Summary of calorimetry (B) and new idea (D) sessions

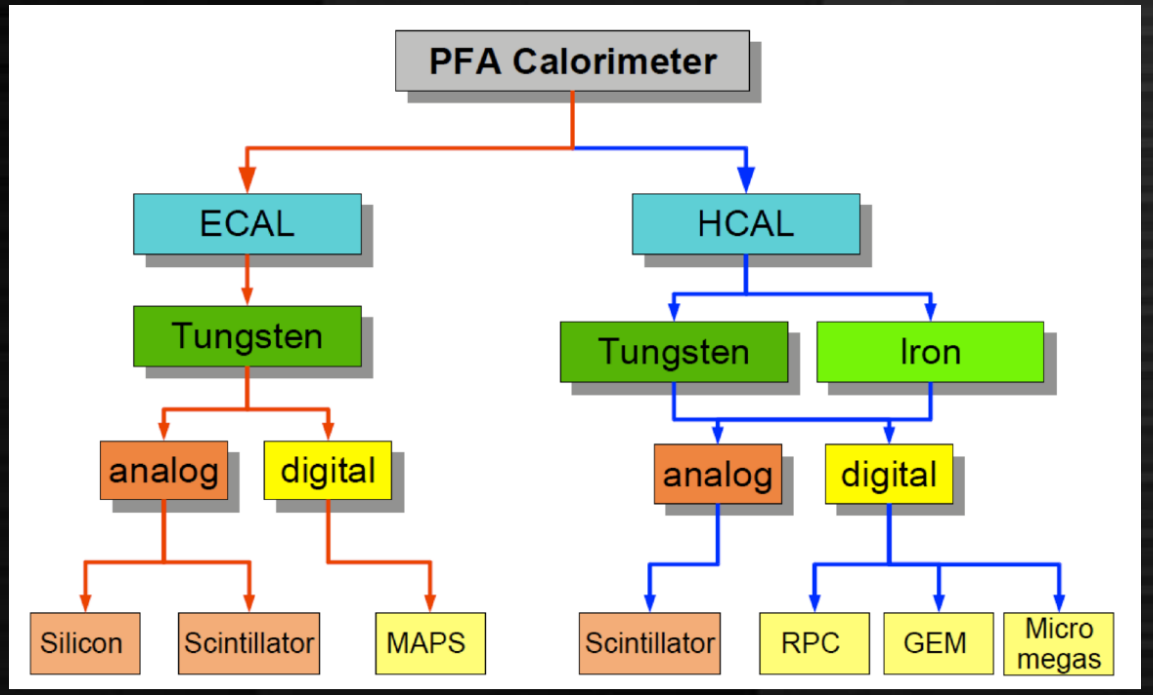
Taikan Suehara (Kyushu U.)

on behalf of conveners of session B/D

Statistics of the sessions

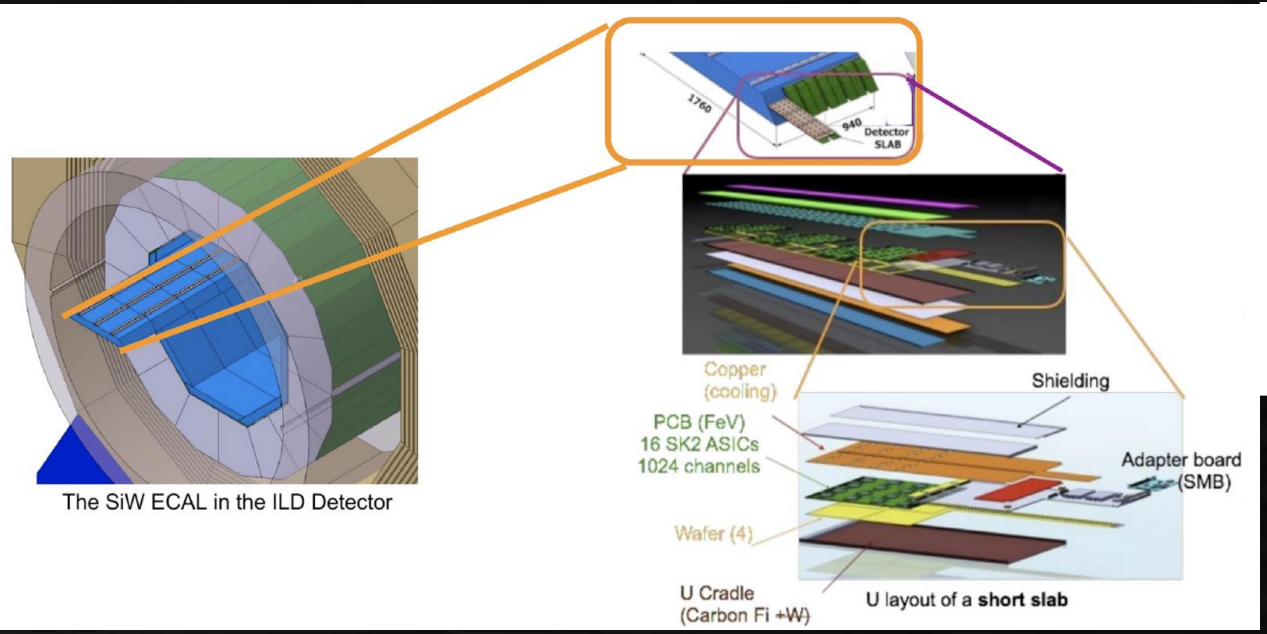
- Calorimetry talks (10)
  - ILD SiW-ECAL (3)
  - SiD MAPS-ECAL (1)
  - ILD SciW-ECAL / AHCAL (3)
  - SiD DHCAL (1)
  - FCAL (1)
  - Calibration (analysis) (1)
- New Ideas (5) "New technology" part of session D is included in the tracking summary
  - High-granular dual readout calorimeter (3)
  - Calorimetry with timing (1)
  - Ring-imaging Chrenkov (1)

5 more talks in
the joint session with software
(already summarized by Thomas)

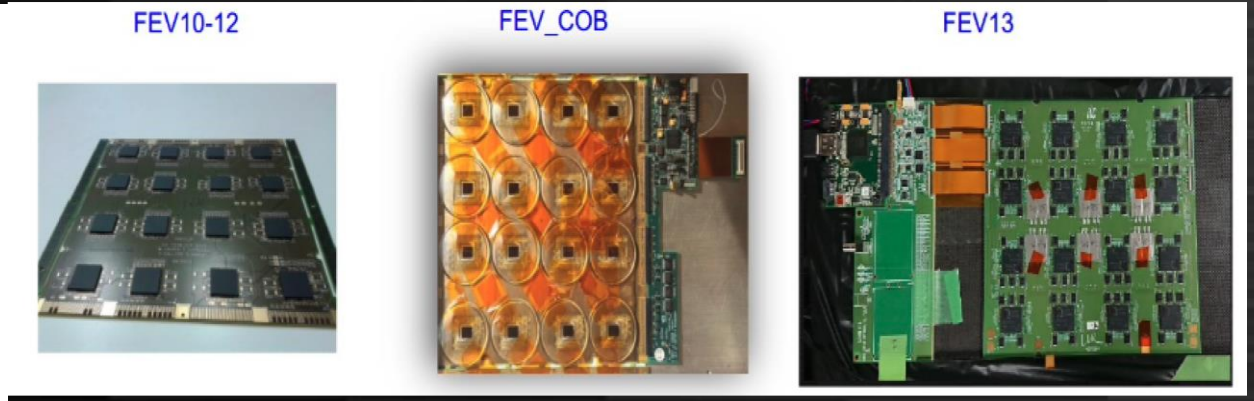


ILD SiW-ECAL

Status of the technological prototype of the CALICE highly granular SiW-ECAL
by Fabricio Jimenez Morales (LLR)

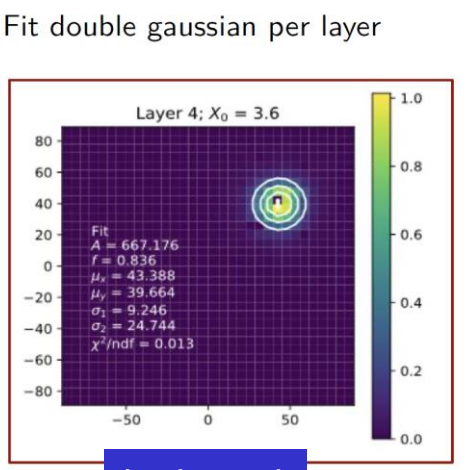


The SiW ECAL in the ILD Detector

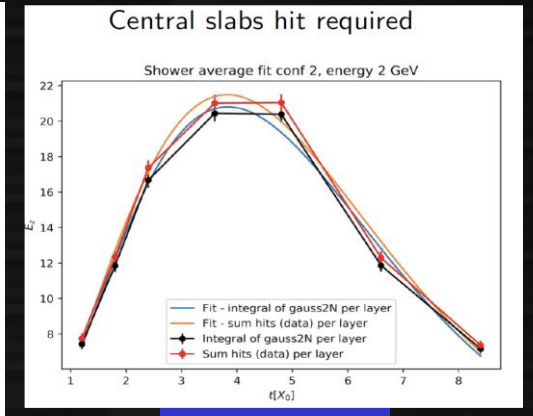


Many version of technological prototypes already developed and tested, nicely working

Analysis on test beam data

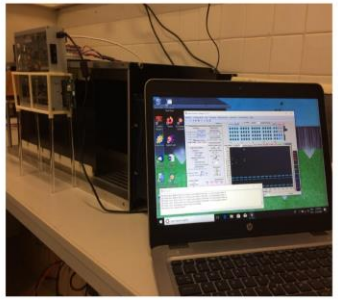


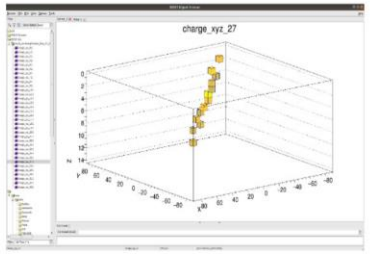
horizontal



longitudinal

Preparation for the test beam at DESY next week!





Ready for test beam next week!!

