R&D on Experimental Technologies

Calorimetry for Future Accelerator Experiments
Proposed R&D at CERN

May 2018

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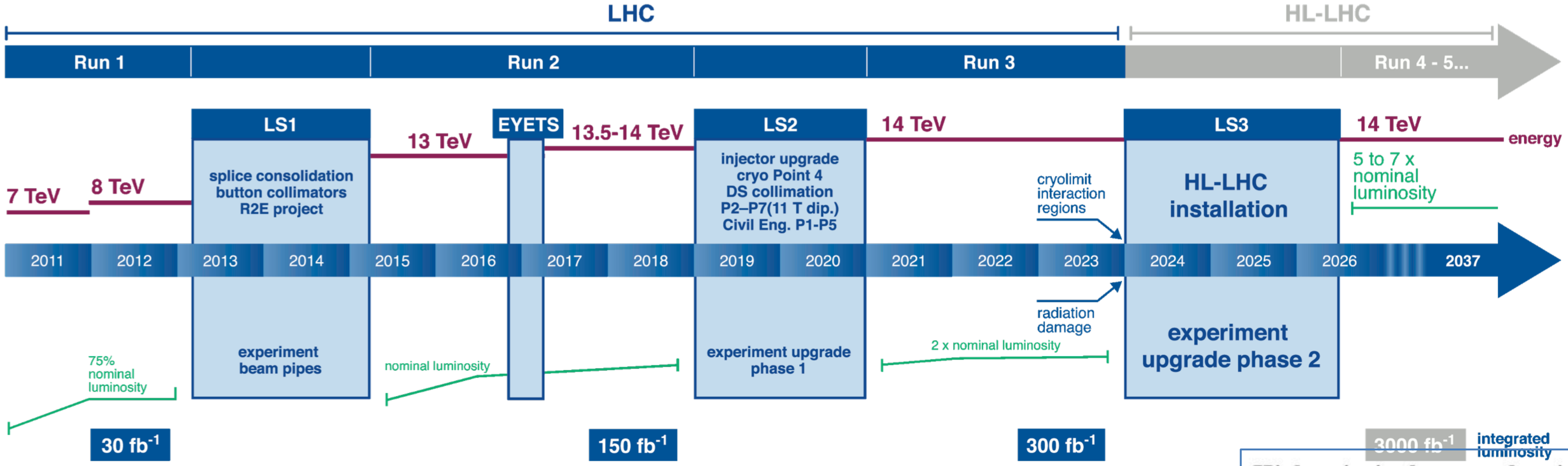
Outline of today's talk:

- Introduction
- Calorimetry for future accelerator experiments
- Proposed R&D at CERN
- FCC-hh
- LHCb Upgrade II
- CLIC/CLD

Introduction



European Strategy:
https://cds.cern.ch/record/1567258/files/esc-e-106.pdf

- **European Strategy (2013):**
  - Top priority to fully exploit the LHC (possibly until ≈2037) (c)
  - CERN should propose post-LHC accelerator projects (d)
- **Two major upgrades of the machine and the experiments** foreseen in 2019-2020 and 2024-2026
  - Production underway for **Phase I Upgrades** of experiments
  - Strong R&D programs for the **Phase II Upgrades** of ATLAS and CMS (TDRs finalized 2017/2018)

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

Introduction

- Beyond that, **R&D for the next generation of accelerators and accelerator experiments** has started
- **In this talk I will only speak about detector R&D**
  – See other talks at this WS for CERN accelerator projects
- At **CERN** strong involvement in detector **R&D for CLIC, FCC-ee and FCC-hh (and also Upgrade II of LHCb)**
- Recently CERN EP department has launched an **R&D program on new detector technologies**
  – 8 working groups
  – First workshop took place at CERN (https://indico.cern.ch/event/696066/)
  – Second workshop and final document planned for fall 2018 → decision on which proposals will be supported
  – In the following I will report on **existing and possible future R&D in the field of calorimetry** (WG3)

R&D on Experimental Technologies

EP department is launching an R&D programme on new Detector Technologies. This initiative, which spans a 5-years period from 2020 onwards (with a possible extension by another 5 years), covers detector hardware, electronics and software for new experiments and detector upgrades beyond LHC phase II.

Working groups have formed for the key themes. They are studying the state of the art, limitations and main challenges in the various domains and define an ambitious and focused work programme with milestones, deliverables and resource estimates.

Interested colleagues - no matter if engineer or physicist, staff or user, at CERN or elsewhere - are invited to contribute to the definition of the R&D programme. Please inscribe to a mailing list below. There is also a general email list for those, who just want to be informed about progress and events: EP-RDET-General.

After a sucessful Workshop 1 (16 March 2018, see the indico site) with more than 460 registered participants we are foreseeing our 2nd Workshop on 25 September 2018. We aim at preparing a report summarizing the proposed R&D programme in November.

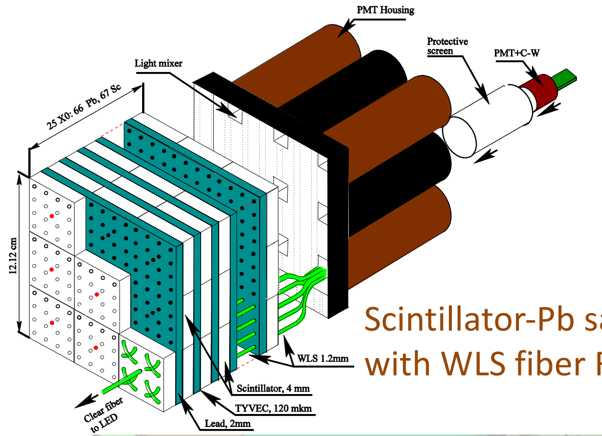
Working Groups	Convenors	Mailing Lists	WG site *)
Silicon detectors	Heinz Pernegger, Luciano Musa, Petra Riedler, Dominik Dannheim	EP-RDET-WG1-Si	WG1-Si
Gas detectors	Christoph Rembser, Eraldo Oliveri	EP-RDET-WG2-Gas	WG2-Gas
Calorimetry and light based detectors	Martin Aleksa, Carmelo d'Ambrosio	EP-RDET-WG3-Cal-Light	WG3-Cal-Light
Detector Mechanics	Corrado Gargiulo, Antti Onnela	EP-RDET-WG4-Mech	WG4-Mech
IC technologies	Federico Faccio, Michael Campbell	EP-RDET-WG5-IC	WG5-IC
High Speed Links	Paolo Moreira, Francois Vasey	EP-RDET-WG6-Links	WG6-Links
Software	Graeme Stewart, Jakob Blomer	EP-RDET-WG7-Software	WG7-Software
Detector Magnets	Herman Ten Kate, Benoit Cure	EP-RDET-WG8-Magnets	WG8-Magnets

https://ep-dep.web.cern.ch/rd-experimental-technologies

CALORIMETRY FOR FUTURE ACCELERATOR EXPERIMENTS

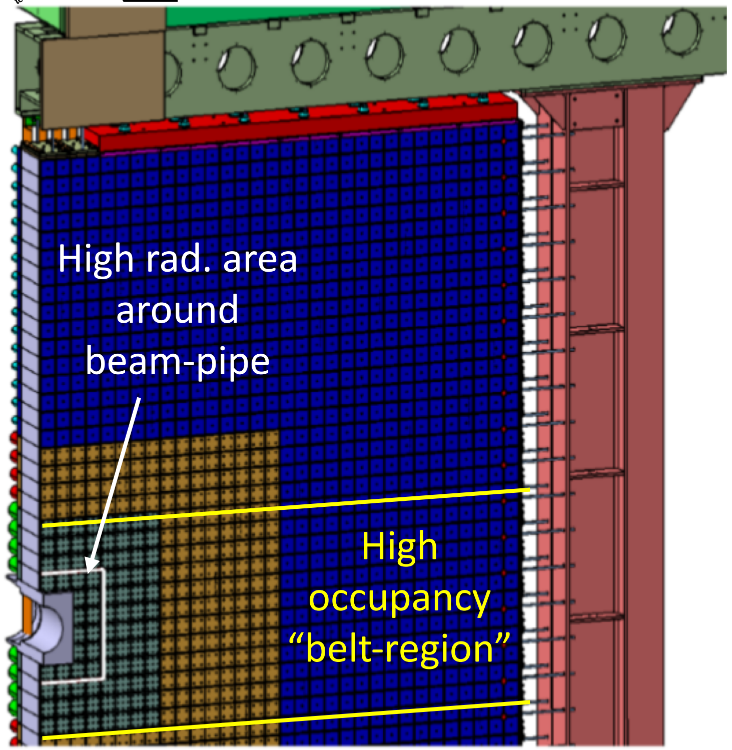
LHCb Upgrade II Beyond HL-LHC

- Current LHCb ECAL is a Scintillator/Pb Shashlik calorimeter ($50m^2$),
  - electronics upgrade (40MHz read-out) planned for Run 3 (Upgrade I)
- **LHCb Upgrade II** (planned for LHC Run 5, starting 2031)
  - Exchange ECAL in high occupancy “belt-region” compatible with luminosity up to $L=2x10^{34}$ $cm^{-2}s^{-1}$.
  - ***Radiation doses*** of up to ~3 MGy and $\sim 3 \cdot 10^{15} cm^{-2}$ for 1 MeV n eq. at 300 fb^{-1}
  - Include ***timing information*** to mitigate multiple interactions/crossing
  - Keep good EM energy resolution of order $\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$
  - Reduce occupancy and improve spatial resolution in inner region
    - Reduce Molière Radius (to ~2-3cm)
    - Reduce cell size (inner region) to ~ 2cm x 2cm
  - Fast response (40 MHz read-out)
  - Respect dimensional constraints of a module: 12 x 12 cm^2 outer dimension
- **Possible Options:**
  - Homogeneous crystal calorimeter with longitudinal segmentation:
    - Fast and radiation hard crystals with high light yield
  - Sampling calorimeter: (e.g. Shashlik or SpaCal type)
    - Tungsten or tungsten alloy as converter ($R_M \sim 1cm$)



