Studies on Wide Dynamic Range SiPMs with Large Pixel Densities

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On behalf of CEPC Calorimeter Working Group

The 20th International Conference on Calorimetry

in Particle Physics

May 20-24, 2024, Tsukuba

SiPM in Optical Calorimeters

SiPM is widely used in future colliders

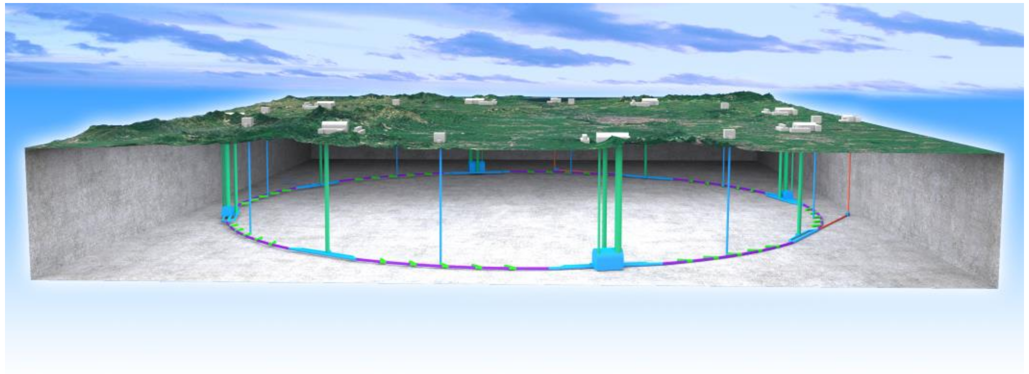
~8000ph/MeV for BGO, dynamic range is essential for homogenous calorimeter readout by SiPM

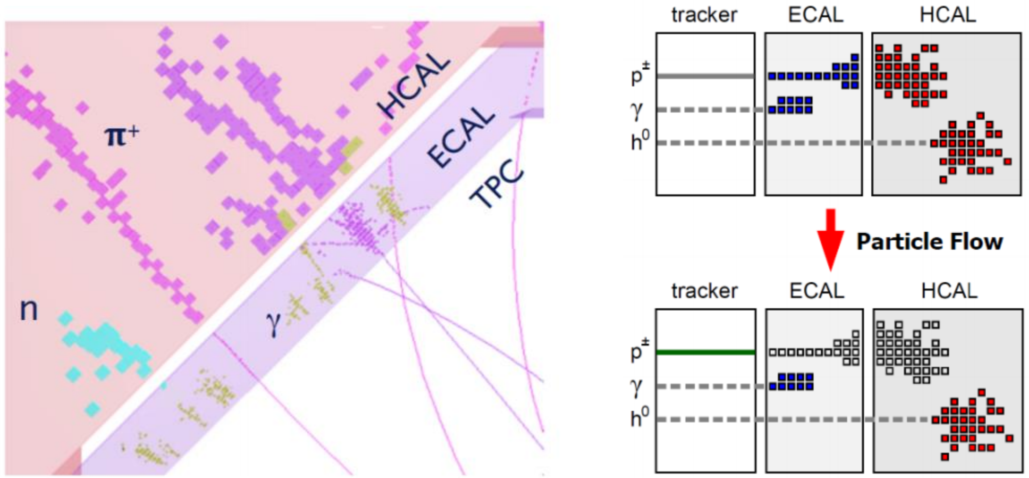
Project	Scintillator/WLS	Photodetector	DRDTs	Target
Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters				
HGCCAL	BGO, LYSO	SiPMs	6.1, 6.2	e^+e^-
MAXICC	PWO, BGO, BSO	SiPMs	6.1, 6.2	e^+e^-
Crilin	PbF_2, PWO-UF	SiPMs	6.2, 6.3	$\mu^+\mu^-$
Task 3.2: Innovative Sampling EM calorimeters				
GRAiNITA	$ZnWO_4$, BGO	SiPMs	6.1, 6.2	e^+e^-
SpaCal	GAGG, organic	MCP-PMTs,SiPMs	6.1, 6.3	e^+e^-/hh
RADiCAL	LYSO, LuAG	SiPMs	6.1, 6.2, 6.3	e^+e^-/hh
Task 3.3: (EM+)Hadronic sampling calorimeters				
DRCal	PMMA, plastic	SiPMs, MCP	6.2	e^+e^-
TileCal	PEN, PET	SiPMs	6.2, 6.3	e^+e^-/hh
Task 3.4: Materials				
ScintCal	-	-	6.1, 6.2, 6.3	$e^+e^-/\mu^+\mu^-$/hh
CryoDBD Cal	TeO, ZnSe, LiMoO NaMoO, ZnMoO	n.a.	-	DBD experiments

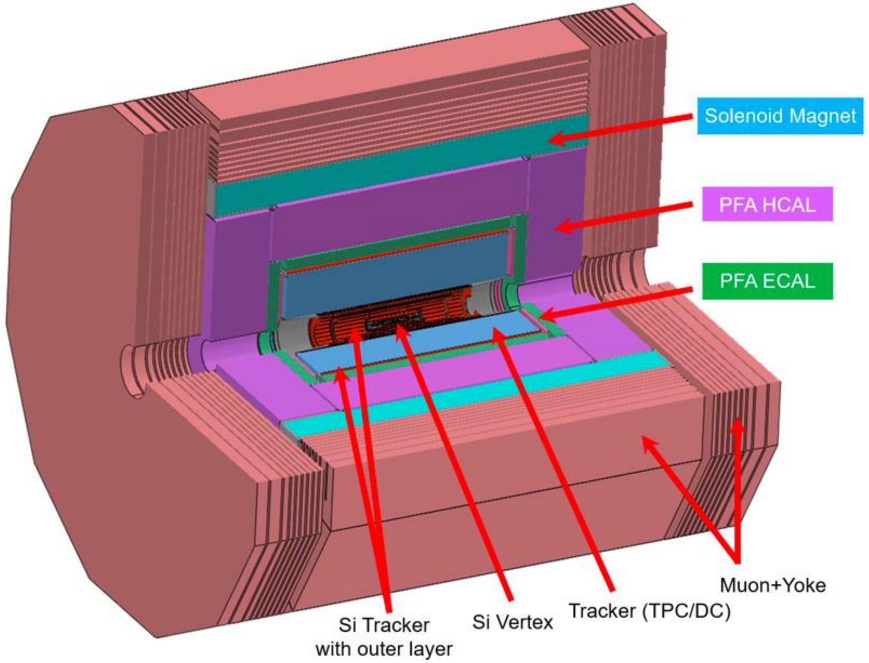
DRD 6: Calorimetry

New Detector for CEPC

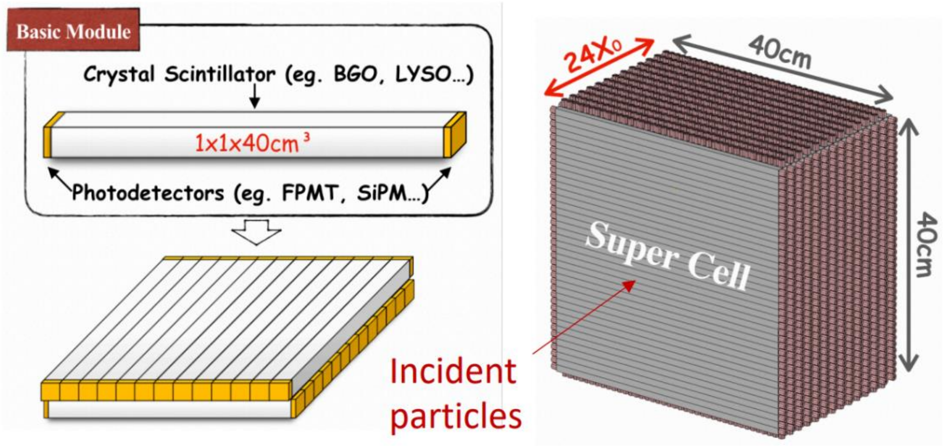
- CEPC: future lepton collider
  - Higgs/W/Z bosons, top, BSM searches, etc.
  - Precision jet measurement
  - Particle-Flow Algorithm (PFA)
    - High-granularity calorimeter: separation of showers
- "CEPC 4th concept" detector design
  - High-granularity crystal ECAL with homogenous structure
    -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

