Intrinsic Time Resolution of the SiPM-on-Tile Technology

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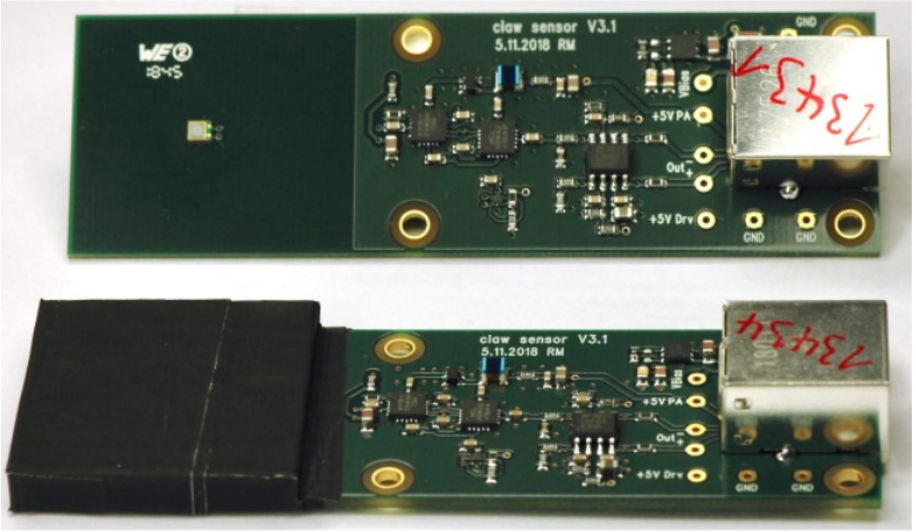
Contribution to the
CALICE Collaboration Meeting

2022-04-22

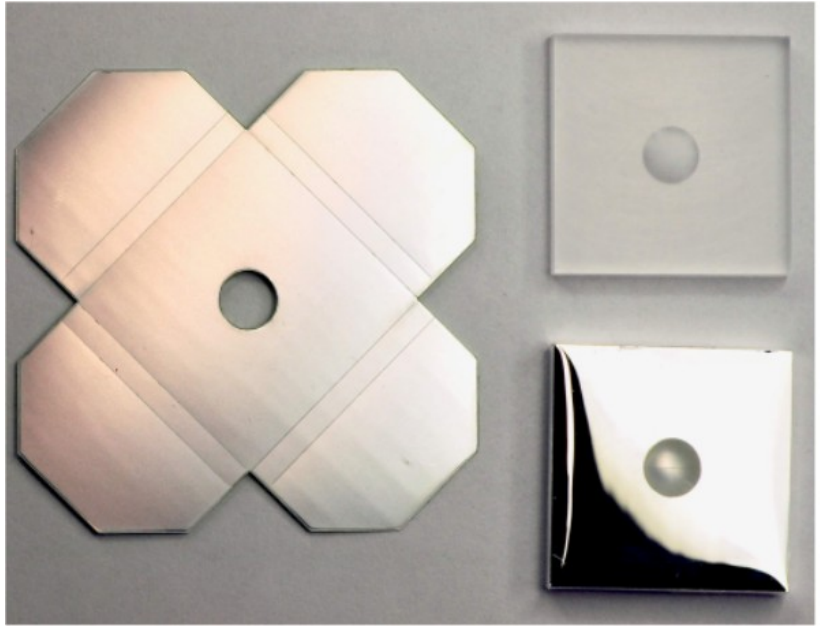
MAX-PLANCK-INSTITUT
FÜR PHYSIK

SiPM-on-Tile Timing Study (STS)

- Hardware for timing study: CLAWS boards
- SiPM: Hamamatsu S13360-1325PE
- Record full analog waveforms



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

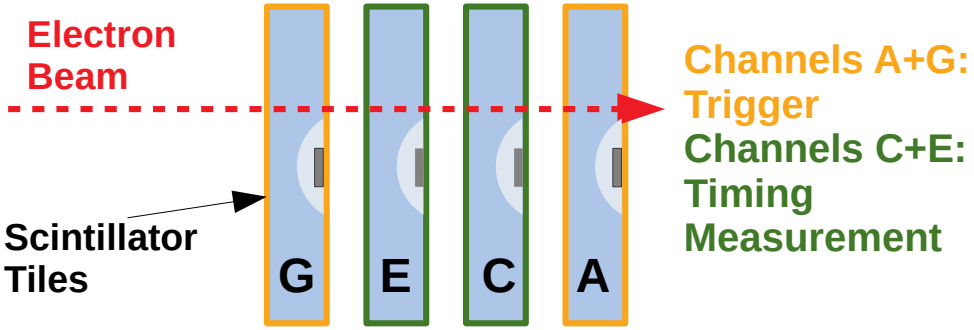


Part 1: Test Beam Measurements

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

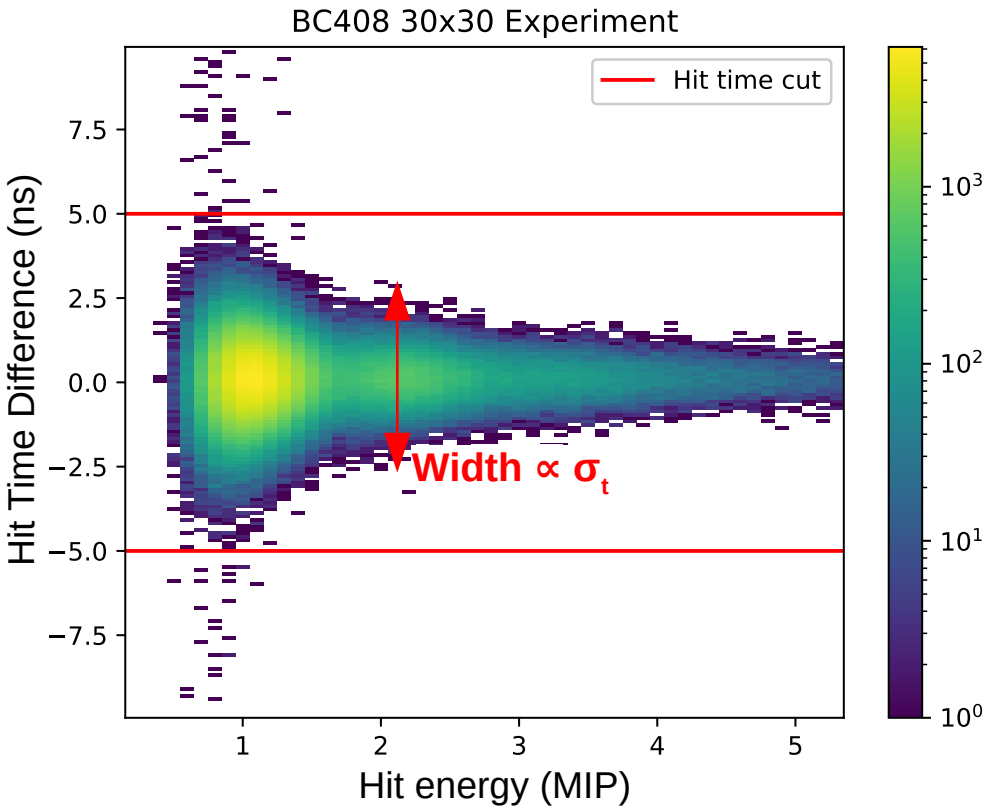


Setup at the Test Beam:

Calculating the Time Resolution

- Hit time difference
  → eliminate trigger effects
- Time resolution: **width** of the hit time distribution, divided by $\sqrt{2}$
- 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:

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

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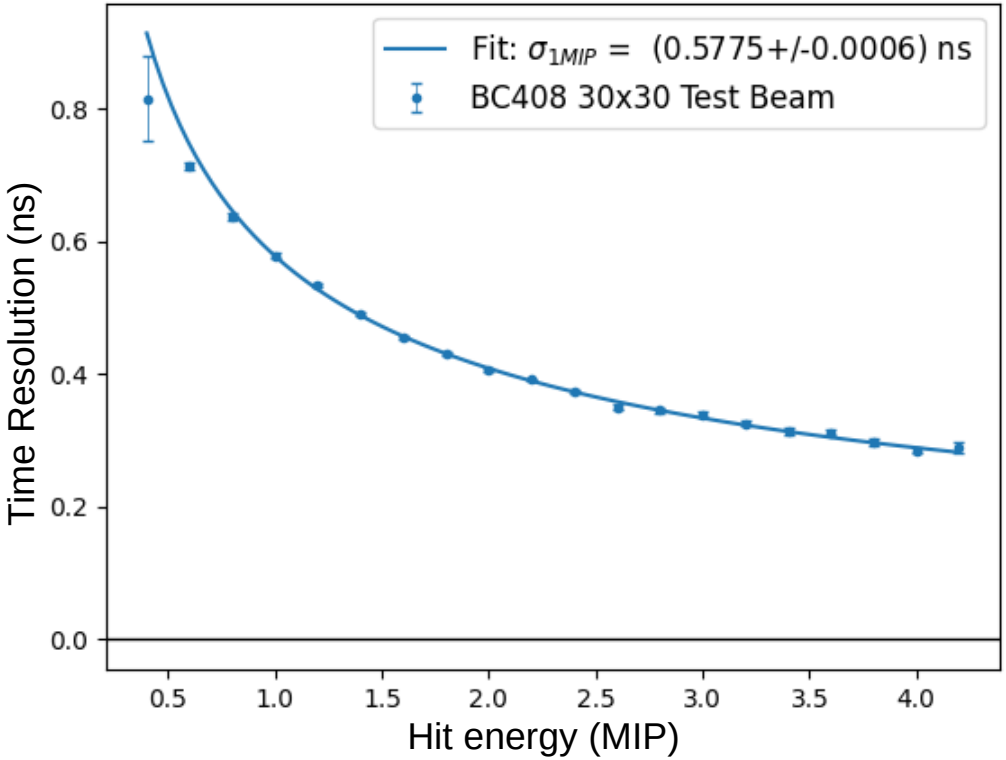
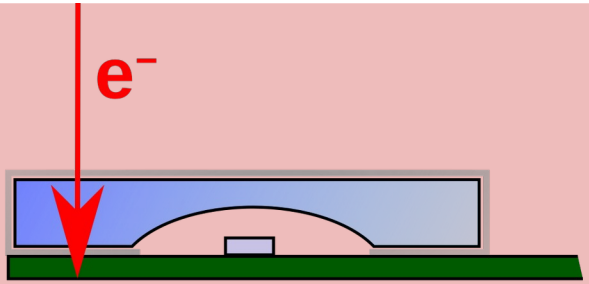
40x40	(700.7 ± 0.8) ps



Part 2: Breaking Down the Signal Creation

How can we disentangle the different factors that contribute to time resolution?