- >15 layers ready for beam test
- FEV10, 11, 12, 13 and COB

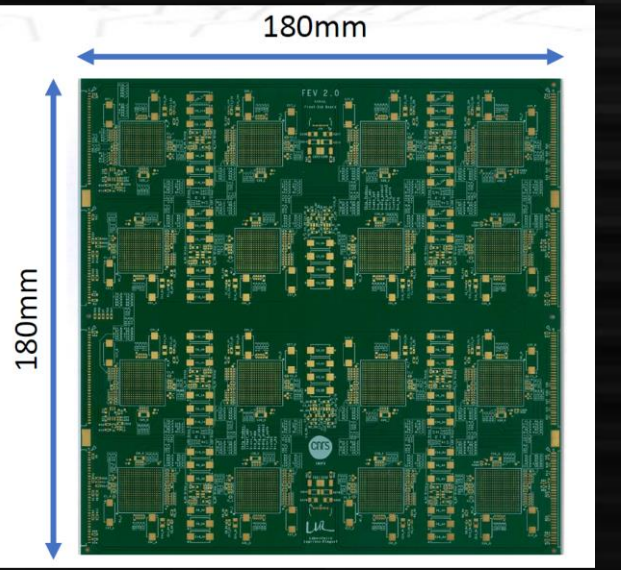
Cosmics / injection
Trigger threshold tuning
Masking noisy channels
Calibration of delay

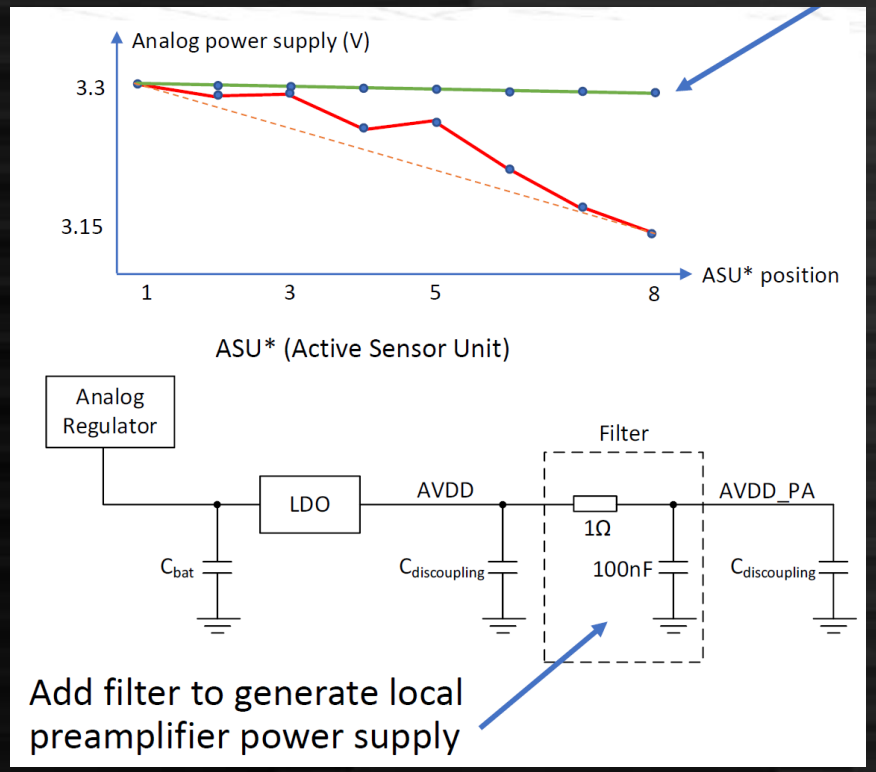
ILD SiW-ECAL

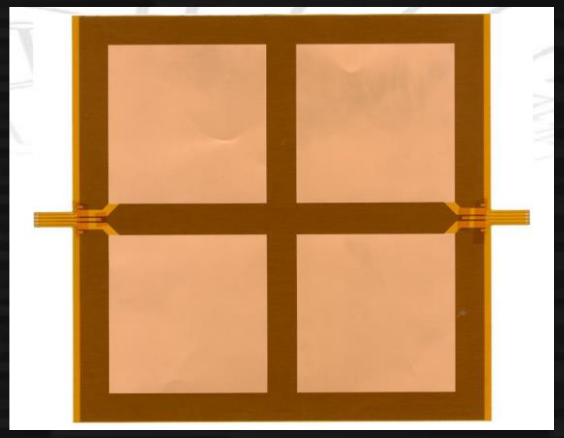
A new (Very) Front End Board for the ILD SiW ECAL
by Jerome Nanni (LLR)

Design new front-end board (FEV2.0)

- Dedicated and designed for long SLAB
- Upgrade LV power distribution
  - 1 analog LDO per chip
  - 1 digital LDO per 4 chips
  - Optimize capacitance for power-pulsing
- Upgrade buffer for slowcontrol
- Change HV distribution for wafer
  - Add HV filter per wafer
  - FEV drive HV instead of kapton
- New HV kapton
  - 1 per FEV instead of 1 per SLAB







New HV kapton

Development of FEV2.0 to fix long-slab problems

- Enforcing power line for long transportation
- Better interconnection
- Separate HV flexible circuit for easier assembly

First test forseen in November/December

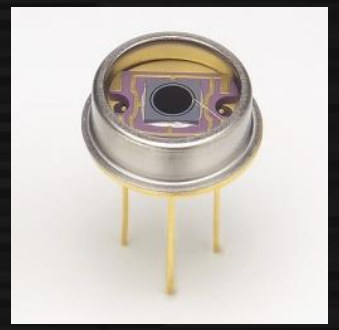
ILD SiW-ECAL(?)

Measurements of LGAD/APD devices for application to ILD SiW-ECAL
by TS (Kyushu U.)

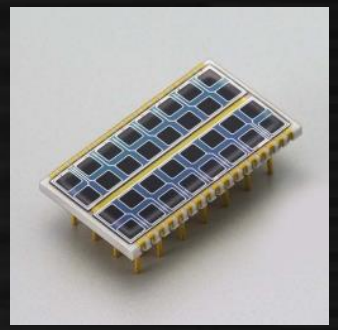
- Replace (part of) ECAL with LGAD for O(10 ps) timing measurement

Spec no.	type	V_{BR}[V]	dimension [mm]
S8664	Inverse	400	3ϕ, 5ϕ, 5 x 5 mm
S5344/5345	Inverse	150	3ϕ, 5ϕ
S2384/2385	Normal	150	3ϕ, 5ϕ
S6045	Normal	200	3ϕ, 5ϕ
S8550-02	Inverse	400	32ch, 1.6 mm cells

Hamamatsu APDs for trial

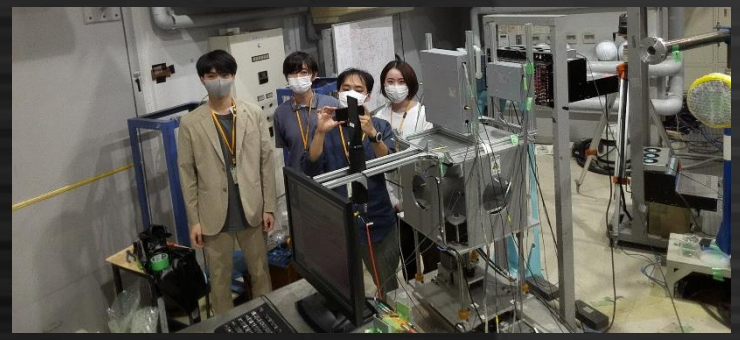


Single-cell APD
(S8664-50K)



Multi-cell APD
(S8550-02)

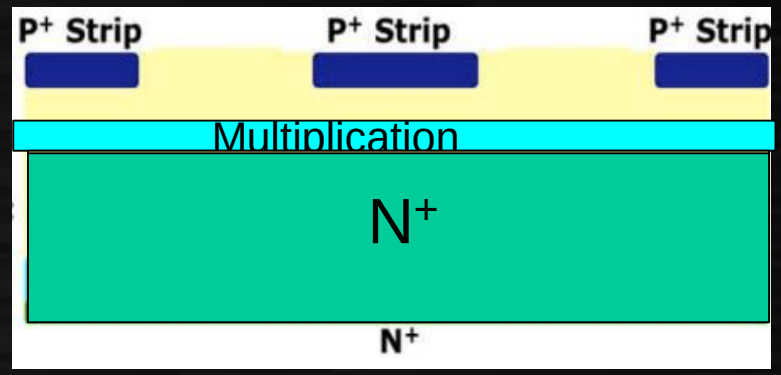
3 GHz amplifier developed in KEK
Timing @ 50% signal (by oscilloscope)



Test beam at Tohoku
October 2021

Sensor	Amp. th.	Time reso.
S8664-50K (inverse)	20 mV	123 psec
	40 mV	63 psec
S2385 (normal)	20 mV	178 psec
	40 mV	89 psec

Obtained timing resolution
(still affected by noise,
to be studied in more detail)



Inverse type (single-sided):

MAPS ECAL (SiD)

The SiD Digital ECal based on Monolithic Active Pixel Sensors
by Jim Brau (U. Oregon)

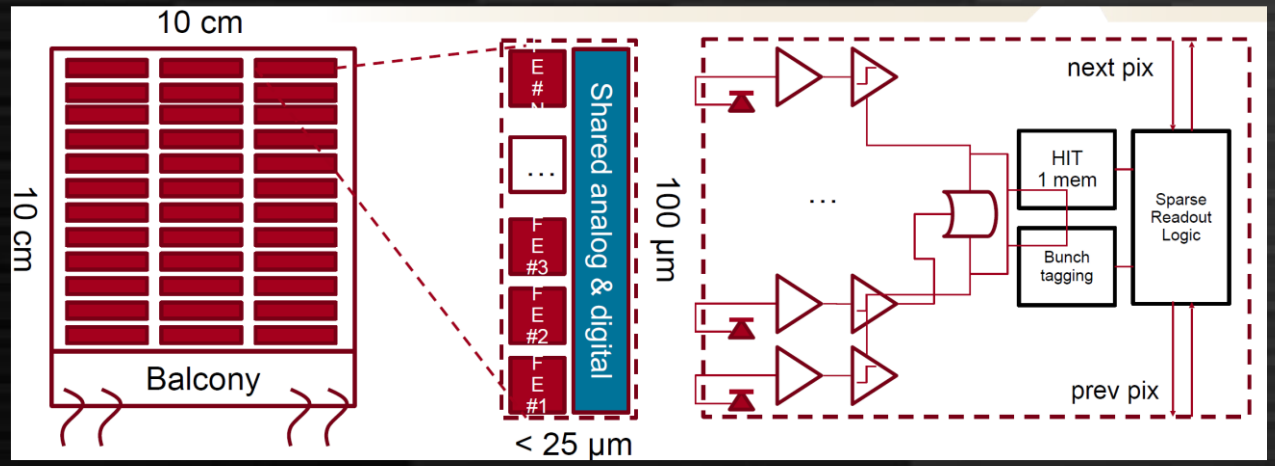
25 x 100 μm² monolithic pixels
Common design to trackers

Benefits of large-area MAPS:

- Standard CMOS foundry, low resistivity: **cost ⇩**
- Sensing element and readout electronics on same die
  - In-pixel amplification: **noise ⇩, power ⇩**
  - No need for bump-bonding: **cost ⇩**
- Area > 10x10 cm² → enable O(1) m² modules

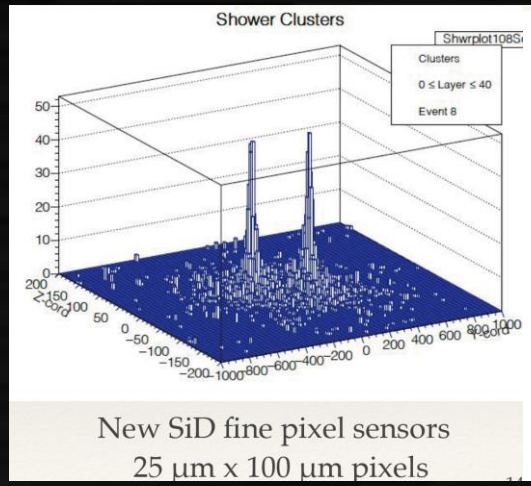
Several design challenges:

