DR Activities in the US

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On behalf of the CALVISION team

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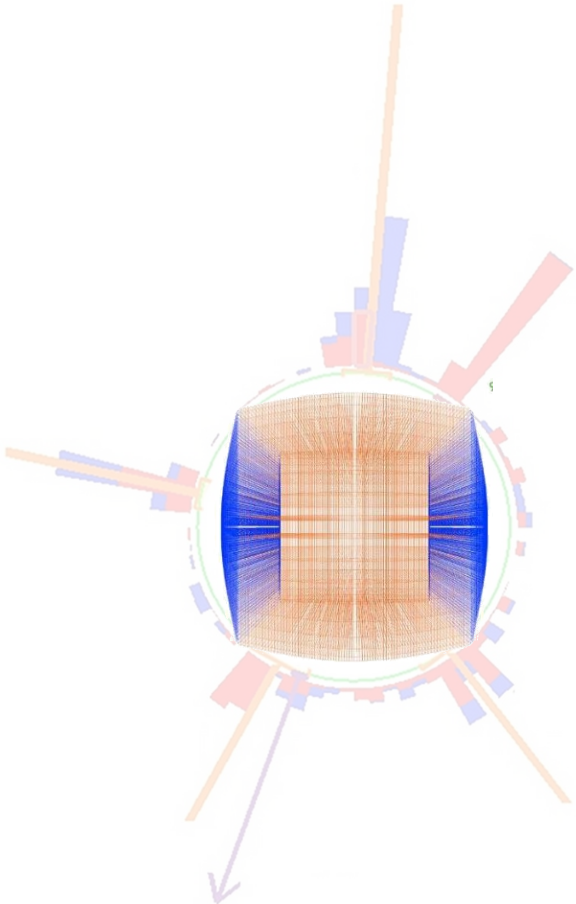


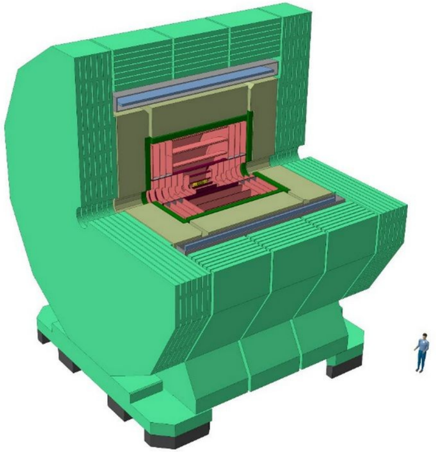
This talk greatly benefits from presentions by Sarah Eno, Marco Lucchini, and the CALVISION team

Detector Concepts

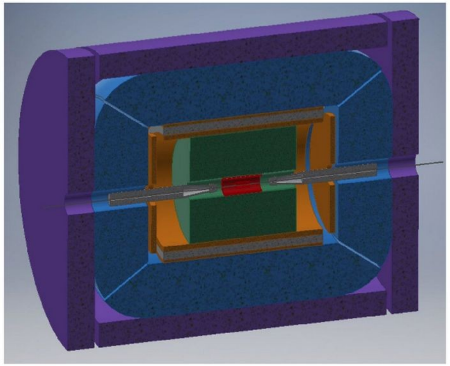
Background on calorimetry options:

- 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.

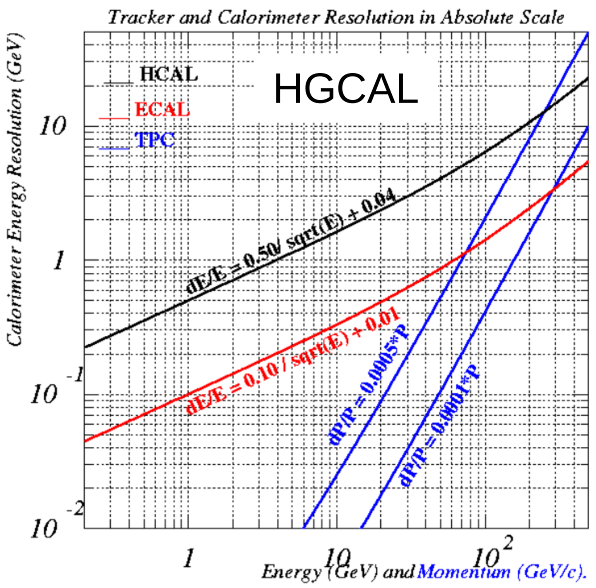


CLD proposed for FCC-ee
(PFA calorimetry)

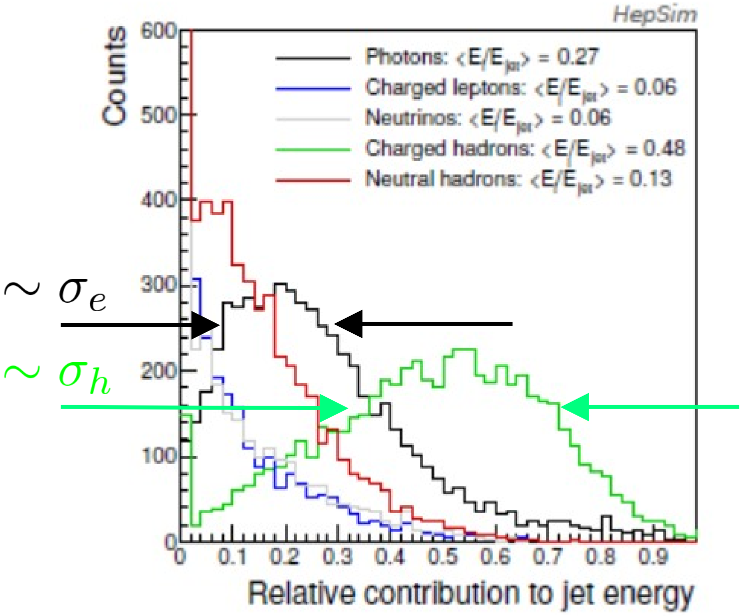


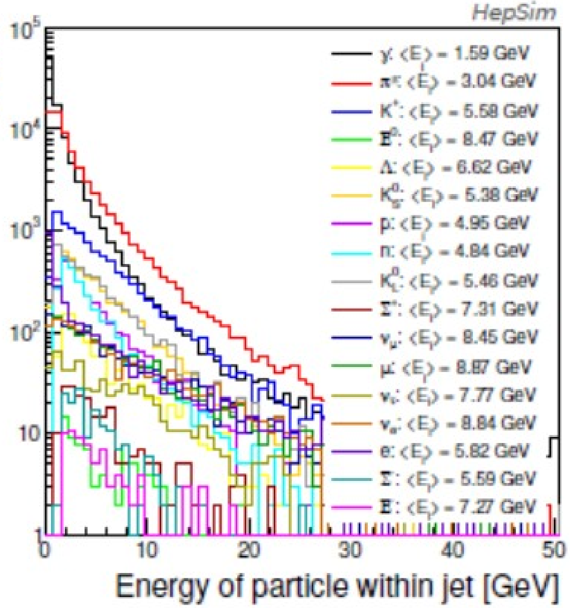
IDEA proposed for FCC-ee and CEPC
(DRO calorimetry)

Fluctuations => moderate calorimeter resolution



$$\sigma_{Jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{Had.} + \sigma^2_{elm.} + \sigma^2_{Confusion}}$$





"Simple" physics to improve performance:

- Improve sampling (lower stochastic terms)
- Response linearity, uniformity, address e/h

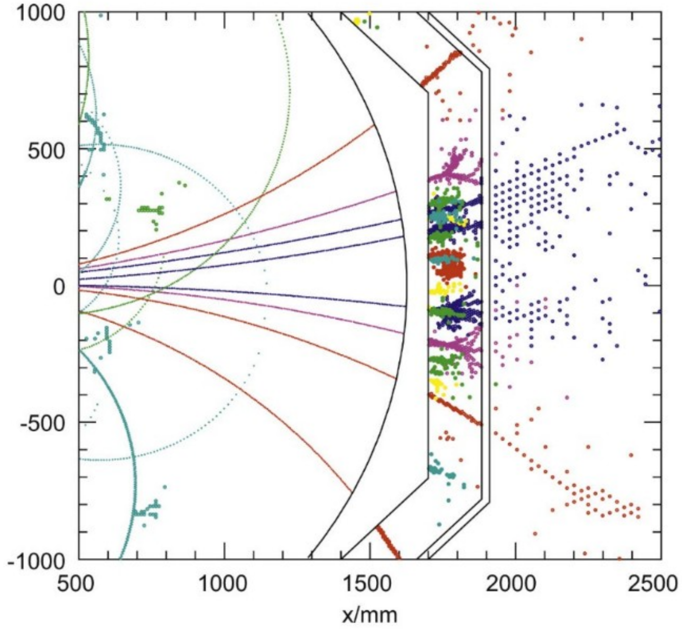
(simultaneous) Calorimeter resolution requirements much better than 50% HAD and 10% EM stochastic terms is where we all want to take the state of the art

PFA Calorimetry

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

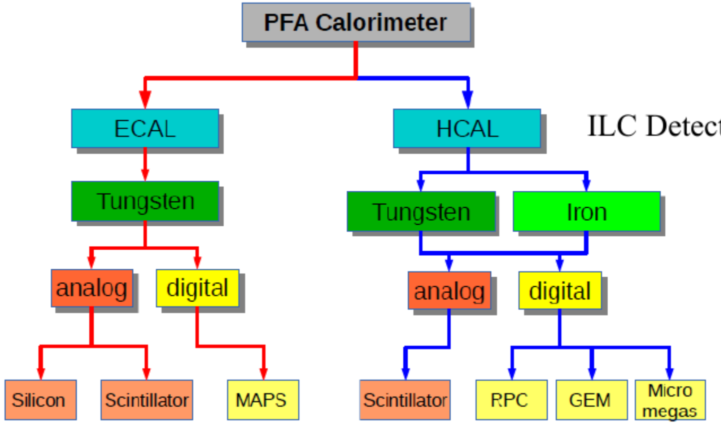
- Charged particles in the tracking detector
- Photons in the electromagnetic calorimeter
- Neutral hadrons in the hadronic calorimeter

Extensive R&D by the CALICE Collaboration



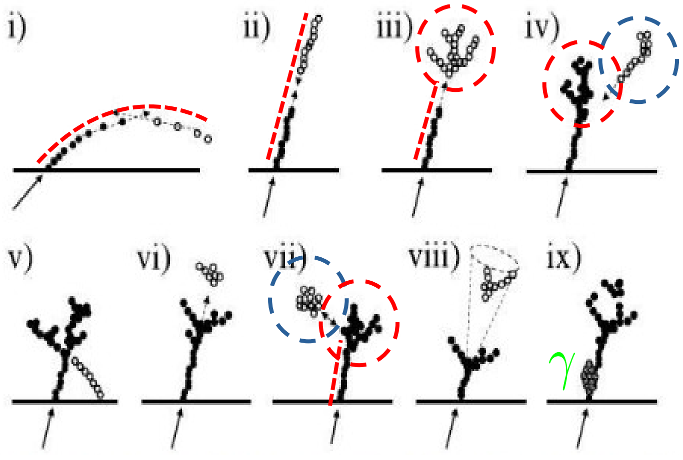
Characteristics:

