Supplementary material in backup

Stereo Crystal Ecal: Input Materials

Huaqiao Zhang (IHEP)

For Stereo Crystal Ecal study team

Updated:

1: refined electronics design

2: refined endcap conceptional design

3: refined mechanics design

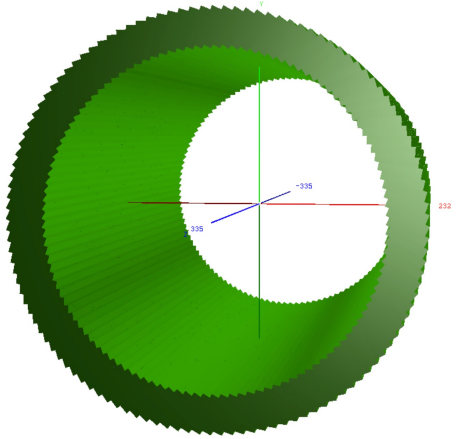
4: gamma + charged pi separation

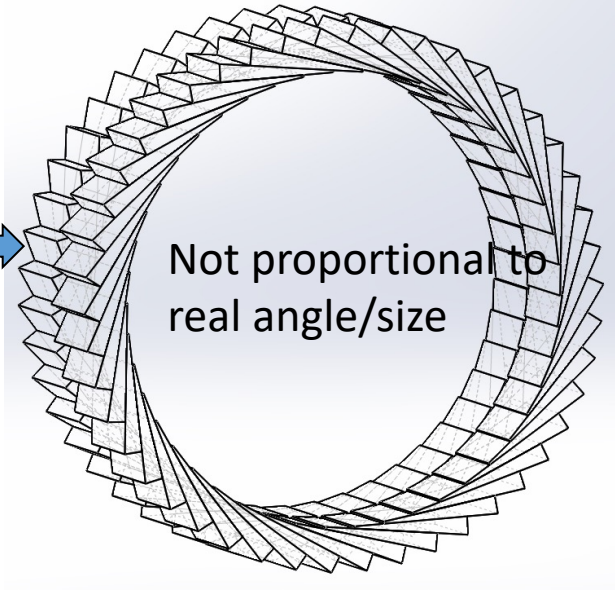
5: comparison of SiPM/APD/PD

Stereo Crystal Electromagnetic Calorimeter: Design

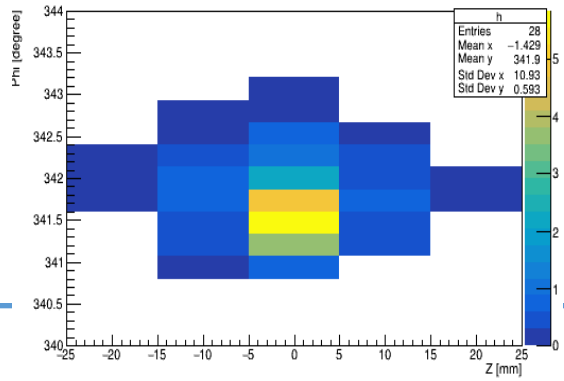
- To improve the 3D position resolution
  - Pointing angle of even layers alone Z: α
  - Pointing angle of odd layers alone Z:

  $\alpha' = -\alpha$
- Benchmark design:
  - α=20 degrees
  - R segmentation = 10
  - Crystal: (8-8.1)*10*284 mm^3
  - Readout: SiPM (or APD/PD) + electronics
  - Cooling pipe planted into the outside of the mechanical support
  - 24X0+10mm electronics+10mm support + 10 mm contingency = 300mm



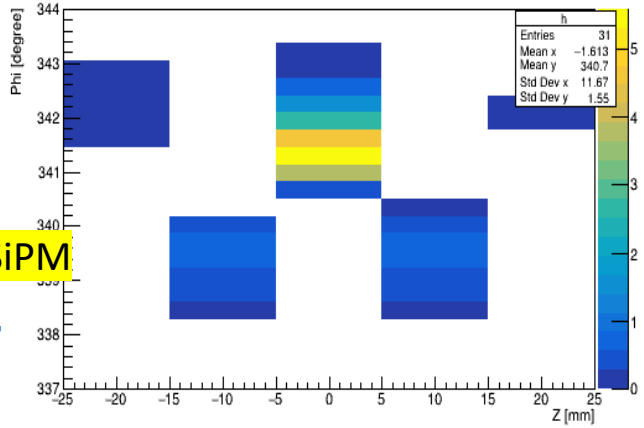


Traditional Crystal Ecal



BGO+SiPM

SCEcal



Left eye

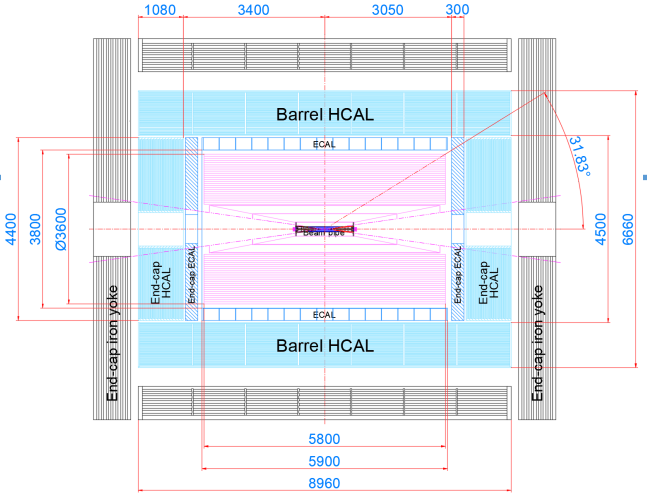
Right eye

Performance

Items	Priority	Results / Status	Remarks
Boson Mass Resolution	A	H→di-photon: 0.3%(1.3%) with 2MeV(50MeV) thr. H→gg is under study	BMR < 4% CEPCSW fullsim
Intrinsic EM/hadronic energy resolution	A	Stochastic term: 0.9%(3.2%)/sqrt(E) with 2MeV(50MeV) thr.	CEPCSW fullsim
Separation power		5 GeV gamma/gamma, >80%@15mm 5 GeV gamma/10 GeV Pi: >60%@15mm	CEPCSW fullsim
Lepton ID in jets		preparing	Clear shape difference seen(backup)
Timing capability		Could have, accuracy depending on the sensitive material	No showstopper
π^0 reconstruction		Studying	CEPCSW fullsim
Pile-up at Z-pole		-	No showstopper

- Priority/importance for performance requirements: (A) must-have; (B) plus; (C) not essential

Cost



Cost table template for ECAL

Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for ECAL	1900 mm	350 mm	NA
Length for barrel; Outer radius for endcap	5900 mm	1900 mm + $24X_0$	NA
Longitudinal Depth	$24X_0$ (Thickness depends on each option)		NA
Modularity	#modules in phi, #rings along Z	Assuming ideal geometry if no design?	NA
Material Volume (m^3)	20.26	7.27	27.5
Readout channels	827180	320040	1,144,428
Power dissipation (kW)	16.5kW	6.4kW	22.9kW
Cost: sensitive materials	1316.9M RMB	472.5M RMB	1789M RMB
Cost: electronics	62.8M RMB	24.3M RMB	87M RMB
			1876 MRMB

SiPM + Electronics
- SiPM: 56RMB/piece
- Electronics: 20RMB/ch

BGO:
- BGO: 65RMB/cc (SIC)
  - (R.Y. Zhu 42-50RMB/cc)

Power:
- 20mW/ch(Half of HGCal/ch)

Technical readiness level

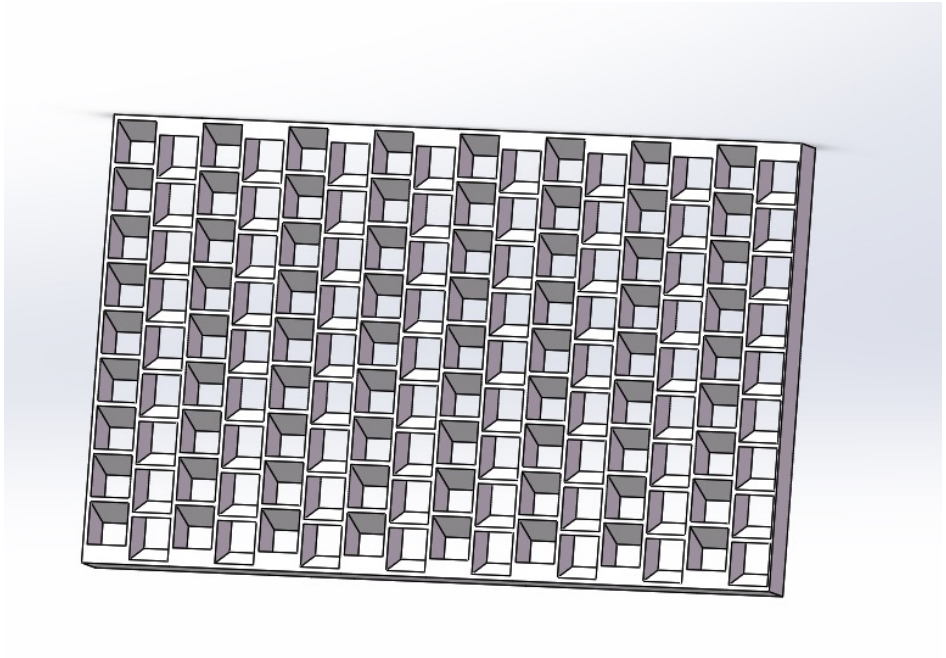
- Status and plans of simulation studies and R&D (a table template)
- Person power: Xiao ZHAO, Chaochen Yuan, Han WANG, Liheng Huang, Lianyou Shan, Huaqiao ZHANG, Yunlong ZHANG

