‘CALICE’ calorimeters for FCC-ee ?

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Not officially reviewed by ~~for the CALICE collaboration~~

FCC Contacts
11/06/2021

CNRS IN2P3 Les deux infinis
École Polytechnique
Institut Polytechnique de Paris
AIDA 2020
TNA support + WP14

Introduction

CALICE dans 1 nouvelle phase :

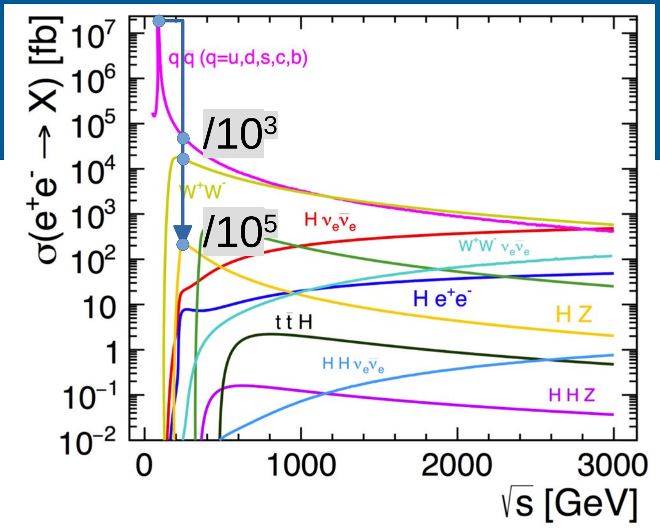
- Construction du 1er grand calorimètre HG (HGCAL : 6M voix)
- R&D en «phase finale»
  - Construction calo = ~8 ans → **5–7 ans de R&D**

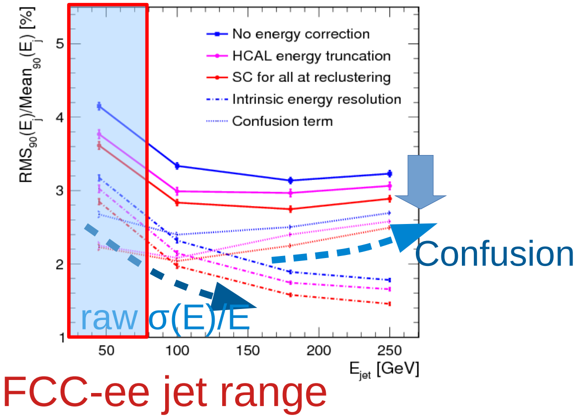
Bcp élements à prendre en compte

- stabilité, fiabilité (MTBF) → redondance,
- Power & Cooling
- Performances (Pic du Z ≠ WW & “Colline du Higgs”)
  - RAW (single part) Résolution E, t → (PID, Reco) → Jets, FS

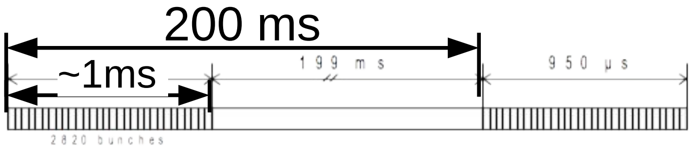
Projets FCC-ee et ILC :

- besoin de fixer les paramètres → TDR
- nv techno: Timing, ML, Capteurs, …





PP ↔ Cont



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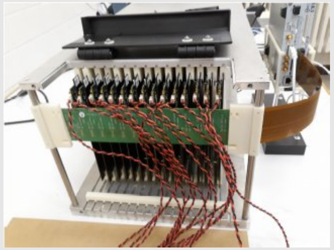
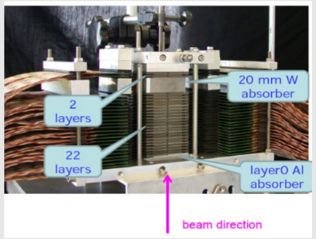
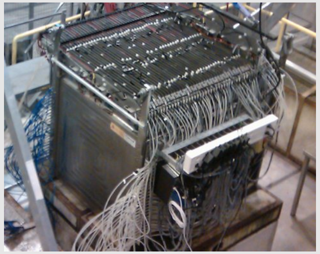
État de l'art

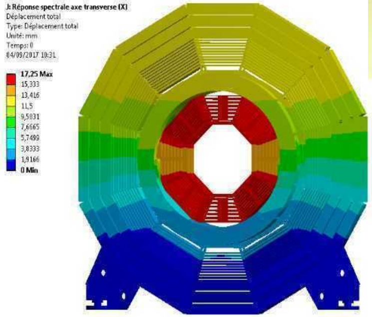
4,5 prototypes, 15^{+} ans de R&D, (prêts à être) Testés

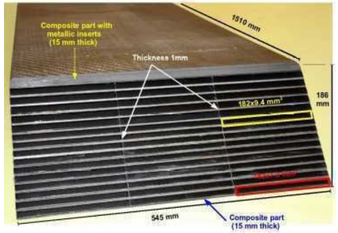
Si-ECAL	(ALICE FoCAL)	Scint-ECAL	AHCAL	SDHCAL
				
0,5×0,5 cm^2 ×15 couches +W	0,003×0,003 cm^2 × 24 layers +W (MIMOSA)	0,5×4,5 cm^2× ×30 couches + SS	3×3 cm^2 × 38 couches	1×1 cm^2 × 48 couches+SS
Résolution ~ R_M ✔ Intégration ✔ Cout ~ Calibration ✔✔	Résolution ✔ R_M ✔✔ Intégration ? Coût ?? Calibration ?	Résolution ✔ R_M ? Intégration ~ Coût ✔ Calibration ~	Résolution ✔ λ ✔ Intégration ~ Coût ✔ Calibration ~	Résolution ✔ λ ✔ Intégration (Gaz) ~ Coût ✔✔ Calibration ~
LLR, IJCLab, LPNHE, (LPSC) IFIC, Kyushu, KEK, ...	DE, NL, CERN	Shinshu, IHEP (CN)	DESY + DE	IP2I, LPC, (LAPP) CIEMAT, Shanghaï

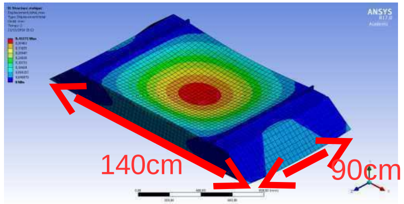
Long travail d'intégration et compréhension

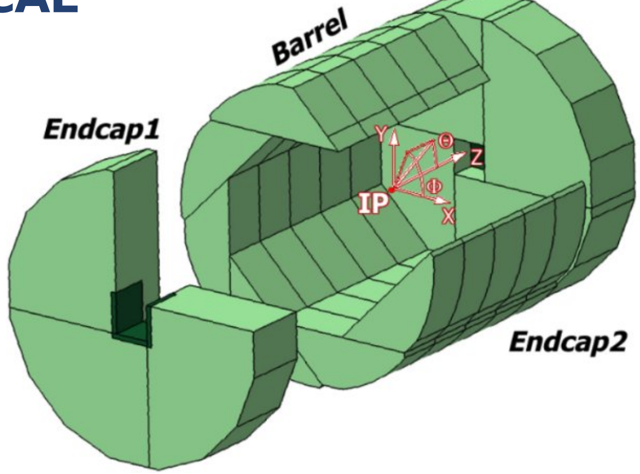
Modèle ILD : « à la Videau», AHCAL

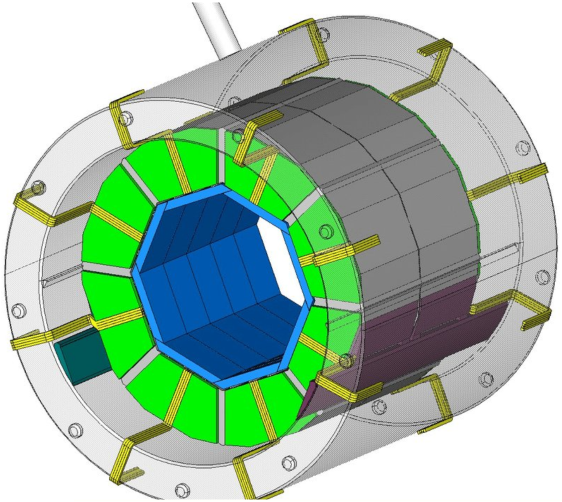
- Structure Fibre de Carbone

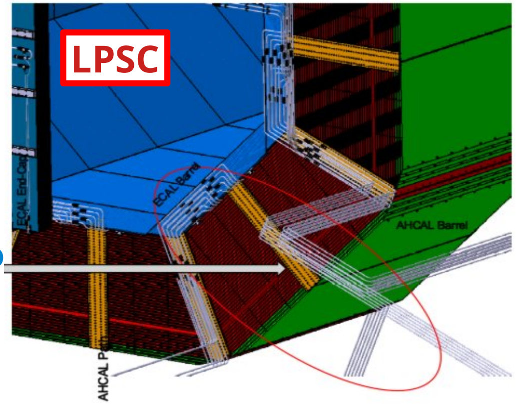












Communauté autour du Particle Flow

- ILCSoft: PandoraPFA, Arbor (IP2I, LLR), Simu → DD4HEP, KEY4HEP
  - EUDET, AIDA, AIDA–innova

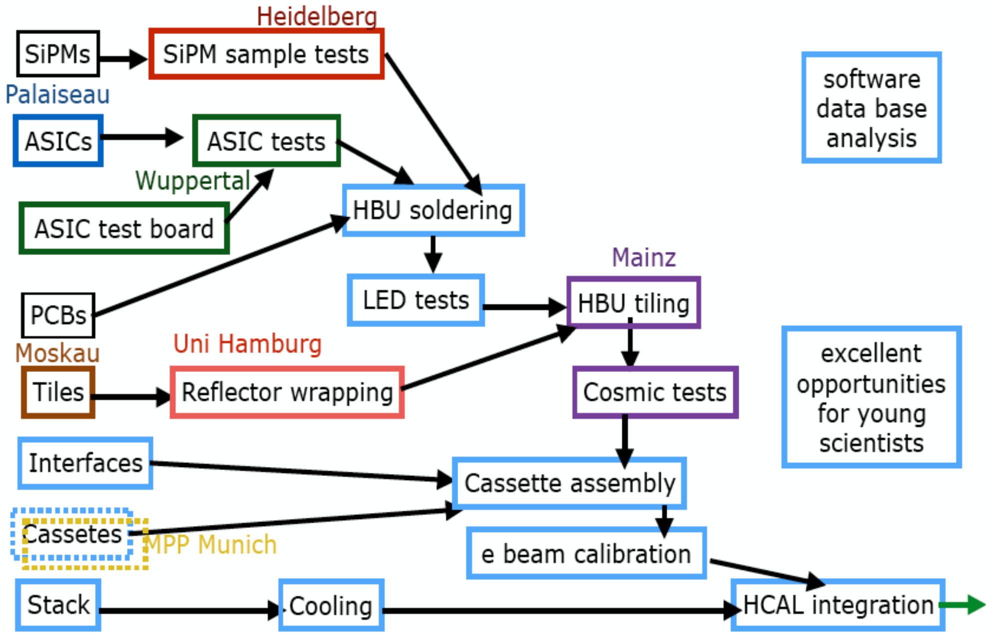
Inconvénients & Solutions

Complexité de mise en œuvre

- industrialisation
  - partiellement commencé avec Si-ECAL, AHCAL pour HGCAL
- assurance QA

