Summary of Calorimetry

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March 21 2021

Presented in the 2021 CPAD Instrumentation Frontier Workshop at Stony Brook, NY

A Brief Overview

- More than 40 abstracts received, showing enthusiasm of the community.
- 23 presentations given in 5 CAL sessions (C1 to C5: 5, 5, 5, 3 and 3) and 2 EC sessions, covering simulation (3), high granularity (HG, 5), dual readout (DR, 7), organic (7) and inorganic (7) scintillators for Mu2e (2), EIC (1), Higgs factory (9) and HL-LHC/FCC-hh (11).
- All presentations respond to the PRD for calorimetry from the 2019 DOE BRN Study:

Priority Research Direction
PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements
PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments
PRD 3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification

Calorimetry Session 1

C1-1: Digital Hadron Calorimeter

- The first Digital Hadron Calorimeter was built and tested successfully. By construction, the DHCAL was the first large-scale calorimeter prototype with embedded front-end electronics, digital readout, pad readout of RPCs and extremely fine segmentation.
- Fine segmentation allows the study of electromagnetic and hadronic interactions with unprecedented level of spatial detail, and the utilization of various techniques not implemented in the community so far (software compensation, leakage correction, …).
- Standard Geant4 simulation package fails to reproduce data well. Some optional packages allow big improvement in the agreement. The disagreements are at the very fine level of detail which is not available in conventional calorimeters.

The concept of Digital Hadron Calorimetry is validated.

C1-2: CMS HCAL

UNIVERSITY OF MARYLAND

- ***D*** **increases linearly** vs logR for dose rates up to 70 Gy/hr.
- Above 70 Gy/hr:
  - for PVT, it is **constant** or **continues to rise**
  - for PS, it is **constant** or **decreases**

  Depending on doping concentration.
- Results from varying thickness rods suggest that **damage to the initial light output is dominant** for thicknesses up to 1 cm.
- **Thicker samples** will be **more sensitive** to color center absorption.
- For the blue scintillator (EJ-200), the transmission measurements indicate **damage to the fluors**.

C1-3: HG Strip ECAL

- Scintillator ECAL
  - In order to realize PFA and high jet energy resolution, high granular calorimeter is requirec
  - Virtual segmentation : 5 × 5 mm² with scintillator strips in x-y configuration
- R&D status
  - Small-pixel SiPM developed for large dynamic range
  - Bottom-center SiPM coupling gives the best performance
  - Double SiPM readout tested, and detection layer developed
  - Polystyrene-based scintillator produced by injection moulding has good light yield and capability for large-scale production
  - Fully integrated electronics developed
- Sc-ECAL technological prototype
  - Full 32 layers and mechanical structure constructed
  - High efficiency and 2 mm position resolution achieved
  - Cell-to-cell MIP calibration implemented
  - LED calibration such as inter-calibration is on going
- Test beam experiments
  - Test beam using electron beam at DESY in 2021
  - Combined test beam experiments together with other CALICE calorimeter prototype
    - such as AHCAL
- Remaining
  - Detector assembly system for large-scale production
  - Test of power pulsing operation of integrated electronics for ILC Sc-ECAL
  - Optimization of cooling system of integrated electronics for CEPC Sc-ECAL
    - Continuous operation required for CEPC

C1-4: CMS HGCAL

CALICE-inspired HGCAL effort will provide valuable experience to the field of constructing a PF-inspired calorimeter.

HGCAL project is moving towards production through an extensive series of prototypes and test setups.

Extensive work on managing trade-offs and challenges, including:

- Mechanical design.
- Active sensor elements (including an important QC program).
- Readout electronics and ASICs.

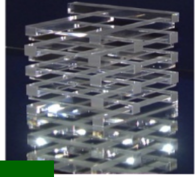
Lots of work ahead to complete the construction.

The HGCAL experience should increase our confidence that other calorimeters of this basic type can be successfully constructed at future experiments.

C1-5: HG SiPM on Tile for Higgs factory

- SiPM-on-Tile calorimetry offers high granularity and good energy resolution at reasonable cost
- Performance demonstrated with CALICE AHCAL physics prototype
- Engineering design demonstrated with CALICE AHCAL technological prototype
- SiPM-on-Tile technology can be adapted to different conditions
  - CMS HGCAL
  - DUNE Near Detector
- Open for new ideas, e.g. timing information in compensation methods
- **Active community, new collaborators welcome!**

Calorimetry Session 2



Conclusion

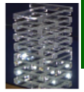
C2-1: Hadron Simulation

- Many ways to configure and customize Geant4 physics to meet your requirements.
- Validation is a continuous effort.
- Geant4 under active development, it's continuously being improved.
- Geant4 is very well documented, open source, provides many excellent examples and tutorials and has very active user community.
- Very good tool to learn and teach physics ☺.
- Geant4 needs user feed back to identify shortcomings and bugs.
- We need a program to systematically study the dynamics of hadronic showers. Geant4 is a very powerful predictive tool that allows to:
  - Identify the most important contributions, variables and particle types,
  - Develop and test new concepts and ideas and make predictions with high confidence
  - Identify observables that can be tested in small experimental test setups.
  - ...
- Simulation is important. The US community needs to stay actively involved (funded).

C2-2: Inorganic Scintillators

The HL-LHC and FCC-hh requires fast and rad hard calorimetry. The **RADiCAL** concept uses radiation hard LuAG:Ce ceramics as WLS for LYSO:Ce crystals for an ultra-compact, fast and longitudinally segmented shashlik calorimeter.
Undoped BaF_2 crystals provide ultrafast light with sub-ns decay time and a good radiation hardness up to 100 Mrad. Yttrium doping suppresses its slow light and promises an **ultrafast calorimeter**. R&D is needed for optimizing yttrium doping and radiation hardness in large size BaF_2:Y crystals for Mu2e-II. Solar-blind VUV photo-detectors are also needed for controlling the radiation induced readout noise.
The longitudinally segmented **Calvision** crystal ECAL with dual readout combined with a IDEA HCAL promises excellent EM and Hadronic resolutions for the Higgs factory.
Homogeneous HCAL (**HHCAL**) promises the best jet mass resolution by total absorption with a challenge in cost. R&D is needed for cost-effective mass produced inorganic scintillators.
Novel inorganic scintillators will play important role in all these calorimeter concepts

Acknowledgements: DOE HEP Award DE-SC0011925

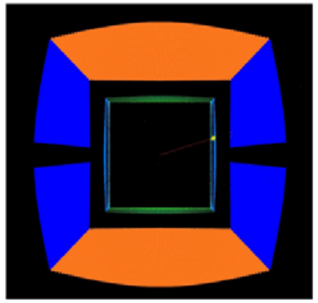


C2-3: Calvision for Higgs Factory

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).

