A Dual Readout Calorimeter with a Crystal ECAL

Jianming Qian
University of Michigan

On behalf of the CALVISION team

S. Eno, A. Belloni, C. Tully, R. Hirosky, S. Chekanov, S. Magill, N. Akchurin, H. Newman, R.-Y. Zhu, J. Hirschauer, H. Wenzel, J. Qian, B. Zhou, J. Zhu, M. Demarteau, P. Harris

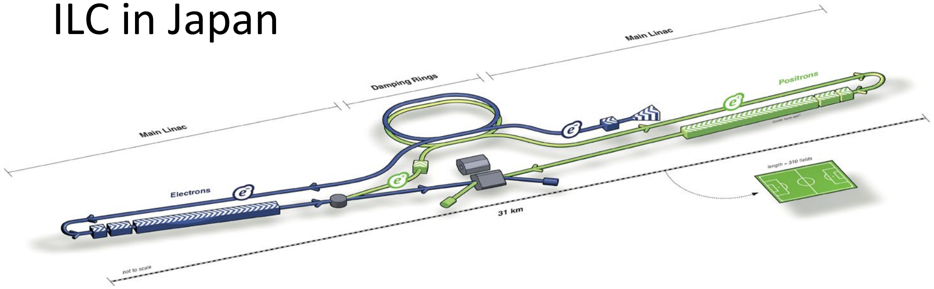
CPAD Instrumentation Frontier Workshop 2021
Stony Brook, March 18-22, 2021

(Disclaimer: many slides are courtesy of Sarah and Marco, thanks!)

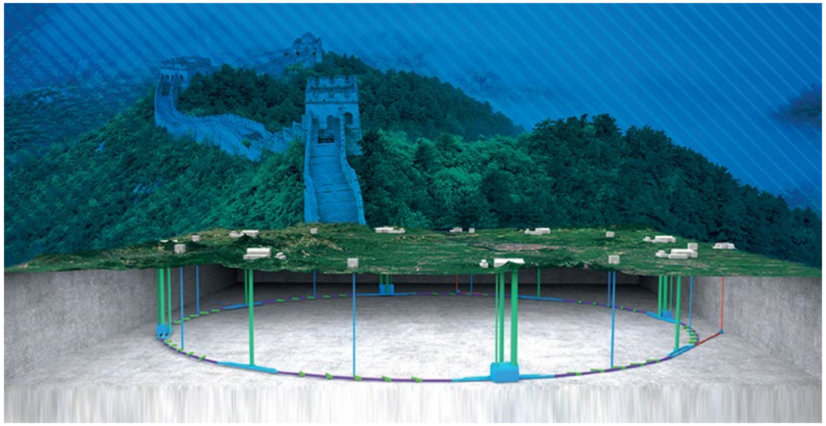
Higgs Factories

Next collider will most likely be an electron-positron collider with studying the Higgs boson as one of its main physics goals.

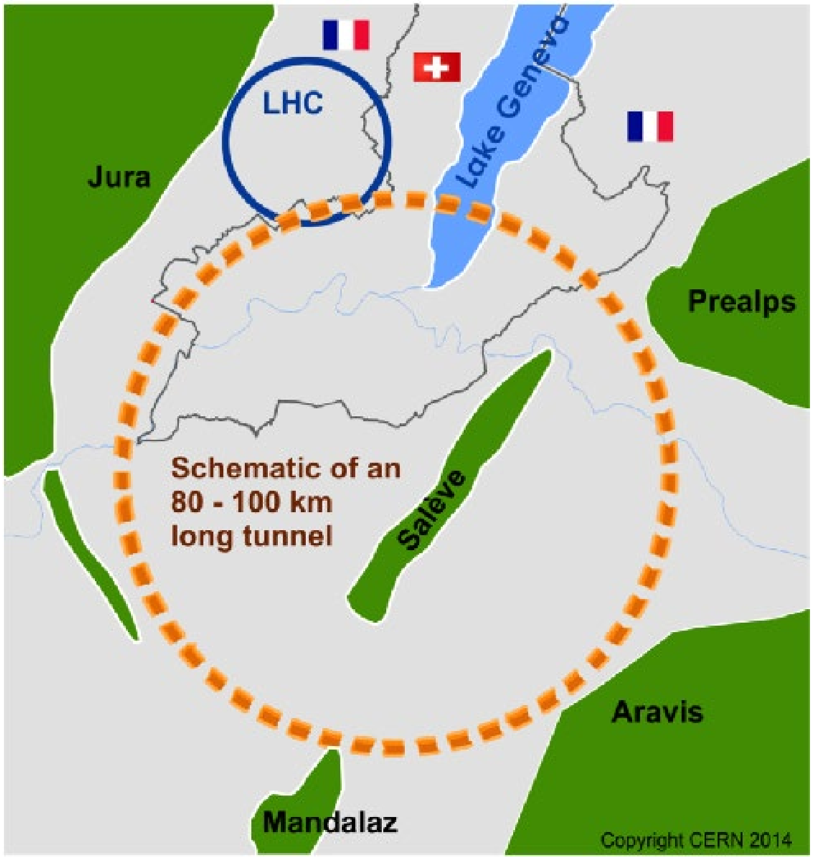
ILC in Japan



CEPC in China



FCC-ee at CERN

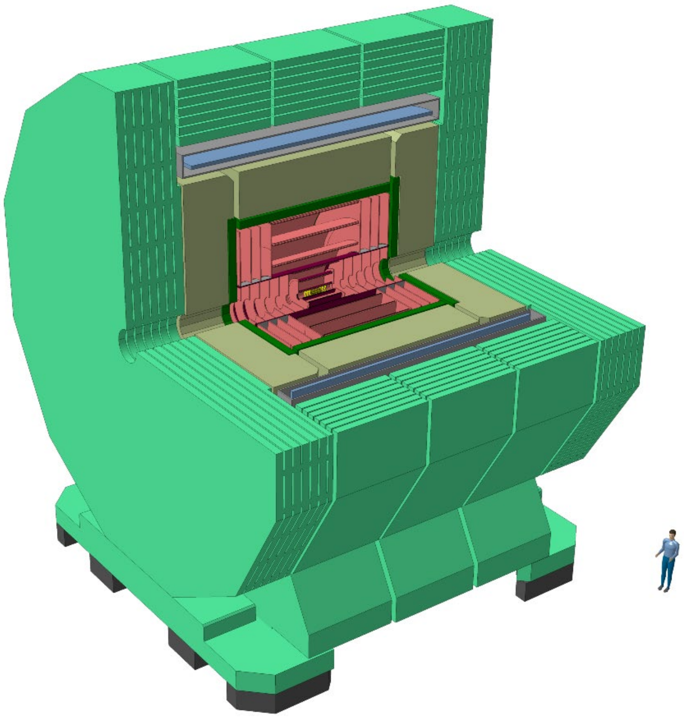


Detector Concepts

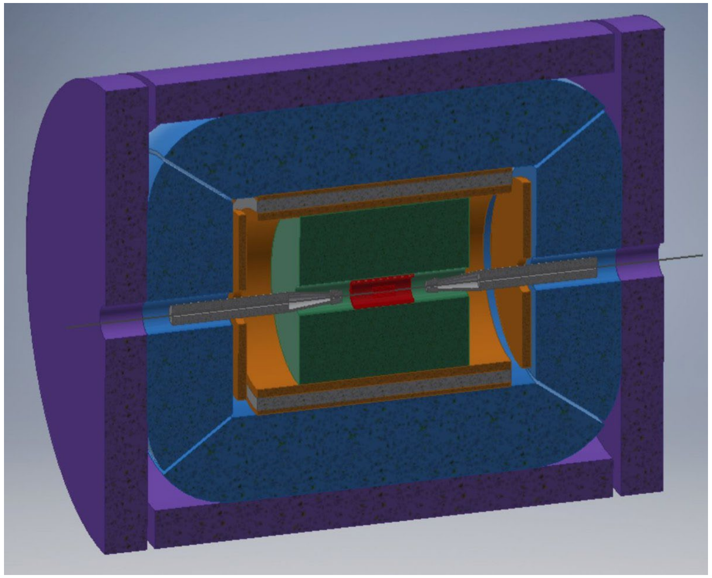
In terms of calorimetry options, there are two main concepts:

- Particle Flow Algorithm (PFA) calorimeter (ILC, CLIC, FCC-ee, CEPC);
- Dual Readout (DRO) calorimetry (FCC-ee, CEPC).

