Overview of Calo Technologies for FCCee

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Calorimeters at FCC-ee: what for ?

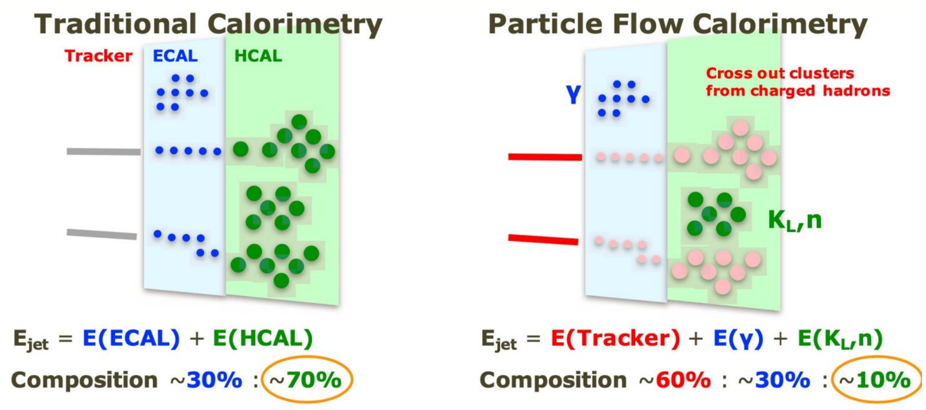
FCC-ee: a specific set of requirements

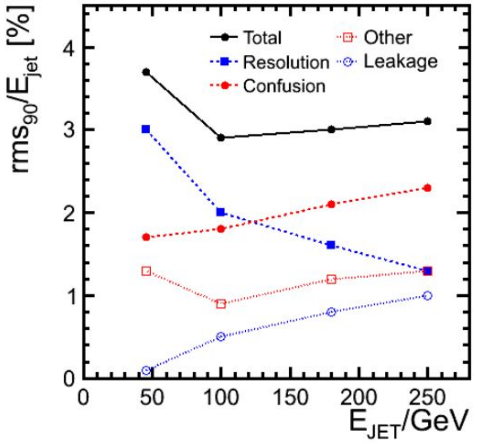
- Energy resolution: "only" for photons and neutral hadrons
  - But: ideally photons as low as 200 – 300 MeV
- Dynamic range: 200 MeV – 180 GeV
  - vs LHC: 6 TeV jets !
- Granularity: PID, disentangle showers for PFlow
  - But: how granular exactly ?
- Hermeticity, uniformity, calibrability, stability
  - Low systematics for precision measurements
  - Complex engineering questions
- No need to be particularly fast
  - But: can precise timing help in reconstructing showers ?

A quest for ultimate jet energy resolution

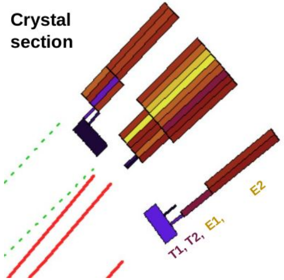
PFlow PFlow PFlow

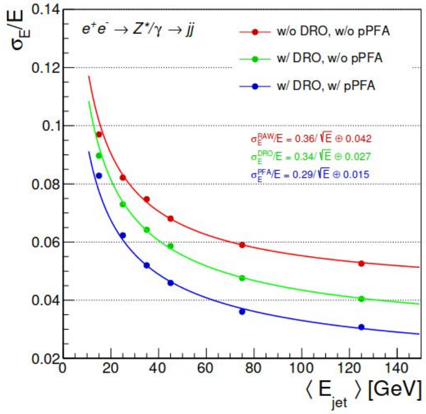
- Basic principles well known
- What granularity do we really need at FCC-ee (vs ILC optimisation: 1TeV c.o.m) ?
- New ideas for new calos (crystals DR study)





