Prospects for Detector concepts / Calorimetry

Vincent Boudry

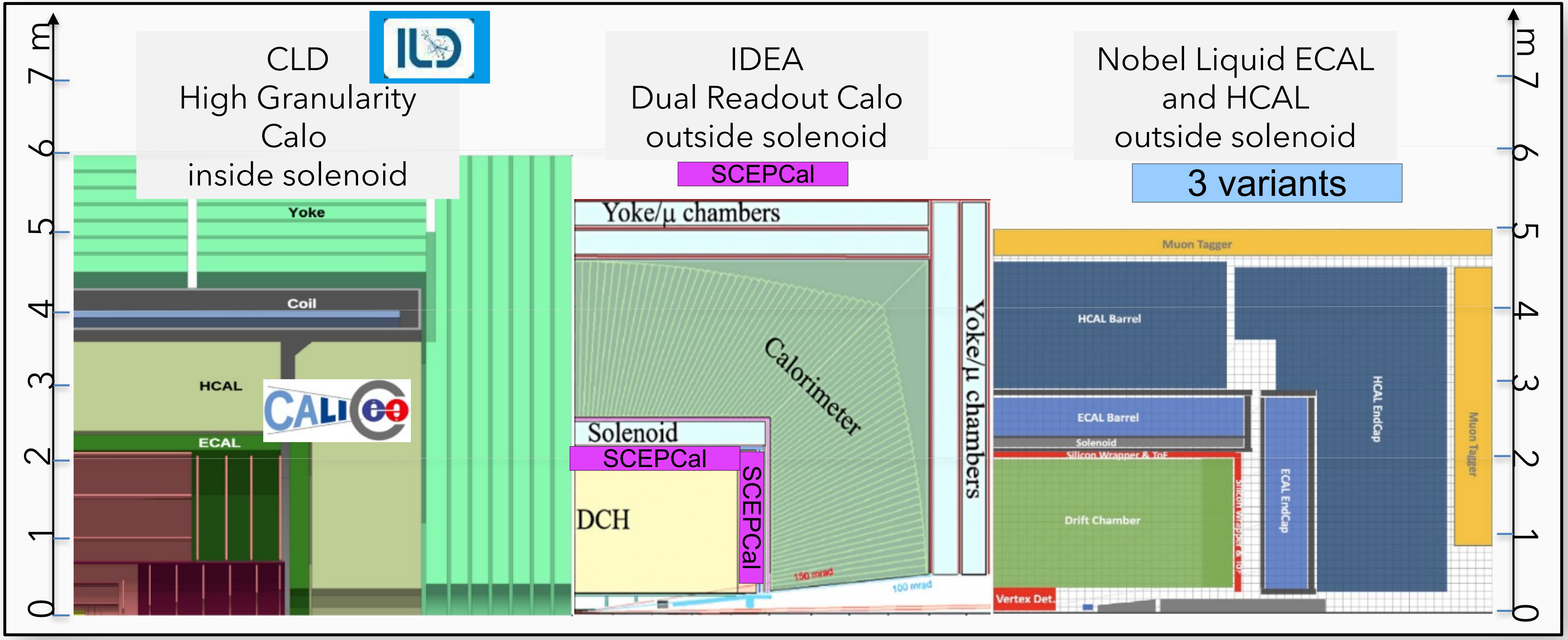
Institut Polytechnique de Paris

FCC FR+IT
24/11/22, Lyon

Detector Concepts 3++

D. Contardo (Mod)

Concepts defined 1st order by : CALO + TRACKER + SOLENOID Position



D. Contardo (Mod)

Discussed :
Here Brass

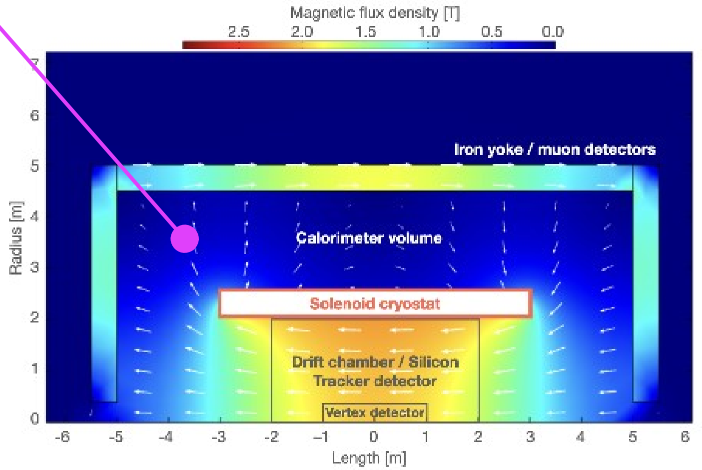
Uniform with
S. Steel

HCAL can use Iron absorber to act as field return yoke

2T thin solenoid w/ calorimetry outside

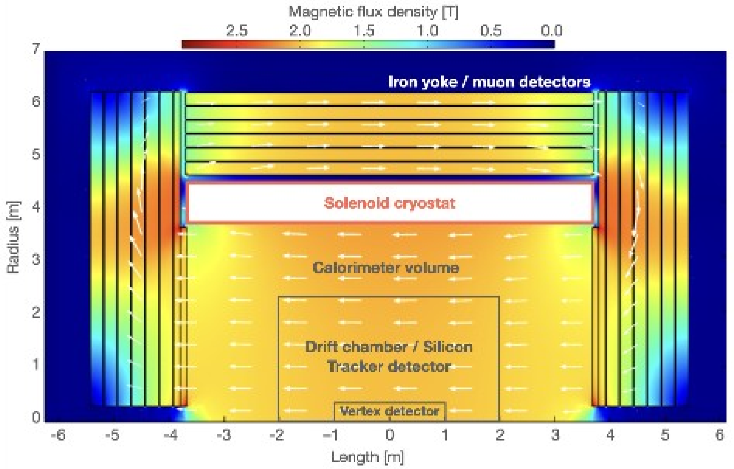
R&D to develop high-strength Al-stabilized NbTi superconducting cable and light vacuum vessel*

$< 0.5\text{-}1 X_0$ and $\simeq 0.1\ \lambda$



CMS-like solenoid w/ calorimetry inside

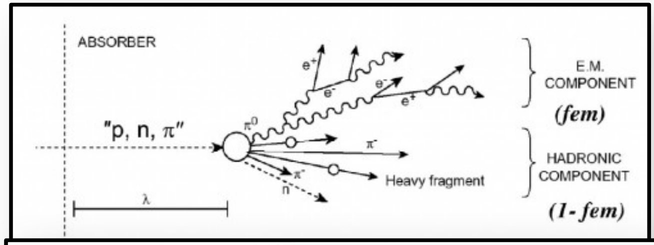
B up to 4T above Z-peak energy



- Studies in calorimetry outside concepts with parameterized X/X_0 and λ for performance and to assess if B > 2T possible
- Realistic field maps modeling in simulation to study systematics on p_T measurement

IDEA: Dual Readout (only)

Romualdo Santoro



$$E = \frac{(E_S - \chi E_C)}{1 - \chi}$$

$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C}$$

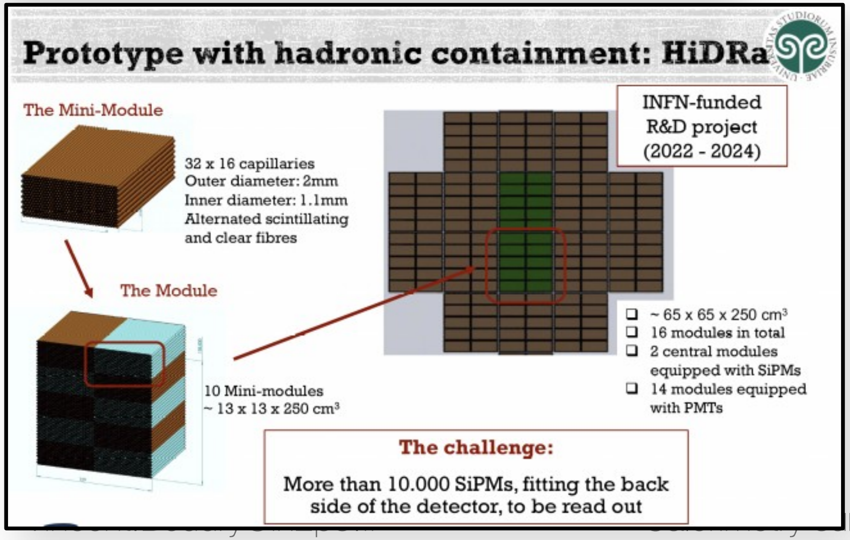
χ does not depend from energy and particle type. It is detector dependent: it can be measured on beam tests

