Studies on Wide Dynamic Range SiPMs with High Pixel Densities

Zhiyu Zhao (TDLI/SJTU)

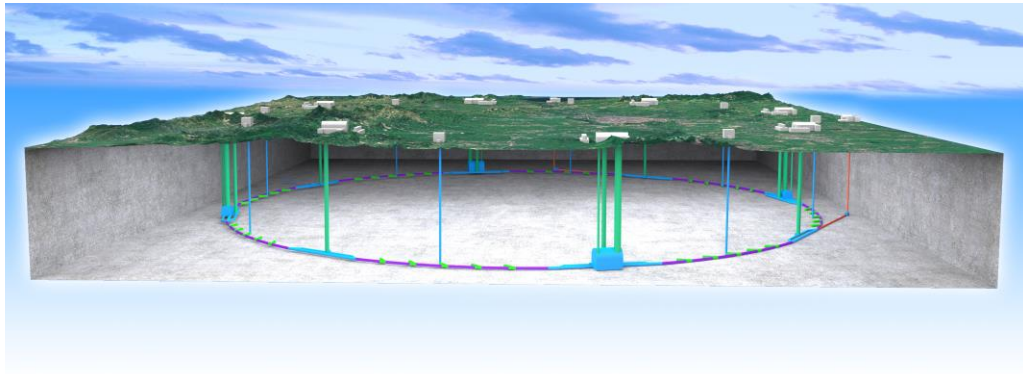
CEPC Calorimeter Working Group

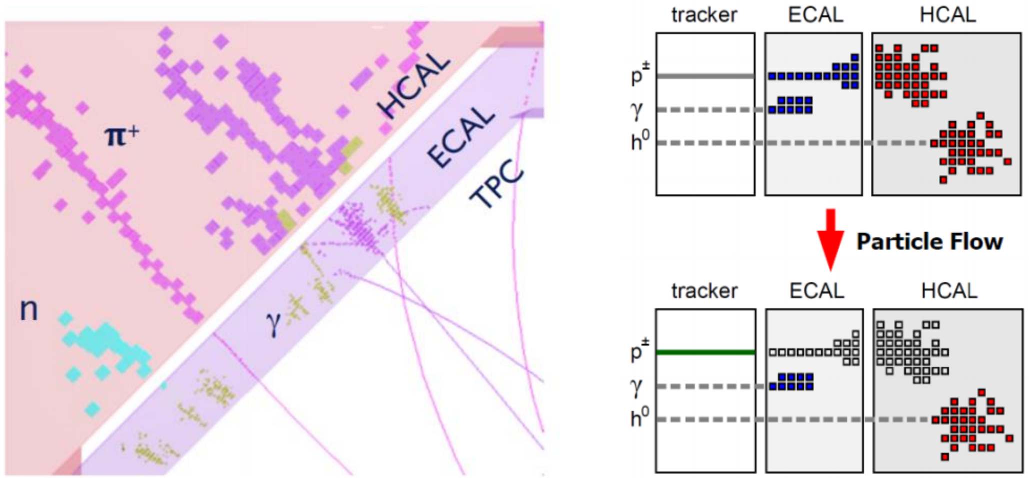
Technology & Instrumentation in Particle Physics (TIPP2023)

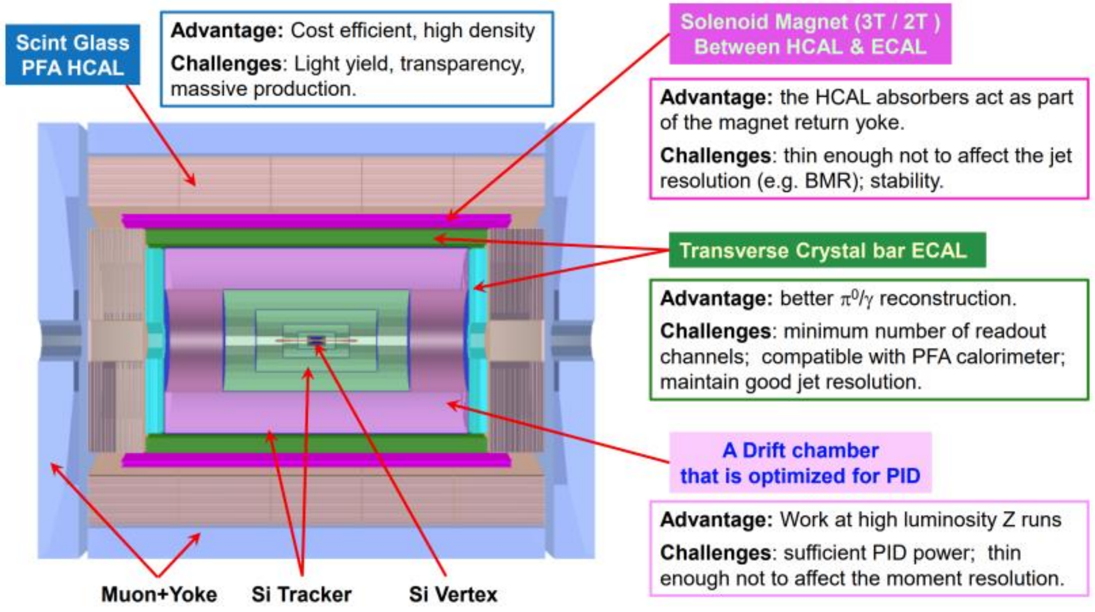
2023.9.7

New Detector for CEPC

- CEPC: future lepton collider
  - Higgs/W/Z bosons, top, BSM searches, etc.
  - Precision jet measurement
  - Particle-Flow Algorithm (PFA)
    - High-granularity calorimeter: separation of showers
- “CEPC 4th concept” detector design
  - High-granularity crystal ECAL
    - 5D detector: 3D spatial + energy + time
    - Excellent energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$

