Crystal/glass calorimeter option (electromagnetic sector): input materials

Yong Liu (IHEP)

Mar. 9, 2024

CEPC Calorimeter Weekly Meeting

Performance: long-crystal design

Items	Priority	Results / Status	Remarks
Boson Mass Resolution	A	TBD (ongoing studies)	Required BMR < 4%
Intrinsic EM energy resolution	A	$1.5-2\%/\sqrt{E(GeV)}$	Geant4 full simulation + digitisation
Separation power		Results for γ/γ and γ/π; no results for π/π	gamma/gamma, gamma/hadron, hadron/hadron
Lepton ID in jets		No results	
Timing capability		~1.3ns (MIP); 0.34ns (shower maximum)	DESY Beamtest results for long BGO bars (40/60 cm)
π^0 reconstruction		No results	
Pile-up at Z-pole		No results	

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

Performance: short-crystal design

Items	Priority	Results / Status	Remarks
Boson Mass Resolution	A	3.6-3.7 %	1cm³ BGO cubes for Higgs to gluon jets
Intrinsic EM energy resolution	A	$1.5-2\%/\sqrt{E(GeV)}$	Geant4 full simulation + digitisation
Separation power		Results for γ/γ and γ/π; no results for π/π	gamma/gamma, gamma/hadron, hadron/hadron
Lepton ID in jets		No results	
Timing capability		TBD	Ongoing studies in simulation and beam tests
π^0 reconstruction		Simulation results	1cm³ BGO cubes
Pile-up at Z-pole		No results	

Performance: scintillating glass option

Items	Priority	Results / Status	Remarks
Boson Mass Resolution	A	No results	Studies can be planned (Expect similar performance as crystal cubes)
Intrinsic EM energy resolution	A	$2-3\%/\sqrt{E(GeV)}$	Geant4 full simulation + digitisation;
Separation power		No results	Studies can be planned
Lepton ID in jets		No results	
Timing capability		TBD (ongoing studies)	1cm³ glass cube: 14 ps (MIP), 5-7 ps (shower maximum)**
π^0 reconstruction		No results	Studies can be planned
Pile-up at Z-pole		No results	

* **Glass** is a promising option in the form factor of cubes/short bars, in terms of technical feasibility and cost effectiveness

** Based on a reference on 2016 CERN beamtest results (Crystal Clear Collaboration)

Cost: long crystal design

Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for ECAL	1900 mm	400 mm	NA
Length for barrel; Outer radius for endcap	5900 mm	1900 mm + $24X_0$ (*2168.3mm for BGO*)	NA
Longitudinal Depth	$24X_0$ (268.3 mm BGO)		NA
Modularity	28 modules in phi, 15 rings along Z	No concrete design (ideal cylinder for now)	NA
Material Volume (m^3)	20.2	7.6	27.8
Readout channels	0.92 M	0.35 M	1.3 M
Power dissipation	18.4 kW	7.0 kW	25.4 kW
Cost: sensitive materials	80.8M €	30.4M €	111.2M €
Cost: FE electronics	2.3M €	0.9M €	3.2M €

* Note: ECAL endcaps will encompass barrel

(Preliminary) Key components and materials
SiPM ($3x3mm^2$): 9 EUR / pc
FE electronics: 2.5 EUR / ch
Crystal: 4 *EUR / cm³* (tentative; pending reply)
Power: ~20 mW / ch

(References also attached)

Cost: short crystal design (one scenario)

Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for ECAL	1900 mm	400 mm	NA
Length for barrel; Outer radius for endcap	5900 mm	1900 mm + $24X_0$ (*2168.3mm for BGO*)	NA
Longitudinal Depth	$24X_0$ (268.3 mm BGO)		NA
Modularity	28 modules in phi, 15 rings along Z	No concrete design (ideal cylinder for now)	NA
Material Volume (m^3)	20.2	7.6	27.8
Readout channels	4.5 M*	1.7 M*	6.2 M*
Power dissipation	90 kW	34 kW	124 kW
Cost: sensitive materials	80.8M €	30.4M €	111.2M €
Cost: FE electronics	11.3M €	4.3M €	15.6M €

* Dependent on the longitudinal granularity: hereby assuming 6 longitudinal layers

(Preliminary) Key components and materials
SiPM ($3x3mm^2$): 9 EUR / pc
FE electronics: 2.5 EUR / ch
Crystal: 4 EUR / cm^3 (tentative; pending reply)
Power: ~20 mW / ch

(References also attached)

Cost: scintillating glass option ("optimal PFA-performance" scenario)

Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for ECAL	1900 mm	400 mm	NA
Length for barrel; Outer radius for endcap	5900 mm	1900 mm + $24X_0$ (*2168.3mm for BGO*)	NA
Longitudinal Depth	$24X_0$ (27cm)		NA
Modularity	28 modules in phi, 15 rings along Z	No concrete design (ideal cylinder for now)	NA
Material Volume (m^3)	20.2	7.6 m^3	27.8 m^3
Readout channels	20.2 M*	7.6 M*	27.8 M*
Power dissipation	404 kW	152 kW	556 kW
Cost: sensitive materials	20.2M €	7.6M €	27.8M €
Cost: FE electronics	50.5M €	19.0M €	69.5M €

(Preliminary) Key components and materials
SiPM ($3x3mm^2$): 9 EUR / pc
FE electronics: 2.5 EUR / ch
Glass: 1 *EUR / cm^3* (tentative)
Power: ~20 mW / ch

* Dependent on the longitudinal granularity: hereby assuming 28 longitudinal layers

Technical status: simulation and R&D

- Status and plans of simulation studies and R&D: details in the table below
- Person power: IHEP (Fangyi Guo, Yong Liu, Baohua Qi, Weizheng Song, Shengsen Sun, Yang Zhang), SIC-CAS (Junfeng Chen), SJTU/TDLI (Jiyuan Chen, Haijun Yang, Zhiyu Zhao)

Category	Status	Long crystal bars	Short crystal bars
Technical Readiness Level	Full Simulation (system level)	CEPCSW: barrel geometry; reconstruction (ongoing developments)	CEPCsoft: full geometry, Arbor
	Full Simulation (module level)	Geant4 simulation, digitisation (module 40x40x28 cm^3)	Geant4 simulation, digitisation (flexible module dimensions)
	Prototyping R&D (common)	High pixel density SiPMs (6/10 um pixel pitch), front-end electronics (ASICs), timing resolution	
	Prototyping R&D (modules, units)	Crystal module (12x12x24 cm^3); long crystal bars (40/60 cm)	No module developments; Short bars (2/4cm)

- Scintillating glass option: EM performance studies with Geant4 simulation + digitisation (Baohua Qi)

References for calorimeter cost estimates

Yong Liu (IHEP)

March 8, 2024

Aim: to collect references including TDRs and other project documents to provide solid inputs to the cost estimates of CEPC calorimeters for the ***CEPC Reference Detector TDR***

ILD-ECAL options

ILC TDR Volume 4 (Detectors): page 306

ECAL major components

Table III-7.3
Expected prices for major components in the calorimeters, see text for further comments. Except where explicitly stated all current costs are based on actual costs of components procured for the prototypes.

Material	Cost [ILCU]	System	Comment
Tungsten	123/kg	SiECAL, ScECAL, AHCAL, FCAL	quote from manufacturer (130 EUR/kg)
Stainless Steel	5/kg	AHCAL, SDHCAL	processing costs to be added (1-4 EUR/ kg)
Si sensors	$3/cm^2$	SiECAL	based on extrapolation of current quotation of 5 EUR/ cm^2
SiPM	1/pc	ScECAL, AHCAL, muon	based on manufacturer extrapolation, current price 7-10 EUR/piece
ASIC	0.22-0.25/ch	SiECAL, ScECAL, AHCAL	current price 0.5 EUR/ch
ASIC	0.1/ch	SDHCAL	current price of 0.18 EUR/ch
PCB	$7900/m^2$	SiECAL	prototype
PCB	$2600/m^2$	ScECAL	extrapolated from prototype price of $10800/m^2$
PCB	$1800/m^2$	SDHCAL, AHCAL	for AHCAL extrapolated from prototype price of $10800/m^2$

Total ECAL cost

Table III-7.4
Cost table of the electromagnetic calorimeter.

SiECAL		ScECAL	
Item	Cost [kILCU]	Item	Cost [kILCU]
Tungsten	16310	Tungsten + carbon parts	18500
Carbon fiber structure	2130	Module realisation	1700
Silicon sensors	75000	Scintillators	1030
Readout ASIC	16500	Photo Detectors	10200
Readout Board	21000	Readout ASIC	2500
Materials	1300	Readout Board	25000
Cables, connectors	2220	Readout System	6200
Tooling	9300	Cables, connectors	1000
Assembly	13500	Power supplies	4100
Integration	500	Tooling	3800
Sum SiECAL	157760	Sum ScECAL	74000

ILD: HCAL, magnet and yoke

ILC TDR Volume 4 (Detectors): page 308

HCAL options: AHCAL and SDHCAL

Table III-7.5
Cost breakdown for the two HCAL options AHCAL and SDHCAL.

AHCAL		SDHCAL	
Item	Cost [kILCU]	Item	Cost [kILCU]
Absorber	5200	Absorber	6500
Module production	3400	Module mechanics	2300
Cassettes	2100		
Scintillators	1500	RPC incl cassettes	6800
Reflective Foil	1200		
Photo sensors	7700		
ASIC	1800	ASIC	6600
Readout Board	13200	Readout Board	13000
Readout	2300	Readout	2000
Cabling, connections	1000	Elec Integration	1600
HV/ LV supplies	1000	Services incl. HV/ LV	200
Cooling system	1000	Cooling System	1000
		Gas System	900
Tooling, testing	500	Testing	200
Assembly, installation	2800	Assembly, tooling	3900
DAQ	200		incl.
Sum AHCAL	44900	Sum SDHCAL	44800

HCAL options: AHCAL and SDHCAL

Table III-7.6
Cost table of the coil and the iron yoke.

