# Crystal calorimeter

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# Introduction

## The main tasks of the calorimeters

detection of gamma-quanta and other neutral particles with high efficiency
Photon and electron energy measurements
photon coordinates determination
electron/hadron separation
neutral trigger and total energy trigger signal generation

**Short radiation length (high Z and density)**

**High output signal**

**High collection efficiency for the scintillation light or ionization**

**Radiation tolerance**

**Consistency with the existing photosensors**

**Availability of a large volume of material**

# Crystal calorimeters for medium energy (20 MeV~10 GeV)

**CLEO, Belle, BaBar, BES III**

**Common features**:

Acceptance close to 4π.

Usage of alkali-halide crystals with highest light output - CsI, NaI.

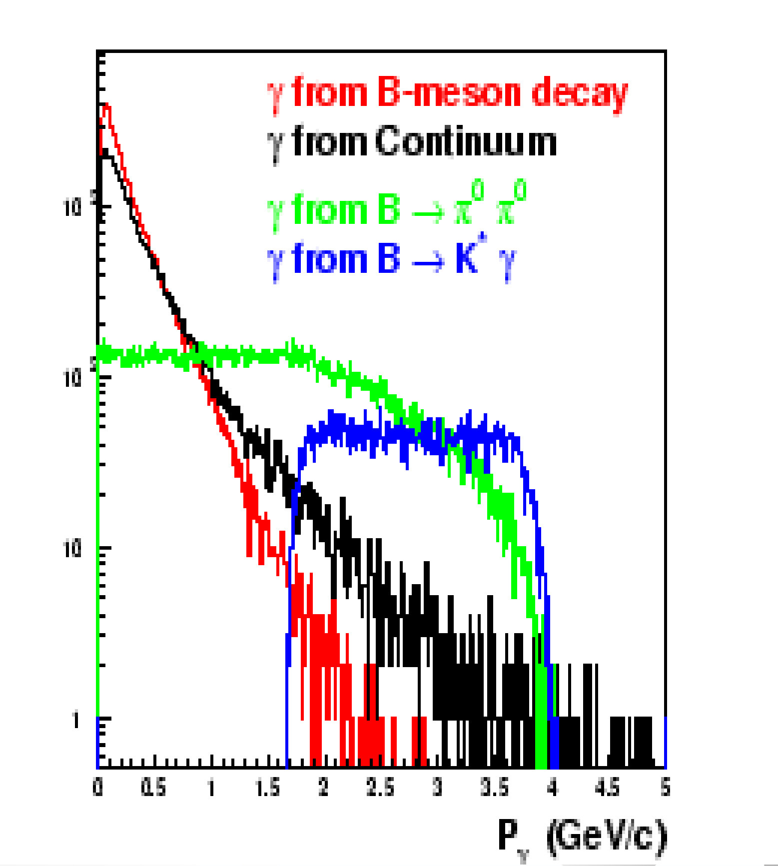
The calorimeter thickness is 15-17 $X_0$.

Transverse crystal size is 1-1.5 $R_M$.

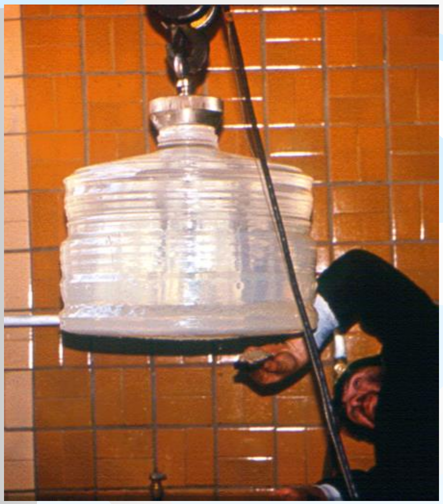
The energy resolution is about 2% at 1 GeV. This dominated by the rear leakage providing the main $E^{-1/4}$ dependence with the "technical" contribution from the material in front of the calorimeter and calibration

