R&D on Experimental Technologies

WG3 Report – Part 1: Calorimetry

March 2018

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Scope of WG3 "Calorimetry and Light Based Detectors"

Our Roadmap

Future Calorimeters

Summary of Input Received

THANK YOU for all the Input Received!

WG3 meeting on Feb. 27 plus many discussions (https://indico.cern.ch/event/704508/)

… now it’s time to digest

INTRODUCTION

Scope of WG3 "Calorimetry and Light Based Detectors"

- **Two large areas:** Calorimetry on the one hand and light based detectors on the other hand (two areas often interconnected)
- **Calorimetry:**
  - Which technologies could be suitable for future accelerator experiments (LHC beyond HL-LHC (e.g. LHCb Upgrade), FCC-ee, FCC-hh, CLIC, ILC, CepC, …)?
    - What are the challenges for calorimetry for future accelerator experiments?
      - Pile-up, radiation hardness, high resolution, particle ID, boosted objects, particle flow, timing….
    - Active materials: Scintillators/crystals, Si, noble liquids, gas + ? → Radiation hardness, low temperature operation,…
  - Which relevant R&D exists in these areas?
  - Which R&D will be necessary to assure that future accelerator experiments can be built in O(20) years?
    - R&D on promising technologies
    - Including special focus on timing capabilities
    - Including R&D on engineering challenges (e.g. cryostats, feed-throughs,…)
  - → We should propose a solid R&D plan in fall (can/should build on R&D carried out for HL-LHC)
- **Light based detectors:**
  - General detector concepts, (ex. vertexing and tracking with light, Cherenkov detectors,…);
  - Scintillator materials (in- and organic, photonics, Cherenkov materials,…);
  - Photodetection: vacuum, solid-state and gas based photodetectors;
  - High Energy environment (high spatial and/or time resolutions, high rates/occupancies, rad. hardness, …).

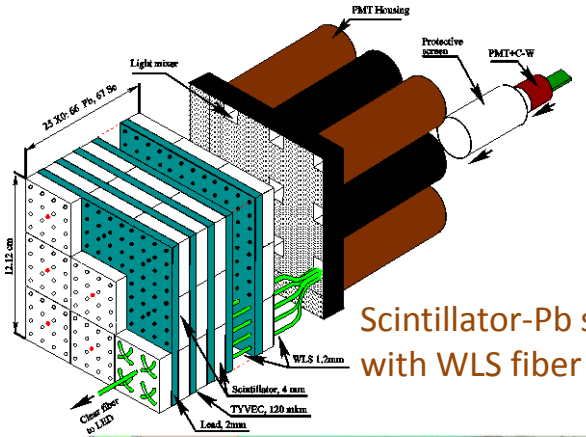
Our Roadmap…

- **Contacted group of experts to join the working group to cover expertise of the full field**
- **First General WG3 Meeting on Feb. 27 (https://indico.cern.ch/event/704508/)**
  - Brainstorming session: Asked everybody who wants to participate to prepare 2 slides on present R&D projects at CERN in the field of WG3, the needs of future accelerator experiments (beyond LHC Phase II upgrades) and ideas on R&D to make sure that these needs could be satisfied.
  - Very diverse feedback and ideas received (***THANK YOU!***), very long agenda (20 contributions), allowed us to collect information on current landscape and ideas for future
- **Today (1st R&D workshop)** we present this input received.
- After the 1st workshop the goal is to **consolidate and evaluate those R&D proposals**
  - Additional information from experts, additional information from those presenting proposals, discussions with stake-holders (like detector groups of future accelerator experiments).
  - We have to make sure not to forget important topics (together with experts covering the full field)
  - Working group meetings to report on the progress and discuss (also meetings in sub-groups).
- **Summer/Fall: Convergence to a proposal for the R&D report**, incl. concrete R&D lines, milestones, deliverables, resource estimates
- **Platform for information exchange inside our WG3:**
  - EP-RDET-WG3-Cal-Light@cern.ch (100 members) and
  - sharepoint area https://espace.cern.ch/ep-rdet-wg3-cal-light/SitePages/Home.aspx (newsfeed and file upload)

CALORIMETRY FOR FUTURE ACCELERATOR EXPERIMENTS

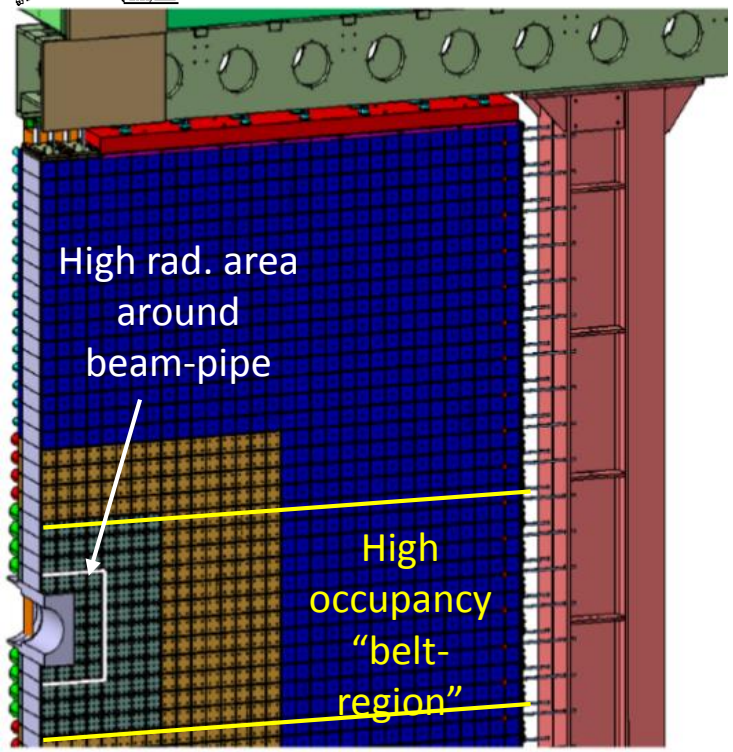
LHCb Upgrade Beyond HL-LHC

- 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 ~3·10^{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 ~ 1cm)