Both PFA and DRO calorimetry are optimized to achieve a jet energy resolution of $3-4\%$ at ~ 100 GeV, allowing for the separation of $W \to q\bar{q}'$ and $Z \to q\bar{q}$ decays.



CLD proposed for FCC-ee
(PFA calorimetry)

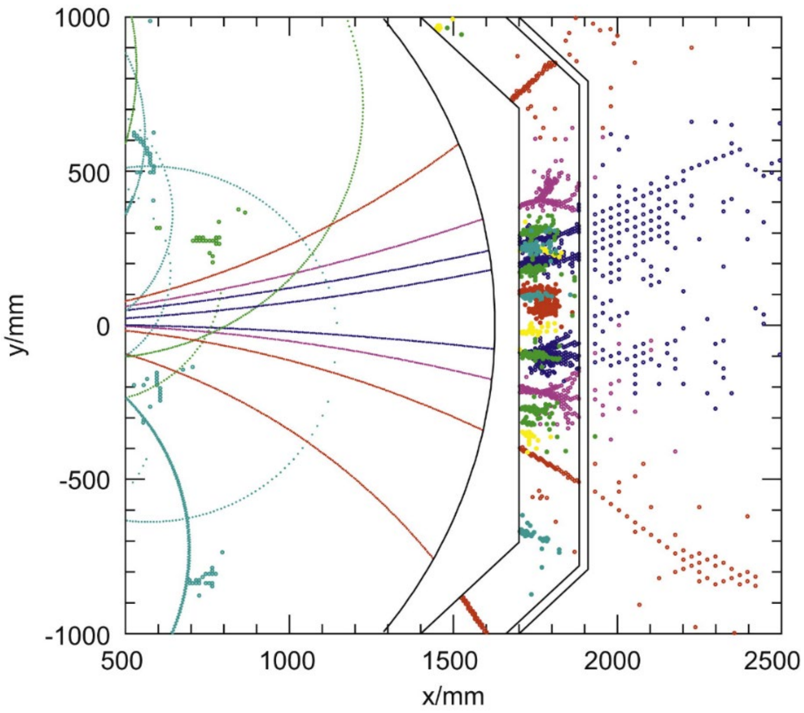


IDEA proposed for FCC-ee and CEPC
(DRO calorimetry)

PFA Calorimetry

Sampling calorimeter, reconstruction and identification of individual particles in showers, measuring energy in the most suitable sub-detector for the particle type:

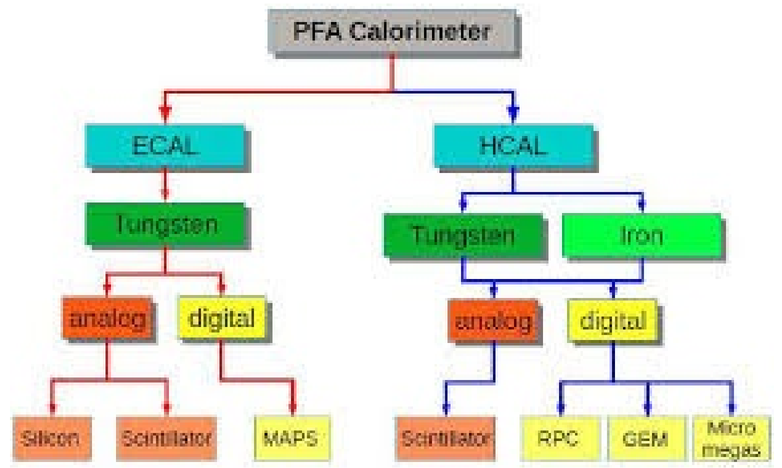
- Charged particles in the tracking detector;
- Photons in the electromagnetic calorimeter;
- Neutral hadrons in the hadronic calorimeter



Characteristics:

- High granularities $\Rightarrow$ large channel counts;
- relatively small sampling fractions

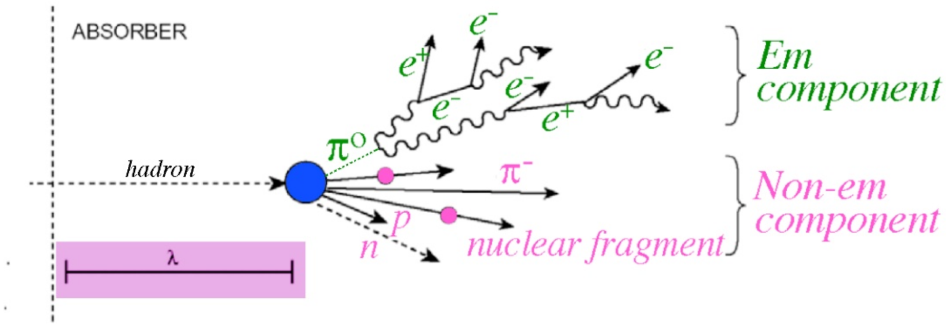
Extensive R&D by the CALICE Collaboration



Dual Readout Calorimetry

Sampling calorimeter, reading out both scintillation and Cherenkov light to disentangle EM and hadronic components shower-by-shower, allowing for the corrections for different EM and hadronic responses.

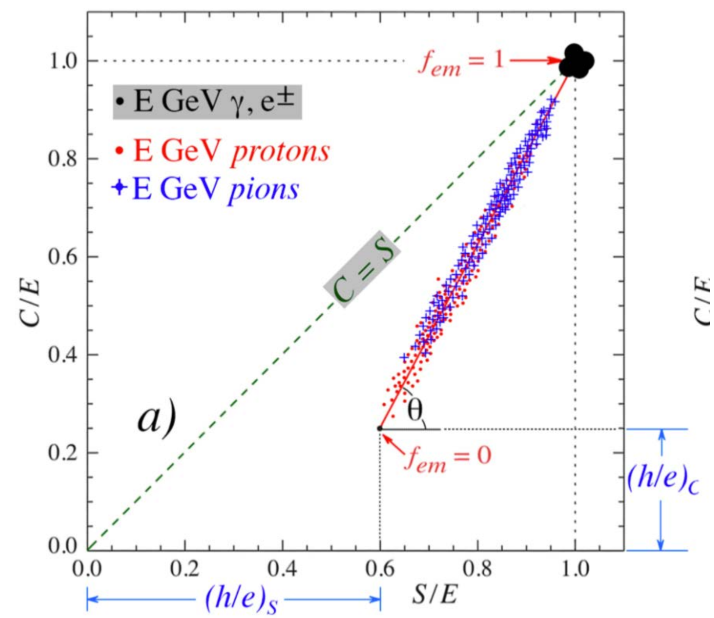
Scintillation – sensitive to dE/dx energy loss $\Rightarrow$ charged particles;
Cherenkov – relativistic charged particles, mostly electrons.



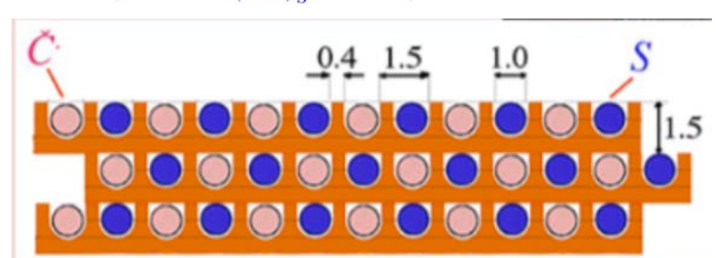
$$\left.\begin{aligned}\frac{S}{E} &= f_{em} + \left(\frac{h}{e}\right)_S (1 - f_{em}) \\ \frac{C}{E} &= f_{em} + \left(\frac{h}{e}\right)_C (1 - f_{em})\end{aligned}\right\} \Rightarrow E = \frac{S - \chi C}{1 - \chi}$$

$$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

The detector response parameter χ is measured separately



Extensive R&D by the RD52 collaboration
$\Rightarrow$ Clear and scintillation fibers for C/S readout.
Challenges: large channel count, lots of fibers!