Nouveau type de calorimètre

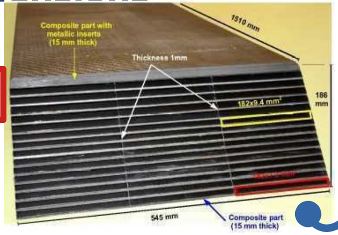
- nv solutions: combinaisons ?
  - Si: PIN-Diode + LGAD,
  - Scint: Orga + Crystaux



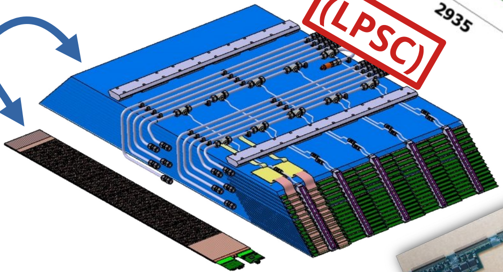
Reste à faire

Prototypes technologique de grandes dimensions

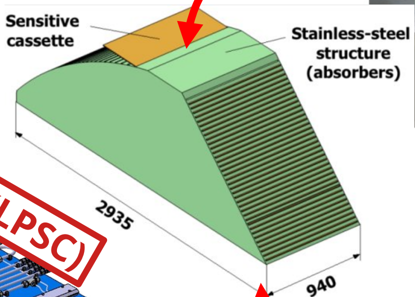
LLR

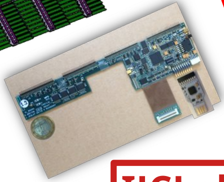


LLR + IJCLab



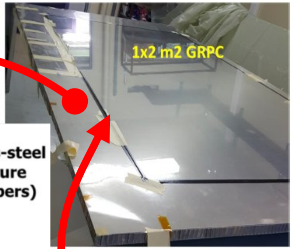
(LPSC)

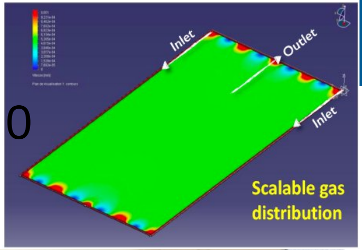


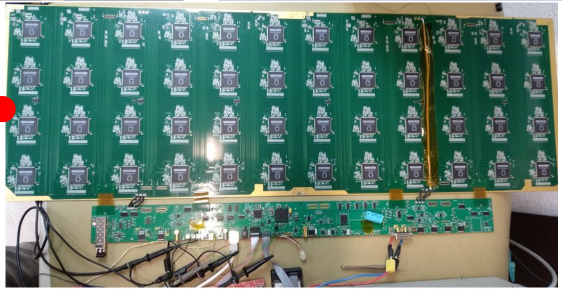


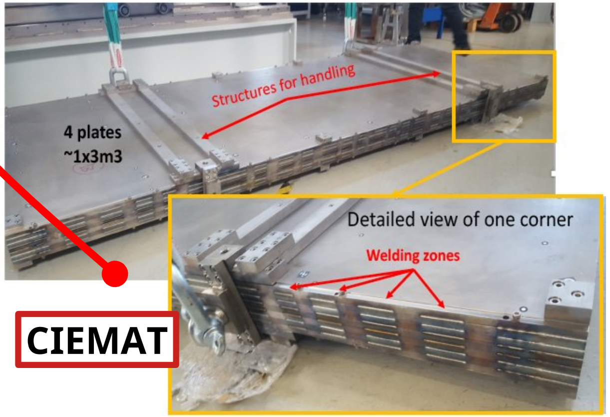
IJCLab

IP2I









CIEMAT

Electron beam welding

Pilotes (« modules-0 »)

- 3×1m² HCAL's
- 1.5×0.2m² × 3–5 ECAL

Intégration du «timing centimetrique» : 1 cm = 30 ps.

- Partout ?
- Couche(s) dédiées ?

} **Besoin d'études approfondies**

Electronique « v3 » Ωmega

- full 0-suppr, power, timing, nv techno (AMS → TSMC)

Conclusion

Technologies matures

- mais place pour amélioration (et donc groupes)
  - Timing
  - Algo
  - Techno

Travail d'affinement / optimisation

  - fait pour ILC 250~500 GeV → 90 (Z), 360 (top)
  - coûts / perf.
  - ex: nv techno (wafers 8'')

Bcp de nv techno

- (Si, Crystal, Gas, Elec, DMAPS)
- µ-cooling in calo ?

Bonus

What is a 'CALICE' calorimeter ?

1) It is not a calorimeter

- Calorimetric SYSTEM: **ECAL+HCAL** + (thin) High Performance Tracker (system)

2) Optimised for Particle Flow

- NOT the best calorimeter system (= Best Raw Energy measurement)
- Measurement and Identification of all particles ⊃(esp) in jets, τ, …
  - Best Boson mass measurement $\mathrm{H} \rightarrow \mathrm{ZZ}, \mathrm{WW}; \mathrm{Z}, \mathrm{W} \rightarrow \mathrm{jj}$.

$$\Delta(M_Z, M_W) \Rightarrow \sigma(E_j)/E_j \sim 30\%/\sqrt{E} \sim 3\%$$

3) CALICE = R&D on detectors (prototypes)

SiD, ILD, CLICdet, CECP$_{\textbf{Baseline}}$ = detector concepts implementing CALICE

Detector Parameters

- Cell lateral size
  - Shower separation (EM~2×cell size)
  - Cell time resolution (3cm/c ~ 100ps)
    - Time performance for showers
      - ParticleID, easier reconstruction
- Longitudinal segmentation
  - sampling fraction
    - E resolution (ECAL ~15%/√E)
  - shower separation/start
- ECAL inner radius; Barrel Z_{Start}
- ECAL–HCAL distance
- Barrel–Endcap distance
- Dead-zones sizes (from Mechanics, Cooling)

Number of cells ↗ ⇒ Cost ↗
Cell density ↗ ⇒ Power consumption ↗
Time resolution ↘ ⇒ Power ↗

thr. passive vs active cooling
dead-zones ↗

Inner Radius ↗ ⇒ Tracking performance ↗
Cost ↗² (⊃ Magnet, Iron)
Gaps ↗ ⇒ PFlow performances ↘

NEED TO BE FULLY RE-EVALUATED

Review of physical implication (from TeV): see Linear collider detector requirements and CLD, F. Simon @ FCC-Now (nov 2020)
Physics Requirement studies @ 250 GeV: see Higgs measurements and others, M. Ruan @ CEPC WS, (nov 2018)

Particle Flow Approach

Full Reconstruction of single particles

- Charged mostly from tracker
- Neutrals only from calorimeters

Large Tracker

- Precision and low X_0 budget
- Pattern recognition

High precision on Si trackers

- Tagging of beauty and charm

Large acceptance

HG Imaging Calorimetry

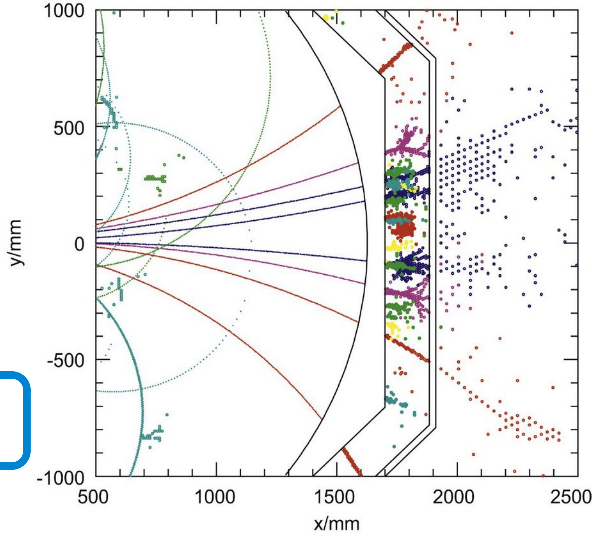
Particle Flow Algorithms :

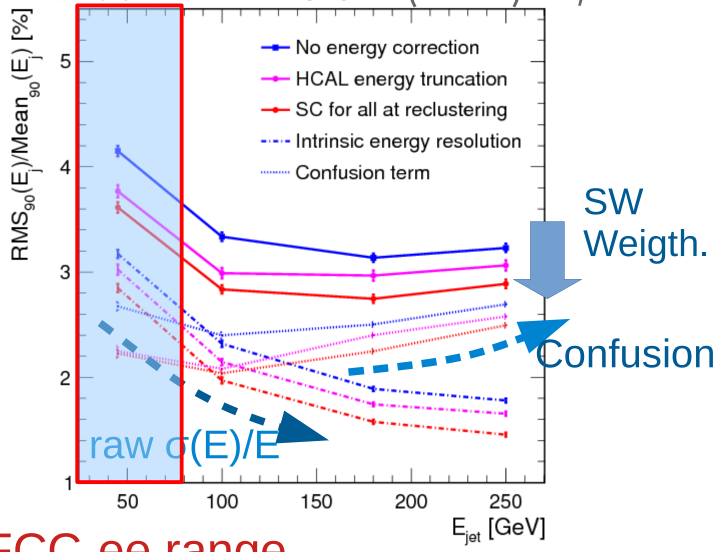
- Jets = 65% charged Tracks + 25% γ ECAL + 10% h^0 E+HCAL
- TPC $\delta p/p \sim 5 \cdot 10^{-5}$; VTX $\sigma_{x,y,z} \sim 10$ μm