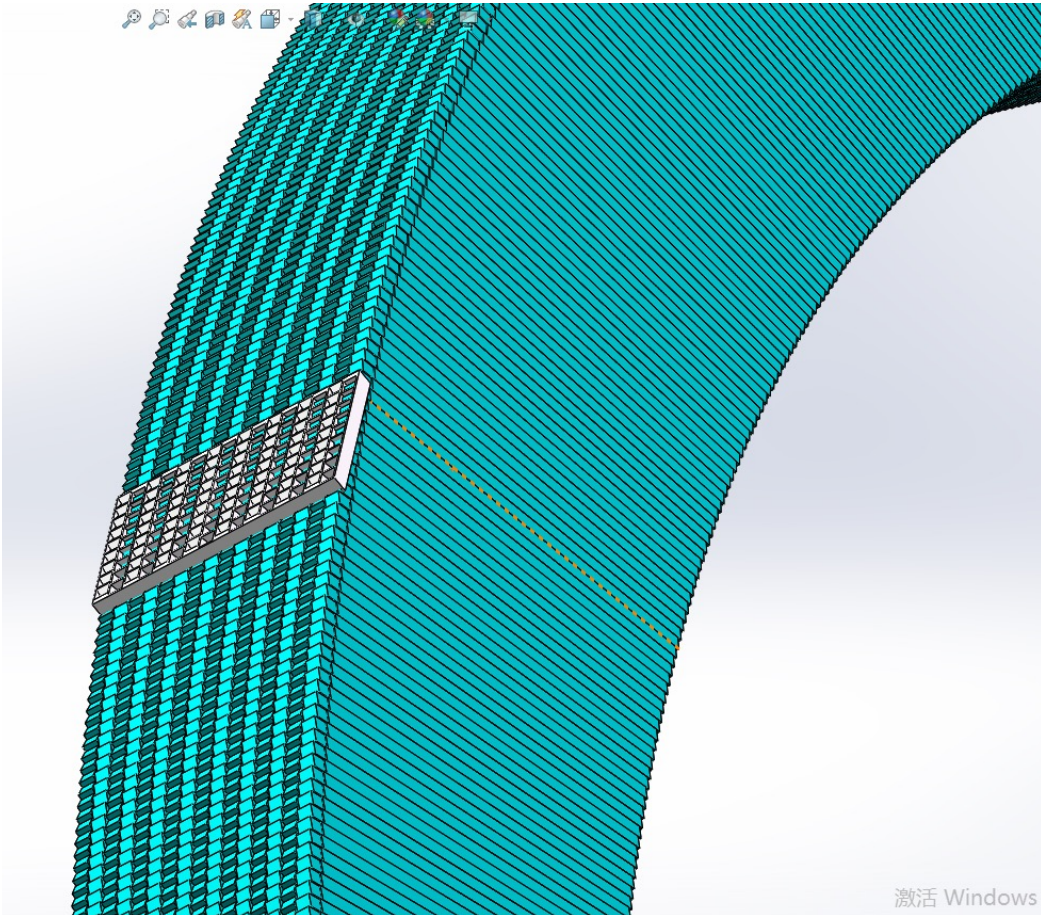
Category	Status	Design 1	Other Alternative Design (if any)
Technical Readiness Level	Full Simulation (system level)	V1 Implemented in CEPCSW	
	Full Simulation (module level)	V1 Implemented in CEPCSW	
	Prototyping R&D (common)	L3 Ecal, CEPC 4D crystal Ecal	
	Prototyping R&D (modules, units)		No BGO module, GEO with Sc. In preparing

1	桶部	单位（毫米）					
2	内部直径	3800	最大外部直径	4400	长度	5900	
3	晶体	BGO（24X0=26.88cm）	市场参考价格：	￥65.00/cc			
4	大小	(8.0-8.1)*10*284	数量	827180=1402*590	体积	20.26m3	
5	重量	144.5吨	价格	13.169亿			
6	机械设计	纯圆桶					
7	外径面支撑/悬挂		内径面辅助		轴向20个单元		
8	竖直组装，旋转90度后推入						
9	总厚度：	24X0 + 1cm电子学 + 1-2cm支撑=300mm					
10							
11	端盖*2	单位（毫米）					
12	内部直径	700	外部直径	3800+2*24X0	厚度	24X0*2	
13	晶体	BGO（24X0）	市场参考价格：	￥65/cc			
14	大小	8*10*284	数量	317248	体积	7.27 m3	
15	重量	51.8吨	价格	4.725亿			
16	机械设计						
17	内径面支撑，外表面固定						
18	总厚度：	24X0 + 1cm电子学 + 1-2cm支撑=300mm					
19							
20	电子学	1,147,220=827180+320040					
21	前端板	1.6mm	母版	1.6mm	间隙	2mm	
22	功耗	22.9kW(20mw/channel)	电子学价格	20/ch			
23	SiPM	56/ch	总价格	87MRMB			
24	散热系统	厚度2mm					