An example geometry with Copper absorber

Performance Comparisons

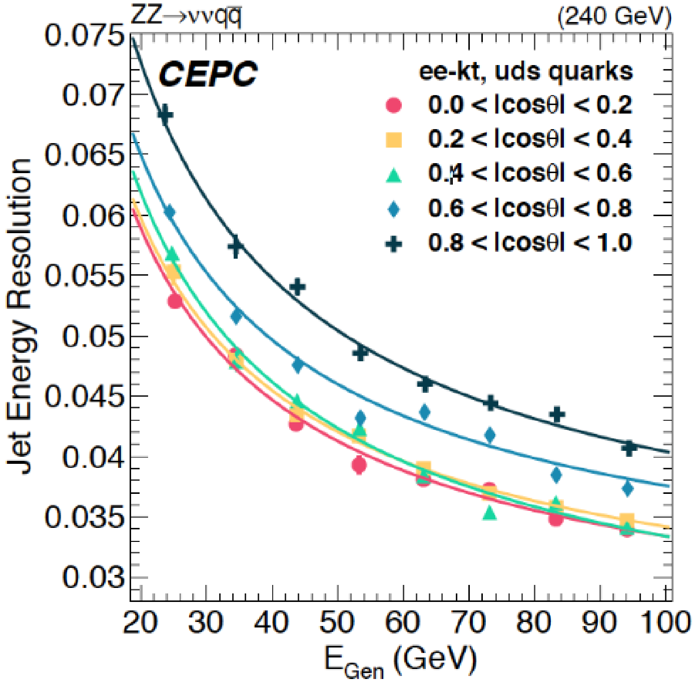
Both PFA and DRO calorimeters are optimized for hadronic Energy Resolution: $\sim 40\%/\sqrt{E}$.

EM Energy Resolutions are mediocre at the best

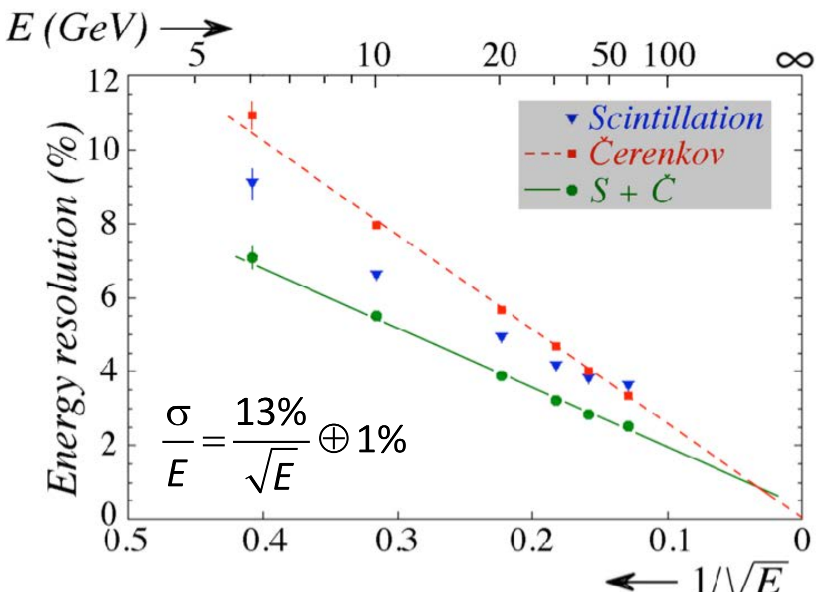
$\sim 20\%/\sqrt{E}$ for a PFA calorimeter

$\sim 13\%/\sqrt{E}$ for a DRO calorimeter

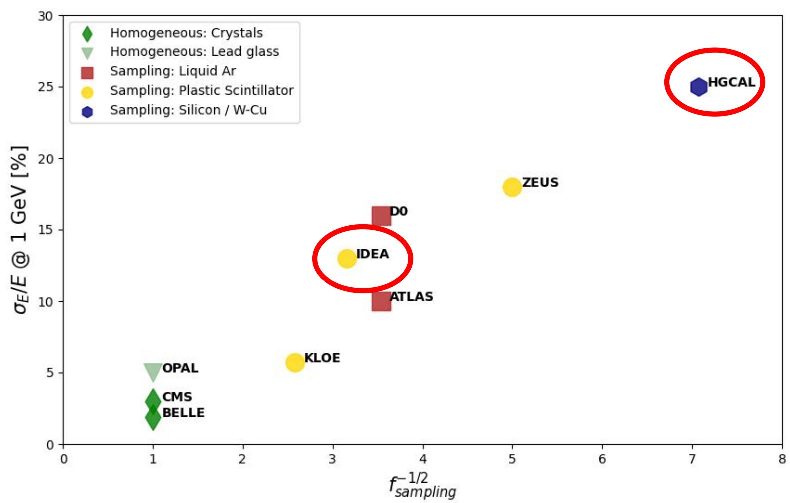
largely due to poor sampling fractions.



PFA jet energy resolution (simulation)

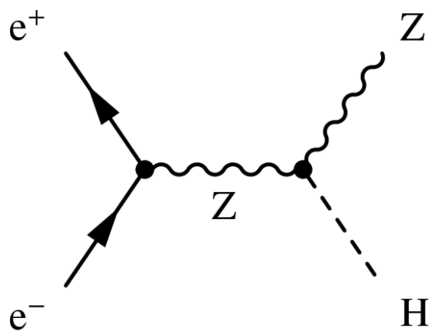


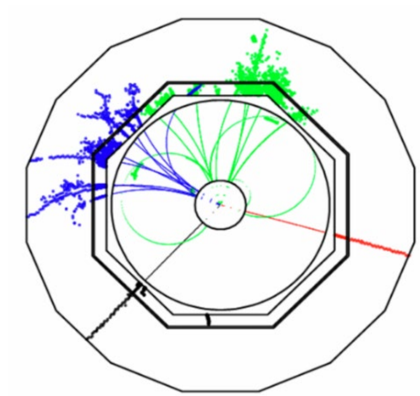
DRO EM energy resolution



Comparison of EM energy resolution

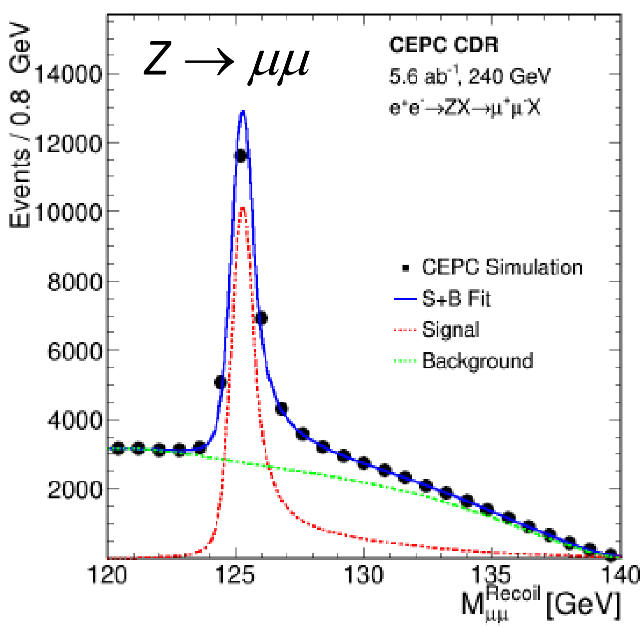
Improving Higgs Tagging

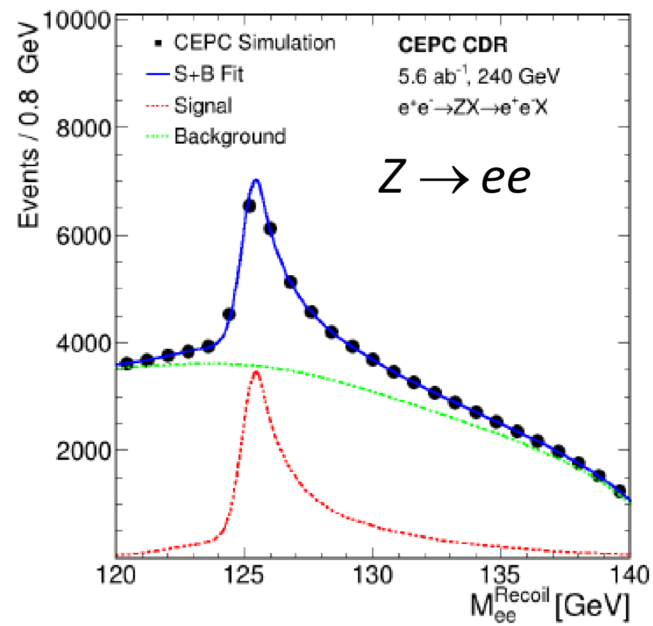




For Higgs factories, the main Higgs production process is $e^+e^- \to ZH$. Higgs bosons are "identified" through the recoiling mass method.