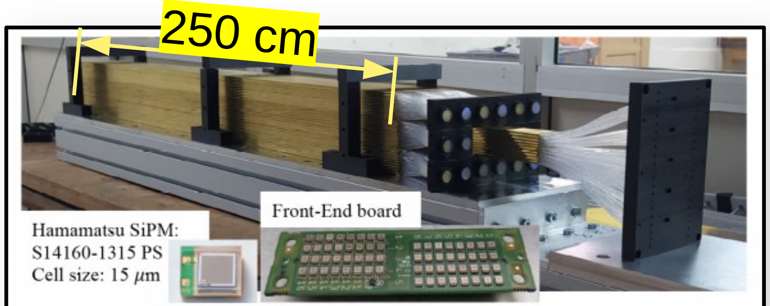
Principle:

- Compensation of the imbalance EM/Had resp. by 2 measures with ≠ e/h : **S**cint and **C**herenkov
- χ measured in beam tests

$$E_S = E\left(f_{em} + \left(\frac{h}{e}\right)_S (1 - f_{em})\right)$$

$$E_C = E\left(f_{em} + \left(\frac{h}{e}\right)_C (1 - f_{em})\right)$$



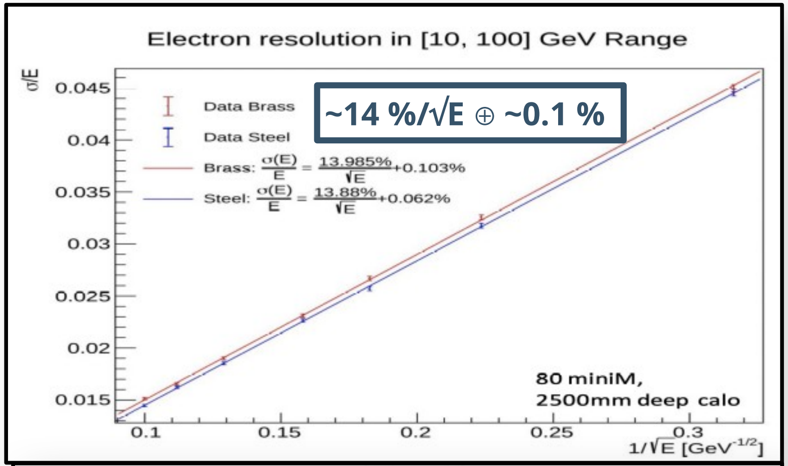


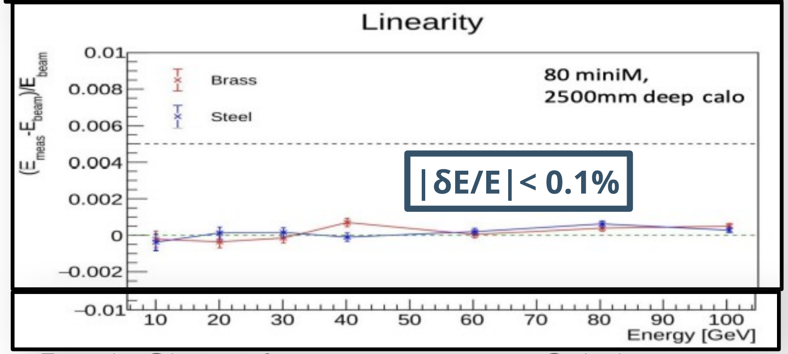
- A small prototype has been tested on beam in 2021 (@DESY and @CERN) with electrons ranging from 1 to 100 GeV
- The prototype was made of brass capillary tubes (2 mm outer diameter) each hosting a fibre of 1 mm diameter: : (10x10x100 cm³)
- There are 9 towers containing 16x20 capillaries with alternating scintillating and clear fibres
- The central tower is equipped with SiPMs while the surrounding towers are connected to PMTs (costs saving reason)

Prelim data

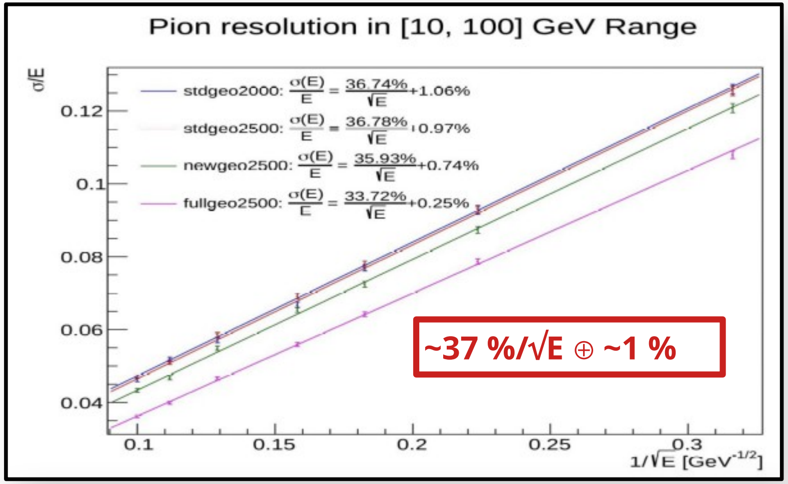
IDEA: HiDRa simulations

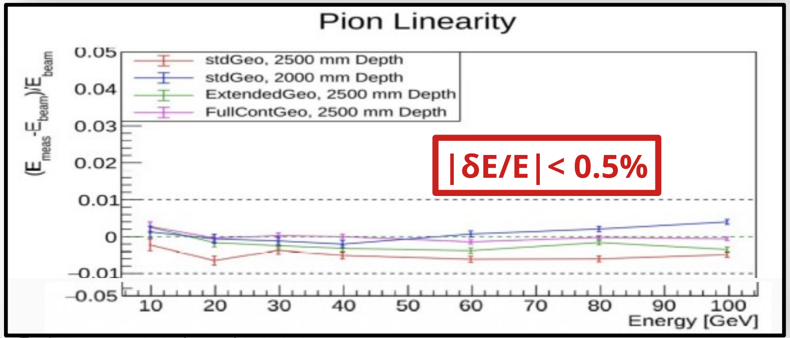
Electrons: Brass & S. Steal



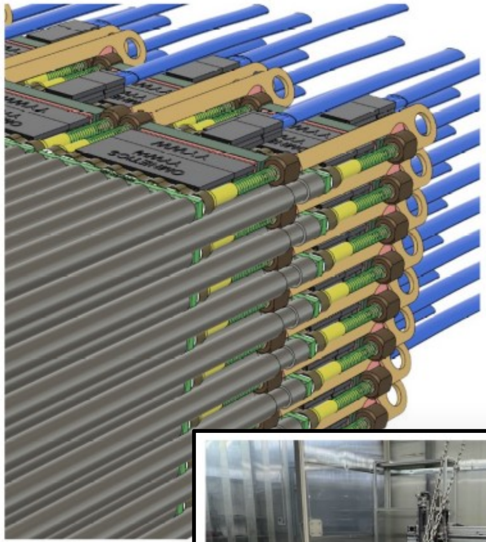


Pions :