Jet energy resolution

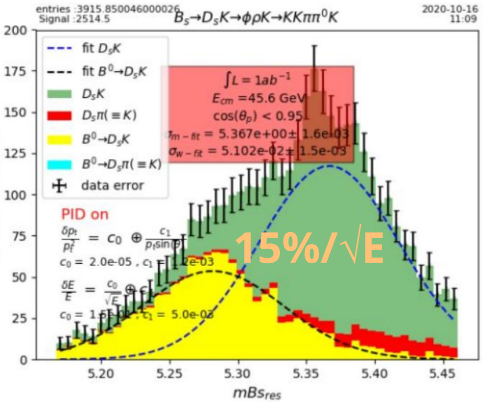


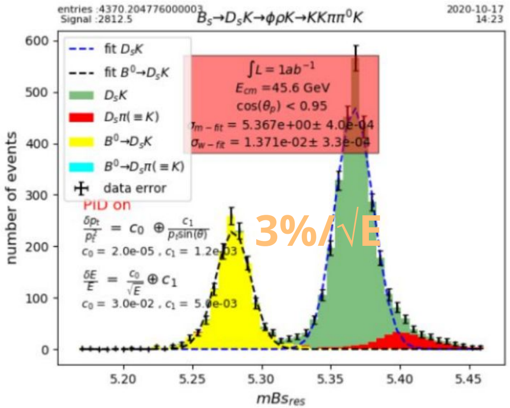


FCC-ee unique challenges

O(10^{11}) B and τ at 45 GeV !!!

- Some channels require very high EM resolution
  - More examples ?
- τ physics: reconstructing the decays
  - Means π^0 reconstruction and ID
  - Count close-by π^0
  - Granularity
- BSM, e.g ALP searches
  - photon resolution, photon pointing





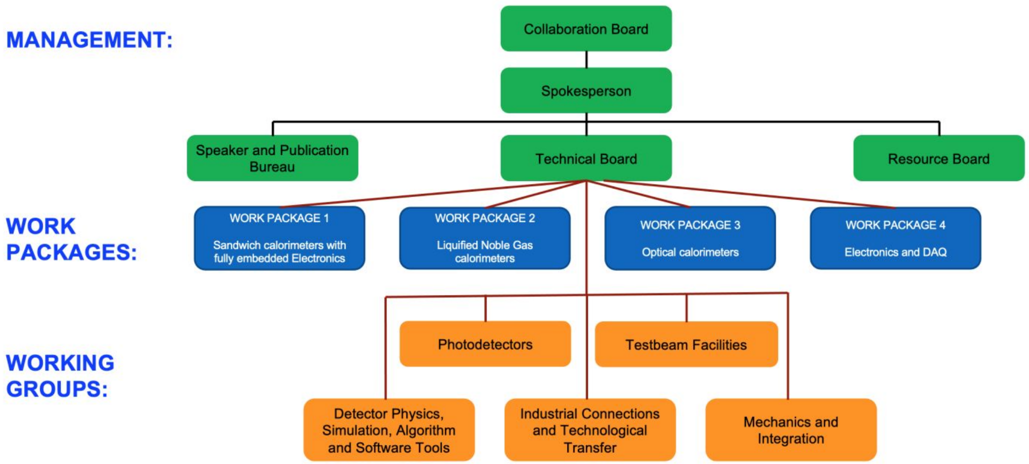
Gen ↓ / Recon →	$\pi^\pm \nu$	$\pi^\pm \pi^0 \nu$	$\pi^\pm 2\pi^0 \nu$	$\pi^\pm 3\pi^0 \nu$	$\pi^\pm 4\pi^0 \nu$
$\pi^\pm \nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^\pm \pi^0 \nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^\pm 2\pi^0 \nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^\pm 3\pi^0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

FCC-ee calorimeters landscape: DRD6

Detector R&D (DRD) collaborations implement the ECFA Detector R&D Roadmap

- DRD6 on Calorimetry with 4 work packages and several transversal activities (TB, Materials, SW, …)
  - First Collaboration meeting: April 9-11 at CERN
  - Organised by CERN, but truly international collaboration

