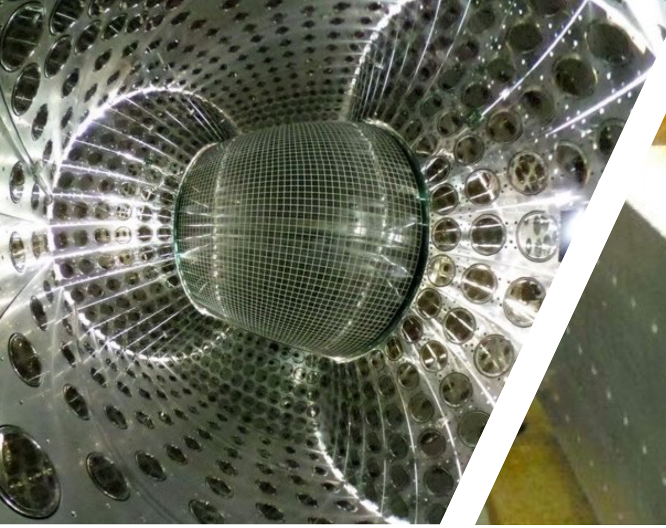
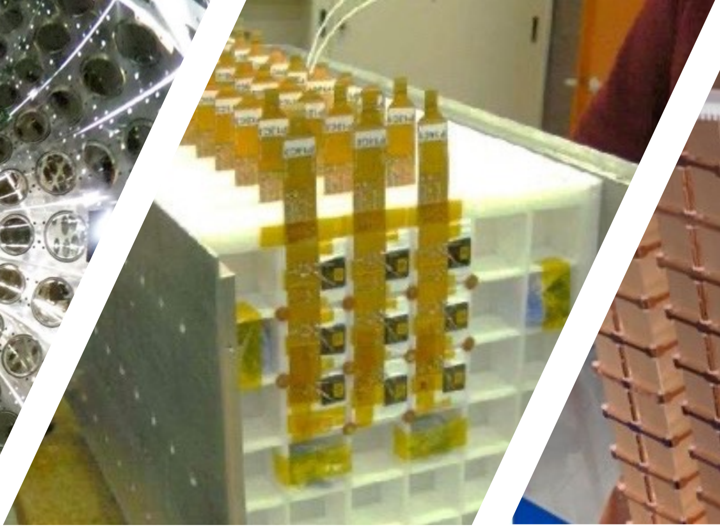
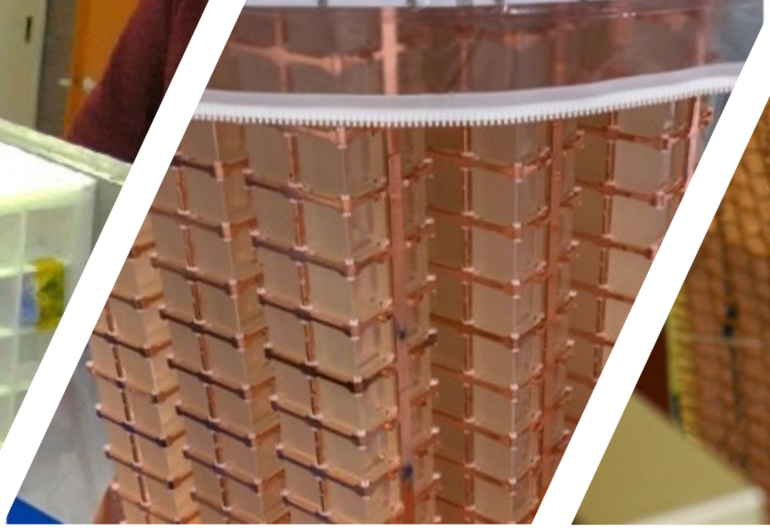
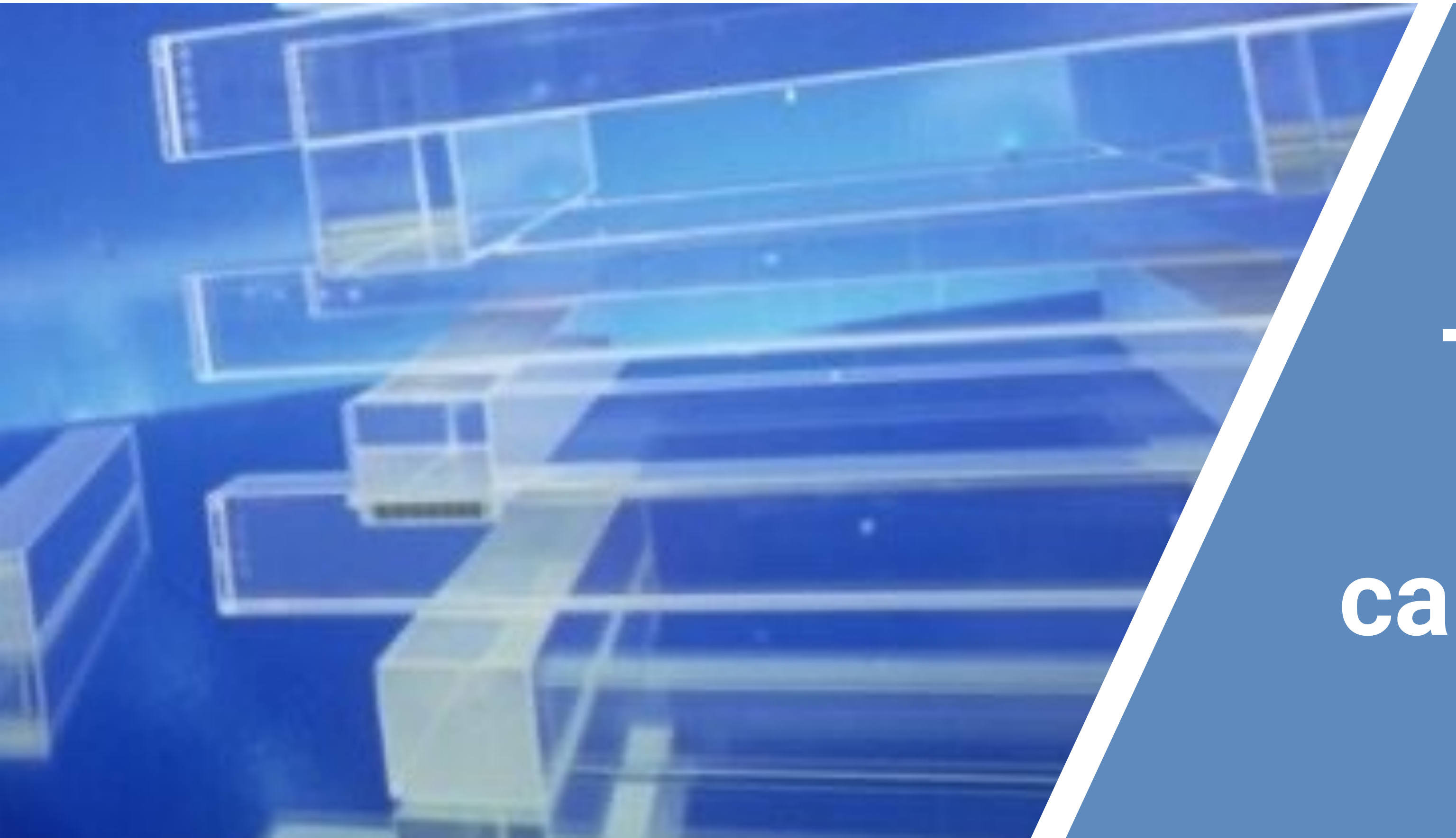






Francesca Cavallari (INFN Roma)

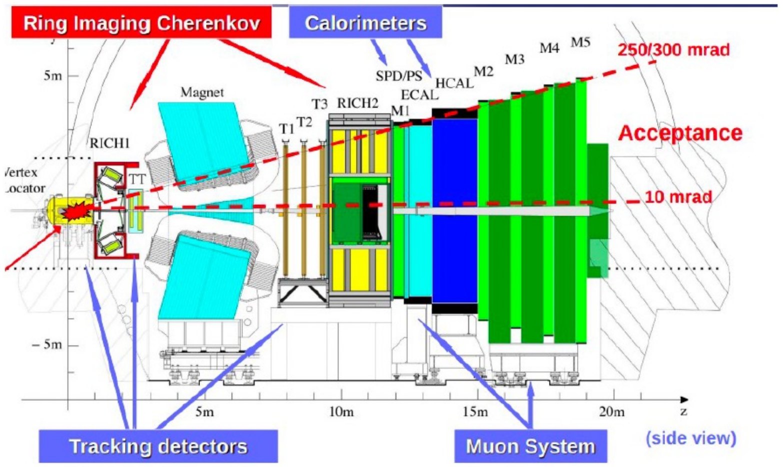
Trends and future applications in calorimetry towards DRD6

