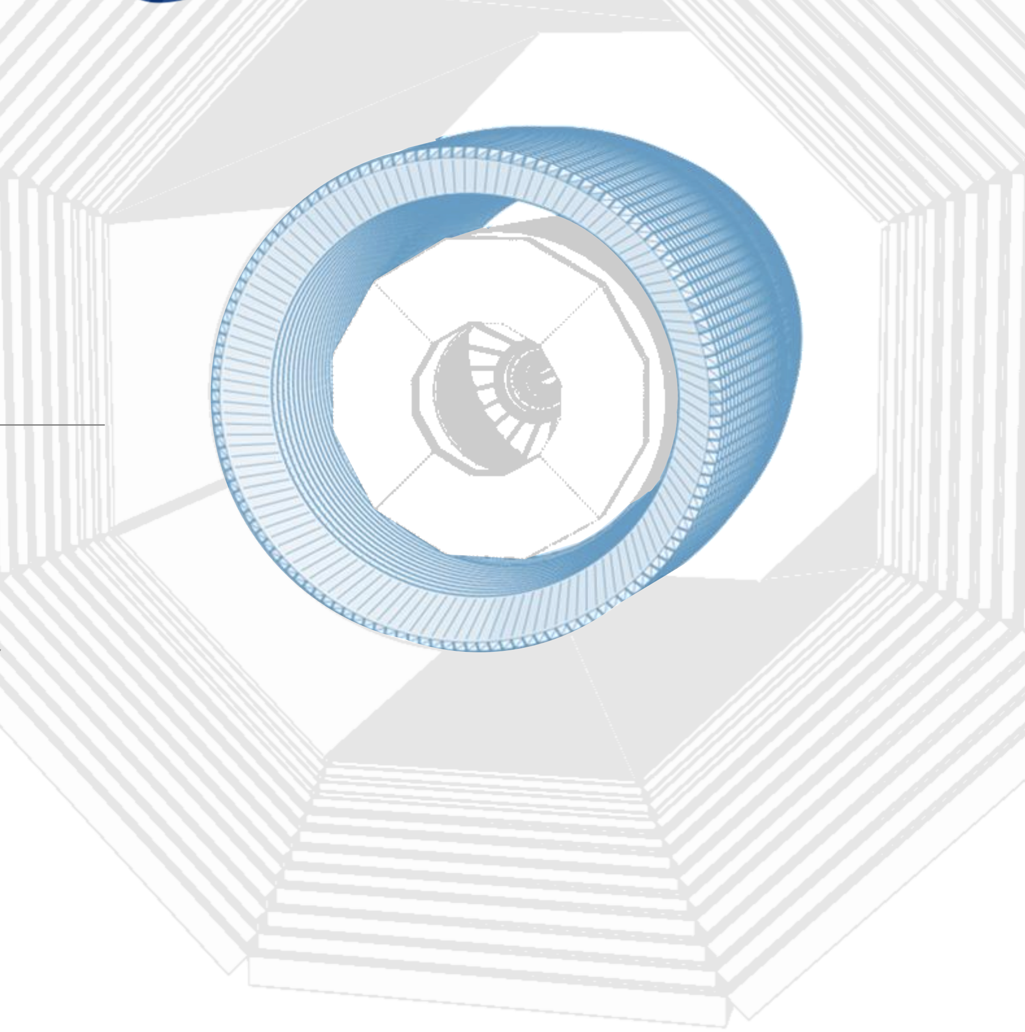
BSO for electromagnetic calorimeter R&D on STCF



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Supervisor: Haiping Peng

Thesis Proposal Talk

2025.10.14

Outline

- Introduction
  - Electromagnetic calorimeter
- Super Tau-Charm Facility
  - Accelerator
  - Physics
  - Detector
- BSO Research
  - Challenges in EMC design and operation
  - Selection of crystals
  - BSO properties
  - EMC design
  - BSO Performance Test
- Summary and Prospects

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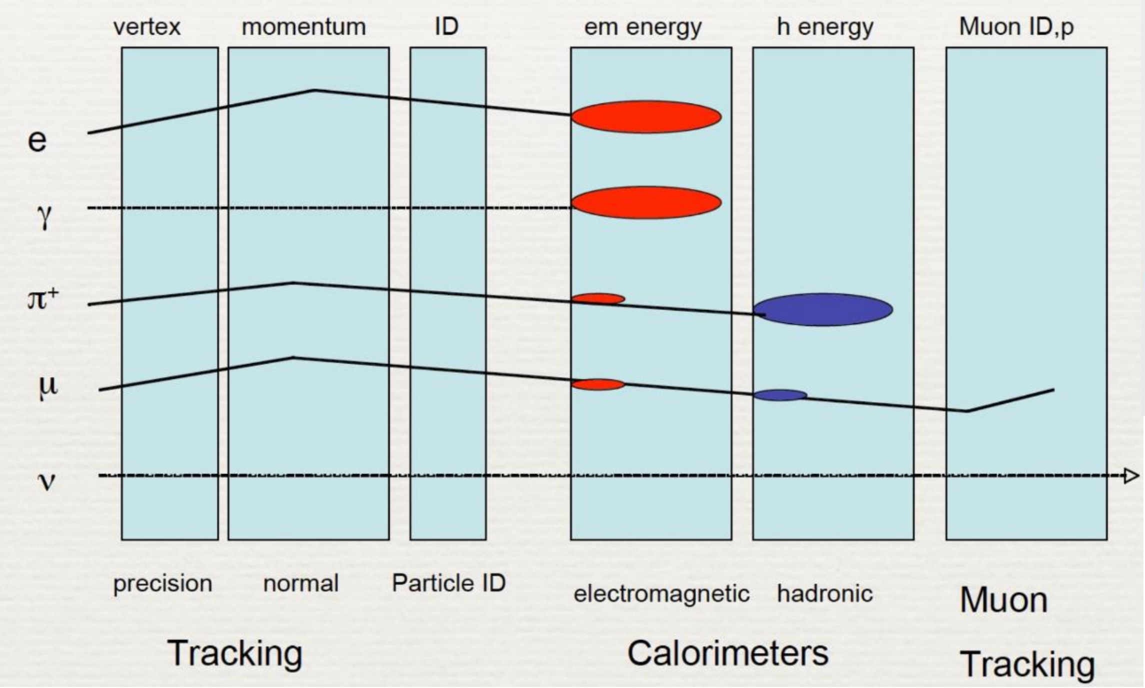
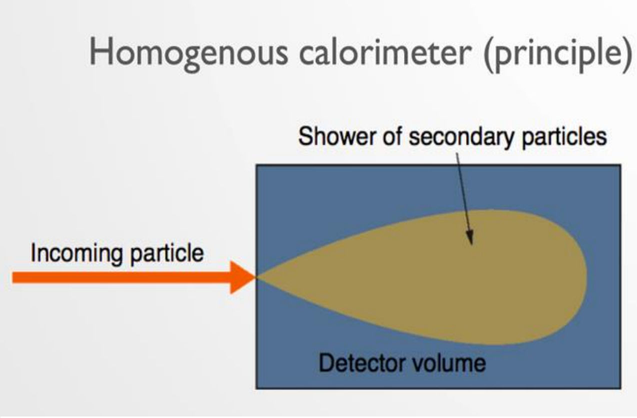
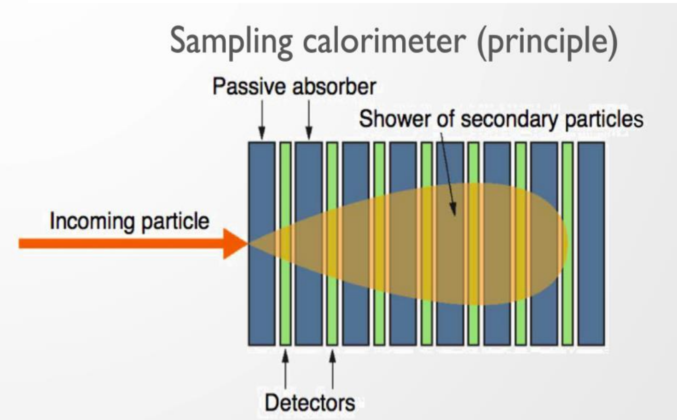
Calorimeter Features