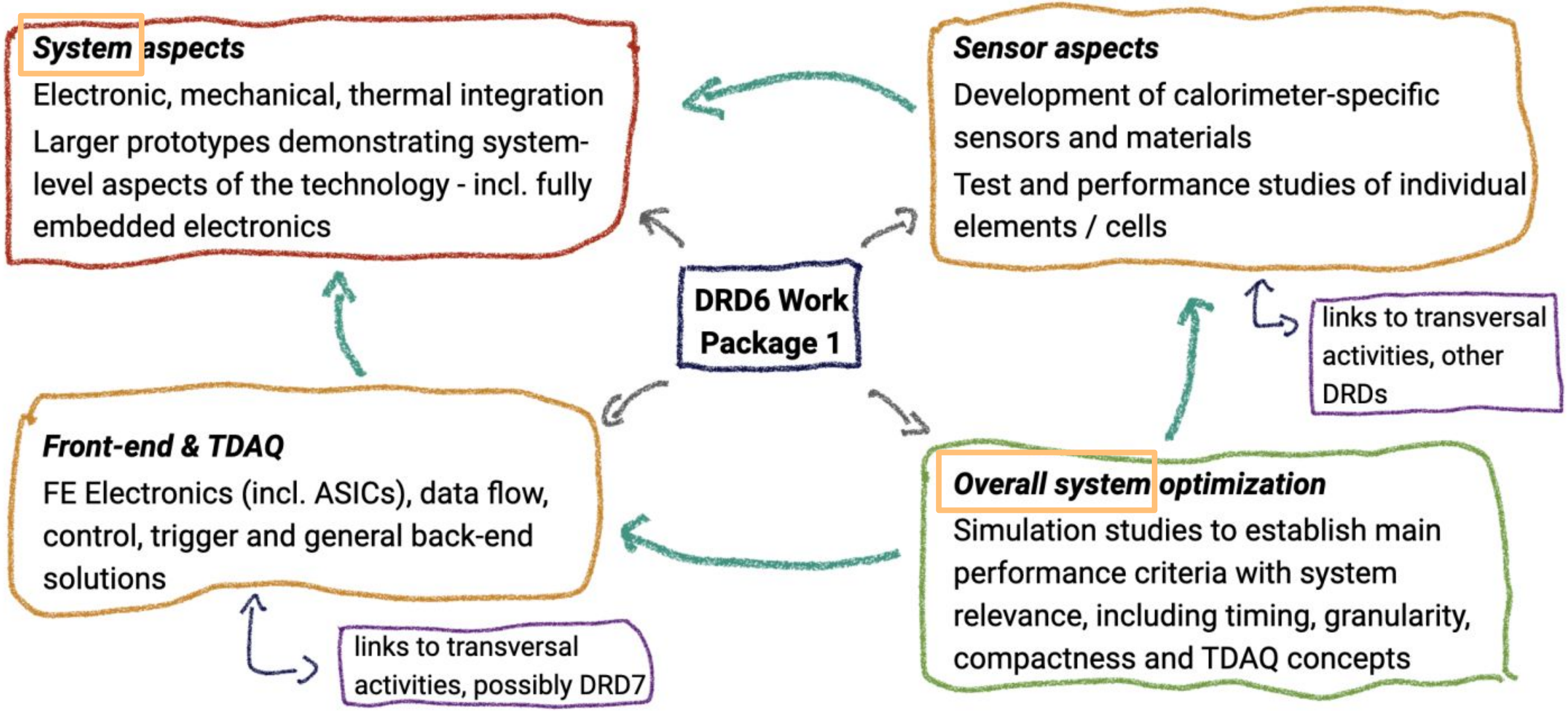


- Not only targeted at FCC-ee
  - Also: LHCb SPACAL, MuC, future hadron collider, CEPC…

- Mission:
  - Bring a diverse set of calorimeter technologies to a level of maturity such that they can be considered for a technology selection of future experiments
  - Maturity demonstrated with **full-scale prototypes**

WP1: Sandwich calos with fully embedded electronics

To some extent, continuity of CALICE projects. Hermeticity, compactness.