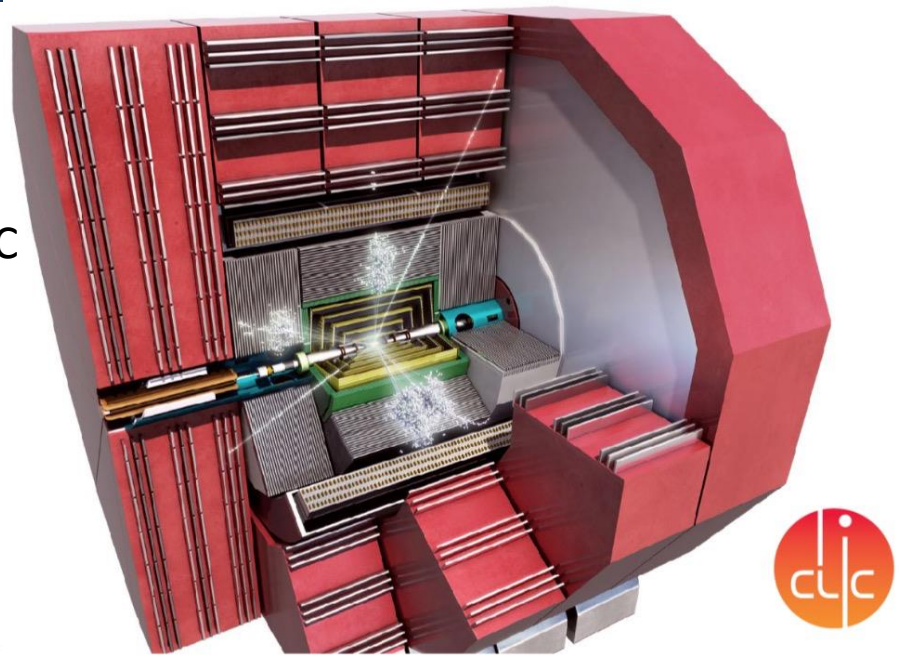
LHCb today

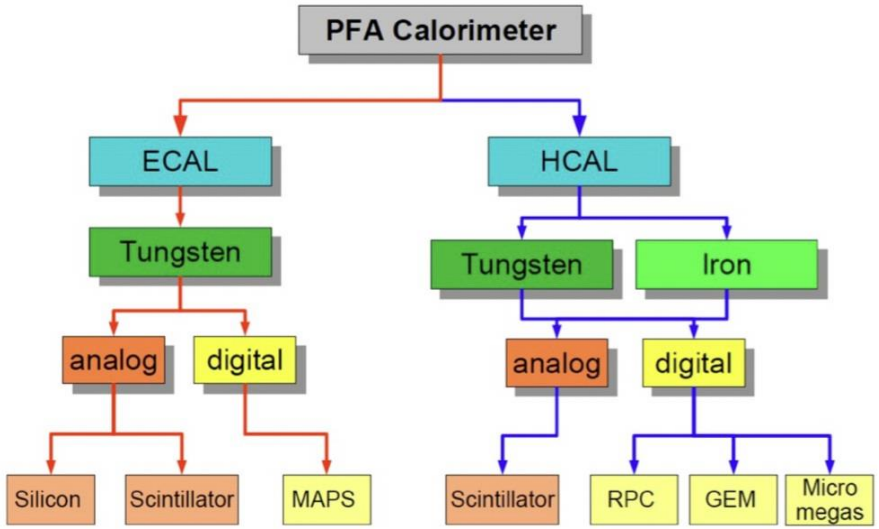
Scintillator-Pb sandwich with WLS fiber R/O



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**

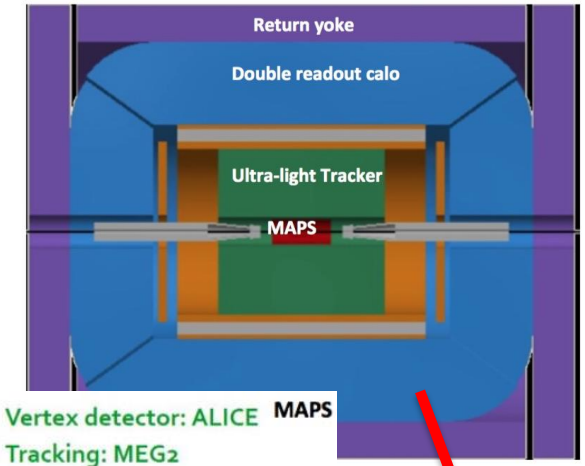




FCC-ee (CepC)

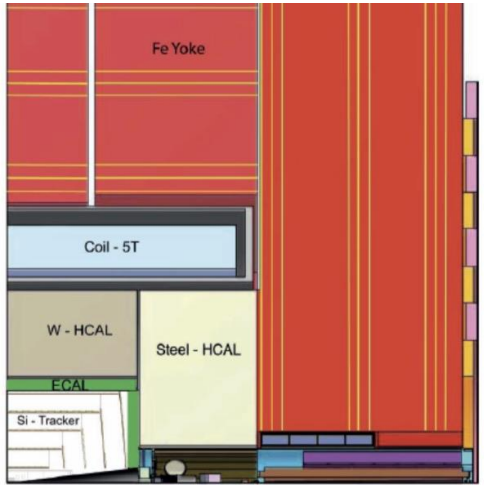
- **Calorimetry requirements**:
  - ***Excellent jet energy resolution*** (~30%/√E)
  - Radiation tolerance and bandwidth requirements benign compared to LHC
  - Particle ID
- **→ Calorimetry also based on particle flow**
  - Same technologies as for CLIC/ILC under study
  - On top of that fibre-sampling 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)

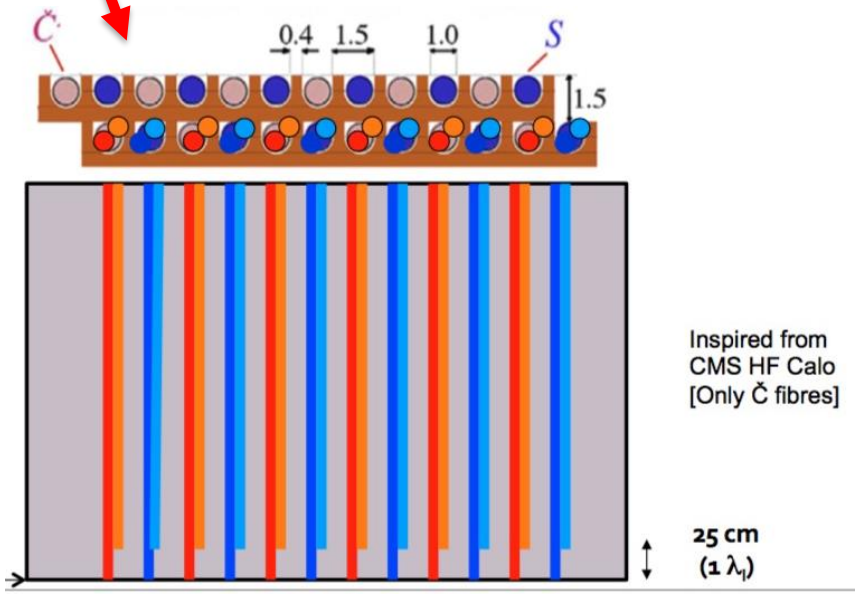
"IDEA"



- Vertex detector: ALICE MAPS
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

"CLIC-detector revisited"