Good EM energy resolution will benefit the Higgs boson tagging.





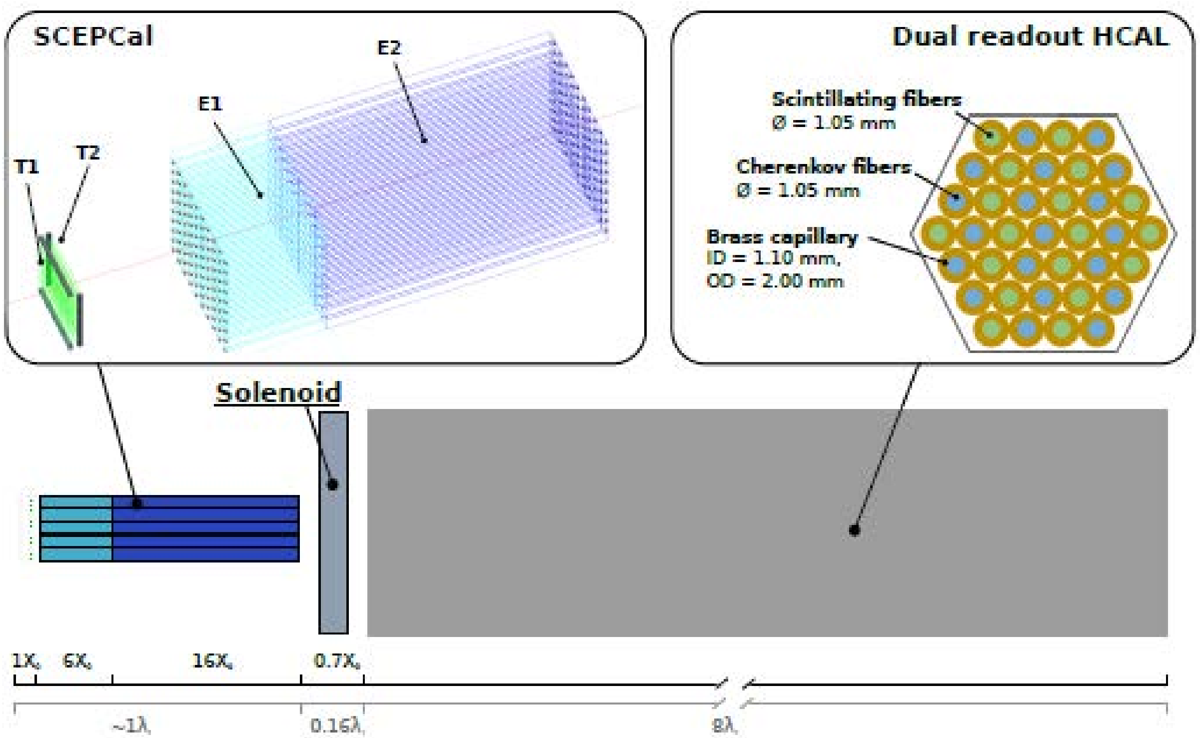
Much worse recoil mass resolution in the electron channel due to Bremstrahlung radiation, need to have good EM resolution for the radiation recovery.

A DRO Calorimeter with a Crystal ECAL?

Crystal ECALs have very good EM resolutions, $\sim 3\%/\sqrt{E}$ or better, but they suffer from large non-iniform h/e responses.

Can we combine the strengths of a crystal ECAL with that of a DRO calorimeter?
Can a DRO crystal ECAL help to mitigate its impact on hadronic energy resolution?

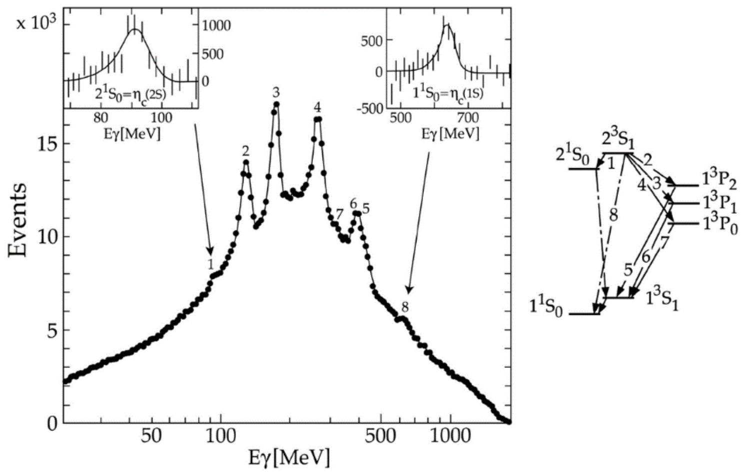
An example design by Eno, Lucchini, and Tully et al. (arXiv:2008.00338)

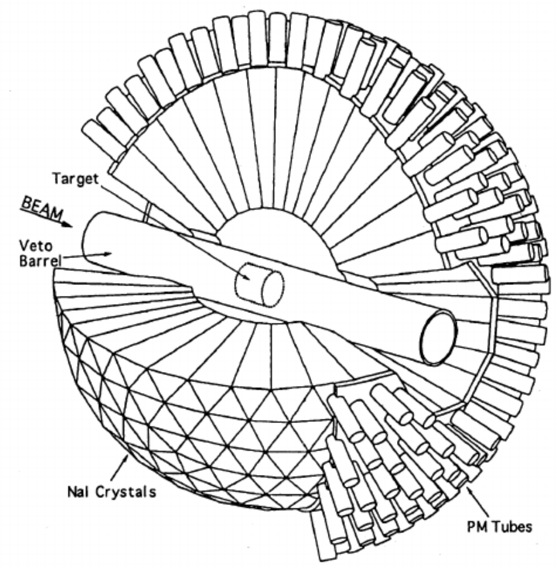


Explore crystal DRO using both wavelength filters and timing structure

History of Crystal Calorimeter

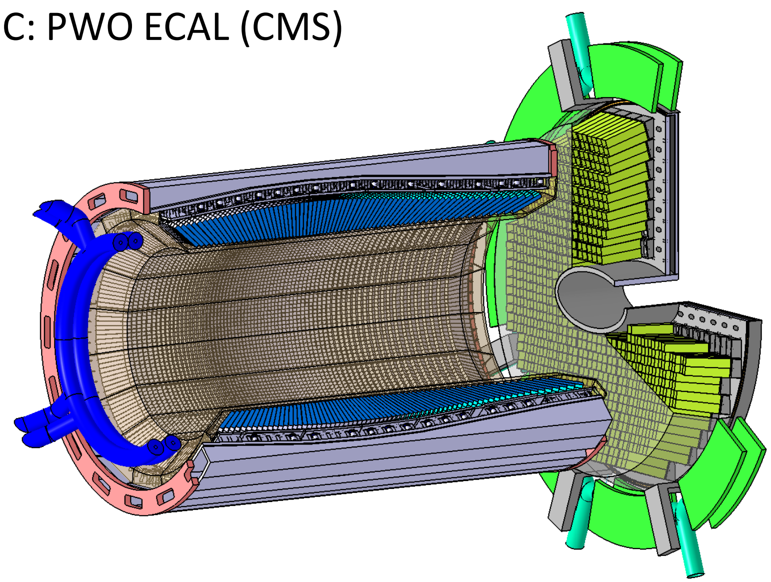
SPEAR: Crystal Ball detector for Charmonium physics (1979).