- High granularities ⇒ large channel count
- relatively small sampling fractions



ILC Detector TDR

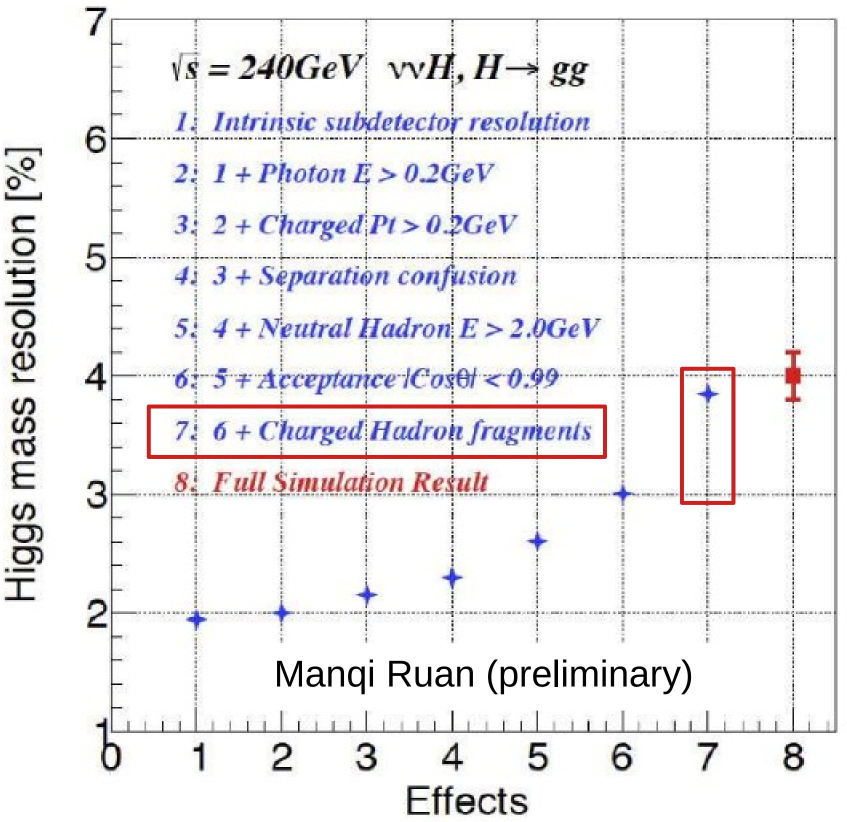
Example from PFA fast simulation



Topological clustering with high granularity calorimetry
Tracks, charged and neutral calo clusters, associated photon radiation

Reliance on pattern recognition/track matching for precision measures

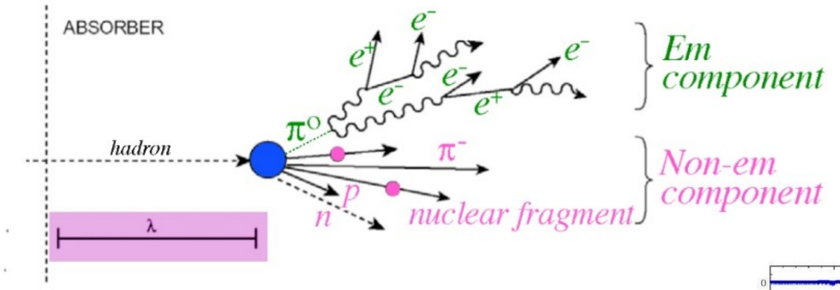
Moderately good resolution achievable
~50% HAD and 10% EM stochastic terms



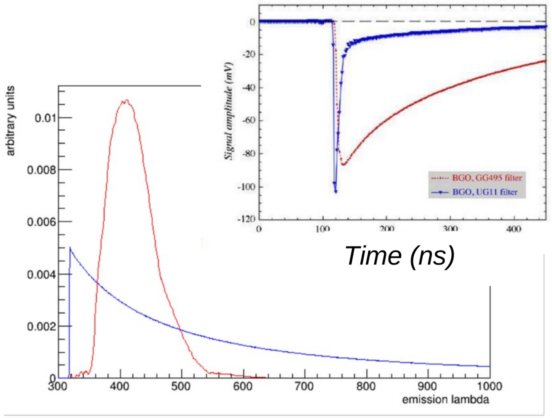
- Pattern recognition is challenging
- Advantages/ complications of large channel counts
- Hadronic resolution remains a leading driver

Dual readout motivation

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



- Cherenkov – relativistic charged particles, mostly electrons
  - Fast, UV to IR light
  - Few photons: require sensing w/ high eff, large area, directionality?
- Scintillation – sensitive to dE/dx energy loss ⇒ charged particles
  - Slower response, scintillator characteristic τ
  - Large signals: smaller, cheaper sensors?



DREAM/RD52/IDEA: sampling terms of 3% for e/γ and 30% for hadrons*

- Use Cherenkov light to measure, shower-by-shower, the fraction of the shower energy in pizeros.
- Use scintillation light to measure all ionizing energy deposits.
- Apply a scale correction that depends on this ratio.

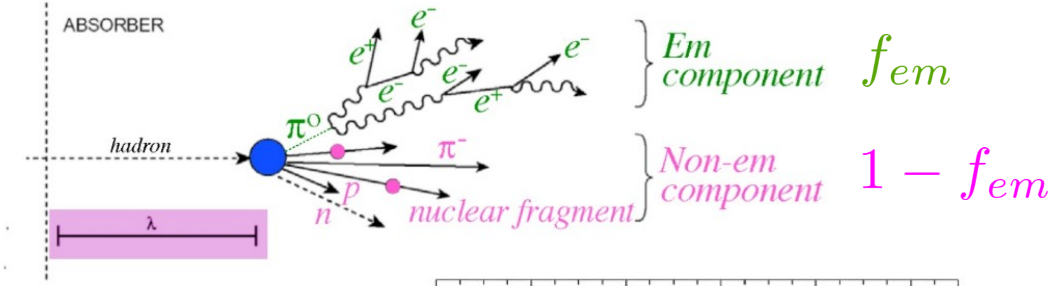
*See eg: arXiv:1807.03853

10.1103/RevModPhys.90.025002

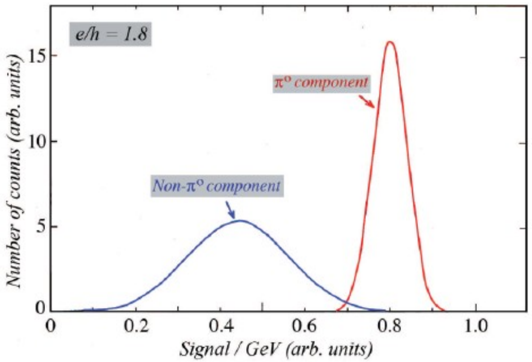
Dual readout motivation

Exploit the fact the e/h is different for Scintillation and Cherenkov readout

- Apply event-by-event e & h corrections



Fluctuations driving hadronic resolution



$$S = E\left[f_{em} + \left(\frac{h}{e}\right)_S (1 - f_{em})\right]$$
$$C = E\left[f_{em} + \left(\frac{h}{e}\right)_C (1 - f_{em})\right]$$

⇩

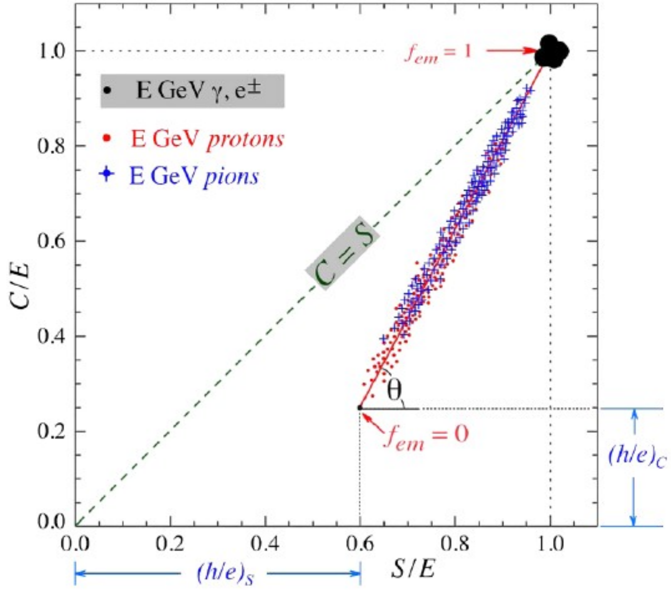
$$\frac{S}{E} = \left(\frac{h}{e}\right)_S + f_{em}\left[1 - \left(\frac{h}{e}\right)_S\right]$$
$$\frac{C}{E} = \left(\frac{h}{e}\right)_C + f_{em}\left[1 - \left(\frac{h}{e}\right)_C\right]$$

$$E = \frac{S - \chi C}{1 - \chi}$$

$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C} = \cot\theta$$

A single correction factor, χ, is independent of the incident hadron's energy

Realizing the performance requires sufficiently good S/C measurements

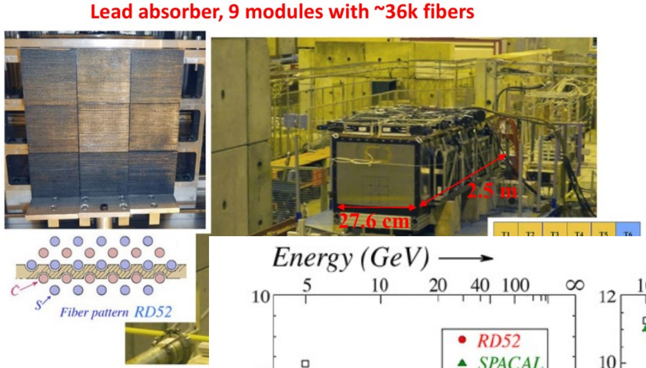


“Traditional” DRO vs crystal calorimeters

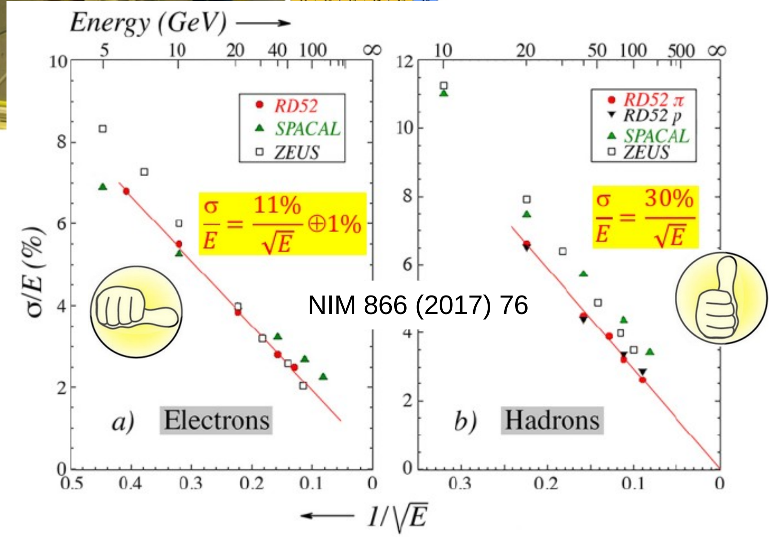
DREAM/RD52/IDEA collaborations

(Rev. Mod. Phys. Vol 90, April 2018)