ECFA

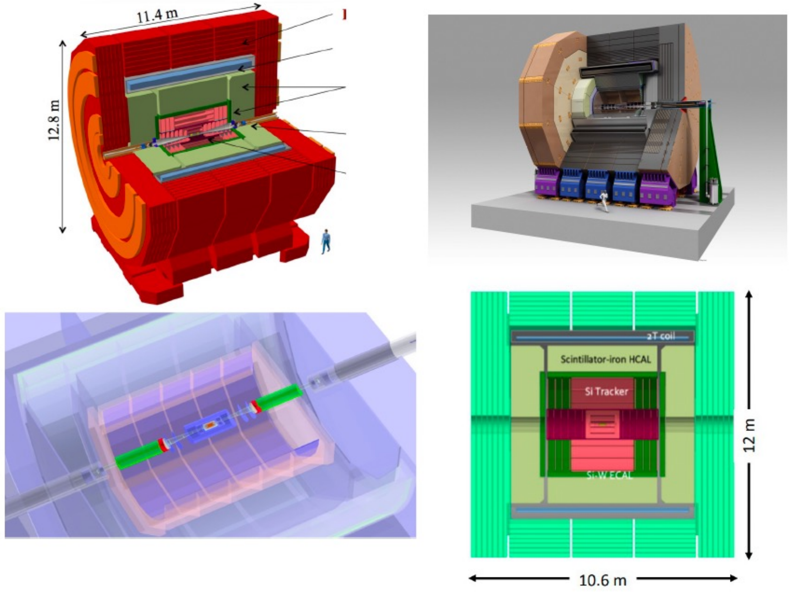
(Main) Target Projects of Detector R&D

European Strategy Update

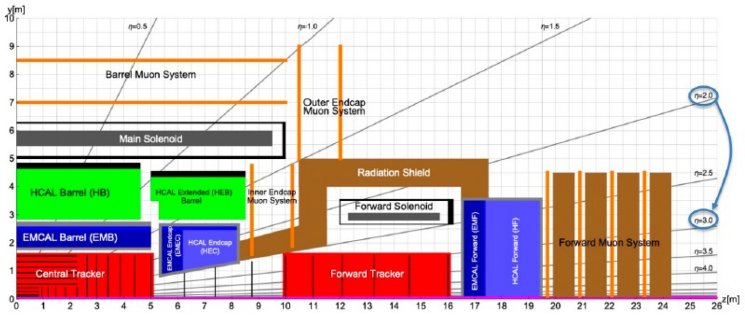
HL-LHC after LS4



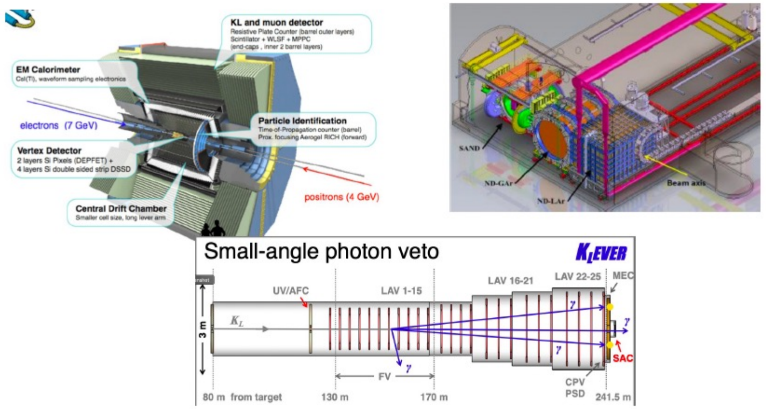
Higgs Factories



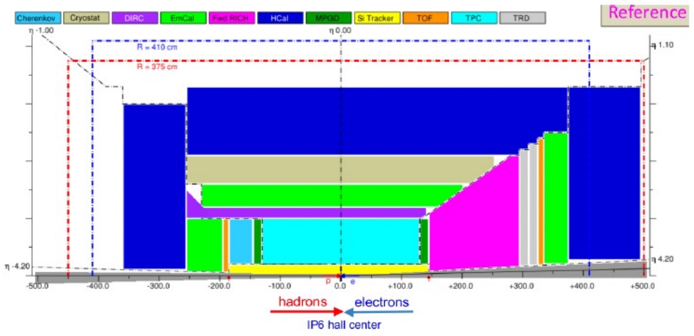
Future hadron colliders (including eh colliders)



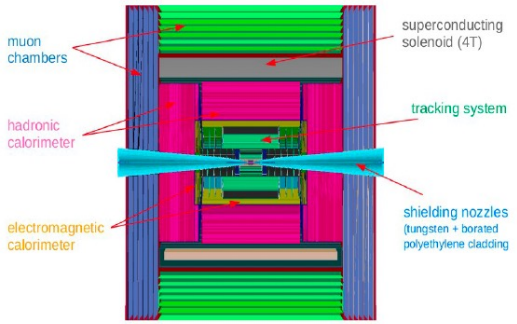
SuperKEKB, DUNE ND and Fixed Target



EiC



Muon Collider



Toward DRD – Suggested implementation timeline

Through 2023, mechanisms will need to be agreed with funding agencies in parallel to the process below for country specific DRD collaboration funding requests for Strategic R&D and for developing the associated MoUs.

Q4 2022	Outline structure and review mechanisms agreed by CERN Council. Detector R&D Roadmap Task Forces organise **community meetings** to establish the scope and scale of community wishing to participate in the corresponding new DRD activity. (Where the broad R&D topic area has one or more DRDTs already covered by existing CERN RDs or other international collaborations these need to be fully involved from the very beginning and may be best placed to help bring the community together around the proposed programmes.)
Q1 2023	**DRDC mandate formally defined** and agreed with CERN management; Core DRDC membership appointed; and EDP mandate plus membership updated to reflect additional roles.
Q1-Q2 2023	**Develop the new DRD proposals** based of the detector roadmap and community interest in participation, including light-weight organisational structures and resource-loaded work plan for R&D programme start in 2024 and ramp up to a steady state in 2026.
Q3 2023	**Review of proposals by DRDC** leading to recommendations for formal establishment of the DRD collaborations.
Q4 2023	DRD Collaborations receive formal **approval from CERN Research Board**.
Q1 2024	New structures operational for ongoing review of DRDs and R&D programmes underway.

Through 2024, collection of MoU signatures

Towards Implementation of DRD Calorimetry

- Entry point, "DRD Calo indico page": https://indico.cern.ch/category/12772/
  - Information on important events and access to relevant documents
  - Note also the Q&A Doc
  - 184 people from four regions registered so far
- Organisation of 1st Community Meeting On 12 January 2023
  - Get impression on plans for different key technologies
  - Get feedback/input by community on roadmap process and the implementation
  - Conveners and speakers of today's sessions are also entry points for interested groups to join the DRD calorimetry
- Proposal phase until 1st of July 2023
  - Input-proposals (until 1st of April 2023)
    - Proposal team will get in contact with stakeholders and ask for input-proposals
    - Contact persons will be assigned for the different topics
  - 2nd community meeting around middle of April
    - Presentation of input-proposals (w/o disclosing confidential information)
    - Presentation of a WP Structure of DRD Calorimetry
      - Existing R&D collaborations may serve as guidance
  - Input-proposals will be condensed into a DRD Calorimetry proposal until (about) 1st of June 2023
    - Further iteration with stakeholders, community and higher level bodies

Roberto Ferrari (INFN-Pavia, co-convener), Roman Pöschl (CNRS/IN2P3/IJCLab, co-convener)
Felix Sefkow (DESY, member of coordination group), Martin Aleksa (CERN), Etiennette Auffray (CERN),
Dave Barney (CERN), Tommaso Tabarelli de Fatis (University and INFN Milano-Bicocca),
Gabriella Gaudio (INFN-Pavia), Frank Simon (KIT/MPP)

Existing calorimetry collaborations and way forward

- European projects such as AIDAInnova and EURO Labs
- CERN EP R&D programs
- Existing collaborations (Atlas, CMS, NA62, DUNE, …)
- R&D collaboration and communities (Calice, CalVision, Crystal Clear …)
- Detector concept groups (ILD, SiD, IDEA, …)

- The various groups will concentrate on the Calorimetry R&D of their choice and develop/adapt them, if possible, to the requirements of the future detectors.
- The funding for the specific sub-tasks will come from the Funding Agencies, the DRD will not fund the specific R&D.
- Collaboration with other geographical areas is encouraged.
- The DRD will be “anchored” at CERN.

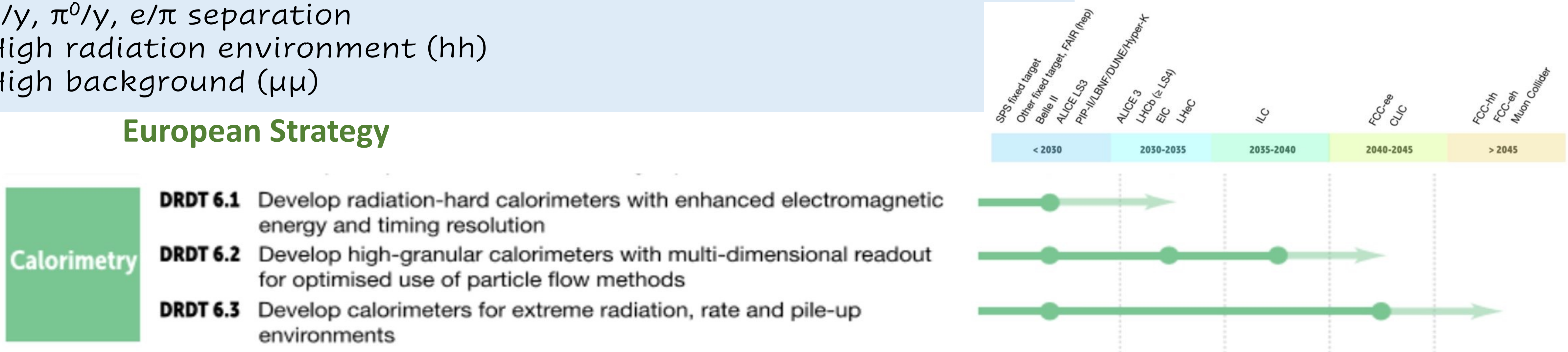
High energy – future colliders

	Ecm(GeV)	Length (km)	L(10^34 cm-2s-1)	Lint(ab-1)	place	possible start of operation
HL-LHC	14000	27	5	3-4	CERN	2028
ILC	250-1000	30	1-10	2-8	Japan	
CLIC	380-3000	11-50	1-8	1-5	CERN	
EIC					US	2030
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	CERN	2070-2090
Muon Collider	3000-10000	4.5-10	1.8-20	10		2045-2060

Requirements for calorimeters

- jets: $\sigma(E)/E$ ~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 $\sigma(E)/E$ ~5%/sqrt(E)
- long lived particles emerging in the calorimeters require timing
- e/γ, π^0/γ, e/π separation
- High radiation environment (hh)
- High background ($\mu\mu$)