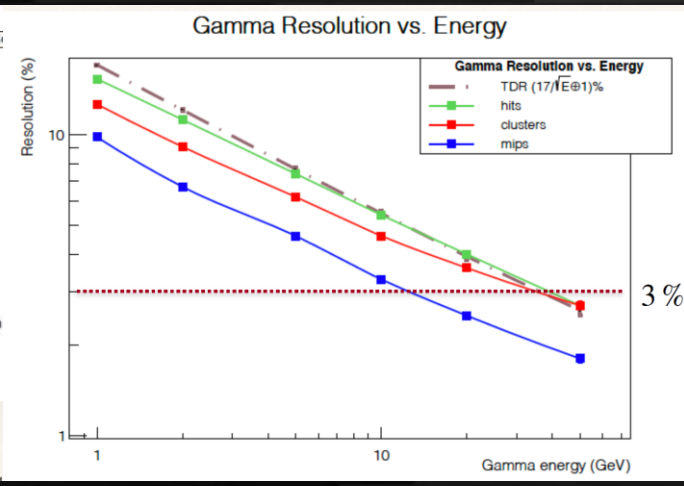
- Large on-die variations, mismatch
- Yield
- Stitching layout rules
- Distribution of power supply
- Distribution of global control signals/references



Parameter	Value
Min Threshold	140 e⁻
Spatial resolution	7 μm
Pixel size	25 x 100 μm²
Chip size	10 x 10 cm²
Chip thickness	300 μm
Total Ionizing Dose	100 kRads
Hit density / train	1000 hits / cm²
Hits spatial distribution	Clusters
Balcony size	1 mm
Power density	20 mW / cm²

Simulations



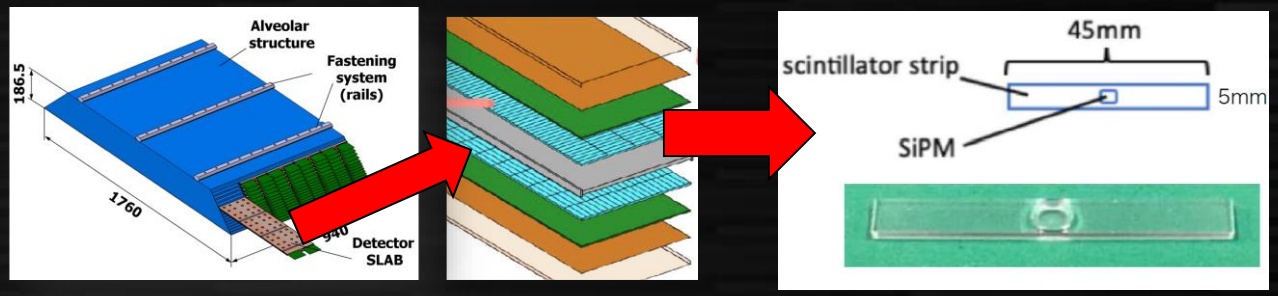


Good resolution obtained
by cluster counting

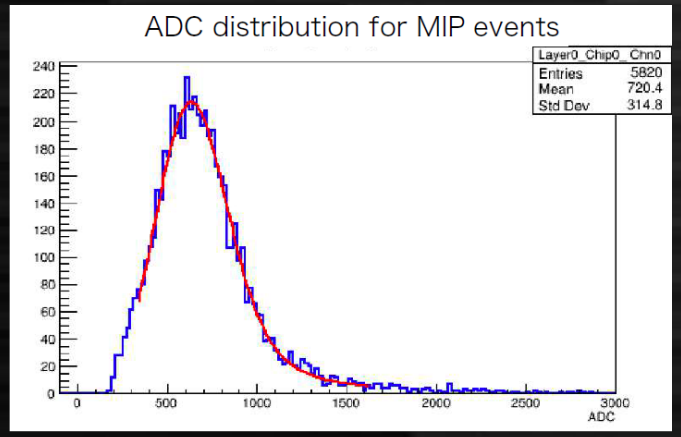
2.25 mm² prototype
production
in 2022 (WP1.2 CERN)

ILD SciW-ECAL

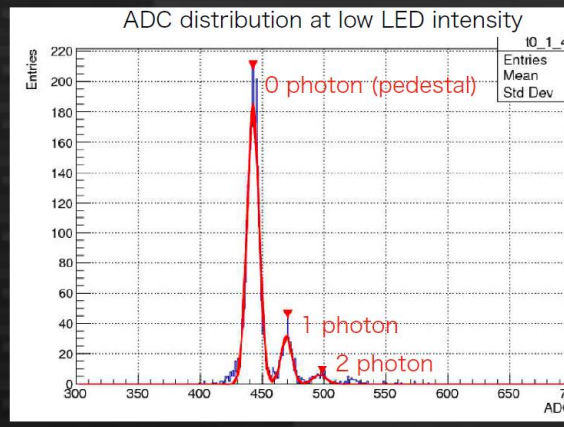
Development of highly granular scintillator strip electromagnetic calorimeter
by Naoki Tsuji (U. Tokyo)



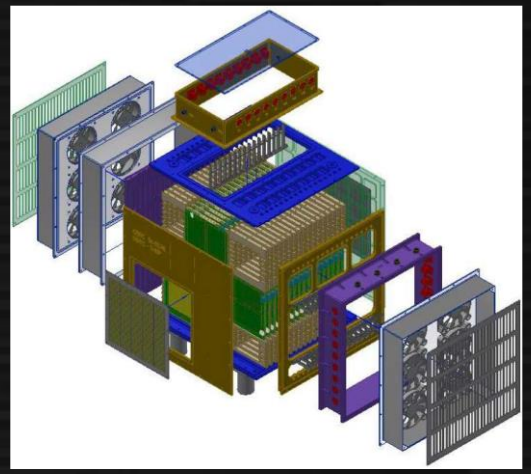
Basic structure similar to SiW-ECAL



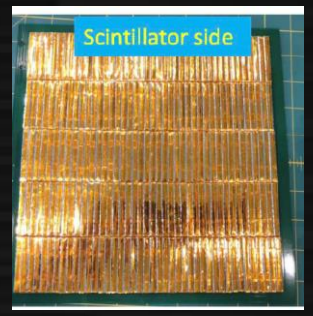
MIP calibration (cosmic)



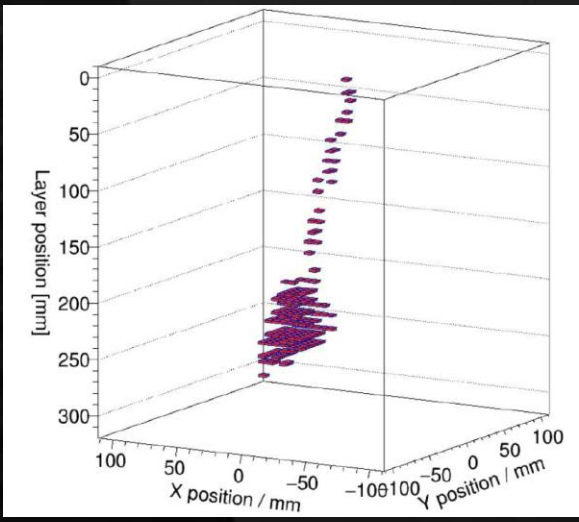
LED calibration



32 layer stack
already available



- Cosmic-ray test
  - MIP calibration implemented, ~10% decline observed in 3 months
  - 2 mm position resolution achieved
- LED calibration
  - Gain calibration implemented, good stability
  - Inter-calibration of high gain and low gain performed
    - Improvement in measurement setups needed
  - CTAP calibration performed
    - Reasonable CTAP probability obtained

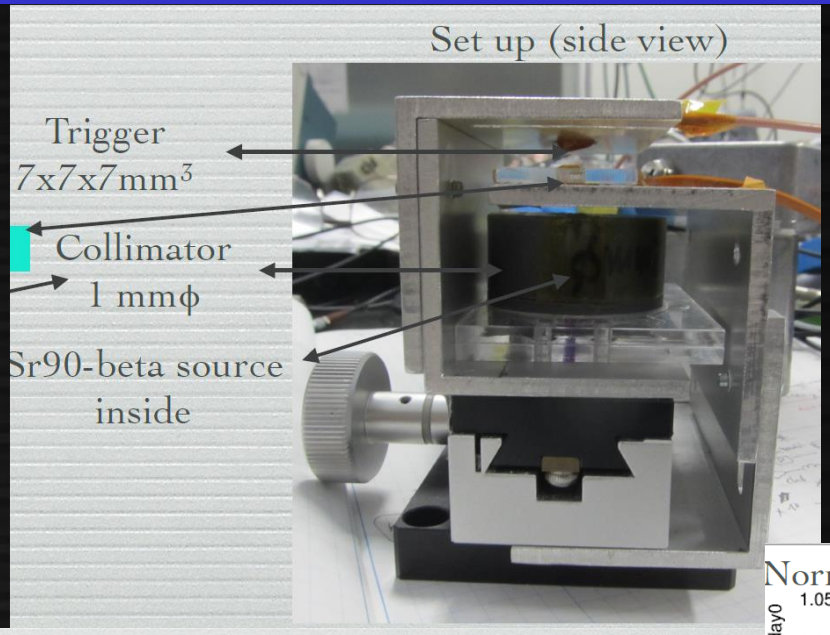


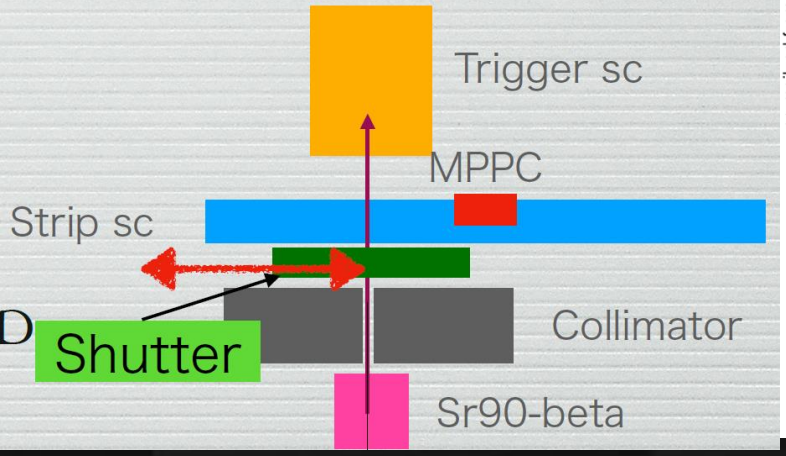
Shower event by cosmic

ILD SciW-ECAL

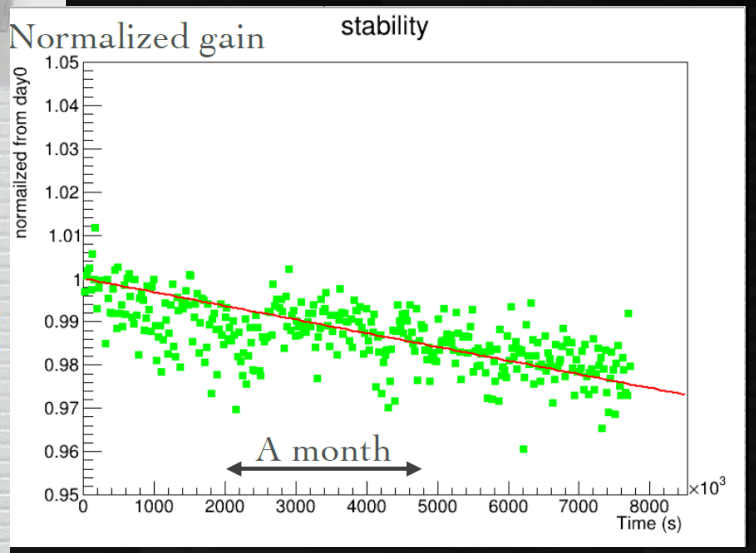
An injection molded strip stability and strip optimization for ILC scintillator ECAL by Tohru Takeshita (Shinshu U.)