Item	Cost [kILCU]	Item	Cost [kILCU]
Coil		**Yoke**	
Conductor and winding	12900	Steel, including machining	80400
Internal Cryogenics	1000	Support	1700
Suspension system	560	Moving System	3500
tooling, assembly	10000	Assembly	6700
Qualification, testing	1100	Survey	500
Ancillaries			
Cryogenics, vacuum	6800	Integration	933
Electrical installation	1700	Field Mapping	560
Control and Safety system	350	Engineering	2200
Sum	131000		

ILD: cost estimate summary

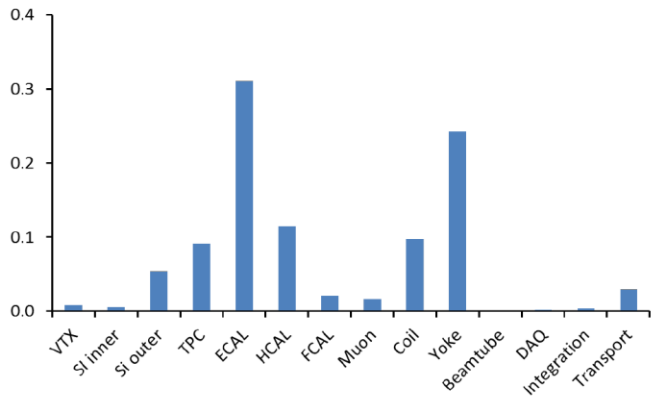
ILC TDR Volume 4 (Detectors): page 308

Table III-7.7
Summary table of the cost estimate of the ILD detector. Depending on the options used the cost range is between 336 Mio ILCU and 421 Mio ILCU.

System	Option	Cost [MILCU]	Mean Cost [MILCU]
Vertex			3.4
Silicon tracking	inner	2.3	2.3
Silicon tracking	outer	21.0	21.0
TPC		35.9	35.9
ECAL			116.9
	SiECAL	157.7	
	ScECAL	74.0	
HCAL			44.9
	AHCAL	44.9	
	SDHCAL	44.8	
FCAL		8.1	8.1
Muon		6.5	6.5
Coil, incl anciliaries		38.0	38.0
Yoke		95.0	95.0
Beamtube		0.5	0.5
Global DAQ		1.1	1.1
Integration		1.5	1.5
Global Transportation		12.0	12.0
Sum ILD			391.8

ILD sub-system: cost contribution percentages

Figure III-7.2
Summary plot of the relative contribution by the different sub-components to the total cost of the ILD detector.



CMS PWO crystal calorimeter

CMS The Electromagnetic Calorimeter Technical Design Report (CERN/LHCC 97–33, CMS TDR 4)

	Barrel	Cost (kCHF)	Funds (kCHF)	Institute
3.1.1	**Crystals**	**22 191**	**22 200**	**ETHZ, CERN, ROME, IN2P3**
	Crystals & Tools	*19 536*		ETHZ, CERN
	Acceptance & Assembly	*2 155*		CERN, ROME, IN2P3, ETHZ
	Manpower Acc & Ass	*500*		CERN, ROME
3.1.2	**Electronics**	**22 308**	**22 300**	**ETHZ, PRINCETON, IN2P3, PSI, NEU, CERN, ROME, MINN., SACLAY, CYPRUS, CROATIA**
	APD, Capsule & Test Equipment	*6 845*		PSI, NEU, MINN., IN2P3, ETHZ, CYPRUS
	Front End Readout	*7 940*		ETHZ, PRINCETON, IN2P3
	Upperlevel Readout	*5 395*		ETHZ, CERN, IN2P3
	Power Supplies, Services & Controls	*2 128*		ROME, SACLAY, CROATIA, ETHZ
3.1.3	**Mechanical Structure**	**8 313**	**8 300**	**ETHZ, IN2P3, ROME, CERN**
	Tooling	*972*		ETHZ, CERN
	Submodule	*3 255*		IN2P3, ETHZ
	Module	*3 118*		ETHZ, ROME
	Supermodule	*968*		CERN, ROME
3.1.4	**Assembly & Installation**	**5 700**	**5 700**	**ETHZ, CERN, SACLAY, ROME**
	Tools & Platforms	*2 800*		ETHZ, CERN
	Cooling System	*500*		CERN
	Manpower	*2 400*		ETHZ, CERN, SACLAY, ROME
3.1.5	**Monitoring**	**1 661**	**1 670**	**SACLAY, CALTECH**
	Light Injection	*543*		CALTECH
	Light Distribution & Control	*1 118*		SACLAY
	Total	**60 173**		