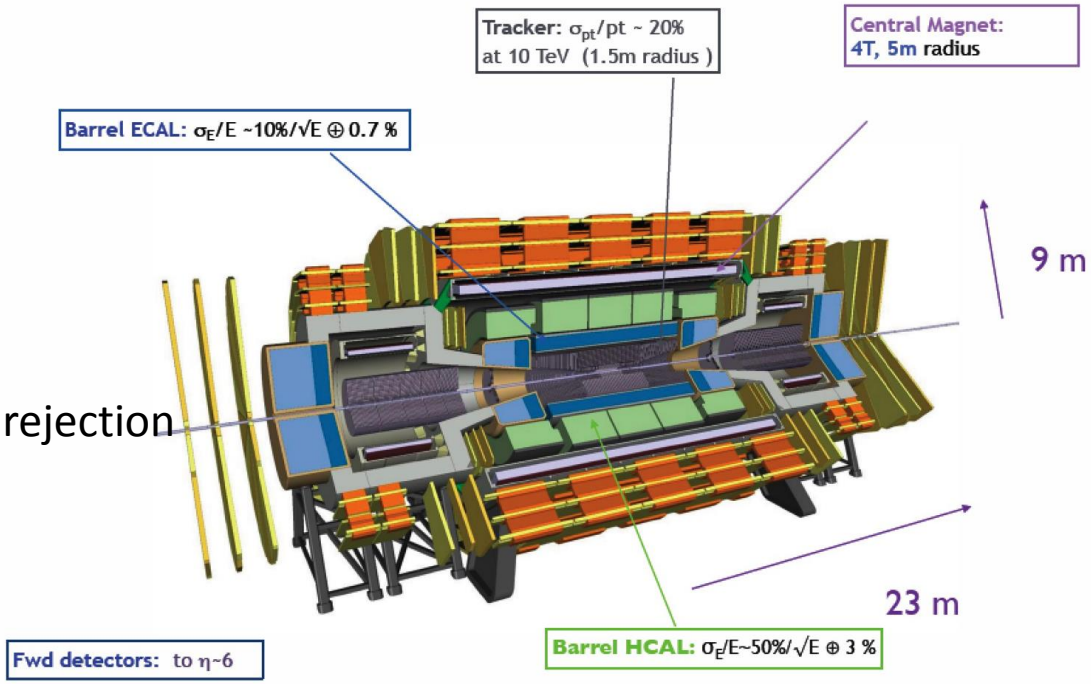


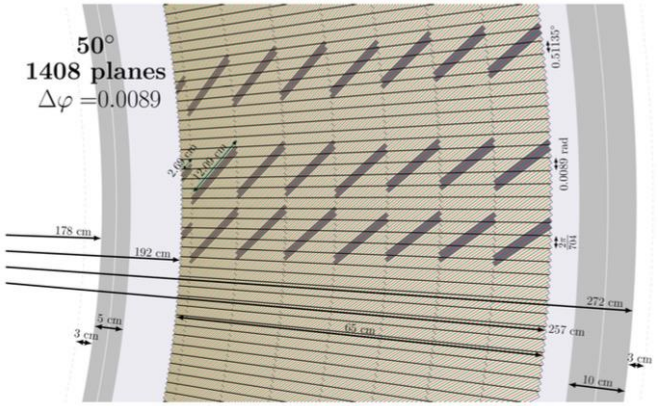


Inspired from CMS HF Calo [Only Č fibres]

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

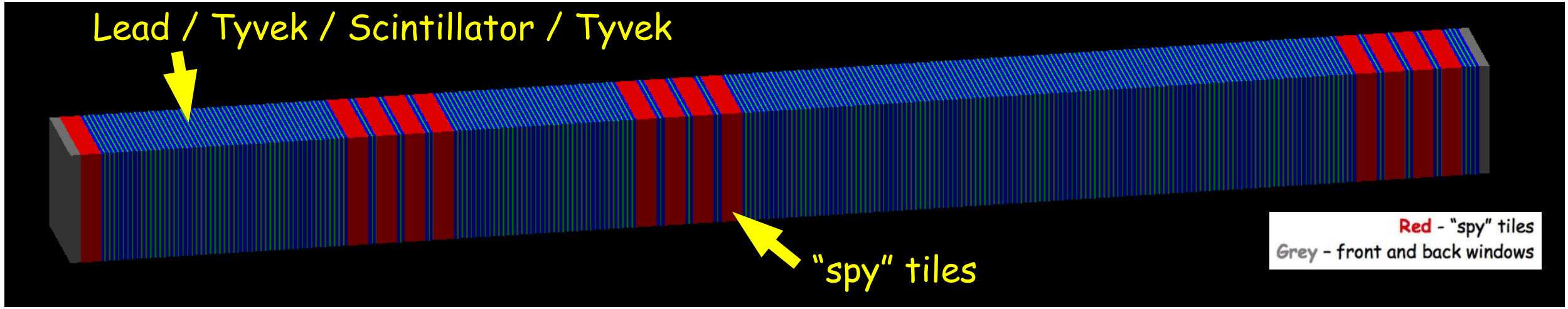




R&D PROPOSALS RECEIVED
CALORIMETRY – SCINTILLATOR/CRYSTAL BASED

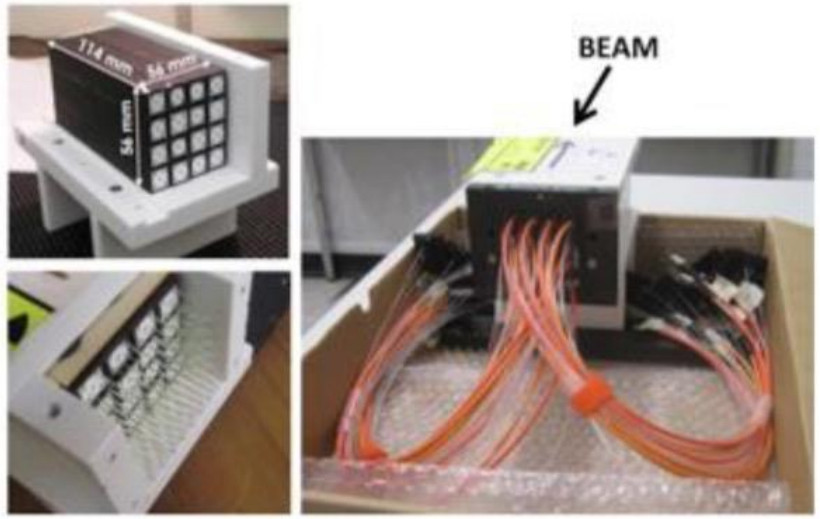
Shashlik Calorimeter Using Spy-Tiles for KLEVER

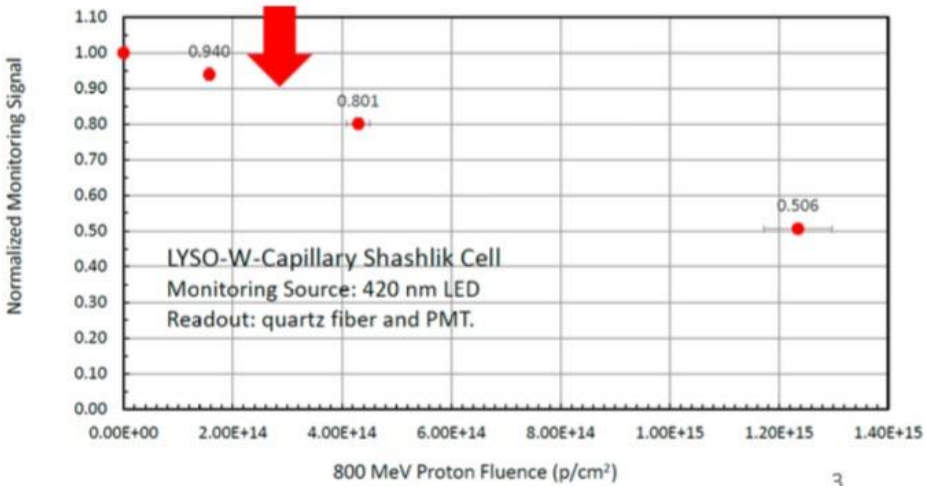
- Presented by Sergey Kholodenko (IHEP Protvino)
- **Proposal**:
  - Improve shashlik calorimeter module by introducing additional tiles (spy tiles) to gain extra information on shower longitudinal profile. Tiles are optically isolated from the rest and read out separately.
  - 6 electronics channels per module
    - 2 channels are from common shashlik readout
    - 1 channel each for each group of spy tiles (start of shower, 5.5 – 6.5 X_0 , 8 X_0 , 21 – 25 X_0)
- Working on first prototype, testbeam planned this year
- **Application**: KLEVER collaboration (installation during LS3) currently evaluating LKr calorimeter vs longitudinally segmented shashlik calorimeter



