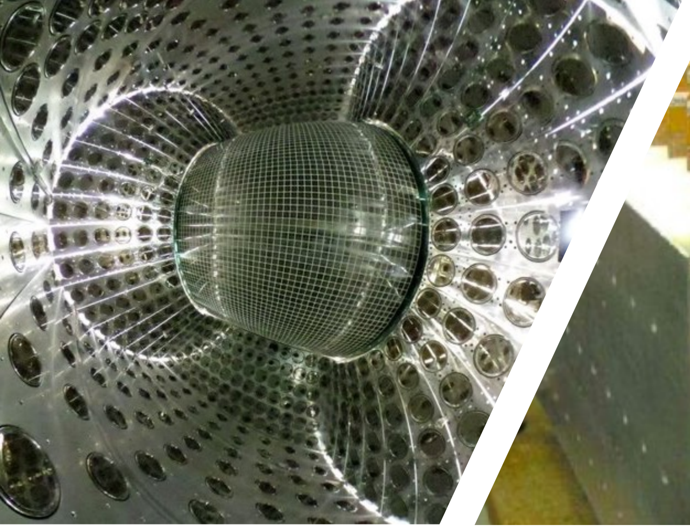
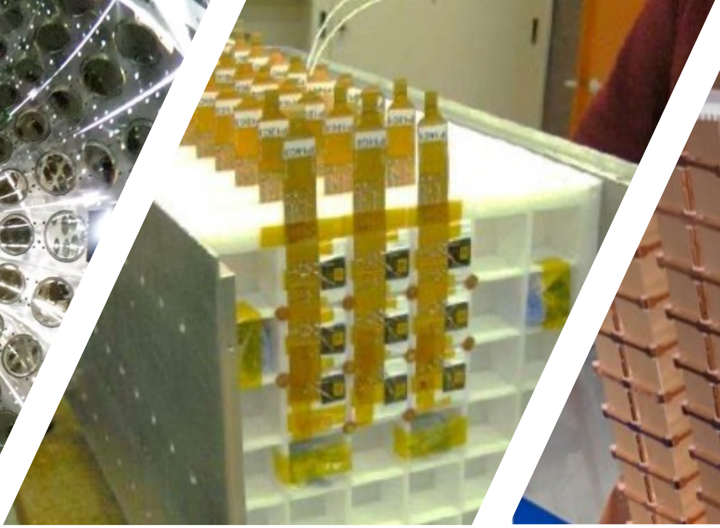
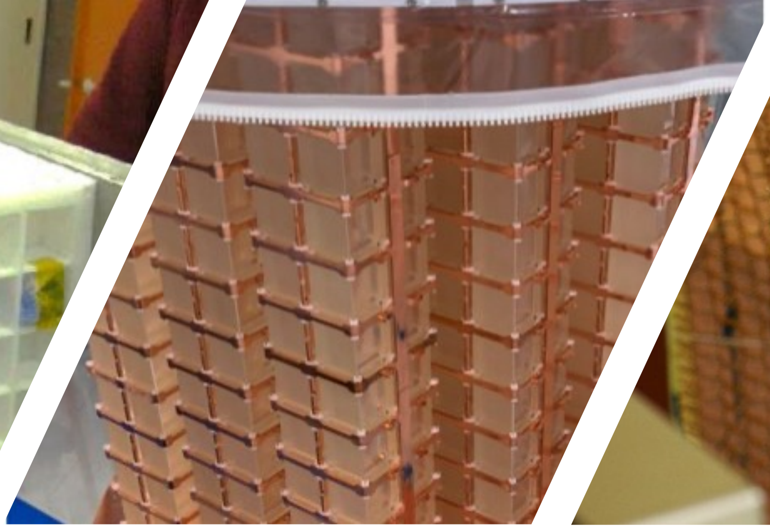
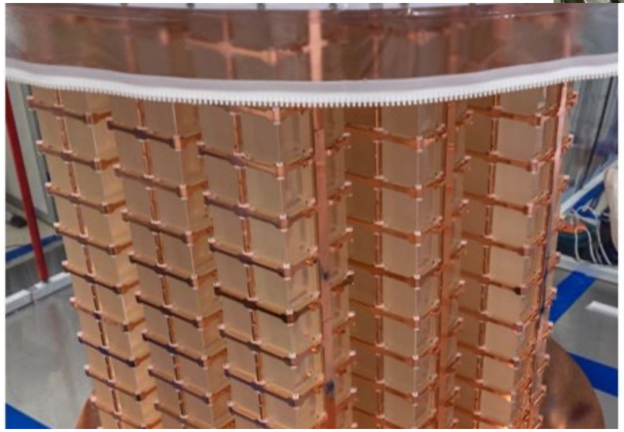




Francesca Cavallari (INFN Roma), Ivano Sarra
(INFN Laboratori Nazionali di Frascati),
Monica Sisti (INFN Milano Bicocca)

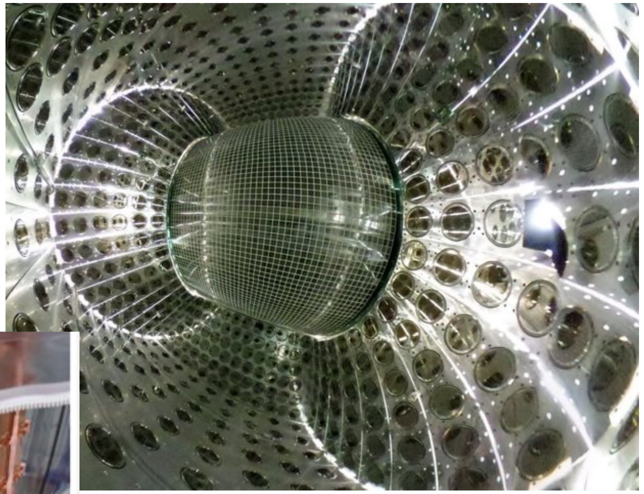
Trends and future applications in calorimetry