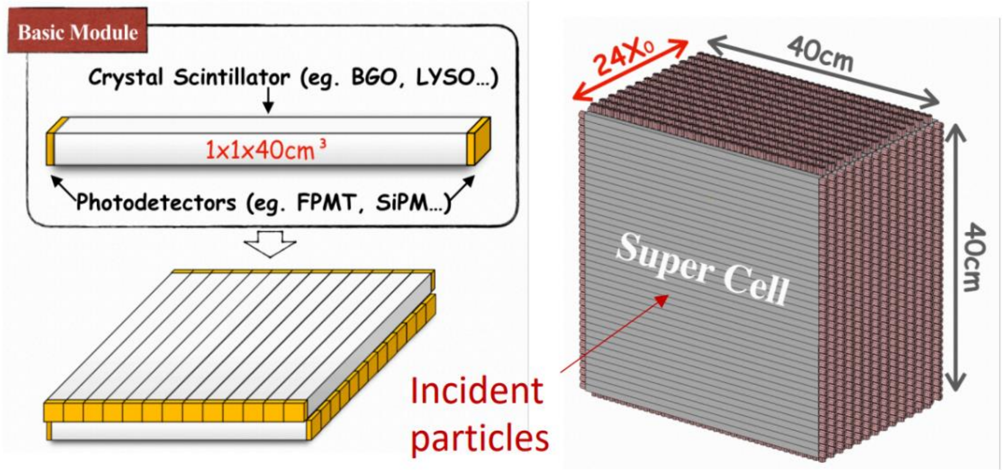


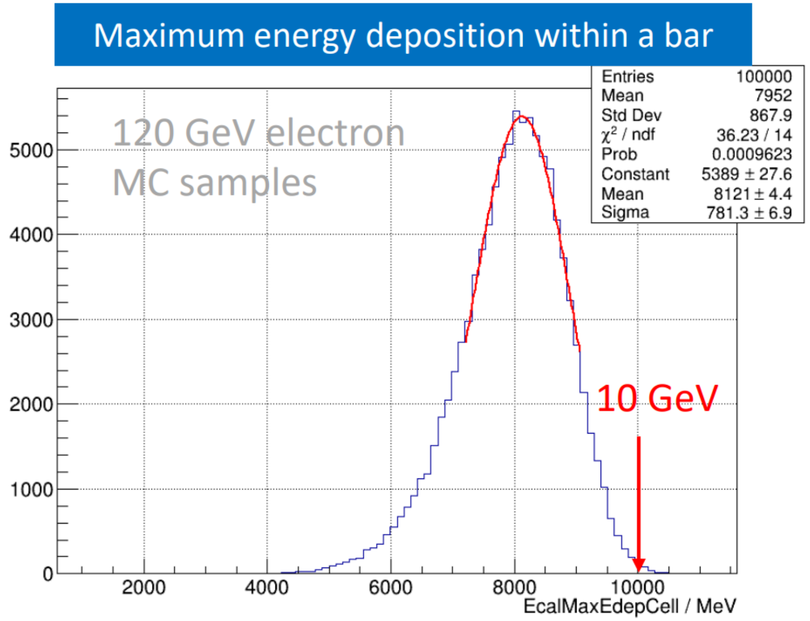




[Development of a novel high granularity crystal electromagnetic calorimeter]

Dynamic Range Requirement of ECAL





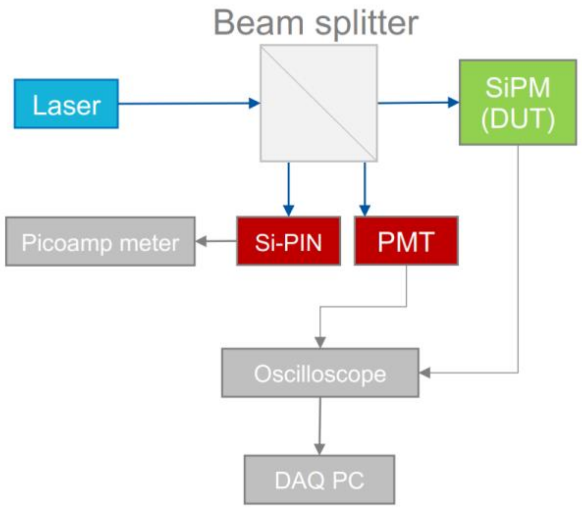
- Highly granular crystal electromagnetic calorimeter for CEPC:
  - Long crystal bars(BGO) are perpendicular between layers → $1 \times 1 \times 2cm^3$ granularity
  - Two sides readout: SiPM as the ideal sensor
- Dynamic range requirement:
  - Maximum energy deposition (from Bhabha electrons): ~10GeV → ~50000 pe(1 side)
  - SiPMs with large dynamic range are needed, but calibration for them is not easy.

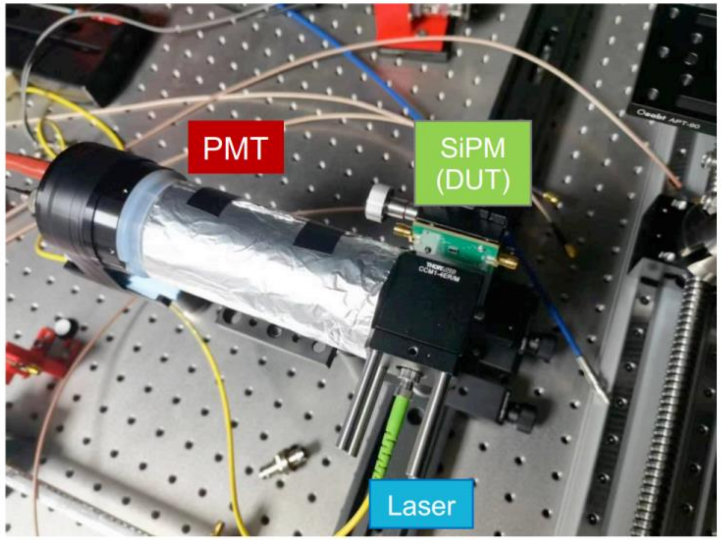
Outline

- Measurement
  - Experiment Setup
  - PMT linear region selection, gain calibration, and pe number calibration by Si-PIN
  - Response curve of SiPMs
- Simulation
  - A model for simulating the number of pe detected by SiPM under different light intensities
- Summary