Optical Detector Development for Calorimetry and Fast Timing

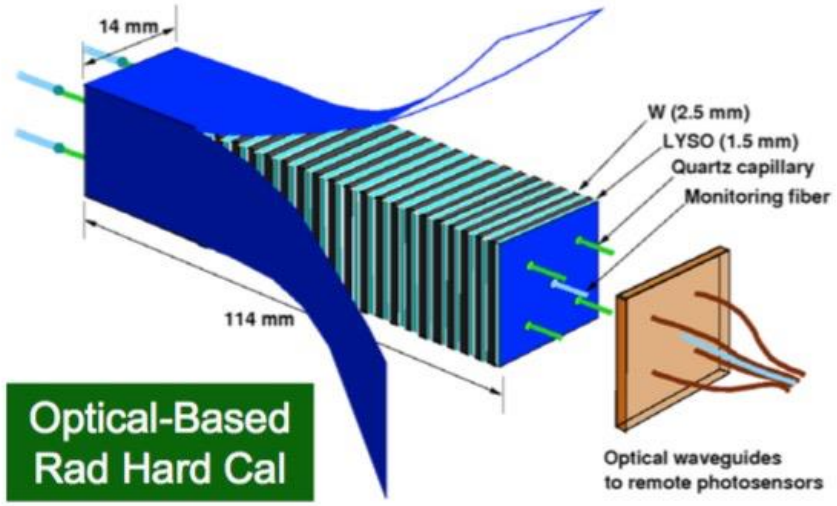
- Presented by Brad Cox (U. of Virginia)
- **Proposal:**
  - R&D on compact, radiation hard optical detectors
  - Crystal and Ceramic Scintillators
    - LYSO(Ce),LYSO(Ce,Ca),LuAG(Ce), LuAG(Pr), BaF2(Y)
  - Organic WLS in Quartz capillary optical elements
    - Thick wall, narrow core.
    - EJ309 based (liquid scintillator) with DSB1 and others spectrally matched to the scintillators
    - Alternative light collection profiles
  - Pixelated Geiger-Mode Photosensors
    - GaInP (gallium indium phosphide) and SiPM
- **Application:** Highly performant energy and timing measurement (e.g. shashlik-like calorimeter modules, fast-timing structures)

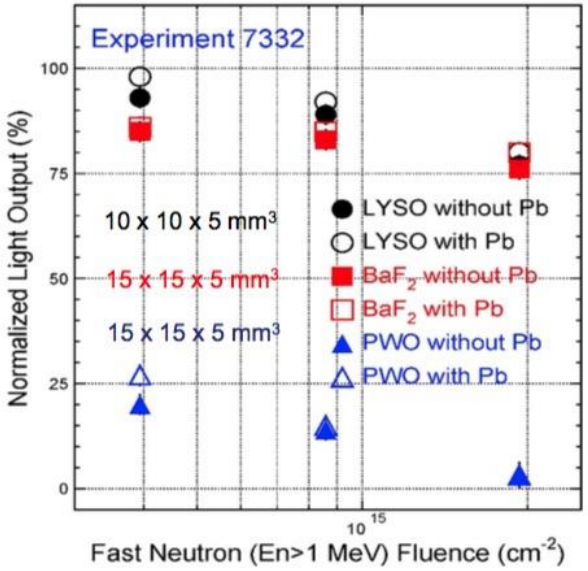


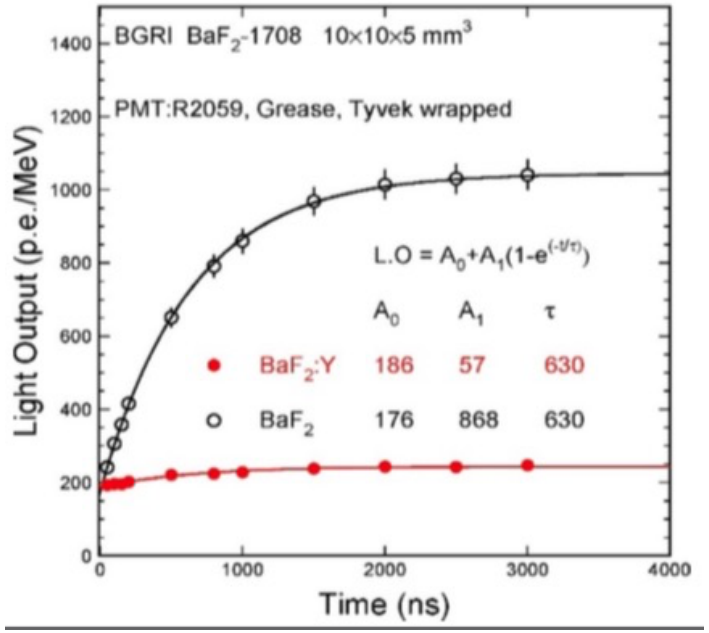


Ultrafast Barium Fluoride Crystals for Future HEP Experiments

- Presented by Renyuan Zhu (CalTEC)
- **Proposal**:
  - R&D on fast crystals
  - With sub-ns decay time/FWHM pulse width and excellent radiation hardness BaF_2 is an ultrafast inorganic scintillator for future HEP calorimeters at the energy and intensity frontiers
  - Yttrium doping is found effective in suppressing the slow scintillation component with 600 ns decay time in BaF_2 ($Y:BaF_2$)
- **Applications:** Optical-based (e.g. shashlik) radiation hard calorimeters,
  - used for Mu2e-II experiment (at Fermilab), $Y:BaF_2$ screen for Marie Project

