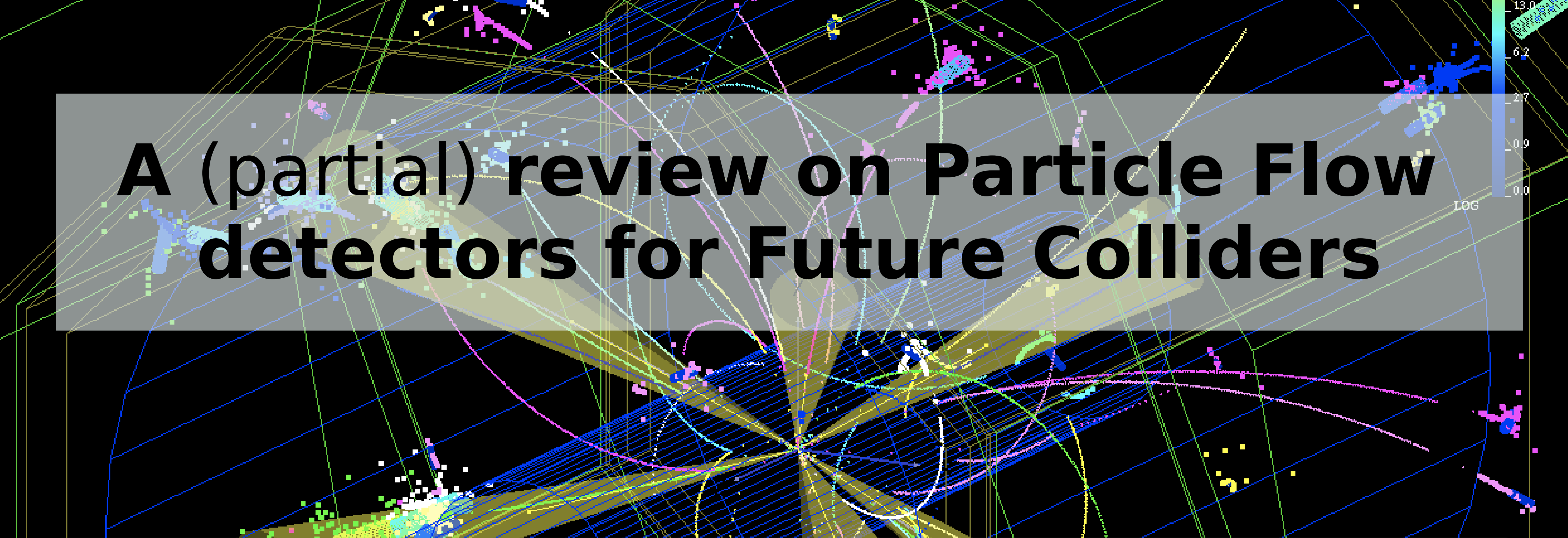
A (partial) review on Particle Flow detectors for Future Colliders



A. Irles,

IFIC Experimental Seminars, 29th March 2021

VNIVERSITAT DE VALÈNCIA

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INSTITUT DE FÍSICA CORPUSCULAR

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

1 **Introduction to Linear Colliders**

2 **Introduction to PFA**

3 **Designing PFA detectors**

4 **R&D on PFA calorimeters**
(technological prototypes)

5 **Benefits of high granularity**
(more than PFA)

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1 **Introduction to Linear Colliders**

2 **Introduction to PFA**

3 **Designing PFA detectors**

More "divulgative"

4 **R&D on high granular calorimetry**

5 **Benefits of high granularity** (besides PFA)

less "divulgative"

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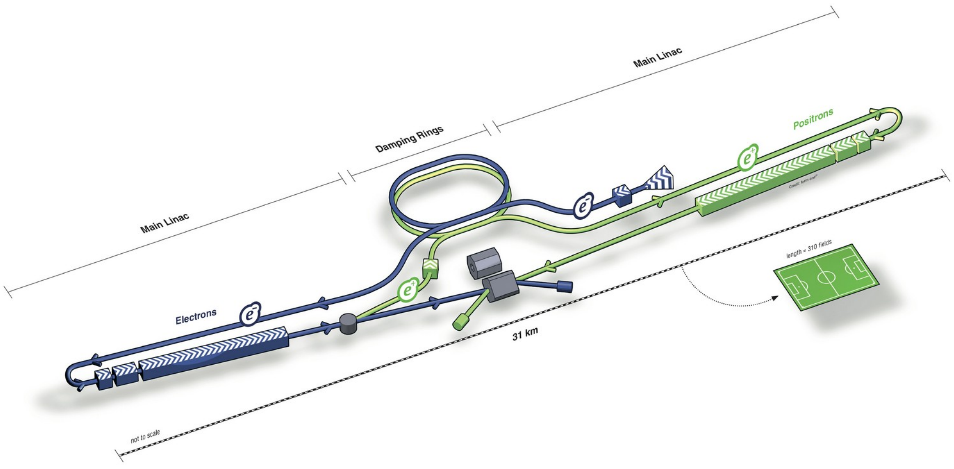
Introduction to Lepton & Linear Colliders



Introduction to Lepton & Linear Colliders

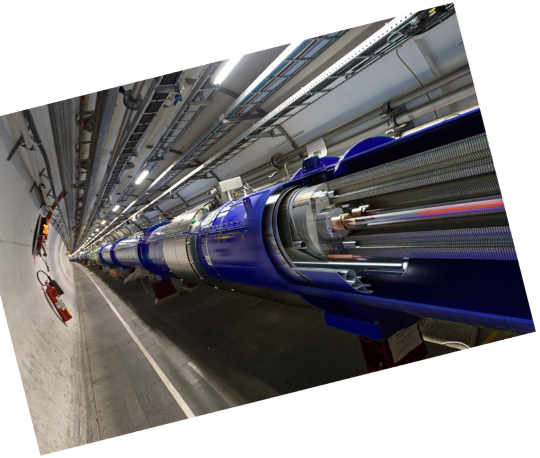
Why emphasis on Future Linear Colliders ?

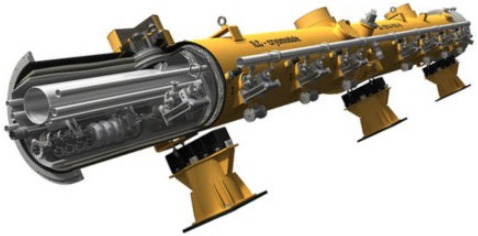
- Personal bias & Lack of time
- More developed future collider projects
- Most of the PFA developments (software & hardware) have been done in the context of LC

However, PFA is also studied and developped for existing colliders (LHC), other future collider projects (CePC, FCC…), and even other fields

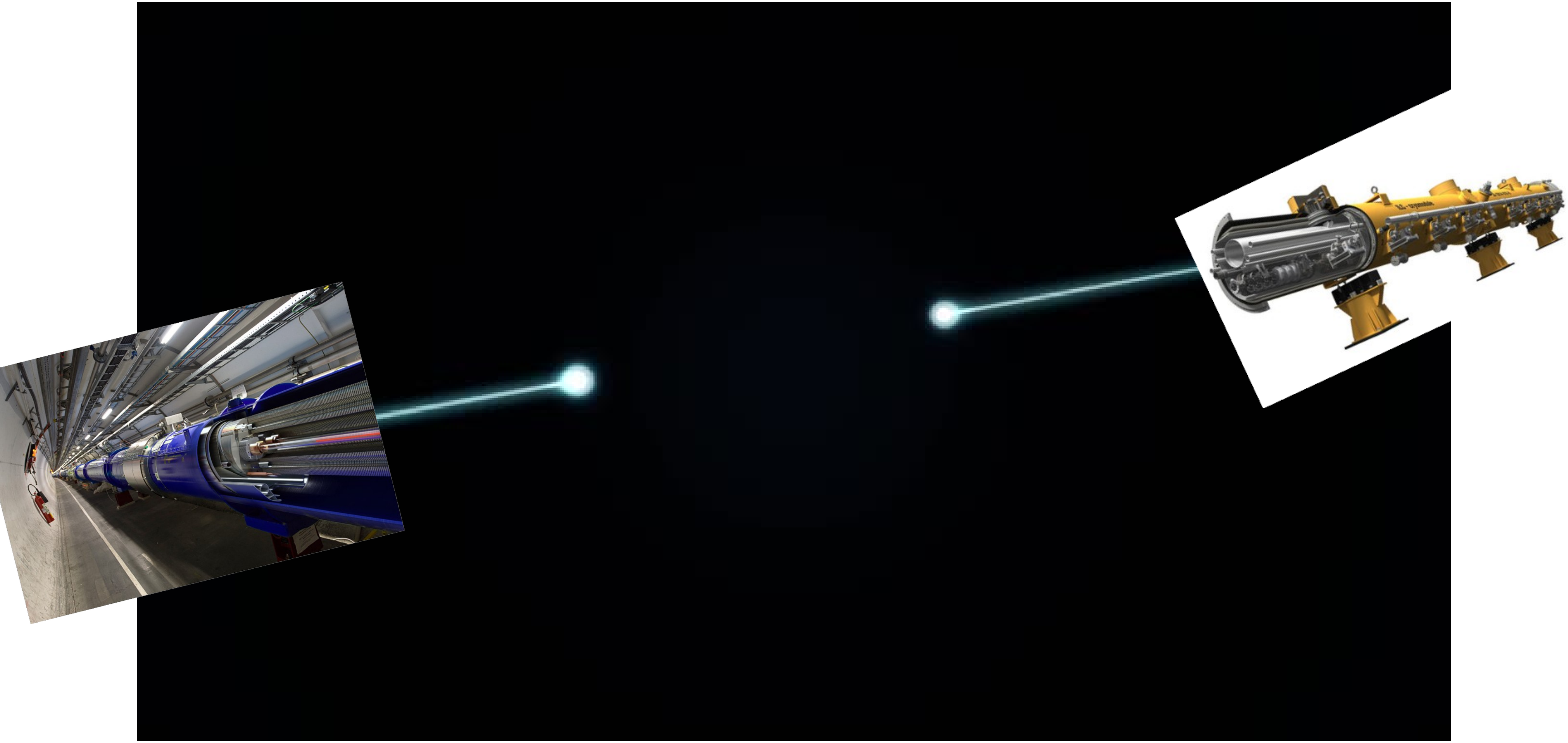
For many reasons we built / project to build Particle Colliders

And we need the best machines

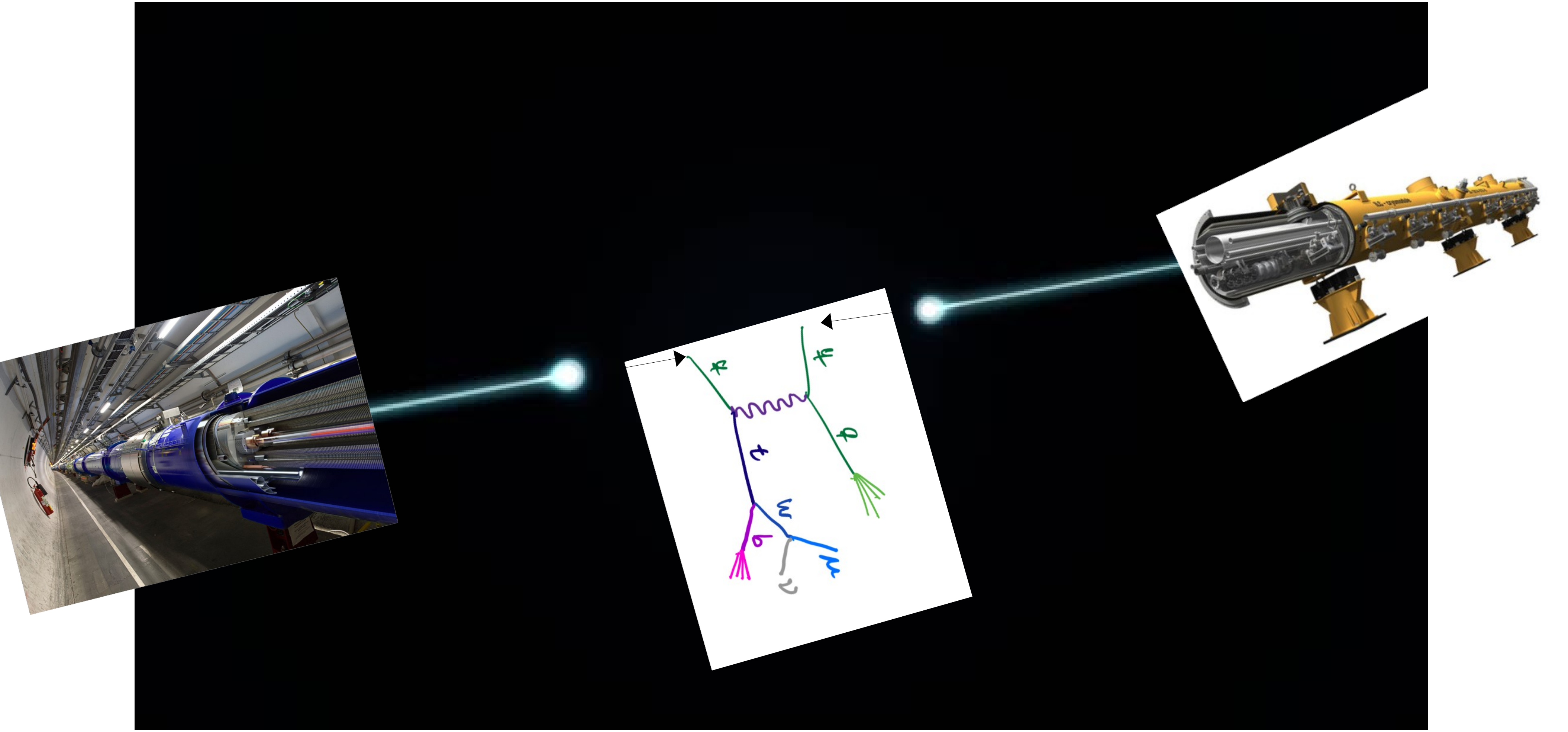




Towards the highest precision in High Energy Colliders

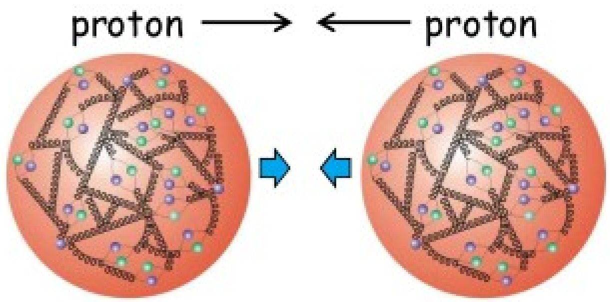


Towards the highest precision in High Energy Colliders



Lepton vs Hadron Colliders

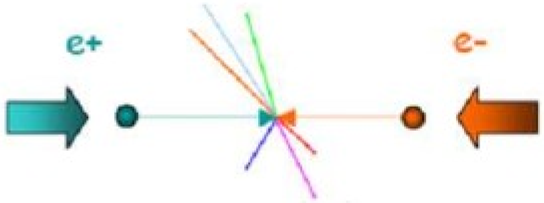
LHC (hadron collider)



collision of two composite particles (with different initial constituents and energies)

electroweak interactions
+ strong interactions

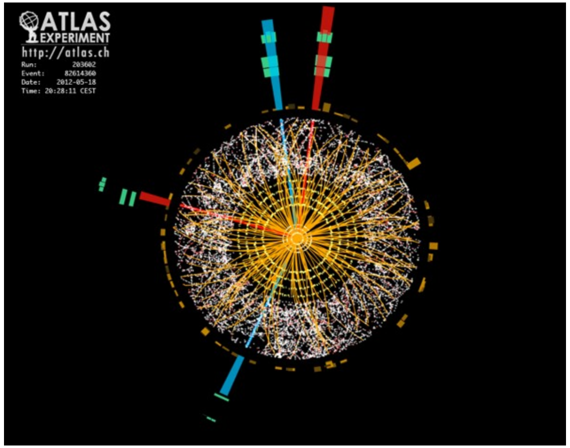
ILC (lepton collider)



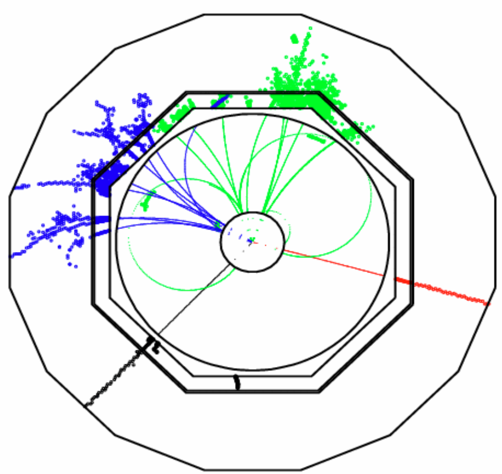
collision of two point-like particles (with exactly defined initial state, quantum numbers and energies)

electroweak interactions

Lepton vs Hadron Colliders



Higgs candidate decaying to 4 electrons (ATLAS 2012))



e-e+ → HZ,
Z → 2 leptons
(ILD simulation)

▶ Hadron Colliders (advantages)

- Larger luminosity (statistics)
- **Larger energy reach**

Energy reach prioritised over precision

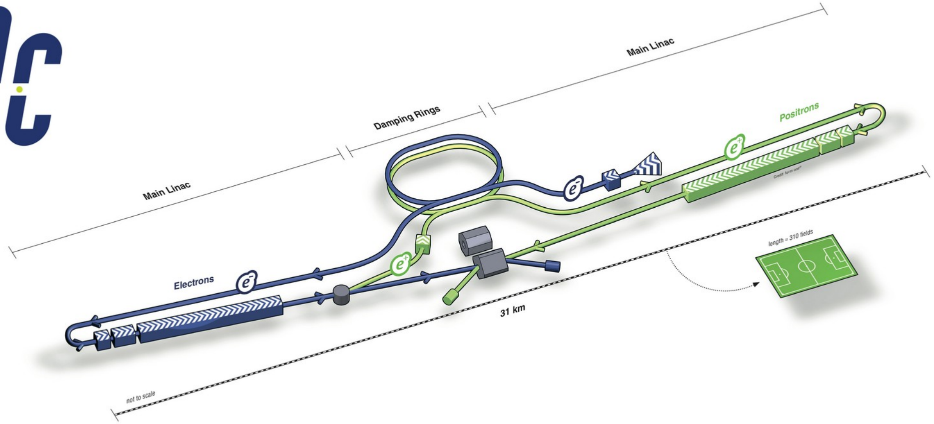
▶ Lepton colliders (Advantages)

- **Well defined initial state (fundamental particles)**
- Well defined interaction energy
- No pile-up, underlying events, etc…

Precision prioritised over energy reach

Linear Lepton Colliders

- Energy: 0.1 - 1 TeV
- **Electron and positron polarisation**
- TDR in 2013
  - + DBD for detectors
- Footprint 31 km
- Initial Energy 250 GeV – *Footprint ~20km*



Under discussion in Japanese Government and international community

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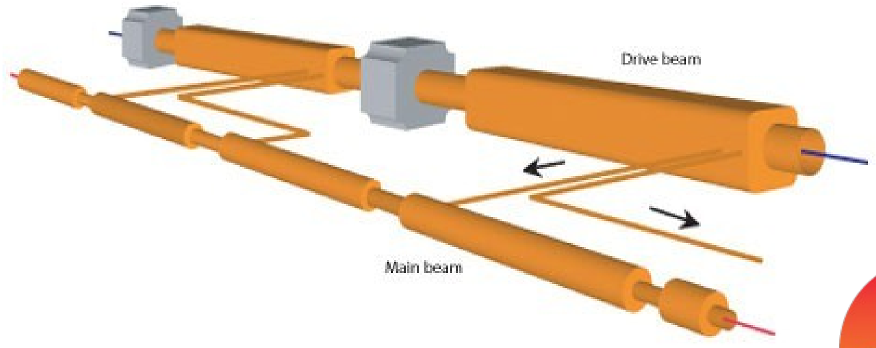


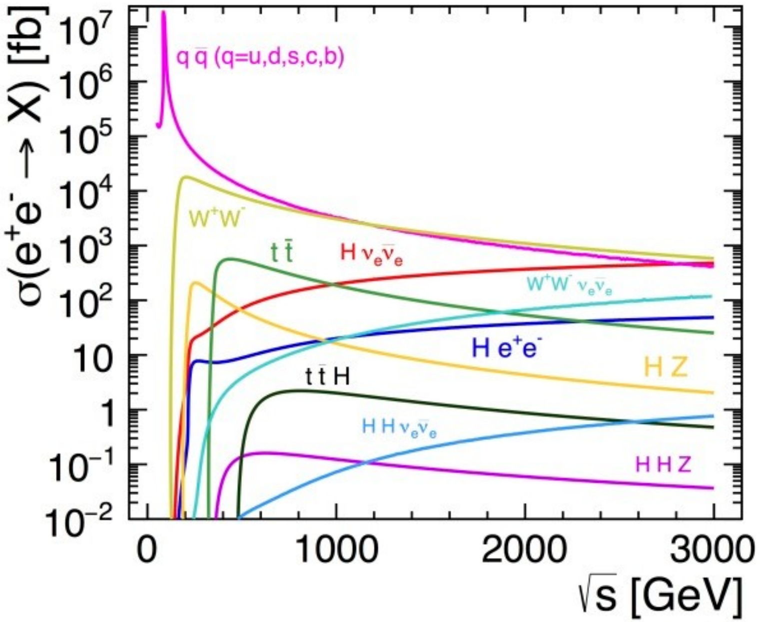
Possible future project of CERN

- Energy: 0.4 - 3 TeV
- CDR in 2012
  - Project Implementation Plan in 2018
- **Electron polarisation**
- Footprint 50km
- Initial Energy 380 GeV – *Footprint ~11km*

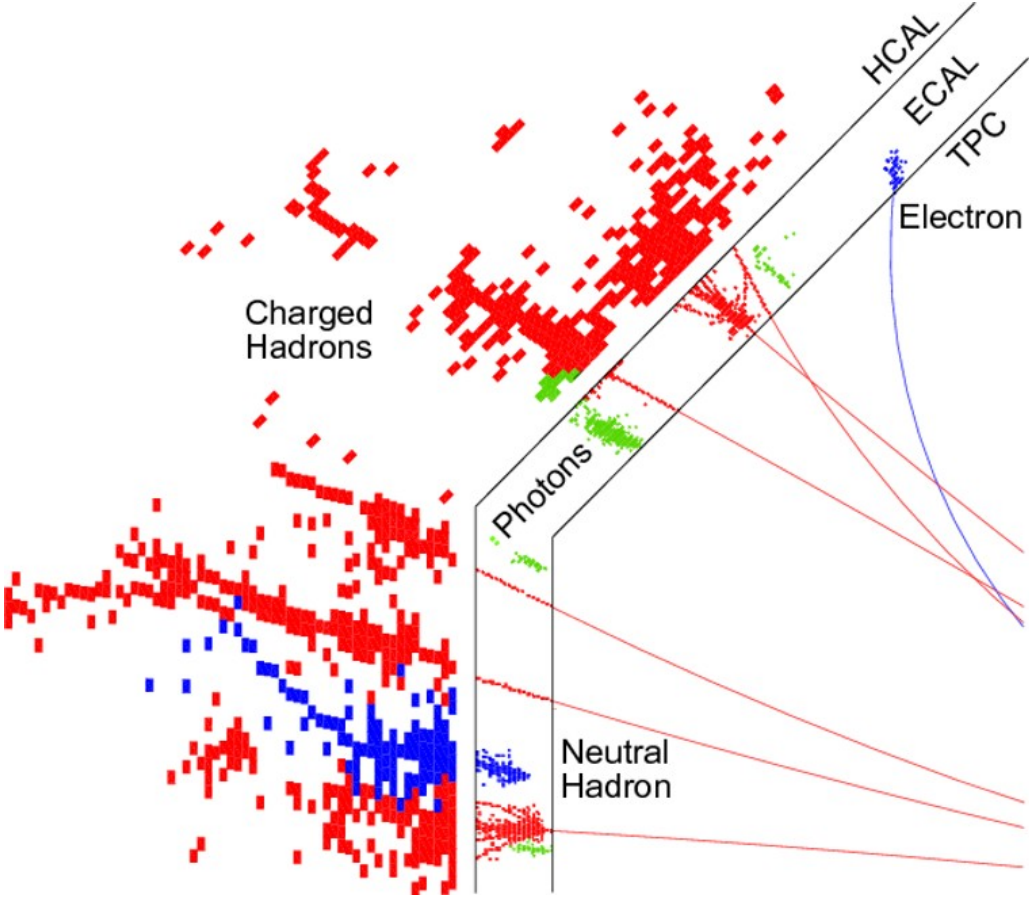
Higgs factories but also...