Summary

C2-4: RADiCAL for HL-LHC/FCC-hh

- RADiCAL R&D to develop highly efficient, ultra-compact and rad hard EM calorimetry elements.

Development and testing of modular elements that can provide:

1. Energy measurement.
2. Shower Max timing measurement.
3. Shower Depth measurements for shower profile measurement.
4. Incorporation of dual readout for both scintillation and Cerenkov measurement – including for timing

- Potential applications in other areas:
  - Hadronic calorimetry
  - Forward calorimetry
  - Scintillation/WLS detection over compact and larger areas
  - Timing detectors

Work Supported by in part by:
Department of Energy: DE-SC0017810.003
National Science Foundation: NSF-PHY-1914059
University of Notre Dame: Resilience and Recovery Grant Program

Summary

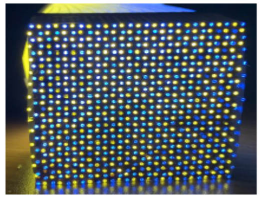
C2-5: HHCAL for Higgs Factory

- To maximally exploit future facilities and advance our understanding of fundamental forces, major improvements in hadron calorimetry are required.
- Progress with development of dense scintillating materials and compact photodetectors enables construction of hadron calorimeters with energy resolution reaching10%/√E
- Significant progress in further understanding of the underlying physics of hadronic showers is being made.
- The potential return on a modest R&D investment could be very large.

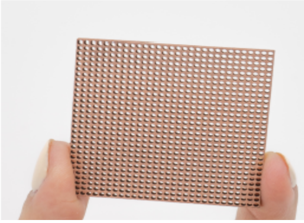
Calorimetry Session 3

C3-1: IDEA DR for Higgs Factory

- Dual-Readout Calorimeter R&D project for future e+e- collider in Korea is very active
  - Build and test full size prototype DRC detector by 2025
  - HW R&D and simulation studies for performance and ML applications on-going
  - Under preparation for test beam 2021
  - Calorimeter design for EIC project with Korea HI community is also on-going



- Innovative 3D-printing module is on-going
  - Collaborating with world-leading 3D metal printing frontier companies
  - Prototype module design and production are underway



- Various Snowmass 2021 studies are on-going

Summary

C3-2: CMS HCAL

- CMS utilizes a variety of data to calibrate the energy measurements obtained from its hadron calorimeter
- Mean noise level of all channels are monitored for each fill of LHC and scale factors are checked for each run period
- HB, HE, HF makes use of azimuthal symmetry of energy flow in minimum bias events for inter-calibration of the channels, while HO uses muons for inter-calibration
- Absolute energy scales in HB, HE are determined using isolated charged hadrons. Energy scale in HF is determined from events of the topology $Z \rightarrow e^+e^-$. Absolute scale in HO utilizes p_T balance in di-jet events
- Using 35.9 fb^{-1} collision data at 13 TeV, calibration constants are determined with systematic uncertainty of 3% for inter-calibration and 2% for absolute calibration

Summary

C3-3: Organic Scintillator

- Scintillator continues to be very important tool for detector design
- Important to keep improving process
  - More light yield
  - Faster materials
  - New methods such as co-molded cladding and through holes
  - New methods for reducing cost/improving material

C3-4: HG SiPM on Tile for Higgs factory

- Zero Degree Calorimeters developed for Run 4 HL-LHC
  - Better energy resolution and γ/n separation
  - Reaction Plane Detector for neutron orientation measurement
- Radiation hard and compact ZDC design
  - Radiation tolerance for increased luminosity in Run 4
  - Compatible with TAXN modification
- Beam tests
  - 2018, 2019, 2021
- Well defined schedule

Calorimetry Session 4

C4-1: EIC Calorimetry — Conclusions

- EIC requires nearly 4π calorimeter coverage with regions requiring high resolution EMCAL and HCAL performance. However, there are severe space limitations, particularly along the beam direction.
- The most demanding requirements for the EMCAL are in the backward direction to measure the scattered electron.
- The most demanding requirements for the HCAL are in the forward direction where one would like to measure all hadrons and the tracking resolution deteriorates due to the axial magnetic field.
- There are a number of promising new technologies to meet these requirements (e.g., new scintillating glasses, W/SciFi and W/Shashlik EMCAL technologies and tilted plate configurations for the HCAL).
- Given that the project is seeking CD2 approval in less than 2 years the schedule is very tight to come up with a detailed detector design.

Summary — C4-2: Multi-Readout Fiber Calorimetry

- We simulated a simple 3D imaging calorimeter with GEANT4.
  - Convolutional Neural Network (CNN) reconstructed energy well. It outperforms conventional calorimeters, e.g. EM-fraction corrected one.
- We started R&D of multi-readout fiber calorimeter with longitudinal segmentation with timing.
  - Bench tests of HW components (fibers, SiPM, FEE) are in progress.
    - SiPM has good potential for precision timing measurement.
  - Full Monte Carlo simulation program will be developed with realistic parameters from the bench tests.
  - The MC program will be used to develop HW design and ML algorithms.
- We are working with the IDEA collaboration on both HW and SW.
  - Longitudinal segmentation with timing will be evaluated with the IDEA prototypes.

Summary of jet substructure studies

C4-3: FCC-hh Simulation

- Boosted jets studied up to 30 TeV in transverse momentum using Geant4 simulation with realistic energy reconstruction
- Jet substructure benefits from HCAL granularity
- HCAL cell size $\Delta\eta \times \Delta\varphi = 0.022 \times 0.022$ (5×5 cm^2) shows significant improvement for physics events compared to $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ (~ CMS, ATLAS)
- Smaller than 0.022 x 0.022 cells show minor improvements for >20 TeV jets

Summary of timing layers studies

- Timing layers with tens of picosecond capabilities complements calorimeters with the standard ~0.5 - 1 ns readout
- Proof of principle for 2 timing layer design (before and after ECAL)
  - in combination with highly-granular ECAL/HCAL can lead to cost optimized calorimeter designs
- Timing layers can be used for:
  - Pile-up mitigation
  - Particle identification (baryons vs pions vs kaons etc.)
  - Reducing confusion terms in PFA → improvements for jets etc
  - b-tagging, lepton-isolation
  - BSM long-lived particles → *See concrete example in backup*
- Timing for boosted jets will further be studied during Snowmass21

