Crystal ECAL for CEPC

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Two ECAL designs in CDR

A priority physics requirement

Jet Energy Resolution (JER)

Both are Particle Flow Oriented

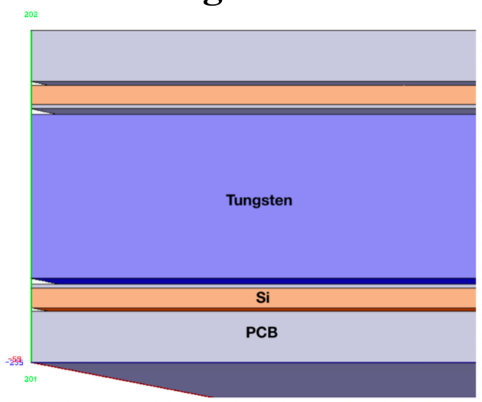
extremely high granularity in three dimensions

promising to achieve unprecedented

JER ~ 3% - 4% @ 100GeV ~ 30%/√E

W/Z/Higgs Boson Mass Resolution (BMR) ~ 3.8%

Silicon-Tungsten Sandwich ECAL



Basic Unit

2 symmetric sensitive **silicon layer**s
- glued on a PCB
- equipped with readout ASICs

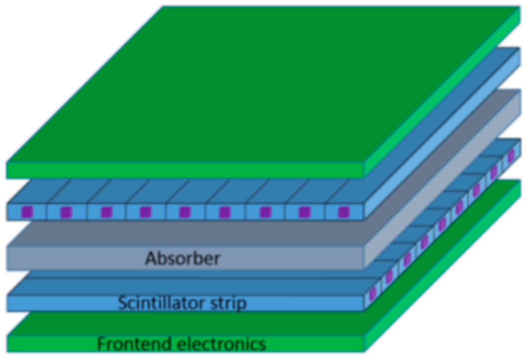
1 **tungsten plate**

Scintillator-Tungsten Sandwich ECAL

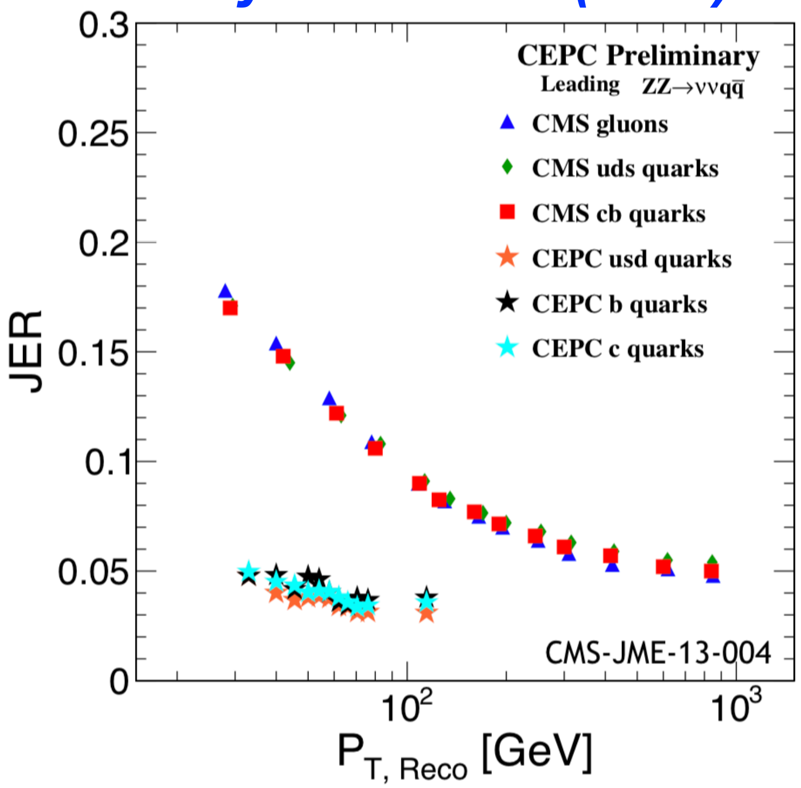
Basic Unit

2 layers of **plastic scintillator strip**
- 2mm thick, 5×45mm² large
- perpendicular to adjacent layer
- attached to SiPM

1 **tungsten plate**



by Peizhu Lai (NCU)



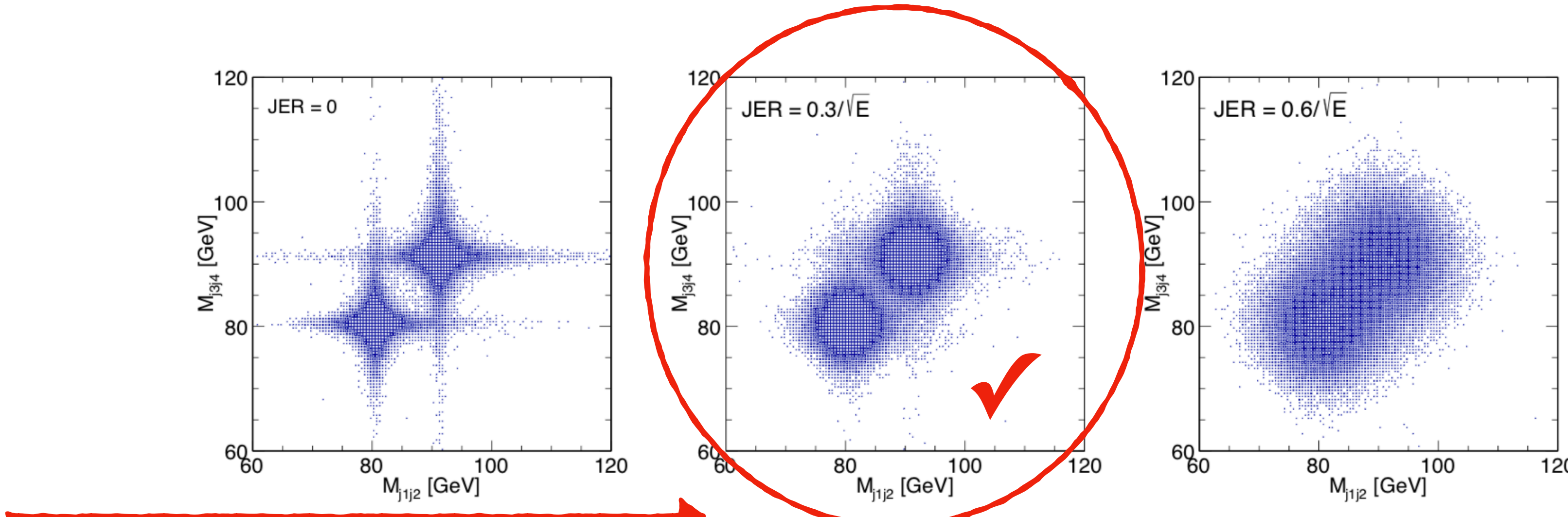


Figure 5.1: Separation of W and Z bosons in their hadronic decays with different jet energy resolutions: (a) $0/\sqrt{E}$, (b) $30\%/\sqrt{E}$, and (c) $60\%/\sqrt{E}$. A jet energy resolution of $30\%/\sqrt{E}$ is required to separate the hadronic decays of W and Z bosons.

Two ECAL designs in CDR

However, for these two ECALs:

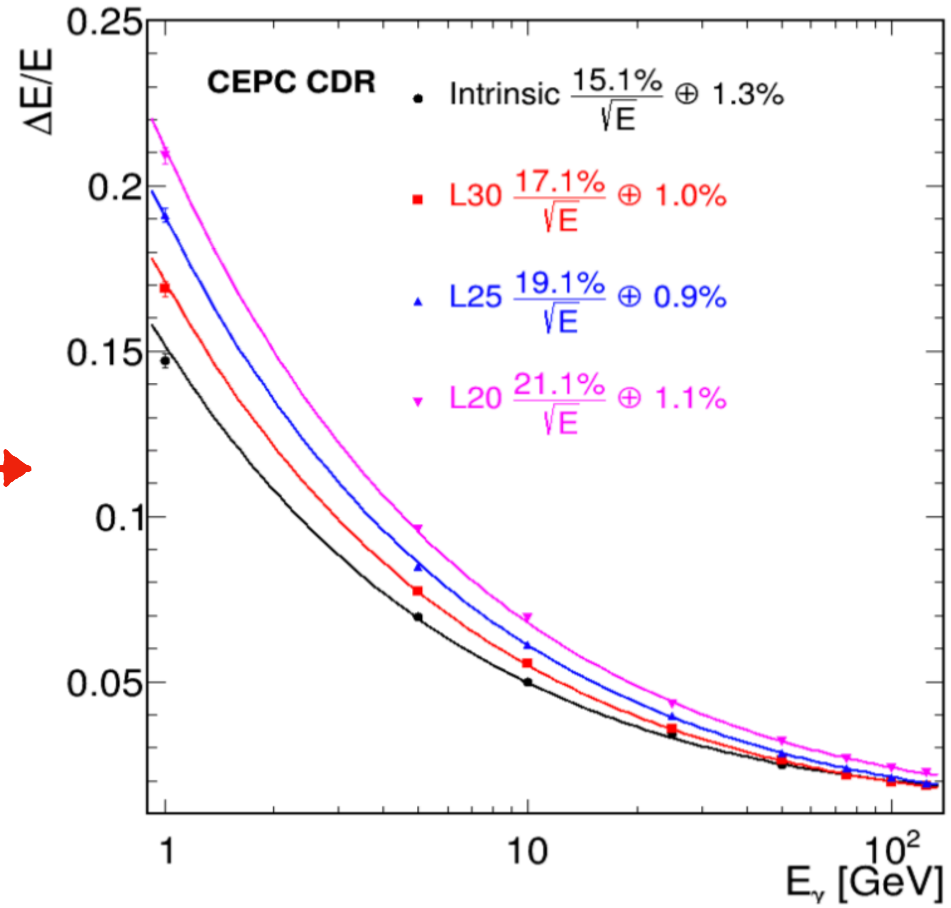
Challenges:

- Extremely high granularity → massive numbers of readout channels
  ~ 25M(ECAL) + 65M(DHCAL)
- Power consumption *~ 146kW(ECAL) + 110kW(DHCAL)*
- Cooling
- Expensive cost of Si and massive readouts

Estimated by Prof. Jianbei Liu Report on CaloWS in March, 2019

Limitation:

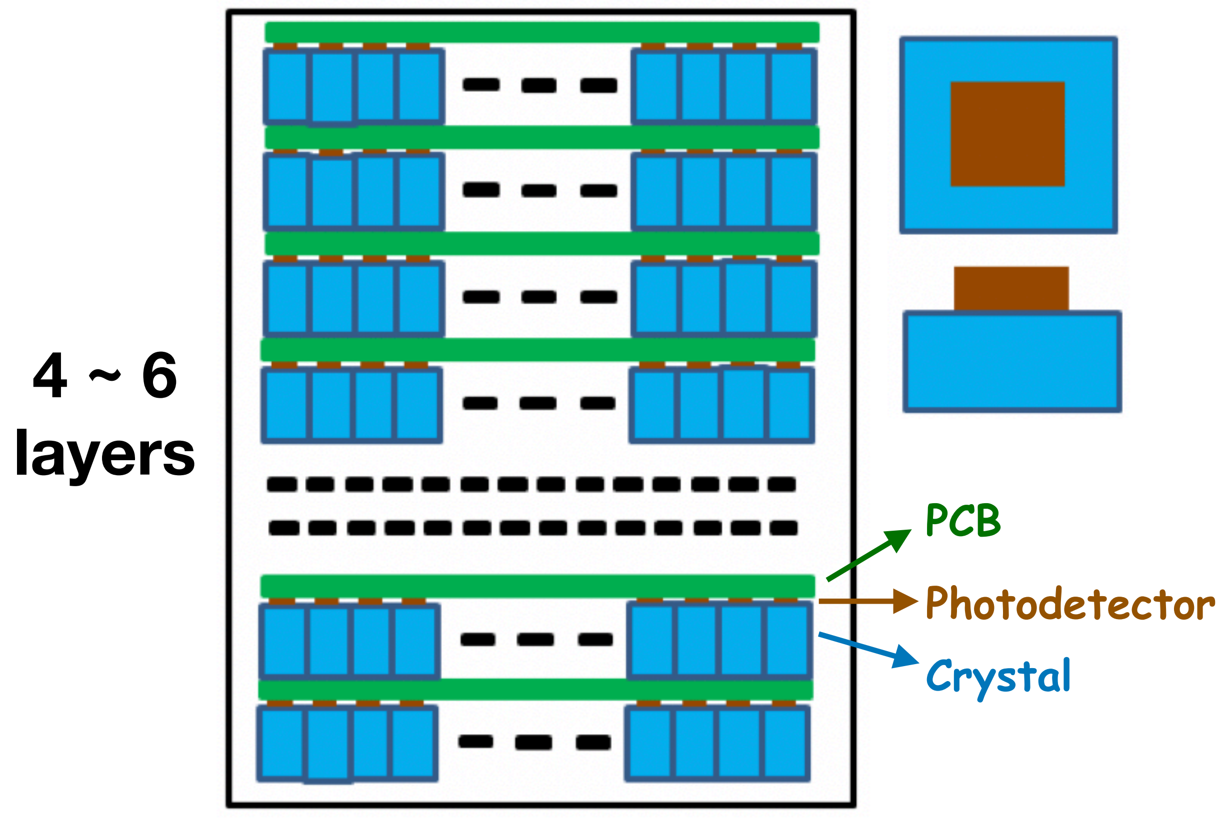
- Sampling ECAL, limited EM resolution
  $\sim 17.1\%/\sqrt{E} \oplus 1.0\%$



Ideas on Homogeneous Crystal ECAL

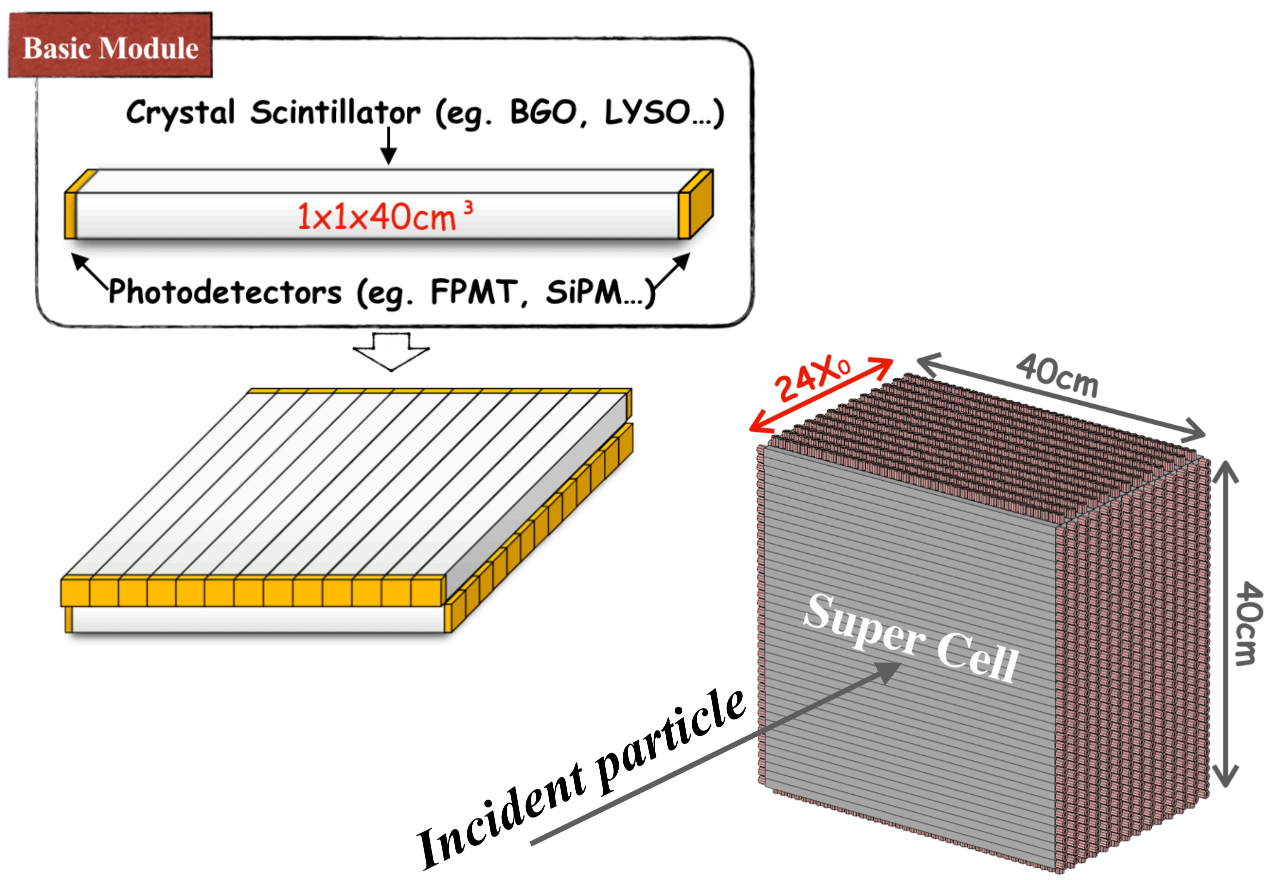
2 basic geometries

Geometry 1:



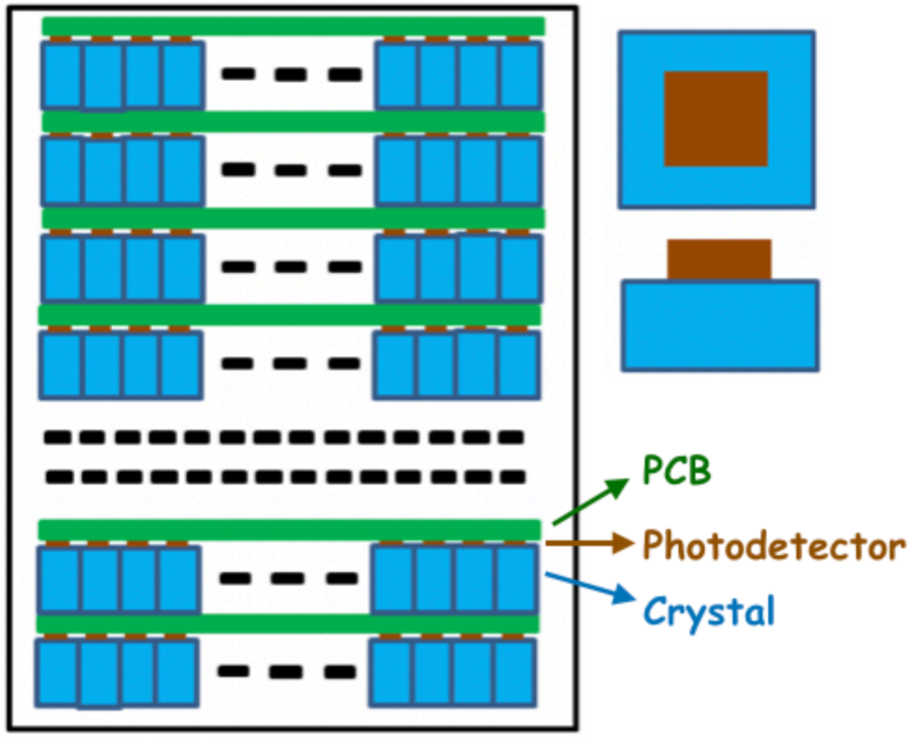
- *Similar to baseline ECAL;*
- *Finely segmented transverse, 1cm×1cm cell;*
- *Limited number of longitudinal layer.*

Geometry 2:



- *Finely segmented longitudinal, 1cm/layer;*
- *Transverse cell, long crystal bar, 1cm×40cm;*
- *Cross structure*
  - *crystal bar perpendicular to adjacent layer;*
- *Time measurement for hit positions*
  - *compensating for transverse granularity.*

Geometry 1



Basic cell:

1×1×(5~7)cm³ crystal bar, single readout

Structure:

4~6 longitudinal layers

Highlight:

#channels, 6~7 times less

reconstruction is compatible with current PFA

Key question:

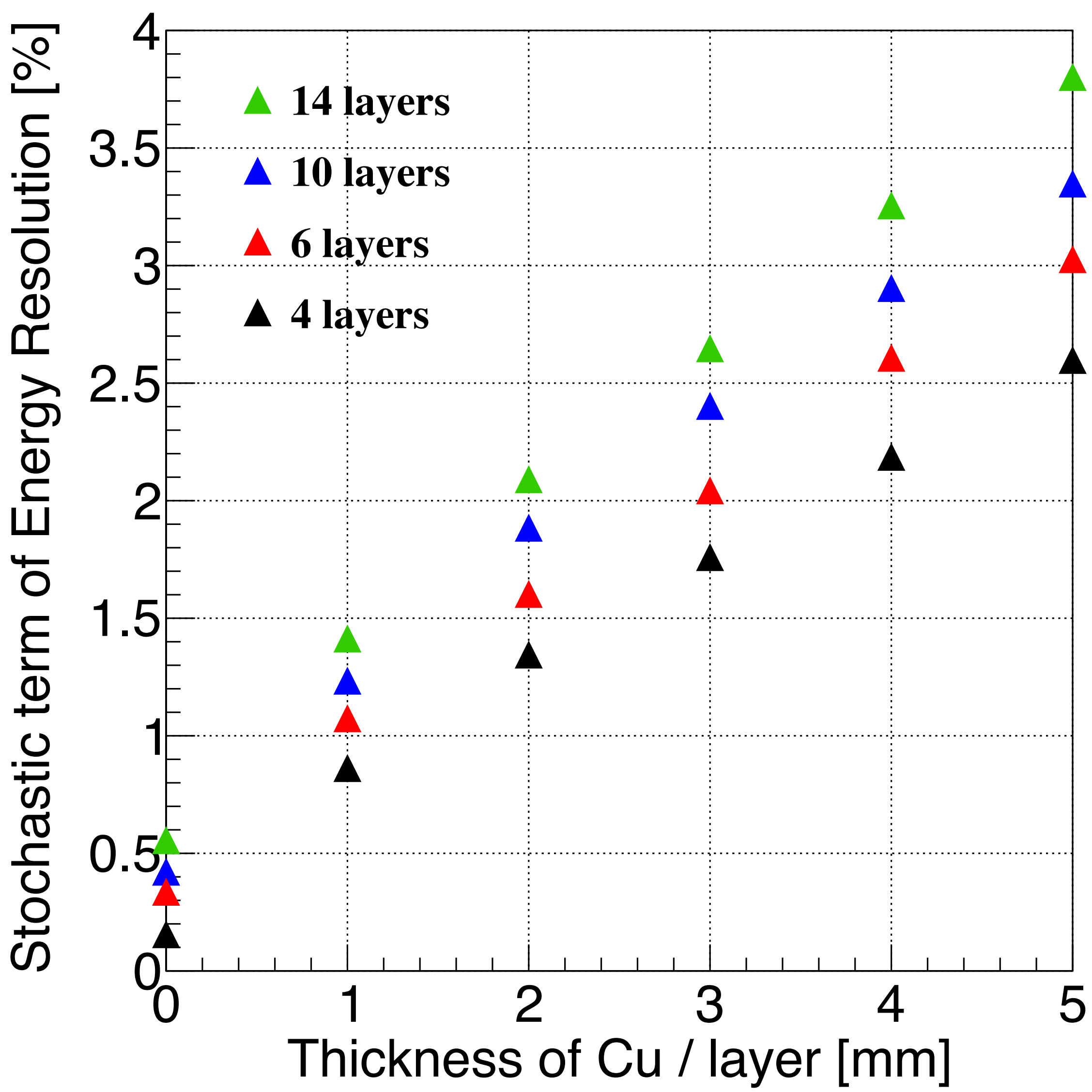
limited longitudinal granularity

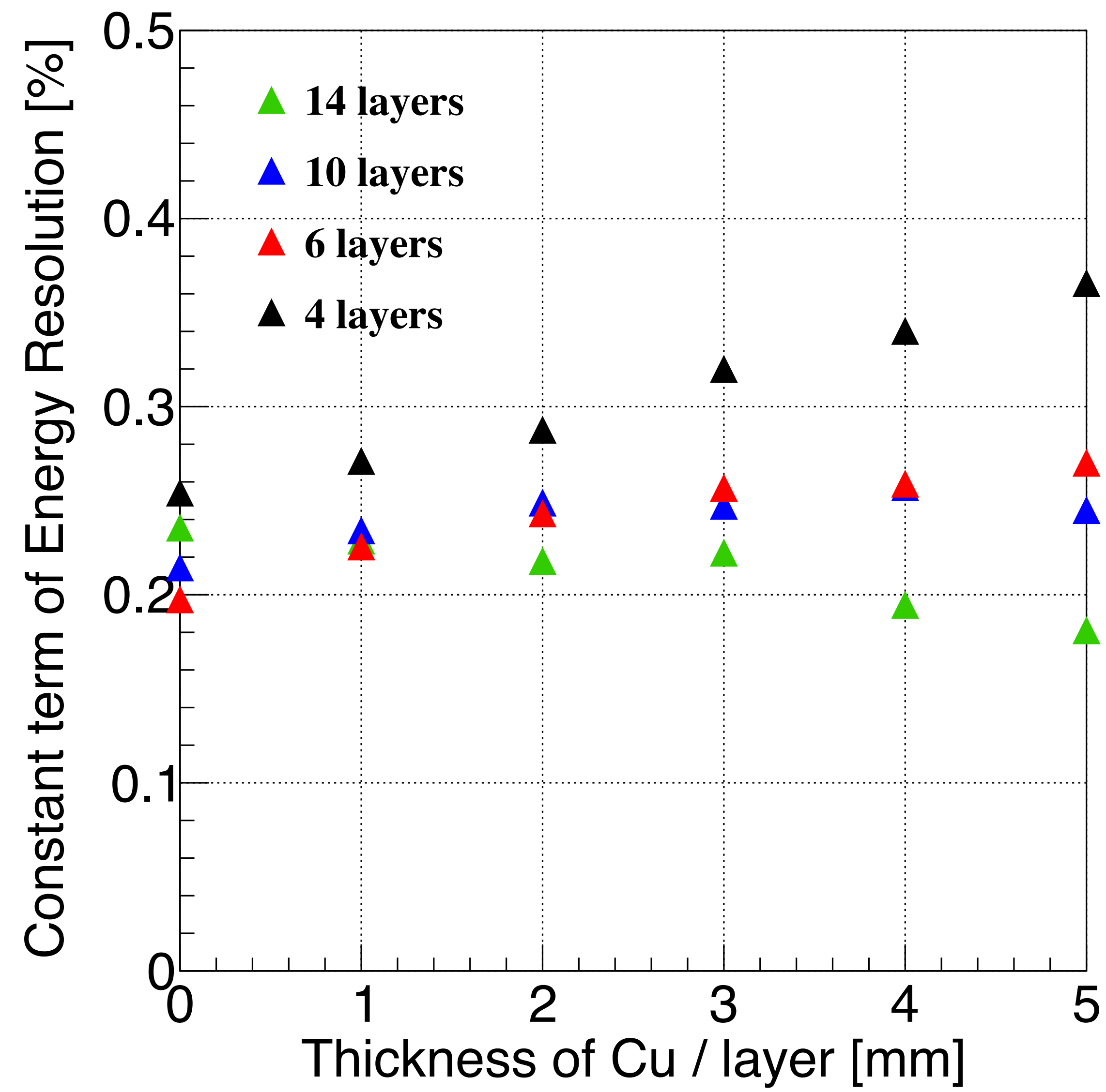
dead material between layers

Dead Material and Layer Number

Model: (Crystal + PCB + Cu) / layer

Crystal, total radiation length = $24X_0$
PCB, 2mm/layer
Cu, represents the dead material between layers (cables, cooling, etc.)
Varying thickness of Cu per layer and longitudinal layer number

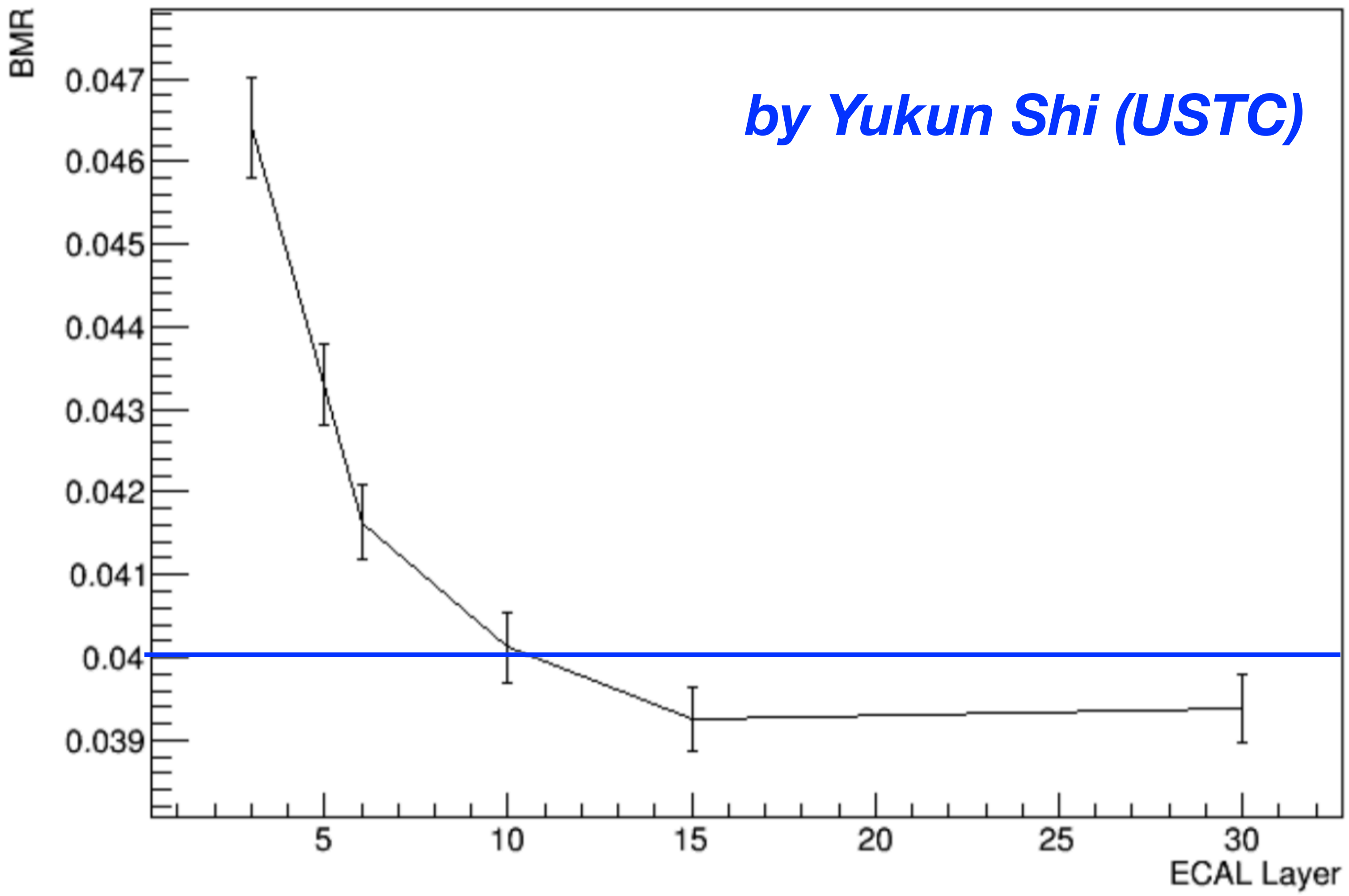




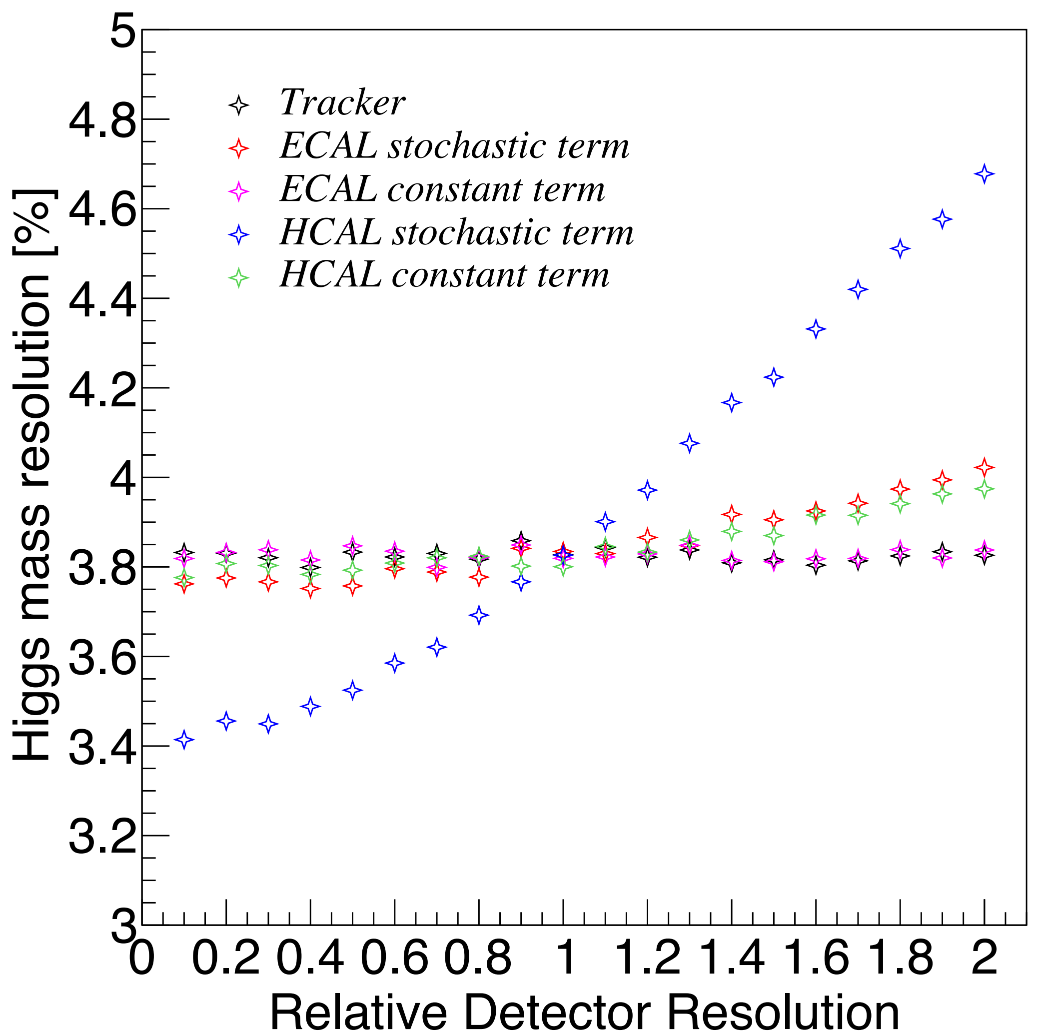
Note: digitization not implemented yet, so energy fluctuations and leakages dominate

Higgs Boson Mass Resolution vs Layer Number

Full simulation of Baseline Si-W ECAL



Fast simulation



10-15 layers can satisfy the requirement of 4% BMR (Boson Mass Resolution).

