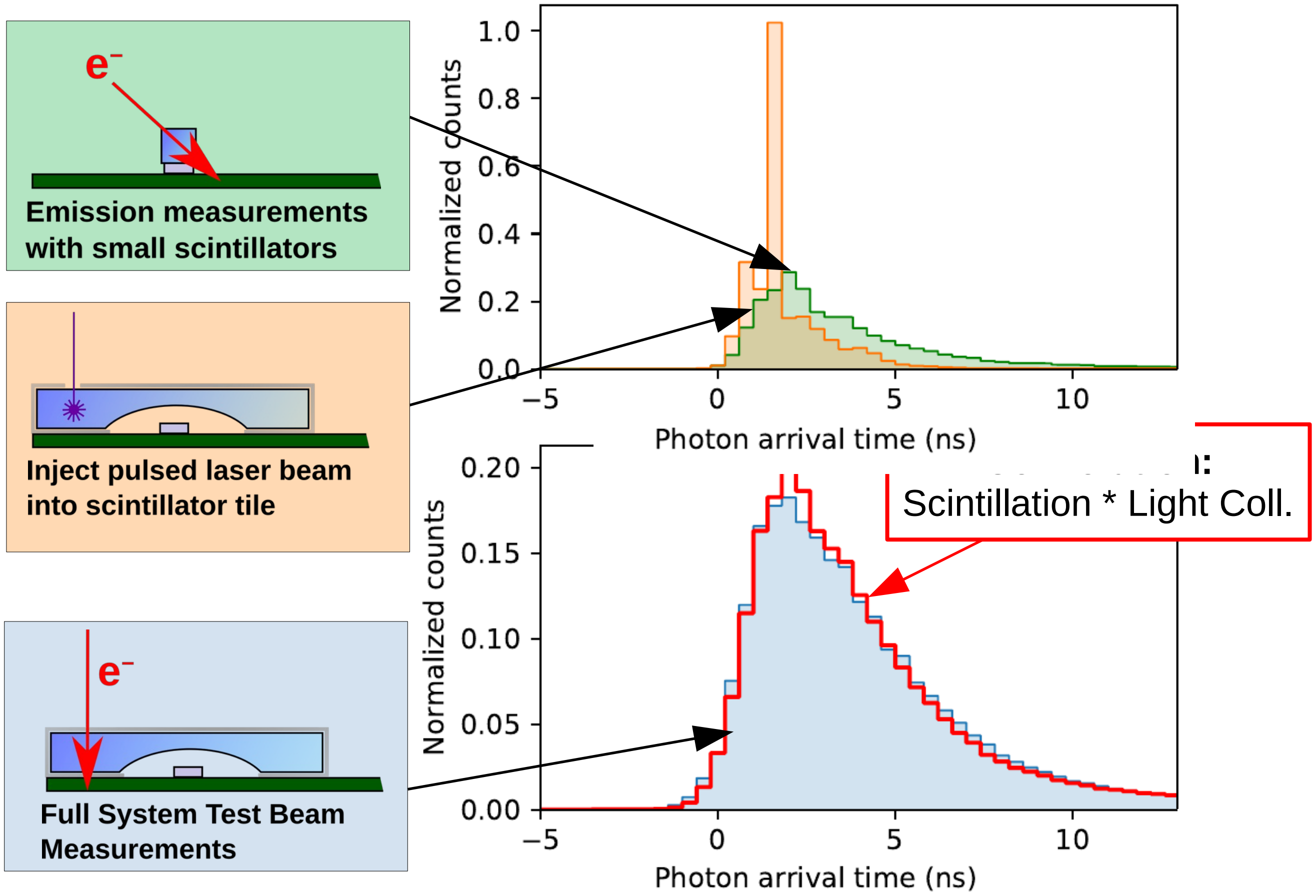


Findings: Fast Hardware Response

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



Findings: Scintillation + Light Collection



Time Structure of Light Collection

- Tile larger → photon time distribution broader
- Light collection „takes longer“
- Used to verify Geant4 simulations