- **All Standard Model particles within reach of planned LC projects**
- High precision tests of Standard Model over wide range to detect onset of New Physics
- **Machine settings can be “tailored” for specific processes**
  - **Centre-of-Mass energy** & **Beams polarisation** (straightforward at linear colliders)

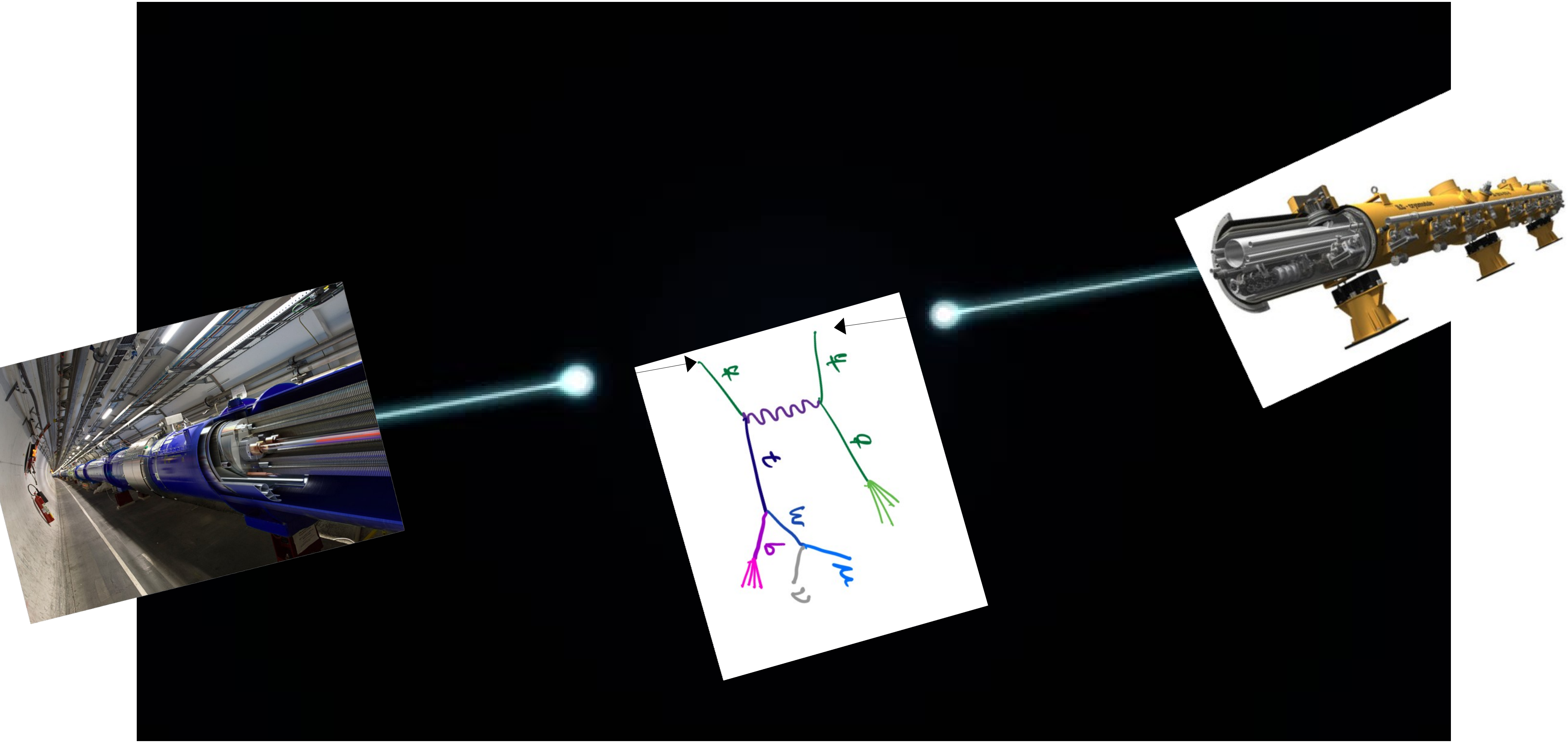
- Higgs factories but also...
  - **“light” qq factory**
    (and Z-factory at Z-pole)
  - **WW factory**
  - **Top-quark factory**
  - **ttH factory**
  - **...**

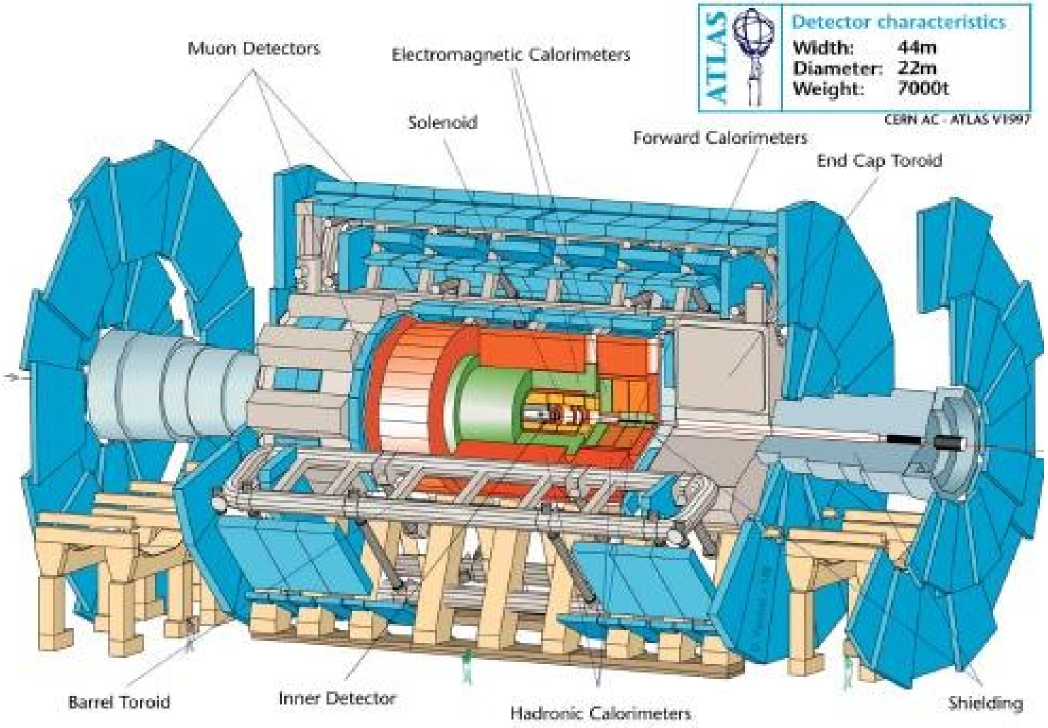


Introduction to the Particle Flow Algorithms (PFA)



Towards the highest precision in High Energy Colliders

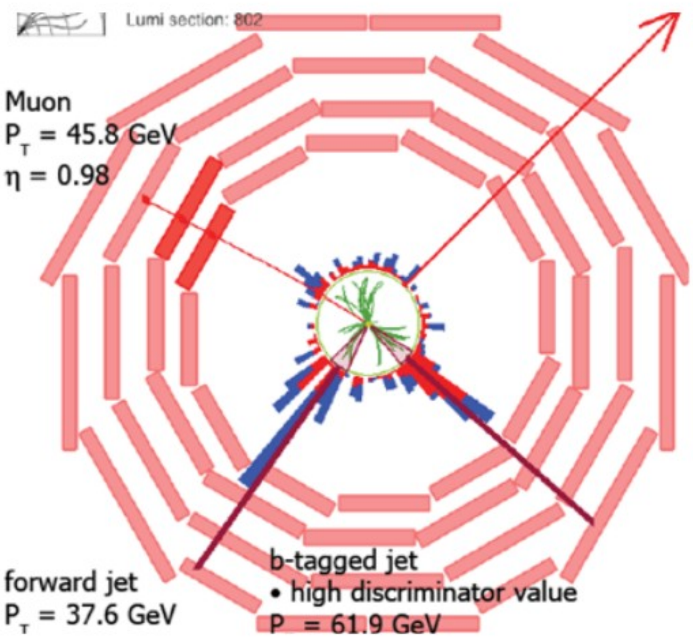


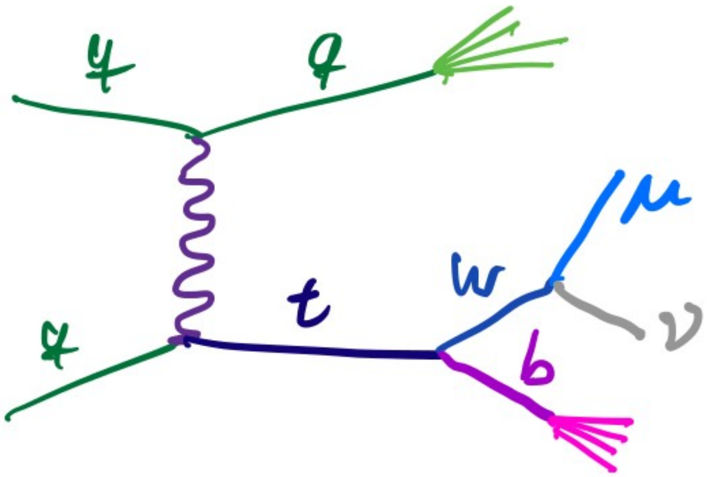


The “tool” to study these collisions:

A Collider Detector

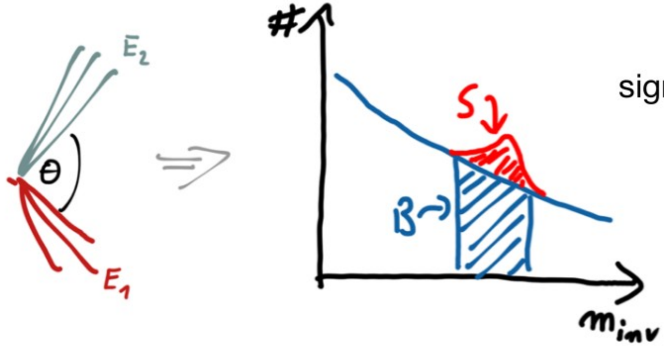
- **Vertex detectors**
  - to identify heavy quarks and leptons
- **Tracking system**
  - to measure the momentum of charged particles via curvature in magnetic field
- **Calorimeter systems**
  - to measure energy of neutral and charged particles via total absorption
- **Muon system**
  - to identify muons, improve momentum measurement





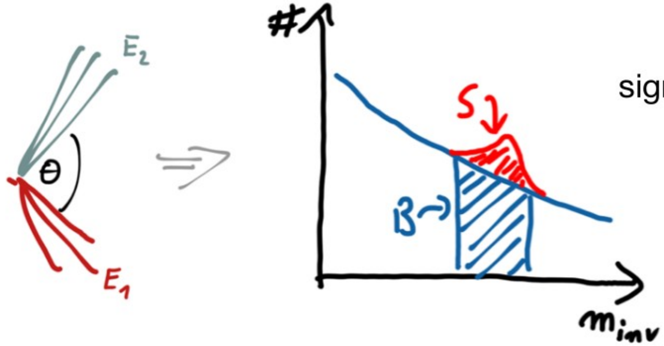
Ideally we would reconstruct every single particle in the event.

In reality: we reconstruct a track (the muon), we detect some missing energy (the neutrino) and we reconstruct two jets ("cones of energy")



significance: $\dfrac{S}{\sqrt{S+B}}$

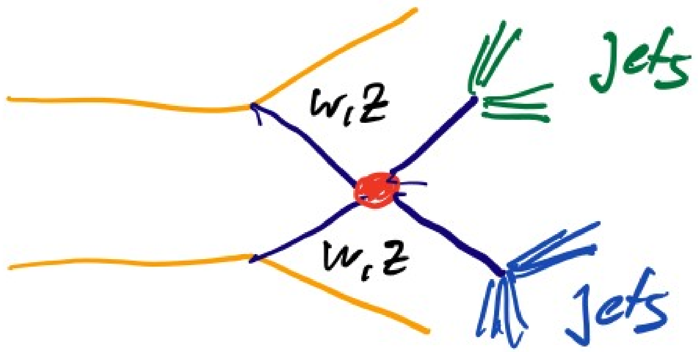
Significance depends on the mass resolution



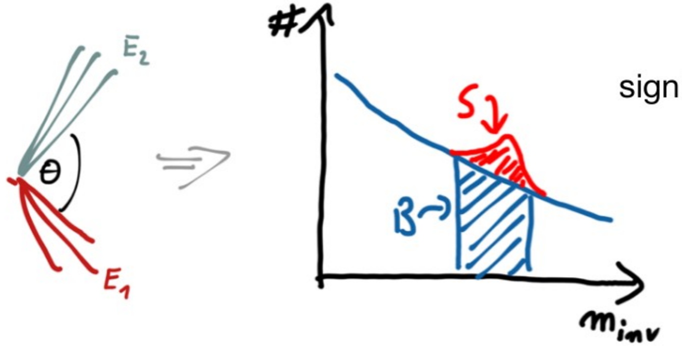
significance: $\frac{S}{\sqrt{S+B}}$

Significance depends on the mass resolution

Typical “PR” example shown by Lepton Collider projects *(aka Higgs Factories)*



In e+e- colliders, we will study the processes
e+e- –>
HZ
ZZ
WW
...



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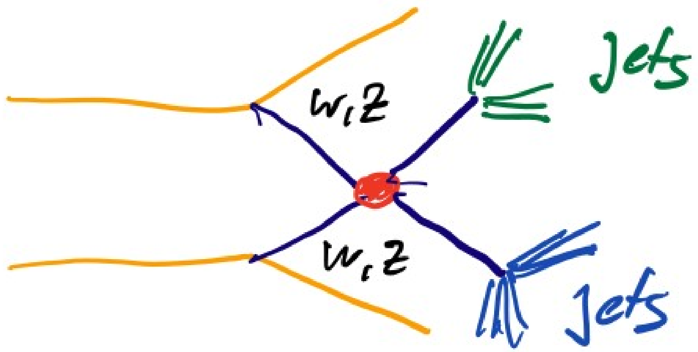

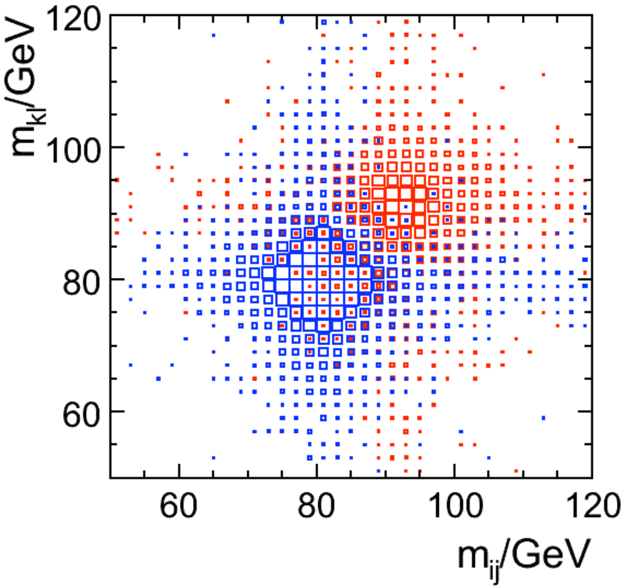

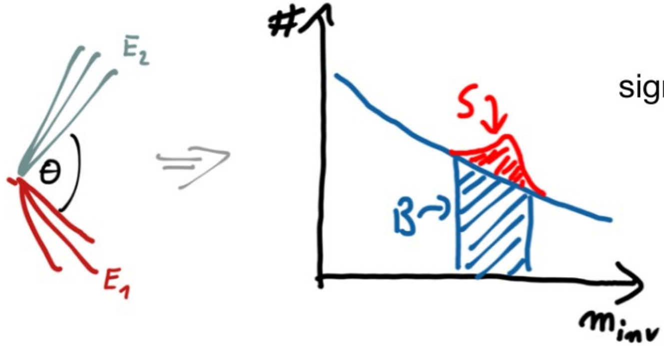

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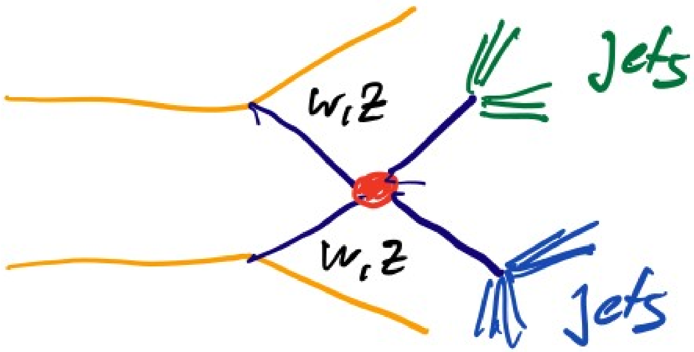
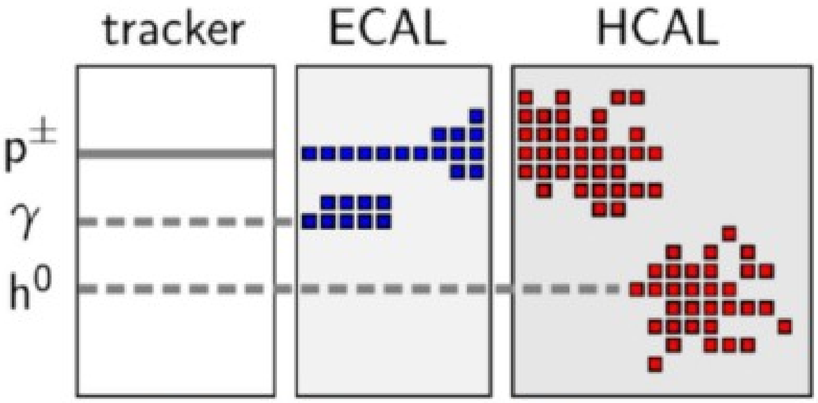


Separation of hadronic final states of heavy bosons:

Requires jet energy resolution of ~ 3.5% over a wide energy range

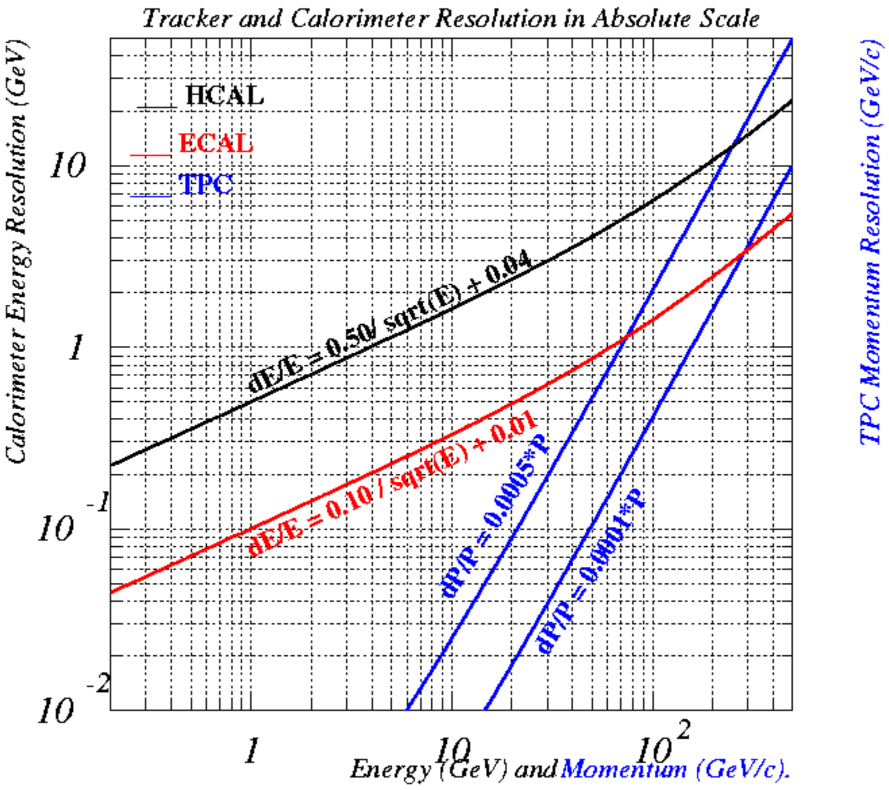
Jet energy resolution

Lepton Collider goal is around dE_{jet}/E_{jet} - 3-4%
(e.g. 2x better than ALEPH / ATLAS)



$$E_{Jet} = E_{Had.} + E_{elm.}$$
$$\sigma_{Jet} = \sqrt{\sigma^2_{Had.} + \sigma^2_{elm.}}$$

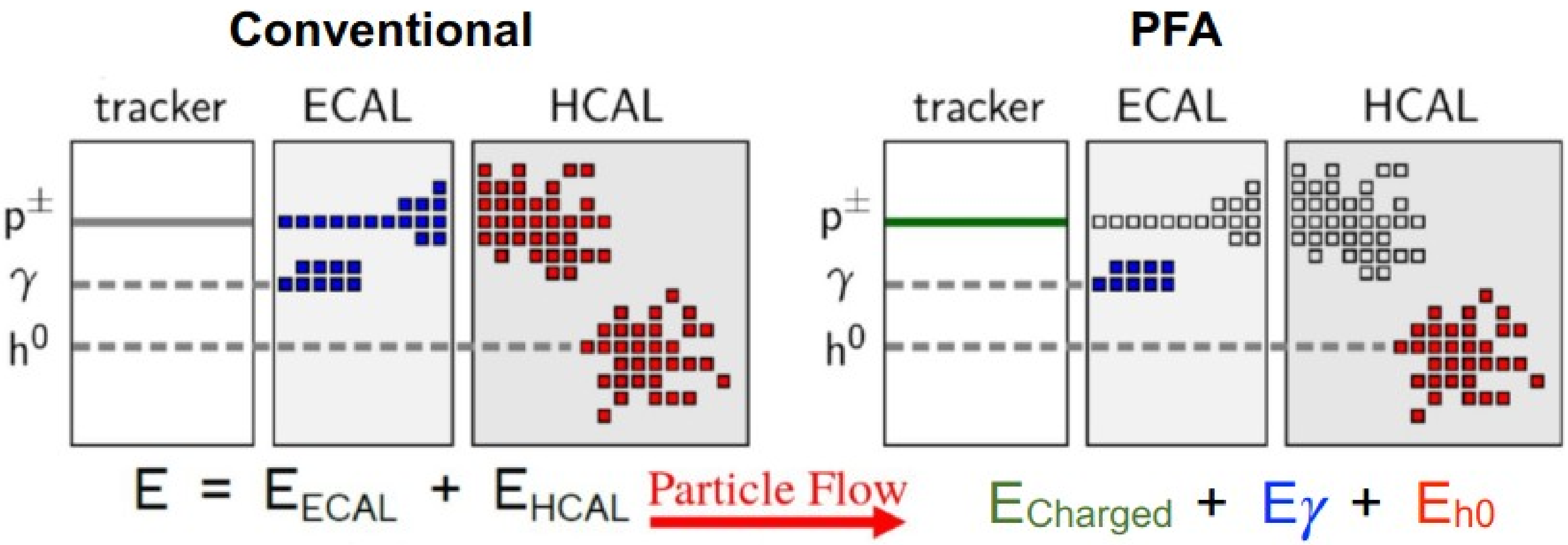
Jet energy resolution



In a "typical jet" the energy is carried by

- **Charged particles (e±, h±,μ±): 65%**
  - Most precise measurement by **Tracker**
- **Photons: 25%**
  - Measurement by Electromagnetic Calorimeter **(ECAL)**
- **Neutral Hadrons: 10%**
  - Measurement by Hadronic Calorimeter **HCAL** and ECAL

Particle Flow Algorithms



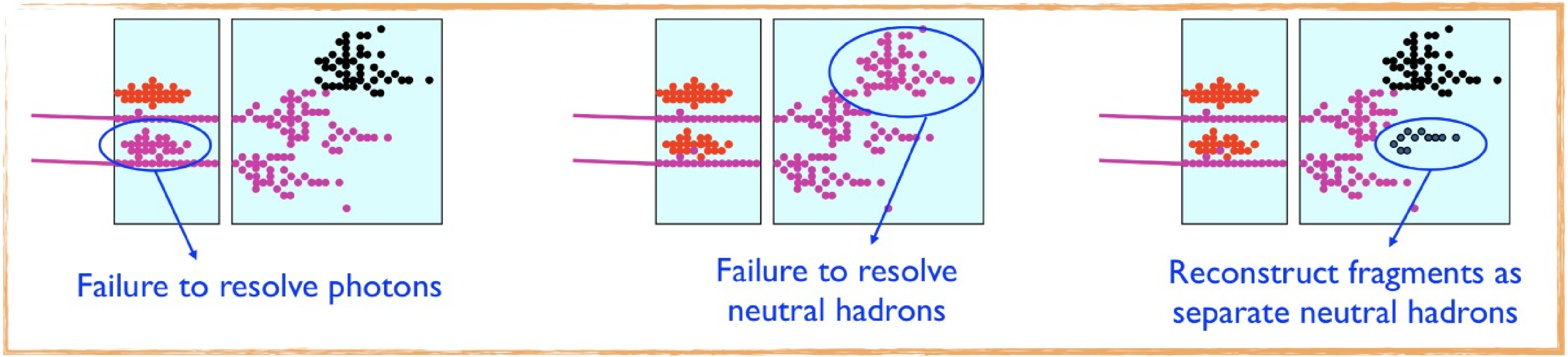
Example: jet created by a proton

"traditional" detector : $E = E_{ECAL} + E_{HCAL}$

Particle Flow detector: $E = E_{track}$

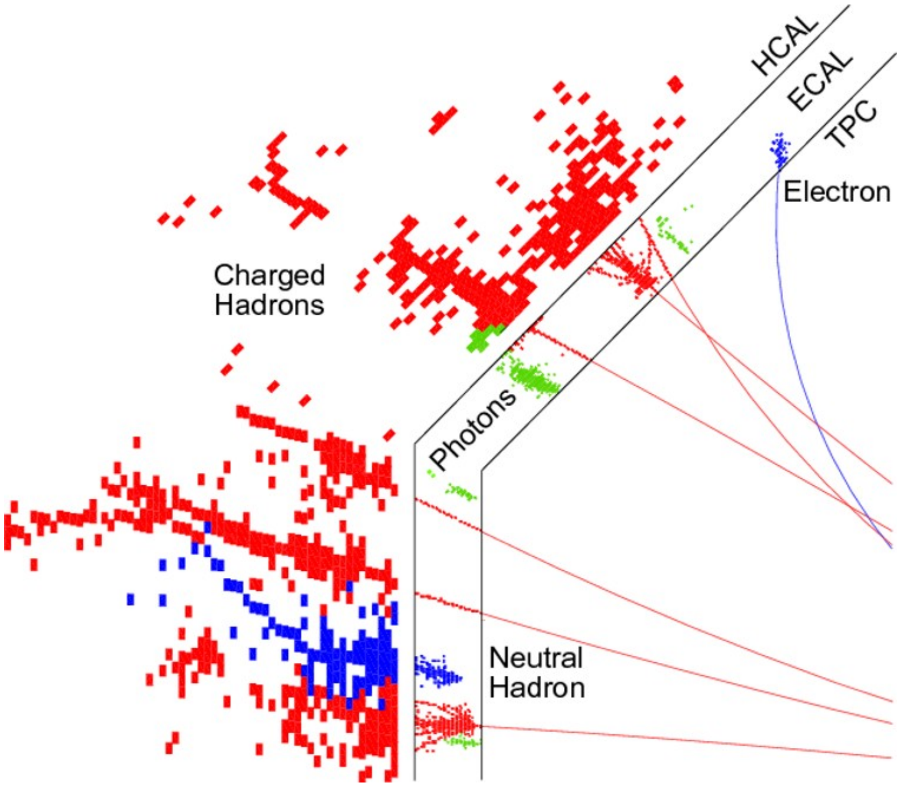
Confusion: Limitations of Particle Flow Algorithms

Types of confusion



Missing energy | **Missing energy** | **Double counted energy**

Particle Flow Algorithms



Concept

- ▶ Base the measurement on the subsystem with best resolution for a given particle type (and energy)
- ▶ Separation of signals by charge and neutral particles in the calorimeters
- ▶ **Single particle separation**

Challenges

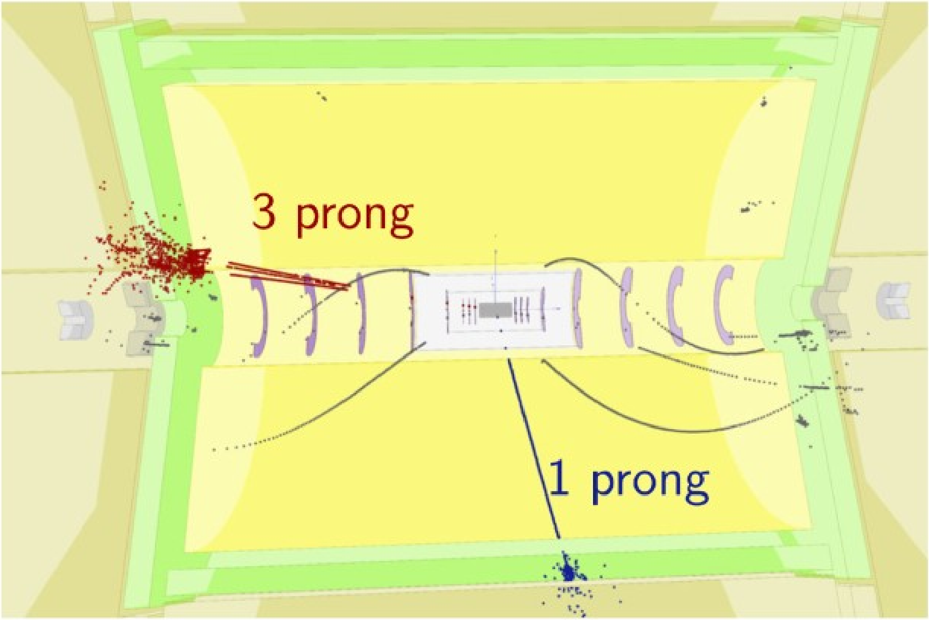
- ▶ Complicated topology by (hadronic) showers
- ▶ Overlap between showers compromises correct assignment of calorimeter hits