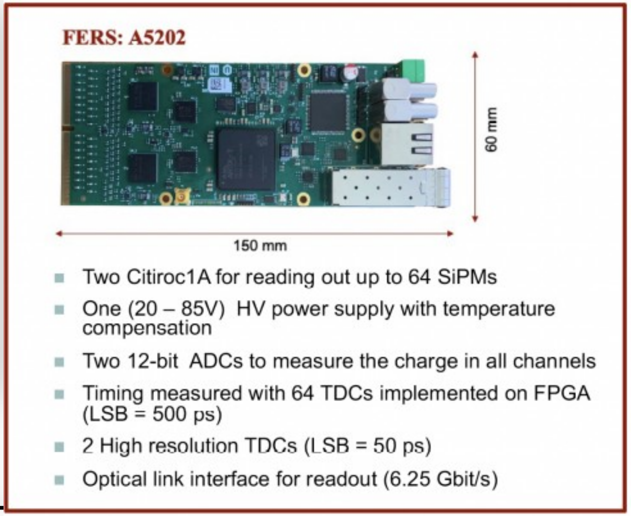


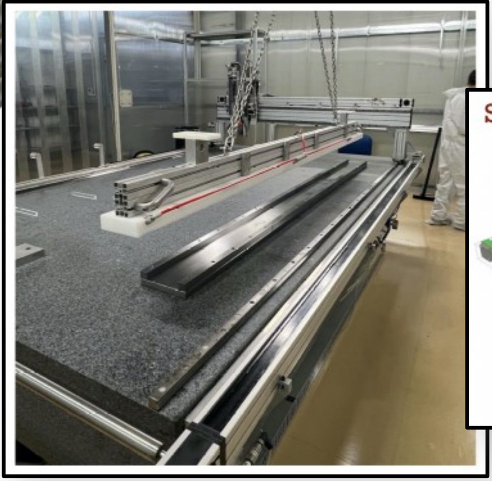
IDEA: Integration

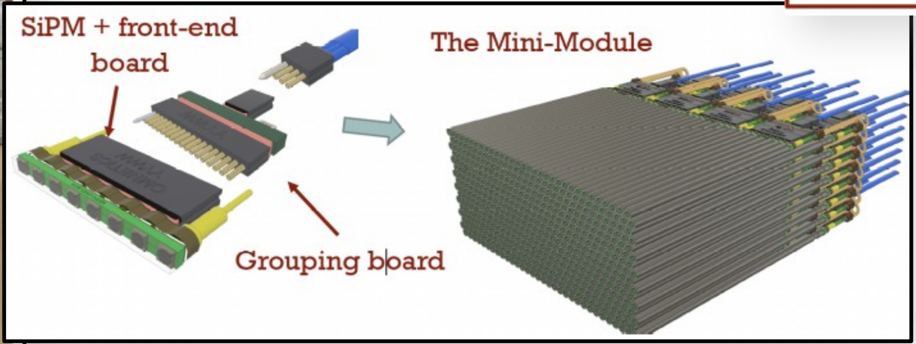


Quite challenging integration that requires:

- Precise assembly procedure
- Compact components: there is almost no space in the rear part of the calorimeter
  - SiPMs
  - Mechanical support
  - Cabling and readout to serve all channels

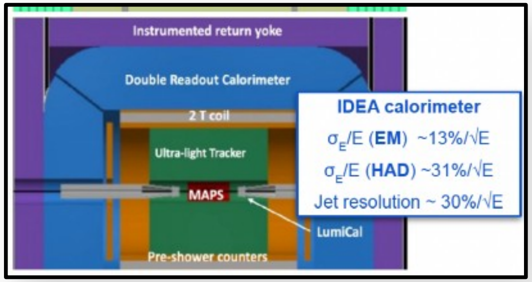






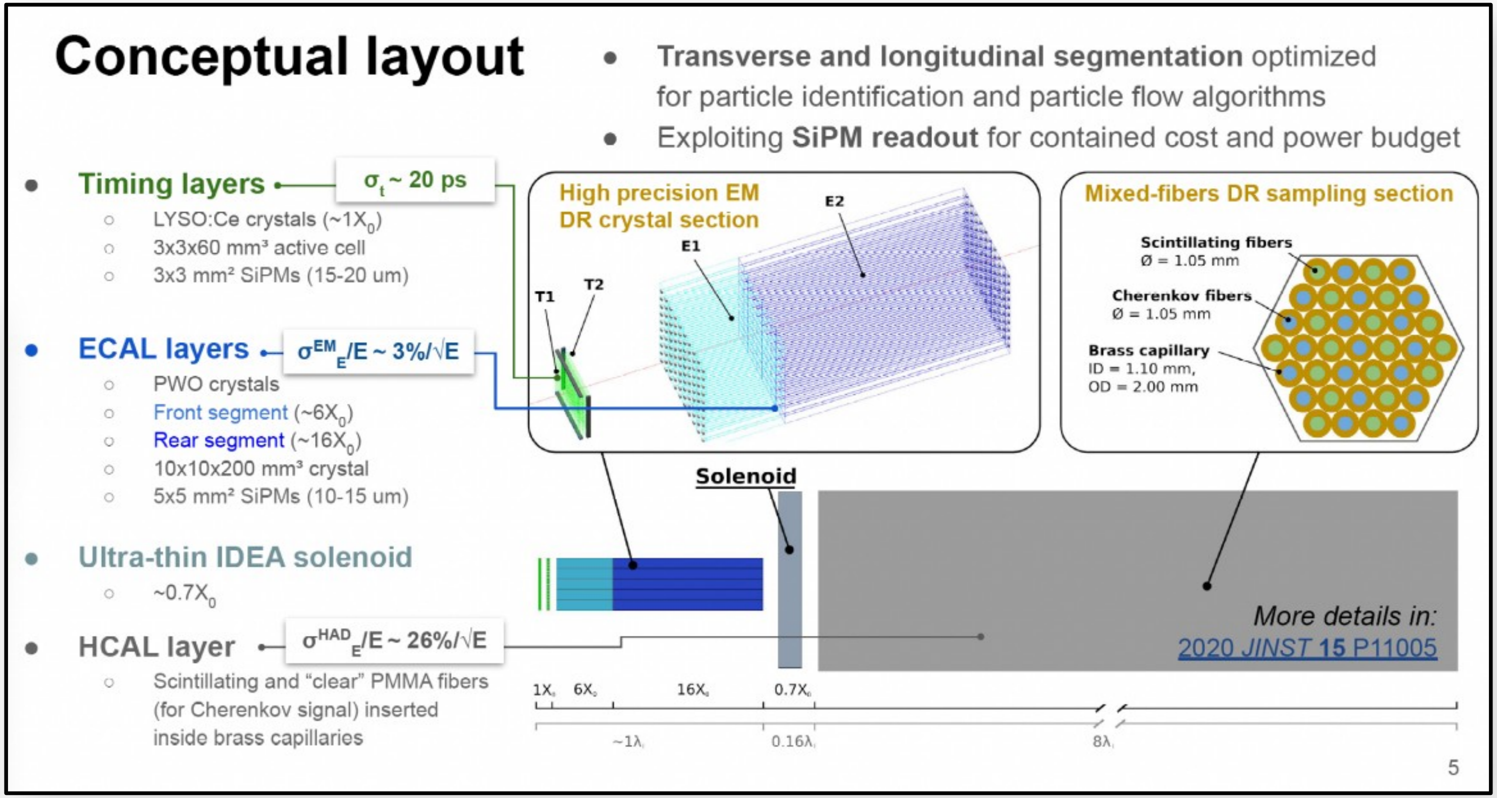
IDEA: Dual Readout with Crystal (High precision ECAL)

Marco Lucchini



A calorimeter with **3%/√E EM** energy resolution has the potential to improve event reconstruction and **expand the landscape of possible physics studies** at e^+e^- colliders

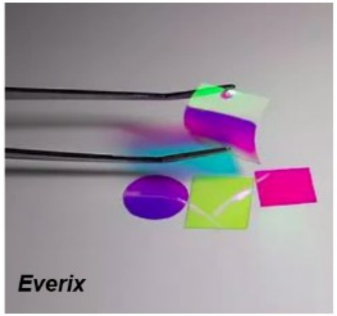
- **CP violation studies** with B_s decay to final states with low energy photons
- **Clustering of π^0's photons** to improve performance of jet clustering algorithms
- **Improve the resolution of the recoil mass signal from Z→ee decays** to ~80% of that from Z→ μμ decays (recovering Brem photons)

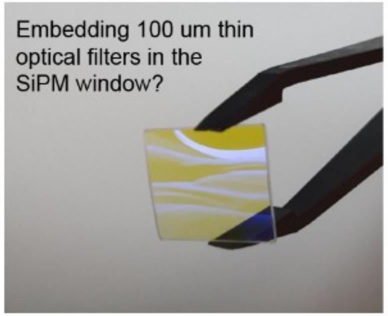


IDEA: Dual Readout with Crystal
(High precision ECAL)

Rear crystal ECAL segment:
Two 4x4 mm² SiPMs with optical filters optimized for scintillation and cherenkov detection resp.