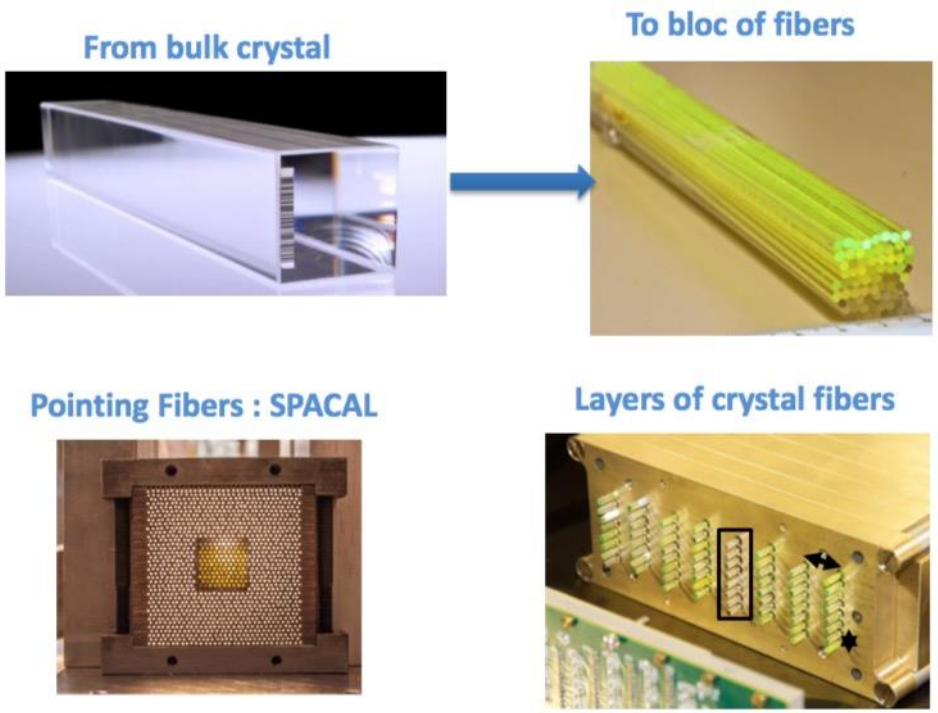






R&D on Scintillating Materials

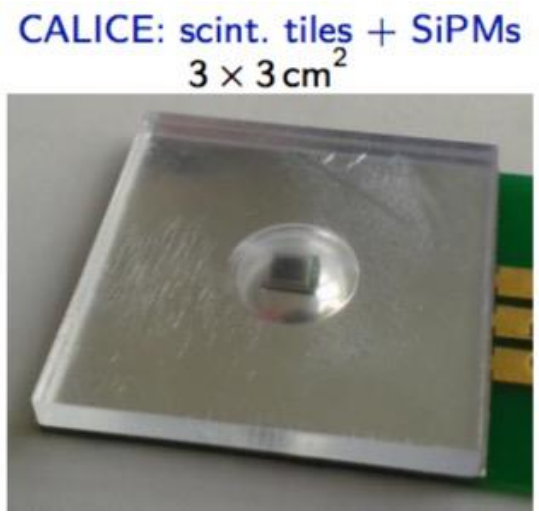
- Presented by Etiennette Auffray (CERN, RD18)
- **Proposal:** R&D on different areas, already strong R&D at CERN by Crystal Clear Collaboration (RD18)
  - Timing performance: understanding and improving the full detection chain
    - scintillator, photodetection, electronics → towards 10ps resolution
  - Radiation hardness:
    - Understanding of radiation damage mechanisms through tests using different radiation sources (gammas, hadrons, neutrons)
    - Scintillator engineering: mixed materials, co-doping
    - Study of temperature dependence of properties of scintillators and photodetectors over a range of 20°C to -40°C
  - Innovative detector concepts:
    - Crystal fibers, Metamaterials
    - Light transport & light collection (surface treatment, photonic crystals, light guide)
- **Application:** CMS barrel timing layer, CLIC/ILC, FCC-ee, LHCb Upgrade II

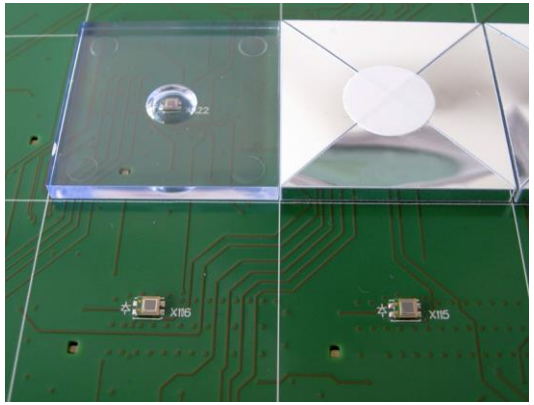


Development of crystal fibres → big flexibility in calorimeter design

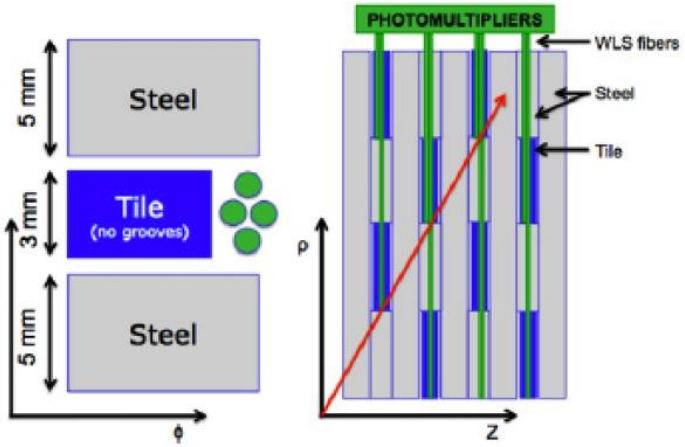
R&D on Scintillator/Fe HCAL

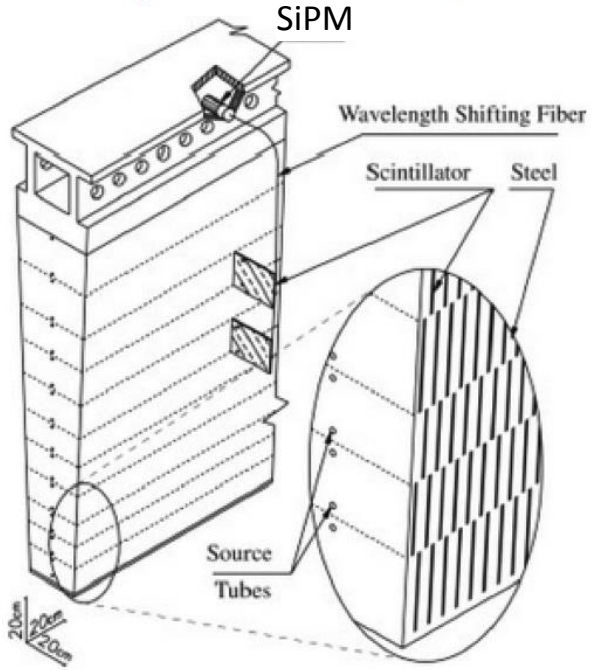
- Presented by Eva Sicking (CERN) (+ baseline for FCC-hh HCAL)
- **Proposal:** Building on existing R&D at CERN inside EP-LCD: R&D on scintillator based highly granular hadronic calorimetry
  - SiPMs integrated in scint. Tiles (CALICE) or read-out via WLS fibres
  - High granularity → SiPMs
  - Understand timing performance
  - Radiation hardness of scintillators, WLS fibres and SiPMs (for FCC-hh)
- **Application:** Studied for CLIC/ILC detector and FCC-hh





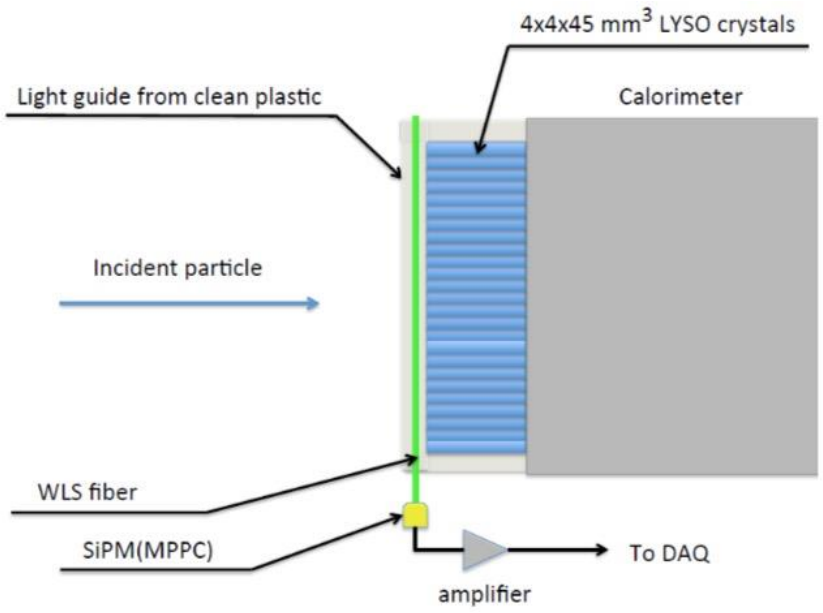
FCC-hh TileCal





Electromagnetic Calorimeter for Low-Energy Photons

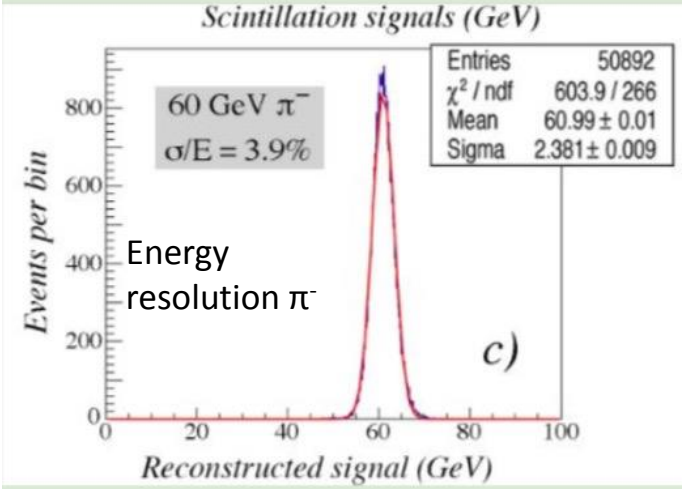
- Presented by Vladimir Poliakov (IHEP Protvino)
- **Proposal:**
  - Develop sandwich electromagnetic calorimeter with high energy resolution of 2-3%/√E to register low energy photons in the range 1-1000 MeV.
  - A crystal (e.g. LYSO) pre-shower can be used in front of sandwich calorimeter to improve the efficiency and resolution for photons in MeV range.
- **Application:** Wide range of possible applications in high energy physics, nuclear physics, medicine, material science and others.
  - 2 versions of NA64 Synchrotron Radiation Detector (SRD): sandwich and LYSO preshower