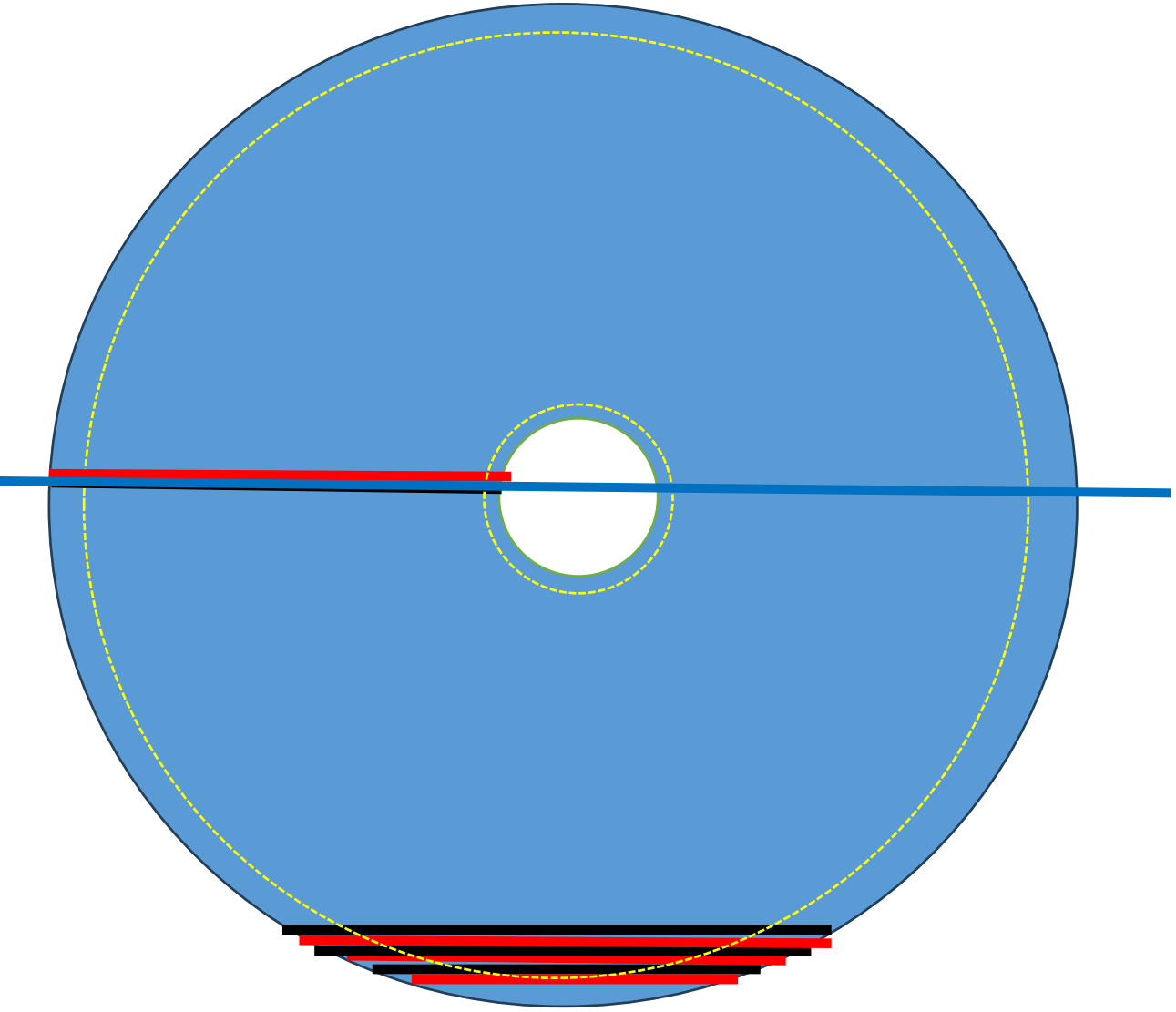
桶部机械结构

侯少静

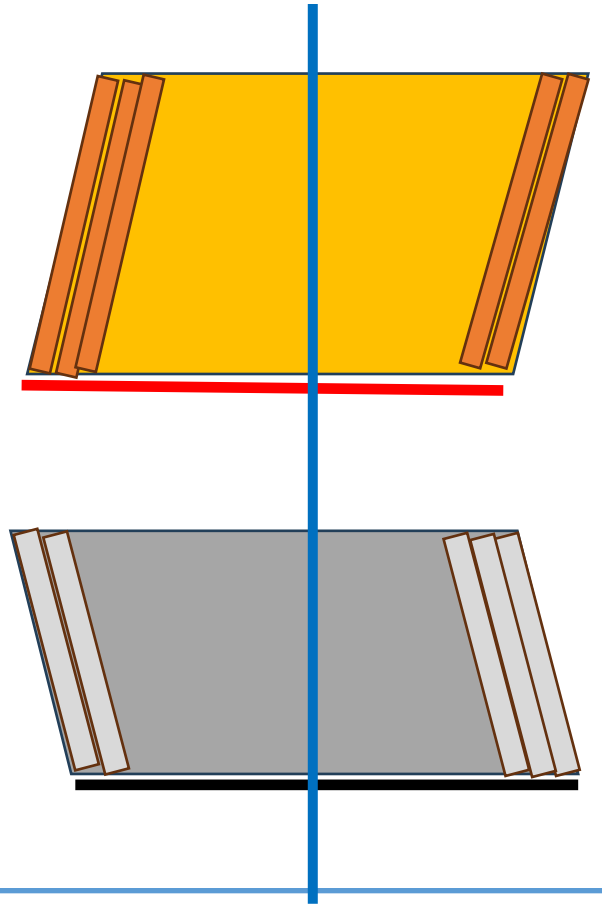




Endcap conceptual design： 机械设计→少静

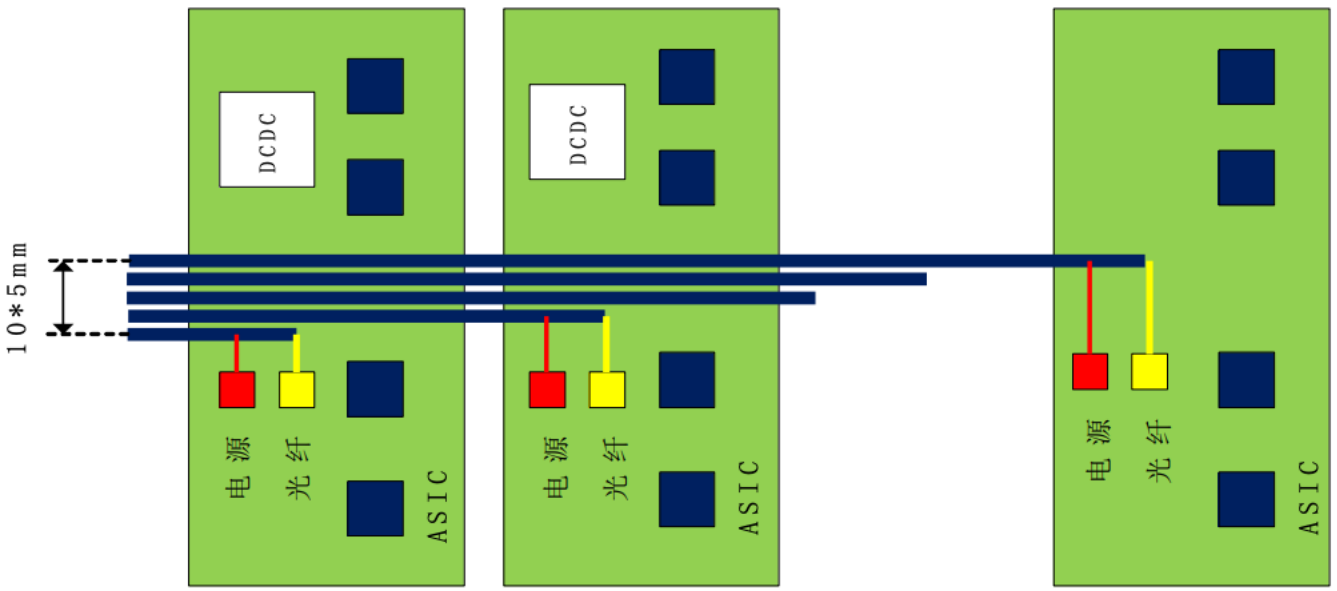


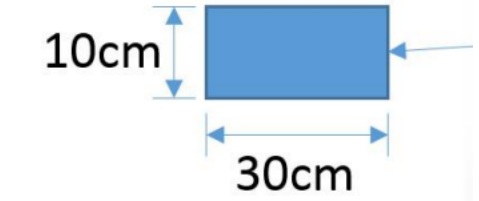
Crystal: 8*10*284mm
Horizontal layers has same point angle
Pointing angle defined as angle w.r.t. beam in the horizontal plane: 20 degree



前端电子学板设计：

常劲帆



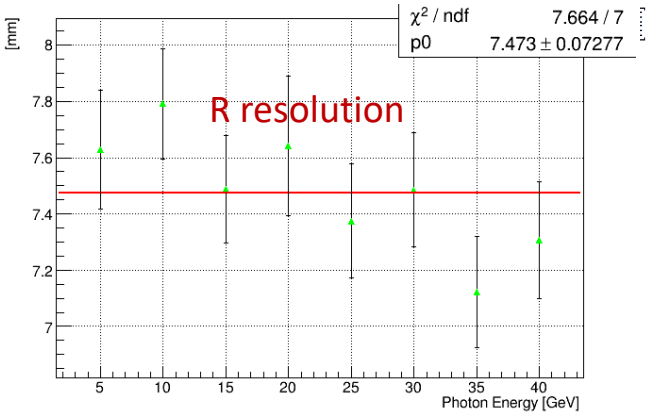


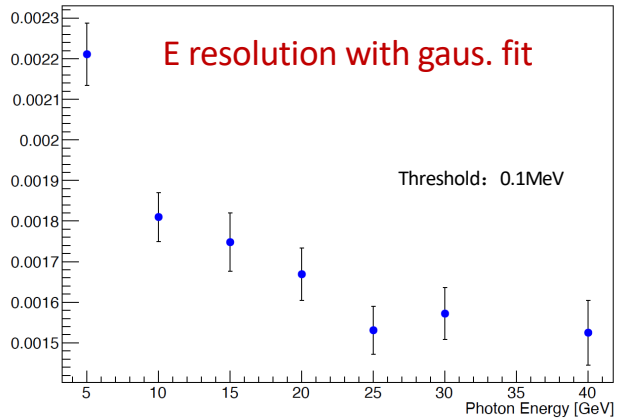
12*30=360个晶体

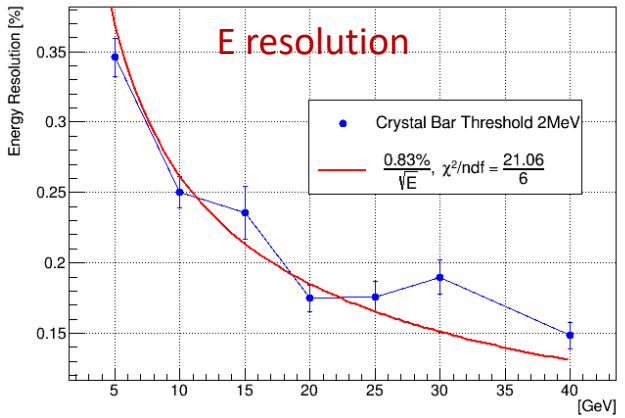
晶体尺寸：
10*8*284mm

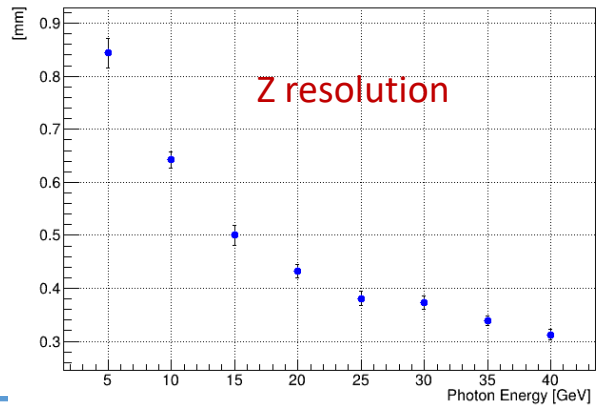
Performance of Energy and 3D positioning resolution

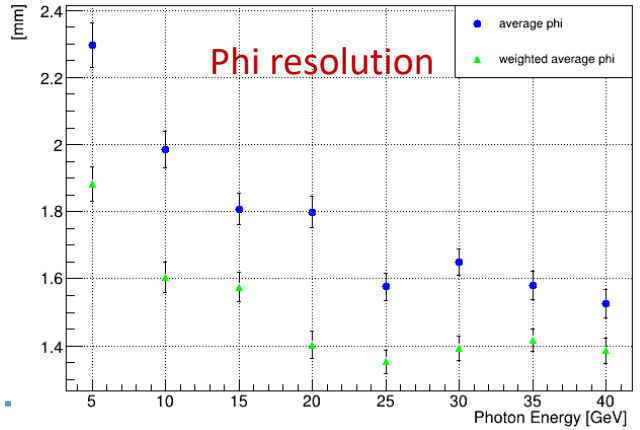
- **5GeV gamma, phi: 10~350°，theta: 90°**
  - Z resolution ~ 0.84 mm;　　Phi resolution ~ 1.9 mm
  - R resolution ~ 7.6 mm;　　Energy resolution as function of energy