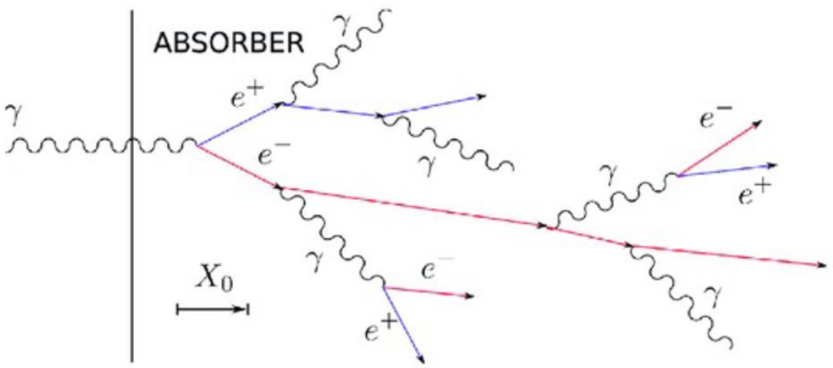


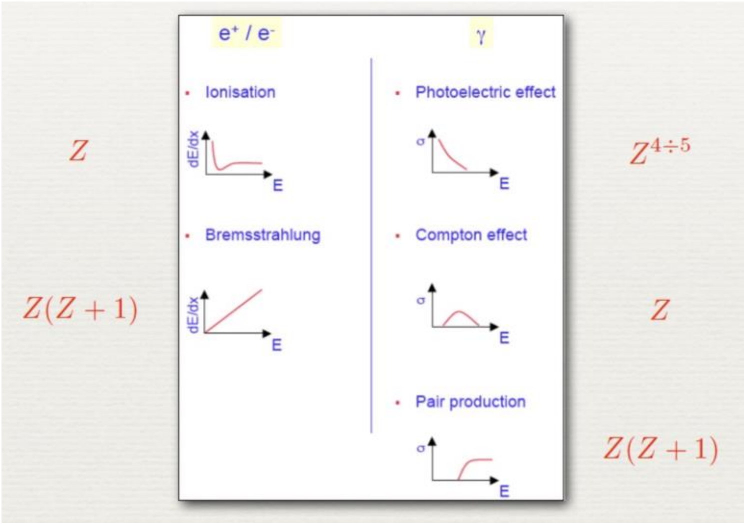
- Sampling Calorimeter
  - Sensitive layers and absorber layers are separated
  - Limited energy resolution ($\frac{5\%-20\%}{\sqrt{E}}$)
- Total-Absorption Calorimeter
  - Sensitive medium is identical to the absorber medium
  - Excellent energy resolution

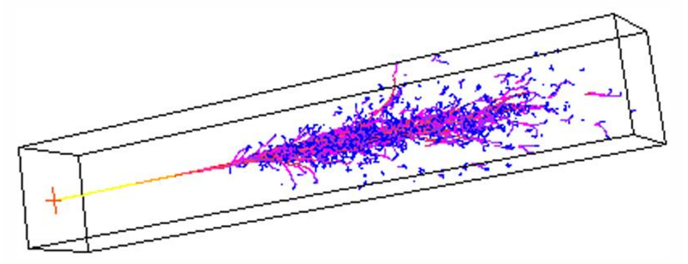
My topic : EM calorimeter on STCF

EM calorimeter	Total Absorption Calorimeter
Hadron calorimeter	Sampling Calorimeter

EM Calorimeter Overview







- ➢ Particle interacts with matter (via pair production and bremsstrahlung), generating electromagnetic showers and depositing energy in the calorimeter.
- ➢ The calorimeter converts this deposited energy into measurable forms such as charge or light, with the resulting signal being proportional to the energy of the incident particle.

Energy Resolution

The energy resolution of an EM calorimeter can generally be expressed as:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c.$$

- $\frac{a}{\sqrt{E}}$ is the **random term**, related to fluctuations in the shower development and signal conversion processes
- $\frac{b}{E}$ is the **noise term**, primarily contributed by electronic noise
- c is the **constant term**, independent of the particle's energy, contributed by factors such as non-uniformity of response, calibration errors, and energy leakage