Understanding the Signal Creation



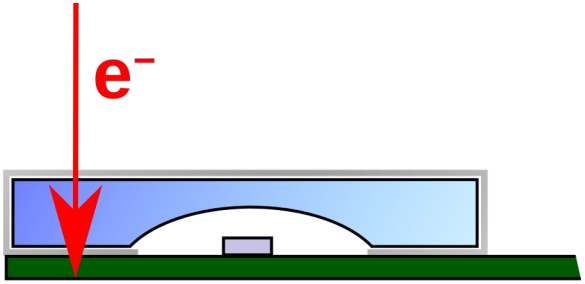
Full System Test Beam Measurements

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

2. Light collection and transport to SiPM

3. SiPM creates electrical signal

Understanding the Signal Creation



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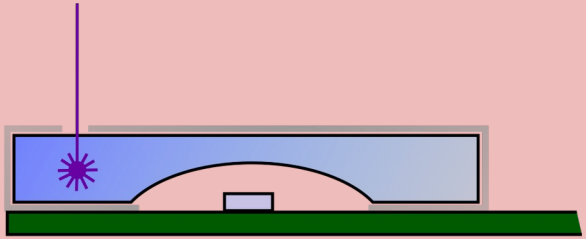

Inject pulsed laser beam into scintillator tile

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

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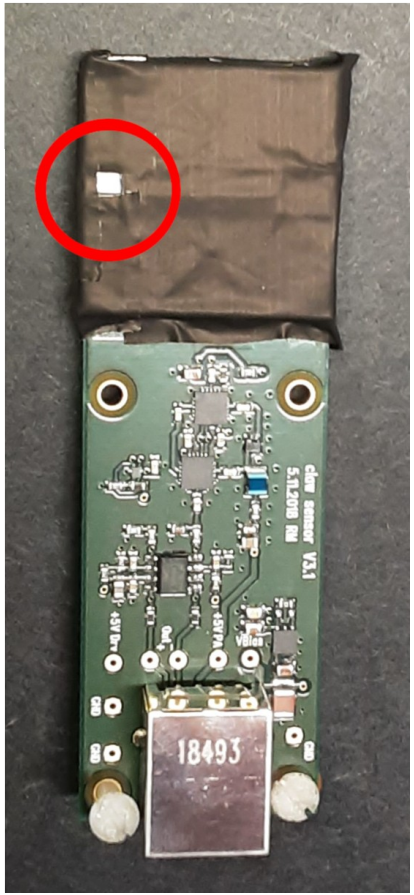
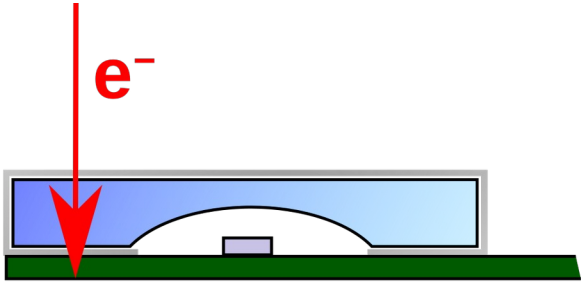


Understanding the Signal Creation



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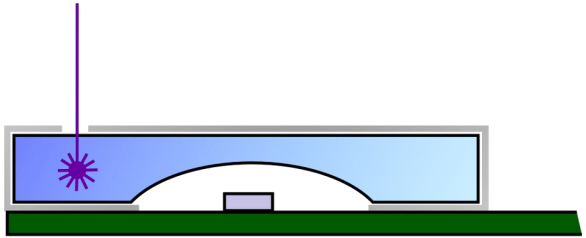

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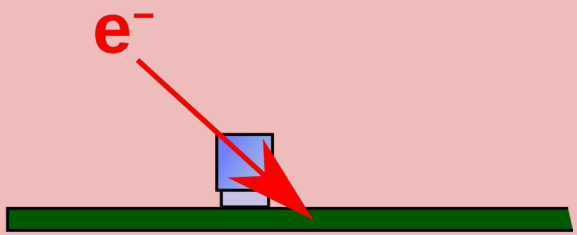
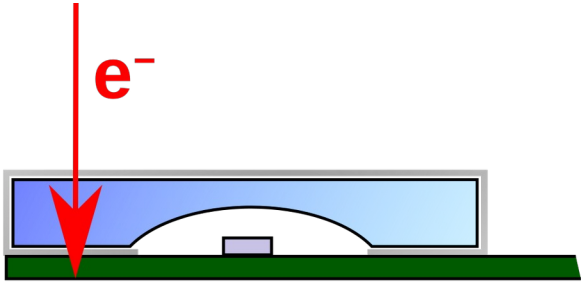


Emission measurements with small scintillators

Understanding the Signal Creation



Full System Test Beam Measurements

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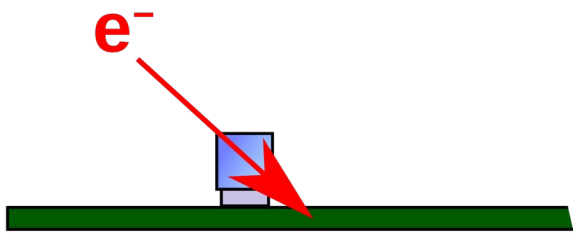
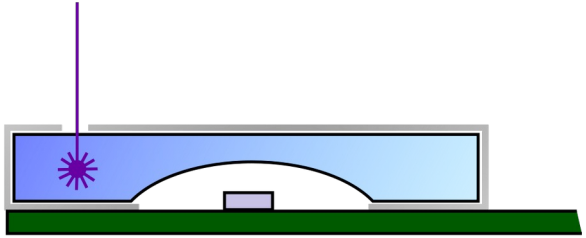
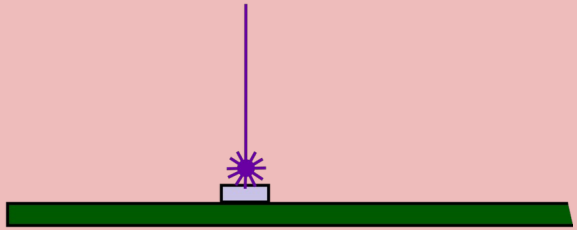


Emission measurements with small scintillators



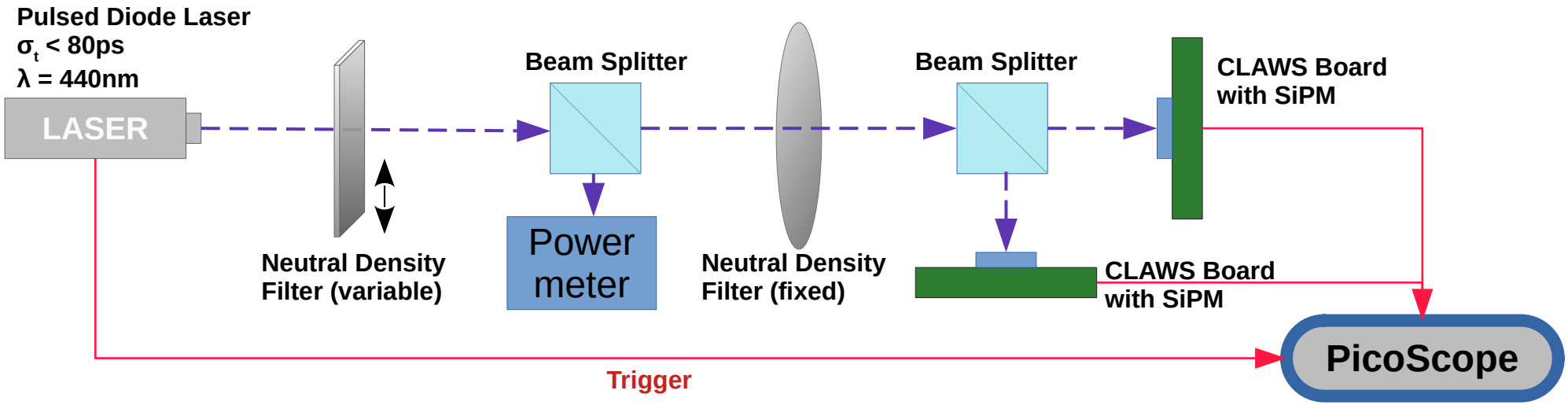
Inject pulsed laser beam into scintillator tile



