Calorimetry

in particle physics experiments

8. Future Calorimetry: New Technologies and Future Colliders

Course roadmap

- **Week 1 (Foundations)**
  - ✓ Lecture 1: Why calorimetry?
  - ✓ Lecture 2: EM shower physics
- **Week 2 (Physics depth)**
  - ✓ Lecture 3: Hadronic shower physics
  - ✓ Lecture 4: Energy resolution from first principles
- **Week 3 (Technology)**
  - ✓ Lecture 5: Calorimeter Technologies (real-life EM and Hadronic calorimeters)
  - ✓ Lecture 6: Calorimeter Design
- **Week 4 (Systems & Future)**
  - ✓ Lecture 7: Signal chain, readout, calibration
  - ✓ Lecture 8: Future calorimetry

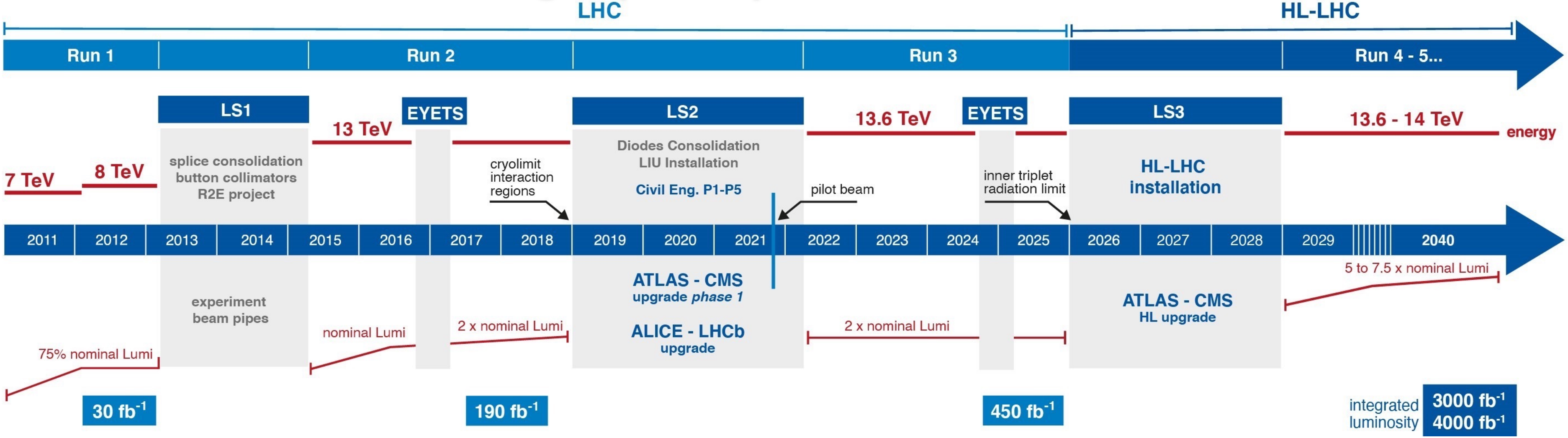
Today's Lecture

- **Week 4 (Systems & Future)**
  - ✓ Lecture 7: Signal chain, readout, calibration
  - ✓ Lecture 8: Future calorimetry
    - *8.1 HL-LHC Challenges pile-up, radiation damage, trigger rates*
      - *Detector consequences: granularity, precision timing, radiation-hard materials*
    - *8.2 CMS HGCAL: a "5D" calorimeter (E + x,y,z + t)*
      - *6M-channel Si+scintillator endcap; shower imaging; $\sigma t < 50$ ps per hit*
    - *8.3 Technologies for future detectors*
      - *SiW ECAL, ALLEGRO LAr, IDEA dual-readout crystals, GRAiNITA*

8.1

HL-LHC Challenges

The HL-LHC challenge: pile-up, radiation, rates

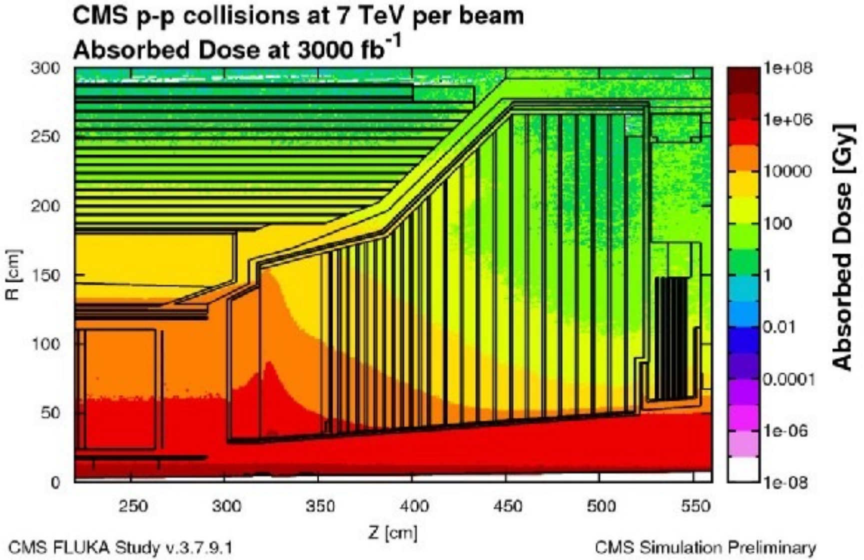


- Three main challenges for calorimetry
  1) **Pile-up**: additional soft pp interactions fill calorimeter with ~1 TeV of noise per event
  2) **Radiation damage**: integrated dose up to 200 Mrad in inner ECAL (CMS endcap)
  3) **Trigger rate**: 40 MHz input; must maintain physics acceptance at 200 PU
- Consequences for detector design
  - ✓ **Higher granularity**: isolate individual particles from pile-up in spatial domain
  - ✓ **Precision timing**: isolate particles from pile-up in time domain (pile-up spread ~ 200 ps)
  - ✓ **Radiation-hard materials**: silicon sensors (for innermost layers), SiPM

<μ> ~ 140-200 PU events per crossing
→ factor ~x4 increase w.r.t. LHC

Radiation environment at HL-LHC vs. current LHC

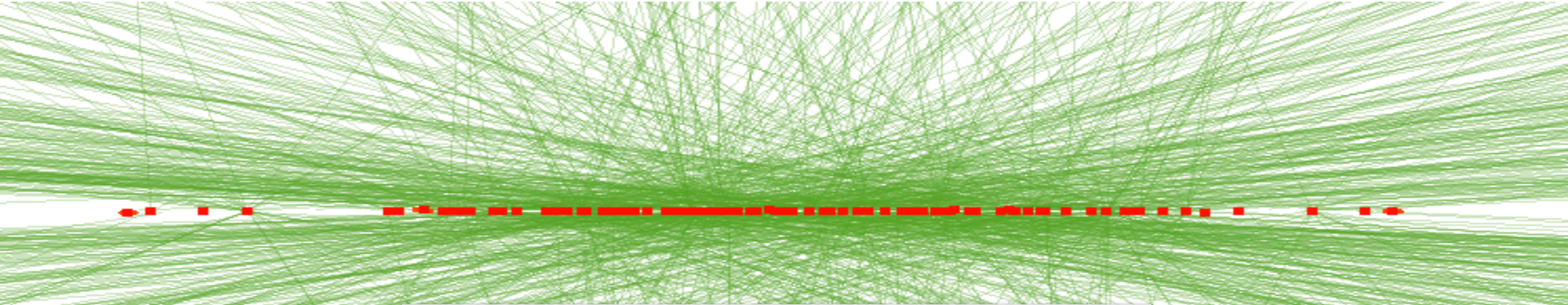
- **Integrated dose after HL-LHC 3000 fb^{-1}**
  - ✓ CMS ECAL barrel: ~10 kGy; endcap (|η|=2.5): ~10 MGy = 1000 Mrad (enormous)
  - ✓ ATLAS LAr: radiation-hard intrinsically; endcap: ~800 Gy (manageable)
- **CMS PbWO4 crystals will survive radiation in EB (but need massive laser correction), EC ECAL crystals (and HCAL scintillators) suffer from irreparable radiation damage after 500 fb^{-1}**
  - ✓ Light yield loss at highest fluence: up to 50% → correctable (but degrades resolution)
  - ✓ CMS Phase-2: keep EB crystals, new all-digital electronics; replace EE with HGCAL (silicon calorimeter)



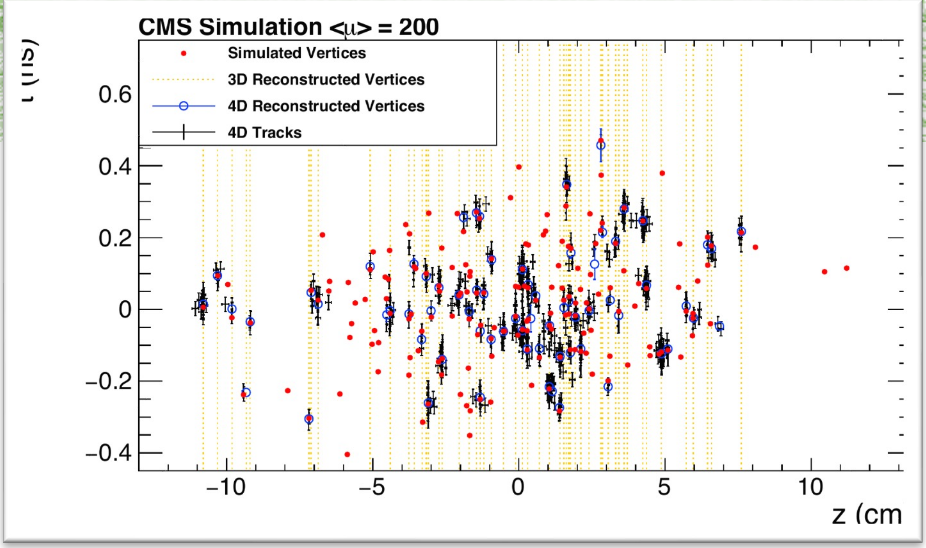
- ***ATLAS Phase-2: LAr itself unaffected by radiation***
  - ✓ *Possibility of FCAL LAr boiling studied (and alternative diamond-based FCAL explored) excluded*
  - ✓ *New all-digital electronics*