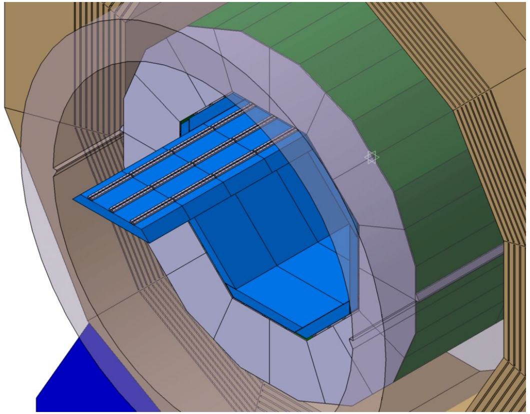


WP1: Projects

Task/Subtask	Sensitive Material/ Absorber	DRDTs	Target Application	Current Status
Task 1.1: Highly pixelised electromagnetic section				
Subtask 1.1.1: SiW-ECAL	Silicon/ Tungsten	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Subtask 1.1.2: Highly compact calo	Solid state (Si or GaAs)/ Tungsten	6.2	e^+e^- collider forward part	Prototypes with non-optimised sensors, Sensor optimisation and data transfer studies ongoing
Subtask 1.1.3: DECAL	CMOS MAPS/ Tungsten	6.2, 6.3	e^+e^- collider central detector. Future hadron collider	Prototypes with non-optimised sensors, Sensor optimisation ongoing
Subtask 1.1.4: Sc-Ecal	Scintillating plastic strips/ Tungsten	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Task 1.2: Hadronic section with optical tiles				
Subtask 1.2.1: AHCAL	Scintillating plastic tiles/ Steel	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Subtask 1.2.2: ScintGlassHCAL	Heavy glass tiles/ Steel	6.2	e^+e^- collider central detector	Material studies and specifications for prototypes
Task 1.3: Hadronic section with gaseous readout				
Subtask 1.3.1: T-SDHCAL	Resistive Plate Chambers/ Steel	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Subtask 1.3.2: MPGD-HCAL	Multipattern Gas Detectors/ Steel	6.2, 6.3	$\mu^+\mu^-$ collider central detector	Small prototype for proof-of-principle, Lateral and longitudinal extension envisaged
Subtask 1.3.3: ADRIANO3	Resistive Plate Chambers +Scintillating plastic tiles/ Heavy Glass	6.1, 6.2, 6.3	e^+e^- collider central detector BSM searches in MeV-GeV range	RPC, Scintillating Tiles advanced status, R&D on heavy glass needed

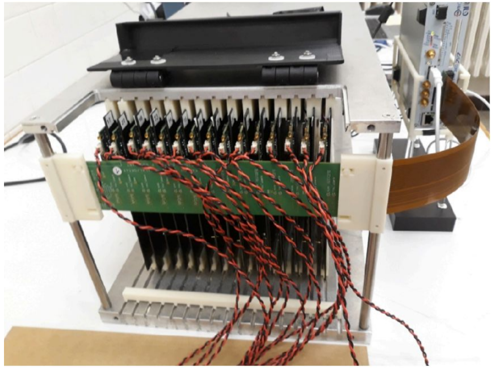
SiW Ecal

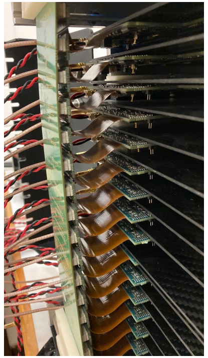
Baseline Ecal in CLD



- 40 layers, 1.9 mm tungsten absorber, 22 X_0
- 0.5 mm thick silicon sensors with 5×5 mm^2 granularity
- $O(10^8)$ cells
  - Super high granularity for PFlow reconstruction
  - Tight integration: compact and hermetic
- EM resolution ~17%/√E

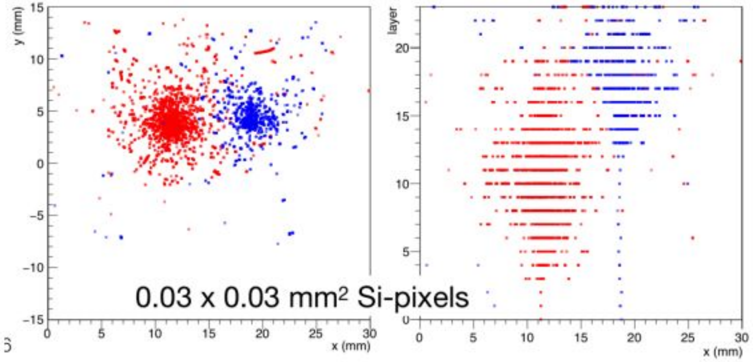
- Challenges:
  - Adaptation to FCC-ee (cooling, power)
  - Granularity re-optimisation ?
  - Study addition of timing
  - System aspects: design engineering module

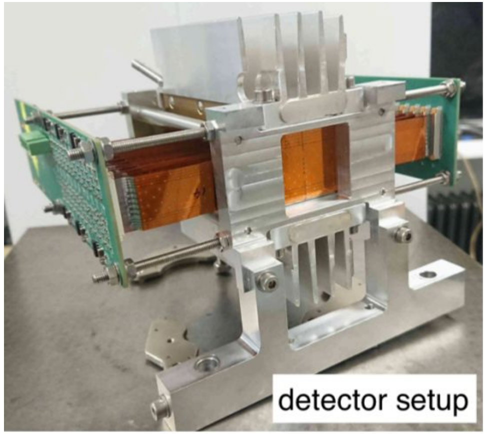




DECAL – Digital ECAL based on MAPS

- A MAPS-based digital Silicon-Tungsten ECAL, building on current DECAL and EPICAL projects
- Fully digital (no energy measurement / cell)
  - 30×30 μm^2 Si pixels
- Main R&D topics
  - Establish requirements of a sensor dedicated for digital calorimetry
  - Design of next-generation sensor with calorimeter-specific optimisation and evaluation of sensor design
  - Aim for small-scale digital ECAL prototype in 2026