The position resolution is about

5 mm/$E^{1/2}$

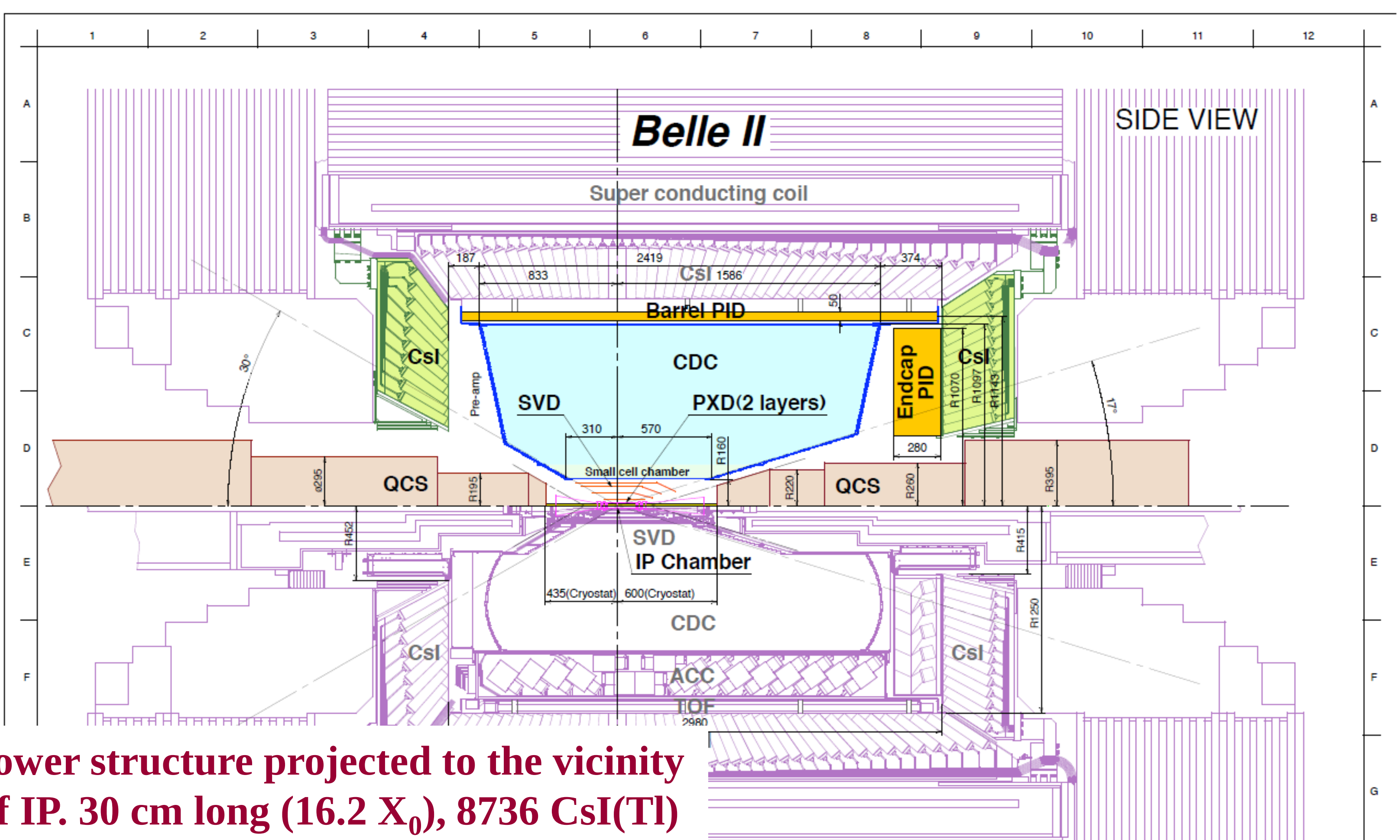


# Alkali-halide crystals for precision calorimetry



| Detector | Crystal type | Crystal number | Thickness $X_0$ | Total mass, ton | $\sigma_E/E$, % %@E(GeV) | Start year | Lab. |
|---|---|---|---|---|---|---|---|
| Crystal Ball | NaI(Tl) | 672 | 15,7 | 4,2 | 2,7 (1) | 1977 | BNL |
| CLEO-II | CsI(Tl) | 7800 | 16,2 | 30 | 2 (1) | 1990 | Cornel |
| CMD-2 | CsI(Na)-(Tl) | 892 | 8,1 | 2,4 | 9 (0,5) | 1992 | BINP |
| SND | NaI(Tl) | 1620 | 13,5 | 3,5 | 5 (0,5) | 1995 | BINP |
| KTeV | CsI, pure | 3256 | 27 | 9 | 1 (1) | 1995 | FNAL |
| KEK-E246 | CsI(Tl) | 768 | 13,5 | 3 | 2,8 (0,2) | 1996 | KEK |
| PSI - $\pi\beta$ | CsI, pure | 240 | 13 | 1 | 2,5(0,07) | 1996 | PSI |
| WASA | CsI(Na) | 1020 | 16,2 | 3,8 | 2 (1) | 1998 | Uppsala |
| KEDR | CsI(Na) | 1312 | 16,2 | 3,2 | 2 (1) | 1998 | BINP |
| Belle | CsI(Tl) | 8636 | 16,2 | 43 | 2 (1) | 1999 | KEK |
| BaBar | CsI(Tl) | 6580 | 16,2 | 30 | 2 (1) | 1999 | SLAC |
| BES III | CsI(Tl) | 6240 | 15.1 | 26 | 2.5(1) | 2008 | Beijing |
| CMD-3 | CsI(Na)-(Tl) | 1152 | 8.1 (15.3) | 2.7 | 4 (1) | 2010 | BINP |

# Belle II Detector (in comparison with Belle)




Tower structure projected to the vicinity of IP. 30 cm long (16.2 $X_0$), 8736 CsI(Tl) crystals (6624 in barrel).

12°< θ < 155° (lab frame)

Inner radius – 1250 mm

Total weight is ~43ton

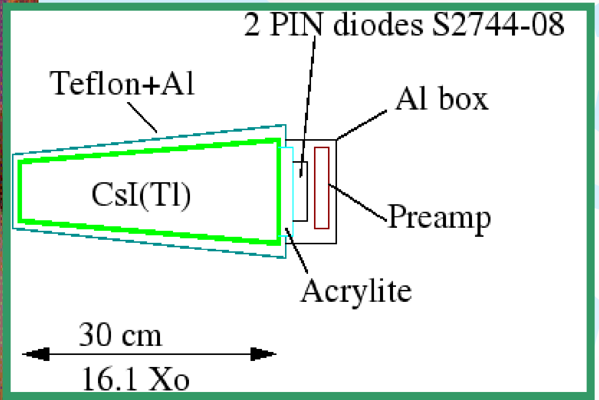
- SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
- CDC: small cell, long lever arm
- ACC+TOF → TOP+A-RICH
- ECL: waveform sampling (+pure CsI for end-caps)
- KLM: RPC → Scintillator +MPPC(end-caps)

# Belle ECL

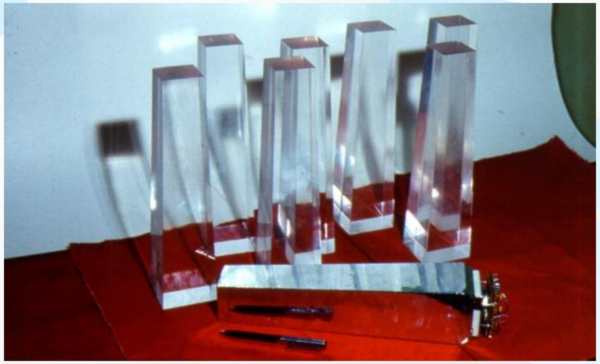
Calorimeter successfully worked for more than 10 years since 1999 to 2010

All 8736 channels are operable (even after great earthquake of 2011)

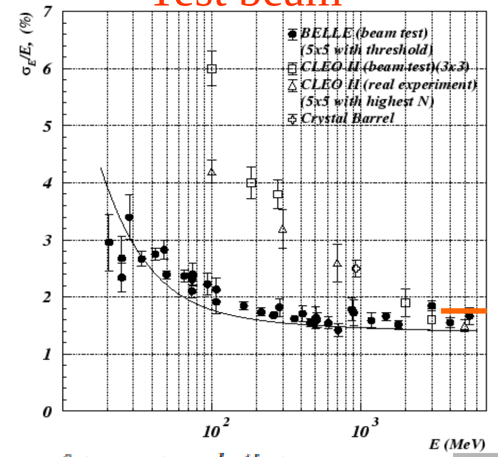
It demonstrated high resolution and good performance.