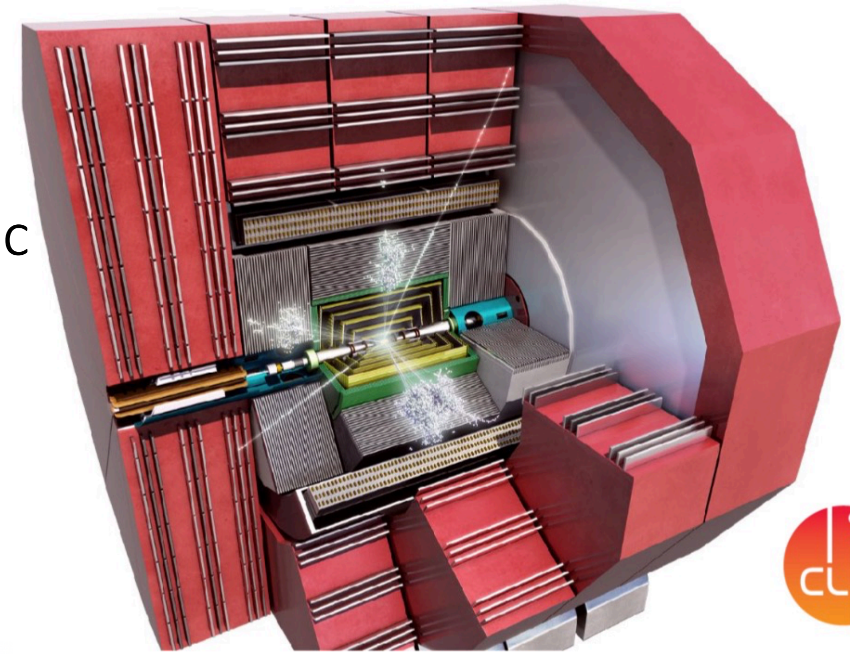
LHCb today

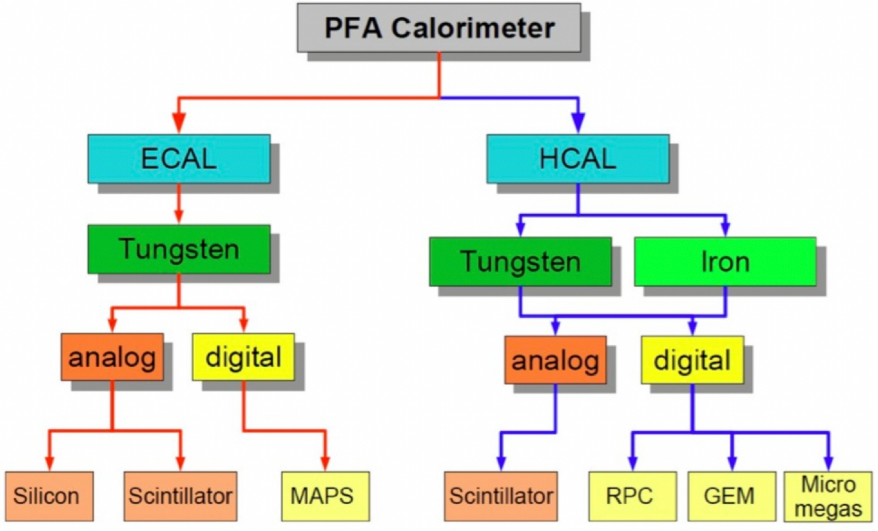
Scintillator-Pb sandwich with WLS fiber R/O



CLIC/ILC – CALICE

- **CALICE Collaboration** (https://twiki.cern.ch/twiki/bin/view/CALICE/CalicePapers)
- **CLIC/ILC calorimeters optimized for Particle Flow (PF)**
  - Radiation tolerance and bandwidth requirements benign compared to LHC
  - But ***higher precision requirements***! (2x for jet energies, 10x for track momenta)
  - High jet energy resolution (3-4% → ~30%/√E)! Separate W and Z decays!
  - Reconstruct each particle individually and use optimal detector (PF)
    - 60% charged, 20% photons, 10% neutral hadrons
  - Requires ***fine 3D segmentation*** (and sophisticated reconstruction software)
  - ECAL few 10 mm^2, HCAL 1-10 cm^2 - millions of channels
  - Granularity and timing (sub-ne accuracy) also essential for pile-up rejection
    - Dominant background from $\gamma\gamma \rightarrow$ hadrons
- **Technologies considered:**
  - Large area silicon arrays
  - New segmented gas amplification structures (RPC, GEM, Micromegas)
  - Silicon photomultipliers on scintillator tiles or strips
- **Large prototypes** exist and have been **tested in testbeams**

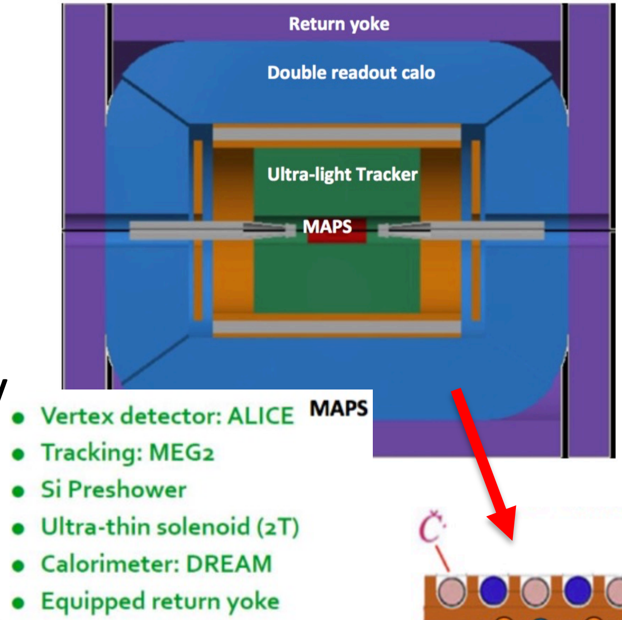




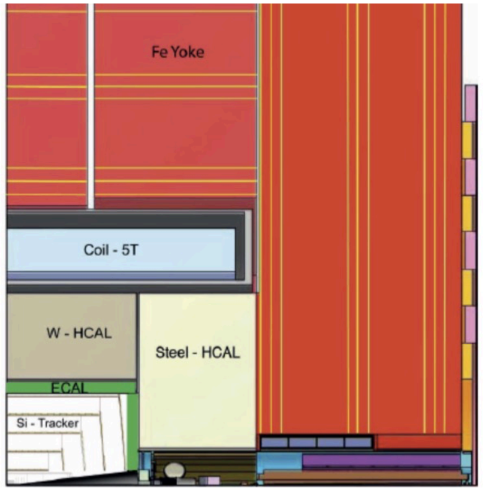
FCC-ee

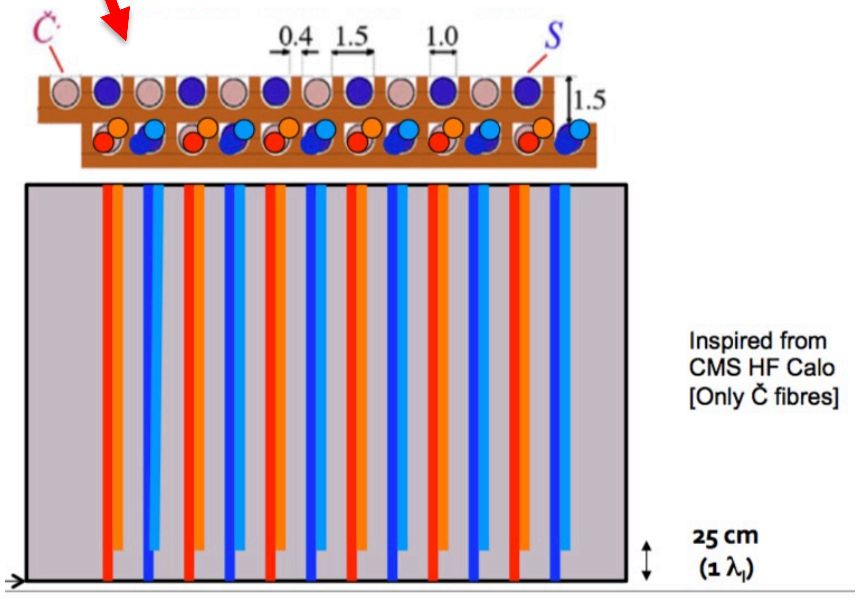
- **Calorimetry requirements**:
  - ***Excellent jet energy resolution*** (~30%/√E)
  - Radiation tolerance and bandwidth requirements benign compared to LHC
  - Particle ID
- **→ Calorimetry also based on particle flow**
  - Same technologies as for CLIC/ILC under study
  - On top of that fibre-sampling dual-readout calorimetry could be a very interesting option for future leptonic colliders
    - Fine transverse granularity
    - Need longitudinal segmentation to separate e/γ from $\pi^{\pm}$! → Idea with fibres of different length
    - Excellent hadronic resolution (simulation ~35%/√E)

"IDEA"