+ timing

H. Videau and J. C. Brient, "Calorimetry optimised for jets," (CALOR 2002)

Pandora PFA: EPJ C77 (2017) 10, 698

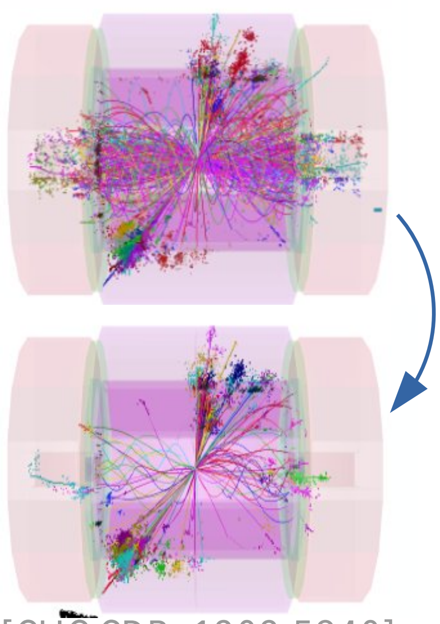




FCC-ee range

Timing in calorimeters: 0.1–1ns range

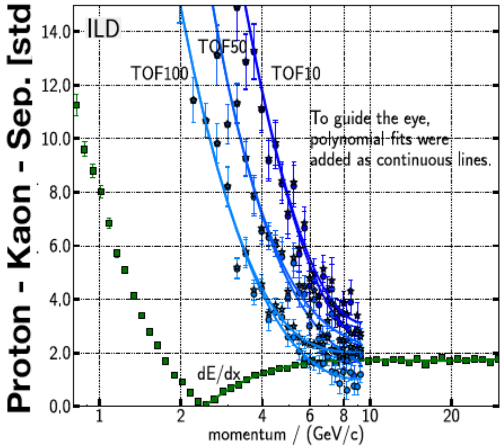
Cleaning of Events



[CLIC CDR: 1202.5940]
adapted from L. Emberger

Particle ID by Time-of-Flight

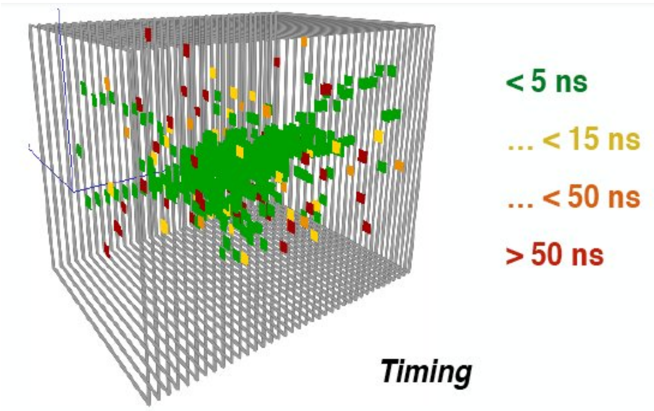
- Complementary to dE/dx
  - here with 100ps on 10 ECAL hits



S. Dharani, U. Einhaus, J. List

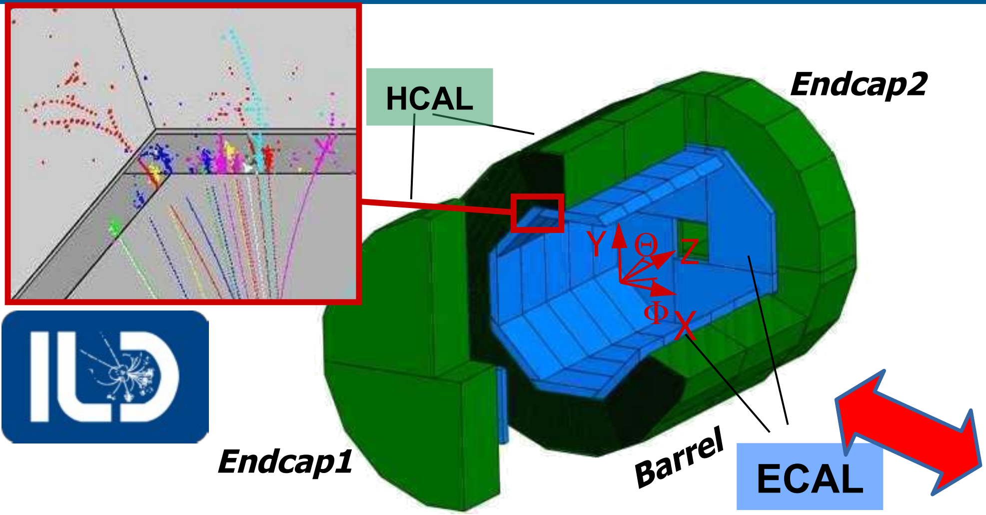
Ease Particle Flow:

- Identify primers in showers
- Help against confusion
- Cleaning of late neutrons & back scattering.



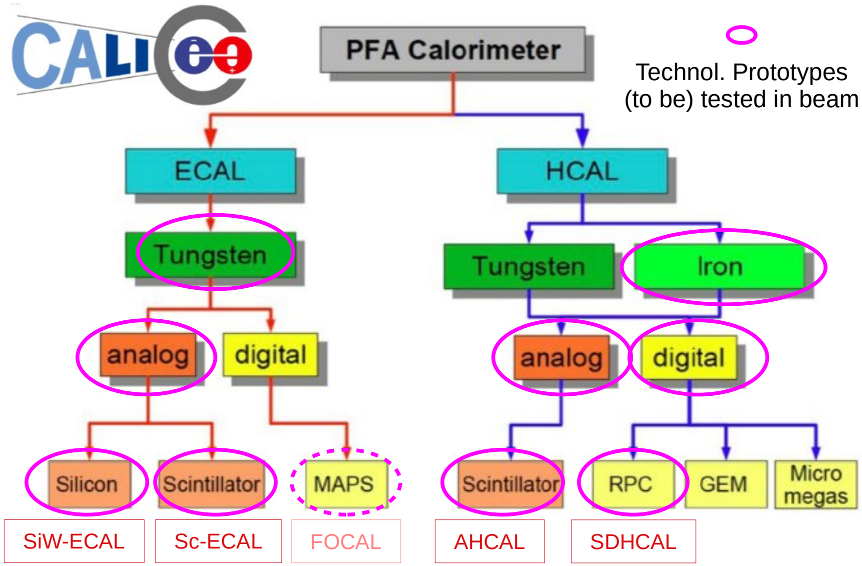
Ch. Graf

Ultra-Granular Calorimeters for Higgs factories: ILD, SiD, CLICdet, CEPC-baseline, FCC



Highly-Granular Calorimeters:

- ECAL @ R = 150–180 cm, |Z|= 200 cm, Thickness~25 cm
  - cell size = 0.5 – 4 cm square (Si) or strip (Sc)
  - 25 – 50 Layers
  - 8 – 70M cells
- HCAL @ ECAL +3 cm, Thickness ~ 150 cm
  - Cell size = 1 – 3 cm, Gas (GRPC) or Sc



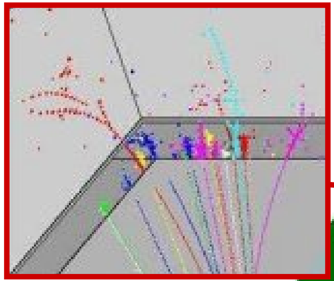
Particle Flow optimised calorimetry

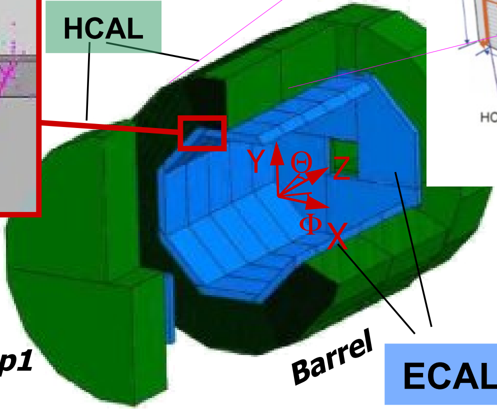
- Standard requirements
  - Hermeticity, Resolution, Uniformity & Stability (*E, (θ,φ), t*)
- Particle Flow requirements:
  - Extremely high granularity
  - Compactness (density)

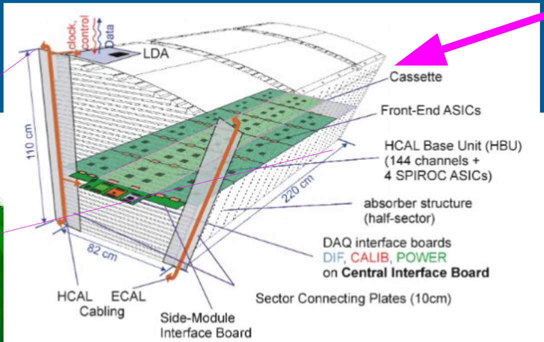
Geometries

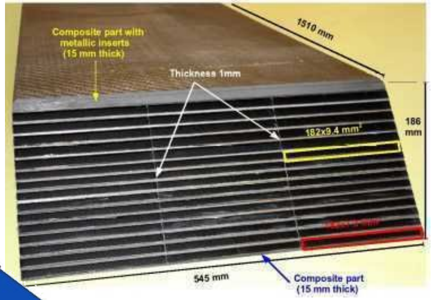
HCAL elec 'accessibilty'