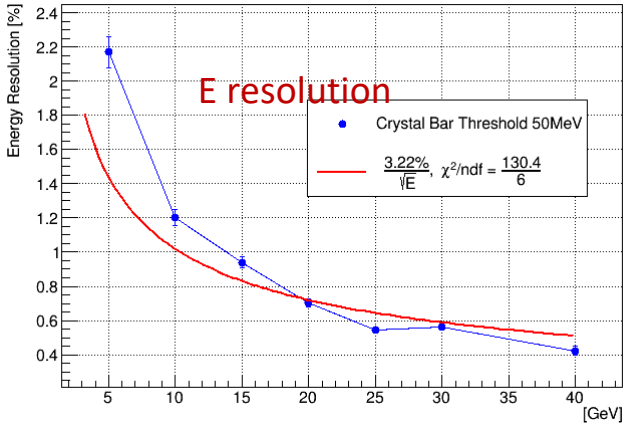






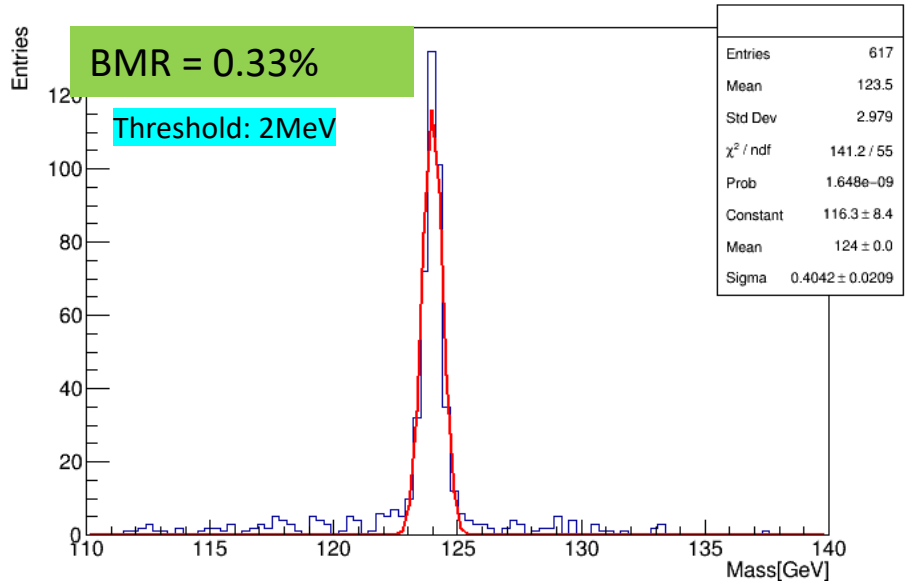


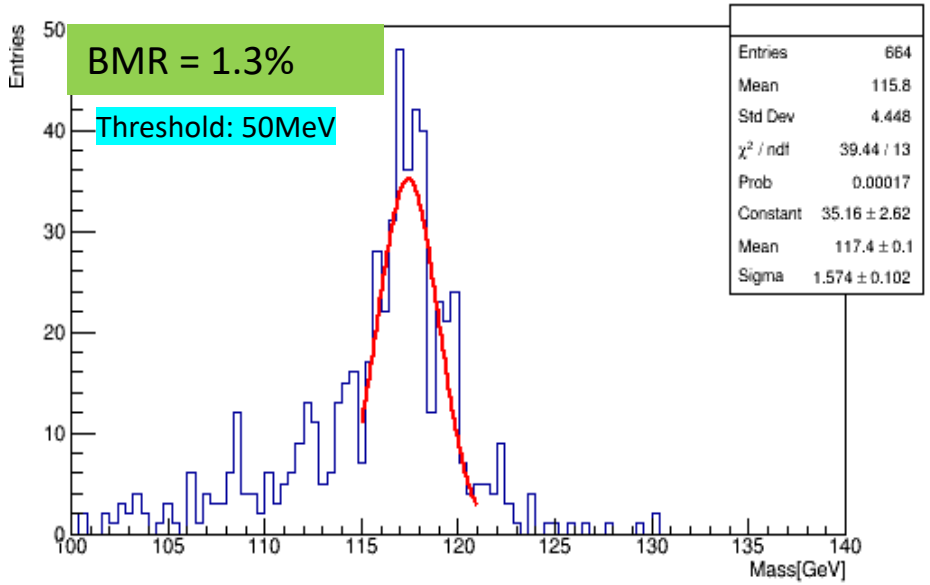




Boson mass resolution in H→ γγ

- Sample: ZH->2neutrinos + γγ at 240 GeV
- Energy, position reconstruction and separation using simplified reconstruction method described above
- Crystal energy threshold: 2 MeV/50MeV

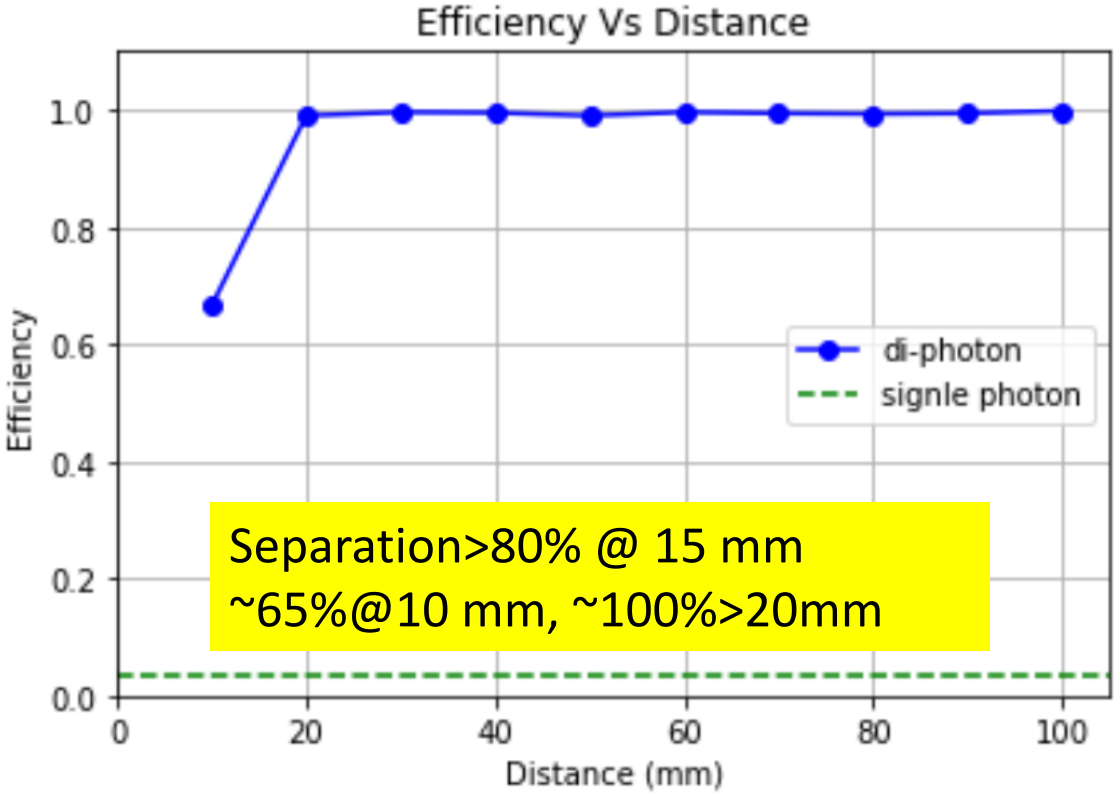


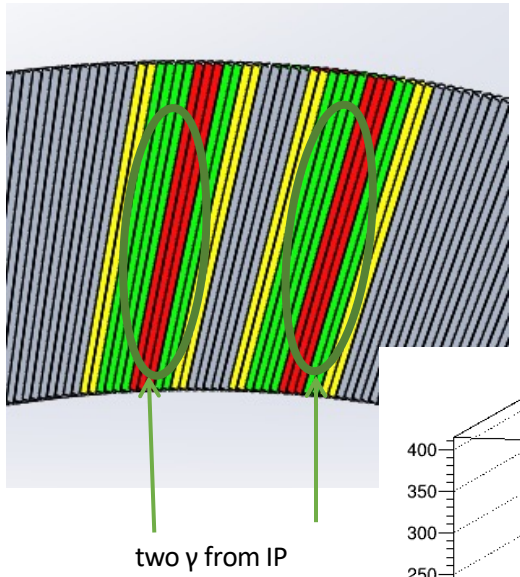


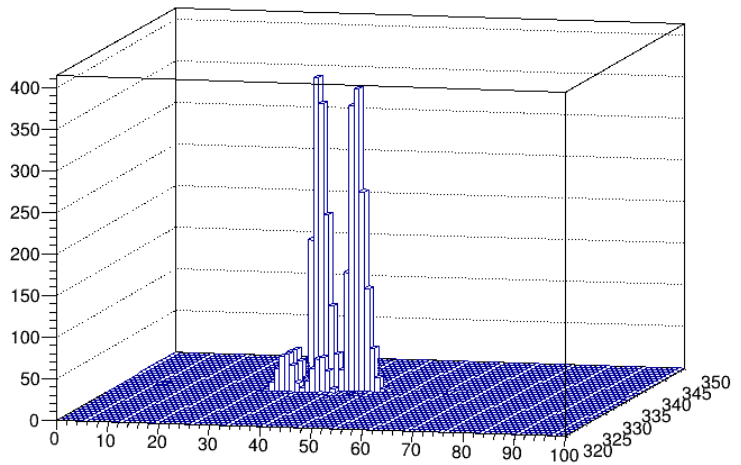
Separation between two 5 GeV photons

- Two 5 GeV photons, vary distance along phi between them
- Success reconstruction: 2 neutral particles, 3.3GeV<Eγ<6.6GeV for each photon
- **Separation and energy regression using end-to-end NN**
  - trained with flat distributed photon energy and distances