Experiment Setup

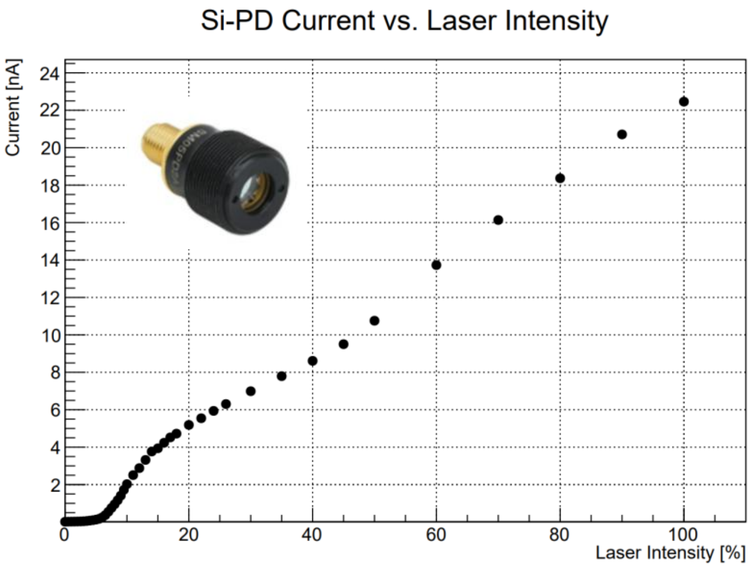
- Devices
  - Pico-second laser: ~40ps pulse width, 405nm wavelength
  - Beam splitter: divide the light between SiPM and PMT
  - SiPM
    - HAMAMATSU S14160-3010PS, $10\mu m$ pixel, $3 \times 3mm^2$, 89984 pixels
    - NDL EQR06 11-3030D-S, $6\mu m$ pixel, $3 \times 3mm^2$, 244720 pixels
  - PMT(HPK R7725): determine the number of pe that SiPM received
  - Si-PIN(Thorlabs): auxiliary scaler
- The linear region of the PMT can be extended by reducing its bias voltage.

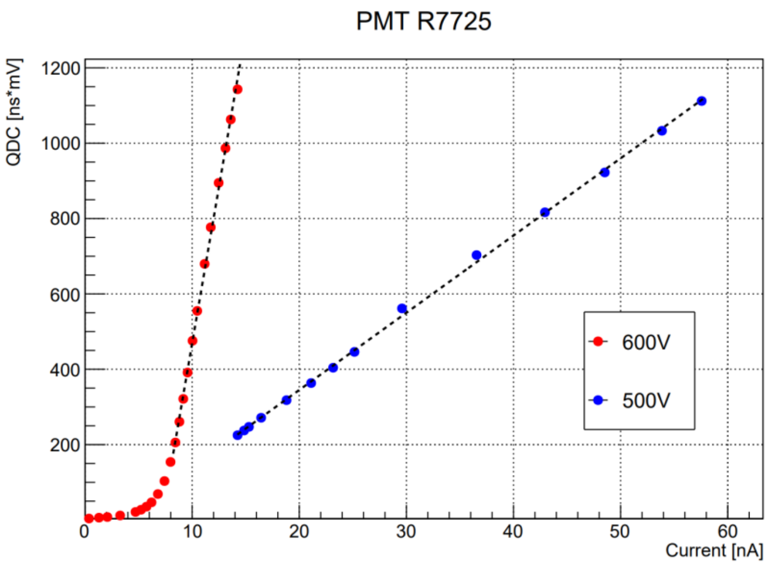


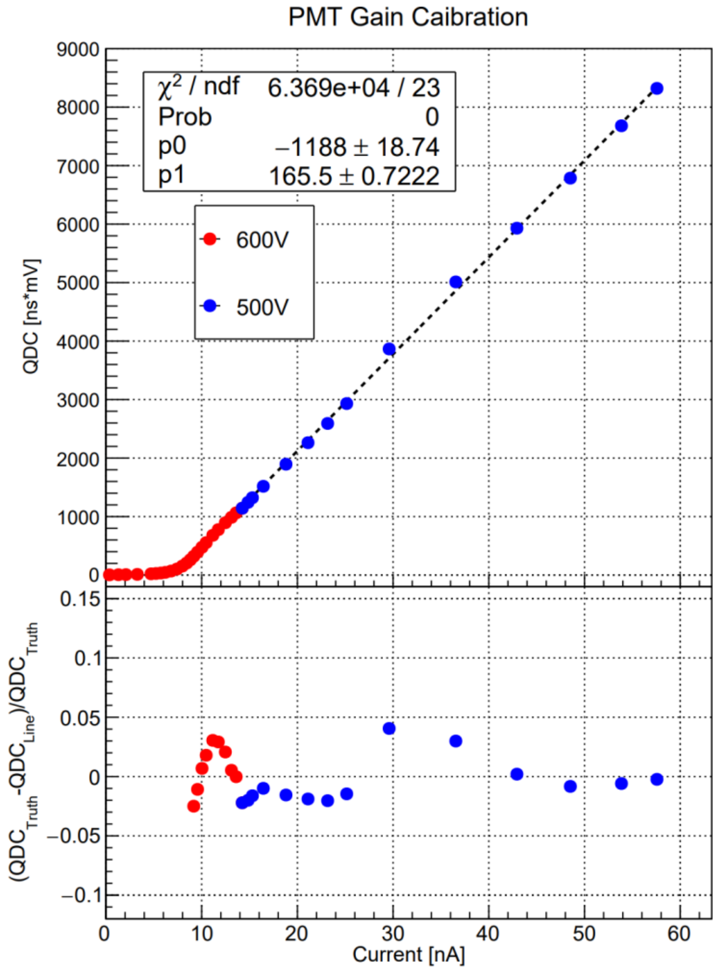


Linear Region Selection for PMT

- Select the linear region of PMT with a Si-PIN at different light intensities
  - Weak light intensity → 600V
  - Strong light intensity → 500V
- Combination of discrete linear regions can keep linear within the whole light range

