暗光计划LYSO晶体电磁量能器设计及单元测试

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on behalf of DarkSHINE Working Group

第二十一届全国核电子学与核探测技术学术年会

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TSUNG-DAO LEE INSTITUTE

Outline

☐ Introduction

☐ Radiation damage estimation for scintillator and SiPM

☐ Unit Test

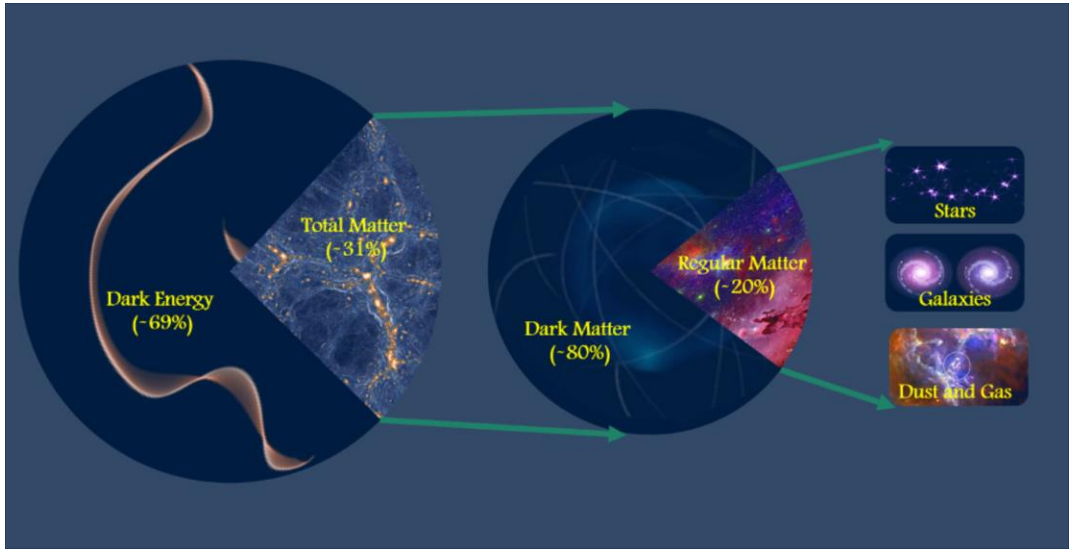
- Intrinsic Radiation test and simulation
- SiPM test: DCR, Dynamic range
- Light yield of the unit with different crystal size, film and SiPM (radiation source&cosmic ray)
- Uniformity scan

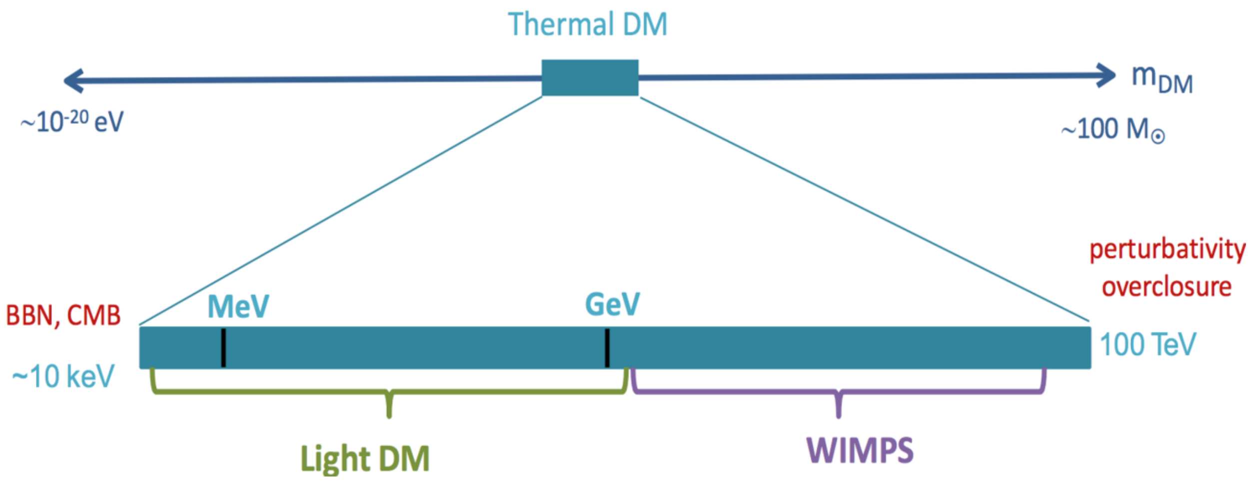
☐ Crystal module design

☐ Summary

Dark Matter Search Experiments

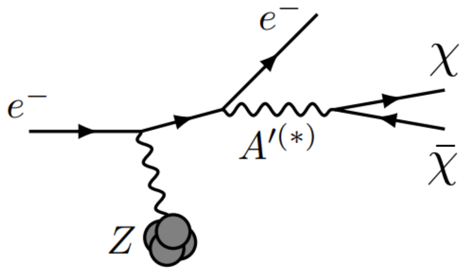
- Evidence from cosmology and astronomy showing that DM exists in the universe.
- Lots of DM search experiments with different approaches:
  - Underground experiments (direct): PandaX, CDEX, LUX, Xenon, …
  - Space experiments (indirect): DAMPE, AMS, …
  - Accelerator-based experiments (production): Belle-II, Bes-III, LHC, NA64, DarkLight, DarkMESA, LDMX…

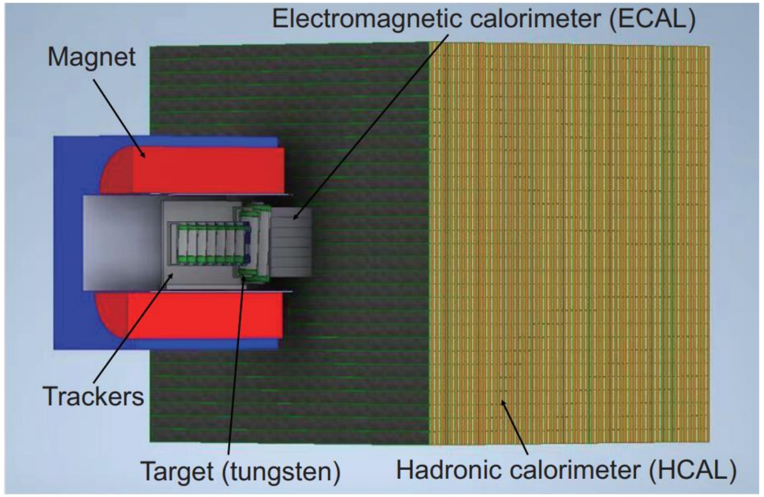


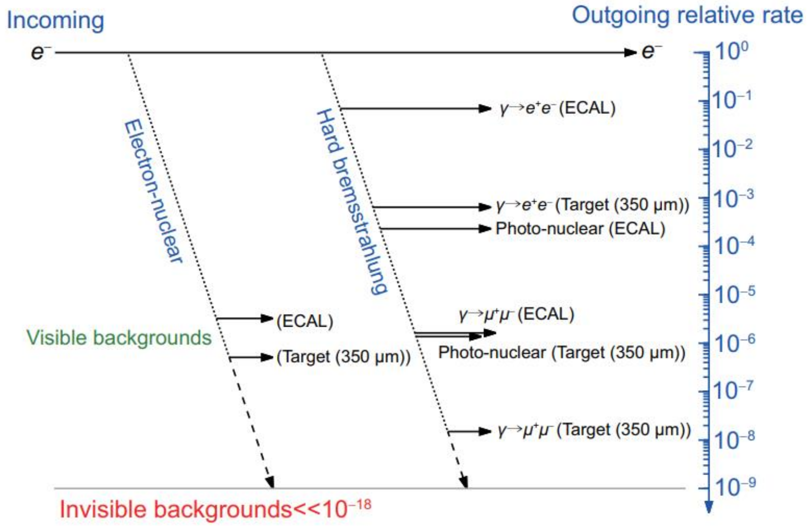


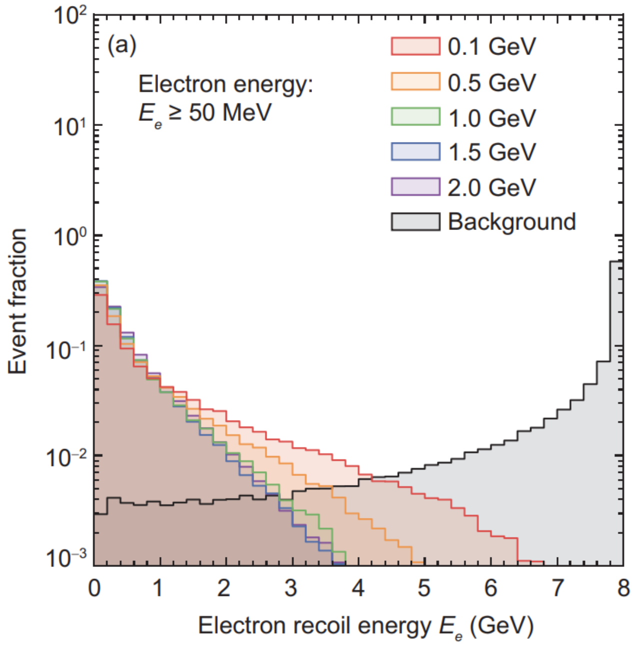
DarkSHINE

- Searching for MeV~GeV light DM with dark photon mediator
- 1~10MHz high repetition rate single electron beam @8GeV to be provided by SHINE, 3×10^{14} EOT
- Invisible decay of dark photon can be detected by energy loss of recoil electron
- Aim to achieve internationally competitive sensitivity in the search for dark photon
  - Innovation: high rate single e-beam, energy loss + momentum loss, homogenous calorimeter, …