  –> Confusion term

- Need to minimize this term as much as possible

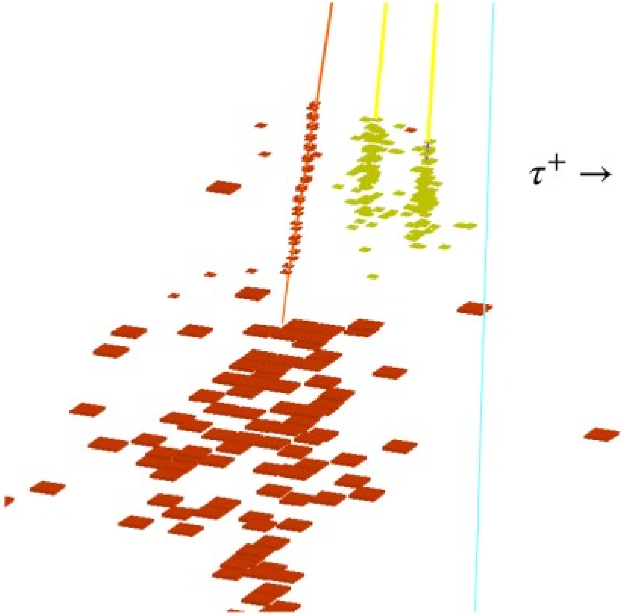
Particle Identification: More than Jet Energy Resolution

A classic example: Tau reconstruction



$$e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow \tau^+\tau^-\nu\bar{\nu}$$

@ 1.4 TeV at CLIC

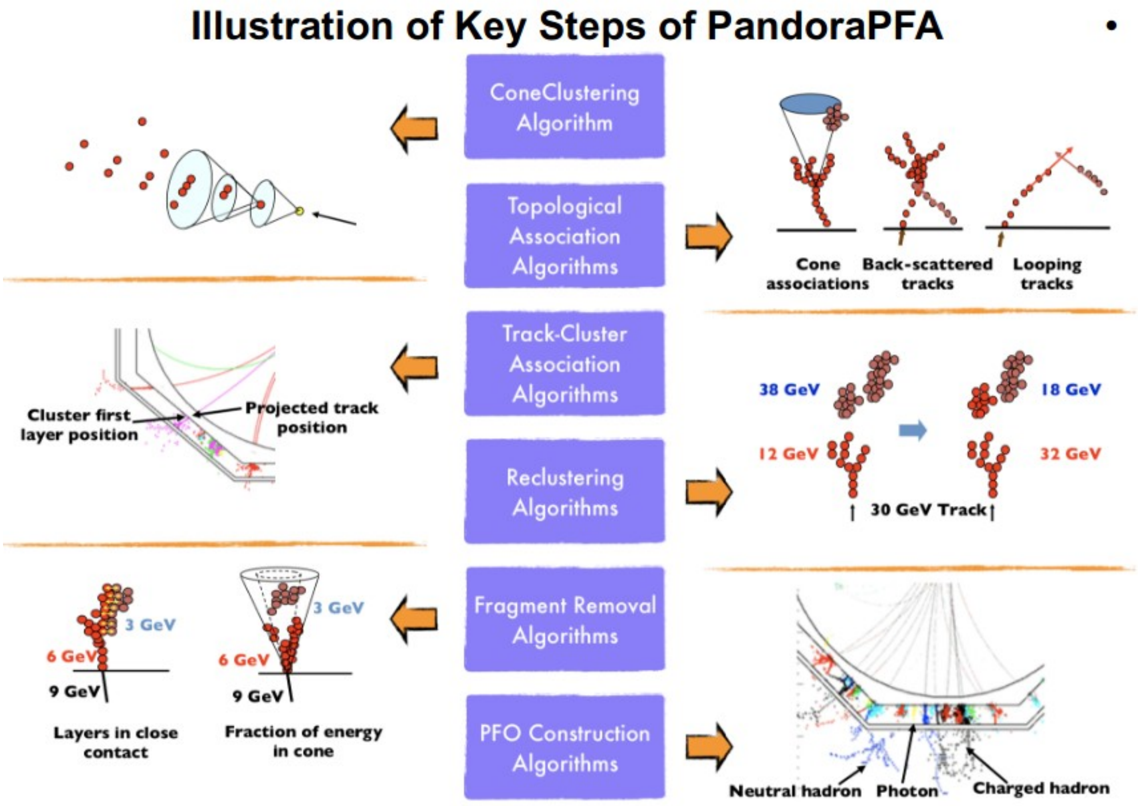


$$\tau^+ \rightarrow 2\gamma(\pi^0) + \pi^+ + \bar{\nu}_\tau$$

- Results in close-by / overlapping electromagnetic and hadronic showers

Pandora Particle Flow Algorithm

A Multi-Algorithm Pattern Recognition Tool



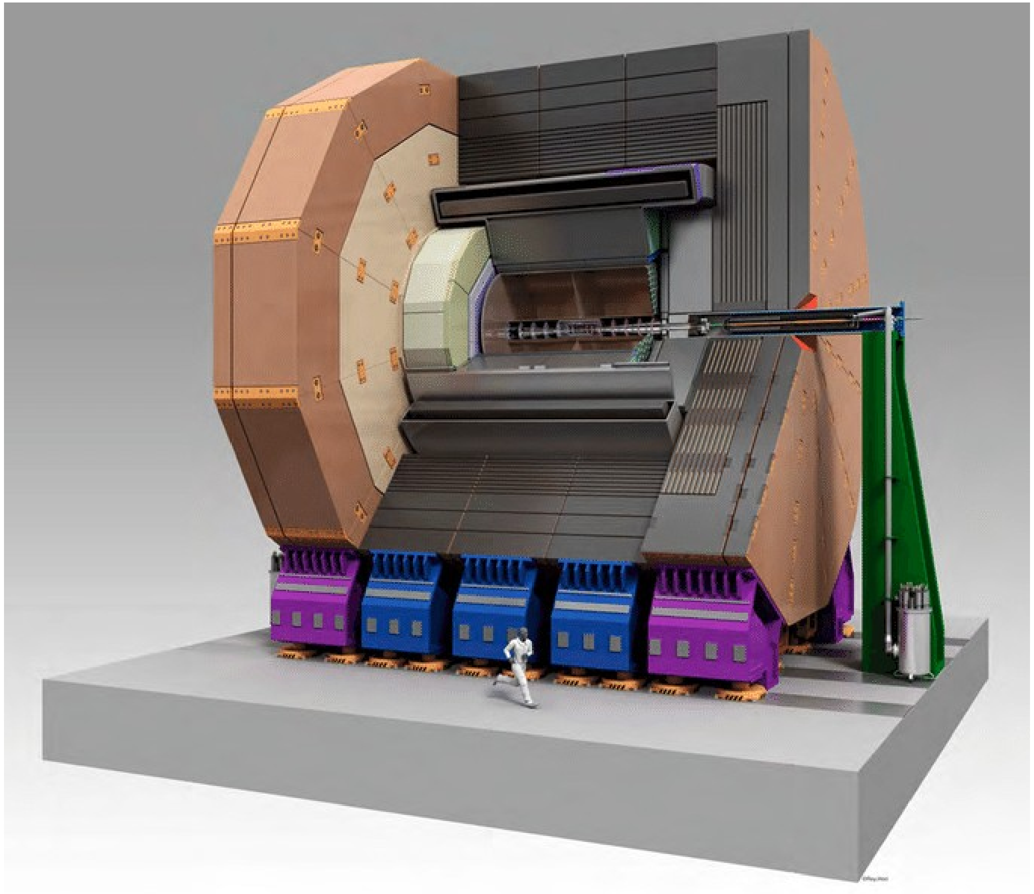
J. S. Marshall: https://indico.in2p3.fr/event/7691/contributions/42712/attachments/34375/42344/3_john_marshall_PFA_marshall_24.04.13.pdf

- PandoraPFA: Complex multi-algorithm chain using pattern recognition for event reconstruction
  - ➡ Performs calorimeter hit clustering, topological associations, …
  - ➡ Highly recursive: Find most accurate reconstruction scenario
  - ➡ Overall goal: Distinguish energy depositions originating from charged and neutral particles in calorimeters and avoid **confusion** among those

Others

- ARBOR PFA
  - Shower development topology in an imaging calorimeter reminds of a tree structure.
  - Backward approach, from leaf to branches to tree with seeds often in the last layers
- APRIL
  - ≈ Arbor PFA with modified cluster merging for SDHCAL
- Garlic
  - Gamma reconstruction at a Linear Collider
- TICL (The Iterative Clustering)
  - a modular framework integrated and under development in CMS software (CMSSW) –> High Granular CMS
- **Very innovative Machine Learning approaches**
  - **Profit from the high granularity (x,y,z,E,t)**

Designing PFA detectors

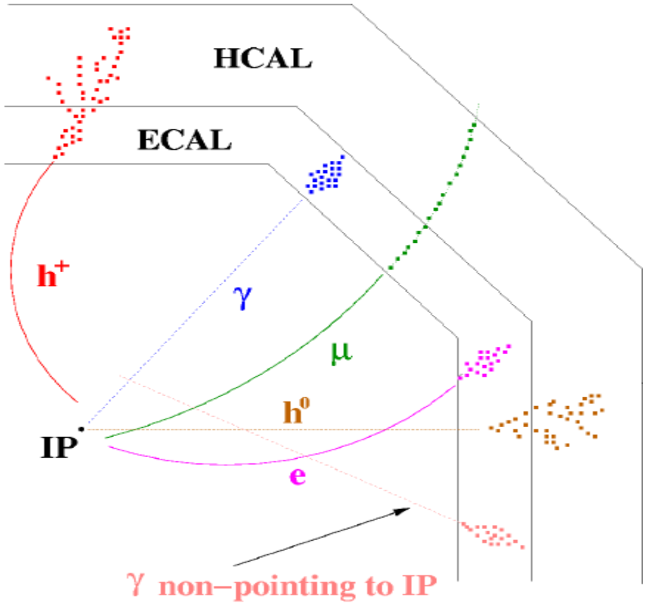


Requirements for PFA oriented detectors

Jet energy measurement by measurement of **individual particles**

Maximal exploitation of precise **tracking** measurement

- ▶ large radius and length
  - to separate the particles
- ▶ large magnetic field
  - To increase separation of neutral/charged particles at calorimeters
  - to suppress very large, low-momentum beam-related backgrounds"
- ▶ “no” material in front of calorimeters
  - Low material budget on the tracker + stay inside coil
- ▶ small Molière radius of calorimeters
  - to minimize shower overlap
- ▶ **high granularity of calorimeters**
  - to separate overlapping showers
- ▶ And fast timing devices



Requirements for PFA oriented detectors

PFA is used currently by some experiments and was used in the past…

… in detectors not fully optimized for Particle Flow Algorithms.

From key requirements from **physics**:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
- **vertexing** (H → bb/cc/ττ)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$
- **jet energy resolution** (H → invisible) 3-4%
- **hermeticity** (H → invis, BSM) θ_{min} = 5 mrad

≈ CMS / 40

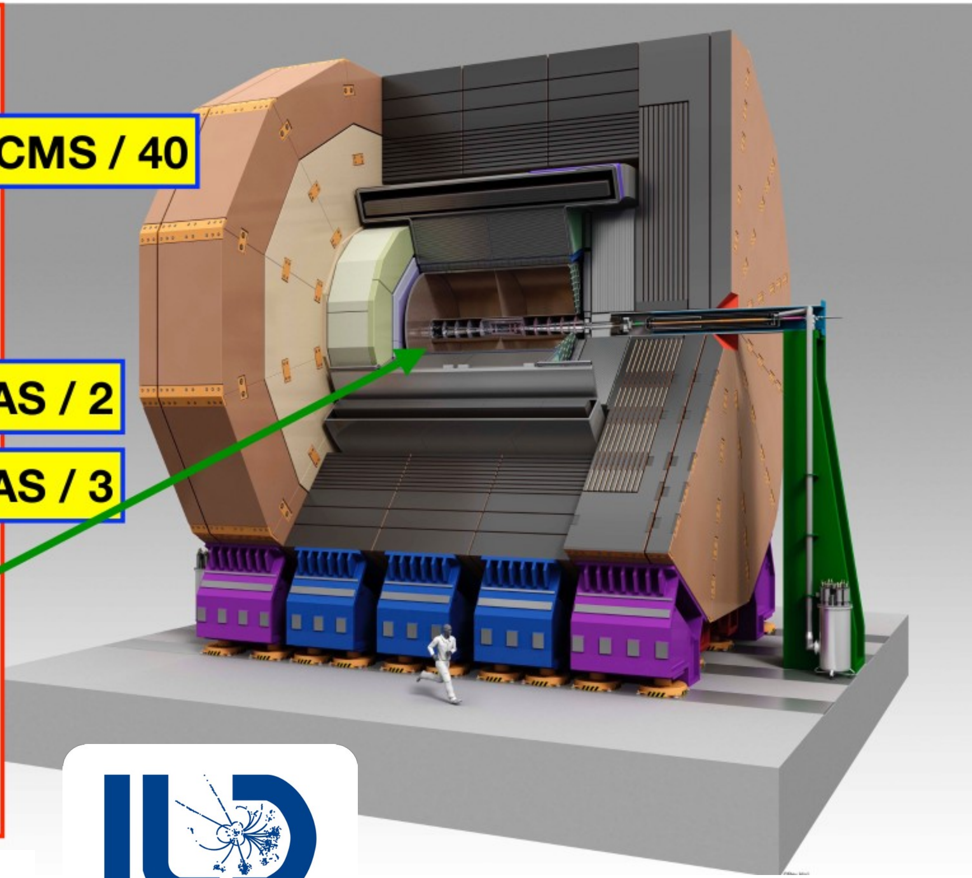
≈ CMS / 4

≈ ATLAS / 2

≈ ATLAS / 3

To key features of the **detector**:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow



Requirements for PFA oriented detectors

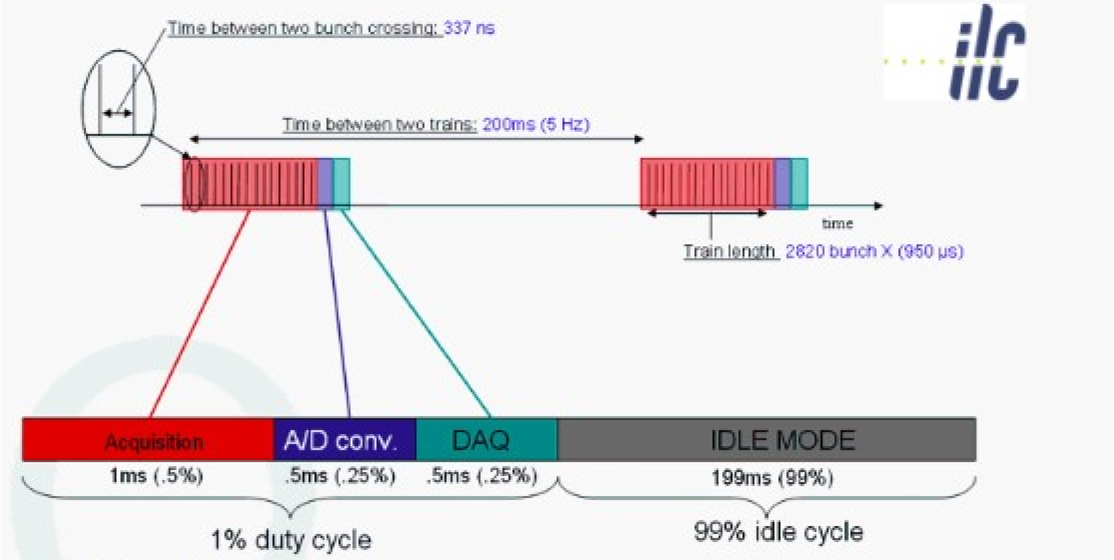
Lepton Colliders (and specially Linear) favor fully optimized PFA detectors

▶ Possible since experimental environment at ILC very different from LHC/LEP:

- much smaller beam spot and beam pipe
- much lower backgrounds
- much less radiation
- Pulsed beam structure that enable **power pulsing** to save energy

low material budget !
triggerless operation ! –> ALL events are recorded

Power pulsing

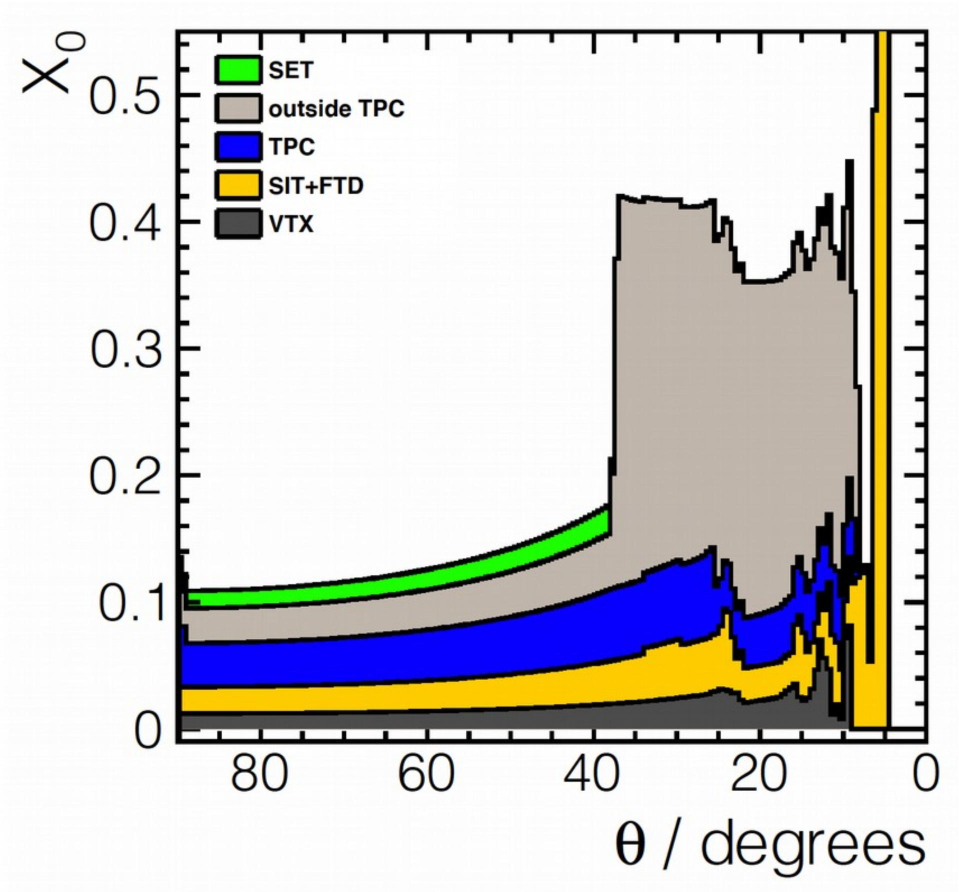


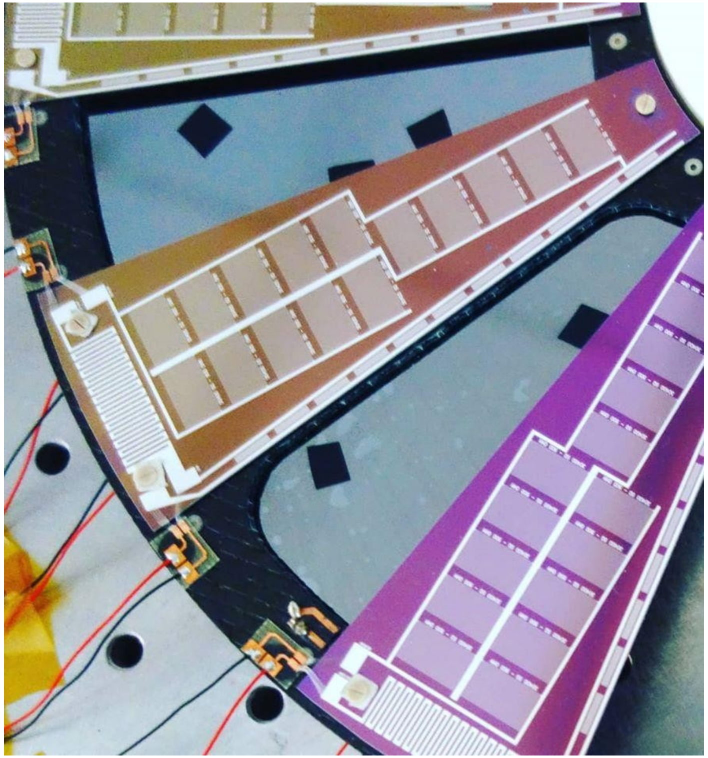
N.B. Final numbers may vary

- Electronics switched on during > ~1ms of ILC bunch train and data acquisition
- Bias currents shut down between bunch trains

Mastering of technology is essential for operation ofILC detectors

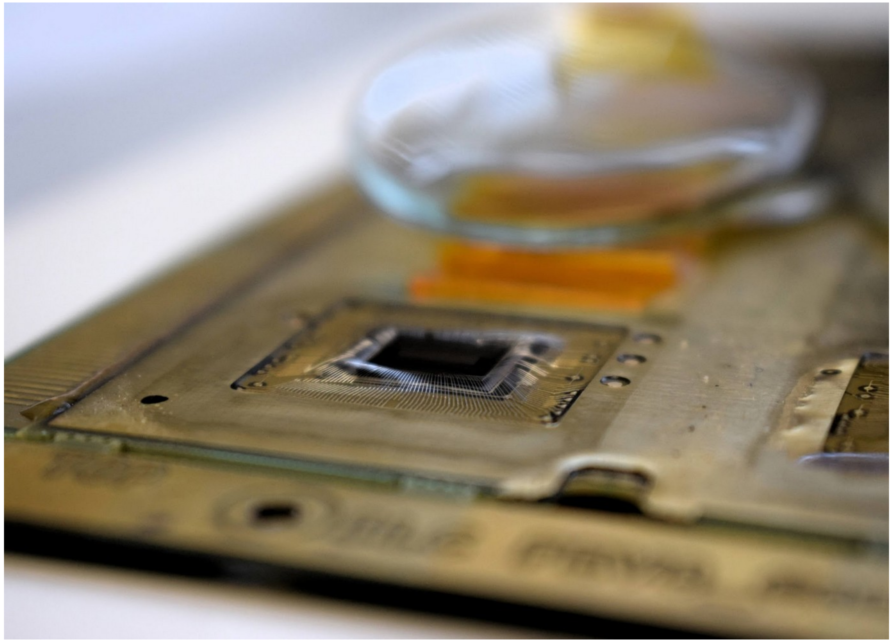
- Data taking for 1ms each 200ms in **autotrigger** mode and **zero supression**
- Low consumption electronics allows avoiding active cooling systems
  - Use also of low consumption sensors
- Data readout integrated in the modules
  - Minimal cabling & support material.
- No dead areas / cracks without instrumentation





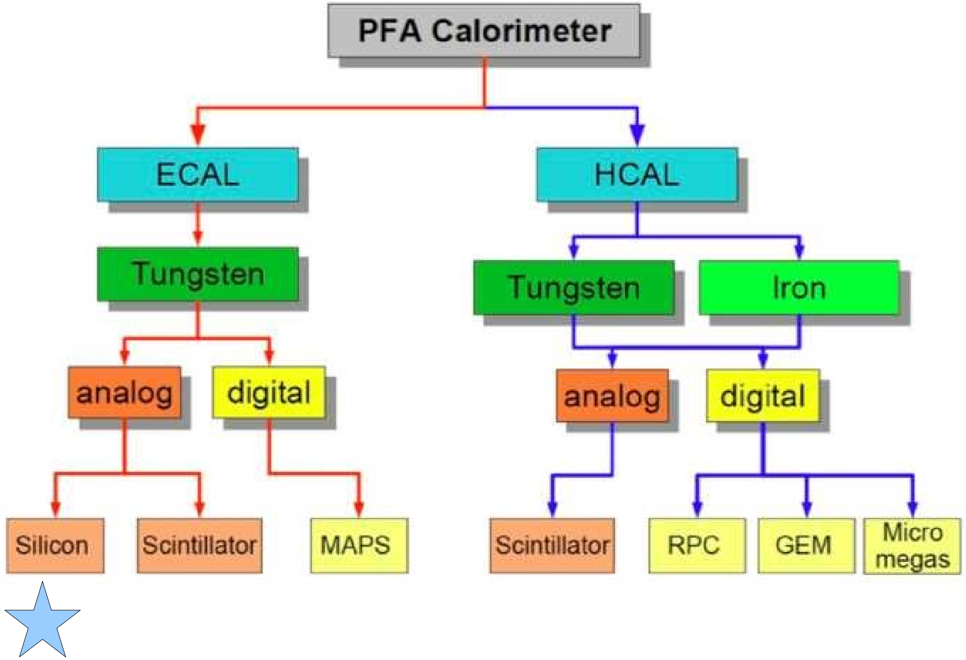
Low mass FTD petal prototype at IFIC (G. Vidal)

R&D on High Granularity calorimeters



Particle Flow Calorimetry R&D

Mainly organised within the CALICE Collaboration



More than 300 physicists/engineers from ~60 institutes and 19 countries coming from the 4 regions (Africa, America, Asia and Europe)

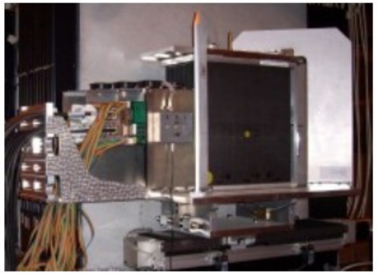
All projects of current and future high energy colliders propose highly granular calorimeters

Techological prototypes

Physics Prototype

Proof of principle

2003 - 2011



Number of channels : 9720

Pixel size: 1x1 cm2

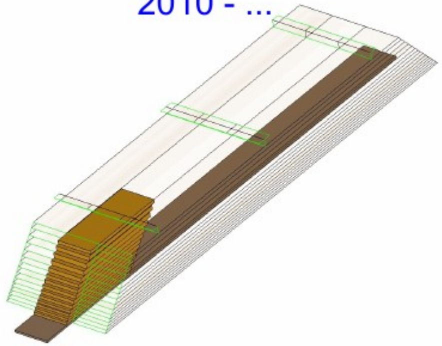
$R_{M,eff}$: ~ 1.5cm

Weight : ~ 200 Kg

Technological Prototype

Engineering challenges

2010 - ...