- **SiPM can operate up to 10^{16} n_eq/cm^2 (>> HL-LHC requirements)**
  - ✓ SiPM dark count rate: increases with radiation; cooling helps; replaceable

HL-LHC pileup



140 PU interactions event



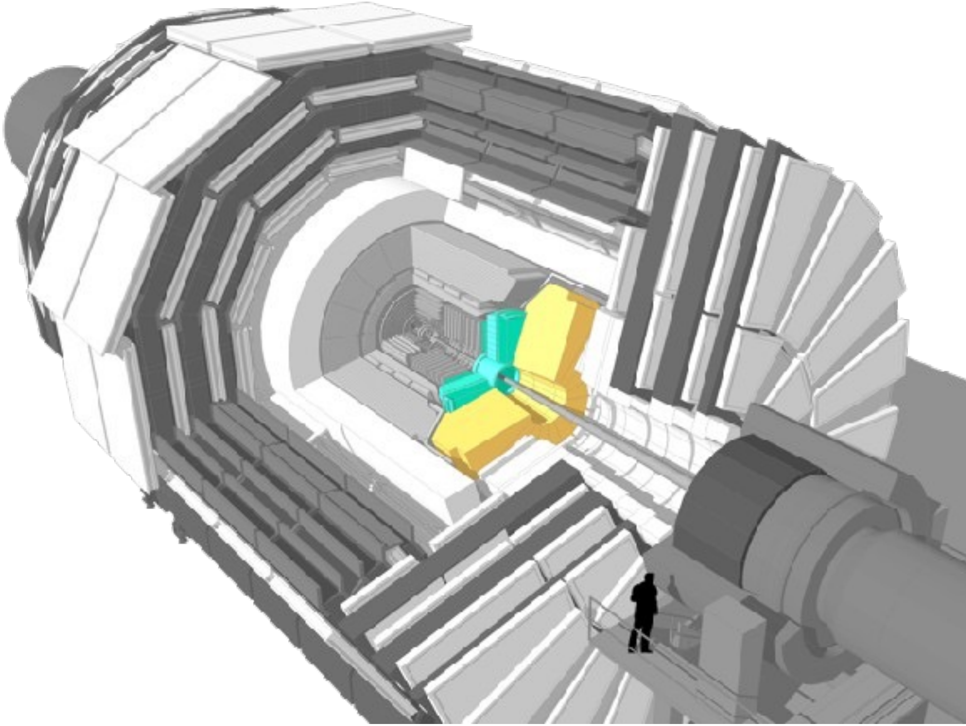
Space-time view
of interaction
vertices

8.2

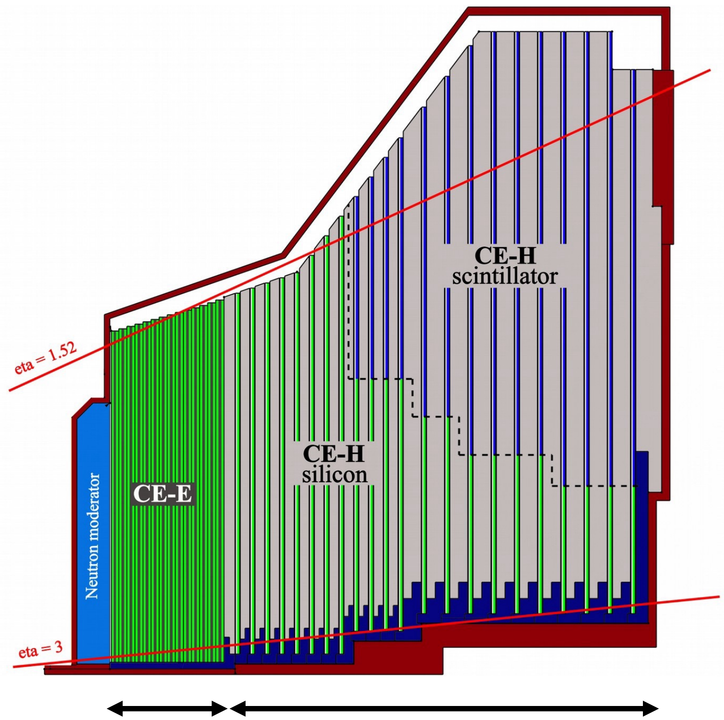
CMS HGCAL High Granularity Calorimeter: a “5D” calorimeter

CMS HGCAL: concept and geometry

- **CMS HGCAL replacing CMS endcap calorimeters**
  - ✓ Coverage: 1.5 < |η| < 3.0; replaces both EE (crystal) and HE (brass-scintillator)
  - ✓ Two sections: CE-E (electromagnetic, W absorber) + CE-H (hadronic, Cu/stainless absorber)
- **CE-E (EM section): 28 silicon layers, W+Cu absorber**
  - ✓ Hexagonal Si cells: 0.52 cm^2 (inner) or 1.18 cm^2 (outer) depending on radius
  - ✓ Total: ~3.9M silicon channels; 25.7 X_0; ~ 1.3 λ_I
- **CE-H (HAD section): 12 layers Si (inner) + 12 layers scintillator tiles (outer)**
  - ✓ Si cells: 1.18 cm^2; scintillator tiles: 4-30 cm^2 (larger where lower occupancy)
  - ✓ Total HAD: 8 λ_I; combined CE-E + CE-H: 9.3 λ_I
- **Total HGCAL: ~6 million readout channels**
  - ✓ vs. ~10000 in current CMS HE



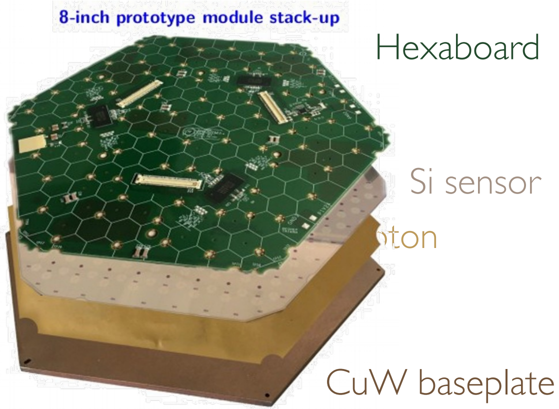
CMS HGCAL: concept and geometry

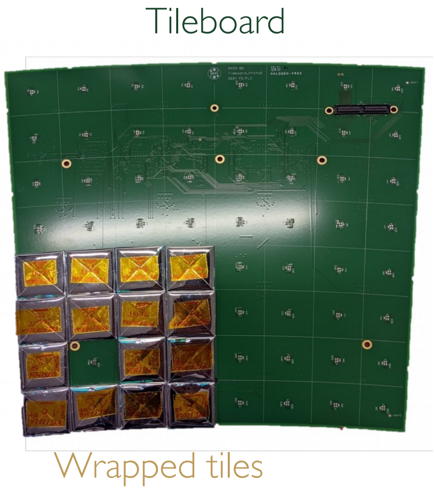


26 layers
Cu/CuW/Pb

21 layers
Steel/Cu

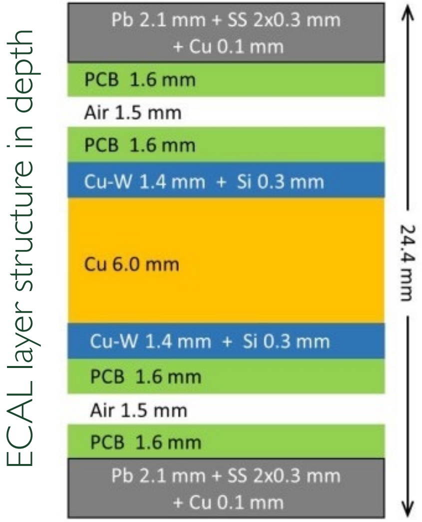
- Silicon sensors in high-radiation regions
  - ✓ 6M channels
  - ✓ Cell size: ~0.5 or 1 cm^2
- Scintillating tiles + on-tile SiPM radiation area
  - ✓ 240k tiles
  - ✓ Cell sizes from ~4 to 30 cm^2

