Tsung-Dao Lee Institute

CALOR 2024 Tsukuba

DARK SHINE

R&D of DarkSHINE ECAL

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On behalf of DarkSHINE Working Group

The 20th International Conference on

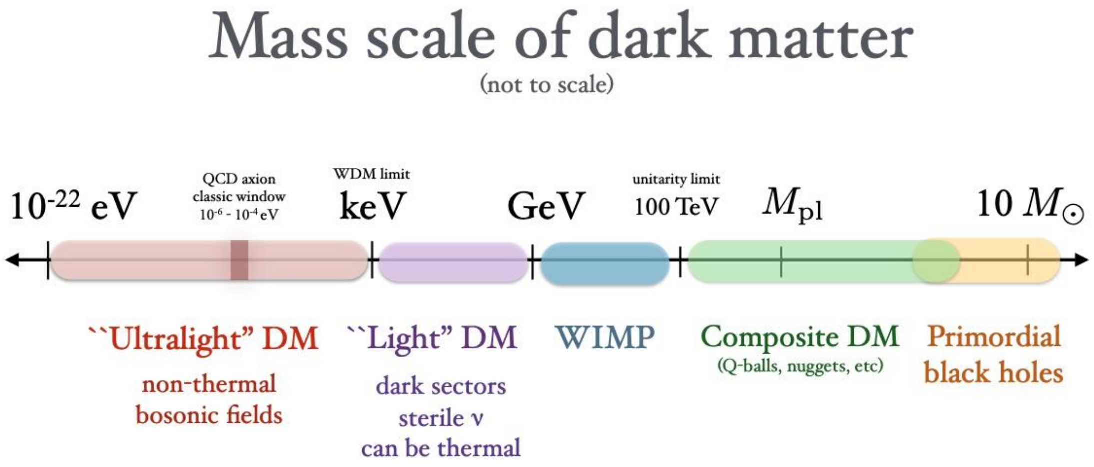
Calorimetry in Particle Physics

May 20-24, 2024, Tsukuba

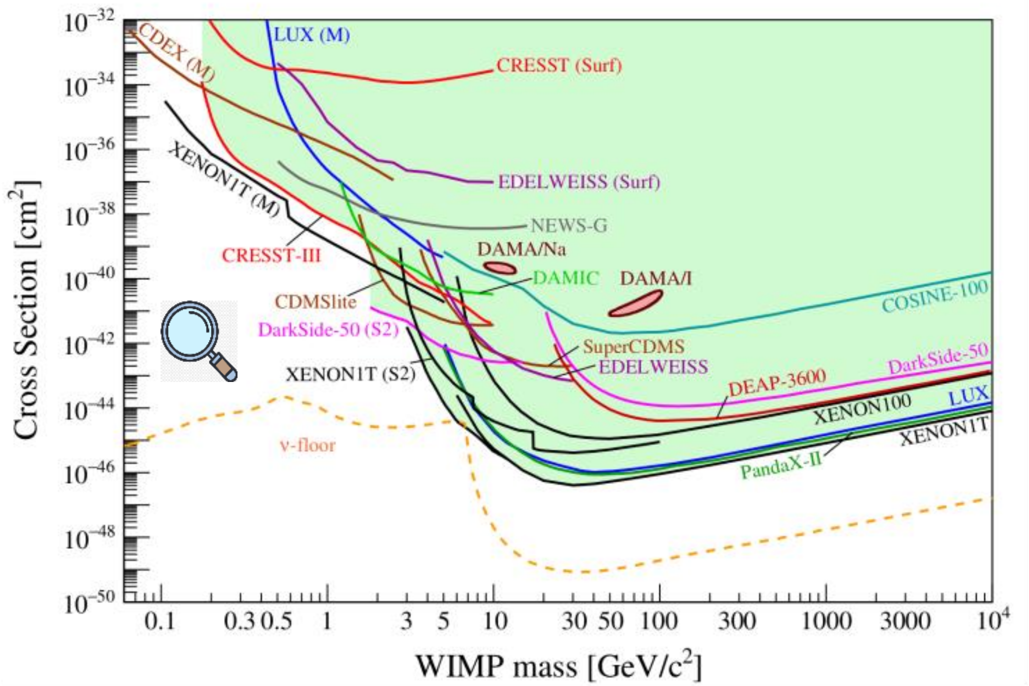
Dark Matter Search

- Dark matter evidence from astronomical observations and gravitational effects:
  - Galactic rotation curves, Gravitational lensing, Cosmic Microwave Background anisotropies, …
- The “freeze-out” mechanism predict the mass of dark matter is mainly distributed from MeV to tens of TeV
  - Weakly Interacting Massive Particles (WIMP): A large parameter space ruled out in GeV~TeV mass range.
  - **Light DM: Sub-GeV mass range not fully explored yet.**

arXiv:1904.07915



APPEC Committee Report: 2104.07634

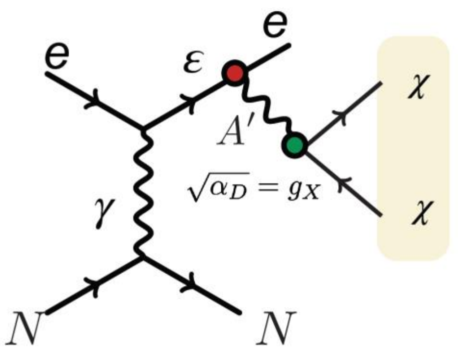


DarkSHINE Experiment Searching for Dark Photon

Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)

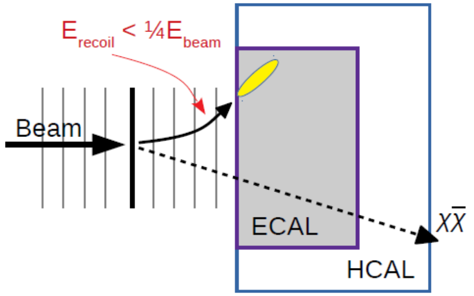
- Dark photon is regarded one candidate particle of light dark matter
- DarkSHINE: fixed target experiment based on single e- beam provided by SHINE
  - Minimal dark-photon model: dark photon bremsstrahlung and its invisible decay
  - 1~10MHz single e- beam @8GeV, up to 3×10^{14} electron-on-target(EOT) per year

INVISIBLE DECAY MODE $m'_A > 2m_X$



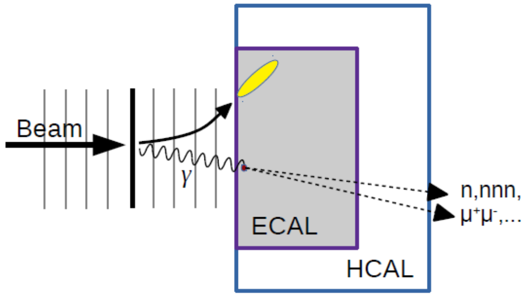
Signal

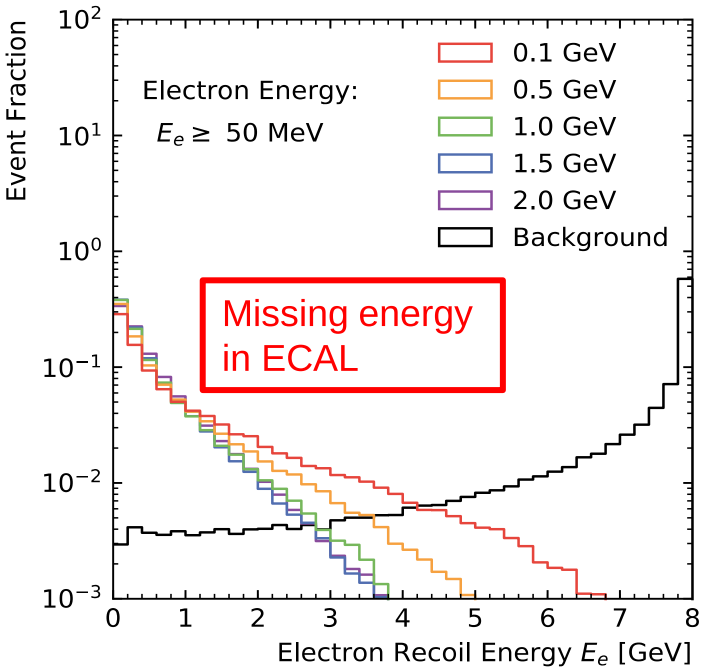
Most of the incident momentum is transferred to DP



Rare background

Missing momentum and missing energy, vetoed by HCAL





Leading background:

Photon bremsstrahlung

Rare background:

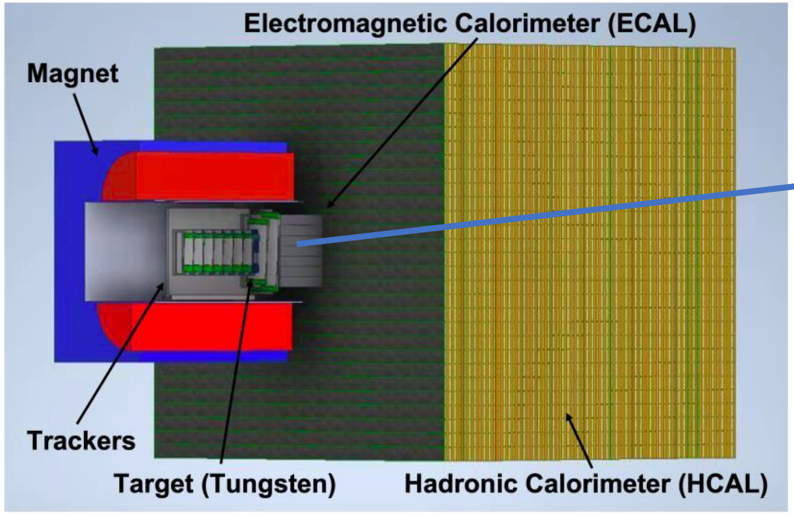
Photon-nuclear, $\gamma \to \mu\mu$, electron-nuclear…

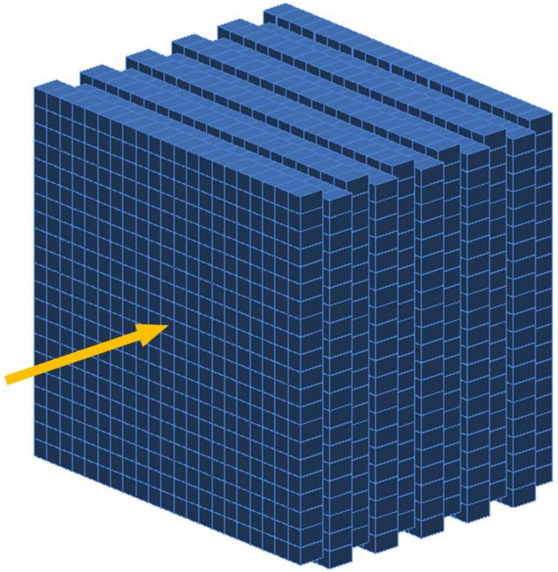
Invisible background:

Neutrino productions (negligible)

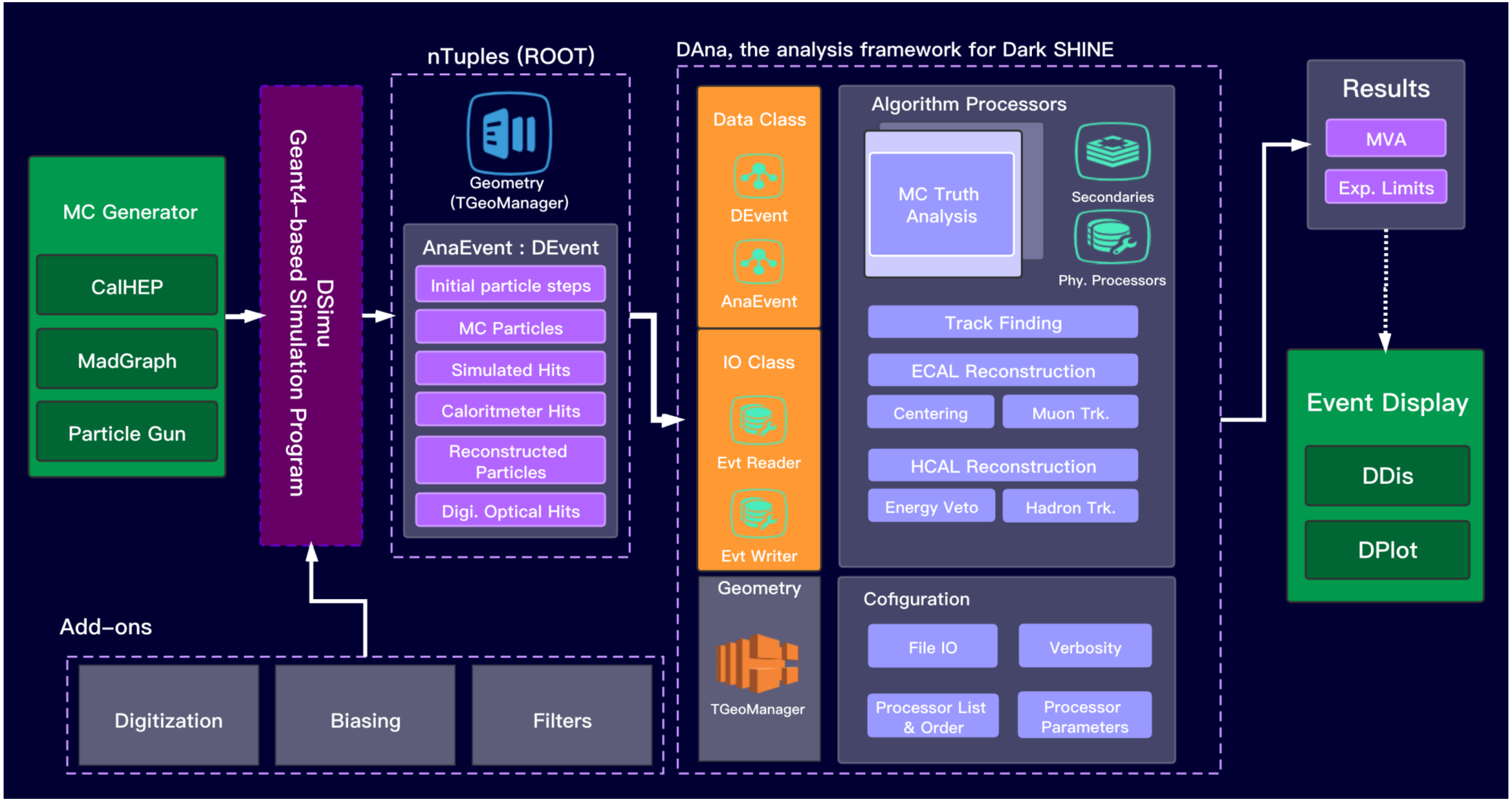
Overview of ECAL in DarkSHINE

- Target: measure the energy of recoil electron and bremsstrahlung gamma
  - Radiation hard: survive in $\sim 10^7 rad$ dose and $\sim 10^{13}\ n_{\mathrm{eq}}$(one year)
  - Large size: contain all of the EM components
  - Fast response: minimum to 1us-100ns time window
- Design: homogeneous LYSO crystal calorimeter
  - LYSO: >30000pe/MeV, 40ns decay time, density $7.2\ g/cm^3$, radiation hard
  - Staggered structure, 3D segmentation, ~39 radiation length





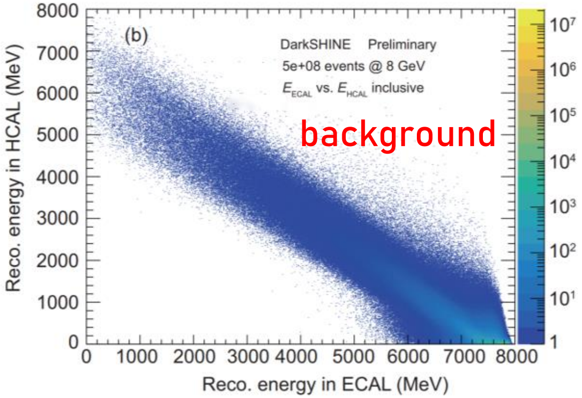
DarkSHINE Software Framework

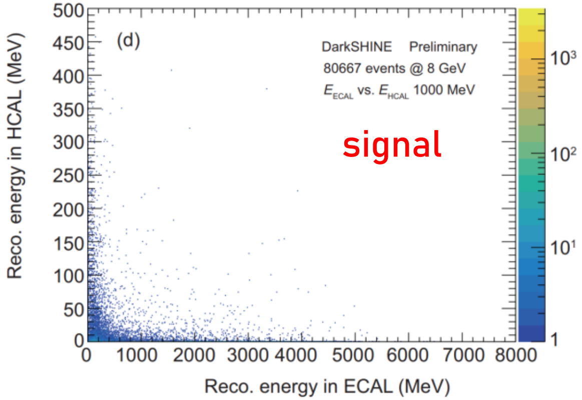


~5ms per event

ECAL Performance in Background Rejection

- Signal region is defined by some different features of signal and background in detector response
  - Track number, missing momentum, missing energy, HCAL veto
  - Only use the total energy of ECAL in the current analysis.
- Zero background can be achieved, for 2.5×10^9 inclusive electron-on-target events(EOTs) and $\sim 10^{12}$ rare process EOTs,
- The Signal efficiency is about 60%.





