Development of technologies for highly granular calorimeters and their performance in beam tests

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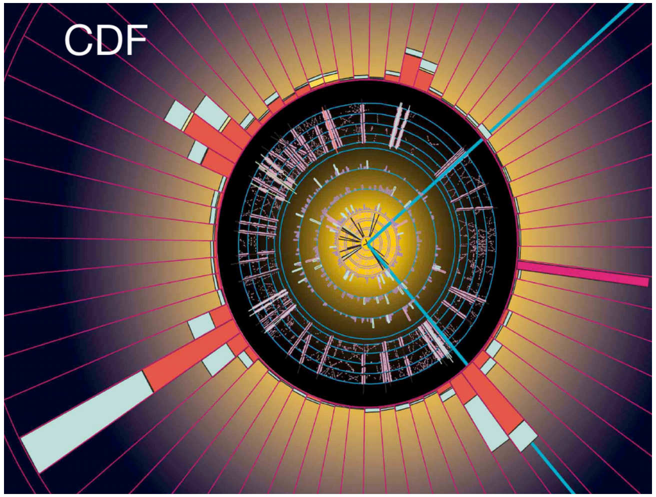
on behalf of CALICE collaboration,
about 300 people, ~15 years of R&D

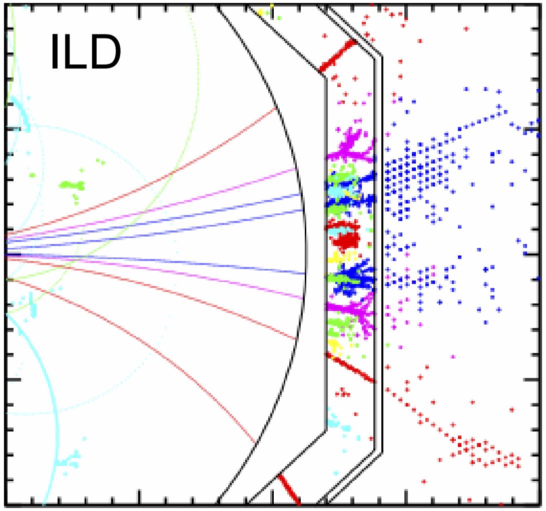
Outline:

- Particle Flow
- Technologies
- Performances and current R&D
- Conclusions

Particle Flow Algorithms (PFA)

Individual reconstruction of jet particles





Charged tracks (65% of jet energy in average) are measured in tracker, photons in ECAL (25%) and only neutral hadrons in HCAL (10%). Quark or gluon (jet) energy resolution is improved almost by 2 compared to traditional calorimetry: 3-4% for 50-500 GeV jets.

To distinguish showers of close-by particles: unprecedented transverse granularity of calorimeters, comparable or smaller than Moliere radius (for pure W / Fe: ρ_M = 9 / 17 mm).

Jet energy uncertainty is dominated by: a) HCAL intrinsic resolution for E(jet) < 70 -100 GeV
b) errors in resolving overlapping showers ("confusion") for higher energies

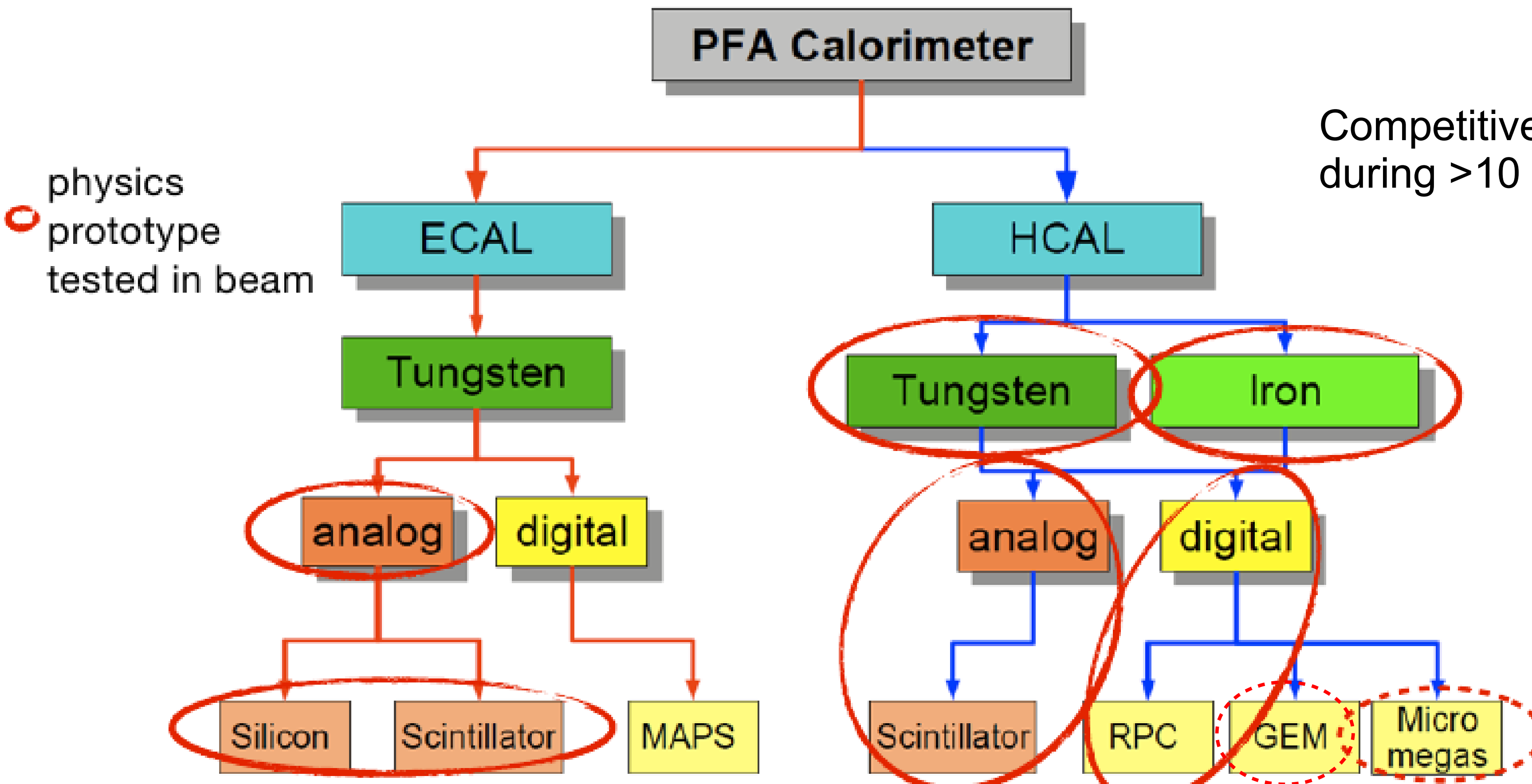
Moderate ECAL resolution $\leq$20% / $\sqrt{E}$ is sufficient.