Calorimetry Session 5

C5-1: Ultra-high Granularity Calorimetry

- Successful test of full digital pixel calorimeter (EPICAL-2)
  - ALPIDE sensor suitable for calorimeter use
  - Technology suitable for high-granularity layers of FoCal (e.g. separation power)
- Good performance from low-energy test
  - Good linearity
  - Energy resolution improved compared to EPICAL-1, close to CALICE SiW ECAL physics prototype
- Next steps
  - Detailed study of shower development
  - Further studies of high-energy behaviour (simulation and SPS test beam)
- Strong potential for other applications

C5-2: Mu2e Mechanics

- Mu2e EM calorimeter mechanical design finalized.
- It took many years of prototyping and engineering to reach this stage!
- Most of the large components already built and tested
- Some parts still being built, but not far in time
- Crystals, SiPMs production concluded, FEE, cables and DAQ boards under production
- **Looking forward to start assembly in the summer!**

European Commission

This work was supported by the European Union's Horizon 2020 research
and innovation program under the Marie Sklodowska-Curie
Grant Agreement no 734303, 822185, 858199, 101003460

C5-3: DR Tile Calorimetry

Fairfie
UNIVERSI

FUTURE Dual Readout

University of Iowa

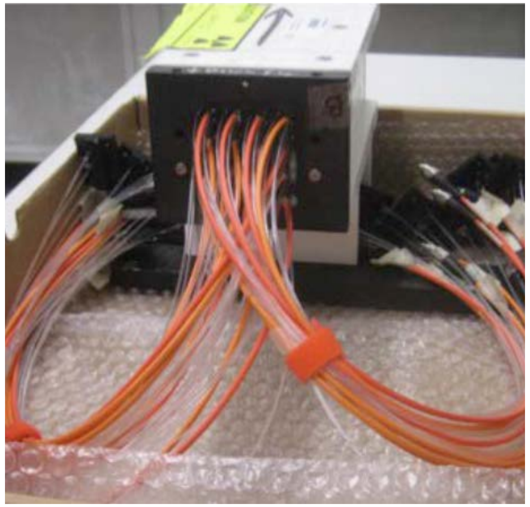
- ***Adding sensor tiles*** relatively insensitive to MIPs, more sensitive to γβ->0
  - increases the contrast between e-m and hadronic energy (enhancing the low energy hadronic signal)
- **Secondary Emission:** Signal scales ~ dE/dx,
  - MIP SE signal ~100x less than that of the energy of the peak signal (peak signal for protons occurs at ~200KeV - n+p->p+n knock-on protons).
- **Homogeneous dense inorganic scintillators** (LYSO, $PbWO_4$,CeF_3, LAr, LXe..)...

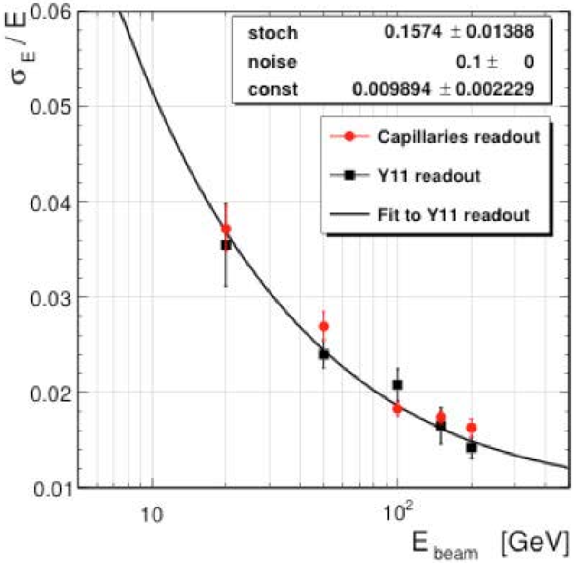
  - h_i/e_i ~ 0.4 and h_c/e_C ~ 0.25, or $[h_i/e_i]/[h_c/e_C]$ ~1.6:

-> *Homogeneous calorimeters cannot achieve dual readout compensation better than ~50%/√E on hadrons, even with perfect separation between scintillator light & Cerenkov light in the homogeneous detector*. [LAr/Ch4 ions instead of Scintillator]

σ_E/E ~15%-18%/√E on jets: *scintillator sensors with h_i/e_i ~ 0.6-0.8 and Cerenkov sensors with $h_c/e_C \leq 0.2$ are needed. To achieve $h_c/e_C < 0.2$, lower n Cerenkov radiators are required(β_{thresh} ->1),. Requires photons for e-m resolution < 70%/√E(GeV) or N_{pe}> 2 pe/GeV.*