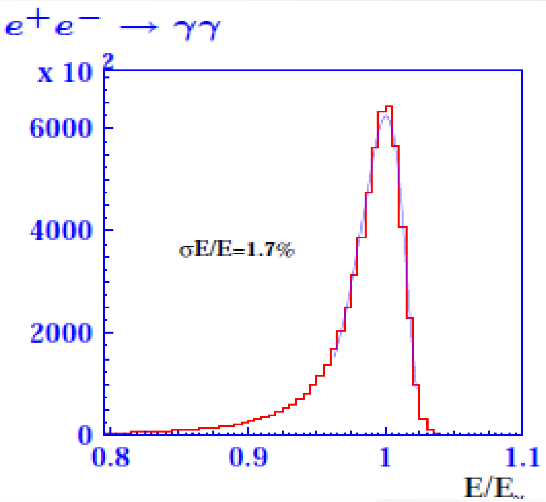


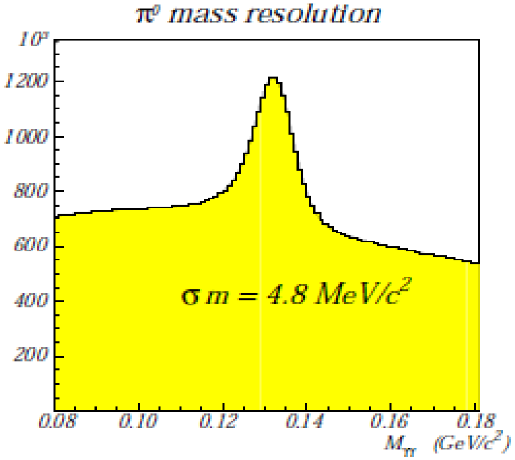

Light output - 5000 ph.el./MeV
electronics noise σ~200 keV



Test beam



# Energy resolution

**Physical reasons** – fluctuations of the leakage of the energy

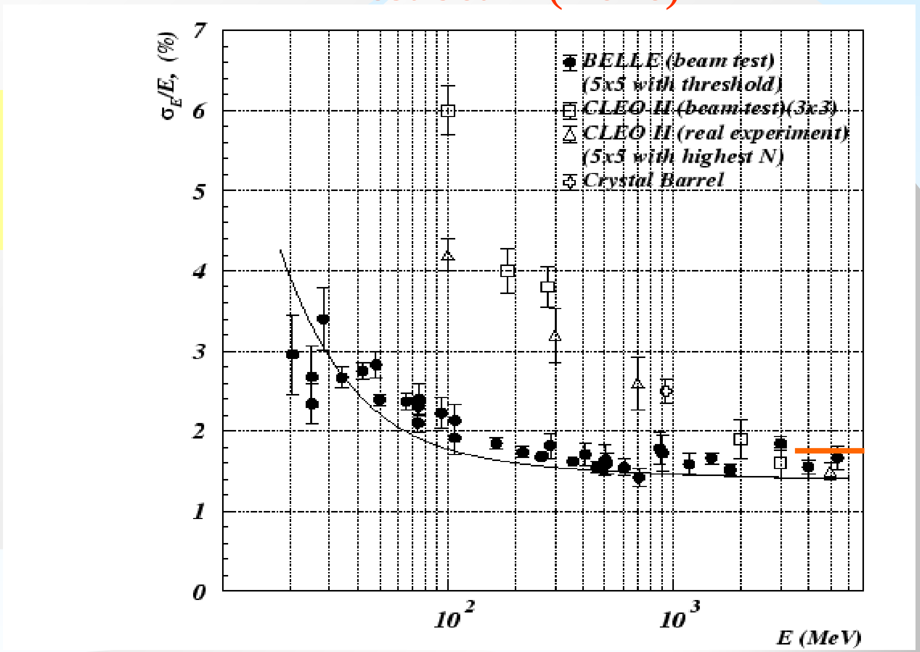
**Technical reasons** – nonuniform response, passive material, photoelectron statistics, electronics noise, etc.

**Energy resolution vs energy**

**is approximated as:**

$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt[4]{E}} \oplus \frac{\sigma_2}{\sqrt{E}} \oplus \frac{\sigma_3}{E} \oplus \sigma_0$$

Test beam (Belle)



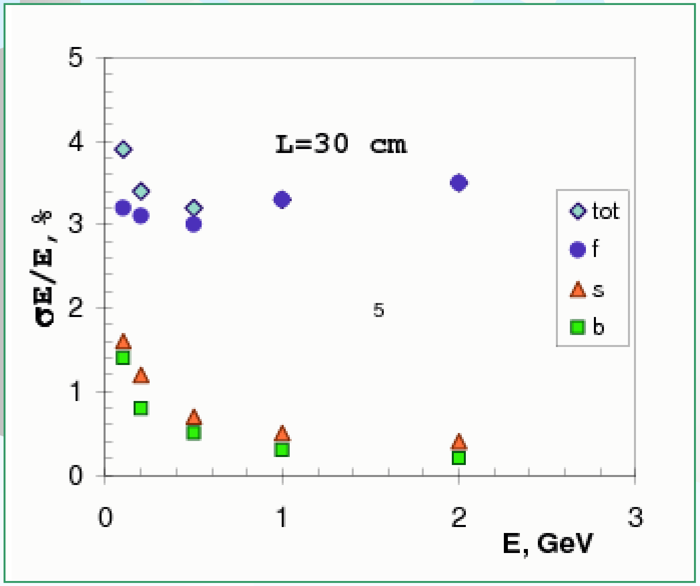

$\sigma_1$ - rear leakage

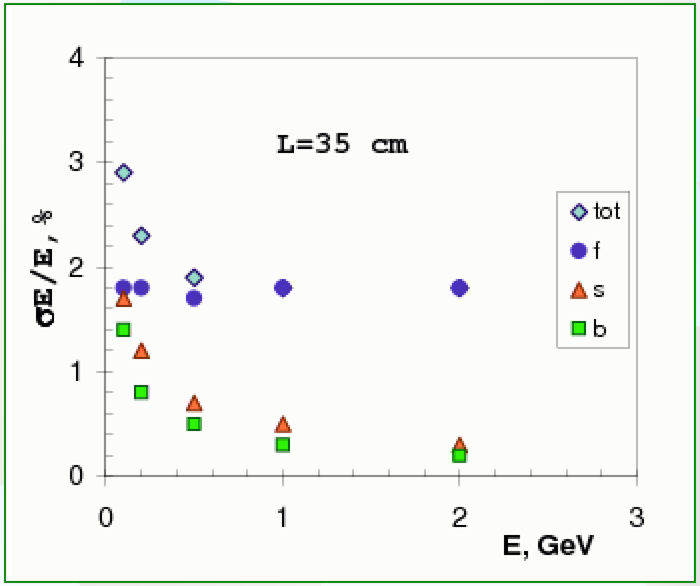
$\sigma_2$ - side leakage, back leakage photoelectron statistics

$\sigma_3$ - electronics noise, dark current noise pile-up noise

$\sigma_0$ - nonuniformity, calibration, rear leakage

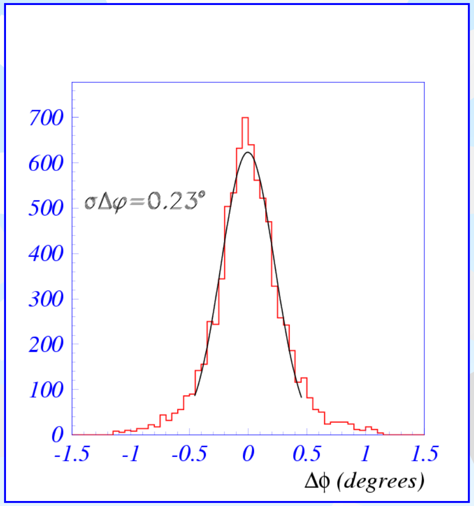
# What is optimal calorimeter thickness?