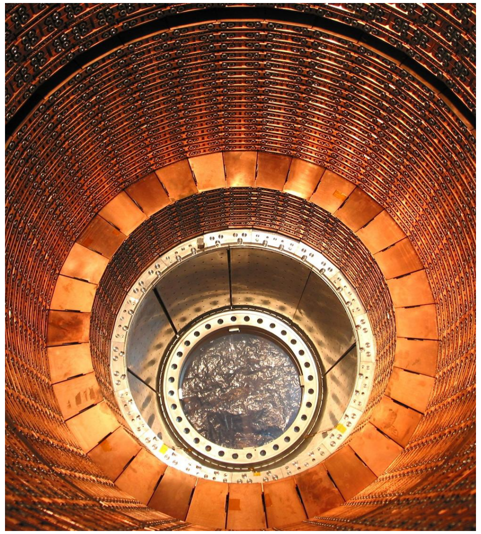
Calorimeter applications

Bolometers for v-less
double beta decay

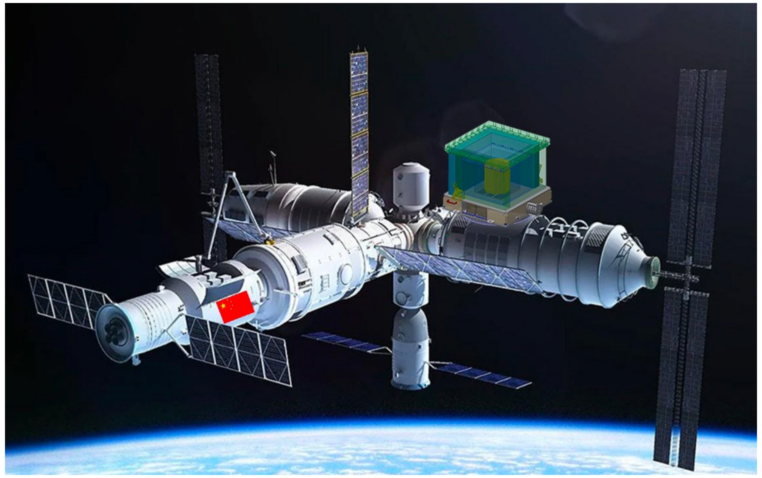


Rare muon decays for Lepton
Flavour Violation search
electrons/photons 50-100 MeV





HL-LHC
e+e- colliders
Muon collider
GeV-TeV electrons, photons, jets
and missing energy

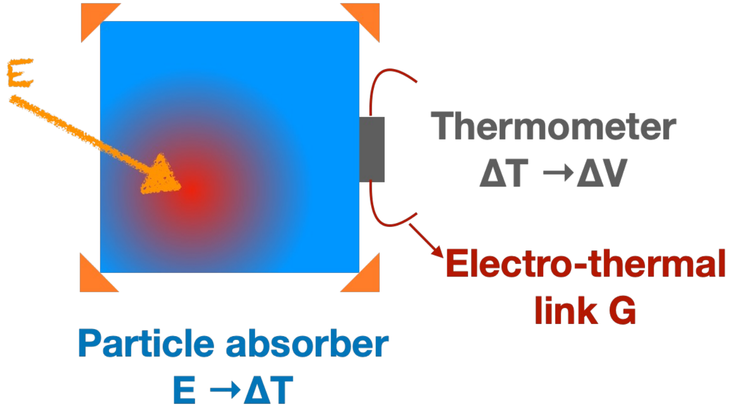


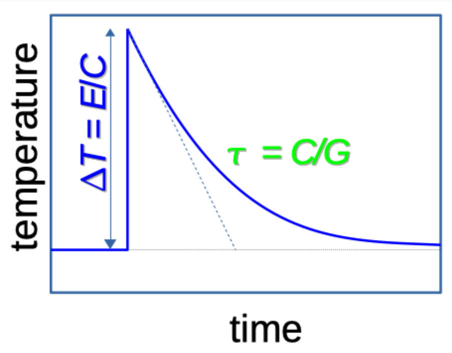
Space experiments for
cosmic ray detection
GeV – 100 TeV
electrons/photons

Disclaimer: selection of material is our choice, based on our knowledge and experience

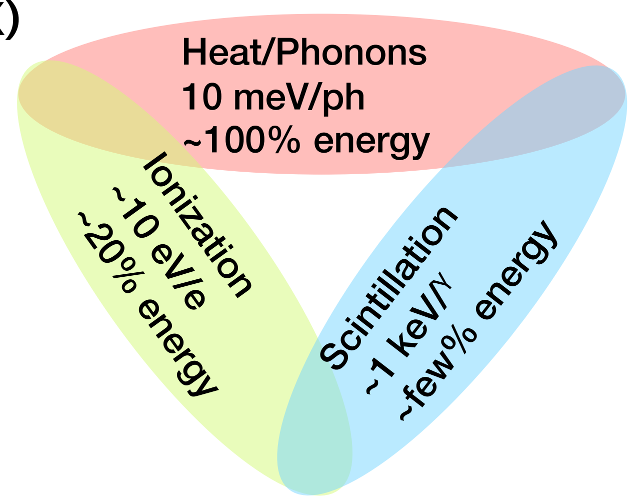
Energy

Low energy - calorimeters for astroparticle physics





- Detection principle: $\Delta T \cong E/C$
  C = total thermal capacity $\Rightarrow$ low C
  $\Rightarrow C \sim T^3 \Rightarrow$ low T ($T \ll 1$ K)
- Energy quanta: phonons



Double read-out technique

- ✦ Excellent energy resolution
- ✦ High efficiency (source=detector)
- ✦ Wide material choice
- ✦ Low energy threshold
- ✦ Fully sensitive to nuclear recoils
- ✦ True calorimeters
- ✦ Radiopure absorbers
- ✦ Particle identification capabilities

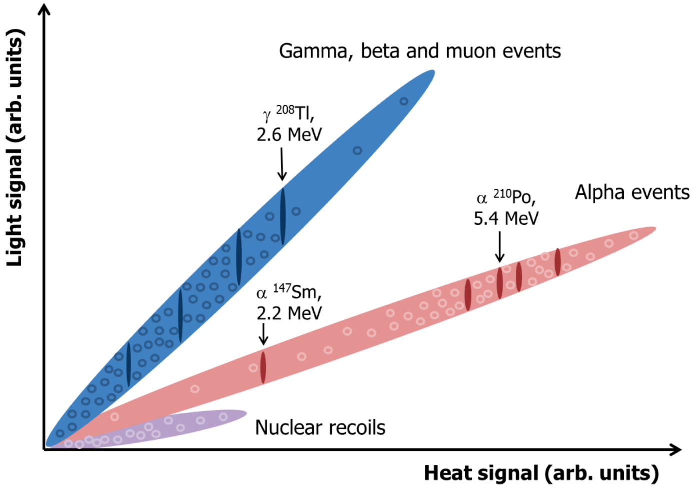
- Slow time responses
- Difficult to reduce close materials (holders, wires, cryostats, …)
- Not easy to run stable

Wide range of applications to rare event exp (energy range ~1 eV - ~10 MeV):

- ❖ Double beta decay searches
- ❖ Neutrino mass direct measurements
- ❖ Dark Matter searches
- ❖ Coherent elastic neutrino-nucleus scattering
- ❖ Astrophysics and cosmology

The thermal sensor is the crucial element. Most common technologies:

- Neutron Transmutation Doped Ge (NTD)
- Transition Edge Sensors (TES)
- Metallic Magnetic Calorimeters (MMC)