Event ratio of background after signal region cut flow

$\sim 10^{12}$ EOTs (EN_ECAL – GMM_target) | $\sim 10^{8}$ EOTs (Hard_brem) | $\sim 10^{9}$ EOTs (Inclusive)

	EN_ECAL	PN_ECAL	GMM_ECAL	EN_target	PN_target	GMM_target	Hard_brem	Inclusive
Total events	100	100	100	100	100	100	100	100
Only 1 track	58.87	70.48	87.36	5.85	5.88	$< 10^{-3}$	78.73	84.40
$p_{tag} - p_{rec} > 4$ GeV	0.0044	0.0033	0.0041	5.58	5.46	$< 10^{-5}$	70.49	4.80
$E_{HCAL}^{total} < 100$ MeV	$< 10^{-3}$	$< 10^{-3}$	0	0.30	0.72	0	69.61	4.76
$E_{HCAL}^{MaxCell} < 10$ MeV	$< 10^{-3}$	$< 10^{-3}$	0	0.13	0.27	0	65.00	4.48
$E_{HCAL}^{MaxCell} < 2$ MeV	$< 10^{-3}$	$< 10^{-3}$	0	0.058	0.095	0	58.14	4.04
$E_{ECAL}^{total} < 2.5$ GeV	0	0	0	0	0	0	0	0

Signal region

ECAL is essential for bremsstrahlung background

BDT for Rare Background Rejection

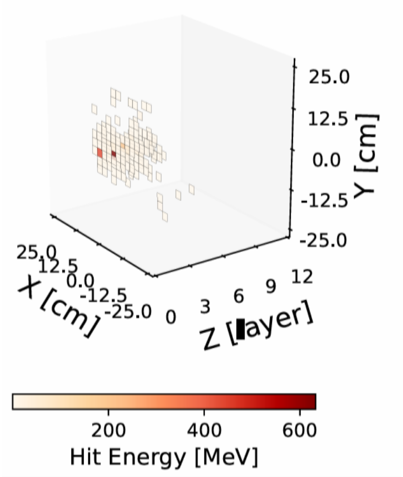
- Rare background is more hard to be rejected by ECAL
  - $\gamma \to \mu\mu$, hadronic interactions
- Current BDT method displays high efficiency for e^-/π^- separation
- To be studied for more types of background

Rank of variables in BDT

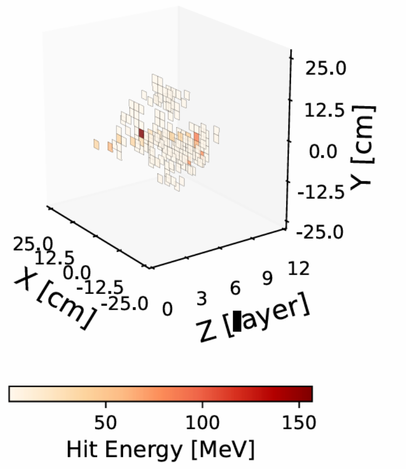
Rank	Variable	Importance
1	Edep	0.05625
2	Emean	0.05329
3	FD 2D mean	0.05284
4	Shower density	0.05196
5	Ecell second	0.04954
6	Nhits	0.04920
7	COG Y mean	0.04876
8	E1E9	0.04828
9	COG X mean	0.04772
10	E1Edep	0.04725
11	Eclus max	0.04685
12	Shower radius	0.04630
13	COG Z mean	0.04424
14	E9Edep	0.04343

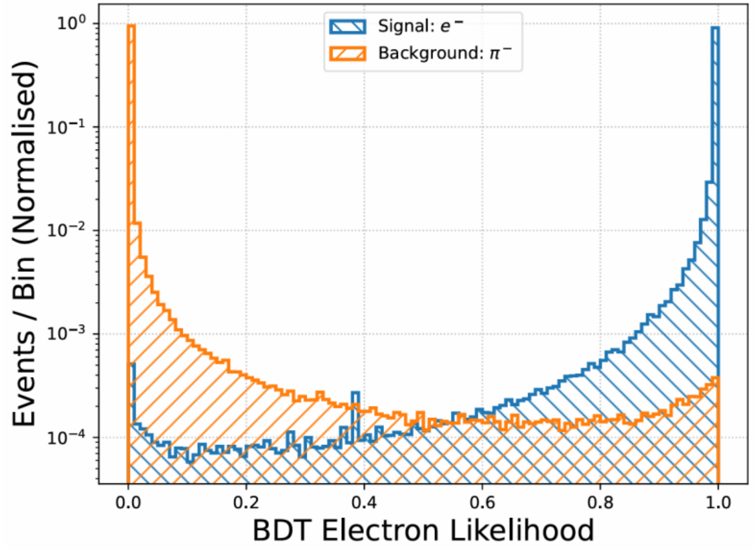
Rank	Variable	Importance
15	E49Edep	0.04214
16	Shower end	0.03568
17	Zdepth	0.03018
18	Emax sec dist	0.02968
19	Shower length	0.02606
20	Hit layer	0.02548
21	Eclus max sec diff	0.02311
22	Xwidth	0.02265
23	Emax sec diff	0.02075
24	Ywidth	0.02043
25	E9E49	0.01637
26	Shower layer	0.01291
27	Eclus max sec dist	0.008642
28	Eclus second	0.000

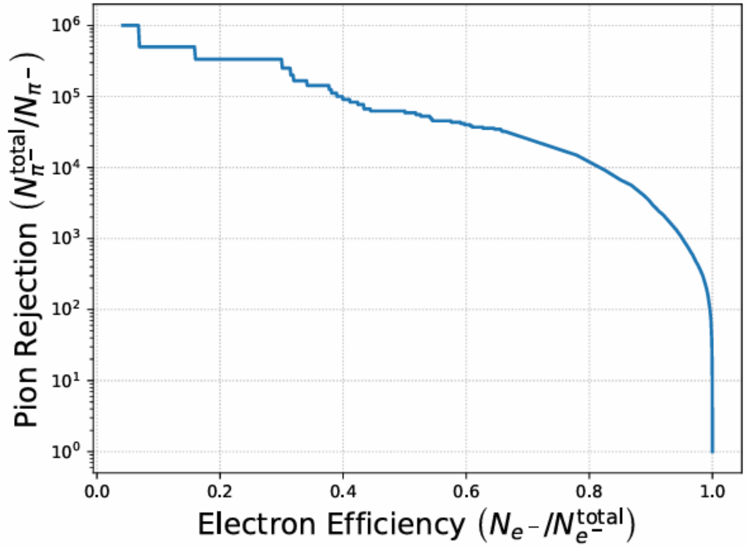
2GeV e^-



2GeV π^-

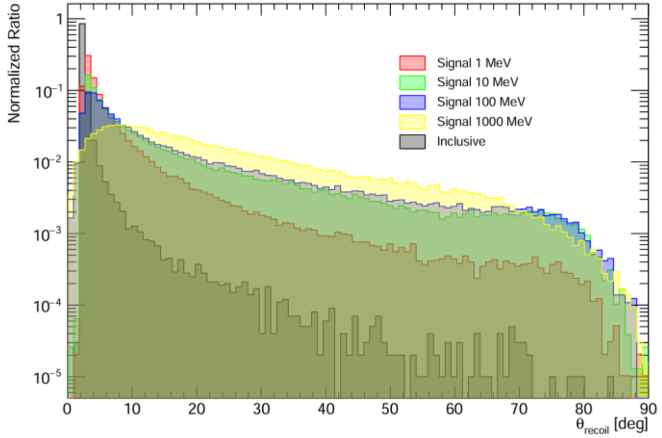






ECAL Size Optimization

Large $m_{A'}$ need large acceptance angle



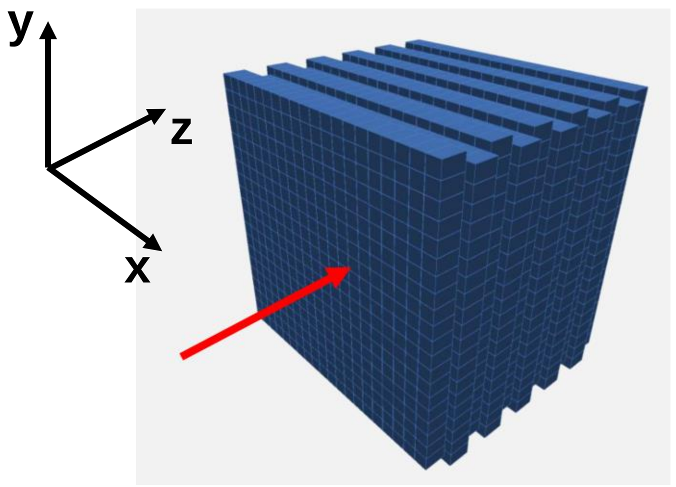
- Optimized the ECAL size to achieve a high signal efficiency while keeping the cost not so large.
  - Basic unit: $2.5 \times 2.5 \times 4cm^3$ LYSO
  - Signal box: $E_{ECAL}^{Total} < 2.5GeV$ & $E_{HCAL}^{Total} < 30MeV$ & $E_{HCAL}^{MaxCell} < 0.1MeV$
- $52.5 \times 52.5 \times 44cm^3$ size is suitable choice

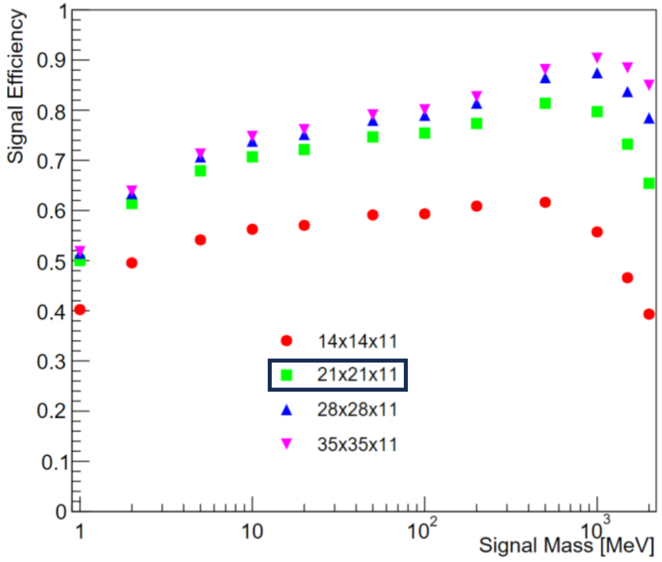
Table 4. Average signal efficiency with changing transverse size of ECAL

Number of crystals	14×14×11	21×21×11	28×28×11	35×35×11
Average signal efficiency(%)	53.32	70.78	75.75	77.62

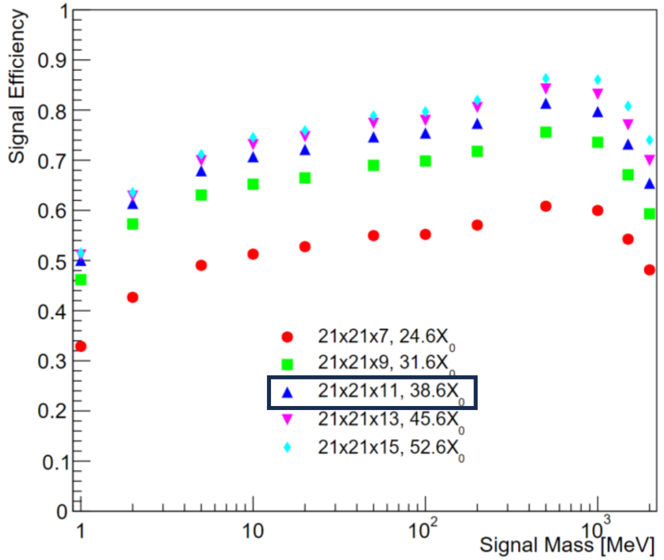
Table 5. Average signal efficiency with changing longitudinal size of ECAL

Number of crystals	21×21×7	21×21×9	21×21×11	21×21×13	21×21×15
Average signal efficiency(%)	52.05	66.32	71.52	74.07	76.71





x-y size

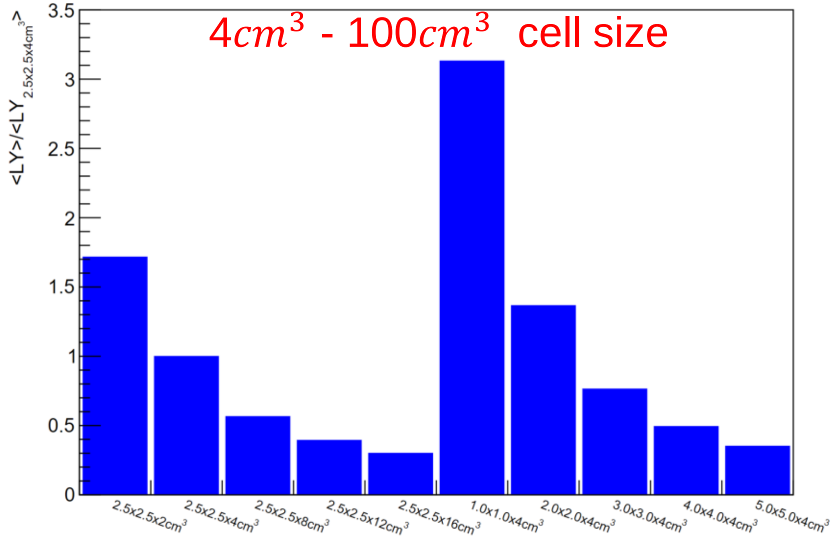


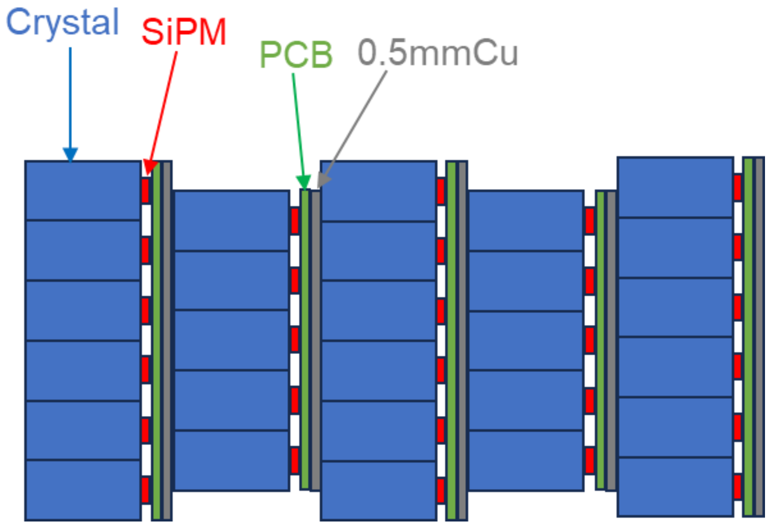
z size

Effect of Cell Size on Energy Resolution

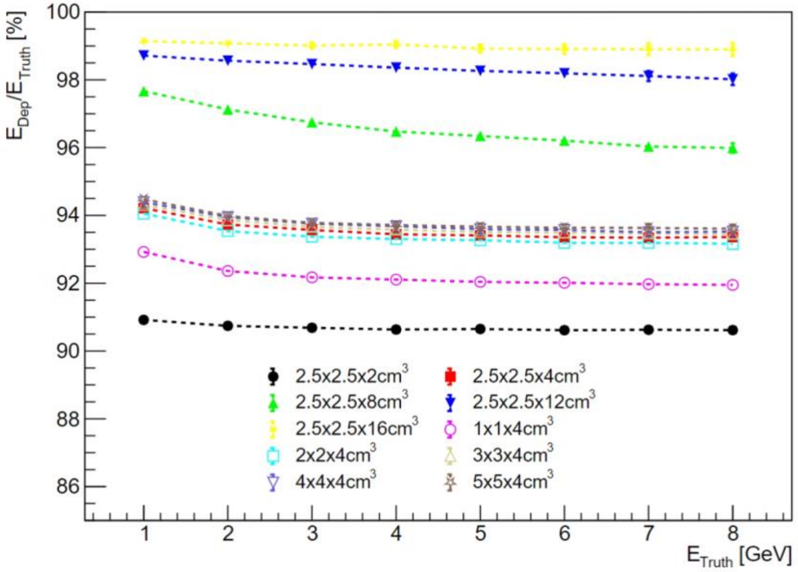
- Cell size will affect on the light yield, crystal energy deposit, amount of passive materials…
- Use a digitization model to parameterize energy smearing of different cell size: Scintillation $\oplus$ SiPM $\oplus$ ADC
- ECAL with $2.5 \times 2.5 \times 4cm^3$ LYSOs has a great energy resolution and a compromise energy containment