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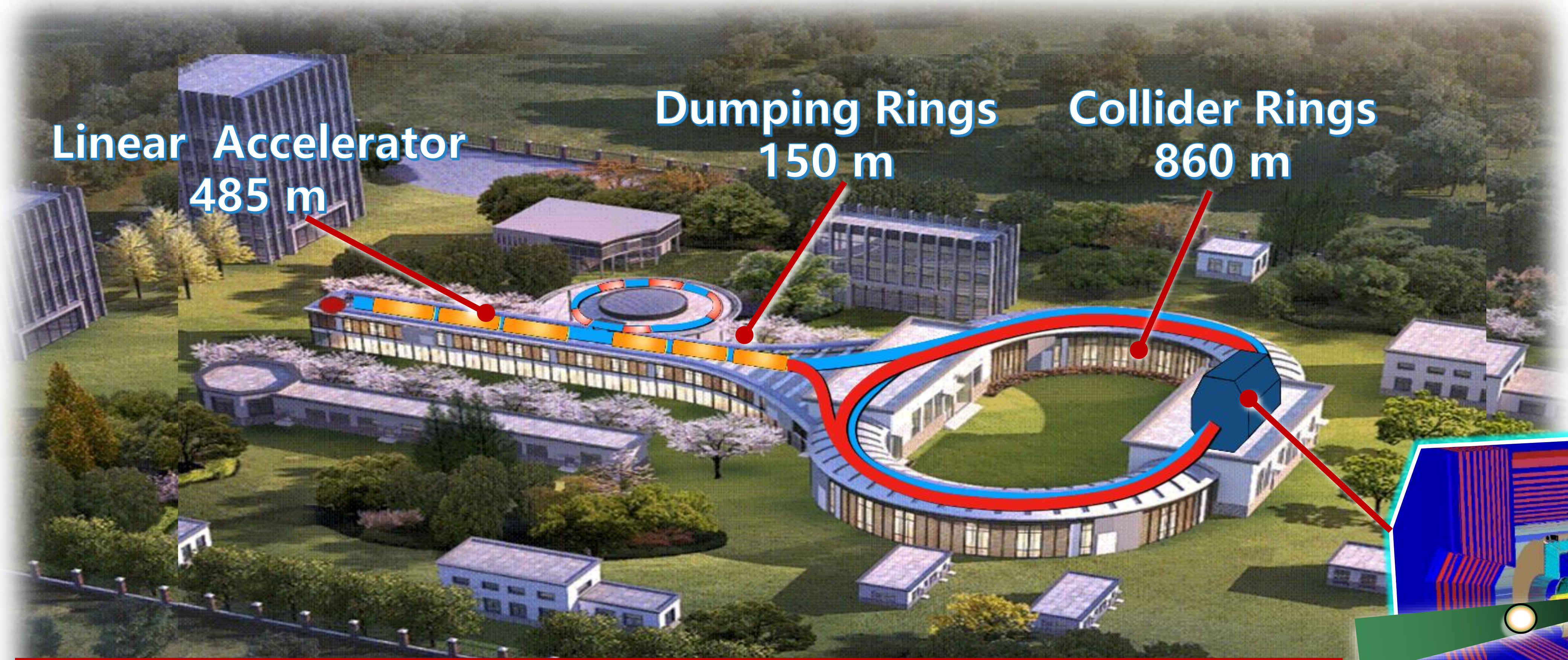
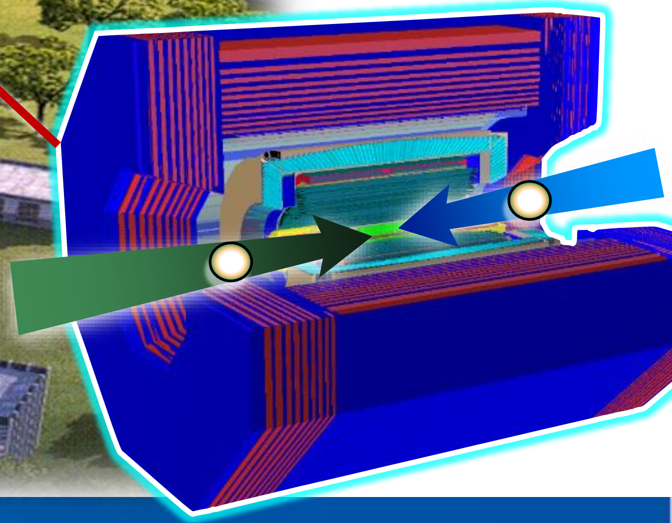
Super Tau-Charm Facility -- Accelerator

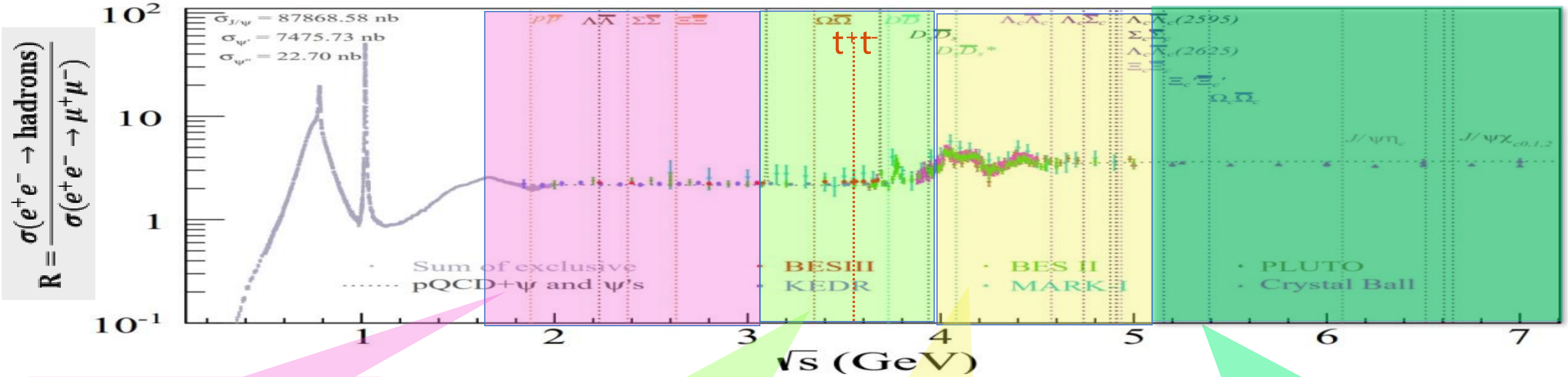




- E_{cm}= 2-7 GeV， Peak luminosity @ $E_{cm} = 4GeV$, $\mathcal{L} > 0.5\times10^{35}$ cm^{-2} s^{-1}
- Site: Hefei's suburban **"Future Big Science City"**

Overview of τ-charm physics

- Transition region between perturbative and non-perturbative QCD
- Rich resonance structure
- Production of low-background tau leptons and charmed hadrons near their production thresholds.



- Nucleon/Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark
- MLLA/LPHD and QCD sum rule predictions

- LH spectroscopy
- Gluonic and exotic
- LFV and CPV
- Rare/forbidden decays
- Physics with τ lepton

- XYZ particles
- Physics with D mesons
- f_D and f_{Ds}
- D_0-D_0 mixing
- Charm baryons

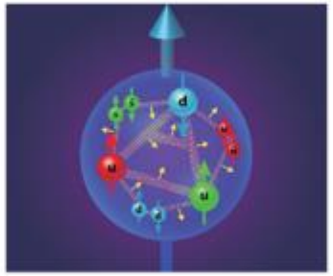
- Di-charmonium state
- New XYZ particle
- Hidden-charm pentaquark
- Multiquark state
- Charm baryons
- Hadron fragmentation

Physics objectives of STCF

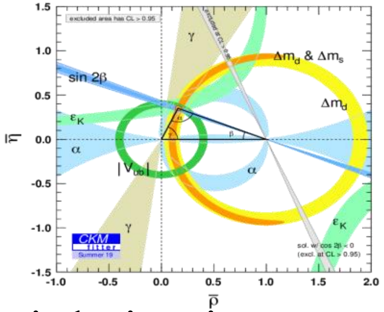
High Statistics, High Precision, Low Background data

- QCD and Hadron structure
  - ☐ Search for Exotic Hadrons

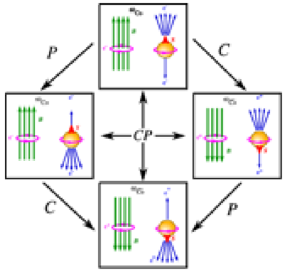
  - ☐ Hadron Structure Studies



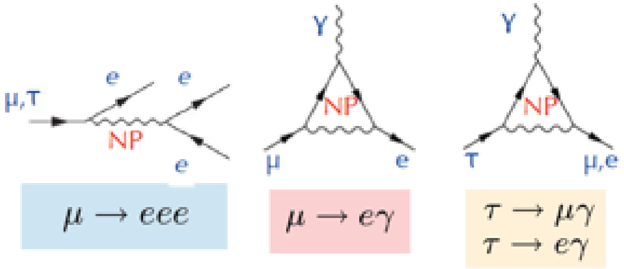
- Flavor Physics and CP Violation
  - ☐ Precision Measurements of the CKM Matrix Elements