Technologies

Best PFA favors ~5x5 / 30x30 mm^2 granularity in analog ECAL / HCAL, but no final word yet.

⇒ Several technologies within CALICE with different granularities

Competitiveness during >10 years :)

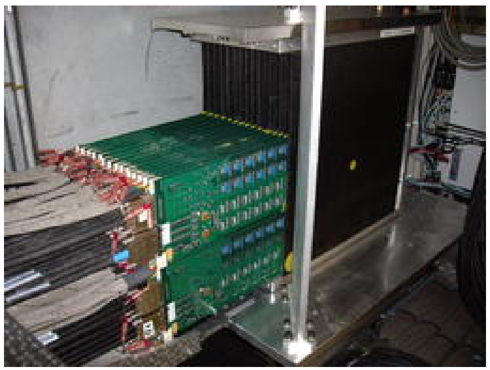


	Silicon	Scintillator	MAPS	Scintillator	RPC	GEM	Micro megas
Pixel, mm^2	10x10 → 5x5	45x10 → 45x5	0.05x0.05	30x30	10x10	10x10	10x10
N channels, $\times 10^3$	10	2		7.6	500+500	2.7	40

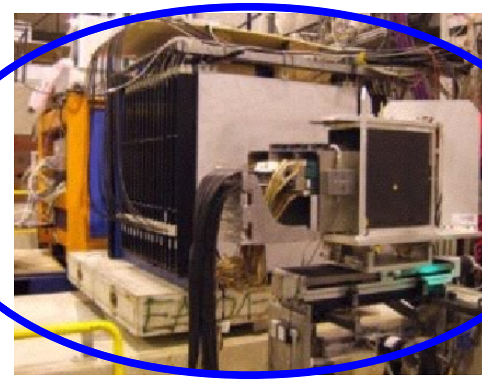
CALICE prototypes

1st generation, “physical” prototypes (2005 - 2011): prove PFA at early stage,
but left out technical issues, electronics not embedded, big power consumption
Excellent results: PFA validation w/ data, detailed shower measurements (next talk by Naomi)

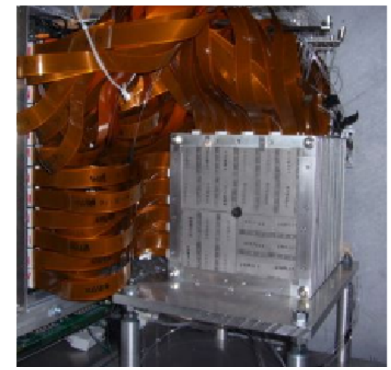
Si W ECAL, 18x18x20 cm^3



$1m^3$ Sc AHCAL + SiW ECAL



Sc W ECAL, 18x18x26 cm^3

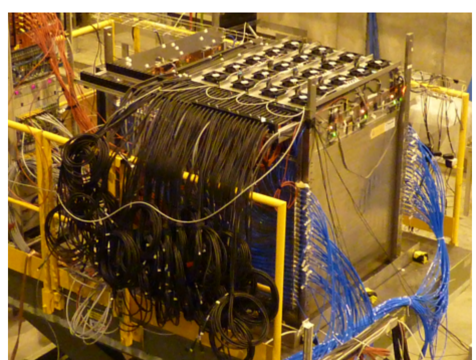


Current 2d generation Si and Sc prototypes: address technological challenges, scalable for ILC

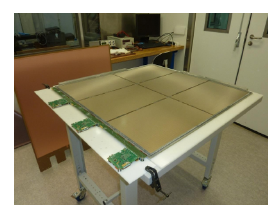
Gas HCAL with embedded electronics, first tests started 2010 - 2012