Crystal light yield vs. Crystal size

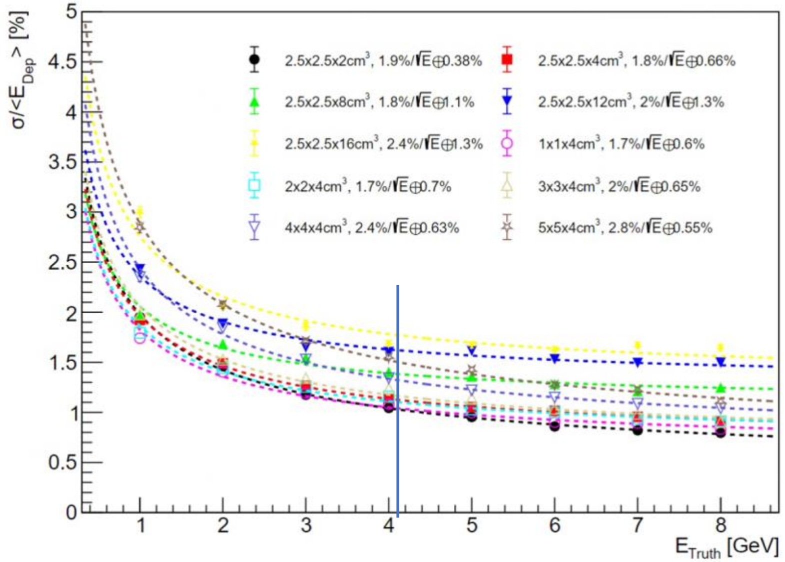




Energy Containment



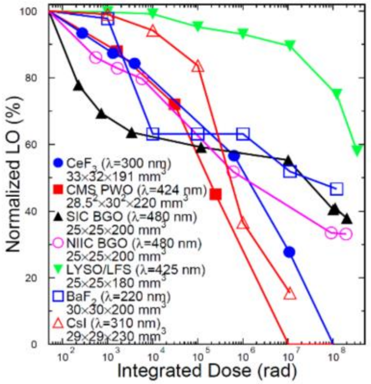
Energy Resolution

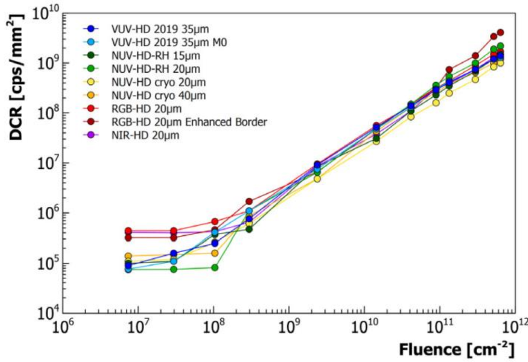


Keep the size of ECAL as a constant

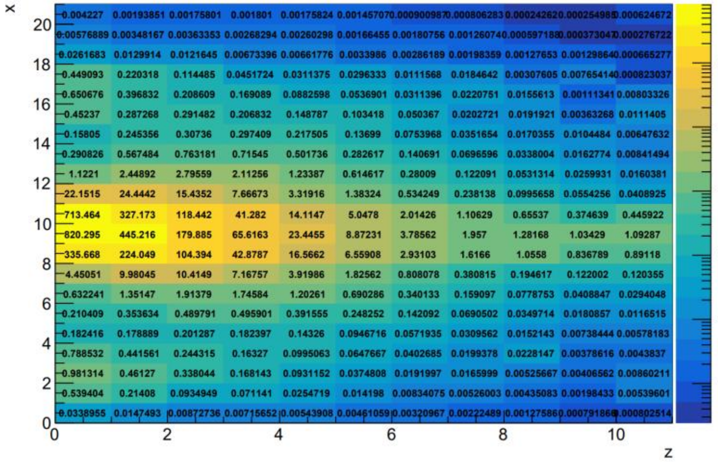
Radiation Damage Estimation

- 10MHz e- beam @8GeV with 3cm radius spot, 3×10^{14} EOTs(one year)
- Under such a powerful and high-frequency beam, detectors are subjected to a huge radiation dose.
- For crystal
  - Damage: light yield reduction, uniformity, phosphorescene
  - Max irradiated cell: ~ 10^7 rad, about 15% light yield reduction
- For SiPM
  - Damage: increase of noise, reduction of resolution
  - Max irradiated cell: ~ 10^{13} equivalent 1MeV neutron flux



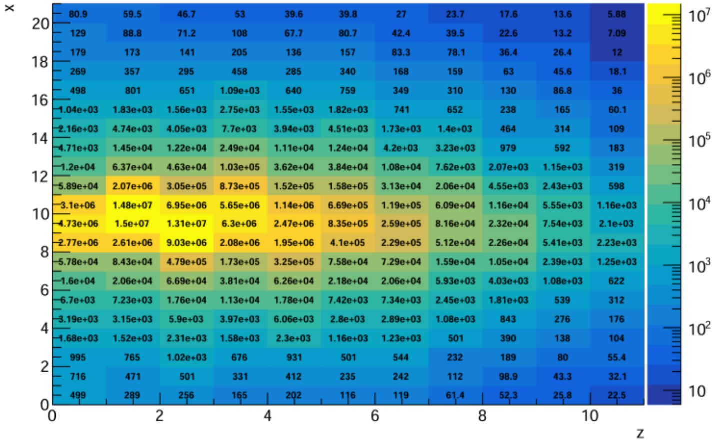


Average Cell Energy Deposit per Event

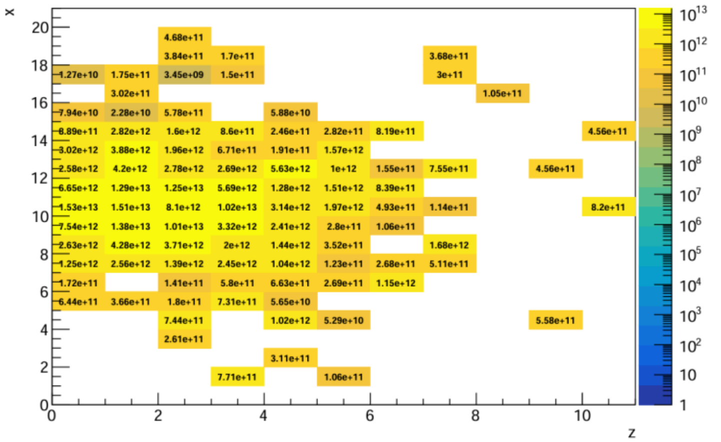


3×10^{14} **Events**

Radiation Dose by Ionizing Energy Loss



Equivalent 1MeV Neutron Fluence on SiPM



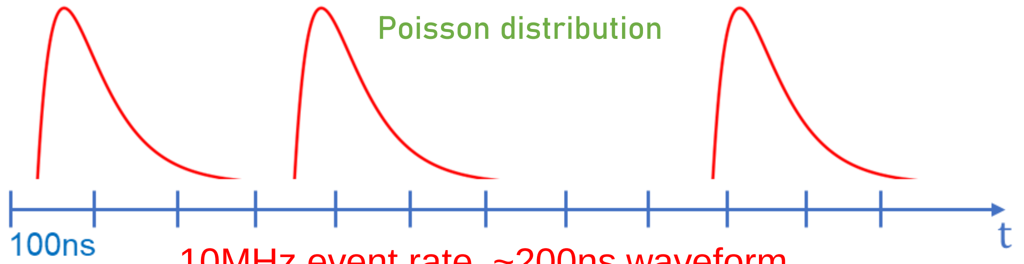
[1] Ultrafast and Radiation Hard Inorganic Scintillators for Future HEP Experiments [2] https://doi.org/10.1016/j.nima.2022.167661 [3] https://doi.org/10.1016/j.nima.2020.164203 [4] https://doi.org/10.1016/j.nima.2009.01.176

LYSO Intrinsic Radiation

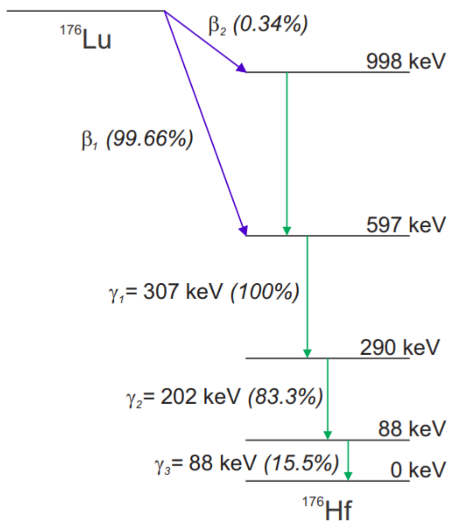
- LYSO intrinsic radiation: $^{176}Lu \rightarrow {}^{176}Hf$
- Energy range=0~1.2 MeV, $T_{1/2} = 3.64 \times 10^{10}\ y$
  - Contribute to noise energy, but a potential calibration source
- At 10MHz event rate, average noise energy from IR for single channel is ~15keV per event

Toy monte carlo to estimate noise energy from IR

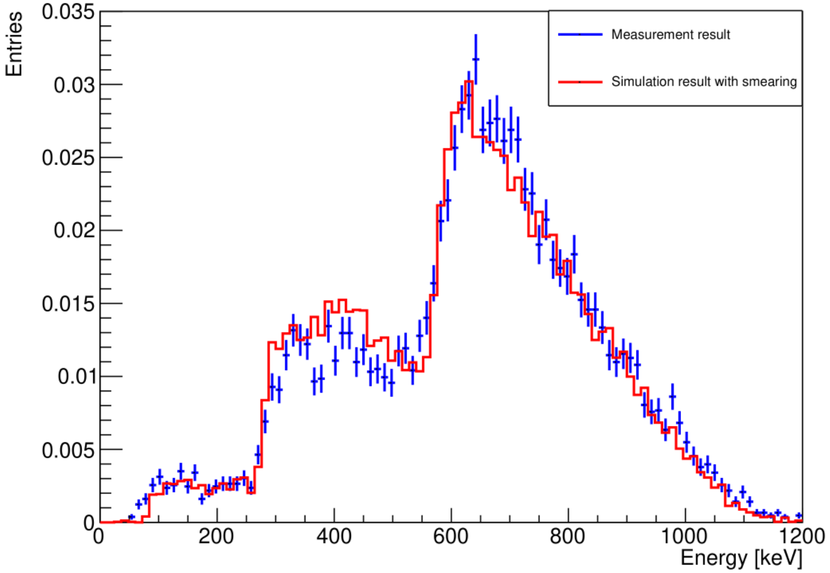
IR signal, ~240k Bq for single crystal($2.5 \times 2.5 \times 4cm^3$ LYSO)



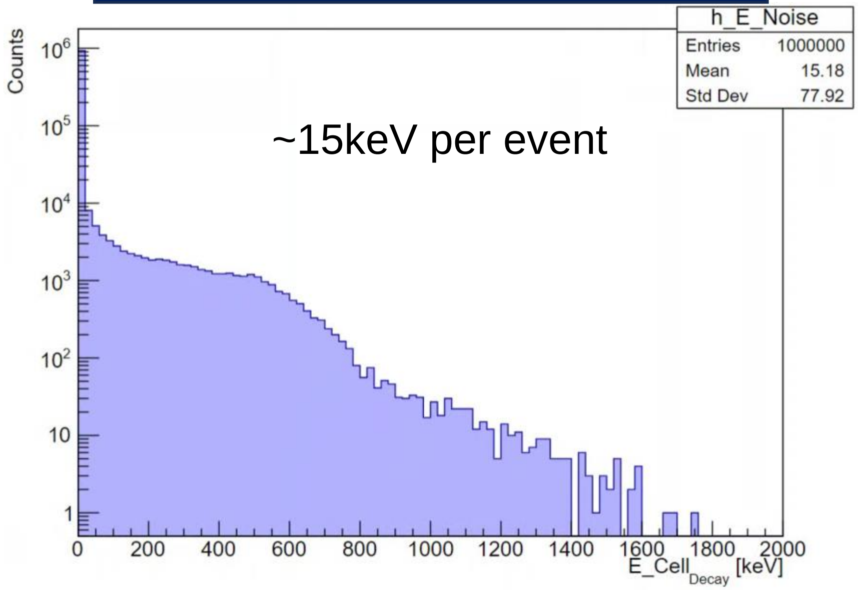
one β decay + three γ decay



Intrinsic radiation Spectrum

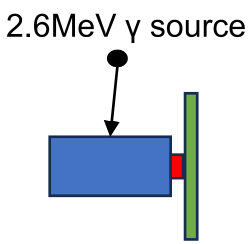


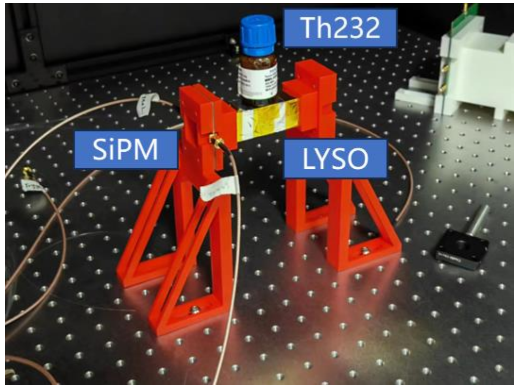
Noise energy from IR

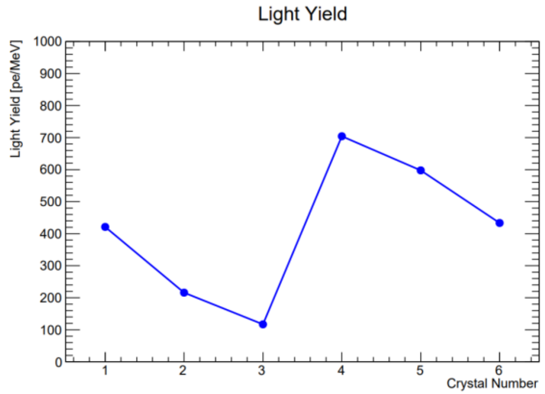


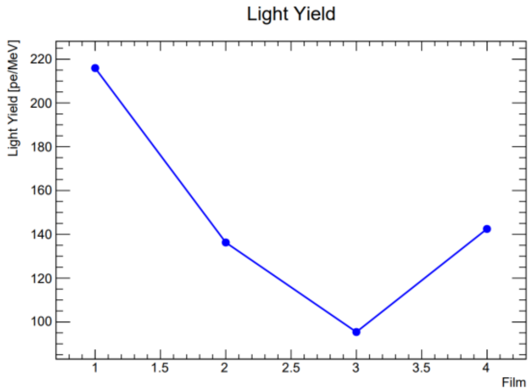
Test of Unit Light Yield

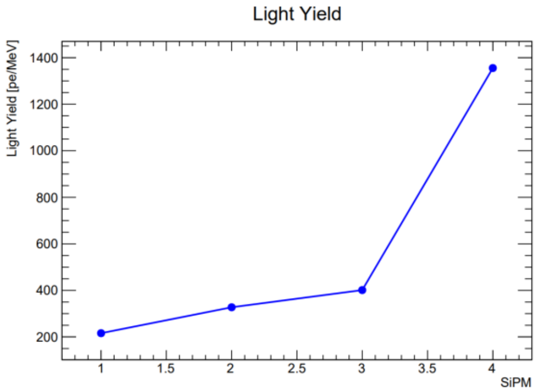
- Test the light yield of crystal unit(LYSO+SiPM) with different crystal sizes, different reflection films, and different SiPMs
- The light yield can be changed from 100-1400p.e./MeV
- Max energy deposit in one crystal ~ 4GeV → 4×10^5p.e. light output