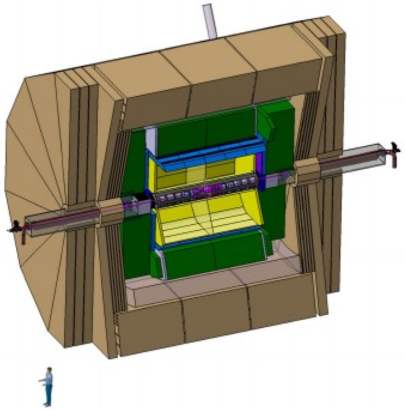
Number of channels : 45360

Pixel size: 0.55x0.55 cm2

$R_{M,eff}$: ~ 1.5cm

Weight : ~ 700 Kg

LC detector



ECAL :

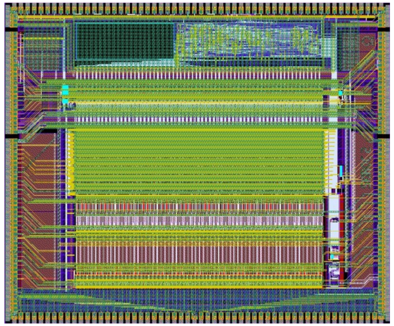
Channels : ~100 10^6

Total Weight : ~130 t

→ **Towards a real detector**

Highly integrated (very) front end electronics

e.g. SKIROC (for SiW Ecal)



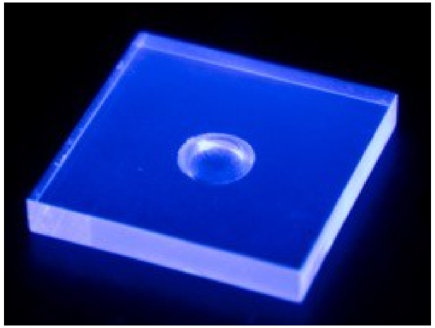
Size 7.5 mm x 8.7 mm,

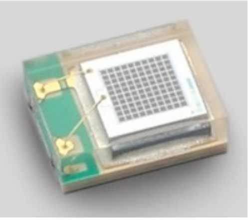
64 channels

- **Analogue measurement**
- **On-chip self-triggering**
- **Data buffering**
- **Digitisation**

... all within one ASIC

Miniaturisation of r/o devices



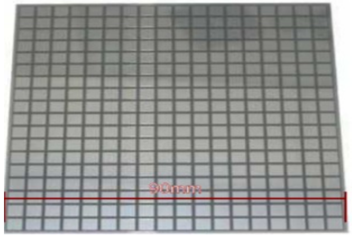


- Small scinitllating tiles
- (Low noise) SiPMs

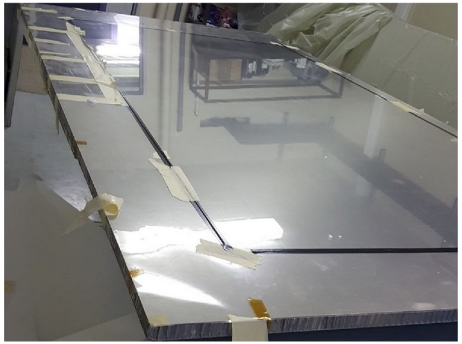
Power pulsed electronics
to reduce power consumption…
Compactness –> no space left for active cooling systems

Large surface detectors

Si Wafer



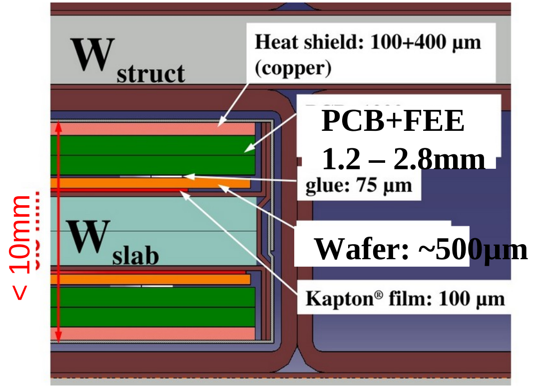
RPC layers



Many things that look familiar to you today were/are pioneered/driven by CALICE

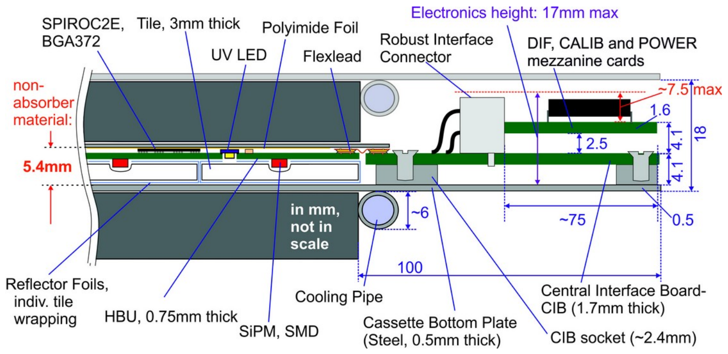
Technological solutions for final detector I

SiW Ecal



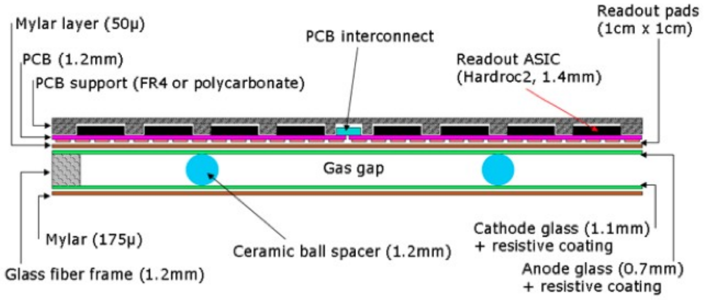
Semi-conductor readout
Typical segmentation: 0.5x0.5 cm^2

Analogue Scintillator HCAL and ECAL



Optical readout
Typical segmentation: 3x3cm^2

Semi Digital HCAL



Gaseous readout
Typical segmentation: 1x1cm^2

Integrated front end electronics

No drawback for precision measurements ***NIM A 654 (2011) 97***

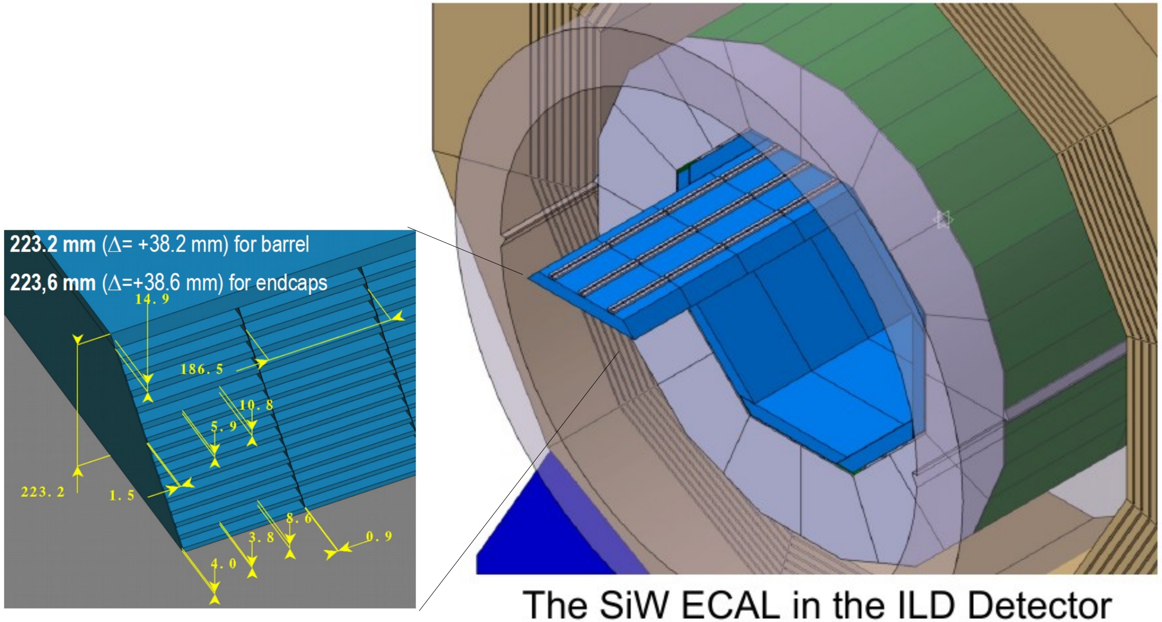
SiW-ECAL for future LC

▶ **Tungsten** as absorber material

- **Narrow showers**
- Assures **compact** design
- Low radiation levels forseen at LC
- X_0=3.5 mm, R_M=9mm, I_L=96mm

▶ **Silicon** as active material

- Support **compact** designs
- Allows **pixelisation**
- **Robust technology**
- **Excellent signal/noise** ratio



The SiW ECAL in the ILD Detector

The **SiW ECAL R&D** is tailored to meet the specifications for the **ILD** ECAL **baseline** proposal

SiW-ECAL for the ILD

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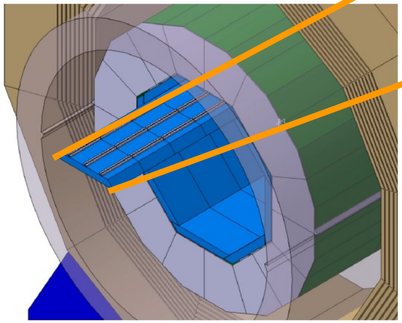
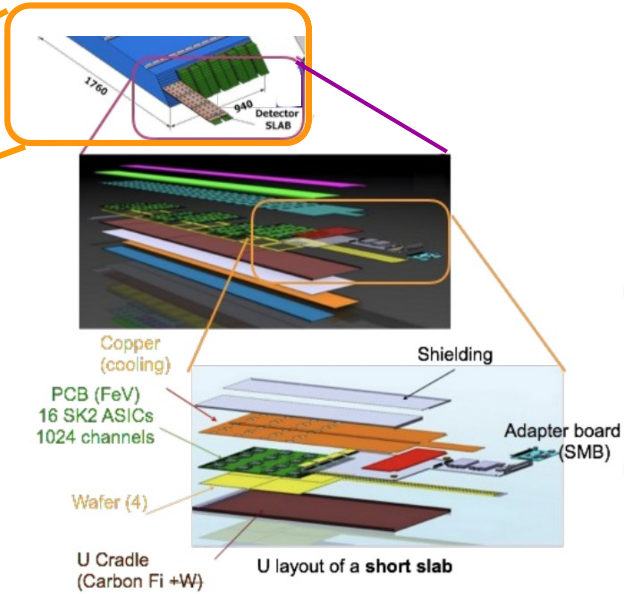


The SiW ECAL in the ILD Detector



- O(10^4) slabs
- O(10^5) ASUs (PCB+wafer+ASIC+DigReadout)
- O($10^{6\text{-}7}$) ASICS
- O(10^8) cells
  - 2000 m^2 of Si
- 130 T of tungsten

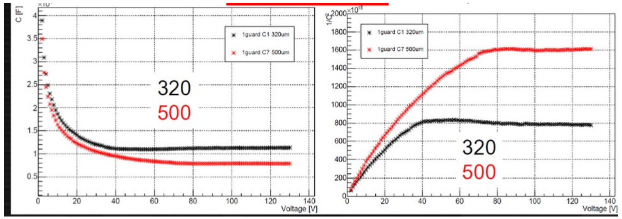
Cell size of 5x5 mm → all cells are self triggered + zero suppression

Successful application of PFA requires calorimeters to be placed insided the magnetic coil

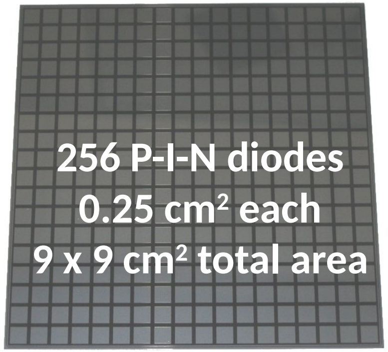
- Very compact design: Thickness of **20 cm for 20-30 active layers + 24X0 tungsten**
- Very limited space for inactive material (PCB, electronic components) → **No active cooling but Power Pulsing**

Sensors: Silicon P-I-N diodes wafers

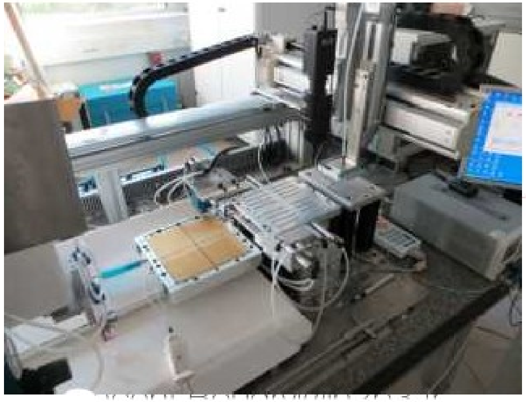
Designed for ILC : **Low cost, ~2000 m2**
Minimized number of manufacturing steps
Target is 2.5 EUR/cm2
Now : ~10 EUR/cm2 (Japan)



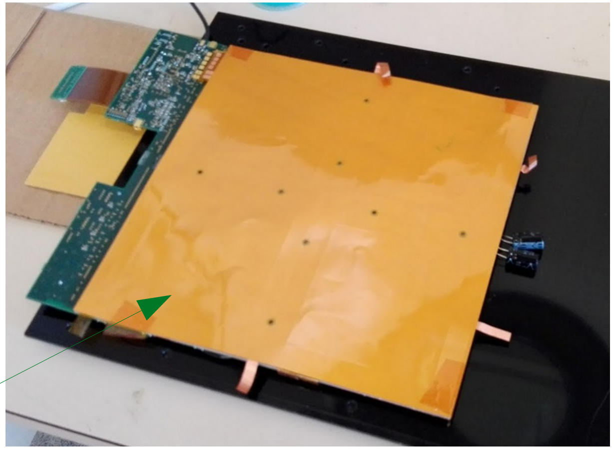
I(V) and C(V) characterization
Breakdown voltage >500V
Current leakage ~1 nA/pixel (chip is DC coupled)
Full depletion at <100 V
(~40 V with 320 um, ~70 V with 500um)
Null C(V) slope to avoid dC/dV noise



EUDET layout
Prototype from Hamamatsu

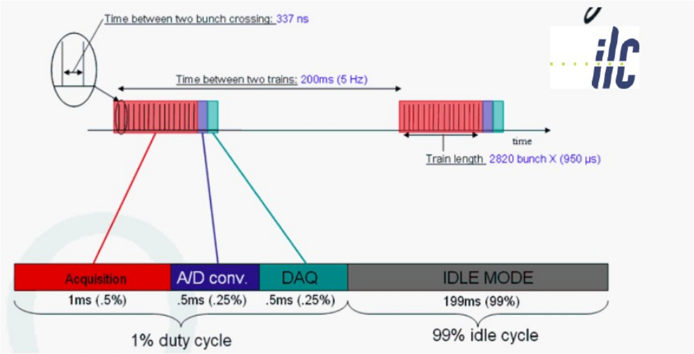


Wafers are glued to PCB (robot at LPNHE & Kyushu U.)

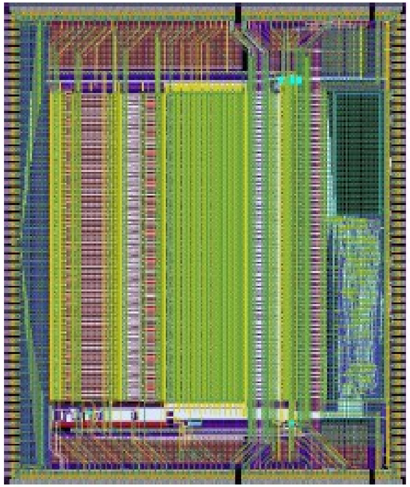


Sensor polarization through HV deliver via a copper/kapton sheet

- **SKIROC** (Silicon Kalorimeter Integrated Read Out Chip)
  - SiGe 0.35µm AMS, Size 7.5 mm x 8.7 mm, 64 channels
  - High integration level (variable gain charge amp, 12-bit Wilkinson ADC, digital logic)
  - **Large dynamic range (~2500 MIPS), low noise (~1/10 of a MIP)**
  - **Dual readout: high and low gain**
  - **Auto-trigger at ~0.5 MIP**
  - Low Power: (25µW/ch) **power pulsing** switch off electronics bias currents during bunch trains



N.B. Final numbers may vary



ΩMEGA Microelectronics

- Prototype version (Skiroc 2 and 2a) for R&D and beam tests
- Definitive version will be optimized for ILC and work in zero suppression conditions.

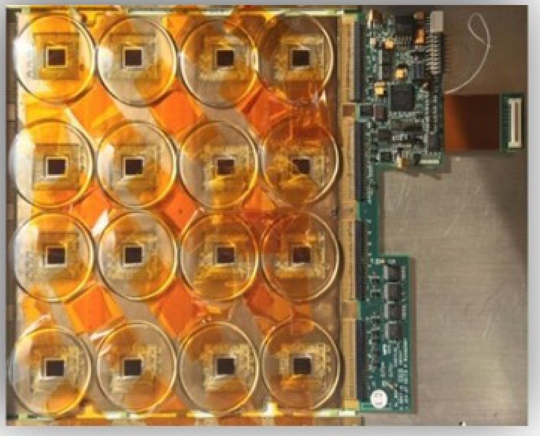
Readout modules

▶ Very dense **PCBs *aka*** **FEV** with 1024 readout channels (with digital, analogue, clock signals) in a 18x18 cm board

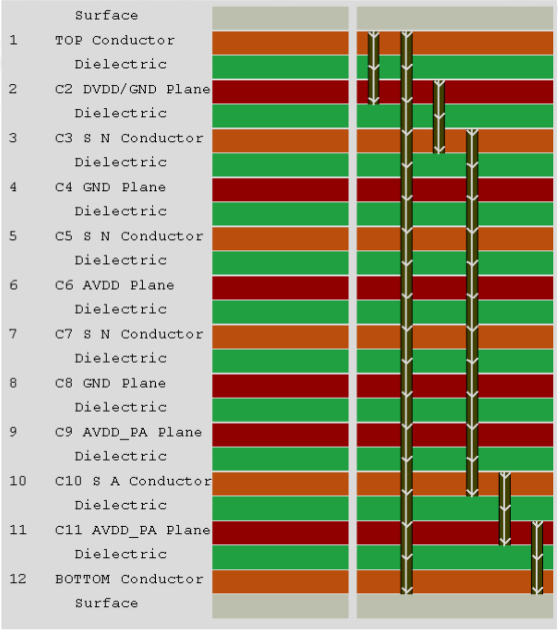
FEV10-12

- ASICs in BGA Package
- Incremental modifications
  - From v10 -> v12
  - **Main “Working horses” since 2014**

FEV_COB



- ASICs wirebonded in cavities
- COB = Chip-On-Board
- Current version FEV11_COB
- Thinner than FEV with BGA
- External connectivity compatible with BGA based FEV10-12



The FEV zoo (from 2014)

- Very dense **PCBs *aka* FEV** with 1024 readout channels (with digital, analogue, clock signals) in a 18x18 cm board

FEV10-12

Validation of the technology concept "culminated" in 2017-18 with a series of test beams

NIMA 2019 162969

- ASICs in BGA Package
- Incremental modifications
  - From v10 -> v12
  - **Main "Working horses" since 2014**

Towards a real detector: challenges

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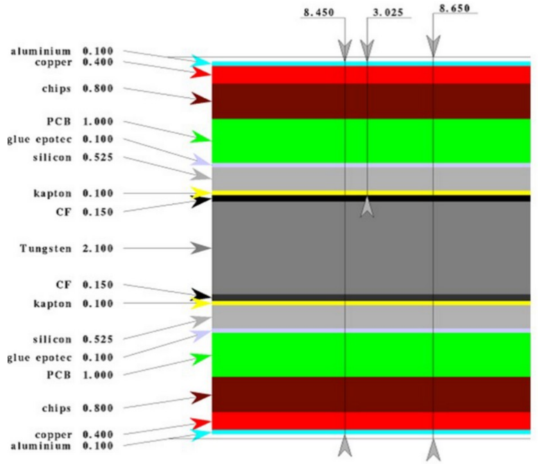
Large scale integrations

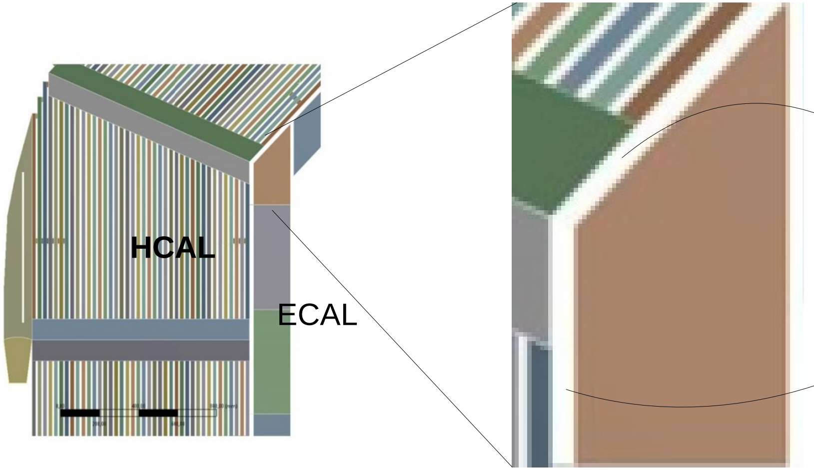
- **Compactification: active units**
  - 2010-2018 (PCB + VFE ~ 2.3-2.8mm thick)
  - But we are working on further compactification → ILD foresees 1.0+0.8 mm thickness for PCBs + Components
- **Compactification: digital readout + cooling**
  - 2018-2020 (core module based DAQ)
- **Power pulsing:**
  - short modules (2014-2018)
  - Long modules (2021-)



1.8 mm for PCB + Components

Very compact layers… but very long!

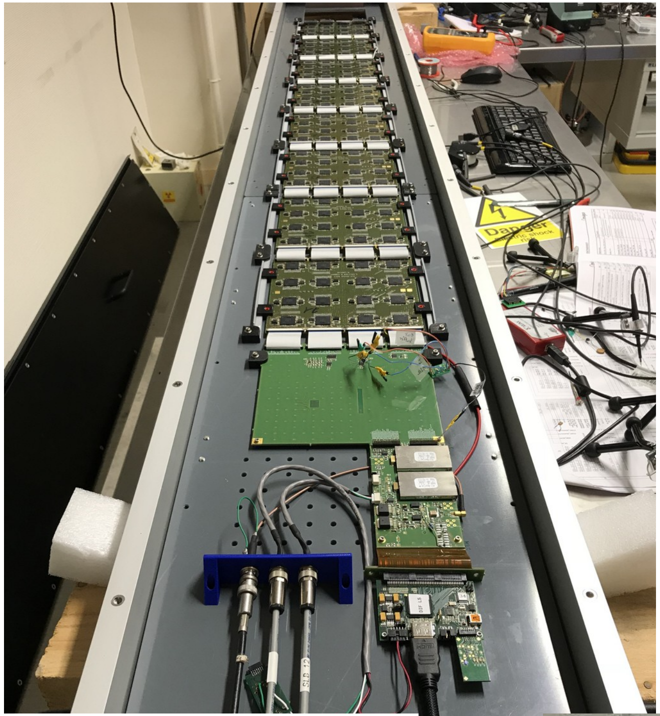
- Long slabs : up to ~15 ASU (~3m)
  - Complex object: mechanics and electronics.
  - Electrical prototype built and tested
  - Started in 2018

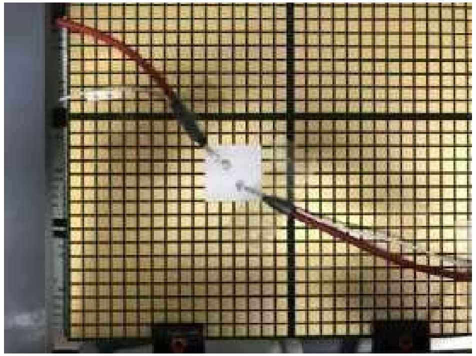


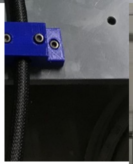
Electrical prototype of Long Slab

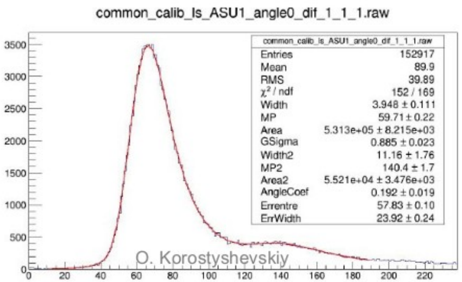
- Daisy chain of 8 ASU (extendable to 12)
- Corresponding to typical barrel length
  - 2m long !

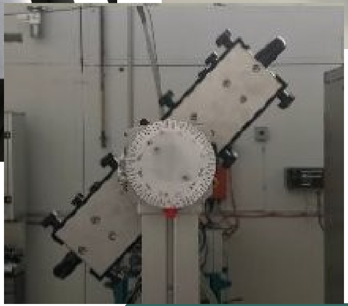
- Electrical, electronic and mechanical challenges
  - Power delivery through the full length
  - Very long signal, control, clock lines
  - Very thin and long modules… with silicon wafers glued in the back







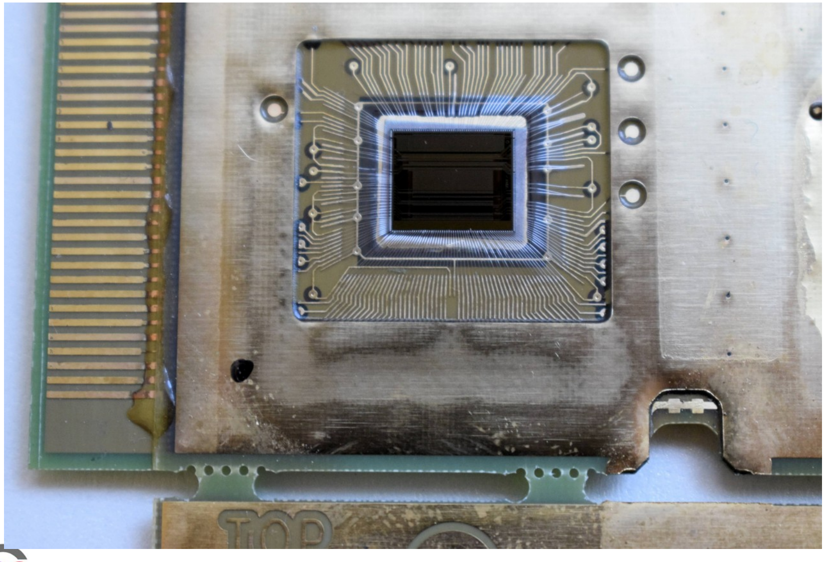




DESY@2018

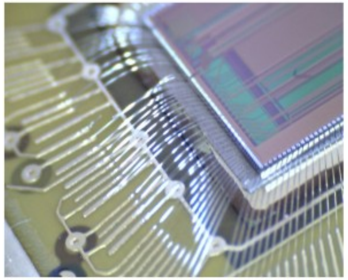
Ultra thin PCBs COB: chip-on-board

- **PCB with naked die placed in carved cavities and wirebonded to the board**
- Very thin board ~1.2mm (ILD requires 1.8mm for board and comp.)
  - 10 layers (+ gnd cupper layer)
  - To be compared with 2.8-3mm of the FEV10-13
  - but they include BGA SKIROCs and extra components as decoupling capacitances…!!

