Simulation Studies of the Effect of SiPM Dark Noise on the Performance of a Highly Granular Crystal ECAL

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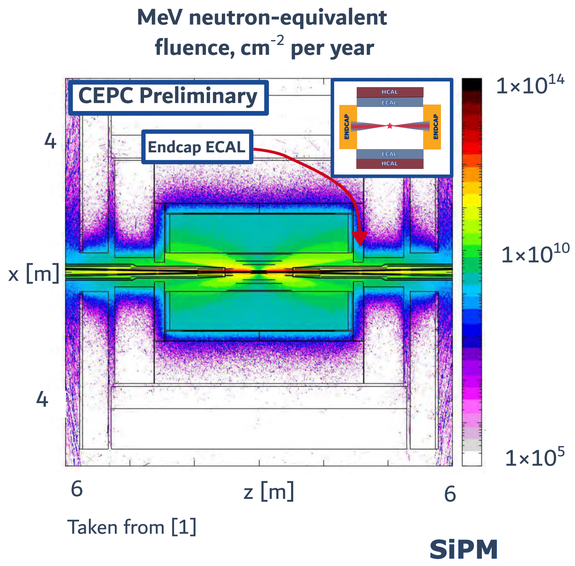
Overview

Fluence At CEPC

- CEPC detector will endure unprecidented fluences during operation;

- Φ ≈ 1×10 cm per year to beam pipe/at endcaps;

- Studies ongoing to reduce damage on instrumentation;

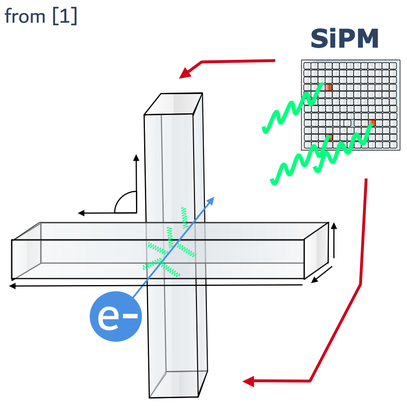


Taken from [1]

Highly Granular Crystal ECAL

- 40 cm scintillating crystal bars (BGO, BSO) provide;
  - granularity to separate individual particles;
  - excellent EM energy resolution (~1-2%/GeV)

- Light signal read out by



Silicon Photomultipliers (SiPM)

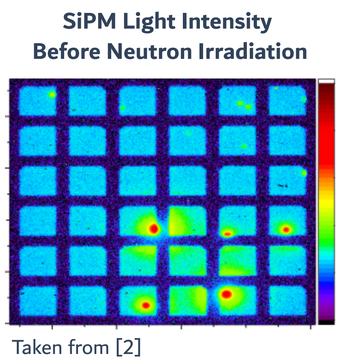
- Hadrons main source of damage for SiPMs (Non Ionising Energy Loss, NIEL);

- Crystal lattice displacement leads to **defects;**

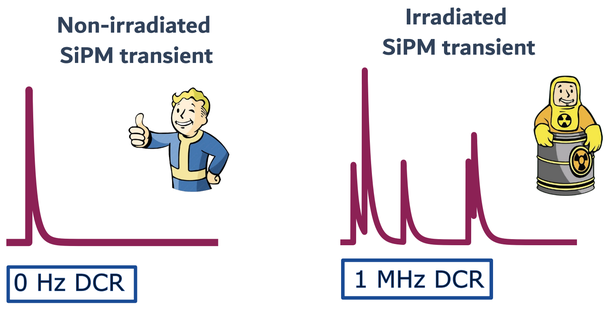
- Defect-assisted trap-hole recombination → **dark noise;**

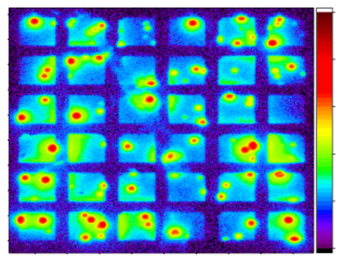
- **Dark noise degrades calorimeter performance;**

- **Additional signal from 'dark counts'**



Taken from [2]