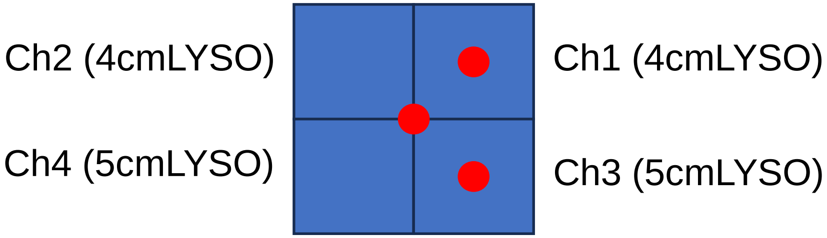
➢ Crystal (ESR, NDL EQR06):
① $2.5\times 2.5\times 2.5cm^3\ LYSO$
② $2.5\times 2.5\times 5cm^3\ LYSO$
③ $2.5\times 2.5\times 10cm^3\ LYSO$
④ $1\times 1\times 4cm^3\ LYSO$
⑤ $1\times 1\times 8cm^3\ LYSO$
⑥ $1\times 1\times 16cm^3\ LYSO$

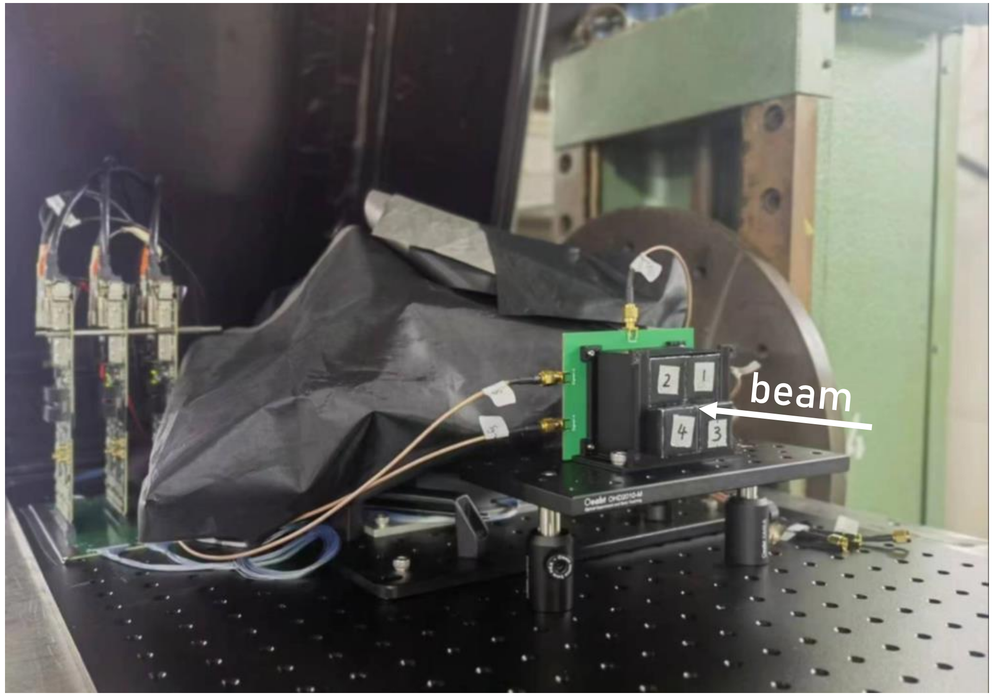
➢ Film ($2.5\times 2.5\times 5cm^3\ LYSO$, NDL EQR06):
① ESR, 1 layer
② Tyvek1, 3 layers
③ Tyvek2, 3 layers
④ Teflon, 3layers

➢ SiPM ($2.5\times 2.5\times 5cm^3\ LYSO$, ESR):
① NDL EQR06-11-3030D-S, 244720 pixels
② NDL EQR10-11-3030D-S, 90000 pixels
③ NDL EQR15-11-3030D-S, 40000 pixels
④ NDL EQR15-11-6060D-S, 160000 pixels

DESY Beamtest of a Small LYSO Module

±5mm beam spot, 1~ 5GeV e-, HPK S14160-3010PS



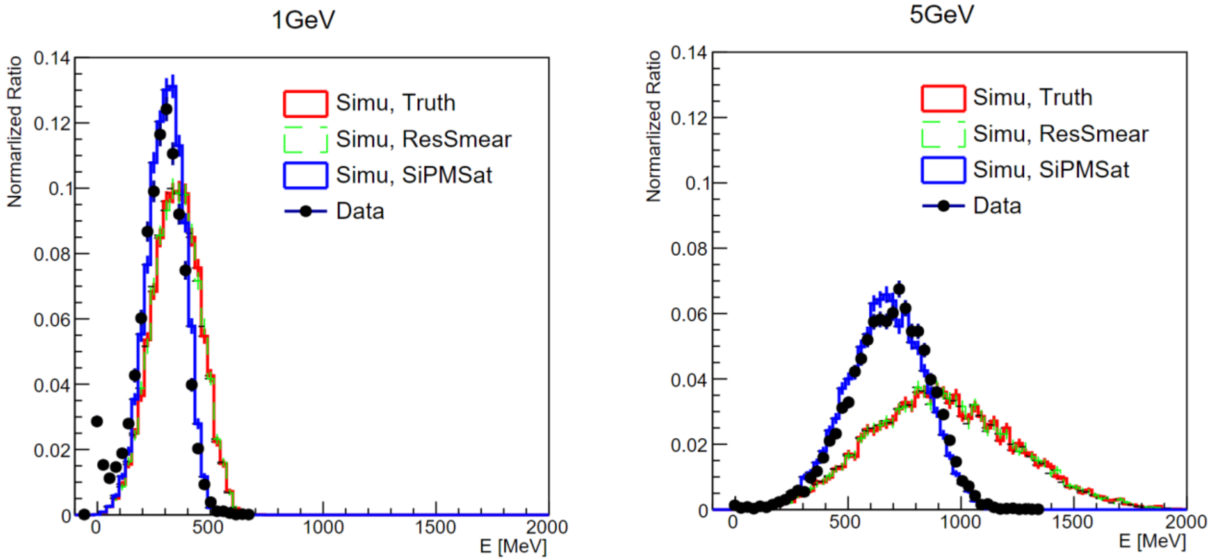


DESY TB22 Oct. 2023

Baohua's talk

- Beamtest is together with CEPC crystal ECAL module
- Energy smearing seems not significant, compared with the energy deposit fluctuation.(~1% vs. ~30% @1GeV)
- SiPM saturation is significant at 5GeV, but can be corrected.

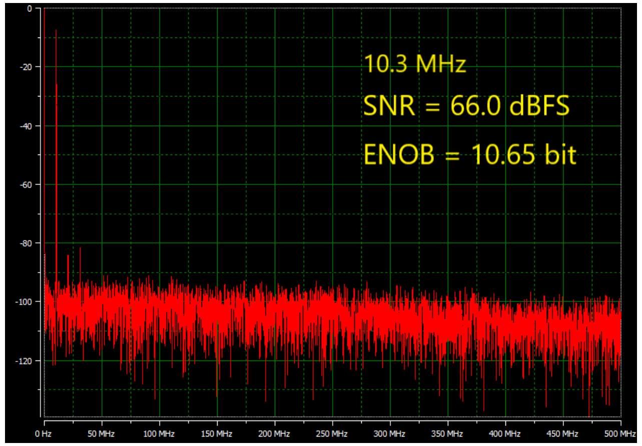
Energy distribution of channel-3

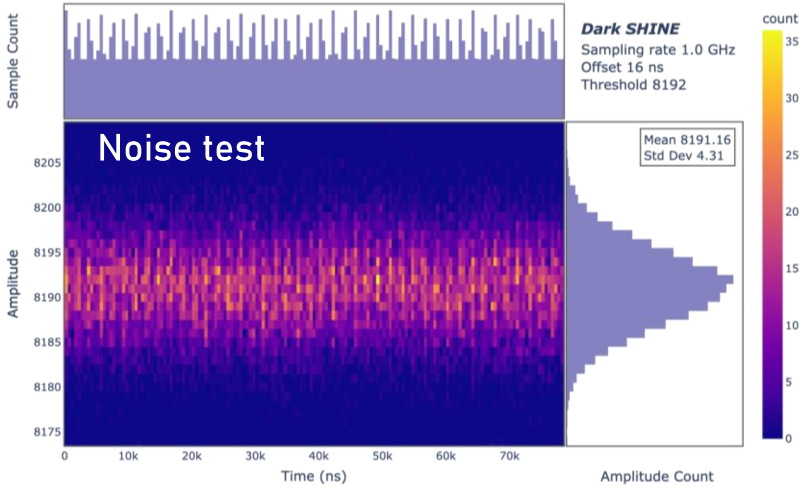


First Version Readout Electronical System

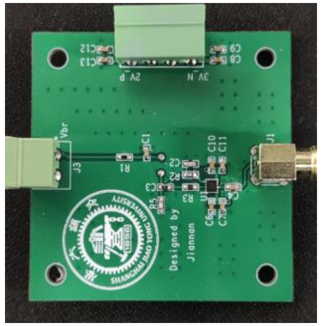
- High speed and high precision ADC
  - ADC: AD9680, 1 GS/s, 14 bit
- FPGA: Kintex-7 XC7K420T-FFG901
- Pre-amplifier: transimpedance amplifier
  - PZC + RCRC filter
  - Dual output: large dynamic range
- LED calibration for SiPM
  - LED driver: nanoseconds width and tunable light intensity

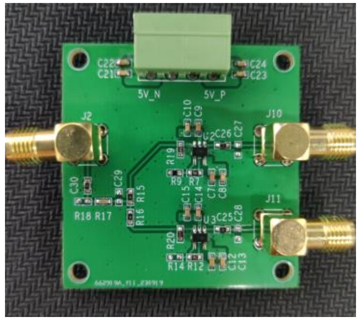
Working on the FPGA firmware and upper PC software



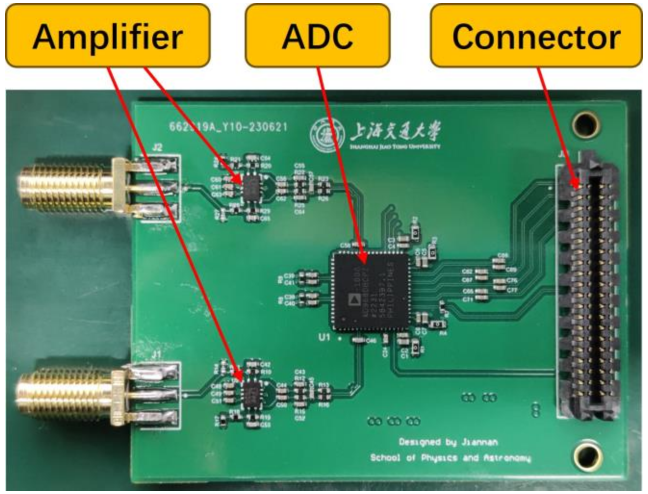


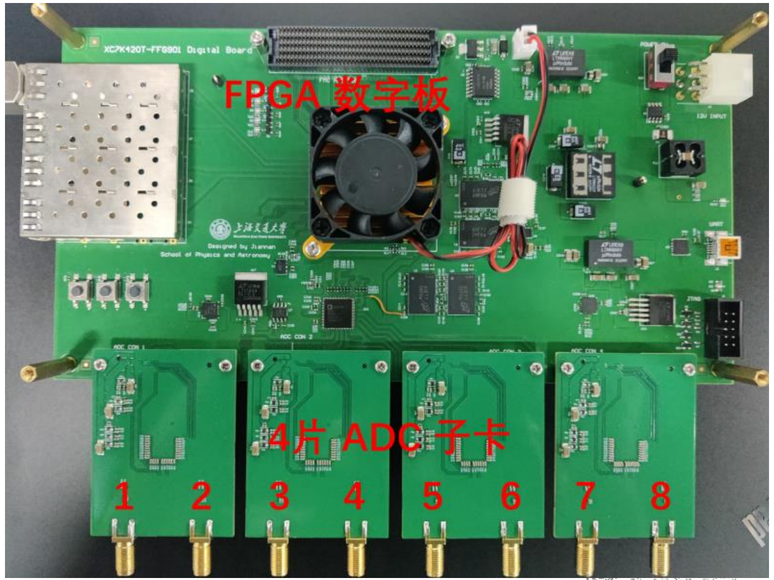
Energy range(MeV)	Amplifier Gain	Output Range(mV)
1~40	200	40~1600
25~1000	1	50~1400





Preamplifier





Summary & Prospects

- ECAL in Dark SHINE: a homogenous LYSO crystal calorimeter
  - Established a complete software framework. Optimized the overall size and cell size of ECAL. Studied the radiation environment in ECAL region.
  - Conducted many unit tests for crystal and SiPM
  - High energy beamtest of a 4-ch small crystal module at DESY in 2023
  - Finished the first version high speed readout electronics system.

- Next
  - Explore the rejection power of ECAL on rare background
  - Preparing a 18-ch LYSO mini-prototype to study the EM performance and more technical issues


Thanks!