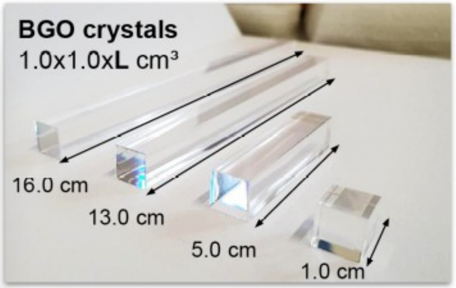
Front crystal ECAL segment:
Single 5x5 mm² SiPM per crystal optimized for scintillation light detection

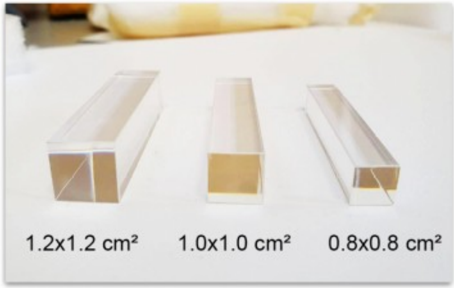


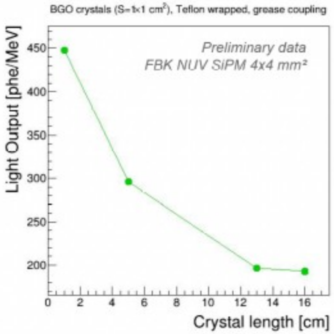


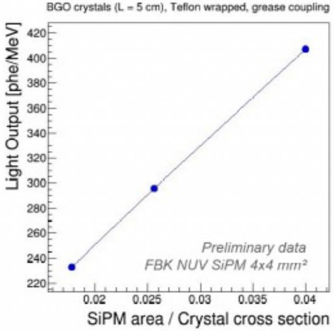
Ongoing R&D: calorimeter cell optimization

- Optimization of crystal cross section (granularity) and longitudinal segmentation
- Evaluation of light output for different crystal and SiPM geometries
- First experimental results available to validate expectations from Geant4 ray-tracing simulation









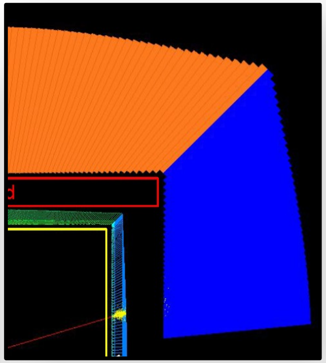
IDEA: Dual Readout with Crystal
(High precision ECAL)

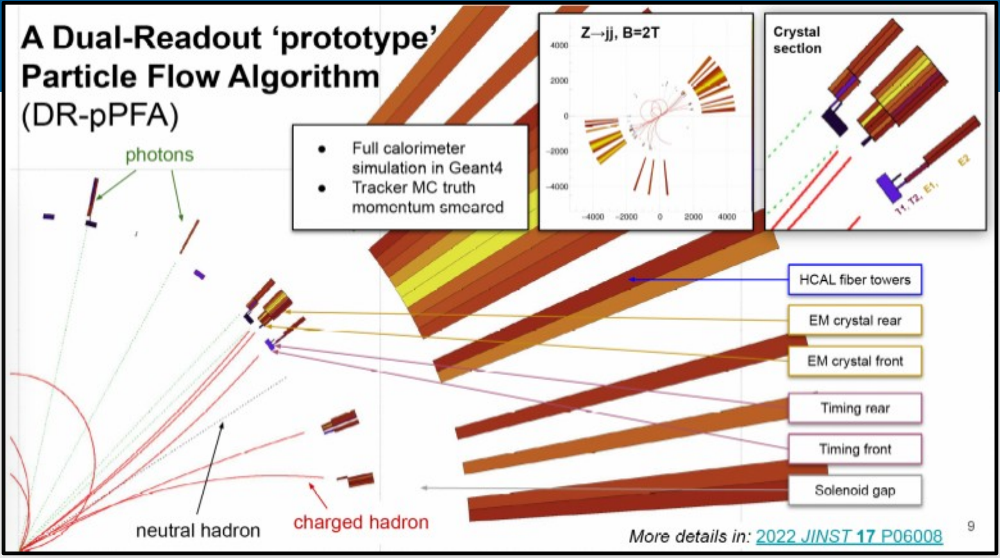
The **dual-readout method** in a hybrid calorimeter

$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1 - \chi_{HCAL}}$$
$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1 - \chi_{ECAL}}$$
$$E_{total} = E_{HCAL} + E_{ECAL}$$

Dual-readout method confirms its applicability in a hybrid calorimeter

- Response linearity to hadrons restored within ±1%
- Hadron energy resolution comparable to that of the fiber-only IDEA calorimeter



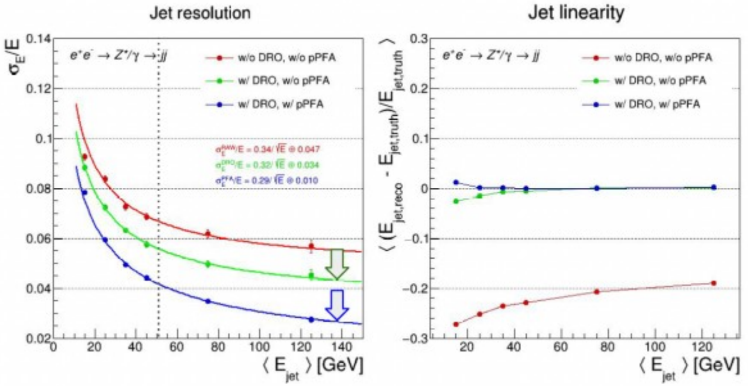


Jet resolution: with and without DR-pPFA

More details in: 2022 *JINST* **17** P06008

Jet energy resolution and linearity as a function of jet energy in off-shell $e^+e^- \rightarrow Z^* \rightarrow jj$ events (at different center-of-mass energies):

- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA



Noble Liquid EM Calorimeter

Nicolas Morange

- An appealing option for FCC-ee
  - Good energy resolution
  - High(-ish) granularity achievable
  - Linearity, uniformity, long-term stability

Excellent solution for small systematics

- Lots of interesting studies / R&D to do
  - Optimization for PFlow reconstruction
  - Achieving very low noise
  - Lightweight cryostats to minimize X_0
  - Designing for improved energy resolution
- **Significant progress in the past year**

Aiming for ~ ×10 ATLAS granularity

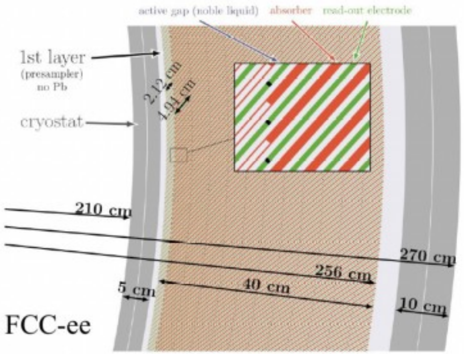
- High granularity required for better PFlow performance (few million cells)
- >6 compartments to compensate LAr gap widening

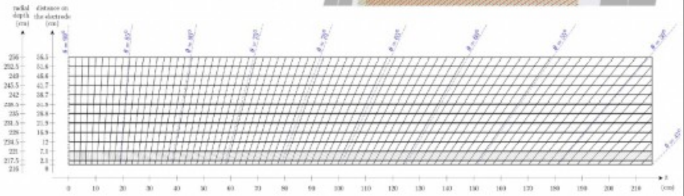
Design driven by readout electrodes

Baseline (conservative) FCCee ECAL barrel design

- 1536 **straight inclined** (50°) 1.8mm **Pb** absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm **LAr** gaps
- 40cm deep (22 X_0)
- $\Delta\theta$ = 10 (2.5) mrad for regular (strip) cells, $\Delta\phi$ = 8 mrad, 12 longitudinal layers
- **Solid aluminum** cryostat
- Implemented in FCC Fullsim

Lots of room for optimization and improvements





Optimizing the energy resolution

Materials

- LAr → LKr:
  - 8%/√E to **5%/√E**
- Pb → W:
  - No improvement in resolution
  - Expected impact on PID to be studied

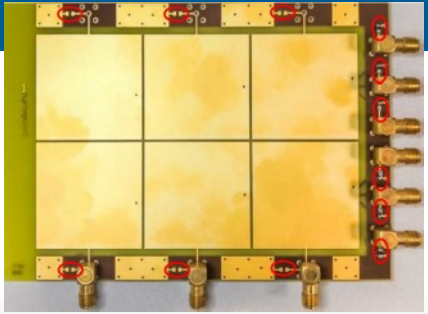
Geometry

- Straight planes → trapezoidal absorbers
  - Better sampling fraction in first layers
  - Small gain in resolution
  - Feasibility ?