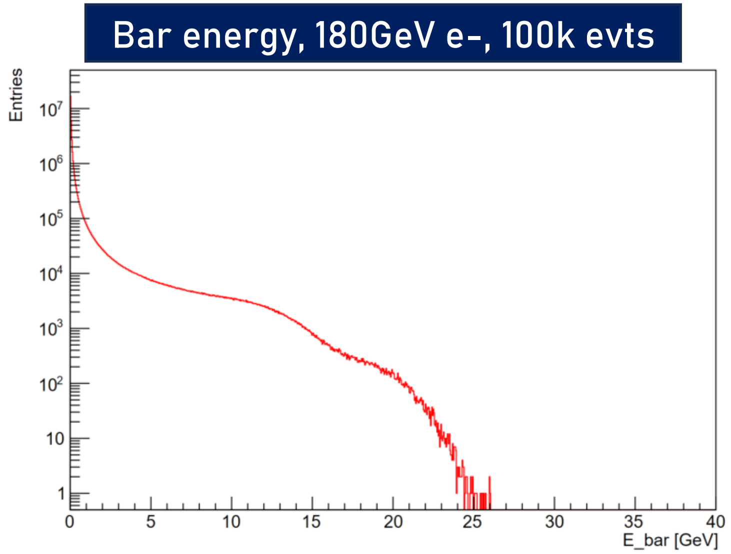






Dynamic Range Specification of Crystal ECAL

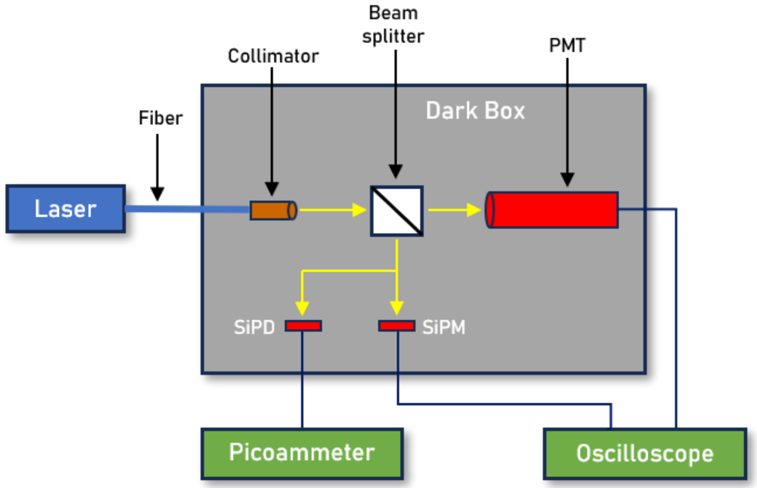




Key Parameters	Value	Remarks
MIP light yield	~200 p.e./MIP	~8.9 MeV/MIP in 1 cm BGO
Dynamic range	1~4.5×10^5 p.e. per channel	Deposited energy up to 40 GeV per crystal bar
Energy threshold	0.1 MIP	Depends on S/N and light yield
Timing resolution	~400 ps @ 1 MIP	Ideal value from Geant4 simulation
Crystal non-uniformity	< 1%	Calibration precision
Temperature stability	Stable at ~0.05 Celsius	Reference from CMS ECAL
Gap tolerance	~100 µm	TBD

Experiment to Measure the Intrinsic Dynamic Range of SiPM

- Setup
  - Pico-second laser: <40ps pulse width, 405nm wavelength
  - SiPM: DUT with large pixel numbers
  - PMT/Si-PD: scaler
- Linear region of the PMT can be extended by reducing its bias voltage



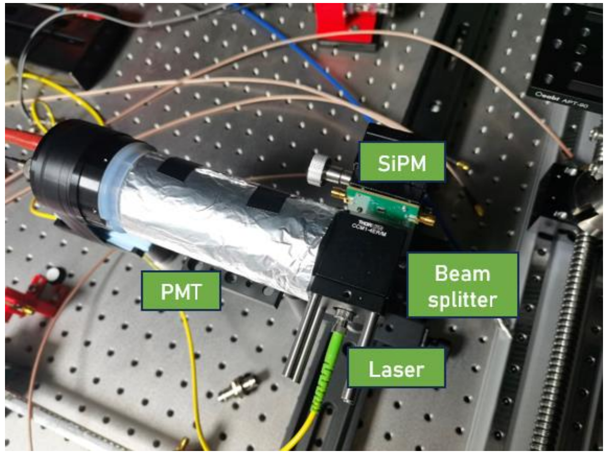
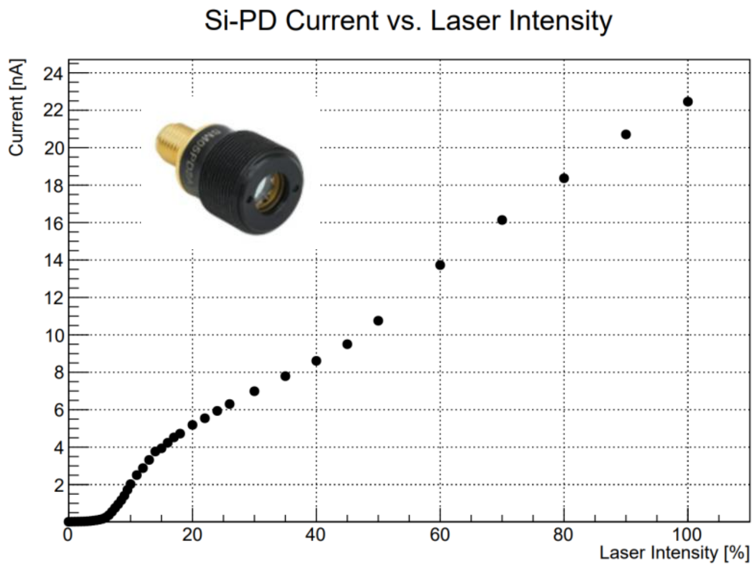


Table of measured SiPMs

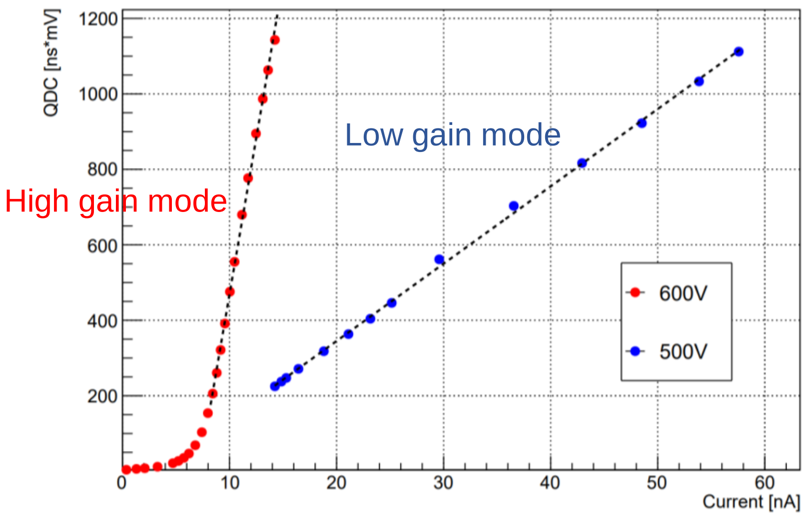
SiPM Model	Active Area(mm^2)	Pixel Pitch(μm)	Pixel Number
HPK S13360-6025PE	6×6	25	57,600
HPK S14160-3010PS	3×3	10	89,984
NDL EQR06 11-3030D-S	3×3	6	244,719