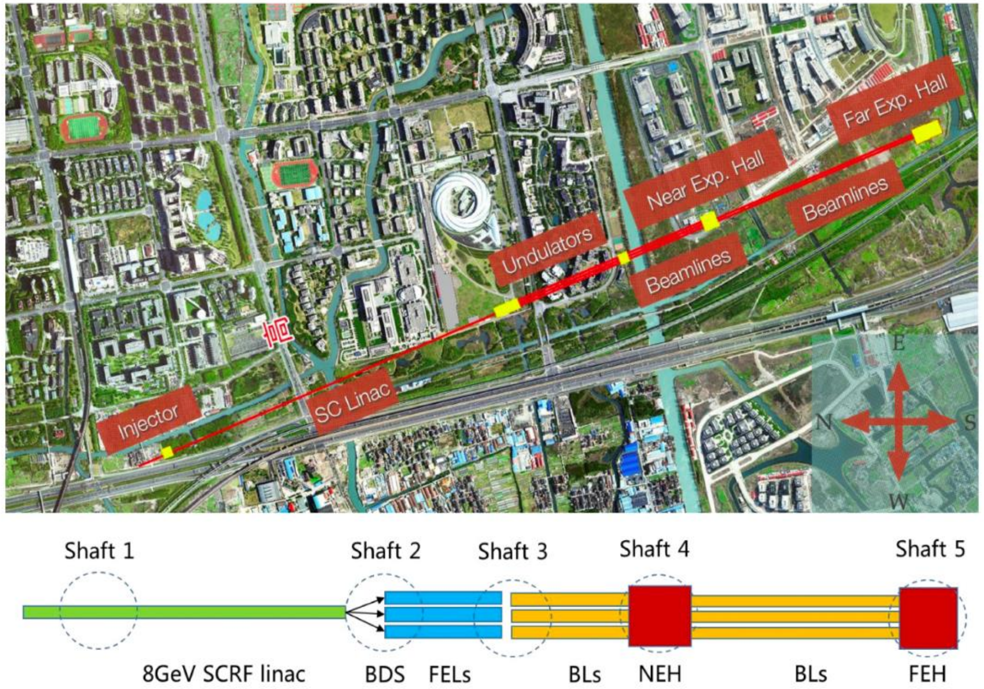
Backup

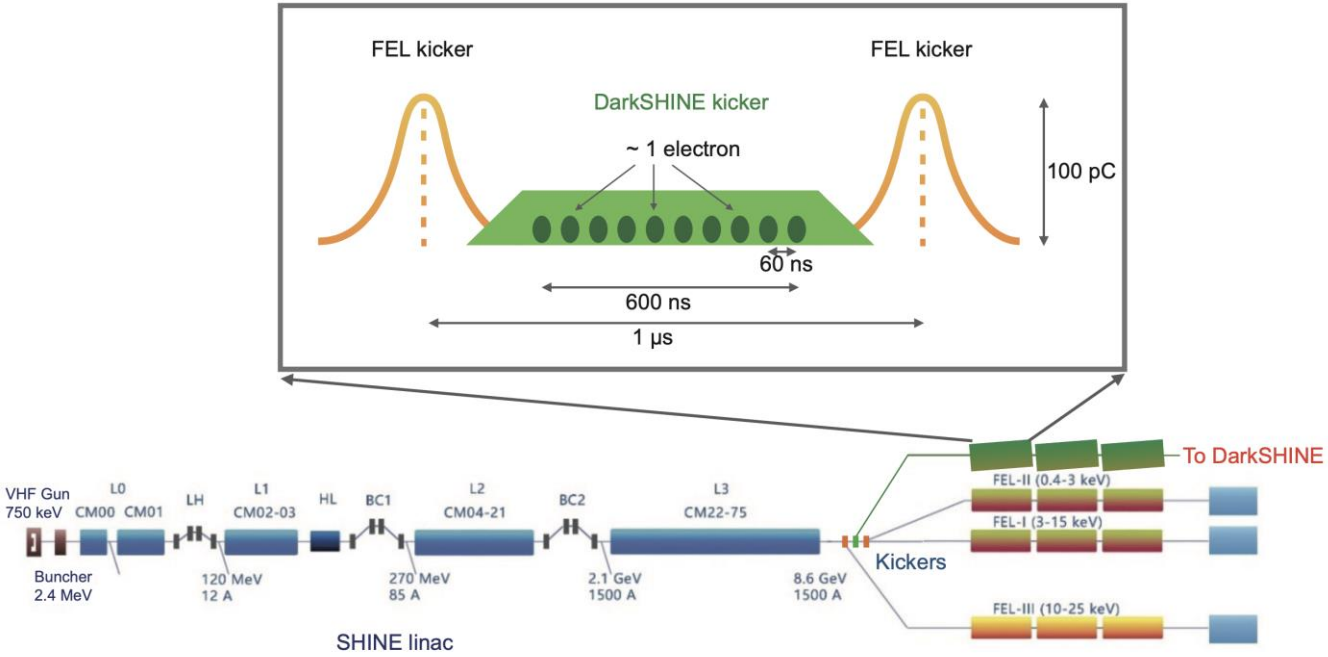
The SHINE Facility

- Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE) can provide high repetition rate single electron beams → with dedicated kicker to be designed and deployed.
- Electron energy: 8 GeV, Frequency: 1MHz
  - Expected to achieve $\sim 3 \times 10^{14}$ electrons-on-target (EOT) per year
- Under construction in ZhangJiang area (2018-2026)

Science Bulletin 61, 117(2016), 720-727

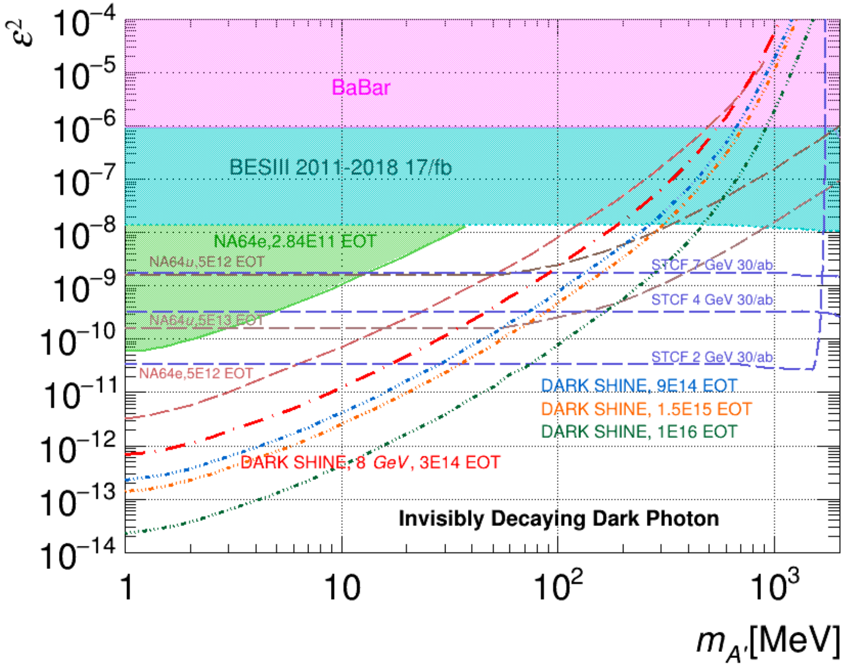
Dedicated to achieve 10MHz single electron beam with high repetition-rate kicker for Dark SHINE

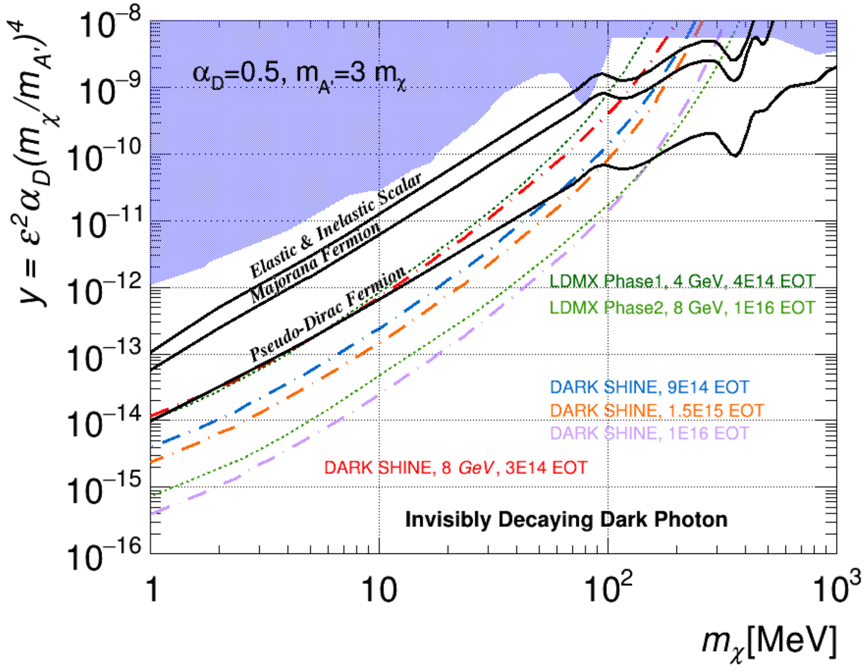




Expected Sensitivity of DarkSHINE

Assuming 0.015 bkg. event/ 3×10^{14} *EOTs*





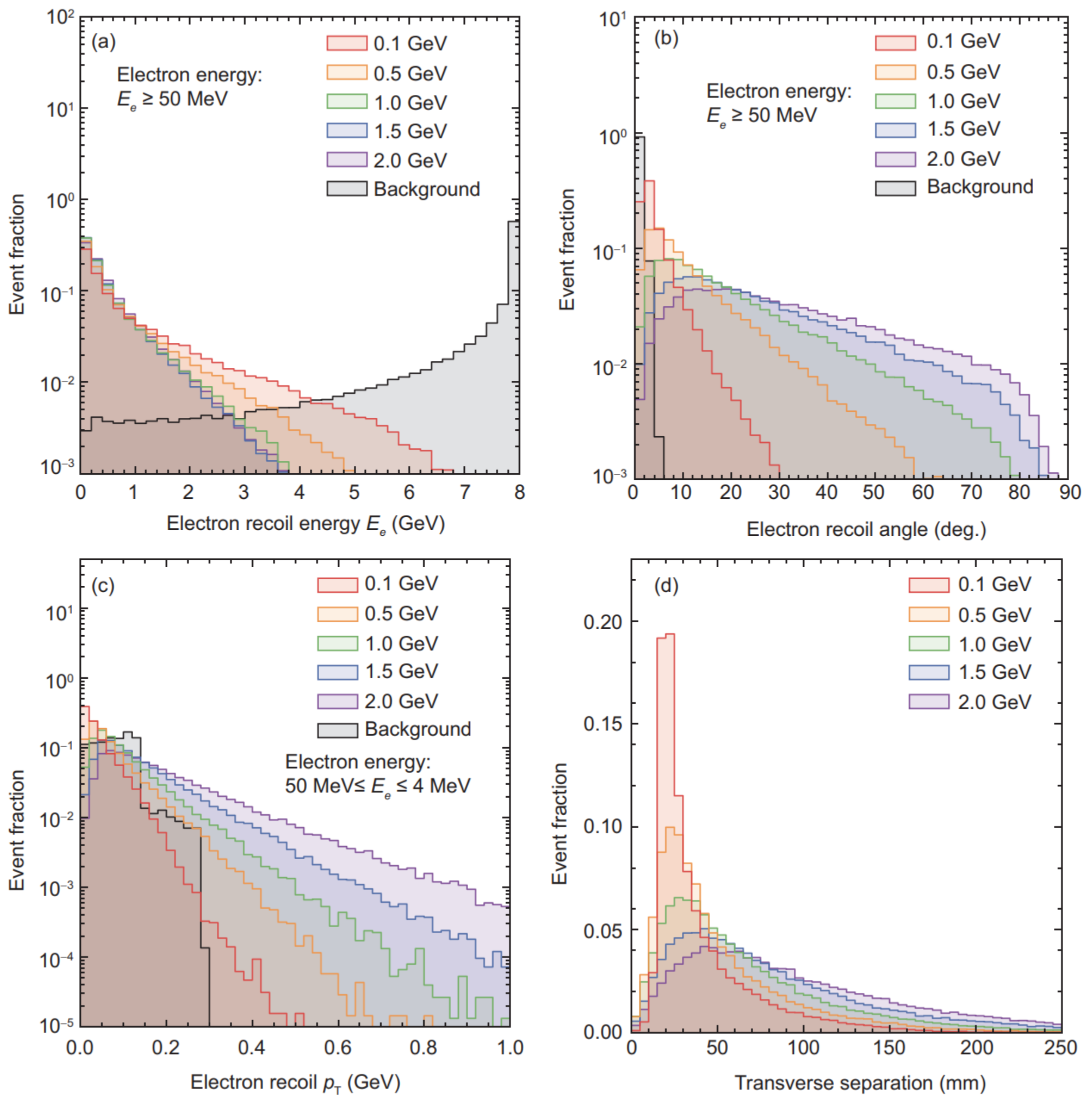
Expected 90% C.L. limit estimated with 3×10^{14} *EOTs (running* ~ 1 *year),* 9×10^{14} *EOTs (*~ 3 *years),* 1.5×10^{15} *EOTs (*~ 5 *years) and* 1×10^{16} *EOTs (with Phase-II upgrade).*

Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)

Signal & Background Features

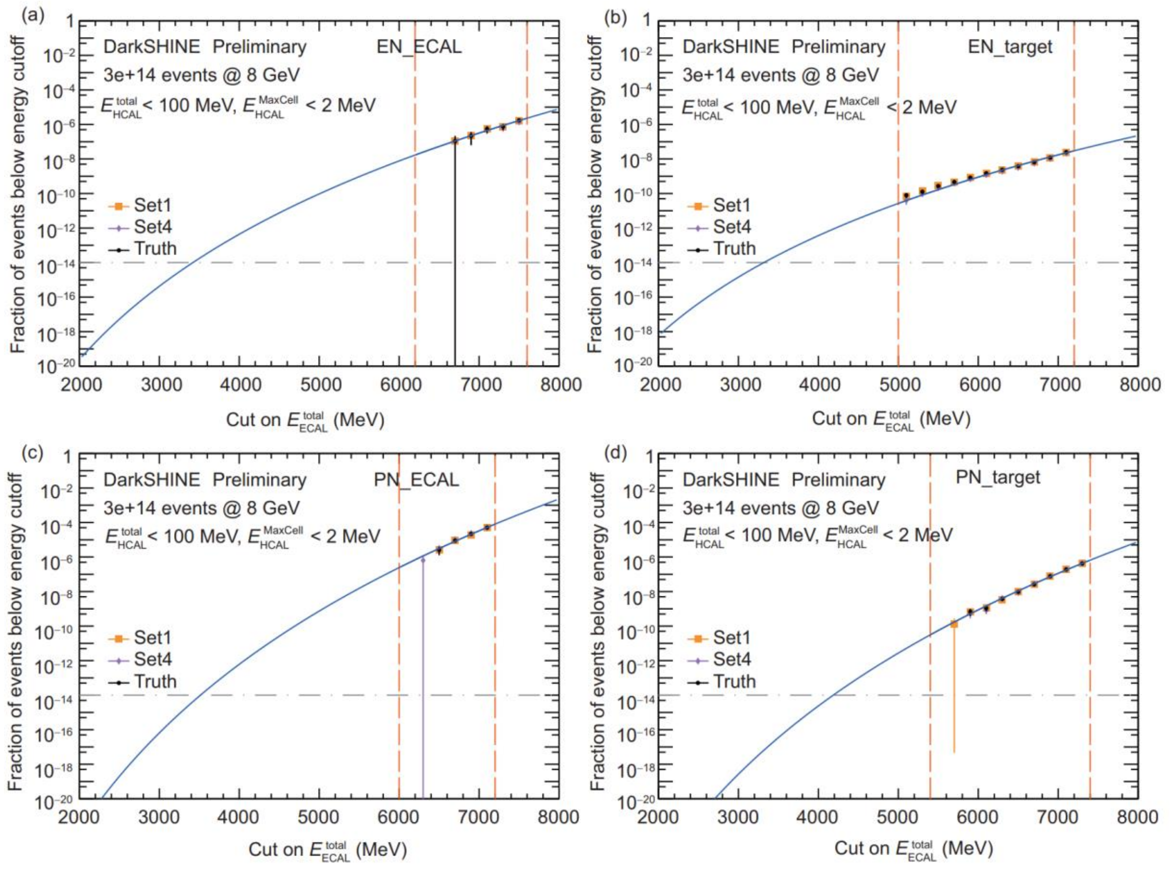
Signal
- Low recoil energy
- Large recoil angle and recoil p_T

Background
- Large recoil energy
- Samll recoil angle and recoil p_T



Background Samples and Extrapolation

Process	Generate events	Branching ratio	EOTs
Inclusive	2.5×10^9	1.0	2.5×10^9
Bremsstrahlung	1×10^7	6.70×10^{-2}	1.5×10^8
GMM_target	1×10^7	$1.5(\pm 0.5) \times 10^{-8}$	4.3×10^{14}
GMM_ECAL	1×10^7	$1.63(\pm 0.06) \times 10^{-6}$	6.0×10^{12}
PN_target	1×10^7	$1.37(\pm 0.05) \times 10^{-6}$	4.0×10^{12}
PN_ECAL	1×10^8	$2.31(\pm 0.01) \times 10^{-4}$	4.4×10^{11}
EN_target	1×10^8	$5.1(\pm 0.3) \times 10^{-7}$	1.6×10^{12}
EN_ECAL	1×10^7	$3.25(\pm 0.08) \times 10^{-6}$	1.8×10^{12}



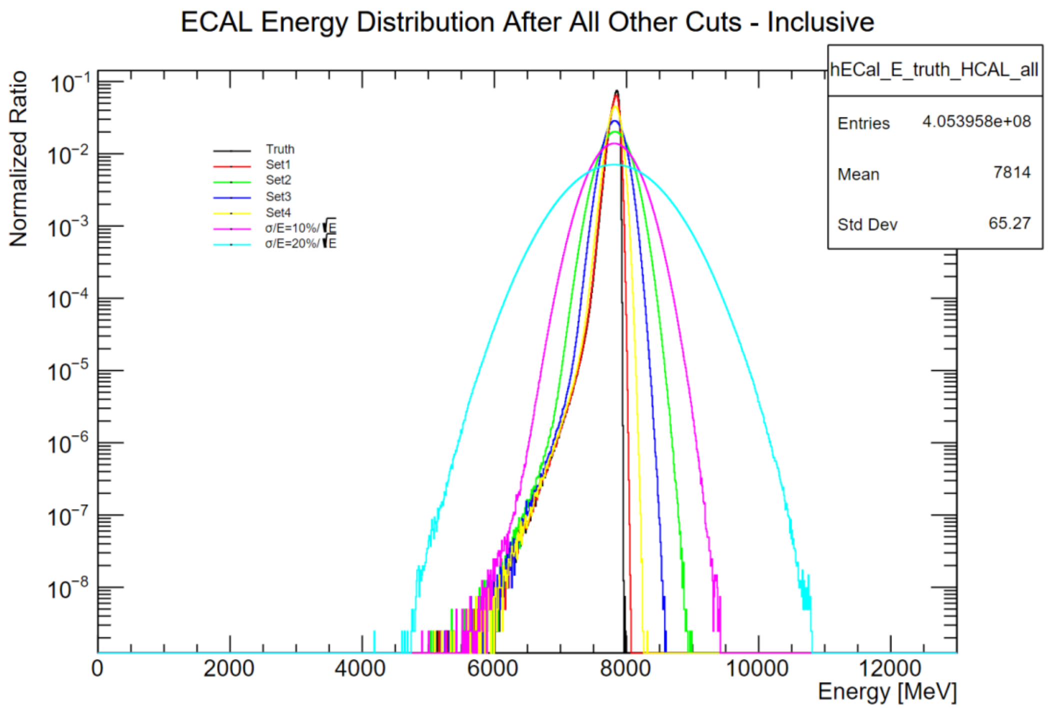
Background Rejection and Signal Efficiency