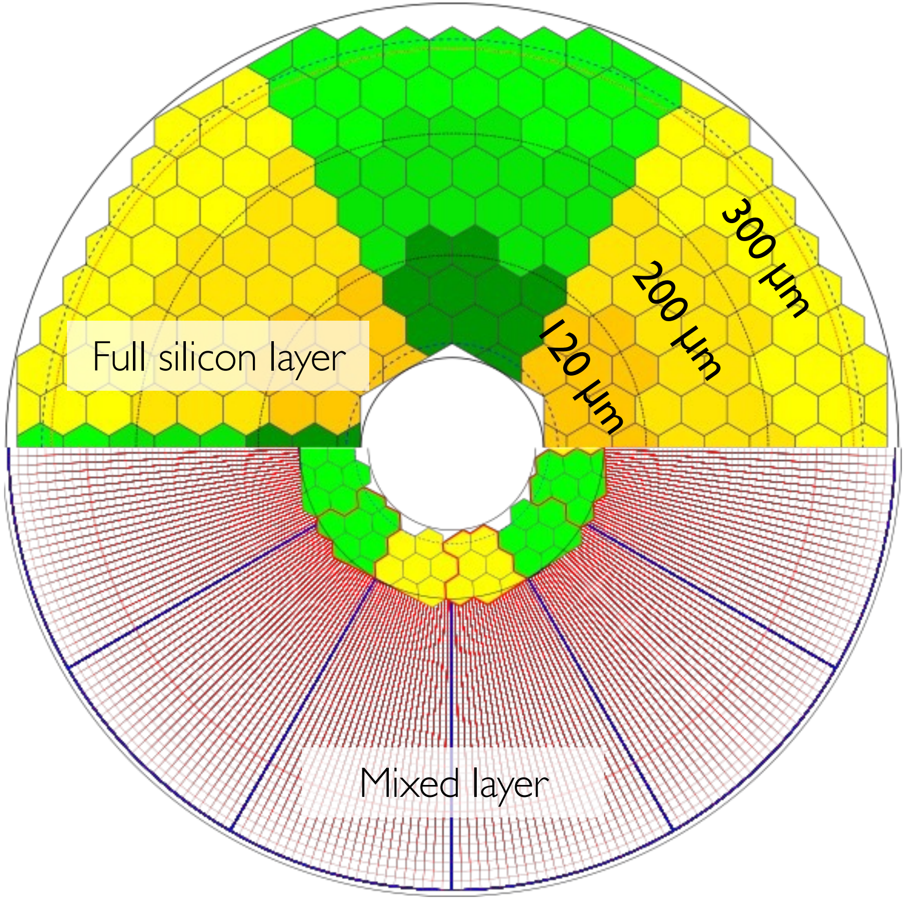




CMS HGCAL: layer structure

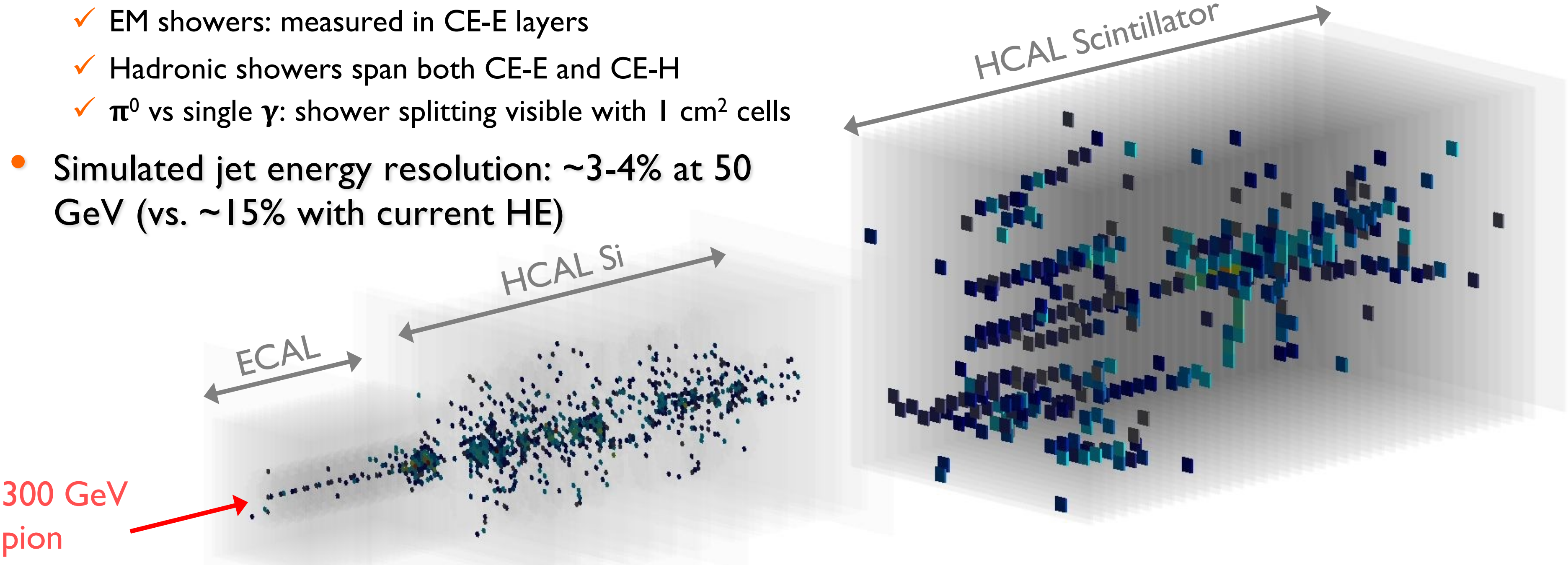
- Silicon
  - ✓ 8” hexagonal wafers
  - ✓ Three thicknesses following radiation profile
  - ✓ 120, 200 & 300 μm
- Scintillator
  - ✓ Full silicon layer
  - ✓ Tile size varies with η (1.5 deg)





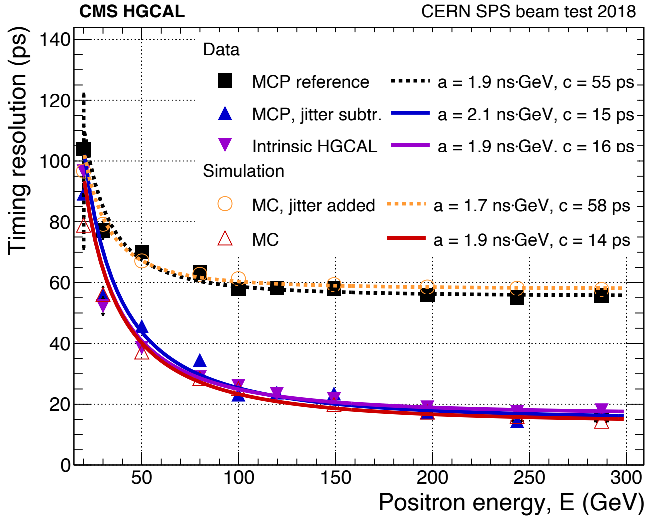
CMS HGCAL: shower imaging and particle identification

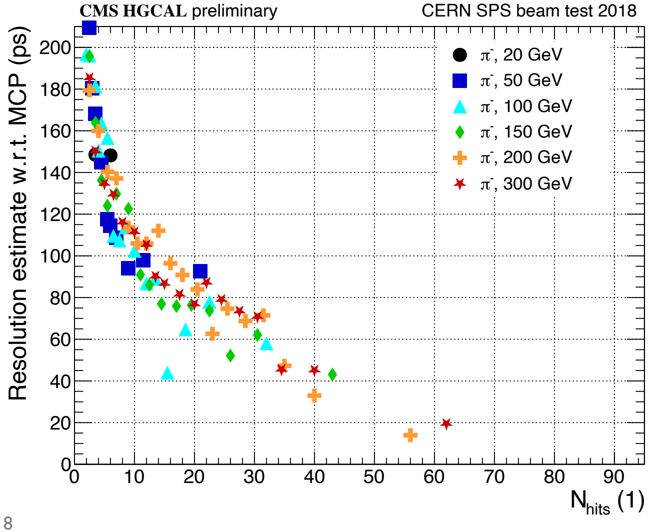
- HGCAL creates a 3D image of every shower
  - ✓ Longitudinal profile: 47 layers; discriminates EM vs. hadronic shower shape
  - ✓ Transverse profile: fine Si cells resolve sub-cm shower features
- Particle identification from shower shape
  - ✓ EM showers: measured in CE-E layers
  - ✓ Hadronic showers span both CE-E and CE-H
  - ✓ π^0 vs single γ: shower splitting visible with 1 cm^2 cells
- Simulated jet energy resolution: ~3-4% at 50 GeV (vs. ~15% with current HE)



CMS HGCAL: timing performance

- **HGCAL includes precision timing: t measured per hit in inner Si layers**
  - ✓ Target: $\sigma_t < 50$ ps per hit in CE-E (silicon layer)
  - ✓ Achieved in test beam: ~ 40 ps per hit at E > 1 GeV
- **Why timing matters against PU?**
  - ✓ PU vertices spread in time: σ_t(vertex) ~ 200 ps at HL-LHC
  - ✓ Associate shower hits to primary vertex in time: reject PU hits > 3 x 50 ps ~ 150 ps from PV
  - ✓ **Effectively "fourth dimension" to separate overlapping showers from different BX**
    - **5D: E + (x,y,z) + t**
  - ✓ *Also adding timing layers to ATLAS and CMS ECAL…*
- **HGCAL timing measurement**
  - ✓ Si cells have intrinsic capacitance C ~ 1 pF; fast shaper; time-walk corrected via Time of Arrival (ToA) stored per hit in HGCAL ASIC
  - ✓ At testbeam, also consider external timing information and jitter





arXiv:2312.14622

8.3

Technologies for calorimetry for future detectors

Requirements on detectors for HET* factories

CERN-ESU-2025-001

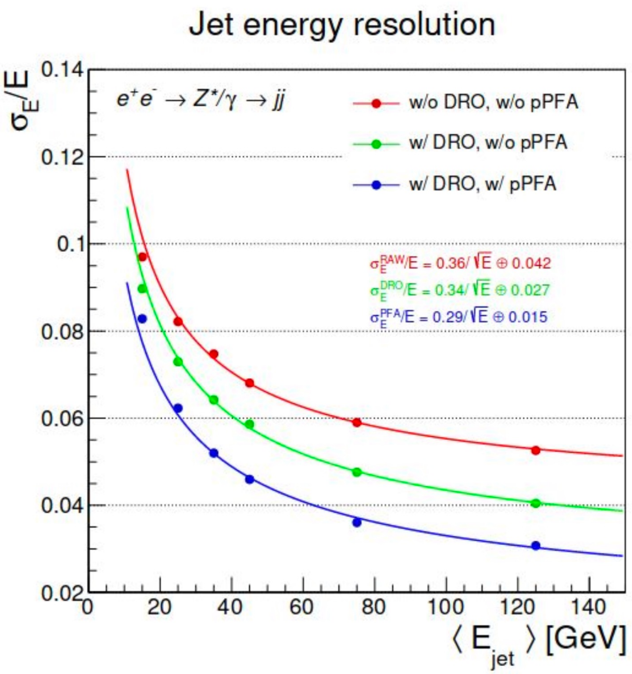
* HET: e^+e^- → Higgs/Electroweak/Top

Performance indicator	Requirement	Physics motivation
Vertex hit resolution and material budget	$\approx 3\,\mu\text{m}$; $\approx 0.1\%\ X_0$ per layer	B-meson, Higgs-boson and τ lepton physics
Momentum resolution	$\sigma(p_\mathrm{T})/p_\mathrm{T} \approx 2\times10^{-5}\cdot p_\mathrm{T}(\mathrm{GeV})\oplus 0.2\%$	$\delta M_H = 4\,\mathrm{MeV}$; $\delta M_Z = 15\,\mathrm{keV}$
ECAL	$\sigma(E)/E \approx \text{few}\%/\sqrt{E(\mathrm{GeV})}$ and high granularity	B-meson, τ and EW physics, π^0 and γ reconstruction
Jet energy resolution	$\approx 30\%/\sqrt{E(\mathrm{GeV})}$	Higgs and multi-jet events
Magnetic field stability/mapping	better than 10^{-6}	Point-to-point energy uncertainty in $\delta\Gamma_Z$
Timing resolution	tens to 100 ps per track	Particle identification; δM_HNL
Particle identification	> 3 standard deviation π–K separation 1 GeV to 30 GeV; standalone muon ID	$H\to s\bar{s}$; $b\to s\nu\bar{\nu}$; long-lived particle searches
Luminosity detector alignment	Position along beam line: $\delta z = 110\,\mu\text{m}$; Inner radius: $\delta R_\mathrm{min} = 1\,\mu\text{m}$	$\delta\mathscr{L} = 10^{-4}$ from Bhabha events at the Z pole energy
Data acquisition and trigger	50 MHz trigger rate and up to 25 $\mathrm{Gbit\,s^{-1}}$ module readout	Processing of beam-induced backgrounds at the Z pole