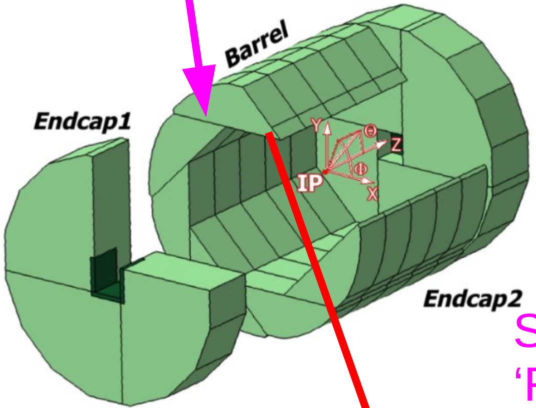
Prism vs diapragm



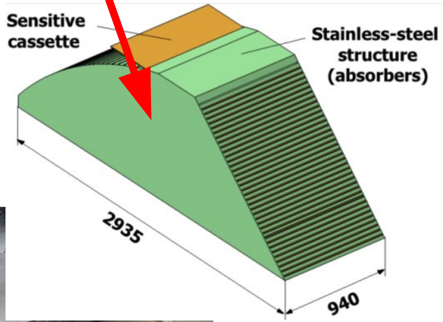


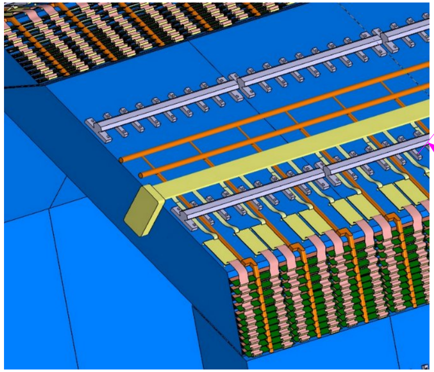


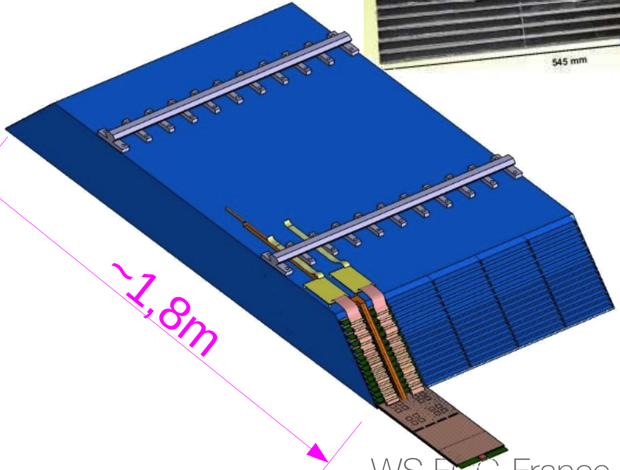




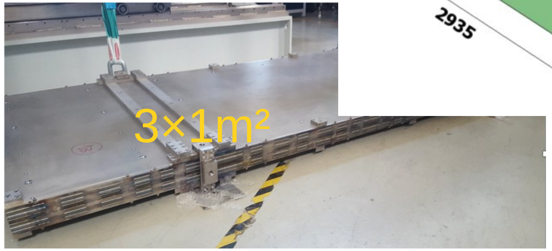
Structural 'Robusteness & Precision'







~1,8m



Electronics & DAQ

Ωmega ASICs:

- A set of ASICs adapted for all CALICE large scale prototypes
  - Gradual improvement
  - Purely digital DAQ
- adapted to ILC conditions
  - **low power** consumption using **power-pulsing (~1%)**
  - **low noise** pre-amp, dual gain 12-bits ADC, ns TDC
  - **self-trigger** with local storage, **delayed** digitization and **read-out**
  - **high integration** (36–64 channels), daisy **chaining** config and readout

R&D:

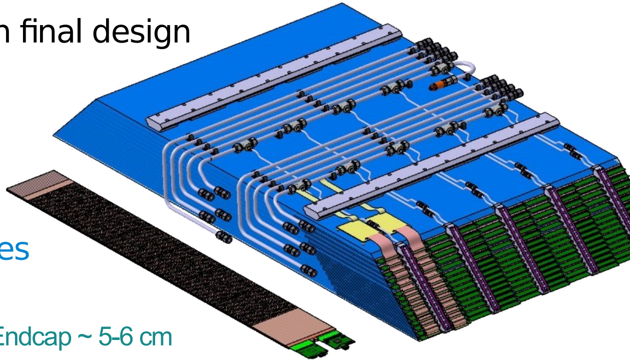
- will required update for final ILC integration:

  ~3^+ years of dev

  - full zero-suppression, I2C bus, new technology
  - Improvement of Timing ? **Learning from CMS-HGCAL ASIC**
- new scheme needed for circular colliders (power, readout)

Technical requirement on prototypes:

- Integration in cassettes 150 – 300 cm long
  - 12k – 27k cells (200–500 ASICs), power pulsed
  - sensitivity to mip signal (tracking)
  - uniformity, stability, linearity
- Reproducibility
  - Typically ~20–50 layers
    - will be ~ 10^4 in final design



DAQ:

- Low power,
  Small size interfaces
  - ECAL-HCAL = 3 cm,
    HCAL–Coil or Barrel–Endcap ~ 5-6 cm
- Single side readout

Pulsed Powering in 3-4T field…

- Passive cooling, local power management

Validation of prototypes: common goals

⇐ many already achieved with physical prototypes

Scientific goals:

- Energy & Time measurements:
  - Linearity & Resolution to single e, π in 1–200 GeV (⇒ input to jet simulations for PFA)
  - Saturation effects
- 5D Shower profiles
- Particle Flow Algorithm (PFA) tests : shower separation, reconstruction, identification

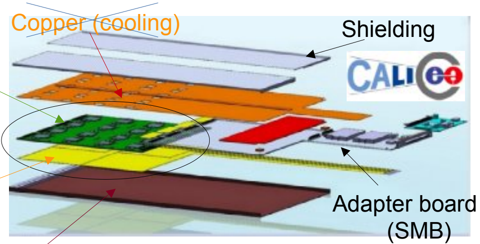
Technical goals:

- Operation of **scalable design** with **power-pulsing**
- **Low-Energy Calibration** with muons **(mips)** position scans, [**High Energy: e, π**]
  - **Signal-to-noise of trigger** (limited memories)
  - **Uniformity**: Efficiency, Mean response (Light Yield, Mip Peak, Multiplicity)
  - Input for **realistic digitization models** ⇒ input to simulation: prototype and Particle Flow
- **Scientific goals (again):** improved granularity, design, etc…
- Running as close as possible to **ILC mode** (200 ns BC), relaxed mode for practical reasons (typ. 4 µs BC)

Silicon-Tungsten ECAL

Prototypes for the ILD/ILC

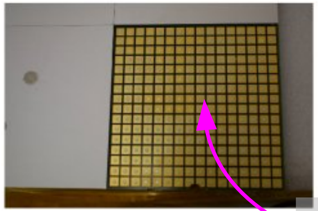
- cells of ~5×5 mm², density = 2.6k–3k cell/dm³
- Ωmega's Skiroc2/2a, 64 ch ASICs
- 25 µW/ch with 1% Power Cycle (0.3W for proto)

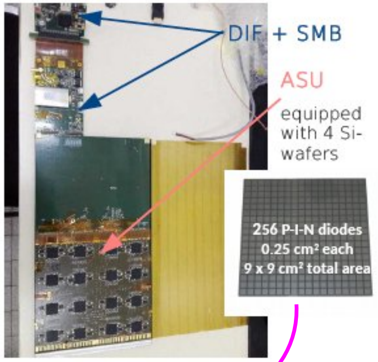


U layout of a **short slab**

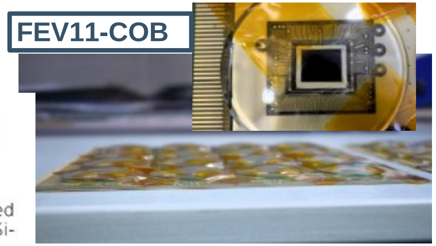
Technological prototype

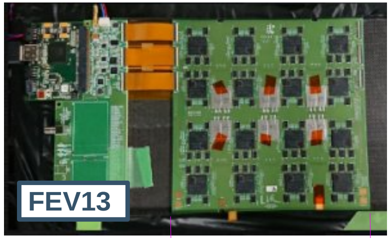
- "Physical prototype" (2005–11): 10k cells, ρ =1.5k cell/dm³
- S/N = $MPV_{mip} / \sigma_{Noise} \geq 10$
- Stacks with **15+7** layers of 1024 ch (15360 cells in a single readout)
  - mix of PCB versions (v10, 11, 12, 13),
    ⊗ packaged and on-board ASIC's
    ⊗ 320, 500, 650 µm Silicon wafers
  - New Integrated DAQ,
    1st prototype toward ILD-like (≤3cm)



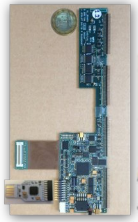


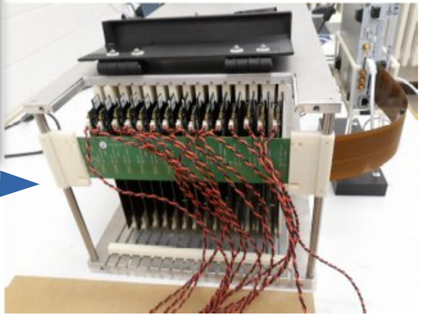
Glued, w floating GR

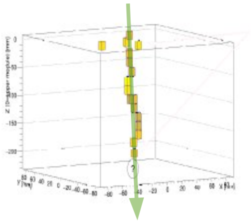


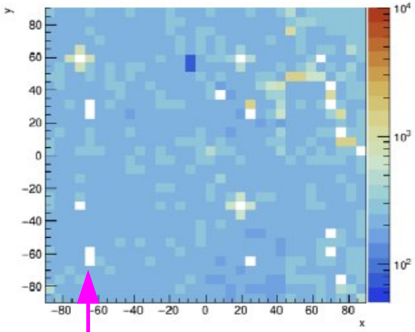


183mm







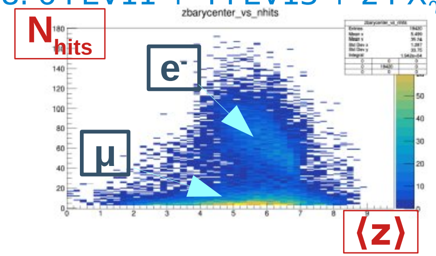


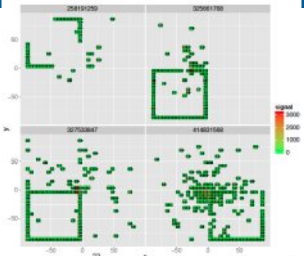
Noisy cells removed ~ 1–3 %

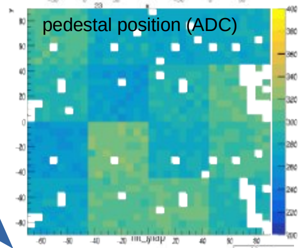
Silicon-Tungsten ECAL: Developments

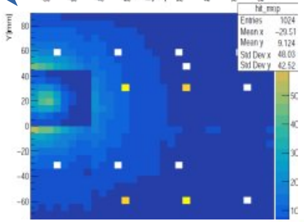
Improvement in design

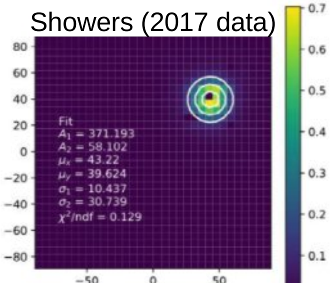
- CERN 2015 “naked FEV11” (320 µm)
  - S/N_{ADC} ~ 16–17
  - Ring X-talk / 10 wrt Phys. Proto.
- CERN 2017: 7 FEV11 (320 µm)
  - S/N_{ADC} ~ 20.3 ± 1.5
  - 8% masking, 1T operation
- DESY 2018: 7 FEV11 + 1 FEV13 (650µm)
  - S/N_{ADC} ~ 30.3 – 40;
  - S/N_{TRIG} ~ 11.6±0.7 ⇒ Cut ~ 1/3 mip @ 4σ
- CERN 2018: 6 FEV11 + 4 FEV13 + 24 X_0 W