Operation Modes Selection for PMT

- Select the linear regions of PMT with a Si-PIN at different light intensities
  - High gain mode: 600V bias voltage, applied in weak light
  - Low gain mode : 500V bias voltage, applied in strong light
- Combination of discrete linear regions can keep PMT's linear output within the whole light range

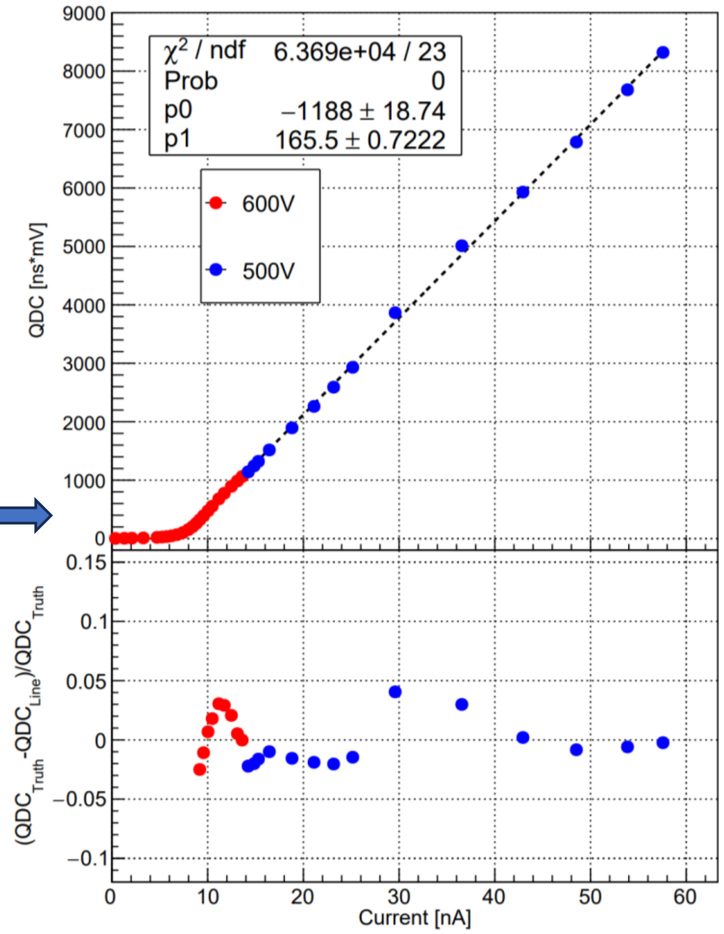


PMT response



- Low gain mode has a wider linear area

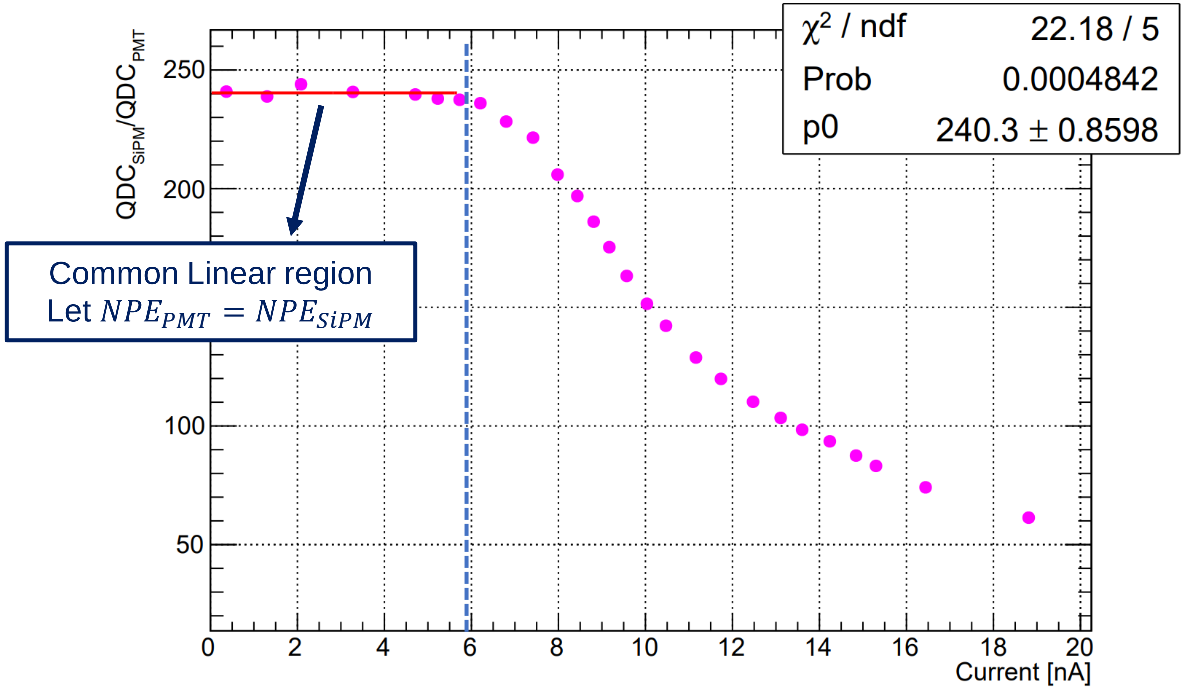
PMT response after modes combination



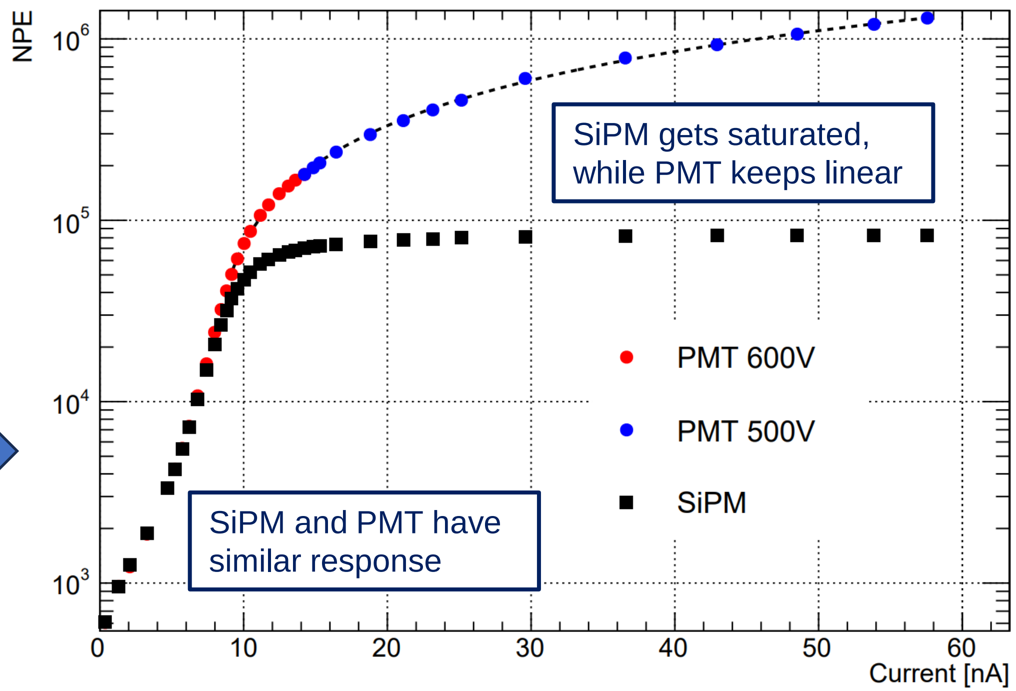
PMT Gain Calibration

- Gain of PMT at 600V is not high enough to discriminate single pe
- Let the number of pe detected by PMT same as that by SiPM at weak light region
- After calibration, Linear region of PMT can cover the response range of SiPM