Software

- MVA calibration
  - improves constant term
- Clustering
  - Large effect, to be studied further

Noble Liquid Calorimeters : R&D's



Next generation cryostats

Minimizing dead material in front of calo

- Crucial for low energy measurements at FCCee
- Ongoing R&D for cryostats using new materials and sandwiches
  - Generic R&D at CERN as cryos will be used for solenoids i all experiments
  - Synergy with progress in aerospace
  - Test microcrack resistance, sealing methods, leak and pressure tests
  - Address CFRP/Metal interfaces
- Promises for **"transparent" cryostats**: few % of X_0 !

NASA's lineless cryotank

Small scale electrode @ IJCLab

- Detailed measurements of cell properties and cross-talk effects
- Frequency behaviour
- **Good overall agreement with simulations on large frequency range**

Larger scale electrode @ CERN

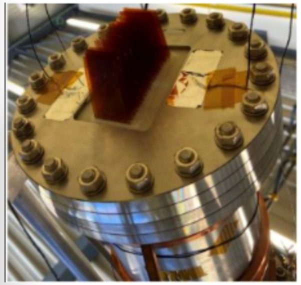
- 1:1 scale θ chunk: 16 towers with different layouts

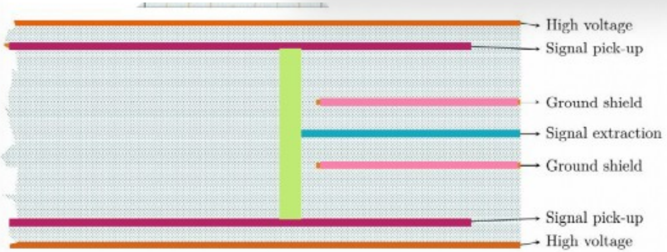
Signal extraction from cryostat

- High density feedthroughs needed in case readout electronics outside of cryostat
- Aim for ~ ×5 density and ~ ×2 area wrt ATLAS

Successful R&D on connector-less feedthrouhgs at CERN

- Prototypes of 3D-printed epoxy resins structures with slits for strip cables, glued to the flange
- Leak tests and pressure tests at 300 K and 77 K
  - **Suitable materials identified: G10 structure with slits + indium seal + Epo-Tek glued Kapton strip cables**
- Stress simulations of complete designs at 300 K and 77 K





Noble Liquid

Noise and cross-talk considerations

Goals

- Low noise to measure photons **down to 200 MeV**
- Measure MIPs with good S/N
- **Sub-percent** cross-talk

Cold electronics ?

- Noise master formula: $N \sim C_d \sqrt{\frac{4kT}{g_m \tau_p}}$
- Cold electronics: gain on C_d, T and g_m
- **Extremely low noise easily achievable**

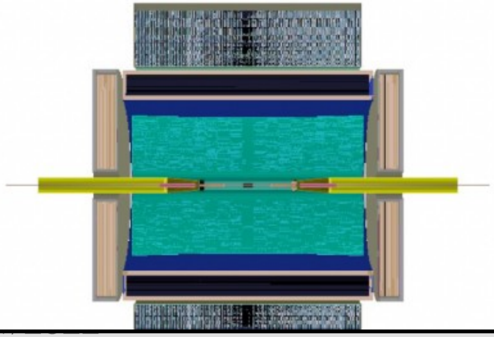
- Challenges:
  - Heat dissipation
  - Difficulty for repair
- We know how to do it:
  - DUNE example
- Very first studies
  - HGCROC in Liquid N at IJCLab

Towards a detector concept

- Based on IDEA design but using Noble Liquid for ECAL
- Performance impact of position of solenoid to be studied in simulation

Implementation in FCCee Fullsim

- ECAL endcaps
  - Parallel disks, 1.5mm Pb, 2mm LAr gaps
  - Total thickness 45cm
- HCAL barrel
  - Based on Iron-Scint Tile design for FCChh
  - 13 compartments, $\Delta\theta \times \Delta\phi = 0.025 \times 0.025$
- Cryostat: more realistic implementation



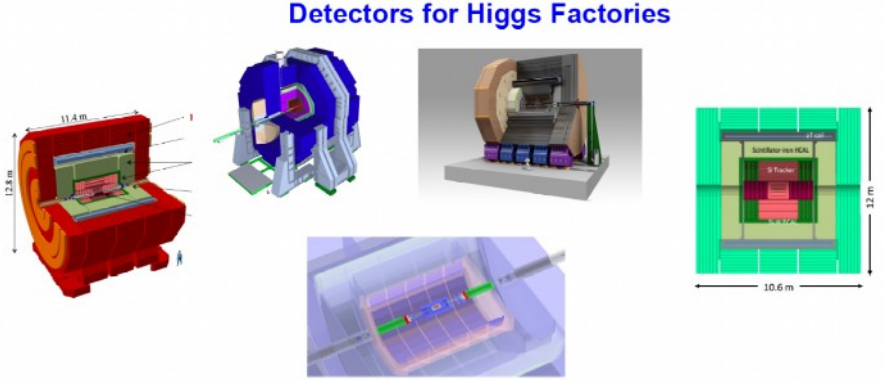
CALICE: Highly Granular Calorimeters

Roman Pöschl

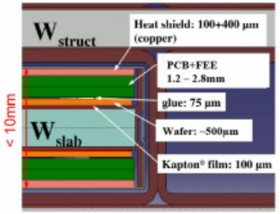
Si-W ECAL	(ALICE FoCAL)	[Scint-W ECAL]	AHCAL	SDHCAL
0,5×0,5 cm² ×15 (→30) Si layers + W	0,003×0,003 cm² × 24 MIMOSA layers + W	0,5×4,5 cm² ×30 Scint+SiPM lay. + SS	3×3 cm² × 38 Scint+SiPM lay. + SS	1×1 cm² × 48 layers GRPC + SS

V. Boudry, FCC Workshop

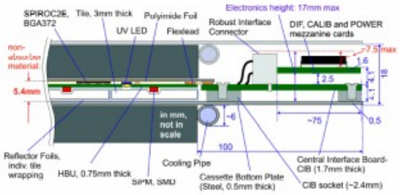
- The federation under one roof allows for common development and comparison on equal footing