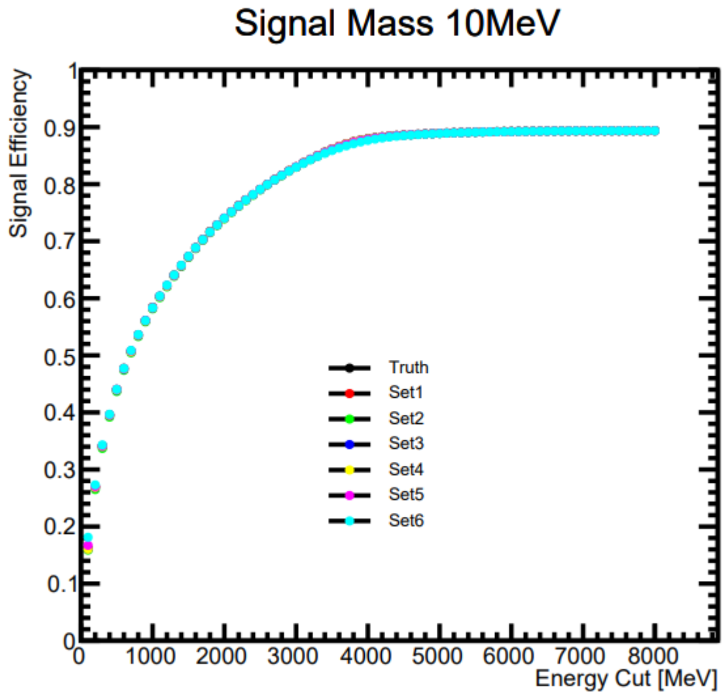
- Set1~Set4: Energy smearing for cell energy
- Others(σ/E): Energy smearing for total energy
- For 4e8 inclusive events, DarkSHINE detector system can reject all of the background events, even with a ECAL of 20% energy resolution.

	cube	Wrapper	SiPM Size	coupling*QE	Yield/MeV
R90_LYSO	2.5*2.5*4cm	Ref=90% (ref.)	$9mm^2$	20%	30000(LYSO)
R10_LYSO	2.5*2.5*4cm	Ref=10% (abs.)	$9mm^2$	20%	30000(LYSO)
R90_S9_PWO4	2.5*2.5*4cm	Ref=90% (ref.)	$9mm^2$	20%	200(PWO)
R90_S36_PWO4	2.5*2.5*4cm	Ref=90% (ref.)	$36mm^2$	20%	200(PWO)

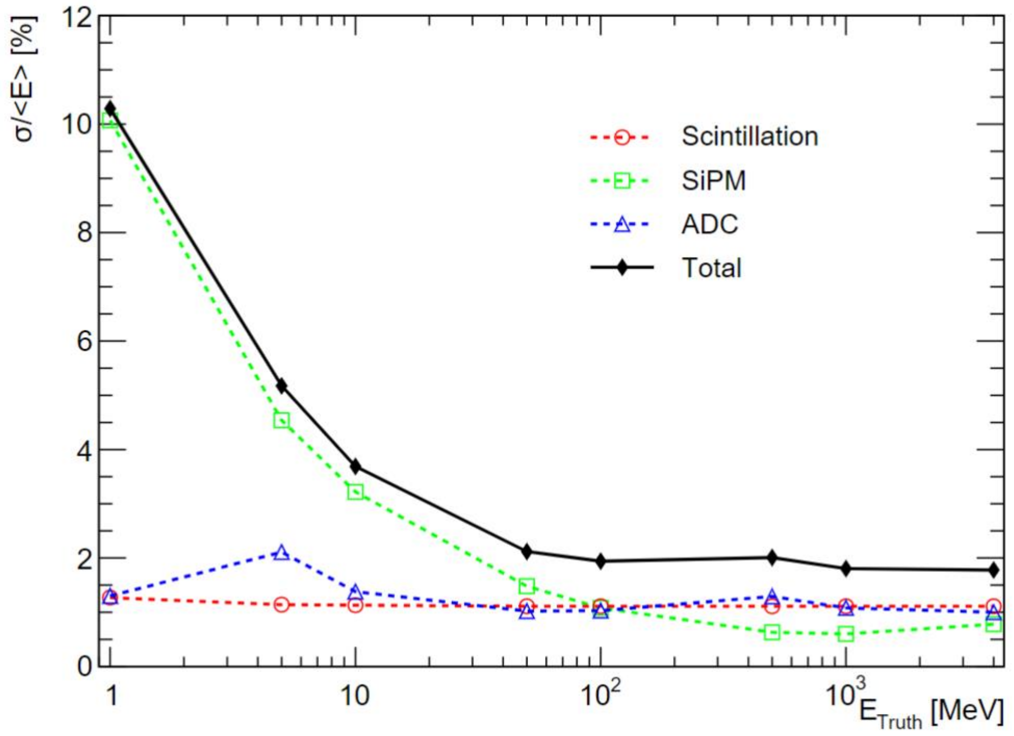
Smearing method

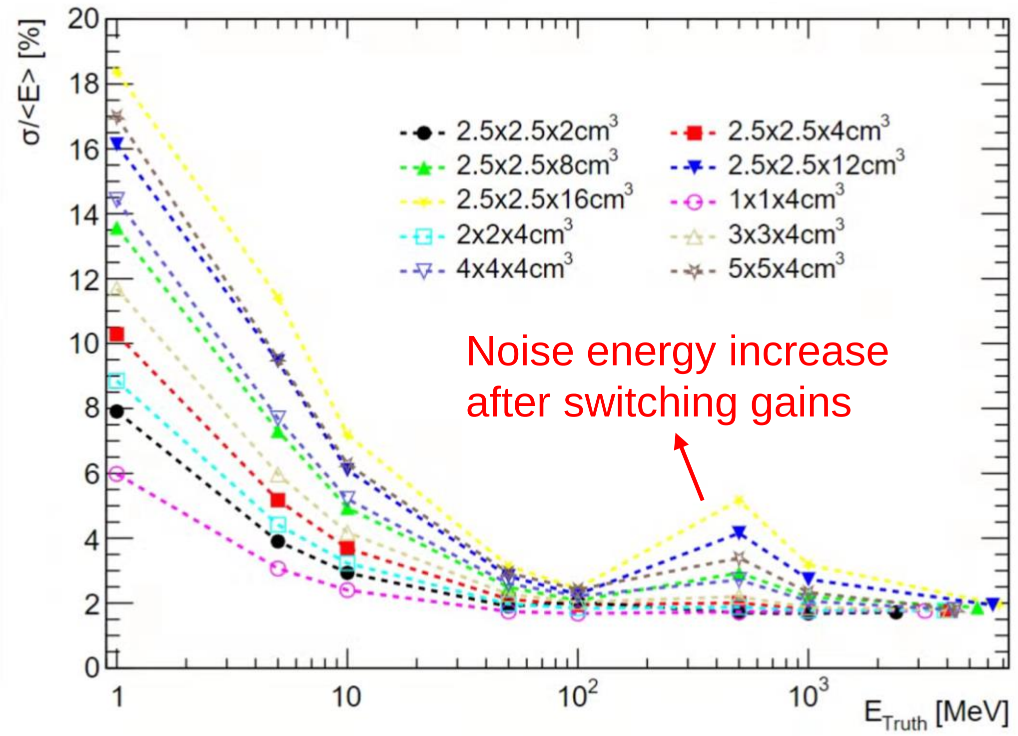
The smearing of ECAL is done in reconstruction/analysis level. For each ECAL cell, the energy of hits are summed, then Gaussian function is used to do the smearing, with the mean value set to truth energy and sigma from the formula $\frac{\sigma}{E} = \frac{A}{\sqrt{E}} + B + \frac{C}{E}$. The A B C parameters are extracted from standalone simulation with optical process enabled.





Performance of Digitization Algorithm



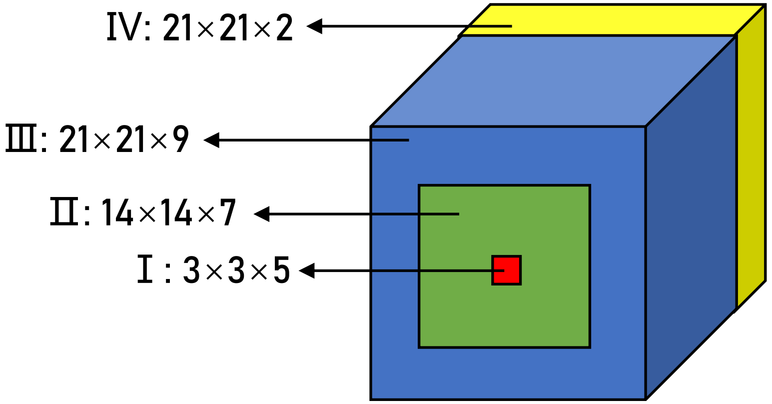


- $2.5 \times 2.5 \times 4cm^3$ LYSO
- SiPM digitization dominates in low energy region(E<100MeV)
  - If no saturation correction, the resolution will be better
- Scintillation and ADC has greater contribution when E>100MeV
  - Constant trends come from crystal light yield calibration uncertainty(Scintillation) and SiPM gain calibration uncertainty(ADC)

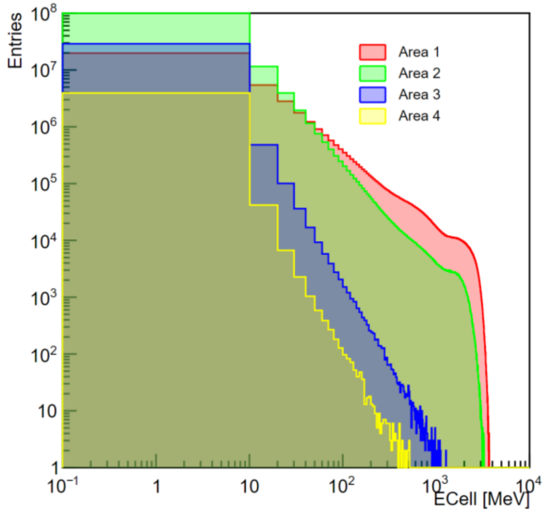
- Smaller crystal has a better single-cell resolution
- Resolution at low energy region can be roughly consistent with the experimental results

Dynamic Range of Cell

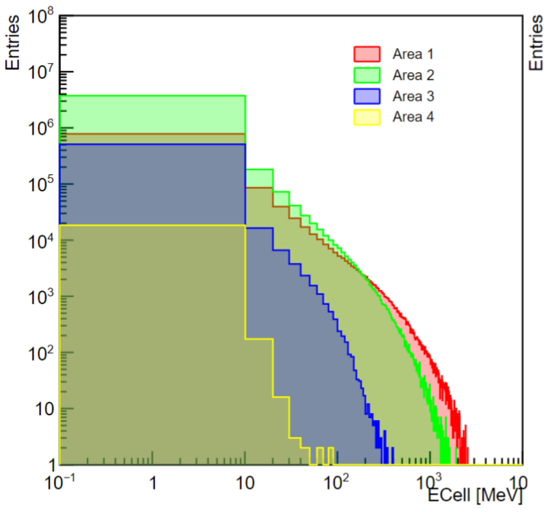
- The maximum energy deposit in single crystal cell is about 4GeV
- The hottest crystal is always located in the central area, both for background and signal processes
- At least 3GeV cell dynamic range is required
  - Ecell_Max: saturation value of the energy deposit in crystal



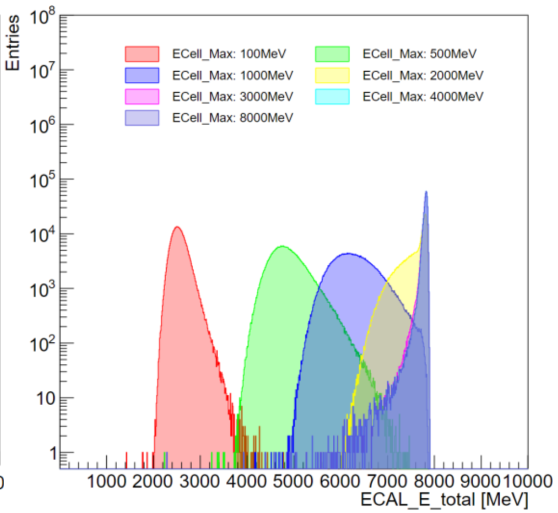
E_Cell: Inclusive



E_Cell: Signal 1000MeV



E_ECAL: Inclusive



- It is possible for Area-3 and Area-4 to set a smaller dynamic range
- Small dynamic range will result in false signal

Event ratio of $E\_ECAL < 4GeV$

ECell_Max	Inclusive	Signal 1 MeV	Signal 1000 MeV
100 MeV	~100%	100%	100%
500 MeV	0.1%	90.57%	99.5%
1000 MeV	~0	76.78%	98.56%
2000 MeV	~0	73.75%	98.32%
3000 MeV	~0	73.75%	98.32%
4000 MeV	~0	73.75%	98.32%
8000 MeV	~0	73.75%	98.32%

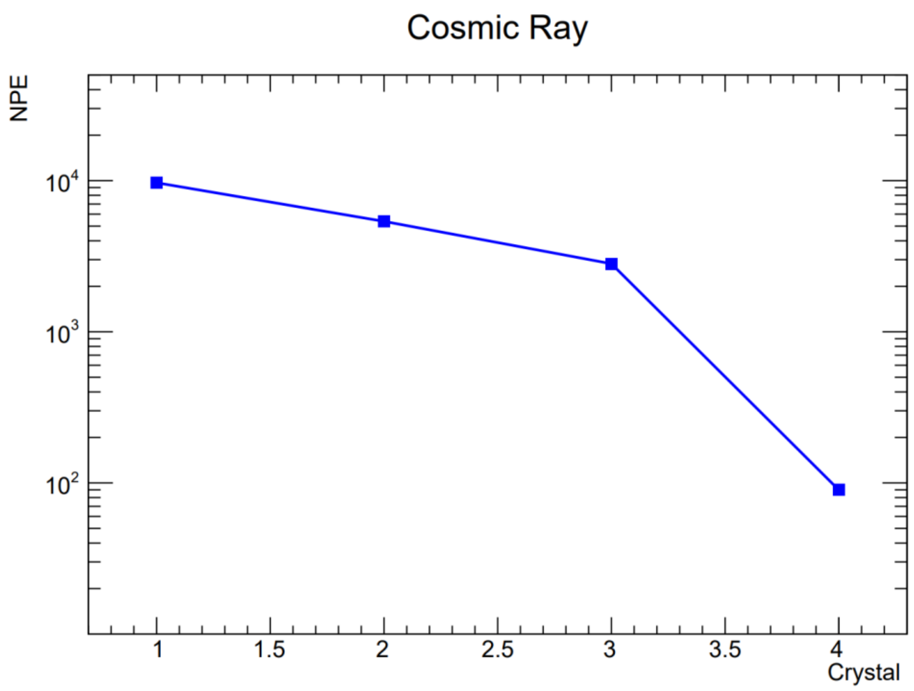
Cosmic Ray test

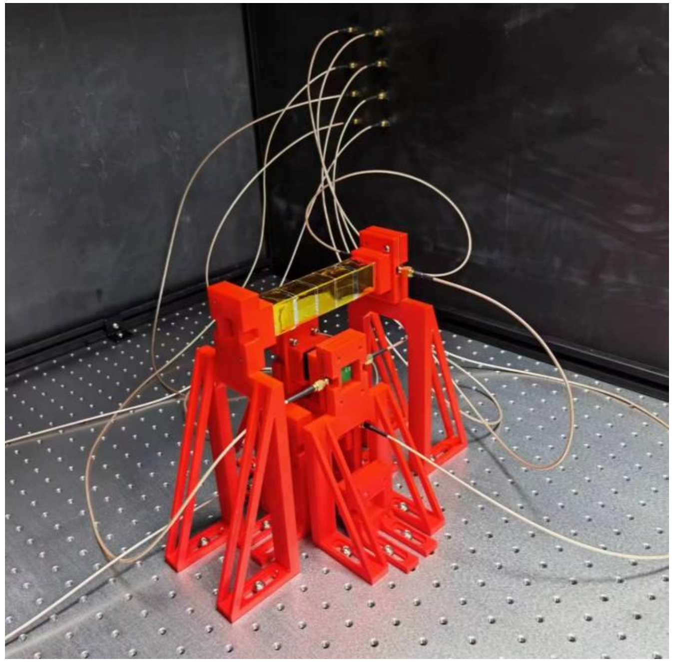
① $2.5 \times 2.5 \times 2.5cm^3\ LYSO$, ESR, SiPM NDL EQR06, ~9684pe