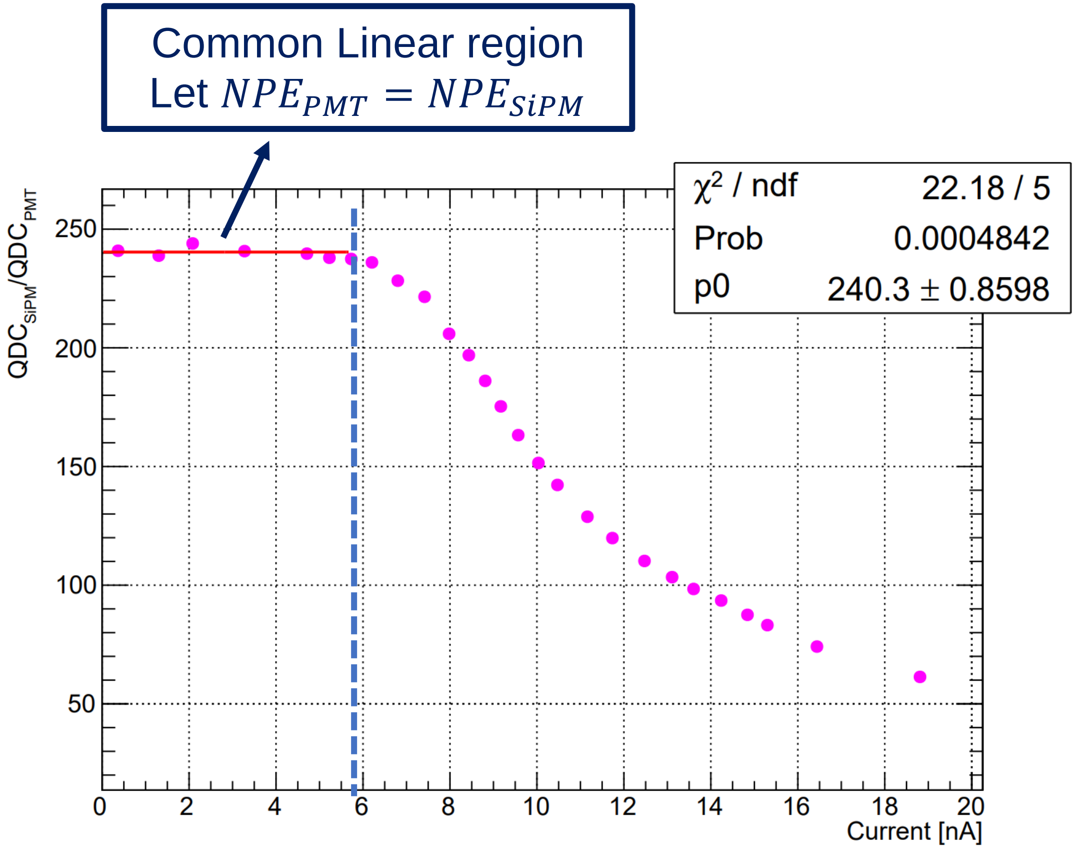


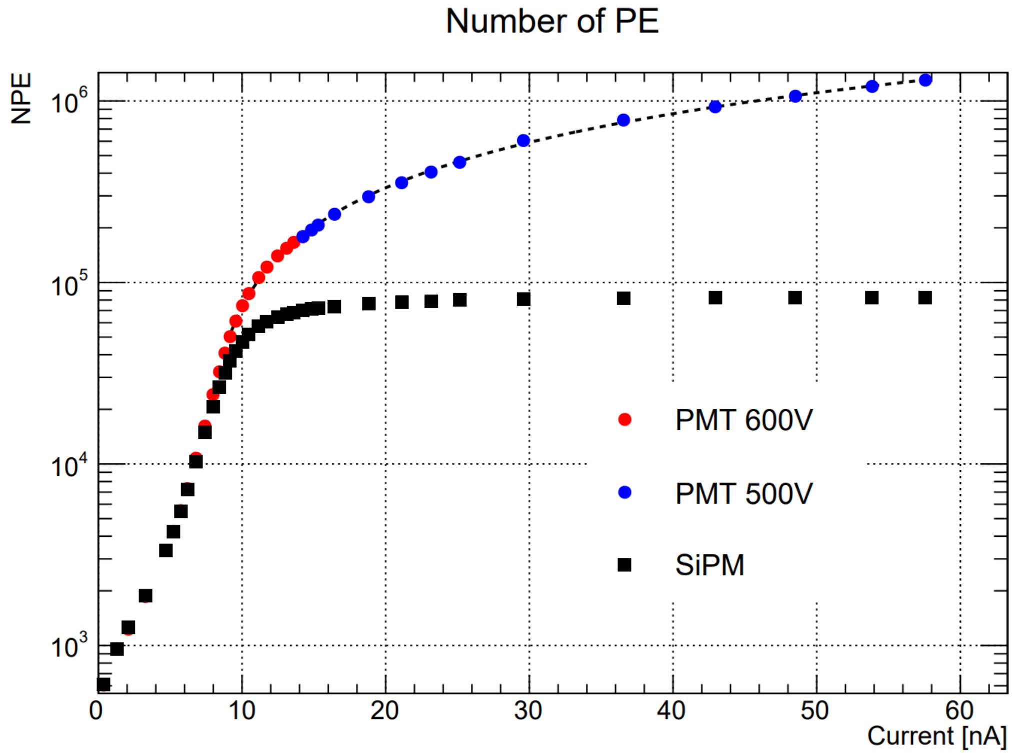




Number of pe Calibration

- Gain of PMT is not high enough to discriminate single pe with 600V bias voltage
- SiPM calibrates PMT in weak light intensity region





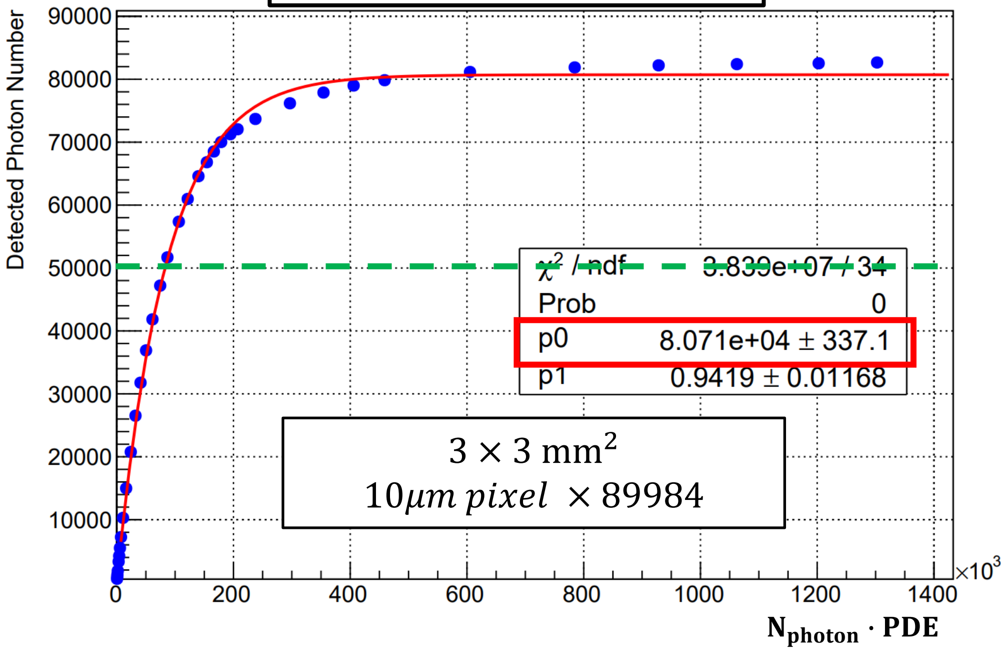
SiPM Dynamic Range Calibrated by PMT

- SiPMs:
  - HAMAMATSU S14160-3010PS, $10\mu m$ pixel, $3 \times 3mm^2$, 89984 pixels
  - NDL EQR06 11-3030D-S, $6\mu m$ pixel, $3 \times 3mm^2$, 244720 pixels
- Picosecond laser as source, no pixel recovery effect
- Saturation value of 3010PS is close to its pixels number. But the result of EQR06 is quite different, only half of its pixels number.
  - Limit by laser power? Spot non-uniformity? Calibration bias?