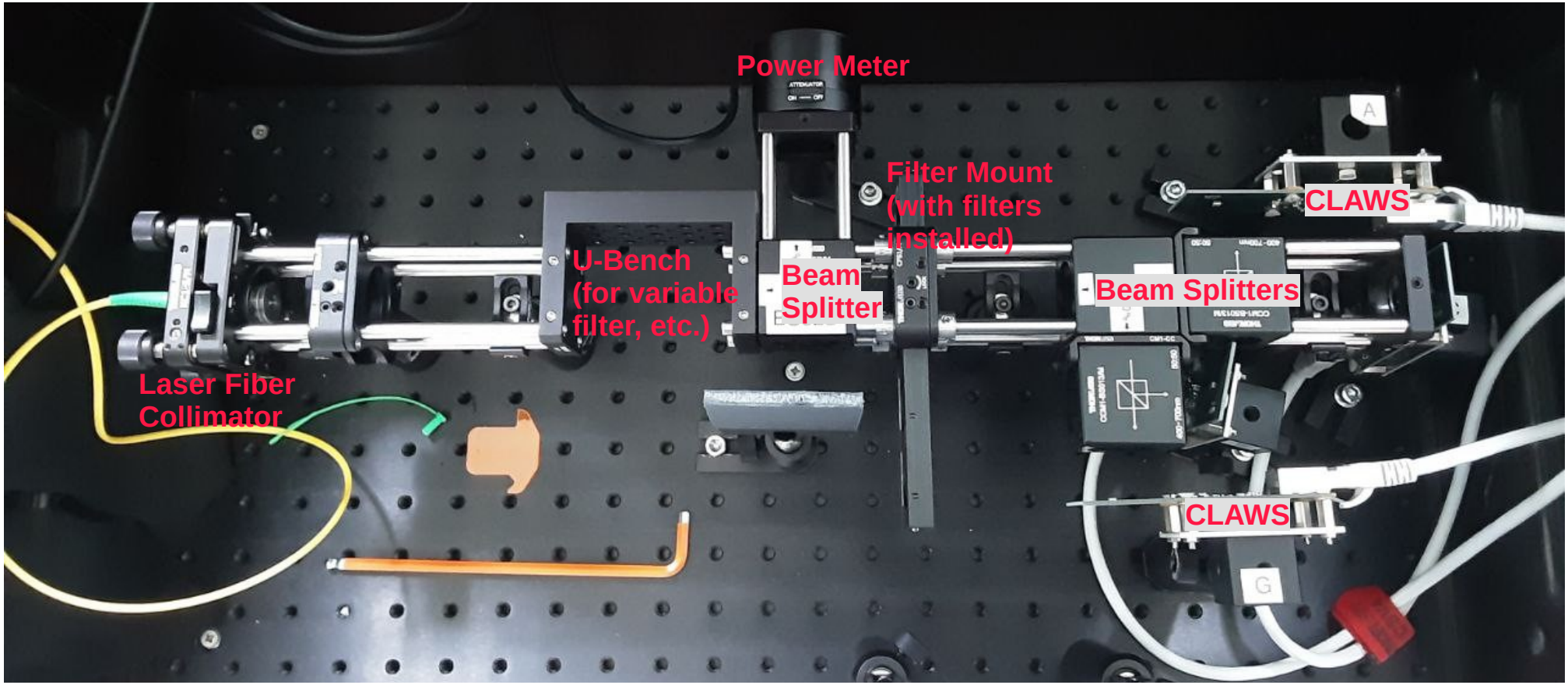
Induce signal on SiPM with laser pulses

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

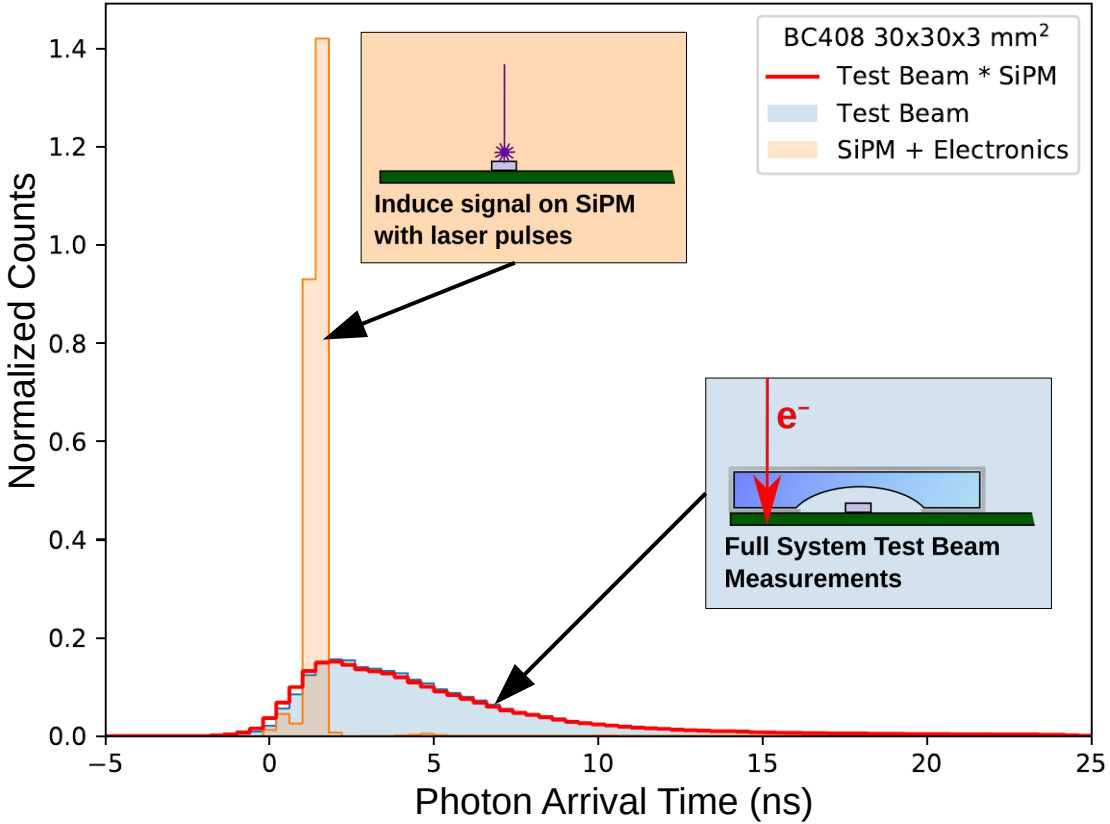


Laser Setup: Inside the Dark Box

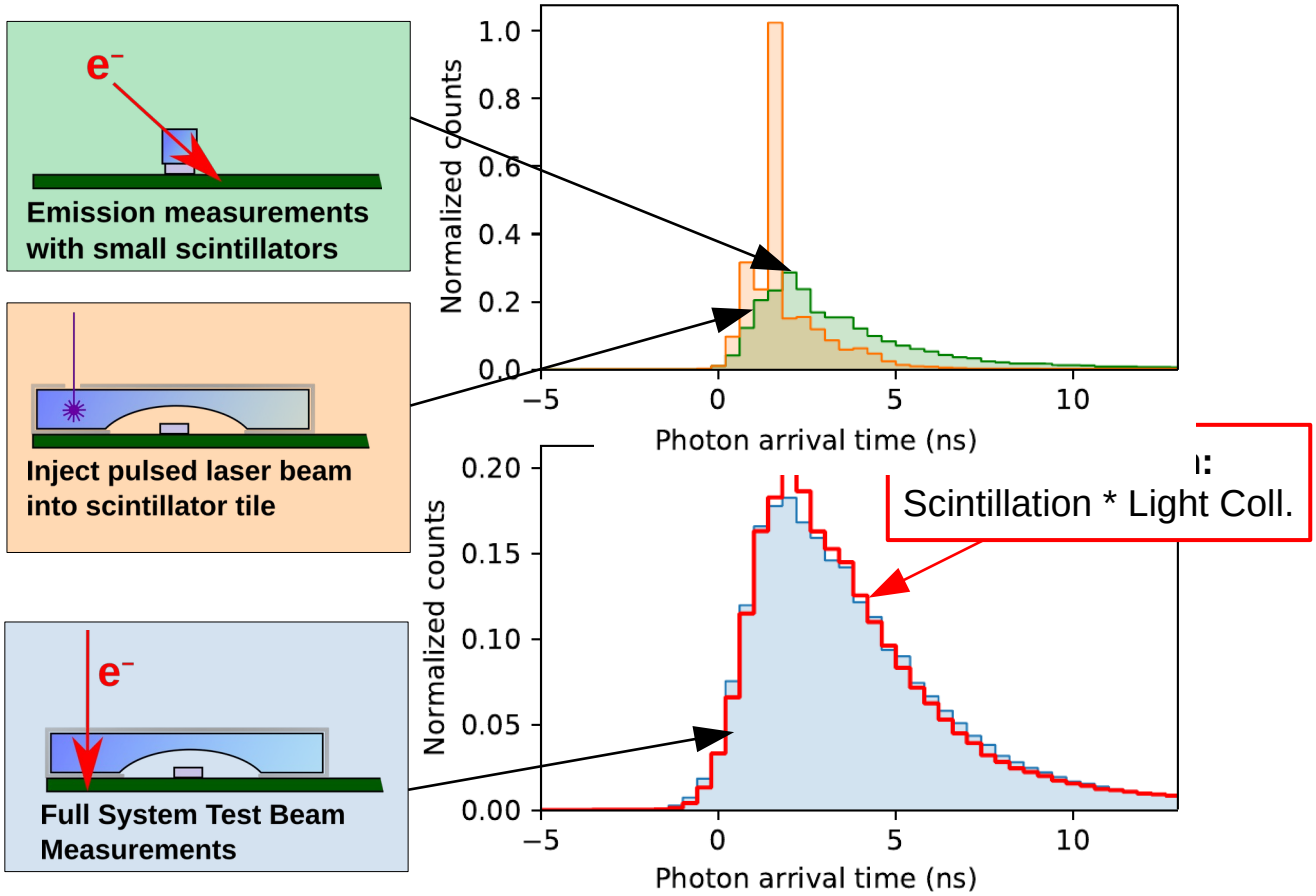


Findings: Fast Hardware Response

- 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

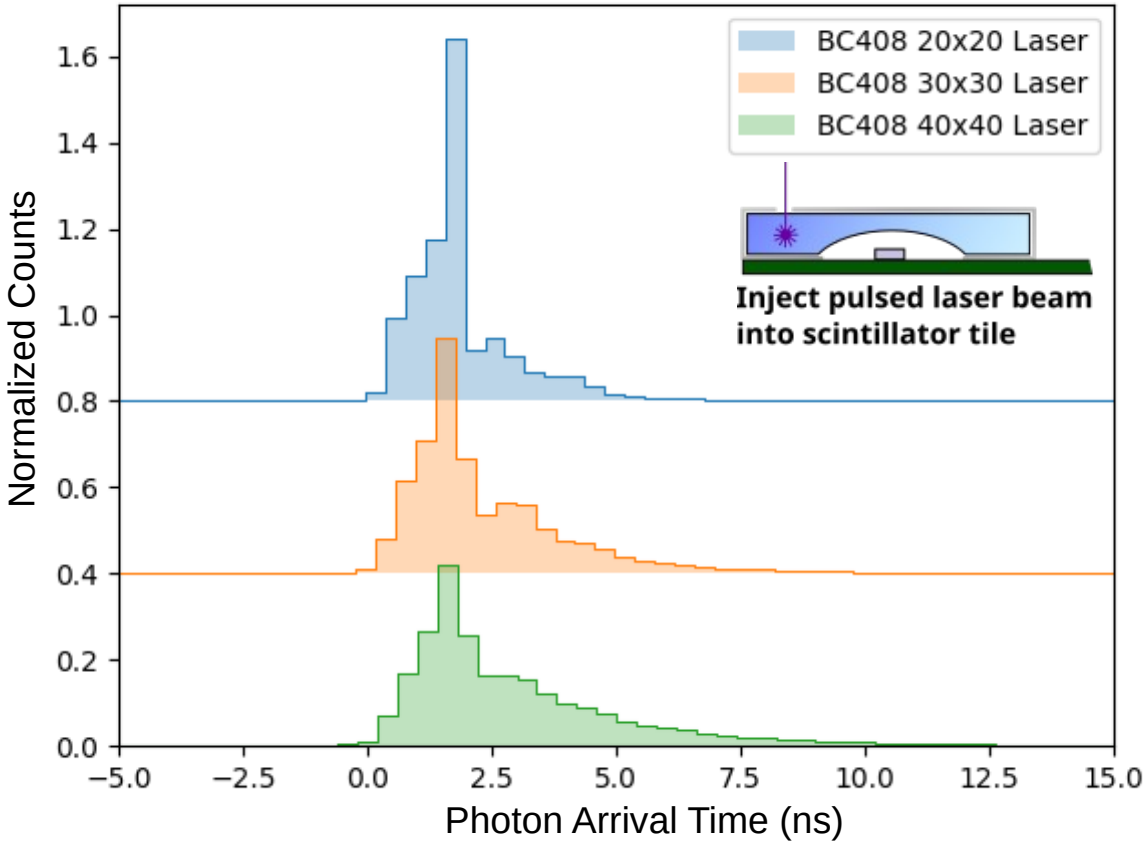


Findings: Scintillation + Light Collection



Time Structure of Light Collection

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



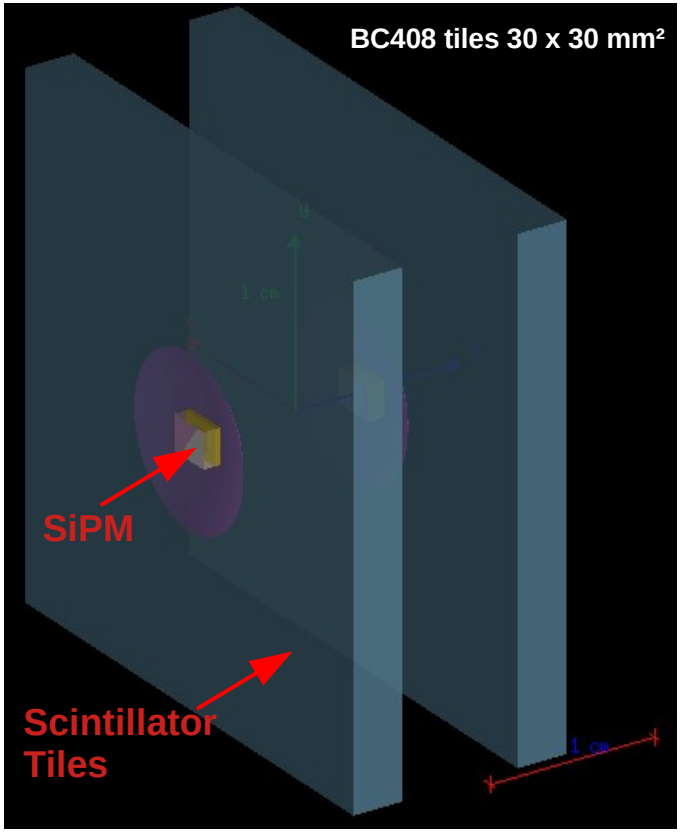
Part 3: Simulating the Test Beam Setup

Now that we understand the processes in the SiPM-on-tile configuration, let‘s simulate the process.

Geant4 Simulation

Concept of the Geant4 Simulation:

- Two scintillator tiles 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