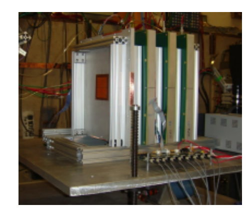
DHCAL, RPC, $1m^3$

SDHCAL, RPC, $1.3m^3$



Micromegas:
4 layers x $1m^2$





3 x 0.1 m^2 double +
single thick GEM

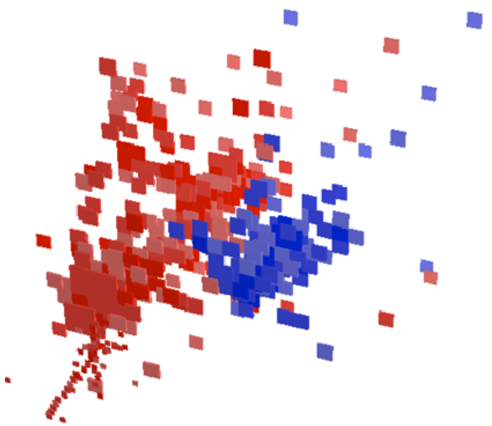
plus dedicated experiments for timing measurements in hadronic showers

PFA proof with data

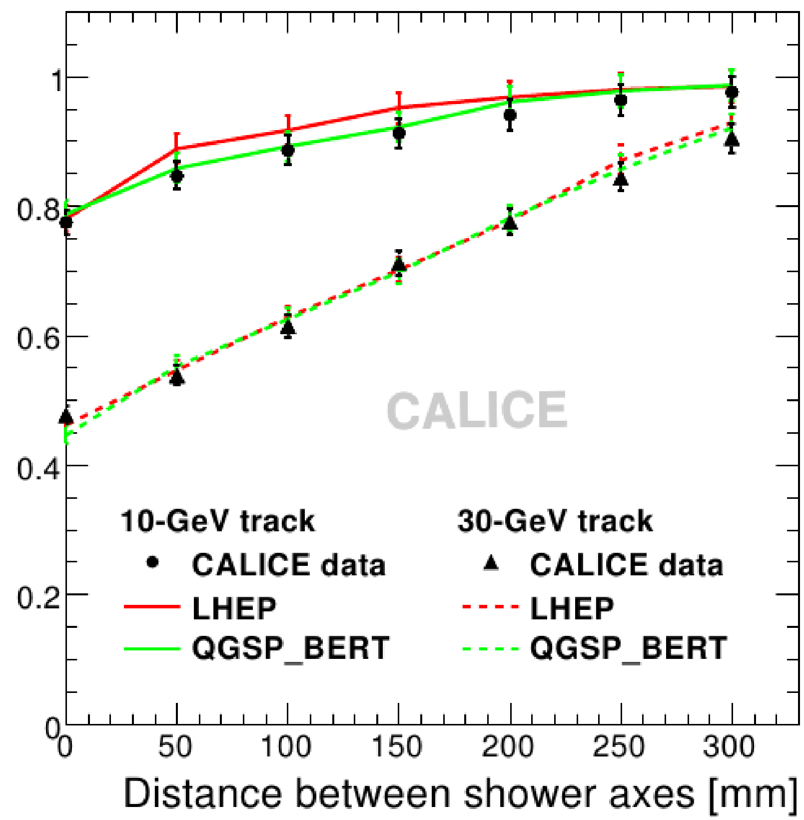
Intrinsic HCAL resolution (dominant contribution at lower jet energies) is well reproduced by MC. Key question: whether MC reproduces confusion in resolving close-by showers.

Modeled by overlap of single particle events (full PFA validation is impossible in test beams without jets).

Probability to reconstruct 10 GeV within $\pm 3\sigma$ of “neutral” shower vs. distance from 10 or 30 GeV shower, JINST 6, P07005 (2011)



1m^3 Sc AHCAL + SiW ECAL



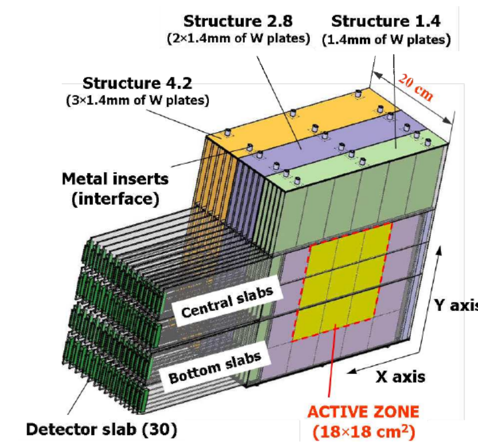
MC two-particle separation is confirmed

Technologies: silicon

p-n junction without amplification, key features:
- easily segmentable (5x5 mm^2 pixels),
- stable response (7000 e-holes / MIP / 100 um thickness), intrinsically linear,
  no dependence on environmental changes, stable in time (several years of beam tests)

$\Rightarrow$ lowest systematics, best granularity

but: high cost (~ 2.5 EUR / cm2 for mass production, less expensive than tracker Si)

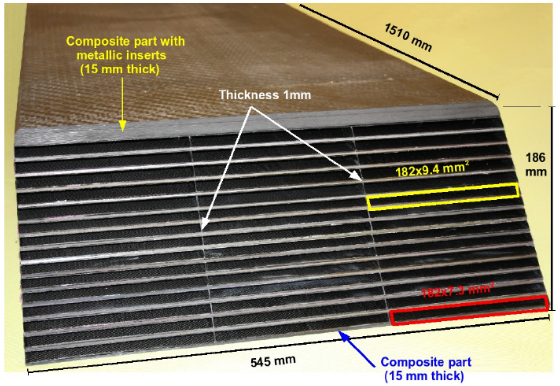


Energy resolution of ECAL physical prototype, NIM A608 (2009) 372:

$$(16.6 \pm 0.1)\% / \sqrt{E} \oplus (1.1 \pm 0.1)\%$$

in agreement with MC: $17.3 / \sqrt{E} \oplus 0.5\%$.