Stability of injection-molded scintillator

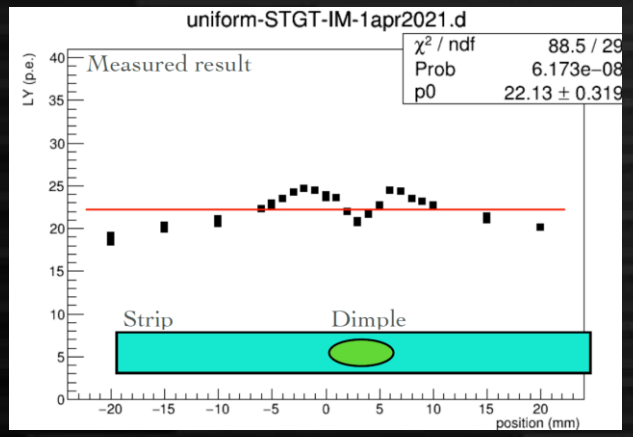




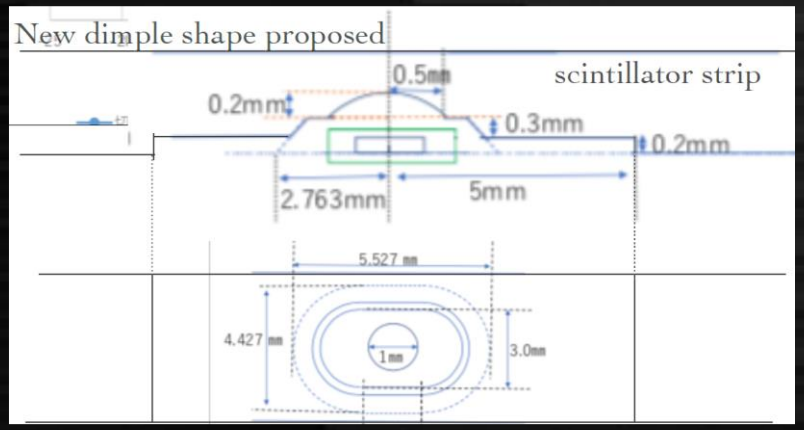
Gain drop of 0.027%/day seen, under investigation



Optimization of dimple shape



Current version gives 0.1% worse JER due to the non-uniformity

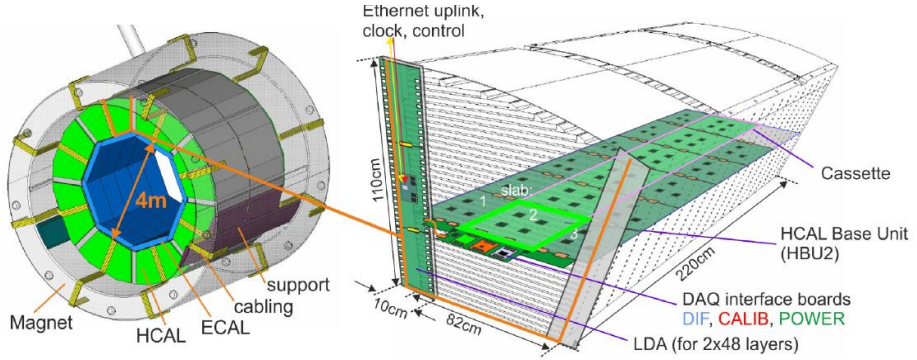


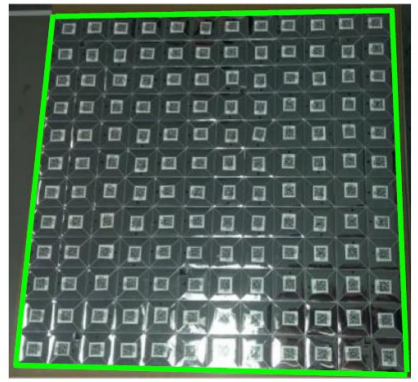
New dimple shape proposed simulation OK, but having a dip with measurement; under investigation

B-3

CALICE AHCal

Antoine Laudrain

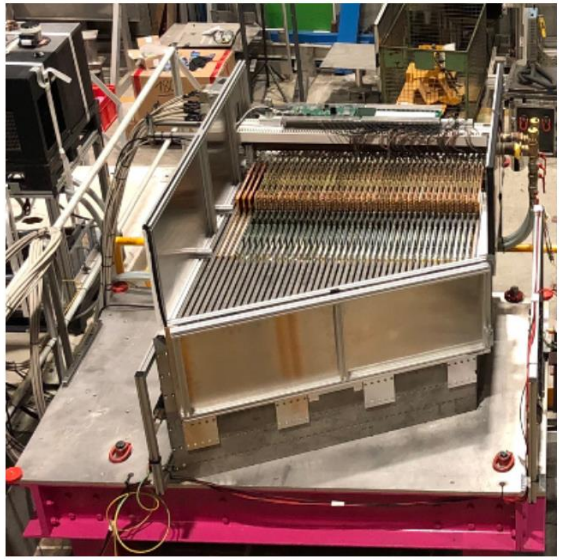




Target **hadronic calorimetry with a few % resolution**.

Test-beams @ CERN SPS in 2018:

- 1 board = 36x36 cm² (144 channels)
  - Fully integrated (readout, power supply, calibration LED)



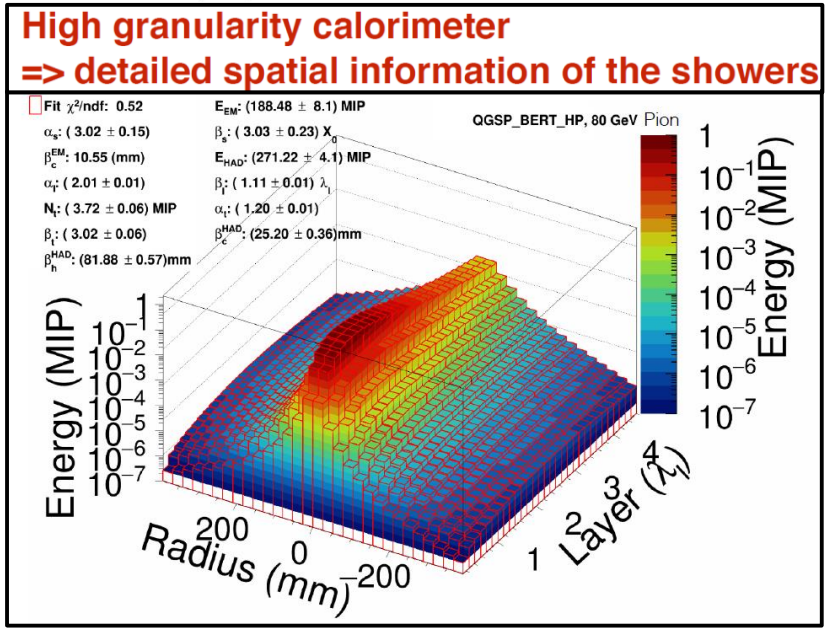
- 38 layers (72x72 cm²: 4 boards each) with 1.7 cm steel absorber (4λ)
- ~ 22'000 channels, < 1‰ dead channels
- Very stable running, basically noise-free!

← Beam:

- Muons
- Electrons, 10-200 GeV
- Pions, 10-200 GeV

Total: ~100M events

High granularity calorimeter
=> detailed spatial information of the showers



B-3

CALICE AHCal

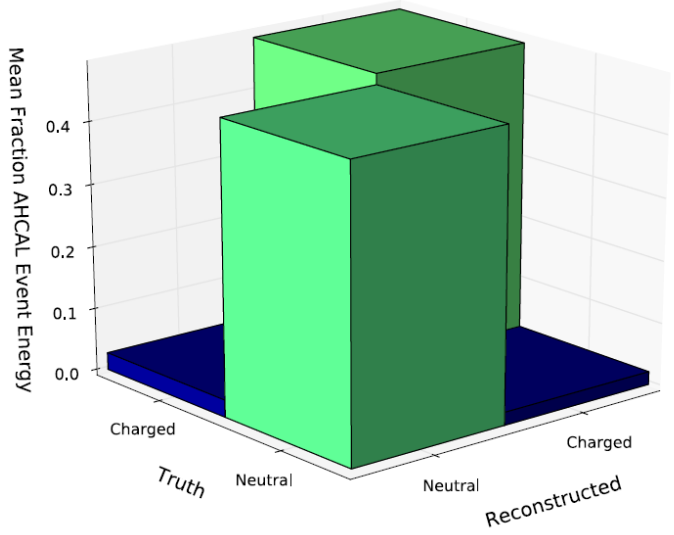
Antoine Laudrain

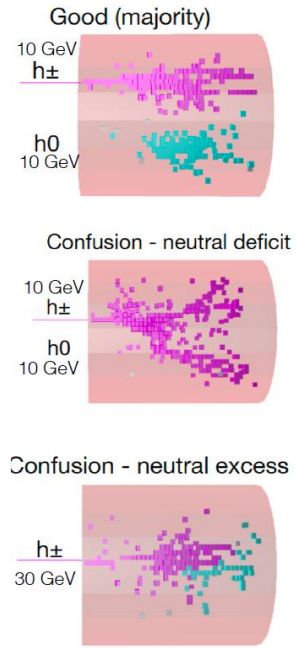
Calorimeter for ILC

+

Limit of PFA: “confusion”

10 GeV Neutral + 10 GeV Charged, 300mm, Confusion 3D, QGSP



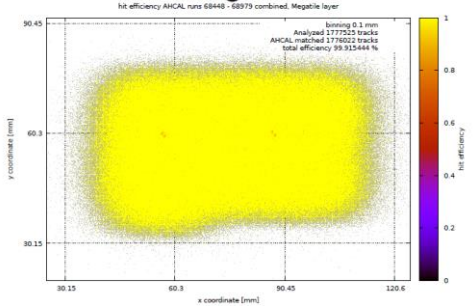


Ongoing study: impact of confusion on energy resolution.

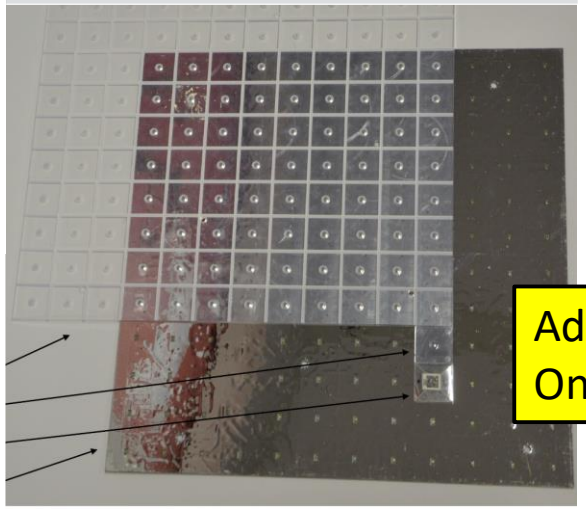
Novelty

22’000 channel technological prototype:
feasibility demonstrated, but painful assembly.