	Endcap	Cost (kCHF)	Funds (kCHF)	Institute
3.2.1	**Crystals**	**7 700**	**7 700**	**ETHZ, CERN, UK**
	Crystals & Tools	*7 200*		ETHZ, CERN
	Acceptance & Assembly	*500*		UK, CERN, ETHZ
3.2.2	**Electronics**	**6 900**	**6 900**	**ETHZ, UK, RDMS**
	VPT & Test Equipment	*2 000*		UK, RDMS, ETHZ
	Front-End Readout	*2 400*		ETHZ
	Upperlevel Readout	*1 800*		ETHZ
	Power Supplies, Services & Controls	*700*		UK, ETHZ
3.2.3 & 3.2.4	**Mech. Structure & Assembly**	**2 500**	**2 500**	**UK + RDMS**
3.2.5	**Monitoring**	**500**	**500**	**SACLAY**
3.2.6	**Preshower**	**5 400**	**5 400**	**CERN, GREECE, RDMS, INDIA**
	Total	**23 000**		

A 3-D view of the barrel and endcap electromagnetic calorimeter is shown in Fig. 1.5.

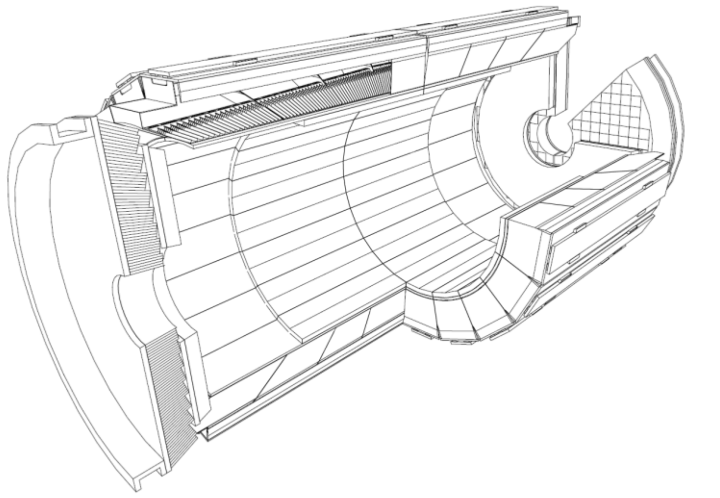


Fig. 1.5: A 3-D view of the electromagnetic calorimeter.

Table 1.2: ECAL design parameters

Parameter	Barrel	Endcaps
Pseudorapidity coverage ECAL envelope: r_{inner}, r_{outer} [mm] ECAL envelope: z_{inner} z_{outer} [mm]	$\lvert\eta\rvert < 1.48$ 1238, 1750 0, ±3045	$1.48 < \lvert\eta\rvert < 3.0$ 316, 1711 ±3170, ±3900
Granularity: $\Delta\eta \times \Delta\phi$ Crystal dimension [mm^3] Depth in X_0	0.0175×0.0175 typical: $21.8 \times 21.8 \times 230$ 25.8	0.0175×0.0175 to 0.05×0.05 $24.7 \times 24.7 \times 220$ 24.7
No. of crystals Total crystal volume [m^3] Total crystal weight [t]	61 200 8.14 67.4	21 528 3.04 25.2
Modularity 1 supermodule/Dee 1 supercrystal unit	36 supermodules 1700 crystals (20 in ϕ, 85 in η) –	4 Dees 5382 crystals 36 crystals

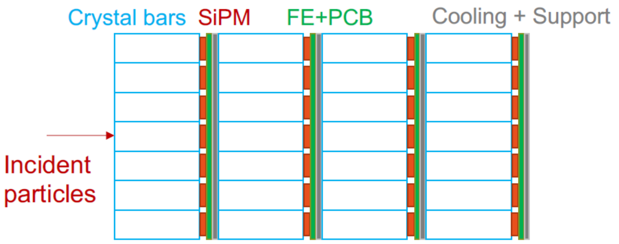
Barrel
- Funds: 22M CHF
- Volume: 8.14 m³
- Unit cost: 2.7CHF/cc