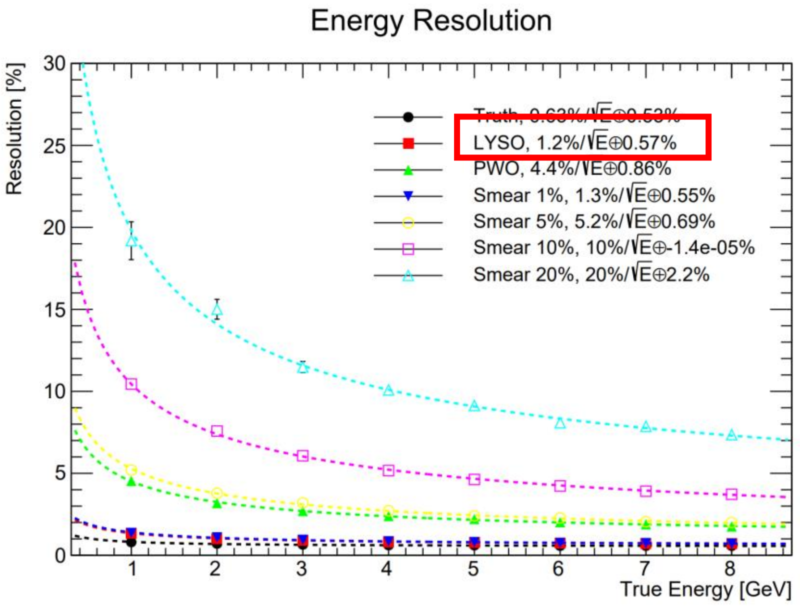


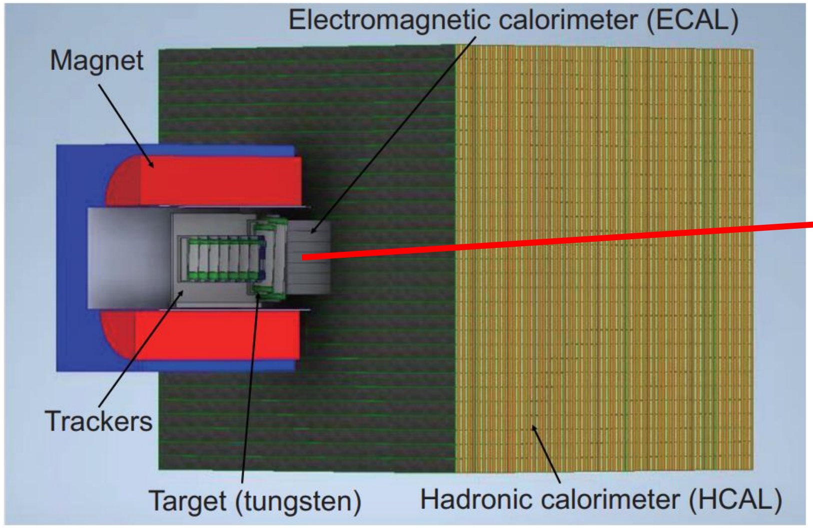


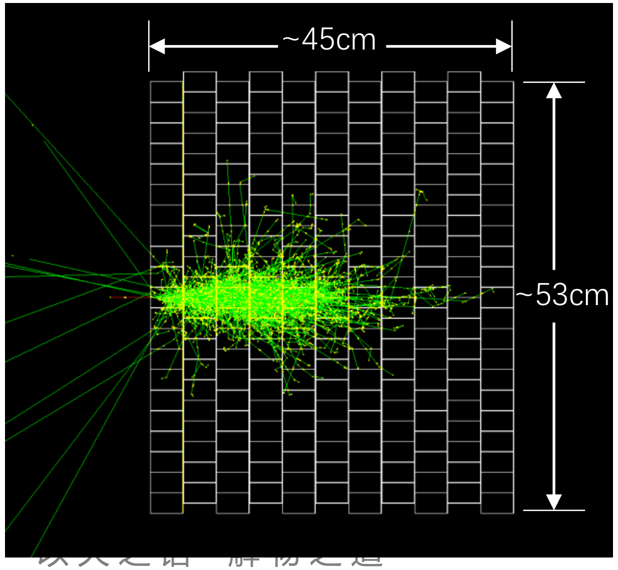


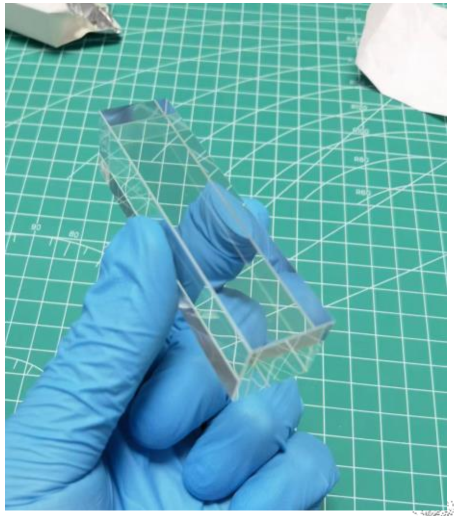
Electromagnetic Calorimeter (ECAL) of DarkSHINE

- Precise measurement of EM clusters
- Requirements:
  - Radiation hard to survive in $\sim 10^7 rad$ dose
  - High density: contain all of the EM components
  - Fast response: minimum to 100ns time window
  - Sensor with large dynamic range
- Design: LYSO crystal calorimeter with homogeneous structure
  - LYSO: ~30000pe/MeV, 40 ns decay time, density $7.2\ g/cm^3$, 1.14cm X_0, radiation hard
  - SiPM readout
  - Total length ~39 X_0



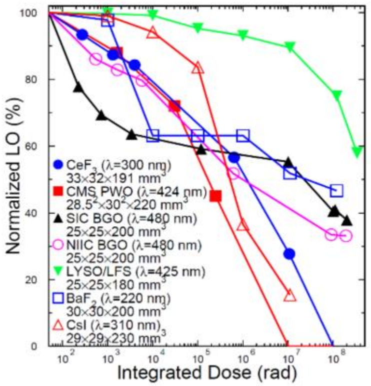


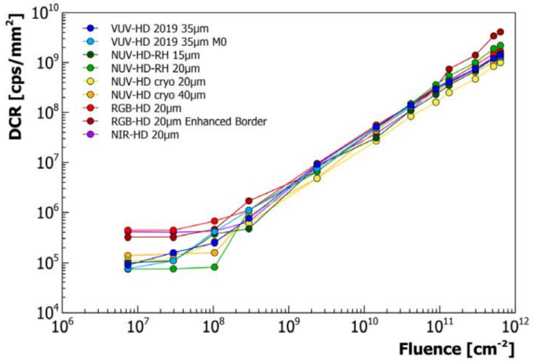




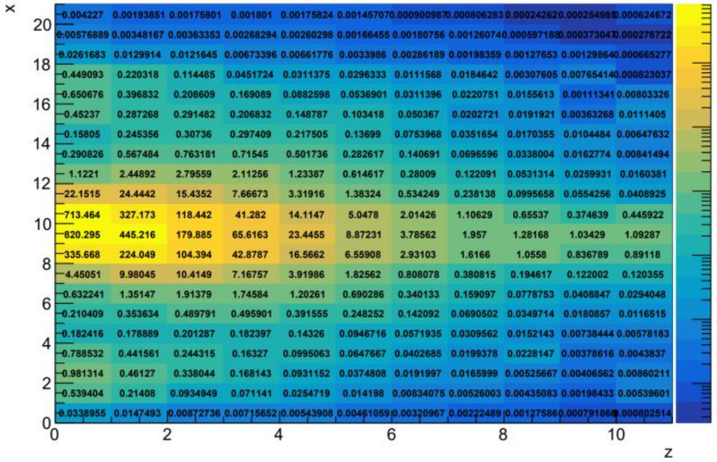
Radiation Damage Estimation

- 1~10MHz e- beam @8GeV with 3cm radius
- 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 fluence





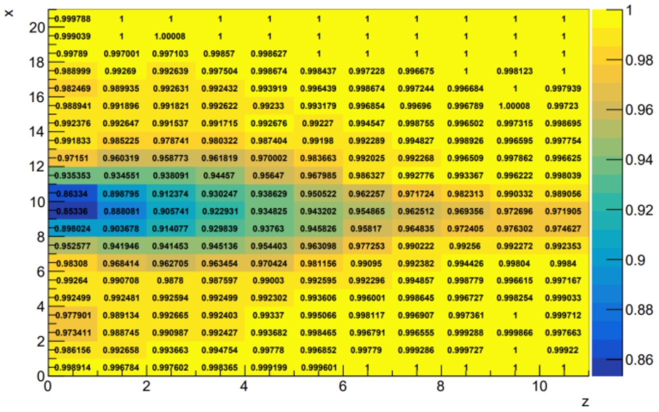
Average Cell Energy Deposit per Event



0.004227	0.00193851	0.00175801	0.001801	0.00175824	0.00145707	0.000900987	0.000806283	0.00024262	0.000254985	0.000624672
0.00576889	0.00348167	0.00363353	0.00268294	0.00260298	0.00166455	0.00180756	0.00126074	0.000597188	0.000373047	0.000276722
0.0261683	0.0129914	0.0121645	0.00673396	0.00661776	0.0033986	0.00286189	0.00198359	0.00127653	0.00129864	0.000665277
0.449093	0.220318	0.114485	0.0451724	0.0311375	0.0296333	0.0111568	0.0184642	0.00307605	0.00765414	0.000823037
0.650676	0.396832	0.208609	0.169089	0.0882598	0.0536901	0.0311396	0.0220751	0.0155613	0.00111341	0.00803326
0.45237	0.287268	0.291482	0.206832	0.148787	0.103418	0.050367	0.0202721	0.0191921	0.00363268	0.0111405
0.15805	0.245356	0.30736	0.297409	0.217505	0.13699	0.0753968	0.0351654	0.0170355	0.0104484	0.00647632
0.290826	0.567484	0.763181	0.71545	0.501736	0.282617	0.140691	0.0696596	0.0338004	0.0162774	0.00841494
1.1221	2.44892	2.79559	2.11256	1.23387	0.614617	0.28009	0.122091	0.0531314	0.0259931	0.0160381
22.1515	24.4442	15.4352	7.66673	3.31916	1.38324	0.534249	0.238138	0.0995658	0.0554256	0.0408925
713.464	327.173	118.442	41.282	14.1147	5.0478	2.01426	1.10629	0.65537	0.374639	0.445922
820.295	445.216	179.885	65.6163	23.4455	8.87231	3.78562	1.957	1.28168	1.03429	1.09287
335.668	224.049	104.394	42.8787	16.5662	6.55908	2.93103	1.6166	1.0558	0.836789	0.89118
4.45051	9.98045	10.4149	7.16757	3.91986	1.82562	0.808078	0.380815	0.194617	0.122002	0.120355
0.632241	1.35147	1.91379	1.74584	1.20261	0.690286	0.340133	0.159097	0.0778753	0.0408847	0.0294048
0.210409	0.353634	0.489791	0.495901	0.391555	0.248252	0.142092	0.0690502	0.0349714	0.0180857	0.0116515
0.182416	0.178889	0.201287	0.182397	0.14326	0.0946716	0.0571935	0.0309562	0.0152143	0.00738444	0.00578183
0.788532	0.441561	0.244315	0.16327	0.0995063	0.0647667	0.0402685	0.0199378	0.0228147	0.00378616	0.0043837
0.981314	0.46127	0.338044	0.168143	0.0931152	0.0374808	0.0191997	0.0165999	0.00525667	0.00406562	0.00860211
0.539404	0.21408	0.0934949	0.071141	0.0254719	0.014198	0.00834075	0.00526003	0.00435083	0.00198433	0.00539601
0.0338955	0.0147493	0.00872736	0.00715652	0.00543908	0.00461059	0.00320967	0.00222489	0.00127586	0.00079186	0.000802514