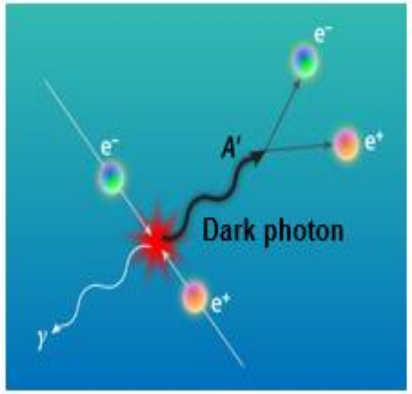
  - ☐ CP Violation in Leptons and Baryons



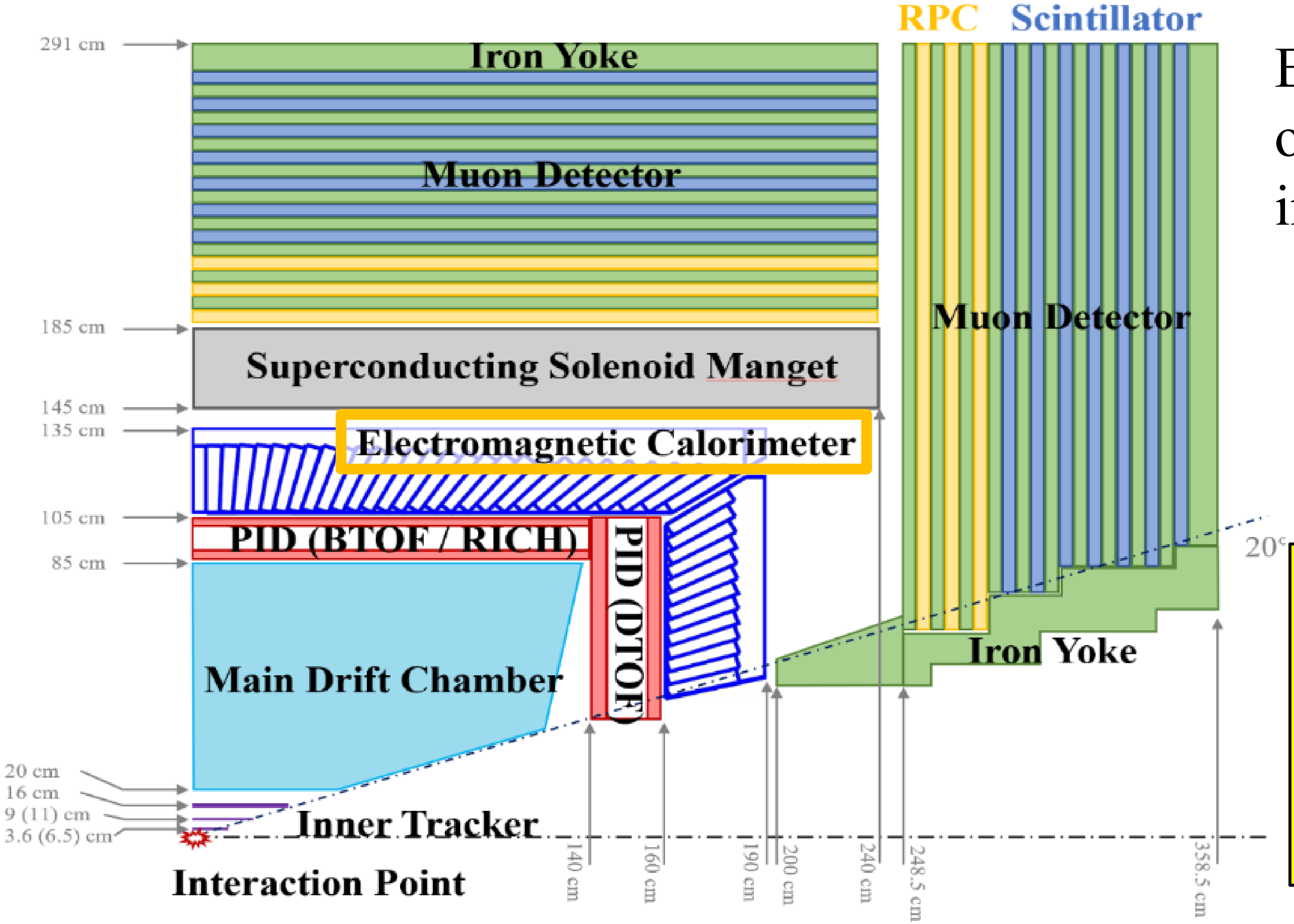
- New Physics Searches
  - ☐ Lepton Flavor Violation



  - ☐ Dark Photon Searches



Super Tau-Charm Facility -- Detector



Electromagnetic Calorimeter : obtaining neutral particle information (γ, n, $\bar{n}$, K_L)

- 4-momentum of photon
- Neutral particle identification
- Neutral event timing
- ……