- Geant4: adapted code from Yong Liu



Energy-Dependent Time Resolution (1)

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

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

Tile size	Fit value for σ_1
20x20	(382.8 ± 0.3) ps
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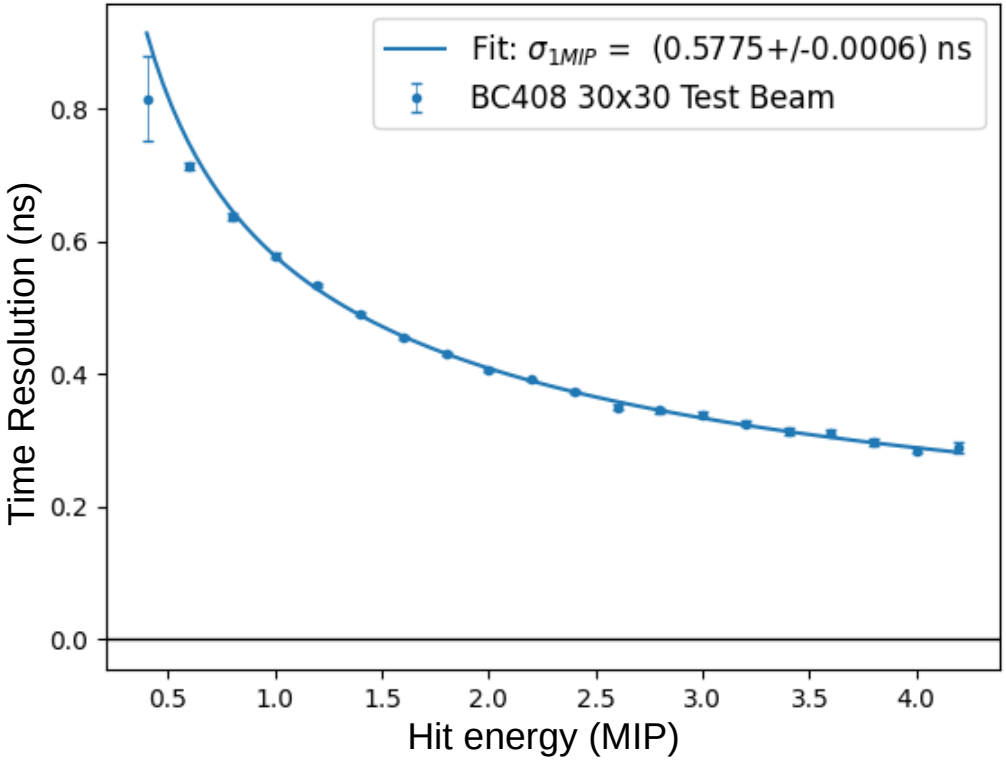


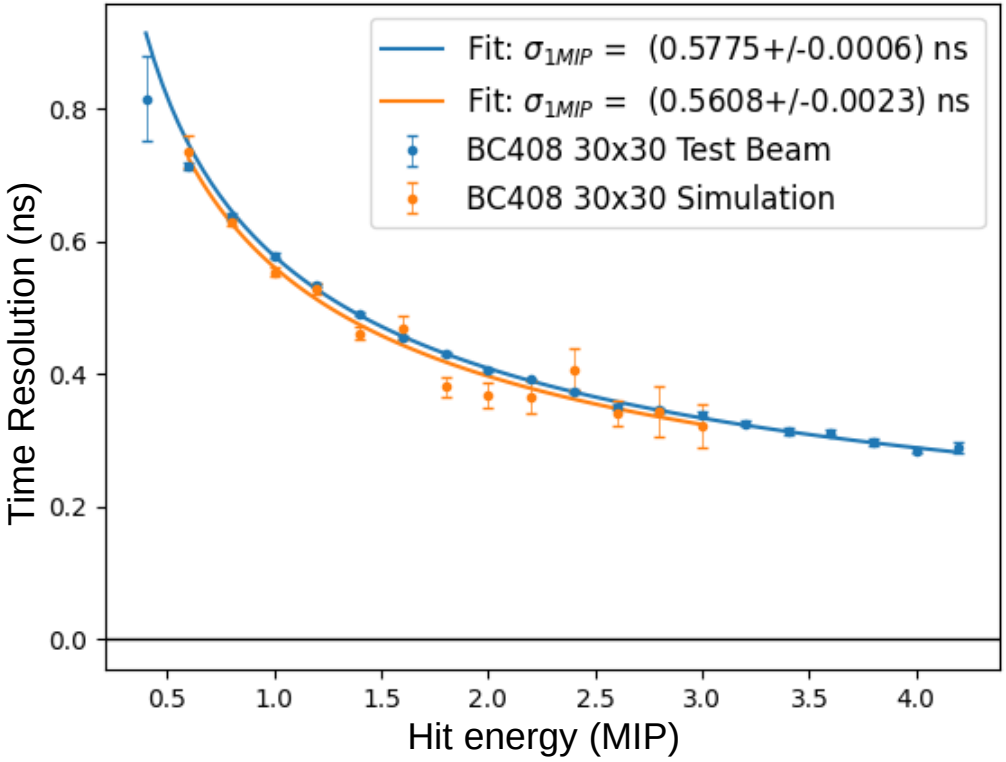
Energy-Dependent Time Resolution (2)

- 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

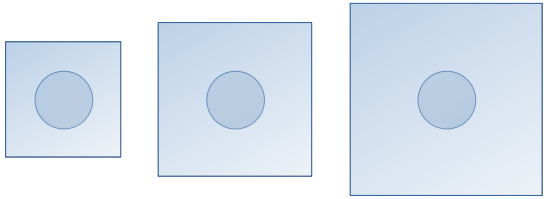


→ Let‘s use the simulations to study more different SiPM-on-tile configurations

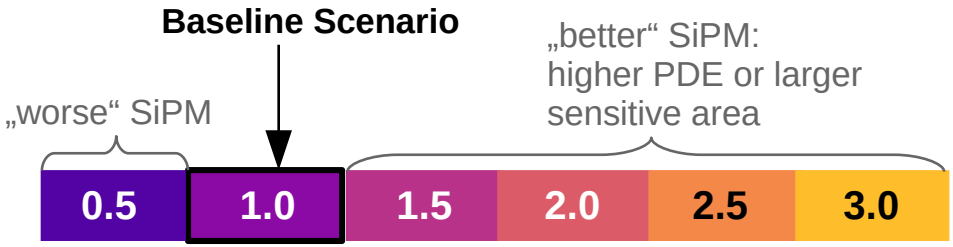
Simulation Study of SiPM-on-tile

Input Parameters:

- Scintillator tile size *A*:

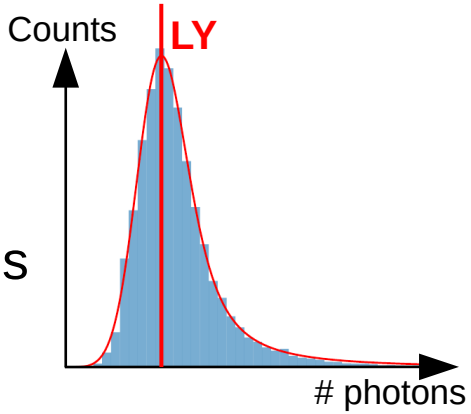


- SiPM photon detection capabilities: *rPDE* = detection efficiency relative to measured case



Output Variables:

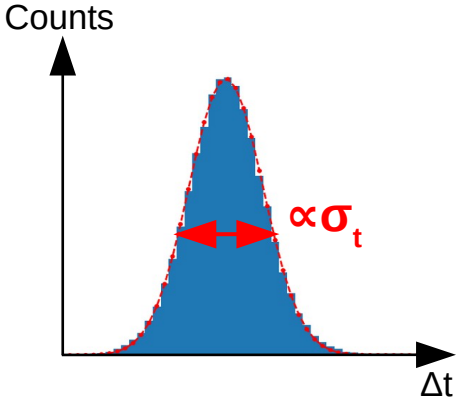
- Light Yield:
  Most probable number of photons for a MIP



- 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)

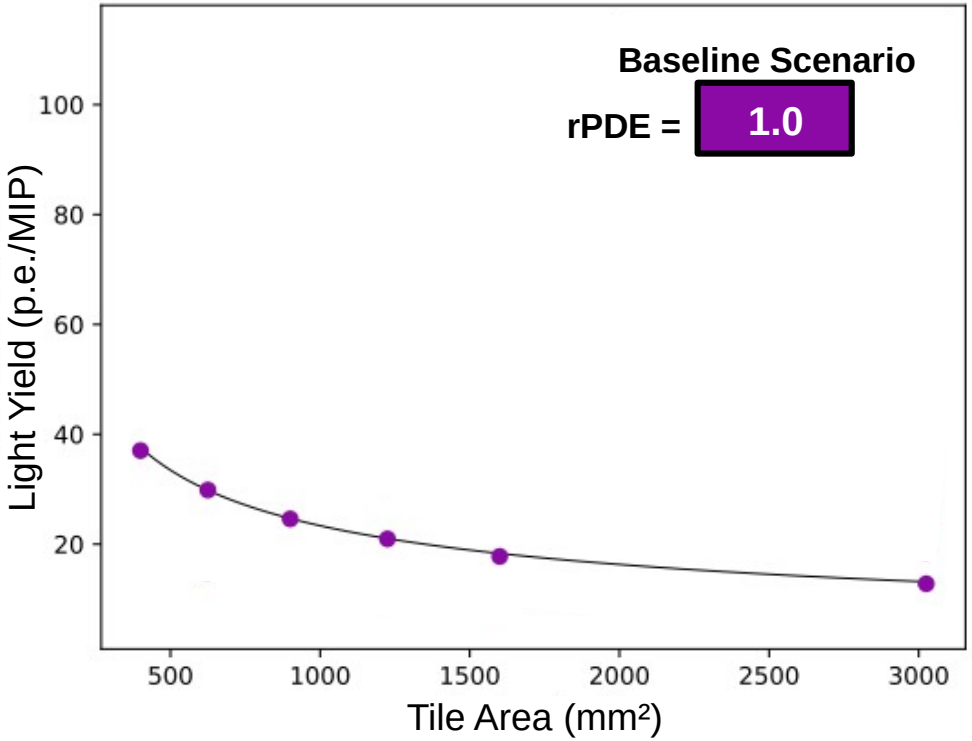


Light Yield

- 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.