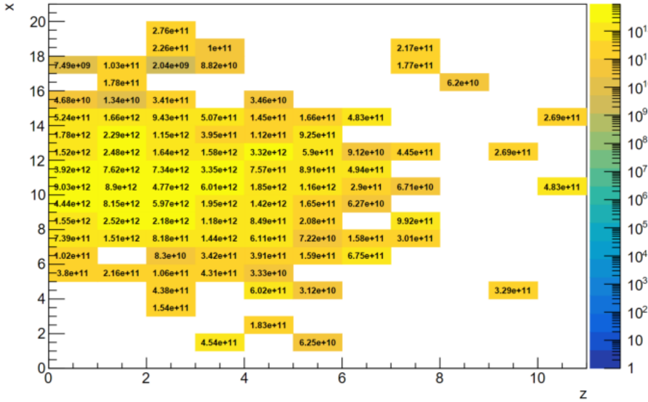
3×10^{14} Events

Light Yield Reduction of LYSO



0.999788	1	1	1	1	1	1	1	1	1	1
0.999039	1	1.00008	1	1	1	1	1	1	1	1
0.99789	0.997001	0.997103	0.99857	0.998627	1	1	1	1	1	1
0.988999	0.99269	0.992639	0.997504	0.998674	0.998437	0.997228	0.996675	1	0.998123	1
0.982469	0.989935	0.992631	0.992432	0.993919	0.996439	0.998674	0.997244	0.996684	1	0.997939
0.988941	0.991896	0.991821	0.992622	0.99233	0.993179	0.996854	0.99696	0.996789	1.00008	0.99723
0.992376	0.992647	0.991537	0.991715	0.992676	0.99227	0.994547	0.998755	0.996502	0.997315	0.998695
0.991833	0.985225	0.978741	0.980322	0.987404	0.99198	0.992289	0.994827	0.998926	0.996595	0.997754
0.97151	0.960319	0.958773	0.961819	0.970002	0.983663	0.992025	0.992268	0.996509	0.997862	0.996625
0.935353	0.934551	0.938091	0.94457	0.95647	0.967985	0.986327	0.992776	0.993367	0.996222	0.998039
0.86334	0.898795	0.912374	0.930247	0.938629	0.950522	0.962257	0.971724	0.982313	0.990332	0.989056
0.85336	0.888081	0.905741	0.922931	0.934825	0.943202	0.954865	0.962512	0.969356	0.972696	0.971905
0.898024	0.903678	0.914077	0.929839	0.93763	0.945826	0.95817	0.964835	0.972405	0.976302	0.974627
0.952577	0.941946	0.941453	0.945136	0.954403	0.963098	0.977253	0.990222	0.99256	0.992272	0.992353
0.98308	0.968414	0.962705	0.963454	0.970424	0.981156	0.99095	0.992382	0.994426	0.99804	0.9984
0.99264	0.990708	0.9878	0.987597	0.99003	0.992595	0.992296	0.994857	0.998779	0.996615	0.997167
0.992499	0.992481	0.992594	0.992499	0.992302	0.993606	0.996001	0.998645	0.996727	0.998254	0.999033
0.977901	0.989134	0.992665	0.992403	0.99337	0.995066	0.998117	0.996907	0.997361	1	0.999712
0.973411	0.988745	0.990987	0.992427	0.993682	0.998465	0.996791	0.996555	0.999288	0.999866	0.997663
0.986156	0.992658	0.993663	0.994754	0.99778	0.996852	0.99779	0.999286	0.999727	1	0.99922
0.998914	0.996784	0.997602	0.998365	0.999199	0.999601	1	1	1	1	1

Equivalent 1MeV Neutron Fluence for SiPM

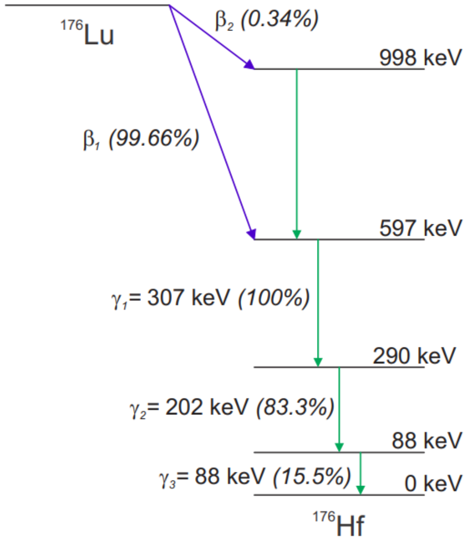


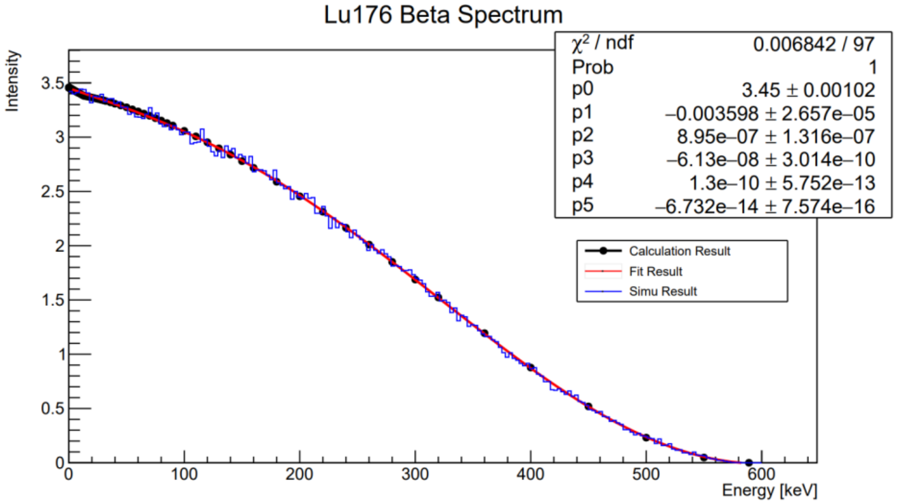
		2.76e+11								
		2.26e+11	1e+11				2.17e+11			
7.49e+09	1.03e+11	2.04e+09	8.82e+10				1.77e+11			
	1.78e+11							6.2e+10		
4.68e+10	1.34e+10	3.41e+11		3.46e+10						
5.24e+11	1.66e+12	9.43e+11	5.07e+11	1.45e+11	1.66e+11	4.83e+11				2.69e+11
1.78e+12	2.29e+12	1.15e+12	3.95e+11	1.12e+11	9.25e+11					
1.52e+12	2.48e+12	1.64e+12	1.58e+12	3.32e+12	5.9e+11	9.12e+10	4.45e+11		2.69e+11	
3.92e+12	7.62e+12	7.34e+12	3.35e+12	7.57e+11	8.91e+11	4.94e+11				
9.03e+12	8.9e+12	4.77e+12	6.01e+12	1.85e+12	1.16e+12	2.9e+11	6.71e+10			4.83e+11
4.44e+12	8.15e+12	5.97e+12	1.95e+12	1.42e+12	1.65e+11	6.27e+10				
1.55e+12	2.52e+12	2.18e+12	1.18e+12	8.49e+11	2.08e+11		9.92e+11			
7.39e+11	1.51e+12	8.18e+11	1.44e+12	6.11e+11	7.22e+10	1.58e+11	3.01e+11			
1.02e+11		8.3e+10	3.42e+11	3.91e+11	1.59e+11	6.75e+11				
3.8e+11	2.16e+11	1.06e+11	4.31e+11	3.33e+10						
		4.38e+11		6.02e+11	3.12e+10				3.29e+11	
		1.54e+11								
				1.83e+11						
			4.54e+11		6.25e+10					

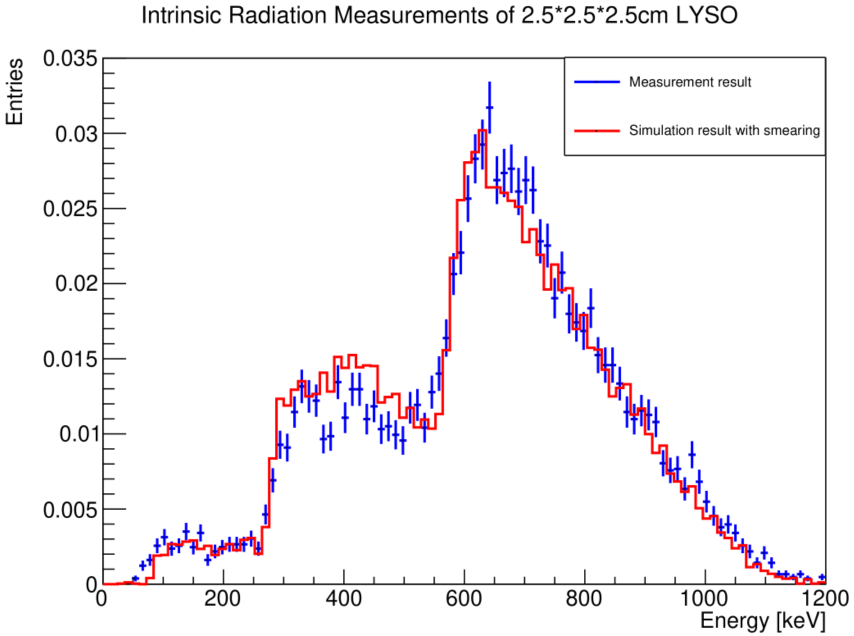
[1] Ultrafast and Radiation Hard Inorganic Scintillators for Future HEP Experiments [2] https://doi.org/10.1016/j.nima.2022.167661
[3] https://doi.org/10.1016/j.nima.2020.164203 [4] https://doi.org/10.1016/j.nima.2009.01.176

LYSO Intrinsic Radiation

- The radioactivity is from element $^{176}_{71}Lu$, consist of one β decay and three ensuing γ decay
- Fit and sample the beta spectrum of $^{176}_{71}Lu$ according to theoretical calculations. And then simulate emission and absorption of e- and γ in LYSO with Geant4.
- Energy range=0~1.2 MeV, $T_{1/2} = 3.64 \times 10^{10}\ y$, potential online calibration source!