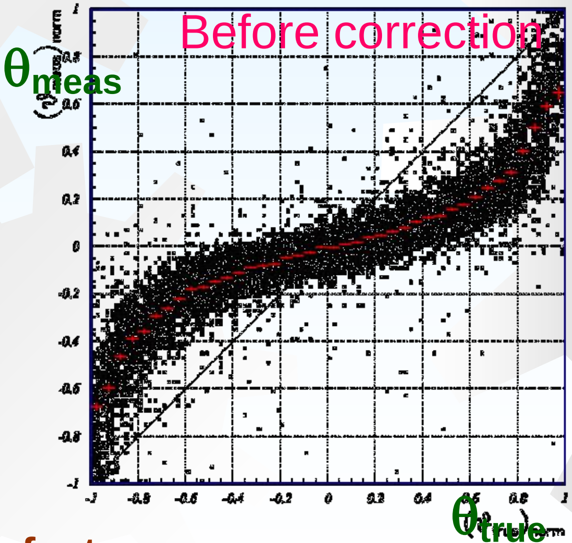



# Calorimeter angular resolution

Photon angles (or coordinates) in the crystal calorimeters are measured usually as corrected center of gravity of the energy deposition:



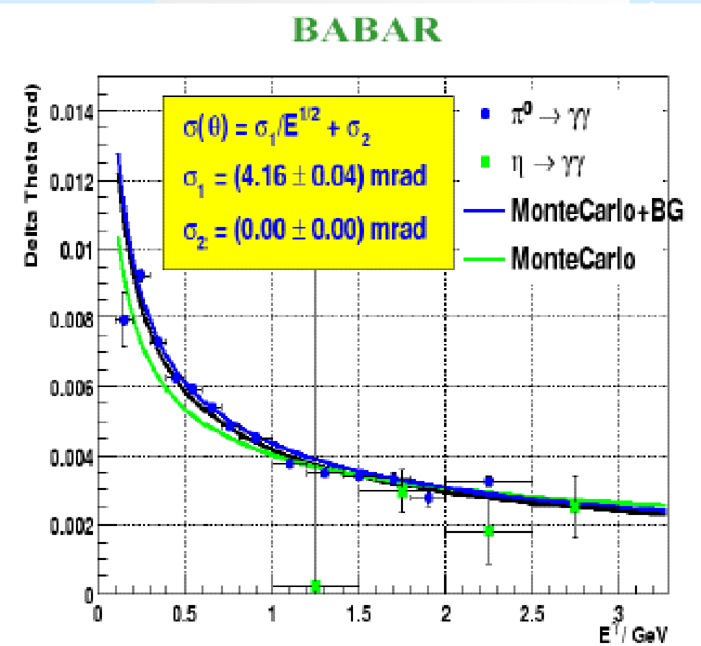

$$\theta_\gamma = \frac{\sum \theta_i E_i}{\sum E_i} F_\theta(\varphi, \theta, E) \qquad \varphi_\gamma = \frac{\sum \varphi_i E_i}{\sum E_i} F_\varphi(\varphi, \theta, E)$$

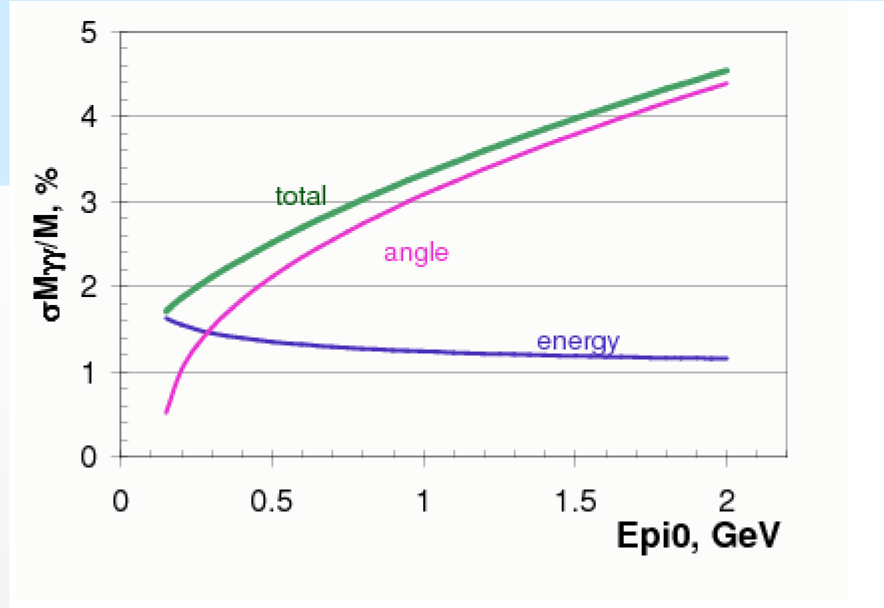



Correction functions (F) can be usually written as a function of one of the angles and energy.

# Angular resolution

**depends on the energy and the calorimeter granularity.**




**Principle limitation of the shower position resolution comes from the number of particles in the shower.**

$$\sigma_r \approx \frac{R_M}{\sqrt{N_{tot}}} = \frac{R_M}{\sqrt{E_\gamma / E_{cr}}}$$