RADiCAL: LYSO/LuAG Shashlik Cal



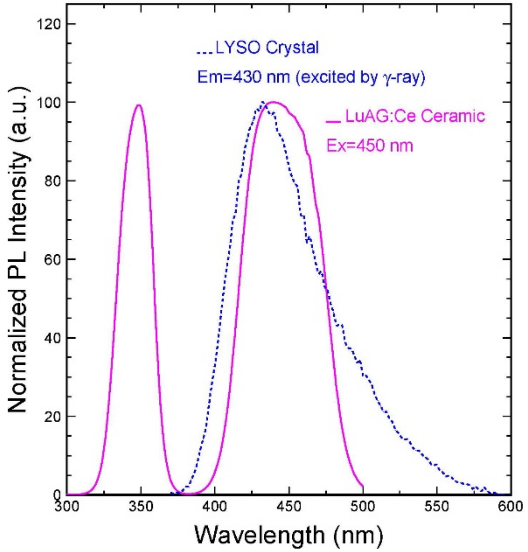


A 4x4 LYSO/DSB1 capillaries show consistent resolution with LYSO/Y11

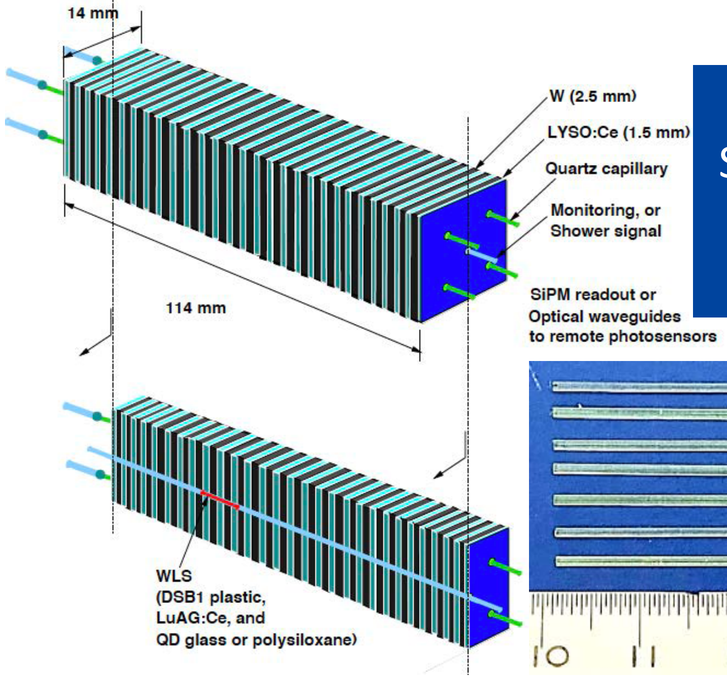
Excitation of LuAG:Ce ceramics matches well LYSO:Ce emission: RADiCAL