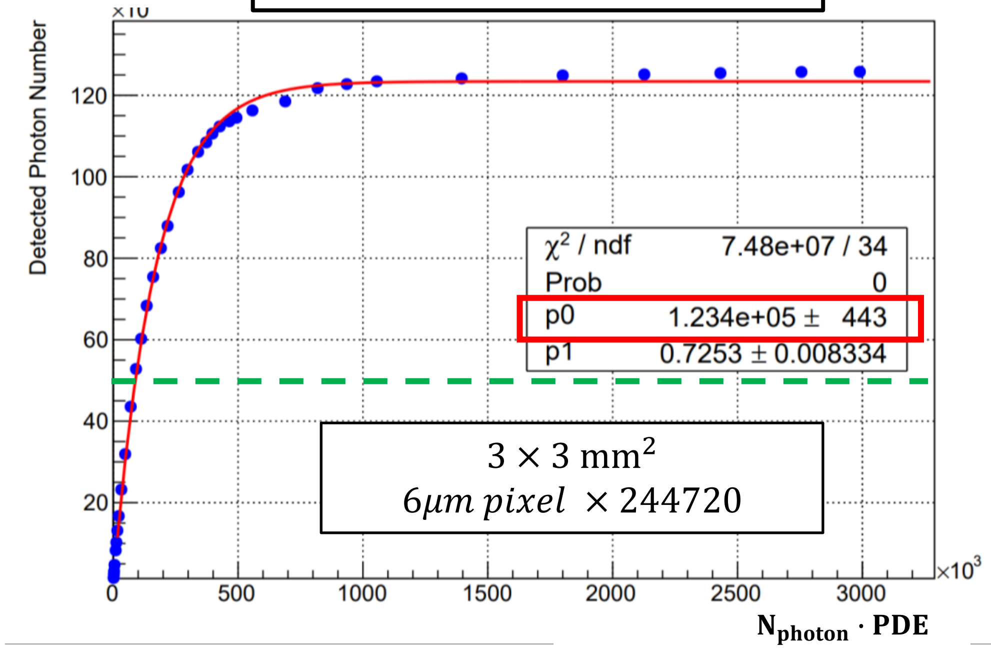
$$\boldsymbol{p_0} * \left(\mathbf{1} - \boldsymbol{e}^{\frac{-\boldsymbol{p_1} * \boldsymbol{x}}{\boldsymbol{p_0}}}\right)$$

- $\boldsymbol{p_0}$: effective pixels number
- $\boldsymbol{p_1} \cdot \mathbf{x}$: $N_{photon} \cdot PDE$