Low energy - future challenges

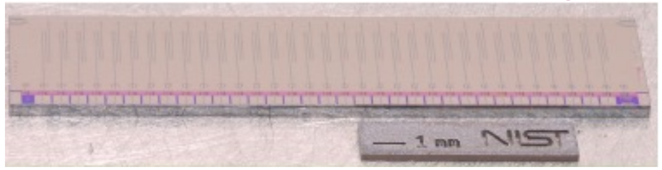
Background reduction

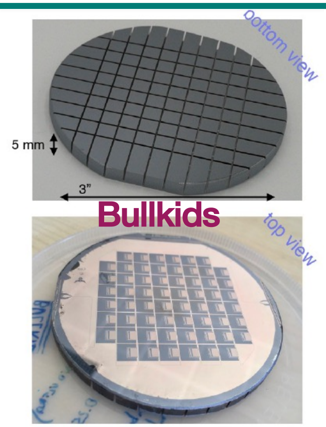
- α - β/γ discrimination with high resolution detectors in large arrays
- minimize passive materials
- discriminate β background
- remove pile-up events
- event topology reconstruction

Main R&D developments:

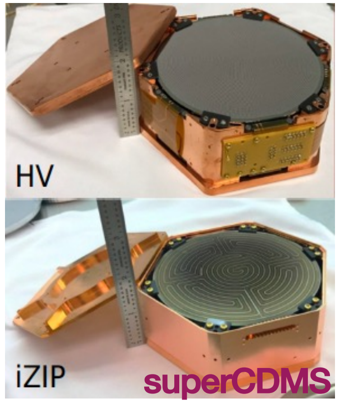
- Thermal sensor technologies for faster response
- Particle absorbers with event identification capability

HOLMES microwave multiplexing



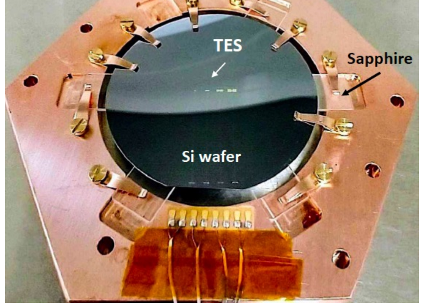


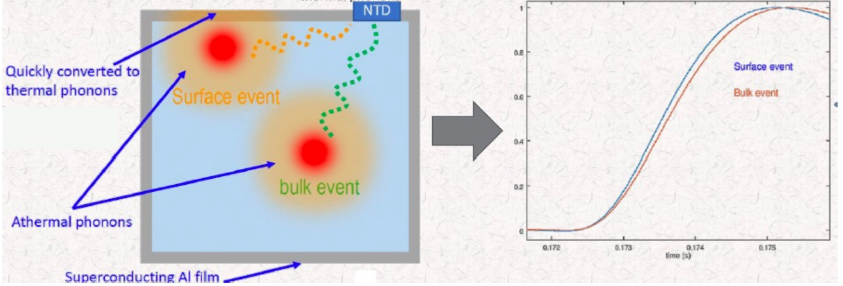
Bullkids



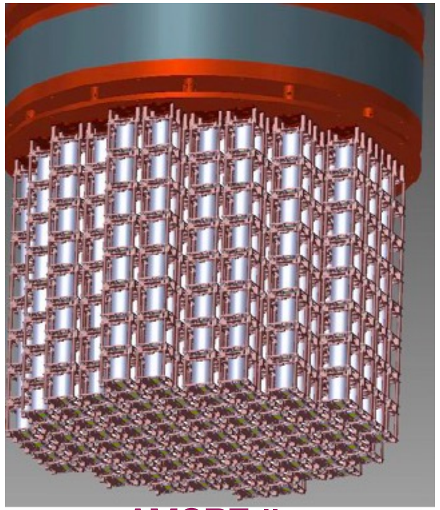
superCDMS

CUPID R&D



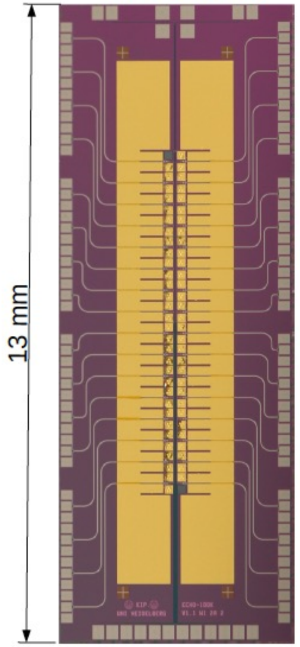


CROSS



AMORE-II

ECHo-100k

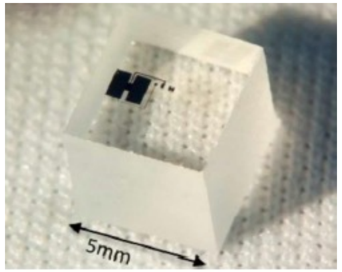


64 pixels

Very large microdetector arrays

- multiplexed readout
- increase single pixel activity
- ultra-low energy threshold

Ricochet CryoCube

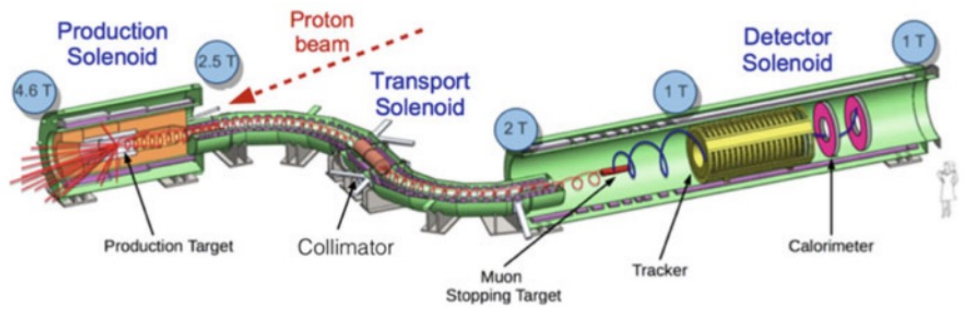


NUCLEUS 0.5g Al_2O_3

Middle energy – Intensity Frontier

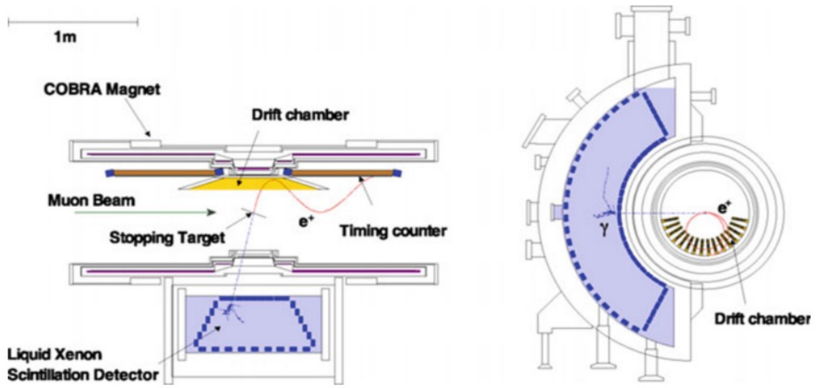
Charged Lepton Flavor Violation experiments
- cLFV processes are thought to be powerful tools to investigate the physics beyond the Standard Model (SM) as all of them are extremely suppressed in the framework of SM
- There are intensive efforts ongoing to find signals of cLFV processes at high-power proton accelerator facilities in Japan, the US, and Switzerland.