RADiation hard **i**nnovative **CAL**orimetry

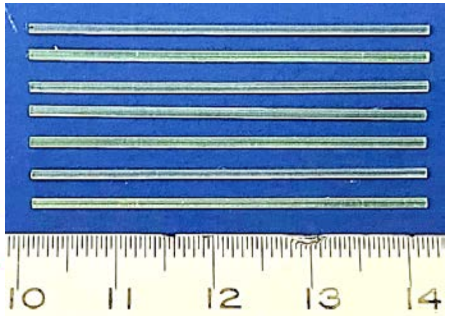
R. Ruchti, in the 2021 CPAD workshop

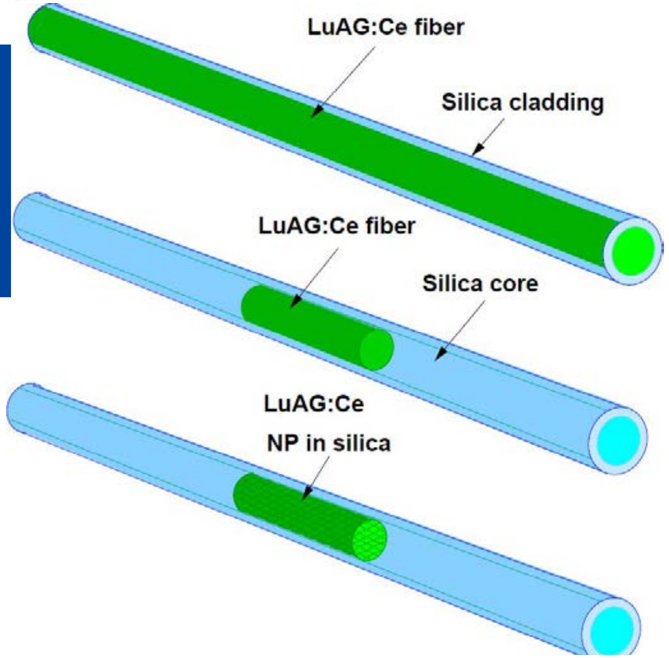


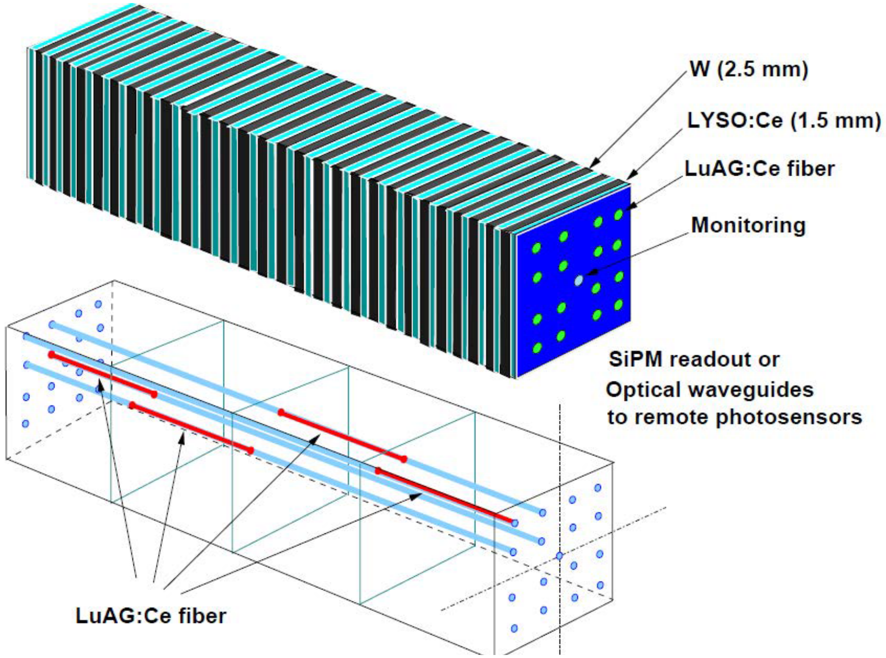
C2-4: RADiCAL for HL-LHC/FCC-hh



Φ1x40 mm SIC LuAG:Ce ceramic LHPG fibers

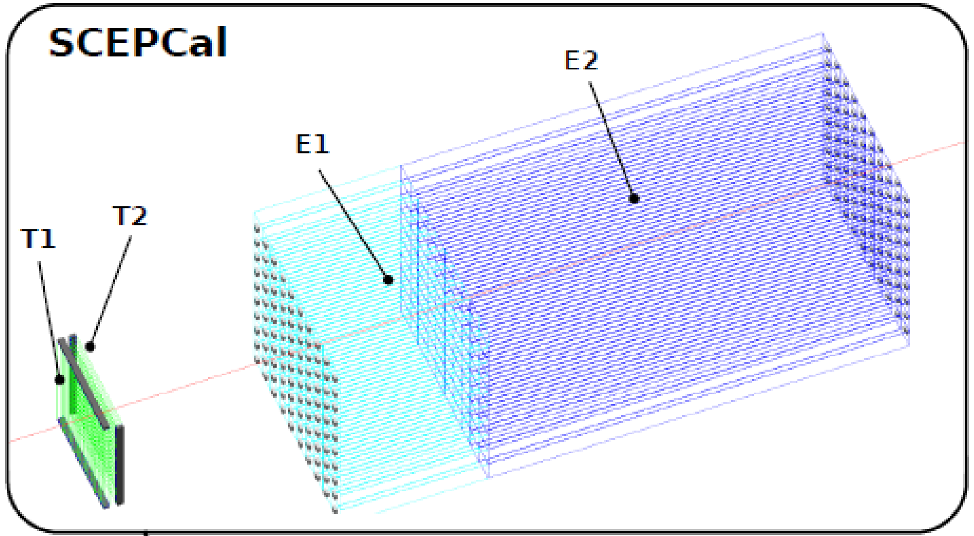


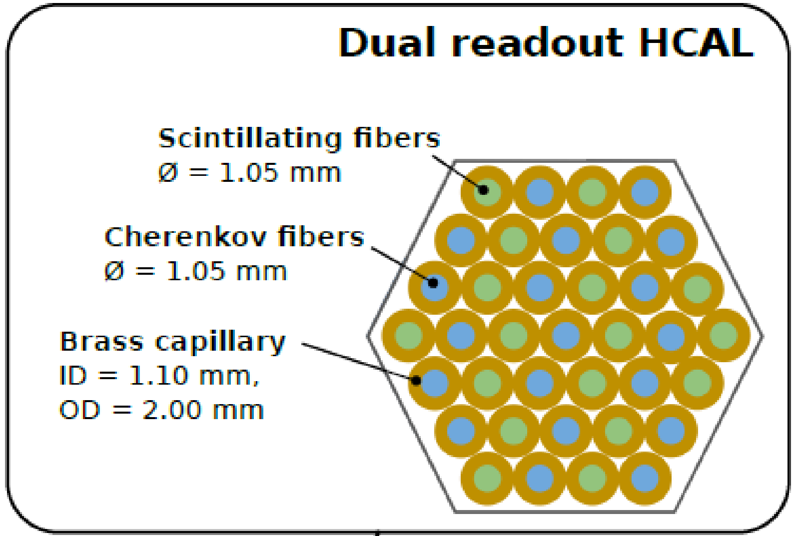


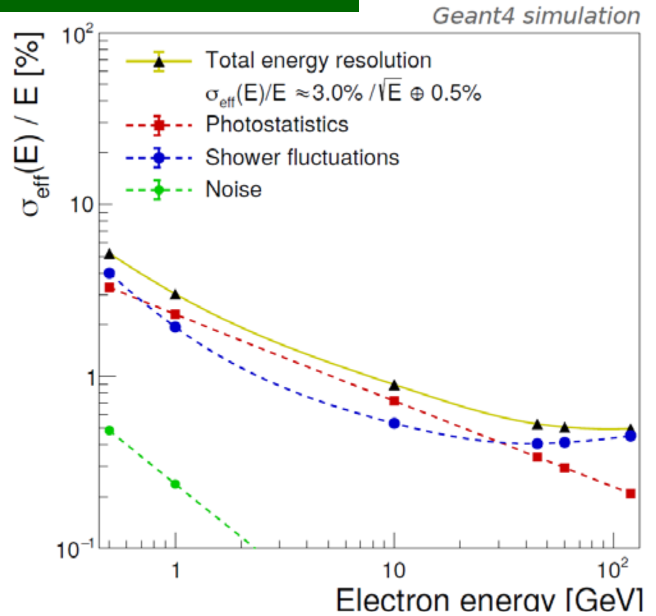


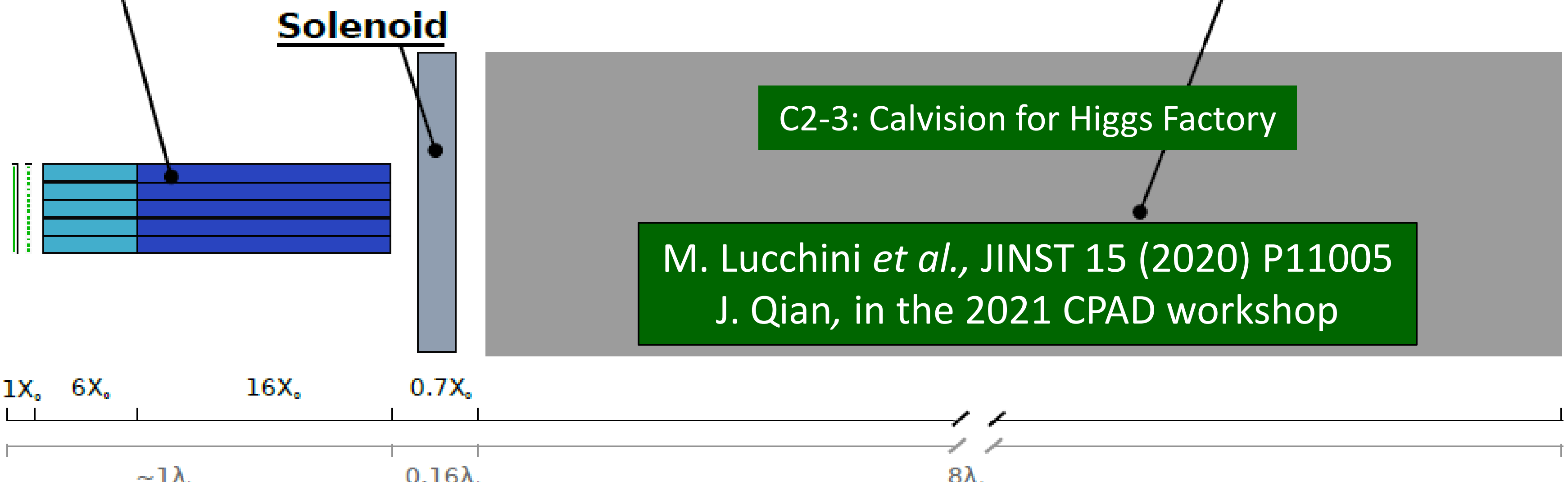
Calvision: Longitudinally Segmented Crystal ECAL