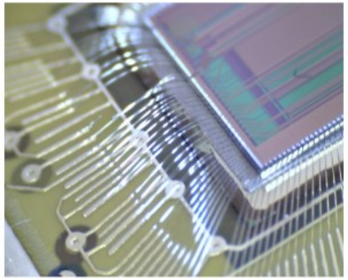


SUNGKYUNKWAN UNIVERSITY(SKKU) EOS CORPORATION

Zoom into ASIC cavities



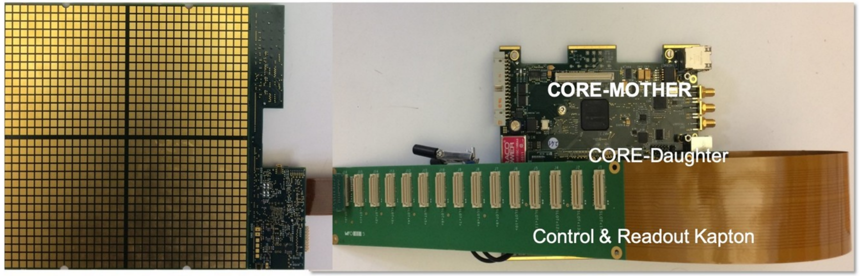
Before application of epoxy



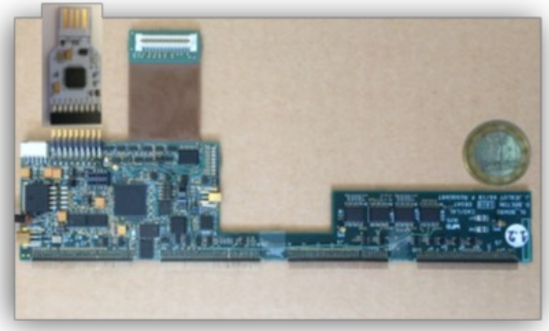
After application of epoxy

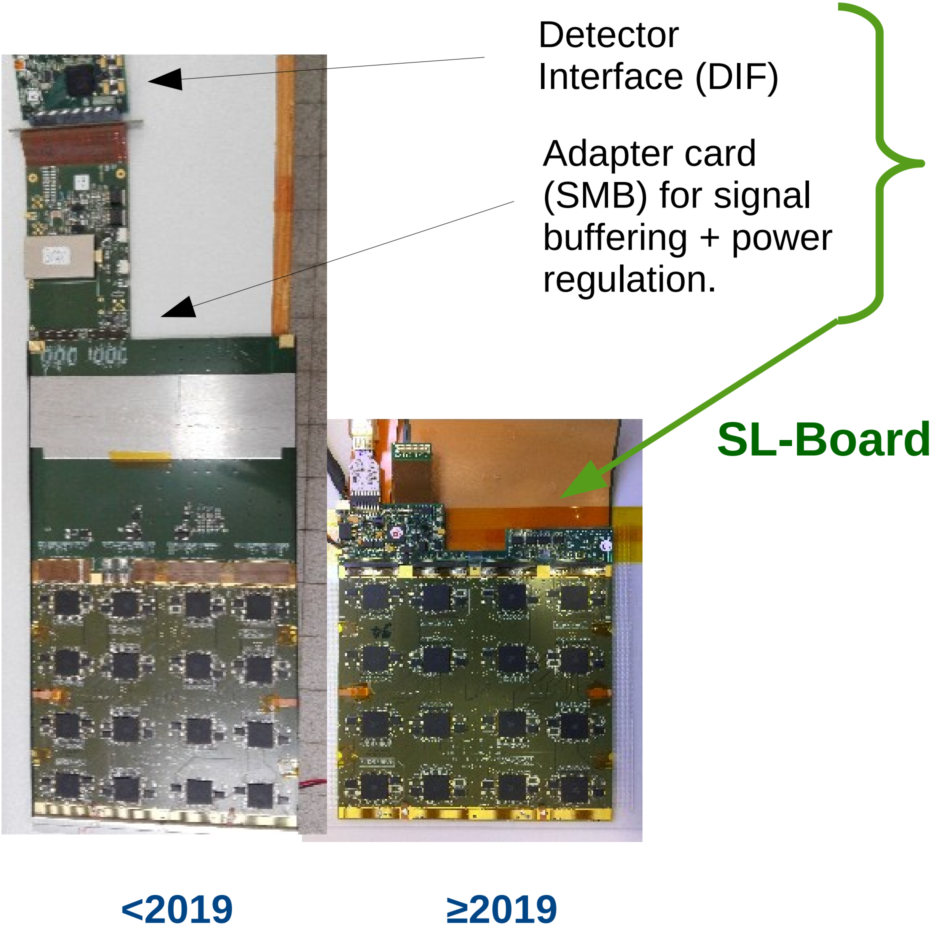
Ultra compact DAQ

- **Core Mother / Daughter system**
  - Controlling /reading up to 30 Slboards



- **The SL-Board**
  - **the sole interface for the ~10,000 channels of a 2m slab**



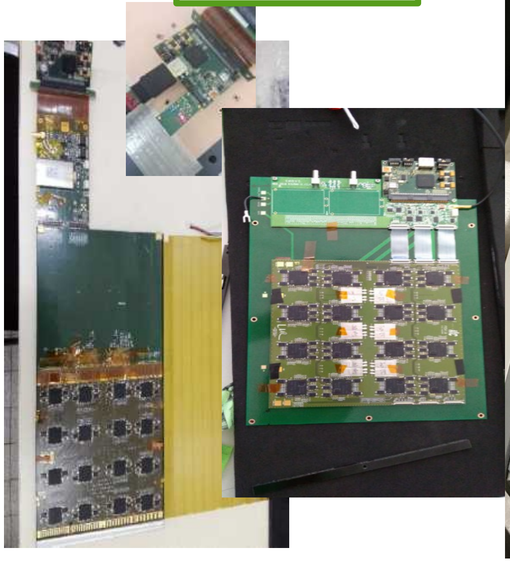


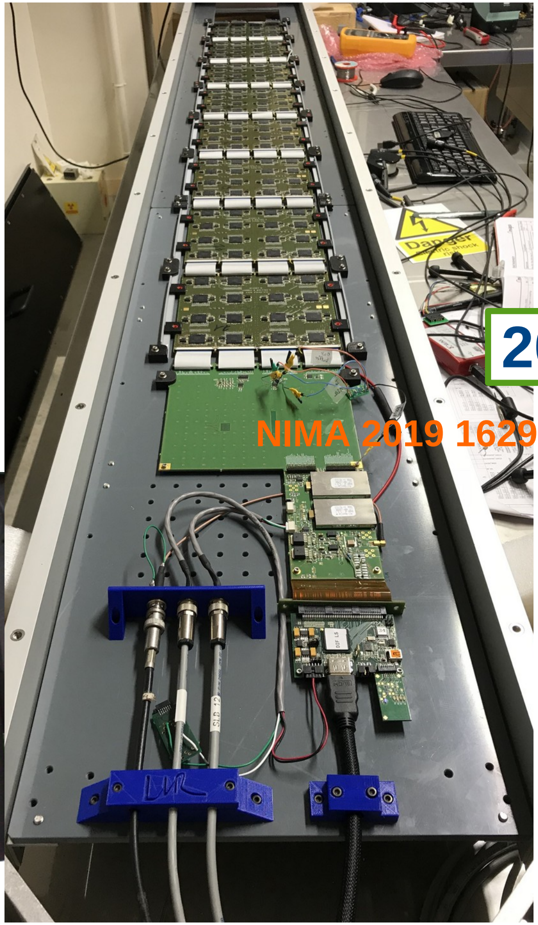
The new DAQ fits the tight space requirements of the ILD

Technological prototype: time travel

2010-2015

2010-18





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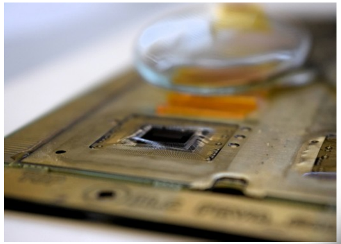
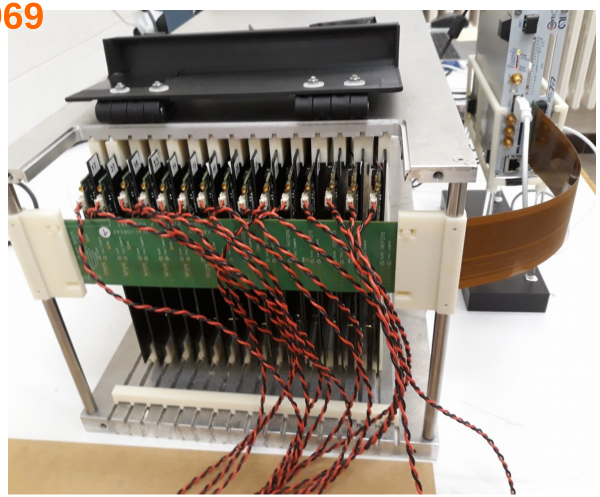
2018-20



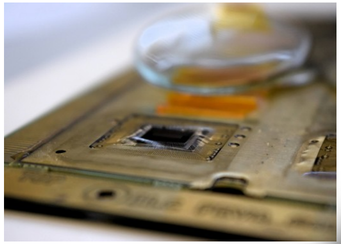


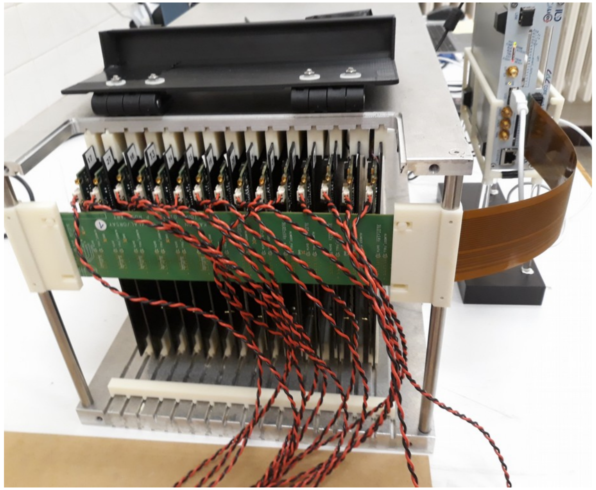
Ready for beam test… and for a LC

- **15 layers since 2020… ~15k calorimeter readout cells**
  - More than CMS (before upgrades)
  - In a suitcase-size detector

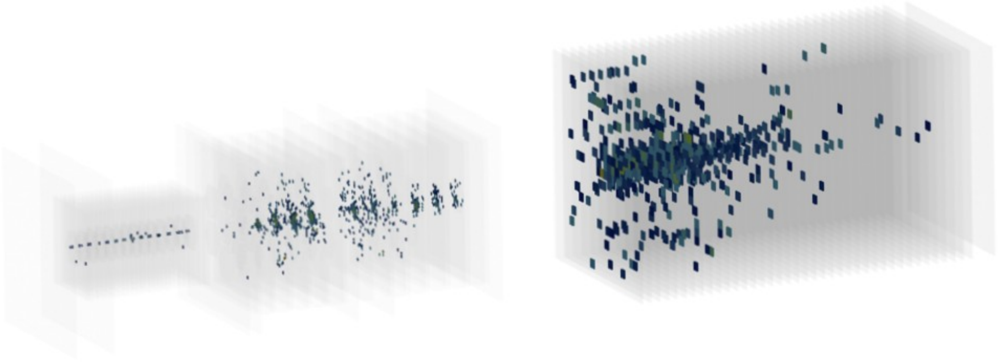
- **Prototype with components that fit LC requirements**

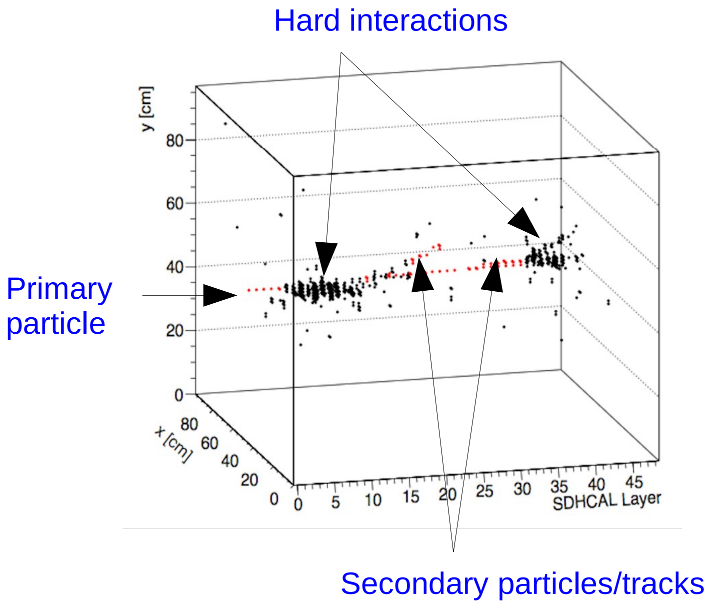
- **Ready for beam test** in ~~March 2020, December 2020~~, ~~May 2021,~~ Autumn 2021?



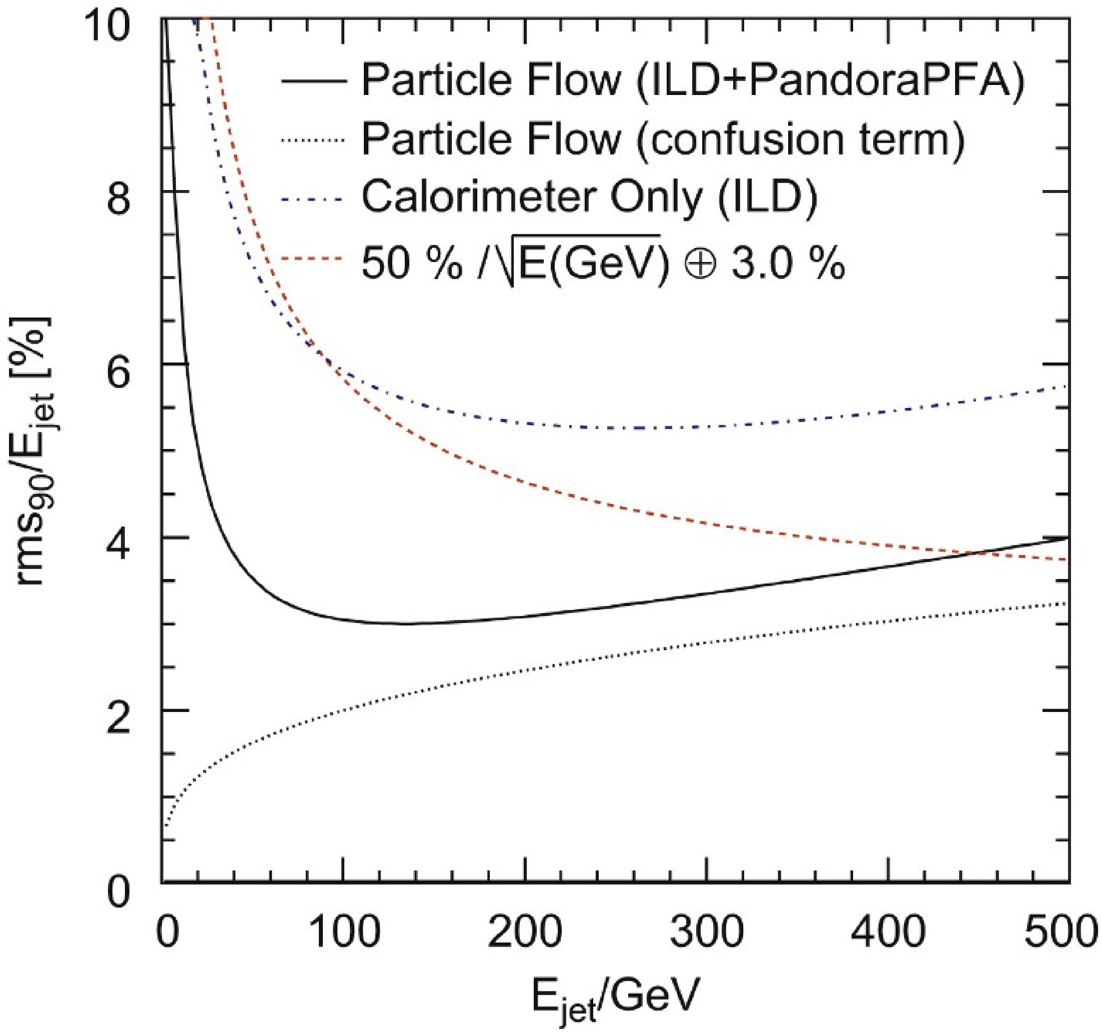




What High Granular calorimeters offer ?
(besides PF)

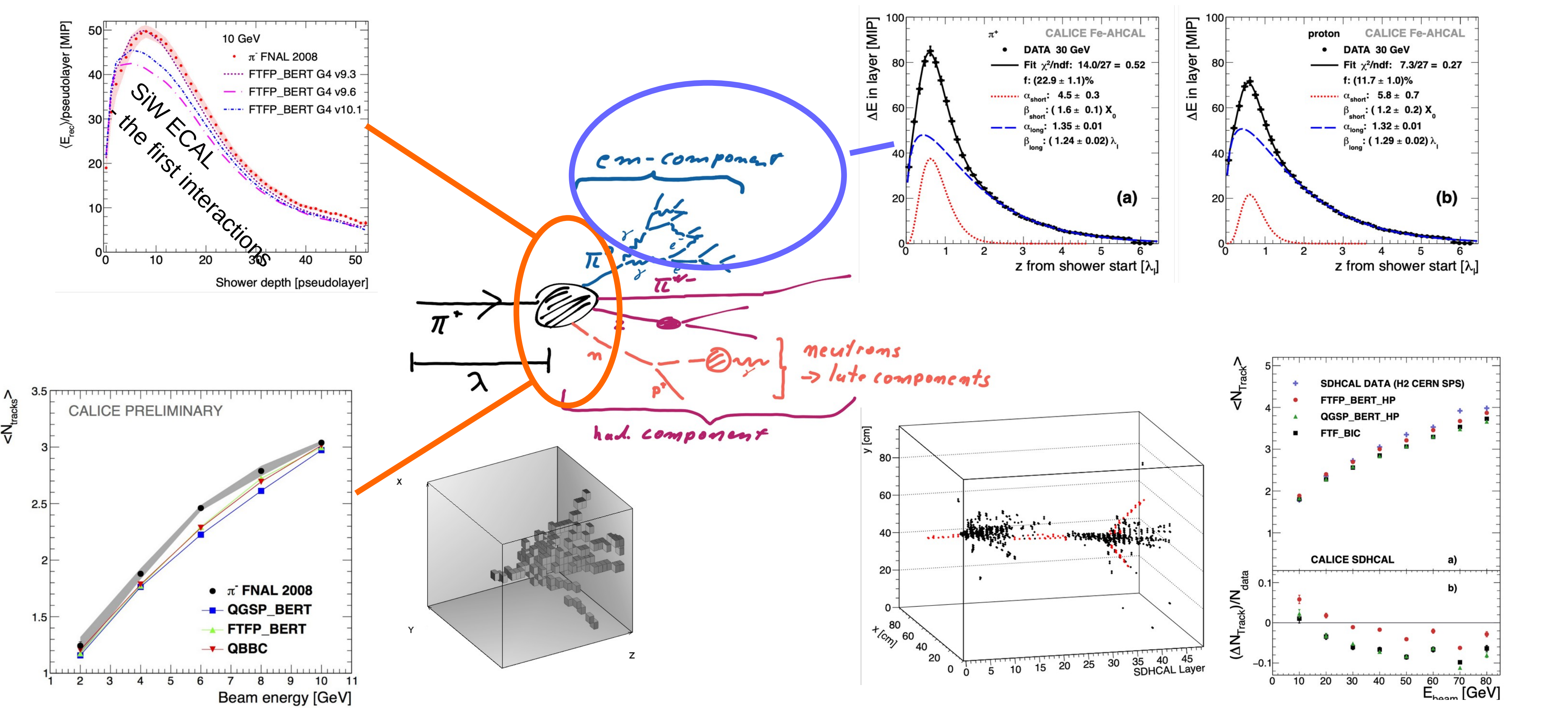




High granular calorimetry

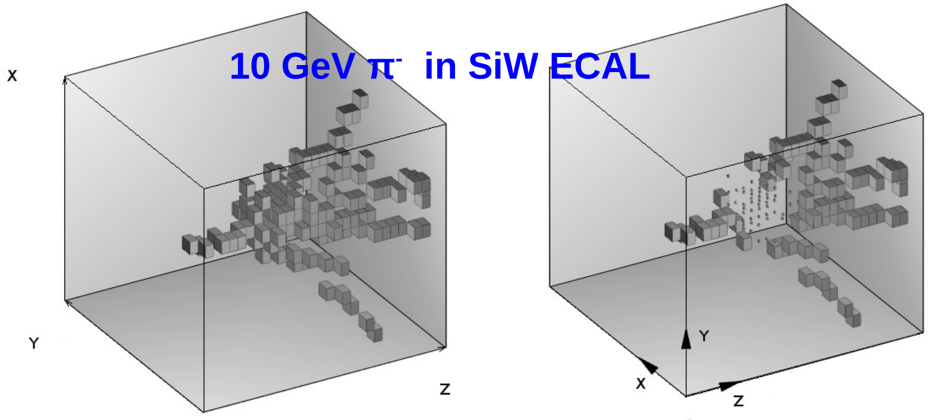


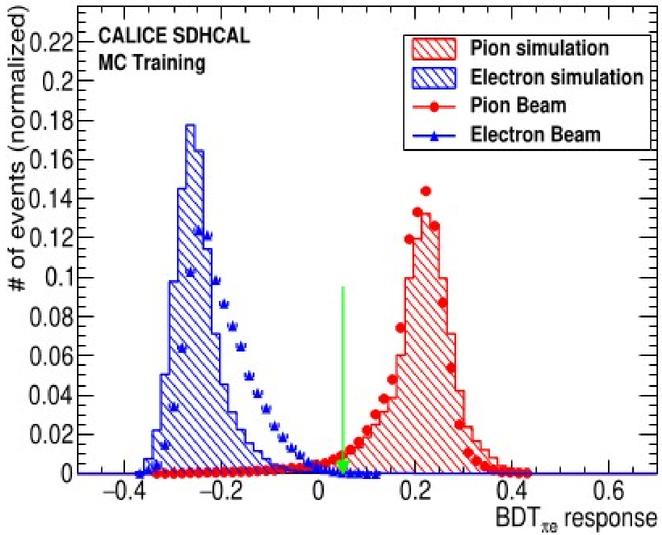
High granularity calorimeters: more than "only" PFA



F. Simon, FCCee Meeting, Jan. 2020

High granularity calorimeters: more than “only” PFA





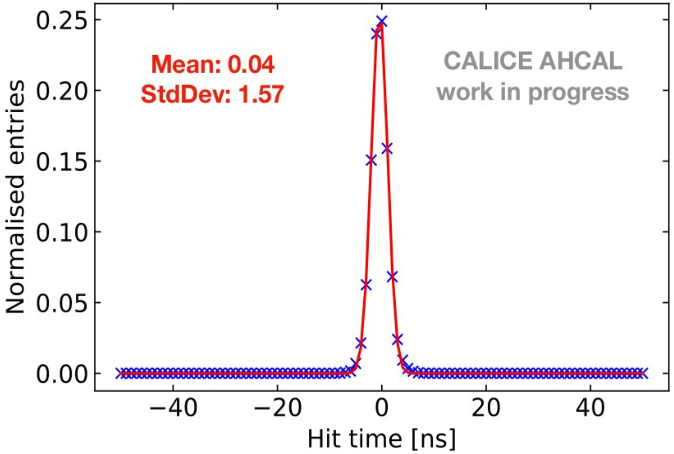
- **study of first hadronic interaction in the SiW-ECAL** (physics prototype)
  - NIM A 937 (219) 41-52

- **SDHCAL** using 6 variable discriminnating **BDT for Particle Identification** [JINST 15 (2020) P10009]

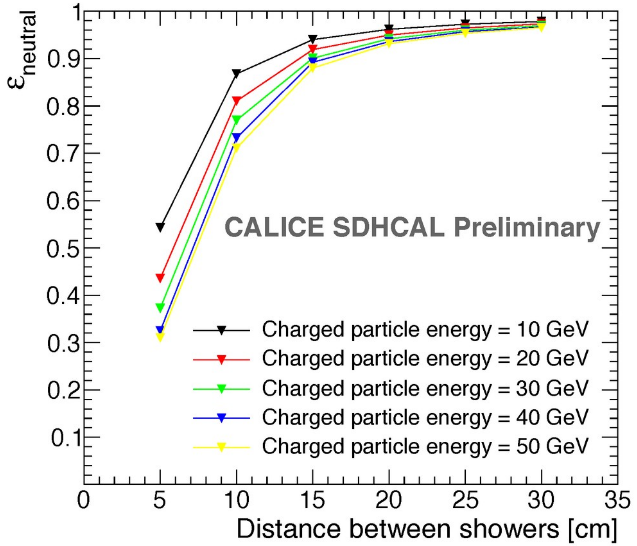
The unprecedented granularity of the proposed calorimeters offers also unprecedented capabilities to study the development of showers

High granularity calorimeters: more than "only" PFA

Clock frequency 5 MHz,
Powering pulsing



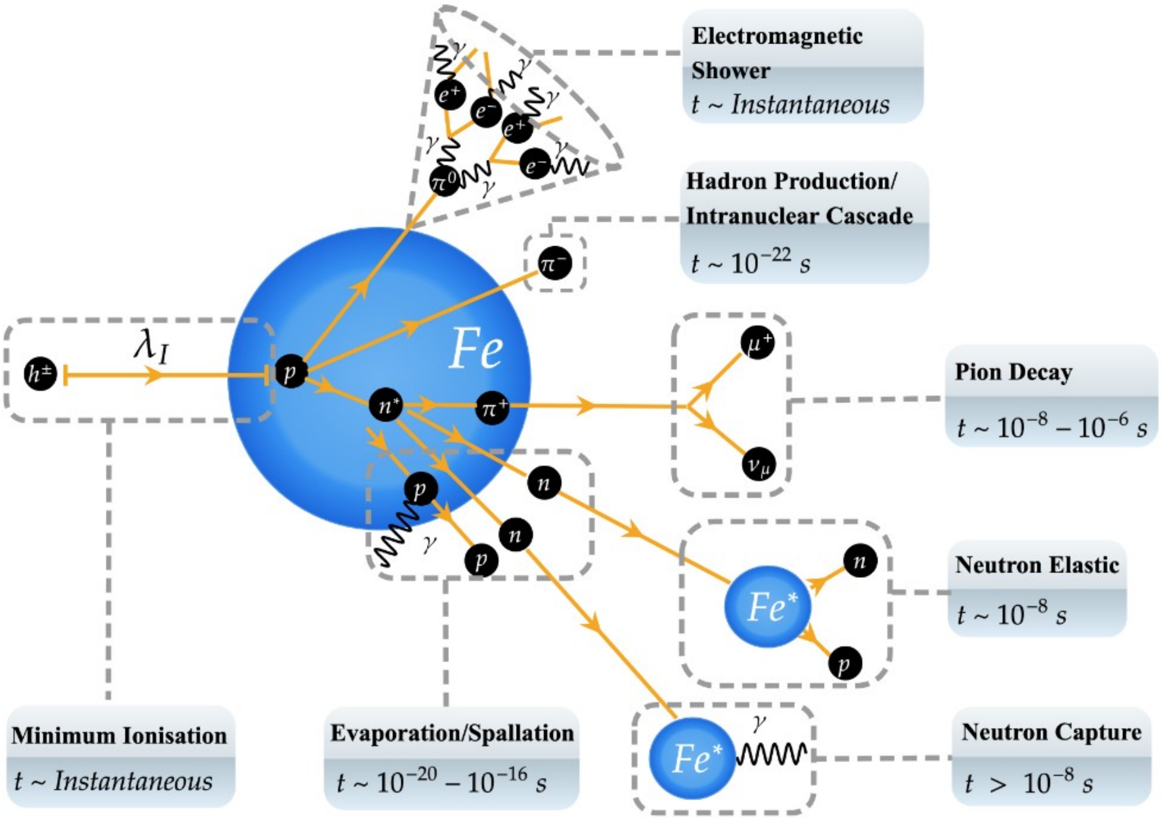
- Hit time resolution: Results from **2018 beam test** of **AHCAL** with muons
  - Encouraging results (1-2 ns resolution)
  - Distinction between slow and fast components in the showers (neutral vs charged)



