Overview of Higgs Factories / ILC and Silicon-based Calorimeters

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Physics of Higgs factories

Fundamental questions

- (Grand) Unified theory
- Matter-antimatter asymmetry
- Dark matter / dark energy
- Inflation / vacuum stability
- Light neutrino mass
- Anomalies (μ g-2, R(K) etc.)

↓

Beyond Standard Model (BSM) is necessary!

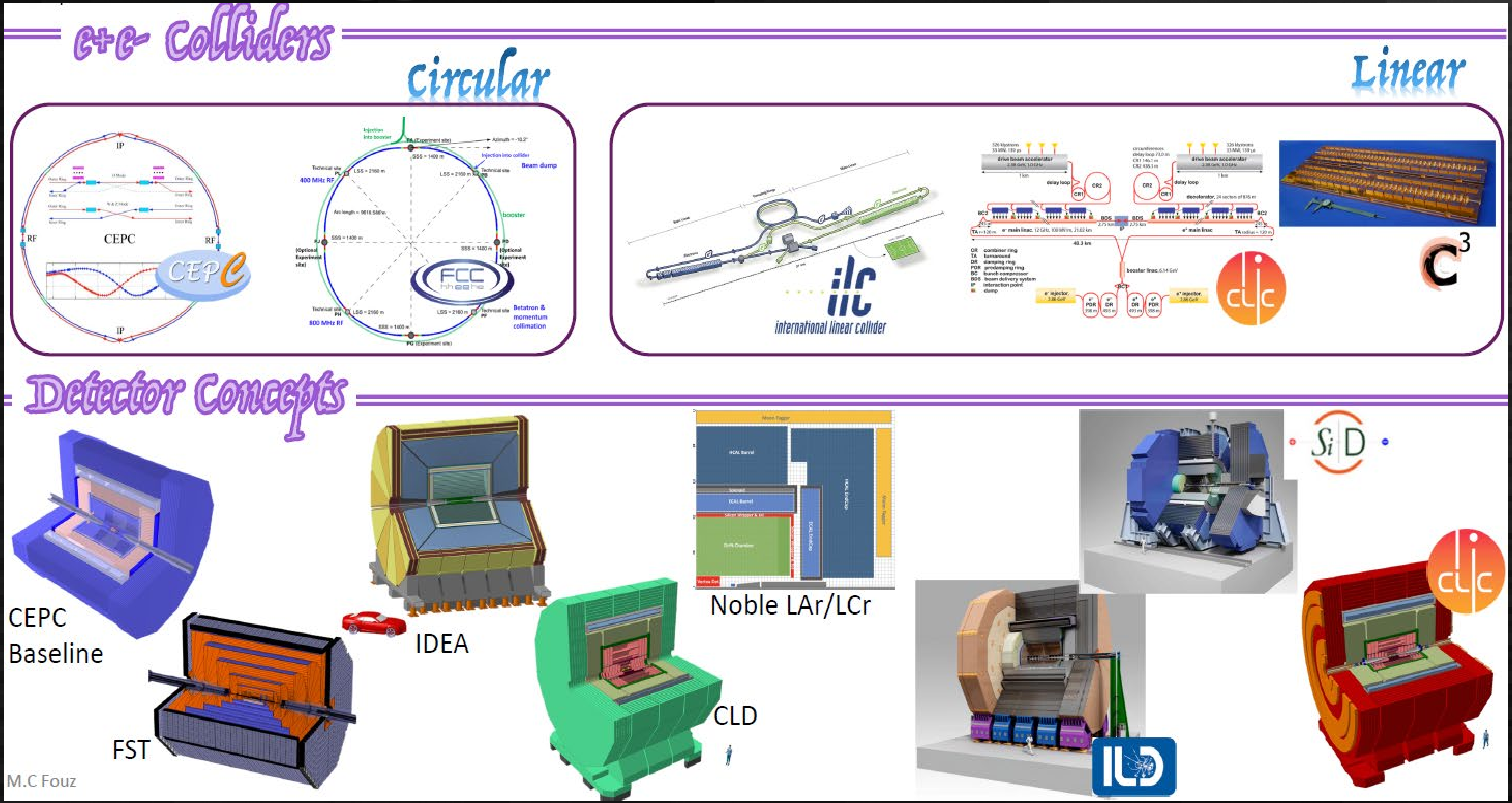
- TeV BSM
  - SUSY, Composite Higgs, Extra dimension…
- Light BSM
  - ALPs, dark photon, …