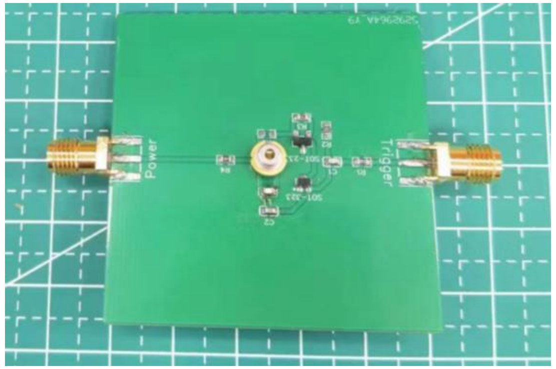
HPK S14160-3010PS



NDL EQR06 11-3030D-S

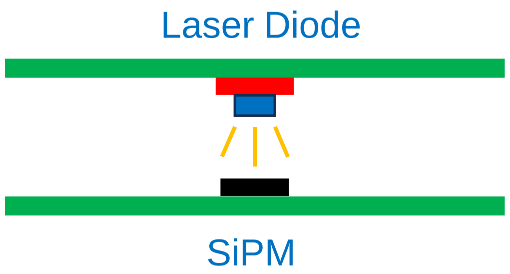


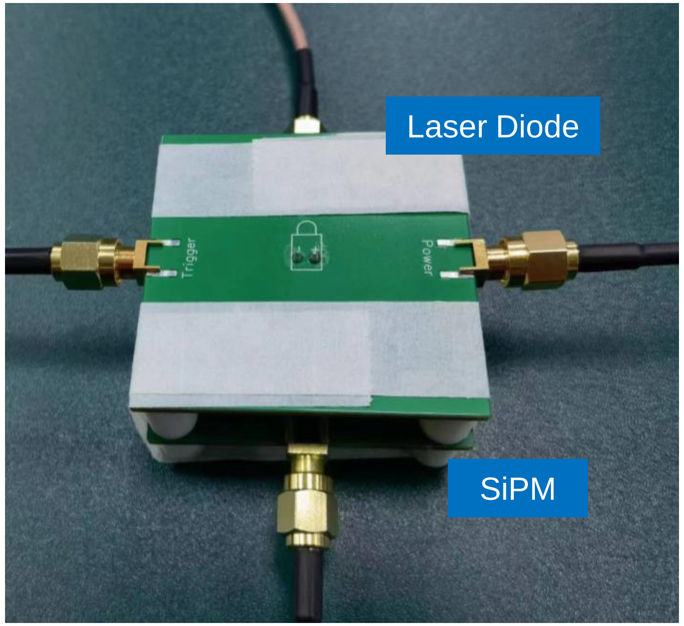
Measurement with Laser Diode

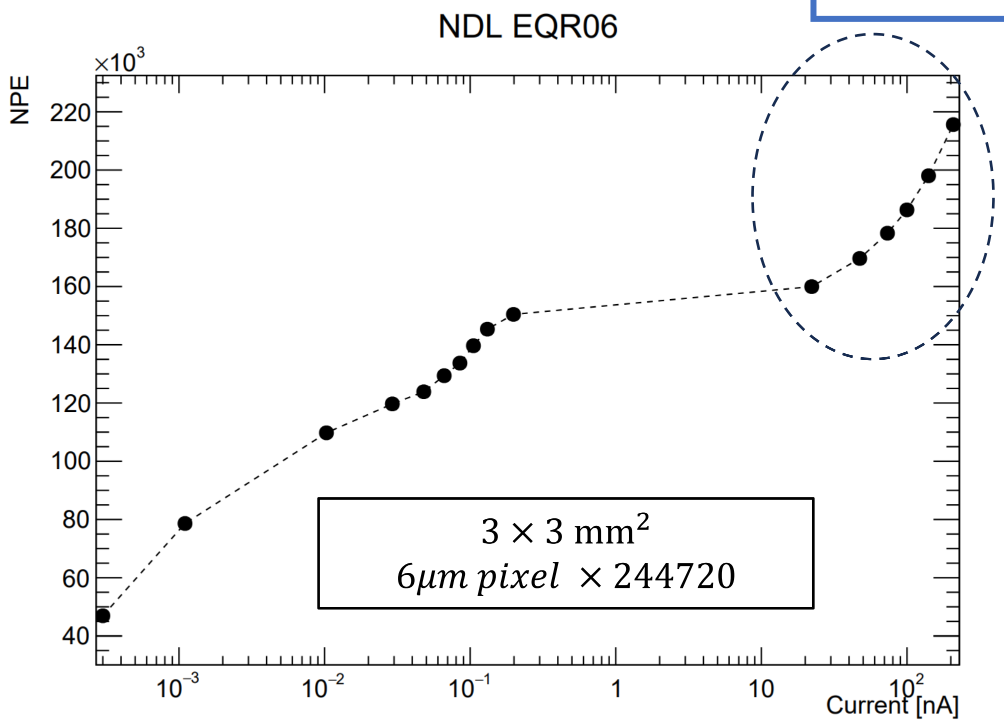


- Laser diode with a driver circuit
  - 1.6W diode, 450nm peak wavelength,<5ns pulse width, kHz trigger rate(by AWG), 0~30V power supply
- The pulse duration is longer than pixel recovery time. The detected pe number can exceed the saturation value.

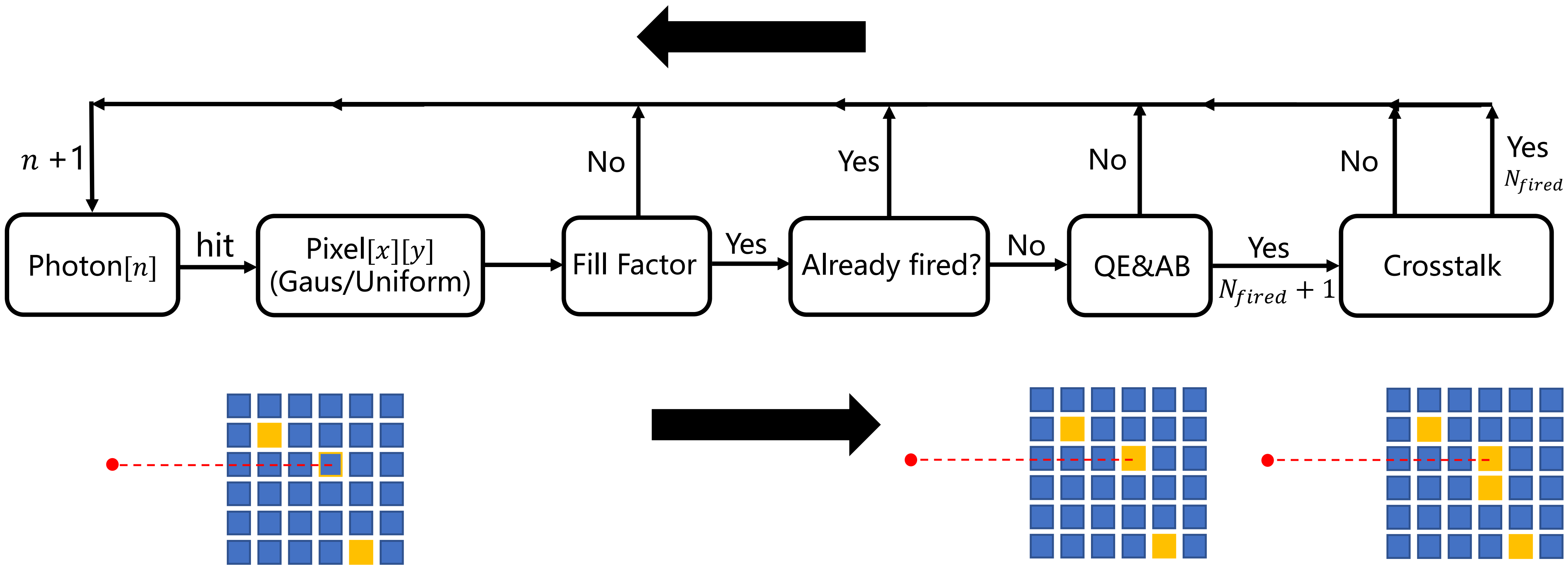
Pixel recovery and multi-fired







A Toy Monte Carlo of SiPM



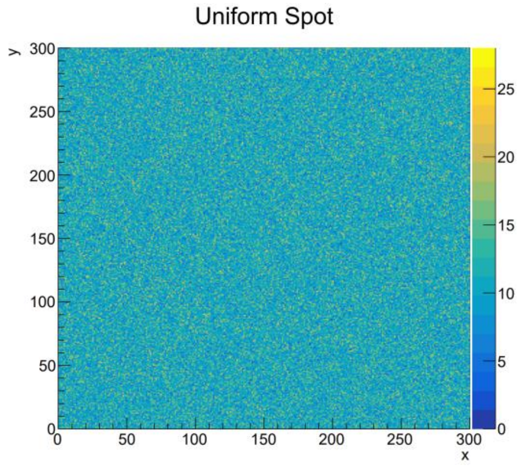
- Light spot: 2D Gaussian, uniform
- Pixel number: 300×300 for HPK S14160-3010PS
- Fill factor filter: $A_{random} < F$, F = Fill Factor
- QE&AB filter: $A_{random} < Q$, Q = Quantum efficiency & Avalanche breakdown triggering probability, $F \times Q = \mathrm{PDE} = 15\%@405\mathrm{nm}$
- Crosstalk filter: $A_{random} < C$, C = Crosstalk probability = 1%