Specific requirements on calorimeters for HET* factories

* HET: $e^+e^- \rightarrow$ Higgs/Electroweak/Top

- Energy coverage (dynamic range): **200 MeV - 180 GeV**
  - ✓ vs LHC: up to 6 TeV jets !
  - ✓ moderate depth: **22 X_0, 6-8 λ_{int}**
- Energy resolution: **3-4 % di-jet mass resolution**
  - ✓ Differentiate W vs Z origin of di-jet systems
  - ✓ Implication for jet energy resolution: **$\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]**
  - ✓ Particle flow for jets!
    - Resolution "only" for photons and neutral hadrons (but ideally photons as low as 200-300 MeV)
- Granularity
  - ✓ PID
  - ✓ Disentangle showers for particle flow
- Hermeticity, uniformity, stability
  - ✓ Low systematics for precision measurements
  - ✓ Complex system-level engineering questions
- No need to be particularly fast



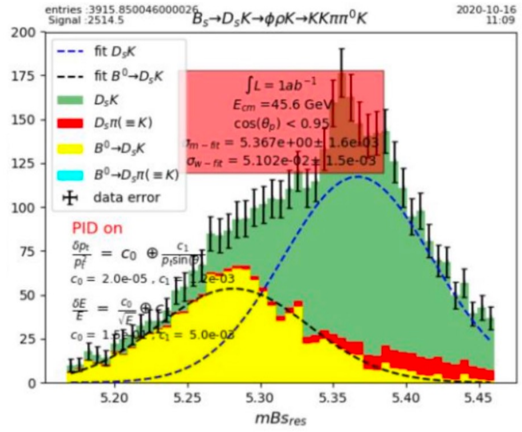
Some unique challenges at HET factories!

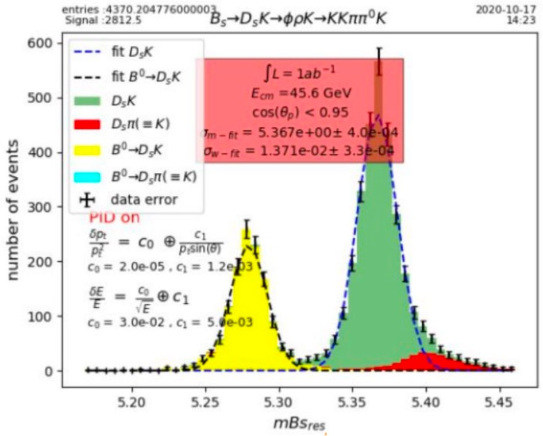
O(10^{11}) B and τ at 45 GeV at FCC-ee!

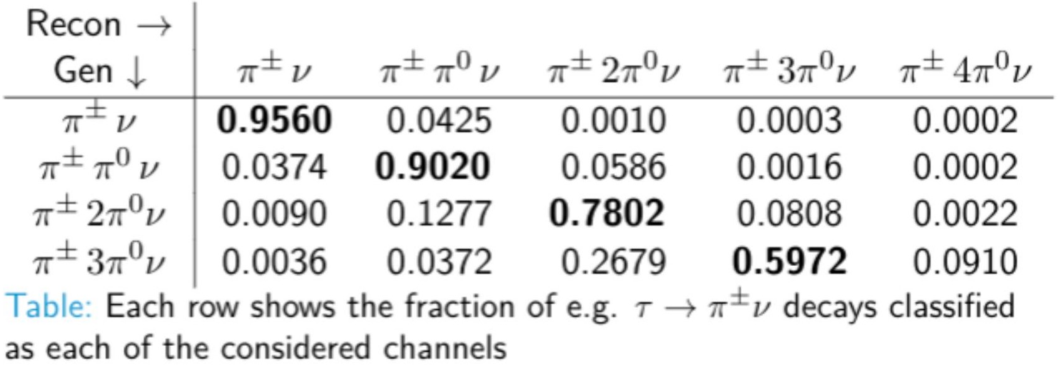
- Some physics channels especially require extreme EM resolution

- τ physics needs to reconstruct τ decays → granularity
  - ✓ π^0 reconstruction and ID
  - ✓ Count close-by π^0

- BSM with **γ** in final state (e.g ALP searches)
  - ✓ Photon resolution
  - ✓ Photon direction







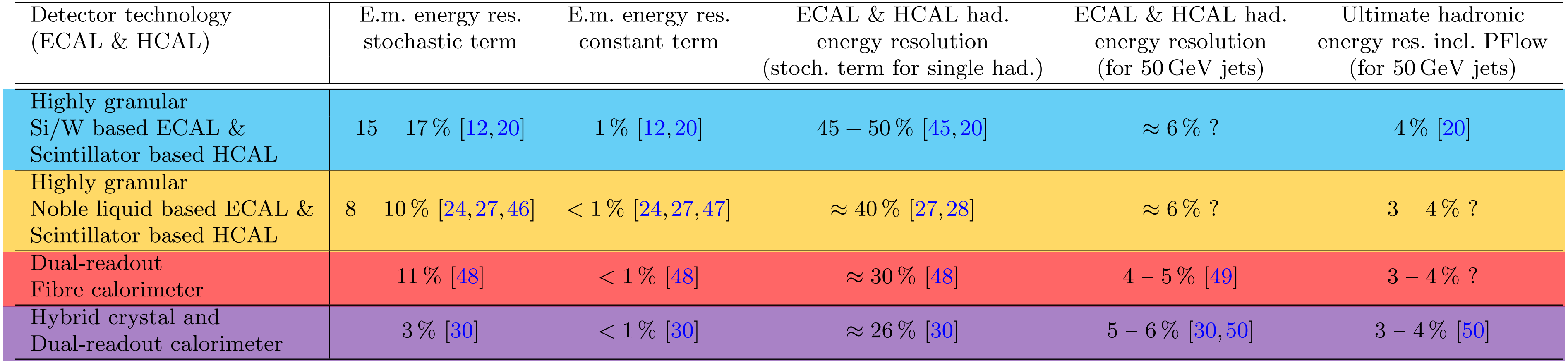
Recon → Gen ↓	$\pi^\pm \nu$	$\pi^\pm \pi^0 \nu$	$\pi^\pm 2\pi^0 \nu$	$\pi^\pm 3\pi^0 \nu$	$\pi^\pm 4\pi^0 \nu$
$\pi^\pm \nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^\pm \pi^0 \nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^\pm 2\pi^0 \nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^\pm 3\pi^0 \nu$	0.0036	0.0372	0.2679	**0.5972**	0.0910

Table: Each row shows the fraction of e.g. $\tau \to \pi^\pm \nu$ decays classified as each of the considered channels

Calorimetry options being pursued

- All options aim at particle flow reconstruction!
  - ✓ In general, all have good jet energy resolution
  - ✓ Varying ECAL resolution (highest EM resolution required for B physics)
  - ✓ Varying segmentation (impact on PF, shower shapes for $\boldsymbol{\gamma/\pi^0}$, cluster pointing and $\boldsymbol{\gamma}$ position)
  - ✓ Varying operational stability and cost

arXiv:2109.00391

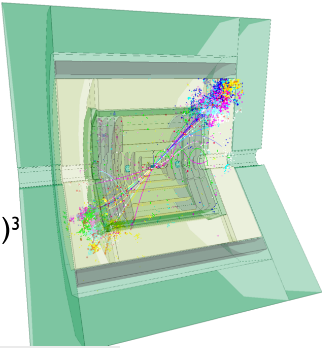


Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	$15 - 17\,\%$ [12,20]	$1\,\%$ [12,20]	$45 - 50\,\%$ [45,20]	$\approx 6\,\%$?	$4\,\%$ [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	$8 - 10\,\%$ [24,27,46]	$< 1\,\%$ [24,27,47]	$\approx 40\,\%$ [27,28]	$\approx 6\,\%$?	$3 - 4\,\%$?
Dual-readout Fibre calorimeter	$11\,\%$ [48]	$< 1\,\%$ [48]	$\approx 30\,\%$ [48]	$4 - 5\,\%$ [49]	$3 - 4\,\%$?
Hybrid crystal and Dual-readout calorimeter	$3\,\%$ [30]	$< 1\,\%$ [30]	$\approx 26\,\%$ [30]	$5 - 6\,\%$ [30,50]	$3 - 4\,\%$ [50]

Table 1. Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists.

Calorimetry options being pursued

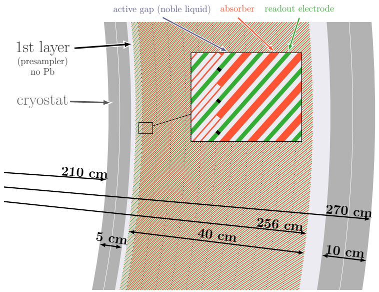
Highly granular Si/W based ECAL & Scintillator based HCAL



- ECAL: Tungsten-silicon
  - ✓ Extremely fine segmentation: $(0.5\ \text{cm})^3$
- HCAL: Steel-scintillator; SiPM-on-Tile
  - ✓ Fine segmentation: $(2.5\ \text{cm})^3$

EM: σ(E)/E ≃ 16%/√E
Jet: σ(E)/E ≃ 3-4% @ 50 GeV

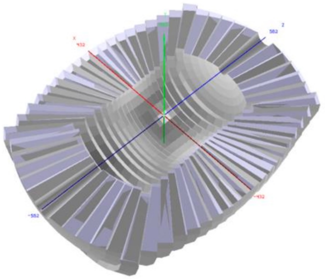
Highly granular Noble liquid based ECAL & Scintillator based HCAL



- ECAL: Pb+LAr (or W+LKr); warm or cold electronics
  - ✓ Fine longitudinal sampling (w.r.t. ATLAS, 4 → 12 layers)
- HCAL: Scintillating tile (e.g. CALICE or ATLAS)