- Sampling calorimeter with Pb or copper absorber
- Clear and scintillation fibers for C/S readout

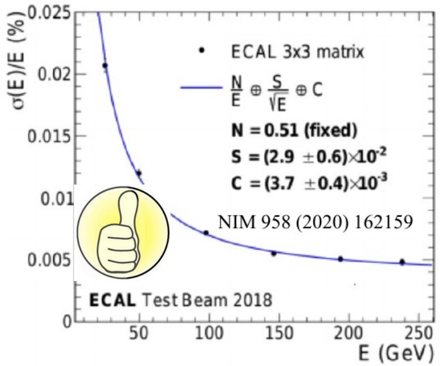


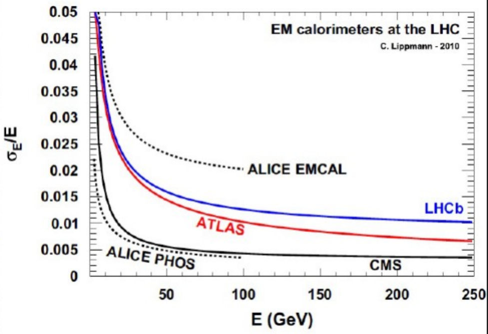
Demonstrated impressive $\sigma(E_{had}) = 30\%/\sqrt{E}$



NIM 866 (2017) 76

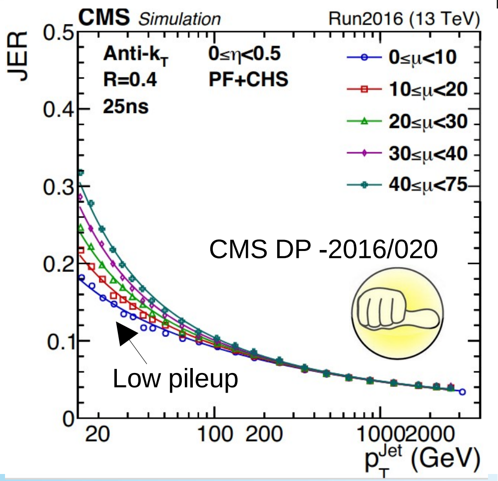
Homogeneous crystal calorimeters have excellent E_{EM} resolutions, ~3%/√E or better!





Next step: aim to combine the best of both worlds

More feasible now due to low cost, high-QE SiPM availability



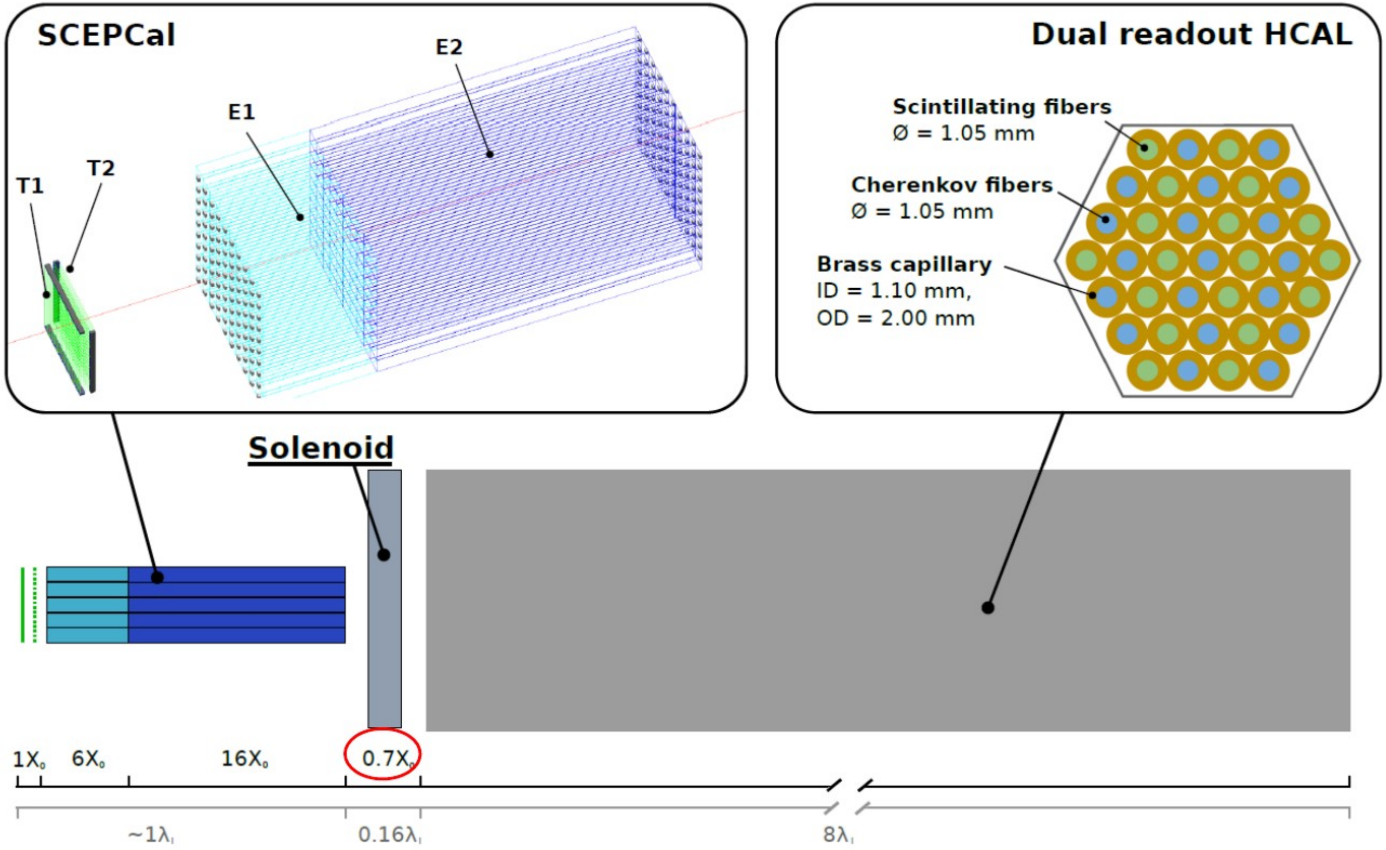
CMS DP -2016/020

A Segmented DRO Crystal ECAL + DRO Fiber HCAL

Concept:

- (Optional) timing layer
- Segmented ECAL
- Thin solenoid
- DREAM/RD52 style HCAL

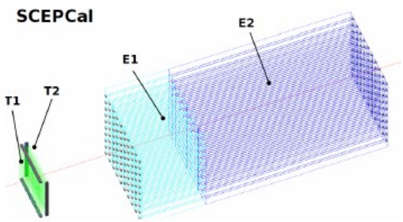
SCEPCal:
Segmented
Crystal
Electromagnetic
Precision
Calorimeter



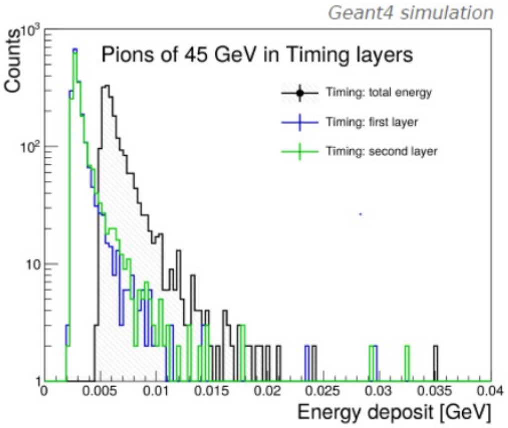
Timing layer concept

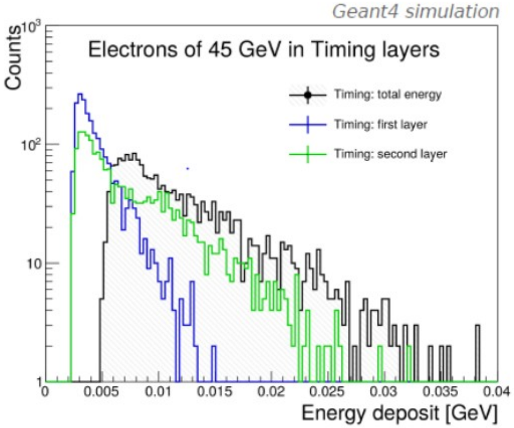
Two timing layers (σ_t~20 ps)

- Similar timing performance as the CMS barrel MIP Timing detector
- LYSO:Ce scintillating crystals (~0.8 X_0), O(10^4) photons/MeV
- 3×3×100 mm3 thin crystal bar
- 3×3 mm2 SiPM (15-20 μm cell size)
- Orthogonal layers => position resolution ~ 1 mm in x-y directions
- Excellent timing resolution will be useful for searches of long-lived particles, and for providing new possibilities for identification of charged hadrons through TOF

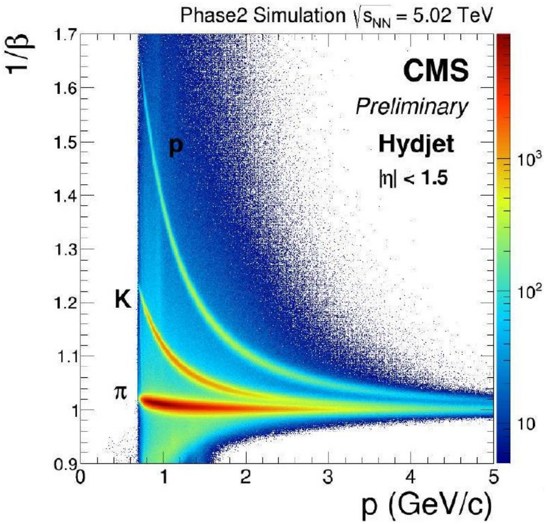


e/π separation





Flavor physics

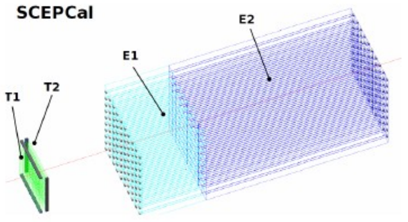


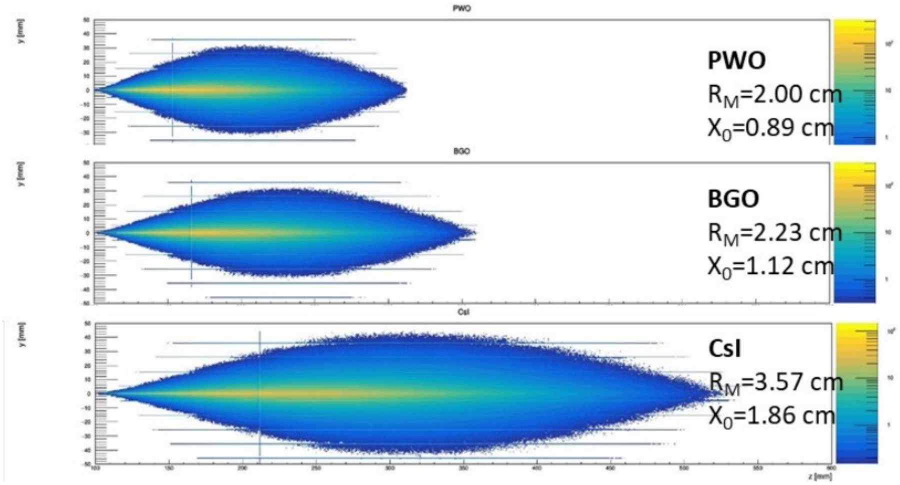
Segmented ECAL

Two layers w/ high density (short X_0, small R_M)