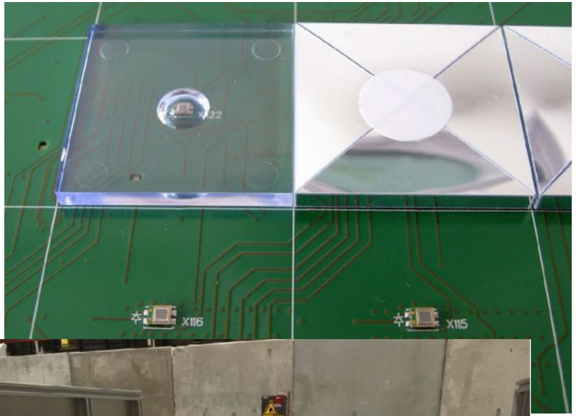




SiPM-on-Tile AHCAL

Baseline HCal in CLD. Same technology as used in CMS HGCal.

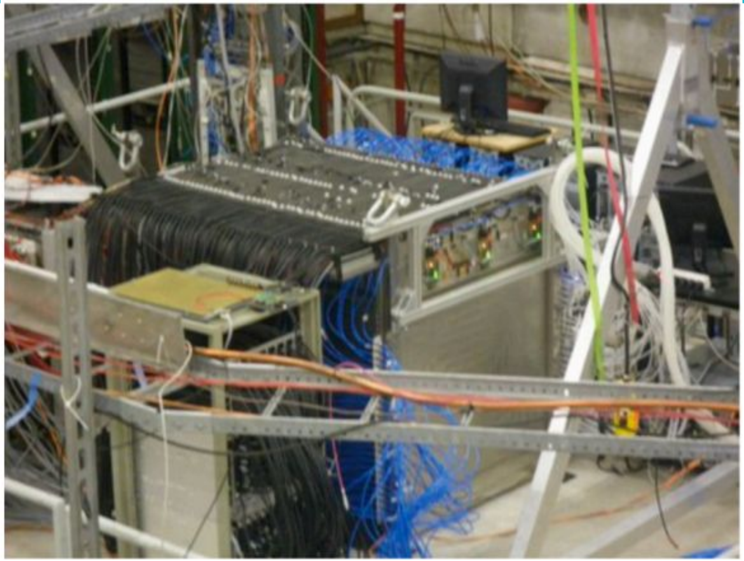
- SiPM-on-tile / steel HCAL
  - Builds on CALICE AHCAL prototype
  - Wrapped scintillator tiles directly read by SiPM
- Main R&D topics
  - Adaptation of detector concept to circular colliders with continuous readout
    - Data rates, cooling
  - Corresponding hardware developments: ASICs, readout, thermal and mechanical designs, scintillator geometry

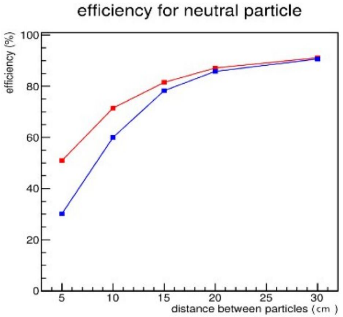


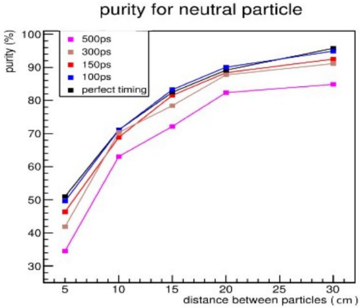
T-SDHCAL

- A RPC-based semi-digital HCAL with timing capability
  - Builds on CALICE SDHCAL technological prototype
  - Use of more eco-friendly gases

- Main R&D directions
  - Simulation studies extending to time information
  - Study and development of cooling and cassette concepts
  - Fast timing electronics, DAQ system
  - Aim to conclude initial R&D to propose a concept by 2026