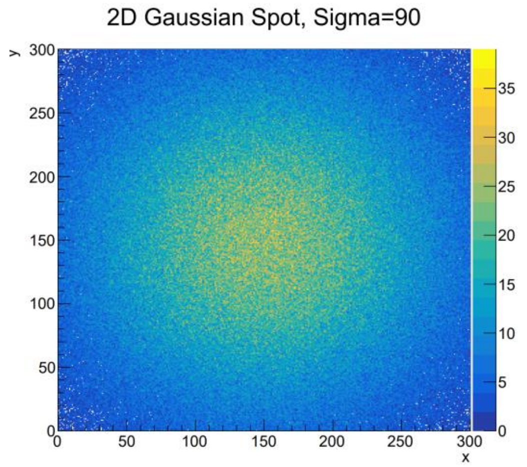
Simulation Results

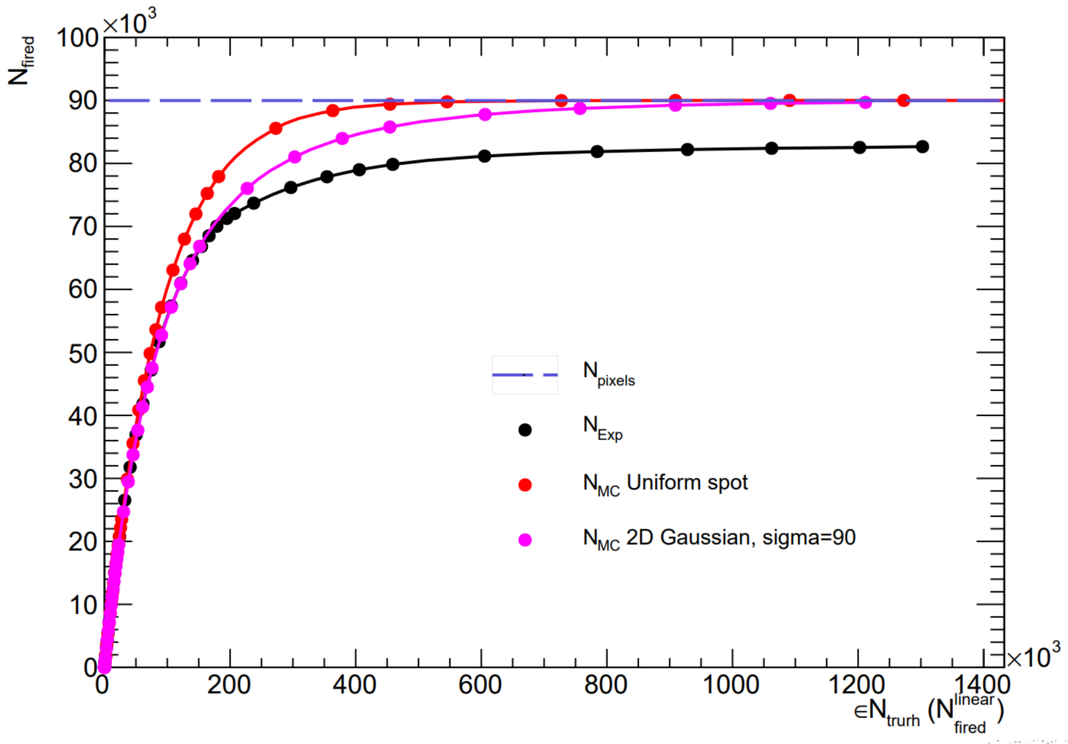
- All incident photons arrive on SiPM at the same time. No pixel recovery effect.
- Simulation is higher than experiment data.
  - Check the actual spot shape with CMOS(to be done)

HPK S14160-3010PS

- $3 \times 3mm^2$, $10\ \mu m$ pixel $\times$ 89984
- PDE=15% at 405nm
- Crosstalk=1%







Pixel Response Model with Recovery

- Pixels in SiPM can be recovered and fired multiple times if the pulse of light has a long duration.
- Gain and quantum efficiency will decrease if the pixel is not fully recovered.

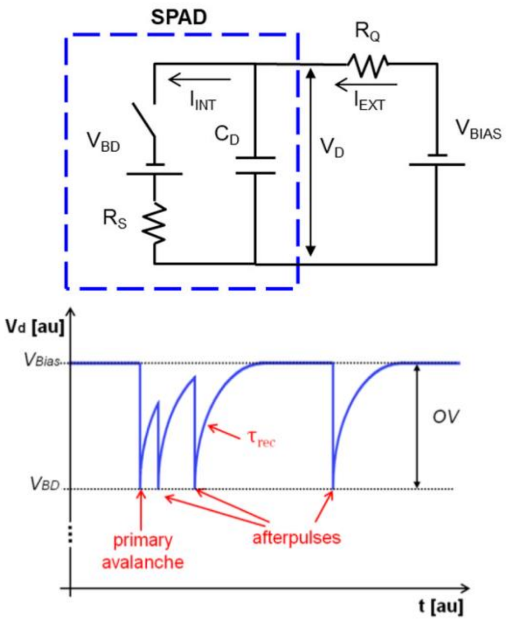
Signal function

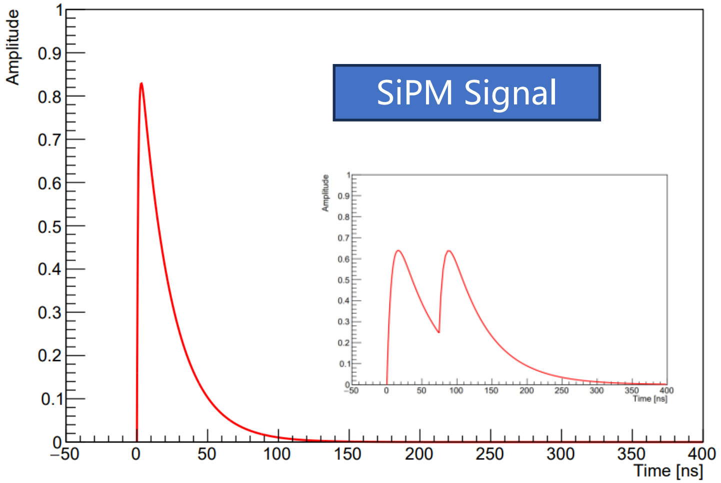
$$A(t) = \left(1 - e^{-\frac{t}{\tau_1}}\right) \cdot e^{-\frac{t}{\tau_2}}$$

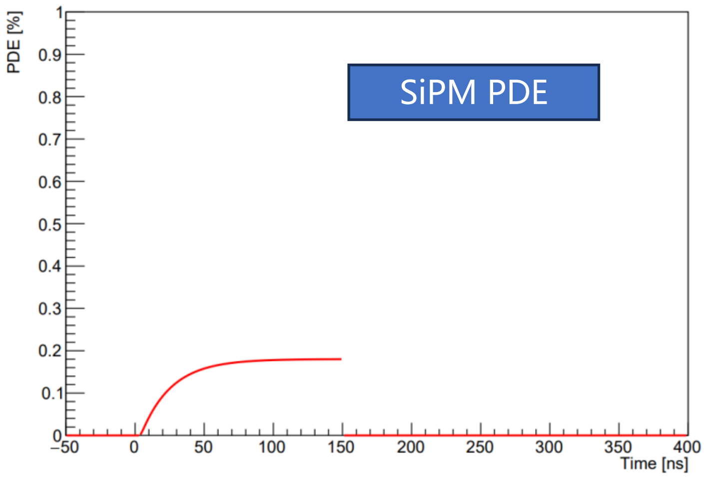
- τ_1: discharge time constant, ~1ns for S14160-3010PS
- τ_2: recharge time constant, ~22ns for S14160-3010PS