Megatile



Megatile concept



Naked Megatile

Naked single tile

Wrapped single tile

HBU

Added value: uniform detection efficiency
Ongoing optimization: edge channels performance

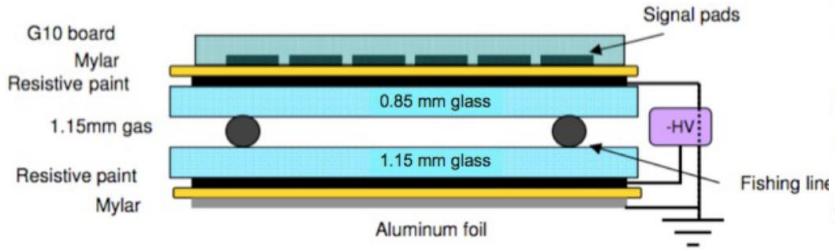
B-3

Digital Hadron Calorimetry

Burak Bilki

- Be easy to construct, robust, reliable, easy to operate, …

→ Resistive Plate Chambers



Gas: Tetrafluorethane (R134A) : Isobutane : Sulfurhexafluoride (SF_6) with the following ratios 94.5 : 5.0 : 0.5

High Voltage: 6.3 kV (nominal)

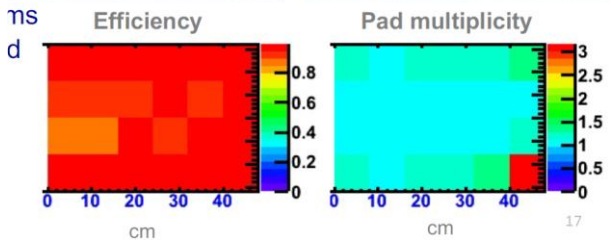
Average efficiency: 96 %

Average pad multiplicity: 1.6

+ Recent Hardware Development:
1-glass and semi-conductive glass RPCs

1-glass RPCs

Built several large chambers
Tests with cosmic rays very successful
→ chambers ran for months without problems
Both efficiency and pad multiplicity look good
Good performance in the test beam



DHCAL in Test Beams

FNAL

> 20M events

FNAL

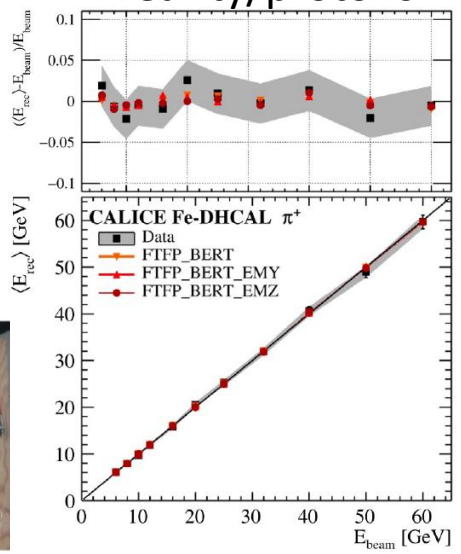
Nov 11

~ 2M events

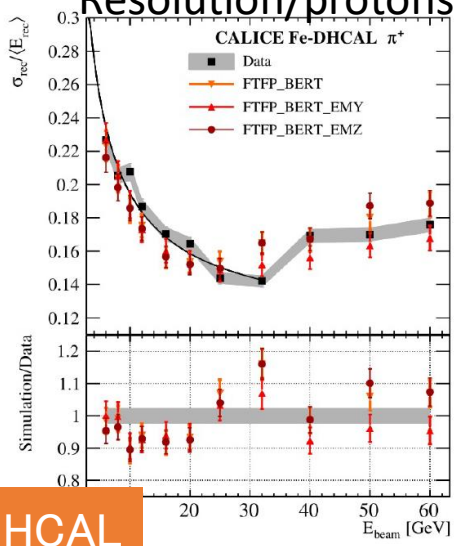
CERN

> 40M events

Linearity/protons



Resolution/protons



W–DHCAL

$$\frac{\sigma(N)}{N} = \frac{\alpha}{\sqrt{E}} \oplus C$$

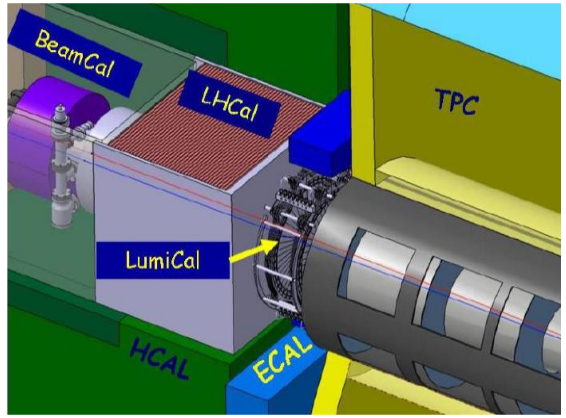
Particle	α	c
Pions	(68.0±0.4)%	(5.4±0.7)%
Electrons	(29.4±0.3)%	(16.6±0.3)%

B-3

Forward calorimeters

Alina Neagu

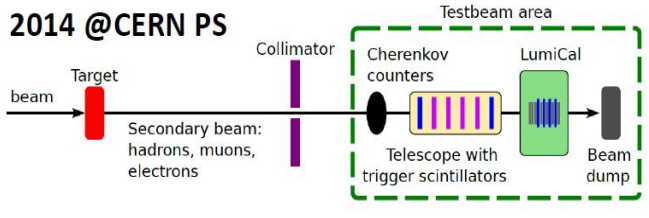
- optimisation of the design in the very forward region
  - detector technology development
    - MC simulation studies
- development of readout electronic
- performance measurements of prototype detectors in the beam



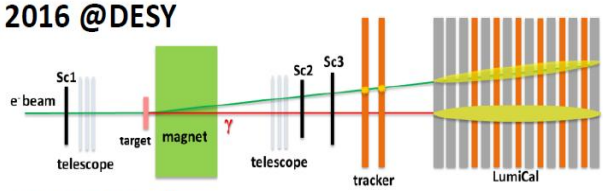
Beam-test campaigns

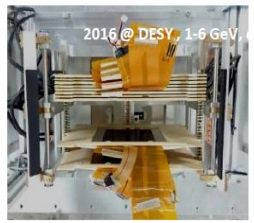
tests of multi-plane operation of the forward detector prototyp

2014 @CERN PS

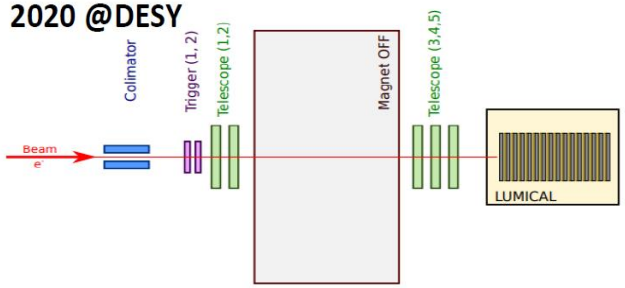


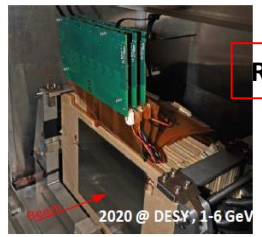
2016 @DESY





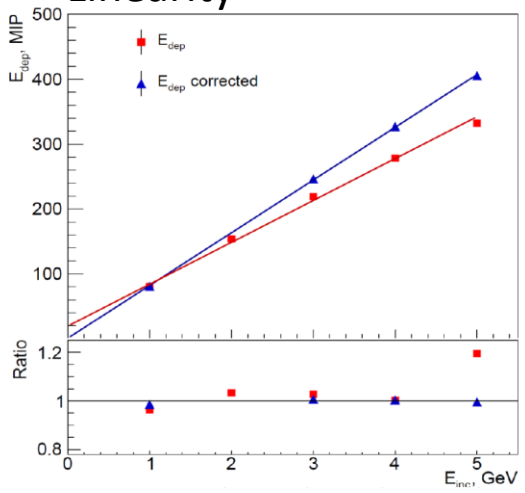
2020 @DESY



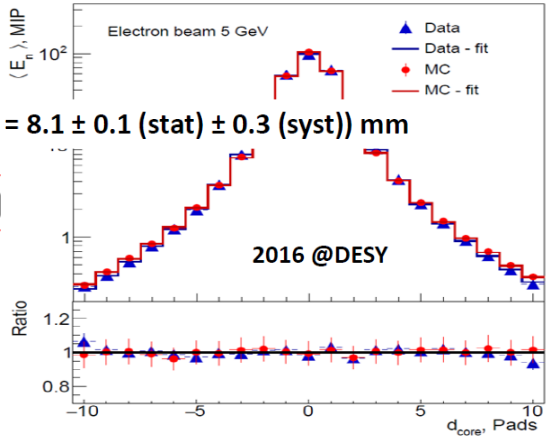


R_M(2020)

Linearity

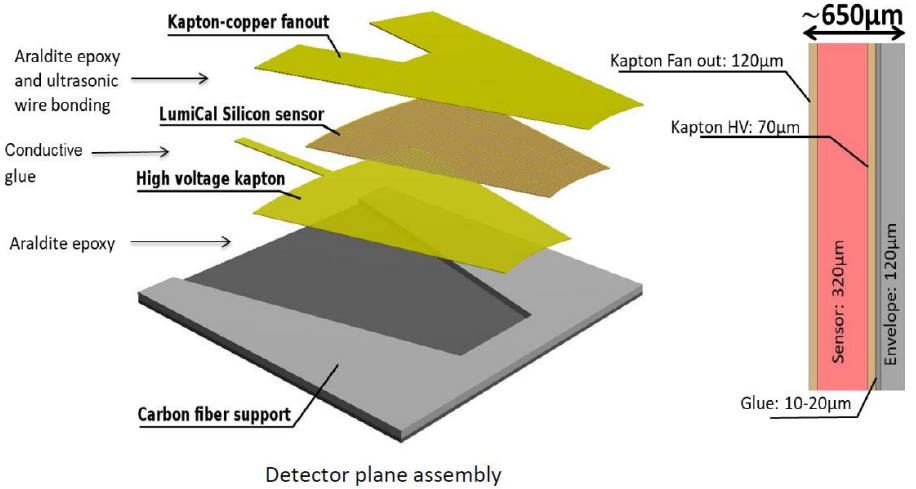


Moliere radius



- R_M = 8.1 ± 0.1 (stat) ± 0.3 (syst)) mm

LumiCal thin prototype module



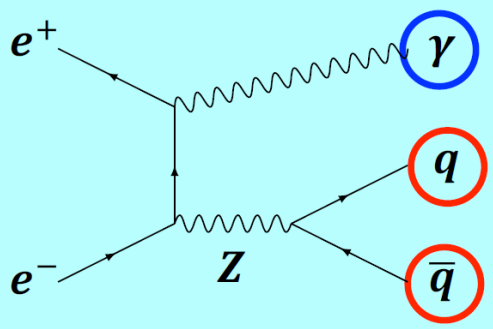
Detector plane assembly

A prototype of a highly compact forward calorimeter is demonstrated in test beams

Calibration of JES

Jet energy calibration using $e^+e^- \to \gamma Z$ process at the ILC
by Takahiro Mizuno (Sokendai)