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.108.052002

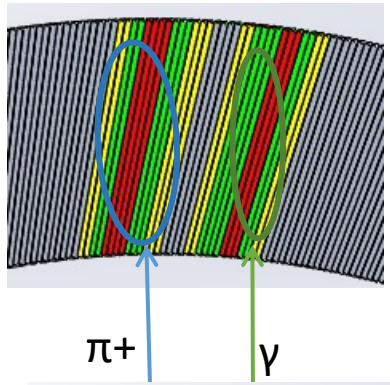


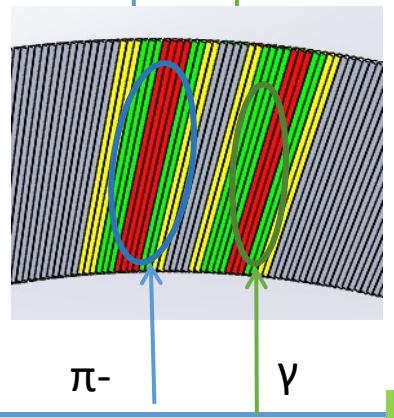


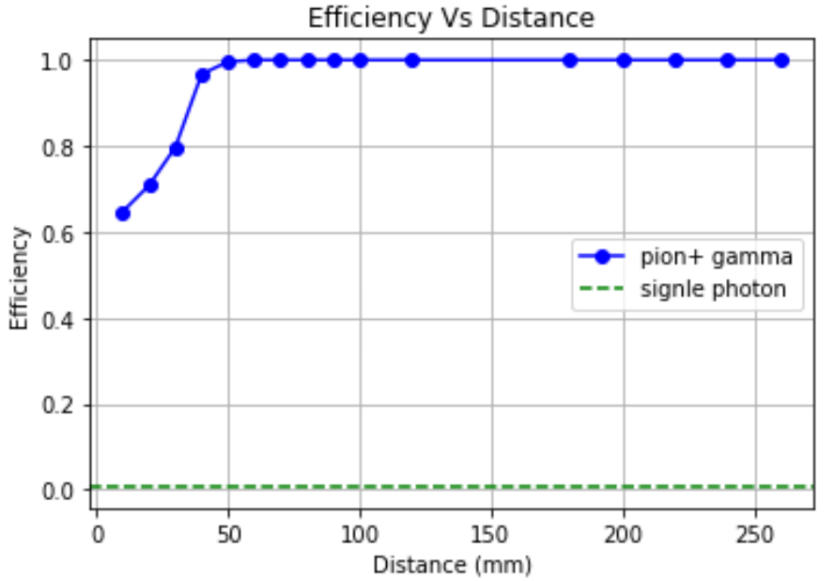


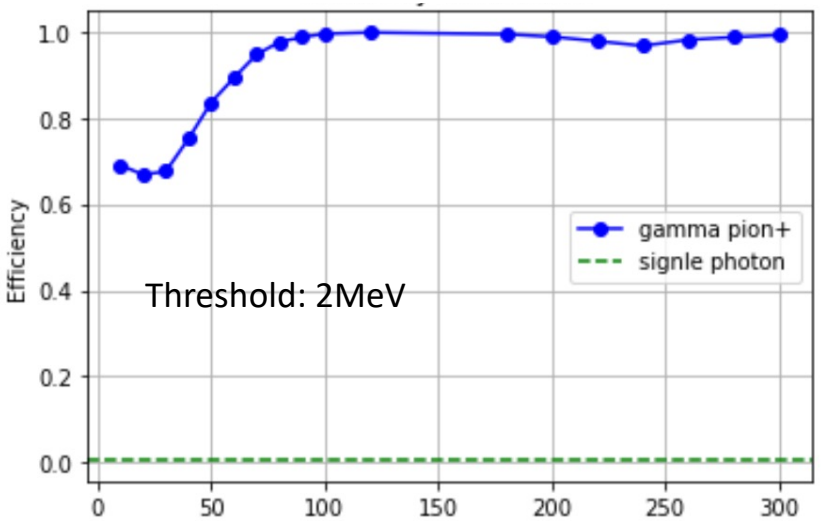
Separation between γ/π

- 5 GeV γ/10GeV π, vary distance along phi between them
- Separation use end-to-end NN
- Success reconstruction: 3.3GeV<E_γ<6.6GeV not yet applied
- Different π/γ separation power: pointing angle / magnetic field









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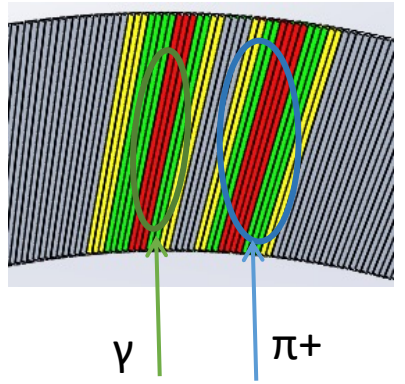
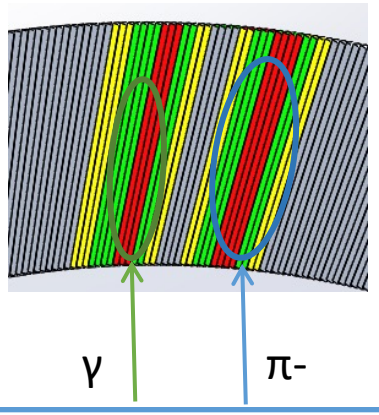


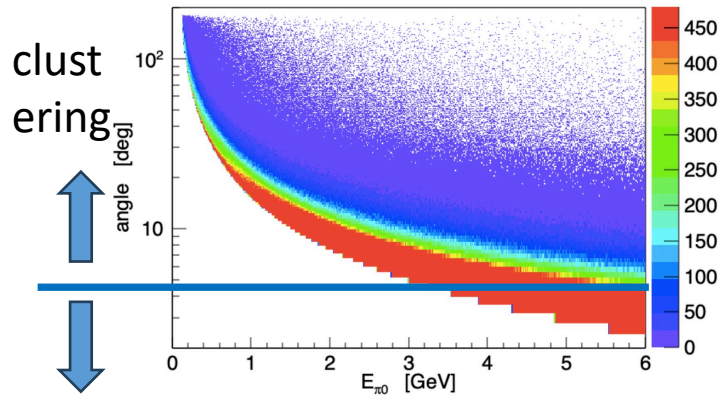


Trained with a sample of 1-10GeV γ, 2-20GeV pi+, distance @calor variated around 20 mm

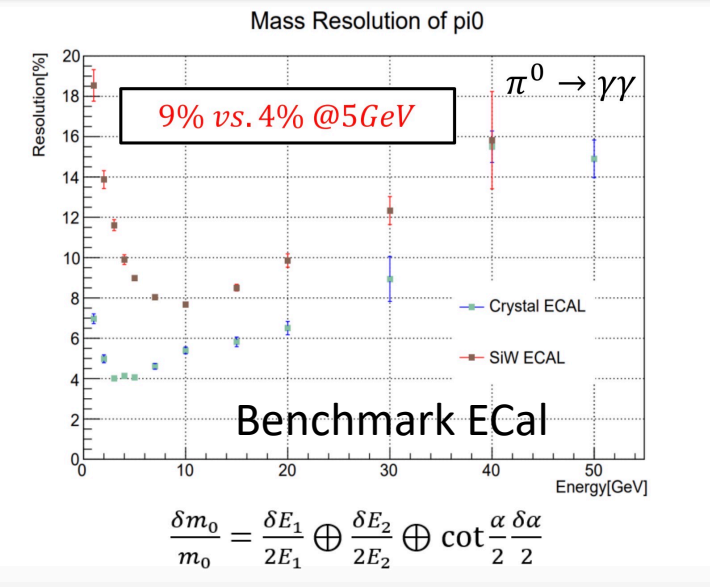
Pi0→2phton invariant mass

- End-to-end NN regression is used
  - Trained with di-photon events with flat distributed momentum from x GeV to XX GeV, distant < 3 degree
  - Apply to samples of pi0→di-photon with different pi0 moment