European Strategy

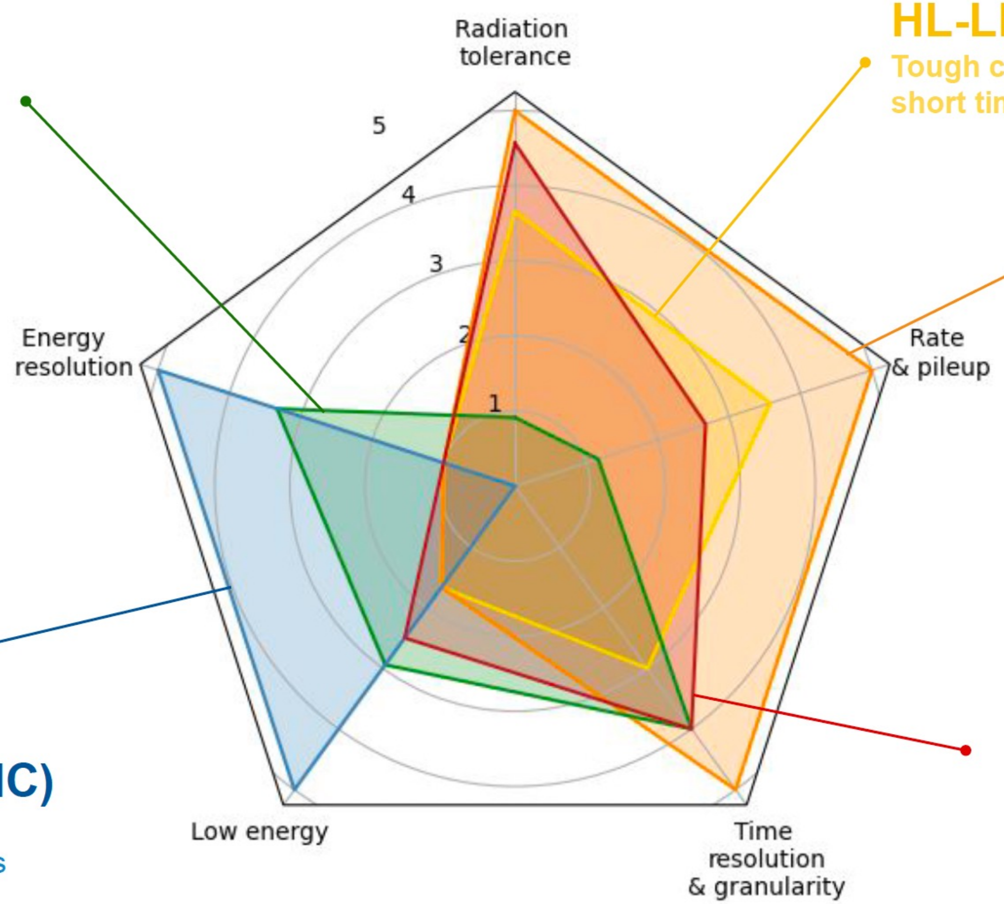


Qualitative representation of **requirements** for calorimetry **at future colliders**

e^+e^- colliders
Precision physics benefits from exploiting the best possible energy and time resolution

HL-LHC
Tough challenges on a short timescale

FCC-hh
Setting the toughest challenge on radiation tolerance and pileup conditions



Very high energy (longitudinal containment)

Strong interaction experiments (e.g. EIC)
Requiring the highest energy resolution for low energy photons

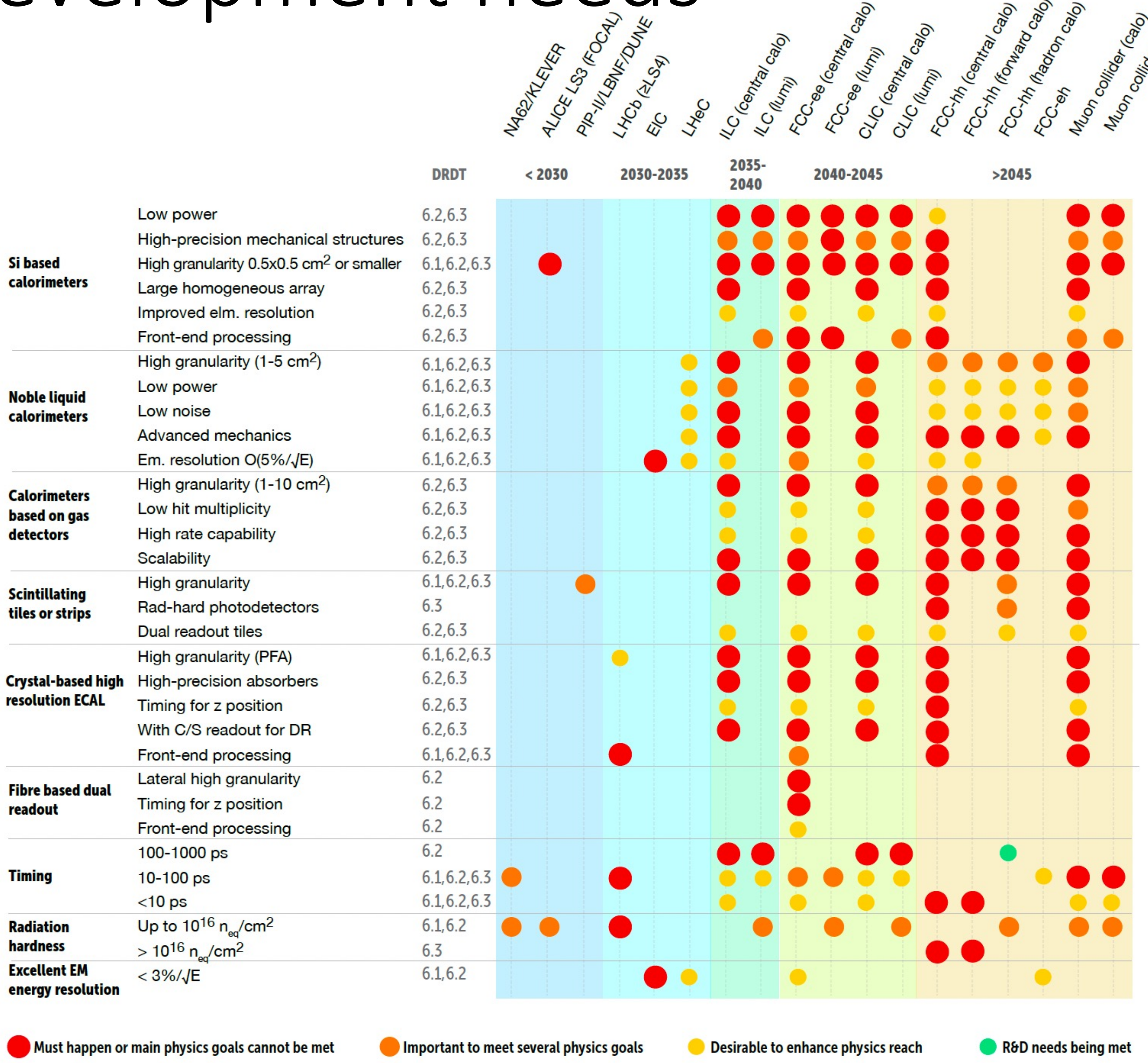
$\mu^+\mu^-$ colliders
High beam induced background and radiation levels, need for ambitious time resolution

Inspired from https://indico.cern.ch/event/994685/

From M. Lucchini

Key technological development needs

- Key technologies and requirements are identified in Roadmap
  - Si based Calorimeters
  - Noble Liquid Calorimeters
  - Calorimeters based on gas detectors
  - Scintillating tiles and strips
  - Crystal based high-resolution Ecals
  - Fibre based dual readout
- R&D should in particular enable
  - Precision timing
  - Radiation hardness
- R&D Tasks are grouped into
  - Must happen
  - Important
  - Desirable
  - Already met



Trends in Calorimetry

Calorimeter Upgrade for the HL-LHC,

Particle flow calorimeters,

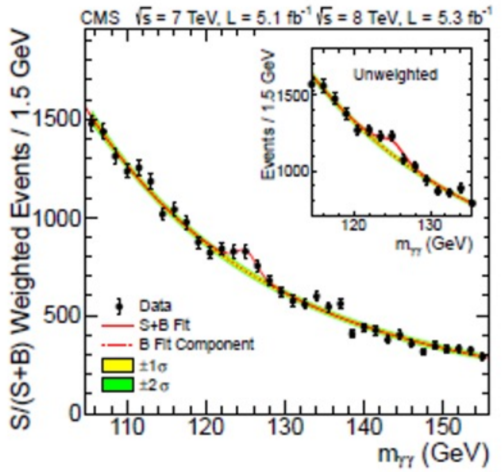
light based calorimeters and crystal developments,

noble liquids-based calorimeters

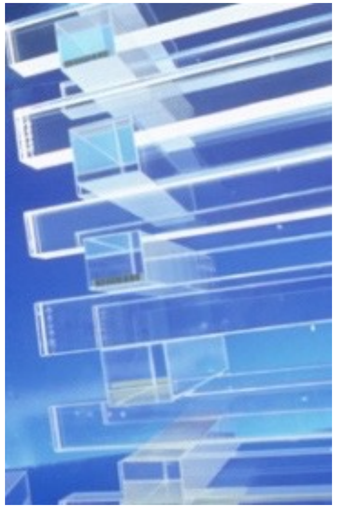
Disclaimer: personal choice of material ! many more new ideas

Upgrades of Atlas and CMS calorimeters for HL-LHC

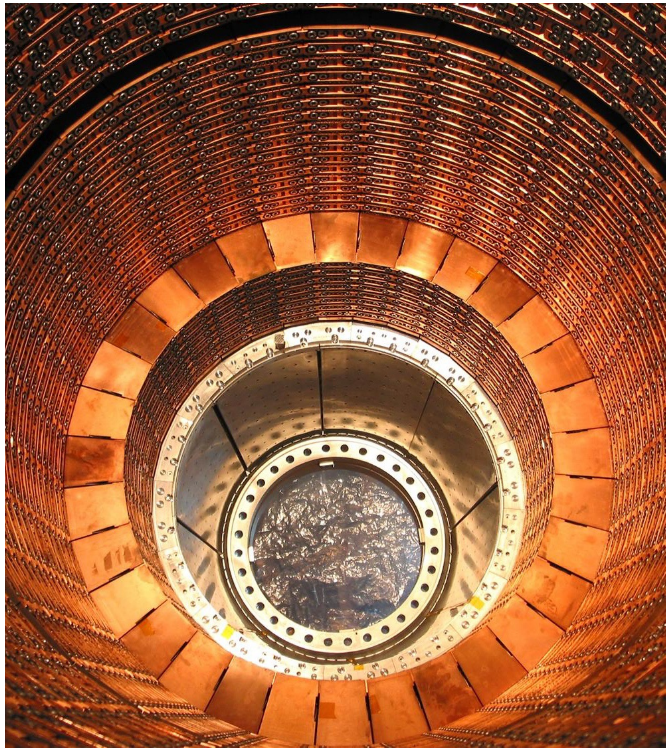
Use of calorimeters at the LHC:
- measure/identify photons with excellent energy resolution (H->yy)
- measure/identify electrons
- measure hadrons/jets and missing energy



- 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.