Mu2e (US) / COMET (Japan)



- μ stopped on Al target @ 10 GHz then $\mu N \rightarrow eN$
- $\sigma(E)/E$ of O(< 10 %) for 105 MeV electrons
- Detectors in vacuum ~ 10^{-4} Torr
- Detectors in ~ 1 Tesla magnetic field

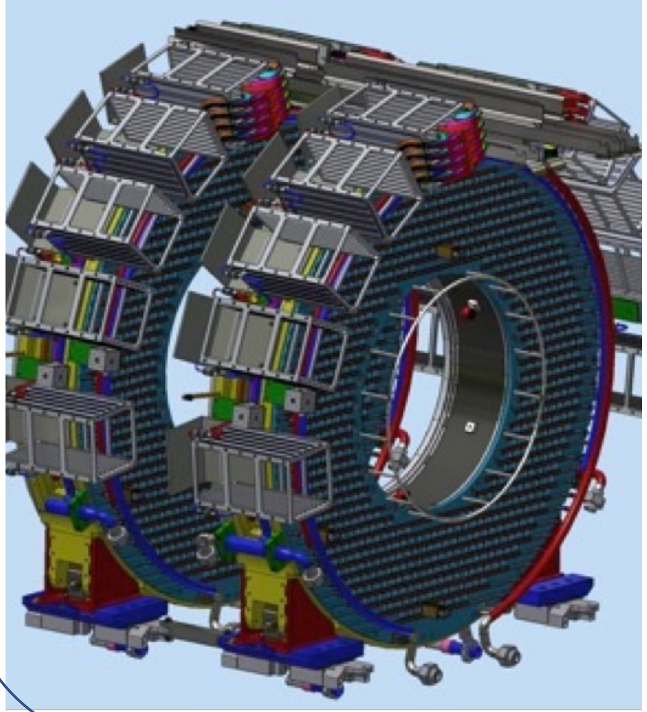
MEG/MEG II (PSI, Switzerland)

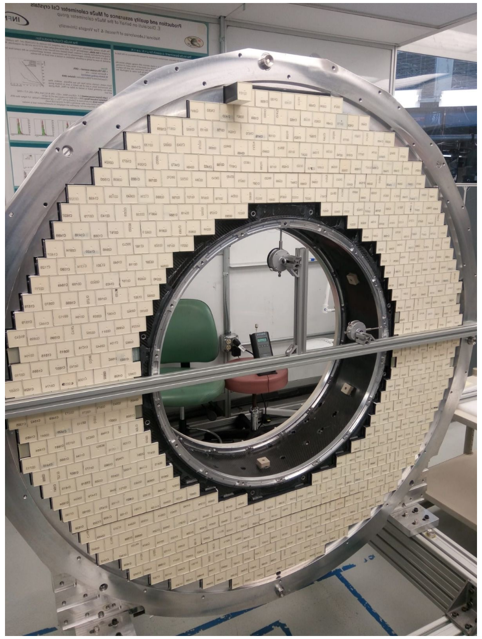


- μ stopped on plastic film @ 30 MHz
- μ->eγ (55 MeV)
- $\sigma_E(E)/E$ of 1-2% for 55 MeV photons

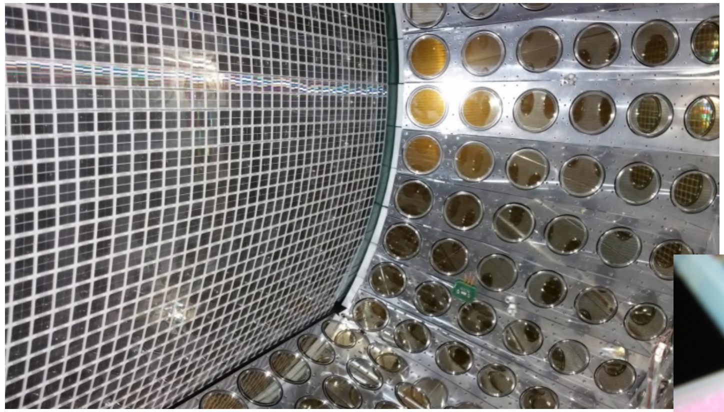
Calorimeters for cLFV experiments

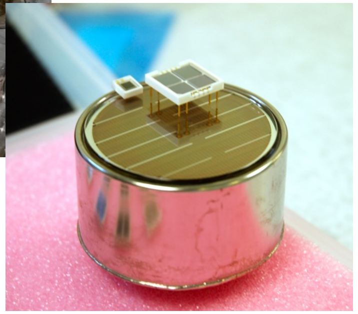
Mu2e: ECAL: undoped CsI + SiPM
1500 channels
- in vacuum, 1T mag field, TID 90 krad
  and fluence of 3×10^{12} n/cm^2





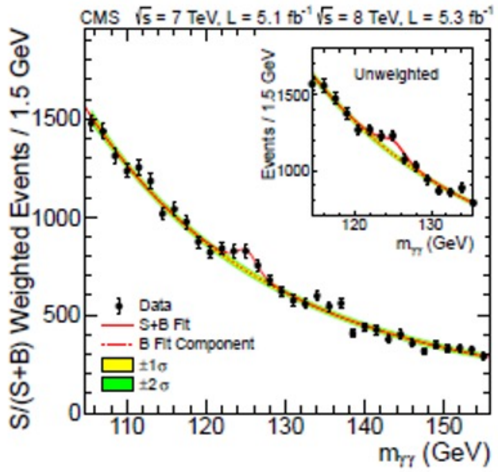
MEG II: Liquid Xe (165K) + PMT and SiPM
4700 channels
σ(E)/E ~1.1% with the SiPM, 2.4% with PMT