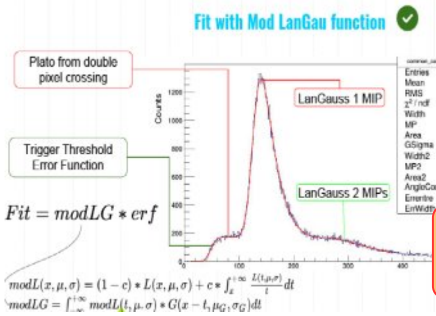


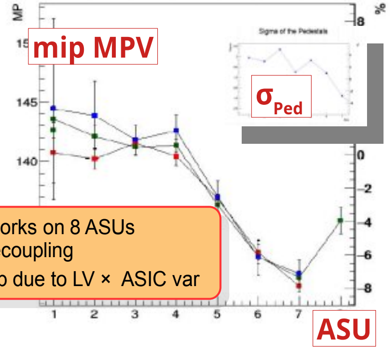
Ready for physical beam test

- March 2020 † ⇒ ~~Nov 2020~~ + 2021

Long Slab

- 8 ASU’s with baby wafers (2×2cm²)





- Readout works on 8 ASUs with HV decoupling
- ~10 % drop due to LV × ASIC var

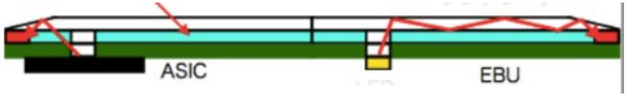
- ⇒ **Improved design (Power, Clock) started**

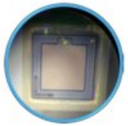
R&D Highly Resistive Silicon Diodes:

- Ref = Hamamatsu “Guard-Ring-less” design
- 6” Towards 8” (à la CMS-HGCAL) × 725µm ?
  - ⇒ cost, design, perf.

Scintillator-Tungsten ECAL

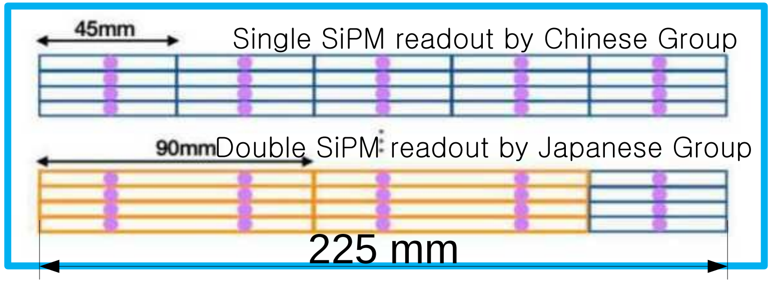
Prototypes for the ILD/ILC & Cl





Baseline SiPM
Hamamatsu S12571-010P
- size: $1mm \times 1mm$
- pitch: $10\mu m$
- number of pixels: 10K

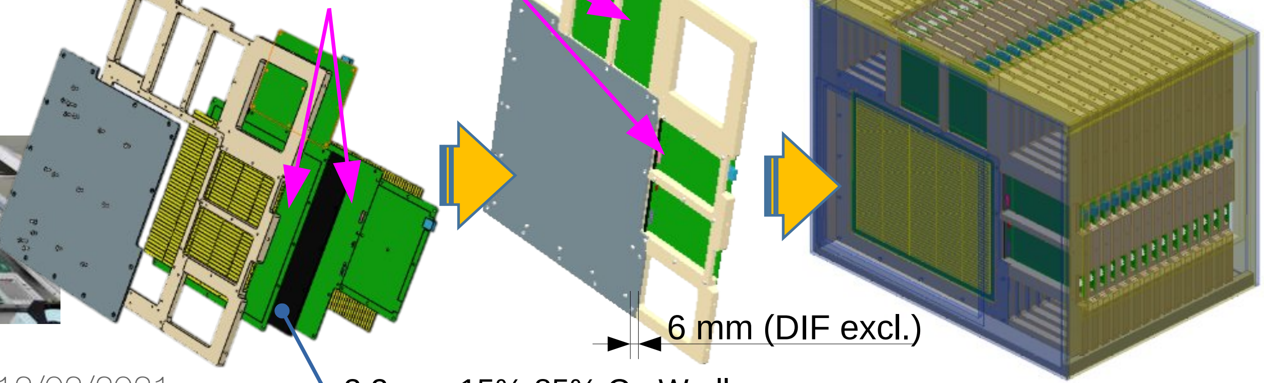
- Ωmega's Spiroc2e, 36 ch ASICs
- 25 µW/ch with 1% Power Cycle
- cells of ~5×45 mm², ρ = 450 cell/dm³



Technological prototype

"Physical prototypes" (2005–11, 2013–15)

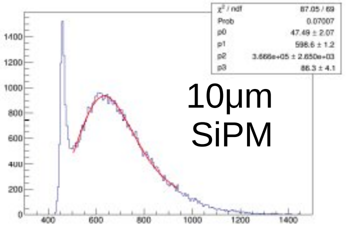
- Stack with 32 layers ready
  - aging test made (48h @ 50°C)
  - being assembled

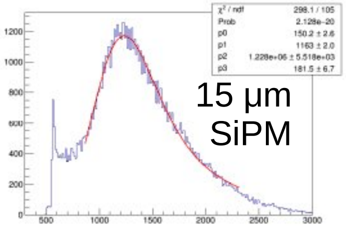


ScECAL: commissioning

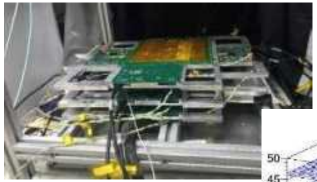
Sr90 Source

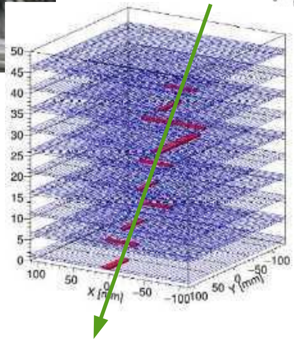
– 25 ns shaping
  auto-trig
  Landau ⊗ Gauss

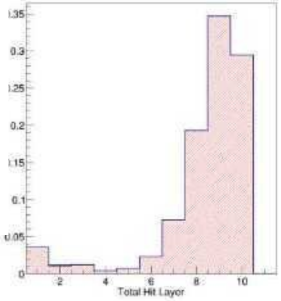




Cosmics test







Beam tests

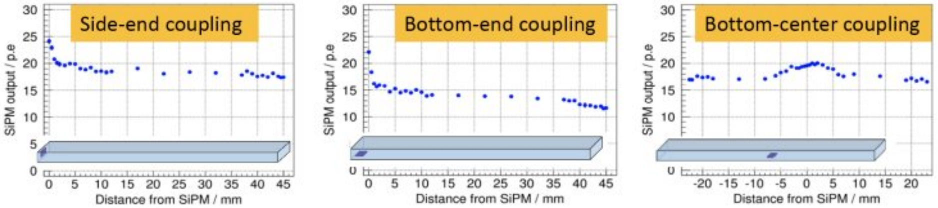
– DESY beginning of 2021 … if travel is permitted

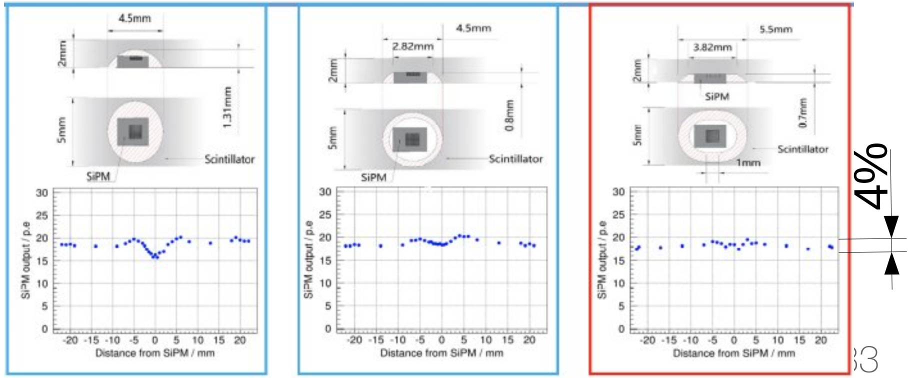
R&D:

– Scintillator – SiPM coupling

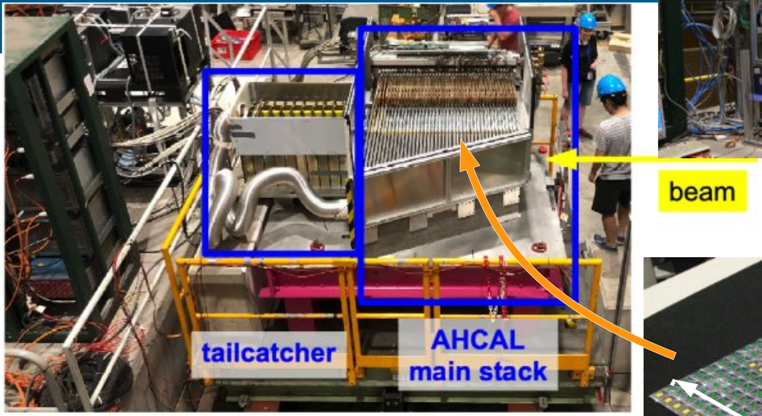
  – non-uniformity ⇒ σ(E) ➚

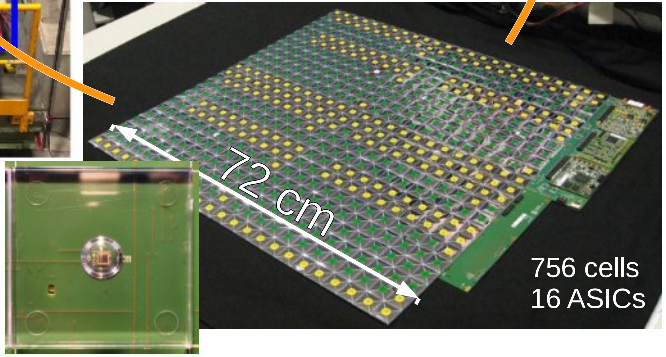
- SiPM position





Scintillator AHCAL





For ILC and CMS

- ILC with Ωmega SPIROC2e
  - HL-LHC will be Ωmega HGROCv3
- 3×3 cm², density ~ 55 cells / dm³

Technological prototype ≥ 2017

Physics prototype ~ 2006-11 (3×3 + 6×6 + 12×12 tiles)

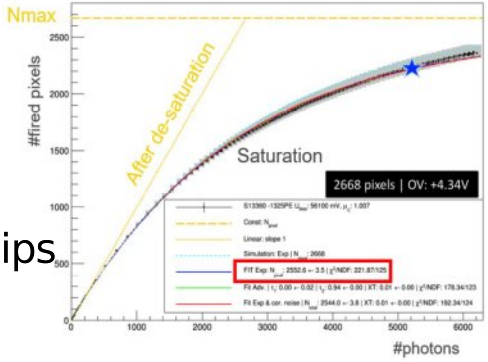
- Uniform 3×3 cm² tiles (moulded) read by SiPM mounted on PCB
- 38 layers of 0,7×0,7 m², 22k cells
  - + additional layers of 6×6 cm²
- 2018: Stand alone tests and with CMS HGCAL
  - 4λ of stainless steel (1.7 cm ×38)

→ Combined beam test with ECALs when ready
→ Stand-alone with full W structure

Online corrections: on SiPM's:

⇒ EM Lin & Resol.