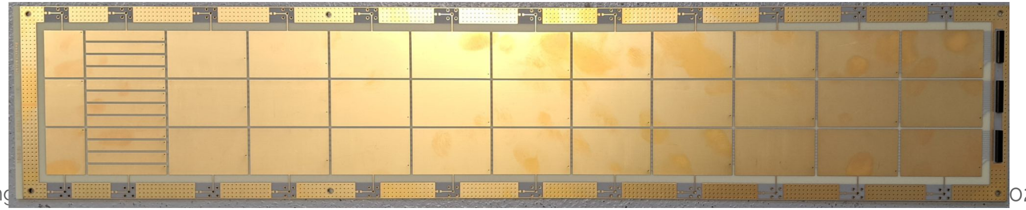


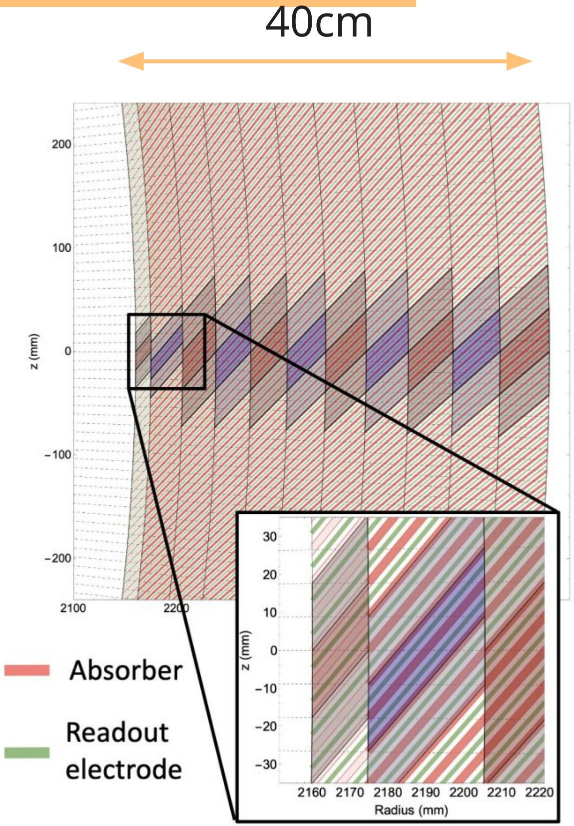
WP2: Liquified noble gases calos

All noble liquid calo community united behind the ALLEGRO Ecal project

- High granularity ($O(10^6)$ cells) noble liquid (LAr/LKr) Ecal using straight readout electrodes
  - Good compromise for granularity, resolution (5-8%/√E), stability, uniformity

- Main R&D topics
  - Optimise design for performance based on simulations
  - R&D on electrodes and absorbers
  - Mechanical design
  - Cold and warm frontend electronics
  - Aim: testbeam module in 2028





WP3: Optical calorimeters

Scintillation / Cerenkov light used in many calo concepts

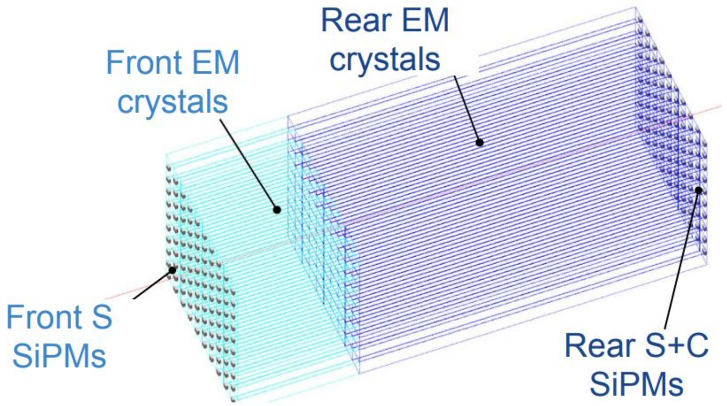
Project	Calorimeter type	Scintillator/WLS	Photodetector	DRDTs	Target
Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters					
HGCCAL	EM / Homogeneous	BGO, LYSO	SiPMs	6.1, 6.2	e^+e^-
MAXICC	EM / Homogeneous	PWO, BGO, BSO	SiPMs	6.1, 6.2	e^+e^-
Crilin	EM / Quasi-Homog.	PbF_2, PWO-UF	SiPMs	6.2, 6.3	$\mu^+\mu^-$
Task 3.2: Innovative Sampling EM calorimeters					
GRAiNITA	EM / Sampling	$ZnWO_4$, BGO	SiPMs	6.1, 6.2	e^+e^-
SpaCal	EM / Sampling	GAGG, organic	MCP-PMTs,SiPMs	6.1, 6.3	e^+e^-/hh
RADiCAL	EM / Sampling	LYSO, LuAG	SiPMs	6.1, 6.2, 6.3	e^+e^-/hh
Task 3.3: Hadronic sampling calorimeters					
DRCal	EM+HAD / Sampling	PMMA, plastic	SiPMs, MCP	6.2	e^+e^-
TileCal	HAD / Sampling	PEN, PET	SiPMs	6.2, 6.3	e^+e^-/hh
Task 3.4: Materials					
ScintCal	-	-	-	6.1, 6.2, 6.3	$e^+e^-/\mu^+\mu^-$/hh
CryoDBD Cal	-	TeO, ZnSe, LiMoO NaMoO, ZnMoO	n.a.	-	DBD experiments