Linearity within 1%



Mechanical structure: self-supporting, 3/5 full scale ILC prototype has been build (5 years of R&D). Alveoli are to hold every 2d W layer with active sensors on both sides.

Power pulsing: switch off front-end currents between ILC bunch trains to reduce power by ~100.
Successfully tested with small technological prototypes.

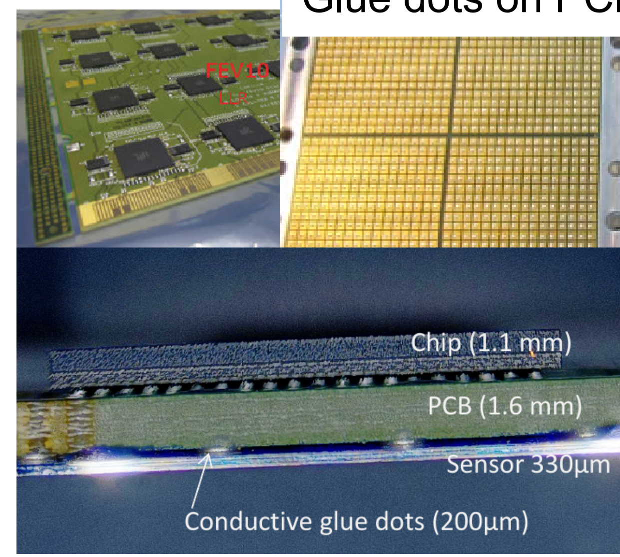
Technologies: silicon

Current R&D on
- embedded electronics for 5x5 mm^2 pixels readout
  from large areas
- production and industrialization of detectors suitable for ILC

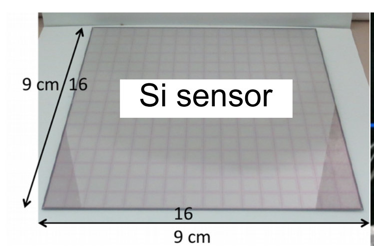
Recently: robot has glued 16 Si sensors pixel by pixel to
4 PCBs with conductive epoxy. 4096 pixels in total.
First cosmic tests are encouraging.

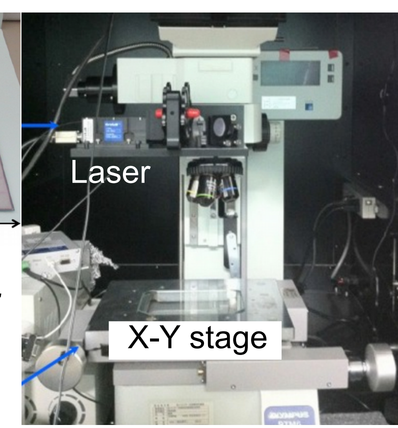
After validating one-PCB detectors: build long ILC detector
element from several (≤10) PCBs.

Glue dots on PCB



- in cooperation with industrial producers:
  optimization of Si sensor design





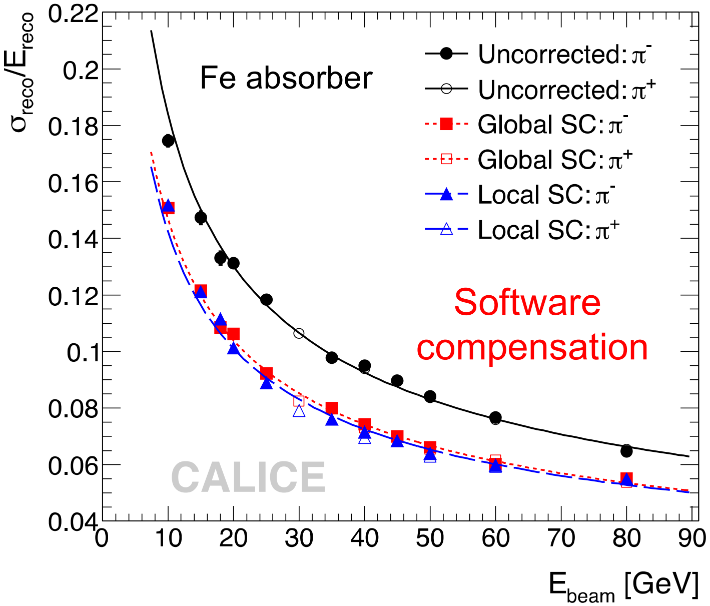
IR laser tests of
sensor x-talks

Technologies: scintillator+SiPM in AHCAL

"Physics" prototype (2006-2012) - first use of SiPMs in big scale, inspired T2K, Belle-2, CMS, medical imaging. Central part w/ 30x30x5 mm^2 tiles, Fe and W absorber.