Approach of Higgs factories

- For TeV BSM
  - Higgs couplings to SM particles up to 1% (~10x better than HL-LHC) with Effective Field Theory
  - Direct search of BSM eg. giving mass-degenerate DM
- For light BSM
  - Higgs rare decay sensitive to hidden particles (Higgs portal)
- Other fundamental probes
  - Higgs self coupling (vacuum structure)
  - Higgs/top mass (vacuum instability)
  - CP structure (Higgs, Z)

Higgs factory + HL-LHC: the way to explore fundamental questions!

Higgs factories and detectors

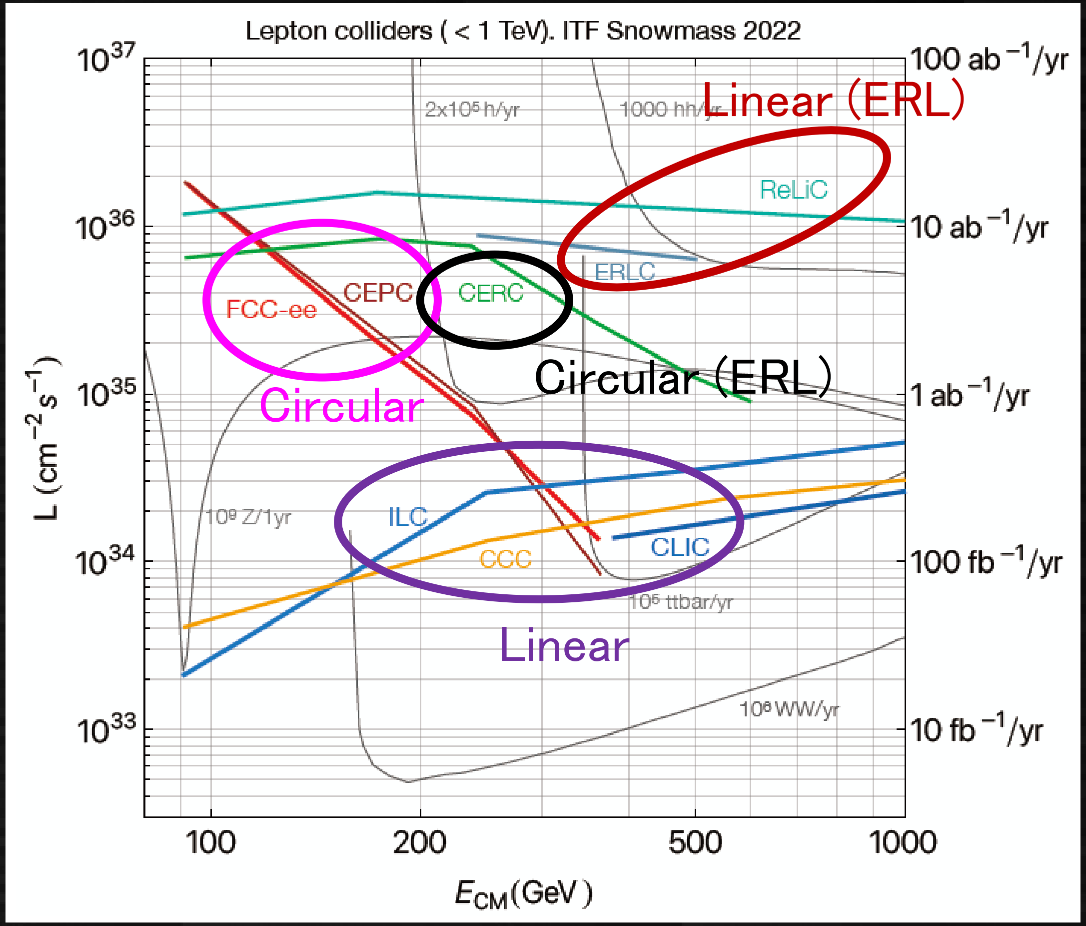


Target Energies of Higgs Factories

- 91~250 GeV — Oblique parameters, W/Z mass, b/τ precise studies
- 250 GeV — Higgs coupling (~1%), Higgs rare decays (for light BSM)
  (TeV BSM indirect search)
- 350 GeV — Top measurement → vacuum stability
- 500–550 GeV — Higgs self coupling (20–30%), ttH coupling
- 1 TeV — Higgs self coupling (10%) → baryogenesis
- 250 GeV – a few TeV — TeV BSM direct search

Natural SUSY (250 GeV – 1 TeV) 1 TeV Higgsino 3 TeV Wino

Linear vs Circular Higgs factories



- Linear Colliders