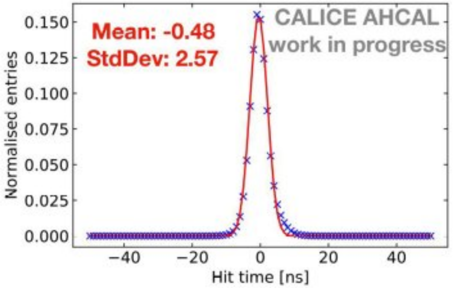
- Gain (Temperature, HV)
- Statistical saturation for $E_{hit} \geq 100$ mips ($N_\gamma \sim N_{pix}$)
  - Corrected for E≤350 mips

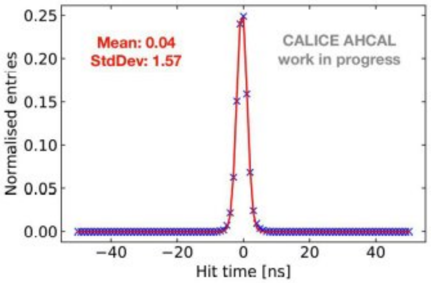


AHCAL analysis

New: Hit time correlation

– Time profile from muons
  - SPIROC : double analog ramp → ADC
  - with clocks
    – at 250kHz (beam test mode) : σ ~ 2.6 ns
    – 5 MHz (ILC mode): σ ~ 1.6 ns



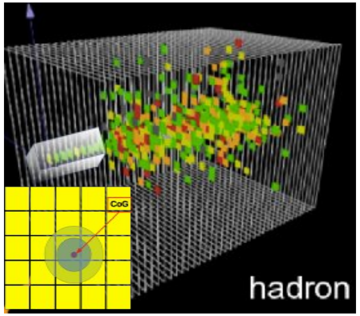


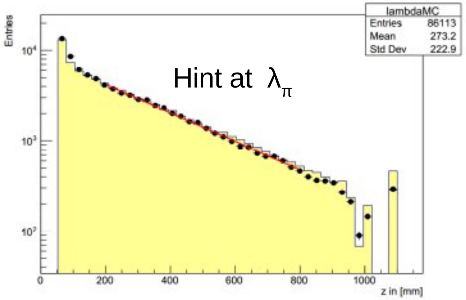
– Goal: 1 ns in ILC mode

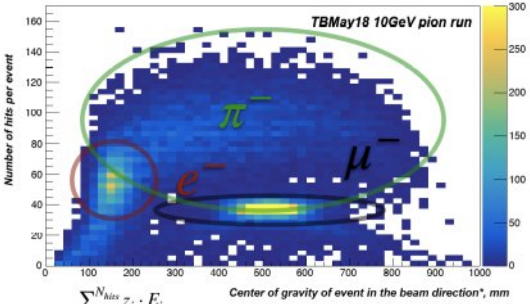
High Level Analyses:

– Shower profiles & PFA tests (≥2011)

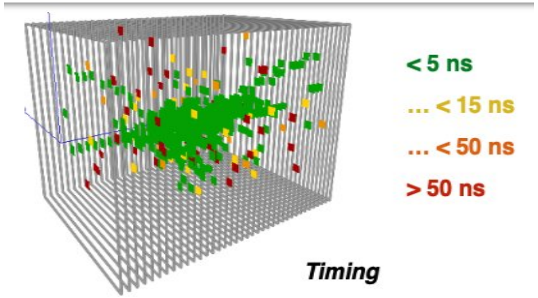
– Shower start, PID, $f_{neutrons}$ (time)



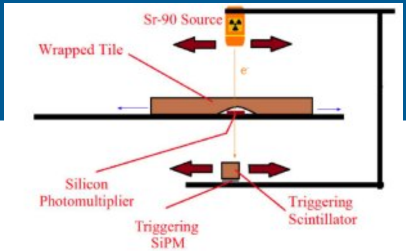


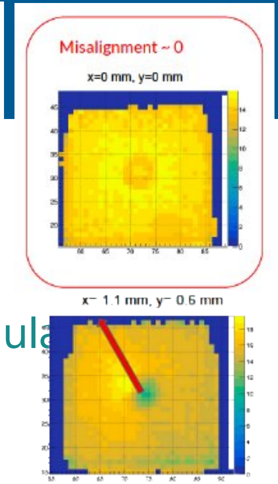


$$* z_{CoG} = \frac{\sum_{i=1}^{N_{hits}} z_i \cdot E_i}{E_{sum}}$$



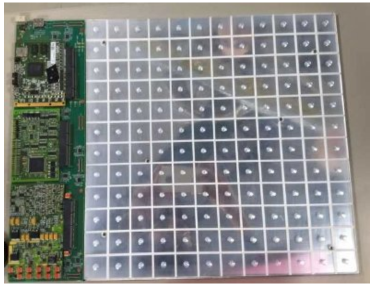
AHCAL developments



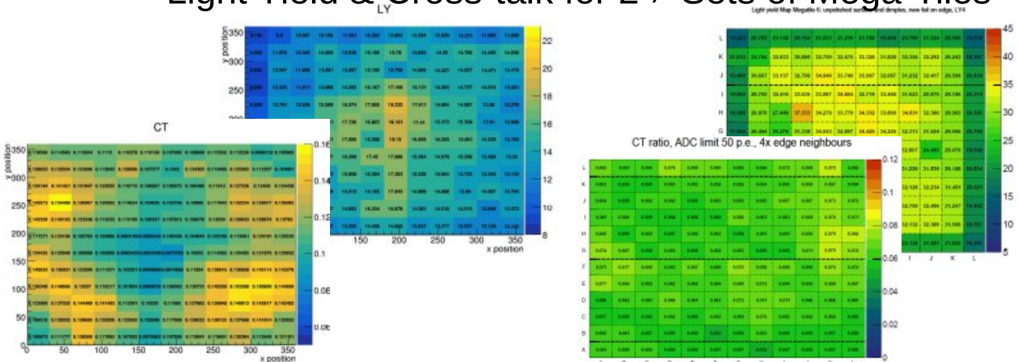


“MegaTiles” R&D:

– Single Scintillator tile with trenches of 3×3 cm²
– 2019 Beam test:
  - Light Yield, Mip resp, Optical Cross-talk
  - Larger Cross-Talk than in cosmics (mechanics)



Light Yield & Cross-talk for 2 ≠ Sets of Mega-Tiles

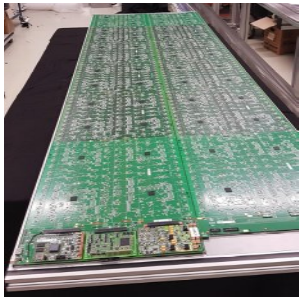


Defects understood; best of both in next beam test (August)

R&D

– Scintillators optimisation
  - Measurements ⇒ Realistic Simula
– SiPM/MPPC evaluations
– ADC consumption (KLAUS Chip)

Long Layer



– 2×6 HBU’s OK in lab…
  - Goals:
    – 3×6 HBU’s (ILD)
    … in a test structure (absorbers)

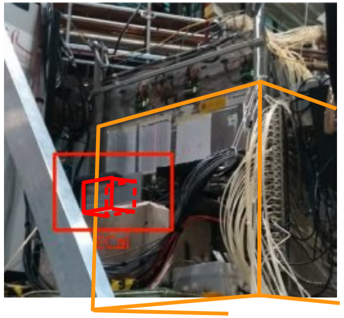
CMS HGCAL:

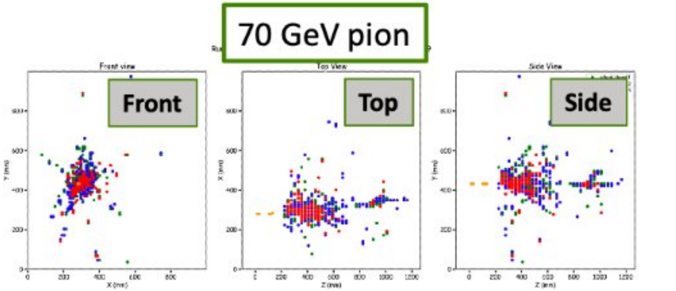
– 1st PCB test in beam in August

SDHCAL: Semi-Digital Gaseous HCAL

Technological prototype ≥ 2011

- Single and multi-gap thin GRPC's
- Cells of 1×1 cm², ρ = 380 cells/dm³
- Ωmega HARDROC2
- 48 layers of 1×1 m², 460k cells, 6λ_I (2 cm Stainless steel)