Weighting hits from regions of lower / higher energy density (hadronic / EM component), allows to compensate AHCAL (e/h=1.2) and improve resolution from 58%/√E to

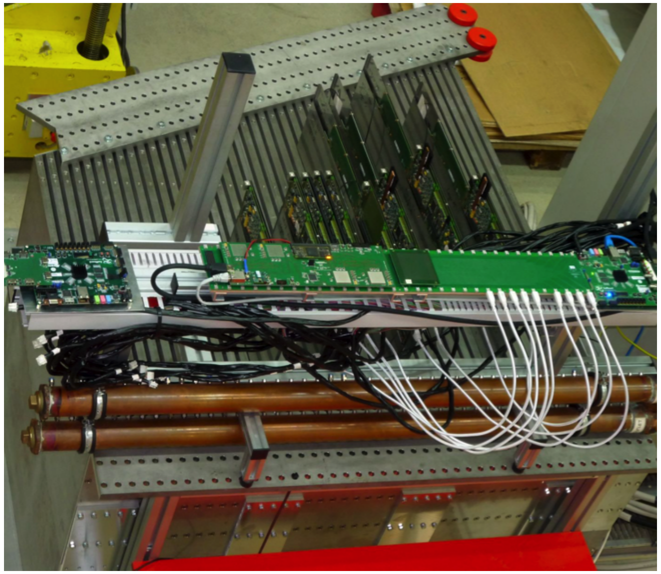
$$\sigma/E = 45.1\% / \sqrt{E} \oplus 1.7\% \oplus 0.18 / E$$



Current, 2d generation "technological" prototype, 30x30x3 mm^2 tiles:

- embedded electronics with realistic interfaces

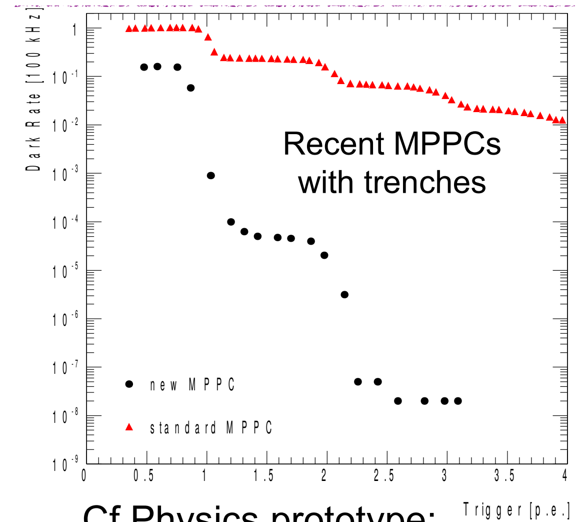
- CERN beam tests of partially instrumented ILD-like module ongoing



Technologies: scintillator+SiPM in AHCAL

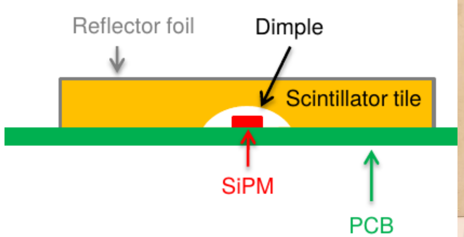
Technological improvements of current SiPMs (driven, in particular, by medical applications):

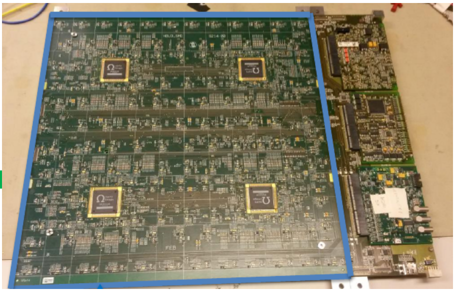
lower dark noise=O(10kHz) and, for SiPMs with trenches, inter-pixel cross-talk ≤0.1%, better temperature stability and device uniformity.



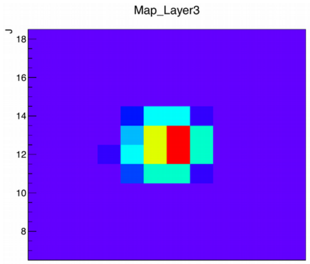
Cf Physics prototype: dark rate 2 MHz, xtalk 30%

Simplification of tiles:
direct optical coupling without WLS fiber to surface-mounted SiPMs





First semi-automatically assembled layer included in beam tests, all channels are fine.



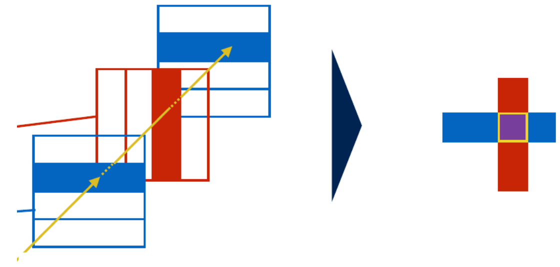
CERN beam profile in automatically assembled layer

Robotic assembly

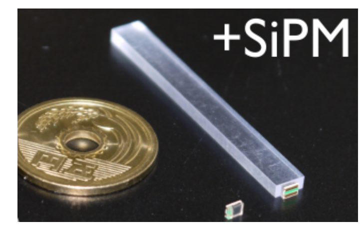
Technologies: scintillator+SiPM in ECAL

Proposed as a less expensive alternative to Si (eg. in back ECAL layers, hybrid ECAL).