$e^+e^- \to \gamma Z$, $Z \to$ 2 jets process

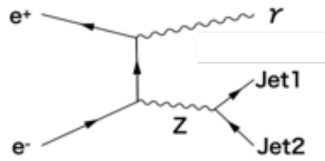


Radiative return events
- High statistics
- Simple topology

→ Good for jet calibration

Angular Method: Reconstructing jet energies based on **jet, photon angles and jet masses** using **4-momentum conservation**

Inputs and outputs
Using (θ_{J1},θ_{J2},θ_γ,φ_{J1},φ_{J2},φ_γ,m_{J1},m_{J2})
-> Determine (P_{J1},P_{J2},P_γ,P_{ISR})



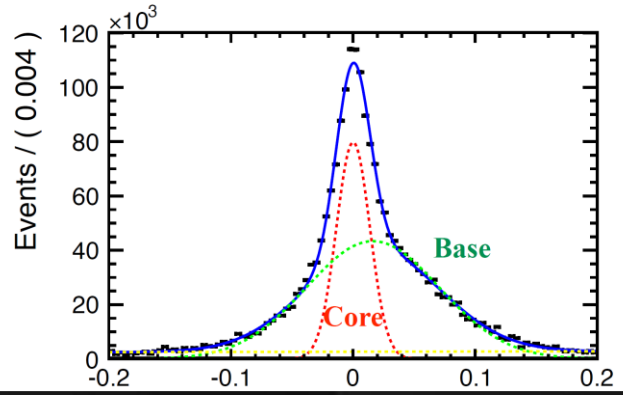
Direction Angle
θ: polar angle
ϕ: azimuthal angle

$$\begin{cases} \sqrt{P_{J1}^2+m_{J1}^2}+\sqrt{P_{J2}^2+m_{J2}^2}+|P_\gamma|+|P_{ISR}| = E_{CM} \ \text{①} \\ \begin{pmatrix} sin\theta_{J1}cos\phi_{J1} & sin\theta_{J2}cos\phi_{J2} & sin\theta_\gamma cos\phi_\gamma \\ sin\theta_{J1}sin\phi_{J1} & sin\theta_{J2}sin\phi_{J2} & sin\theta_\gamma sin\phi_\gamma \\ cos\theta_{J1} & cos\theta_{J2} & cos\theta_\gamma \end{pmatrix} \begin{pmatrix} P_{J1} \\ P_{J2} \\ P_\gamma \end{pmatrix} = \begin{pmatrix} E_{CM}-|P_{ISR}|)sin\alpha \\ 0 \\ \pm|P_{ISR}|cos\alpha \end{pmatrix} \end{cases}$$

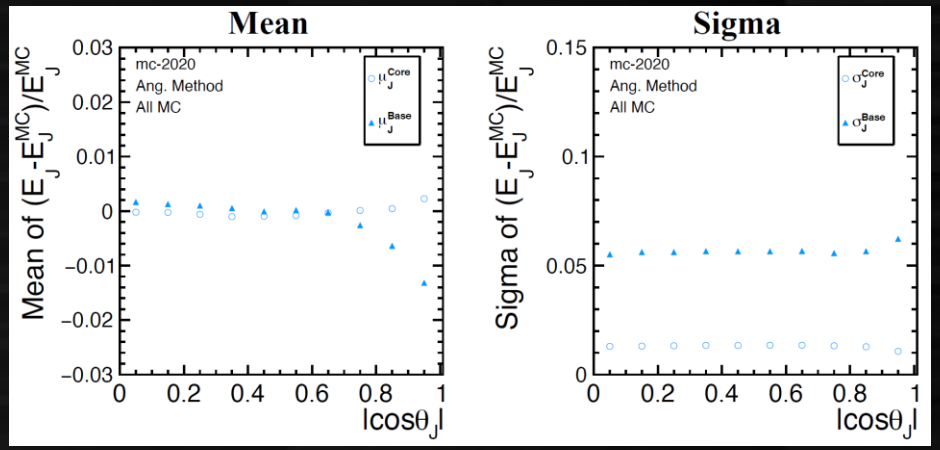
Matrix A — Inverse

Beam Crossing Angle $=2\alpha$ = 14.0 mrad
ISR photon = additional unseen photon

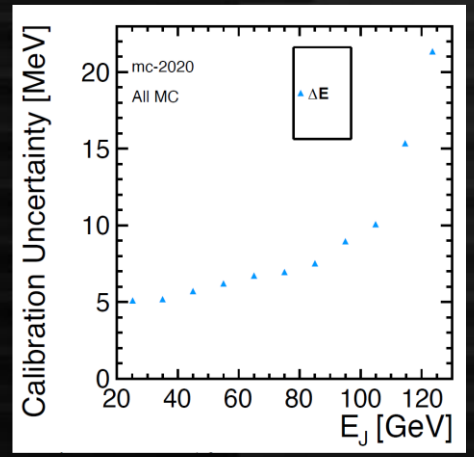
Calibration is based on the mean value of the Gaus (Core).



Calibration

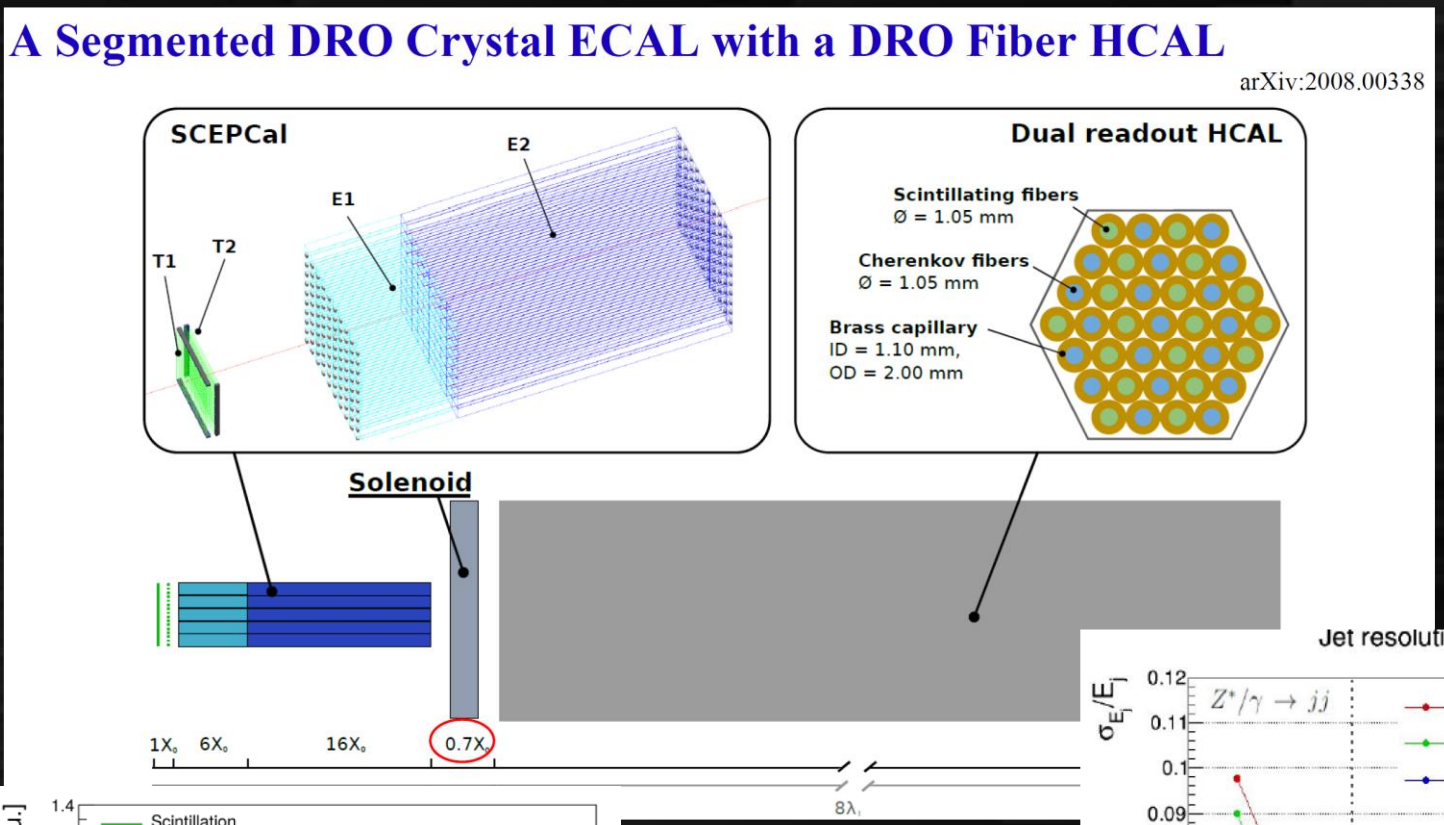


Calibration uncertainty



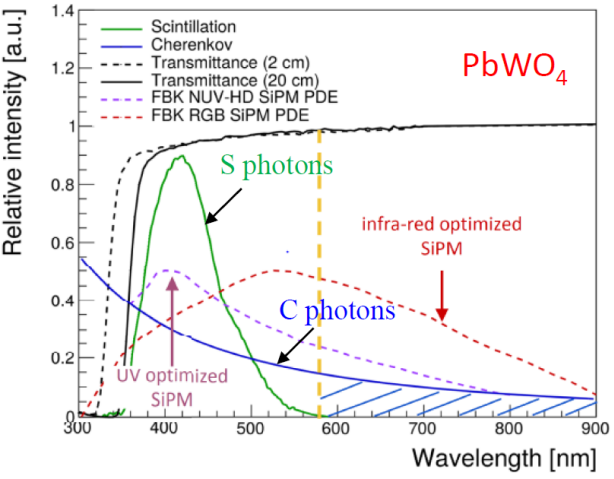
New idea: dual readout + high granularity

A dual-readout crystal electromagnetic calorimeter for future e^+e^- Higgs factories by Junjie Zhu (U. Michigan)

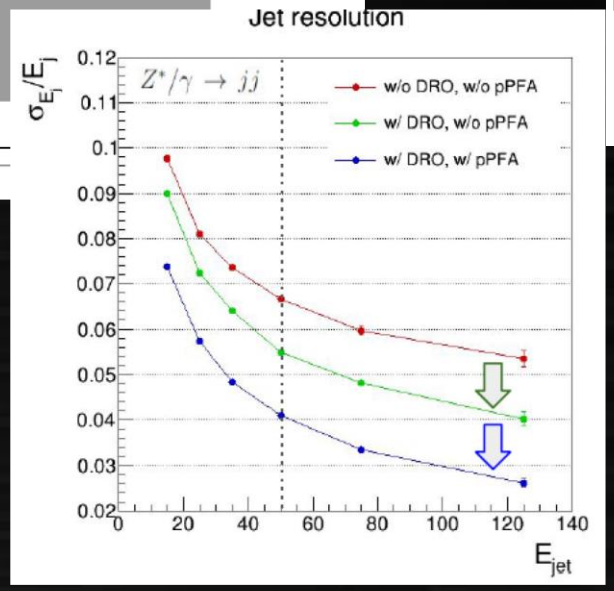


Segmented ECAL

- Two layers with $PbWO_4$ crystals (high density, short radiation length, small Moliere radius, fast signal, reasonable C/S ratio (~30%), cost effective, relatively low light yield)
- BGO and BSO are also good candidates
- Crystal cross-section: 10×10 mm^2
- Two segmented layers:
  - Front segment (~6 X_0, ~50 mm)
  - Rear segment (~16 X_0, ~140 mm)



SiPMs are much better separating sci. and ch. light



Photon resolution helps π^0 reco, radiation recovery, etc.