EM: σ(E)/E ≃ 5-8%/√E
Jet: σ(E)/E ≃ 4% @ 50 GeV

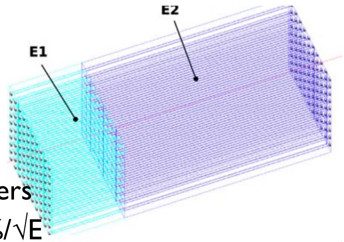
Dual-readout Fiber calorimeter



- ECAL + HCAL: Copper or steel matrix; Cherenkov and scintillating fibres, SiPMs
  - ✓ Very fine transverse granularity
  - ✓ Longitudinal information via timing

EM: σ(E)/E ≃ 11%/√E
Jet: σ(E)/E ≃ 3-4% @ 50 GeV

Hybrid crystal & Dual-readout calorimeter

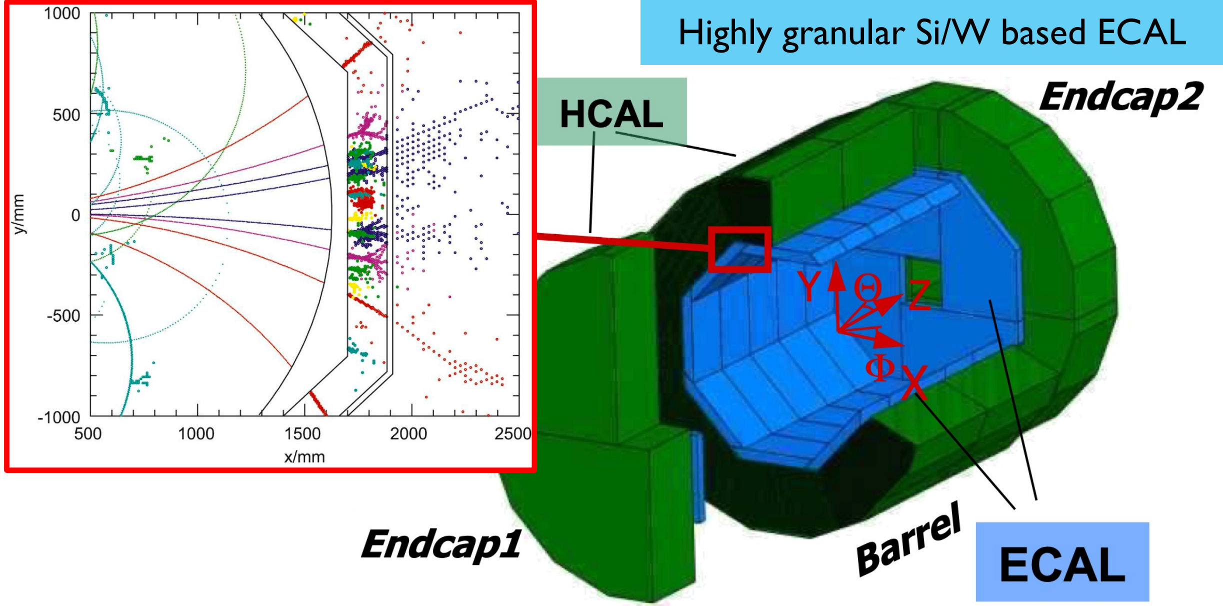


- ECAL: Segmented crystal; SiPMs
  - ✓ Fine transverse segmentation; 2 long layers
  - ✓ Very good EM energy resolution of ~3%/√E
- HCAL: fiber-based Dual Readout calorimeter

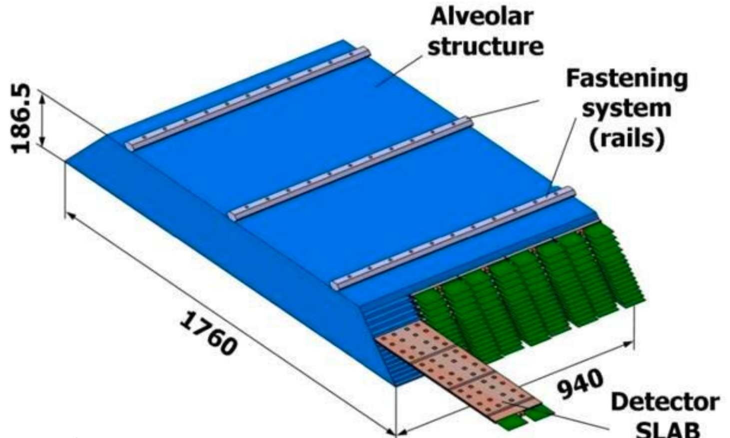
EM: σ(E)/E ≃ 3%/√E
Jet: σ(E)/E ≃ 3-4% @ 50 GeV

SiW ECAL

Highly granular Si/W based ECAL



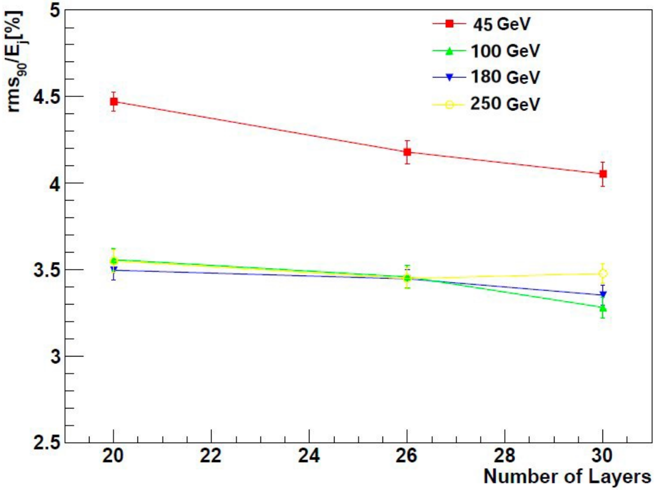
- An “imaging” calorimeter
  - ✓ Tungsten as absorber material
    - X_0 = 3.5 mm, R_M = 9 mm, λ_I = 96 mm
    - Narrow showers → compact design
  - ✓ Silicon (sensors) as active material
    - Support compact design
      - – Sensor + RO < 2mm
    - Allows for ~any pixelisation
    - Excellent signal/noise ratio > 10
  - ✓ Tungsten–Carbon alveolar structure
    - Minimal structural dead-spaces
    - Scalability
- Optimized for Particle Flow: super high granularity!
  - ✓ 30 layers, 2.8 mm tungsten absorber, 24 X_0
  - ✓ 0.5 mm thick silicon sensors with 5 × 5 mm^2 granularity
  - ✓ O(10^8) cells
  - ✓ Tight integration: compact and hermetic
- EM resolution ~16%/sqrt(E)

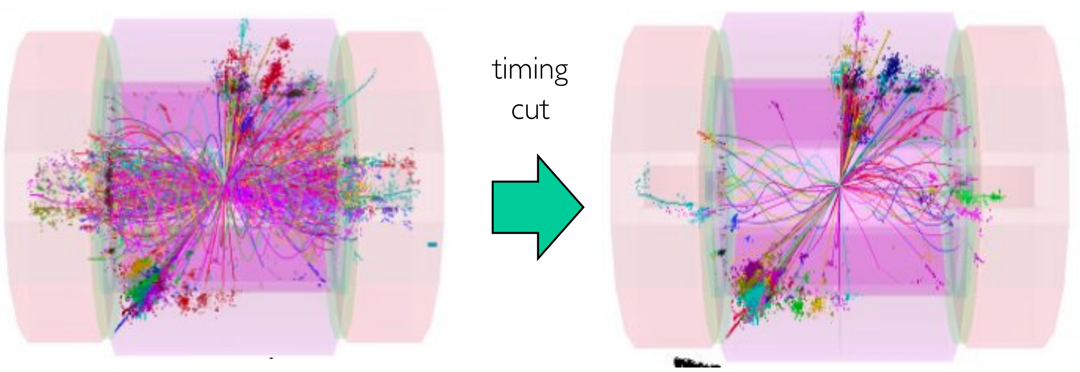


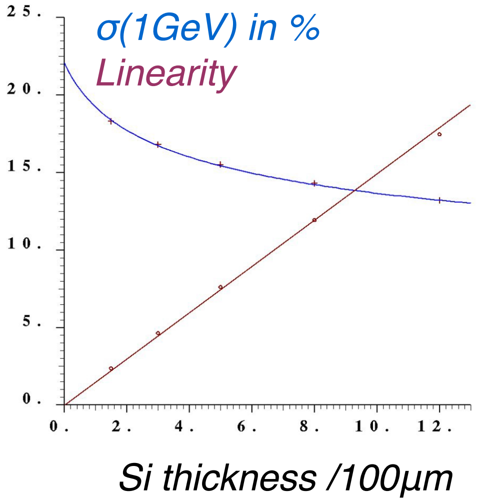
SiW ECAL

Highly granular Si/W based ECAL

- Originally developed for ILC…
- Adaptation to FCC-ee brings challenges
  - ✓ Granularity re-optimization (e.g. reduce the number of layers + thicker sensors)
    - Going from 30 to 26 layers reduces cost; thicker sensors recover the stochastic resolution term
    - Increasing the Si thickness to 725µm
  - ✓ Addition of timing
    - From CMS HGCAL