Aiming at excellent EM and jet resolutions for Higgs Factory



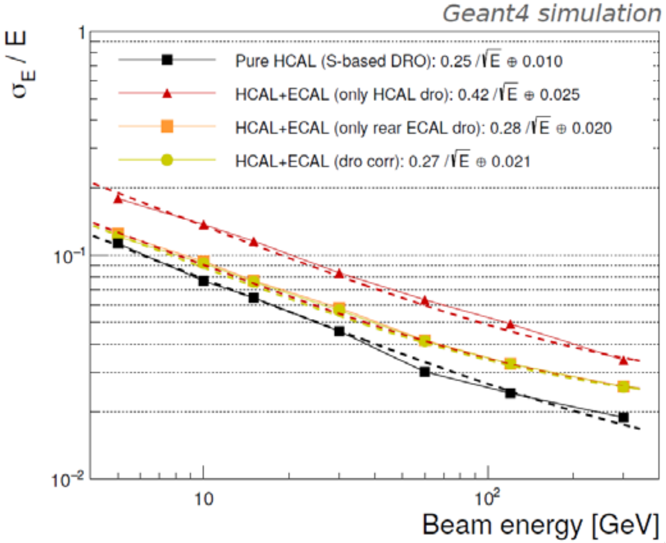






C2-3: Calvision for Higgs Factory

M. Lucchini *et al.*, JINST 15 (2020) P11005
J. Qian, in the 2021 CPAD workshop

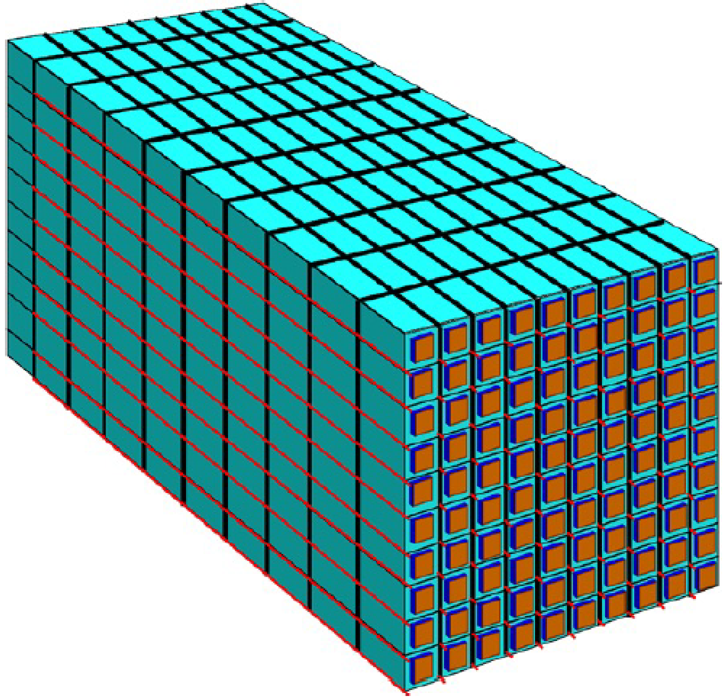


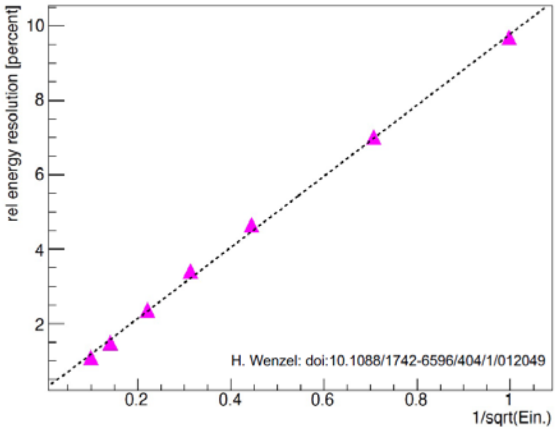
HHCAL: Total Absorption HCAL

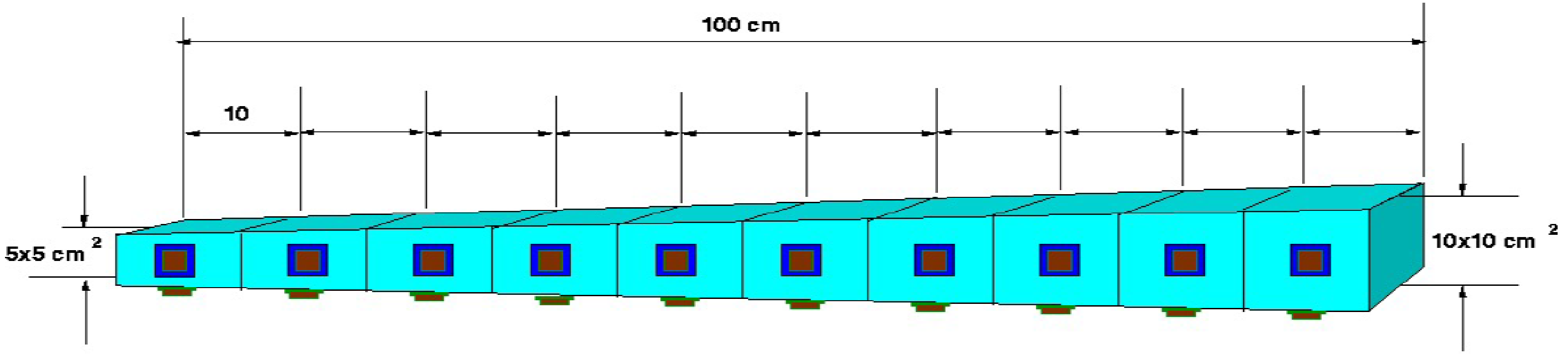
C2-5: HHCAL for Higgs Factory

Technical Implementation

- Until recently the technical challenges were significant to even consider a homogenous calorimeter
- There have been tremendous technical advances that make this option viable with further R&D
  - Low form factor photo-detectors that can operate in a magnetic field (SiPM)
  - High density scintillating crystals/glasses (λ~20 cm)