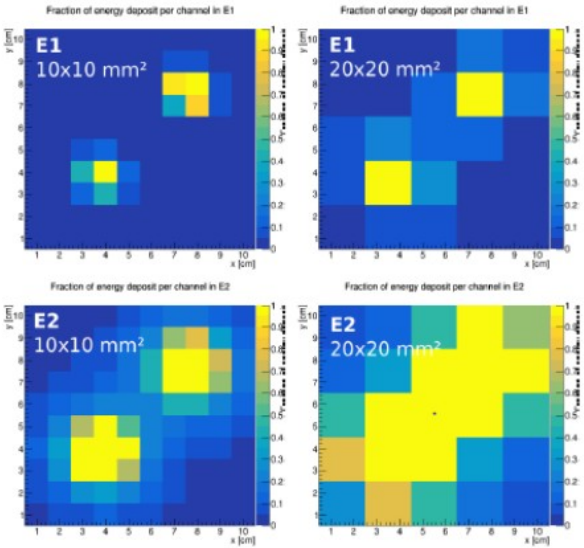
- Fast signal, reasonable C/S ratio cost effective
- **$PbWO_4$**, BGO and BSO are good candidates

Crystal	Density g/cm²	X_0 cm	λ_I cm	R_M cm	Relative Yield	Decay time ns	Refractive index
$PbWO_4$	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





Longitudinal profiles

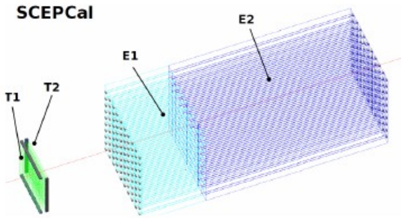


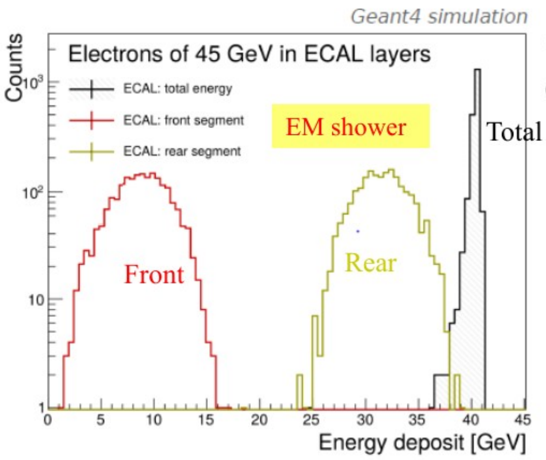
Separation of photons w/ 3° opening angle

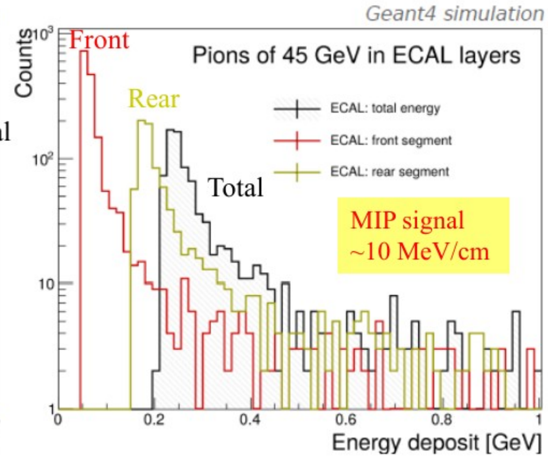
Segmented ECAL

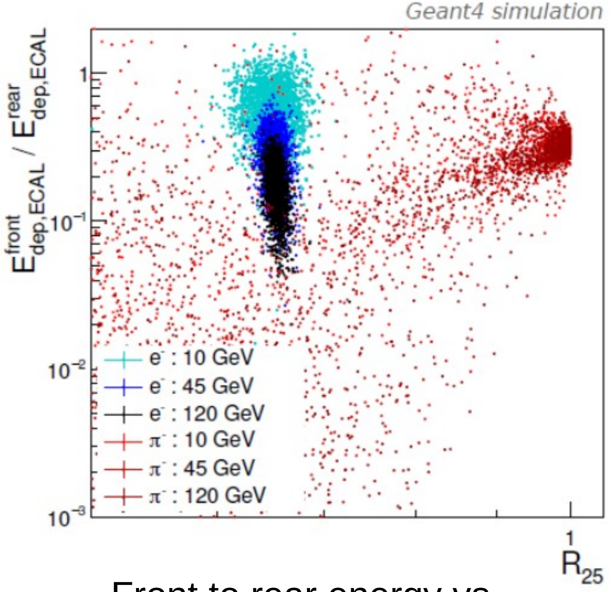
Two segmentation layers

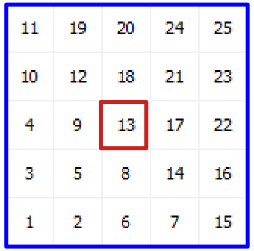
- Front segment (~6 X_0, ~50 mm)
- Rear segment (~16 X_0, ~140 mm)
- Longitudinal segmentation useful for the separation of electrons and pions (can also be included in e/γ, separation methods)











$$R_{25} = \frac{\text{cell 13}}{\text{5x5}}$$

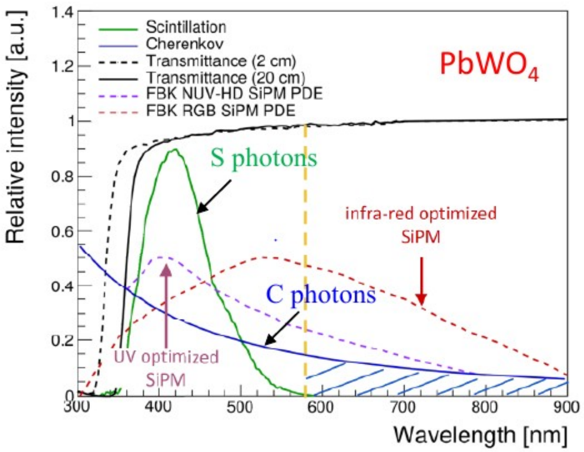
Front to rear energy vs transverse distribution

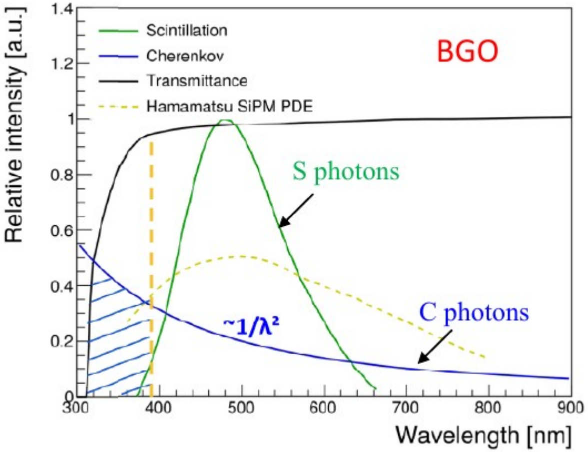
Segmented ECAL

Light collection

- 5×5 mm^2 SiPM (10-15 μm cell size)
  - Rely on optical filters to separate S and C
- 3 SiPMs (one on entrance, two on exit)
  - Front: optimized for scintillation light
  - Rear: two SiPMs optimized for scintillation and Cerenkov light

	Scintillation [photons/GeV]	f_S [%]	Cherenkov [photons/GeV]	f_C [%]
Generated	200000	100	56000	100
Collected	10000	5.0	2130	3.8
Detected by NUV SiPM #1 ($\lambda < 550$ nm)	2000	1.0	140	0.25
Detected by RGB SiPM #2 ($\lambda > 550$ nm)	< 20	< 0.01	160	0.3





Light yield ($PbWO_4$): ~200 S and ~56 C photons/MeV

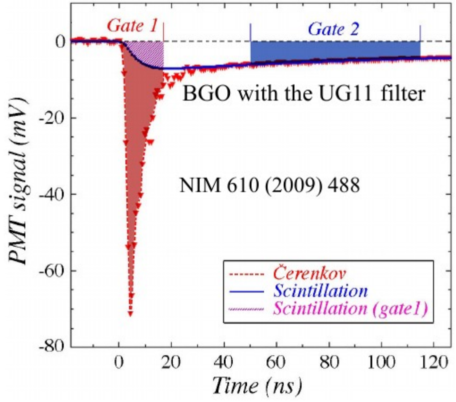
- Local collection eff: ~5% assumed
- PDE: ~20% assumed

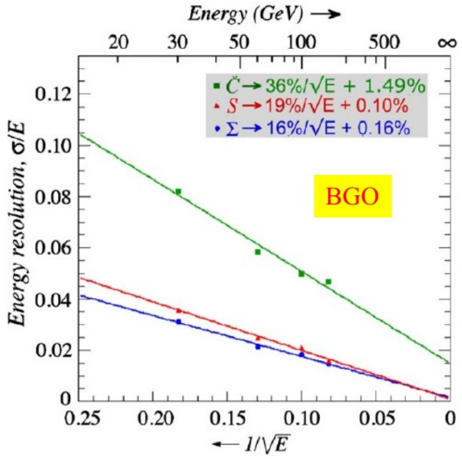
Previous DREAM/RD52 results on DRO Crystal Calorimeter

DREAM/RD52 has previously investigated DRO of crystals with PMTs using BOTH optical filters and timing to separate C and S signals (NIM 686 (2012) 125)

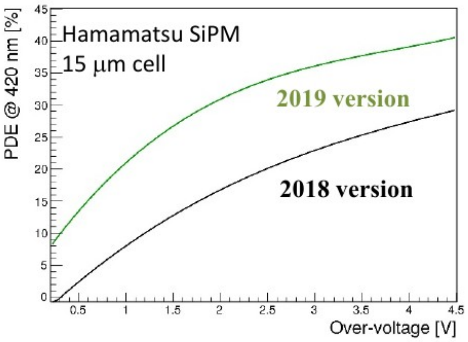
A proof of principle for a DRO crystal calorimeter, but