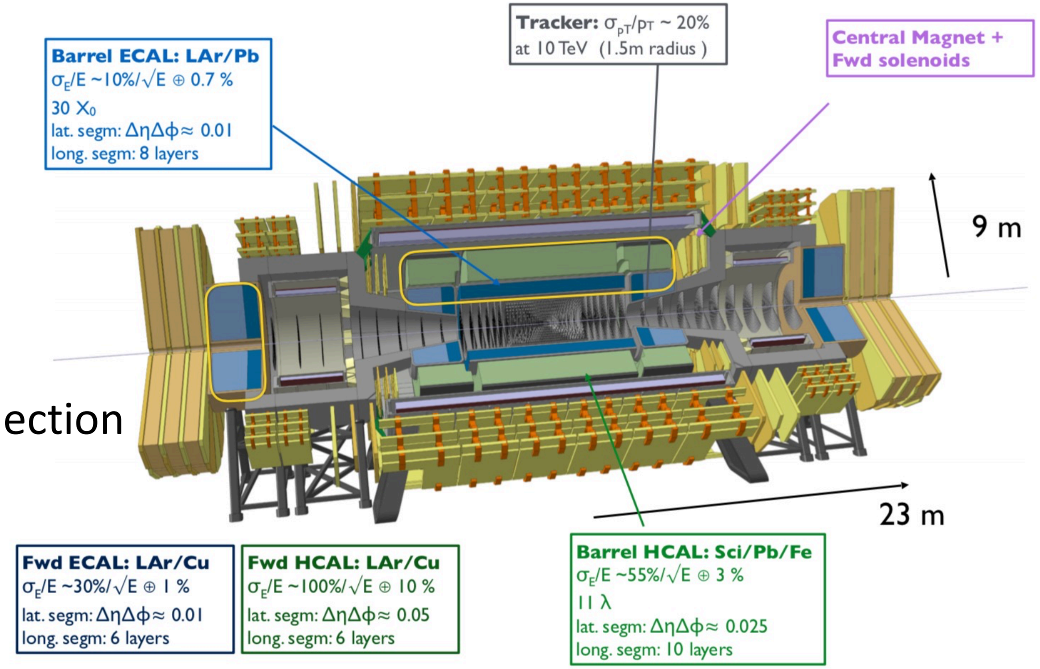
"CLIC-detector revisited (CLD)"

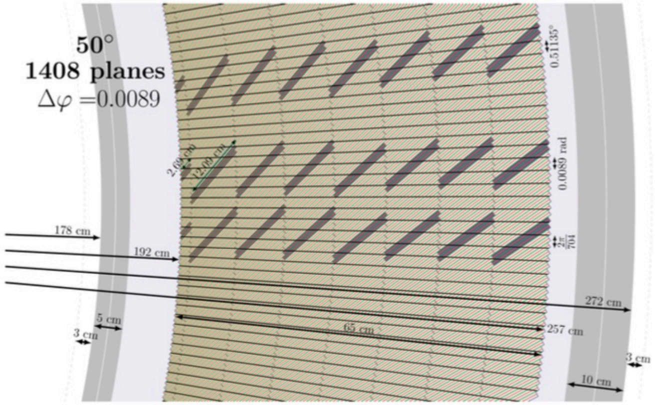




FCC-hh

- **Calorimetry Requirements:**
  - High luminosity → ***high pile-up*** (up to 1000 per BC)
  - ***High radiation*** → 10-30 times more than HL-LHC (!)
    - $2x10^{16} cm^{-2}$ 1 MeV n eq. in end-caps, up to $5x10^{18} cm^{-2}$ in forward region
  - High η coverage
    - Calorimetry (VBF jet tagging) up to |η|=6
    - Precision tracking and precision calorimetry |η|≤4
  - ***High granularity***: PF, Collimated final states, particle ID, pile-up rejection
  - ***High resolution***
    - EM constant term <1% e.g. for Higgs self-couplings H→bb$\gamma\gamma$
    - Hadronic constant term <2-3%
  - ***Timing resolution*** for pile-up rejection
  - Combined measurement with tracker:
    - Particle flow techniques for jets, E_T^{miss}, but also to reject pile-up
- **Possible technologies:**
  - **Highly granular EM calorimeter** based on noble liquids (e.g. LAr/Pb) or Si/W in barrel region (radiation too high in endcaps)
  - **Hadronic calorimeter:** Scintillator/Steel in the barrel, noble liquid based (e.g. LAr/Cu) for the endcaps and forward calorimeter





CALORIMETRY R&D AT CERN

R&D Proposals for post HL-LHC and Current Status

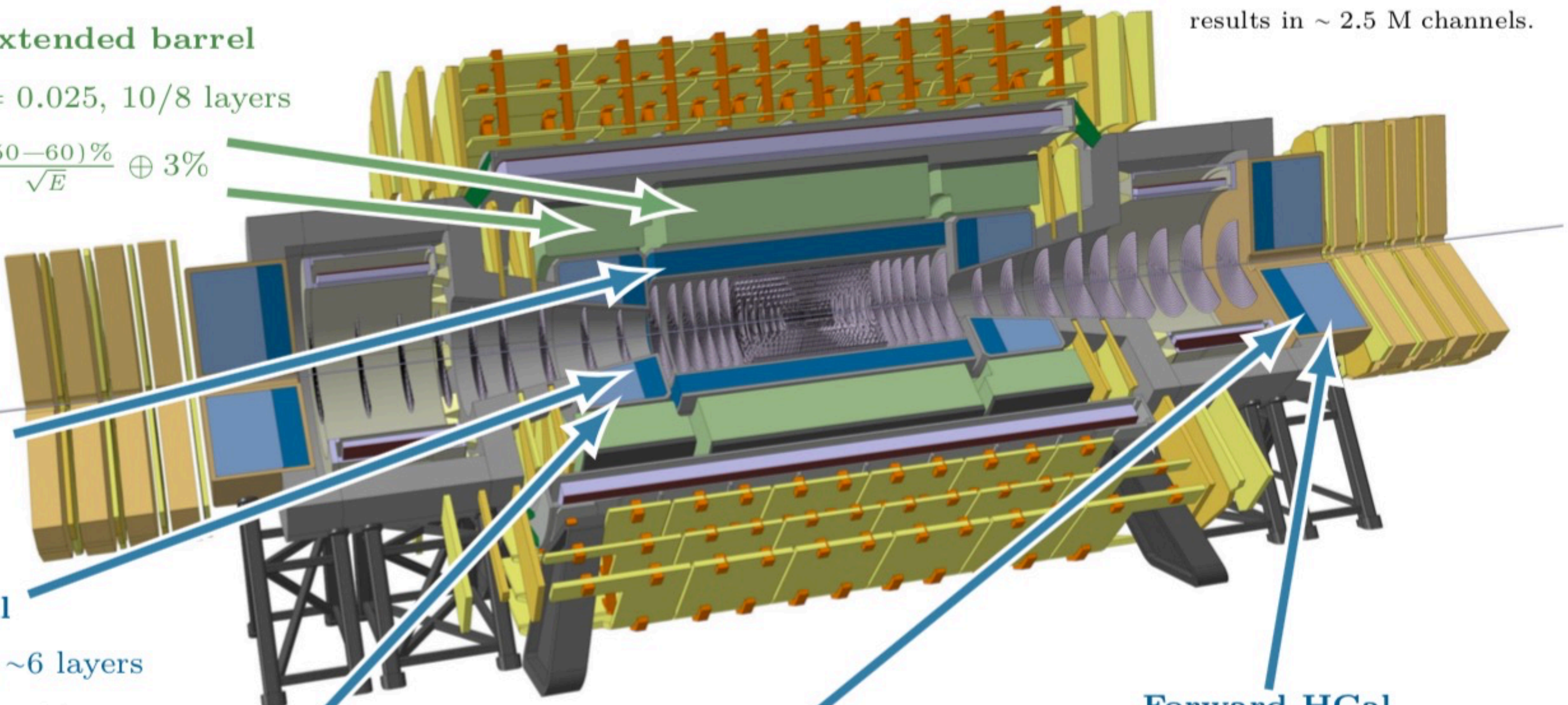
- **R&D proposal on noble liquid calorimetry** (FCC-hh)
  - **Proposed CERN focus:** granularity of read-out electrodes (PCB), spice simulation, PCB design, production and measurements, timing optimization, feedthroughs, LAr properties (LArPulse testbeam)
  - → See later this talk
- **R&D proposal on scintillator based calorimeters** (LHCb ECAL Upgrade II, FCC-hh HCAL, FCC-ee HCAL, CLIC/ILC/CepC HCAL)
  - **Proposed CERN focus:** radiation hardness of scintillator material (including low-temperature operation), timing optimization, Tile read-out via WLS fibres + SiPMs.
  - → See later this talk (LHCb ECAL Upgrade II, FCC-hh HCAL) and other talks in today's session (CALICE)
- **Si-based calorimetry** will profit from CMS HGCal (see dedicated talk in this session), however, some R&D proposed to continue on specific system aspects for CLIC/CLD.
  - **Proposed CERN focus for post HL-LHC:** Power pulsing, system aspects of CLIC/CLD ECAL, build realistic modules including sensors, electronics, absorbers, cooling and services
  - → See later this talk and other talks in today's session (CALICE)
- **R&D proposal on ultra low radiation length cryostats** (for experimental magnets or cryostats for noble liquid calorimetry)
- **For the moment those are proposals, expecting decision on funding in fall 2018.**

FCC-HH CALORIMETERS

FCC-hh Calorimetry

FCC-hh detector

Segmentation not yet optimised, results in ~ 2.5 M channels.