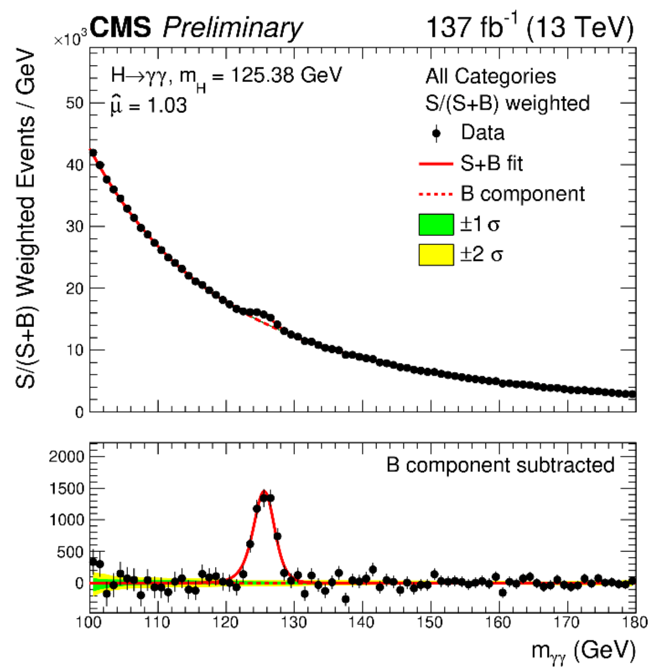




LEP: BGO ECAL (L3), Lead Glass (OPAL)

LHC: PWO ECAL (CMS)





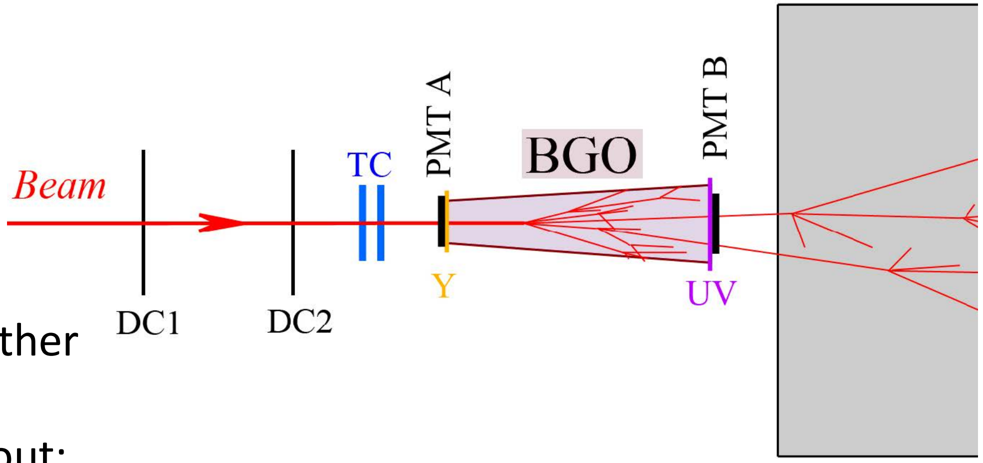
CMS Crystal ECAL

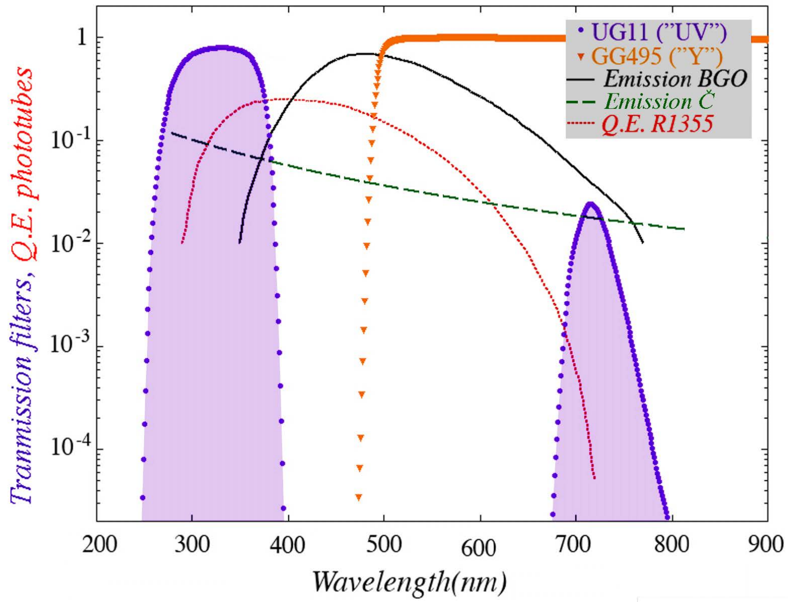
Previous Work

RD52 has investigated DRO of crystals with PMTs using optical filters and timing to separate C and S signals

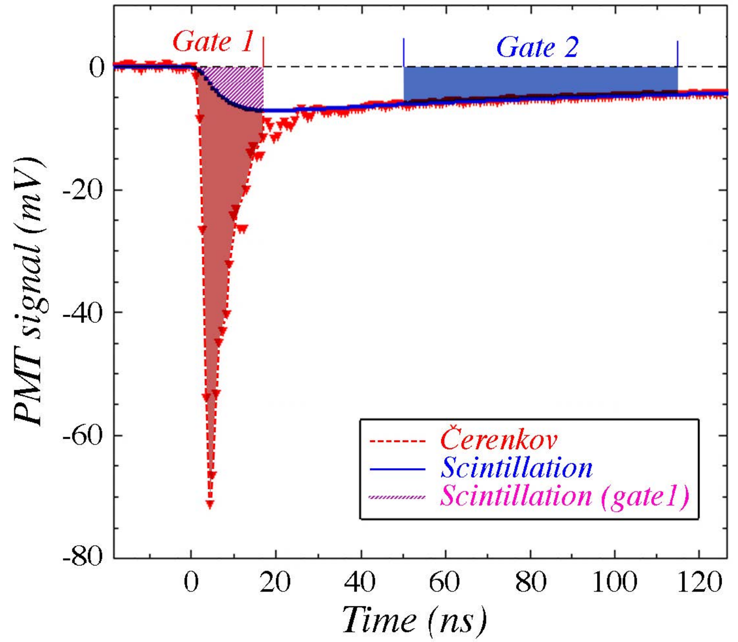
A proof of principle, didn't pursue further for various reasons:

- cost and limitation with PMT readout;
- DRO fiber calorimeter achieved a respectable EM resolution