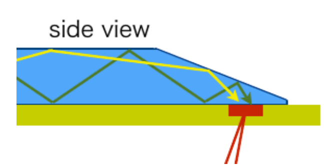
5x5 mm^2 Sc+SiPM solution is more expensive than Si
$\Rightarrow$ make “virtual” 5x5 pixels from intersections of
45x5x2 mm^3 strips of alternating directions, with energy fractions approximately determined from perpendicular strips in adjacent layers.

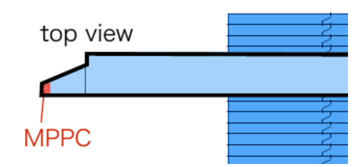


2d phys. prototype, 2-32 GeV:
$(12.8\pm0.4)\%/\sqrt{E} \oplus (1.0\pm1.0)\%$, linearity within 1.6%



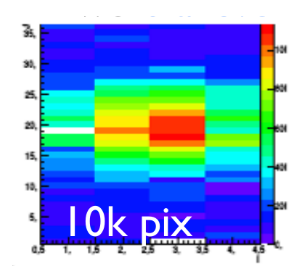
Improvements in technological prototype:
direct SiPM readout from bottom:
no dead space due to SiPM,
suitable for future SiPM surface mounting,
strip shape optimized for higher and more uniform response

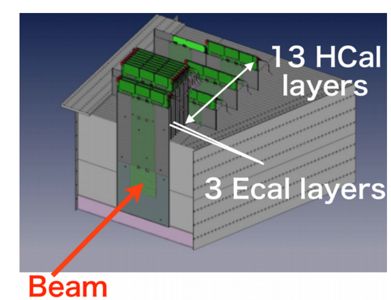




Compared to AHCAL:
- tighter constraints on systematics (roughly by 2.5 = 25% / 10% = EM / neutral hadron E in jet)
- higher dynamic range is required

$\Rightarrow$ 1.6k $\rightarrow$ 10k pixels MPPC





Beam image in 144 strips layer from recent combined w/ AHCAL TB at CERN

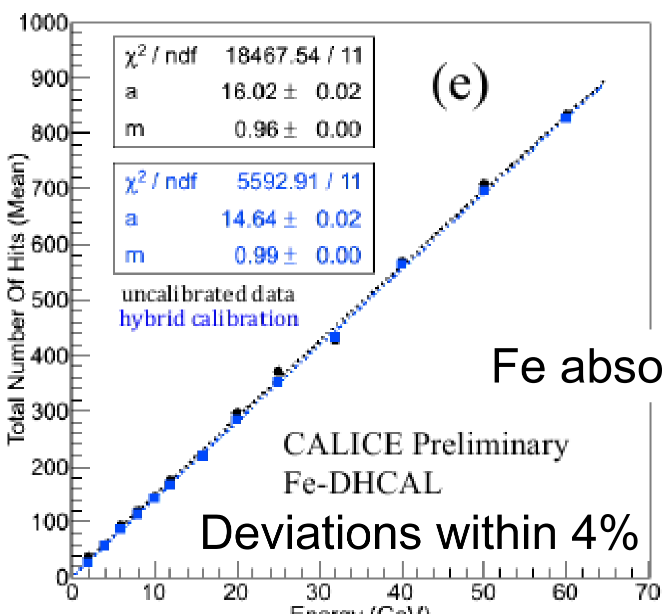
Technologies: gas, DHCAL (RPC)

RPC: easily segmentable, 1x1 instead of 3x3 cm^2 in AHCAL, low cost.
Simpler electronics.

Almost zero sampling fraction, instead of measuring energy: count hits
(related to N charged particles in shower μ E)
D(igital) HCAL – yes/no (1 bit) readout

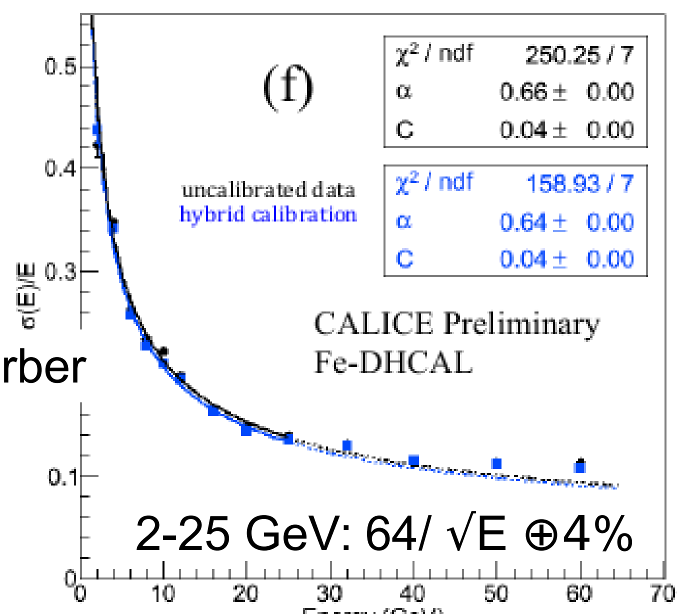
At low energies hit counting is even better than energy measurement due to suppression of Landau fluctuations.
At high jet energies >70-100 GeV, when PFA confusion dominates, 1x1 cm^2 granularity may make better job in pattern recognition.