  - Higher energy extendability (to a few TeV)
  - Slightly lower luminosity at 250 GeV
  - Polarized electron/positron feasible
  - Only ready-to-go e+e− collider: ILC
- Circular Colliders
  - Energy extendability limited to < 500 GeV
  - Extremely high luminosity at Z-pole
    - Tera Z-factory: b/tau physics possible
  - Significantly higher initial cost
    - Due to 100 km tunnel
  - Tunnel can be used for 100 TeV pp collider

European strategy (2020) and Snowmass (2022)

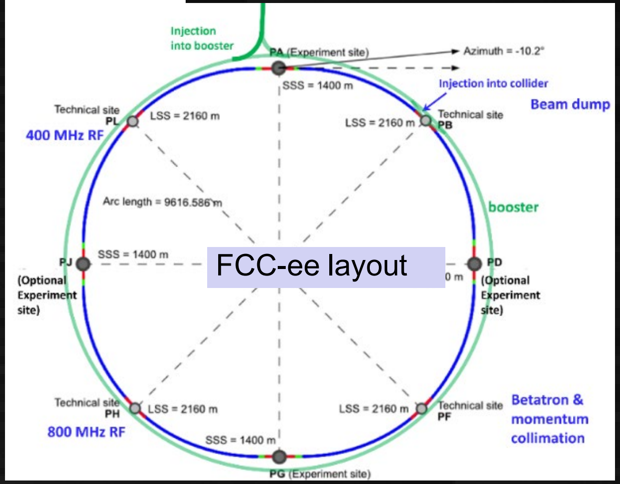
- 2020 European strategy on particle physics
  - Higgs Factory is #1 priority as the next project
  - Feasibility study for FCC (with possible 1st stage as e+e- collision) → 2025
  - ILC is supported if "timely realized" and CERN can be the hub in Europe
- 2022 Snowmass discussion at US (energy frontier)
  - Early realization of any Higgs factory in the world is desired
  - Pursuing Higgs factory at US in case of no HF outside US until ~2040
    - Cool Copper Collider (C3) as a cooled normal-conducting collider
    - Superconducting options (eg. HELEN) are also being investigated