Angles between the 2γ from pi0

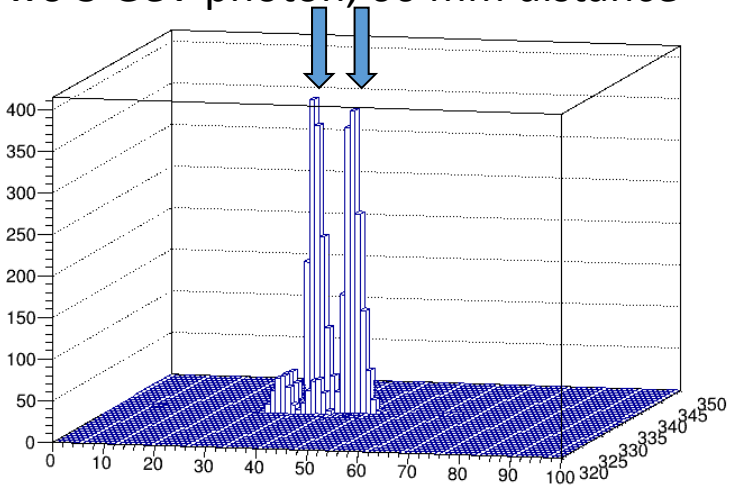


End-to-end NN regression

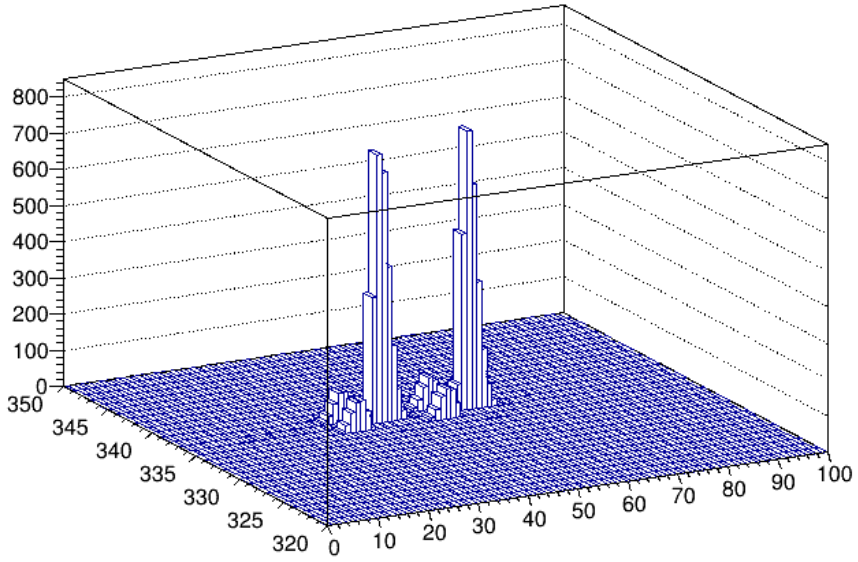


Event display of shower separation/ID

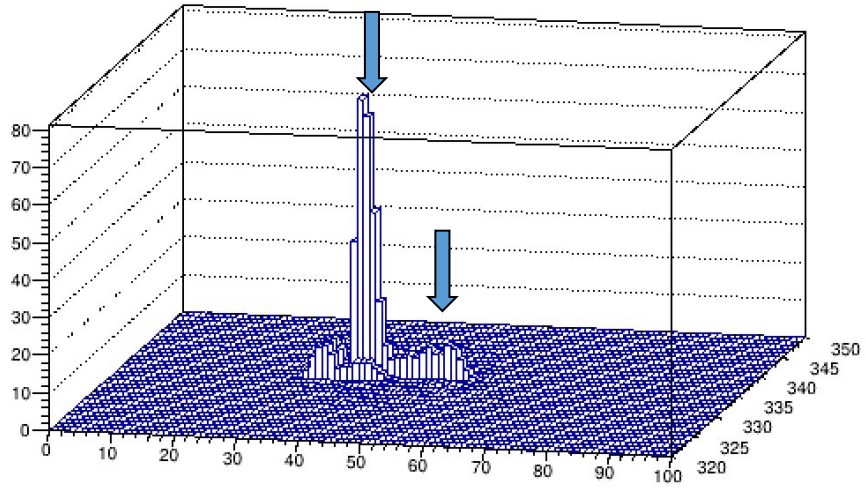
Two 5 GeV photon, 66 mm distance



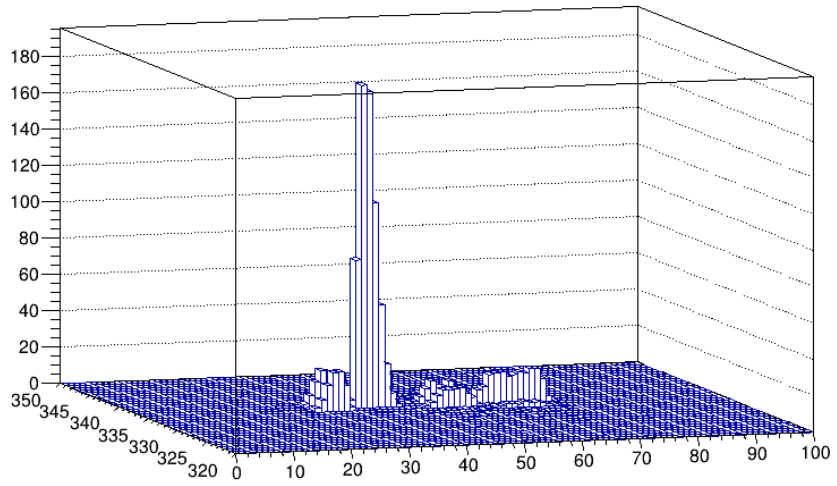
Two 5 GeV photon, 165 mm distance



5 GeV photon and 10 GeV pi-, 66mm



5 GeV photon and 10 GeV pi-, 195mm



SiPM vs APD

- SiPM
  - 60 RMB/piece (From HGCal)
    - 3*3 mm
  - 10^{10} n_{eq}/cm^2 (10^{14} n_{eq}/cm)
    - R&D at IHEP

Package type	face mount type
Number of channels	1 ch
Effective photosensitive area / ch	3 × 3 mm
Number of pixels /ch	89984m
Pixel size	10 μm
Spectral response range	290 to 900 nm
Peak sensitivity wavelength (typ.)	460 nm
Dark count/ch (typ.)	700 kcps
Terminal capacitance/ch (typ.)	530 pF
Gain (typ.)	1.8×10$_5$
Measurement condition	Ta=25 ℃

S14160-3010PS

- APD
  - 20 RMB/piece (From 高能瑞泰,仿制滨松)
    - 3*3 mm
    - R&D needed?
  - Used on CMS (S8664-55)

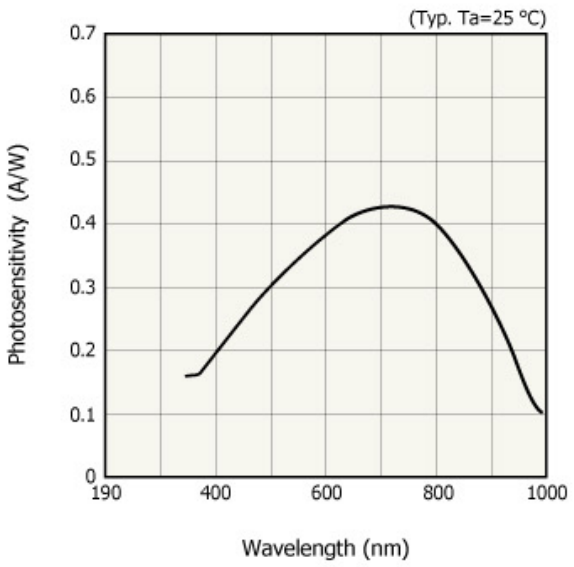
Peak sensitivity wavelength (typ.)	600 nm
Spectral response range	320 to 1000 nm
Photosensitivity (typ.)	0.24 A/W
Dark current (max.)	50 nA
Cutoff frequency (typ.)	40 MHz
Terminal capacitance (typ.)	80 pF
Breakdown voltage (typ.)	400 V
Temperature coefficient of BV	0.78 V/℃
Gain (typ.)	50
Measurement condition	Typ. Ta=25 ℃, unless otherwise noted,
	Photosensitivity: λ=420 nm, M=1

S8664-55

PD

34	Photosensitive area	2.4 × 2.4 mm
35	Number of elements	1c
36	Package	Ceramic
37	Cooling	Non-cooled
38	Reverse voltage (max.)	5 V
39	Spectral response range	340 to 1000 nm
40	Peak sensitivity wavelength (typ.)	720 nm
41	Photosensitivity (typ.)	0.43 A/W
42	Dark current (max.)	5 pA
43	Rise time (typ.)	0.5 µs
44	Terminal capacitance (typ.)	160 pF
45	Noise equivalent power (typ.)	2.1×10-15 W/Hz1/2
46	Measurement condition	Typ. Ta=25 ℃, Photosensitivity: λ=720 nm, Dark

S1227-33BR



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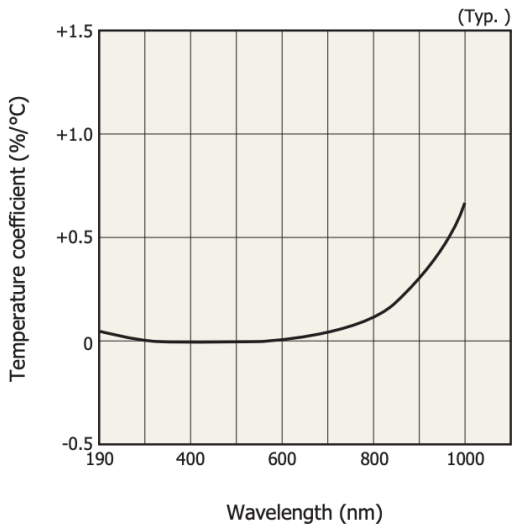
Photosensitivity temperature characteristics



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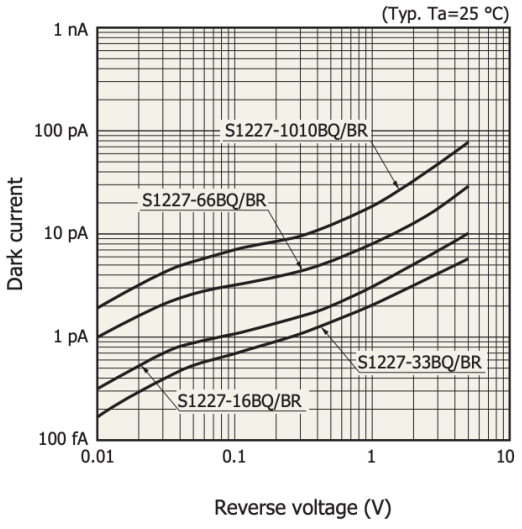
Dark current vs. reverse voltage