500 k channels, 1x1 cm^2 in 1m^2 layers, Fe and W absorber tested at Fermilab and CERN.
Muons: average efficiency 90%, multiplicity 1.6

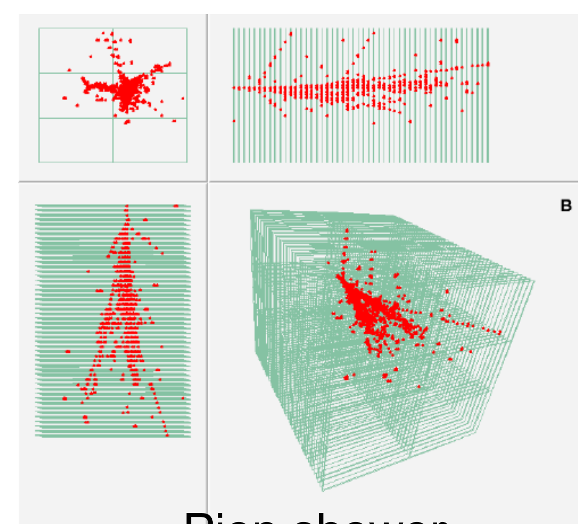


Fe absorber

Deviations within 4%



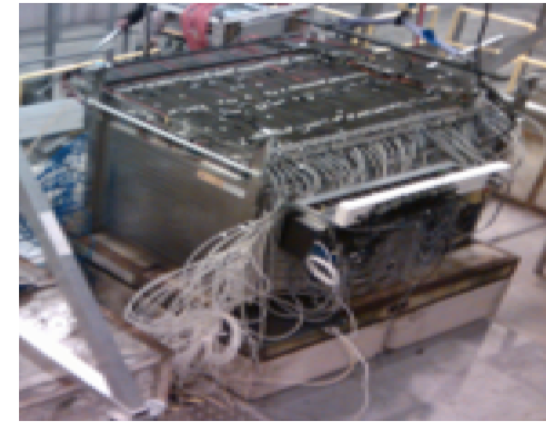
2-25 GeV: 64/ √E ⊕4%



Pion shower

Technologies: gas, SDHCAL (w/ RPC)

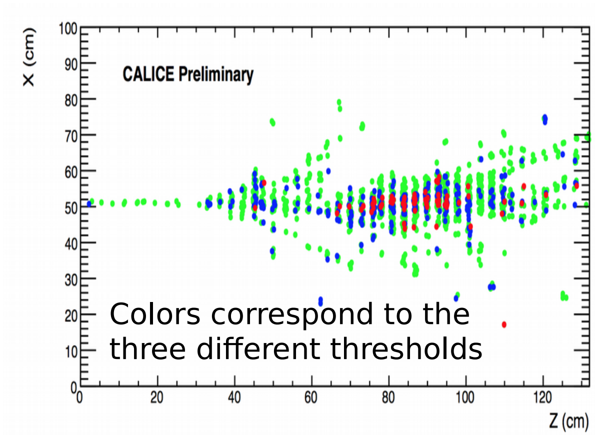
1 bit does not distinguish N particles traversing pixel at high E.

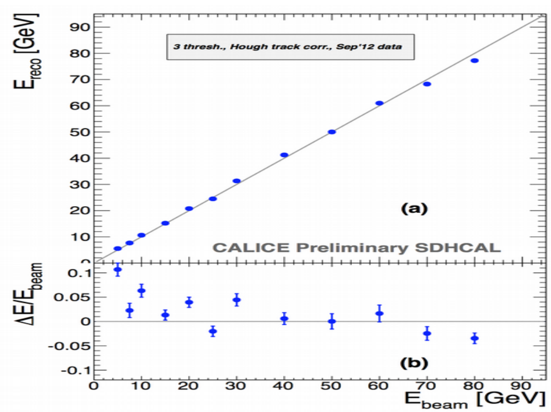


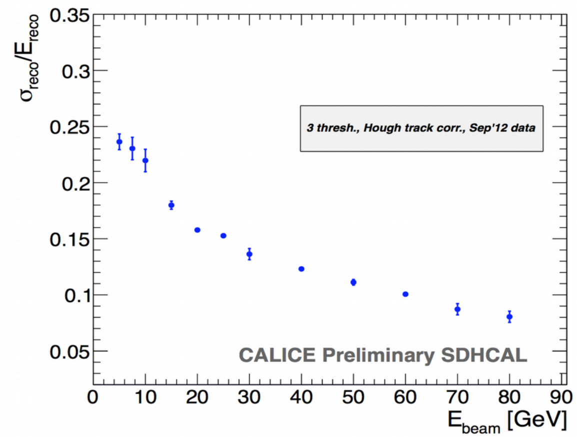
S(emi)D(igital)HCAL: minimal 2-bits analog information, ie. 3 thresholds (1, several or many MIPs), E = weighted sum $\alpha N_1+\beta N_2+\gamma N_3$

Built in 6 months (!) 500 k channels=48 layers X 1m^2 / 1x1 cm^2 pixels.