Nucl. Instr. And Meth. A 595 (2008) 359



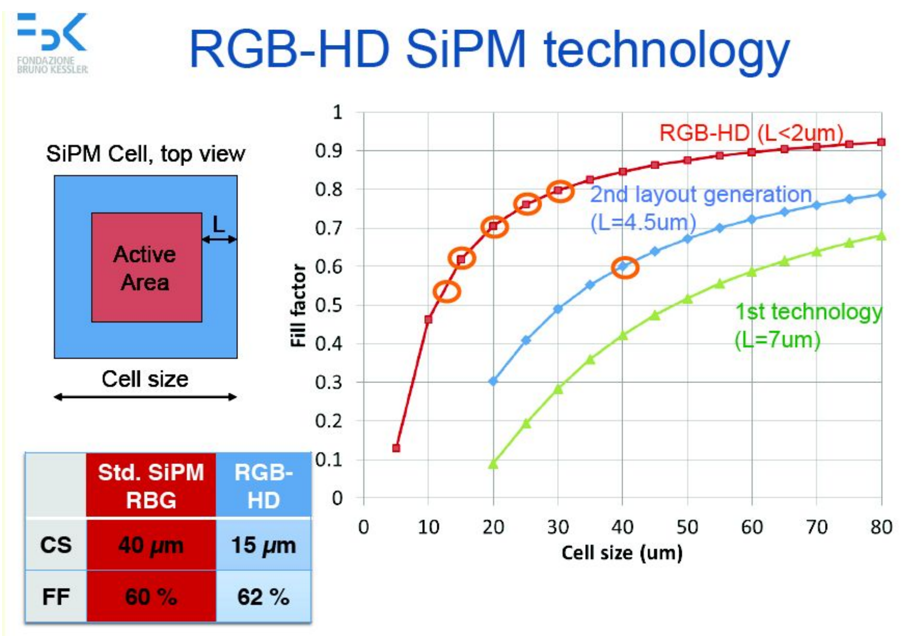
Nucl. Instr. And Meth. A 598 (2009) 710

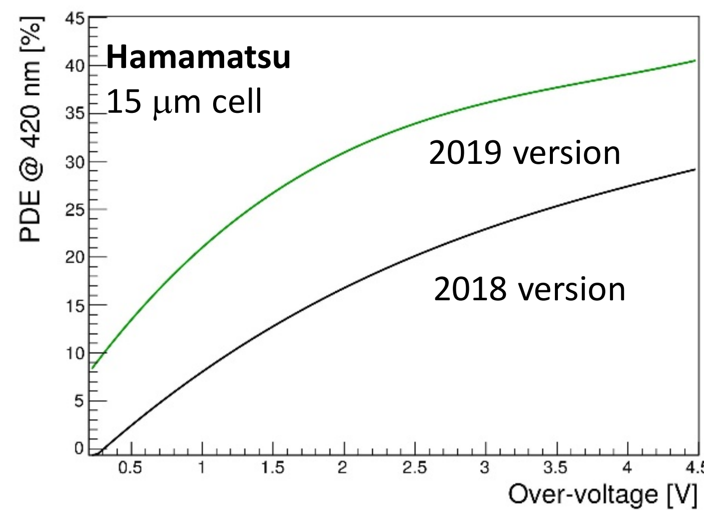
What’s New Since Then?

Technological advancements in photodetectors, particularly the development of Silicon Photomultipliers (SiPMs), have made a DRO crystal ECAL more attractive.

SiPMs offer many advantages over traditional PMTs:
- High Photon Detector Efficiency (PDE);
- Large dynamic ranges;
- Sensitive to a wide range of wavelengths;
- Compact and cost effective; …

SiPMs are relatively new, significant improvements and costs are expected.

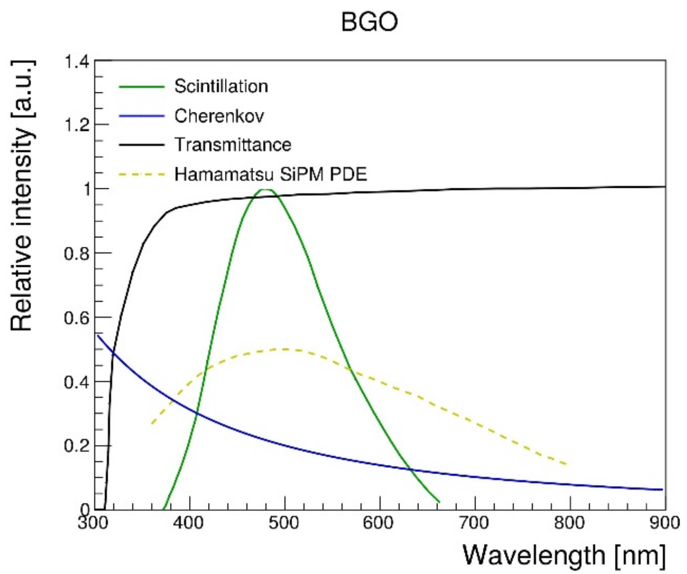




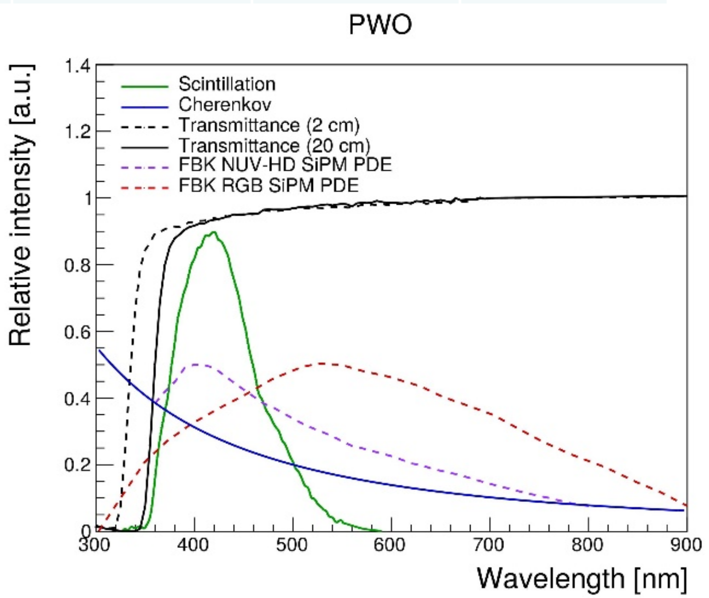
Requirements for Crystals

- Compact: short radiation length;
- Fast signals, high light yields;
- Good separation in wavelengths between S and C signals;
- Cost effective, radiation hard, …

Crystal	Density g/cm²	X_0 cm	λ_I cm	R_M cm	Relative Yield	Decay time ns	Refractive index
PWO	8.3	0.89	20.9	2.00	1.0	10	2.20
BGO	7.1	1.12	22.7	2.23	70	300	2.15
BSO	6.8	1.15	23.4	2.33	14	100	2.15
CsI	4.5	1.86	39.3	3.57	550	1220	1.94

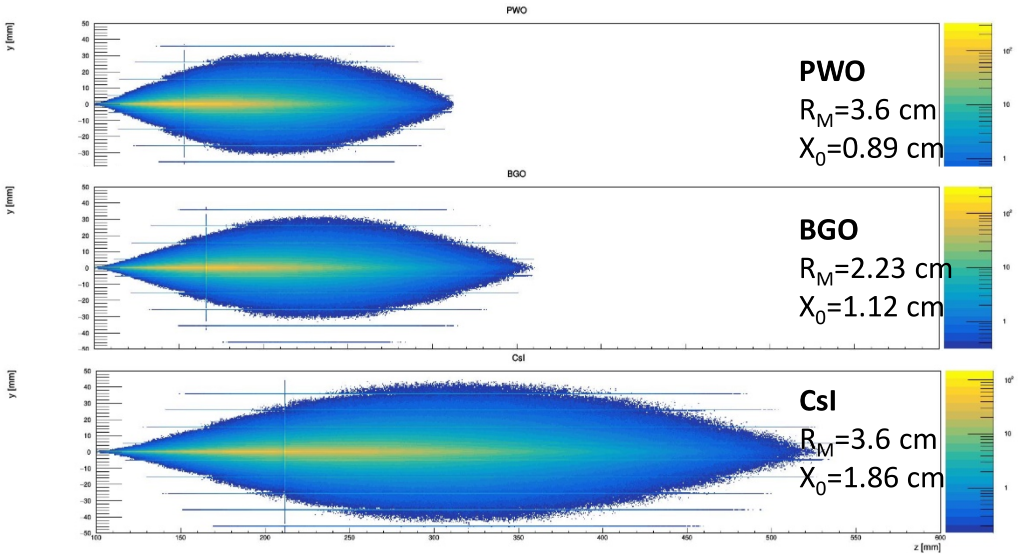


High light yield, but slow



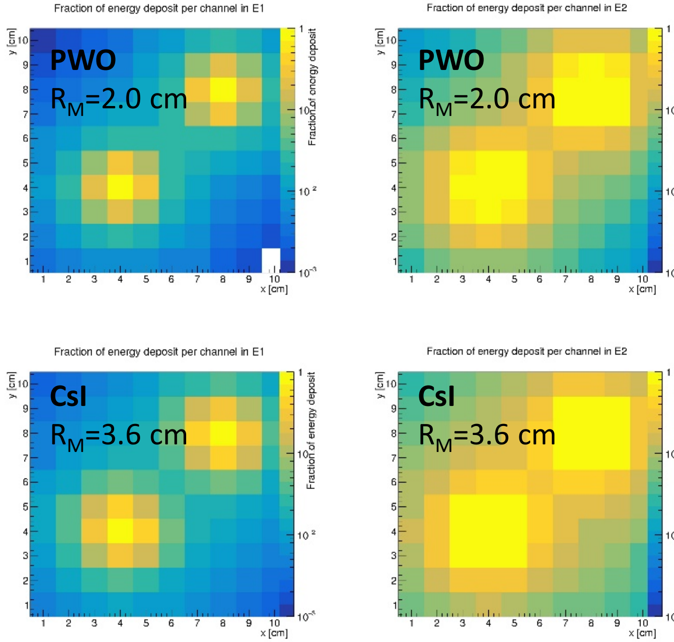
Fast, but low light yield

Some Crystal Options



Longitudinal shower profiles

Transverse two photon separations



PWO:

Fastest, most compact;

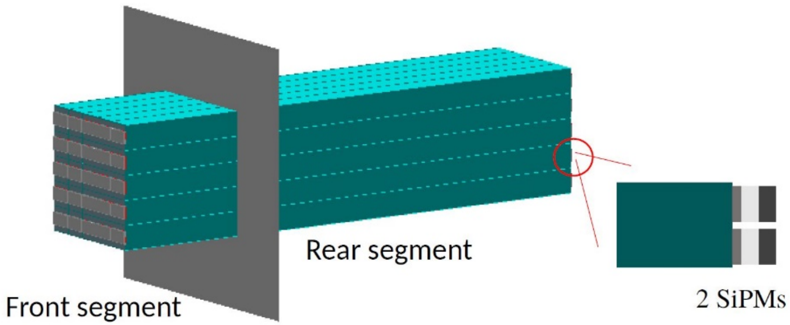
CsI:

the brightest, least compact

BGO:

in between the two

EM Energy Resolution



Front:

Single 5x5 mm^2 SiPM per crystal optimized for scintillator light

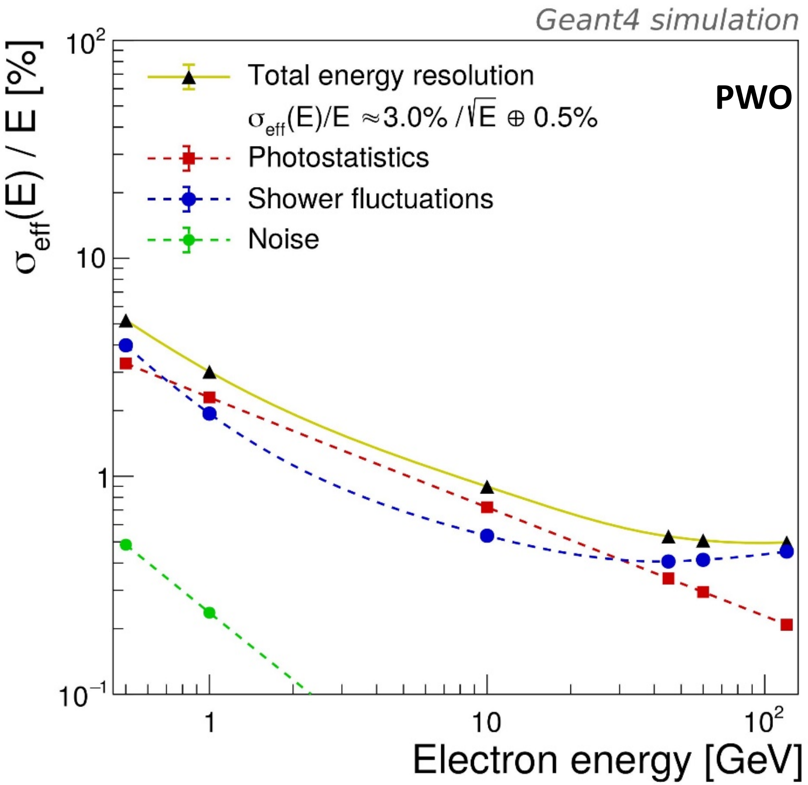
Rear:

2 SiPMs per crystal with optical filters optimized for scintillation and Cherenkov lights

PWO: $\frac{\sigma}{E} \sim \frac{3\%}{\sqrt{E}} \oplus 0.5\%$

Contributions to energy resolution

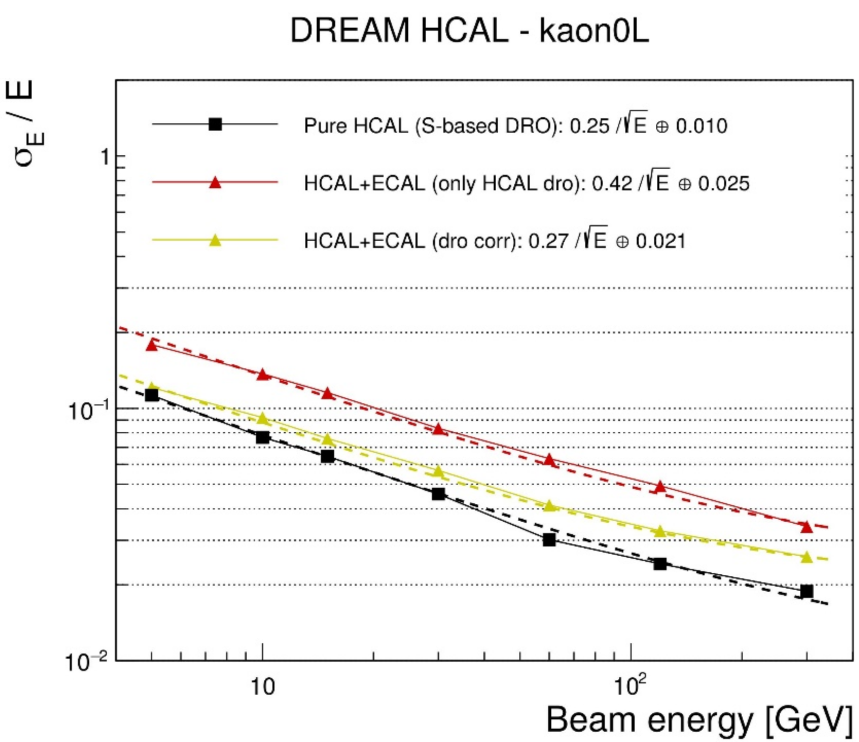
- Shower fluctuations
  Longitudinal shower leakage, materials (tracking, services)
- Photostatistics
  Crystal and SiPM dependent
- Noise
  Negligible because of the high SiPM gain



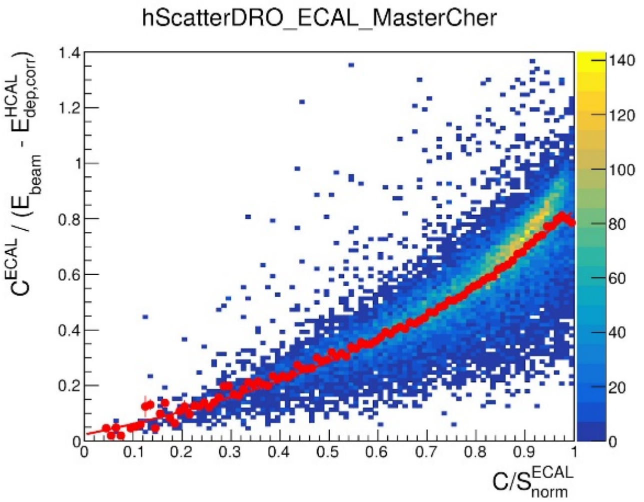
Energy Resolution for Neutral Hadrons

For neutral kaons: $\sim 27\%/\sqrt{E} \oplus 2\%$
slightly worse than a pure DR calorimeter

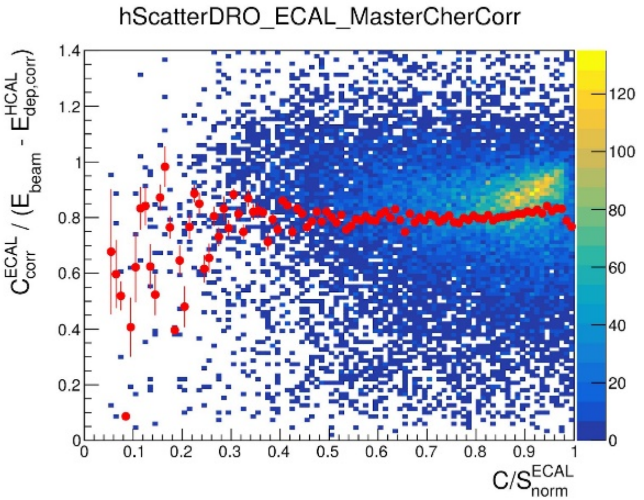
Correct energy deposits in both ECAL and HCAL using DRO information, calibrate the combined ECAL+HCAL energy.