Ratio of SiPM output to PMT output



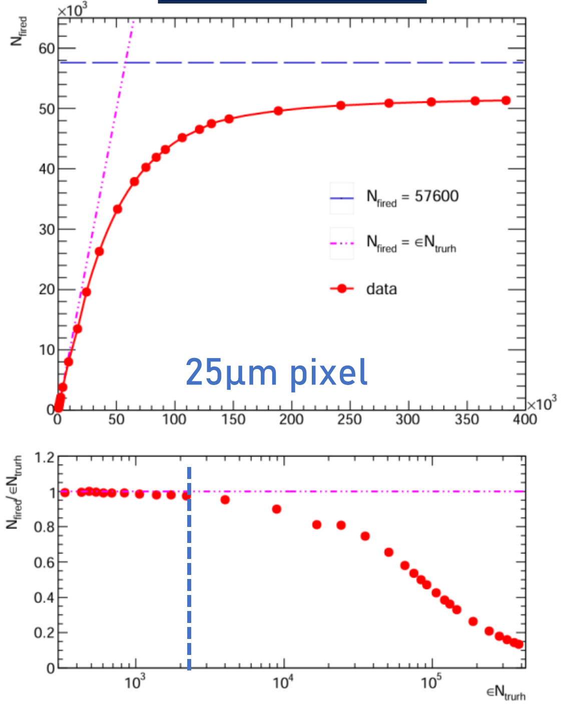
Output comparision



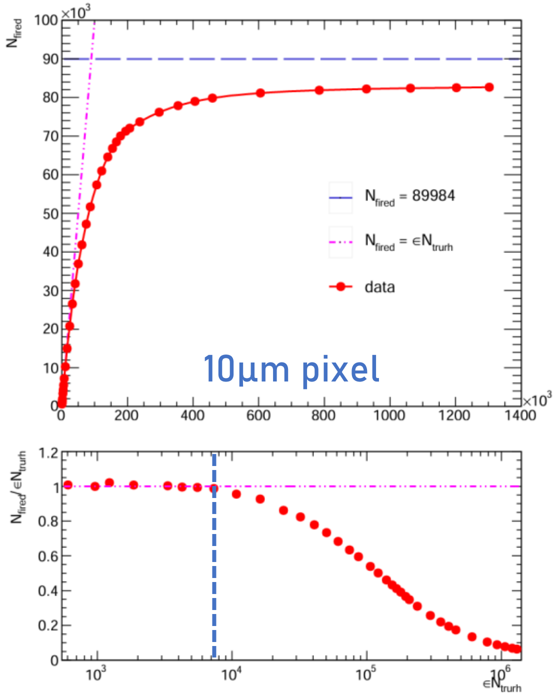
Intrinsic Dynamic Range of SiPM in Laser Test

- Picosecond laser as source, no pixel multi-fired effect
- Saturation values of SiPM with 25μm or 10μm pixels are close to but a little smaller than their pixels number
- For SiPM with 6μm pixels: Non-linearity starts at very beginning region, and the saturation value is only half of its pixel number