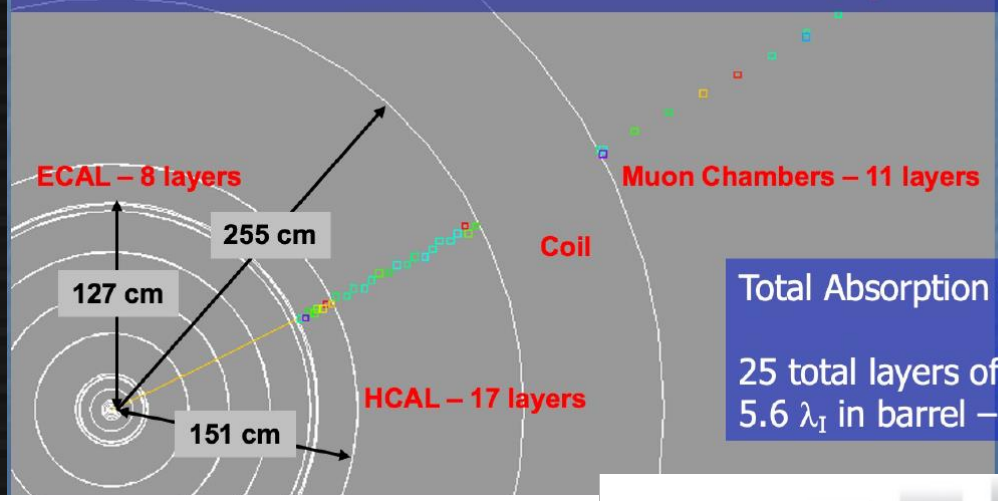
Better jet resolution with particle flow

New idea: dual readout + high granularity

Dual Readout Calorimeter *in SiD02 Shell (Barrel and EC)*

DR ECAL
3 cm x 3 cm x 3 cm BGO
8 layers – 21.4 X_0 (1.1 λ_I)
127 cm IR – 151 cm OR
Scin/Ceren analog hits

DR HCAL
5 cm x 5 cm x 6 cm BGO
17 layers – 4.6 λ_I
151 cm IR – 253 cm OR
Scin/Ceren analog hits



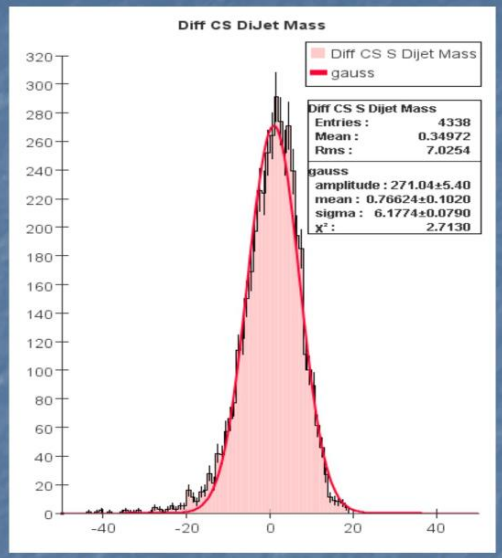
Total Absorption Crystal Calorimeter

25 total layers of BGO
5.6 λ_I in barrel – 2.5 m radius

Homogeneous Hadron Calorimetry for superior dijet mass resolution by Stephen Magill (ANL)

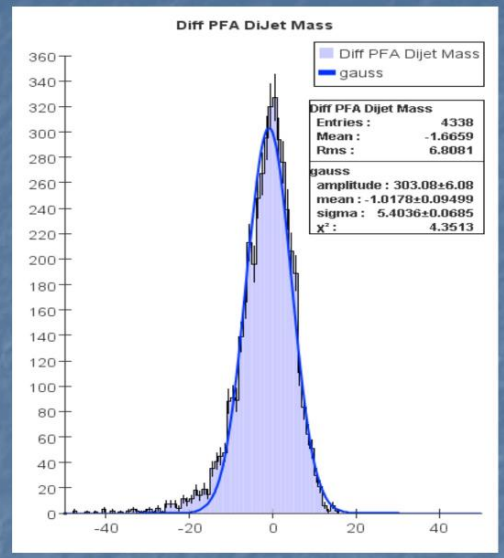
e^+e^- -> ZZ -> $\nu\nu qq$ @ 500 GeV

Difference -> DiJet Mass – qq Mass



C/S-corrected Clusters

$\sigma/M = 0.068$



PFA-enhanced Clusters

$\sigma/M = 0.059$

13% improvement

Scintillation Sensor R&D

-> readout candidates – mm² SiPM, small sensors

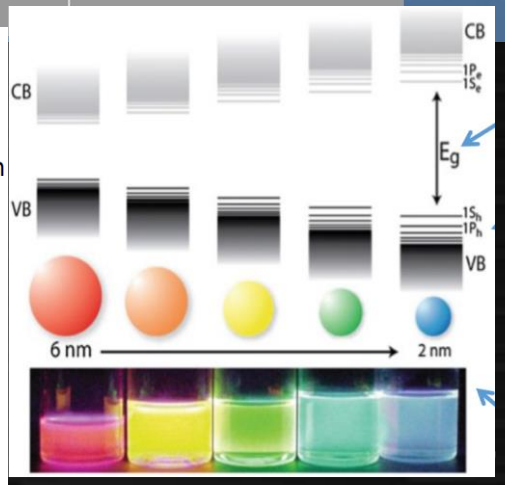
-> want non-prompt, visible long wavelength light – tradeoff with timing, sensor size

Cerenkov Sensor R&D

-> Cerenkov angle ~60° (index of refraction at these crystal densities)

-> use all faces of the crystal to collect UV light

-> emphasis on thin profile to minimize material between crystals



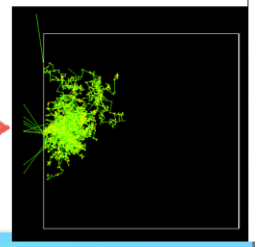
Wavelength conversion by nanoparticles discussed for detection of Cherenkov light

New idea: dual readout + high granularity

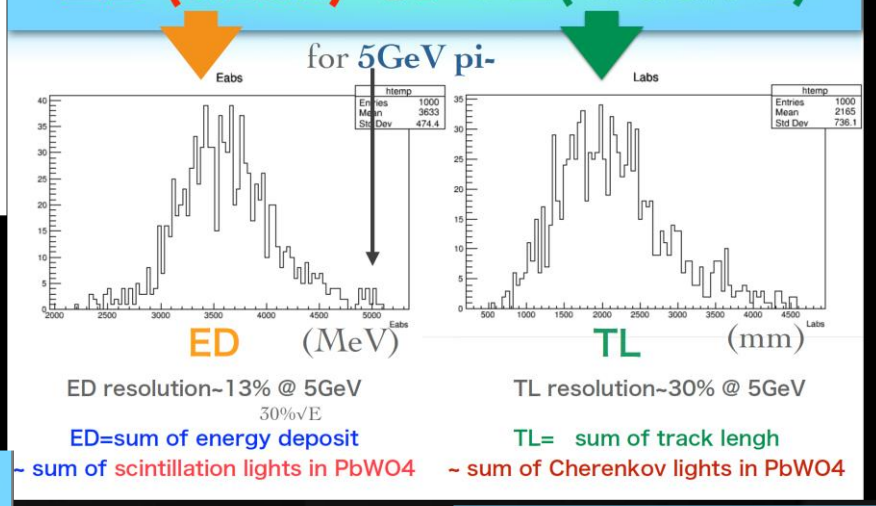
Energy measurement with homogeneous calorimeter
by Tohru Takeshita (Shinshu U.)

Simulation of homo.cal.

- GEANT4 size: 2mx2mx2m : big enough
  - time cut <100ns
- PbWO4: λ_I=16, X_0=225
  - Hadron model = FTFP-BERT
- Two variables:
  charged particles in showers
- TL : Track length ∝ Cherenkov
- ED : dEdx ∝ scintillation
- Light absorption is not taken into account

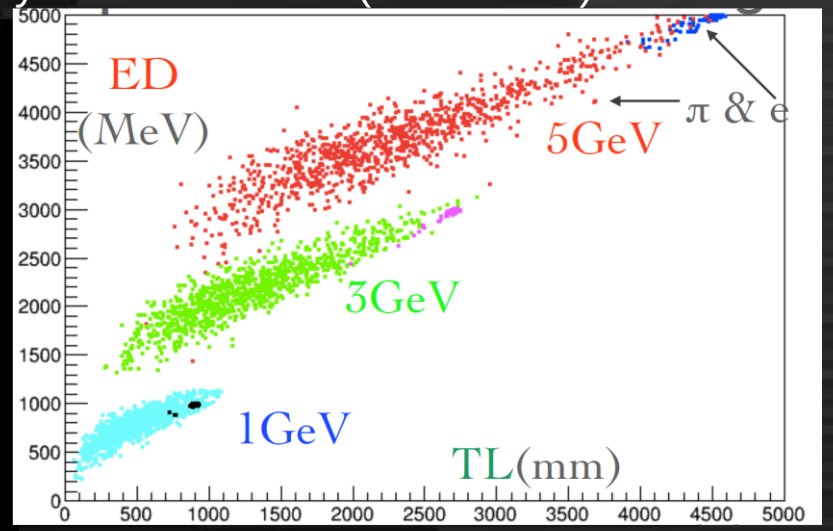


ED(dEdx) & TL(Track L)



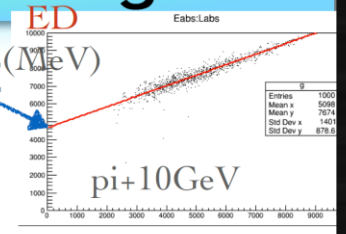
ED resolution~13% @ 5GeV
30%√E
ED=sum of energy deposit
~ sum of scintillation lights in PbWO4

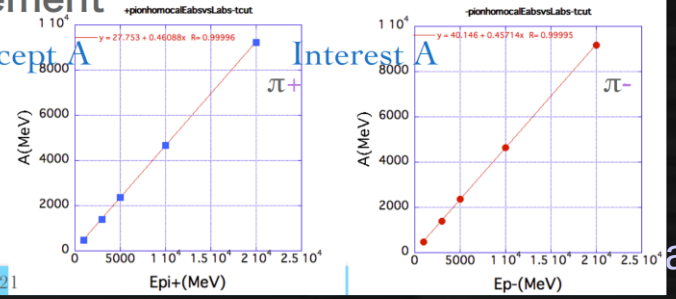
TL resolution~30% @ 5GeV
TL= sum of track lengh
~ sum of Cherenkov lights in PbWO4