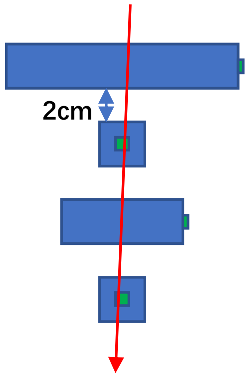
② $2.5 \times 2.5 \times 5cm^3\ LYSO$, ESR, SiPM NDL EQR06, ~5377pe

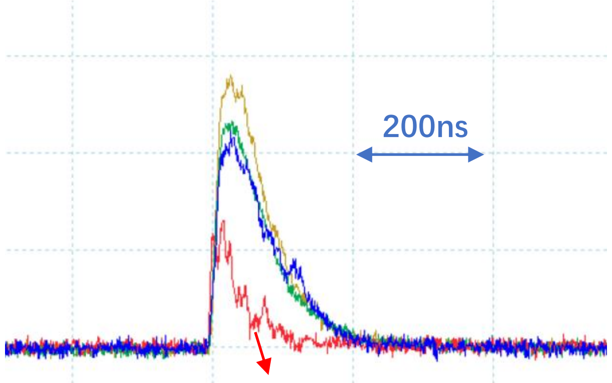
③ $2.5 \times 2.5 \times 10cm^3\ LYSO$, ESR, SiPM NDL EQR06, ~2819pe

④ $2.5 \times 2.5 \times 5cm^3\ LYSO$, black aluminum, SiPM NDL EQR06, ~90pe



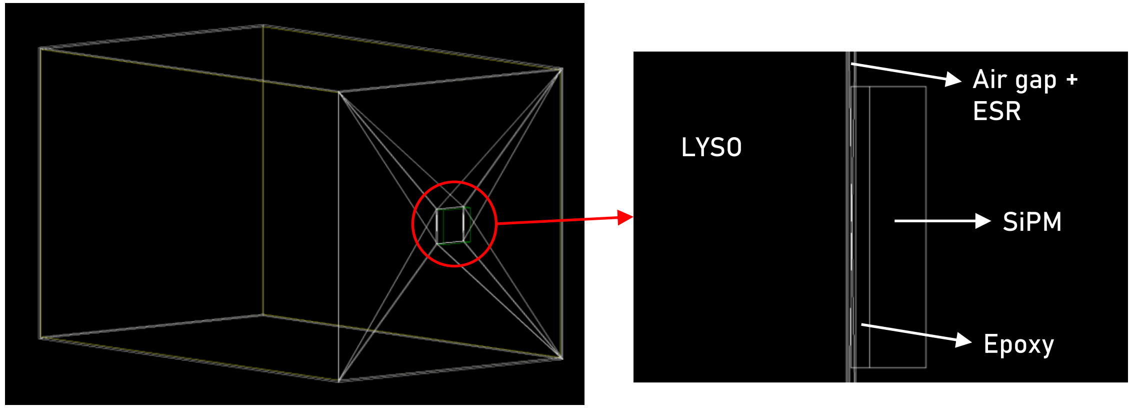




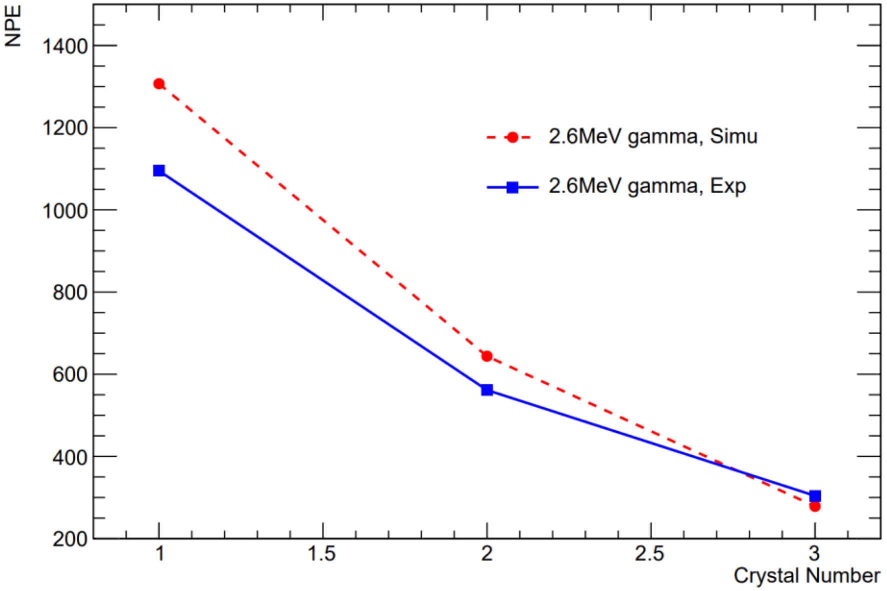


Light Yield Simulation

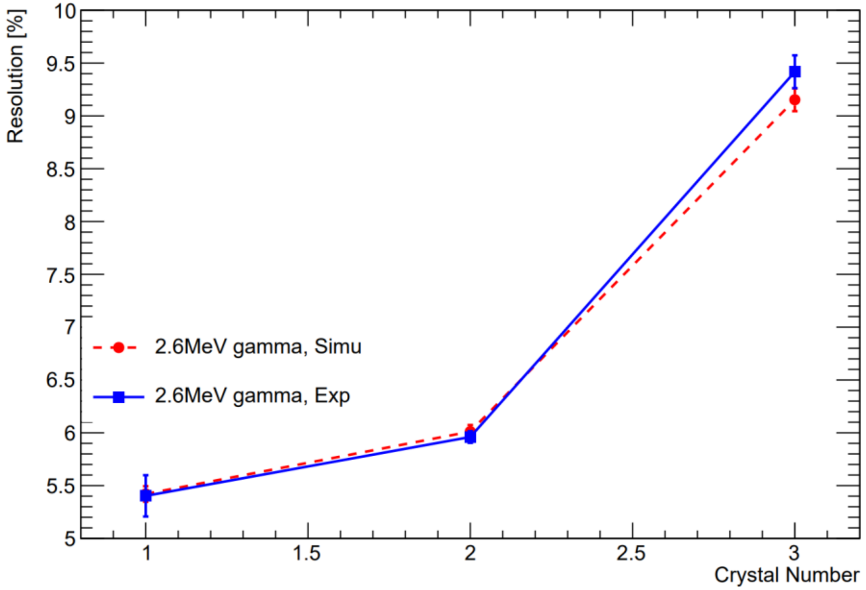
- Crystal Number
  - ① $2.5 \times 2.5 \times 2.5cm^3$ $LYSO$, $5 \times 5mm^2$ window
  - ② $2.5 \times 2.5 \times 5cm^3$ $LYSO$, $5 \times 5mm^2$ window
  - ③ $2.5 \times 2.5 \times 10cm^3$ $LYSO$, $8 \times 8mm^2$ window
- The simulated light yield and resolution roughly match the experimental results



Number of PE



Resolution

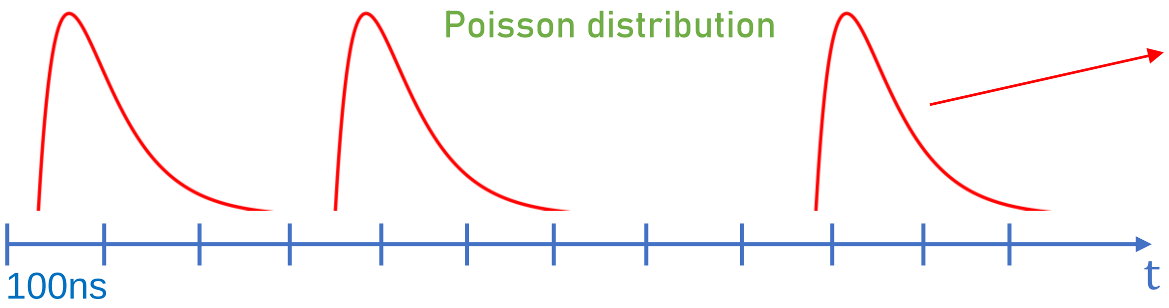


Energy Contributed by Intrinsic Radiation

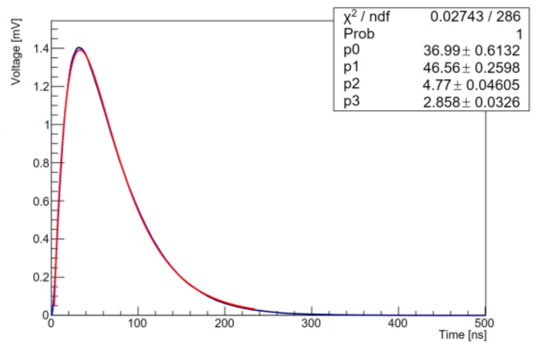
- Estimated the energy deposit by intrinsic radiation in crystal and ECAL at 10MHz event rate
- Average decay energy per event
  - $\langle E\_Cell_{Decay} \rangle \sim 15keV$
  - $\langle E\_Total_{Decay} \rangle \sim 74MeV$
  - Larger if consider absorbing between adjacent crystals

Noise from IR can be partially eliminated by threshold, but it will affect the resolution because threshold also act on the signal.

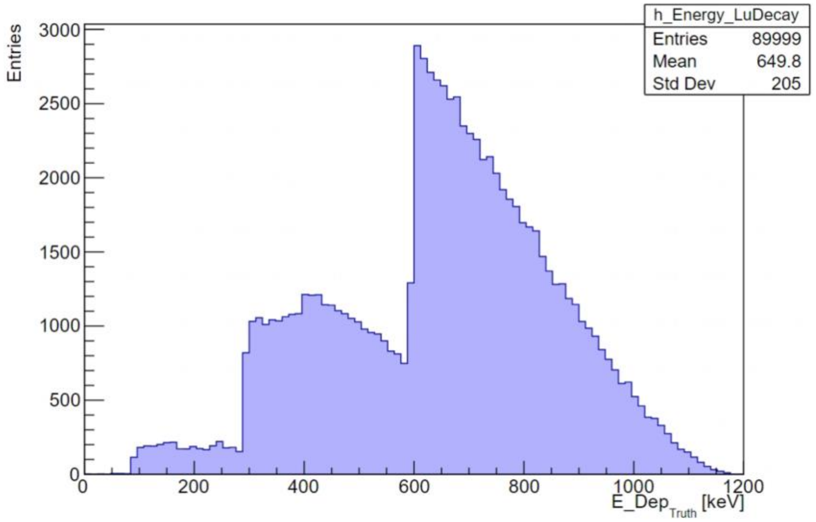
IR signal, ~240k Bq for single crystal($2.5 \times 2.5 \times 4cm^3$ LYSO)



Simulated waveform

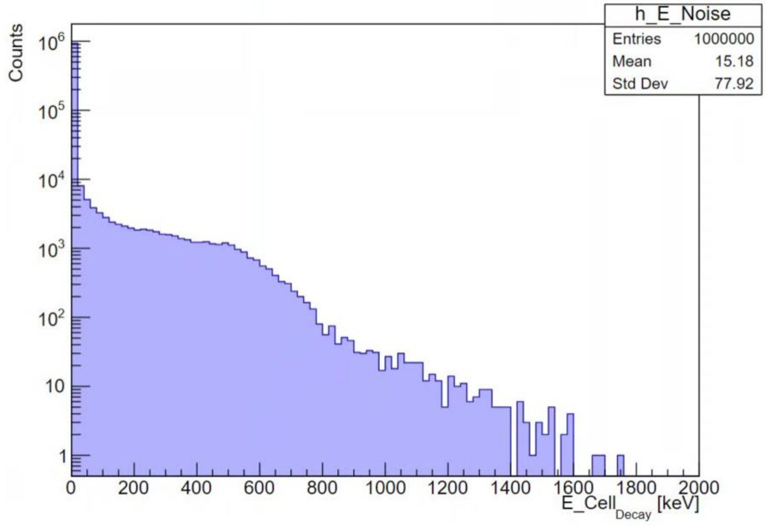


Deposit energy from ^{176}Lu decay



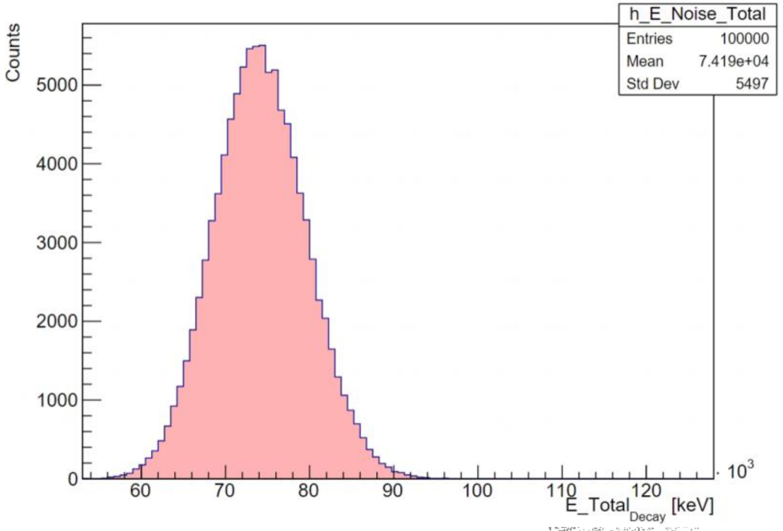
- Sampling with the spectrum for each signal

Cell energy from intrinsic radiation



- LYSO with $2.5 \times 2.5 \times 4cm^3$ size

ECAL energy from intrinsic radiation



- ECAL with 4851 LYSOs

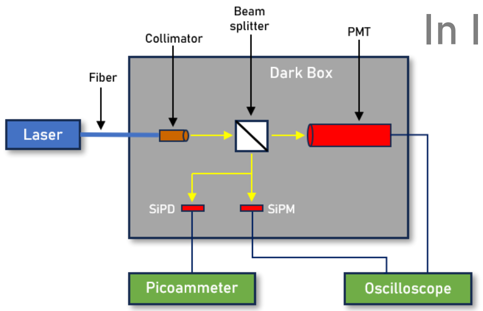
SiPM Dynamic Range Test and Simulation

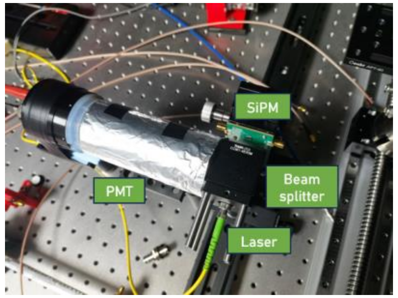
- Experiment to measure the intrinsic dynamic range of SiPM with laser
  - Pico-second laser: <40ps pulse width, 405nm wavelength
  - SiPM: DUT with large pixel numbers
  - PMT/Si-PIN: scaler
- Toy Monte Carlo of SiPM when measuring LYSO scintillation light
  - 2×10^5 photons light input~ 40% non-linearity in SiPM output, can be corrected with this model