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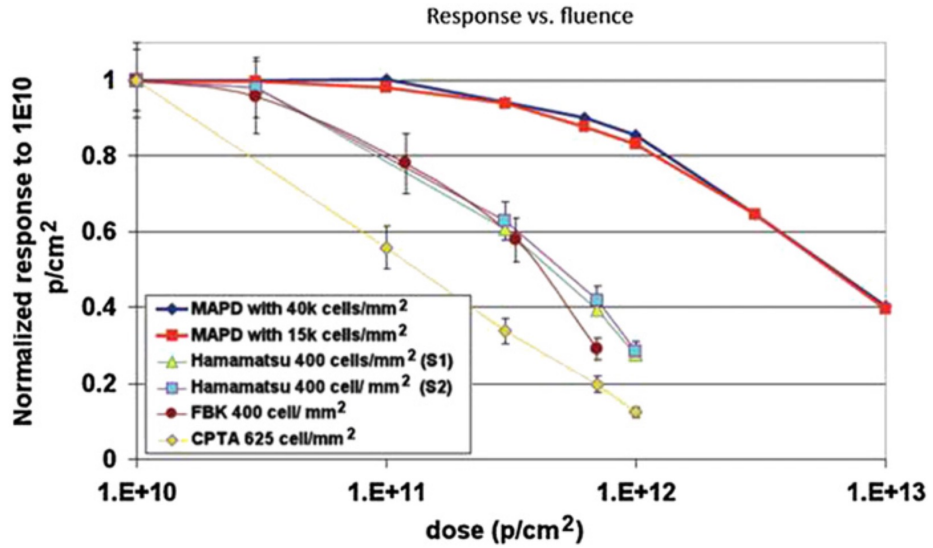
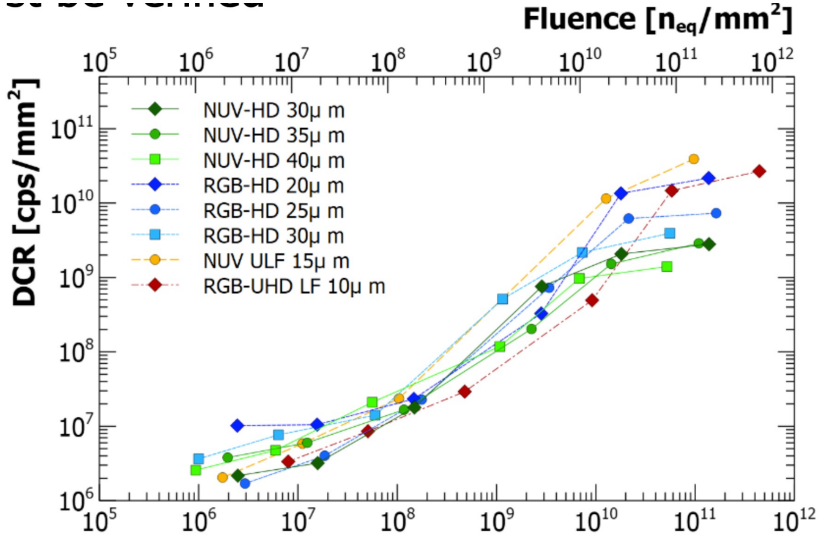
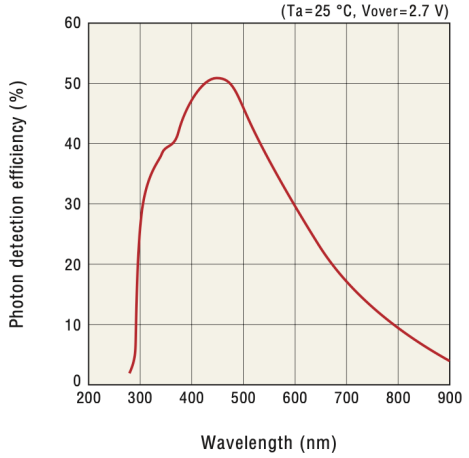
SiPM的信号幅度 VS 辐照剂量



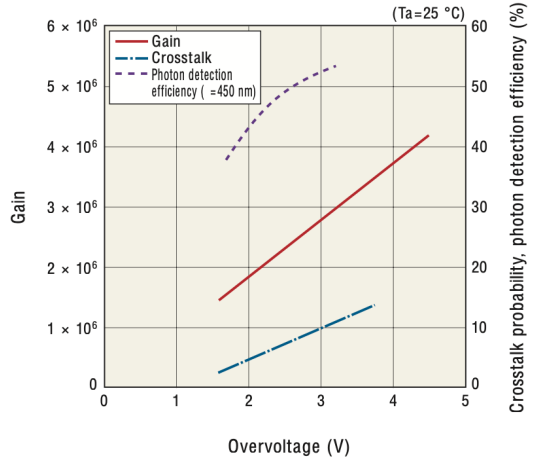
SiPM的暗计数 VS 辐照剂量



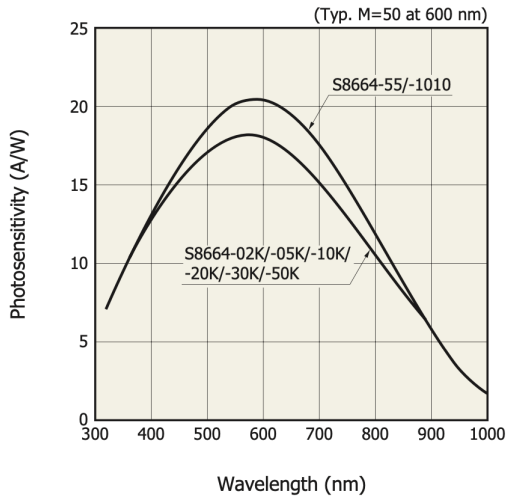
■ **Photon detection efficiency vs. wavelength (typical example)**



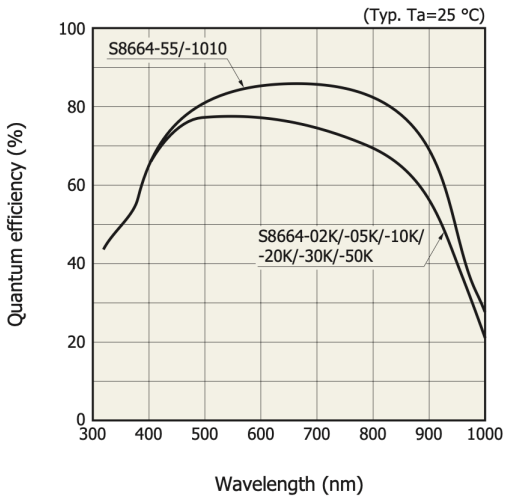
■ **Gain, crosstalk probability, photon detection efficiency vs. overvoltage (typical example)**



■ **Spectral response**



■ **Quantum efficiency vs. wavelength**



SiPM vs APD vs PD

	SiPM （S14160-3010PS）	APD （S8664-55）	PD （S1227-33BR）
价格	中（较高）	中（有不确定性）	低
单光子测量	是	否	否
时间测量	~10ps (lab)	~1ns (CMS)	?
线性范围	差	好	好
抗辐照	中	强	中
是否满足Stereo Ecal要求	是	是	是
刻度…	单光子	激光	氙气灯
已有实验		CMS	L3(its PD is not available now)