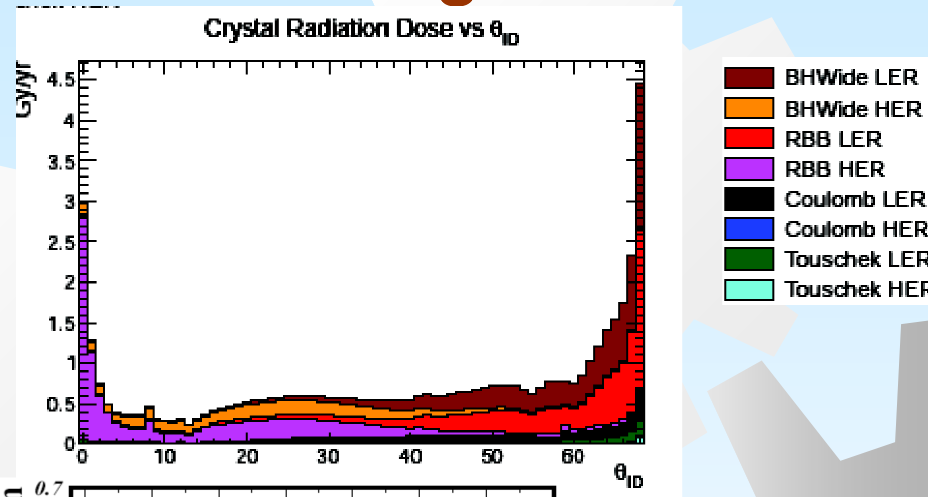
**where $E_c$ is critical energy.This gives for $E_\gamma$ = 1 GeV, $\sigma$ = 4 mm for** CsI

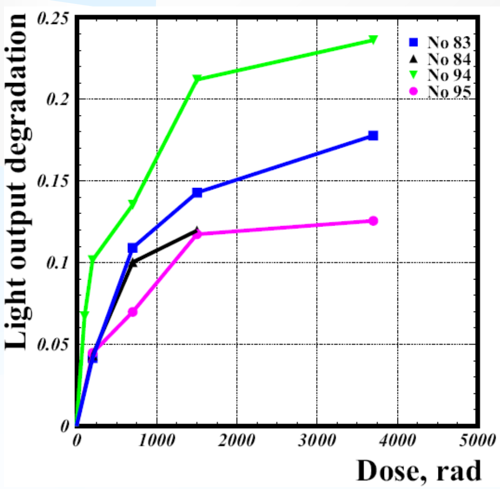
A possibility of the drastical improvement of the angular resolution will be considered in the V.Shebalin’s talk

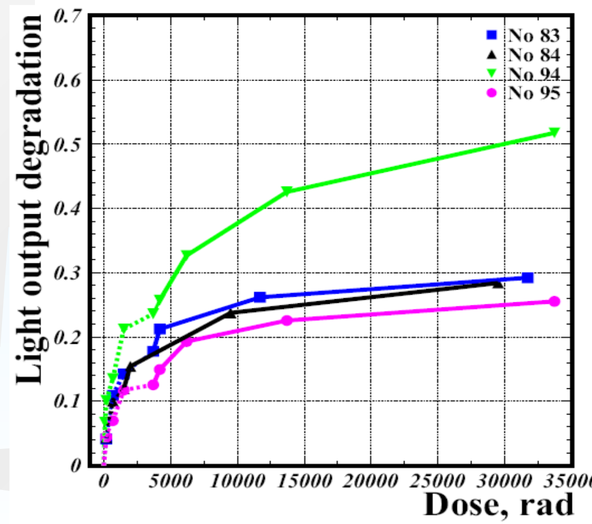
# Calorimeter performance in a view of the luminosity increase –radiation background.

Radiation damage of the crystals: at 1000 fb$^{-1}$ at Belle the absorbed dose reached of about 500 rad in the most irradiated crystals.

**In the most loaded part the light output degradation is about 10%**




D. Beylin *et al.*, Nucl. Instrum. Meth. A 541, 501 (2005),

I.Chakin et al., JINST 12, C06034 (2017)

**Basically – no problem.**

Increase of the PD dark current due to neutron background. By the end of the Belle experiments the PD dark current increased up to 200 nA for the most loaded area.

However, according to the simulstion

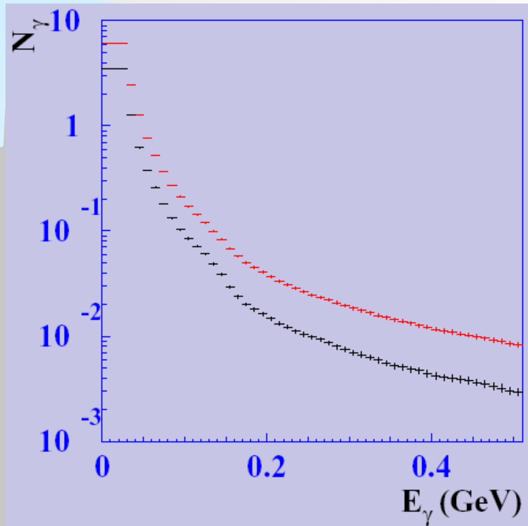
| | | 12th Campaign | 11th Campaign | Tolerance |
|---|---|---|---|---|
| Crystal Radiation Dose | Forward | 3.0 | 3.0 | |
| (Gy/yr) | Barrel | 0.8 | 0.5 | 10 |
| | Backward | 4.5 | 3.1 | |
| Crystal Neutron Flux | Forward | 23 | 24 | |
| ($x10^9 yr^{-1} cm^{-2}$) | Barrel | 5 | 4 | 1000 |
| | Backward | 14 | 12.5 | |
| Diode Radiation Dose | Forward | 0.4 | 0.7 | |
| (Gy/yr) | Barrel | <0.2 | <0.2 | 70 |
| | Backward | 0.8 | 0.64 | |
| Diode Neutron Flux | Forward | 23 | 24 | |
| ($x10^9 yr^{-1} cm^{-2}$) | Barrel | 5 | 4 | 100 |
| | Backward | 15 | 12.5 | |
| Pileup Noise (MeV) | Forward | 4.3 | 3.8 | |
| | Barrel | 3.1 | 2 | 0.8 for Belle |
| | Backward | 8.2 | 5.4 | |
| Reconstructed Cluster | | 3.44 | 2.57 | 6 for Belle |

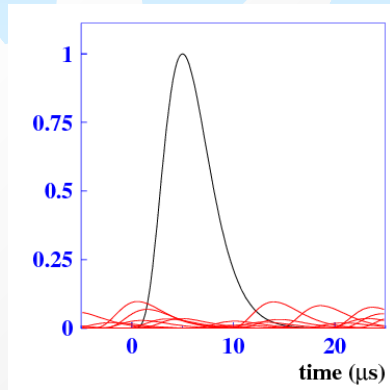
The dark current induced by the expected neutron flux will be still below 1 μA and corresponding noise contribution should be below 1 MeV, still not the most annoying problem.