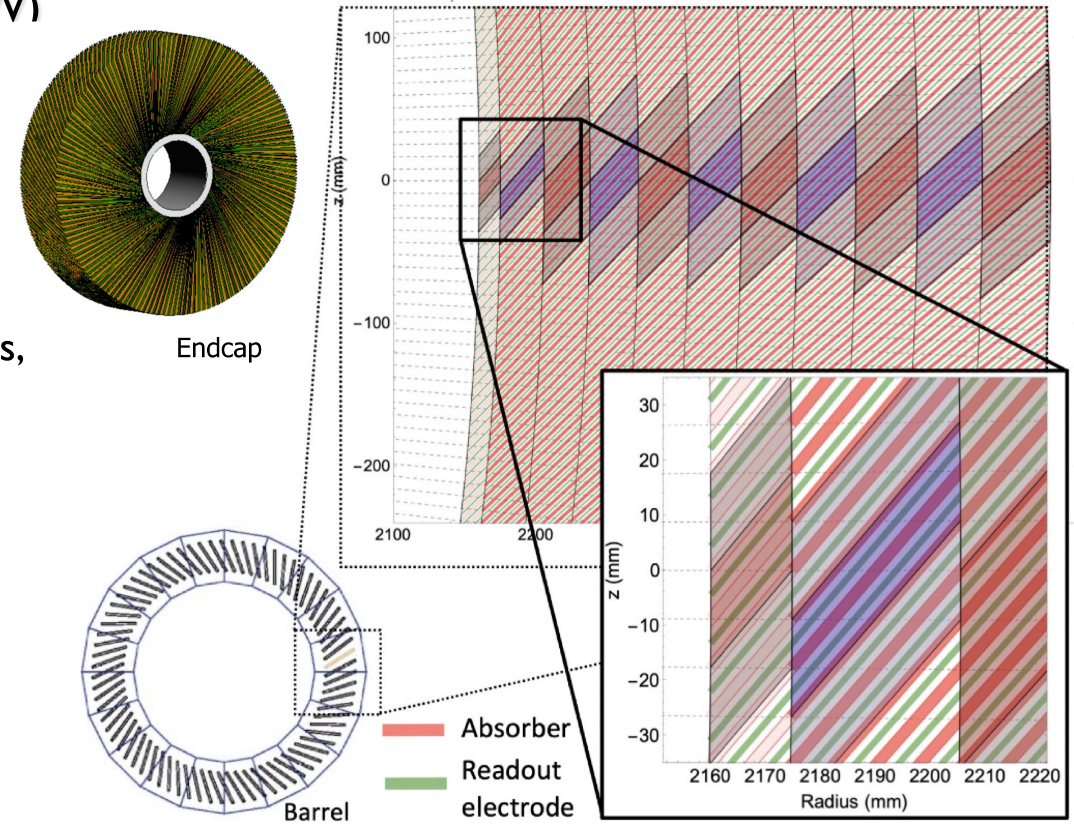




ALLEGRO ECAL

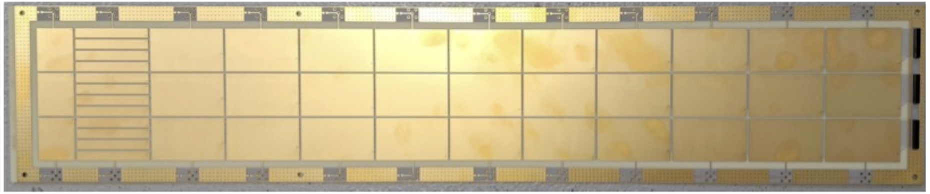
Highly granular Noble liquid based ECAL

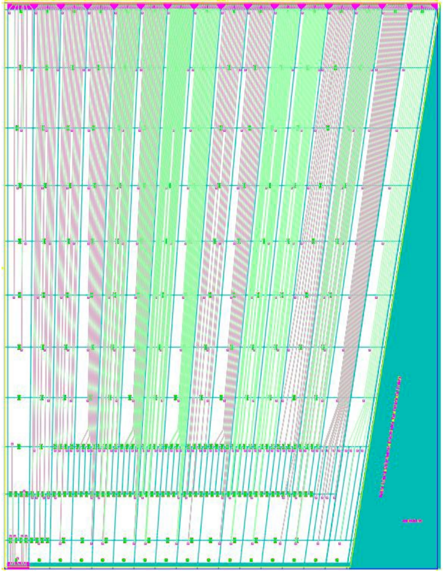
- Noble liquid (LAr/LKr) sampling (Pb/W) sampling calorimeter
  - ✓ Absorber planes inclined in r-phi (barrel) / arranged in turbine-like structure (endcap)
  - ✓ Readout by straight segmented PCB planes alternated to Pb (W) absorbers, gaps in between filled with LAr (LKr)
  - ✓ High granularity via electrode segmentation
    - $O(10^6)$ cells
- Good compromise
  - ✓ Granularity, resolution, stability, uniformity
- EM resolution 5-8%/sqrt(E)

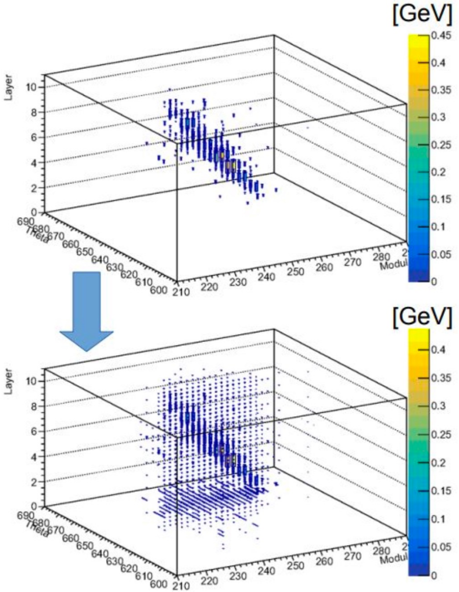


ALLEGRO ECAL

Highly granular Noble liquid based ECAL

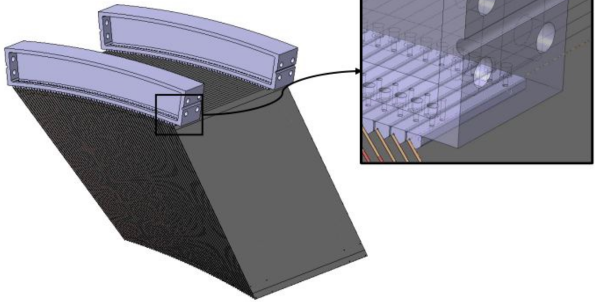




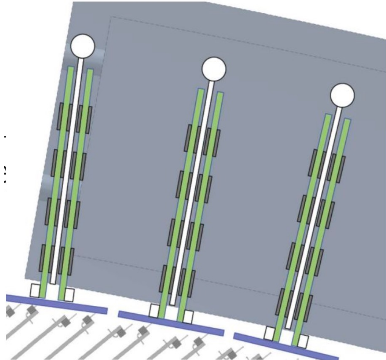


- Granularity achieved by etching readout electrodes
- Colleting signal from inner pads requires long readout lines: cross-talk!
  - ✓ Cross-talk < 0.1% achievable
  - ✓ Negligible impact on γ/π^0 classification

- Fully welded.



- Calorimeter in cryostat: where readout electronics?
  - ✓ Warm electronics: 2M signal cables to route
  - ✓ Cold electronics: need room for boards + HV, powering and signal cables in cryostat
    - Cold FEB along radial direction? RO on PCB?
- Mechanical structure for holding and positioning of absorbers and electrodes

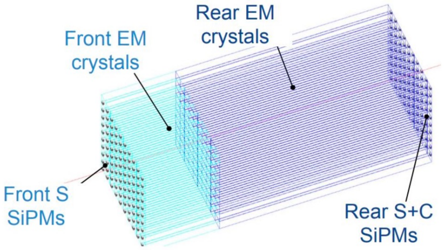


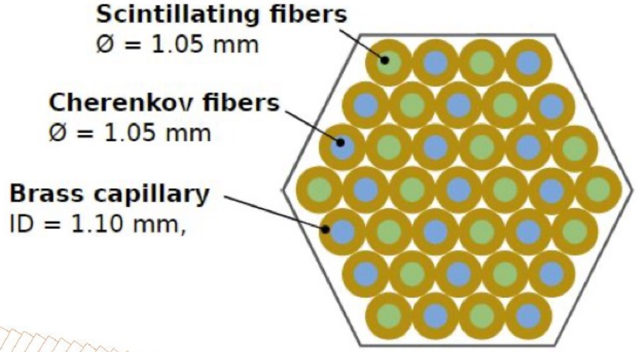
IDEA calorimeter

Hybrid crystal & Dual-readout calorimeter

Dual-readout fiber calorimeter

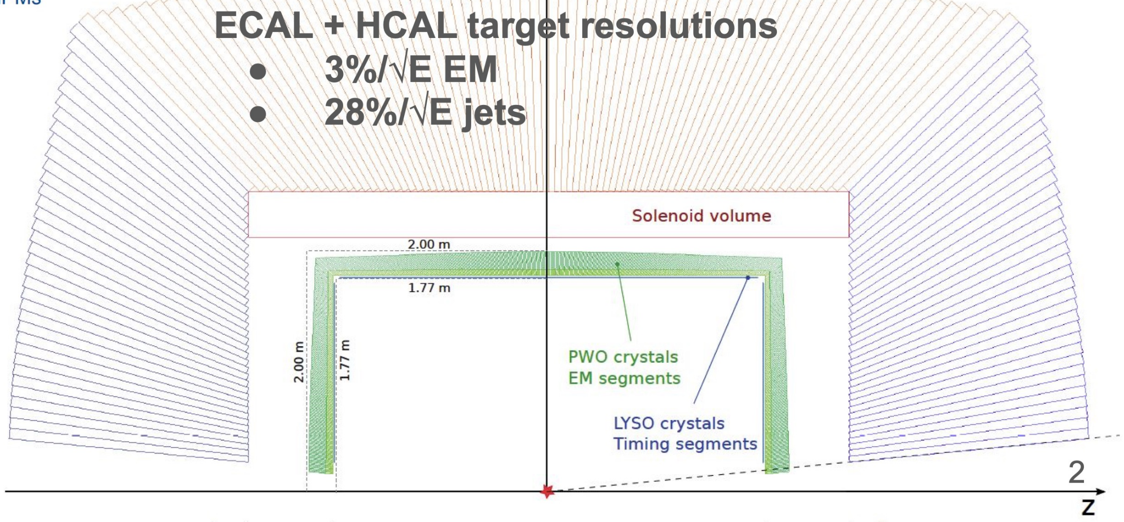
- ECAL: homogeneous dual-readout hybrid crystal
- HCAL: dual-readout fiber hadronic calorimeter





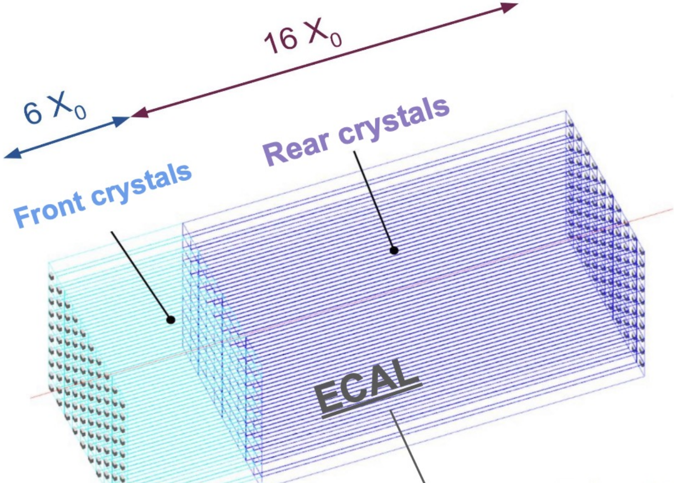
ECAL + HCAL target resolutions

- **3%/√E EM**
- **28%/√E jets**



Dual-readout crystal EM calorimeter

- High density crystals (short X_0, small R_M)
  - ✓ PbWO4, BGO, BSO
- Two layers (e.g. 6+16 X_0)
- Fine granularity: O(cm^2) cross section
- SiPM readout
  - ✓ Front: S
  - ✓ Rear: S + C