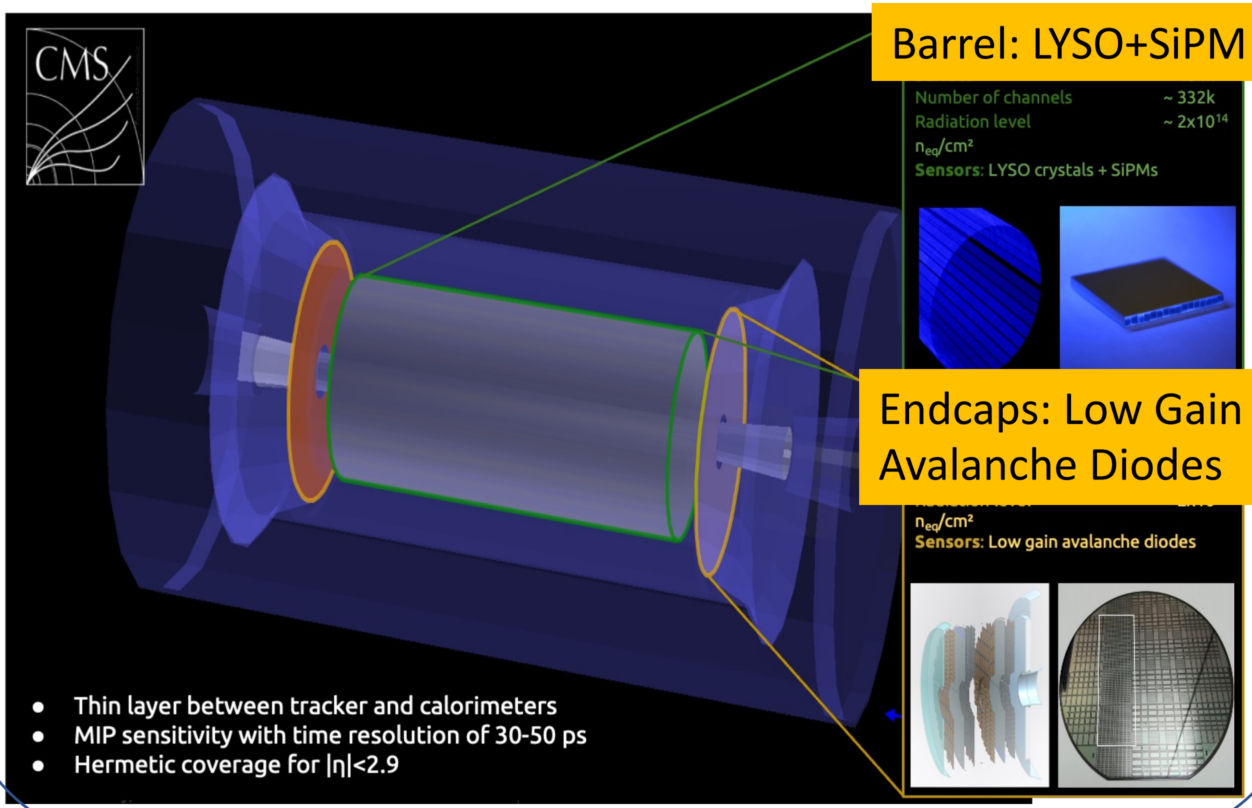


Atlas: e.m. LAr+lead (~200000 ch.)
Longitudinally segmented
Hadr.: Plastic scint.+steel

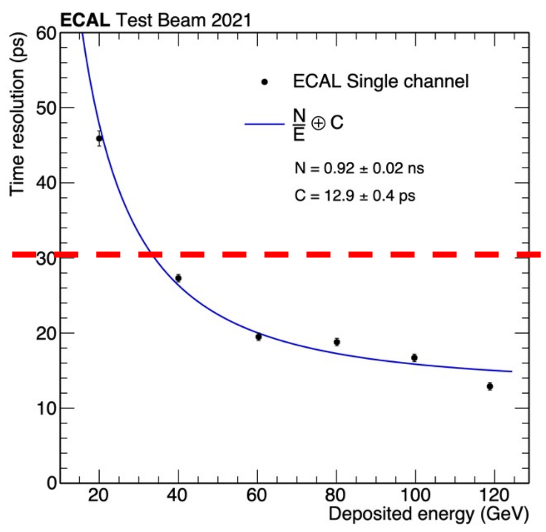
Precision timing at the HL-LHC

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

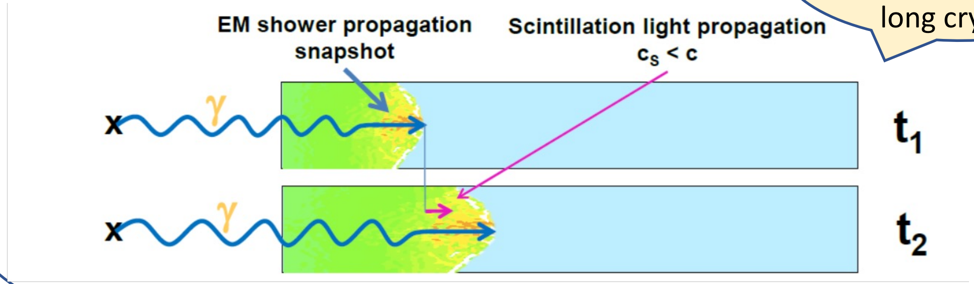


Precision timing with the CMS ECAL



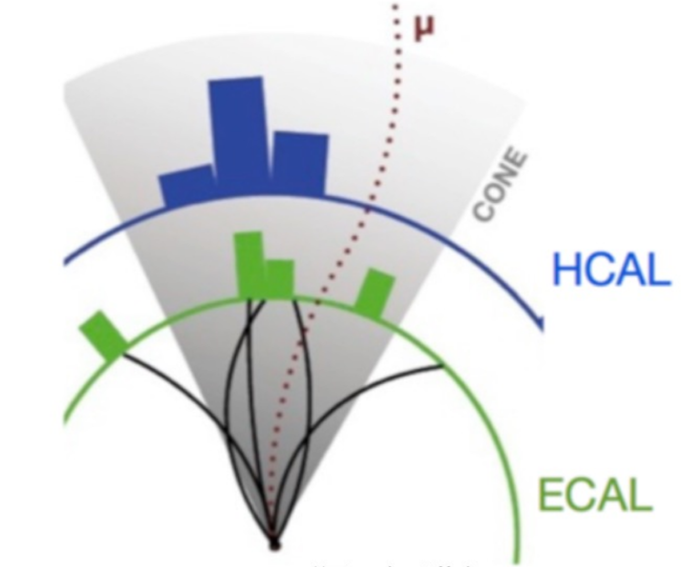
CMS ECAL: $PbWO_4$ crystals+ APD (75000 channels)
with fast electronics and oversampling at 160MHz

The shower front is fast and sharp even for long crystals



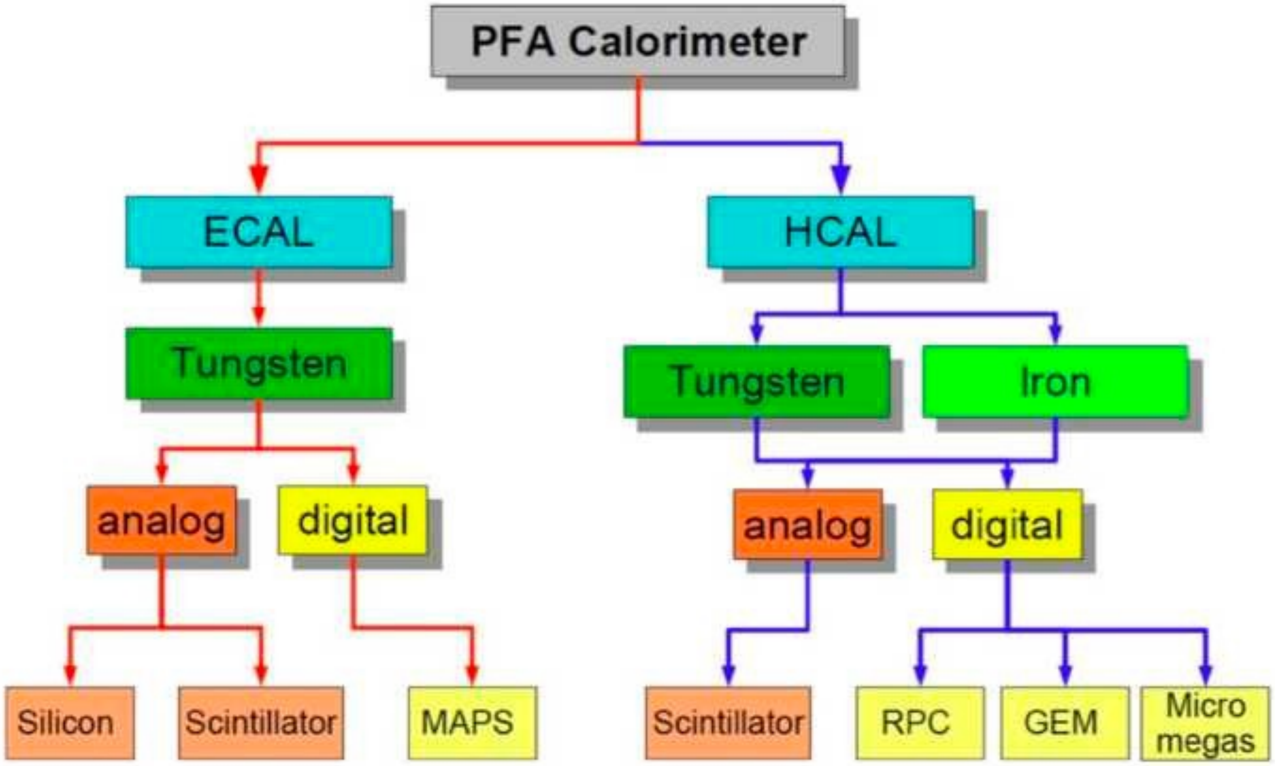
Particle flow calorimeters

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



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

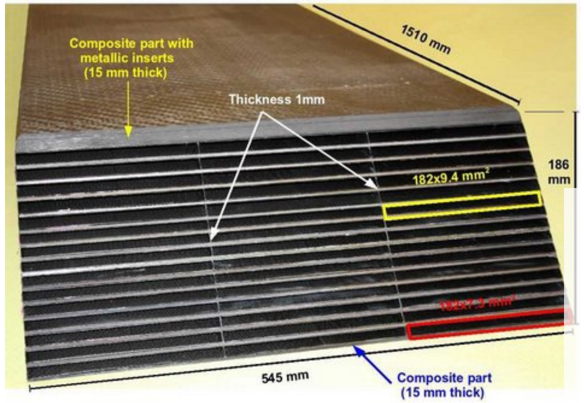
PF calorimeters must
- be very **granular** (large number of channels)
- small X_0 (=> **small gap**) such that objects do not spread and overlap.
- be associated with an **excellent tracker**
- require a **smart clustering software** (also for trigger)
- **still photons and neutral hadrons are measured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