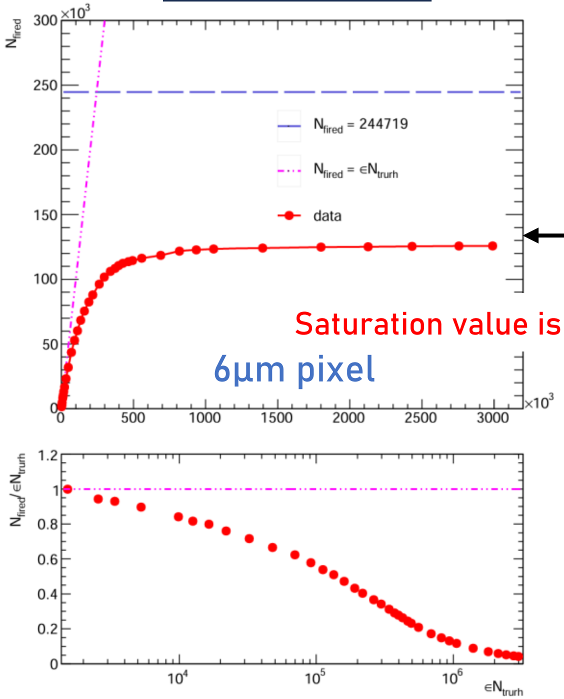
S13360-6025PE



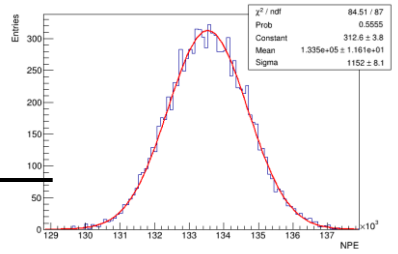
S14160-3010PS



EQR06



Another device also shows similar result

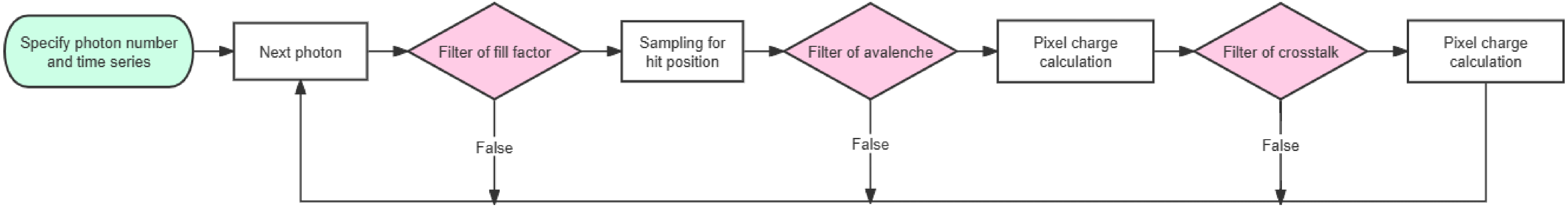


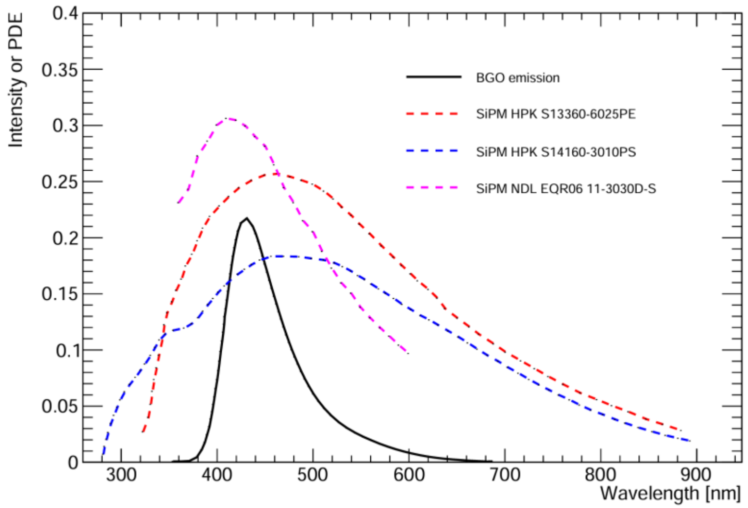
Saturation value is extremely small

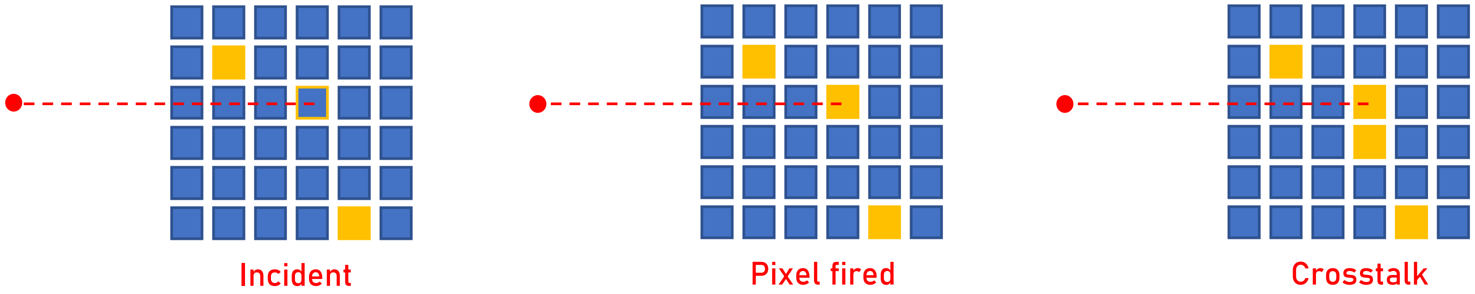
Nonlinearity appears very early

Toy Monte Carlo of SiPM Response

- Major properties of SiPM including:
  - pixel density, fill factor, quantum efficiency & avalanche probability, crosstalk, etc.





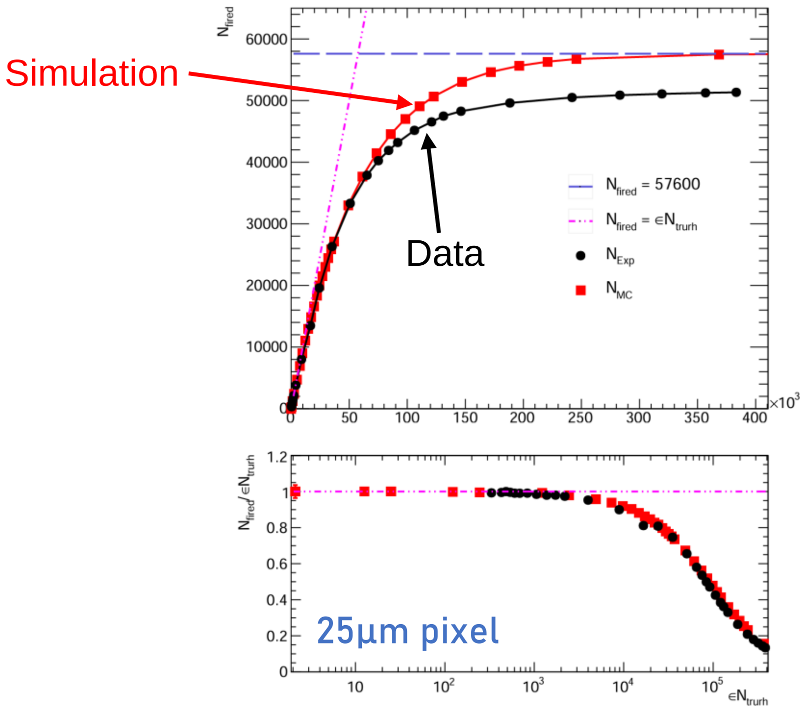


Simulation of SiPM – Laser Light

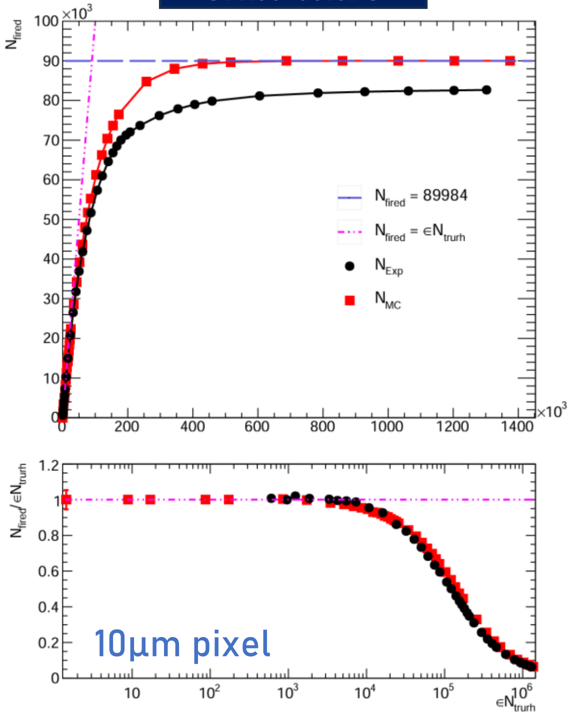
- Assume the detected time is the same for all photons
- Result of MC is strictly saturated to pixel number, a little larger than experiment data.
- If we ignore the gap between data and MC, the simulation results can describe the experimental trend well.

Toy Monte Carlo including
- SiPM pixel density, PDE spectrum, crosstalk
- BGO emission spectrum

S13360-6025PE



S14160-3010PS



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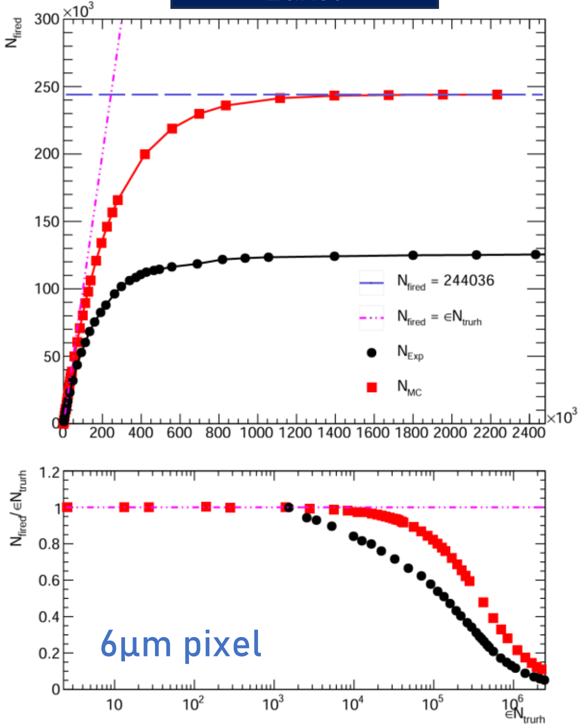
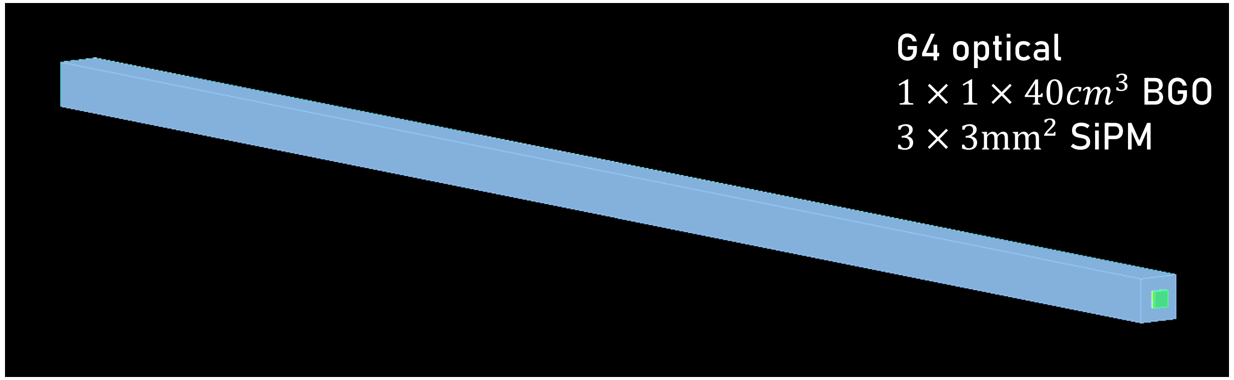
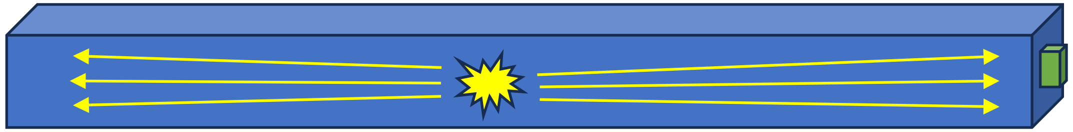