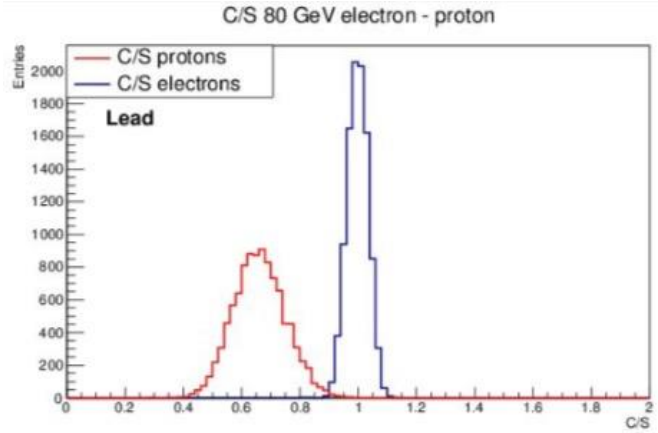
Dual-Readout Calorimetry Development

- Presented by Roberto Ferrari (INFN Pavia)
- **Proposal:** R&D up to now in the framework of RD52 collaboration
  - R&D on dual-read-out (DR) calorimetry for future leptonic colliders.
  - Principle of DR: Correctly reconstruct the energy of em and hadronic showers by means of two independent processes: scintillation and Cherenkov light emission.
  - Feasibility demonstrated by the **DREAM/RD52 Collaboration**
  - Proposing vertical slice testbeam with drift chamber, preshower, DR calorimeter, muon spectrometer
    - Full-containment hadronic module was never built, need to test ultimate hadronic resolution of ~30%/√E
- **Application:** fibre-sampling dual-readout calorimetry interesting option for future leptonic colliders (FCC-ee)

test beam 2015: 70%/√E (leakage)
simulation ~ 35%/√E (ideal detector)



Particle ID

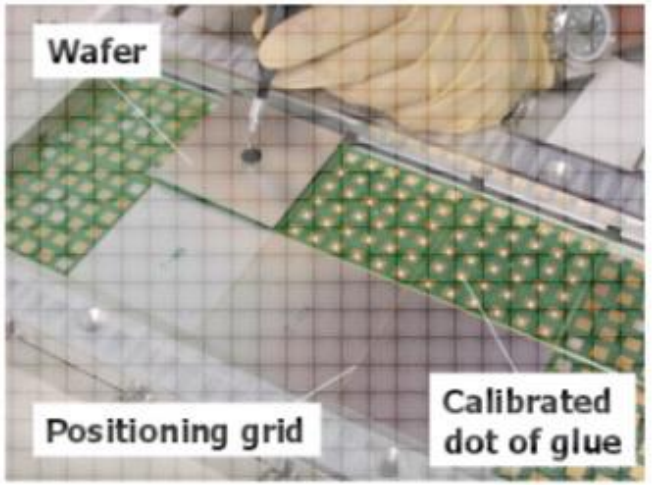


R&D PROPOSALS RECEIVED
CALORIMETRY – SILICON BASED

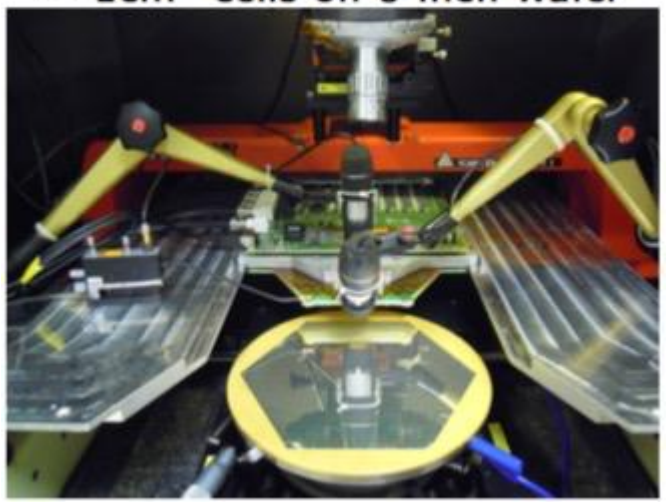
CALICE Silicon PIN Diodes, CMS HGCAL Si Sensors

- Presented by Eva Sicking (CERN)
- **Proposal:** Building on existing R&D at CERN inside EP-LCD group
  - R&D on highly granular calorimeters using Si as active material
  - Such calorimeters are optimized for particle flow, 3D imaging
  - Many technical challenges will be addressed within the CMS HGCal project
    - Mass production, detector integration, cooling, radiation hardness
  - In view of CMS HGCal developments, revisit CLICdet layout choices
    - E.g. hexagonal silicon sensors instead of square sensors, absorber choice
    - Rethink compact integration concepts
  - Challenges not covered by CMS HGCal are addressed within CALICE
    - Power pulsing (possible due to low duty cycle at CLIC)
    - Indirectly cooled planes (incl. active layers and readout electronics)
- **Application:** Fine-grained calorimetry for all future particle physics experiments
  - Need for R&D on timing resolution (down to 10-20ps hit timing)
  - Cost-effective solutions
  - Radiation hardness (especially for HL-LHC and FCC-hh)