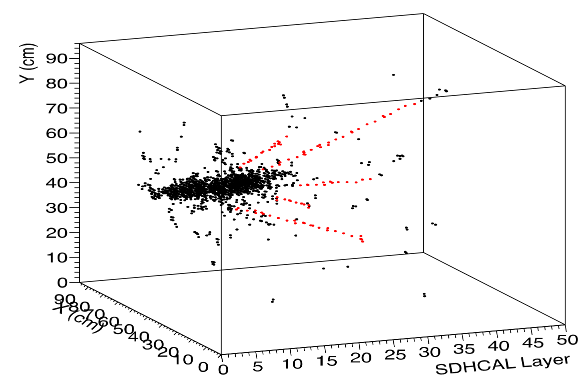
Simple electronics, tests of power pulsing and auto-triggering in 2012, first in CALICE. 3d generation of readout CALICE (ROC) chips with zero suppression is tested only by SDHCAL.







Thanks to high granularity, Hough transform finds tracks in showers (PFA in showers!), useful in energy reconstruction and for in-situ detector calibration



Current R&D:

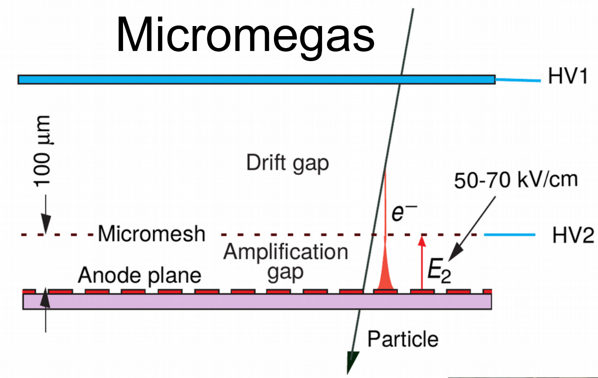
Build and test ILD prototypes >2 m^2

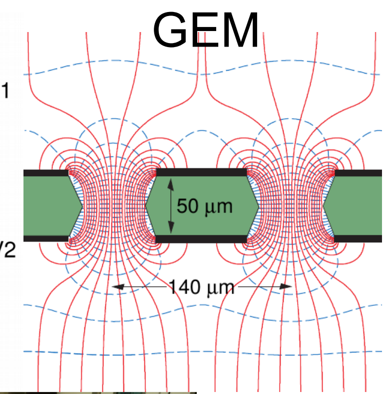
electron beam welding for mechanical structure assembly with min. dead zones,

gas circulation improvement

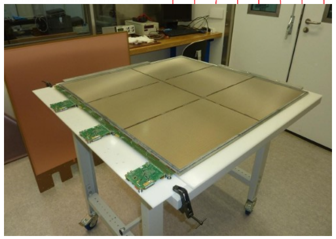
Technologies: SDHCAL w/ Micromegas, GEM

RPC signal saturates if particles crossing a pad are too close.
Migromegas and GEM improve proportionality and dynamic range of semi-digital readout.

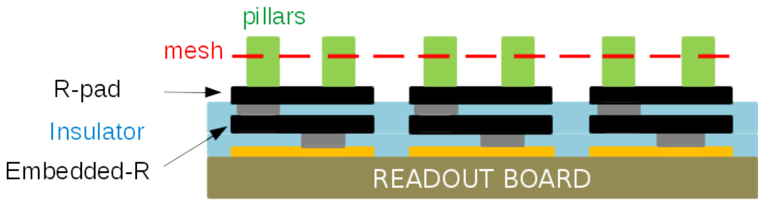




A few 1 m^2 layers of Micromegas have been extensively tested in SDHCAL prototype, NIM A729 (2013) 90, A763 (2014) 221.

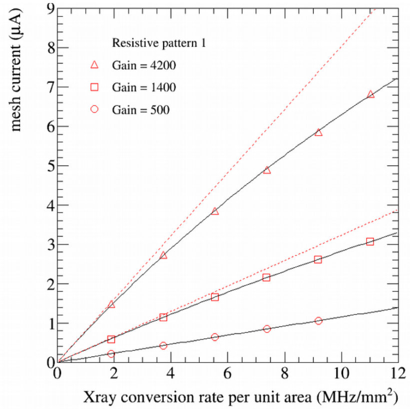


Current R&D: suppress sparking occurring at high rate and high dE/dx by using resistive electrodes, PoS TIPP (2014) 054.



First tests are promising: response insensitive to rates ≤1 MHz/mm^2

Ongoing beam test aims to find minimal resistivity.



As demonstrated by 30x30 cm^2 GEM layers for DHCAL prototype, GEM provides similar performance: efficiency>95%, hits/MIP<1.2.

Conclusions

Highly granular calorimeters are the future for HEP detectors:

- core elements of ILC / CLIC detectors or other future machines
- CMS H(igh)G(ranularity)CAL(orimeter) phase-2 upgrade of ECAL+HCAL endcaps for HL LHC

with Si active detectors very similar to ILC SiECAL, except active cooling for radiation hardness and 25 nsec bunch timing.
Intensive R&D started. Synergy with CALICE, common CERN beam tests planned.
See poster "Electron and Photon performance with the upgraded CMS detector for HL-LHC" by A.Meyer

CALICE is developing various technologies:
- Silicon-Tungsten electromagnetic calorimeters
- Scintillator tiles / strips with SiPM readout for HCAL and ECAL
- RPC, Micromegas and GEM detectors for digital and semi-digital HCAL

First prototypes of all technologies have demonstrated the viability of the detector concepts and validated PFA with data

Second generation prototypes are in construction to demonstrate the technical feasibility for a collider detector environment, in particular, for ILC

In parallel to hardware R&D, CALICE data provides information on hadronic showers with unprecedented level of details, see next talk.