Detected Time of Scintillation Photons

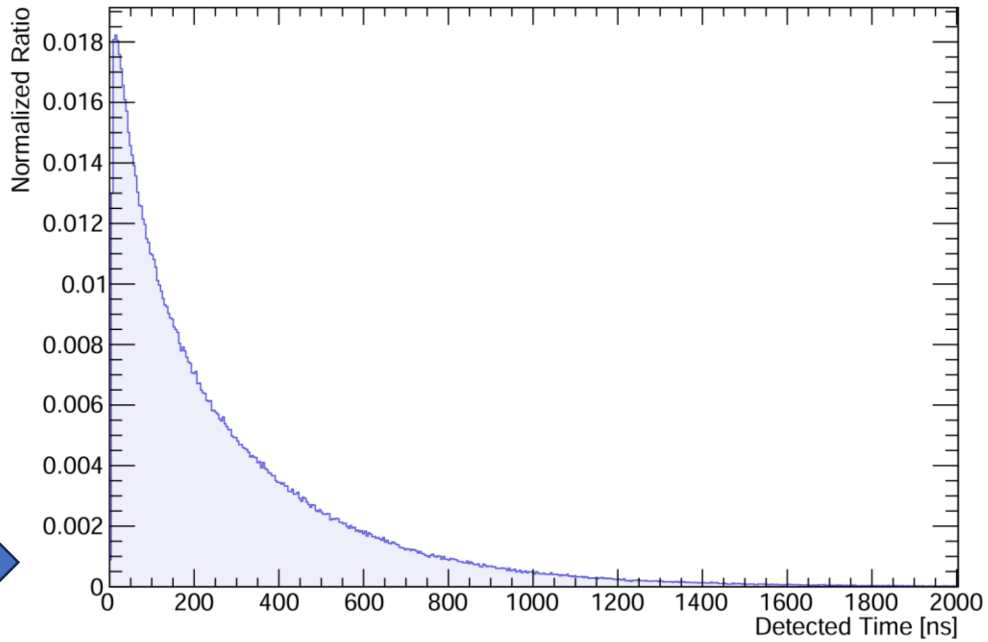
- Photon detected time is critical for SiPM response
- Time duration is ~2μs, because of the slow component(300ns) in BGO and long transportation length
  - Pixels in SiPM can be fired multiple times





A consequence of detected time of scintillation photons

Detected time distribution of scintillation photons

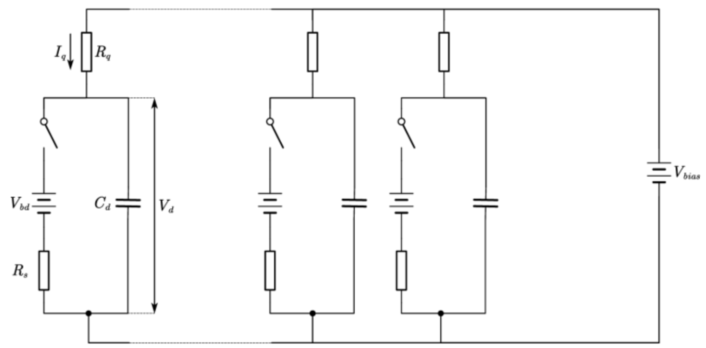


Histogram used for sampling in waveform simulation

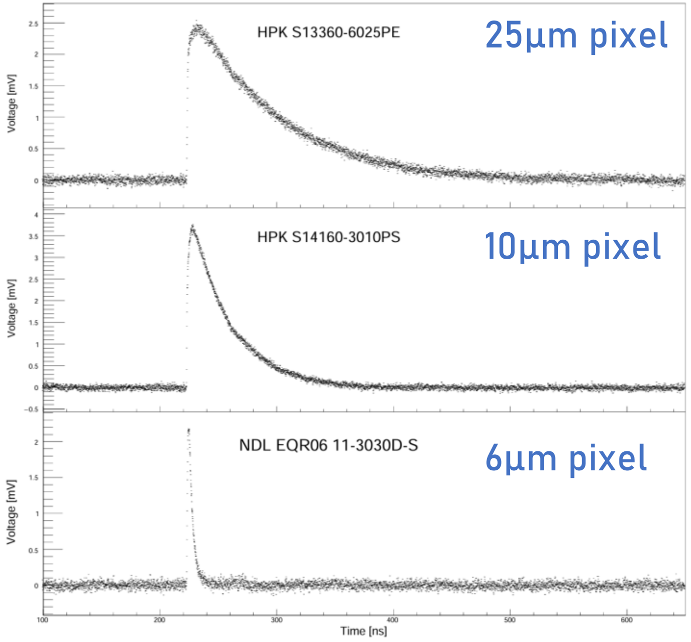
Waveform Simulation and Charge Distribution of Multi-fired Effect

- Number of detected photons can be determined by waveform integral(QDC)
- Waveforms of single photoelectron obtained from fitting for measurement
- For multi-fired situation in single pixel, the total charge is not a simply sum of individual PEs, but depends on recovery state of the pixel