SiW ECAL

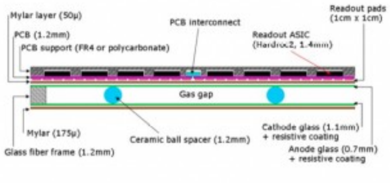


Analogue Hcal and Scintillator Ecal



Optical readout

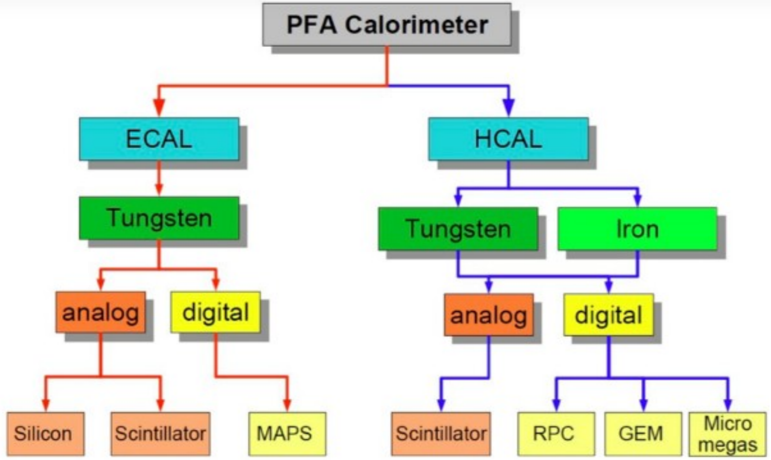
Semi-digital Hcal



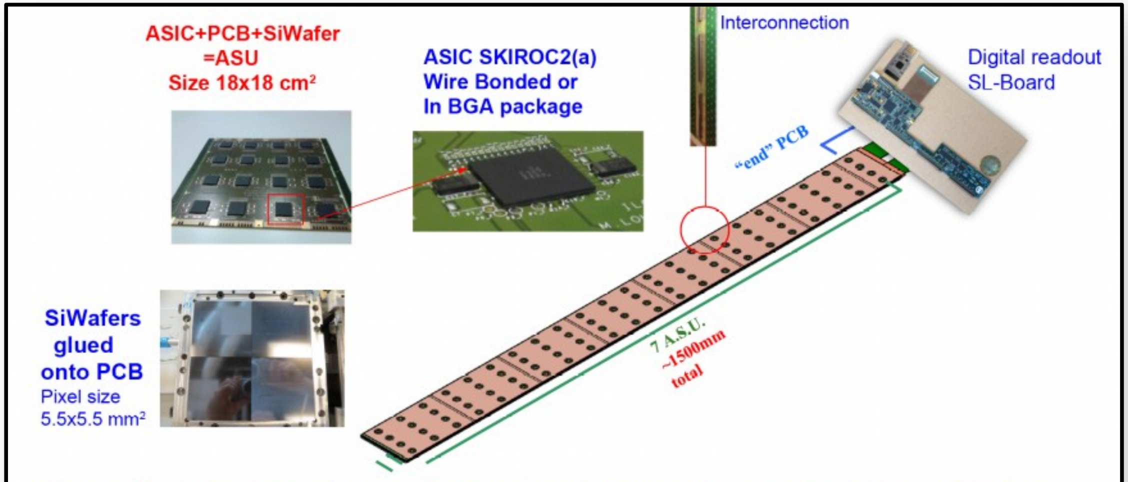
Gaseous readout

- Realistic dimensions
  - Structures of up to 3m
- Integrated front end electronics

  No drawback for precision measurements *NIM A 654 (2011) 97*
- Small power consumption (Power pulsed electronics)



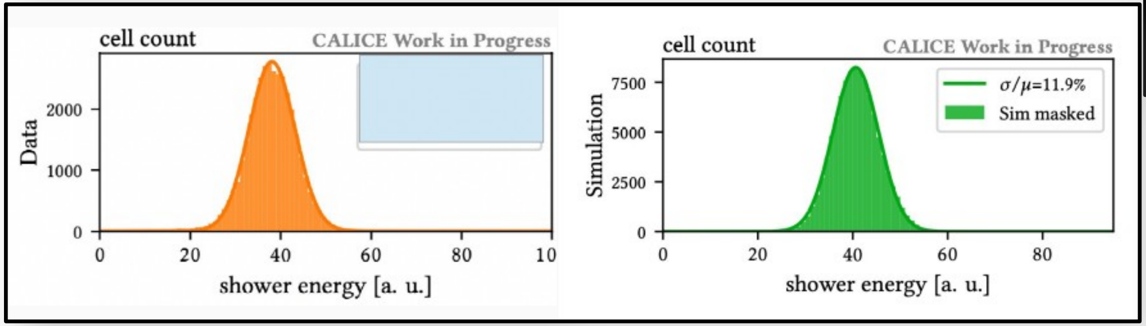
CALICE SiW-ECAL

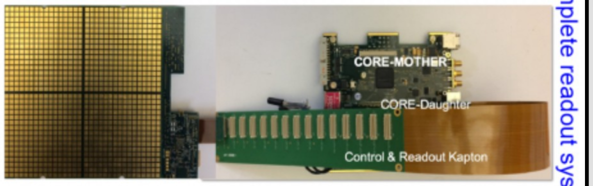


The beam test set ups consist of a **stack of short layers** built from one ASU and a readout card each

- 15 short layers equivalent to 15360 readout cells
  - Up to 21 X_0
  - Overall size 640x304x246mm³
  - Flexible mechanical structure to adapt to beam conditions
- Commissioned 2020-2022
  - ~450000 calibration constants for one ASIC feedback capa setting

Testbeams (finally) in November 2021 and during 2022

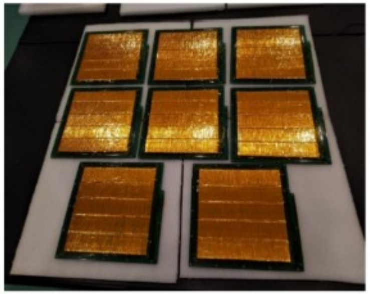


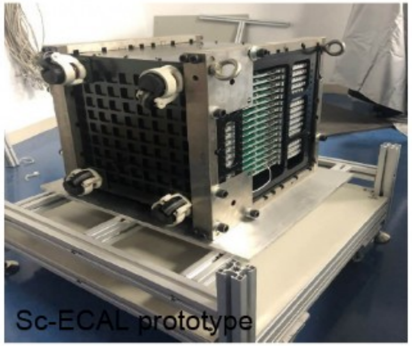


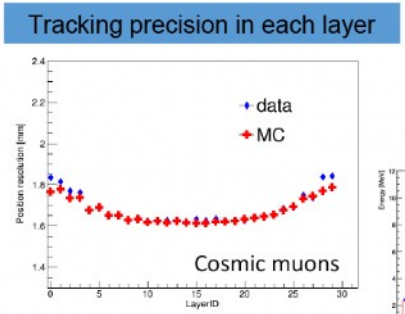
CALICE: Scint-ECAL

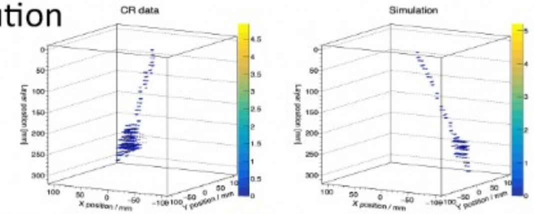
- Sc-ECAL prototype: successful construction during 2019-2020
  - Effective granularity 5×5mm², 32 sensitive layers composed of **scintillating strips** and CuW absorber plates
  - 6700 readout channels in total

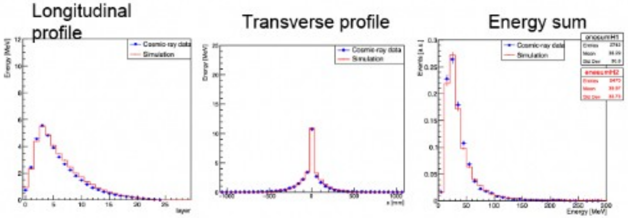
- Successful commissioning and long-term cosmic-ray tests (2020-2021)
  - Calibration of all SiPMs and SPIROC2E chips; MIP response calibration
  - Tracking performance: achieved better than 2mm positioning resolution