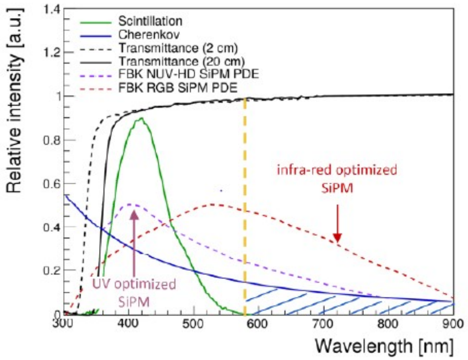
- Worse electron energy resolution (~15-30%/√E) than best xtal calorimeters (~3%/√E)
- Resolution dominated by limited statistics for # of photons detected (only a small fraction of C and S photons are selected)
- Not pursued further:
  - Cost with PMT readout
  - Limited wavelength sensetivity
  - ‘acceptable’ EM resolution demonstrated in fiber calorimeter





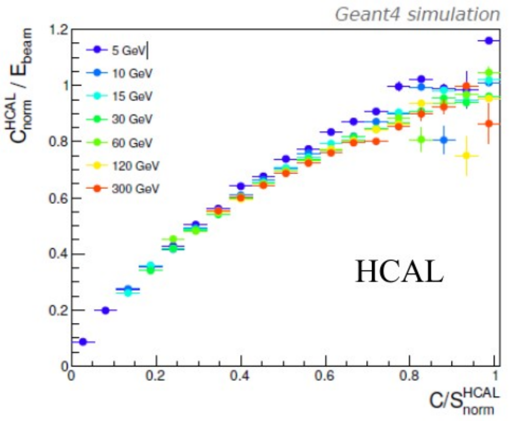
=====>
Today: SiPM performance has vastly improved

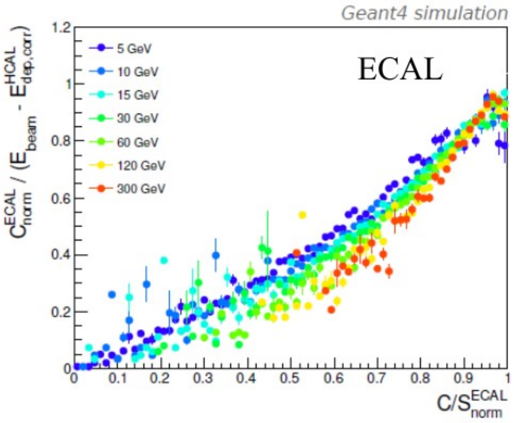




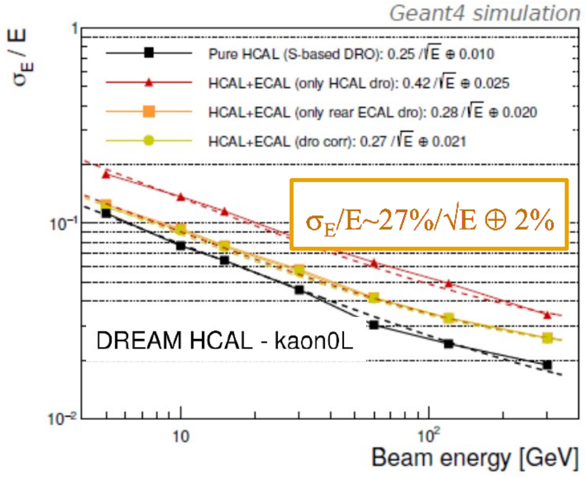
Fast, affordable, tunable λ sensitivity

SCEPCal +DRO HCAL performance studies





Neutral Hadron Energy Resolution

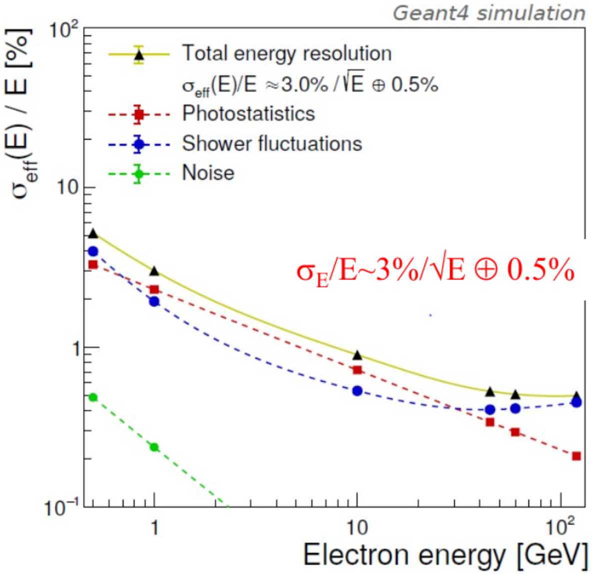


Similar sampling term as that of a pure DRO HCAL

Slightly larger constant term:

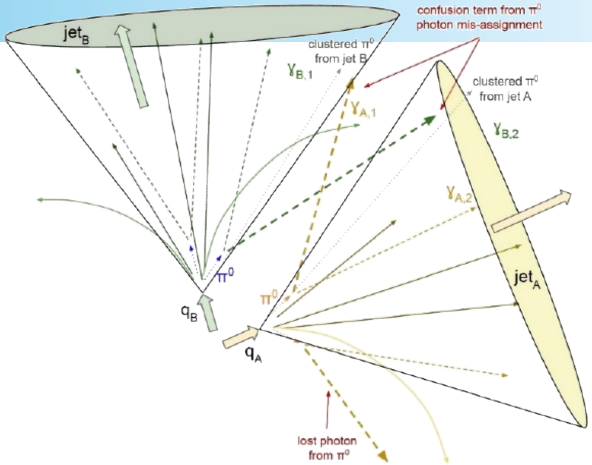
- intrinsic limitation system combining segments with different e/h ratios
- material budget from the ECAL services and the solenoid

Electron energy resolution



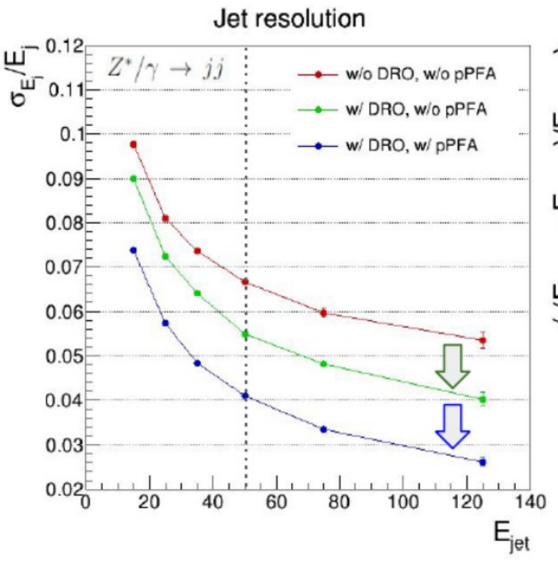
Electron energy resolution maintained at level of best crystal calorimeters

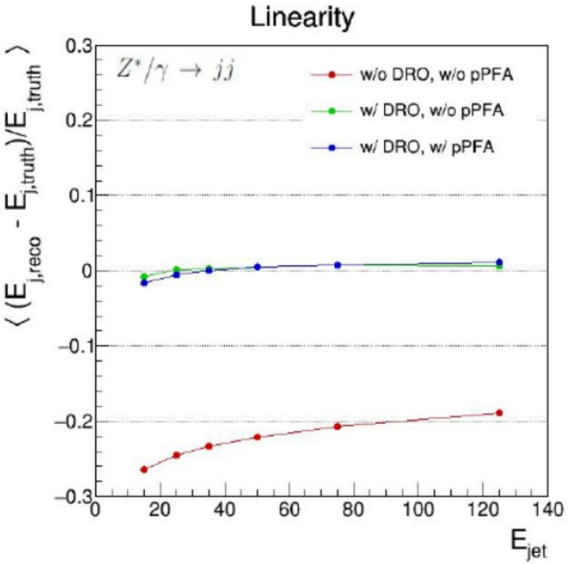
Adding particle flow



The crystal ECAL is "particle-flow friendly"

- Relatively compact showers
  - O(1 mm) transverse segmentation for timing layers
  - O(1 cm) transverse segmentation for ECAL
  - High EM resolution for π^0 clustering
- Improve 'confusion term'
- Timing and dual-readout information for additional handling of particle ID
- Maximally exploit object identification, high resolution and linear response provided by the crystal ECAL to improve the tracker-calorimeter hit matching in PFA





Organization of effort

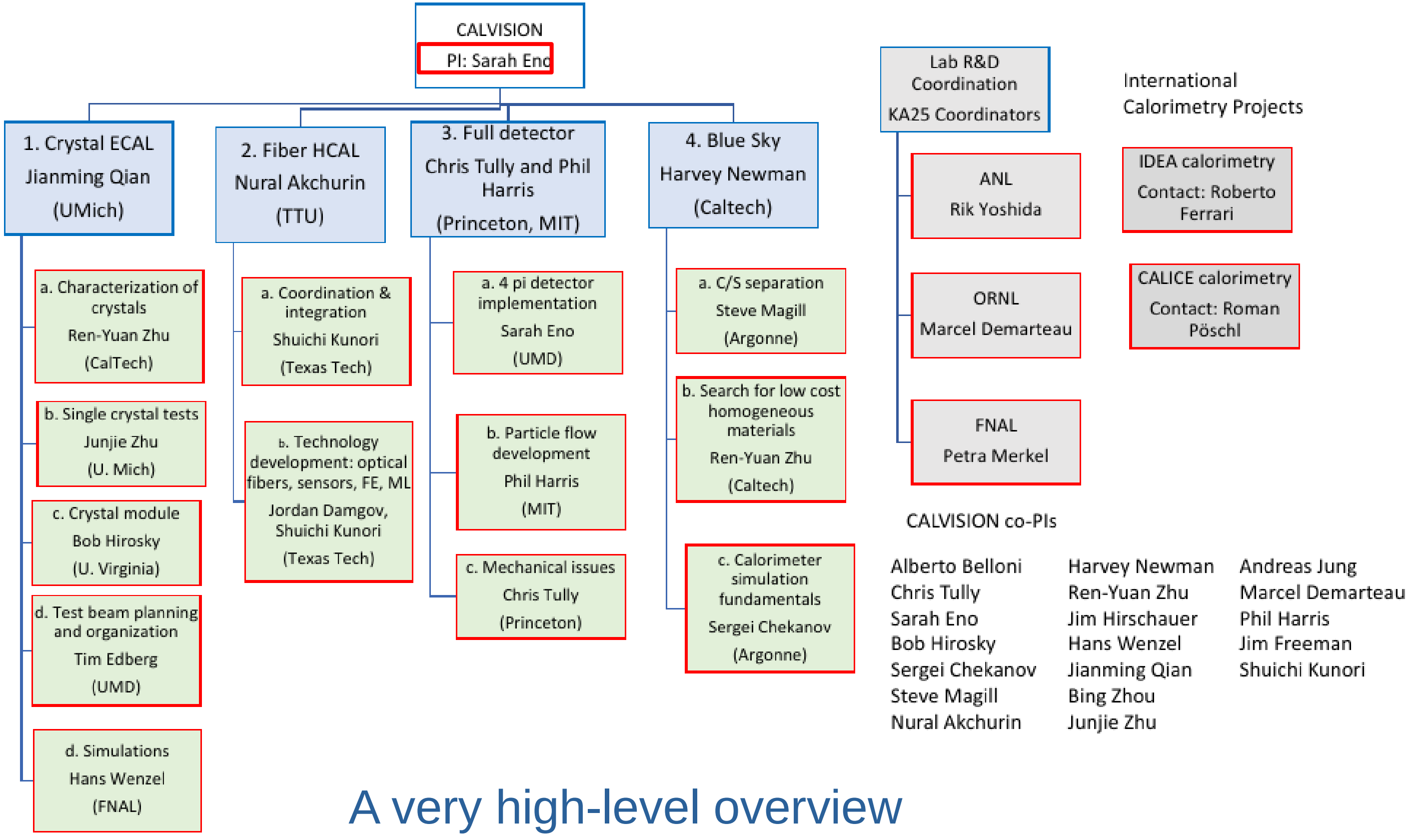
CALVISION Collaboration formed to pursue calorimetry efforts on multiple fronts:

- Crystal DRO Ecal
- Fiber DRO HCAL
- Full Detector studies
- BlueSky R&D

Multi-year efforts proposed in each area.

1st phase is spring '22--'25

- Lower level R&D
- Single modules, small arrays
- materials/technology evaluations
- Scale up modules in next phase



A very high-level overview of planned activities follows

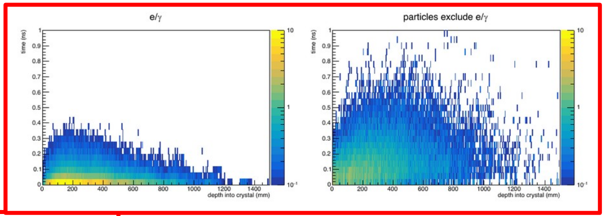
Crystal ECAL

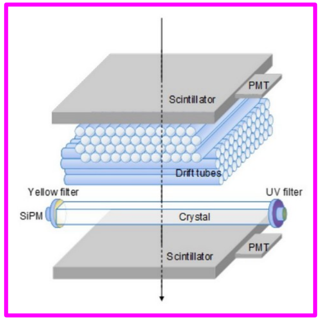
R&D plans

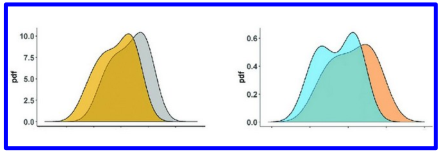
- Crystal properties measurements, light collection studies (fast lasers, sources, cosmics)
- Development of fast optical simulation frmwk(s)
- Mechanical and readout design of modules for 1st test beams
- Portable tracker design for integral DAQ

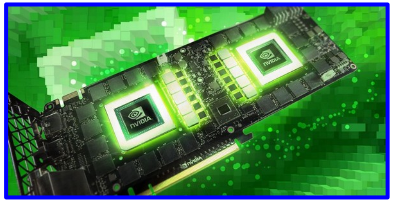
- Test beam w/ single module prototypes
- Measure C and S yields vs particle species
- Continue simulation development, characterize components/materials
- Development of ~8x8 matrix: mechanical, electrical, laser calibration systems

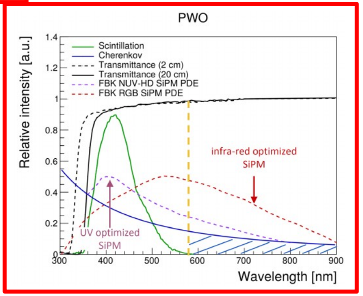
- Beam tests of 8x8 assembly
- Validate, tune simulation
- Prepare new matrix/DAQ for joint tests with fiber HCAL (IDEA collaboration) in next funding cycle

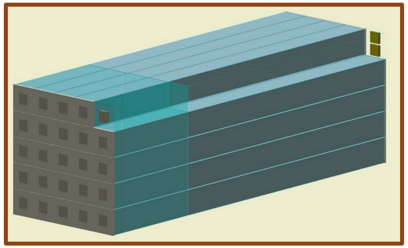


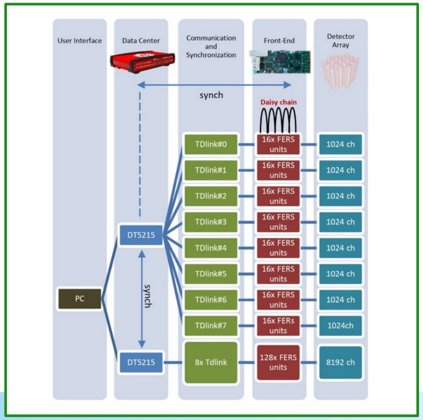






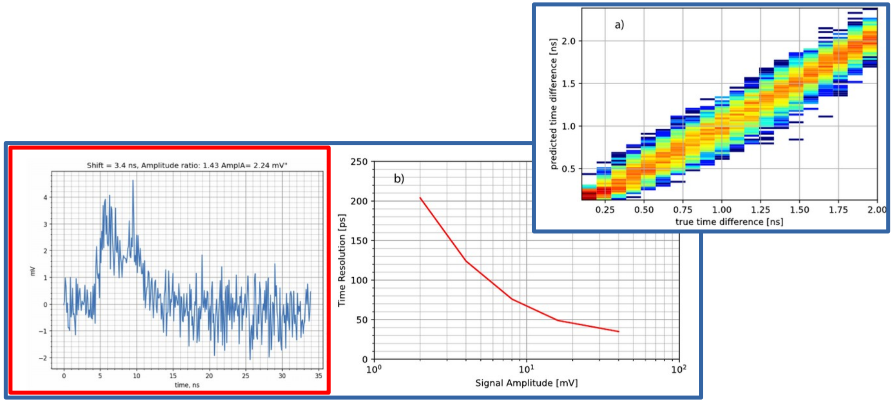


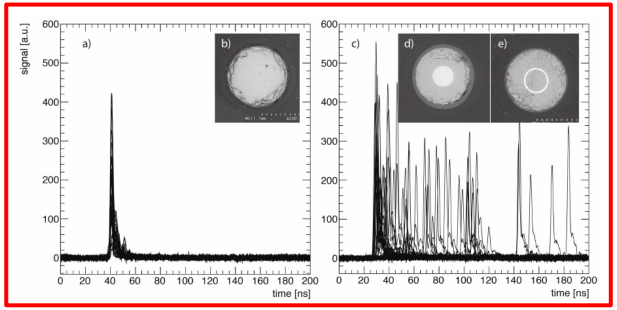


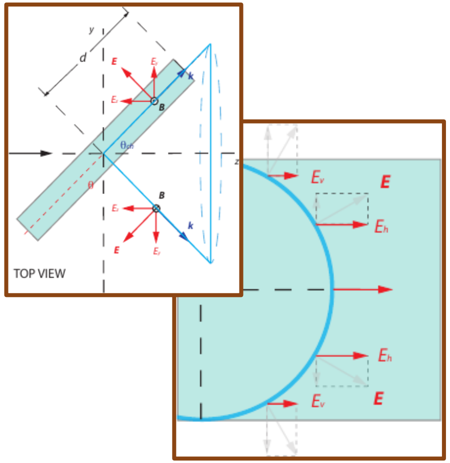


R&D plans

Fiber HCAL







- SiPM and dSiPM, materials characterization
- Develop GEANT4 simulation framework
- Reconstruction algo studies
- Material properties studies
- Explore timing performance using fast lasers

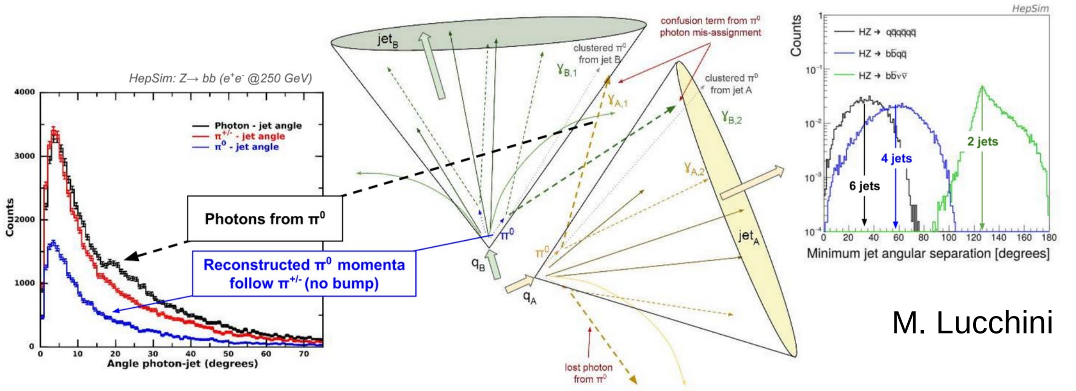
- Scale readout electronics to ~512 channels
- High energy test beams, evaluate performance of fiber types
- Analyze measured waveforms for longitudinal segmentation with timing
- ML studies for on-detector RECO

- Focus on test beam with fast readout capabilities
- Expand channel count
- Develop scalable calibration methods

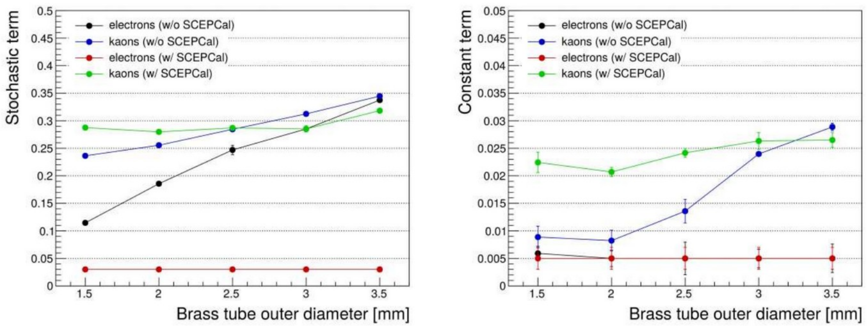
R&D plans

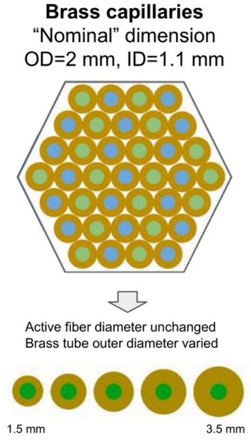
Full detector

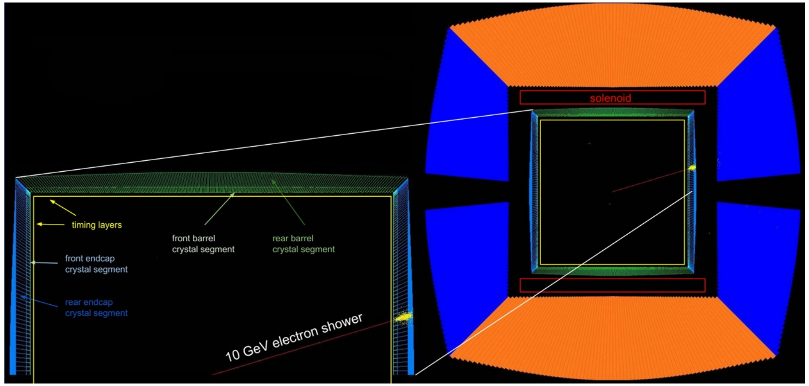
- An overall simulation plan spans 3 years of the proposal
- Develop Hybrid Dual-Readout calorimeter simulation on DD4HEP
- PF/ML/AI studies: neutral hadron clustering, sampling optimizations, deep learning for clustering
- Homogenous HCAL (HHCAL) frame work and studies
- Develop carbon fiber crystal mechanics and large scale structure assemblies