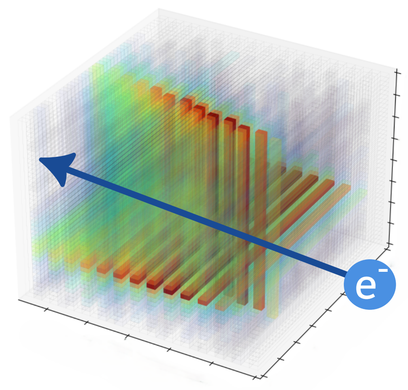


Taken from [2]

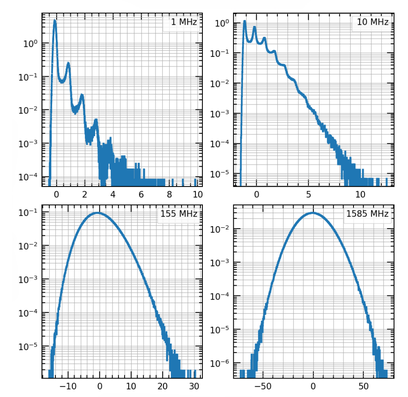
Summary of Study

Simulation

Particle showers
- Geant4 simulation;
- DD4HEP geometry description;
- 1 - 40 GeV electron showers;
- 1×10^4 events per sample;
- Digitisation includes cross-talk and correlated noise;



Dark Noise
- LightSimtastic SiPM simulation [2];
- DCR: 1 MHz - 1.58 GHz, log scale
- 1×10^7 events per DCR sample;
- Resampled per event;



Analysis

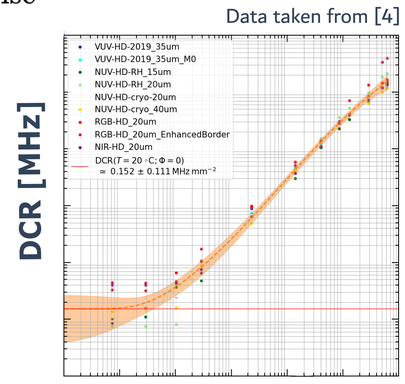
- Dark noise combined with electron simulation using:
  - average crystal light yield, Φ= 200 p.e/MIP;
  - noise threshold, Q_{thresh} = 0.1 p.e;

$$Q_{\text{Signal+DCR}} = \begin{cases} \Phi_{\text{crystal}} \times E_{\text{sim}} + Q_{\text{DCR}} & \text{if } Q_{\text{Signal+DCR}} > Q_{\text{thresh}} \\ 0 & \text{otherwise} \end{cases}$$

- SiPM DCR related to fluence using study of Ref. [4];

- Resolution and linearity obtained using fits of Crystal Ball distribution to reconstructed energy;

Data taken from [4]

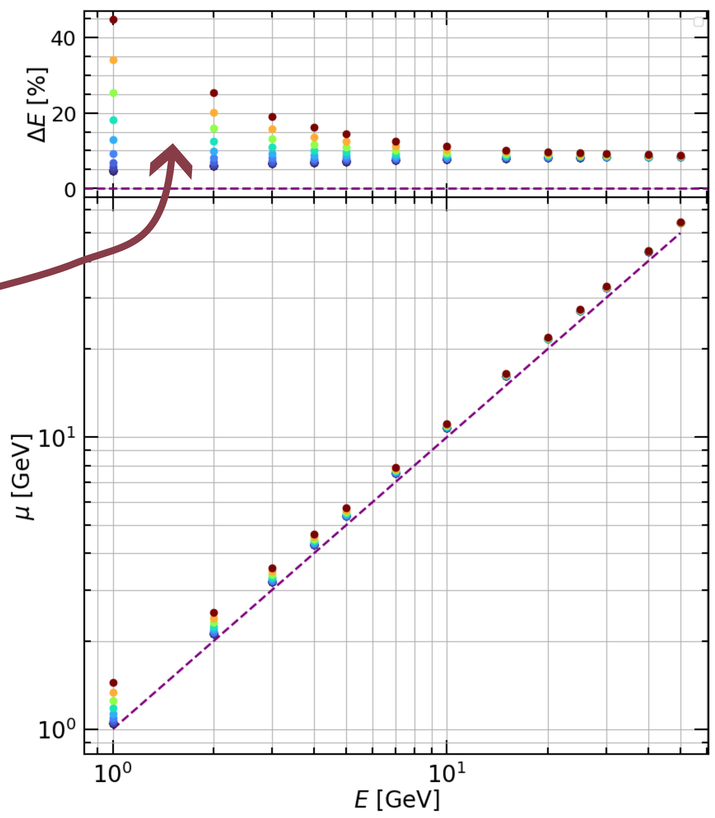


Key Question:

How does irradiation-induced dark noise degrade calorimeter resolution and linearity?

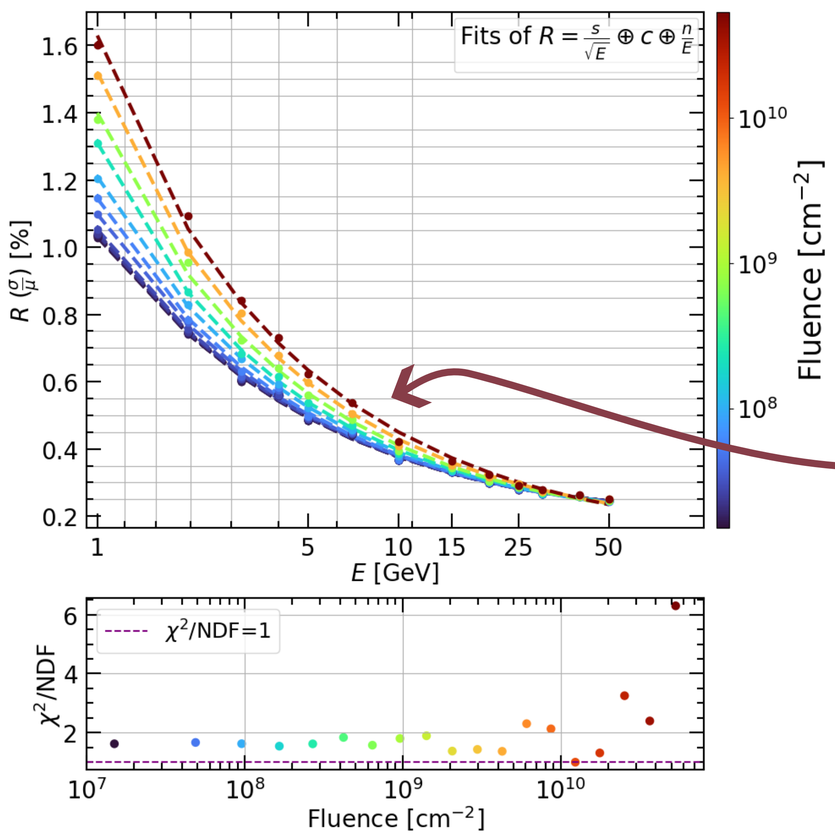
Key Results

Linearity of Response



Linearity for <10 GeV showers degrades by up to 42% after around 1×10 cm fluence

Resolution



EM single-particle resolution degrades by ~0.5% after around 1×10 cm fluence

Take Home Message:

Radiation damage of SiPMs is a critical R&D issue for this calorimeter

[1] The CEPC Study Group, CEPC Technical Design Report -- Reference Detector, arXiv:2510.05260 [hep-ex] (2025), https://arxiv.org/abs/2510.05260.

[2] Engelmann, E., Popova, E., & Vinogradov, S. (2018). Spatially resolved dark count rate of SiPMs. The European Physical Journal C, 78(11), 971. https://doi.org/10.1140/epjc/s10052-018-6454-0

[3] UHH DetLab. (2025). LightSimtastic: A silicon photomultiplier simulation package [Computer software]. GitLab. https://gitlab.rrz.uni-hamburg.de/uhhdetlab/sipm/lightsimtastic

[4] Altamura, A. R., Acerbi, F., Di Ruzza, B., Verroi, E., Merzi, S., Mazzi, A., & Gola, A. (2023). Radiation damage on SiPMs for space applications. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1045, 167488. https://doi.org/10.1016/j.nima.2022.167488