Endcaps
- Funds: 7.7M CHF
- Volume: 3.04 m³
- Unit cost: 2.5CHF/cc

Extra Slides

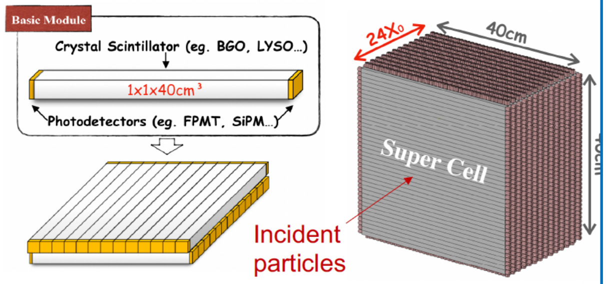
Designs and EM resolution

Design 1: short bars



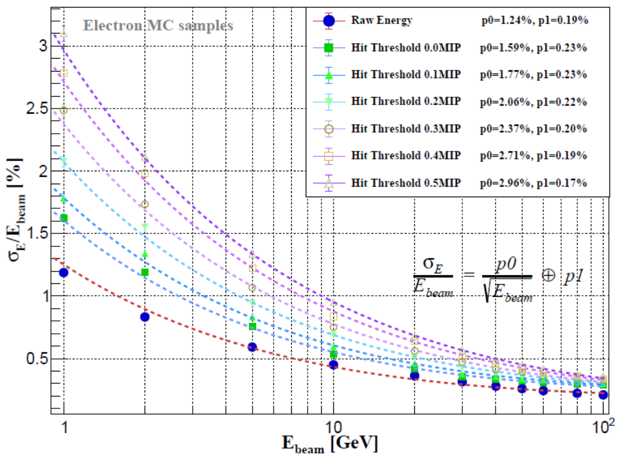
- A natural design compatible with PFA
  - Fine segmentation in Both longitudinal and transverse
  - Single-ended readout with SiPM

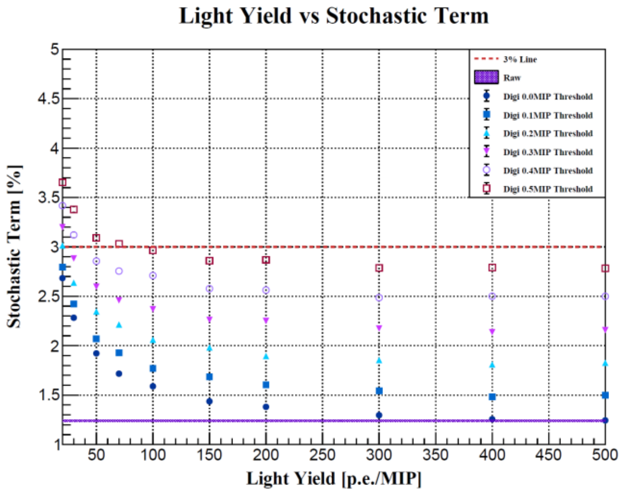
Design 2: long bars



- Long bars: 1×40cm, double-sided readout
  - Super cell module: 40×40cm
  - Crossed arrangement in adjacent layers
  - Fine longitudinal granularity
- Save #channels and minimize dead materials
- Timing at two sides: positioning along bar

Geant4 full simulation + digitisation





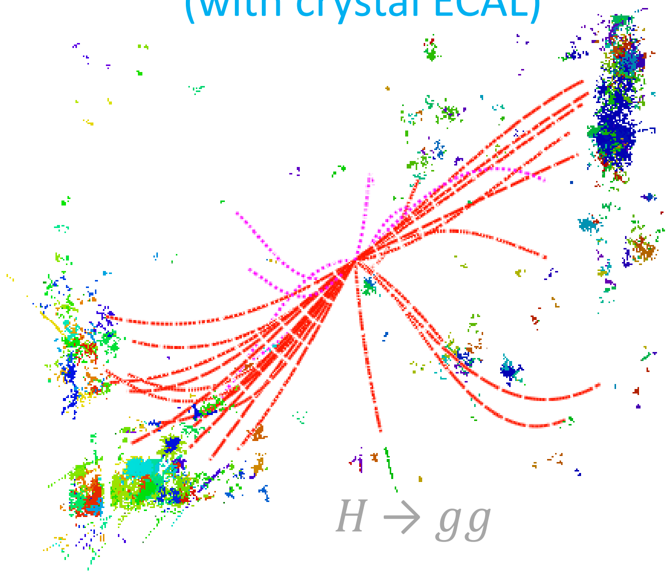
Key Parameters	Value
MIP light yield	~200 p.e./MIP
Dynamic range	$1-10^5$ p.e.
Energy threshold	~0.1 MIP
Timing resolution	1ns (→100 ps?)
Response non-uniformity	<1%
Temperature stability	Stable at ~0.05 ℃
Gap tolerance	~100 μm

Higgs physics performance

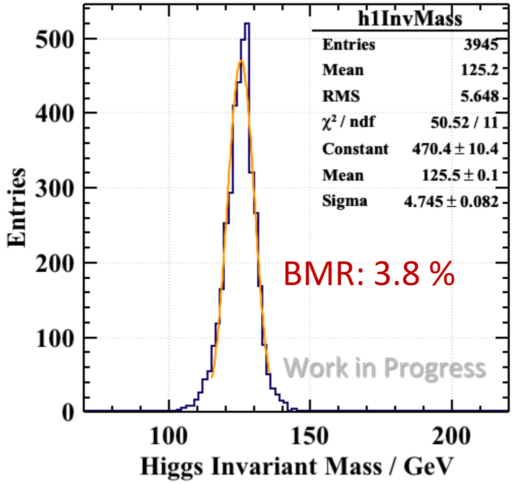
Baohua Qi, Dan Yu (IHEP); Zhiyu Zhao (SJTU)