M. Lucchini



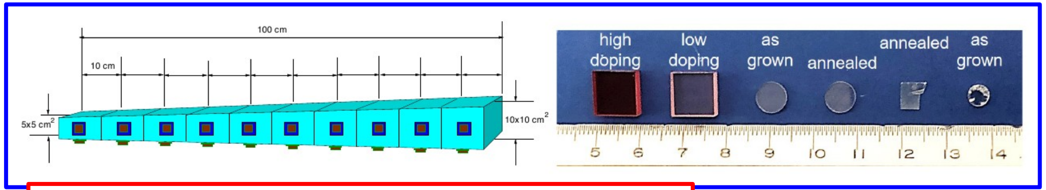


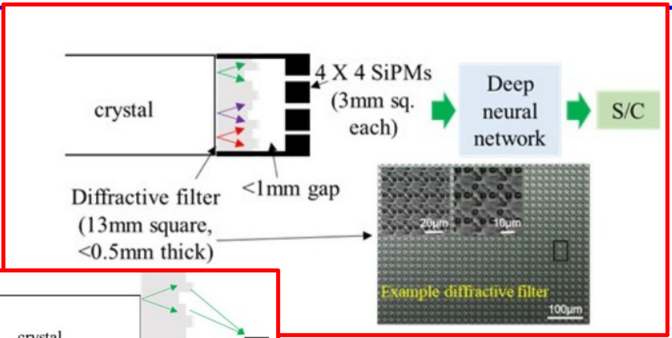


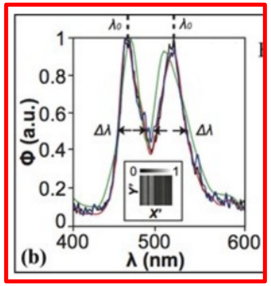
M. Lucchini

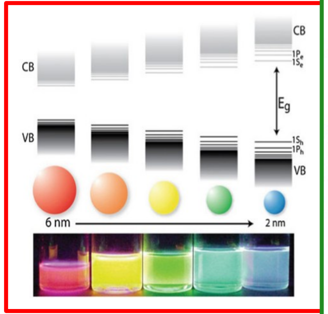
R&D plans

Blue sky









Current SoC-ASIC Projects

Project	Sampling Frequency (GHz)	Input BW (GHz)	Buffer Length (Samples)	Number of Channels	Timing Resolution (ps)	Available Date
ASoC	3-5	0.8	16k	4	35	Rev 3 avail
HDSoC	1-3	0.6	2k	64	80-120	May'21
AARDVARC	8-14	2.5	32k	4	4	Rev 3 avail
AODS	1-2	1	16k	1-4	100-200	Rev 1 avail
STRAWZ	5	2	2k	64	10	Dec'22

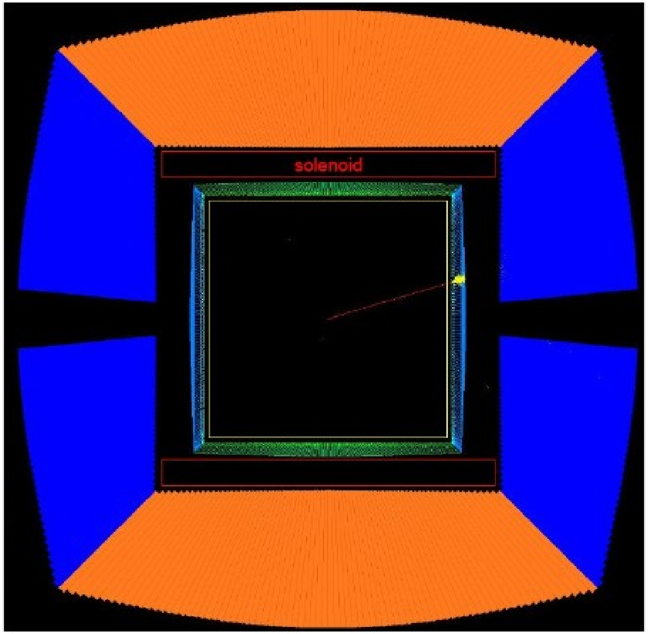
- Survey of potential cost effective inorganic scintillators for HHCAL concept (eg Gd loaded heavy glasses)
- Characterization of test samples, iterate with producers on properties and feasibility of large size samples

- Enhancement studies for C/S light separation, evaluating:
  - Quantum dot waveshifters
  - Interference filters
  - Engineered diffraction filters
  - Field-Programmable Analog Arrays (FPAA) System-on-Chip ASIC platforms
  - Waveform digitizers for real-time processing and classification

- **ASoC**: Analog to digital converter System-on-Chip
- **HDSoC**: SiPM specialized readout chip with bias and control
- **AARDVARC**: Variable rate readout chip for fast timing and low deadtime
- **AODS:** Low density digitizer with High Dynamic Range (HDR) option
- **STRAWZ:** Streaming Autonomous Waveform-digitizer with Zero-suppression

Conclude

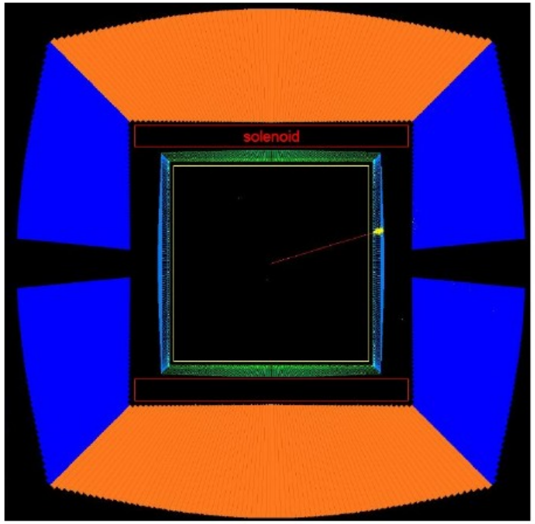
With the advancement in SiPM technologies, a dual readout crystal ECAL becomes an attractive option for future Higgs factories.

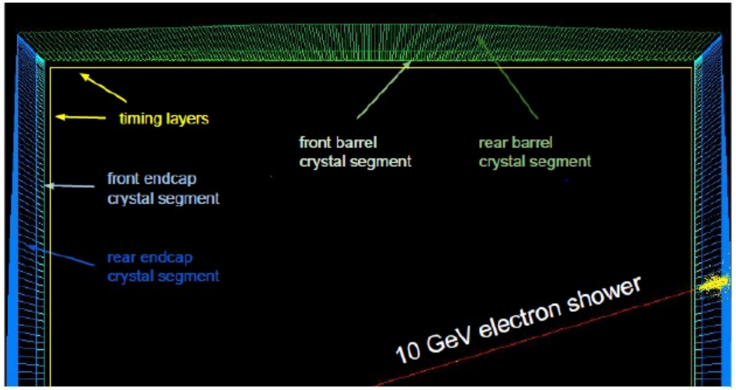


- When combined with the DRO fiber HCAL, state of the art EM energy resolution can be achieved (~3%/√E), while the neutral hadron energy resolution is consistent with a pure DRO hadronic calorimeter
- Significant R&D effort is needed to demonstrate DRO capability of a segmented crystal ECAL through simulation,cosmic ray and beam tests
- Plans include integration with the IDEA detector concept in the simulation to optimize the design of the crystal ECAL
  - The DRO crystal ECAL could also be combined with a high granularity HCAL
- New materials and technologies are developing rapidly, maintain 'blue sky' initiatives for possible performance/cost benefits
- The CALVISION team R&D plans are shovel ready w/ people and laboratory resources. Hoping for positive funding news!