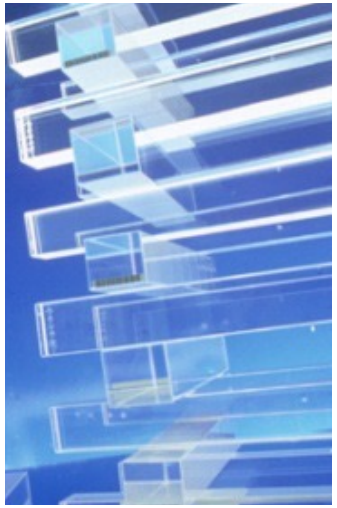


Upgrades of Atlas and CMS calorimeters

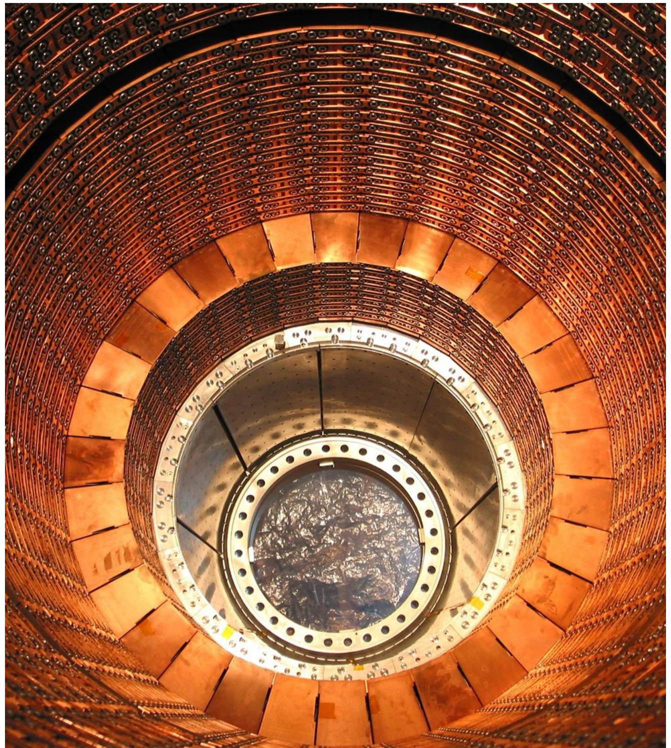
Use of calorimeters at the LHC:
- measure/identify photons with excellent energy resolution (H->γγ)
- measure/identify electrons
- measure hadrons/jets and missing energy



- In preparation for the HL-LHC both Atlas and CMS calorimeters will replace the read-out electronics
- **Streaming of the data** from front-end to off-detector electronics to improve trigger
- Addition of **precision timing (requires large and fast signal)**



CMS ECAL: $PbWO_4$ crystals+ APD (75000 channels)
HCAL: Brass+plastic scint.

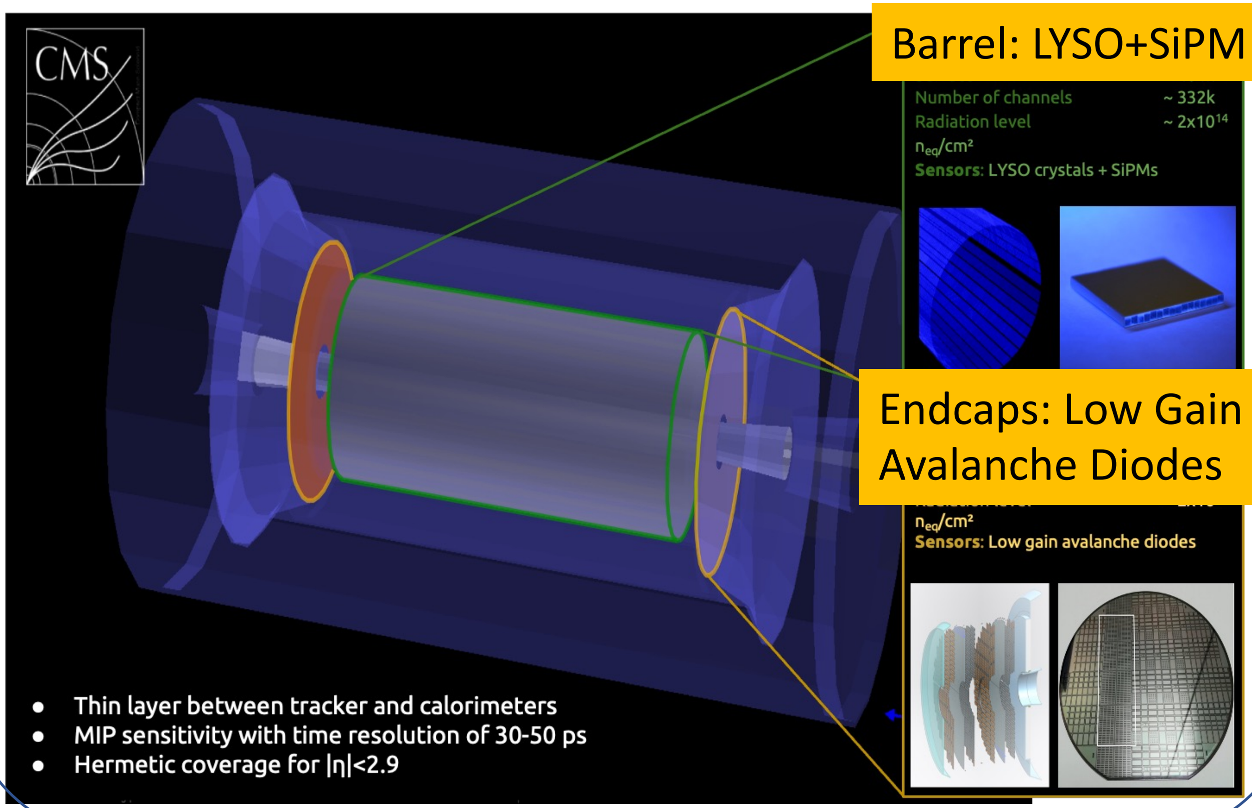


Atlas: e.m. LAr+lead (~200000 ch.)
Longitudinally segmented
Hadr.: Plastic scint.+steel

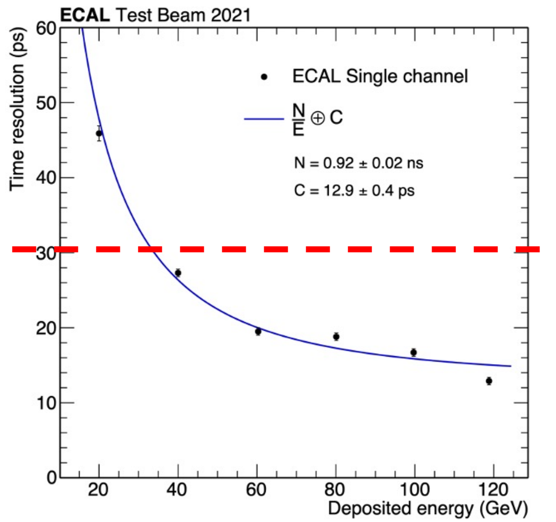
Precision timing at the HL-LHC

Precision timing usage
- for MIPs: to attribute a timing to each track (4D tracking) for vertex identification and pile-up subtraction
- for photons (E>50 GeV): triangulation and vertex identification in H->yy decay