Particle flow calorimeters

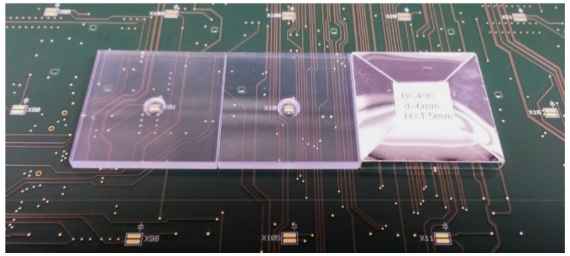
Detector prototypes for Linear Collider

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, and triggerless, cooling and trigger must be added

CALICE AHCAL – SiPM on tile + absorber

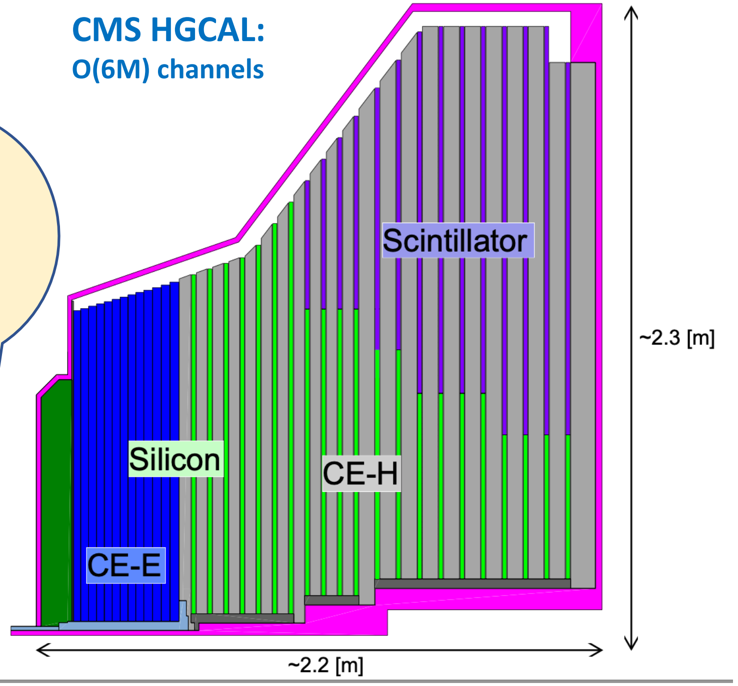


CALICE DHCAL – RPC with small pads + absorber

Upgrade of CMS Endcap calorimeters for HL-LHC

CMS HGCAL:
O(6M) channels

Add a Si layer with increased gain for precision timing

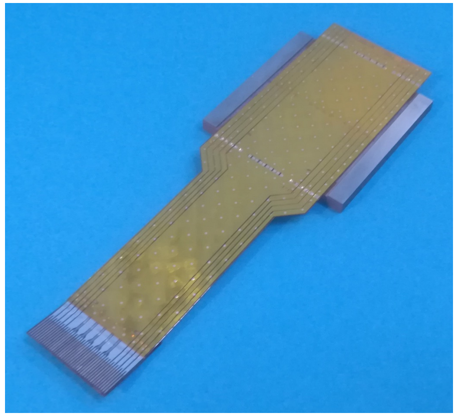


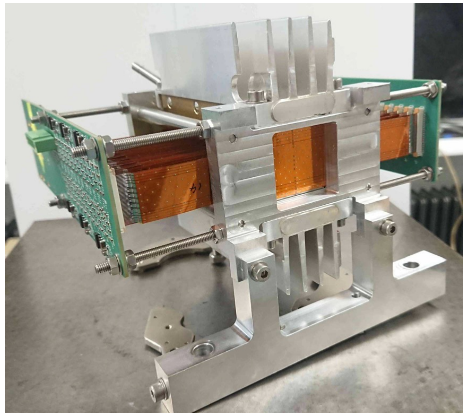
HL-LHC CMS endcap e.m. and hadronic calo
e.m. : absorber+Si sensors
hadr.: absorber+Si or plastic scintillator tiles+SiPM

Particle flow: Upgrade of Alice, FOCAL

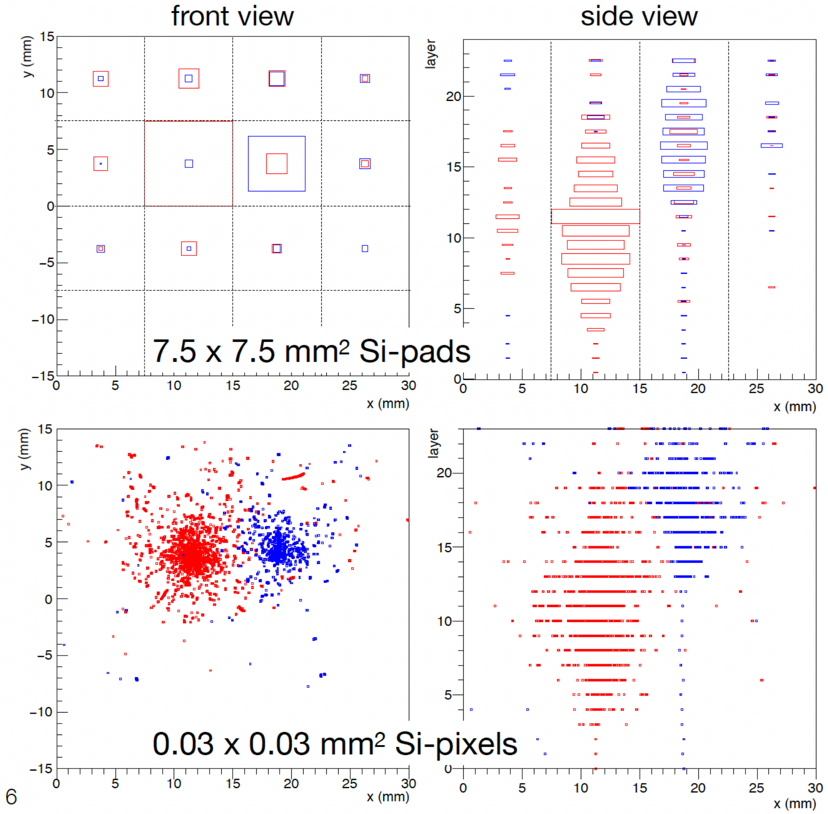
FOCAL calorimeter (forward e and h calorimeter), for photon-π^0 discrimination using for the electromagnetic part Si-W with 2 sections: large pads (1x1 cm^2) and MAPS (30x30 µm^2)

MAPS= Monolithic Active Pixel Sensors





sigma(E)/E~24%/sqrt(E)+2.5%



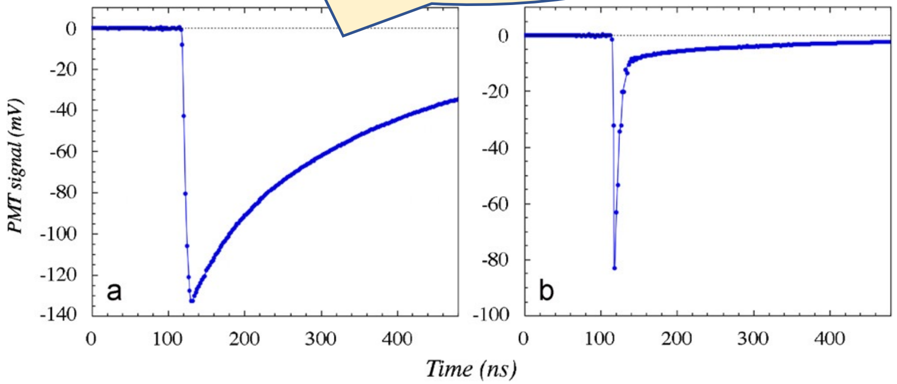
Simultaneous measurement of an electron of 40 GeV (red) and a pion of 20 GeV (blue)

Dual Readout calorimeters

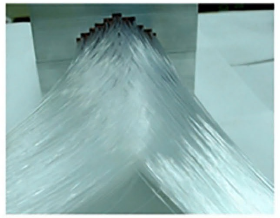
Dual readout principle
- Hadronic showers contain a hadron and e.m. component, which fluctuate very much from shower to shower
- measure hadronic and e.m. components separately in the same detector
- Cerenkov light is produced mostly by e.m. component, dE/dx signal mostly by soft hadrons
- possibly combine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

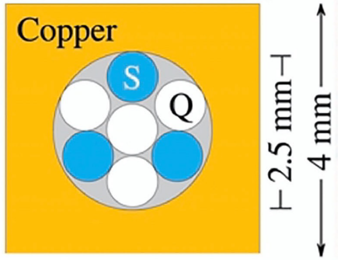
Dual readout and precision ECAL with scintillating crystals

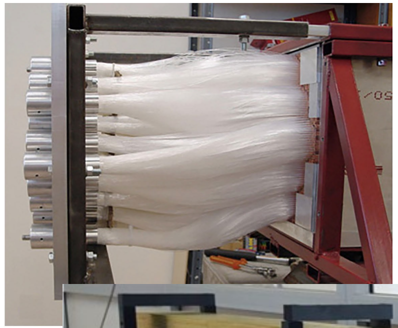
The e and h components can be measured in **scintillating crystals** exploiting:
- The time of arrival
- Wavelength filters



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.