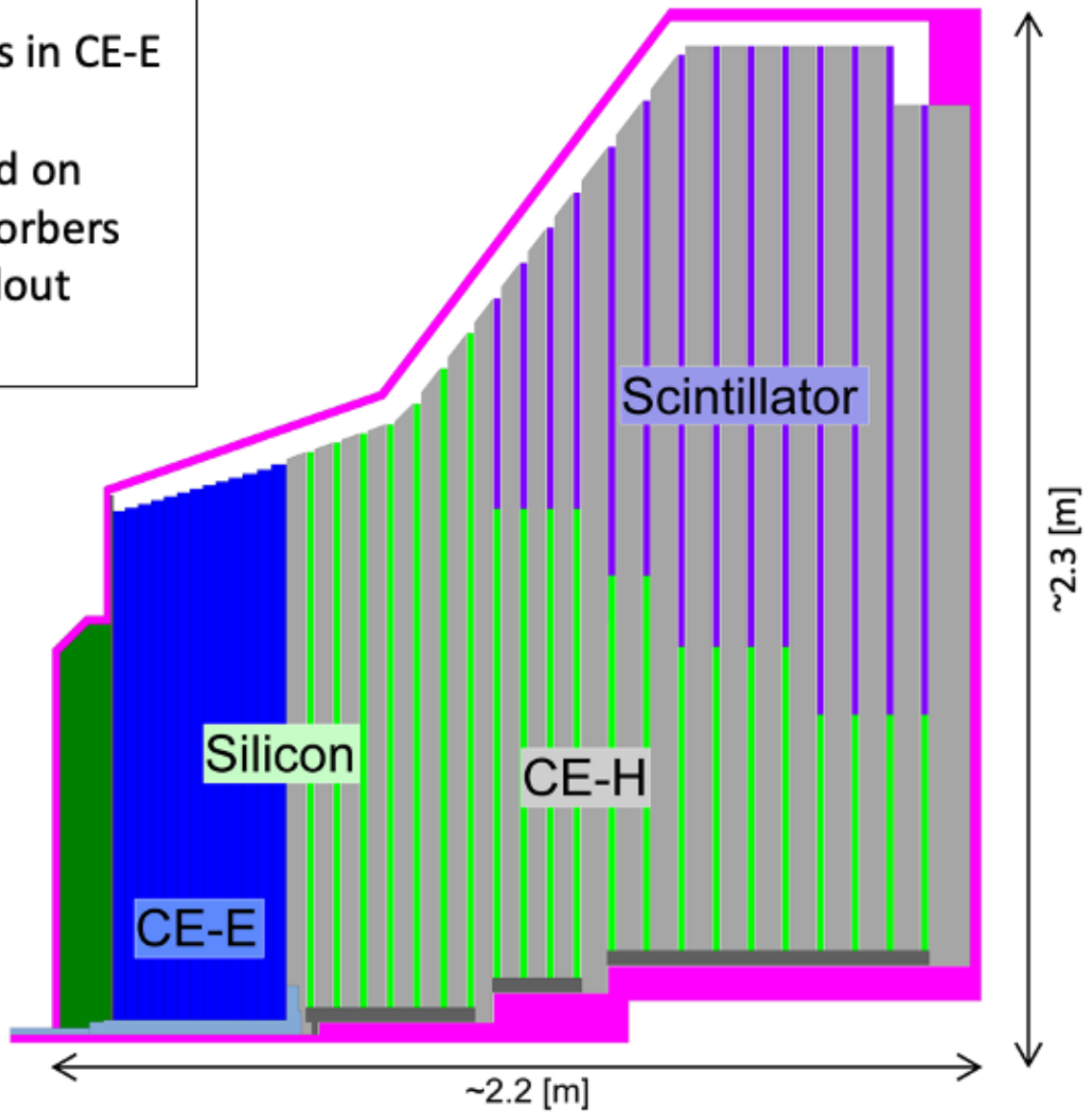
BGO： 8-10 photon/keV
Lower threshold： 2MeV: → 20,000 photons * efficiency

Active Elements:

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

Key Parameters:

Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m^2 Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm^2 cell size
~370m^2 of scintillators in ~3700 boards
~240k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap



Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 26 layers, 27.7 X_0 & ~1.5λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~8.5λ

Cost from CMS HGCal (kCHF)

- Electronics： 6M Si + 240k Sc

4.6.1	Front-end System (Silicon sensors)	5,778
4.6.2	Front-end System (Scintillator/SiPM sensors)	872
4.6.3	Front-end System (Common to Silicon and SiPM)	4,164
4.6.4	Clock and Control	500
4.6.5	Power Distribution	4,448
4.6	**Electronics and Electrical Systems**	**15,762**
4.7.1	DAQ	2,447
4.7.2	Trigger	3,779
4.7	**Backend System (Trigger and DAQ)**	**6,226**
4.8.1	DCS	257
4.8.2	DSS	341
4.8	**Slow control**	**598**

SiPM + Sc. (4-30 cm2 cell, 240k ch, 370 m2, X mm thick)

4.5.1	SiPM - Photosensors	1,718
4.5.2	Plastic scintillator	832
4.5.3	Wrapping (ESR film)	111
4.5.4	Assembly Centre and Tooling	270
4.5.5	Scintillator/SiPM Module Production	14
4.5	**Scintillator/SiPM Modules**	**2,945**

Si sensors: 620 m2

4.3	Silicon Sensors	**21,513**

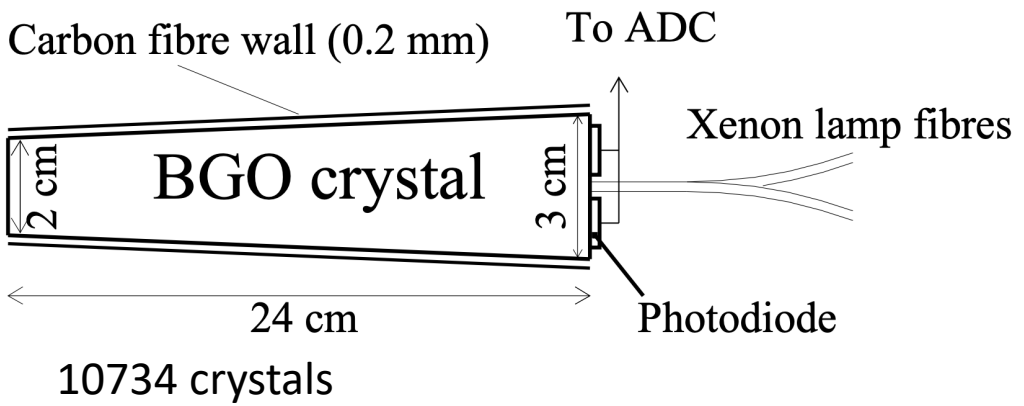
item	Power	SiPM	Plasic Sc. Mat.	FE	BE+Slow C.	Si
numbers	40 mW/ch	7.2CHF/ch	0.22CHF/cm2	2.5CHF/ch	1.1CHF/ch	3.5CHF/cm2
remarks	Half? in e+e	3*3 mm2	No wrapping			

L3 BGO calorimeter:

$$\sigma(E)/E = 3.2\,\%/\sqrt{E} \oplus 0.9\,\%$$

L3: BGO+PD:

- 1200 electron (0.2fC) per MeV shower energy
- Dynamical range: 1MeV to 200 GeV



10734 crystals

Figure 4.10: A BGO crystal.

decreased strongly (up to 50%) with the distance from the front face. After coating the crystals with a 40-50 μm thick layer of high reflectivity white paint, the maximum variations in the collected light flux as a function of the distance from the front face were only about 5%.[10]

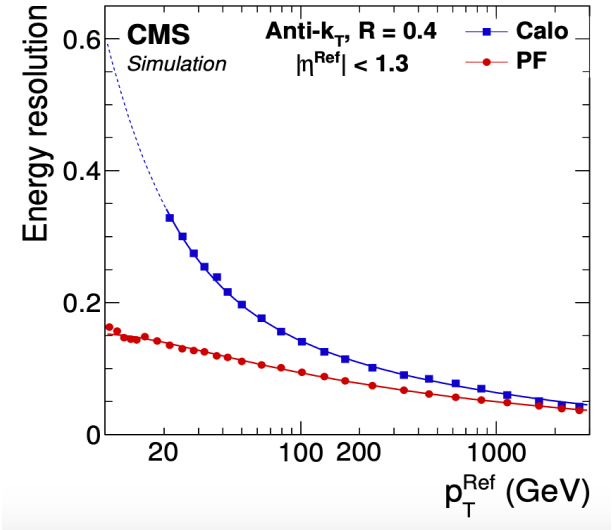
[10] The variations in the crystal light yield were measured using cosmic muons and were required to be less than 10% for all accepted BGO crystals [109].

shape (Figure 4.10) with a front surface of $\simeq 2 \times 2\,cm^2$, a rear surface of $\simeq 3 \times 3\,cm^2$, and a depth of about 21.5 radiation lengths (24 cm). To minimize the mechanical stress, each crystal was housed in its own cell of a carbon fiber support structure. The walls between the crystals were about 0.2 mm thick. The dead material of the walls together with the clearances represented about 2.1% of the solid angle coverage of the ECAL.

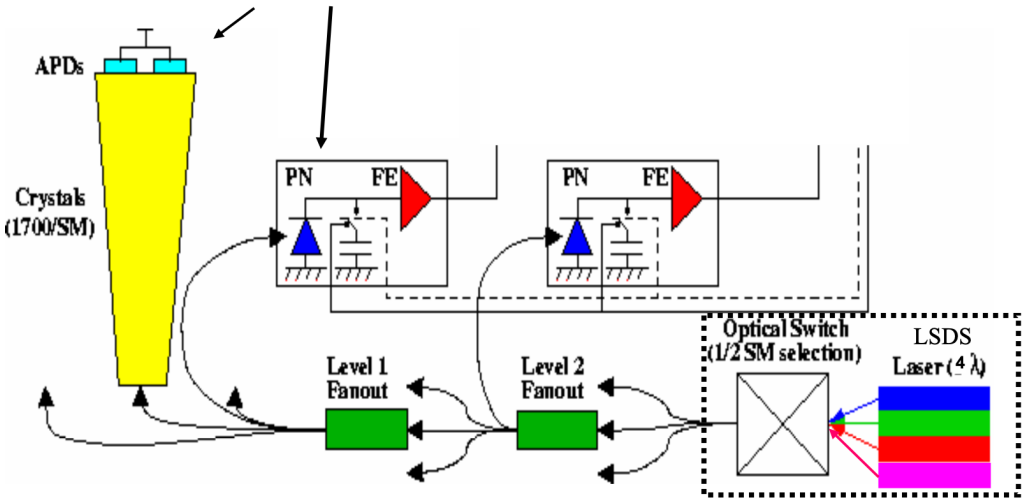
CMS PWO calorimeter

- CMS: PWO+APD
  - 30MeV-2TeV

Contribution	Barrel ($\eta = 0$)	Endcap ($\eta = 2$)
Total stochastic term	2.7%/√E	5.7%/√E
Total constant term	0.55%	0.55%
Total noise (low luminosity) in E_T	155 MeV	205 MeV
Total noise (high luminosity) in E_T	210 MeV	245 MeV



APD/PD monitors the PWO crystals.



The ECAL light monitoring system consists of laser source, optical switch based high-level distribution system and two level fanout system.