PDE function

$$PDE = \begin{cases} 0, & t_0 \sim t_{max} \\ PDE_0 \cdot \dfrac{A_{max} - A(t)}{A_{max} - A_{end}}, & t_{max} \sim t_{end} \end{cases}$$







[1] https://doi.org/10.1016/j.nima.2014.04.045 [2] https://doi.org/10.1016/j.nima.2018.11.119

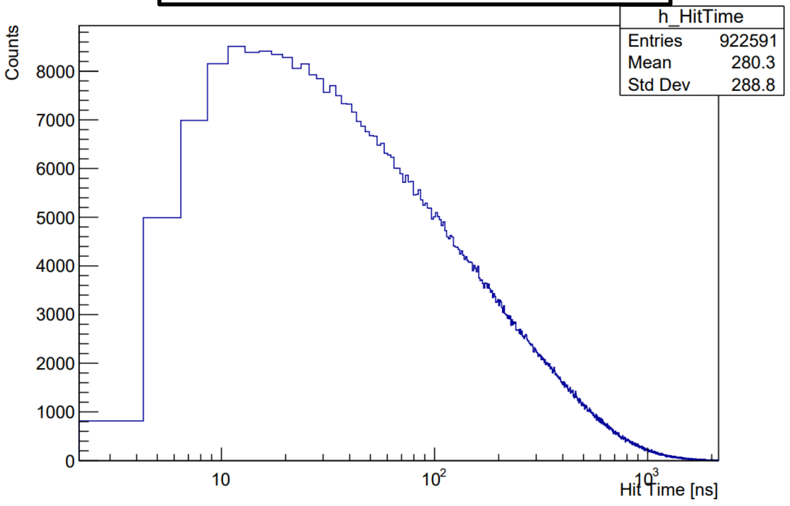
Simulation of SiPM with Recovery

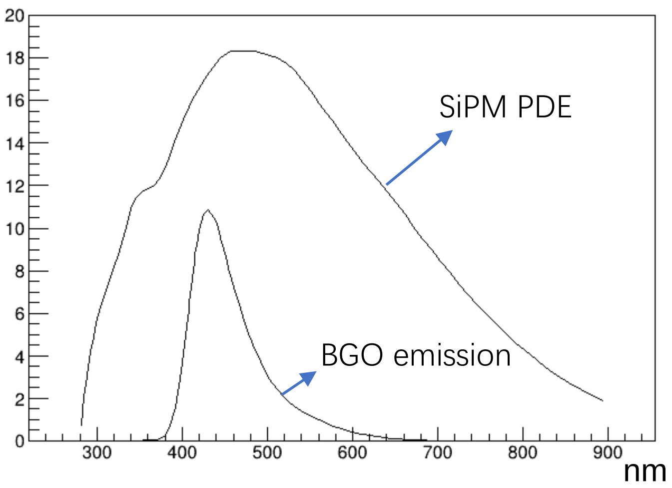
- MC with recovery effect:
  - Incident time of photon comes from Geant4 optical simulation of a $1 \times 1 \times 40cm^3$ BGO crystal bar
  - Uniform light spot on SiPM
  - SiPM PDE spectrum and BGO emission spectrum
- $1 \times 1 \times 40cm^3$ BGO crystal bar readout by SiPMs with $10\mu m$ pixel and $3 \times 3cm^2$ size can maintain linearity >95% at 5×10^4 pe light output

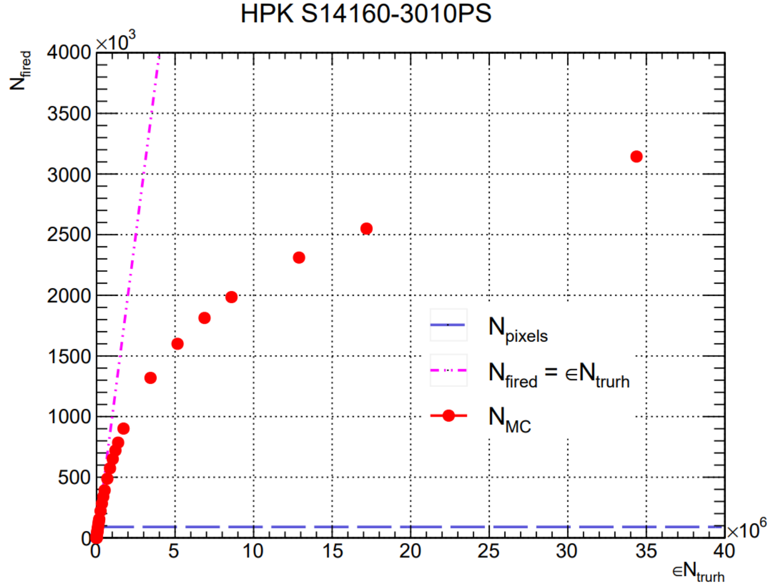
$3 \times 3\ \mathrm{mm}^2$

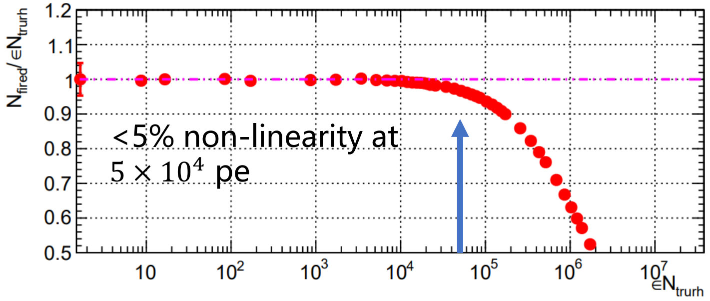
$10\mu m\ pixel\ \times 89984$

Time of photon to hit crystal ends









Summary

- Develop a method to measure the dynamic range of SiPM with large pixel number using PMT.
- Build a MC model for simulating the number of pe detected by SiPM under different light intensities, which contains spot shape, SiPM pixel density, PDE, crosstalk and recovery effect.
- Efforts are still needed to understand the gap between experiment and simulation.