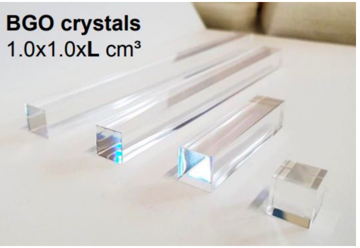


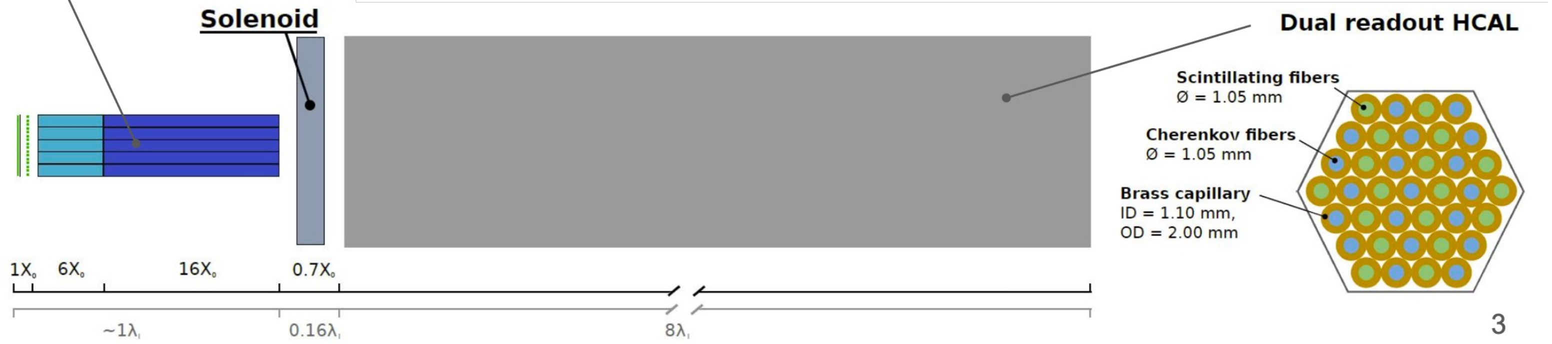
Rear crystal ECAL segment

two SiPMs optimized for S and C detection respectively

Front crystal ECAL segment:

one SiPMs optimized for S detection





Dual-readout strategy in crystals

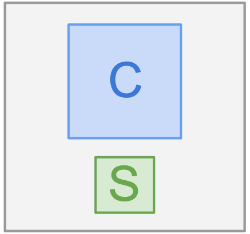
- Cherenkov and Scintillation light detection and separation challenging in homogeneous materials
- C vs S distinctive features
  - ✓ C emission faster than S
  - ✓ C emission spectrum broader than S
  - ✓ C/S separation with filters and pulse shape analysis

Rear crystal ECAL segment

two SiPMs optimized for S and C detection respectively

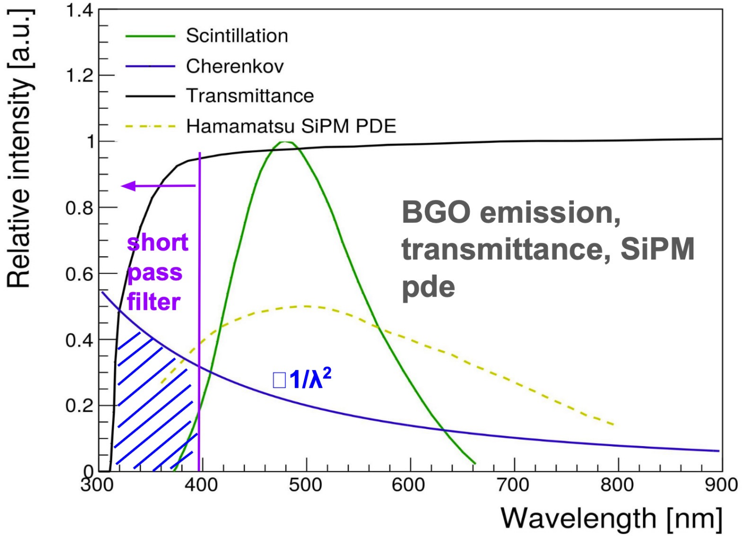
Front crystal ECAL segment:

one SiPMs optimized for S detection

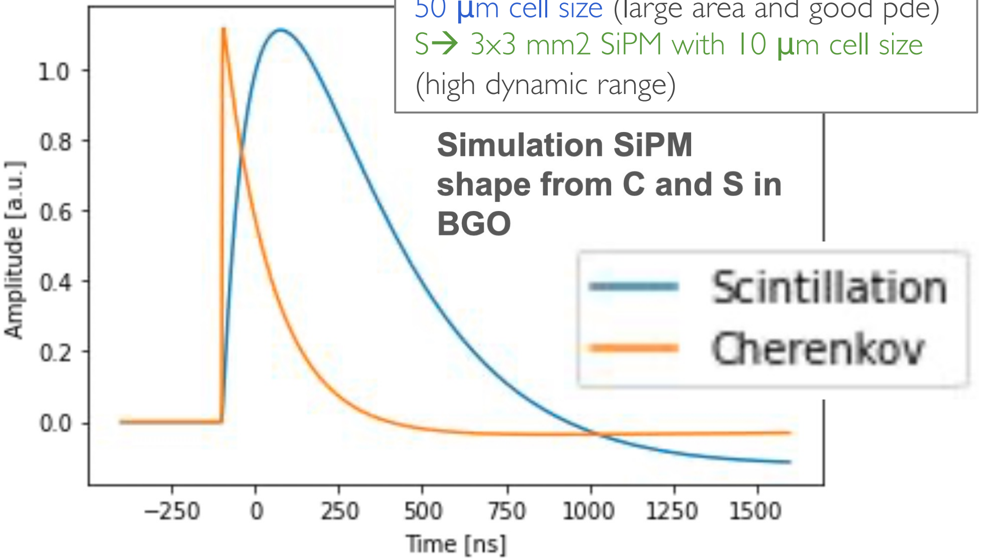


C → optical filter + 6x6 mm2 SiPM with 50 μm cell size (large area and good pde)

S→ 3x3 mm2 SiPM with 10 μm cell size (high dynamic range)



BGO emission, transmittance, SiPM pde



Simulation SiPM shape from C and S in BGO

GRAiNITA

- Better than a sampling calorimeter, cheaper than a homogeneous one!

sampling

$$\frac{\sigma_E}{E} \sim \frac{10\%-15\%}{\sqrt{E}}$$

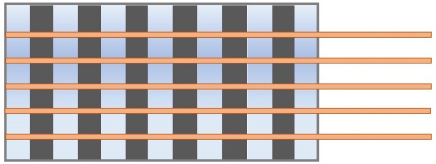
↔

homogeneous

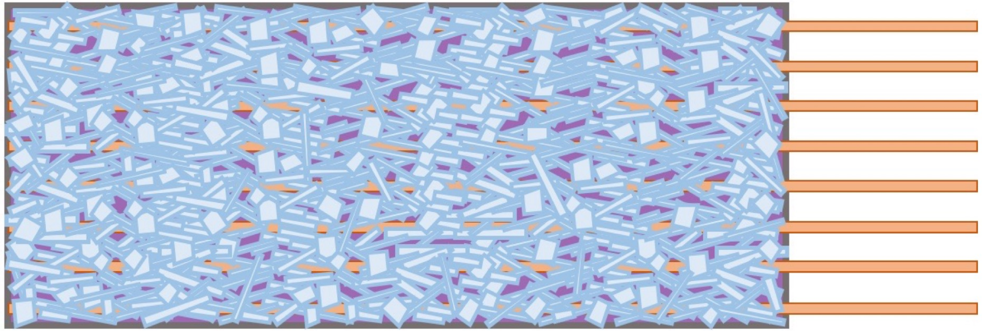
$$\frac{\sigma_E}{E} \sim \frac{1\%-2\%}{\sqrt{E}}$$

- Idea: mixture of inorganic scintillator grains and heavy liquid
  - ✓ Extremely fine sampling
  - ✓ Scintillation light locally contained by refraction/reflections
    - BGO or ZnWO4 crystals
  - ✓ Readout by wavelength shifting fibers
- Excellent expected EM resolution: 2-3%/sqrt(E)

Shashlyk-type calorimeter



“grain” calorimeter



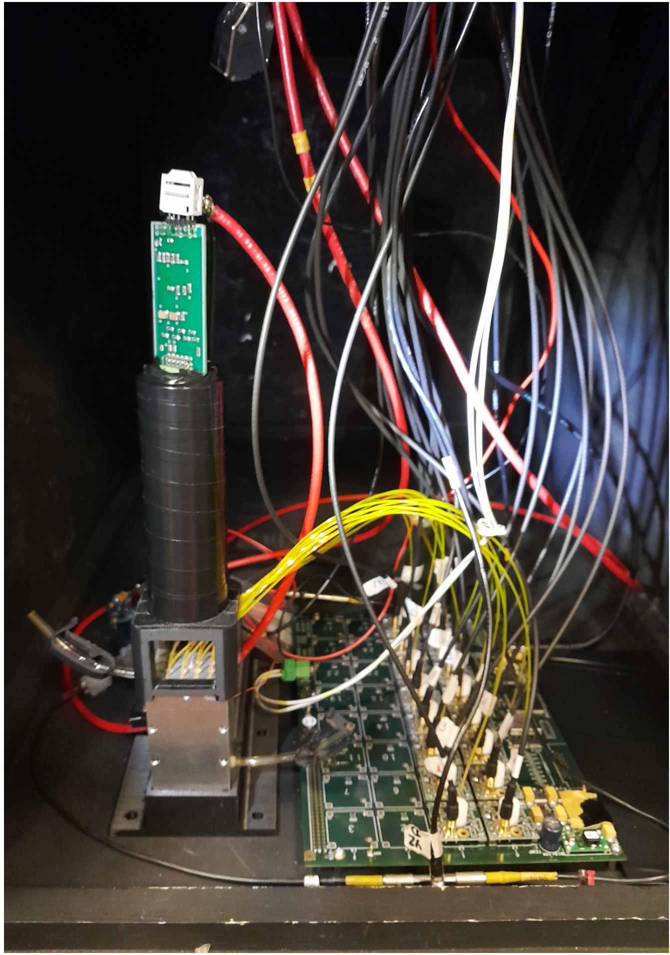
	$ZnWO_4$
Effective Z	61
Density (g/cm^3)	7.87
Refractive index	2.0 - 2.3
Light yield (photons/MeV)	~ 9000
Peak emission wavelength (nm)	480
Decay time (μs)	20
Radiation length (cm)	1.20
Molière radius (cm)	1.98