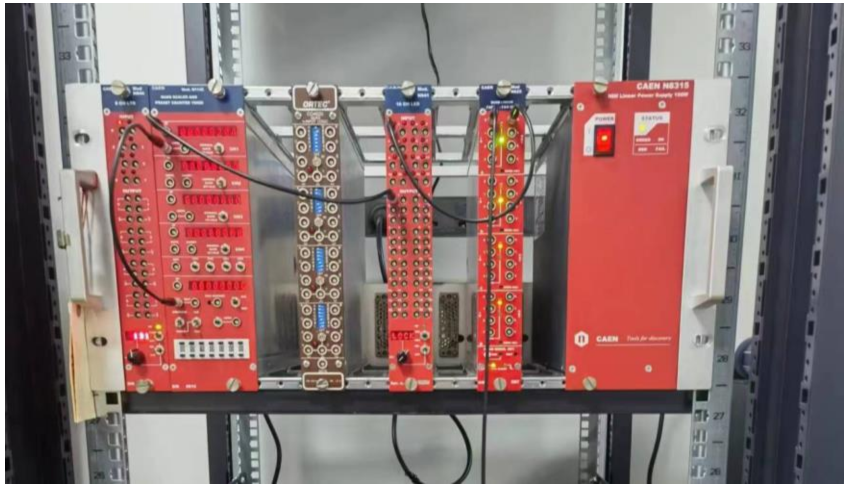


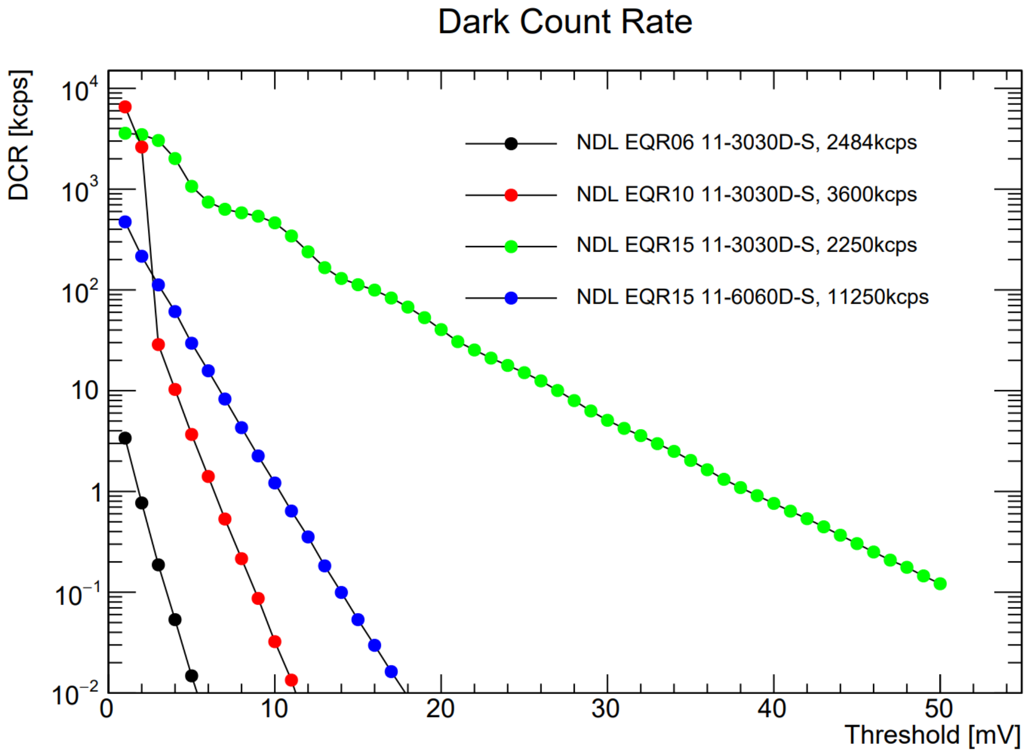


SiPM DCR Test

- SiPM:
  - NDL EQR06 11-3030D-S, 2484kcps, 8×10^4 gain
  - NDL EQR10 11-3030D-S, 3600kcps, 1.7×10^5 gain
  - NDL EQR15 11-3030D-S, 2250kcps, 4×10^5 gain
  - NDL EQR15 11-6060D-S, 11250kcps, 4×10^5 gain

SiPM → ×10 Pre-Amp → LTD → Counter

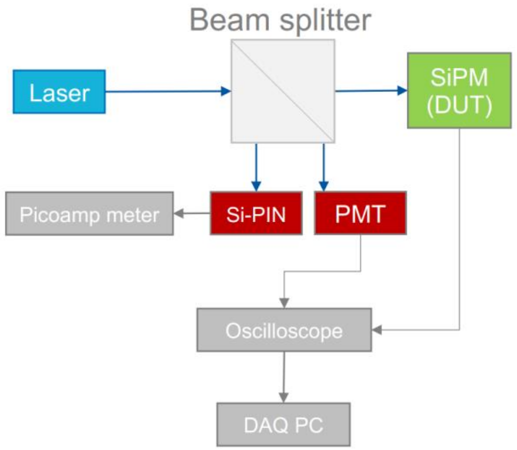


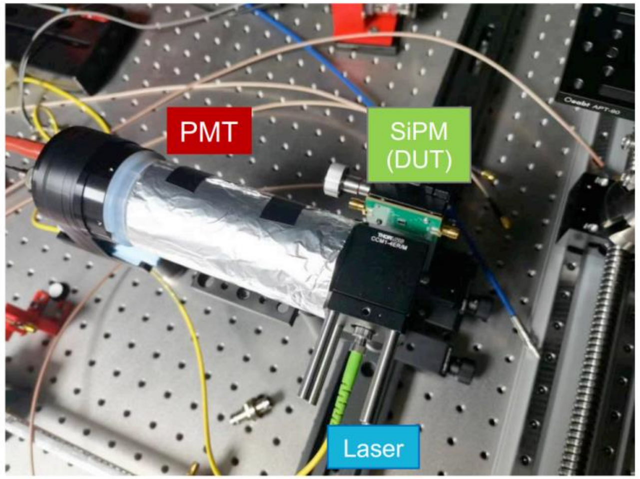


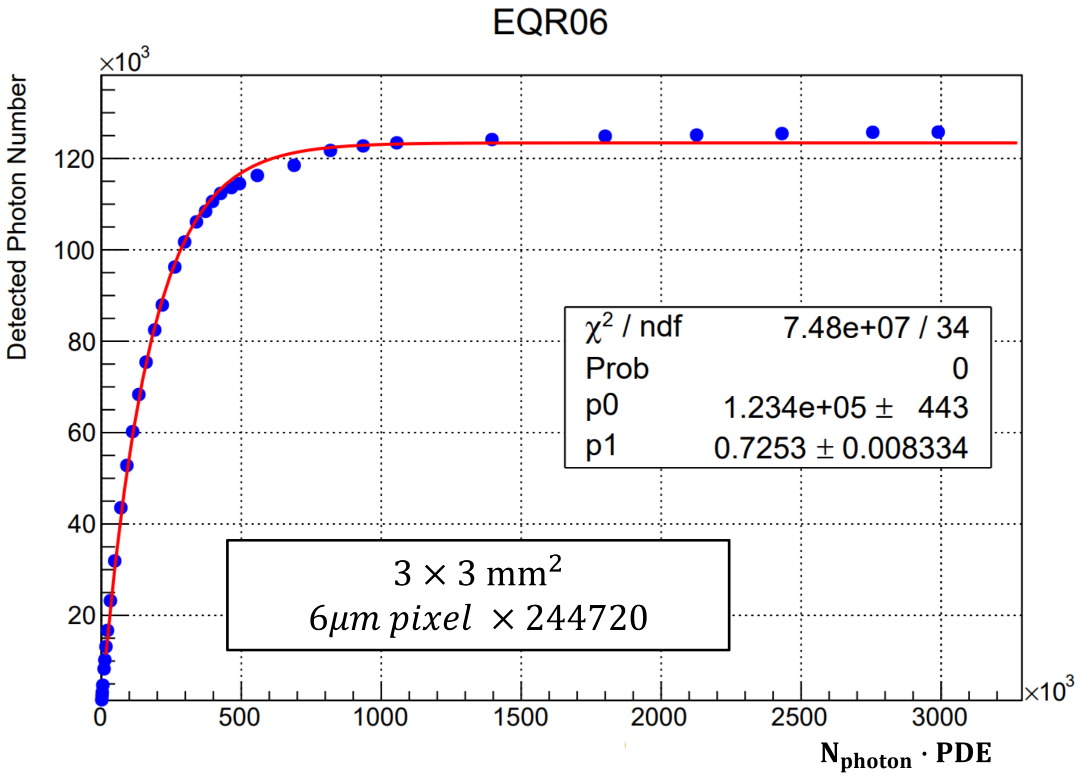
Dynamic Range Test of SiPM with Large Pixel Num

in IHEP

- The central crystal in Dark SHINE could absorb energy about 1GeV, ~200k pe . So we need SiPMs with very large dynamic range. And response measurement for these SiPMs is also necessary.
- Use PMT and Si-PIN to calibrate SiPM output
  - Pico-second laser: ~40ps pulse width
  - Beam splitter: Split light into two beams that are not equal
  - PMT, Si-PIN: reference photosensors