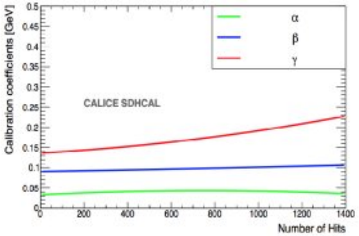




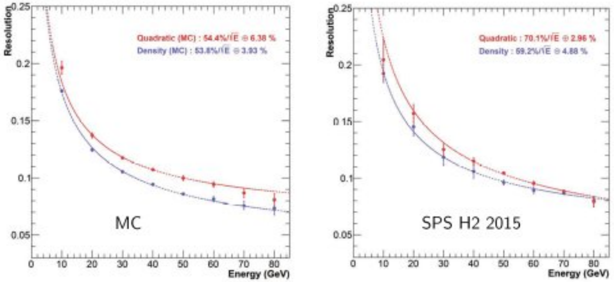
Semi-Digital calorimetry: 3 thresholds

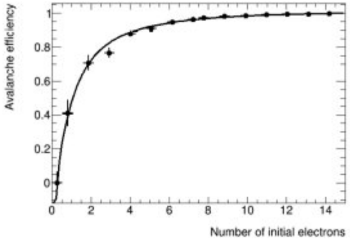
- Uniformity: efficiency & multiplicity
- Threshold optimisations (typ. 1/2 mips, ~5, ~15 mips)
  - and calibration by scans
- Energy measurement:
  - Linearity & Resolution to single e, π, p
  - Simulation: **complex digitization**
    - Large number of overlapping effects in avalanches / readout / time
    - Now, reasonable ≤ 40 GeV e, π

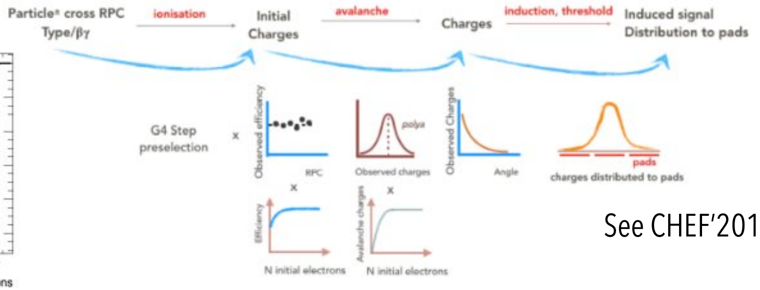
$E_{Quad} = \alpha(N_{tot})\, N_1 + \beta(N_{tot})\, N_2 + \gamma(N_{tot})\, N_3$



$E_{Dens} = \alpha\, B1 + \beta\, B2 + \gamma\, B3$; B_i = Neighbours ≥ thr. i







See CHEF'2019 for details

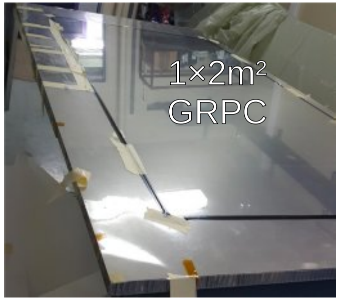
SDHCAL developments

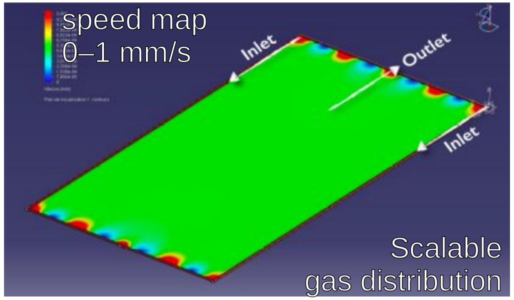
Large cassettes: 1×1 m² → 3×1 m²:

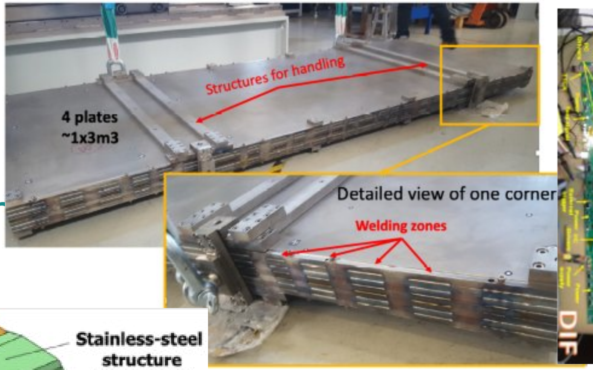
- 432 ASICs HardRoc3:
  I2C, full zero-suppression,
  dynamic range ×3 (15 → 50pC)

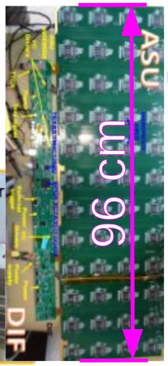
Main goals:

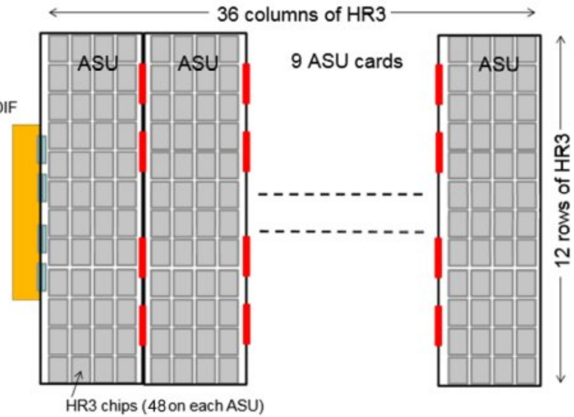
- Sensors: Large uniform GRPC's
- Large & flat PCBs: 32×96 cm²
  - glued on single GRPC chamber
  - interconnections (in 3T field)
- Mechanical assembly
  - Electron Beam Welding

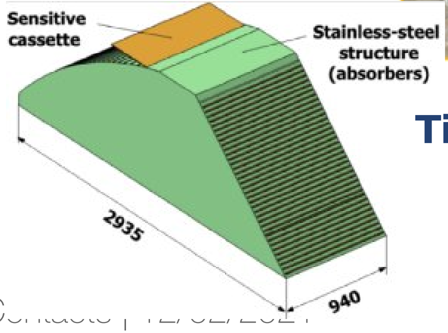












Timing:

Ωmega PETIROC ASIC (20 ps) jitter ⊕ Multi-gap GRPC (60 ps)

Take Home

New version of full technological prototypes getting ready for large BT campaign

⇒ Large knowledge base from previous prototypes & campaigns

within ILC timeline (≤ 5 years of R&D)
and FCC-ee (≤7-8 years of R&D)

Wealth of information, partly explored:

- Digital calorimetry
- in-shower software compensations
- new particle ID variables
- Timing in Calorimeters

Ideal ground for new analysis techniques (Multivariate Analyse, AI)

Many “small scale” R&D

⇒ Model of needed precision (Mechanics, Physics)

CALICE: 15 years of R&D

- have allowed some projects to get a boost
  - CMS HGCAL, Atlas HGTD
- Collaborative approach to realise and compare various ideas & solutions
  - Sharing of information & expertise
    - BT knowledge, DAQ, Simulation & Analysis Tools, …
  - Started as ILC (as in ca**ILC**e)
    - no more directly experiment related Higgs factories, and beyond (FOCAL, CMS-HGCAL)
    - New Topics: timing in calorimeters, Dual Readout, ...
      - Session @ Collab meeting for Outreach.

Vibrant and open community…

ToDo for FCC-ee

Detector R&D

- Power over long slabs
- ASIC's [power]

Detector parameters

- Geometry
- Optimal size ('Tracker vs Confusion') [cost]
- Optimal granularity [power, cost]
- Optimal time accuracy [power]

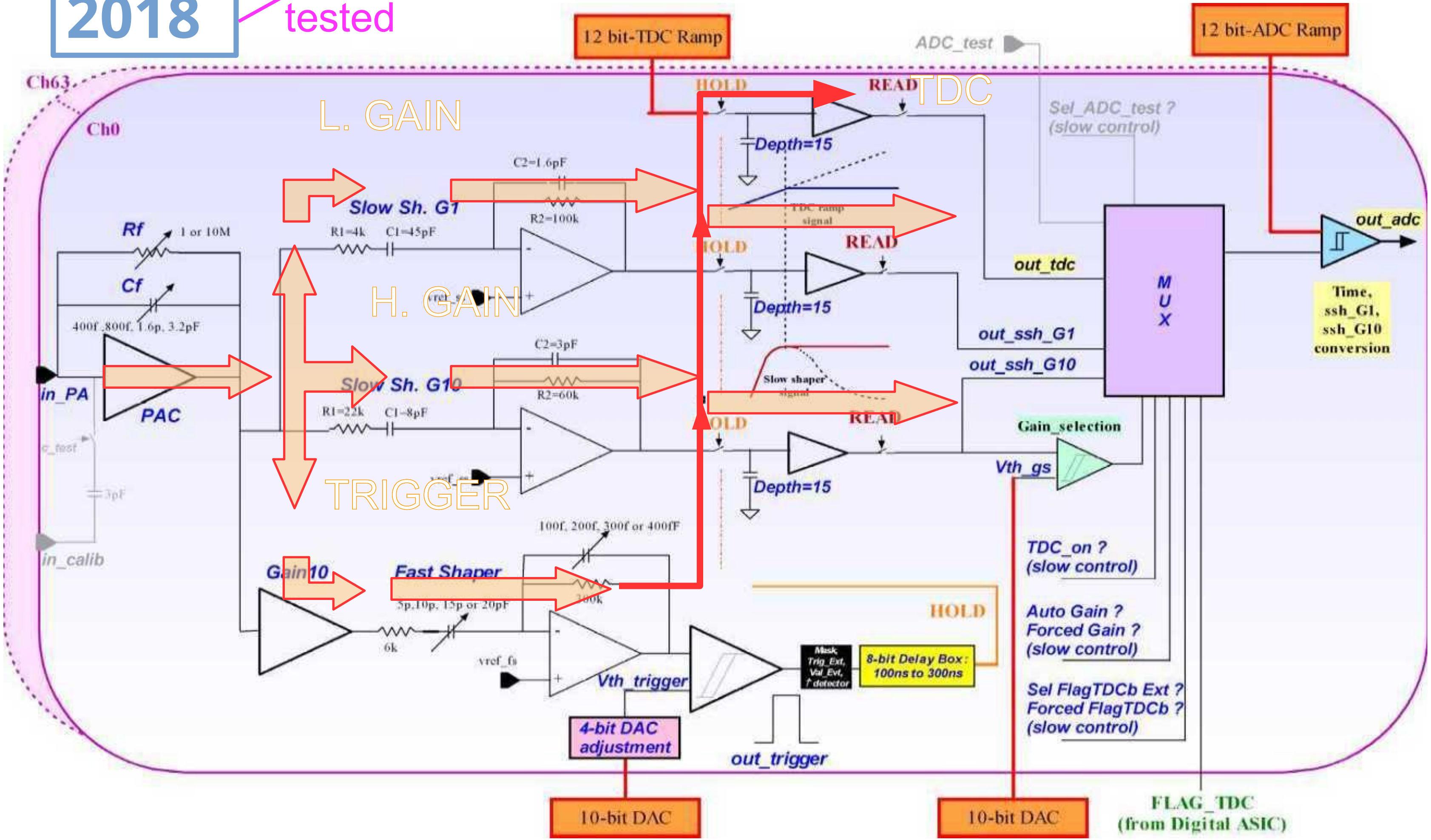
Technical choices

- Sensor types
- Readout scheme
  - Continuous vs Triggered
- Cooling
  - Passive vs Active (CO_2?)