Electromagnetic Calorimeter

E range : 0.025 – 2GeV

Barrel : σ_E/E=2.5% ; Endcap : σ_E/E=4.0%

Time Resolution : ~300ps

Position Resolution : ~5mm

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  - **Selection of crystals**
  - **BSO properties**
  - **EMC design**
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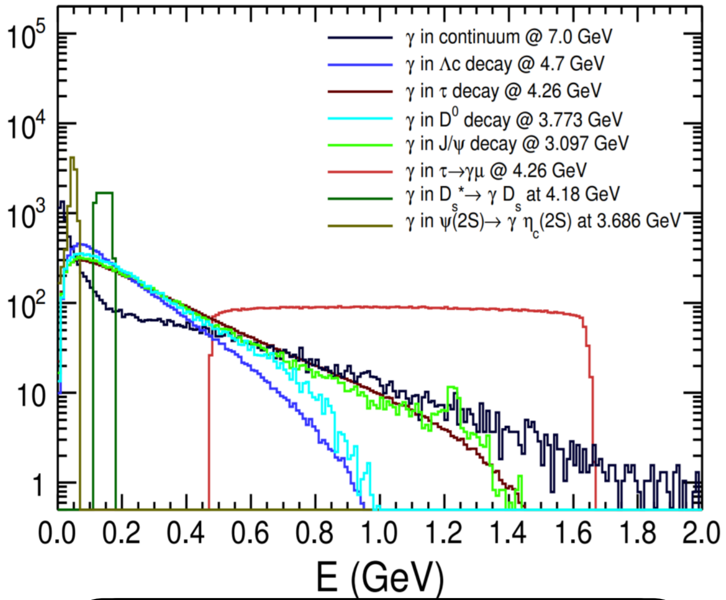
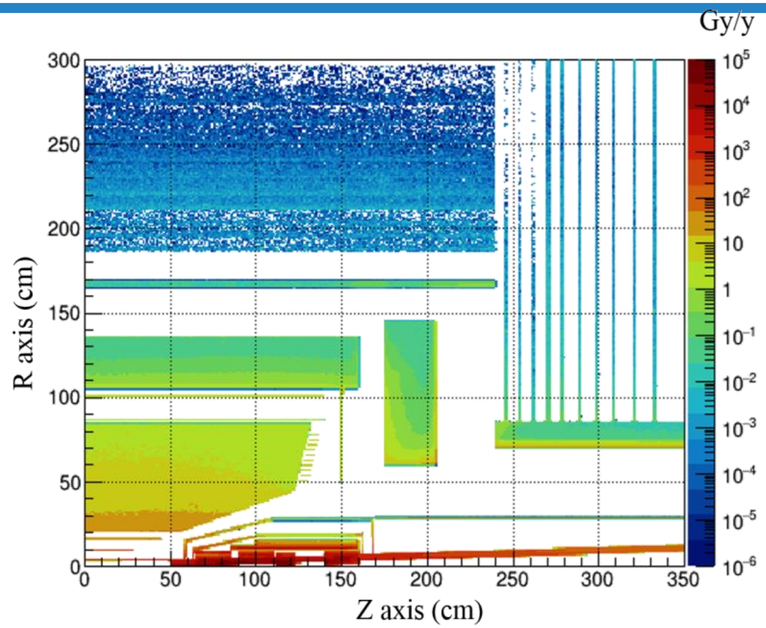
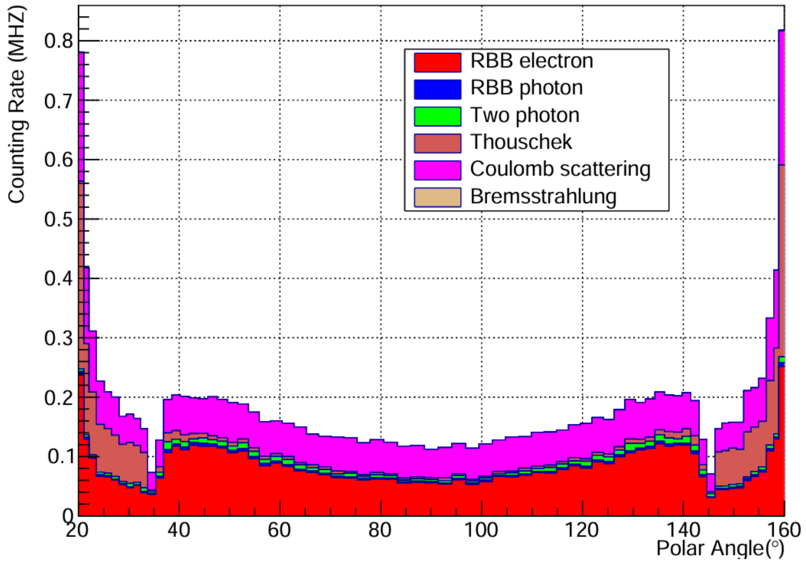
Challenges in EMC design and operation







$E_\gamma = \sim 1$MeV – 3 GeV

High event rate (>400 kHz)

Low noise & Fast Response

Maximum TID more than 40 krad in 10 years

Radiation Hard Crystal

Beam background rate ~

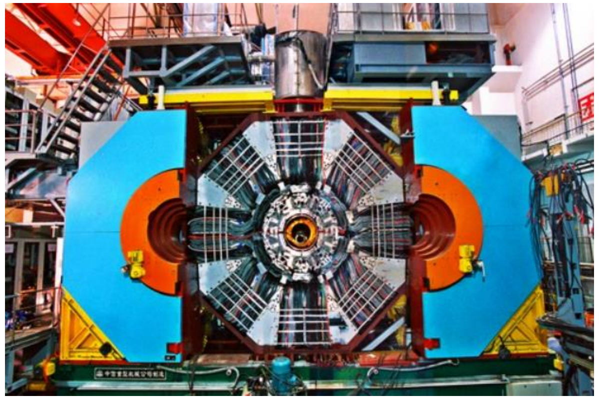
1 MHz per channel

Fast Response

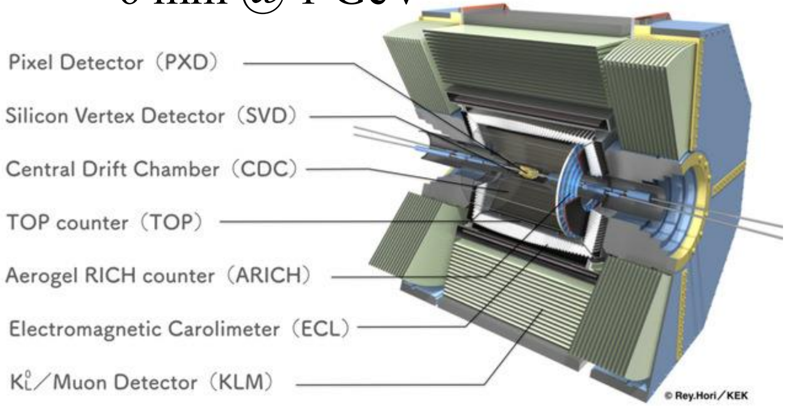
Crystal calorimeter

Crystal calorimeters, known for their excellent energy resolution and superior radiation resistance, are a vital choice for electromagnetic calorimeters.

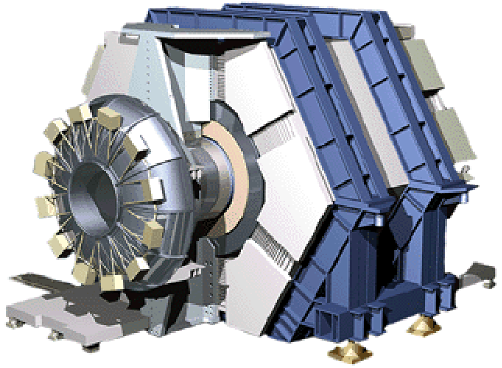
- BESIII Calorimeter
  (CsI(Tl) Full-Absorption Type)
  - Energy Range: 20 MeV – 2 GeV
  - Energy Resolution: Better than 2.5% @ 1 GeV
  - Position Resolution: 6 mm @ 1 GeV



- BELLE Calorimeter
  (CsI(Tl) Full-Absorption Type)
  - Energy Range: 20 MeV – 8 GeV
  - Energy Resolution: Better than 2% @ 1 GeV
  - Position Resolution: 6 mm @ 1 GeV



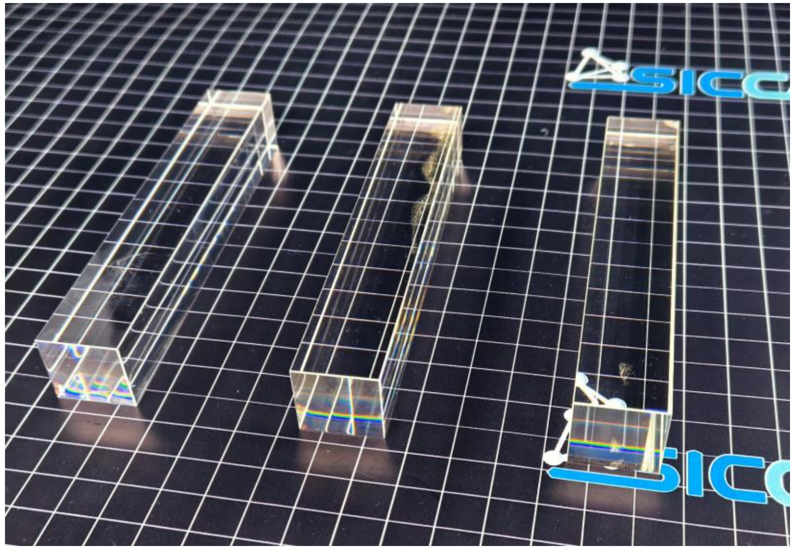
- Babar Calorimeter
  (CsI(Tl) Full-Absorption Type)
  - Energy Range: 15 MeV – 8 GeV
  - Energy Resolution: Better than 3% @ 1 GeV
  - Angular Resolution: 4.16 mrad @ 1 GeV