C signal dependence on C/S ratio (proxy for the EM fraction)



Before correction



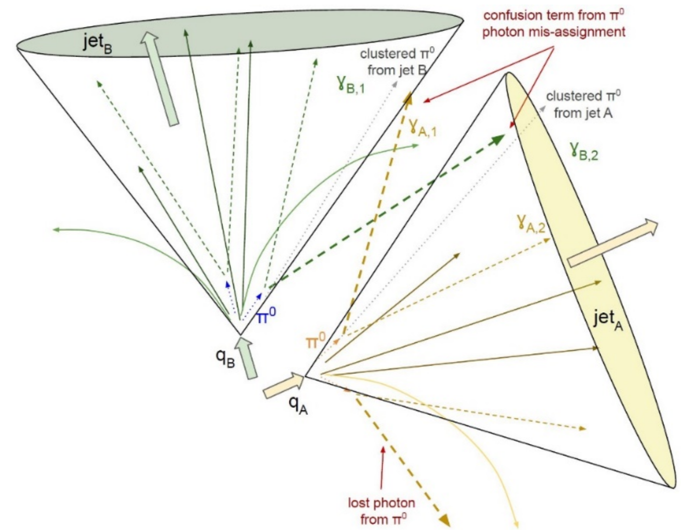
After correction

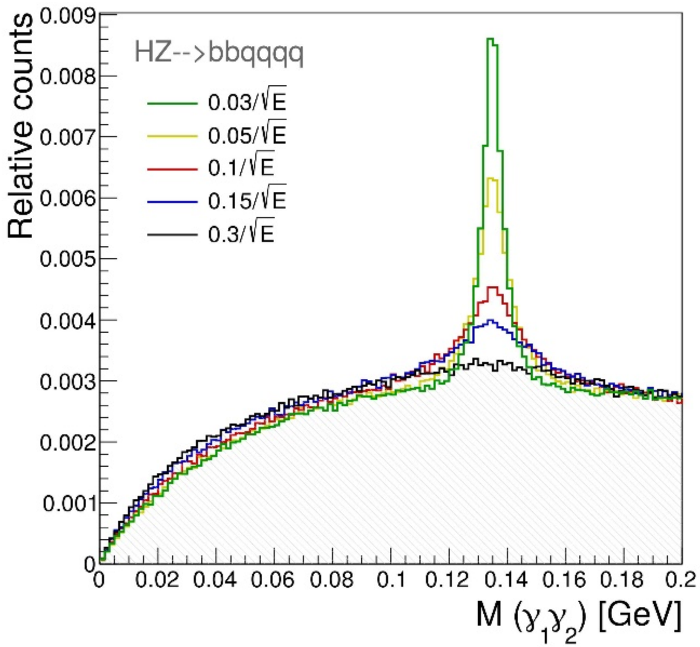
In progress: understanding jet energy resolution.

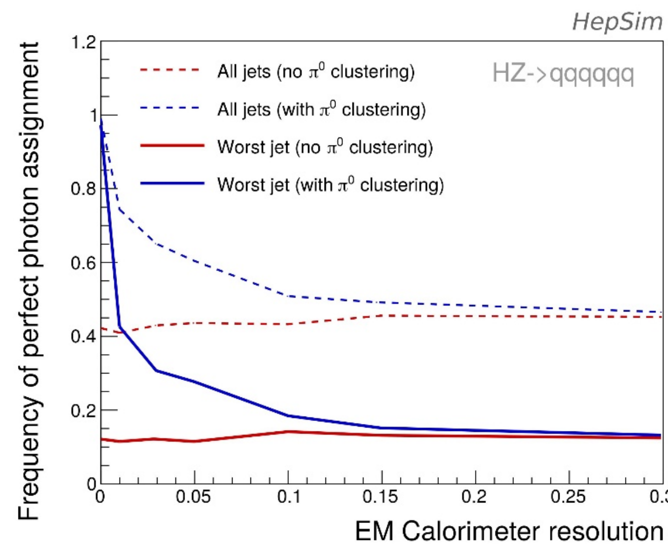
PFA Benefits

Good EM resolution will benefit the PFA too.

In hadronic showers, π^0 is a significant component of neutral particles. Good EM resolution is critical for the π^0 reconstruction and therefore is important for correctly clustering γ's into the right jets.







Fraction of π^0 photons correctly clustered: $\sim 90\%$ for $\sim 3\%/\sqrt{E}$, $\sim 50\%$ for $\sim 30\%/\sqrt{E}$

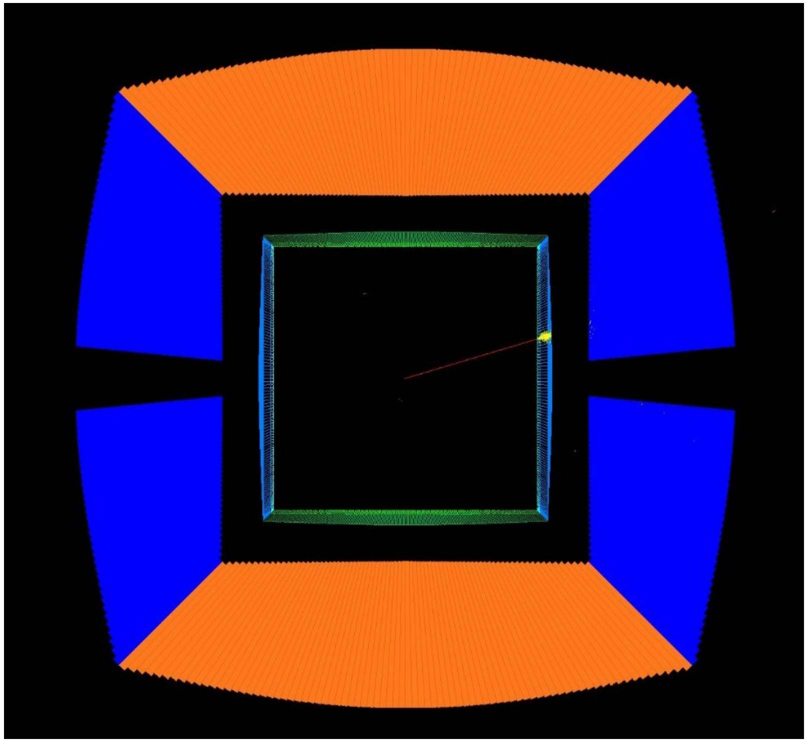
Fraction of photons misclustered: $\sim 10\%$ for $\sim 3\%/\sqrt{E}$, $\sim 50\%$ for $\sim 30\%/\sqrt{E}$

Summary

With the advancement in SiPM technologies, a dual readout crystal ECAL becomes an attractive option for future Higgs factories.

When combined with the DRO fiber HCAL, the EM energy resolution can be significantly improved while the hadronic energy resolution is not expected to be adversely affected.

Significant R&D effort is needed to demonstrate DRO capability of a crystal ECAL through simulation, cosmic and beam tests.



Integration with the IDEA detector concept in simulation to optimize the design of the crystal ECAL.

The CALVISION team plans to carry out of these R&D (if funded).