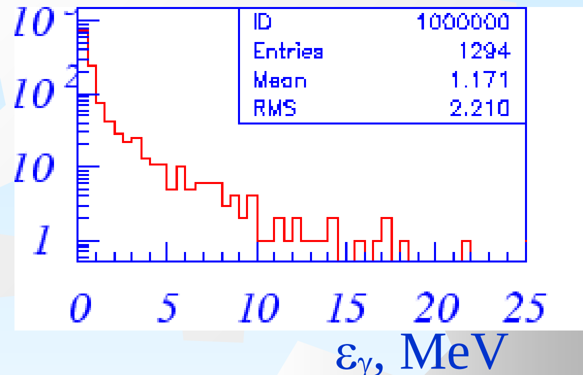
# Pile-up noise

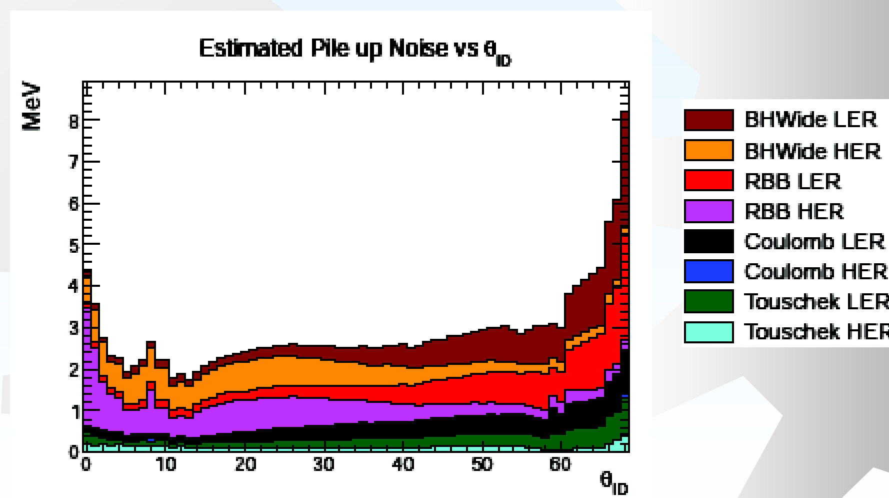
## Fake clusters

$$\sigma_{pile\text{-}up} = \overline{E_\gamma}\sqrt{f_{bkg}\cdot\tau_{eff}} \propto \sqrt{I\cdot P}$$



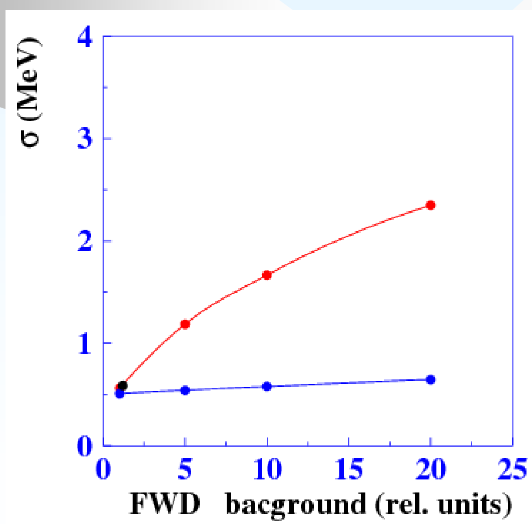

**(E>20 MeV) 6 fake clusters, 3 in barrel 3 in endcaps background**

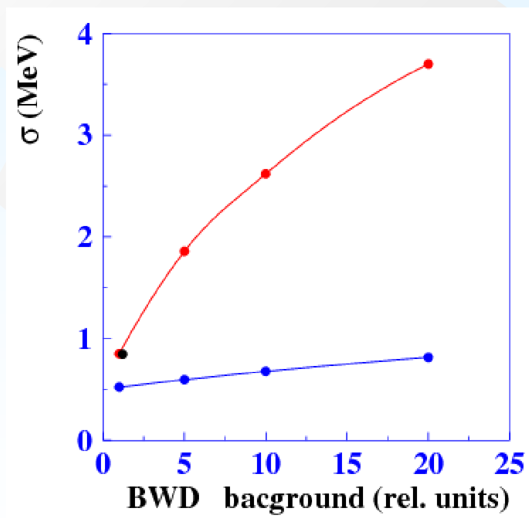
# In spite of the upgraded electronics performance of the end caps is still questionable

## Properties of pure CsI and CsI(Tl) scintillation crystals

| | ρ, g/cm$^3$ | $X_0$, cm | $\lambda_{em}$, nm | N($\lambda_{em}$, nm ) | $N_{ph}$/MeV | T, ns | dL/dT, %/° @20°C |
|---|---|---|---|---|---|---|---|
| Pure CsI | 4.51 | 1.85 | 305 | 2 | 2000-5000 | 20/1000 | - 1.3 |
| CsI(Tl) | 4.51 | 1.85 | 550 | 1.8 | 52000 | 1000 | 0.4 |