- Physics potentials with crystals
  - Photons and jets
- Boson Mass Resolution (BMR)
  - Jets ($H \rightarrow gg$): 3.8 % → 3.6%
  - Photons ($H \rightarrow \gamma\gamma$): 2.1% → 1.2%

Higgs to 2 gluon jets (with crystal ECAL)



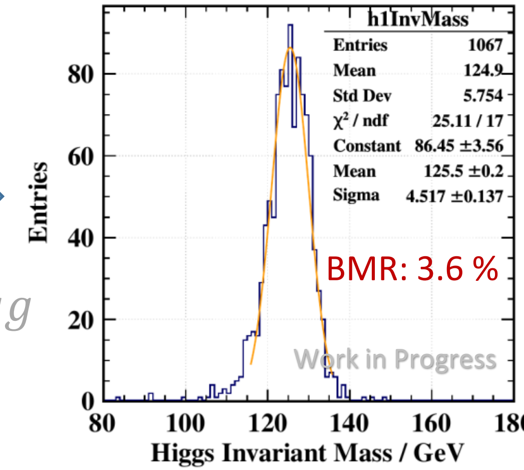
Detector with *SiW-ECAL* option



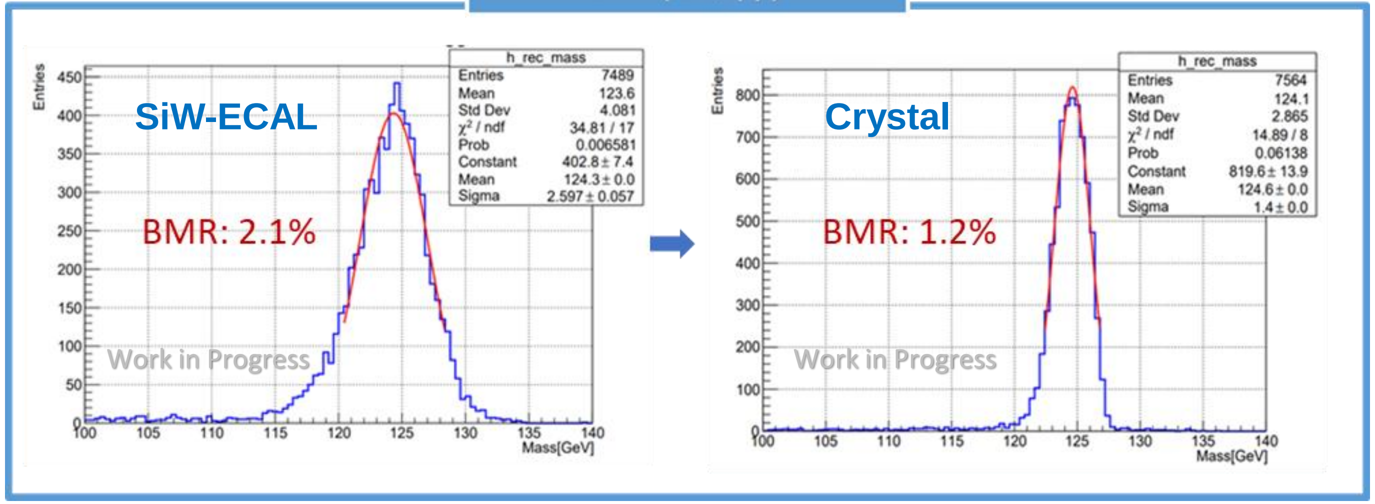
$H \rightarrow gg$

Detector with *crystal ECAL* option

1cm³ cubes



BMR ($H \rightarrow \gamma\gamma$)