HCal barrel/extended barrel

$\Delta\eta = 0.025,\ \Delta\varphi = 0.025,$ 10/8 layers

goal $\frac{\sigma_E}{E} = \frac{(50-60)\%}{\sqrt{E}} \oplus 3\%$

ECal barrel

$\Delta\eta = 0.01,\ \Delta\varphi = 0.009$

~6 layers

goal $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%$

Endcaps ECal

$\Delta\eta = 0.01,\ \Delta\varphi = 0.01,$ ~6 layers

goal $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%$

Endcaps HCal

$\Delta\eta = 0.025,\ \Delta\varphi = 0.025,$ ~6 layers

goal $\frac{\sigma_E}{E} = \frac{(50-60)\%}{\sqrt{E}} \oplus 3\%$

Forward ECal

$\Delta\eta = 0.05,\ \Delta\varphi = 0.05,$ ~6 layers

goal $\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}} \oplus 1\%$

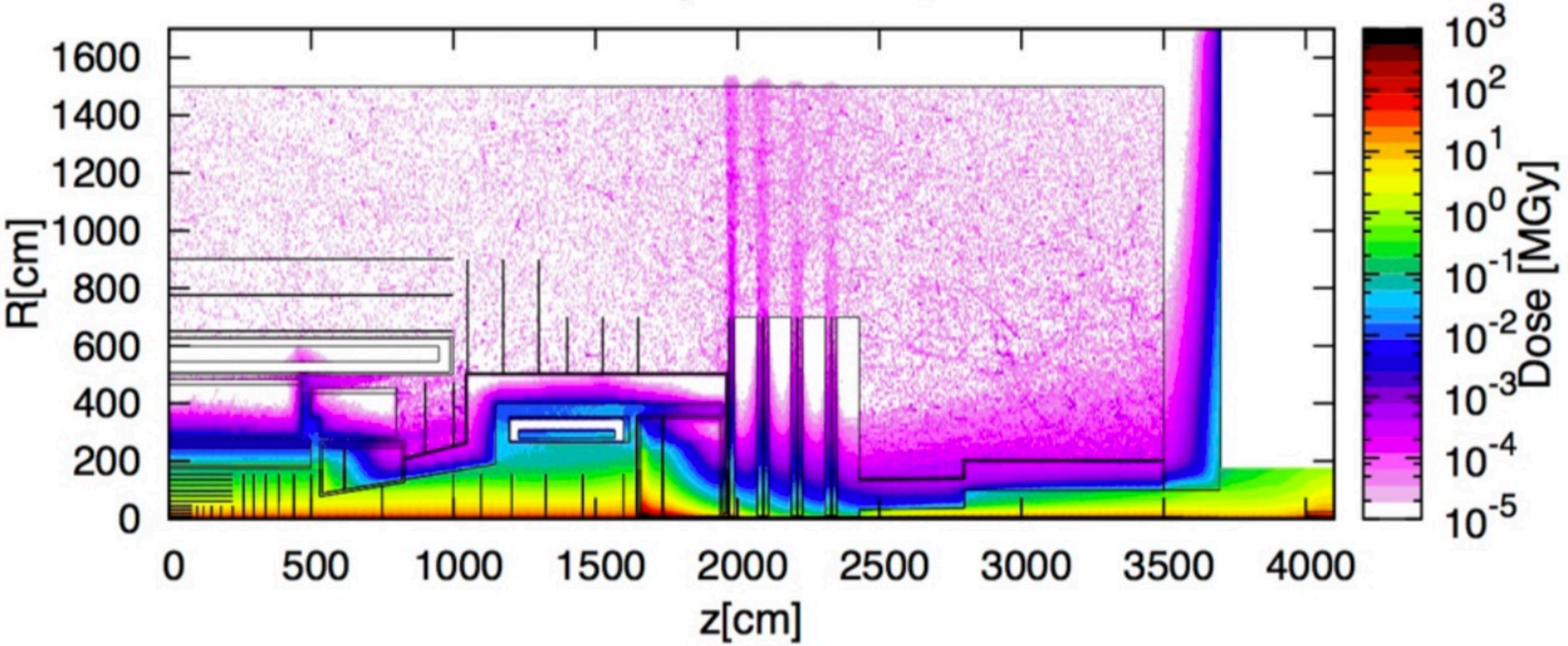
Forward HCal

$\Delta\eta = 0.05,\ \Delta\varphi = 0.05,$ ~6 layers

goal $\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%$

FCC-hh Calorimetry – Radiation Requirements

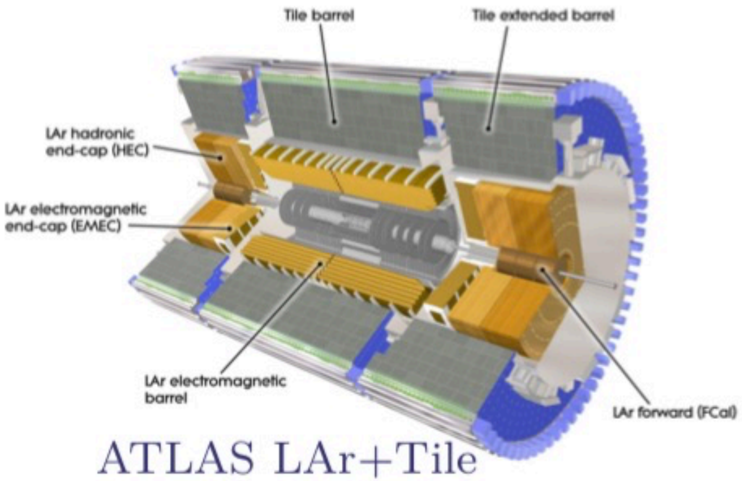
Requirements: radiation



	fluence $10^{14}\mathrm{cm}^{-2}$	dose MGy
ECal barrel	50	0.1
ECal endcap	300	1
ECal forward	5×10^3	5×10^3

	fluence $10^{14}\mathrm{cm}^{-2}$	dose MGy
HCal barrel	3	0.008
HCal endcap	200	1
HCap forward	5×10^3	5×10^3

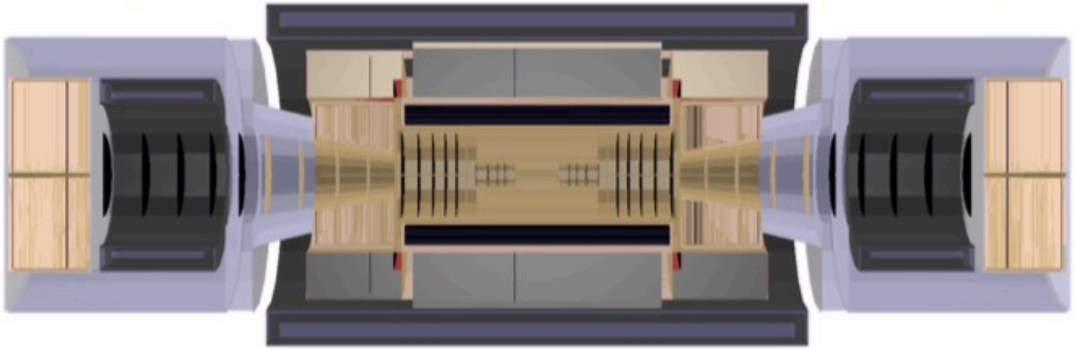
FCC-hh Calorimetry – Radiation Requirements



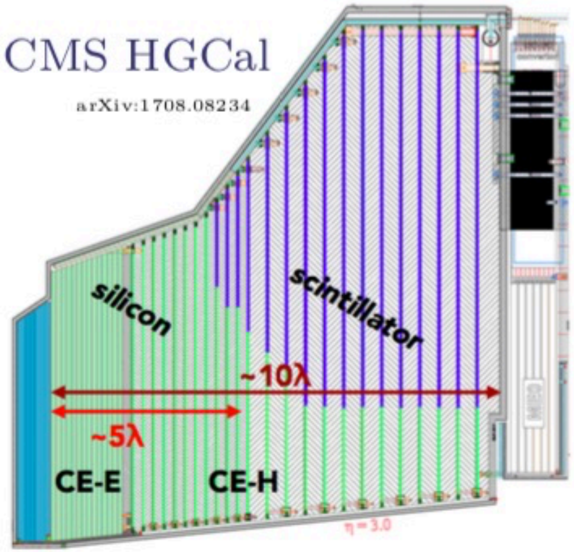
ATLAS LAr+Tile
arXiv:1305.4551

- good instrinsic energy resolution
- radiation hardness
- high stability
- linearity and uniformity
- easy to calibrate