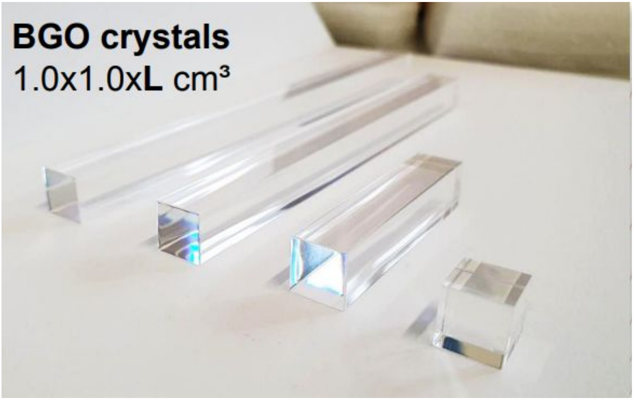
In addition: **R&D on crystals** and other scintillating materials

MAXICC / CalVision

Ecal for IDEA detector concept

- Homogeneous EM calorimeter based on segmented crystals with dual-readout
  - High density scintillating crystals with good cherenkov yield
  - Dedicated optical filters and SiPMs to readout S and C from same active element
  - Promise 3%/√E + DR capability
  - Synergies within Calvision, IDEA and CERN Crystal Clear collaborations



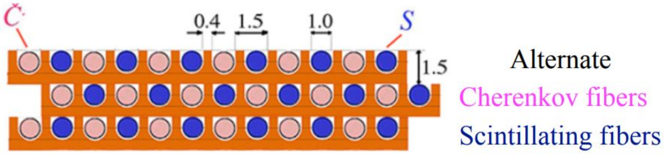


- Main R&D Topics
  - Identification of optimal crystal, optical filters and SiPM candidates
  - Proof-of-concept with lab measurements and prototypes
  - EM scale prototype for beam test

Dual Readout calorimeter

Main / Hcal calorimeter for IDEA detector concept

- Longitudinally unsegmented dual-readout sampling calorimeter
    - Scintillation and Cherenkov fibres inside an absorber groove
    - Reaches 30%/√E for single hadrons ⇒ ultimate resolution for jets
    - O(130 M) fibers for O(15 M) channels

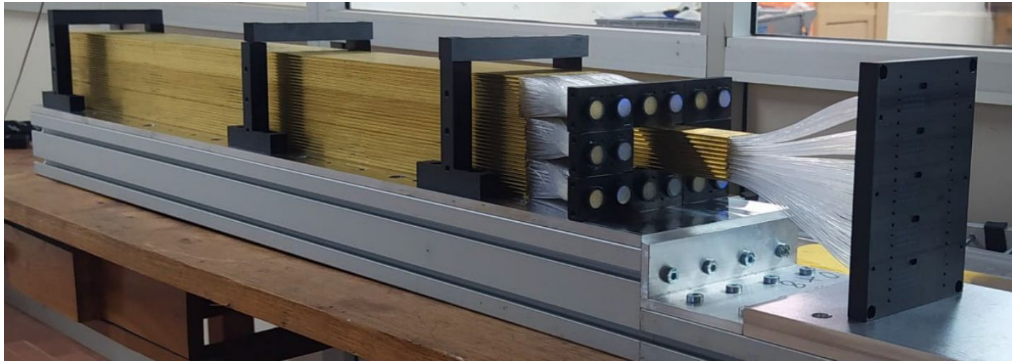


$$S = E\left[f_{em} + (h/e)_S(1 - f_{em})\right]$$

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

$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with:} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

- Main R&D Topics
    - Develop scalable readout electronics
    - Optimize metal matrix mechanics for large production
    - Develop mechanical model of full system with services
    - Testbeam with Hidra2 prototype