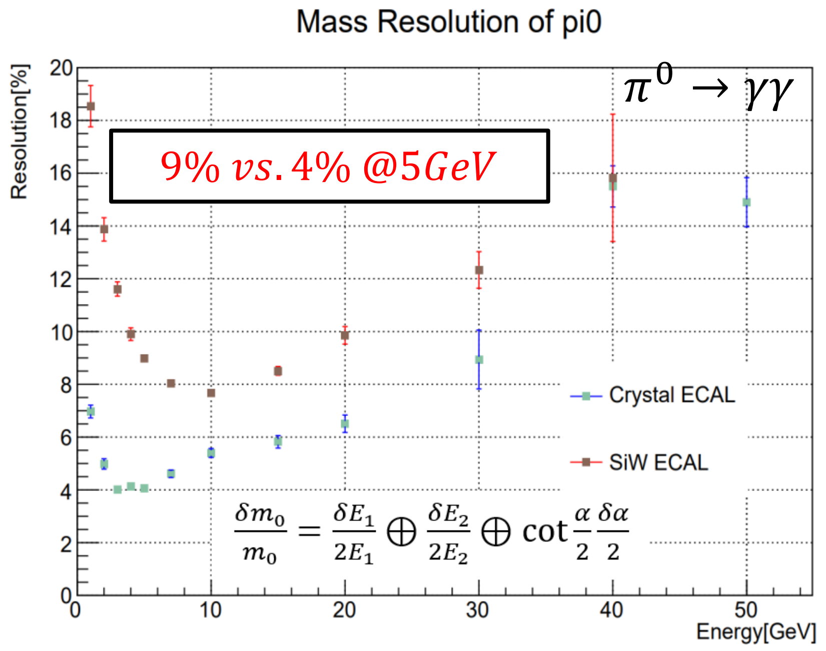
Flavor physics performance

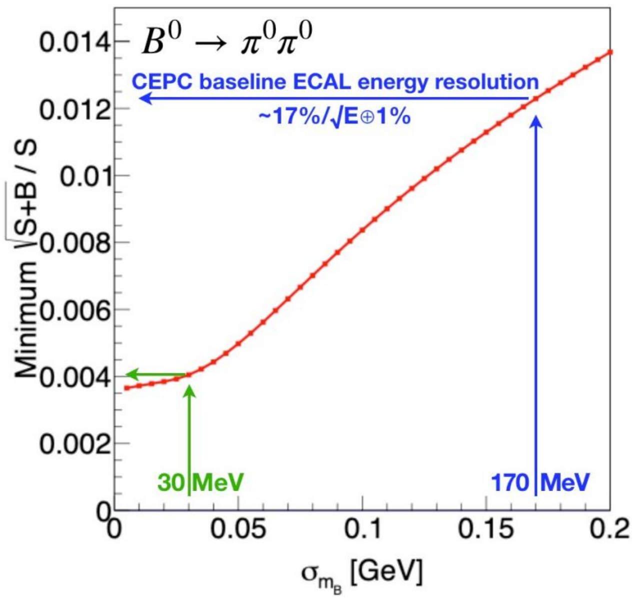
Zhiyu Zhao (SJTU), Yuexin Wang (IHEP)

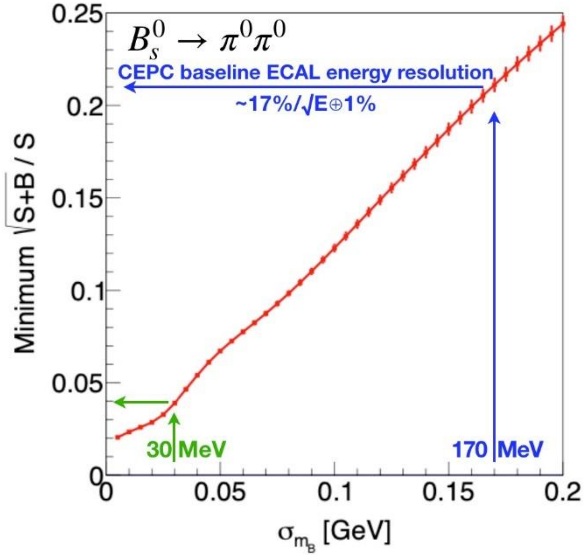
- Crystal ECAL
  - Higher sensitivity to photons and much better EM resolution
- Potentials for π^0/γ in flavor physics

B0 to pipi @CEPC(CEPC Flavor Physics/New Physics/Detector Technology Workshop, Fudan, 2023), Yuexin Wang

ECAL Resolution	σ_{m_B} (MeV)	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$
$17\%/\sqrt{E}\oplus 1\%$	170	~1.2%	~21%
$3\%/\sqrt{E}\oplus 0.3\%$	30	~0.4%	~4%