FCC calorimetry

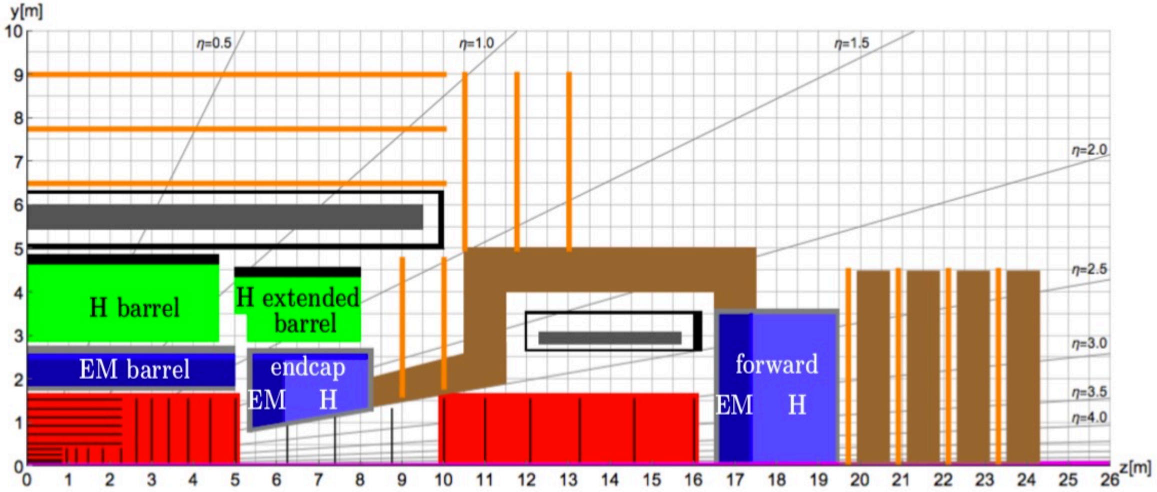


CMS HGCal
arXiv:1708.08234



- high granularity
- particle flow

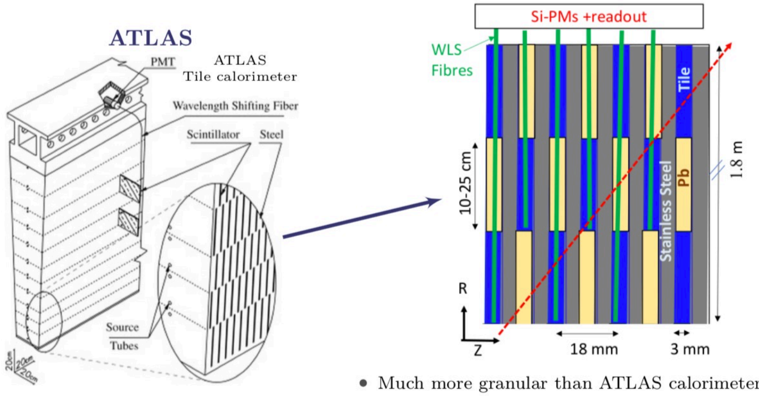
FCC-hh Calorimetry - Technologies



"Reference" detector: based on liquid argon and scintillators

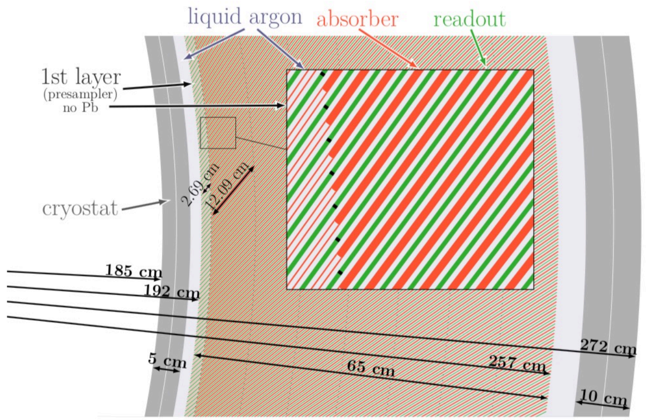
- ECal: LAr used for barrel, endcap and forward detector;
- HCal: scintillator in the barrel, LAr in endcap and forward detector ($1.4 < |\eta| < 6$): radiation hardness;

Hadronic calorimeter barrel



- Much more granular than ATLAS calorimeter (×10);
- $\Delta\eta = 0.025$, $\Delta\varphi = 0.025$, 10 longitudinal layers;
- High longitudinal and lateral segmentation possible with SiPMs;

Electromagnetic calorimeter barrel

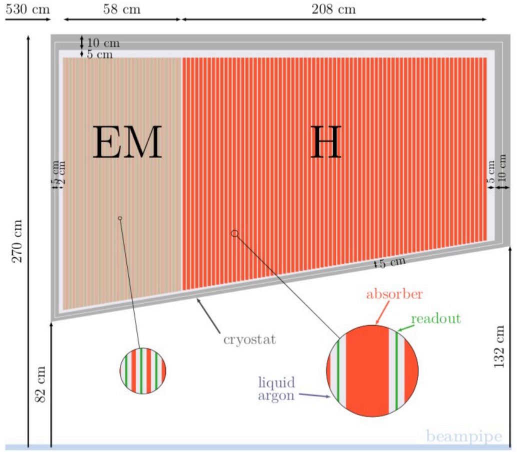


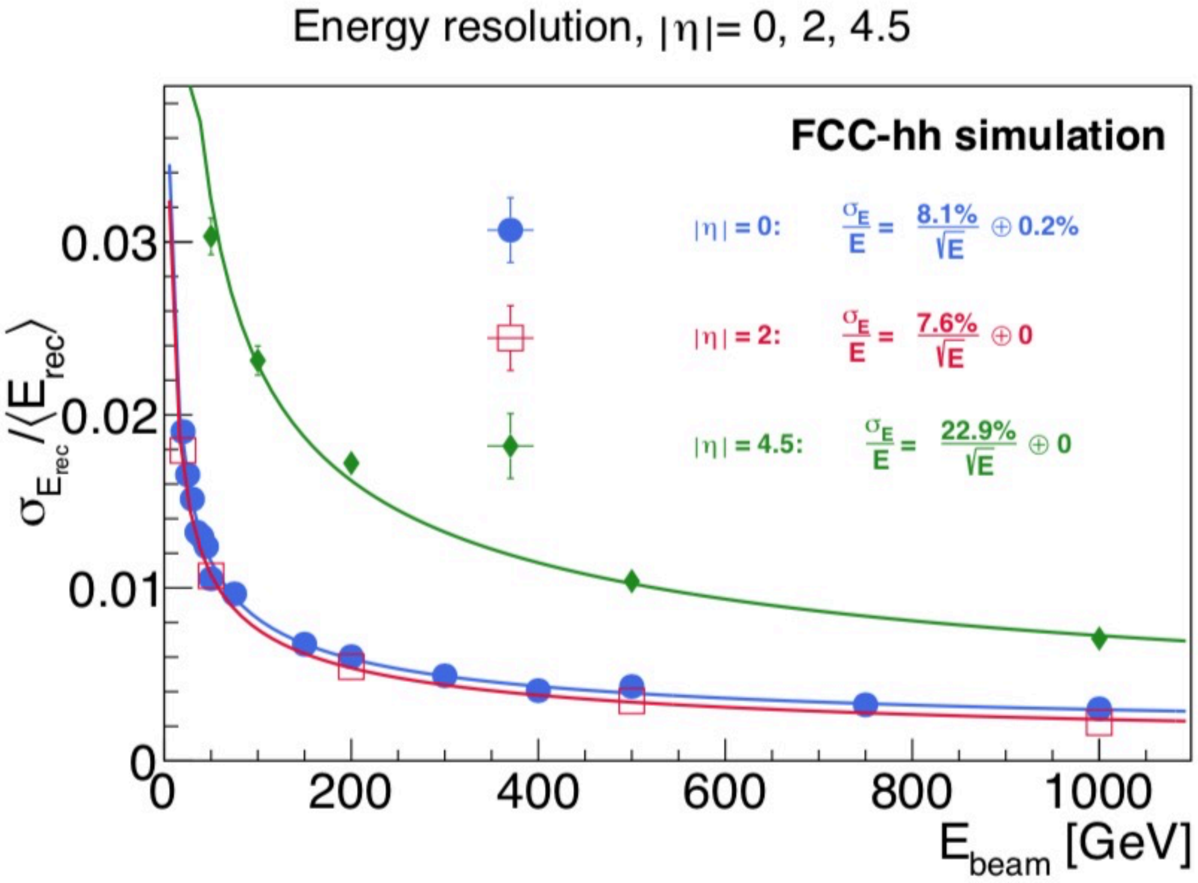
- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;

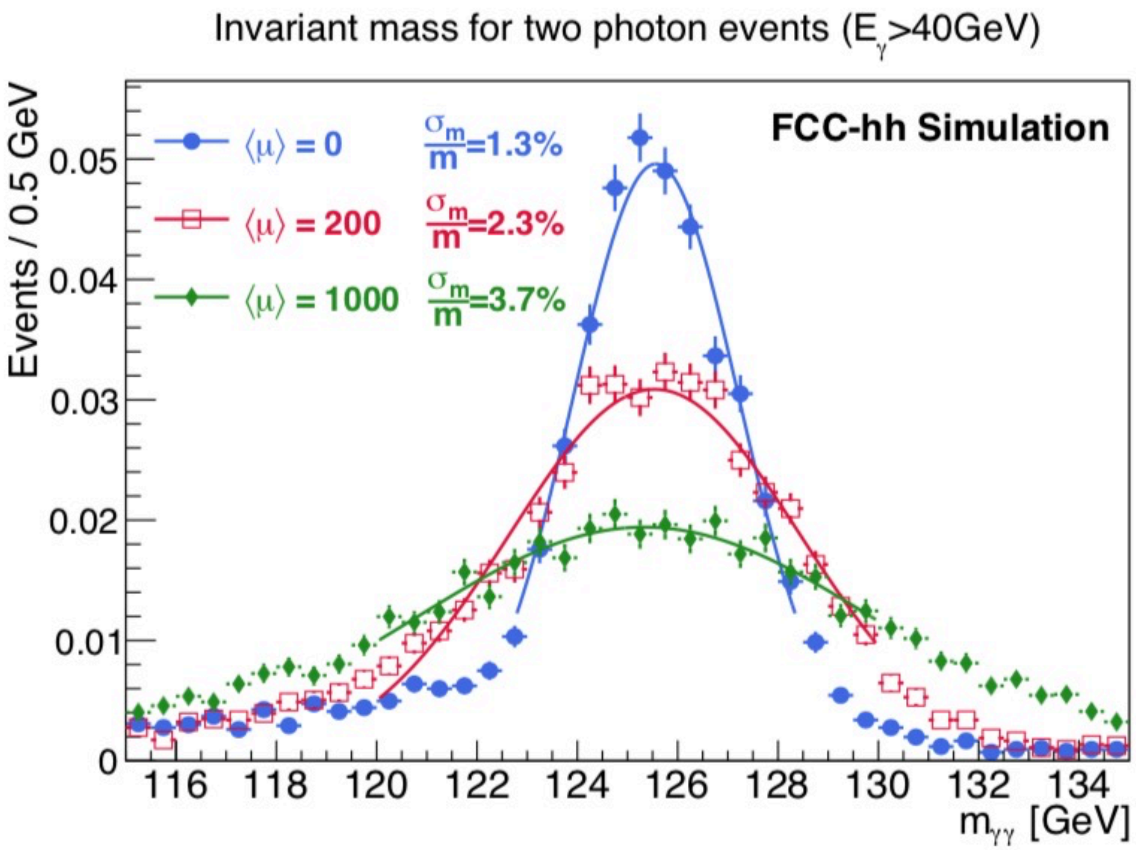
LAr ECal: Achieving high granularity by multi-layer electrodes (PCBs) $\Delta\eta \mathrm{x} \Delta\varphi \approx 0.01\mathrm{x}0.01$ (4x finer strips), 8 longitudinal layers (incl. presampler)