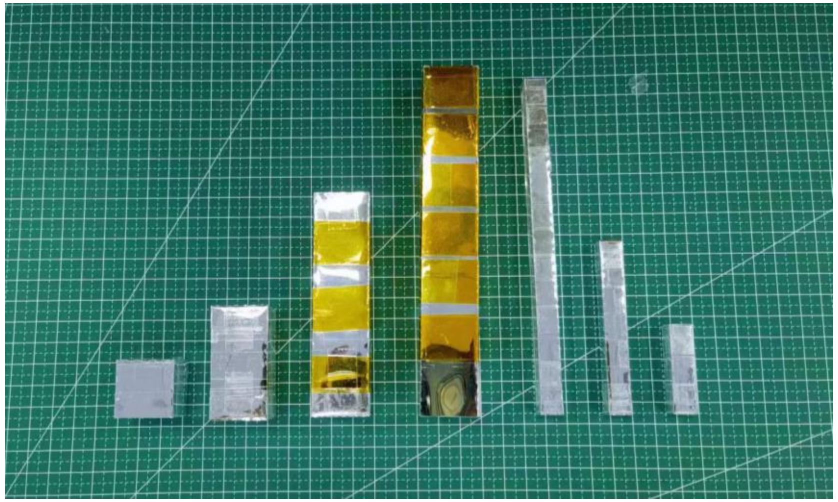


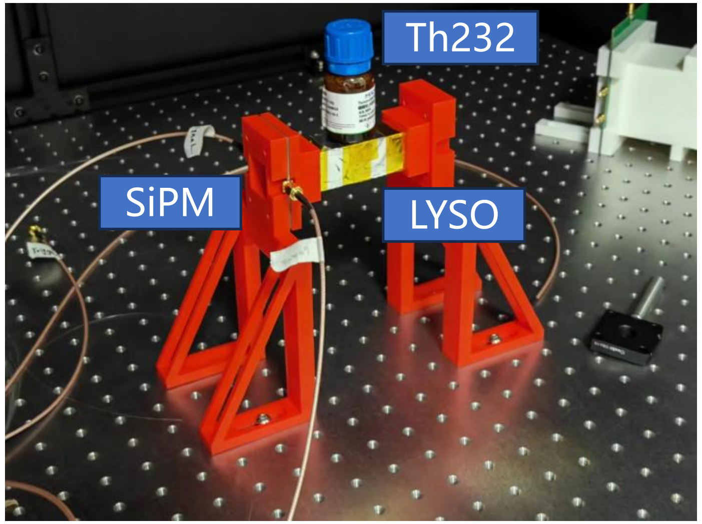


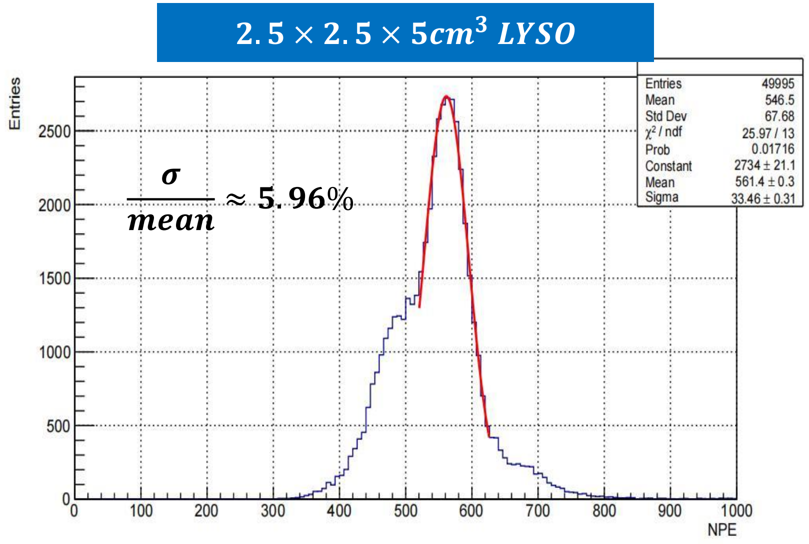
大动态范围SiPM的响应刻度-NED2023

Radioactive Source Test

- $2.5 \times 2.5 \times 5cm^3\ LYSO$ covered by reflective film (ESR)
- Th-232， 2.6MeV gamma
- SiPM: NDL EQR06 11-3030D-S, 244720 pixels
- Light yield: 216 pe/MeV (~1GeV for the hottest crystal, ~220k pe)



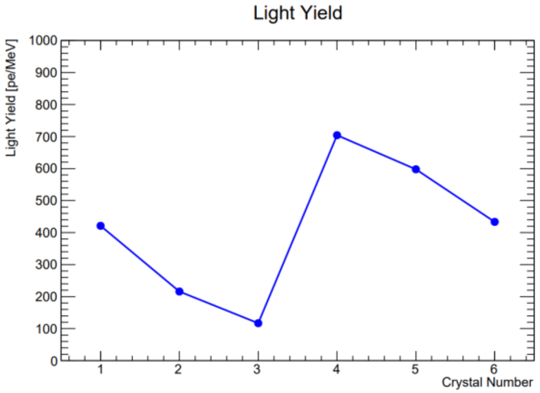


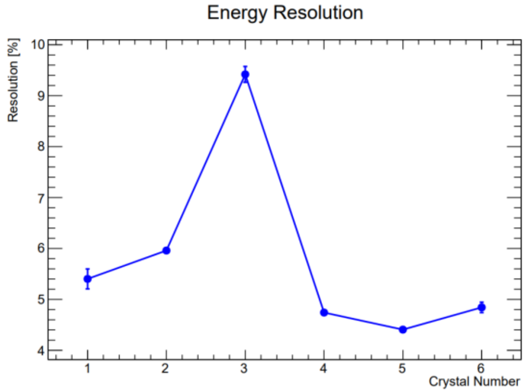

$\mathbf{2.5 \times 2.5 \times 5cm^3\ LYSO}$

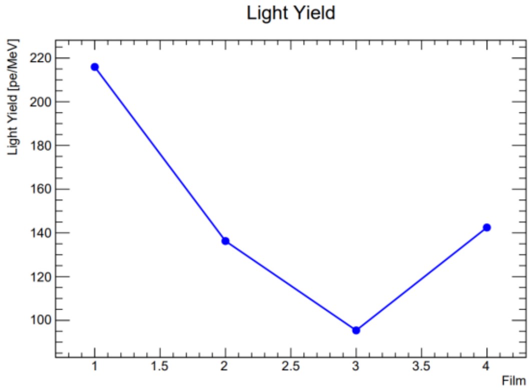
Light Yield and Energy Resolution of Units

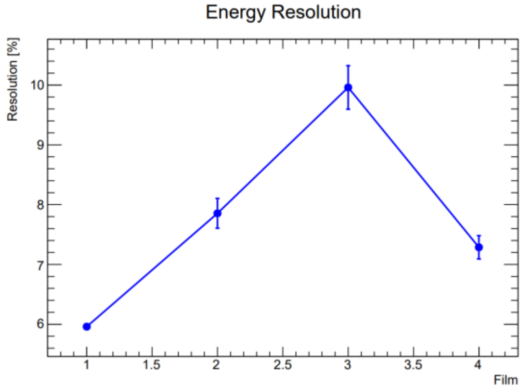
- Crystal (ESR, NDL EQR06):
  - ① $2.5 \times 2.5 \times 2.5cm^3\ LYSO$
  - ② $2.5 \times 2.5 \times 5cm^3\ LYSO$
  - ③ $2.5 \times 2.5 \times 10cm^3\ LYSO$
  - ④ $1 \times 1 \times 4cm^3\ LYSO$
  - ⑤ $1 \times 1 \times 8cm^3\ LYSO$
  - ⑥ $1 \times 1 \times 16cm^3\ LYSO$
- Film ($2.5 \times 2.5 \times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

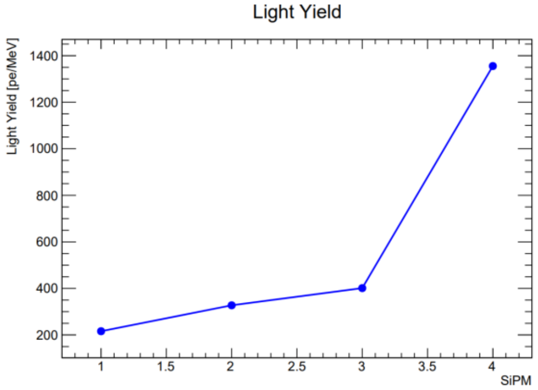
100~1400 PE/MeV, minimum coupling ~ 100 -> 1GeV = 100k PE