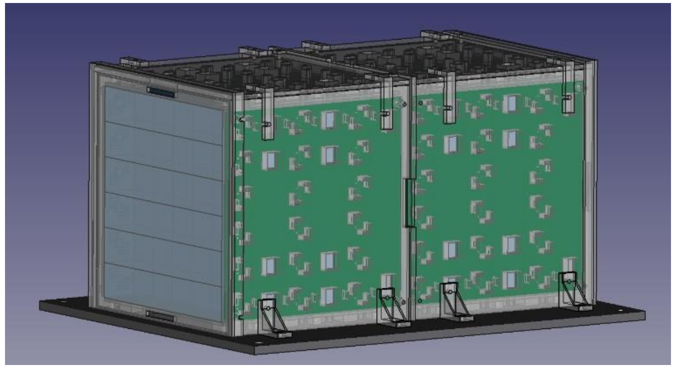


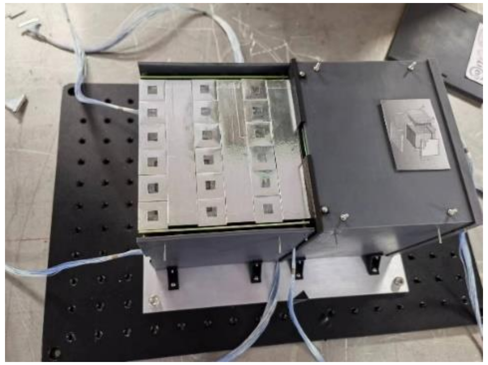


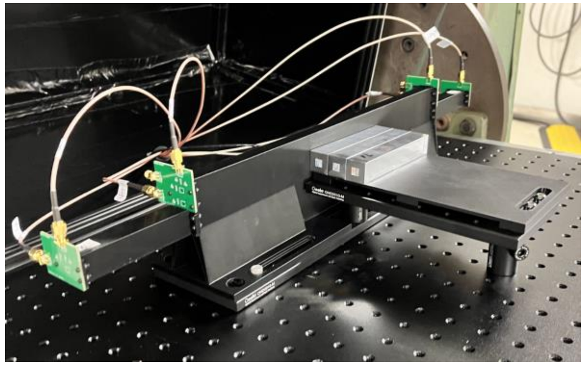


JHEP12(2022)135

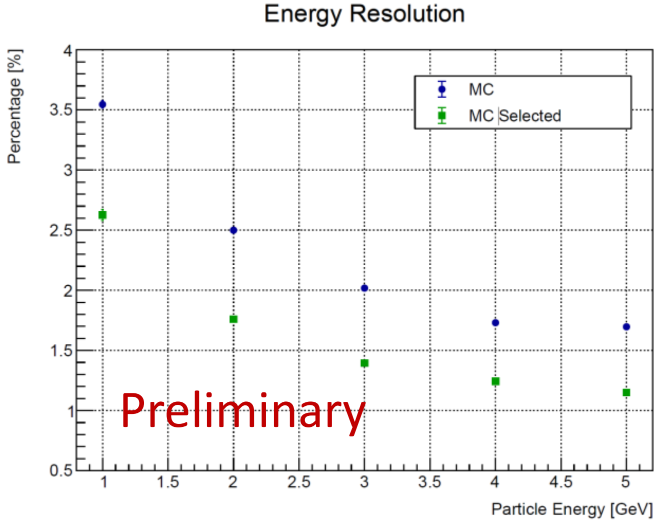
Crystal ECAL: prototyping and beamtests





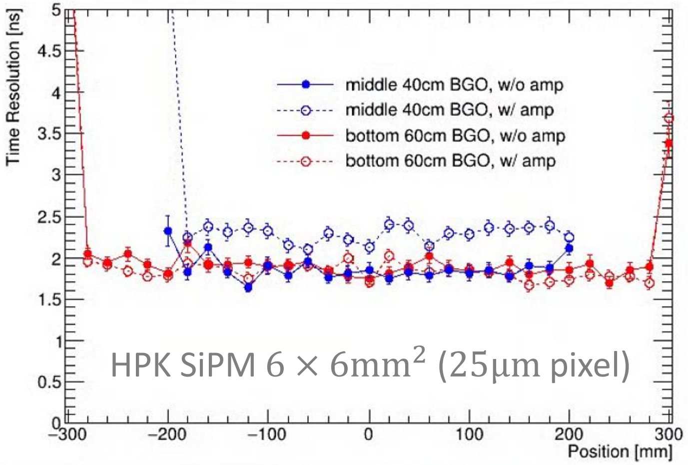


Expected performance at CERN PS-T9

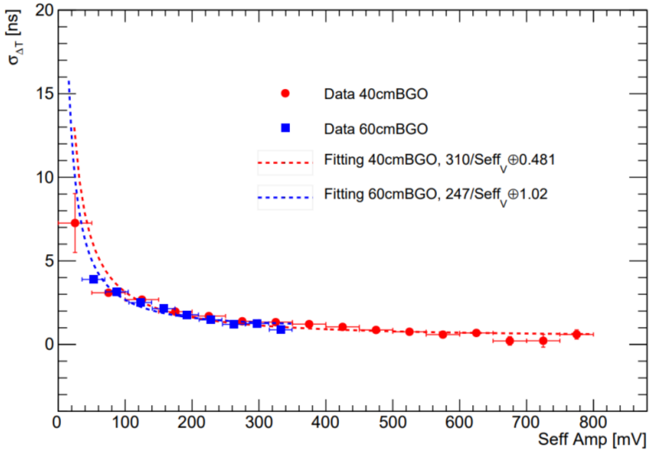


Based on PS-T9 beamline document: 0.5% (FWHM) of beam spread (from Lattice)

Resolution of time difference at two ends



Time Resolution vs Signal Amplitude



- Timing resolution (MIP level): ~1.8 ns (two ends) → ~1.3ns (single end)
- Timing resolution (upstream crystals as pre-shower): ~0.34 ns (single end for large signals)