Intercept of fitting line

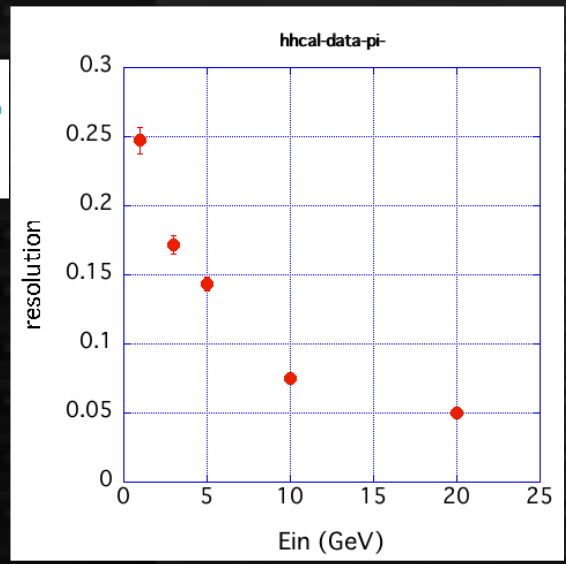
- Intercept A(E) is proportional to incident E
  ED=A(E)+B*TL
- A(π+) ~ A(π-)
- Good linearity :energy measurement





ED=A(E)+B*TL
B=(ED-A(E))/TL

If perfect separation of sci and ch possible, one can get 20%/√E energy resolution with PbWO4



New idea: 5D particle imaging at calorimeters

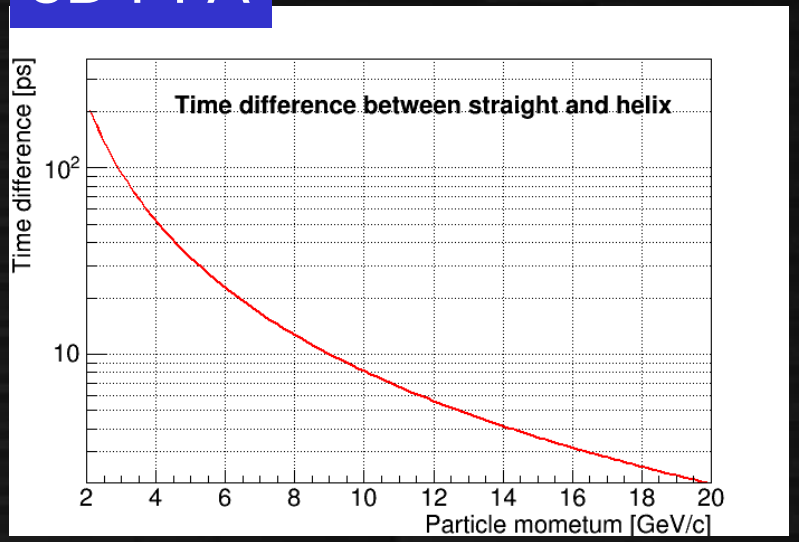
Review of advantages of measuring pico-sec timing (per particle) at calorimeters

Possible target:

- 10 ps (eq. 3 mm) for hadron showers
- 1 ps (eq. 0.3 mm) for EM showers

Physics potential and technologies for "five-dimensional particle imaging device" by TS (Kyushu U.)

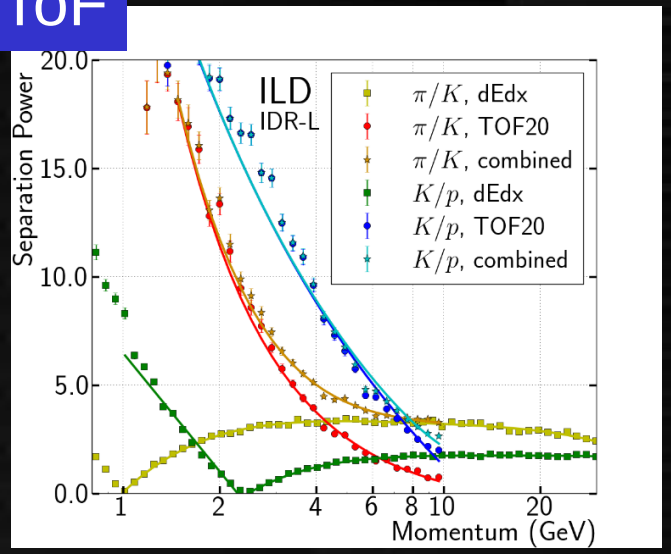
5D PFA



Photons and tracks can be separated by timing

10 ps: up to 9 GeV

ToF

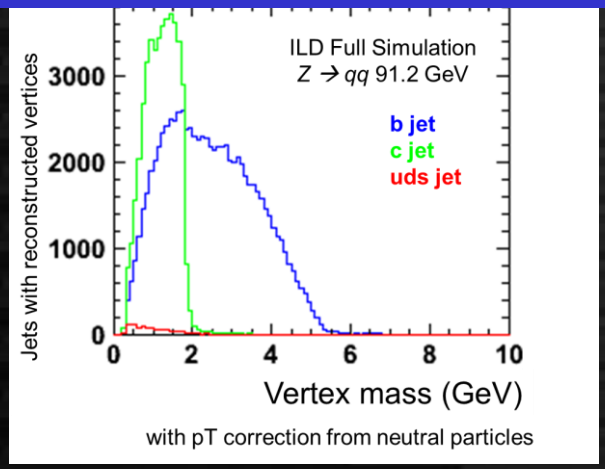


Up to ~5 GeV with 20 psec

improvements on reconstruction ongoing

Averaging over many hits essential

Flavor tagging (b/c/s)



Identifying secondary π^0 to improve vertex mass reconstruction

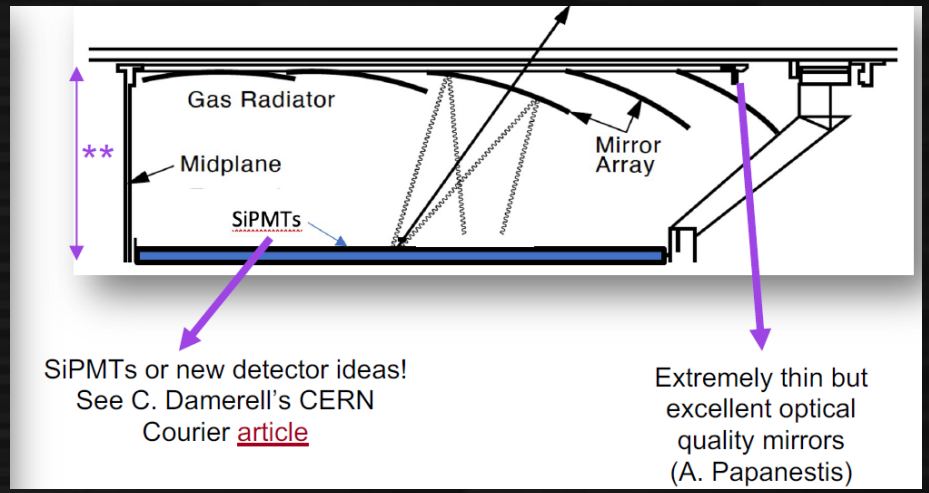
hadron PID can also be utilized

Also usable for long-lived search (decaying to neutrals)

New idea: RICH for PID of hard hadrons

- $H \to ss$: likely out of experimental reach unless enhanced by BSM
- $H \to cs$: BSM models allow for the 1st & 2nd generation fermion masses to be an additional source of EW symmetry breaking
  - Charged heavy Higgs can undergo flavour violating decays (e.g., cs)
    - both **s/c-tagging** can help here

→ Detector aiming strange tag!



Readout with SiPMs
ToF can be done in parallel

New ideas for K/π discrimination @ ILC
by Valentina Cairo (SLAC)

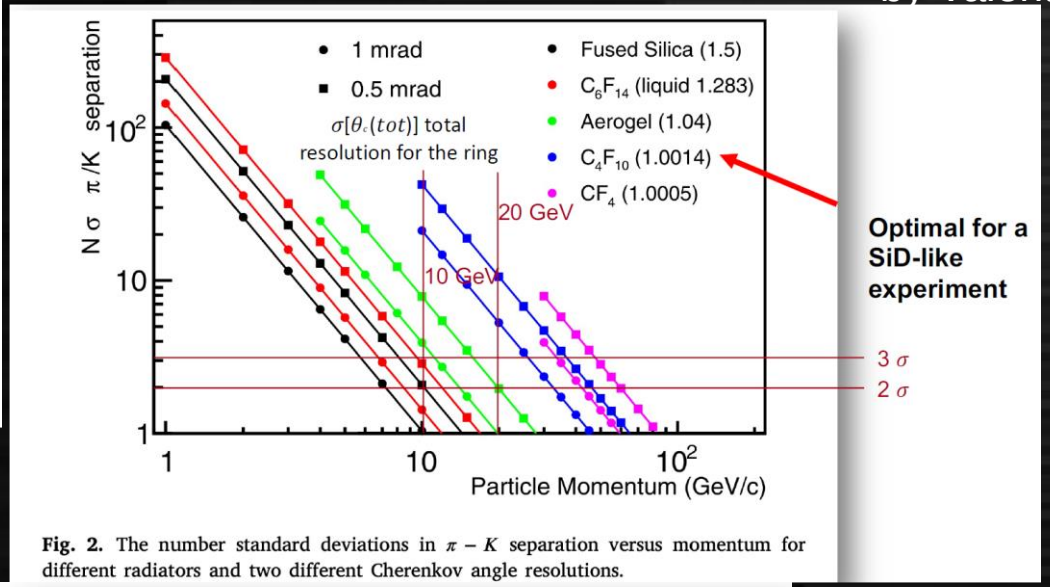
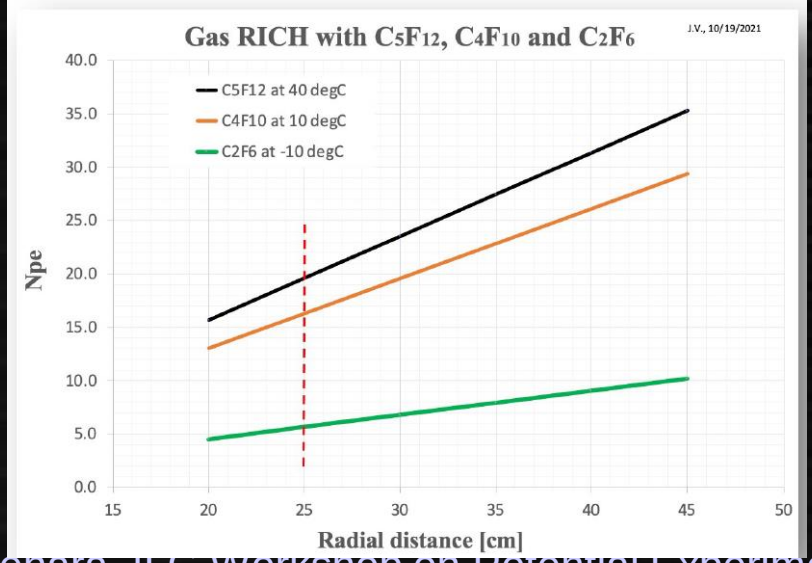


Fig. 2. The number standard deviations in $\pi - K$ separation versus momentum for different radiators and two different Cherenkov angle resolutions.

Cherenkov can do K/π separation at tens of GeV (with C4F10 gas)



20-25 cm necessary to obtain 15-20 pe

Final remarks

- Good mixture of matured and advanced concepts

Matured

- SiW-ECAL
- SciW-ECAL
- AHCAL
- DHCAL
- LumiCal

(Almost) ready for large-scale prototype
Prepare for quick realization of 4-5 years to real detector construction

Advanced

- MAPS ECAL
- High-granular dual readout ECAL/HCAL
- LGAD ECAL
- RICH

Additional physics impact to experiment with novel technologies
Still needs intensive effort to realize as a real detector
More friendly to newcomers?