- **SDHCAL**: Separation of 10 GeV between neutral hadron and charged hadron [CALICE-CAN-2015-001]
  - More than 90% efficiency and purity for distances ≥ 15 cm

The unprecedented granularity of the proposed calorimeters offers also unprecedented capabilities to study the development of showers

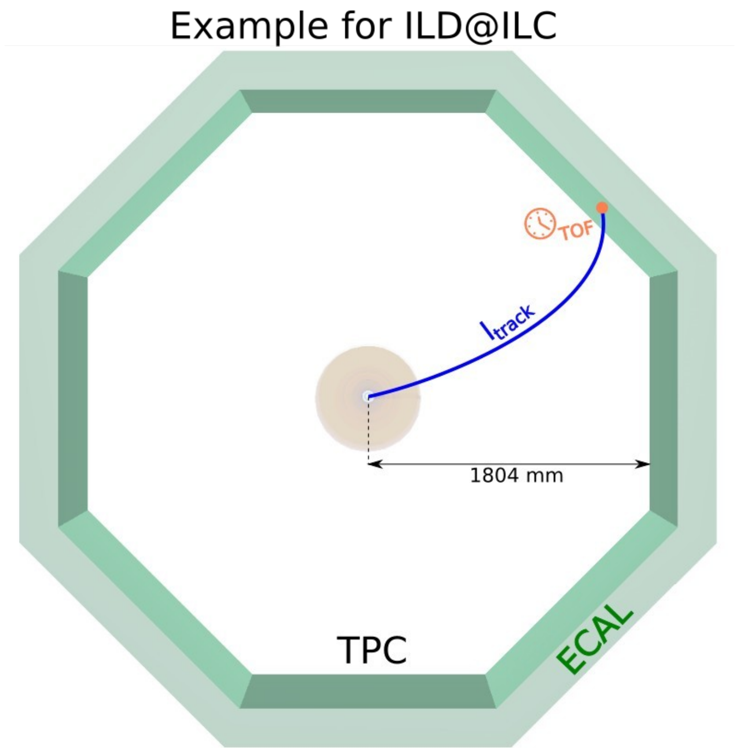
Timing in calorimetry

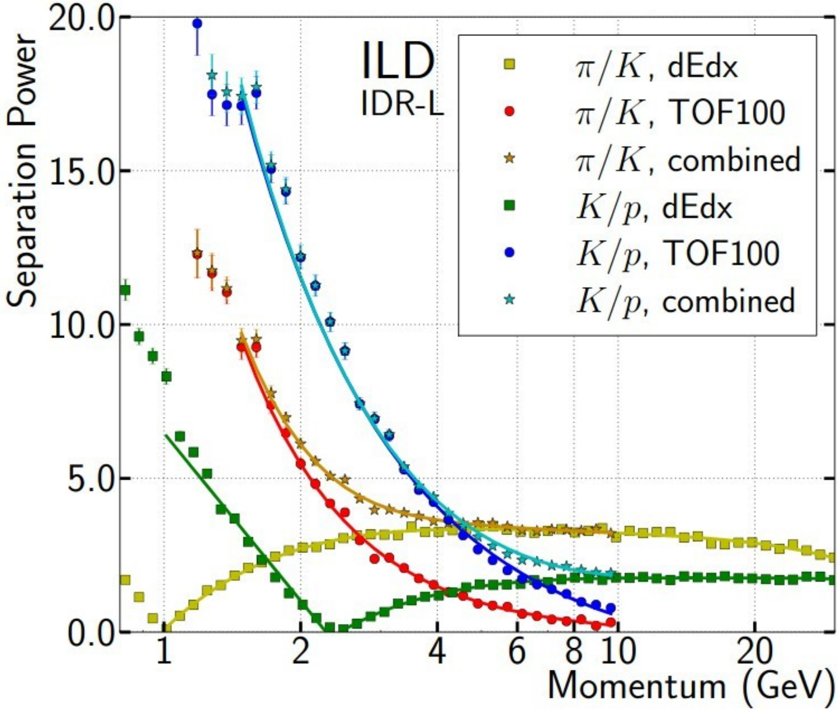


Timing measurements for shower developments

- Neutral and slow components
  - Require ~ns precision
  - Reachable today with “standard” silicon, scintillators calorimeters
- ~0.1 ns scale: near the corner
  - with “standard” silicon sensors (HGCAL)
  - GRPC (20ps)

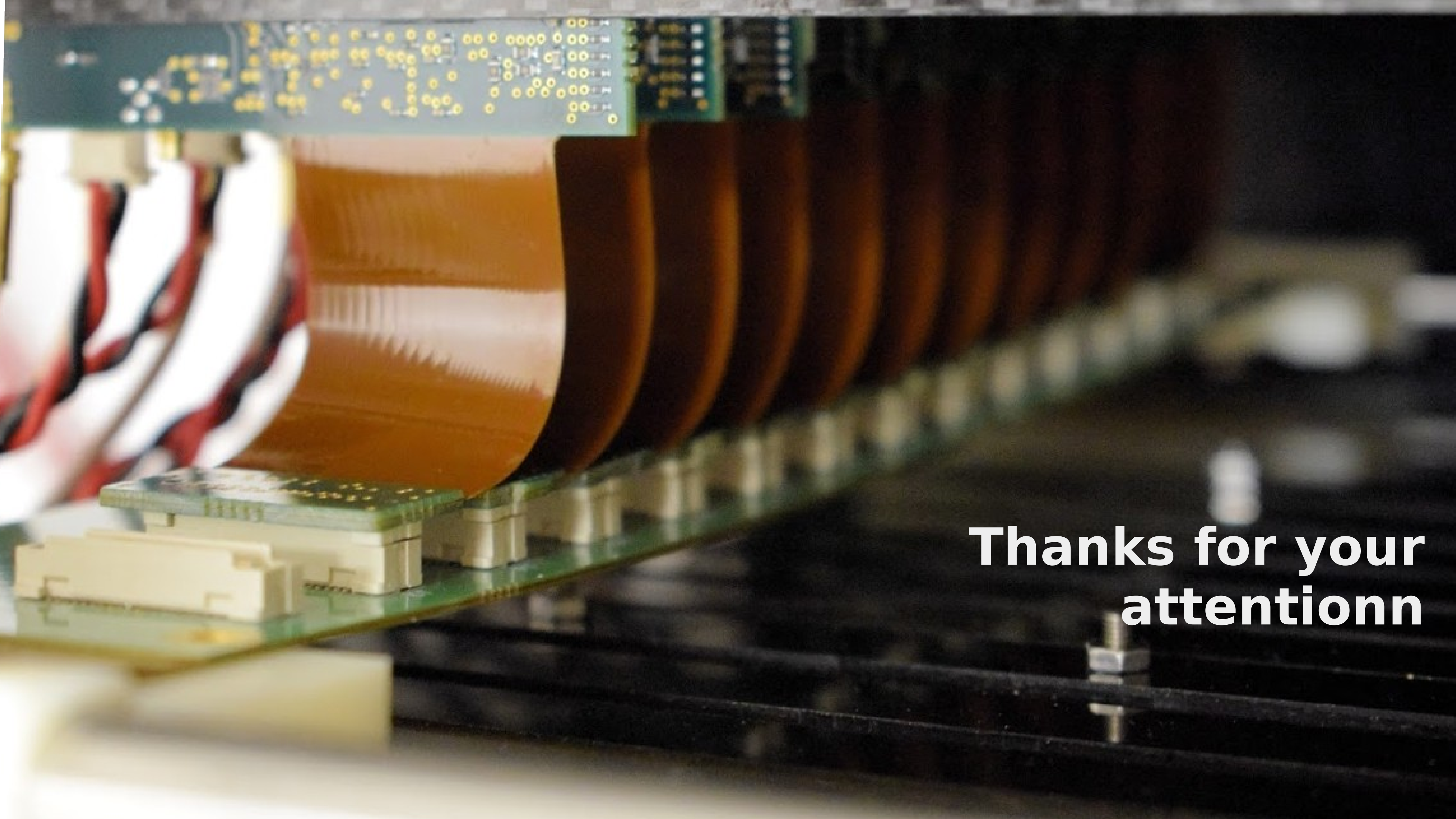
Timing for Particle Identification





Adding few ECAL layers with high time resolution for Time Of Flight measurements

- LGAD sensors with ~O(10ps)
- Drawback: high power consumption.


Thanks for your attentionn

Back up slides

Granularity Requirements

Physics drivers

- Granularity goals defined by hadronic shower physics: Segmentation finer than the typical structures in particle showers in all 3 dimensions

➯ X_0 / ρ_M drive ECAL and HCAL (electromagnetic subshowers)

Depends on material:
- in W: X_0 ~ 3 mm, ρ_M ~ 9 mm
- in Fe: X_0 ~ 20 mm, ρ_M ~ 30 mm

NB: Best separation for narrow showers particularly important in ECAL
➯ Use W in ECAL!

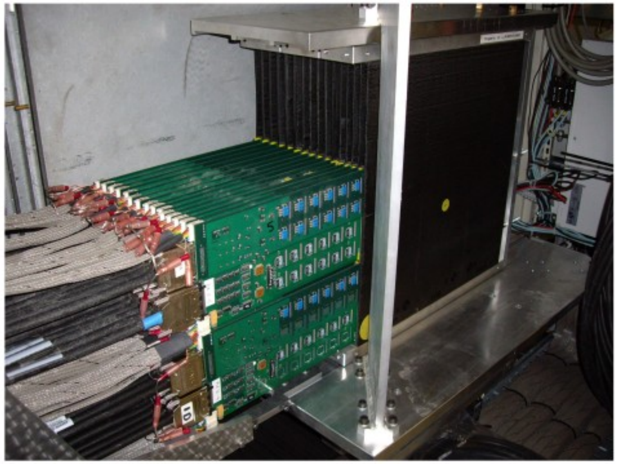
When adding active elements: ~ 0.5 cm^3 segmentation in ECAL, ~ 3 - 25 cm^3 in HCAL

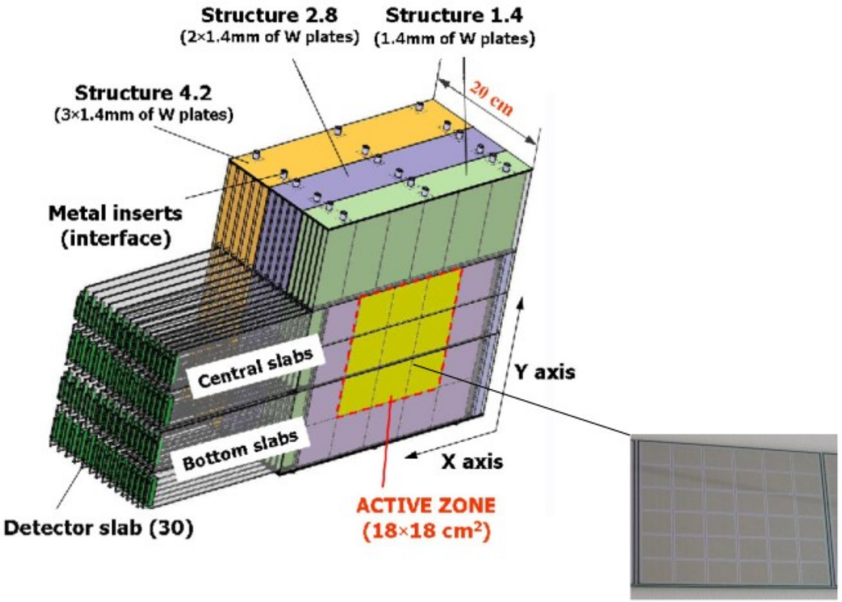
In addition: type of readout highly relevant: Need "analog" information for energy measurements - can be achieved also with "particle counting", requiring correspondingly higher granularity to avoid saturation effects

N.B.: In particular in the ECAL, a granularity significantly below the typical shower width can be highly beneficial

➯ *10s to 100s of millions of detector cells (or even more!) for full systems*

- Sampling calorimeter
- Absorber: Tungsten plates1.4-4.2mm:
- Active material: silicon P-I-N Diodes
  Thickness 525µm
- Granularity: 10x10mm^2





Three modules of with increasing W thickness

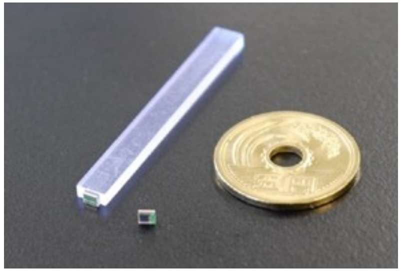
Total depth: 24 X_0, 1 λ_I

Active Zone 18x18 cm^2

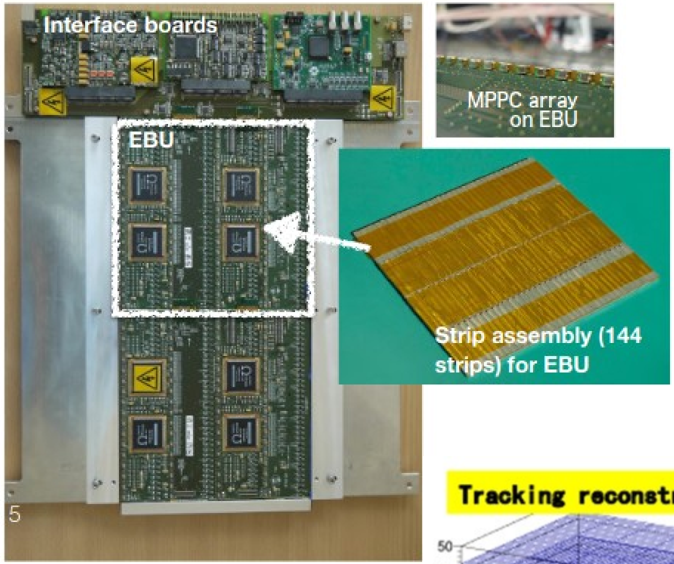
Total: 9720 Pixels/Channels

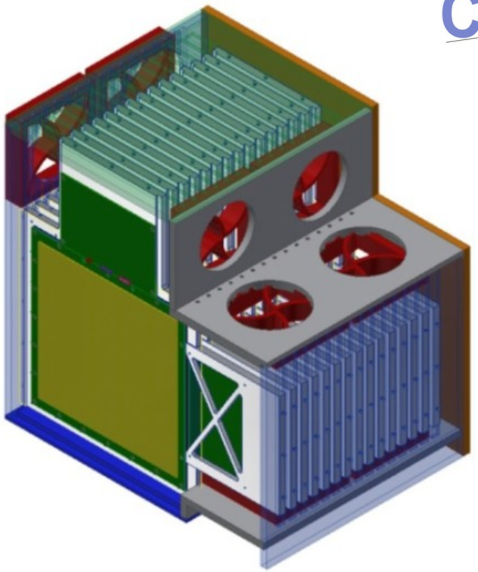
CALICE Sc-ECAL

A 32-layer prototype is under construction in China.
Option for CEPC and ILC electromagnetic calorimeters.

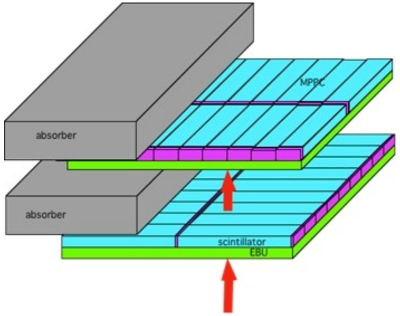


45×5×2mm³ scintillator strips
2.45×1.9×0.85 mm³ SiPM

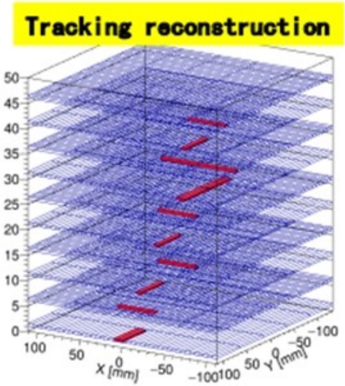


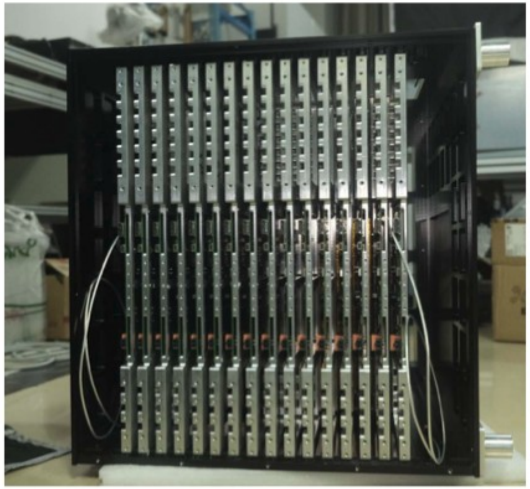


Test beams at DESY early 2021

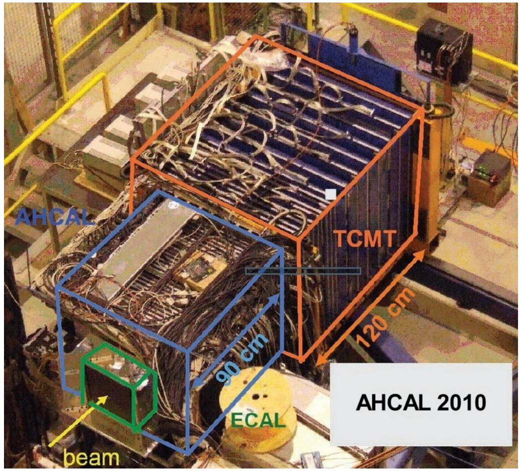


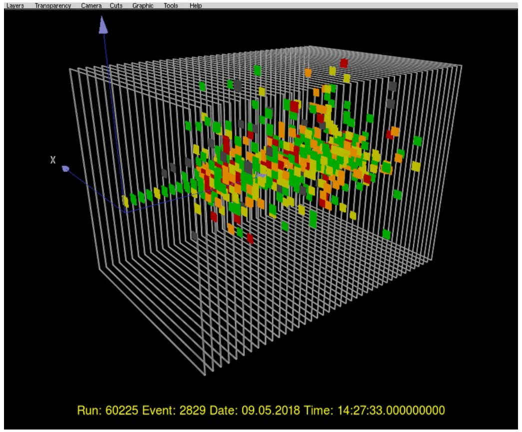
Strips could be read at both ends of longer strips
to increase accuracy and provide redundancy.





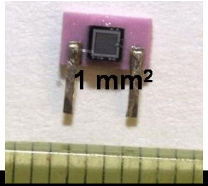
CALICE – Analogue HCAL

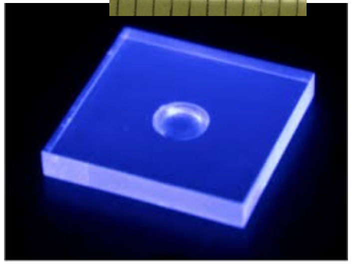




38 layers
$72 \times 72 \times 2.5$ cm^3 / layer
22,000 tiles

SiPM under the tiles for better uniformity and light collection





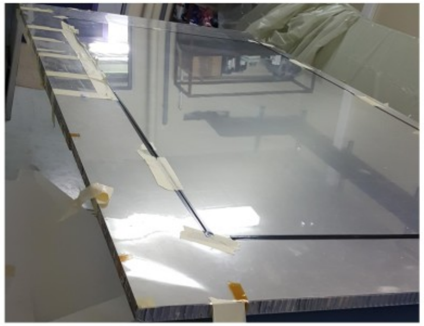
3x3cm^2 tiles

each cell also provides time information with ~1ns resolution

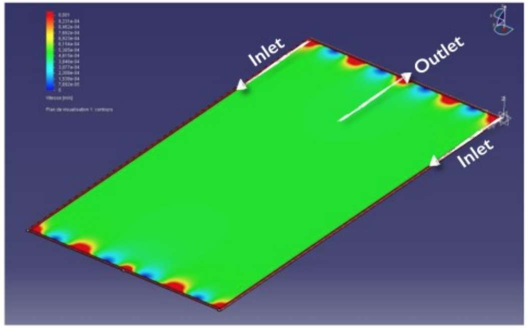
a true 5D "pixel" detector: x,y,z,E,t

Semi Digital-HCAL

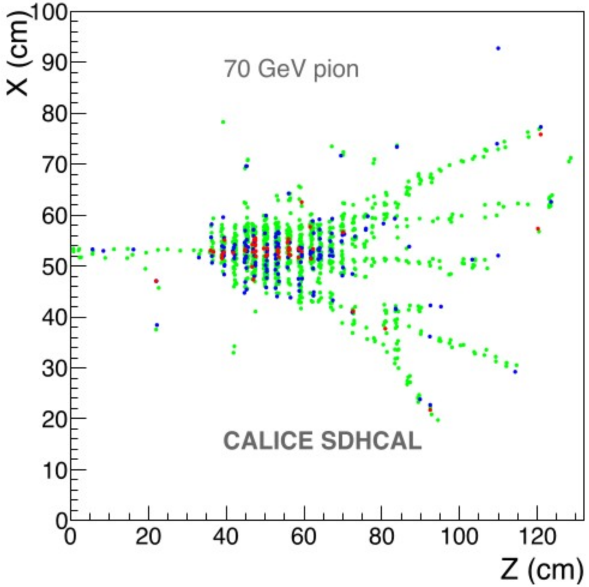
2 m^2 RPC assembled



Scalable gas distribution



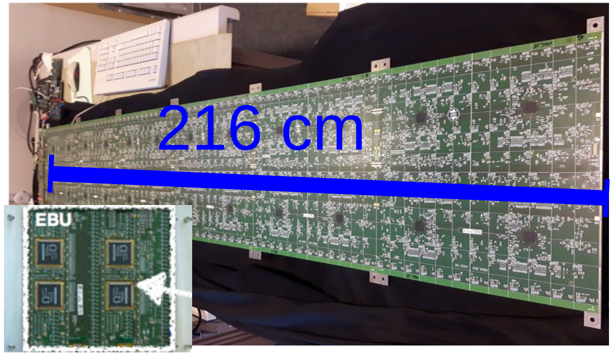
- ▶ 48 layers × 26 mm, also made of glass RPC.
  - 96 × 96 channels per layer, i.e.
  - ~440000 1×1 cm^2 readout channels.
- ▶ Semidigital readout
  - 3 tunable energy thresholds – 0.1MIP -5 MIP - 15 MIP
  - thresholds coded into 2 bits → pads with few, many or lots of hits.
- ▶ Optimize hadronic shower reconstruction via choice of thresholds.
- ▶ Better linearity response, improved energy resolution.