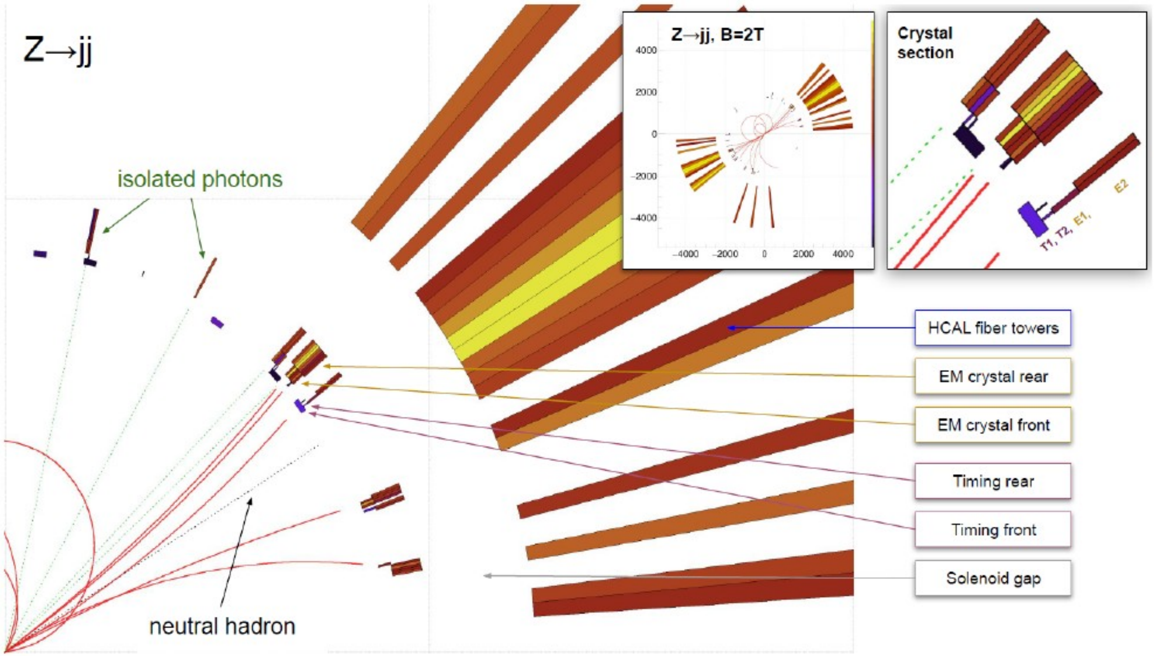
Additional slides

GEANT Simulation: Z->jj Event Display



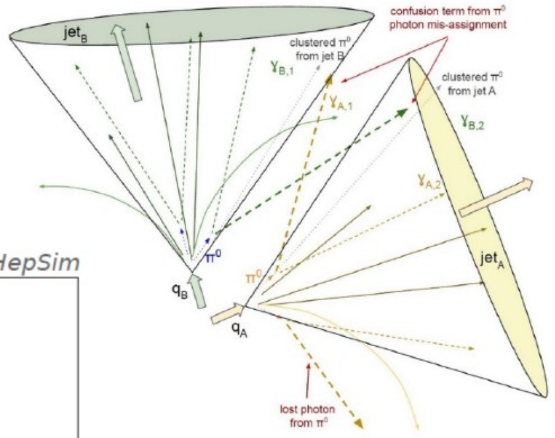


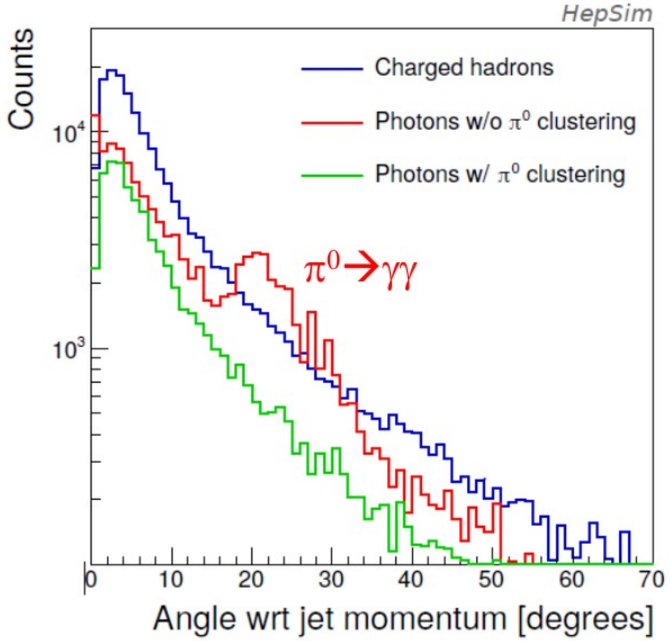
Lucchini, EPS-HEP Conf 2021

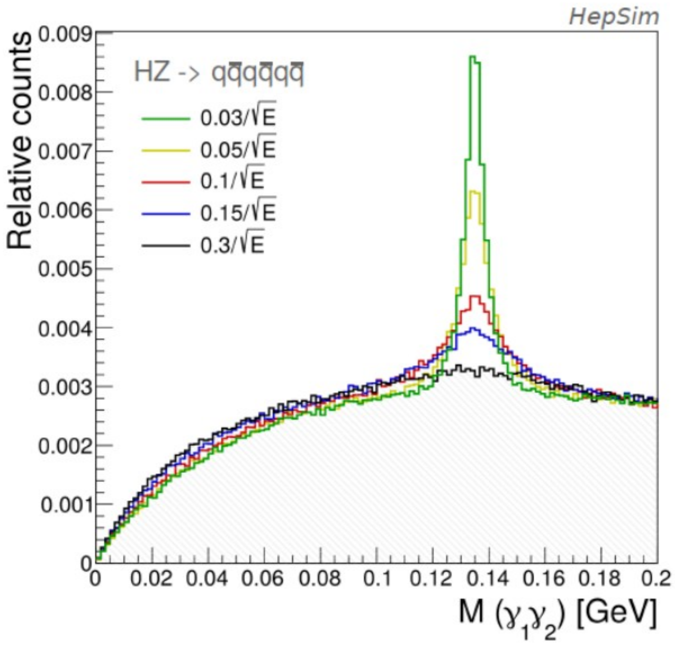


Advantages with a High-resolution EM Calorimeter

- 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

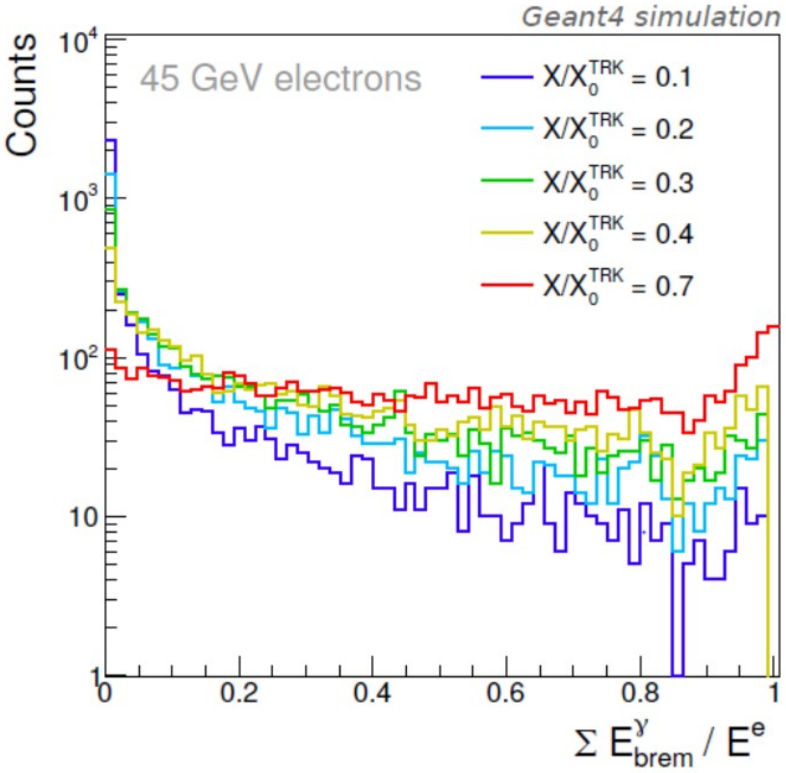


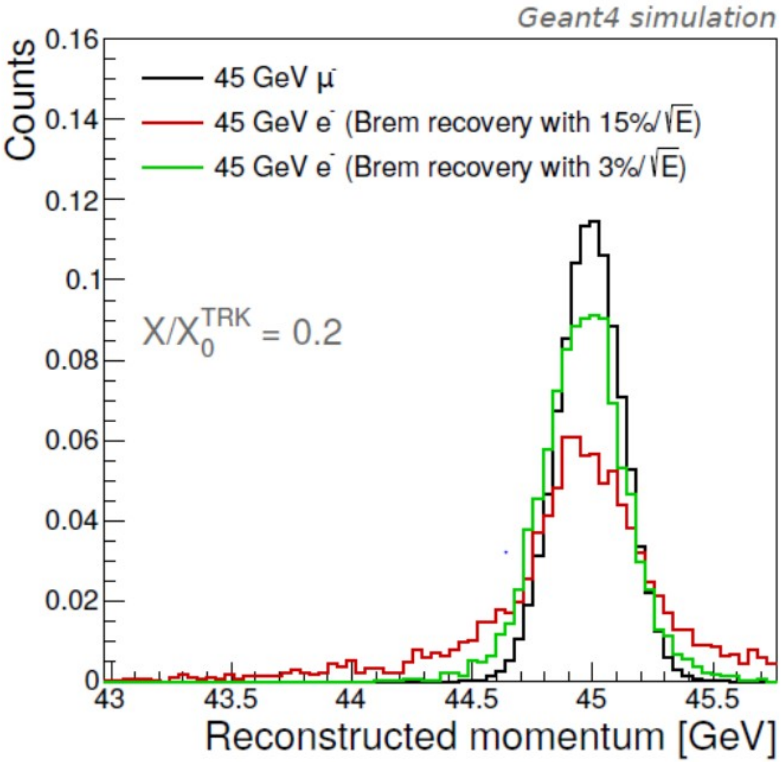




Advantages with a High-resolution EM Calorimeter

- Recovery of photons from bremsstrahlung

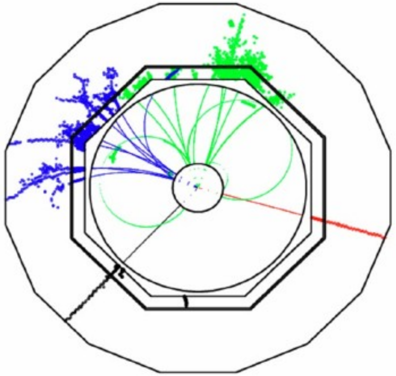


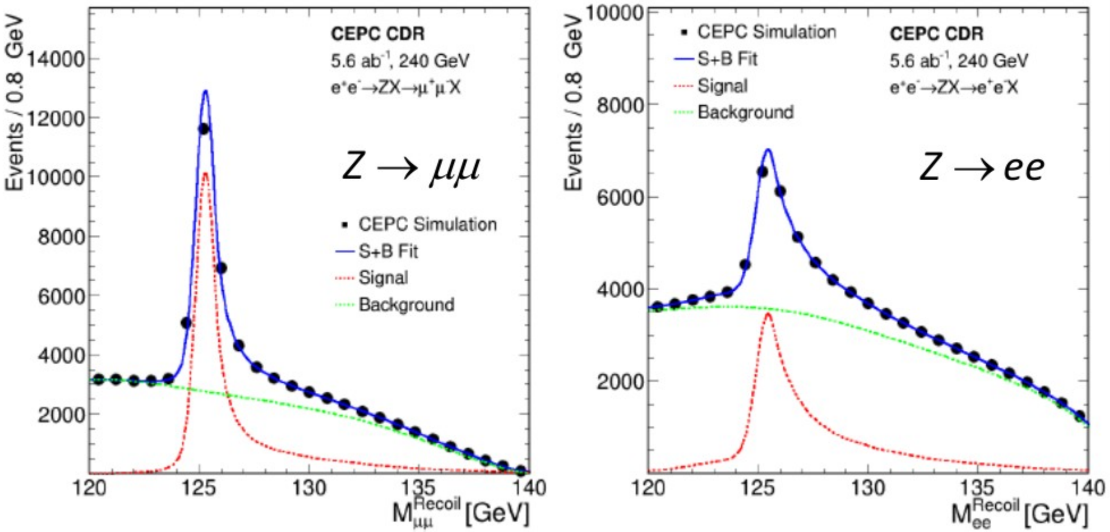


Electrons: tracker measurement + photons

Advantages with a High-resolution EM Calorimeter

- Improve Higgs tagging: the Higgs boson from the $e^+e^- \rightarrow ZH$ process can be identified through the recoil mass of the Z boson → identify the Higgs boson without looking at the Higgs boson





Much worse recoil mass resolution in the Z → ee channel due to bremsstrahlung radiation, need to have good EM resolution for the radiation recovery