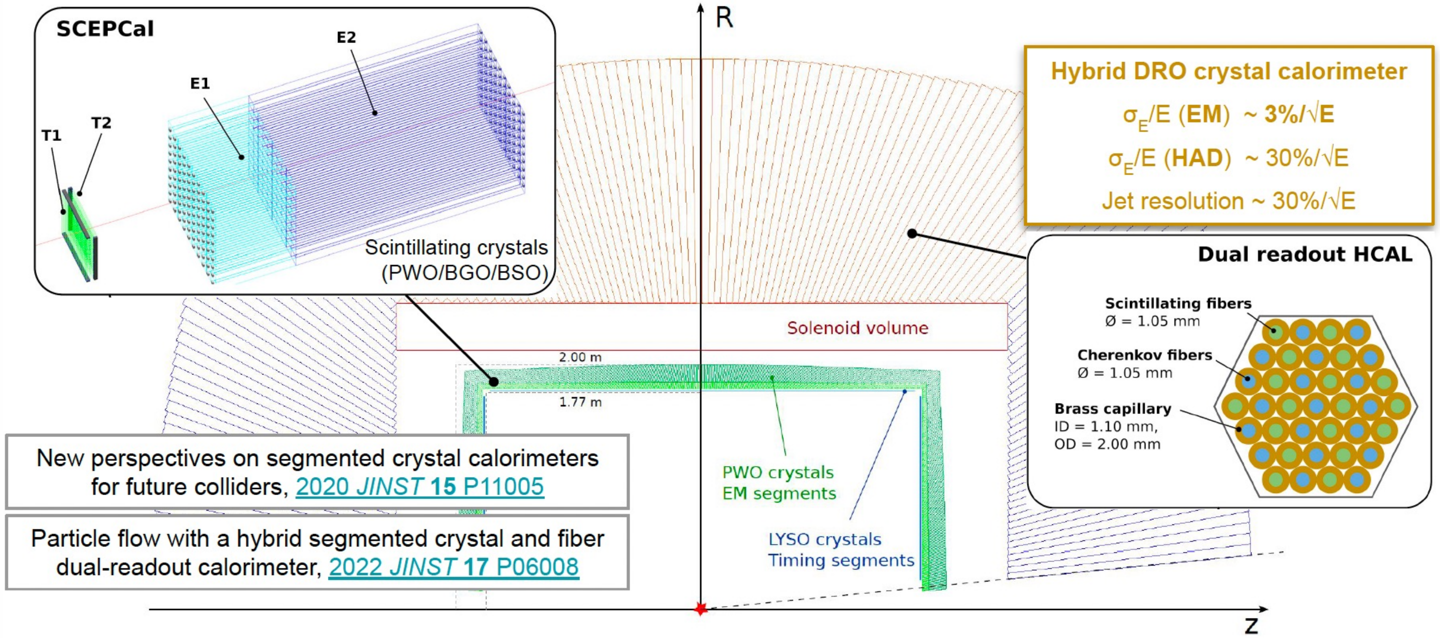
Also proposed for IDEA@FCC-ee

Dual Readout + Crystal e.m. calorimeter

Segmented Crystal EM Precision Calorimeter

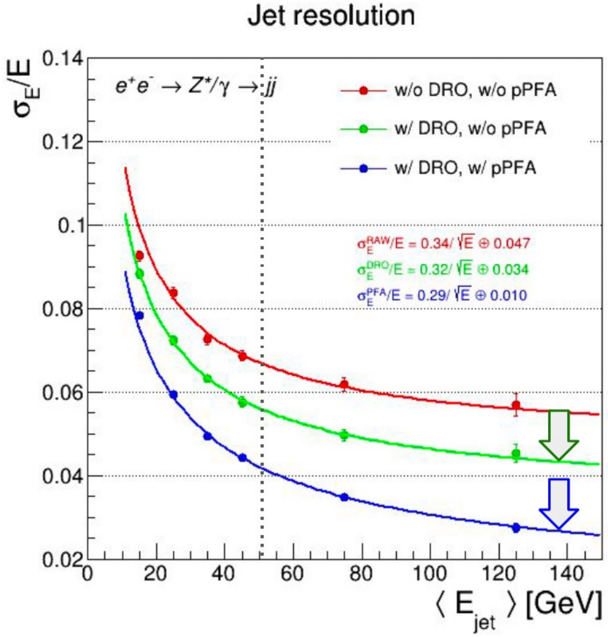
- **Includes timing and dual-readout** capabilities for optimal integration with a dual-readout fiber calorimeter à la IDEA and PFA algorithms (see presentation by R.Santoro)
- **Ongoing efforts** within the **US Calvision, IDEA** and CERN **Crystal Clear** collaborations
  - Proof-of-concept with lab measurements and prototypes (PWO, BGO, BSO, … with SiPMs)
  - Ongoing simulation effort in DD4HEP and FCC software + DR-PFA developments

Target application: **e^+e^- colliders**



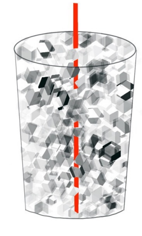
New perspectives on segmented crystal calorimeters for future colliders, 2020 *JINST* **15** P11005

Particle flow with a hybrid segmented crystal and fiber dual-readout calorimeter, 2022 *JINST* **17** P06008

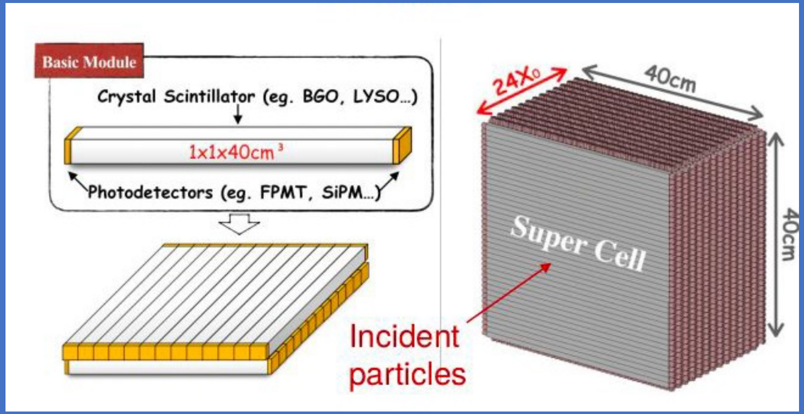


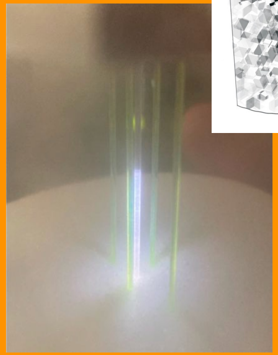
Other Crystal developments

Many new designs and solutions, here are a few personally selected ideas



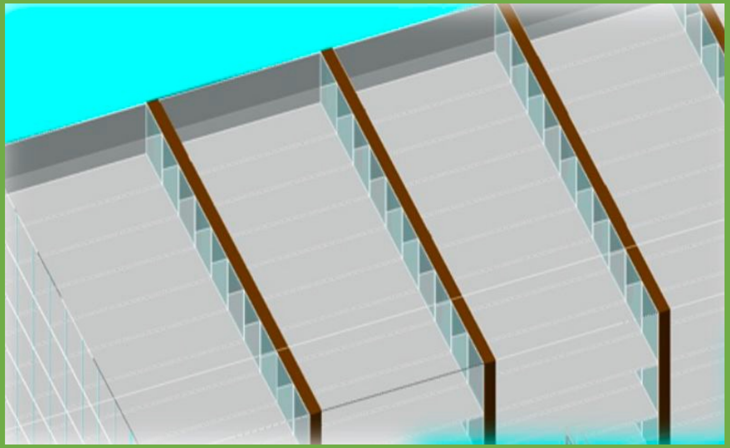
For CEPC

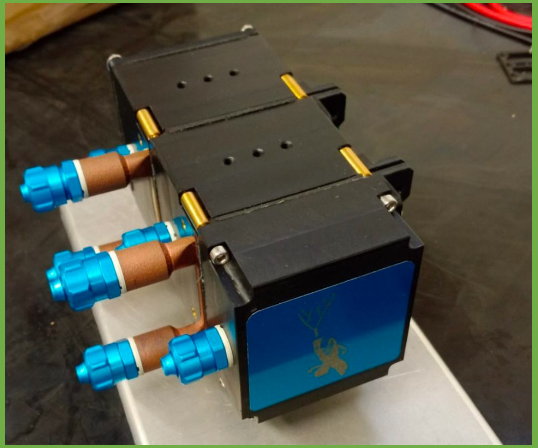




GRAiNITA:ZnWO4 grains+propanol+WLSF

CRILIN
PbF_2 / PWO-UF
UV-extended SiPM readout
Tiny and segmented crystals
Requirement of rad-hardness and precision timing for beam induced background subtraction





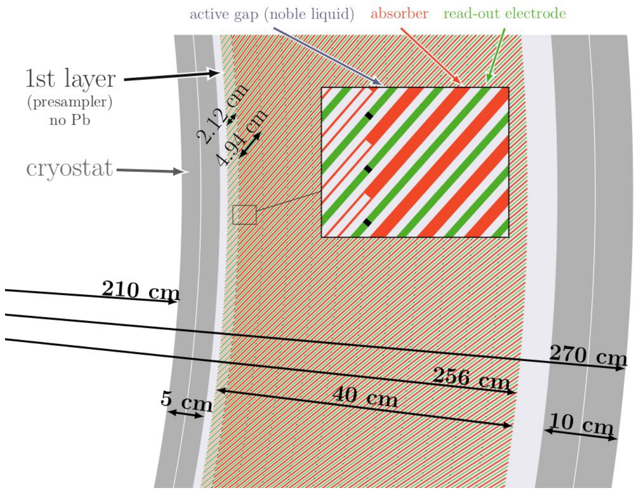
CRILIN (Frascati)
For the muon collider

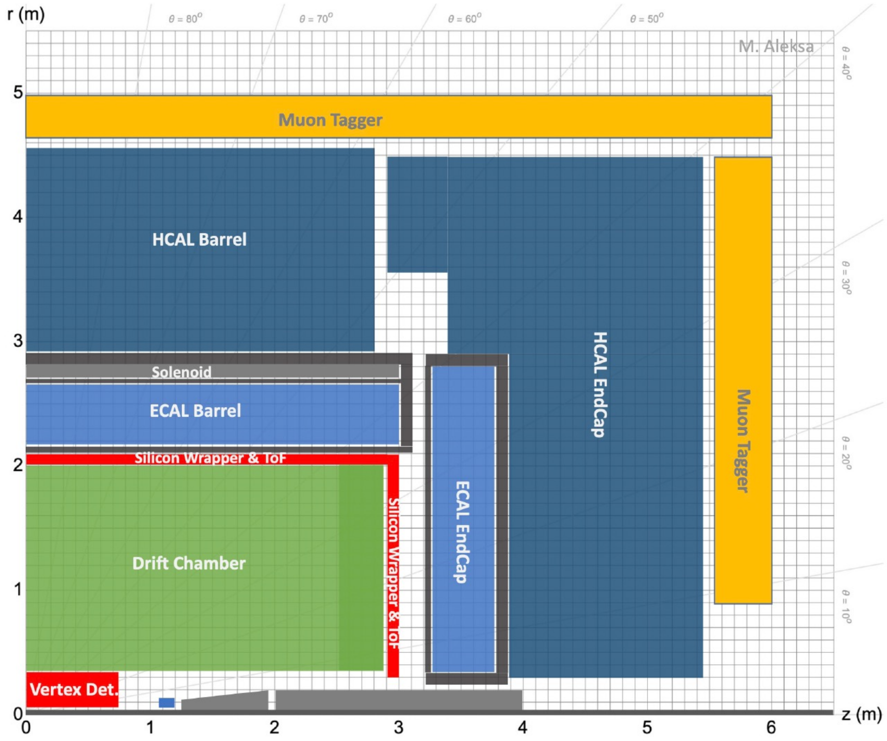
Noble liquids

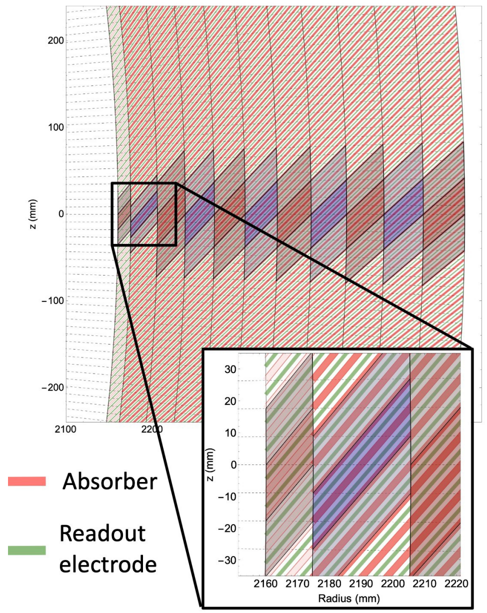
Building on the Atlas LAr calorimeter know-how,