SiPM electronical model

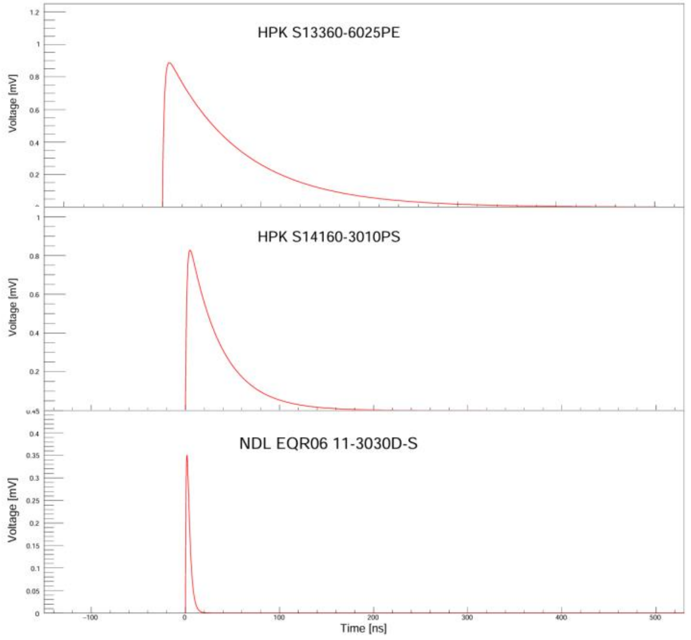


Waveforms from measurement

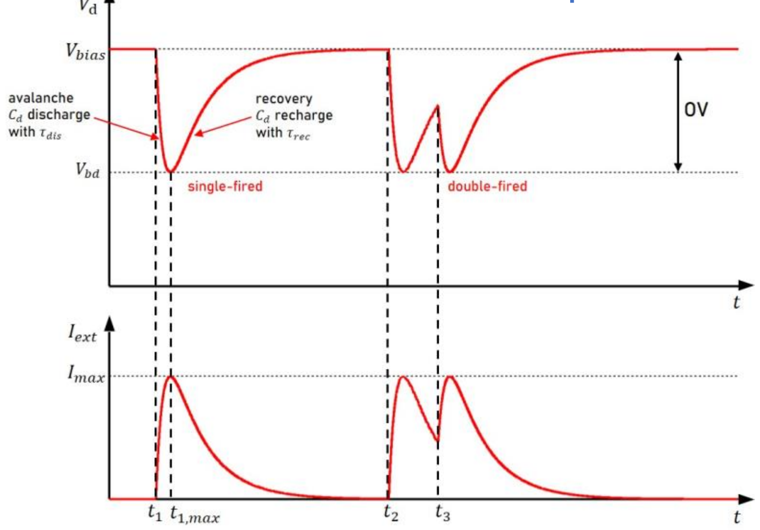


Laser test

Waveforms in simulation



Multi-fired within one pixel



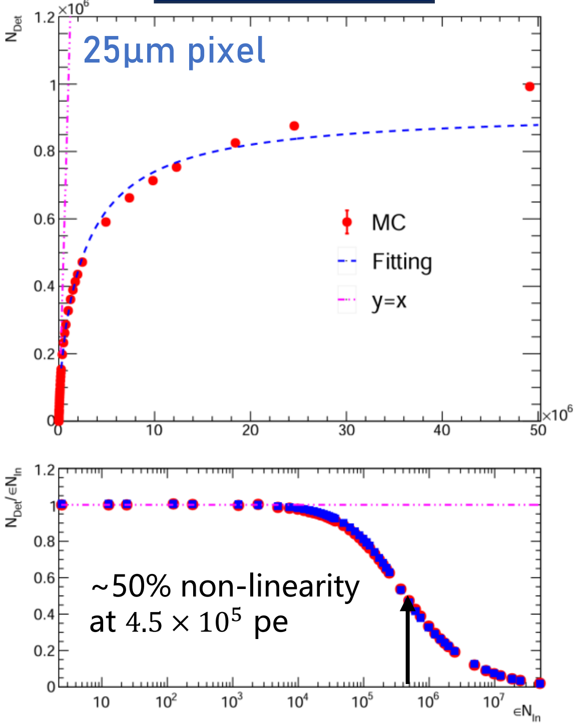
Assume PDE is in proportional to OV

Simulation of SiPM – BGO Scintillation Light

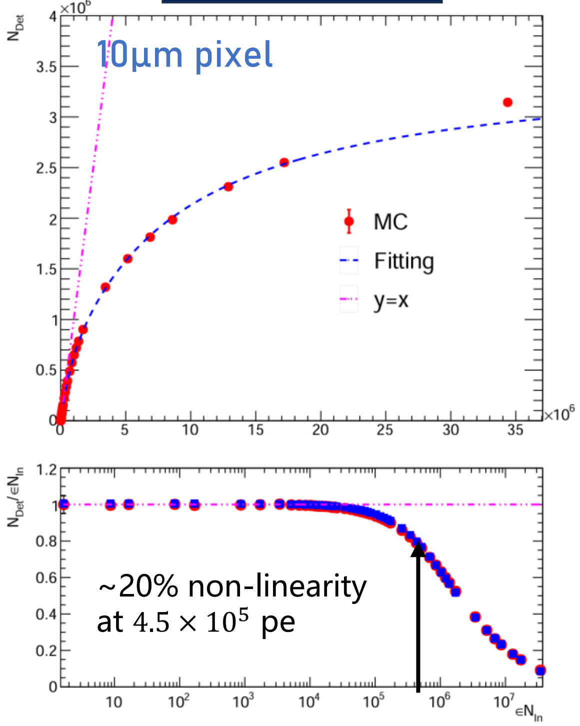
Toy Monte Carlo including
- SiPM pixel density, PDE spectrum, crosstalk, waveform properties, pixel multi-fired effect
- BGO emission spectrum, detected time of scintillation photon

- 6μm SiPM displays enough dynamic range(<5% non-linearity at 4.5×10^5 pe) for ECAL specification
- Provide a method to correct on the saturation effect of SiPM

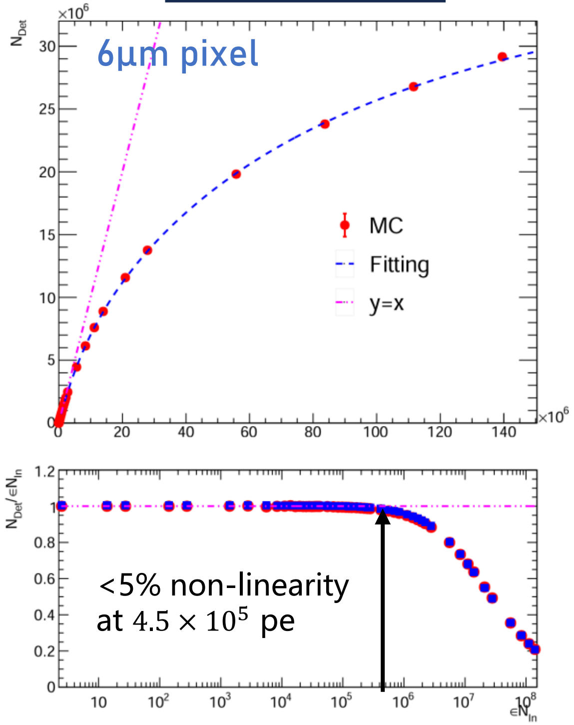
S13360-6025PE



S14160-3010PS



EQR06



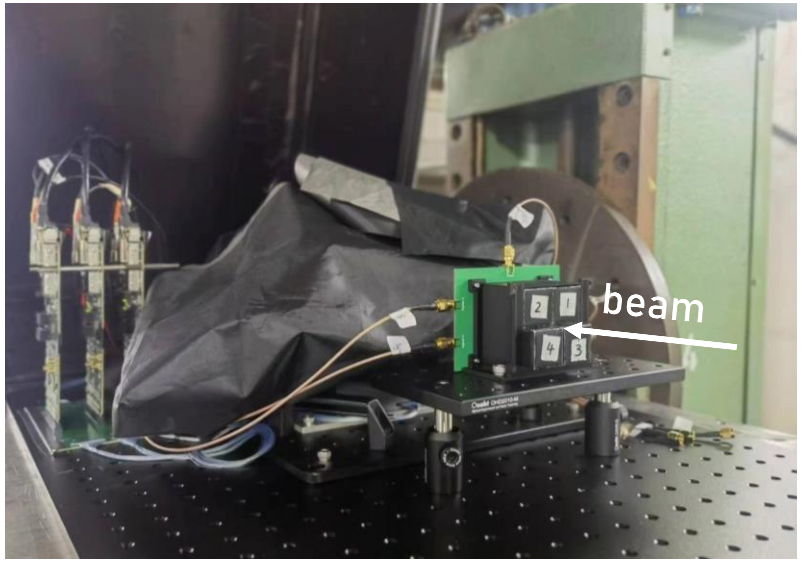
Fitting function:
arxiv.1510.01102

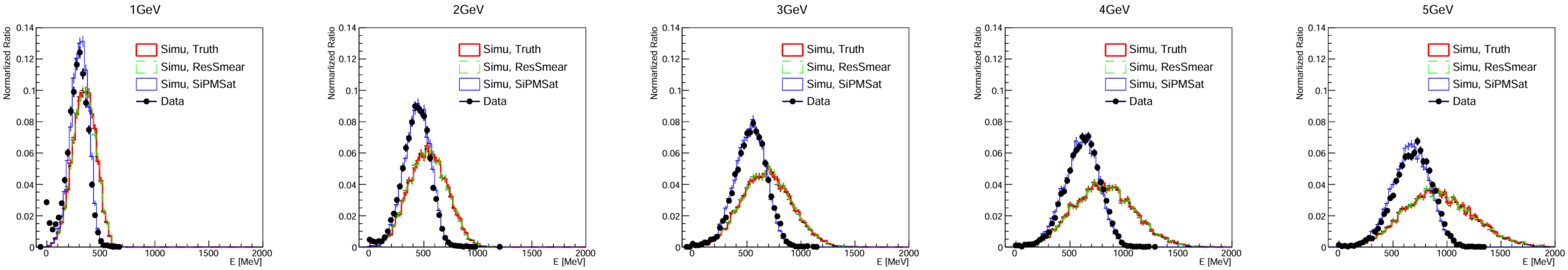
Examination with Beamtest

- Beamtest of LYSO crystals to examine the saturation correction method
  - $2.5 \times 2.5 \times 4/5cm^3$ LYSO, HPK S14160-3010PS, ~150 p.e./MeV
- Simulated energy deposit deviates significantly from data, because of the large light output by LYSO
- SiPM saturation can be well described with Toy Monte Carlo