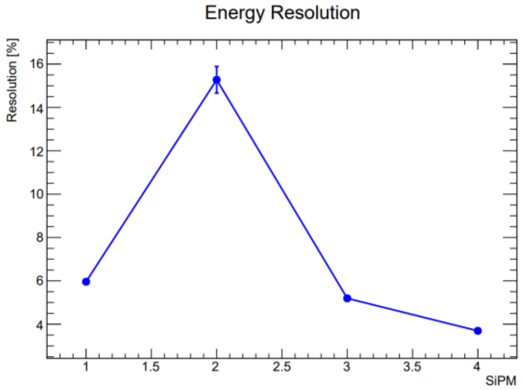

Light Yield


Energy Resolution


Light Yield


Energy Resolution


Light Yield


Energy Resolution

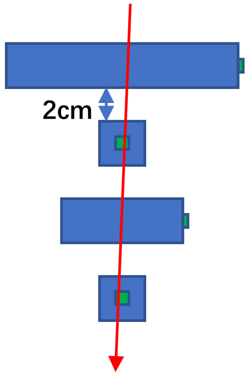
Cosmic Ray test

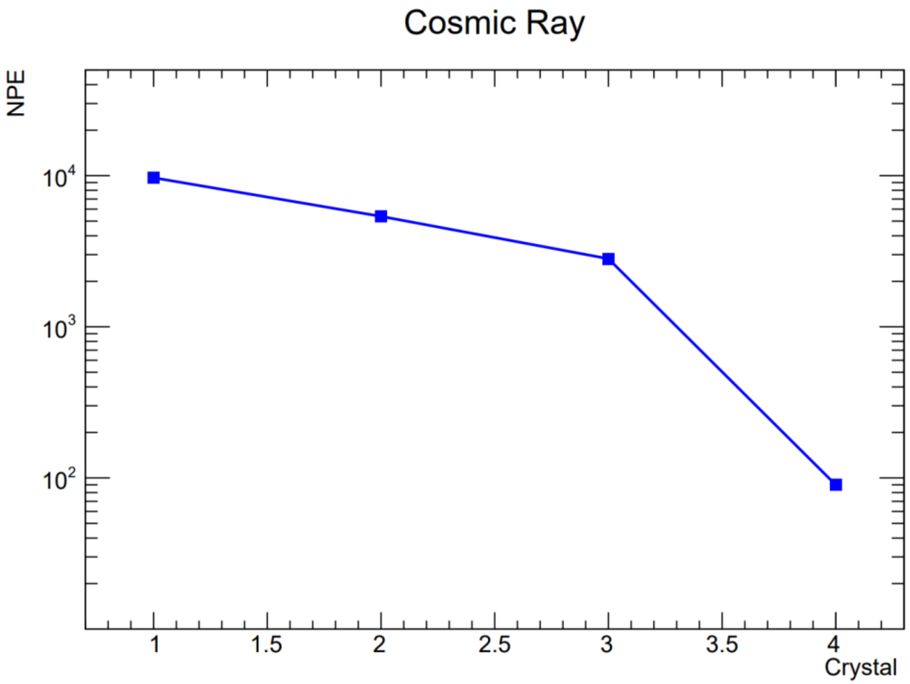
① $2.5 \times 2.5 \times 2.5cm^3\ LYSO$, ESR, SiPM NDL EQR06, ~9684pe

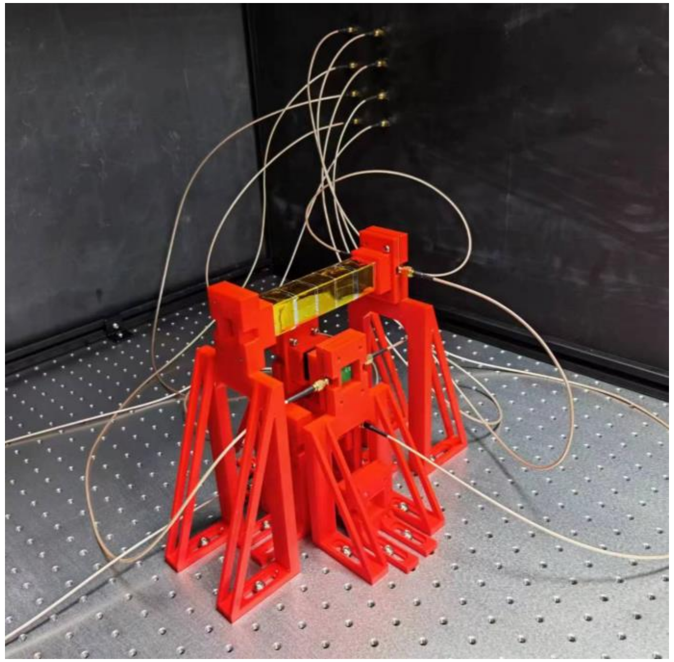
② $2.5 \times 2.5 \times 5cm^3\ LYSO$, ESR, SiPM NDL EQR06, ~5377pe

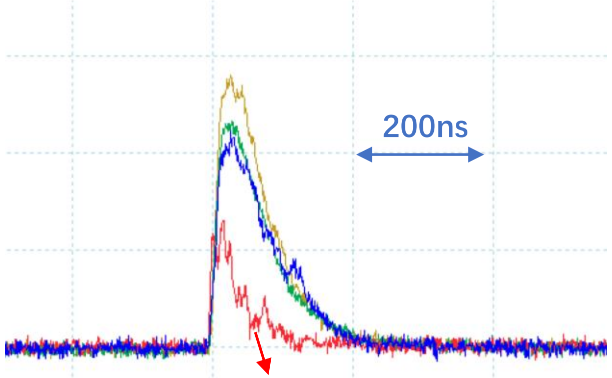
③ $2.5 \times 2.5 \times 10cm^3\ LYSO$, ESR, SiPM NDL EQR06, ~2819pe