Endcaps layout

- both electromagnetic and hadronic calorimeters within same cryostat;
- electromagnetic calorimeter:
  - 1.5 mm lead discs;
  - 0.5 mm LAr gap;
- hadronic calorimeter:
  - 2 cm copper discs;
  - 2 mm LAr gap;
- First layer serves as a presampler;
- Forward calorimeter simulated with same layout;
  - 0.1 mm LAr gap;
  - 1 cm copper discs in ECal;
  - 4 cm copper discs in HCal;







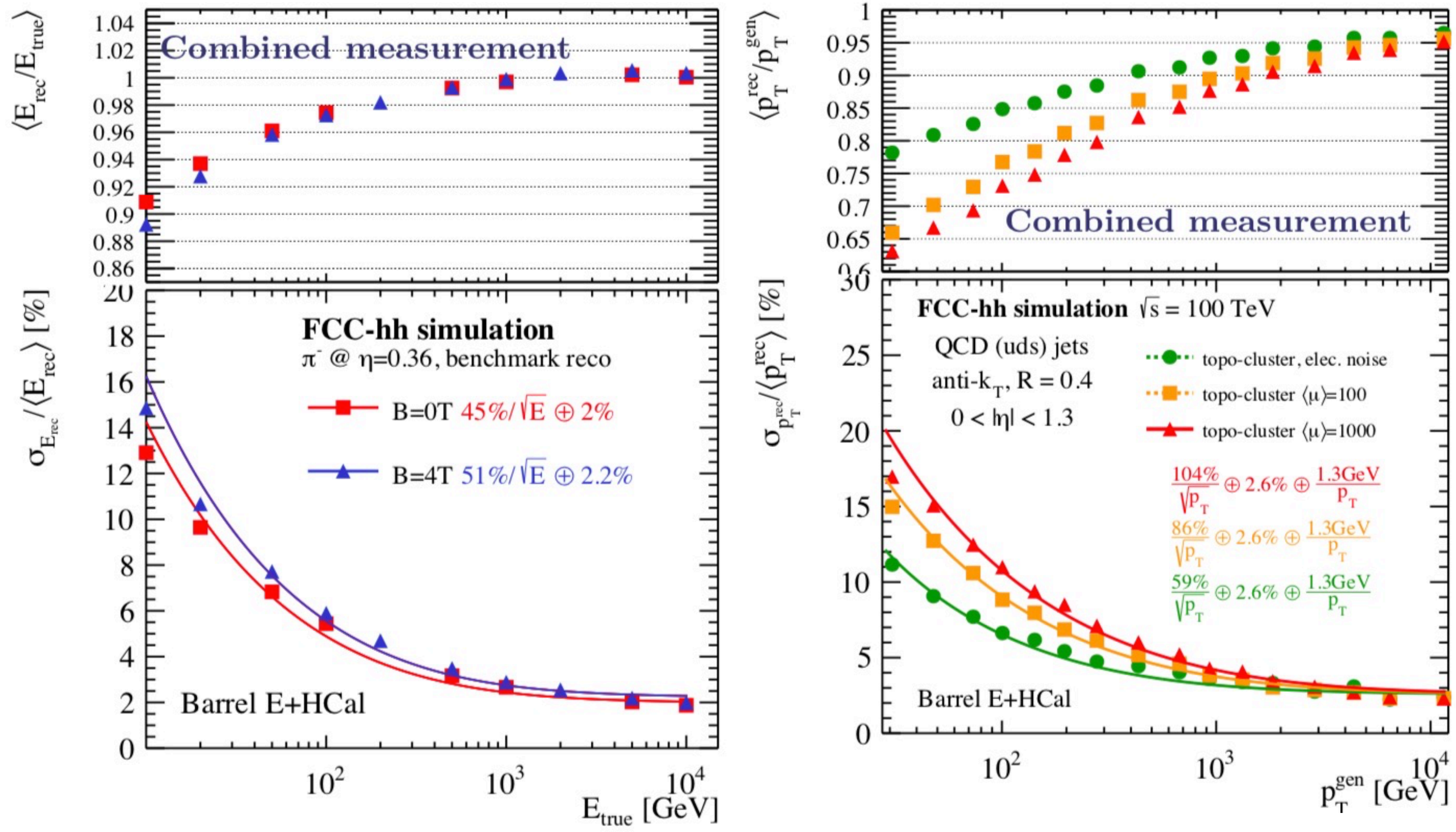
- **Required energy resolution achieved**
  - sampling term < 10%/√Ē, only ≈300 MeV electronics noise despite multilayer electrodes
  - Huge impact of in-time pile-up at <μ> = 1000 of ≈ 4.4GeV pile-up noise (expect small improvement by optimization of cluster size)
  - →Efficient in-time pile-up suppression will be crucial (using the tracker)
  - In-time pile-up impact is independent of the calorimeter type (small improvement possible for W absorbers)

FCC-hh ECal

Proposed Future R&D at CERN

- **High granularity read-out electrodes**: The granularity of noble liquid calorimeters can be easily adjusted to the needs by finely segmented read-out electrodes (multi-layer PCBs). Such electrode PCBs need to be designed, simulated, produced and tested. Special focus has to be given to the resulting electronics noise of the full system including read-out electronics. The final granularity needed will be defined by performance requirements which will be simulated using FCC SW. For this purpose the FCC SW will need some further developments such as the implementation of particle flow or other novel reconstruction techniques. Based on the obtained results a small test module will be designed, produced and tested at the testbeam (2023).
- **Timing resolution**: Noble liquid calorimeters have intrinsically good timing resolution due to their fast signal rise-time and their homogeneous active material. Timing resolution will be essential for future applications in accelerator experiments, limits of MIP timing and timing resolution of showers, involving the full read-out chain, will be explored in simulation and optimized.
- **LAr properties and performance under high ionization rates**: In parallel it is essential to measure and simulate LAr properties and calorimeter performance under high ionization rates covering space charge build-up, initial and bulk recombination, surface charge accumulation and the role of impurities (testbeams planned at Protvino and CERN by collaboration of 6 institutes, HiLum2 (CERN participating with infrastructure)).
- **High density signal feedthroughs**: The large granularity will require an increased signal density at the feedthroughs (FT) of up to 20-50 signals/cm2 which is a factor ~5-10 more than in ATLAS (ATLAS used gold pin carriers sealed in glass). Novel technologies have to be developed with industry & CERN cryo lab.
- **Ultra Low Radiation Length Cryostats**: To meet the design goal for minimum radiation length, thus lowering wall thicknesses and mass of next-generation cryostats, carbon fibre reinforced polymeric-based composites will be explored and compared to advanced metal or hybrid honeycomb structures. Technology -, and materials development of cryogenic fuel tanks will be addressed. Thin-ply hybrid laminates and out-of-autoclave curing are projected as candidate materials and process. A table top demonstrator will be built.

FCC-hh HCAL+ECAL Performance



- **Required energy resolution achieved**
  - Single pion resolution ≈50%/√Ē, constant term < 2.5%
  - Jet resolution for no-pile-up achieved < 60%/√Ē (B=0T)
  - High granularity → particle flow techniques will be used to improve resolution

Proposed Future R&D at CERN

- Due to the relatively modest radiation requirements (TID 8kGy in the tiles) the reference design makes use of organic scintillator tiles read out by wave-length shifting fibres and SiPMs to profit from a factor 4 increase in lateral granularity with respect to ATLAS TileCal.
- The proposed R&D will be done in close collaboration with industry and several institutes part of the ATLAS TileCal collaboration and will make use of the infrastructure of the TileCal lab in B175 at CERN.
- Identification and qualification measurements of components before and after radiation (tiles, WLSs, SiPMs, calibration systems), optimization of the optics concept (WLS, coupling to SiPMs), optimization of mechanics,...
- An ATLAS spare mechanics module will be re-instrumented with FCC-hh components to do cosmics tests and possible testbeam measurements (profiting from ATLAS TileCal table and testbeam infrastructure).

CLIC DETECTOR ECAL / CLD ECAL AT FCC-EE

CLIC Detector ECAL / CLD ECAL at FCC-ee

- The CLIC detector and the CLD detector at FCC-ee propose very similar highly granular calorimeter designs, which are optimized for Particle-Flow Analysis (PFA): compact sandwich structures for the electromagnetic (ECAL) and hadronic (HCAL) sections in a barrel and end-cap geometry located inside the central detector solenoid.
- The new CMS highly granular endcap calorimeter HGCal for the HL-LHC phase-2 upgrade will comprise similar technologies. Therefore much will be learned for the CLIC/CLD calorimetry through the HGCal development and construction in the coming years, such as: sensor development and procurement, detector integration, cooling integration (without power pulsing), calibration, full system aspects, mass production.
- Strong CERN participation in the CMS HGCal project will also profit to pursue calorimetry R&D for CLIC. The main differences between CMS HGCal and CLIC reside in the readout timing and the power pulsing.
- At CLIC, power pulsing will result in a strong reduction factor in heat dissipation between the sandwich layers → passive conductive cooling along the absorber → power pulsing enables a larger effective density of the calorimeter and more compact particle showers.