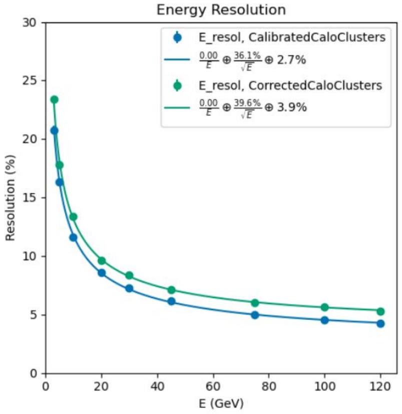


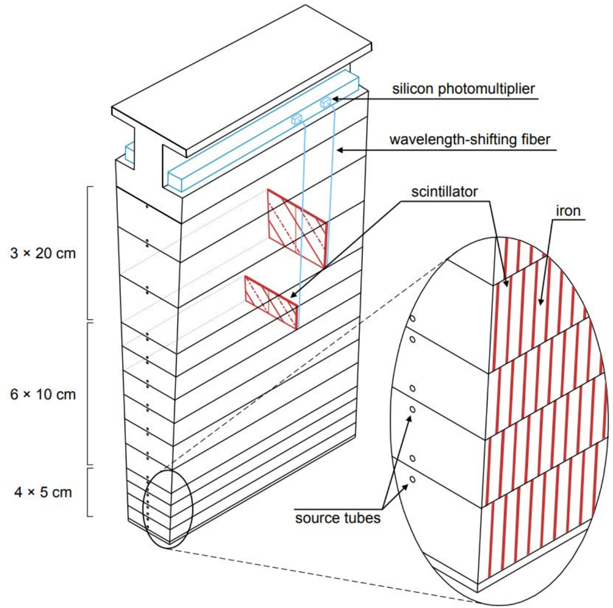
TileCal

Used in ALLEGRO concept

- High-granularity version of ATLAS TileCal hadronic calorimeter
  - 5mm steel absorber plates alternating with 3mm Scint.: 8 - 9.5λ
  - SiPM readout through WLS
  - Cost-effective solution

- Main R&D topics
  - Exploration of scintillators
  - Optimisation of WLS and SiPMs for readout efficiency
  - Build testbeam module

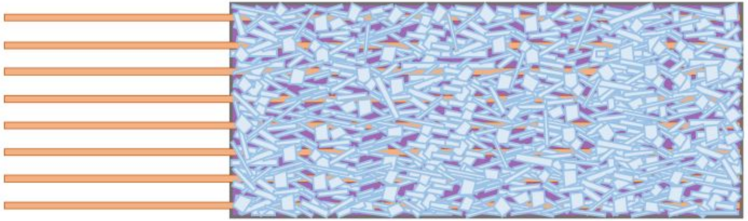




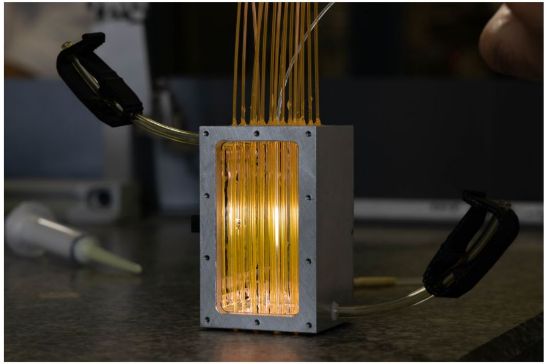
GRAiNITA

A novel type of calorimeter ~ next-gen shashlik

- Use grains of inorganic scintillating crystal readout by wavelength shifting fibers
  - Light spatially confined by refraction/reflections



- Excellent expected EM resolution: 2-3%/√E
  - Using BGO or $ZnWO_4$ crystals
  - First small 16-channel prototype used with cosmics
- Main R&D topics
  - R&D on crystal grains
  - Aim for larger prototype to validate on testbeam



Conclusions

- Huge diversity of calorimeter concepts for FCC-ee
  - Apologies to those I did not have time to feature !
- Some building on proven technologies
  - Pushing those technologies to their limits
- Some coming to fruition after years of R&D
  - Challenge for calorimeters tailored for ILC: adaptation to FCC-ee conditions
- Some brand new ideas
- In all cases:
  - Long road ahead to get to large scale prototypes
  - System-level concerns and engineering challenges are numerous to achieve highest performance at FCC-ee