CALICE: silicon PIN diodes
$1 \times 1\,\mathrm{cm}^2$ in 6×6 matrices

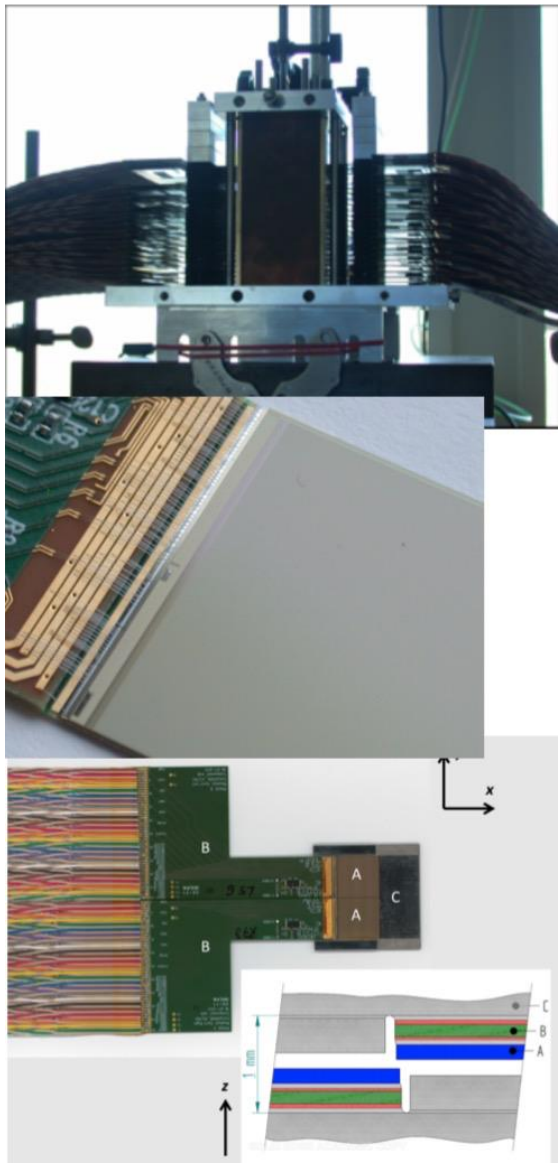


CMS HGCal silicon sensor
$\sim 1\mathrm{cm}^2$ cells on 8-inch wafer



High Granularity Digital Calorimeter

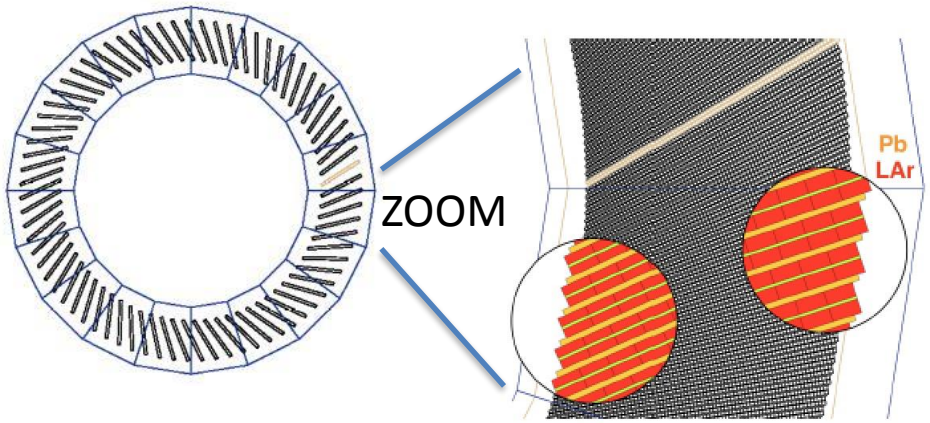
- Presented by Thomas Peitzmann (NIKHEF)
- **Proposal:**
  - R&D in the context of FoCal in ALICE
  - Si/W sampling EM calorimeter (24 layers, $1X_0$ each)
    - Digital read-out, proof of principle with slow MIMOSA sensor in testbeam, 30µm pixels
      - Working on faster ALPIDE sensor (faster, gated, radiation hard, ok for ALICE, MAPS device)
    - Very compact (R_M=10.5±0.5 mm)
    - Full 3D imaging, extremely good position resolution, reasonable energy resolution, good linearity (30µm pixels)
- **Application:** Under investigation for FCC-hh EM calorimeter, ALICE FoCal.



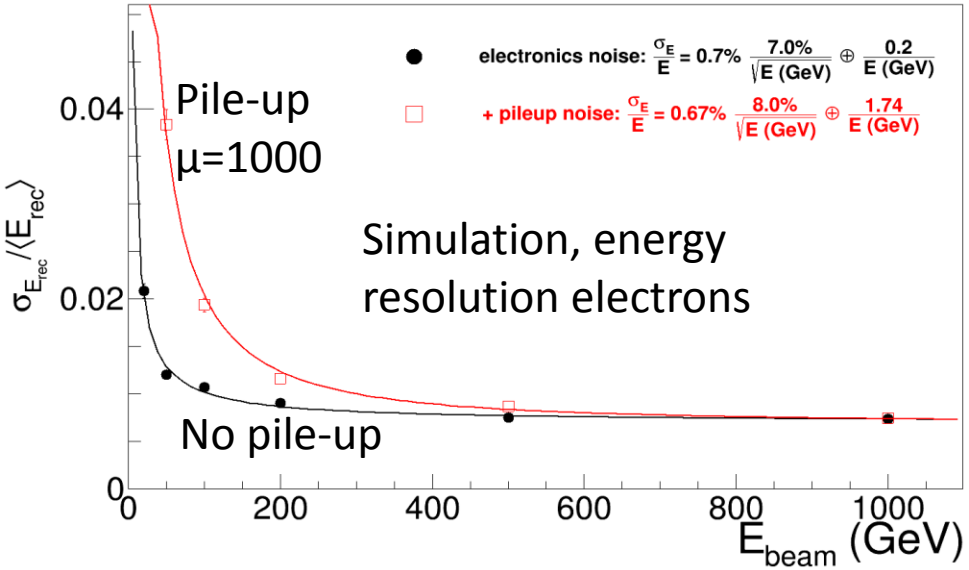
R&D PROPOSALS RECEIVED
CALORIMETRY – NOBLE LIQUID BASED

High Granularity EM Calorimeter for FCC-hh

- Presented by Anna Zaborowska, Martin Aleksa (CERN)
- **Proposal:**
  - **R&D on granularity limits of a noble liquid calorimeter:**
    - High granularity will be essential for future calorimeters (3D imaging, pile-up suppression, particle ID, jet substructure,…)
    - Granularity can be easily increased in noble liquid calorimeters → fine segmented read-out electrodes (multi-layer PCBs).
    - Scope: Design and spice-simulation of such multi-layer electrodes, construction of small test module that could be cooled down in a cryostat. Testbeam measurements (noise, resolutions, …)
  - **R&D on novel feedthrough technologies** (collaboration with CERN cryo lab and industry):
    - Increasing signal density of feedthroughs to ~ 50/cm^2 which is a ~ factor 5-10 more than in ATLAS
    - Close collaboration with industry, interest from other labs
    - Scope: Survey of existing technologies, adaptation and optimization, design of test feed-through, cold tests and electrical tests of these test feed-throughs.
  - **R&D on low-material cryostat** (collaboration with CERN cryo lab)
  - **R&D on limits of timing resolution for noble liquid calorimeters**
    - Noble liquid calorimeters have intrinsically good timing resolution due to their fast signal rise-time and their homogeneous active material.
    - Scope: Study limits of timing resolution for MIPs and high-energy deposits
- **Application:** Reference detector for FCC-hh EM calorimeter.
  - Extremely radiation hard (liquid active material)
  - Excellent energy resolution, good timing, high granularity

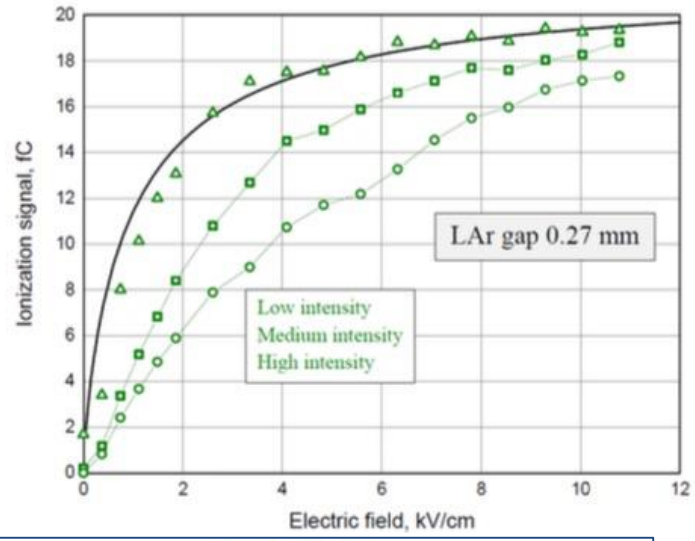


FCC-hh ECAL Barrel geometry



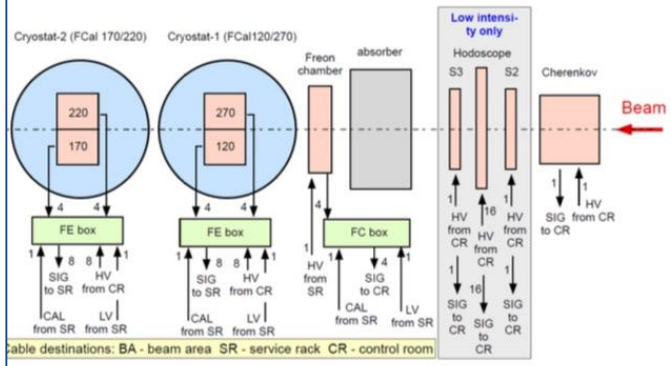
Ionization and Drift Studies for Noble Liquid Calorimeters