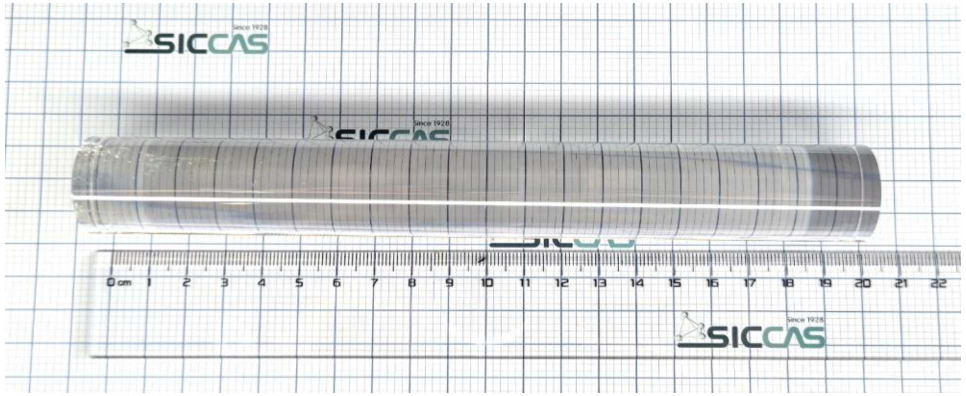


Selection of Crystal Calorimeters for High-Luminosity Experiments

Crystal	CsI:Tl	CsI	BaF_2	BGO	BSO	LYSO:Ce	PWO/PWO:Y
Density (g/cm^3)	4.51	4.51	4.89	7.13	6.8	7.40	8.3
Melting Point (ºC)	621	621	1280	1050	1030	2050	1123
Radiation Length (cm)	1.86	1.86	2.03	1.12	1.15	1.14	0.89
Molière Radius (cm)	3.57	3.57	3.10	2.23	2.33	2.07	2.00
Interaction Length (cm)	39.3	39.3	30.7	22.8	23.4	20.9	20.7
Refractive Index	1.79	1.95	1.50	2.15	2.68	1.82	2.20
Hygroscopicity	Slight	Slight	No	No	No	No	No
Emission Peak (nm)	550	310	300, 220	480	470	402	425, 420
Decay Time (ns)	1220	30, 6	650, 0.9	300	100	40	30,10
Light Yield (ph/MeV)	63,000	1,400 420	13,680 1,560	8,000	2000	32,000	114 40
Temperature Coefficient (%/ºC)	0.4	-1.4	-1.9, 0.1	-0.9	/	-0.2	-2.5
Applications in High-Energy Physics Experiments	BaBar BELLE BES III	KTeV, Mu2e, BELLE	TAPS Mu2e-II	L3,EGG, EIC, CEPC,FCC-ee	EIC,CEPC, FCC-ee	COMET, CMS, PIONEER	CMS, ALICE, PANDA, EIC, FCC-ee

BSO properties





Developed by SICCAS, about 20cm length

Decay constant

- $\tau_1 = 2.4ns\ \ (6\%)$
- $\tau_2 = 26ns\ \ (12\%)$
- $\tau_3 = 99ns\ \ (82\%)$

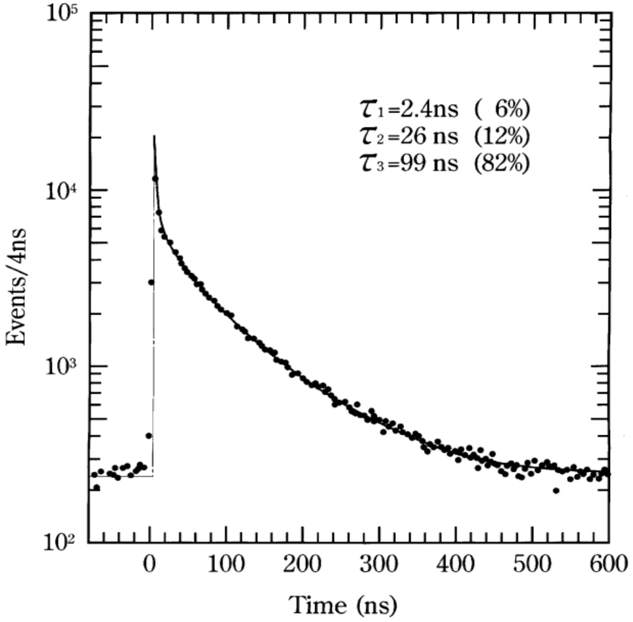


Fig. 8. Luminescence decay time spectrum of BSO.

Luminescence spectrum

- ~ 470nm

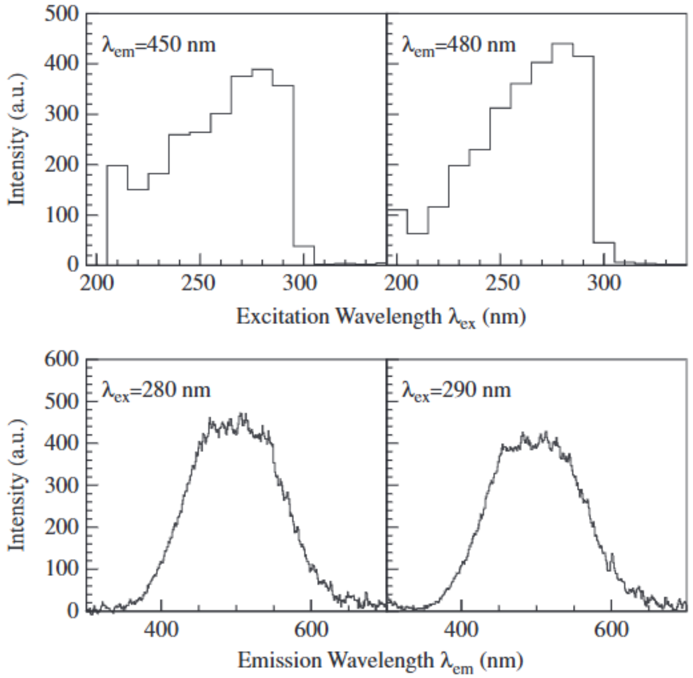


Fig : Each of the upper panels shows an excitation spectrum at an emission wavelength of 450 nm (left) and 480 nm (right), respectively. The lower panels show emission spectra at an excitation wavelength of 280 nm (left)and 290 nm (right).