6 layers may be acceptable thanks to the better EM resolution.

< 5 layers may need further optimization of Particle Flow Algorithm.

Anomalous large signals caused by photodetectors

Anomalous large signals: ECAL spikes

Origin: particles deposit energy in photodetectors (APD)

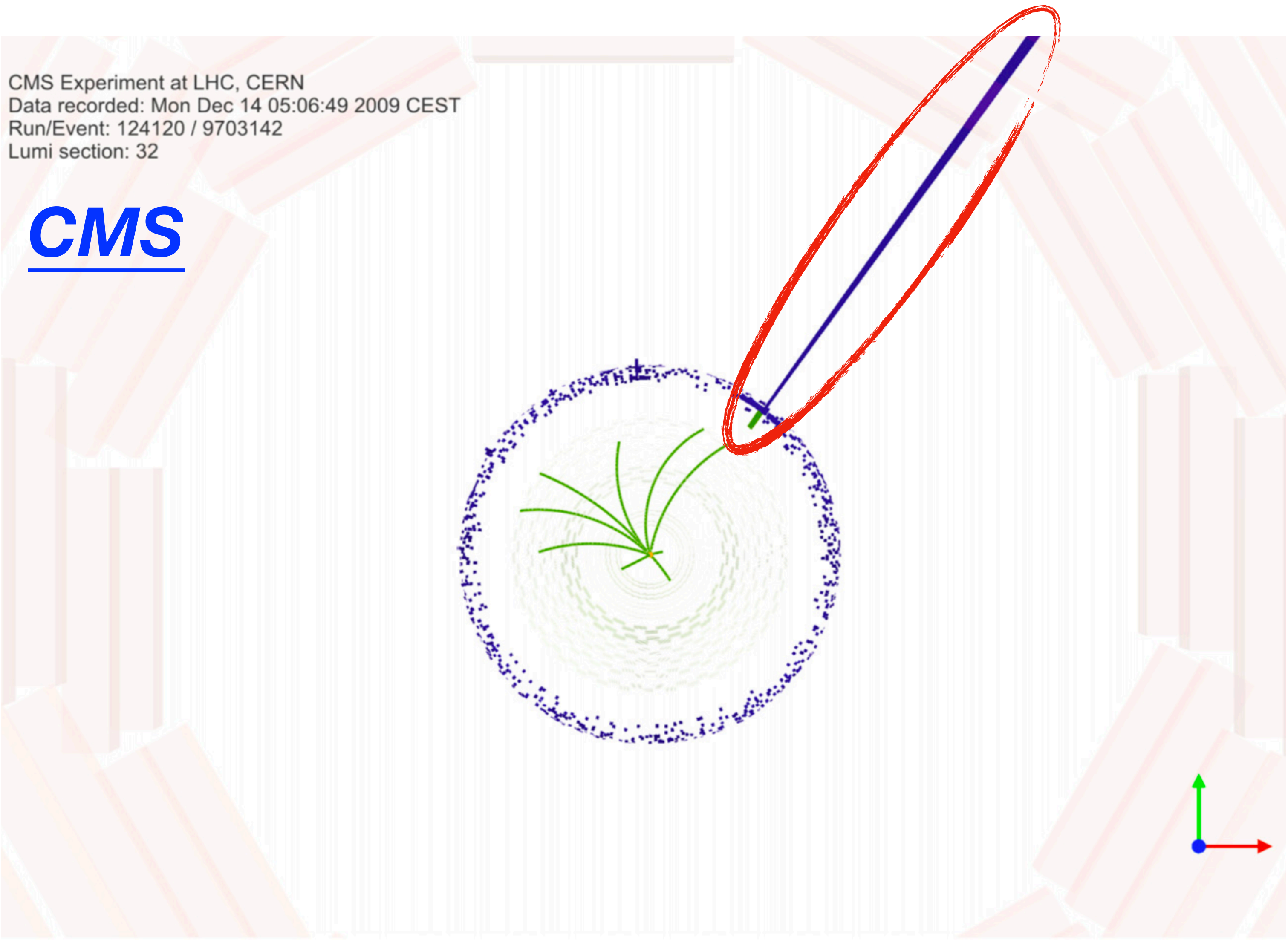
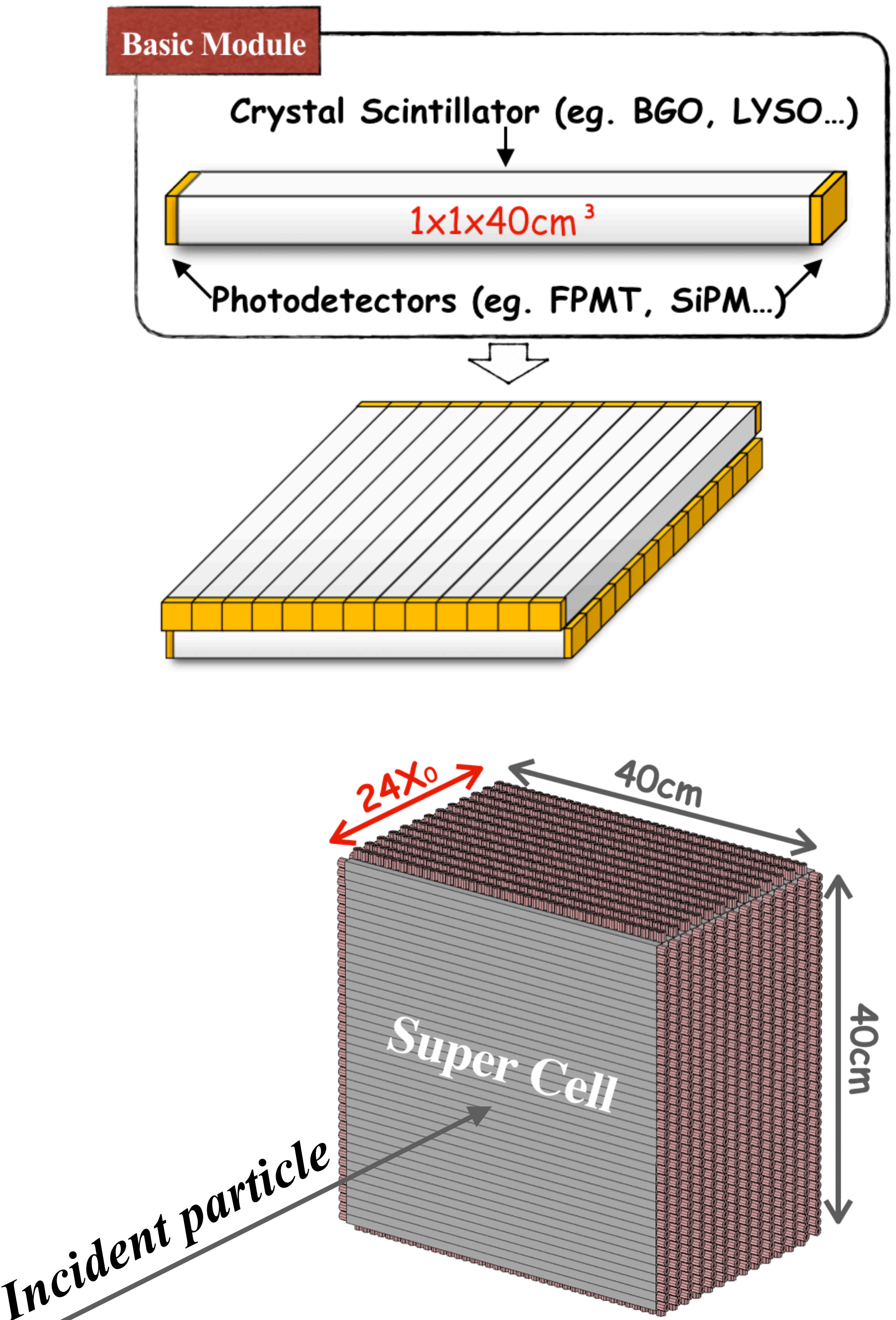


Fig. 2. CMS event display of a pp collision event, showing an isolated ECAL spike (top-right) simulating a 690 GeV transverse energy deposit.

Also observed in Belle/BESIII *CsI(+PIN diode)* ECAL, can not be ignored!

How about other photodetectors? such as SiPM, need dedicated study...