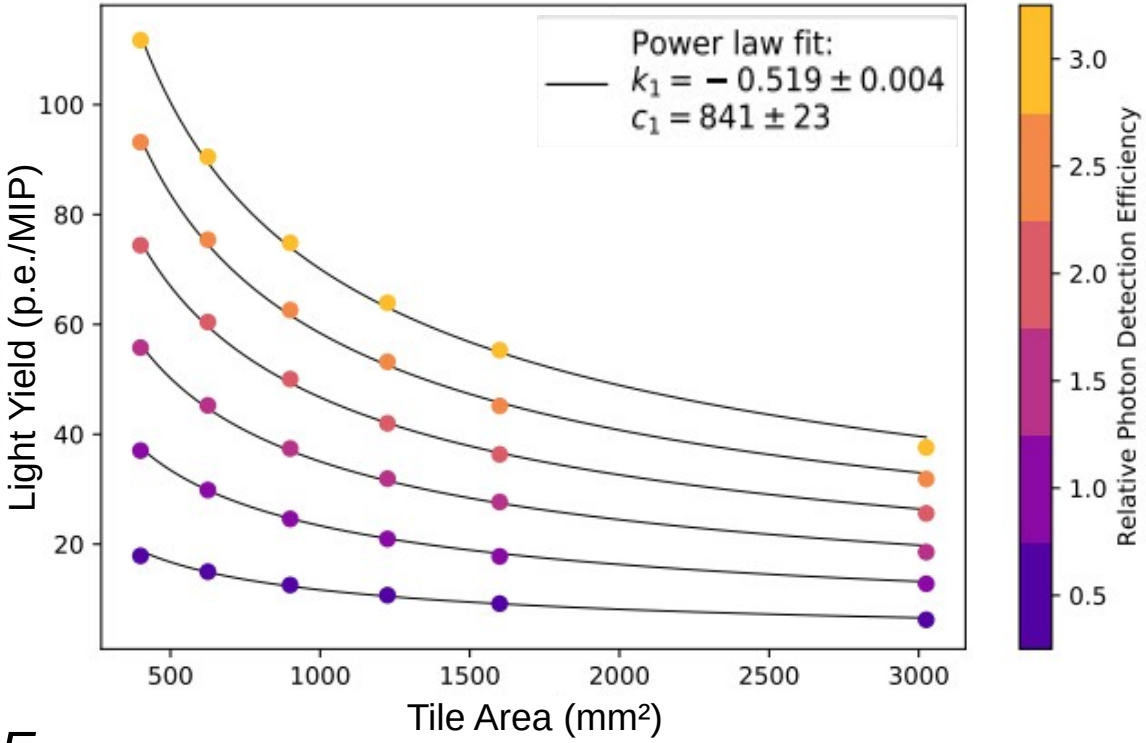


Light Yield

- 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*

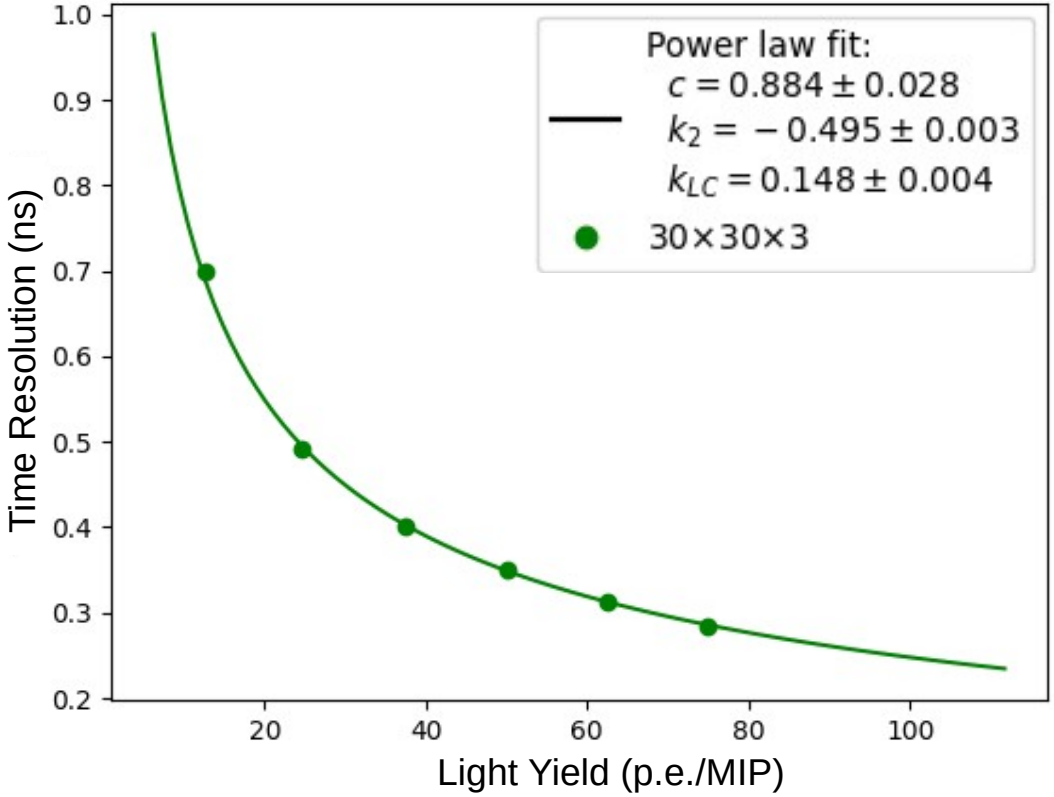


Time Resolution

- 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

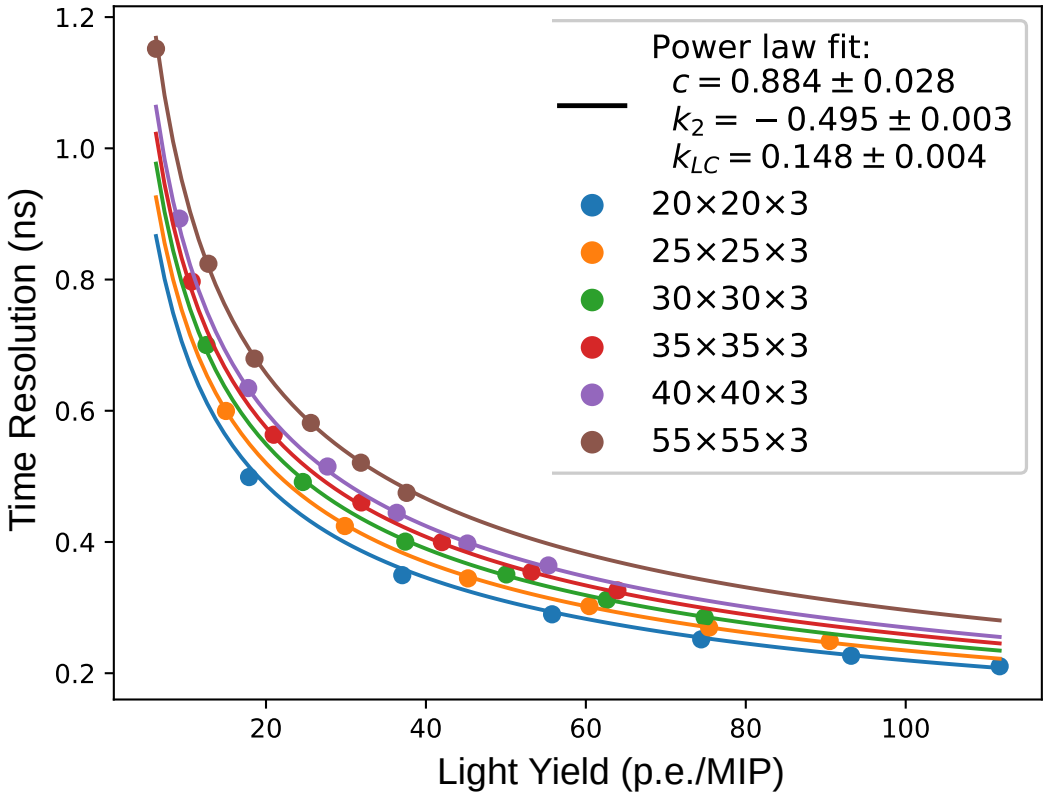


Time Resolution

- 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

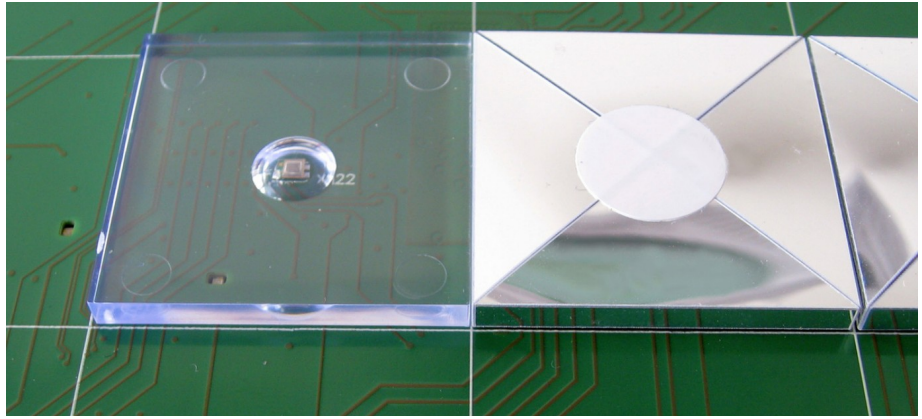
Set of two equations connects

- 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

Conclusion and Outlook

Conclusion and Outlook

Achievements:

- Two successful test beam weeks
- 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:

- 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
  - Light losses in the experiment?
  - Polished dimple necessary?

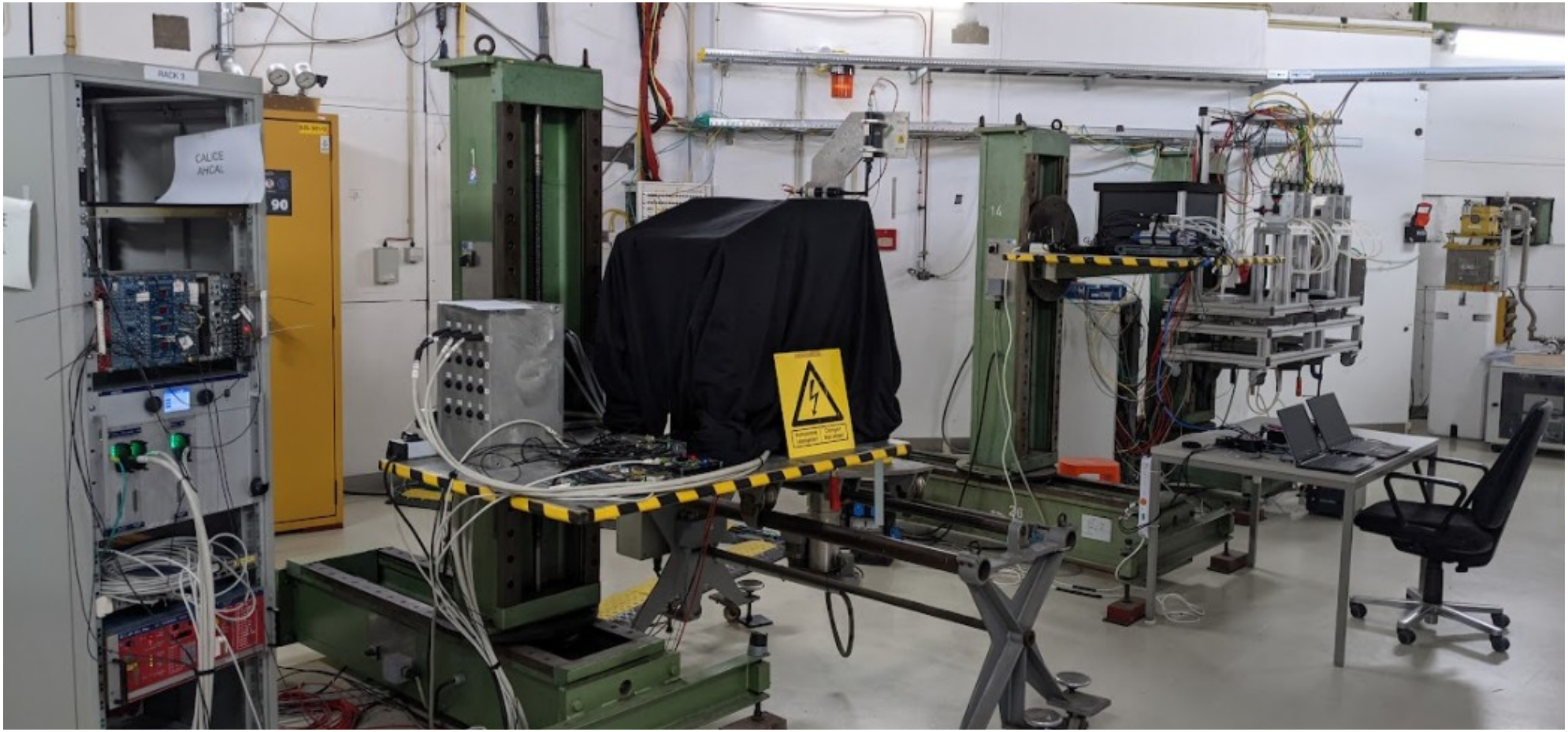
Backup Slides

SiPM: Hamamatsu S13360-1325PE

Number of channels	1 channel
Effective photosensitive area	1.3 x 1.3 mm^2
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

Test Beam Setup



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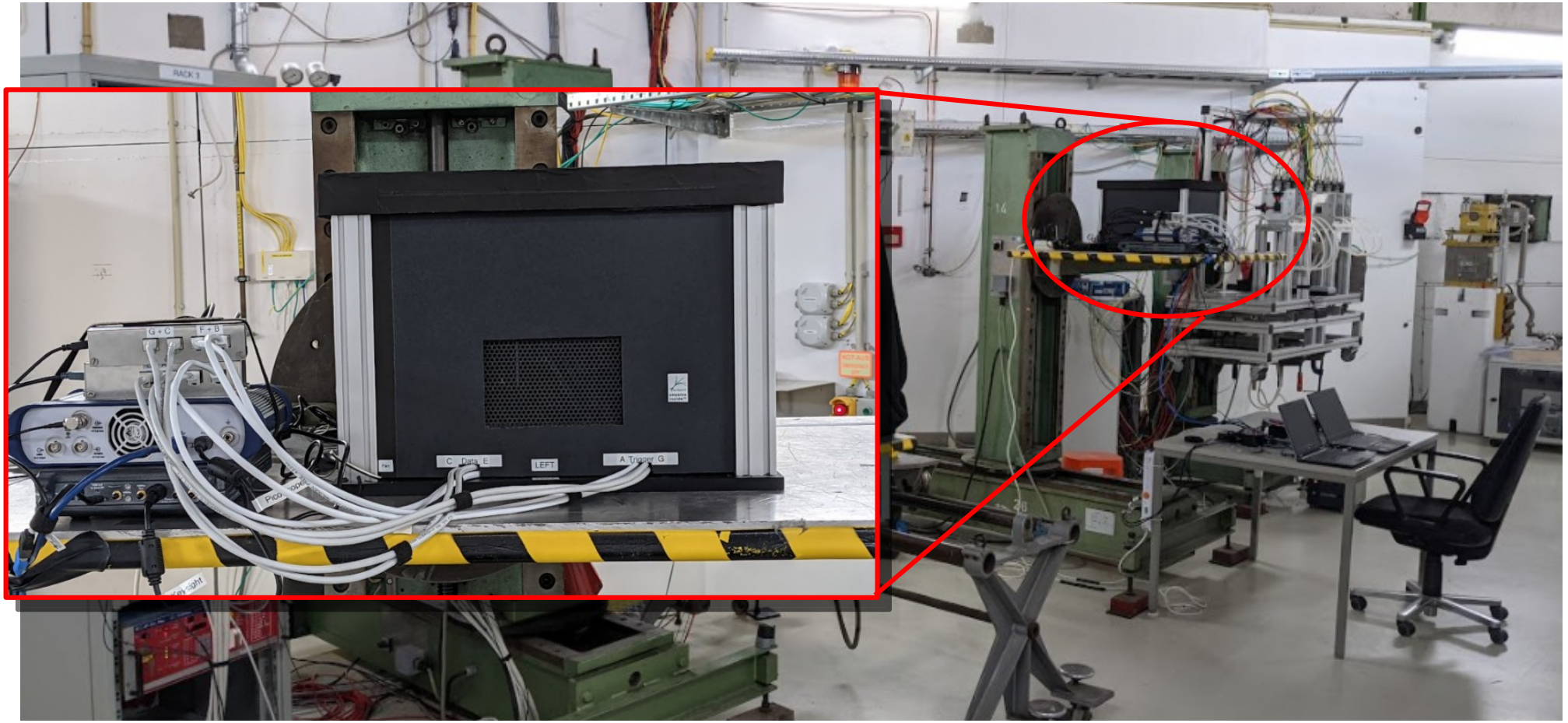