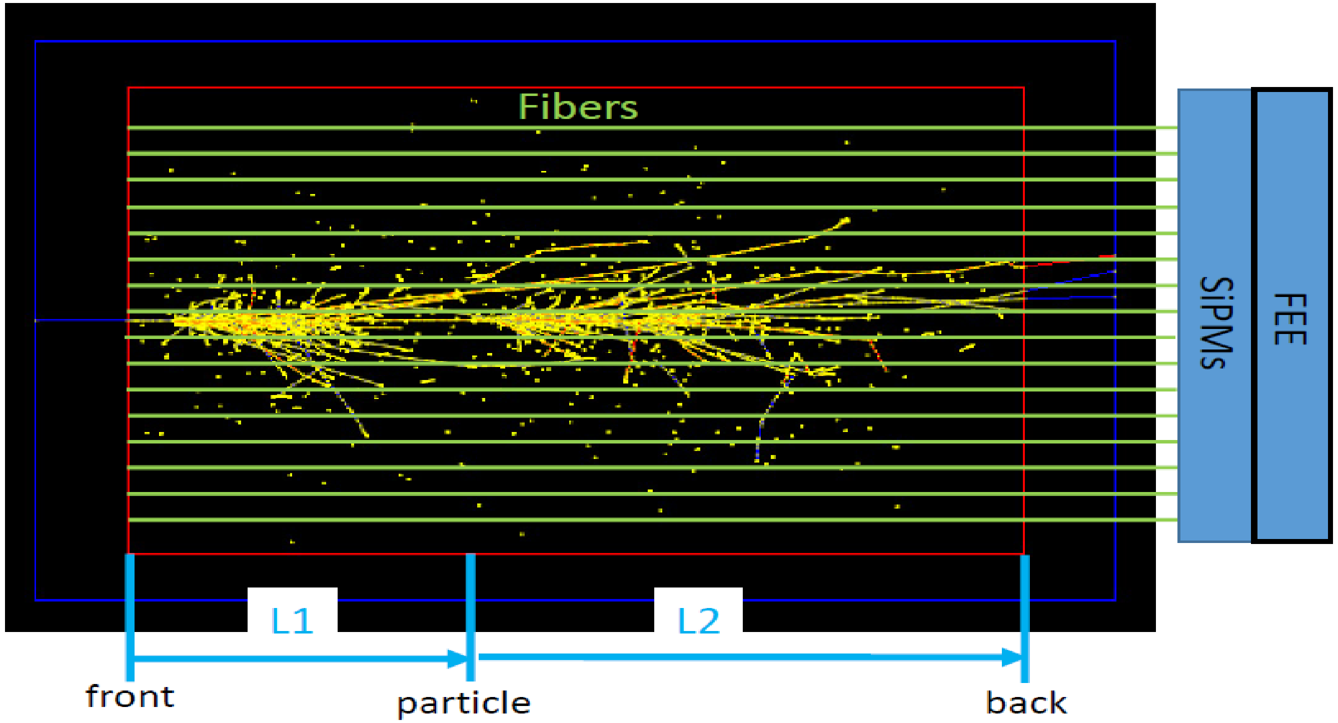






Longitudinal Segmentation of Multi-readout Fiber Calorimeters by Timing for 3D Imaging Cal

Fiber Calorimeter with Longitudinal Segmentation with Timing



Signal Time = L1/c + L2/kc,
c = velocity of particle
kc = velocity of light in fiber (k~0.6)
ΔL = 2 cm = 44 ps

- ❖ Channel counts reduction
  3D Calo: Nx * Ny * Nz
  Nz → 1
- ❖ Major Components:

- ❑ Absorber
- ❑ Fibers
- ❑ SiPMs
- ❑ Frontend Electronics
  - Amplifiers
  - Waveform digitizers
- ❑ DAQ

➢ R&D on bench started!

C4-2: L. Segmented DR for Higgs Factory

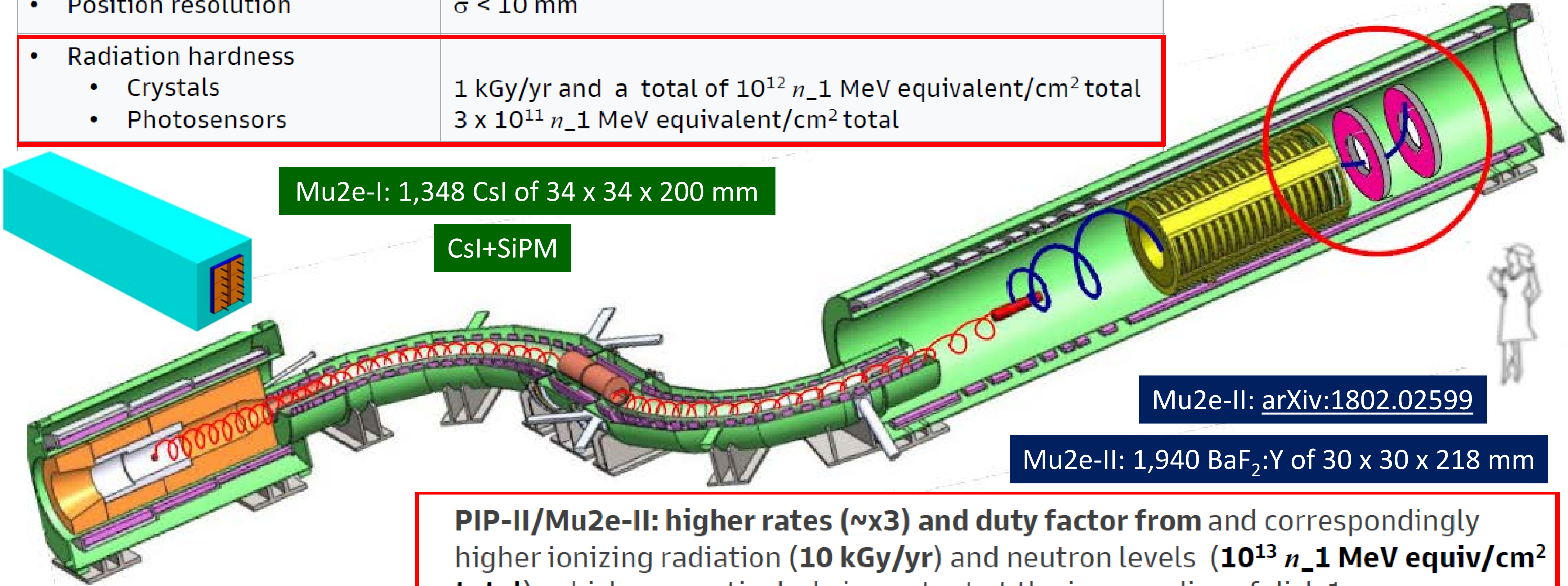
Mu2e Ultrafast Calorimeter

• Energy resolution	σ < 5% (FWHM/2.36) @ 100 MeV
• Time resolution	σ < 500 ps
• Position resolution	σ < 10 mm
• Radiation hardness • Crystals • Photosensors	 1 kGy/yr and a total of 10^{12} n_1 MeV equivalent/cm^2 total 3 x 10^{11} n_1 MeV equivalent/cm^2 total