SiW Ecal

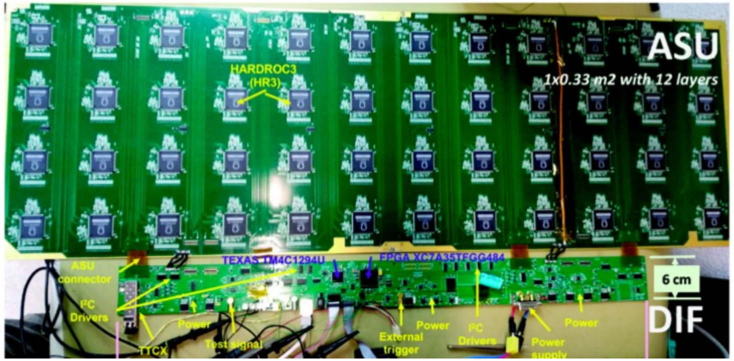
Semi-conductor readout

Analogue Hcal and Scintillator Ecal



Optical readout

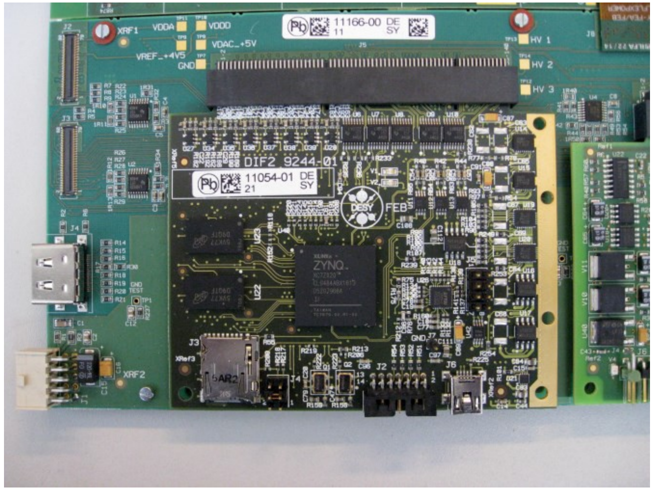
Semi-digital Hcal



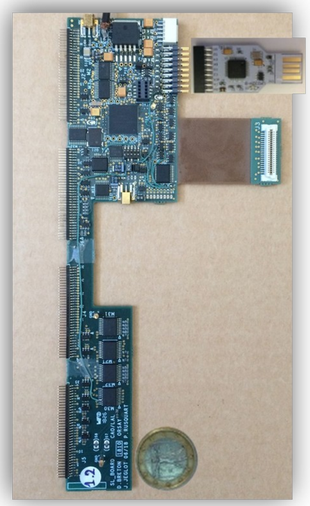
- Realistic detector dimensions
  - Structures of up to 3m in length (more than 10000 cells)
  - With compact external components
- Challenge for the power pulsing techniques (for the power consumption management)

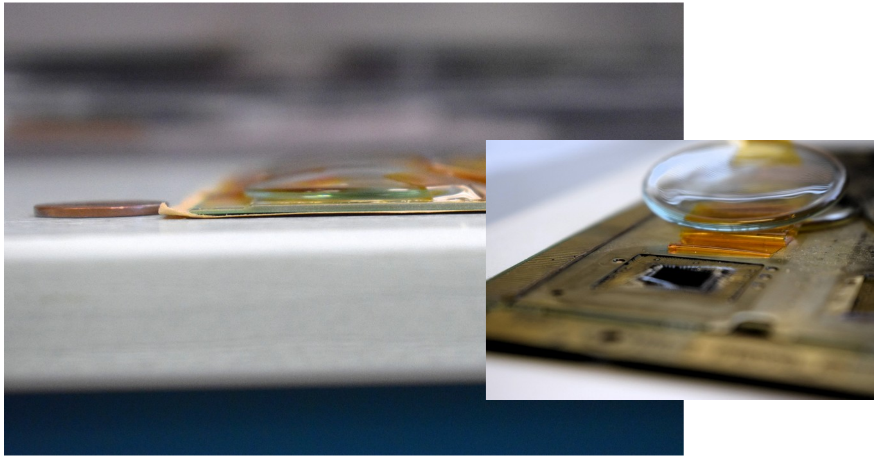
Technological solutions for final detector III

Current detector interface card - AHCAL

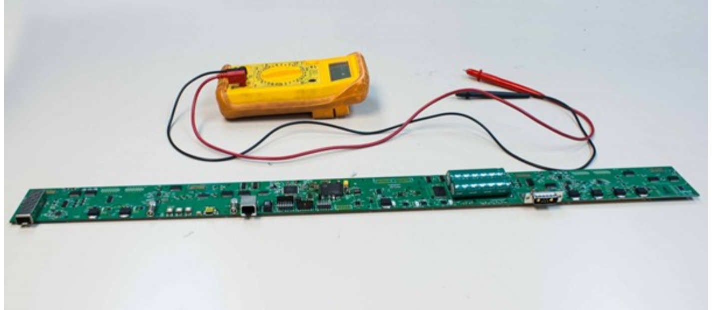


Current detector interface card and thin detection unit – SiW Ecal





Current detector interface card - SDHCAL



- "Dead space free" granular calorimeters put tight demands on compactness
- Current developments within CALICE meet these requirements
  - Unique successes in worldwide detector R&D
- Can be applied/adapted wherever compactness is mandatory
- Components will/did already go through scrutiny phase in beam tests

TB@2017: SiW-ECAL 7 layers

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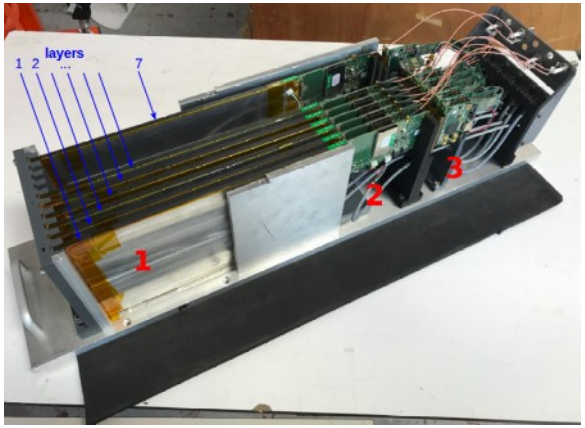
▶ **Setup** :

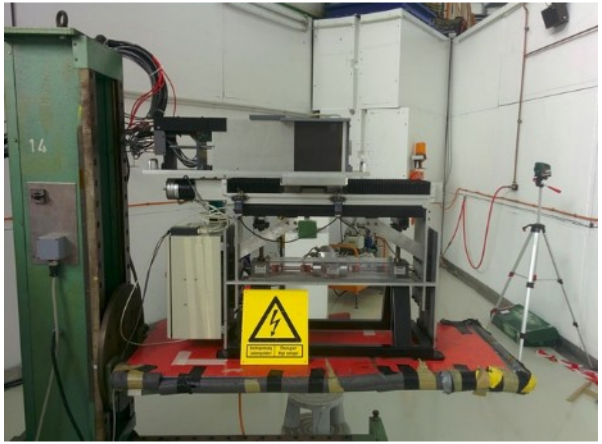
- 7 short slabs each equipped with 4 325um Si wafers and 16 Skiroc2
- **Skirocs working in Power pulsing and ILC mode** (emulated ILC spill conditions)
- **More than 7000 calorimeter cells!!**

▶ **Physics program:**

- **Calibration** run with 3 GeV positrons perpendicular beam without tungsten absorber plates
- **Electromagnetic showers program.**
- **Calibration** run with 3 GeV positrons in **~45 degrees** (6 slabs)
- **Magnetic field tests** with 1 slab (up to **1 T**)

Results published in NIMA 2019 162969





Results presented in **IEEE2017 (poster), LCWS2019 (parallel) CHEF2017 (parallel) and VCI2019 (Plenary)**

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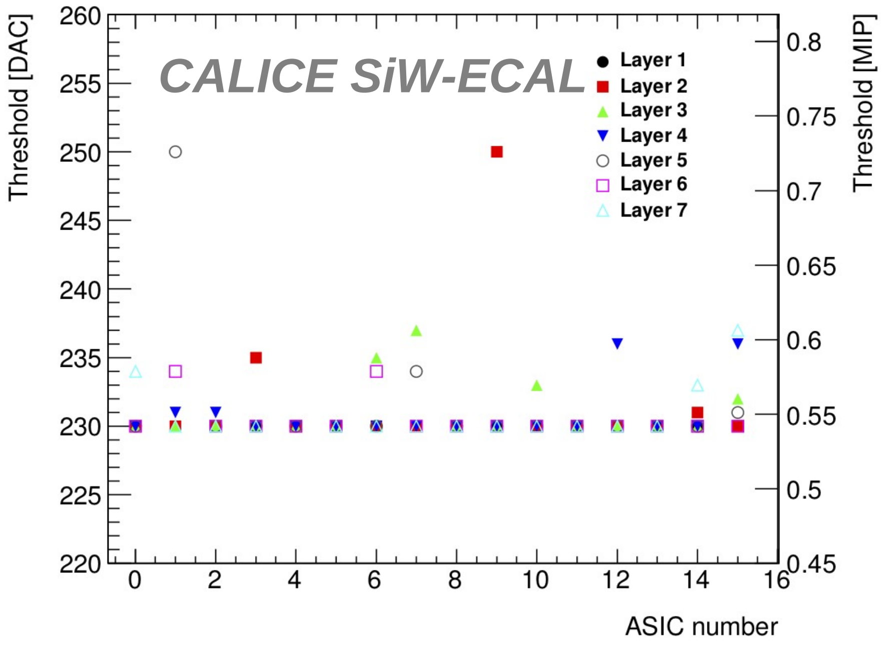
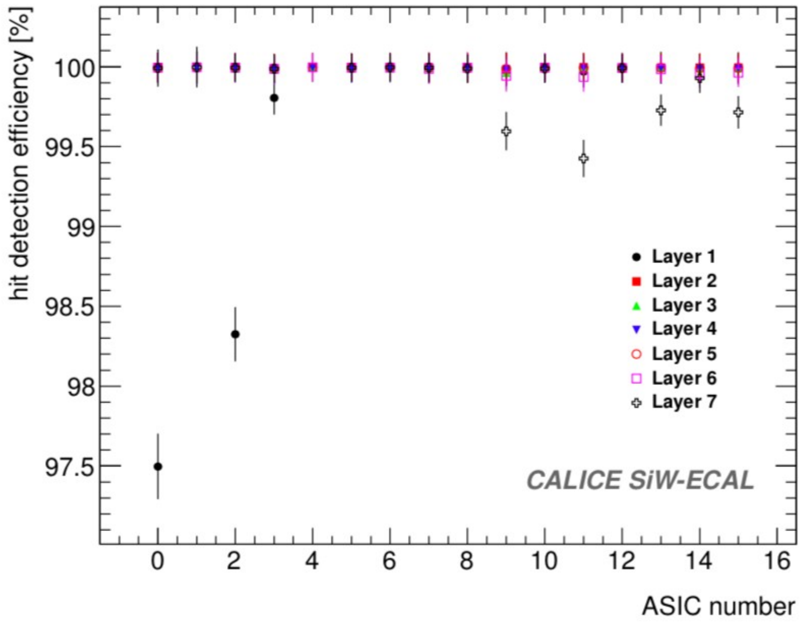
Arxiv:1810.05133



Trigger thresholds uniform at around 1/2 MIP

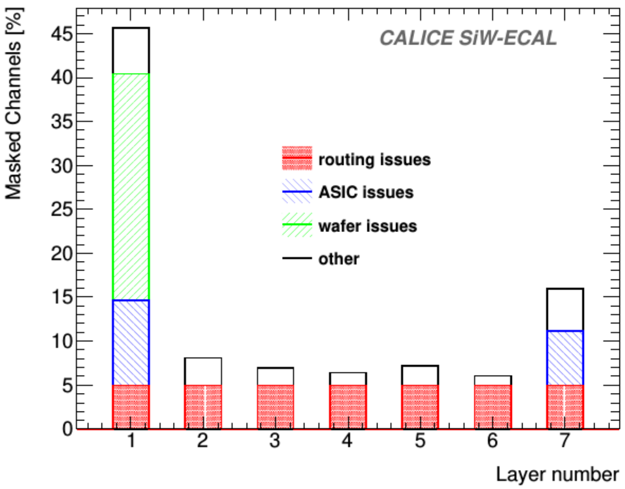


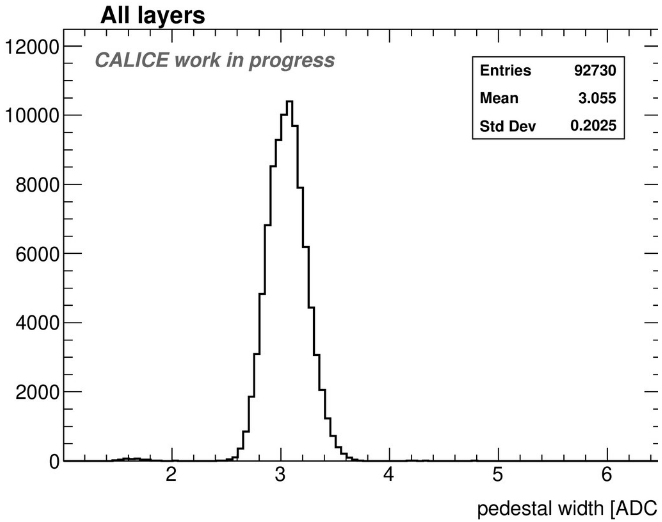
MIP Detection efficiency ~100%

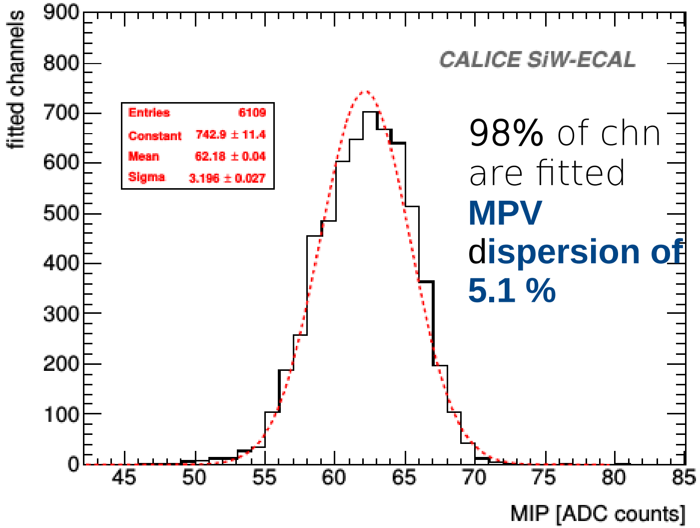
PFA requires small pixel size, large segmentation and pattern at low energy:
a) Access to small signals -> Low self-trigger thresholds (with zero supression and high S/N ~10 at MIP)✔
b) Tracking in calorimeters -> High MIP detection efficiency ✔

Commissioning & single cell calibration

- Masking of noisy channels (~6-8% in each slab except if other issues are present)
- Self trigger optimization. Calibration (DAC to Energy) done only for one ASIC and assumed common for all.
- Homogeneous distribution of the witdth of pedestal distributions
- Single cell calibration homogeneity at 5% level





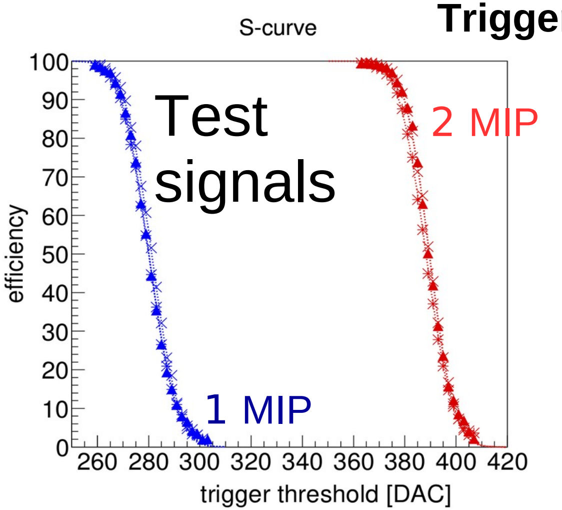


Results published in NIMA 2019 162969

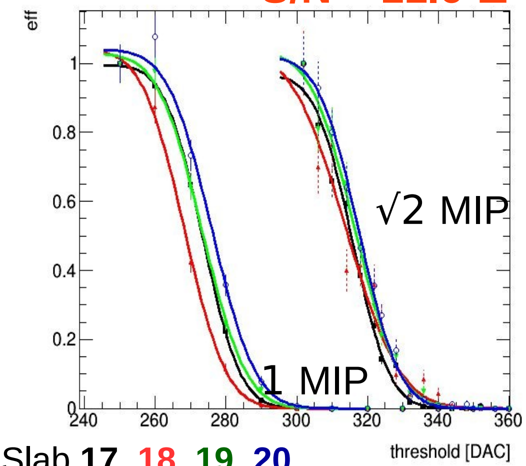
Arxiv:1810.05133

▶ Objective: Trigger and readout of small signals, **Design criterion: S/N ~ 10:1**

Trigger curves



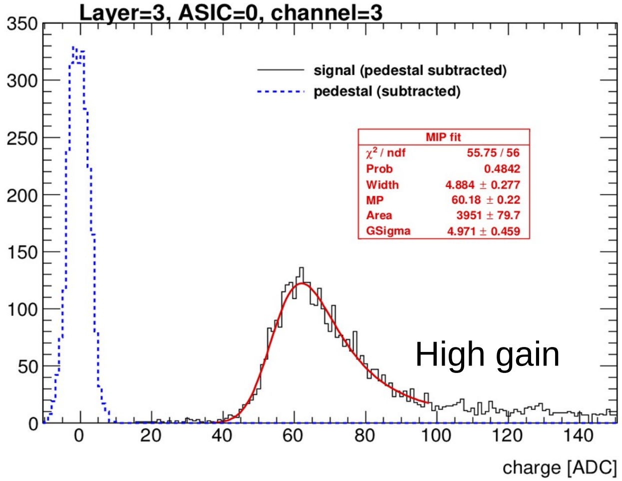
S/N = 11.6 ± 0.7



Slab **17**, **18**, **19**, **20**,
High gain

ILD baseline
requirements: S/N=10

Charge measurement

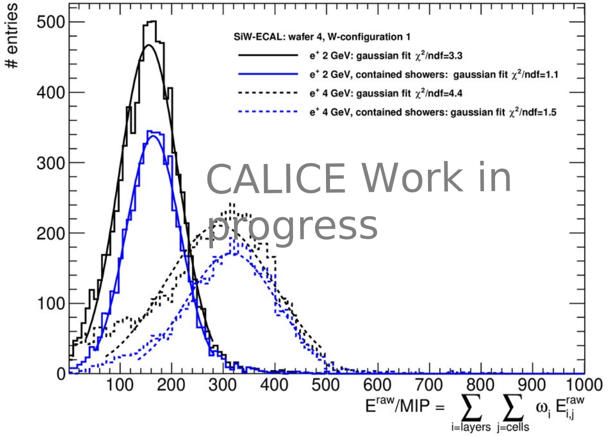


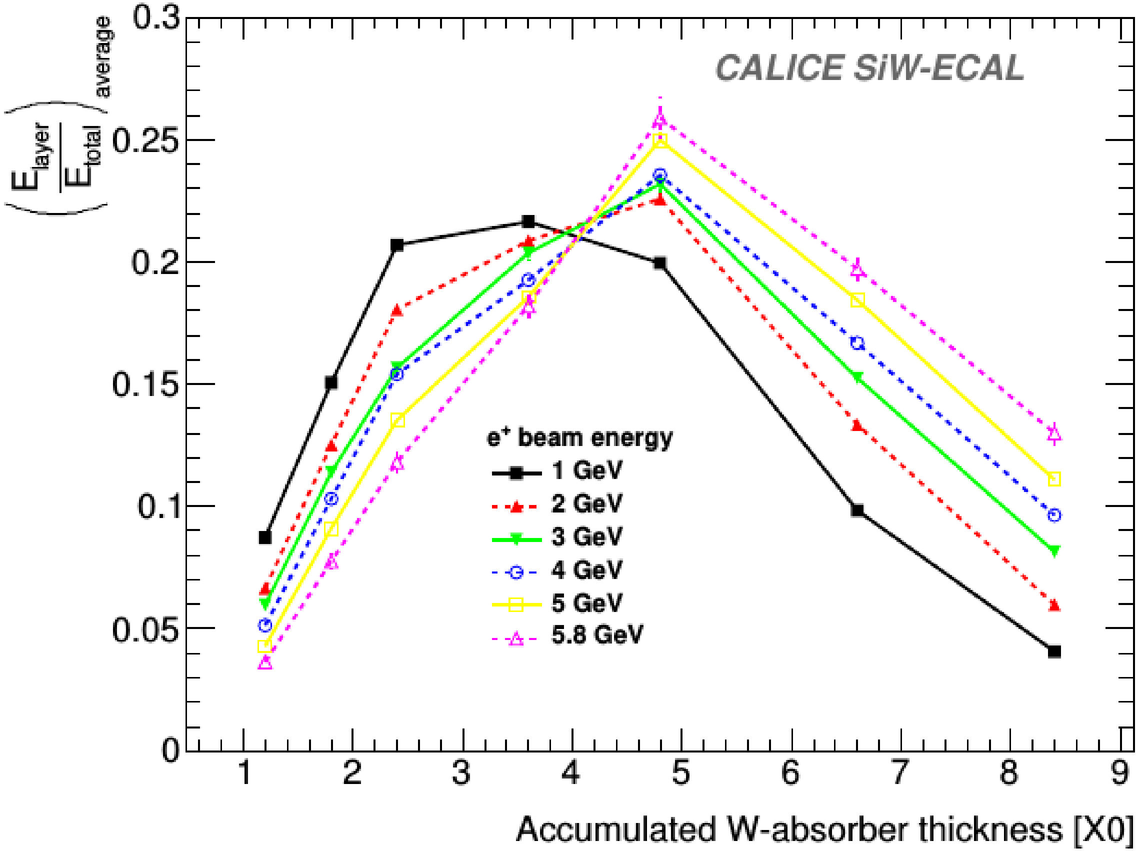
S/N ~ 20

Ability to trigger on small signals and to read them out for analysis

Raw shower profiles

- ▶ Qualitatively analysis: performance of the SiW-ECAL for low energy electromagnetic shower profiles.
- ▶ Comparison of raw shower profiles for several energies.



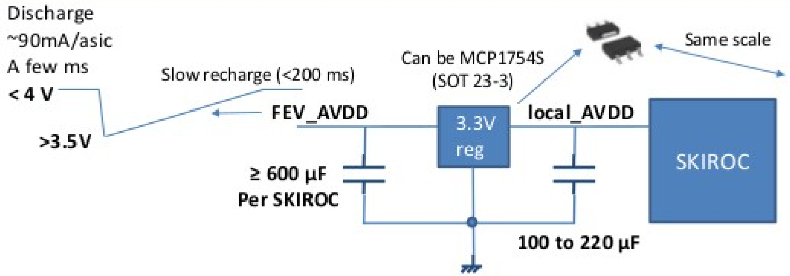


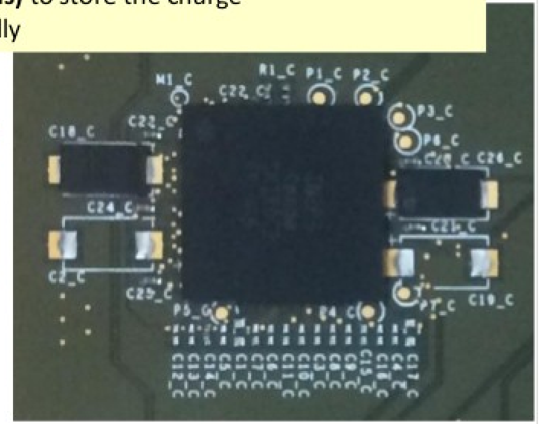
- ▶ Dedicated studies (MC comparisons, etc) to come

Under study: Power Pulsing

Two remarks:
1) High-value flat capacitors (**Murata**) actually have a poor **ESR** (**order of Ohms**) => not adapted to high currents
2) It is better that **the AVDD of the SKIROC chips does not vary** during the power pulsing

⇒ two actions:
1) Put **enough lower-value capacitors** with very **good ESR (~ tens of mOhms)** to store the charge
2) AND add an **individual regulator** for producing each SKIROC's AVDD locally





Example of Discharge/Recharge Cycle for one SKIROC block:
- Current of 90 mA during 2.5 ms in 600 µF => ΔV ~ 0.4V
- Total FEV capacitance ~ 15 000 µF
- Reload current can be as low as 15 mA/ASU

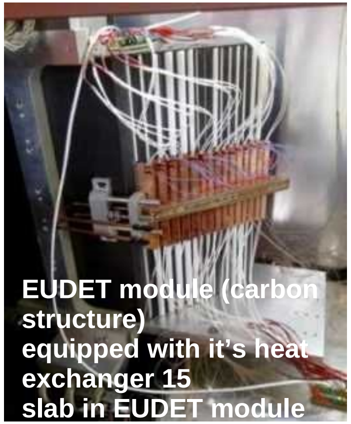
There are already 4 slots for decoupling capacitors around the SKIROC chips. More can be added if required (space is available).

There is **no more effect of the variations of AVDD on the SKIROC chips**
The only constraint is to **keep AVDD > 3.5 V.**
The higher the capacitance, the lower the variations => look for the optimum (~1000 µF ?)...

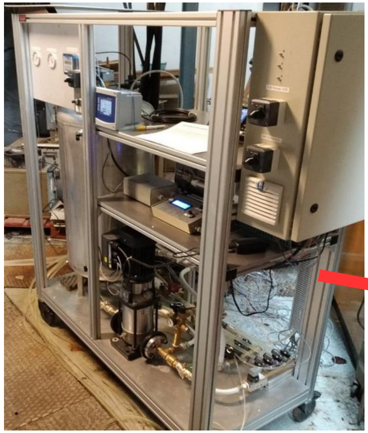
Calice Collaboration Meeting – Sept 2020 – IJCLab Orsay 24

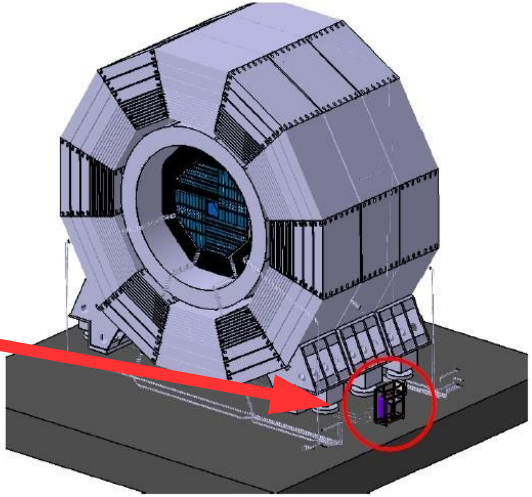
Slides from J. Maalmi (online CALICE Meeting 2020)

SiECAL Electrical Services and Cooling



EUDET module (carbon structure) equipped with it's heat exchanger 15 slab in EUDET module



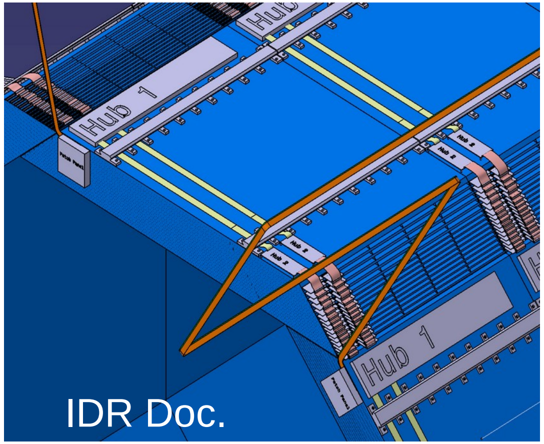


▶ **Real size water cooling demonstrator for the ECAL**

- CFRP+W structures + Silicon detectors
- full size leak-less cooling-loop on 3 levels (13m-10m- 9m)
- Updated in AIDA2020 DR 14.8 and IDR document

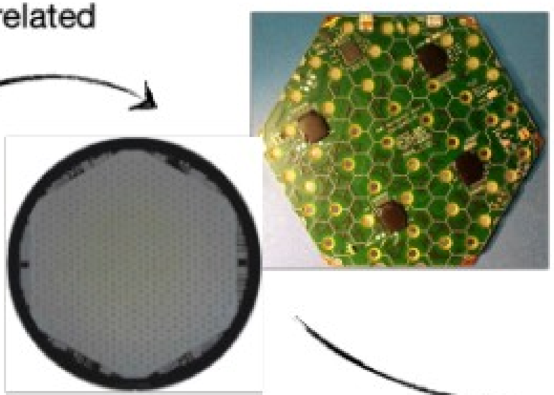
▶ **CORE Module and SL-Board modules** are **designed to fit the space requirements** of the cooling system / services system

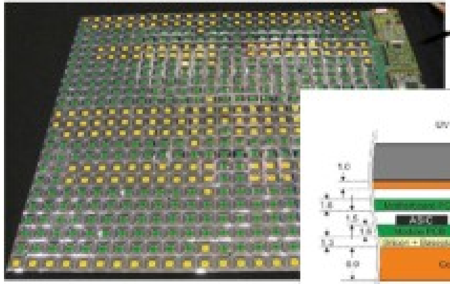
- Tests of compatibility to be done

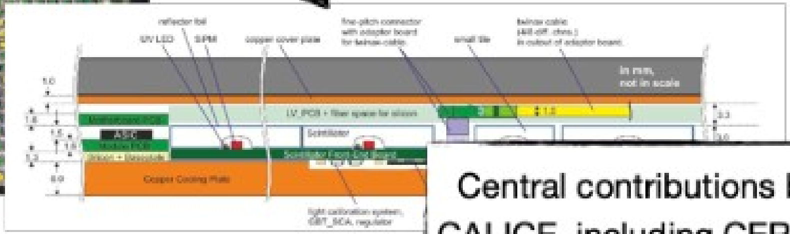


- The developments in CALICE have paved the way for a number of applications of highly granular calorimeters and related technologies in HEP

Most prominent: The CMS Endcap Calorimeter Upgrade HGCal







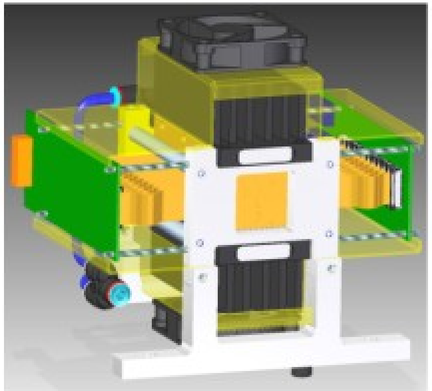
Central contributions by groups very active in CALICE, including CERN, DESY, LLR, OMEGA.

Spinoffs of CALICE R&D II

FOCAL MAPS ECAL:
Ultrahigh granular calorimeter is under consideration for ALICE (and also SiD-ILC, FCC-hh...)