## Expected improvement with pCsI



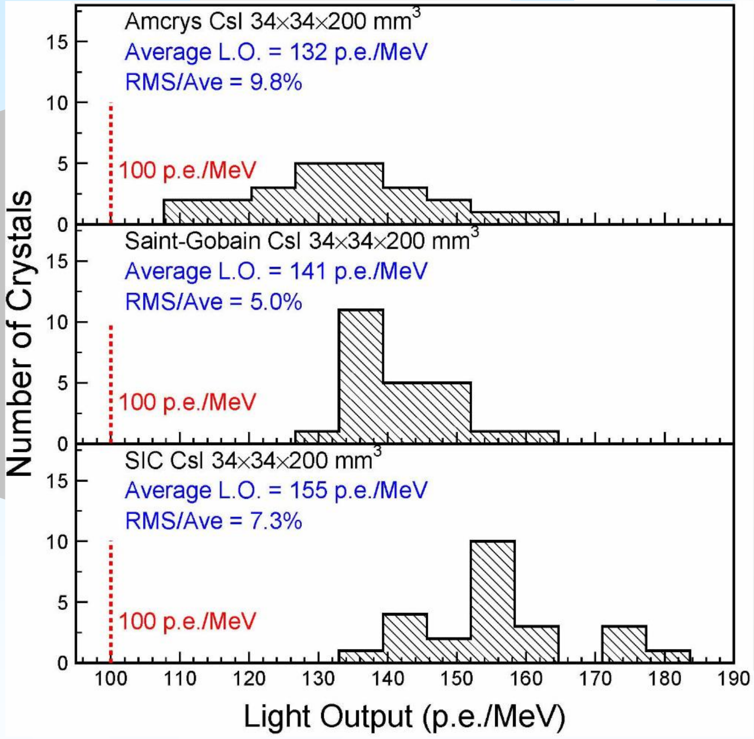



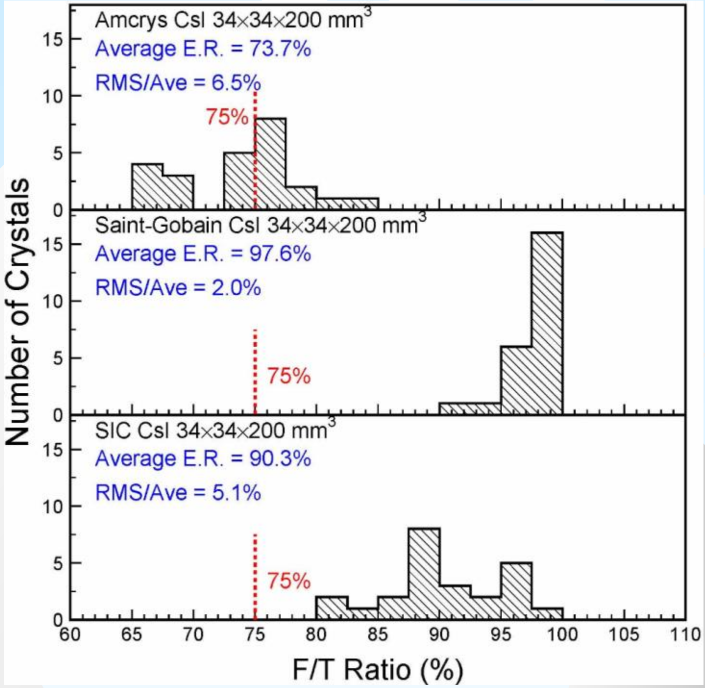

**Time information allows to suppress the fake clusters for endcaps by a factor of 7x30=200 by rejecting wrong time clusters due to shorter decay time of the pure CsI**

# Pure CsI for Mu2e Experiment

674 undoped CsI crystals of 20×3.4×3.4 $cm^3$

SiPM of 6x6 $mm^2$, UV sensitive

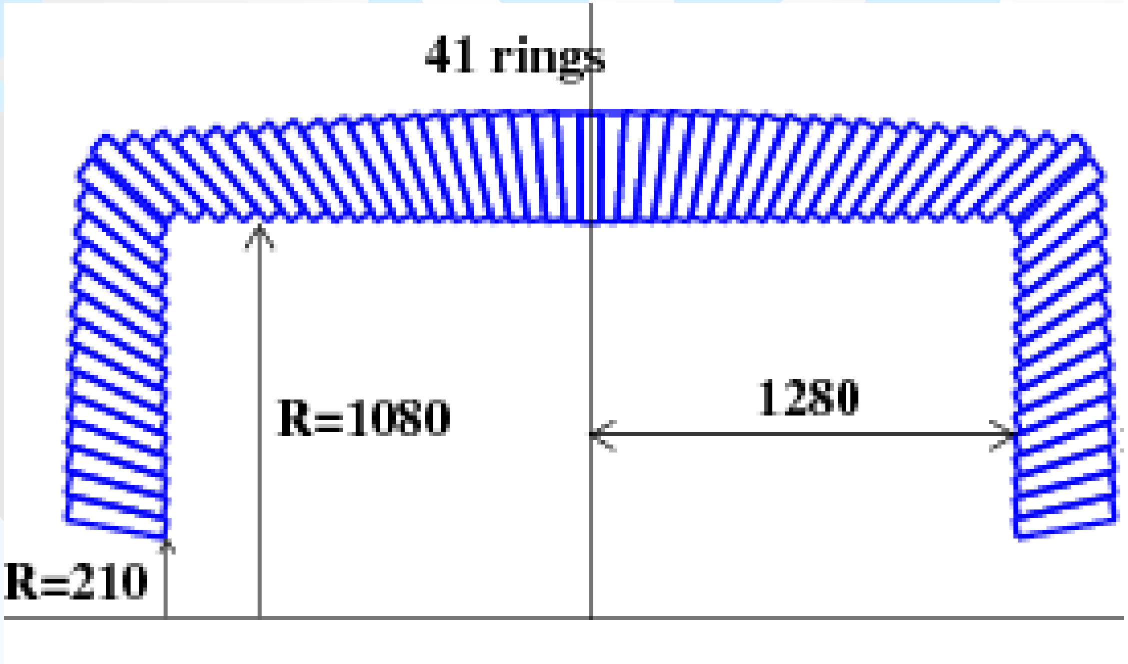


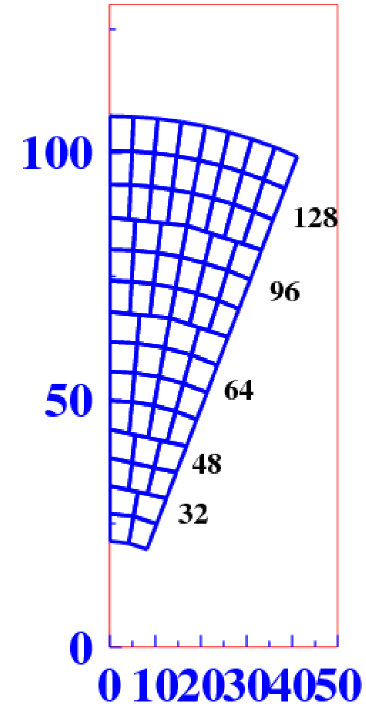





N. Atanov et al., IEEE TRANS. NUCL. SCI. VOL. 65 (2018)

# Calorimeter for the BINP C-Tau Factory detector




**Baseline is pure CsI calorimeter.**

**An option – pure CsI is in the end caps and CsI(Tl) – in the barrel. Background simulation is highly needed!**

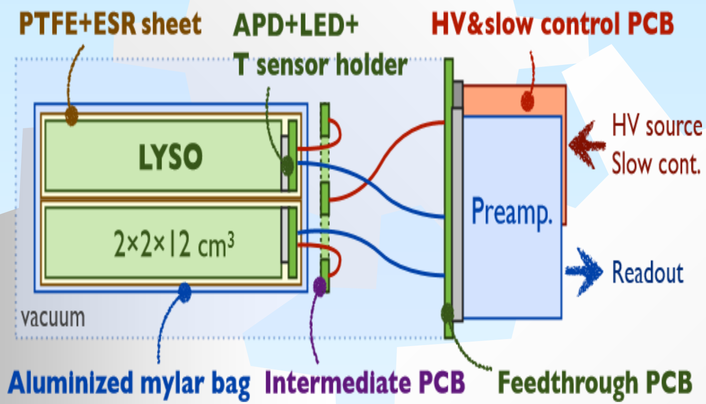
Will be discussed in the D.Epifanov talk