Dedicated timing detector for MIPs

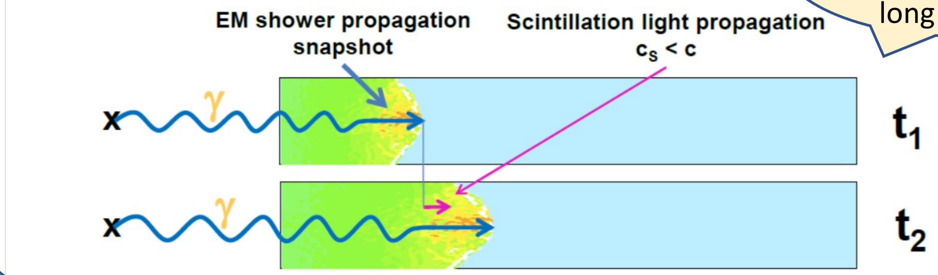


Precision timing with the CMS ECAL



CMS ECAL: $PbWO_4$ crystals+ APD (75000 channels)
with fast electronics and oversampling at 160MHz

The shower front is fast and sharp even for long crystals



High energy – future colliders

	Ecm(GeV)	Length (km)	L(10^34 cm-2s-1)	Lint(ab-1)	place	possible start of operation
ILC	250-1000	30	1-10	2-8	Japan	
CLIC	380-3000	11-50	1-8	1-5	CERN	
FCC-ee	90-365	100	230-1.5	75-0.8	CERN	2045-2060
CEPC	90-240	100	70-7	16-5.6	China	
FCC-hh	100000	100	5	20-30		2070-2090
Muon Collider	3000-10000	4.5-10	1.8-20	10		2045-2060

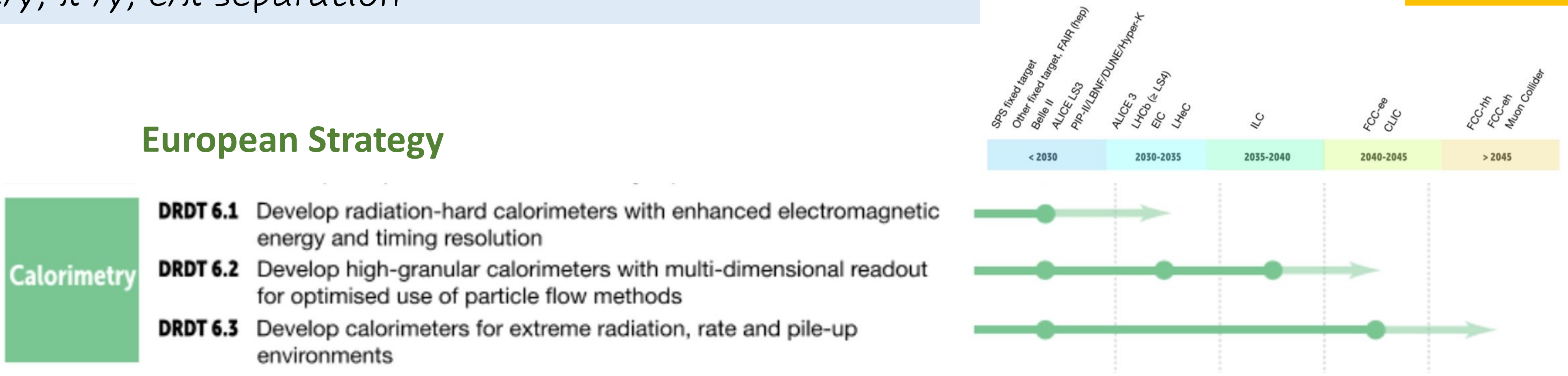
Requirements for calorimeters

- jets: σ(E)/E ~30%/sqrt(E) to separate Z and W hadronic decays
- photons: single photon channel requires photon energy precision
- B decays involving π^0 require granularity and resolution σ(E)/E ~5%/sqrt(E)
- long lived particles emerging in the calorimeters require timing
- e/γ, π^0/γ, e/π separation

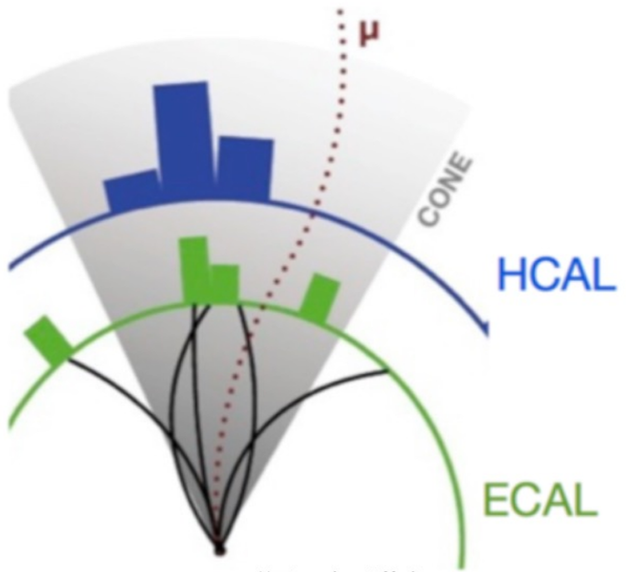
Particle flow calorimeters

Dual readout calorimeters

European Strategy



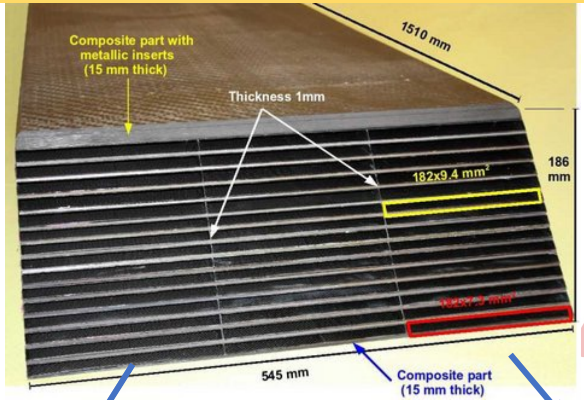
Particle flow calorimeters



"Typical" jet:
- ~62% charged particles (mainly hadrons)
- ~27% photons
- ~10% neutral hadrons
- ~1% neutrinos

Particle Flow principle
- Measure charged particle momenta with the tracker and subtract their clusters from the calorimeters
- Measure only neutral objects with the calorimeters

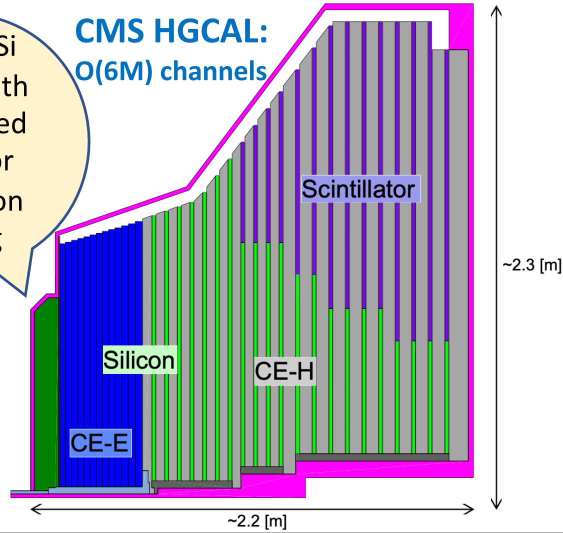
CALICE SiW ECAL (cell size 0.5x0.5cm2, 40 layers) O(100M) channels
Also proposed for CLD@FCC-ee, CEFC, EIC