Numbers for FOCAL assuming ≈ 1m² detector surface

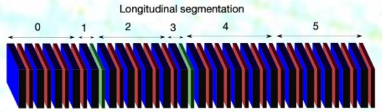
	LG	HG
pixel/pad size	≈ 1 cm²	**≈ 30x30 µm²**
total # pixels/pads	≈ 2.5 x 10^5	**≈ 2.5 x 10^9**
readout channels	≈ 5 x 10^4	**≈ 2 x 10^6**



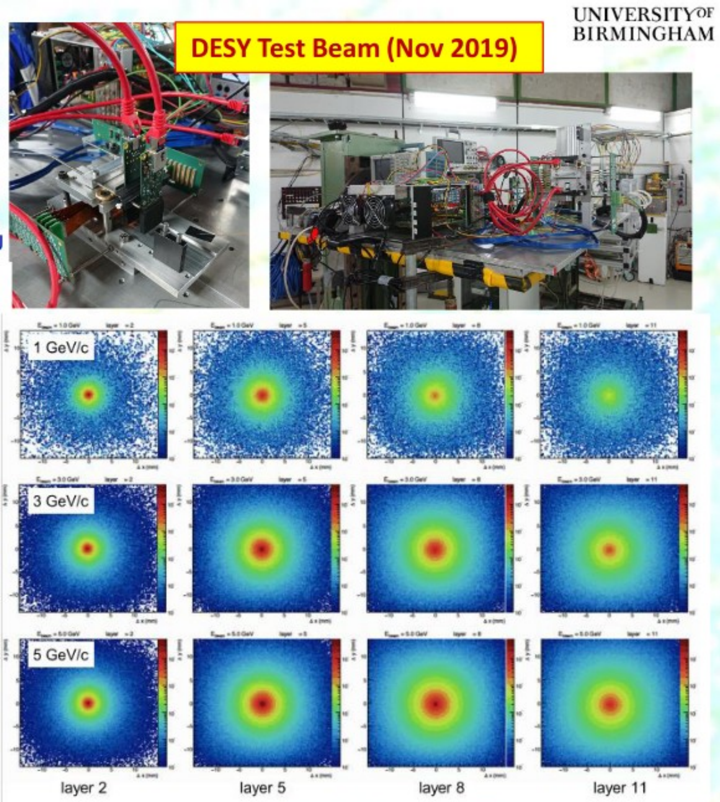
- Recent Testbeams with
- MIMOSA for HG
- Prototype with ALPIDE under construction

▶ TestBeam in Nov2019 & Feb2020

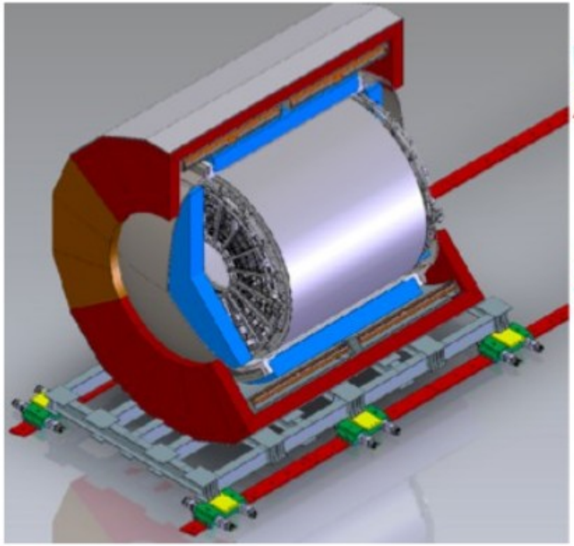
- 24 layers,
- 48 ALPIDE sensors,
- 24M pixels

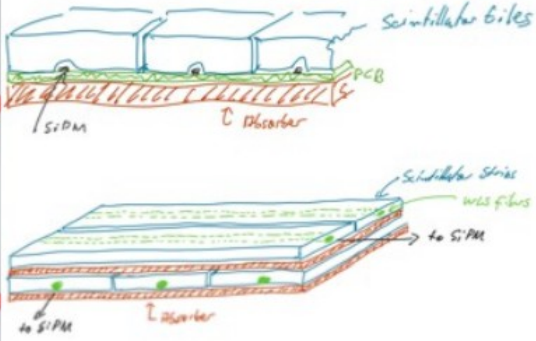


New ALPIDE CMOS sensor based 3cm×3cm area 24 layer stack



Spinoffs of CALICE R&D III

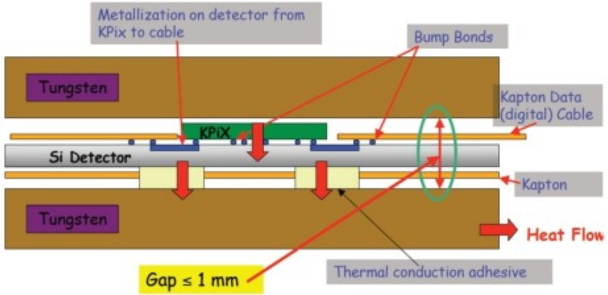




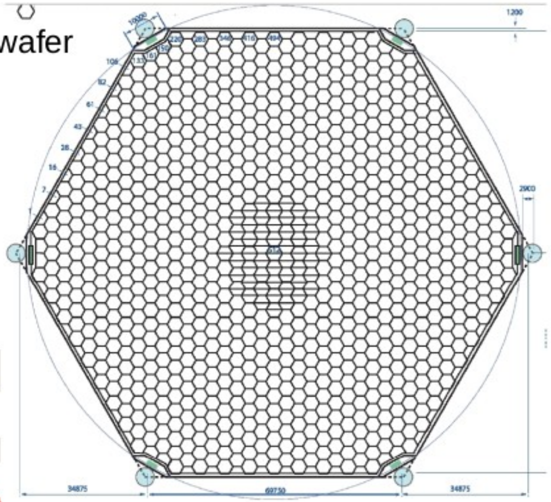
- SiPM-on-Tile and scintillator strips as active material for DUNE Near Detector
- Similar requirements on compactness as lepton collider detectors
  - Study of adaptation of CALICE technologies ongoing
  - Including first discussions on engineering level

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



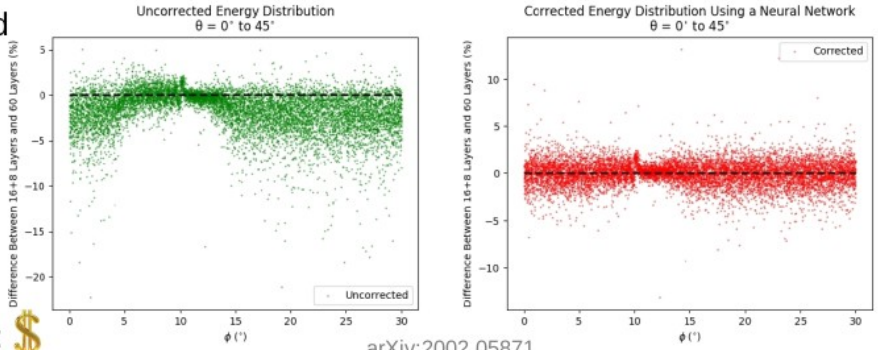
arXiv:1306.8329 - ILC TDR 4: Detectors

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: $



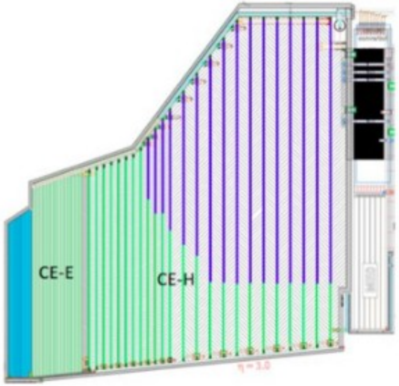
arXiv:2002.05871

Common beam tests

SiW ECAL/SDHCAL (2018)

CALICE meets CMS

Common beam tests since 2017



- Common beam tests benefit from common approach within CALICE
- But also from wider networking activities such as EUDAQ2 of AIDA2020
- More common beam tests to come after CERN shutdown

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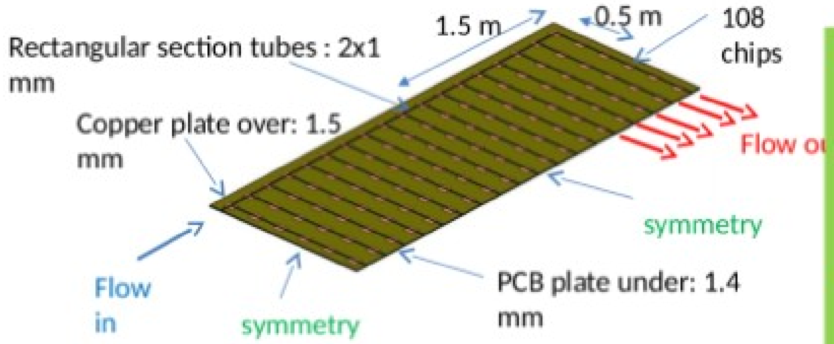
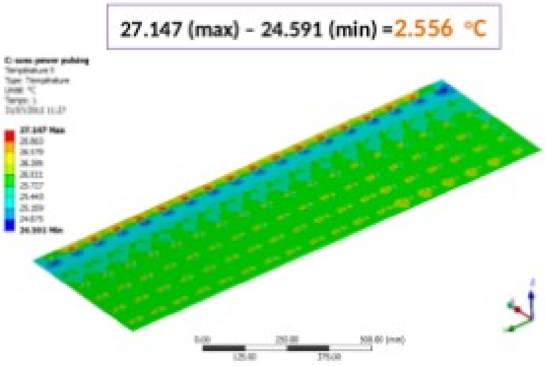
Power pulsing at LC <-> No power pulsing at Circular Colliders => Strong heat dissipation

Example:

CALICE SDHCAL



- A water-based cooling system inside copper tubes in contact with the ASICs to absorb excess heat.
- Temperature distribution in an active layer of the SDHCAL.



Water cooling : h = 10000 W/m²/k

Thermal load : 80 mW/chip

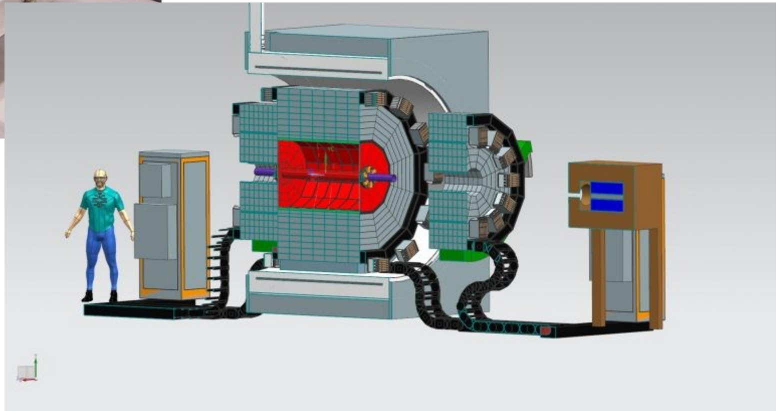
8

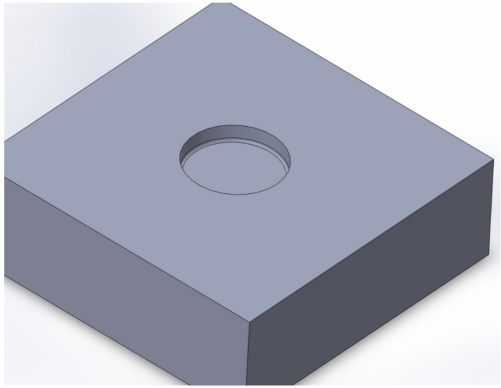
CEPC Xtal Calo Workshop – July 2020 33

- See Cristal Calorimetry talks from yesterday.
- Another example: ADRIANO2 calorimeter (REDTOP detector)

ADRIANO2 merges the benefits of a dual-readout and of a CALICE-type calorimeter, creating the base for a new generation of high-performance detectors.

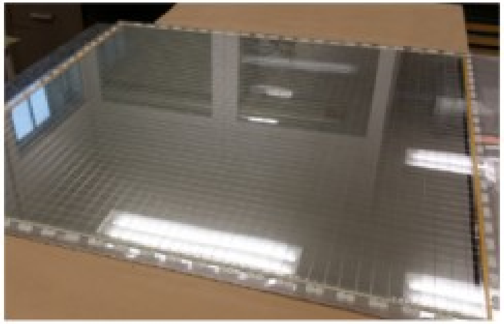
- Active mat.1: Plastic scintillator
- Active mat.2: heavy dense glass (only sensible to charged particles via Cherenkov rad). Fast detectors !
- Another example: ADRIANO2 detector





The next decade: ps timing in calorimeters

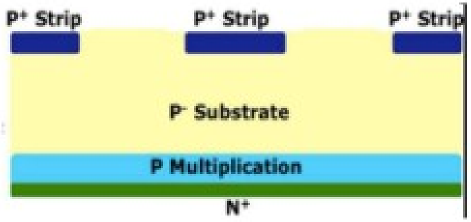
Pioneered by LHC Experiments, timing detectors are/will be also under scrutiny by CALICE Groups



Under development:
GRPC with
PETIROC

- < 20ps time jitter
- Developed for CMS Muon upgrade

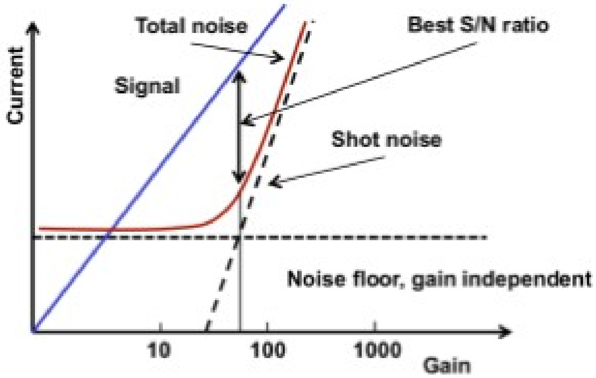
Inverse APD as LGAD?



Inverse APD
by Hamamatsu

Gain ~ 50

Theory says, need comparatively small amplification

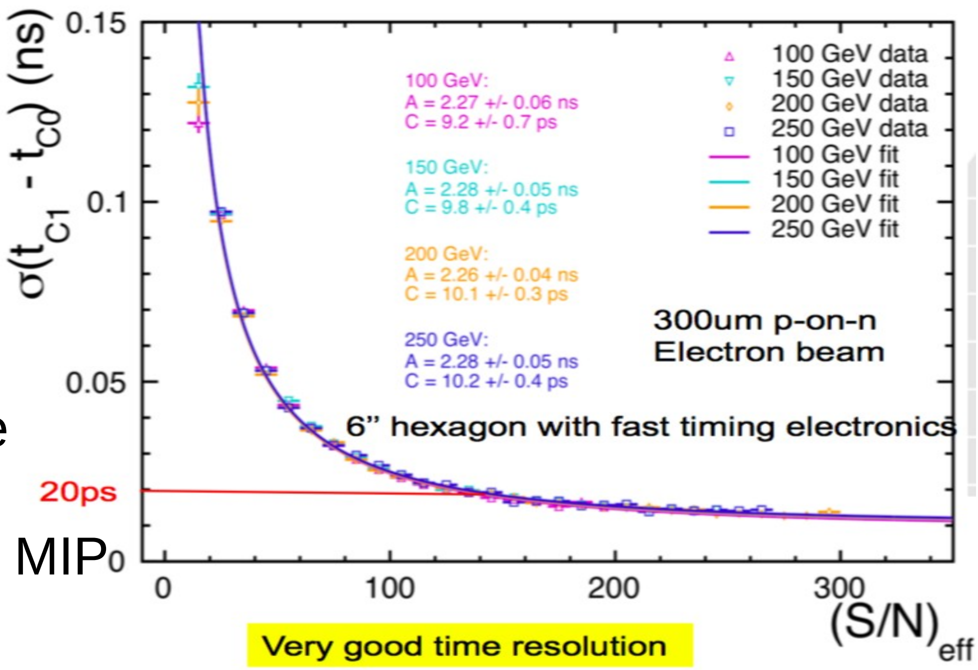


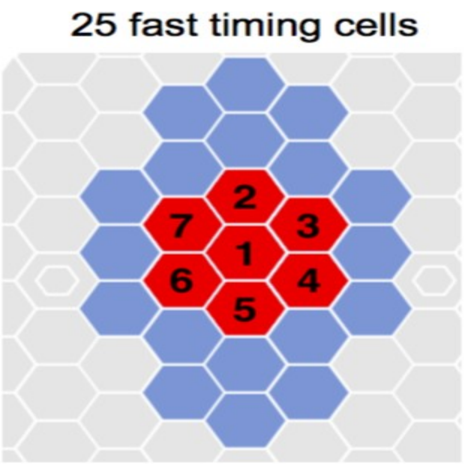
- Shot noise may be limiting factor
- Expect interesting comparison between inverse APD and LGAD as e.g. used by ATLAS
- Not that Members of CALICE are also members of ATLAS-HGTD

Expect interesting results on timing detectors from CALICE in coming years

Note:

Readout here
DRS 4ASIC
(S/N)~6.5@1 MIP





R. Poeschl
CEPC Xtal Calo
Workshop – July 2020

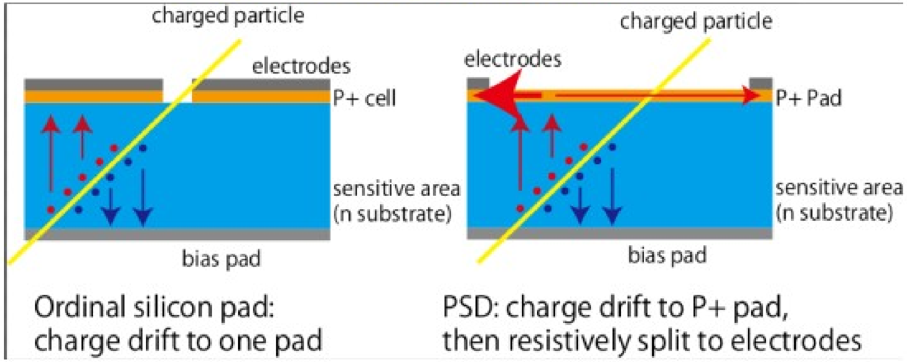
Timing error:

The pulse **slew-rate (slope) dV/dt** is the critical parameter for timing consideration
For signals of many MIPs, only jitter σj = Noise/(slope) is relevant if the time measuring circuit is under control.

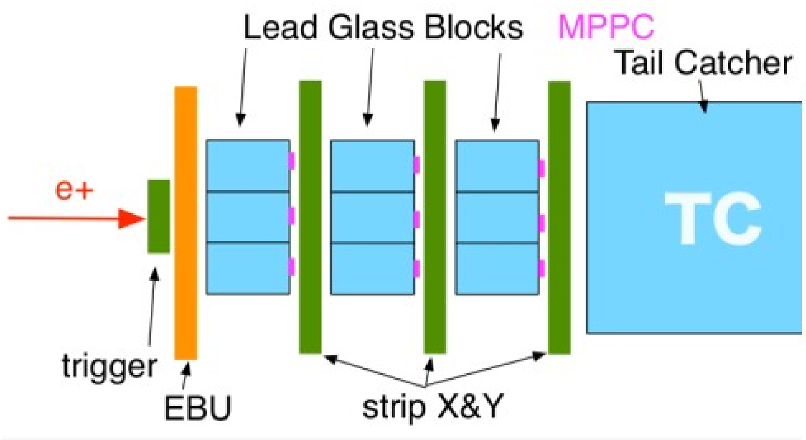
Note that for N concurrent MIPs, the jitter is σj (N) = 1/N* σj (MIP) if an adequate TDC/digitisation is used
The is the "root cause" for the good timing resolution in calorimeters.

R&D on materials

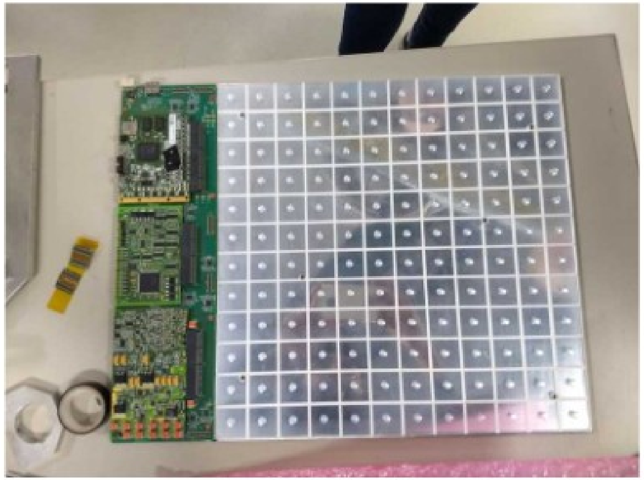
Position Sensitive Devices



Prototype of Crystal calorimeter



Megatiles for scintillator based calorimeters



- Tests in lab ...
- ... but also in beam tests
  - Megatiles and LG-Calo in 2019

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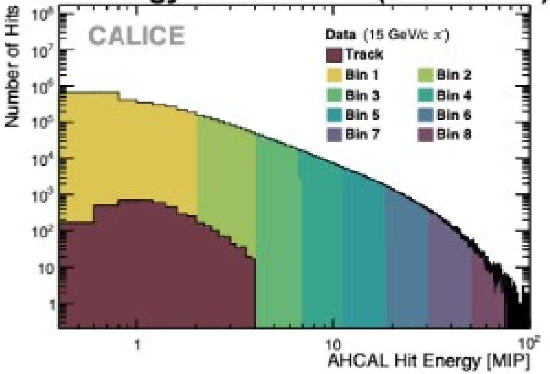
Software Compensation - Analogue Calorimeters

JINST 13 P12022 (2018)

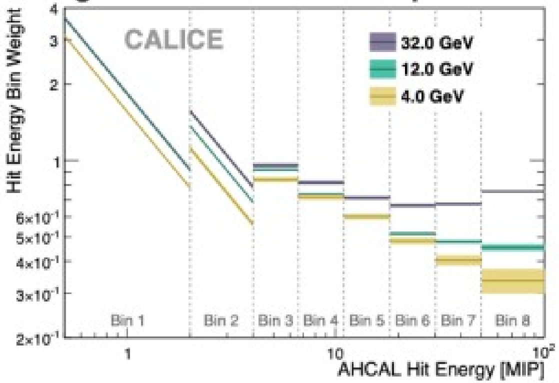
Basic Concept

- Local energy density within shower depends on origin of energy deposits
  - ➡ Higher density for EM component
  - ➡ Lower density for HAD component
- e/h response compensation by a assigning energy-dependent weights to hits before summing up corresponding hit energies to global energy sum
  - ➡ Significant improvement of energy resolution

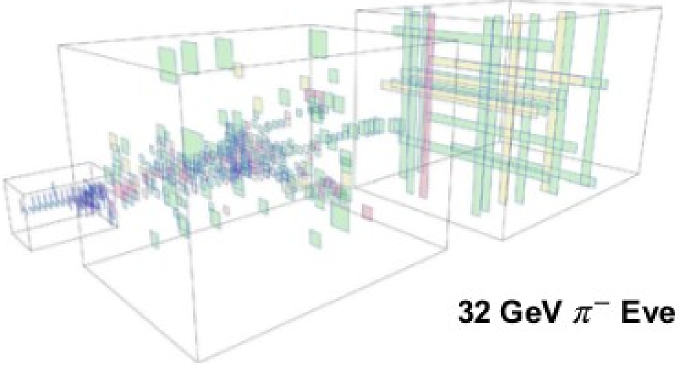
Hit energy distribution (15 GeV π^-)



Weights for Software Compensation



Combined Testbeam: ScW ECAL + AHCAL+ TCMT

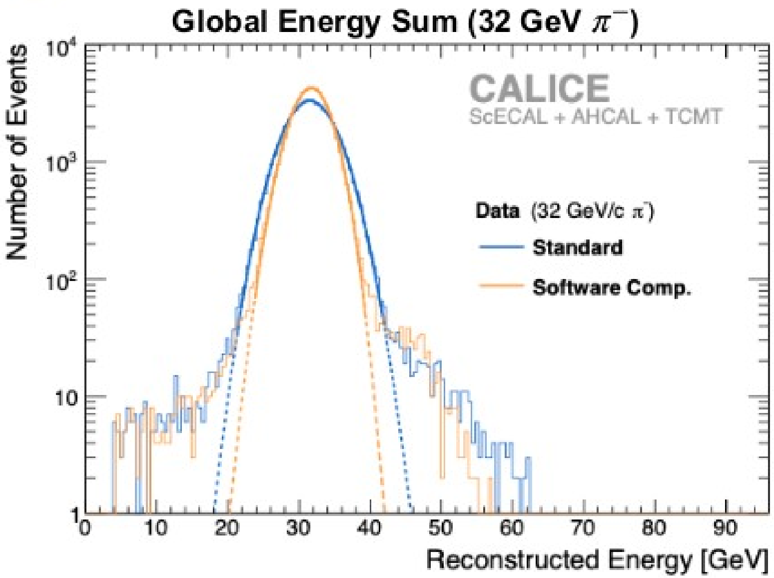


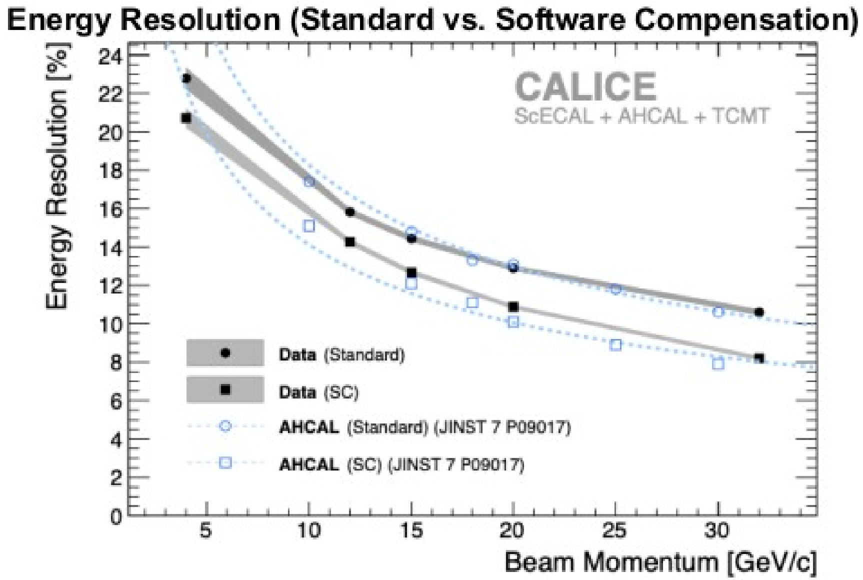
32 GeV π^- Event

Software Compensation - Analogue Calorimeters

JINST 13 P12022 (2018)
JINST 7 P09017 (2012)

Energy Reconstruction Performance





- Within CALICE collaboration software compensation is studied for a variety of detector prototypes
- Here: Combined test beam of ScECAL + AHCAL + TCMT (4-32 GeV π^- @ FNAL)
  - ➡ Energy resolution significantly improved by 10-20% compared to standard reconstruction
  - ➡ With software compensation: **~44.3% /** $\sqrt{E(GeV)}$ $\oplus$ **~1.8%**