# Other scintillators

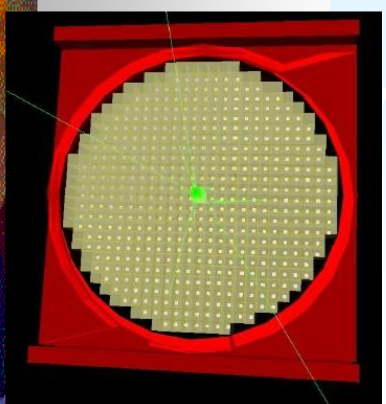
http://scintillator.lbl.gov/    Contains 564 entries

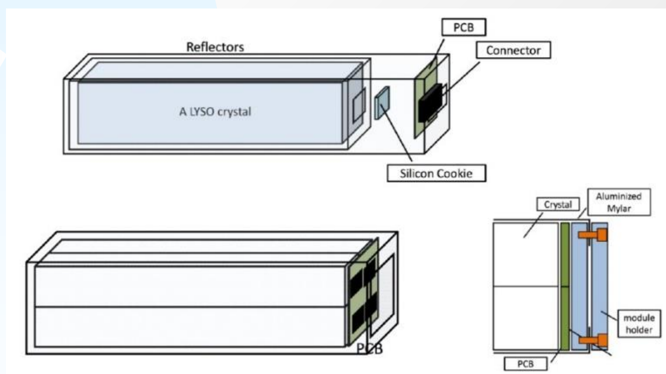
| | ρ, g/cm³ | $X_0$, cm | $\lambda_{em}$, nm | $n(\lambda_{em})$ | $N_{ph}$/MeV | τ, ns |
|---|---|---|---|---|---|---|
| CsI(Tl) | 4.51 | 1.85 | 550 | 1.8 | 52000 | 1000 |
| Pure CsI | 4.51 | 1.85 | 305 | 2 | 2000-5000 | 20/1000 |
| BGO ($Bi_4Ge_3O_{12}$) | 7.13 | 1.12 | 480 | 2.1 | 9000 | 300 |
| $LaBr_3$(Ce) | 5.1 | 1.95 | 380 | 1.9 | 63000 | 30 |
| LSO (Lu2SiO5:Ce) | 7.41 | 1.14 | 420 | 1.8 | 27000 | 40 |
| LYSO ((Lu,Y)2SiO5:Ce) | 7.1 | 1.20 | 400 | 1.8 | 33000 | 30 |
| LuAP $LuAlO_3$(Ce) | 8.34 | 1.08 | 365 | 1.9 | 20500 | 20 |
| GSO (Gd2SiO5:Ce) | 6.71 | 1.37 | 440 | | 8000 | 40 |
| GAGG (Gd3Al2Ga3O12(Ce)) | 6.63 | 1.59 | 520 | | 46000 | 90 |

# COMET electron calorimeter

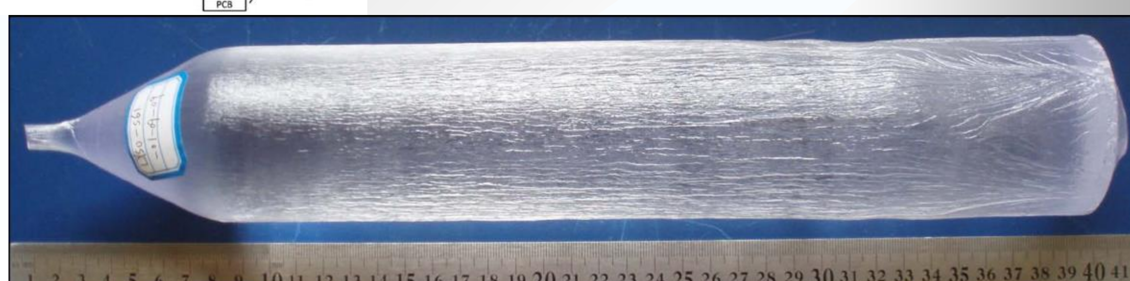



About 2000 LYSO crystals (~500 ECAL modules) are needed to cover the detector region of 50cm radius.





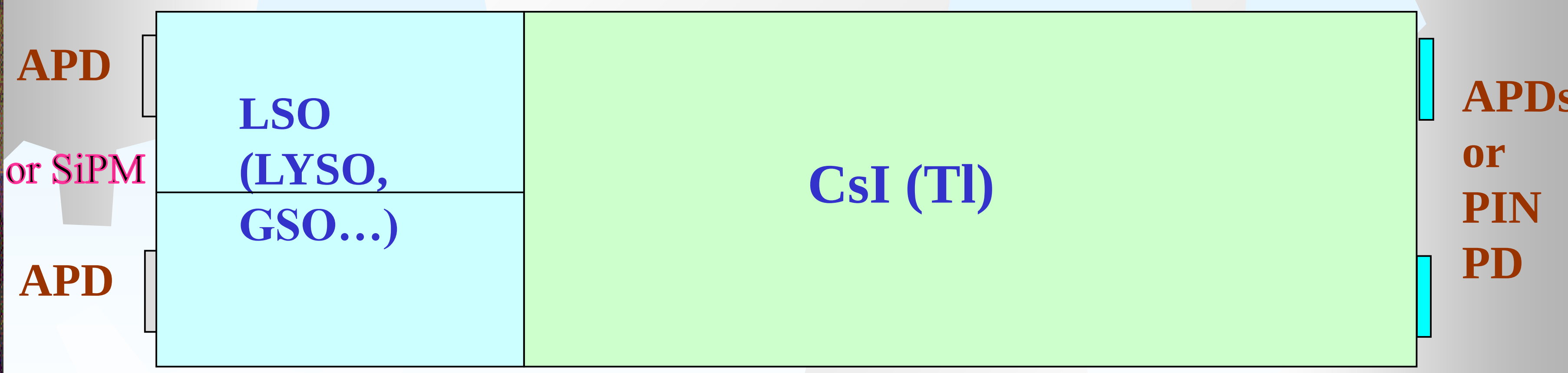

Schematic layout of the electron calorimeter system; (right top) single LYSO crystal module structure + 1 APD on PCB, (right bottom) ECAL module structure with 2 × 2 LYSO crystals.



# Combined calorimeter element?

5cm LSO suppress the background rate by factor about 15

The light readout from LSO crystals can be made by two 1 × 1 cm$^2$ APDs or(and) SiPM. The option is needed to study.



# Conclusion

There are nine and sixty ways of
constructing tribal lays,
And every single one of them is right.
*Rudyard Kipling. "In the Neolithic Age"*

**However, we have to find an optimal material and design of the calorimeter to build it in a reasonable time for a reasonable cost and still with proper quality.**

**To do that we need new ideas and a joint active R&D work of many interested physicists**