C2-2: Ultrafast BaF_2:Y Calorimetry

Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm

CsI+SiPM

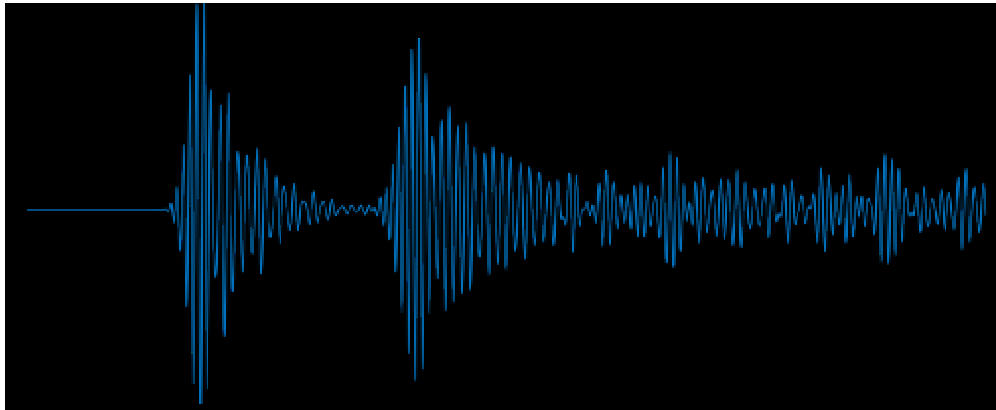


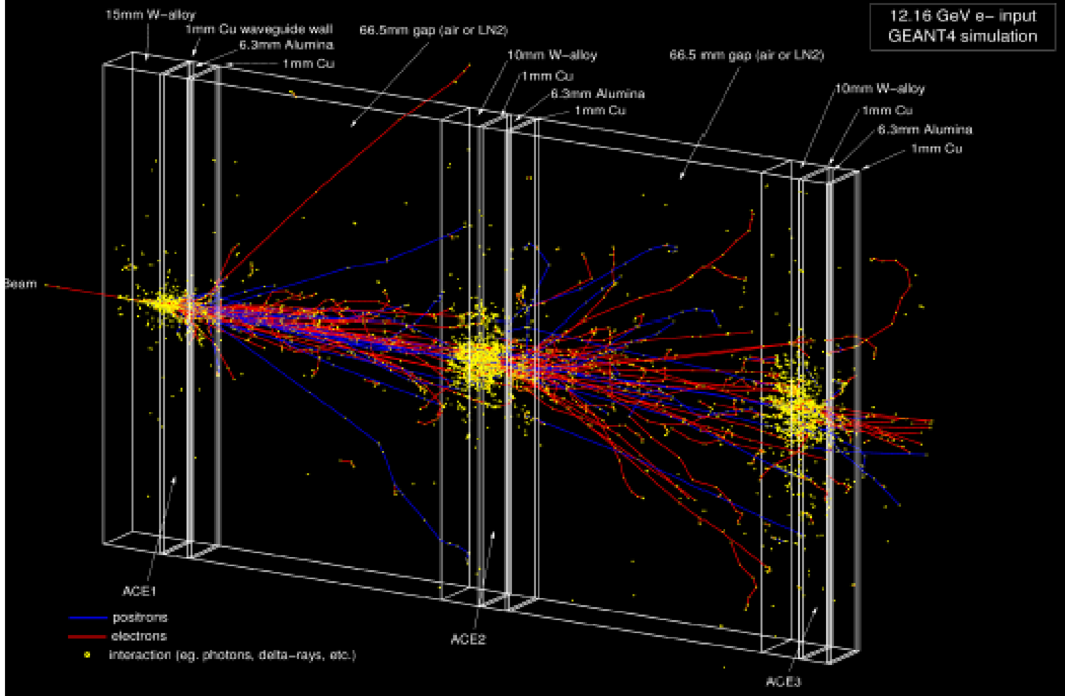
Mu2e-II: arXiv:1802.02599

Mu2e-II: 1,940 BaF_2:Y of 30 x 30 x 218 mm

PIP-II/Mu2e-II: higher rates (~x3) and duty factor from and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**10^{13} n_1 MeV equiv/cm^2 total**), which are particularly important at the inner radius of disk 1

C3-5 Askaryan Calorimetry





5D Picosecond Timing Layers for Future Calorimeters

Updates from the
Askaryan Calorimeter Experiment (ACE)

Remy Prechelt[1]
for the ACE Collaboration

P. W. Gorham[1], J. Bynes[1], B. Fox[1], C. Hast[2], B. Hill[1], K. Jobe[2], C. Miki[1], M. Olmedo[1], R. Prechelt[1], B. Rotter[1], D. P. Saltzberg[3], S. A. Wissel[4], G. S. Varner[1], S. Zekioglu[3]

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[3]Univ. of California, Los Angeles (UCLA),
[4]Penn. State University (PSU)

Calorimetry Summary

Session#	Abstract#	Presenter	Simulation	HG	DR	Organic Scintillators	Inorganic Scintillators	HL-LHC/ FCC-hh	Higgs Factors	Topic
C1-1	64	ONEL, Yasar							1	DHCAL
C1-2	43	PAPAGEORGAKIS, Christos				1		1		CMS HCAL
C1-3	76	TSUJI, Naoki		1		1			1	Strip ECAL
C1-4	169	KOLBERG, Ted		1				1		CMS HGCAL
C1-5	81	KRUEGER, Katja		1		1			1	SiPM on Tile
C2-1	136	WENZEL, Hans-Joachim	1		1		1			GEANT 4
C2-2	51	HU, Chen			1		1	1	1	Ino. Scintillator
C2-3	49	QIAN, Jianming			1		1		1	Calvision, IDEA
C2-4	56	RUCHTI, Randy					1	1		RADiCAL
C2-5	118	DEMARTEAU, Marcel			1		1		1	HHCAL
C3-1	57	YOO, Hwidong			1				1	IDEA
C3-2	127	BHOWMIK, Debabrata				1		1		CMS HCAL
C3-3	61	FREEMAN, James				1		1		CMS HCAL
C3-4	159	WANG, Quan						1		HL-LHC FCAL
C3-5	35	PRECHELT, Remy								Askayan Cal
C4-1	52	WOODY, Craig				1	1			EIC CAL
C4-2	100	KUNORI, Shuichi	1		1				1	L. Segmented DR
C4-3	45	CHEKANOV, Sergei	1					1		FCC-hh
C5-1	67	PEITZMANN, Thomas		1				1		Ultra HG
C5-2	12	PASCIUTO, Daniele					1			Mu2e Mechanics
C5-3	90	WINN, David			1	1			1	DR with Tile
EC-2	77	GONSKI, Julia						1		ATLAS LAr F. Board
EC-10	188	KROHN, Michael		1				1		CMS HGCAL