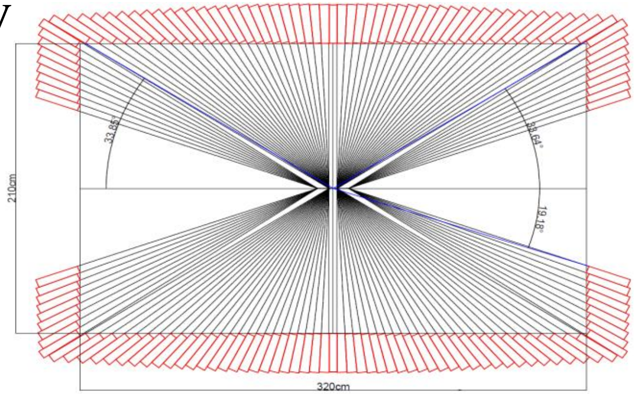
Comparison between BSO and pCsI

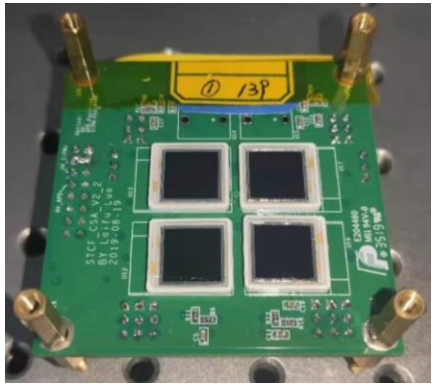
Crystal	CsI	BSO
Density (g/cm^3)	4.51	6.8
Melting Point (ºC)	621	1030
Radiation Length (cm)	1.86	1.15
Molière Radius (cm)	3.57	2.33
Interaction Length (cm)	39.3	23.4
Refractive Index	1.95	2.68
Hygroscopicity	Slight	No
Emission Peak (nm)	310	470
Decay Time (ns)	30, 6	100
Light Yield (ph/MeV)	1,400 420	2000
Temperature Coefficient (%/ºC)	-1.4	/
Applications in High-Energy Physics Experiments	KTeV, Mu2e, BELLE	EIC,CEPC, FCC-ee

1. Emission Peak
   - BSO : ~ 470nm (visible)
   - pCsI : ~ 310nm (ultraviolet)
2. Radiation Length and Molière Radius
   - BSO < pCsI , can decrease the crystal size, further improve position resolution
3. Cost
   - Raw materials : Bi_2O_3 and SiO_2 is cheap
4. Mechanical properties
   - Vickers microhardness of BSO (approximately 7.5 GPa) and its fracture toughness are superior to those of pCsI,

EMC existing design

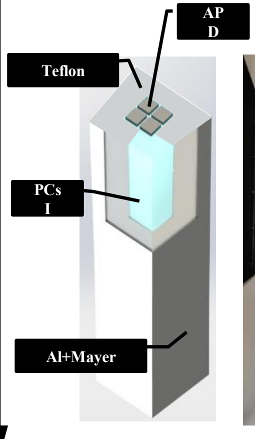
Compact Geometry
- Non-IP oriented design
- Unit size
  - $15X_0$ length
  - ~1 R_M radius





High Q.E. APD & Fast CSA Electronics
- Hamamatsu S8664 APD x4
- Shaping time = 100 ns
- parallel JFET as input stage

Fast and Radiation Hard Crystal (pCsI)
- 30 ns decay time
- Cost-effective
- >10 krad tolerance

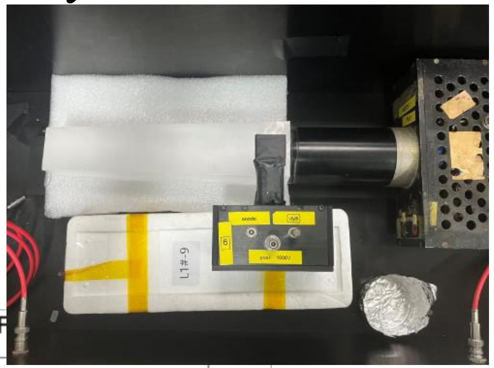


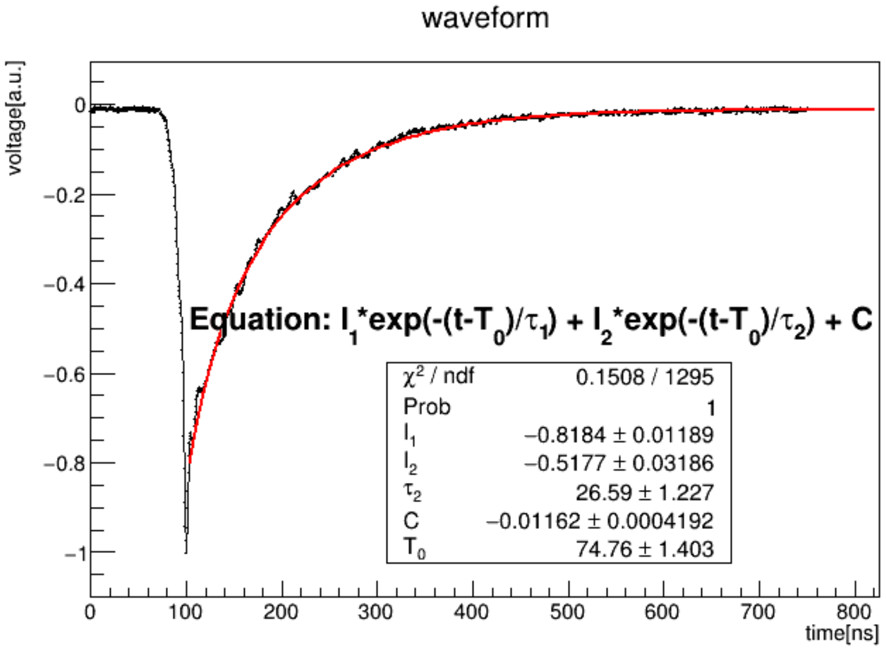
Unit Cosmic Ray Test
- High reflectance Teflon
- L.Y. = 155 p.e./MeV
- Equivalent Noise Energy = 1.2 MeV