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







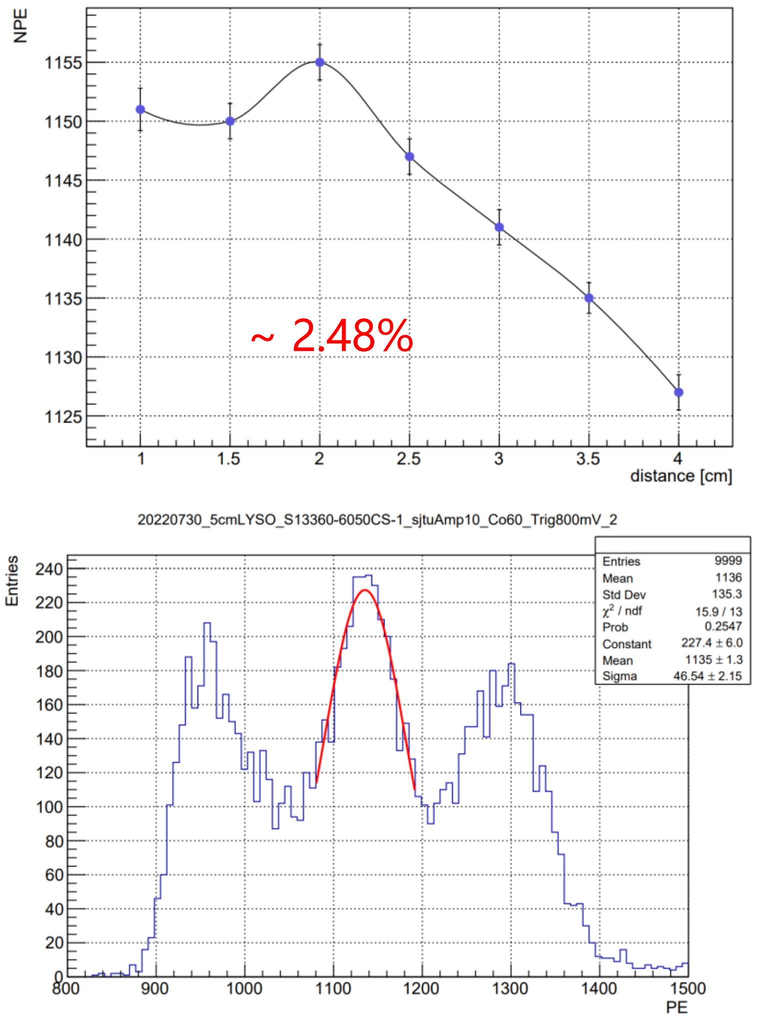


Signal from LYSO covered by black aluminum foil is smaller(~1/70) but faster

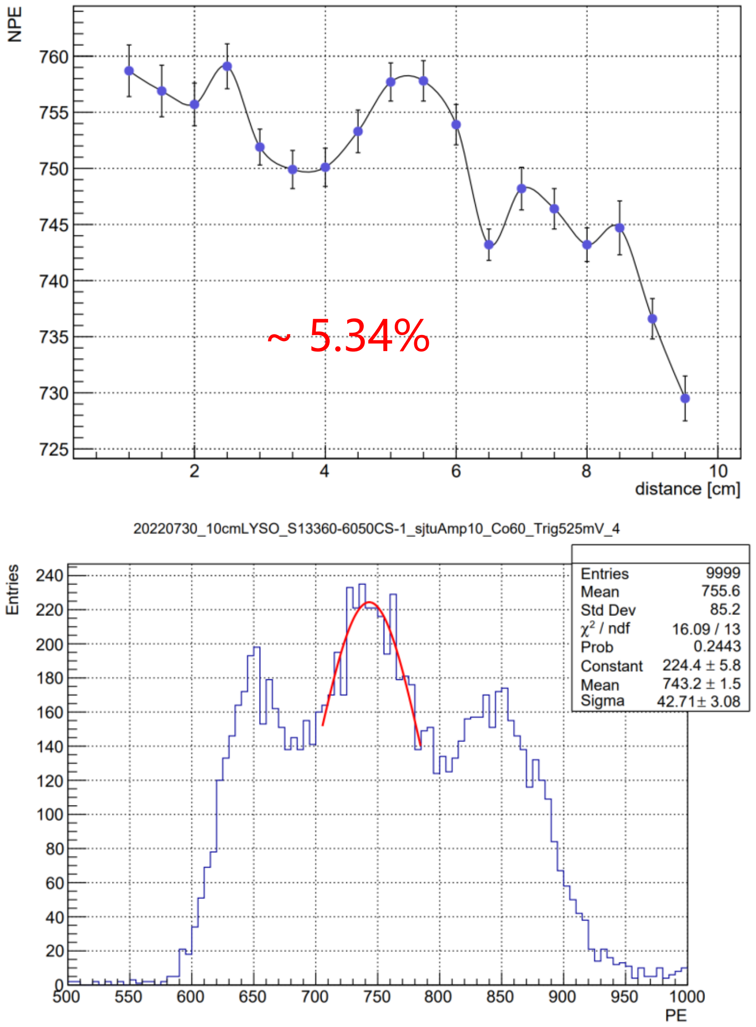
Uniformity Scan

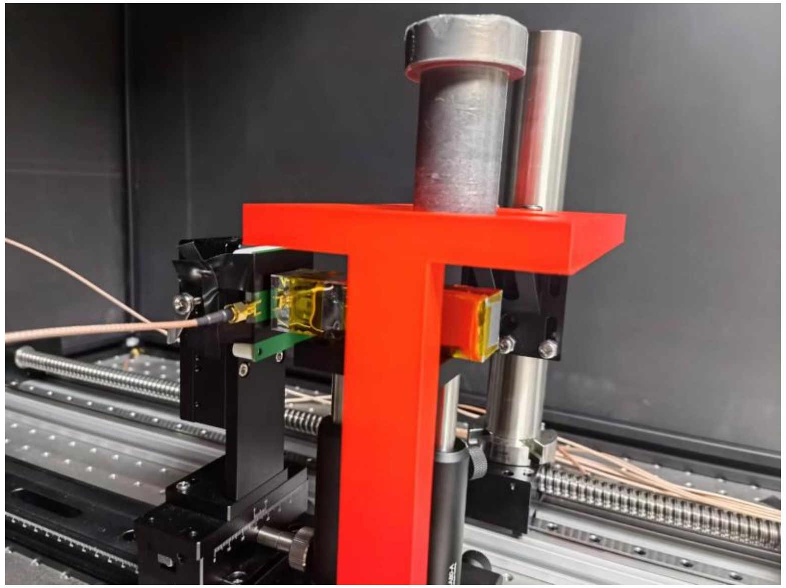
in IHEP

5cm LYSO



10cm LYSO

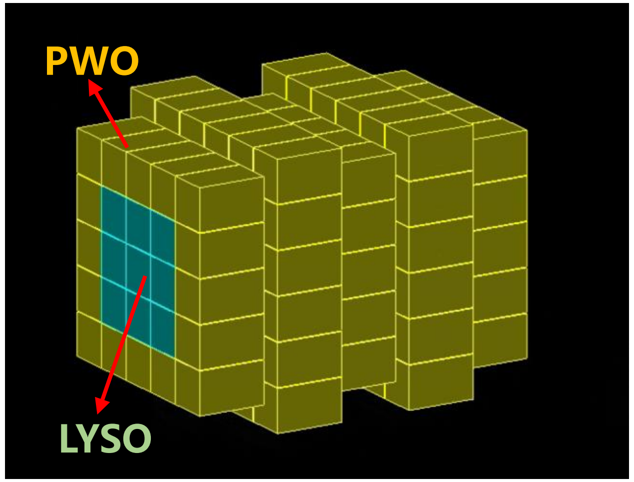


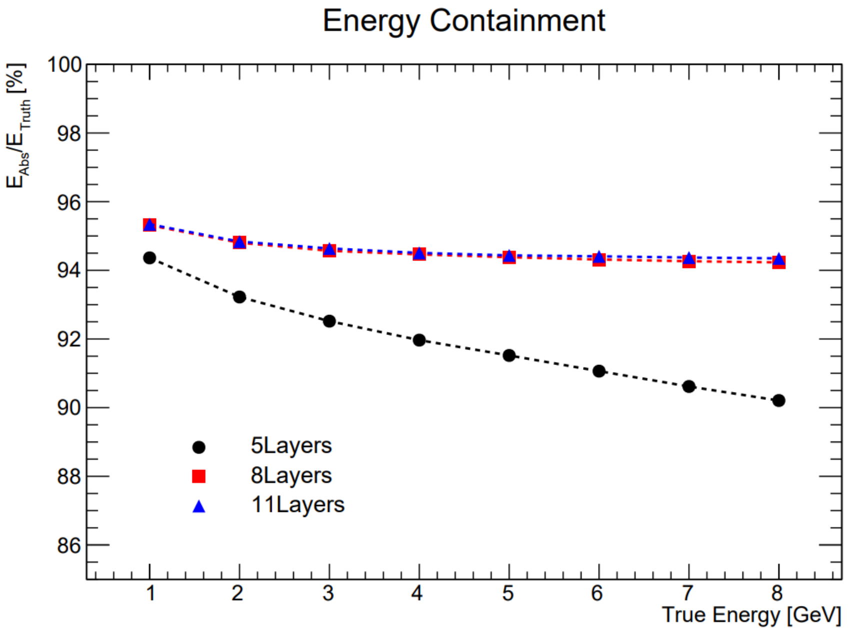


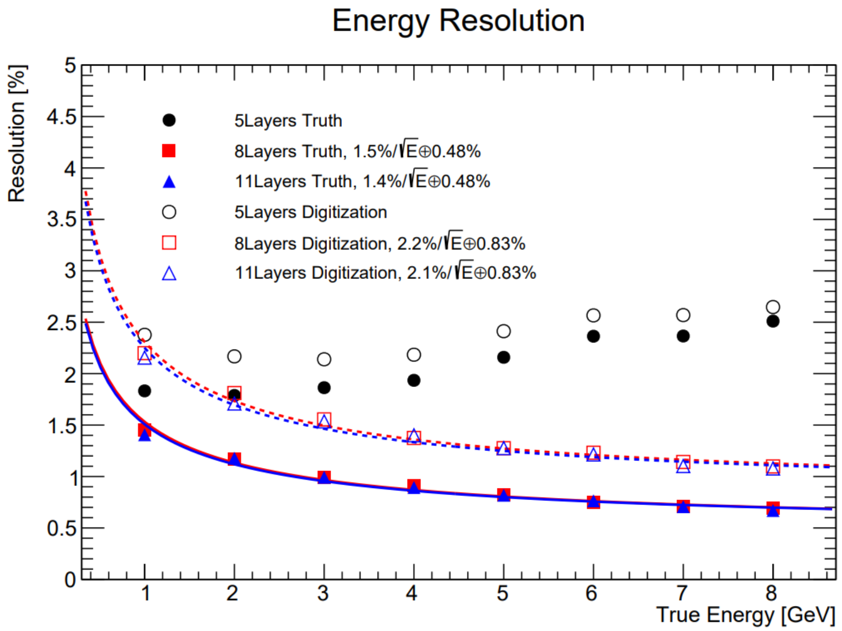
- Use $^{60}_{27}Co$ to scan the crystal, about 0.5cm per step. The response of SiPM gets smaller as the source moves away from the SiPM.
- Uniformity looks good for crystal shorter than 5cm.

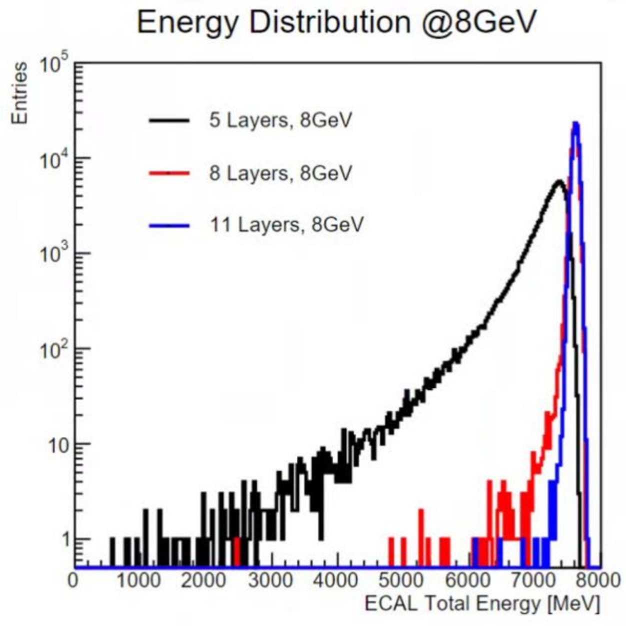
Module Performance

- Staggered structure to prevent particle leakage
- $2.5 \times 2.5 \times 4cm^3$ LYSO&PWO, 147/244/330 of 5/8/11 layers module(38 LYSOs)
- We choose LYSO, which has high radiation resistance, as the core detector. And PWO, which is denser and more economical, as the outer detector.
- Energy resolution is better than 3%. No energy leakage below 2.5 GeV for 11 layers module, 1e5 events.









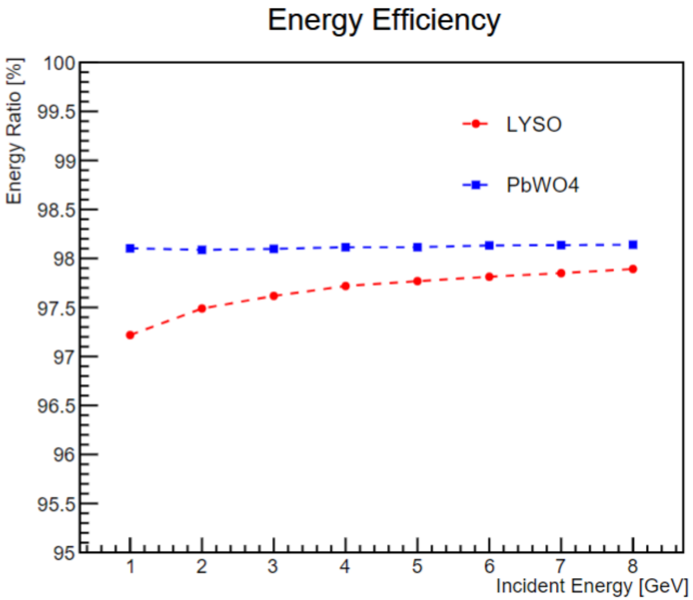
Summary

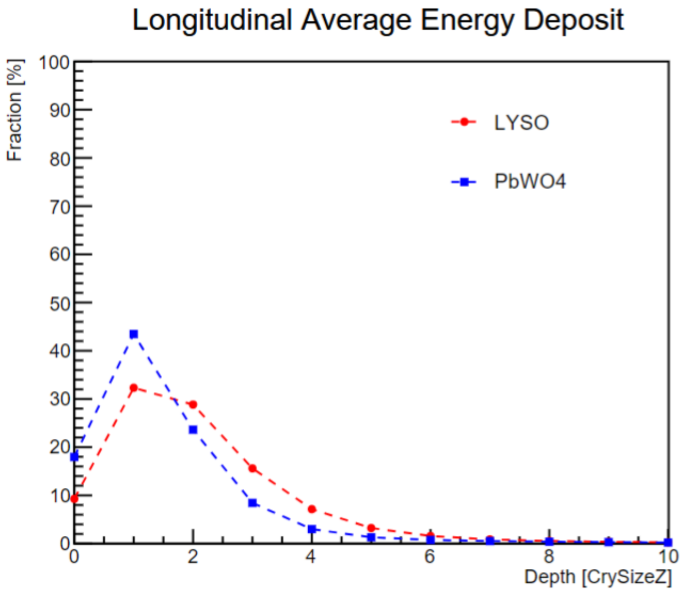
- The LYSO crystal ECAL in DarkSHINE has a very good energy resolution(1.2%/√E⊕0.57%). But radiation damage is also significant, especially for SiPMs($10^{13}\ n_{eq}$). SiPMs with radiation hardness are needed.
- We have finished many measurement works for crystals and SiPMs. The light yield for the unit can be about 100~1400 pe/MeV with different couplings. It is too large to consider further attenuation.
- A LYSO/PWO hybrid crystal module is proposed for system performance validation.