- Presented by Leonid Kurchaninov (TRIUMF)
- **Proposal:** Quantify performance of LAr calorimeters at high ionization rates
  - Space charge build-up
  - Initial recombination (yield)
  - Bulk recombination
  - Surface charge accumulation
  - Role of electro-negative impurities
  - Electrical discharges
  - ….
  - Experimental measurements
    - Ion drift mobility at high beam intensity
    - Electron yield (HV curve)
    - Electrons trapping at electrodes
    - Electron lifetime (bulk recombination)
    - N2 and O2 admixtures
    - Ionization enhanced HV dischargers
  - Modelling of high-rate performance
- **Planning testbeams**
  - HiLum2 in Protvino and LArPulse at CERN
  - Existing collaboration of 6 institutes with interest in long-term development



HiLum2 setup

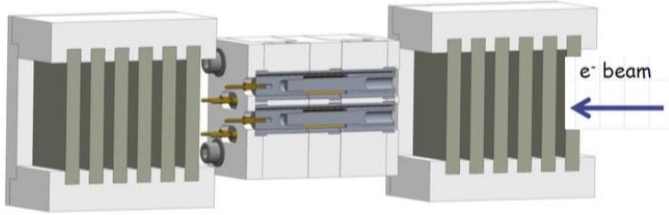
- High intensity 50-GeV proton beam
- Setup exists at IHEP, Protvino: 4 LAr mini-modules



- Beam time 1 (2) per year
- Tests in 2016, 2017; plans for 2018-20

LArPulse

- High intensity Sr-90 source. Pulses from ~100 GeV electrons
- Recently proposed. Setup under construction at U. Arizona. Beam at CERN

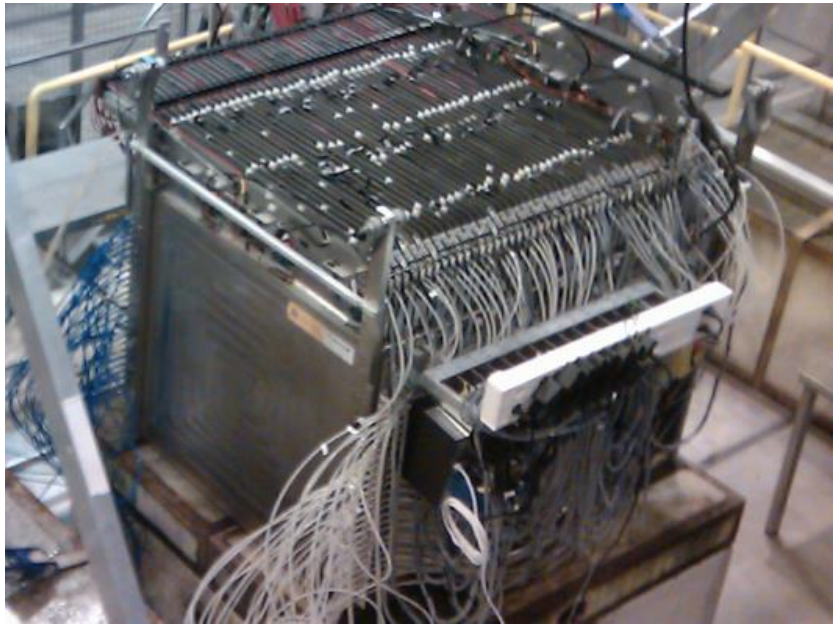


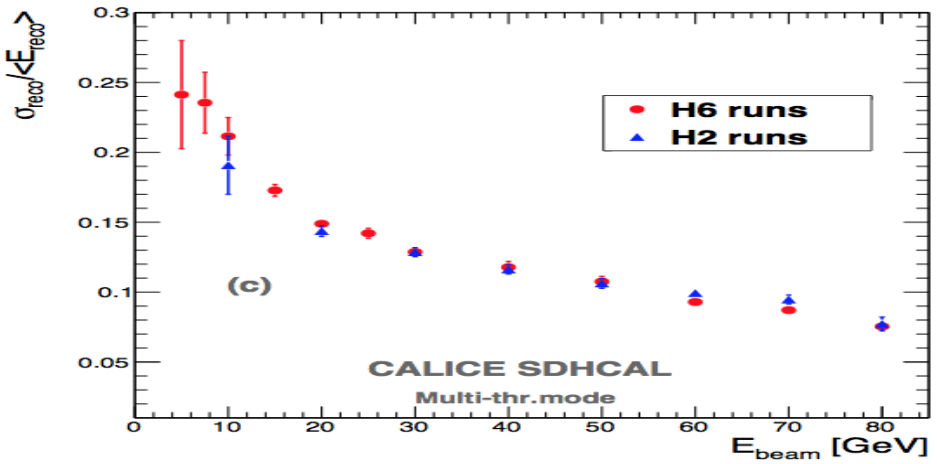
- Possible first beam test after LS2

R&D PROPOSALS RECEIVED
CALORIMETRY – GAS DETECTOR BASED

HCAL with Gaseous Detectors

- Presented by Imad Laktineh (IPN Lyon)
- **Proposal:**
  - **R&D on semi-digital HCAL**
  - Ultra-granular HCAL (1cm^2 granularity) can provide a powerful tool for the PFA leading to excellent Jet energy resolution
  - **Active material:** Gaseous detectors, RPCs, but also GEM or Micromegas
  - **Challenges:** homogeneity for large surfaces, thin thickness, mechanical structure,…
- **Application:** ILD (SDHCAL), other future leptonic colliders?
  - Testbeam with technological prototype





CONCLUSIONS – CALORIMETRY

Summary – Calorimetry

- **Received very diverse input on existing and proposed R&D projects (link)**
- **Large variety of active materials considered for calorimetry for future accelerator experiments. R&D needs depend on technology:**
  - **Scintillator/crystal based**
    - Radiation hardness of crystals, fibres, SiPMs (Photon detection → see next talk)
    - Timing performance: understanding and improving the full detection chain
  - **Si based**
    - Cost-effective solutions
    - Radiation hardness
    - Timing resolution (down to 10-20ps hit timing)
  - **Noble liquid based**
    - High granularity challenge → read-out electrodes, feedthroughs
    - Noble liquid properties under high ionization rates
    - Cryostats with minimal material
    - Timing performance (down to 20ps for showers)
  - **Gaseous detectors based**
    - Homogeneity, mechanical structures, reliability
- **Presented projects clearly not exhaustive! Please contact us, if you find important ideas missing!**
- **The next step is to further evaluate the challenges in each field and converge on proposals of R&D projects**

Backup

Our goals

Slide by C. Joram

In one year from now we should …

- have defined a convincing and ambitious **R&D programme over 5 years**, which covers the most relevant technologies for the years >2025.
  - break down in **work packages**
  - work plan with **deliverables, milestones**
  - resources needs (CHF and FTE)
  - risks, fall backs, alternatives
- have written a **comprehensive report**, describing
  - context and motivation
  - state of the art
  - main challenges
  - proposed R&D (as above)
  - outlook on further future
  - some ideas on management & reporting

100+ pages ?