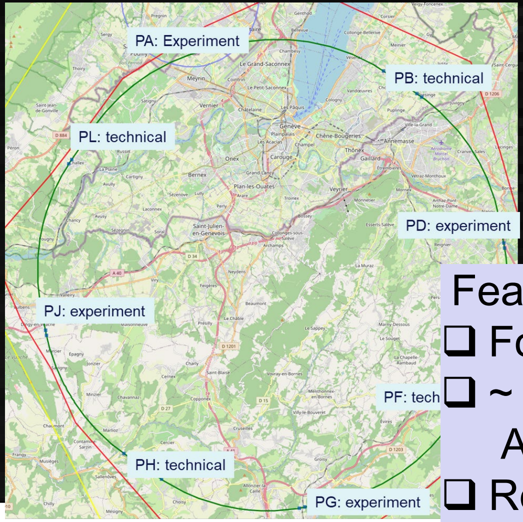
  → P5 at US DOE ongoing

F. Gianotti, Snowmass Summer study

FCCee at CERN

91.1 km ring, 2 IP, energy 91-350 GeV

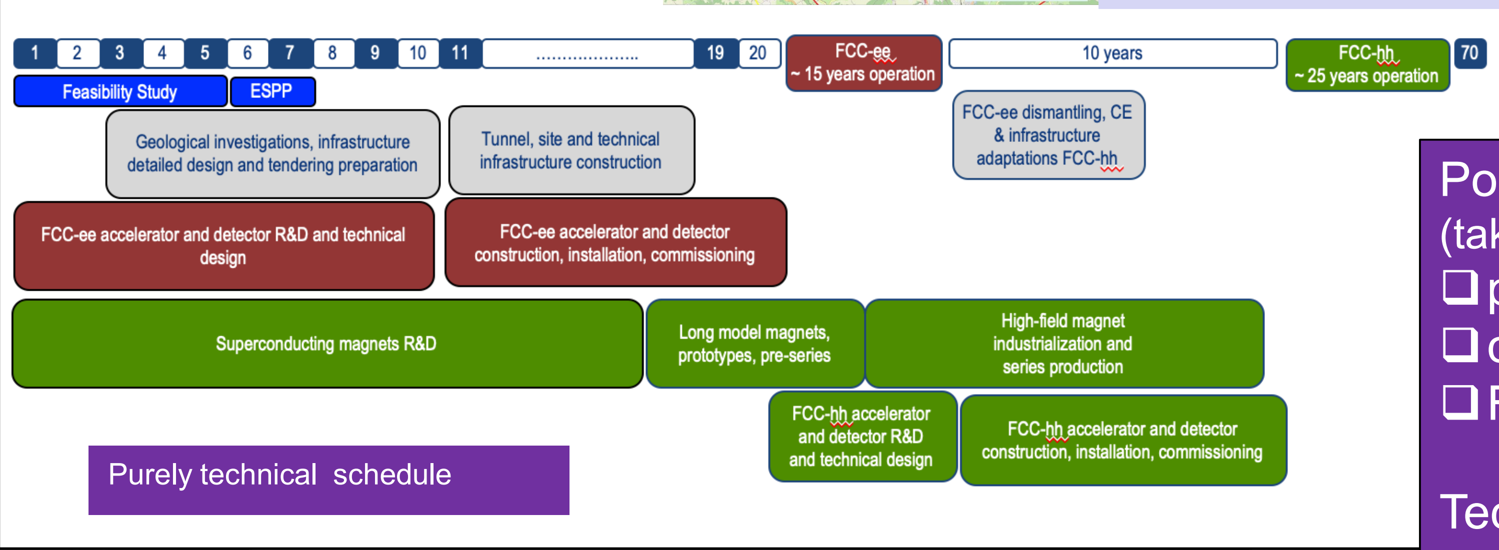




Numbers are for 100 km ring

	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	230 x10^{34} 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

Feasibility Study:
- ❑ Focus is on FCC-ee and magnet R&D
- ❑ ~ 40 MCHF/year from CERN budget (half for magnet R&D)
  Additional funding from EU and collaborating institutes (e.g. CHART)
- ❑ Results will be summarised in Feasibility Study Report end 2025