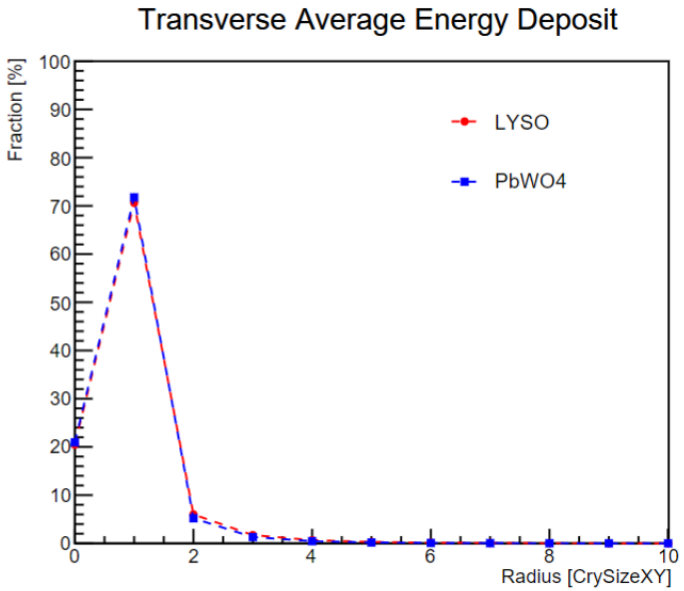
Backup

Module Size Optimization

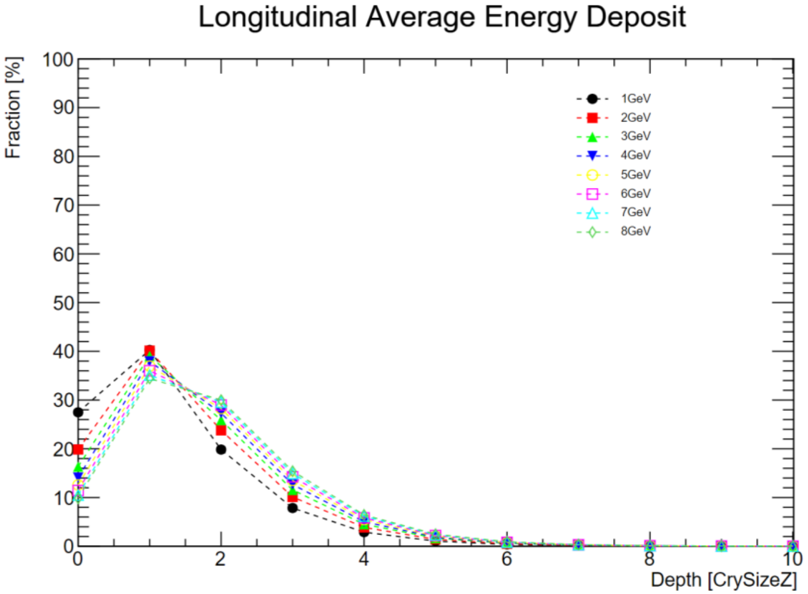
- Standalone simulation, $2.5 \times 2.5 \times 4 cm^3$ LYSO, $21 \times 21 \times 11$ crystals, 8GeV e-
- Truth analysis
- PWO ($8.3\ g/cm^3$) has a larger density than LYSO($7.2\ g/cm^3$). So the energy efficiency is higher, and the shower is smaller in PWO ECAL. And PWO also have a fast decay time(30ns), which is important for our detector.

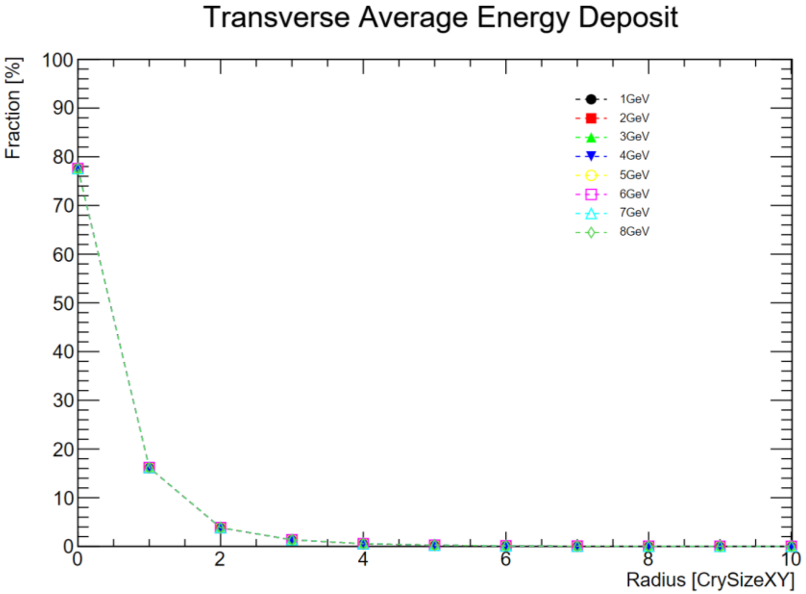




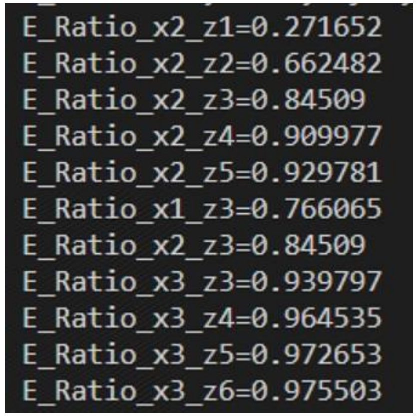


Module Size Optimization





1GeV



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E_Ratio_x2_z3=0.84509
E_Ratio_x2_z4=0.909977
E_Ratio_x2_z5=0.929781
E_Ratio_x1_z3=0.766065
E_Ratio_x2_z3=0.84509
E_Ratio_x3_z3=0.939797
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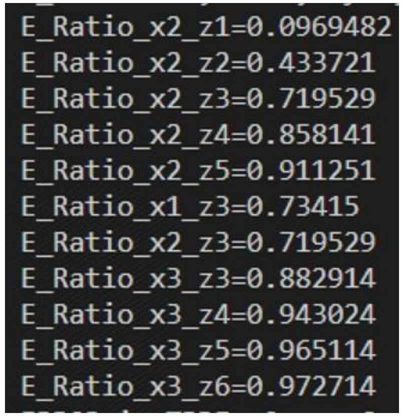
```

8GeV



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E_Ratio_x2_z5=0.911251
E_Ratio_x1_z3=0.73415
E_Ratio_x2_z3=0.719529
E_Ratio_x3_z3=0.882914
E_Ratio_x3_z4=0.943024
E_Ratio_x3_z5=0.965114
E_Ratio_x3_z6=0.972714
```
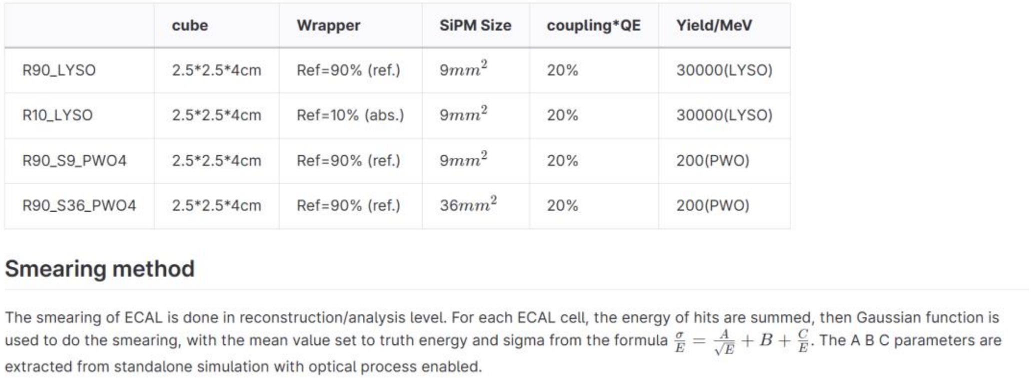

x1: only one central bar
x2: one central bar with one layer of barrel
x3: one central bar with two layers of barrel

- A module with LYSO core and PWO barrel is good choice
- For the transverse size, 3 layers is ok. Then it is better to number of z layers.
  - ￥7000 for one LYSO, ￥1500 for one PWO ($2.5 \times 2.5 \times 4cm^3$)
  - x2_z4: 36 crystals (36 LYSO). 91% ~￥25w
  - x3_z5: 125 crystals (36 LYSO + 89 PWO), one PWO layer at the end. 96% ~￥38w
  - x3_z6: 150 crystals (36 LYSO + 114 PWO), two PWO layers at the end. 97% ~￥42w
- We can even take this module to do a 8GeV test beam.

Background Rejection and Signal Efficiency

- Set1~Set4: Energy smearing for cell energy
- Others(σ/E): Energy smearing for total energy
- For 1e10 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.