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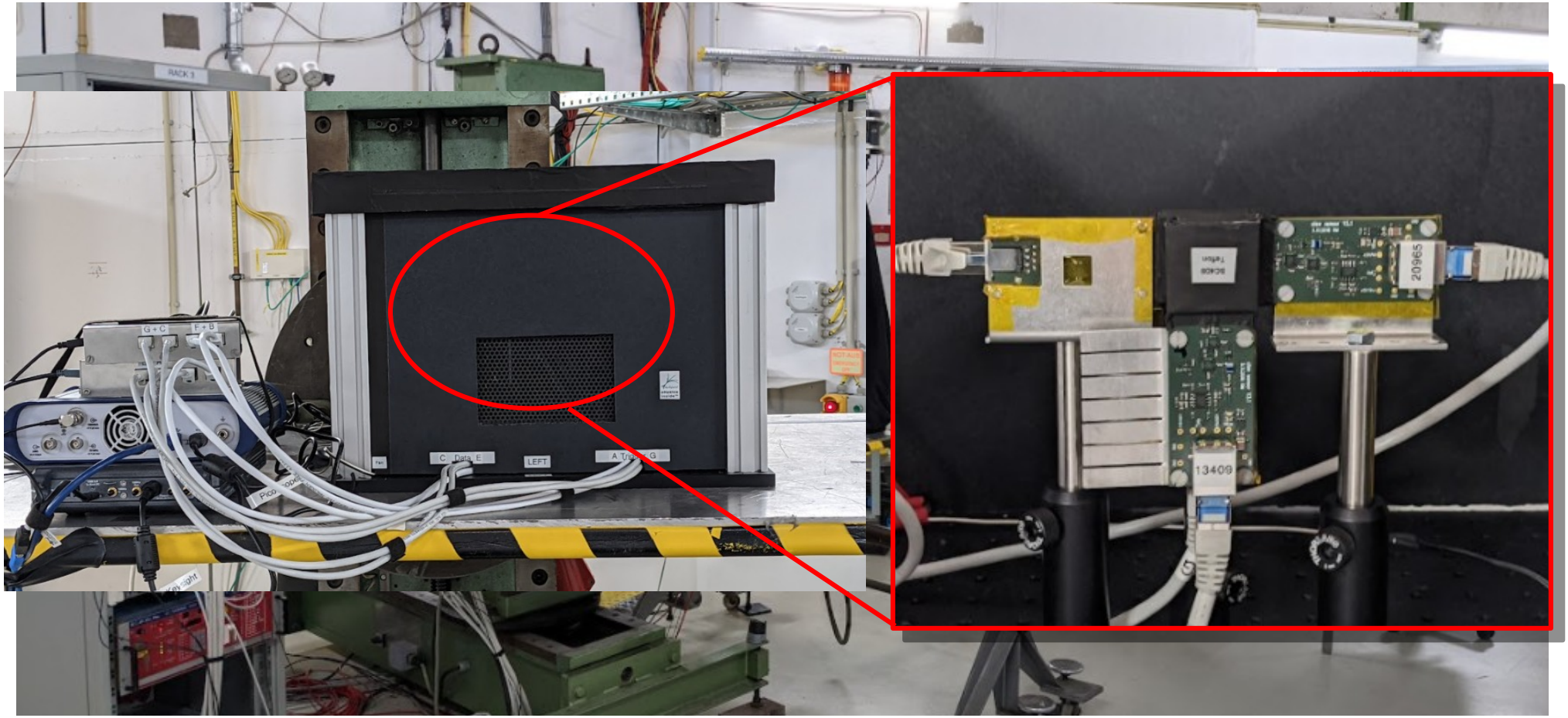
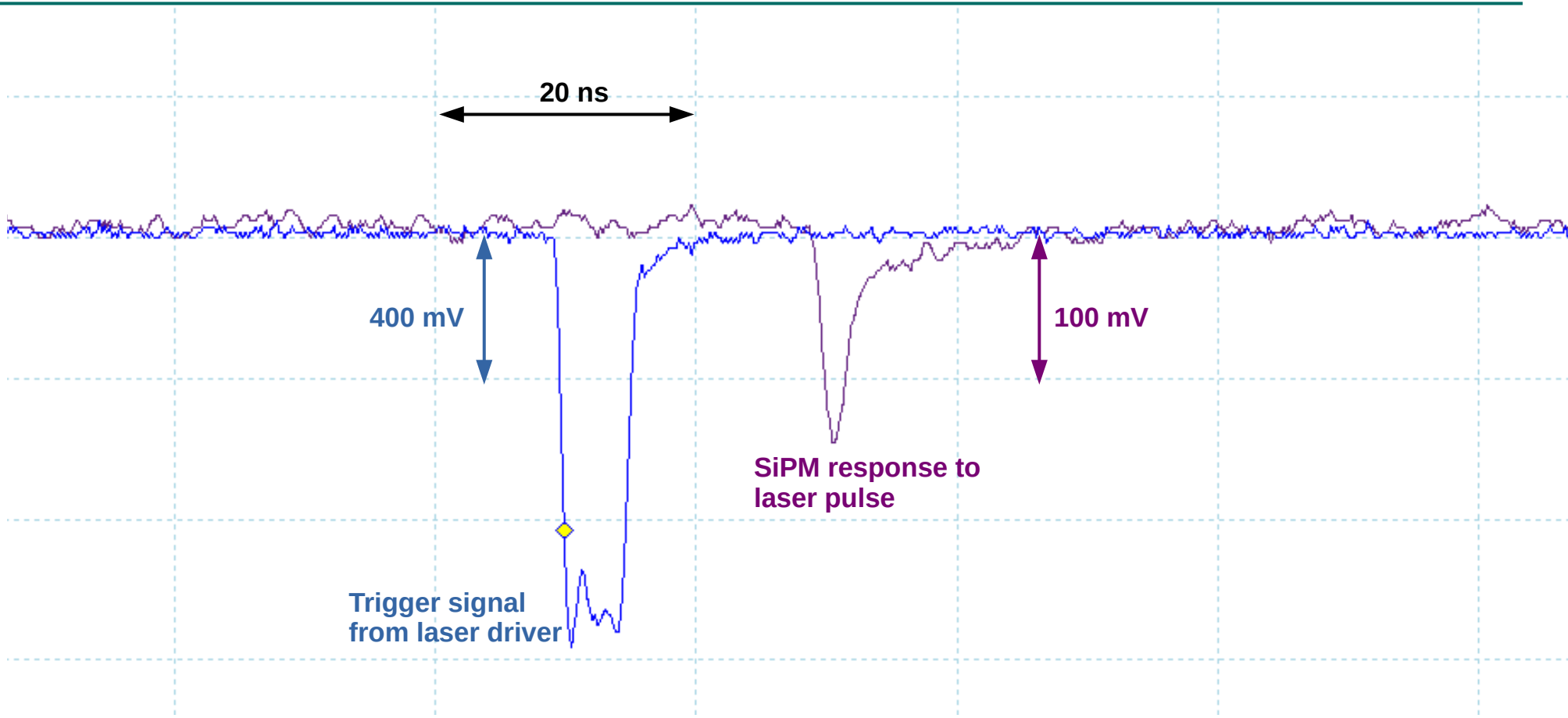


First Laser Event



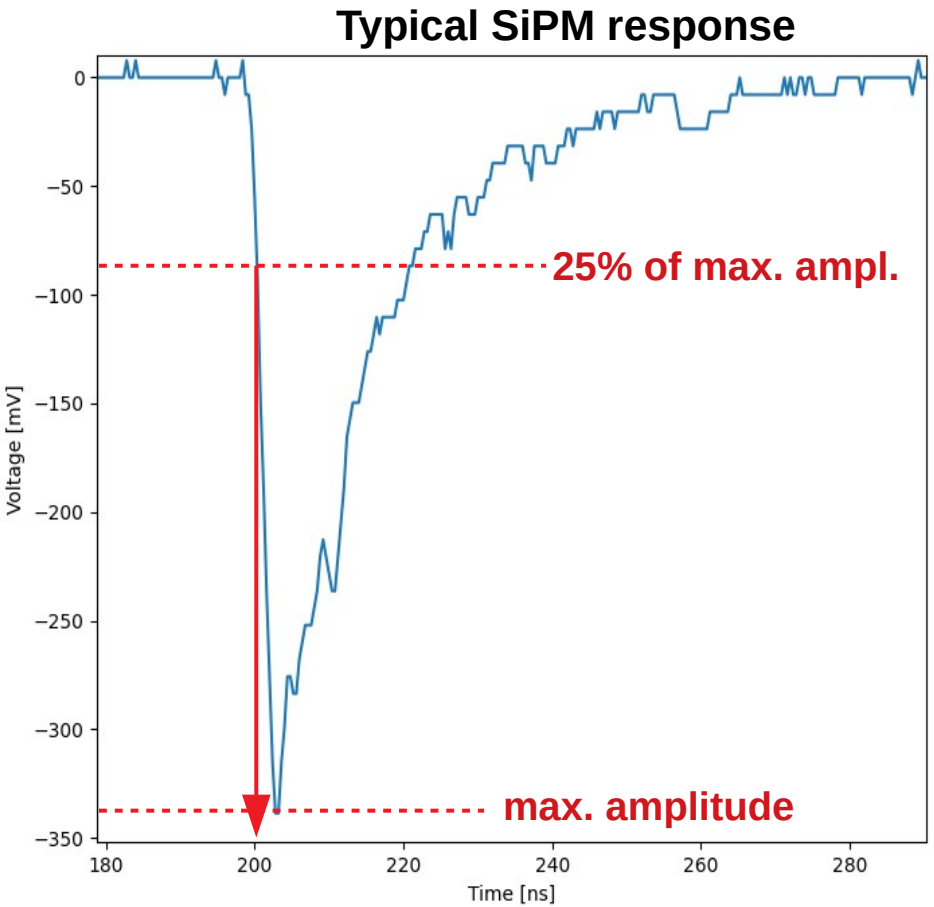
Calculating the Time Resolution (1)

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

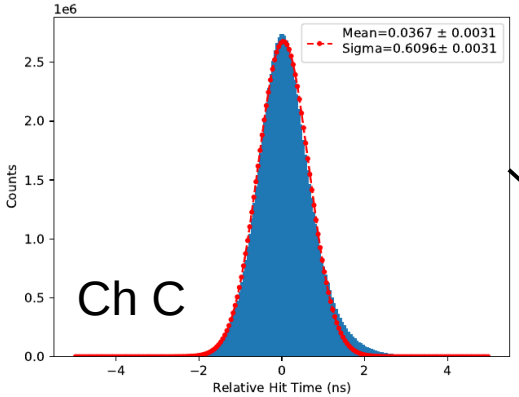
Leading Edge Method:

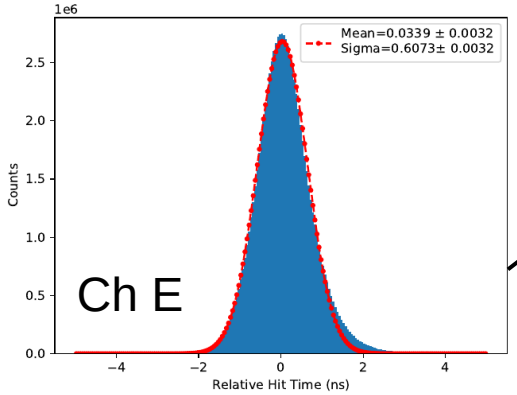
- Set threshold to fixed voltage

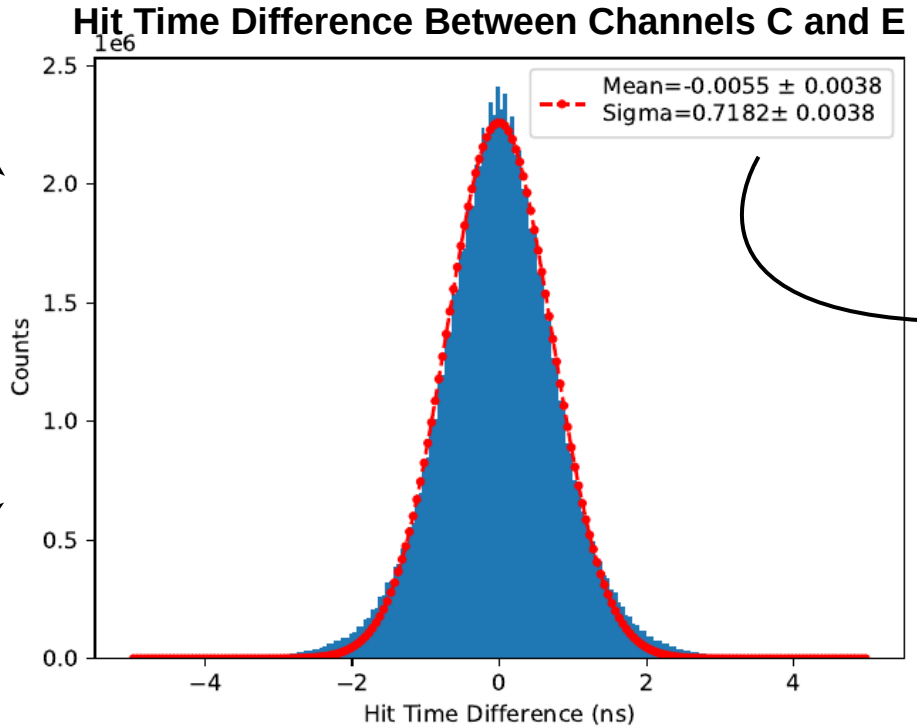


Calculating the Hit Time Difference

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



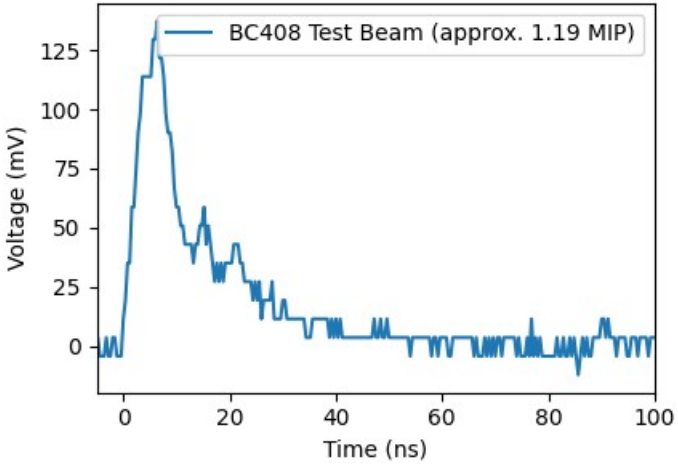




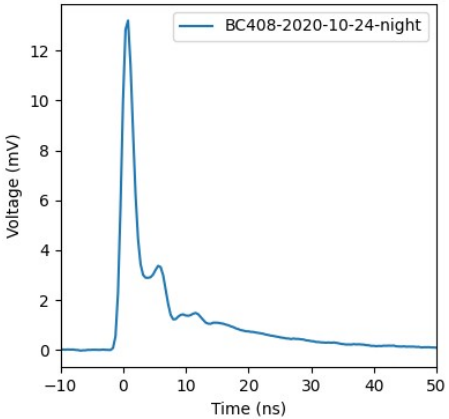
Single Channel Time Resolution:

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

Waveform Decomposition



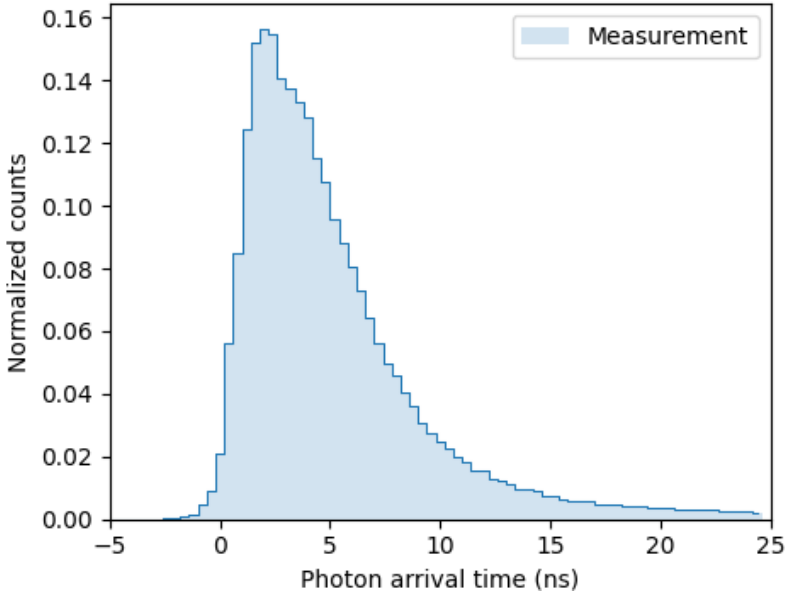
SiPM response for each measured event.



Average 1 p.e. waveform from a measurement

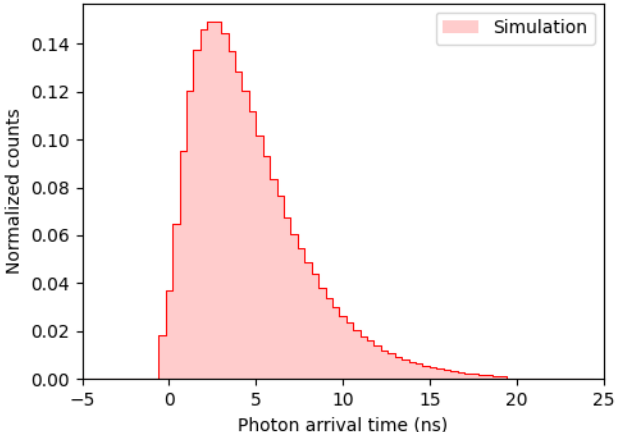
minus

Subtract 1p.e. waveforms

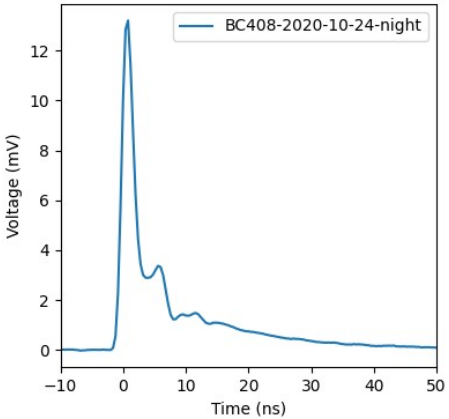


Extrapolate photon arrival times at the SiPM

Simulation: Waveform Generation



Photon arrival times from Geant4 simulations

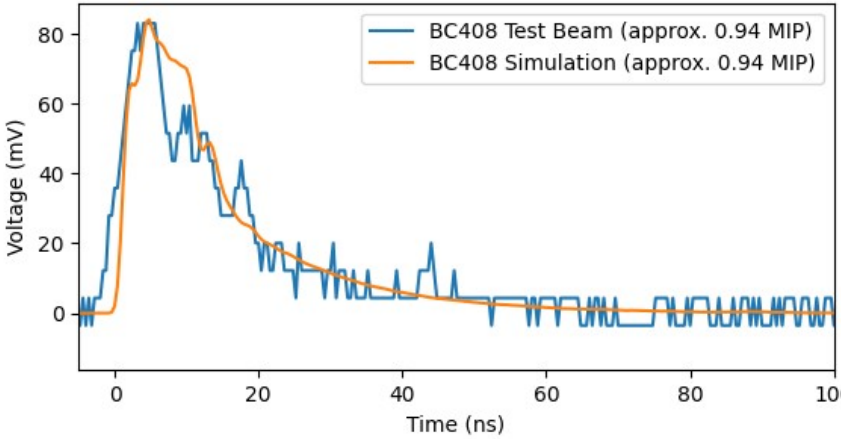


Average 1 p.e. waveform from a measurement

plus

Stack 1p.e. waveforms

SiPM response for each simulated event.

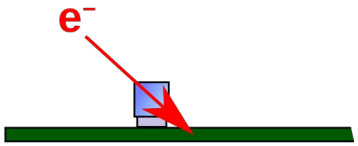


Caveat: „Light collection term“ needs to be adjusted so that amplitudes agree (once for all measurements)

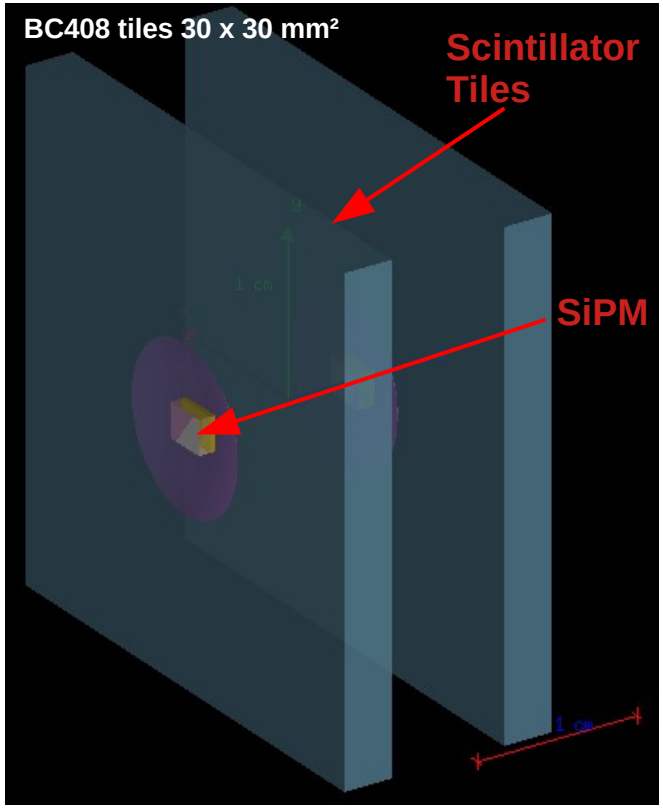
Geant 4 Simulations

- 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



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