Extras

SKIROC2 / 2A Analogue core

2018 tested

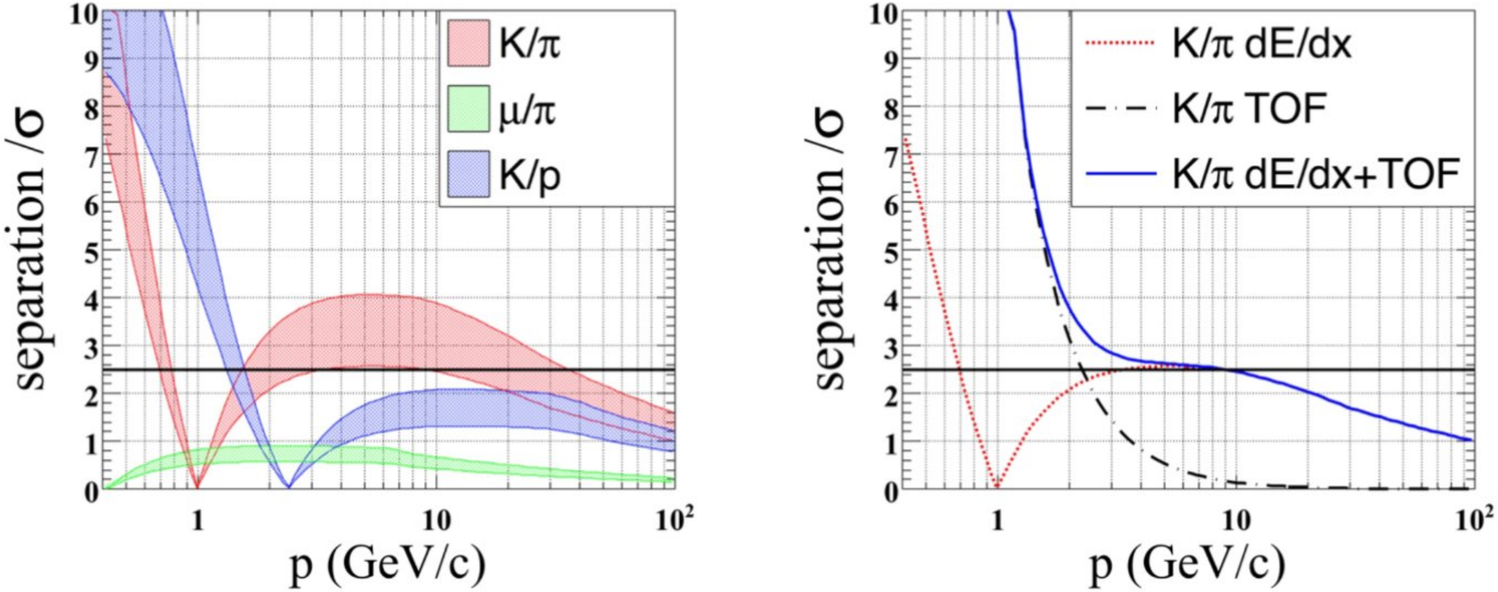


Similar to SiD Kpix

- 64 channels
- Preamp
  + 2 (auto)Gains
  + TDC (~1.4ns)
- Auto-triggered
  - per cell adj.
- 15 (×2) analogue memories
- Low consumption
  - 25 μW/ch with 0.5% ILC-like duty cycle
- Power-pulsed

Not final chip
(full 0-suppr.)

Kaon



Highly appreciated in flavor physics @ CEPC Z pole

TPC dEdx + ToF of 50 ps

At inclusive Z pole sample:

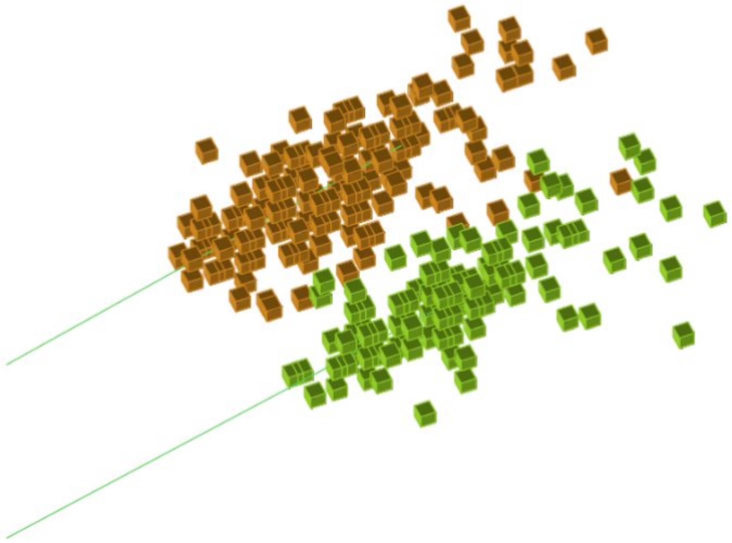
Conservative estimation gives efficiency/purity of 91%/94% (2-20 GeV, 50% degrading +50 ps ToF)

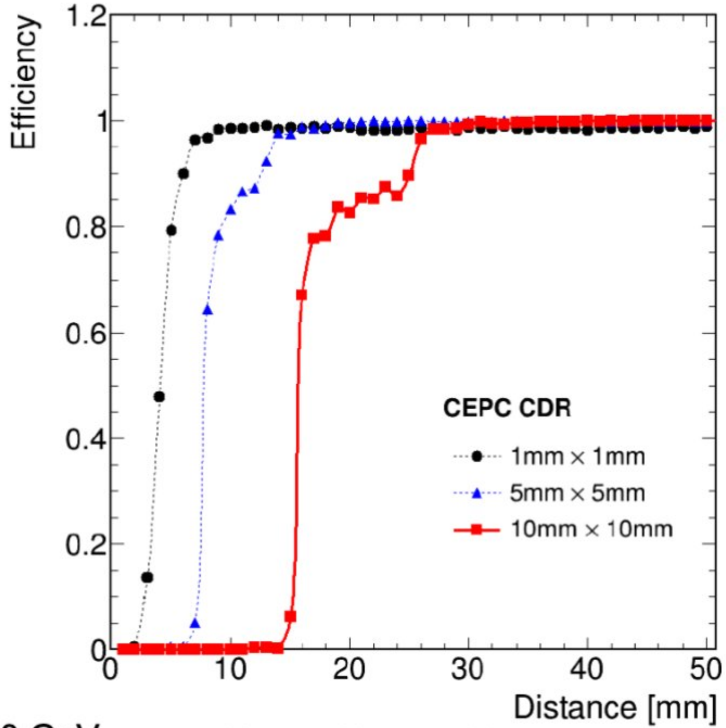
Could be improved to 96%/96% by better detector/DAQ performance (20% degrading + 50 ps ToF)

18/11/19 CEPC WS@IHEP 26

CEPC-DocDB-id: 172
https://arxiv.org/abs/1803.05134
Eur. Phys. J. C (2018) 78:464

Clustering





Critical energy to separate an evenly decay π_0: 30 GeV

See Hang Zhao's talk

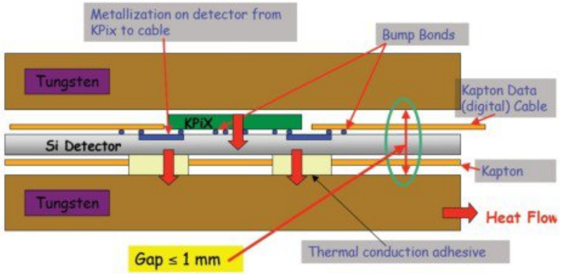
18/11/19 CEPC WS@IHEP 27

SiD SiW-ECAL (not CALICE, but ‘CALICE-like’)

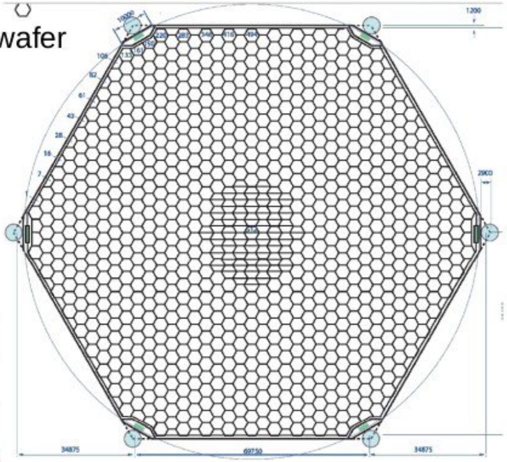
SiD – Si-W ECAL

Design configuration: “(20+10)”, i.e.
- 20 thin W layers (2.5 mm)
- 10 thick W layers (5.0 mm)

} + 30 Si layers



6” wafer

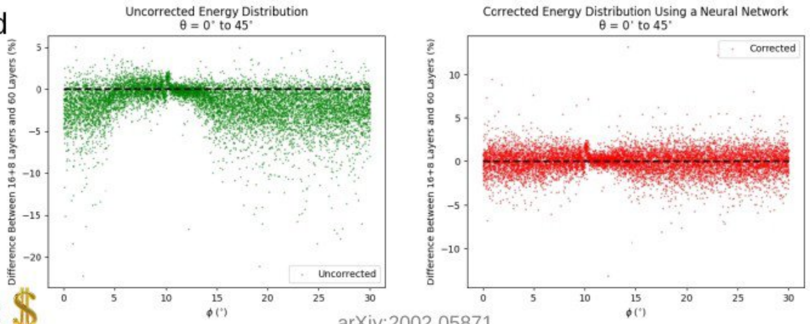


arXiv:1306.8329 - ILC TDR 4: Detectors

Energy leakage of electromagnetic particles estimated by analyzing the patterns in total energy deposition in each layer using neural networks.

(18+6) vs (60+0) GEANT4 models, with:
- energies range: 20 – 300 GeV
- incidence angles $\theta = 0° - 45°$
- azymuthal angles $\phi = 0° - 30°$

Design performance possible with 16+8 configuration: $



arXiv:2002.05871

A crack-less ECAL geometry