R&D of DarkSHINE ECAL

Beamtest at DESY TB22, Oct. 2023, 1-5GeV e-





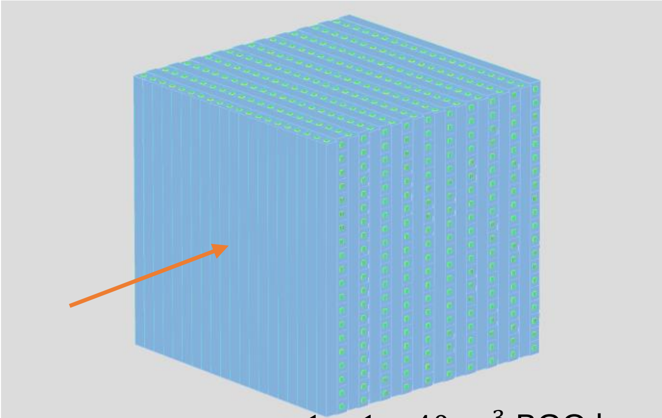
Summary & Prospect

- Design an experiment to measure the dynamic range of SiPM with large pixel number using PMT.
- Build a MC model for simulate SiPM behavior when measuring the laser light and scintillation light. The model can be used to correct the saturation effect of SiPM.
- Need more tests to understand the gap between experiment and simulation.
- Examine the method with more types of scintillators and SiPMs.

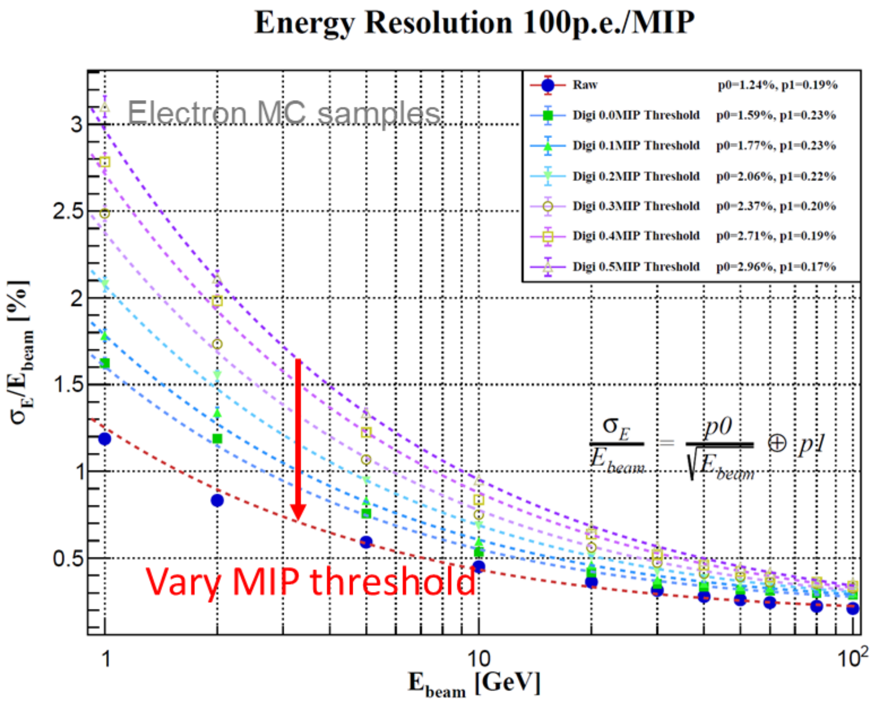
EM Energy Resolution: Threshold and Light Yield Requirements

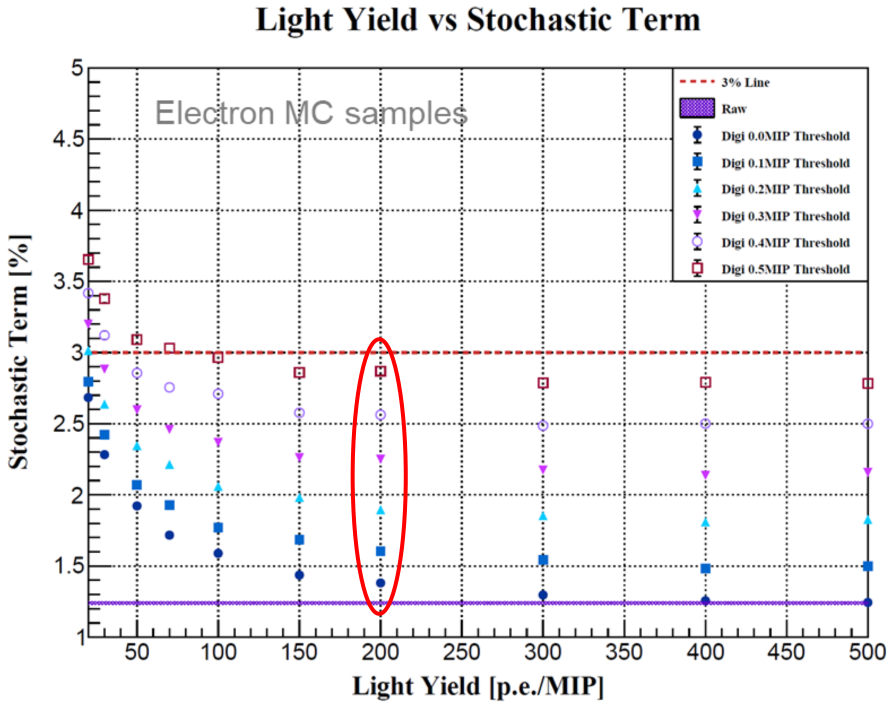
- Impact of hit threshold and light yield
  - Digitization: photon statistics (crystal + SiPM), electronics resolution
  - 200 p.e./MIP is enough for $3\%/\sqrt{E}$, low threshold is promising for $1.6\%/\sqrt{E}$

Geant4 Simulation (v10.7)

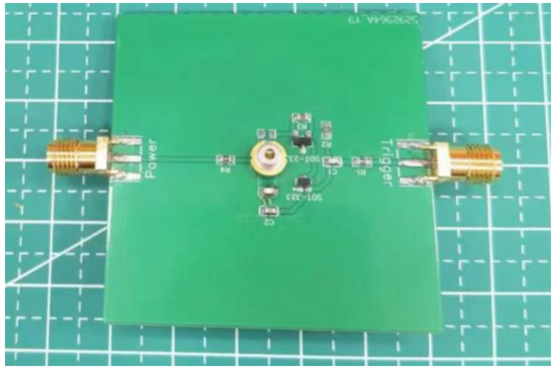


$1 \times 1 \times 40 cm^3$ BGO bars





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.