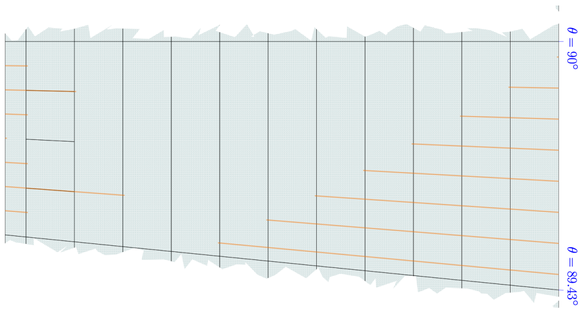
Adding desired high granularity feature and light-weight cryostat targeting FCC-ee

Could also resist high radiation and rates of FCC-hh







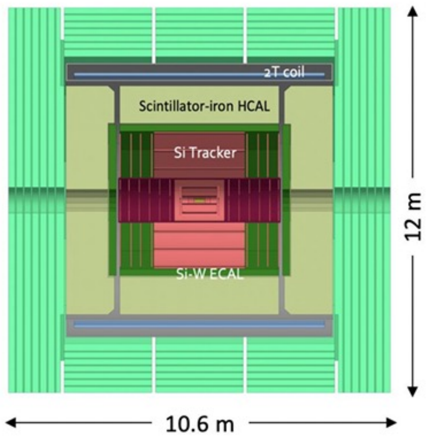


Addition of longitudinal granularity using multi-layer PCB, first test shows limited cross-talk

Also proposed for FCC-ee and FCC-hh

A design for FCC-ee central calorimeter system

CLD

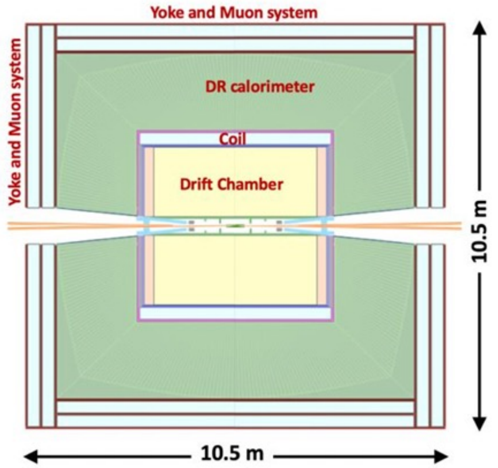


- Full Silicon vertex detector + tracker;
- Very high granularity, CALICE-like calorimetry;
- Muon system
- Large coil outside calorimeter system;

- Possible optimization for
  - Improved momentum and energy resolutions
  - PID capabilities

CDR

IDEA

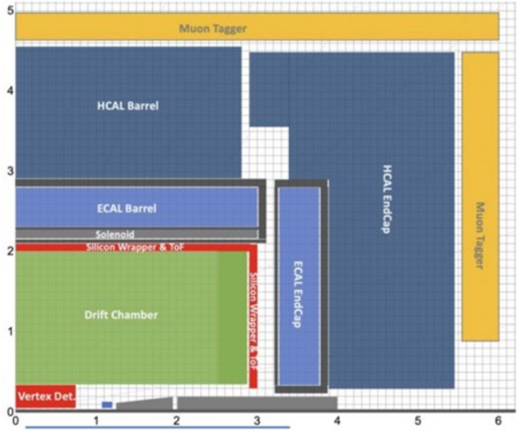


- Si vertex detector;
- Ultra light drift chamber w. powerfull PID;
- Monolitic dual readout calorimeter;
- Muon system;
- Compact, light coil inside calorimeter;

- Possibly augmented by crystal ECAL in front of coil;

Noble Liquid ECAL based

new



- High granularity Noble Liquid ECAL as core;
  - PB+LAr (or denser W+LCr)
- Drift chamber (or Si) tracking;
- CALICE-like HCAL;
- Muon system;
- Coil inside same cryostat as LAr, possibly outside ECAL.

Important points raised at the meeting

The DRD should provide some common tools, some are existing like:

- DD4HEP (detector geometry framework)
- Key4HEP (simulation)
- EUDAQ (common DAQ for testbeams)

Other points that were raised in the talks but not discussed:

- Common testbeam requests
- Common testbeam setup (moving table, lateral and back shower containment detector, hodoscope, timing detector, cold boxes, …)
- Irradiation facilities
- Integration, engeneering support
- Interface to other task forces (electronics, trigger, photon detectors, gas detectors)
- Knowledge transfer and cross-fertilization of fields

Outlook

- Many technological solutions
- Some challenging requirements
- Competence in our institute on calorimeters, crystals, photon sensors, Dual Readout calorimetry, electronics and trigger, simulation, AI & software
- Strong interest in particle physics at colliders
- We must discuss on how to best exploit our knowledge for the future calorimeters and sign-up for the DRDs

Backup

Project	~Earliest Start of data taking	Current Calorimeter options					
		Solid state	Scintilling tiles/strips	Crystals	Fibre based r/o (including DR)	Gaseous	Liquid Noble Gas
HL-LHC (>LS4)	2030			✔	✔		
SuperKEKb (>2030)	2030			✔			
ILC	2035	✔	✔			✔	
CLIC	2045	✔	✔				
CEPC	2035	✔	✔	✔	✔	✔	✔
FCC-ee	2045	✔	✔	✔	✔	✔	✔
EiC	2030		✔	✔	✔		
FCC-hh (eh)	>2050	✔	✔				✔
Muon Collider	> 2050	✔	✔	✔	✔	✔	
Fixed target	“continous”		✔	✔	✔		✔
Neutrino Exp.	2030		✔				(✔)

for IFD 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

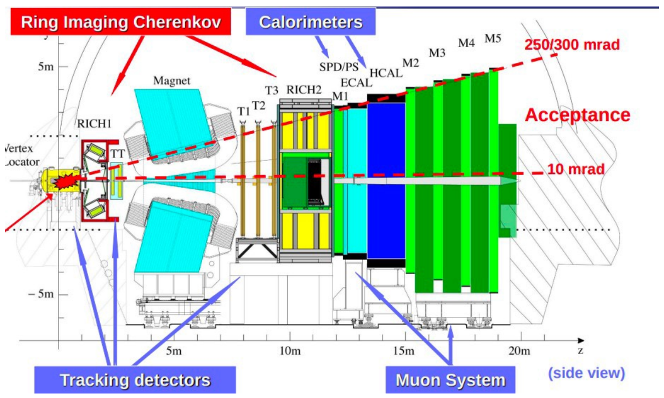
- Are optimal for particle flow techniques combined with good tracker
- Must measure the neutral hadrons and photons well
- Are intrinsically redundant
- Produce a lot of data
- Require a dedicated, sophisticated and fast software
- require some triggering logic on the front-end (today)
- Full data streaming 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

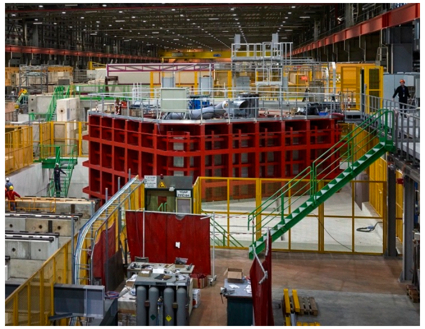
- Allows best resolution for hadrons through measurement of e/h fraction
- Can be combined with a crystal e.m. calorimeter in front through Scintillation/Cerenkov light separation
- Could be made granular
- Can be equipped with precision timing measurement

Future Experimental Facilities

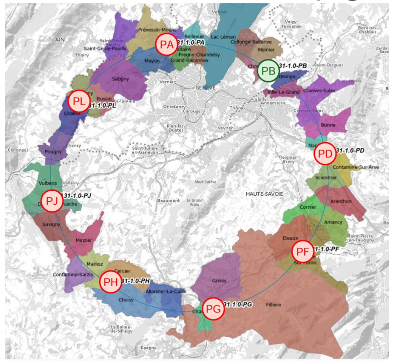
Detector upgrades for the HL-LHC



R&D for long baseline neutrino detectors

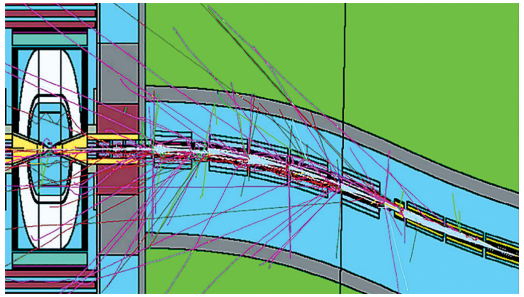


e+e- colliders as H-EW-top facilities (circular and linear)

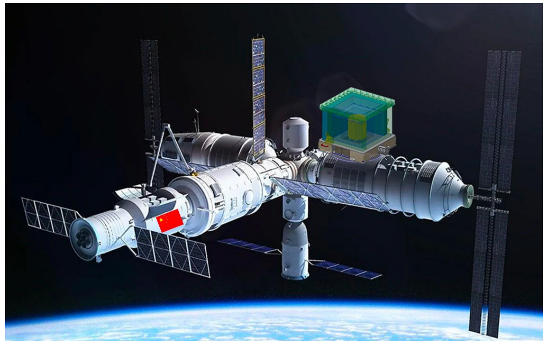


hh colliders at 100 TeV and $\int L=30\ ab^{-1}$ and PU~1000

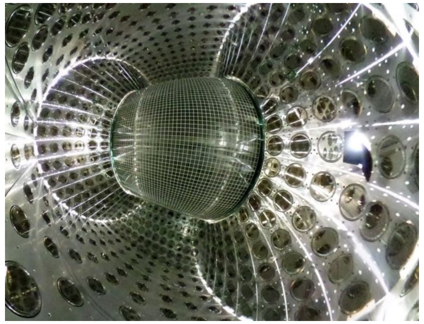
μμ colliders at 10 TeV and $L=10^{35}cm^{-2}s^{-1}$