Parameter	CLIC	CLD at FCC-ee
ECAL sensor	silicon	silicon
ECAL cell size	5 5 mm^2	5 5 mm^2
ECAL absorber	tungsten	tungsten
Number of ECAL layers	40	40
ECAL pulse height accuracy	~12 bits	~12 bits
HCAL sensor	plastic scintillator + SiPM	plastic scintillator + SiPM
HCAL cell size	30 30 mm^2	30 30 mm^2
HCAL absorber	steel	steel
Number of HCAL layers	60	44
HCAL pulse height accuracy	~14 bits	~14 bits
Hit time resolution	1 ns	??
Readout window	~156 ns at 50 Hz	~1 sec continuously
Power pulsing	yes	no
Radiation level NIEL	? $10^?$ $n_{eq}/(cm^2yr)$	? $10^?$ $n_{eq}/(cm^2yr)$
Radiation level TID	? Gy/yr	? Gy/yr
Solenoid field / inner bore radius	4T / 3.5 m	2T / 3.7 m

Proposed Future R&D at CERN

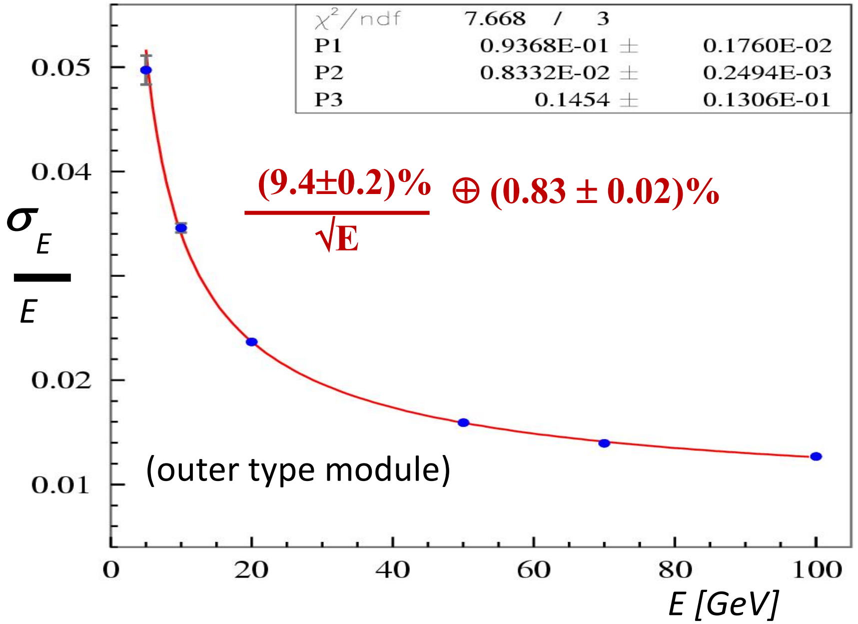
- Continue the calorimeter R&D for CLIC/CLD through participation in CMS HGCal at the current resource level throughout 2019-2022.
- Drawing on the CMS HGCal experience pursue engineering (mechanical + electronics) design studies for CLIC/CLD, both for ECAL and HCAL, in order to present realistic designs ranging from the module level up to the system and integration level during the years 2020-2022.
- Build and test a few realistic CLIC/CLD ECAL modules, including sensors, electronics, absorbers, power pulsing (for the CLIC case), cooling and services during the years 2022-2025.

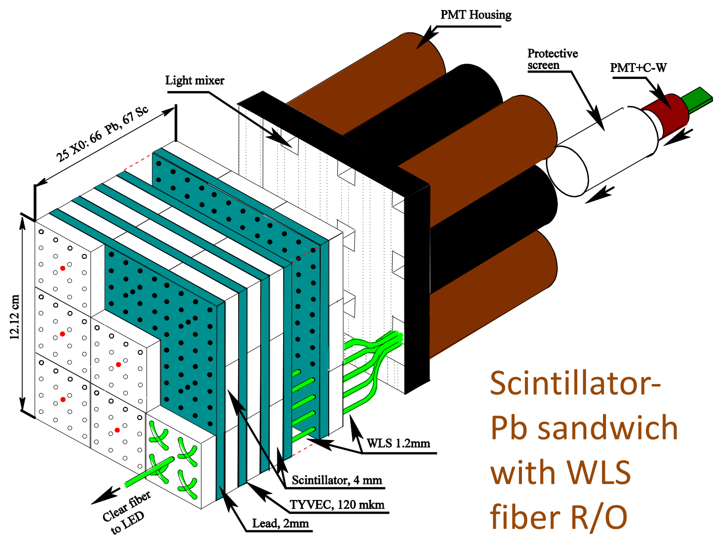
LHCB ECAL UPGRADE II

LHCb Now – ECAL Shashlik modules

- **Current LHCb ECAL**:
  - Large Shashlik array ~50 m^2 with 3312 modules and 6016 channels
  - Modular wall-like structure of 7.8 m x 6.3 m
  - Three sections (Inner, Middle, Outer) of cell size 4x4, 6x6, 12x12 cm^2
  - $\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$