Geometry 2



Basic cell:

1×1×40cm³ crystal bar, two readouts

Structure:

perpendicular to adjacent layer

Highlight:

#channels, ~15 times less

longitudinal granularity guaranteed

using time information for hit positions

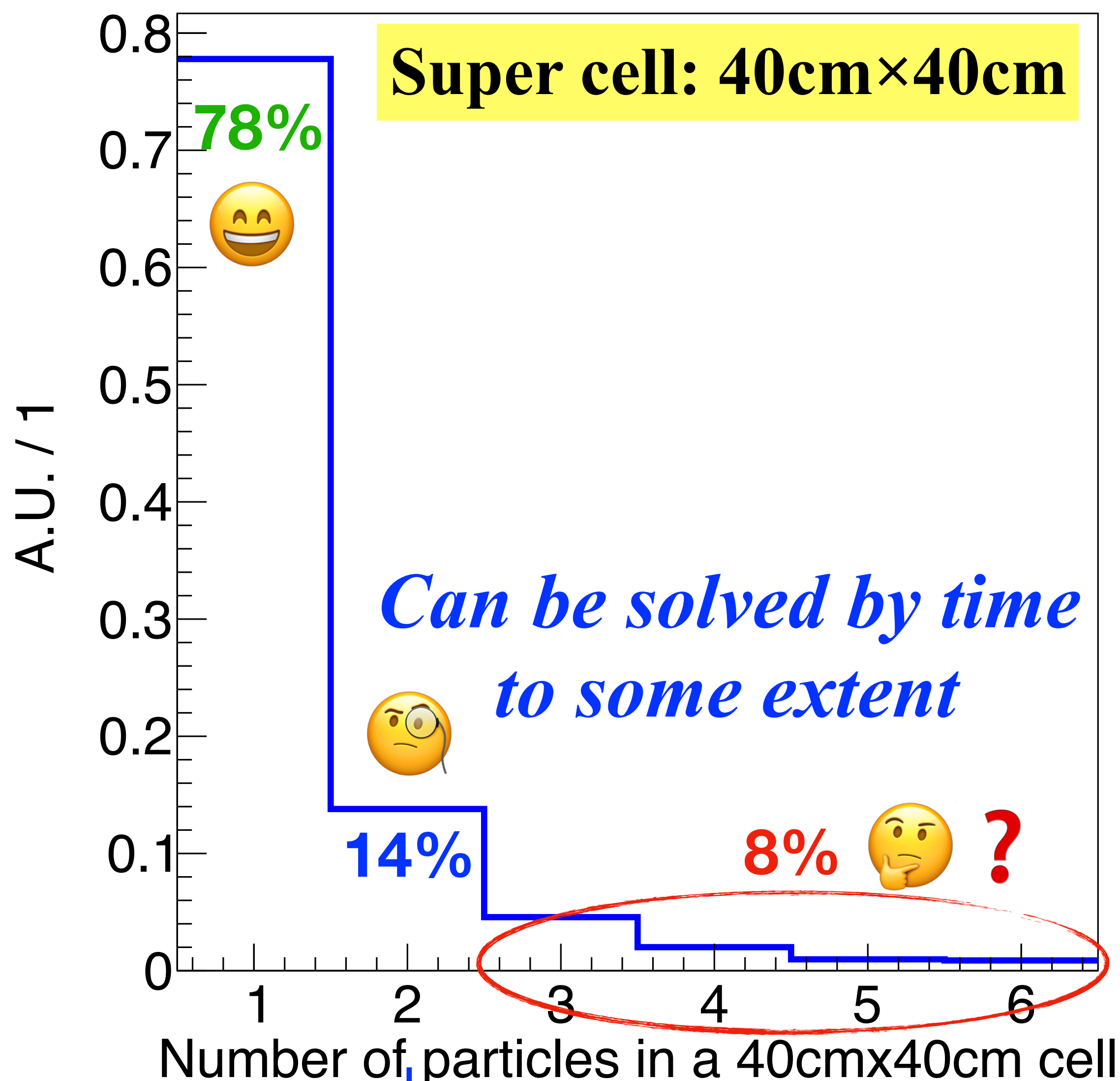
Key question:

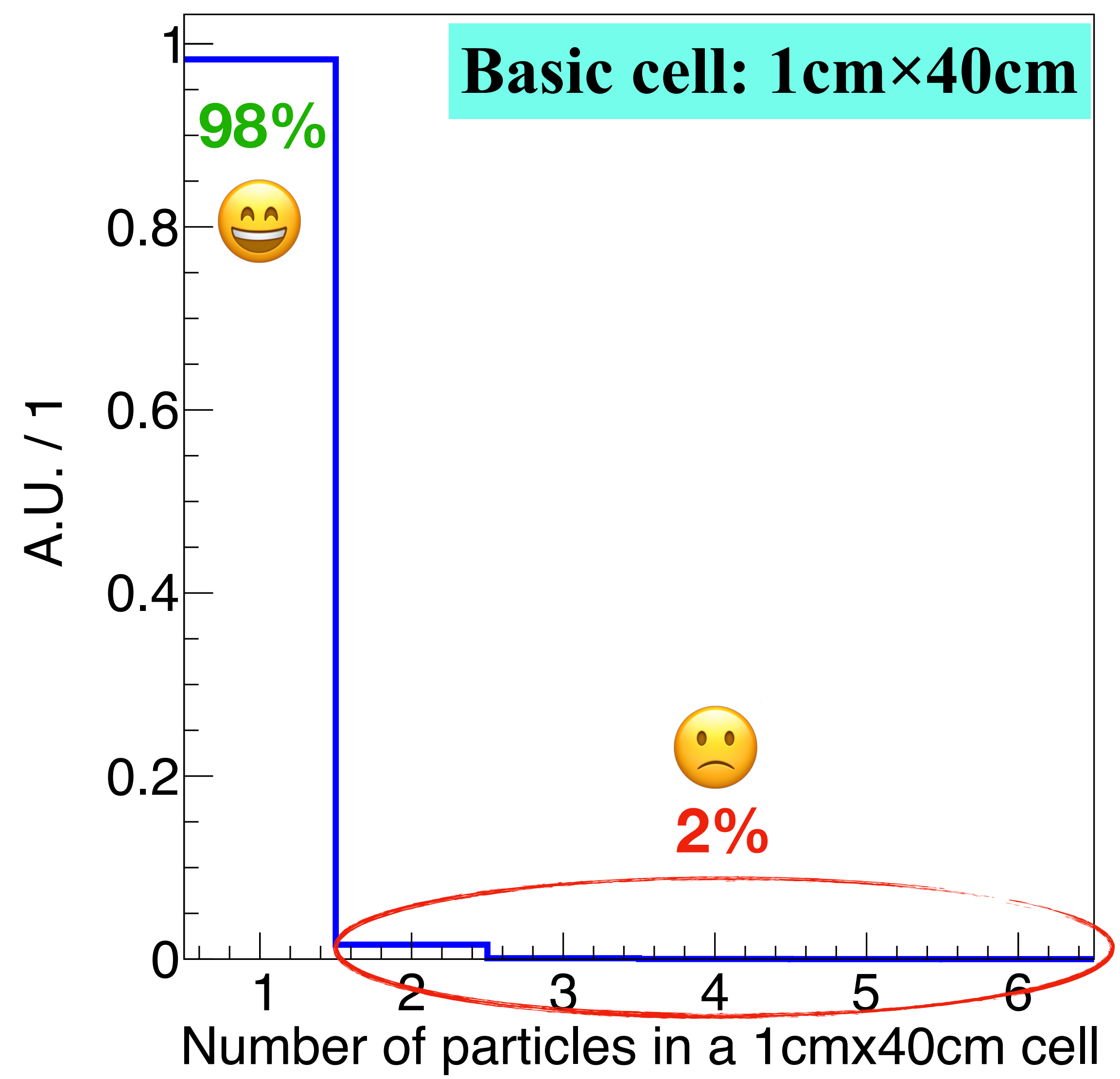
separation of nearby showers

Physics requirement of separation

Proportion of cells with multi-particle?

Z->qq (2 jets)





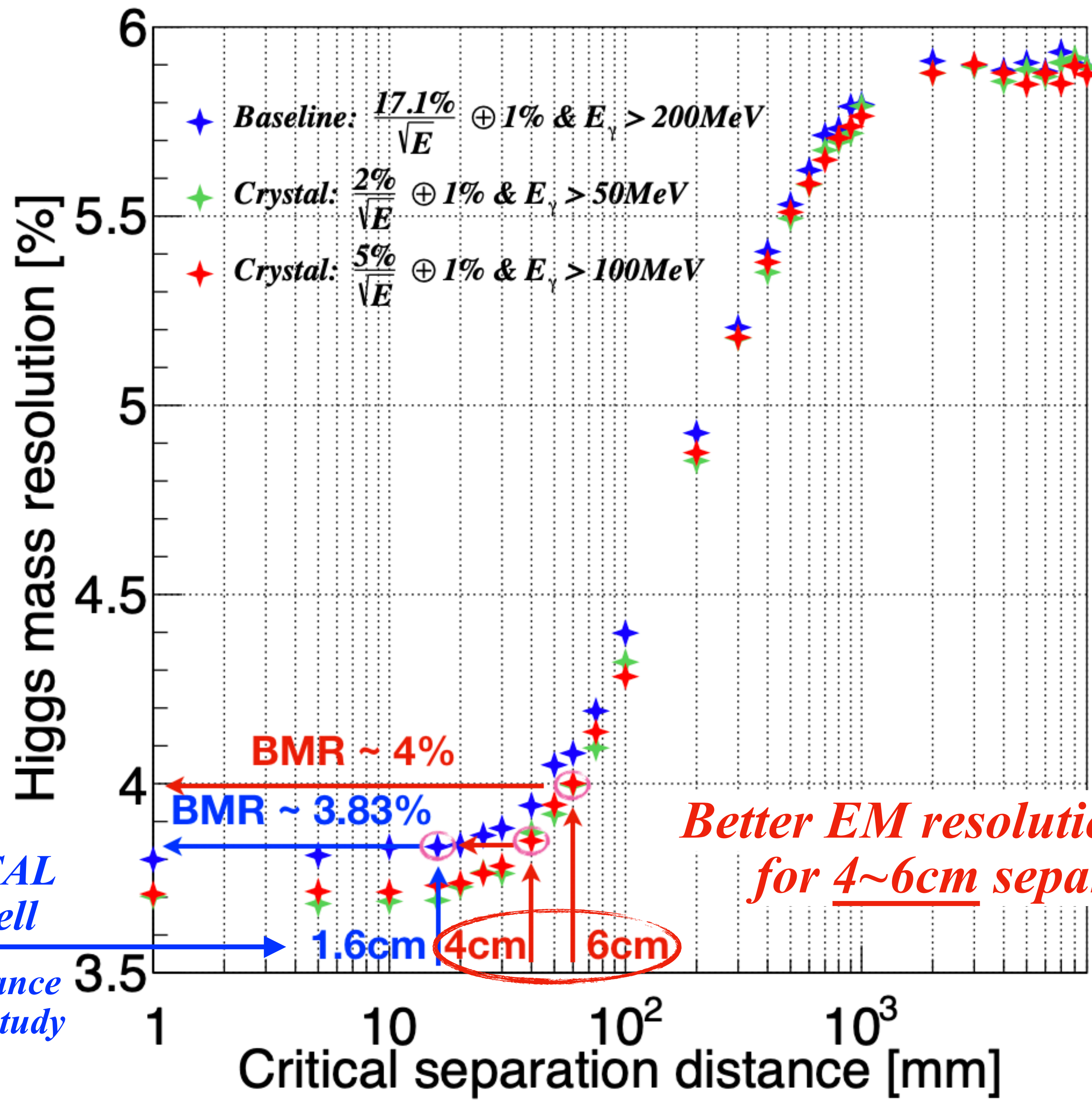
Charged + Charged
Charged + Neutral → Tracker