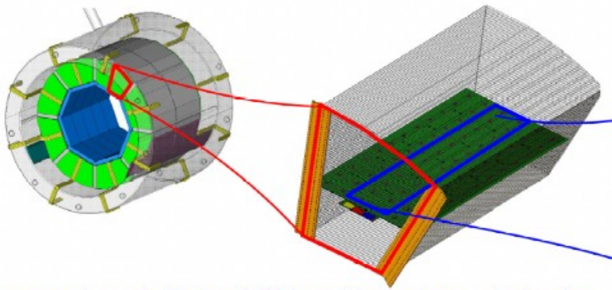


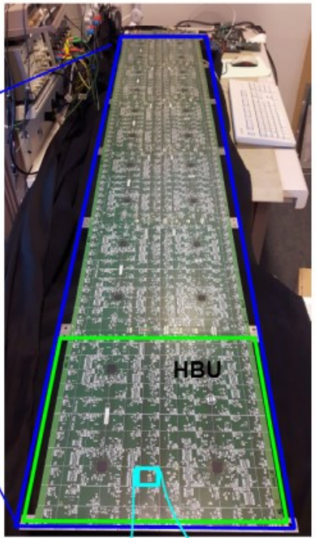




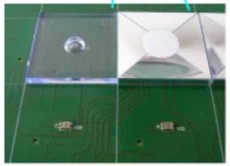
- Gearing up for beam test at CERN in October 2022

CALICE AHCAL



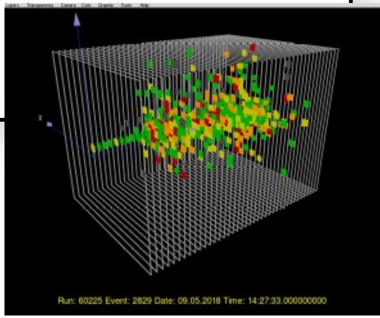


- highly granular scintillator SiPM-on-tile hadron calorimeter, 3*3 cm² scintillator tiles optimised for uniformity
- **fully integrated design**
  - front-end electronics, readout
  - voltage supply, LED system for calibration
  - no cooling within active layers -> **power pulsing**
- **scalable** to full detector (~8 million channels)
- geometry inspired by ILD, similar to SiD and CLICdp
- HCAL Base Unit: 36*36 cm2, 144 tiles, 4 SPIROC2E ASICs
  - slabs of 6 HBUs, up to 3 slabs per layer

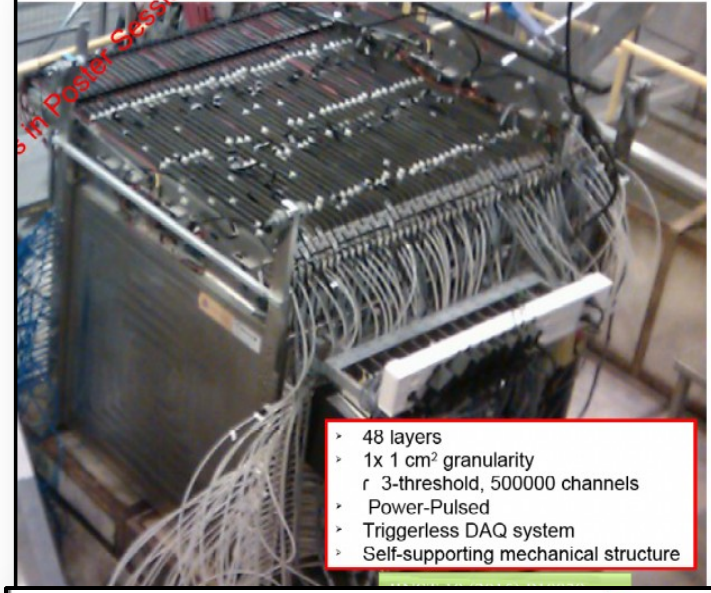


F/I FCC Workshop 2022

- Large enough to contain hadron showers
  - 38 active layers of 72*72 cm²
  - 4 HBUs per module
  - in total: 608 SPIROC2E ASICs, **~22000 channels**
  - SiPMs: Hamamatsu S13360-1325PE
- All modules interchangeable
- Built with scalable production techniques in ~2 years
- Operated in beam tests with muons, electrons and pions at CERN SPS in 2018
  - 3 weeks of beam time
  - Collected O(100) mio events
  - Very stable running
  - **Nearly noise free**
  - **< 1 per mille dead channels**

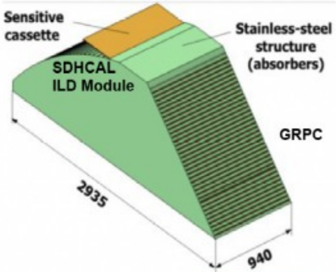


CALICE SDHCAL

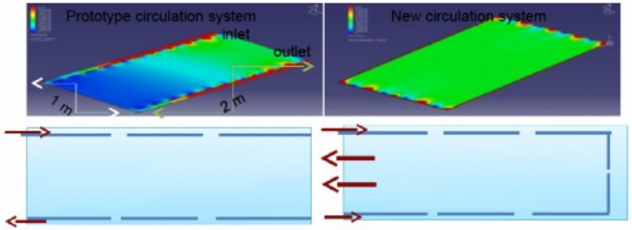


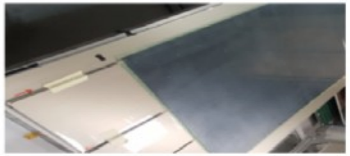
- 48 layers
- 1x 1 cm² granularity
- 3-threshold, 500000 channels
- Power-Pulsed
- Triggerless DAQ system
- Self-supporting mechanical structure

- Detectors as large as 3x1m² need to be built
- Electronic readout should be the most robust with minimal intervention during operation.
- Mechanical structure with minimal dead zone
- Include time information **SDHCAL -> T-SDHCAL**



Large RPC detectors





Large mechanical structure

Flatness
Using roller leveling

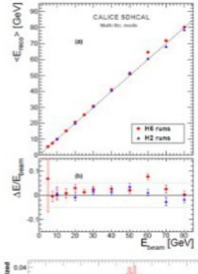
Reduced dead zone
Using electron beam weilding

Highlight II: SDHCAL testbeam

2 weeks of beam test at CERN SPS: 14 - 28 September 2022

$E_{rec} = \alpha(N_{tot})\, N_1 + \beta(N_{tot})\, N_2 + \gamma(N_{tot})\, N_3$

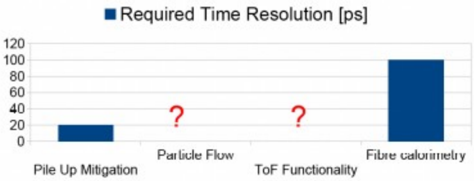
- Observation in previous beam tests: (slightly) different reconstructed hadron energy in two beam lines at SPS, which have different mixtures of pions and protons
- Goal for this testbeam: use Cherenkov detectors to separate pions and protons
- Expectation: pion showers have higher EM fraction and more hits
- Optimise α,β,γ separately for pions and protons
- Investigate calorimeter quantities that might allow pion/proton distinction



CALICE for FCC-ee

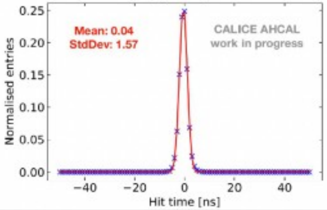
Timing

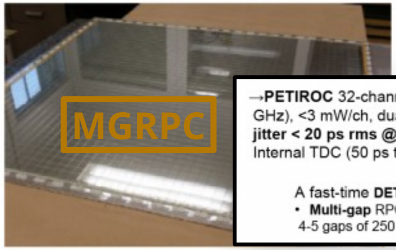
- Timing is a wide field
- A look to 2030 make resolutions between 20ps and 100ps at system level realistic assumptions
- At which level: 1 MIP or Multi-MIP?
- For which purpose ?
  - Mitigation of pile-up (basically all high rate experiments)
  - Support of PFA – unchartered territory
  - Calorimeters with ToF functionality in first layers?
    - Might be needed if no other PiD detectors are available (rate, technology or space requirements)
    - In this case 20ps (at MIP level) would be maybe not enough
  - Longitudinally unsegmented fibre calorimeters

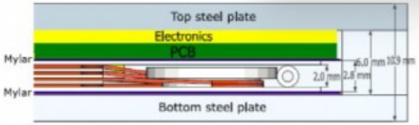


Hit time resolution:
Results from 2018 beam test of AHCAL with muons

Clock frequency 5 MHz,
Powering pulsing







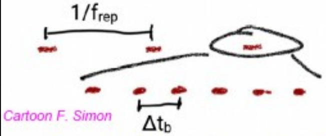
→**PETIROC** 32-channel, high bandwidth preamp (GBWP> 10 GHz), <3 mW/ch, dual time and charge measurement (Q>50 fC)
jitter < 20 ps rms @ Q>0.3 pC
Internal TDC (50 ps time resolution)

A fast-time **DETECTOR**
- **Multi-gap** RPC is an excellent candidate.