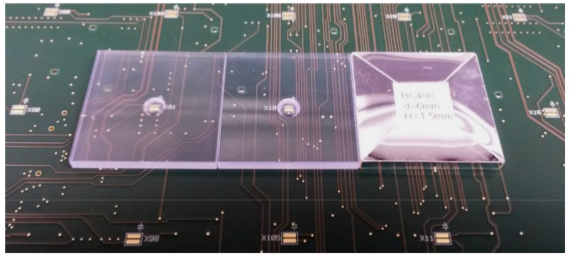
CALICE was designed for operation in power pulsed mode, cooling must be added

Add a Si layer with increased gain for precision timing

CMS HGCAL:
O(6M) channels



CALICE AHCAL – SiPM on tile + absorber



CALICE DHCAL – RPC with small pads + absorber

HL-LHC CMS endcap e.m. and h. calo
e.m. : absorber+Si sensors
hadr.: absorber+Si or plastic scintillator tiles+SiPM

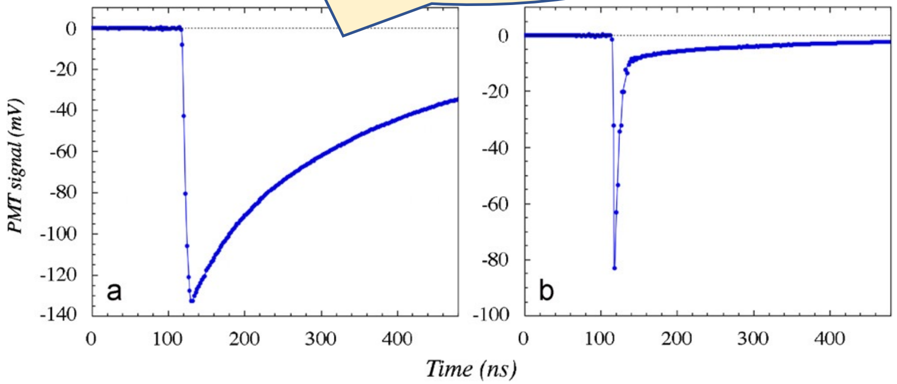
PF calorimeters must
- be very **granular** (large number of channels)
- small X_0 (=> **small gap**) such that objects do not spread and overlap.
- be associated with an **excellent tracker**
- require a **smart clustering software** (also for trigger)
- **still photons and neutral hadrons are measured by the calorimeters** so good energy resolution

Dual Readout calorimeters

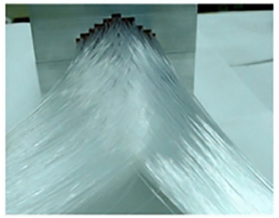
Dual readout principle
- Hadronic showers contain a hadron and e.m. component, which fluctuate very much from shower to shower
- measure hadronic and e.m. components separately in the same detector
- Cerenkov light is produced mostly by e.m. component, dE/dx signal mostly by soft hadrons
- possibly combine with an optimal e.m. calorimeter in front with dual readout as well
- and possibly a timing layer with small crystals

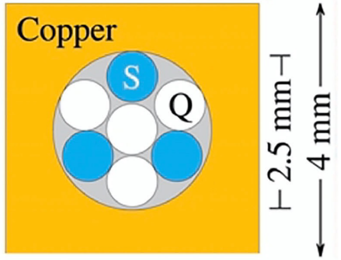
Dual readout and precision ECAL with scintillating crystals

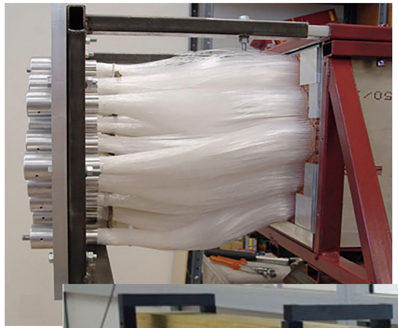
The e and h components can be measured in **scintillating crystals** exploiting:
- The time of arrival
- Wavelength filters



Dual readout calorimeter with absorber and scintillating+quartz fibers







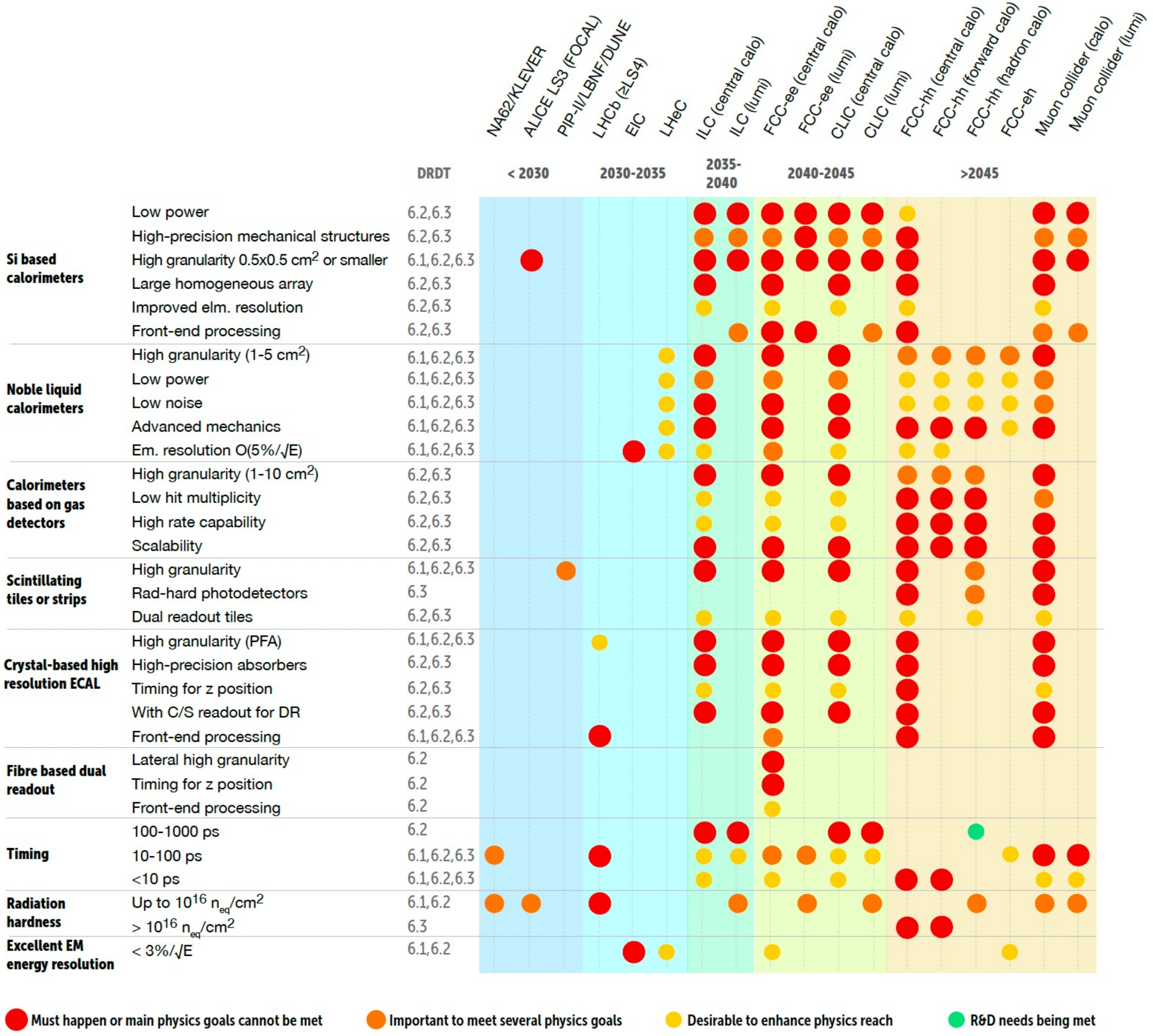
The fibers can be read out with SiPMs for increased granularity