Neutral + Neutral ~25% → Only Calorimeter

Is the real ambiguity, but not so severe

Physics requirement of separation

Guidance from Fast Simulation



Better EM resolution offers a margin for 4~6cm separation distance

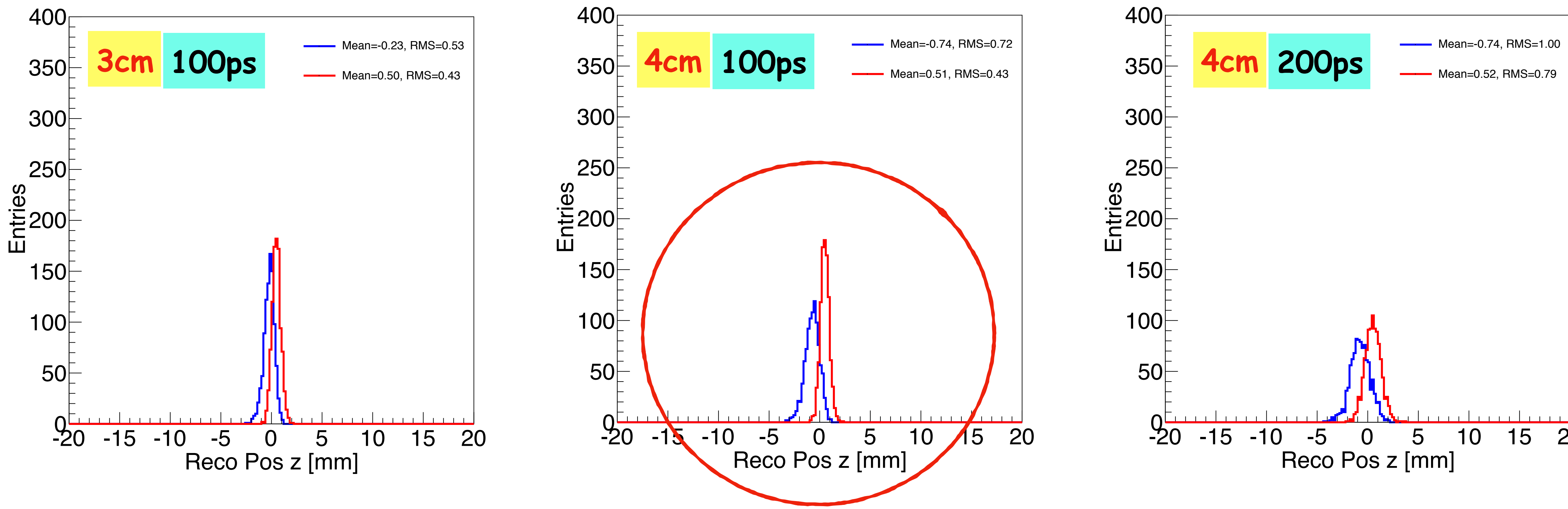
Baseline Si-W ECAL with 1cm×1cm cell

Critical separation distance (Di-photon separation study by Hang Zhao)

Reconstruction of di-photon event

preliminary reconstruction of 2 parallel 5GeV photons

Distance | Time resolution



Separation efficiency of 2-3cm photons ~ 75%

Distance (cm)	7	6	5	4	3	2
γγ	98.40%	98.60%	99.10%	97.70%	98.60%	98.70%
Position Matching	98.20%	97.40%	93.10%	81.20%	79.90%	76.60%
Energy Sharing	98.30%	98.50%	99%	97.60%	98.50%	98.60%
All 3 conditions	98.10%	97.30%	93%	81.10%	79.80%	76.50%

Requirement of time resolution: < 100ps

Critical separation distance:

- **~ 4cm, only using time**
- **~2-3cm, combine time and energy**

Consideration on the choice of crystal

Report by Prof. Renyuan Zhu on CaloWS in March 2019

SIC Crystal Cost for CEPC

Item	Size	1 m³	10 m³	100 m³
BGO	**2.23×2.23×28 cm**	**\$8/cc**	**\$7/cc**	**\$6/cc**
BaF_2:Y	3.10×3.10×50.75 cm	\$12/cc	\$11/cc	\$10/cc
LYSO	20.7x20.7x285 mm	\$36/cc	\$34/cc	\$32/cc
PWO	**20x20x223 mm**	**\$9/cc**	**\$8/cc**	**\$7.5/cc**
BSO	22x22x274 mm	\$8/cc	\$7.5/cc	\$7.0/cc
CsI	**3.57x3.57x46.5 cm**	**\$4.6/cc**	**\$4.3/cc**	**\$4.0/cc**

	X_0 (cm)	$24X_0$ (cm)	Lowest Total Cost (￥)
BGO	1.12	26.72	1.15 billion
PbWO4	0.89	20.71	1.09 billion
CsI (pure)	1.86	47.96	1.35 billion

For only ECAL, no much difference.

For the whole detector, CsI may not make sense.

Consideration on the choice of crystal

	BGO	$PbWO_4$	CsI (pure)	BaF_2 (:Y)	CeF_3	LYSO
Density (g/cm^3)	7.13	8.3	4.51	4.89	6.16	7.4
Radiation Length X_0 (cm)	1.12	0.89	1.86	2.03	1.654	1.14
Moliere Radius R_M (cm)	2.259	1.959-2.19	3.531	3.117	2.398	2.07
Minimum ionization (MeV/cm)	8.918	10.2	5.605	6.374	8.311	?
Refractive Index	2.15	2.20	1.95	1.49	1.62	1.82
Decay Time (ns)	fast 60 slow 300	fast <10 slow 30	fast 6 slow 30	fast 0.6(~2) slow 600	fast 9 slow 30	40
Light Yield (photons/MeV)	8000-12000	100-150	1700	2000/first 2ns 13000/total	4400	30000

Cost ~ Radiation Length & cost of crystal

- ✓ PbWO4, BGO
- ? CsI (pure)

Energy resolution ~ Light Yield

- ✓ BGO, CsI (pure)
- ? PbWO4

Time resolution ~ Decay Time & Light Yield

- ✓ PbWO4, CsI (pure)
- ? BGO

There's no perfect crystal, only suitable crystal to reach a point of balance!

Need further comparison…

Consideration on the choice of crystal

Requirement of time performance: Event rate

$$\frac{dR}{dt} = \mathcal{L} \cdot \sigma_p .$$

Maximum at Z factory, √s = 91.2 GeV

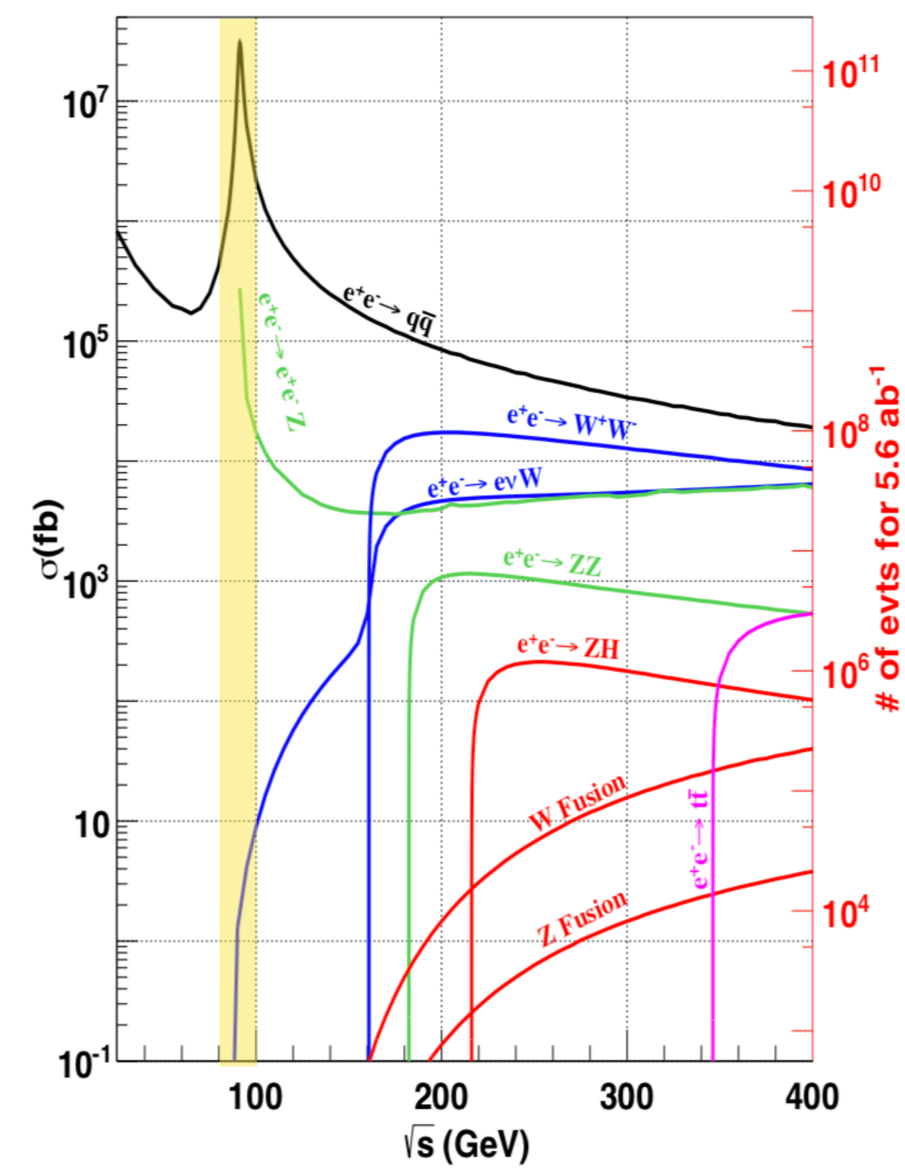
σ_{e+e-} ~ 10^8 fb = 10^{-31} cm^2

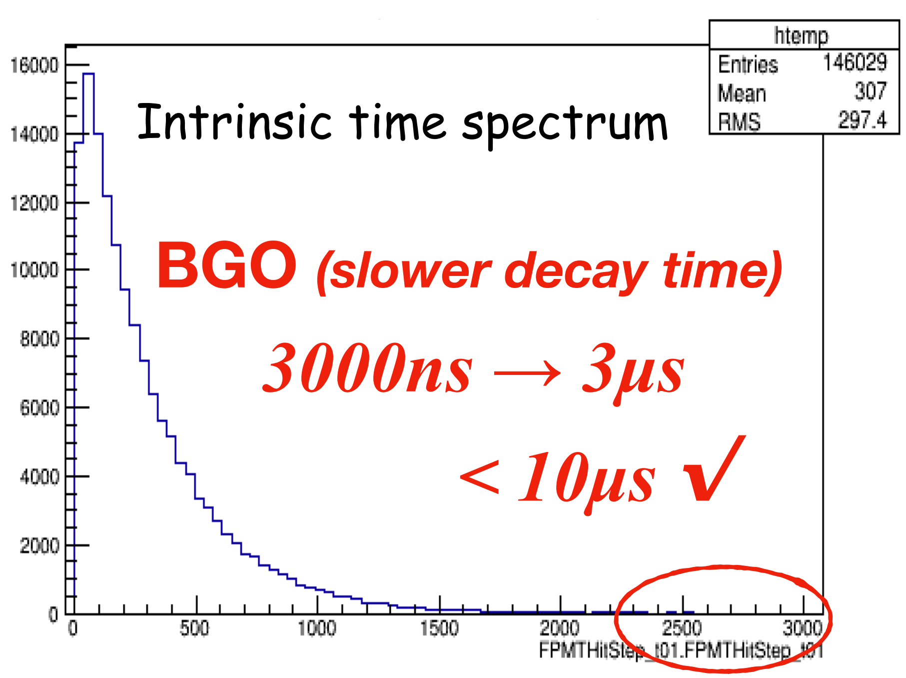
$L = 32\times10^{34}$ cm^{-2}s^{-1} (in CDR), ~ 10^{36} cm^{-2}s^{-1} (expected)

dR/dt ~ 32×10^3 s^{-1} = 32 kHz

→ 3.125×10^4 ns/evt = 31.25 μs/evt

< 30 μs, < 10 μs





Operation mode	$\sqrt{s}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)

Summary

Two basic geometries of Homogeneous Crystal ECAL are discussed:

Geometry 1

- ✓ **Reconstruction is compatible with current PFA**
- **Trade-off between layer number (EM resolution & #channel & cost) and PFA performance (Jet energy resolution)**
- **The choice of photodetector and electronic readout: Dead material and Spike Signal!**

Geometry 2

- ✓ **Separation problem of multi-particle shower is not so severe**
- ✓ **Better EM resolution offers a margin for 4-6cm separation distance**
- **Need further full simulation of PFA to evaluate**

Crystal options

BGO/PbWO4/CsI (pure), need further comparison

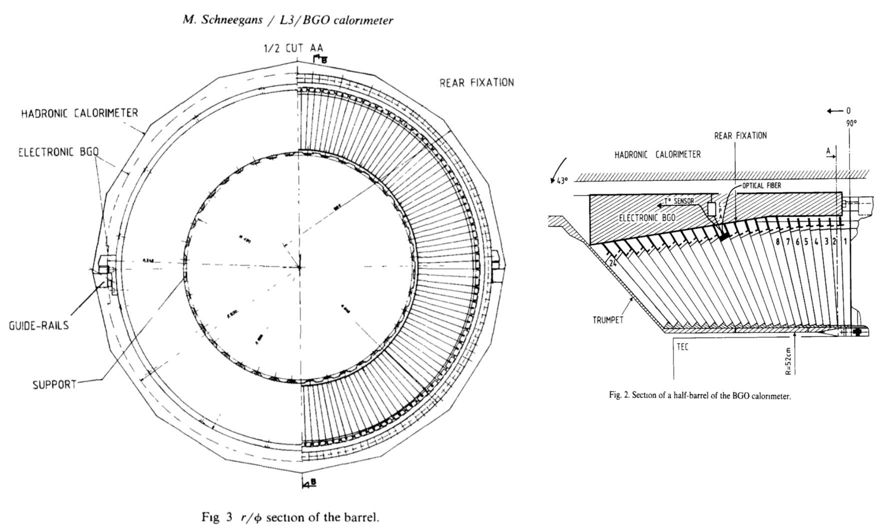
Thanks!

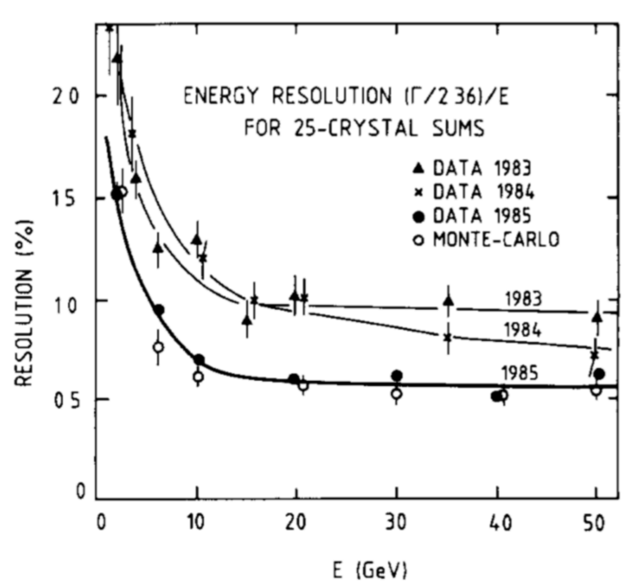
Backup

EM Energy Resolution

From a historical perspective

LEP - L3, BGO

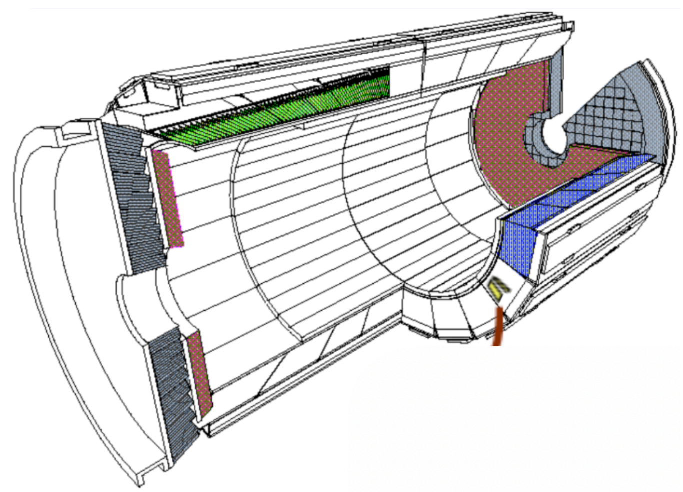


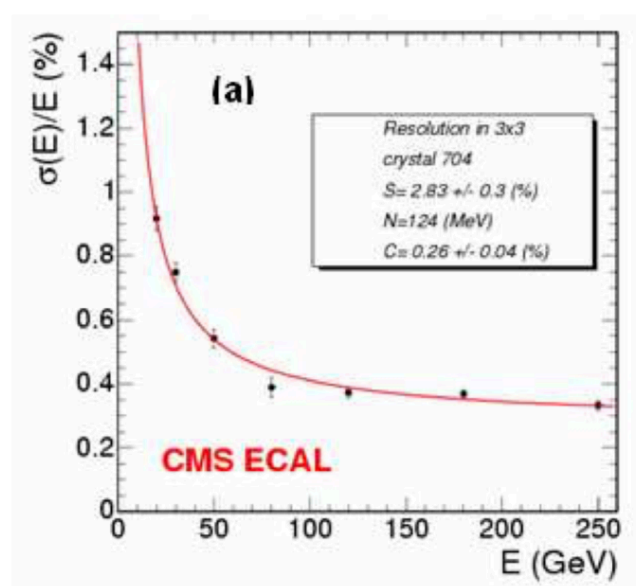


< 2% at 1GeV

The performance now measured in electron beams with final prototypes shows that we are below 2% energy resolution at 1 GeV and near to 5% at 100 MeV.

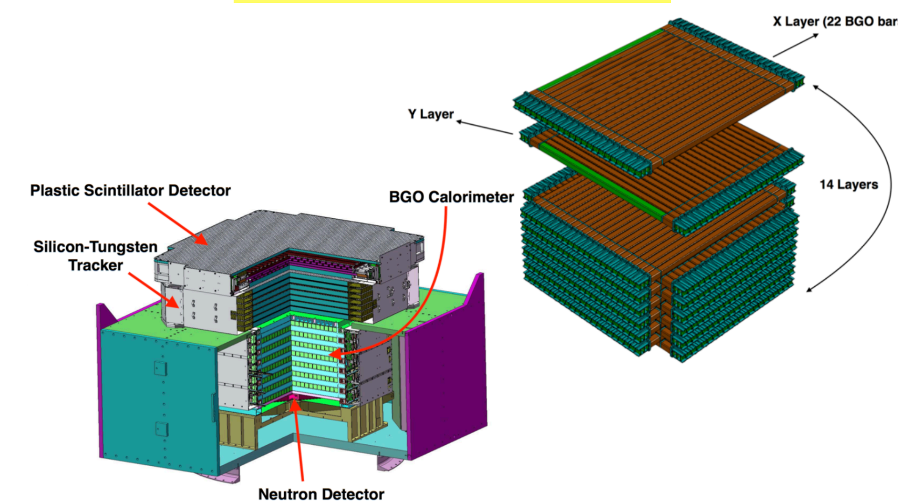
LHC - CMS, PbWO4

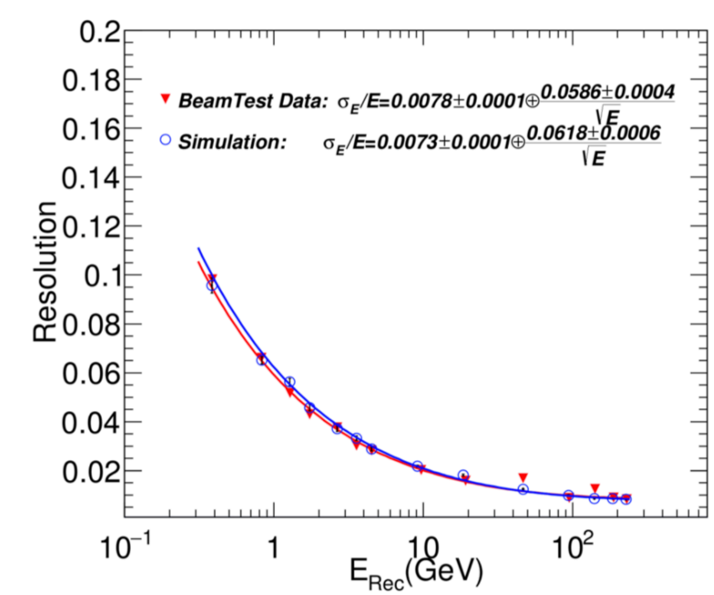




2.8%/√E ⊕ 0.3%

DAMPE, BGO





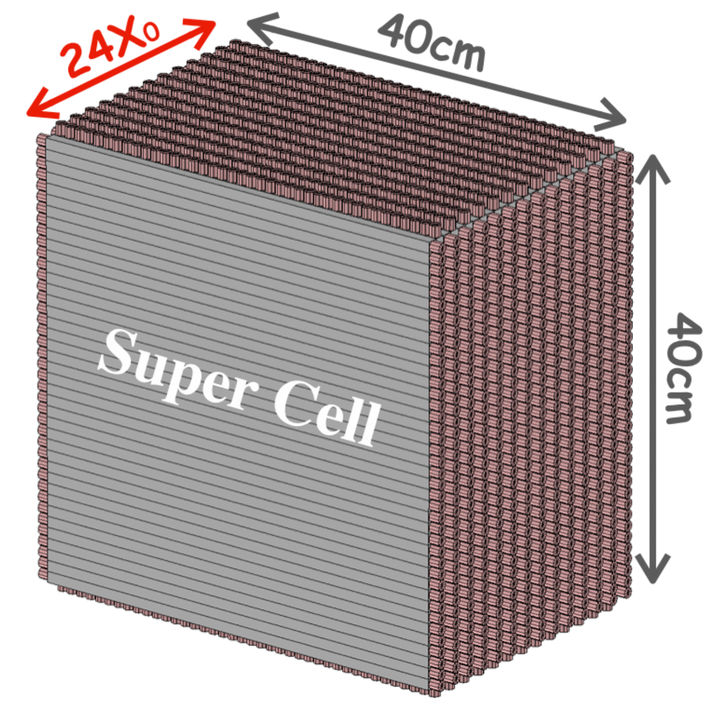
5.86%/√E ⊕ 0.78%

Physics requirement of separation

Analysis at generator level

Physics event:

- **$Z \rightarrow qq$ (2 jets)**



Parameters:

- **TPC Magnetic Field, B=3T**
- **TPC Radius, R=180cm**
- **TPC Barrel Length, L=470cm**
- **ECAL Longitudinal Thickness, $24X_0$**

Analysis level:

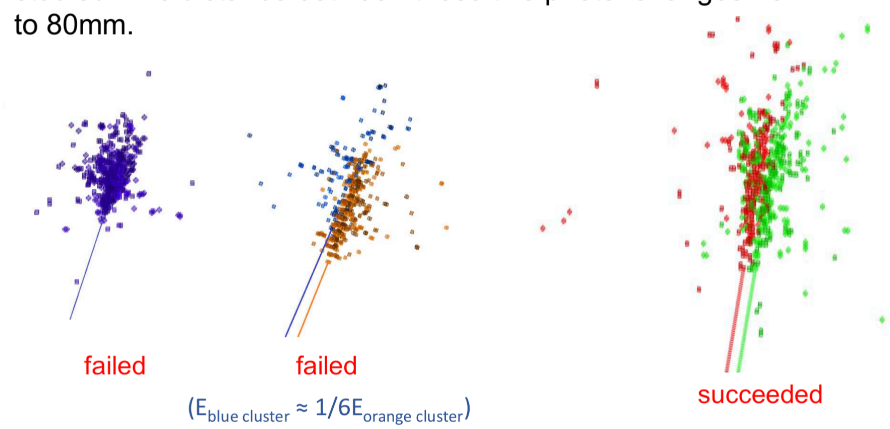
- **Number of supercells with multi particles?**
- **Closest Distance between all final state particles at different depth?**

Physics requirement of separation

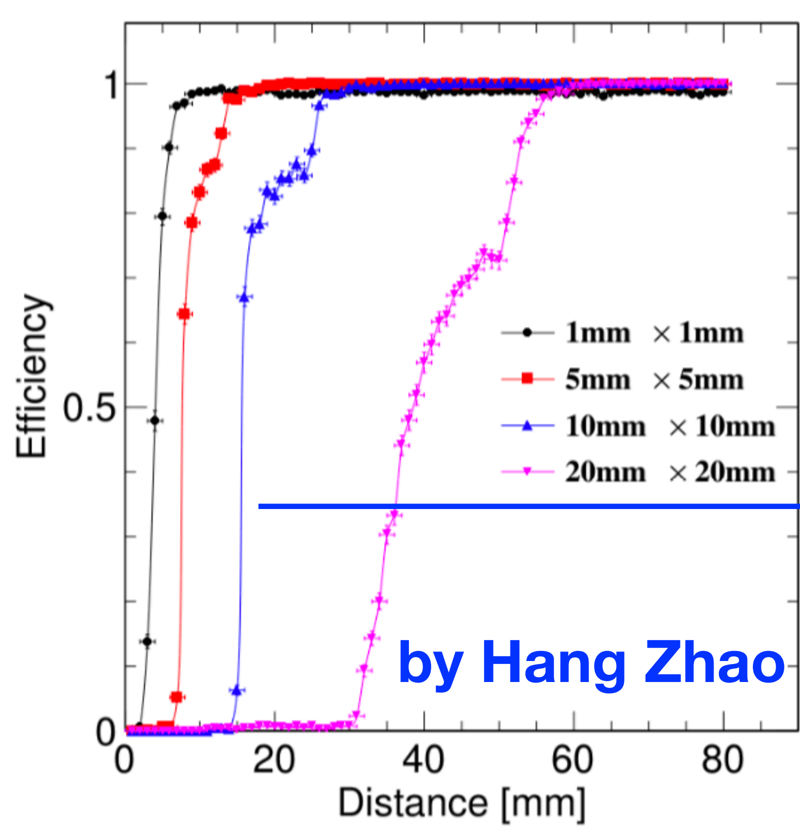
Guidance from Fast Simulation

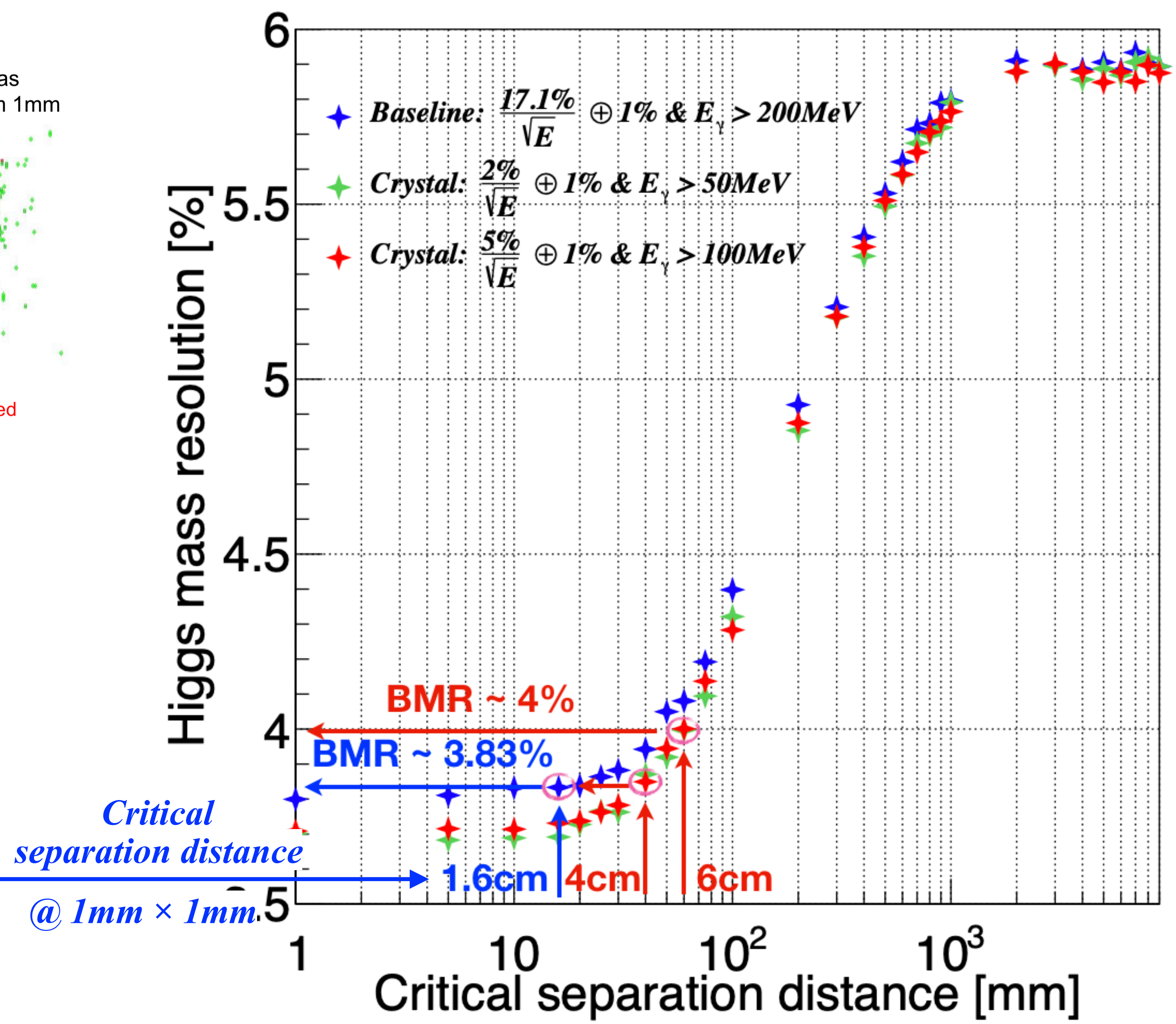
Di-photon Separation Study on Baseline ECAL

The reconstruction efficiency of two parallel 5 GeV photons was studied. The distance between these two photons ranges from 1mm to 80mm.



$1/3E_{All} < E_{photon1} < 2/3E_{All}$ && $1/3E_{All} < E_{photon2} < 2/3E_{All}$: succeeded



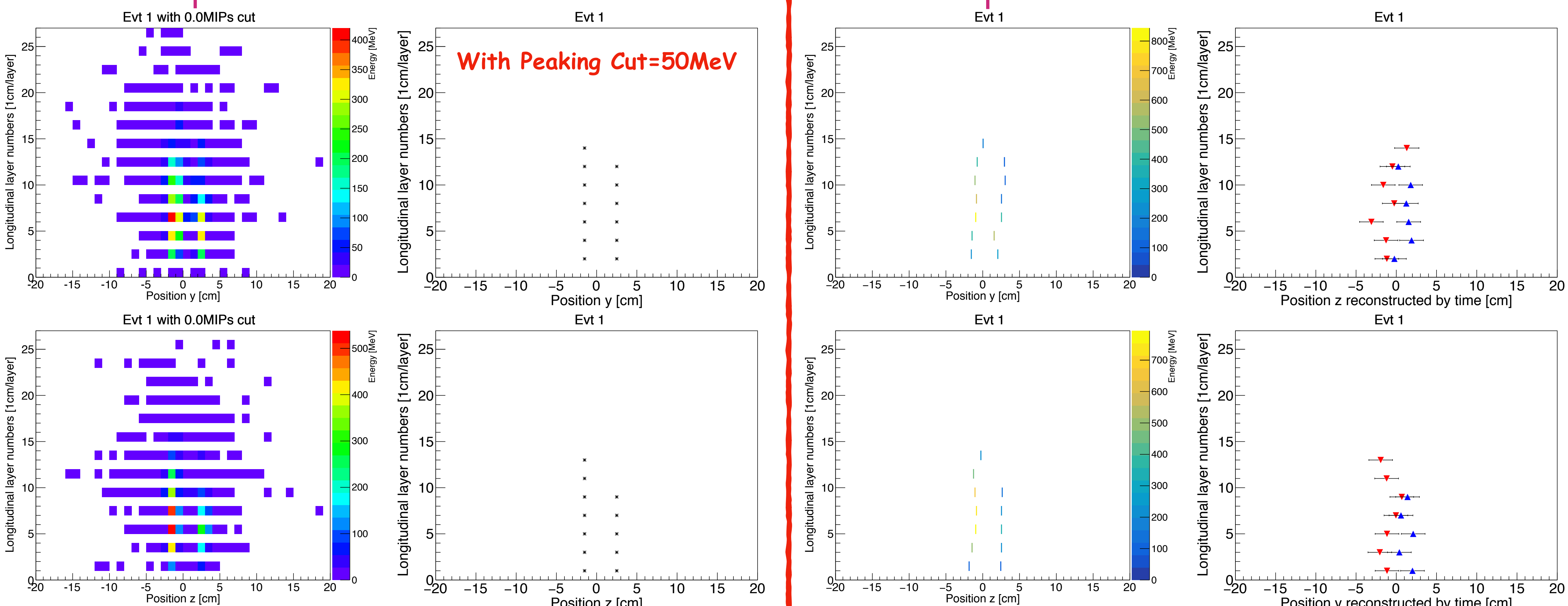


Reconstruction of di-photon event

preliminary idea on reconstruction of di-photon event

Truth energy distribution on two longitudinal planes

Energy sharing
Connect sub-clusters into shower



Find peak layer by layer
local maximum of energy
seed crystal
shower core position

Calculate positions by time

Combine these two positions to match showers in two dimensions to get a complete particle shower

Preliminary estimation

cell size, 10mm ~ 20mm, BMR almost constant
30 layers (BMR=3.9%) -> 6 layers (BMR=4.15%), -6.5%
17%/√E (BMR=3.83%) -> 2%/√E (BMR=3.75%), +2%

-4.5%
BMR=3.971%

fragment -50%, 3.83%->3.5%, +8.5%

+4%
BMR=3.648%

#channel, ~ 5 times less @ 10mm cell
~ 10 times less @ 20mm cell

---

cell size, 10mm ~ 20mm
30 layers (BMR=3.9%) -> 4 layers (BMR=4.4%), -13%
17%/√E (BMR=3.83%) -> 1.7%/√E (BMR=3.75%), +2%

-11%
BMR=4.218%

fragment -50%, 3.83%->3.5%, +8.5%

-2.5%
BMR=3.895%

#channel, ~ 7.5 times less @ 10mm cell
~ 15 times less @ 20mm cell