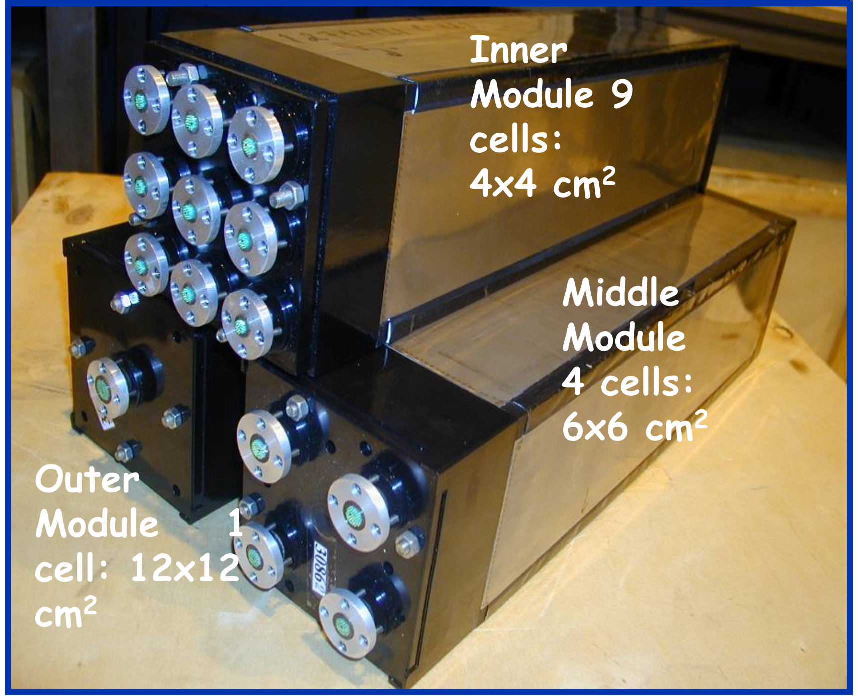
Energy resolution with electrons



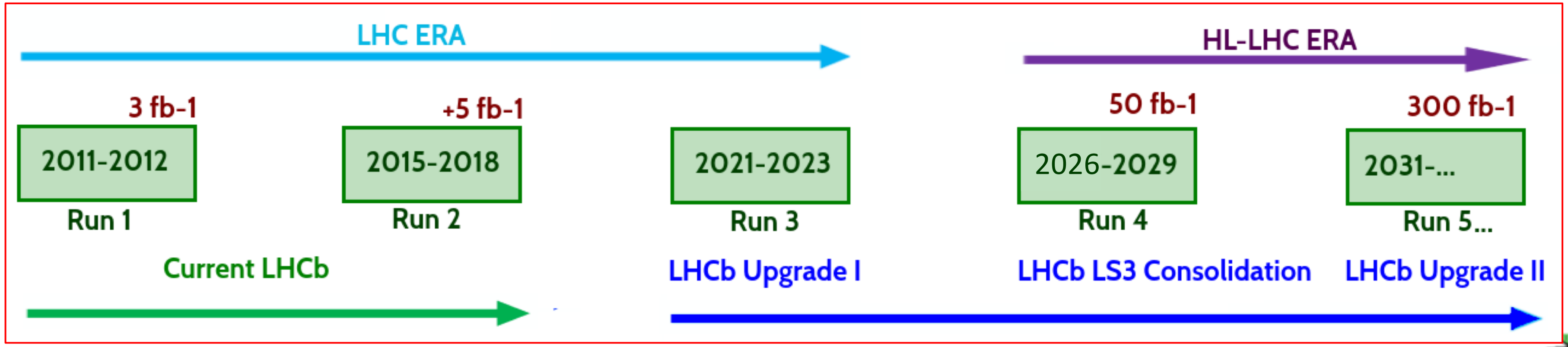


Scintillator-Pb sandwich with WLS fiber R/O

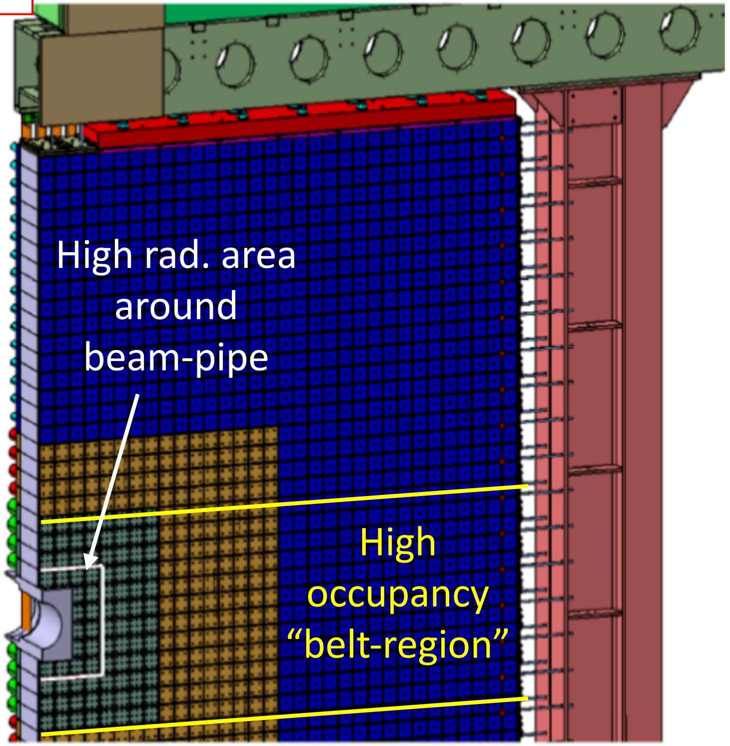
3312 shashlik modules with 25 X0 Pb



LHCb ECAL Upgrades I and II



- **LS2 in 2019/20: LHCb Upgrade I**
  - Keep current ECAL Shashlik modules but upgrade electronics to full 40 MHz readout
- **LS3 in 2024/25: Consolidation**
  - Replace modules around beam-pipe (≥ 32 modules) compatible with L=2x1033 cm-2s-1
- **LS4 in 2030/31: LHCb Upgrade II**
  - Rebuilt ECAL in high occupancy “belt-region” compatible with luminosity up to L=2x10^{34} cm^{-2}s^{-1}
  - Include timing information to mitigate multiple interactions/crossing

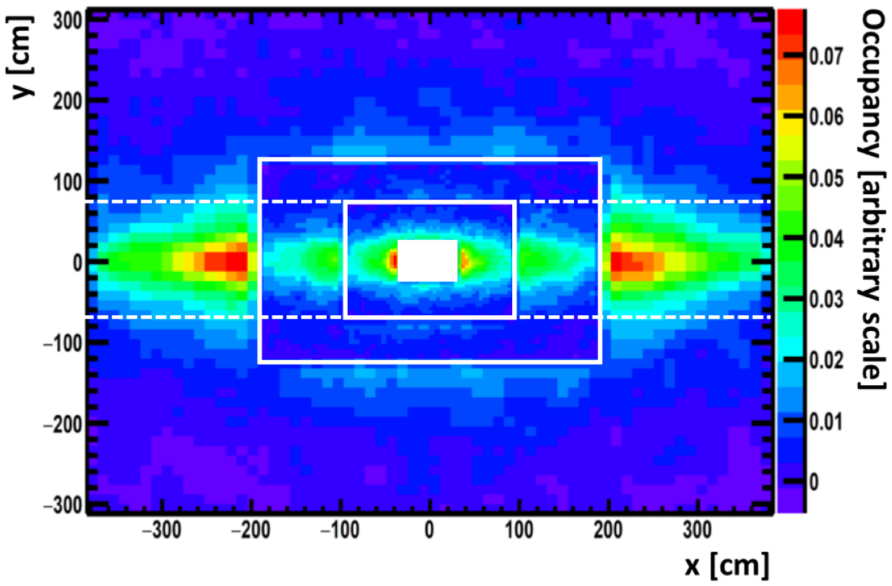


ECAL Requirements for Upgrade II

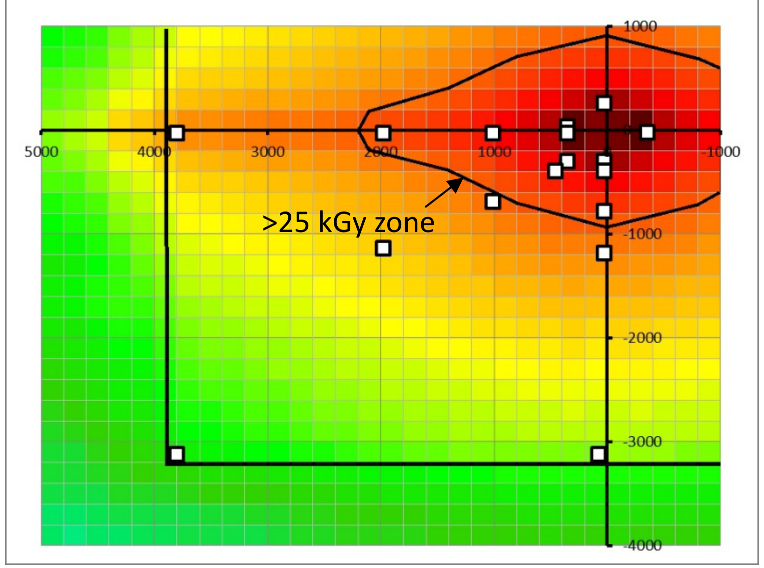
Overall requirements:

- Sustain radiation doses of up to ~3 MGy and ~3·10^{15}cm^{-2} for 1 MeV n eq. at 300 fb^{-1} (in hottest region of the central part, decreasing quickly with distance from beam-pipe)
- Keep good energy resolution of order σ(E)/E ~ 10%/√E ⊕ 1%
- Reduce occupancy and improve spatial resolution in inner region
  - Reduce Moliere Radius (to ~2-3cm)
  - Reduce cell size (inner region) to ~ 2cm x 2cm
- Fast response (40 MHz R/O)
- Respect dimensional constraints of a module: 12 x 12 cm^2 outer dimension

Occupancies in different ECAL regions



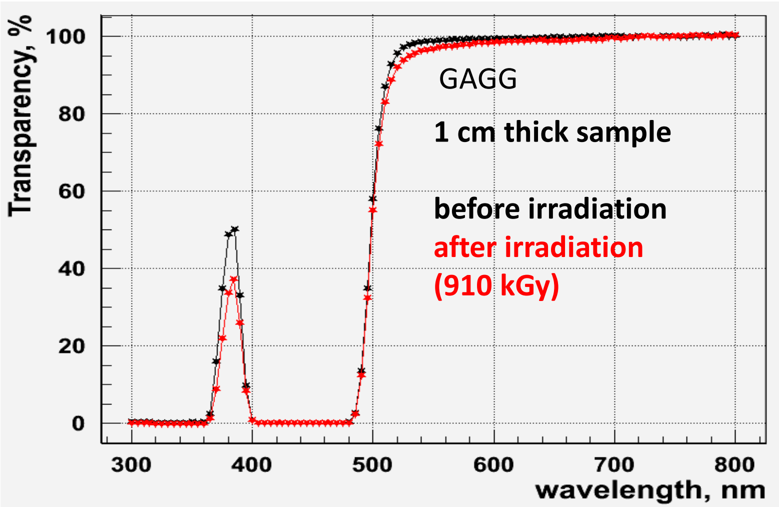
Radiation dose on ECAL front



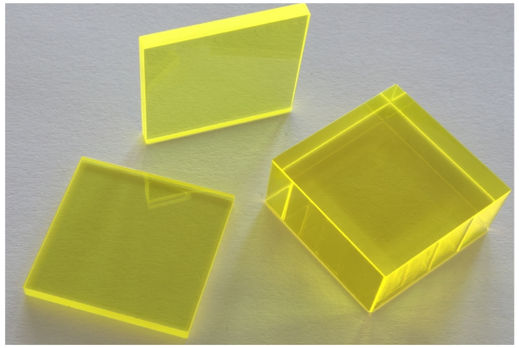
Possible Options for New ECAL Modules

Possible options:

- **Homogeneous crystal calorimeter** with longitudinal segmentation:
  - Fast and radiation hard crystal with high light yield
- **Sampling calorimeter:** (e.g. Shashlik or SpaCal type)
  - Tungsten or tungsten alloy as converter (RM ~ 1cm)
  - Radiation hard crystal as active medium with high light yield and fast response
  - Radiation hard light-guide/fibre to transport light (for Shashlik type)
  - Radiation hard photodetector
  - Include a very fast (crystal) component (~20ps) for pile-up mitigation into module or add "pre-shower timing layer" in front of Shashlik module
- **R&D has started on:**
  - Radiation hard scintillators (e.g. GAGG crystals)
  - Radiation hardness of GaAs photodiodes with epitaxial technology
  - Tungsten alloys (i.e. W-Pb)



Samples of GAGG crystals irradiated at CERN



Proposed Future R&D at CERN

- Assessment of radiation hardness of suitable scintillation detector materials (scintillation characteristics, light yield, and transmission using various radiation sources providing gammas, protons and neutrons).
- The expected radiation environment can make it necessary to operate the photodetectors such as SiPM at low temperatures (-30°C, -40°C) → study radiation hardness of scintillating materials and photodetectors at different temperatures.
- For fast timing, the full detector readout chain has to be optimized in terms of light detection and timing characteristics. This requires time resolution studies on various scintillating materials and on photo detectors, optimization of light collection, shape of the material, etc...

Conclusions

- European Strategy:
  - Top priority to fully exploit the LHC
  - CERN should propose post-LHC accelerator projects
- → R&D on CLIC, FCC-hh, FCC-ee and FCC-eh accelerator & experiments
- CERN EP department is launching an R&D programme on new detector technologies
- In the field of calorimetry R&D projects are proposed on noble liquid based, scintillator based and Si based calorimetry → Decision in fall 2018
- R&D for the next generation of accelerator experiments has started – Very open for collaboration!