The time of arrival can be used to measure the shower depth for electron/photon id.

Also proposed for IDEA@FCC-ee

Agenda for today

09:00	**Trends and future applications in calorimetry** **Speakers**: Francesca Cavallari (Istituto Nazionale di Fisica Nucleare) , Ivano Sarra (Istituto Nazionale di Fisica Nucleare) , Monica Sisti (Istituto Nazionale di Fisica Nucleare)	15m
09:15	**Rapidfire talks**	1h 45m
	Microbolometers **Speaker**: Marco Faverzani (Università & INFN Milano - Bicocca)	8m
	Macrobolometers **Speaker**: Irene Nutini (Istituto Nazionale di Fisica Nucleare)	8m
	New scintillators **Speaker**: Ioan Dafinei (Istituto Nazionale di Fisica Nucleare)	10m
	Discussion on bolometers and new scintillators	10m
	The Mu2e and MEG e.m. calorimeters **Speaker**: Ruben Gargiulo (Istituto Nazionale di Fisica Nucleare)	10m
	R&D for innovative calorimeters with optical readout **Speaker**: Ivano Sarra (Istituto Nazionale di Fisica Nucleare)	10m
	The calorimeter for the IDEA experiment **Speaker**: Marco Toliman Lucchini (INFN & University of Milano-Bicocca)	10m
	Design and optimization of a MPDG-based hadronic calorimeter for future colliders **Speaker**: Anna Stamerra (Istituto Nazionale di Fisica Nucleare)	5m
	Quantum-dot light emitters for chromatic calorimetry **Speaker**: Federica Maria Simone (Istituto Nazionale di Fisica Nucleare)	5m
	Compact calorimeter based on oriented crystals **Speaker**: Alessia Selmi (Università degli Studi dell'Insubria)	5m
	The Demonstrator of the instrumented decay tunnel for the ENUBET monitored neutrino beam **Speaker**: Fabio Pupilli (Istituto Nazionale di Fisica Nucleare)	5m
	Discussione sui calorimetri di media e alta energia	20m



NA62/KLEVER
ALICE LS3 (FOCAL)
PIP-II/LBNF/DUNE
LHCb (≥LS4)
EIC
LHeC
ILC (central calo)
ILC (lumi)
FCC-ee (central calo)
FCC-ee (lumi)
CLIC (central calo)
CLIC (lumi)
FCC-hh (central calo)
FCC-hh (forward calo)
FCC-hh (hadron calo)
FCC-eh
Muon collider (calo)
Muon collider (lumi)
DRDT
< 2030
2030-2035
2035-2040
2040-2045
>2045
Si based calorimeters
Low power 6.2,6.3
High-precision mechanical structures 6.2,6.3
High granularity 0.5x0.5 cm^2 or smaller 6.1,6.2,6.3
Large homogeneous array 6.2,6.3
Improved elm. resolution 6.2,6.3
Front-end processing 6.2,6.3
Noble liquid calorimeters
High granularity (1-5 cm^2) 6.1,6.2,6.3
Low power 6.1,6.2,6.3
Low noise 6.1,6.2,6.3
Advanced mechanics 6.1,6.2,6.3
Em. resolution O(5%/√E) 6.1,6.2,6.3
Calorimeters based on gas detectors
High granularity (1-10 cm^2) 6.2,6.3
Low hit multiplicity 6.2,6.3
High rate capability 6.2,6.3
Scalability 6.2,6.3
Scintillating tiles or strips
High granularity 6.1,6.2,6.3
Rad-hard photodetectors 6.3
Dual readout tiles 6.2,6.3
Crystal-based high resolution ECAL
High granularity (PFA) 6.1,6.2,6.3
High-precision absorbers 6.2,6.3
Timing for z position 6.2,6.3
With C/S readout for DR 6.2,6.3
Front-end processing 6.1,6.2,6.3
Fibre based dual readout
Lateral high granularity 6.2
Timing for z position 6.2
Front-end processing 6.2
Timing
100-1000 ps 6.2
10-100 ps 6.1,6.2,6.3
<10 ps 6.1,6.2,6.3
Radiation hardness
Up to 10^{16} n_{eq}/cm^2 6.1,6.2
> 10^{16} n_{eq}/cm^2 6.3
Excellent EM energy resolution
< 3%/√E 6.1,6.2
Must happen or main physics goals cannot be met
Important to meet several physics goals
Desirable to enhance physics reach
R&D needs being met

Outlook and Experience operating calorimeters for discussion

Crystal calorimeters

- achieve optimal e.m. energy resolution
- require hard work to monitor and calibrate
- Good calibration is needed also for trigger rate stability
- Data streaming off-detector allows more flexibility and future trigger upgrades
- Can achieve precision timing

Higly segmented / Particle Flow calorimeters

- Are optimal for particle flow techniques combined with good tracker
- Must measure the neutral hadrons and photons well
- Are intrinsically redundant
- Produce a lot of data
- Require a dedicated, sophisticated and fast software
- require some triggering logic on the front-end (today)
- Full data streaming is not possible today (perhaps in the future?)
- require detailed simulation effort to describe shower containment and especially for calibration
- Can be equipped with a precision timing layer

Dual readout technique

- Allows best resolution for hadrons through measurement of e/h fraction
- Can be combined with a crystal e.m. calorimeter in front through Scintillation/Cerenkov light separation
- Could be made granular
- Can be equipped with precision timing measurement