4-5 gaps of 250 µm each can provide 100 ps time resolution

Power for continuous operations

- Linear Colliders operate in bunch trains

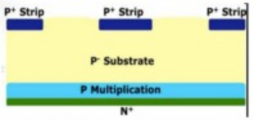


CLIC: Δt_b ~ 0.5ns, frep = 50Hz
ILC: Δt_b ~550ns, frep = 5 Hz (base line)

- Power Pulsing reduces dramatically the power consumption of detectors
  - e.g. ILD SiECAL: Total average power consumption 20 kW for a calorimeter system with 10^8 cells
- Power Pulsing has considerable consequences for detector design
  - Little to no active cooling
  - => Supports compact and hermetic detector design
- Have to avoid large peak currents
- Have to ensure stable operation in pulsed mode
- Upshot: Pulsed detectors face other R&D challenges than those that will be operated in "continuous" mode
  - Tendency: Avoid also active cooling in continous mode

Requires thorought evaluation in simulations ↔ ILD

Inverse APD as LGAD?

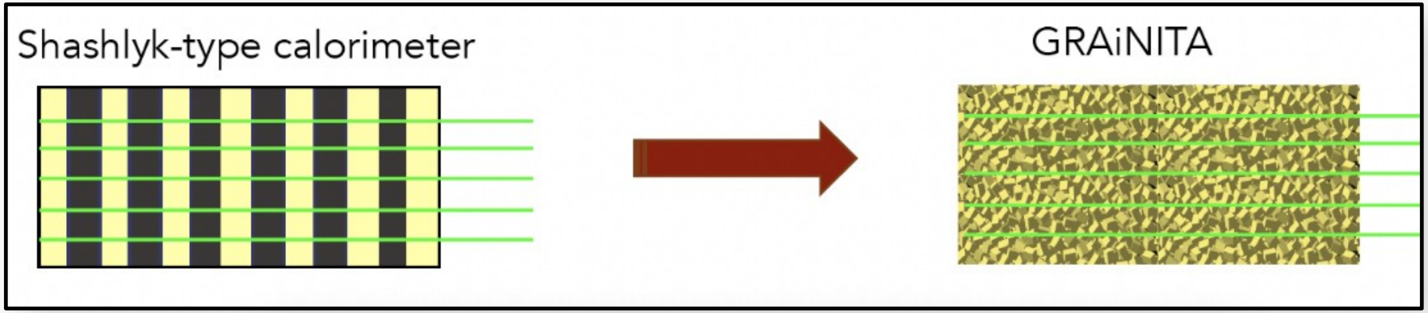


Inverse APD by Hamamatsu

Gain ~ 50

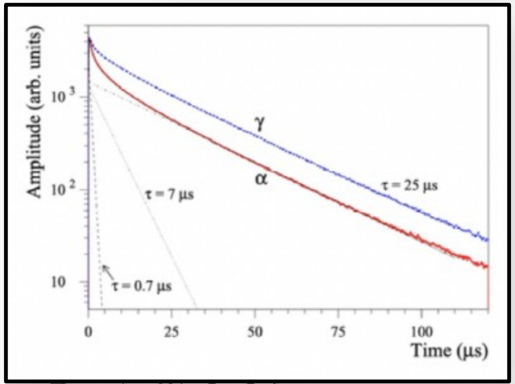
GRAiNITA status report

Marie-Hélène Schune



Typical sampling calorimeters: $\frac{\sigma_E}{E} \sim \frac{10\%-15\%}{\sqrt{E}}$

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



Production under control:
- grains are similar to larger crystals
- homogenous production

Granular scintillator

- local light collection by fibre *à la* LiquidO
  - Local sampling (WLS fibre)

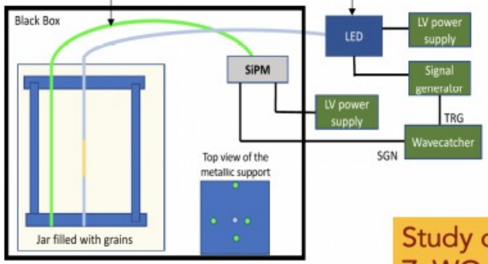
Grain of Crystal

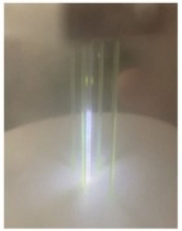
- 0.5–1.0 mm
- Prod (ISMA):
  - Homegenous prod Grains / plates (^{241}Am response)
  - BGO for comparison

$ZnWO_4$:

- d = 7.62, n=2.1
  λ = 480 nm, 10k γ/MeV
- Bath of CH_2I_2 (D=3.3, n=1.7)
- Shape discrim γ vs α

Test benches

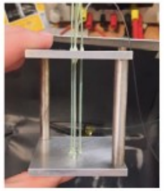




Study of the pulse time delay: average light path in $ZnWO_4$ + propanol ~ 17 cm

Light absorption too large (wrt to kitchen salt test)

< 50 g of $ZnWO_4$



→ new studies with the new $ZnWO_4$ grains, a green LED and a better matched WLS fiber

- Active volume = 2.8 x 2.8 x 6 cm^3 (~200 g of $ZnWO_4$)
- Fibers spacing: 7 mm
- 16 fibers read-out by SiPM
- Possibility to repeat the study with the well known BGO
- Blue/Green LED injected in the middle (& UV LED with a quartz fiber ?)
- Cosmic rays triggering

1] Light absorbtion

- LED pulses

2] WLS fibres

- 4 Kurarai types
  - 1 selected
- Readout with 2 fibres
  ➡ 10% improvement (dropped)

- Y11 (200)
- O2(100)
- O2(300)
- R3(300)

3] 16 fibre bench in preparation

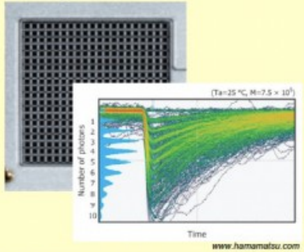
- cosmics
  ➡ position dependance, Nph
- trigger by 2 timepix
  ➡ trajectory

Improvement of readout

Romualdo Santoro

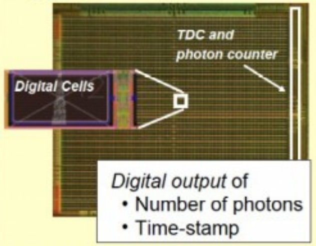
Alternatives should be considered

Analog SiPM



- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

Digital SiPM



- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output

With dSiPM there is no need for analogue signal post-processing

- SPAD array in CMOS technologies may offer the following benefits:
  - to embed complex functions in the same substrate (e.g. SPAD masking, counting, TDCs)
  - the design of the front-end electronics can be optimized to preserve signal integrity (especially useful for timing)
  - the monolithic structure simplifies the assembly for large area detectors
  - development costs can be kept relatively low if the design is based on standard process

See NSS MIC plenary

Conclusions

Missing:

- Forward Calorimetry
  - High Precision of the measurement (position)
    - Luminosity, Beam return
    - Linked to the placing of the magnets, etc
    - Activity mostly outside of FR, IT
- Muon Chambers [Paolo Giacomelli]
  - based on µ-RWell, RPC's
- PicoSec MicroMegas [Florian Brunbauer]

ILD:

- Effort to evaluate the implications of continuous operation during the next months started

Calorimetrers

- very active domain
  - Many R&D, large span of "TRL"
  - Essentially split in IDEA (IT) + CALICE / ℓAr (FR)
- will be affected soon by ECFA DRR reshuffling
  - 1st meeting 12/01 at CERN [see call from R. Pöschl]
- Lively discussion on synergies:
  - SW (Key4HEP, to be completed), TDAQ (EUDAQ), beam test operations, …
  - Common set of events for benchmarks (to be defined)