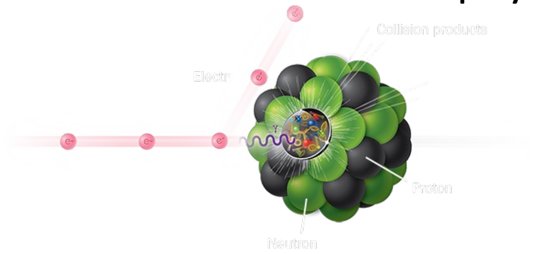
non-accelerator-based experiments, DM, interface with astro-particle physics

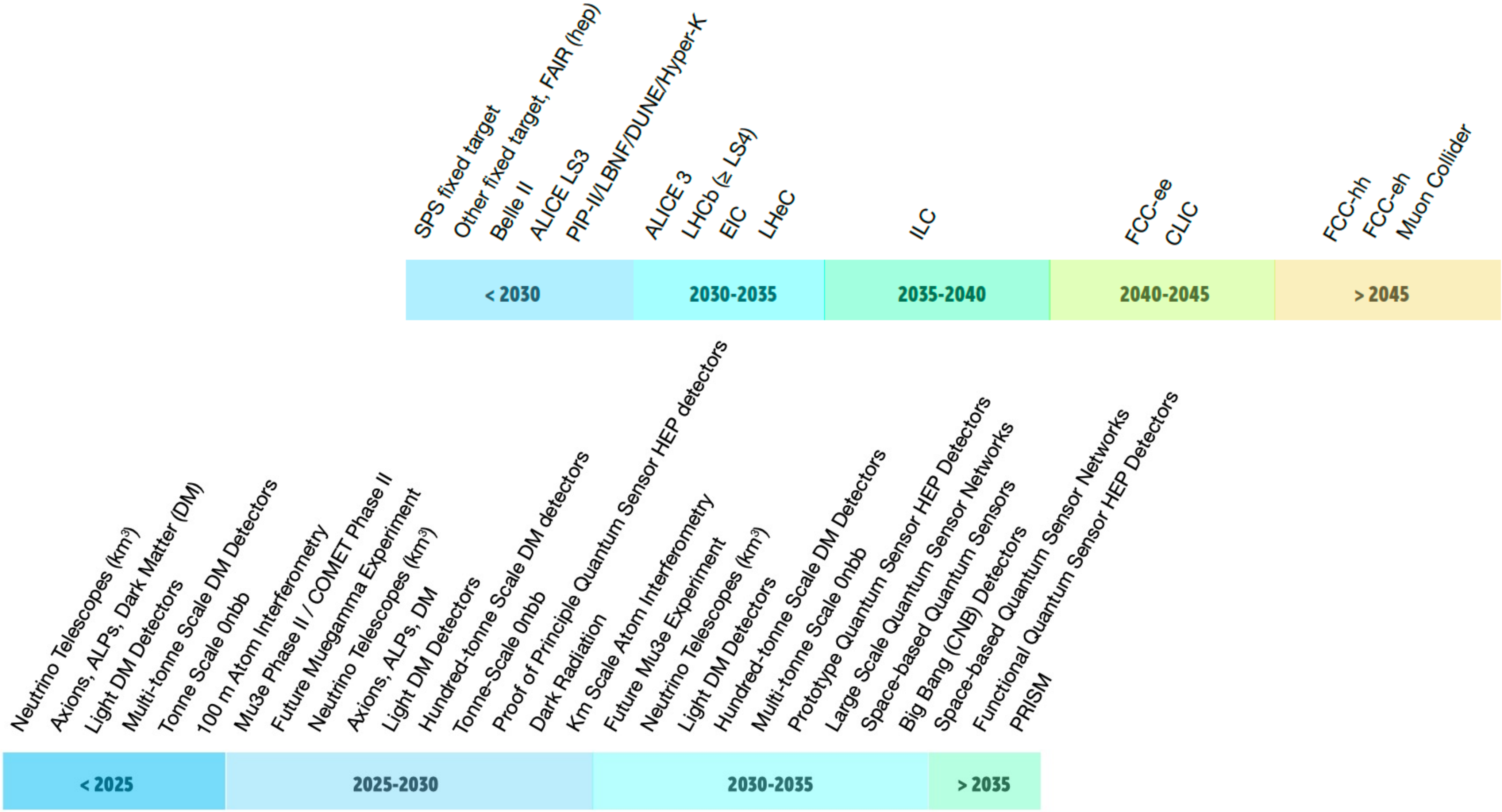


Detector R&D for rare processes, DM, and high precision at storage rings and fixed targets



Studies of partonic structure of the protons and nuclei and interface with nuclear physics, EIC



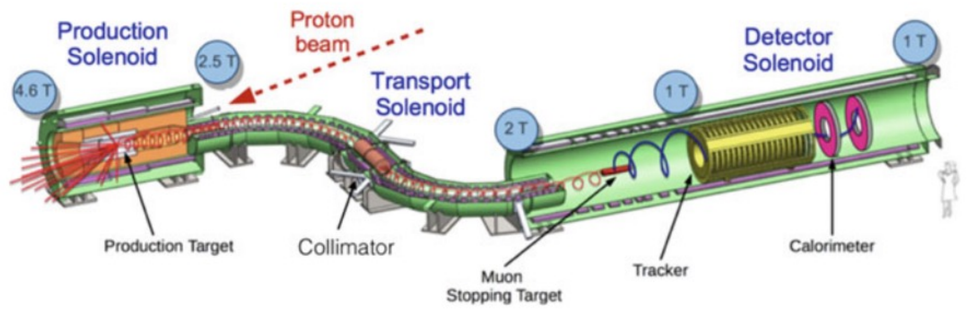


“Technical” Start Date of Facility
(This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)

Middle energy – Intensity Frontier

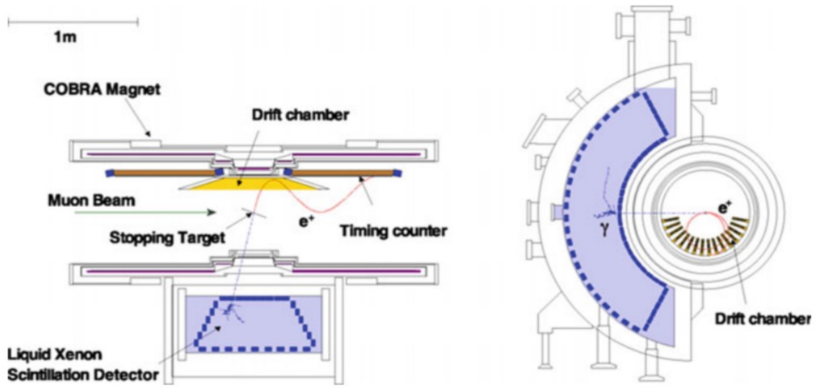
Charged Lepton Flavor Violation experiments
- cLFV processes are thought to be powerful tools to investigate the physics beyond the Standard Model (SM) as all of them are extremely suppressed in the framework of SM
- There are intensive efforts ongoing to find signals of cLFV processes at high-power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

Mu2e (US) / COMET (Japan)



- μ stopped on Al target @ 10 GHz then μN → *e*N
- σ(E)/E of O(< 10 %) for 105 MeV electrons
- Detectors in vacuum ~ 10^{-4} Torr
- Detectors in ~ 1 Tesla magnetic field

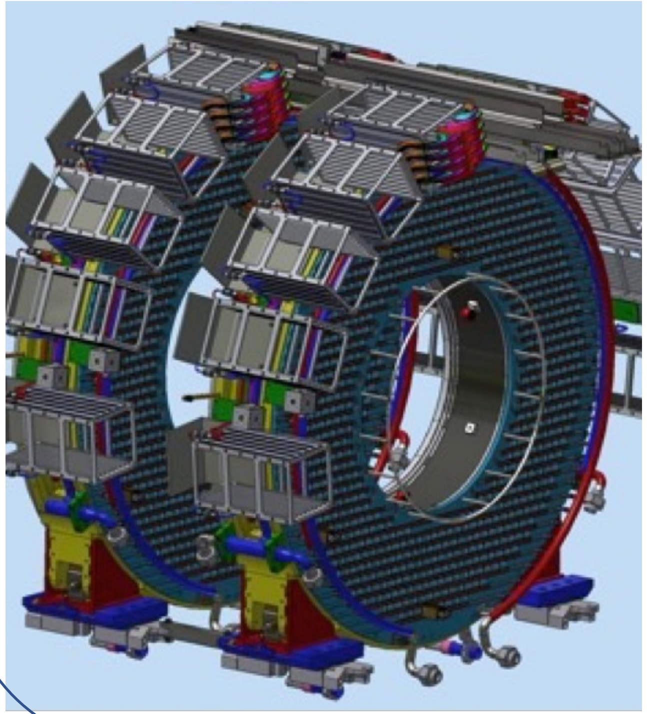
MEG/MEG II (PSI, Switzerland)

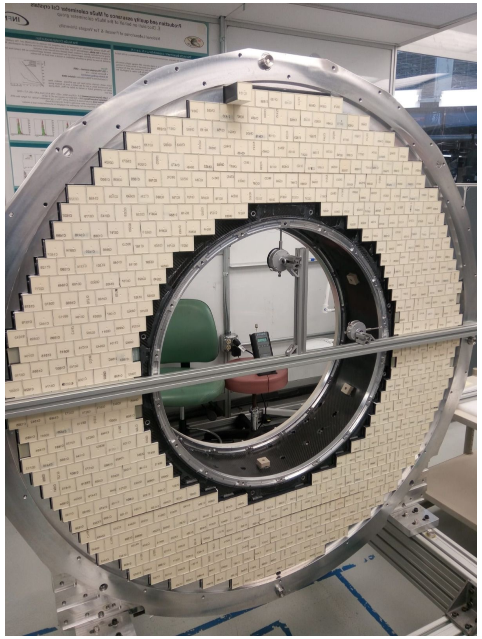


- μ stopped on plastic film @ 30 MHz
- μ->eγ (55 MeV)
- σ_E(E)/E of 1-2% for 55 MeV photons

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