Toy Monte Carlo including

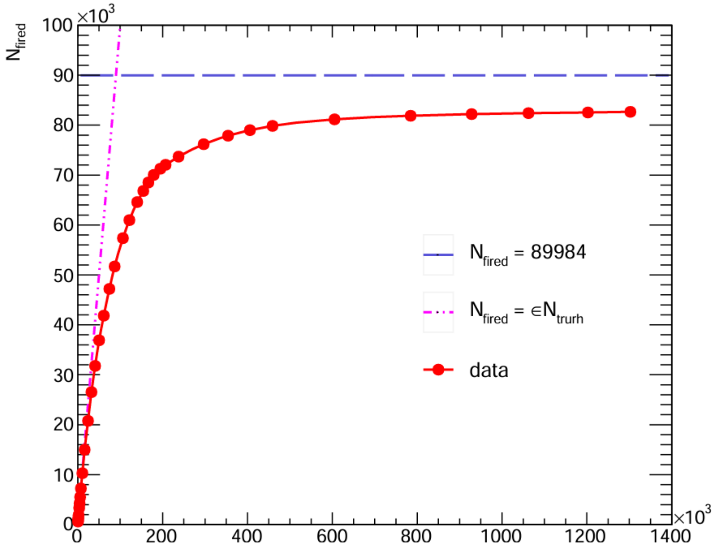
- SiPM pixel density, PDE spectrum, crosstalk, waveform properties, pixel multi-fired effect
- LYSO emission spectrum, detected time of scintillation photon

In IHEP

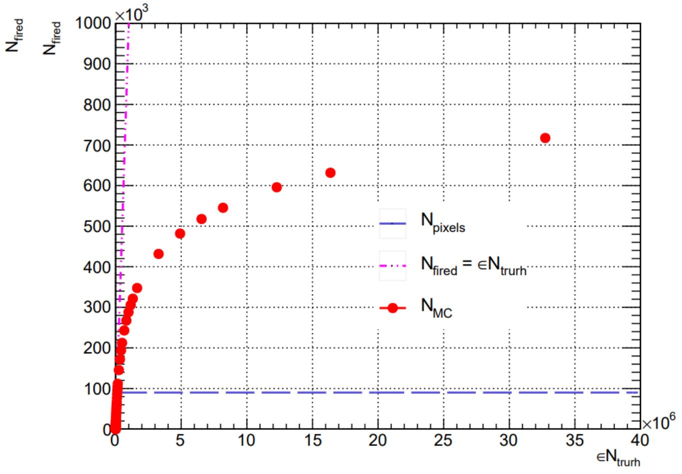


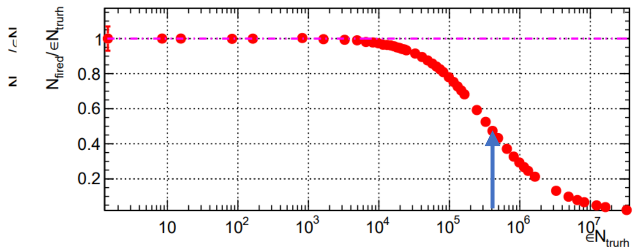


Response of HPK S14160-3010PS



MC of SiPM+LYSO





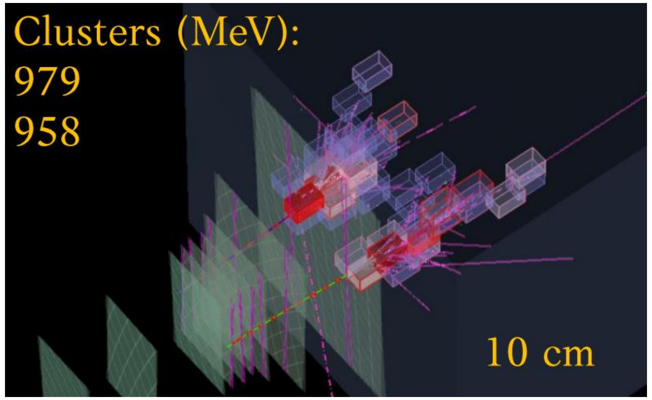
metr

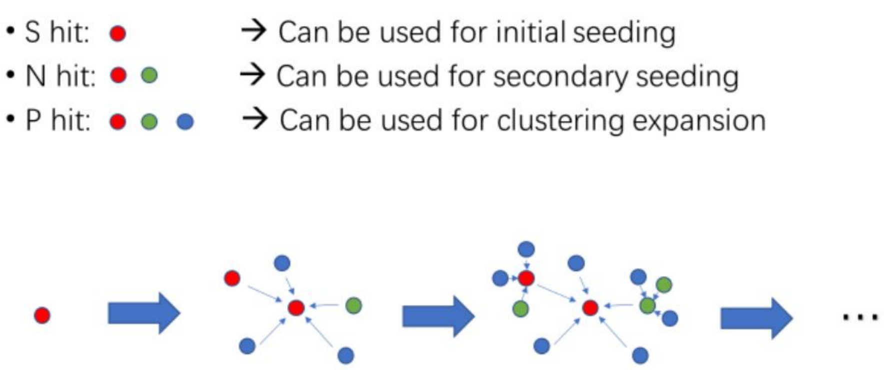
Study on the Dynamic Range of SiPMs with Large Pixel Number

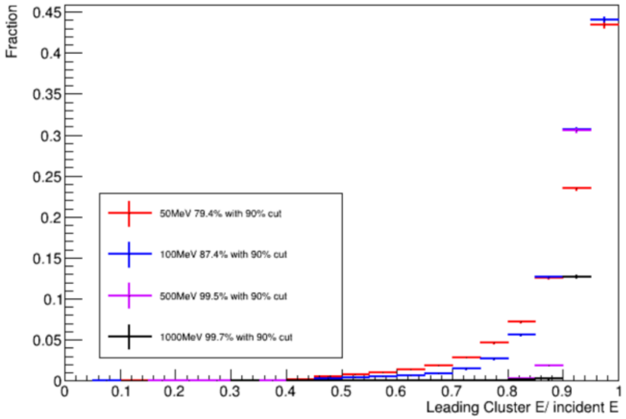
Reconstruction Algorithm

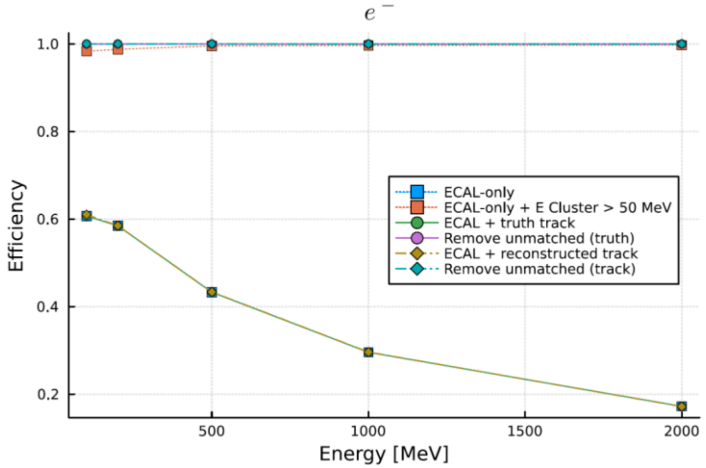
- Motivation: distinguish the multi-particle event, use MVA to explore more physical opportunities
- Cluster Formation → Cluster Splitting → Cluster-track matching
  - Searching local maxima as clustering seed
  - Absorb the neighbor hits and merge clusters as much as possible
  - Split when more than one local maxima
  - Clusters match to track, subclusters matched to the same track merged
- Performance
  - “90% E reconstructed in leading cluster”: 80% for 50MeV e-, ~100% for >500MeV e-
  - Cluster and track can be matched in low energy region

e+/e-



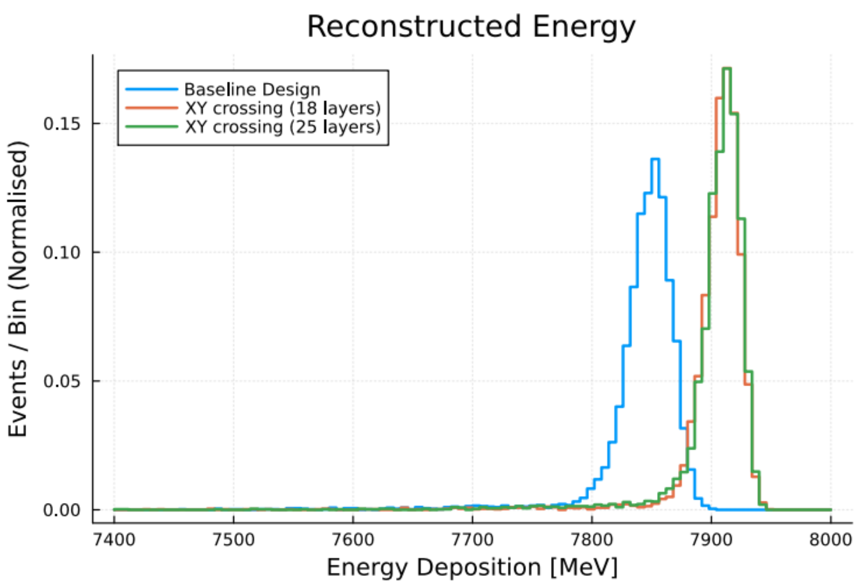


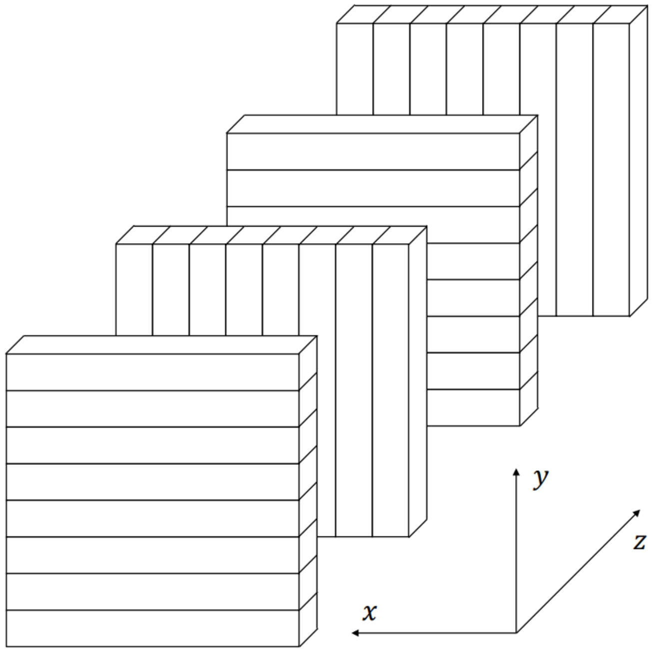




New Design ECAL

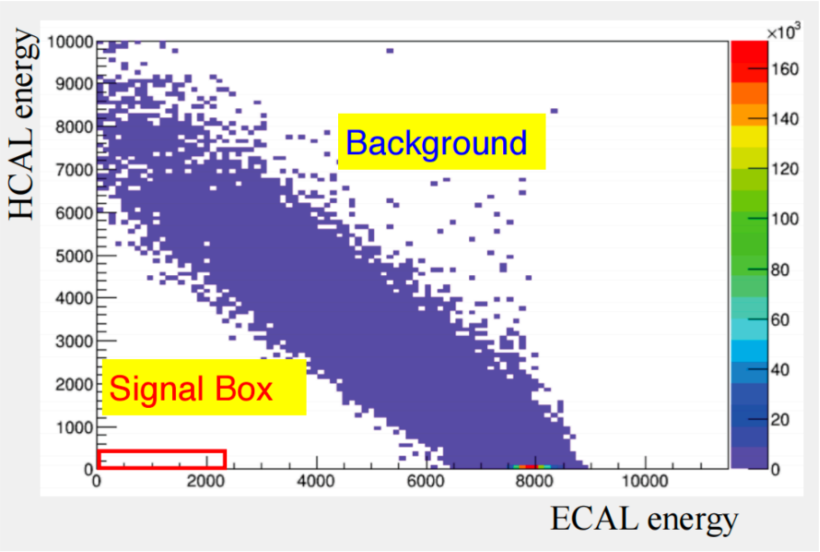
- Crossing long crystal bars to save costs and prevent beam damage to PCB
  - Crystal that longer than 10cm have a higher unit cost.
  - Use some optical glue to get a long crystal – to be validate

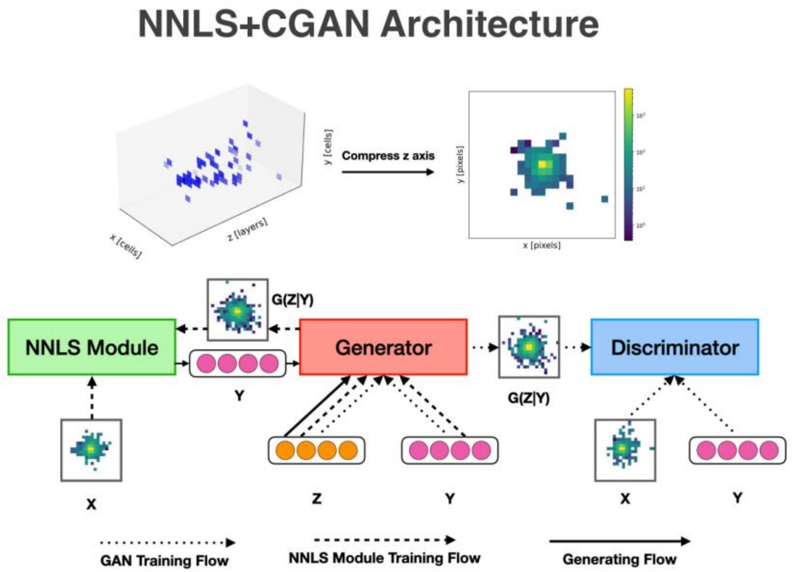


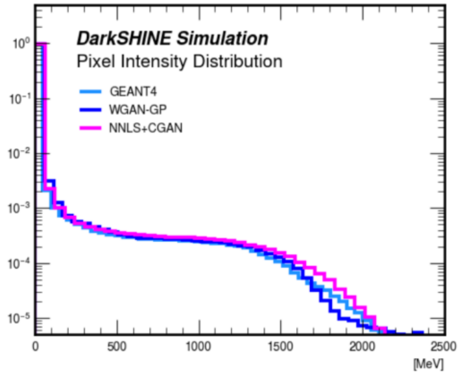


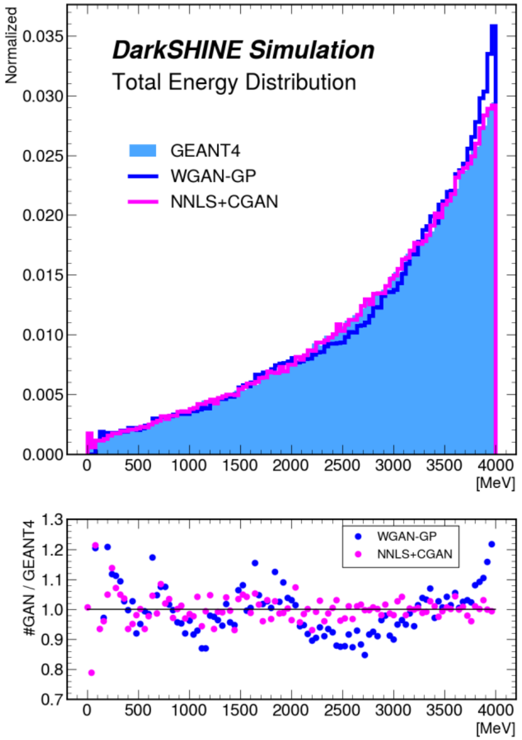
Fast Simulation with Machine Learning

- Motivation: As we increase the simulation statistical quantities, it tends to be more background events closing to signal region
  - Geant4 simulation for 3×10^{14} EOTs will consume a massive amount of resources
    - ~5ms per inclusive event. 3×10^{14} EOTs ~ 10^4 CPUs run for 5 years
  - Generation with deep learning network could save a lot of time/money
- NNLS+CGAN can work for ECAL energy data synthesis
  - $\times 10^4$ speed-up could be achieved
  - Upgrade to provided shower shape for detailed validation









[1] Mirza M, Osindero S. Conditional generative adversarial nets[J]. arXiv preprint arXiv:1411.1784, 2014.
[2] Chen D, Plemmons R J. Nonnegativity constraints in numerical analysis[M]//The birth of numerical analysis. 2010: 109-139.