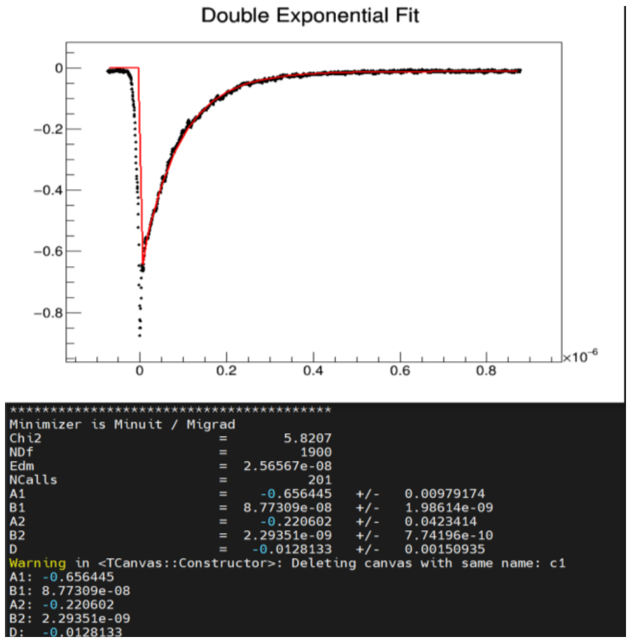
BSO Luminous Component

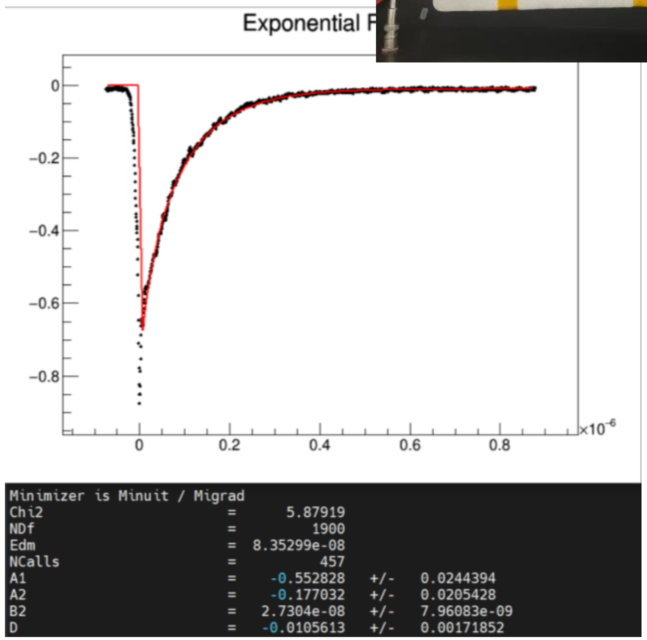
- Limited by the number of waveform samples and resolution of PMT, cannot simultaneously fit three luminous components

- Next attempt : Single-photon method



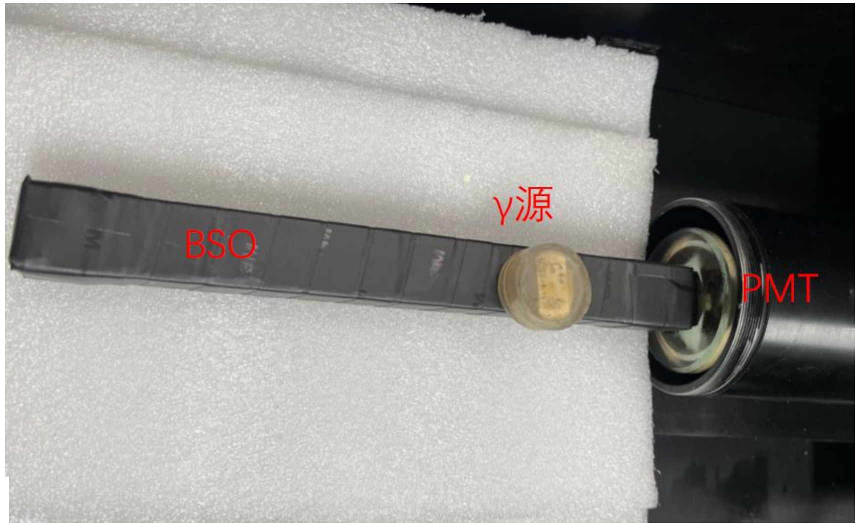


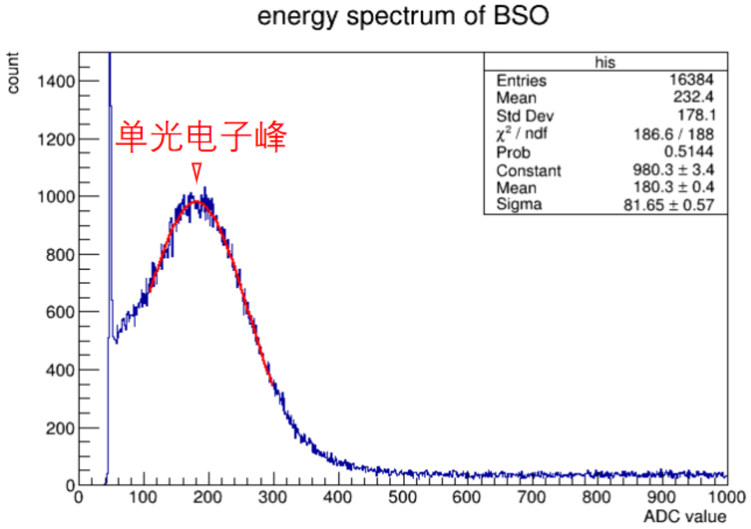




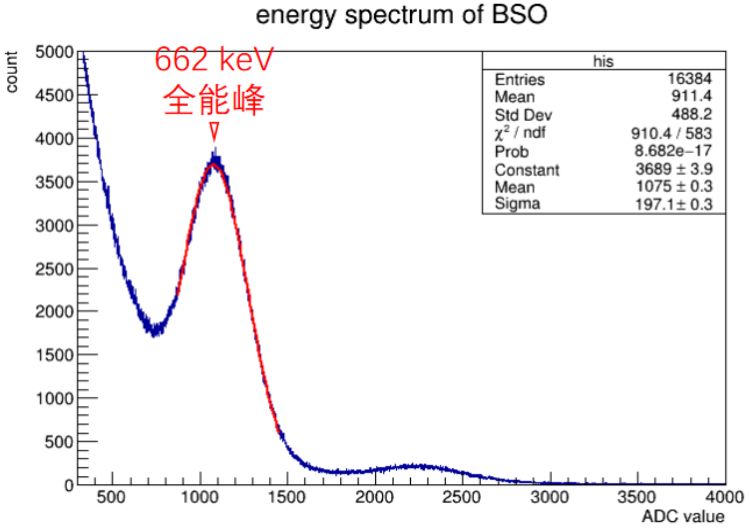
BSO Light Output

- Crystal-coupled PMT readout, using a multichannel analyzer to test the energy spectrum of γ radiation sources
- Calculated light output of the BSO crystal is approximately 90 p.e./MeV





放大倍数×500的单光电子峰



放大倍数×50的^{137}Cs放射源能谱

BSO + PMT → Charge sensitive amplifier → Multi-channel analyzer

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Summary and Prospects

- ✓ Introduce the fundamental principles and selection strategies of EMC
- ✓ Demonstrate the unique properties of BSO
- ✓ A simple measurement was conducted on the physical properties of BSO.
- ■ Next step of research :
  - ➢ Software :
    - ☐ Geometric construction based on OSCAR
    - ☐ BSO simulation using Geant4
    - ☐ EMC simulation based on OSCAR
  - ➢ Hardware :
    - ☐ Basic properties of BSO (e.g. light output)
    - ☐ Detection system building

Research Plan

Finished ： Preliminary measurements of luminescence decay time and light output

Software:

- 2025.10-2025.11 Complete the geometric construction of BSO under OSCAR
- 2025.11-2026.04 Simulate energy deposition in a single or a few crystals, analyzing energy and position resolution by using Geant4
- 2026.04-2026.09 Simulate a large number of electron/positron collision events under OSCAR to test the performance of BSO.

Hardware:

- 2025.10-2025.12 Preliminary Measurement of BSO Properties
- 2025.12-2026.06 Construct the detection system and measure BSO's physical properties
- 2026.06-2026.09 Write paper about BSO properties test, prepare articles for publication

2026.09-2027.03 Write the graduation thesis and prepare for thesis oral defense

Thank you!

Back up