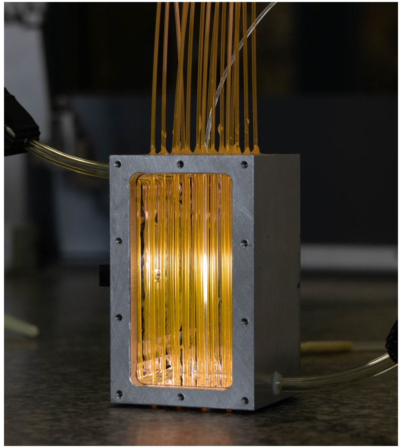
GRAiNITA

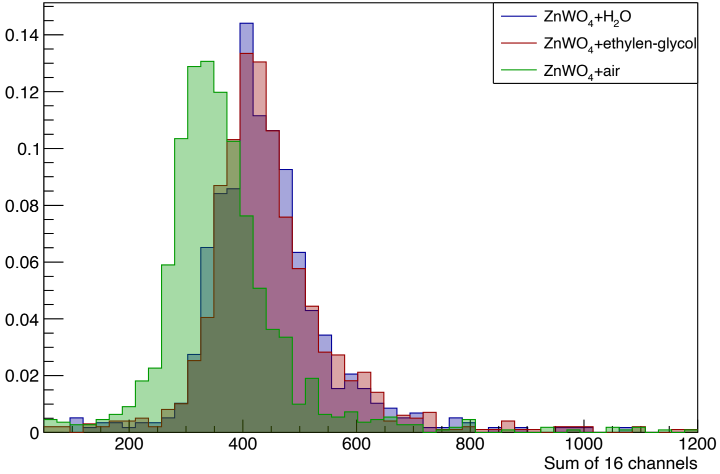
arXiv:2312.07365

“grain” calorimeter

- Small (2 x 2 x 5.5 cm3) prototype
  - ✓ ZnWO4 grains + water or Heavy Liquid (e.g. ethylene +glycol)
  - ✓ 16 WLS fibers read out by SiPM and a Wave-Catcher
    - Depolished fiber in the center to allow for green light injection
- Signal yield larger when medium refractive index is better matched with grains
- Light confinement confirmed
- Possibility of ~1%/sqrt(E) due to photon statistics confirmed
- Currently: uniformity studies (impact on resolution constant term)







Recurring principles across all future designs

- **Four principles appear in every future calorimeter design**
  1) Granularity: finer cells → better particle-shower separation → better jet resolution
  2) Timing: precision timing (< 50 ps) → pile-up rejection → effective luminosity reduction
  3) Multiple information: two (or more) complementary signals (S+C, E+space+t, tracking+calorimetry) beat single measurement!
  4) Simulation-driven design: every detector validated against full Geant4 simulation + test-beam
     - **Role of AI? → Explore MODE Collaboration!**
       - MODE = Machine-learning Optimized Design of Experiments

- **Alternative philosophies (ATLAS vs CMS "bets") persist into future R&D…**
  - ✓ ATLAS-like: modularity, stability, long-term operation → future role for LAr in FCC-hh…
  - ✓ CMS-like: best absolute performance, novel materials → future role for HGCAL, crystals, dual-readout…

- **40+ year journey toward definitive solution to hadronic reconstruction ongoing…**
  - ✓ Hardware compensation → software compensation → dual-readout → particle flow

What will calorimetry look like in 2040?

- **Genuine open questions in calorimeter physics (not yet settled)…**
  - ✓ Will dual-readout become the standard for future HCALs, or will software compensation / particle flow win?
  - ✓ Can timing-capable calorimeters (5D) achieve both energy and timing resolution simultaneously?
  - ✓ Will crystal technology keep up with radiation doses at HL-LHC and FCC?
  - ✓ Can machine learning entirely replace optimal filtering and software compensation?

- **The big question: what is the right technology for a 100 TeV hadron collider?**
  - ✓ FCC-hh: the most extreme calorimetry challenge ever attempted
  - ✓ Current best guess: Si-W ECAL (HGCAL-like) + dual-readout or noble-liquid HCAL
  - ✓ …

Your mission (should you decide to accept it)

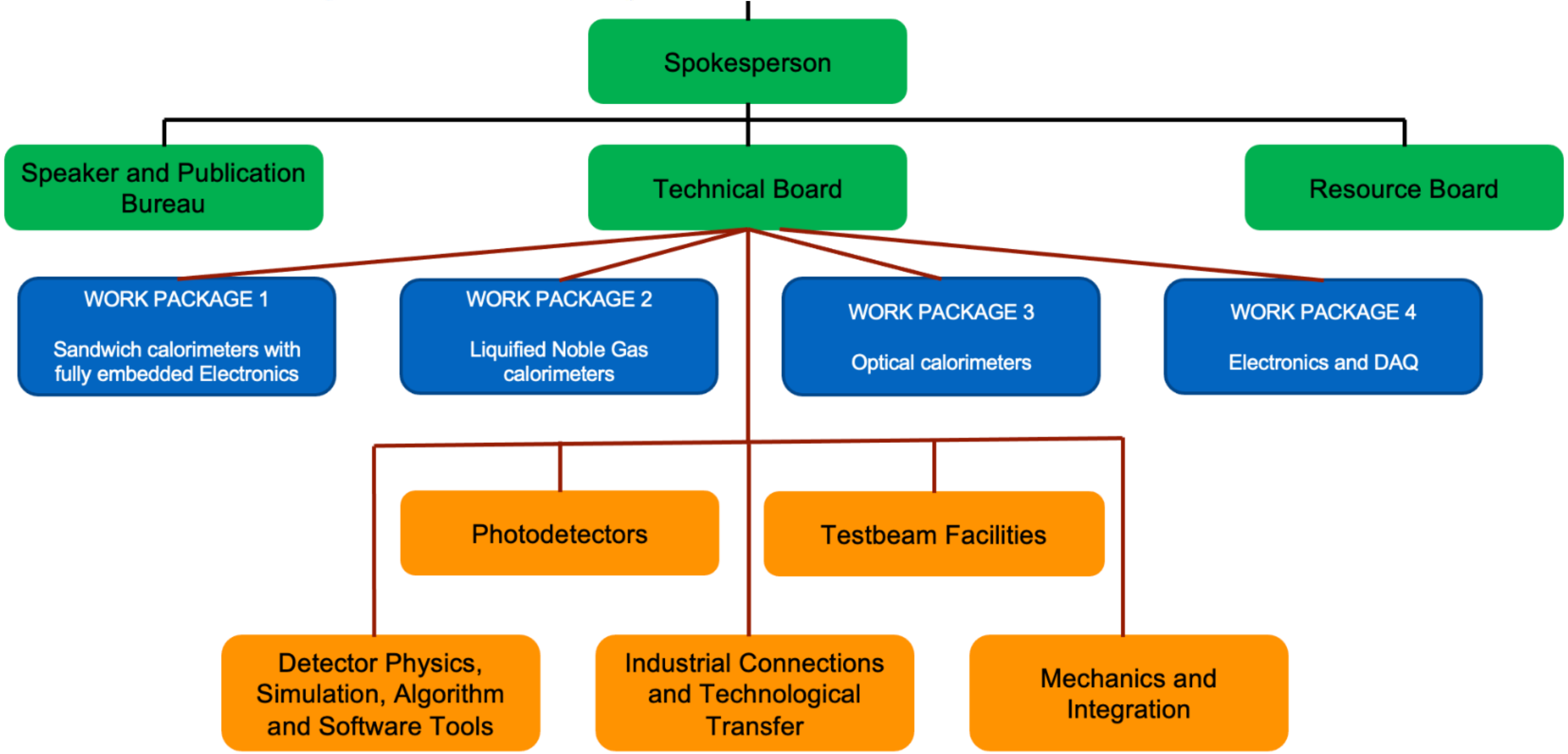
Detector drives physics,
and **physics drives the detector**

Every calorimeter **design decision** connects to
a **specific physics** measurement

Learn the **principles deeply enough**
to **design calorimeters**
for **physics not yet imagined**!

https://drdcalo.web.cern.ch

drdcalo



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WORK PACKAGE 1

Sandwich calorimeters with fully embedded Electronics

WORK PACKAGE 2

Liquified Noble Gas calorimeters

WORK PACKAGE 3

Optical calorimeters

WORK PACKAGE 4

Electronics and DAQ

Photodetectors

Testbeam Facilities

Detector Physics, Simulation, Algorithm and Software Tools

Industrial Connections and Technological Transfer

Mechanics and Integration

Course summary: what you should know by now…

- **L1: Why calorimetry** → detector role in experiments, total energy measurement, physics motivation
- **L2: EM shower physics** → electron and photon interactions; pair production, bremsstrahlung, radiation length X_0; EM shower properties
- **L3: HAD shower physics** → nuclear interactions, shower structure, invisible energy, e/h ratio
- **L4: Energy resolution** → stochastic/noise/constant terms, compensation, e/h formalism
- **L5: Calorimeter technologies** → Cherenkov, scintillation, ionization, electron/hole pairs; crystal properties, noble liquid, silicon calorimetry; silicon-based light readout
- **L6: Calorimeter design** → design principles; dual readout, particle flow philosophy
- **L7: Signal chain and calibration** → preamplifier, signal shaping, OFC, ADC dynamic range; test-beam; hardware, physics and in-situ calibration; JES
- **L8: Future calorimetry** → HL-LHC challenges, HGCAL (5D: E+x,y,z+t); calorimetry R&D for future colliders