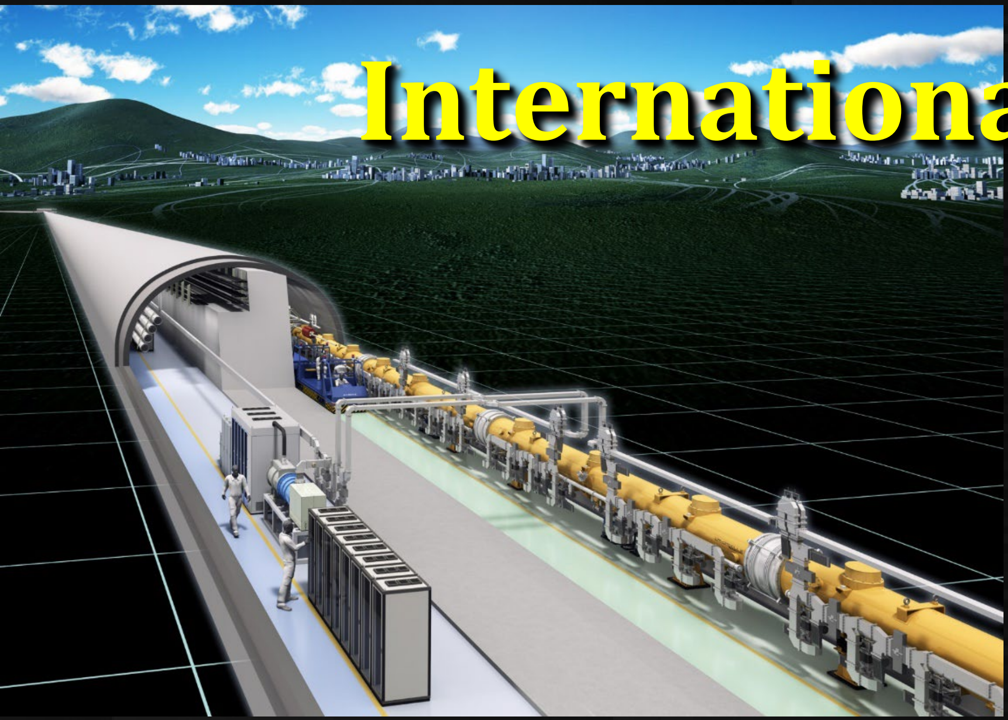


FS includes financial studies

Possible schedule
(taking into account resources constraints):
- ❑ project's approval by end of decade
- ❑ construction's start early 2030s
- ❑ FCC-ee operation: 2048-2063
  (10 years Z, W, H and 5 years tt)

Technical schedule: operation starts early 2040s

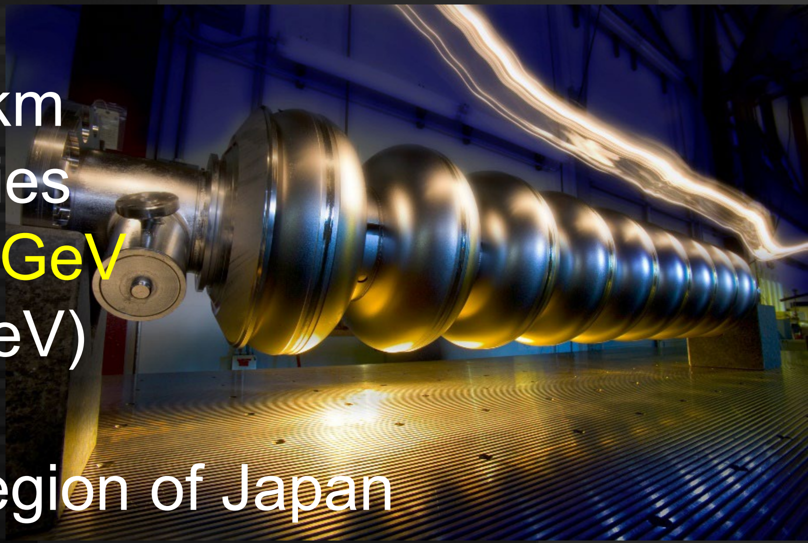
International Linear Collider (ILC)

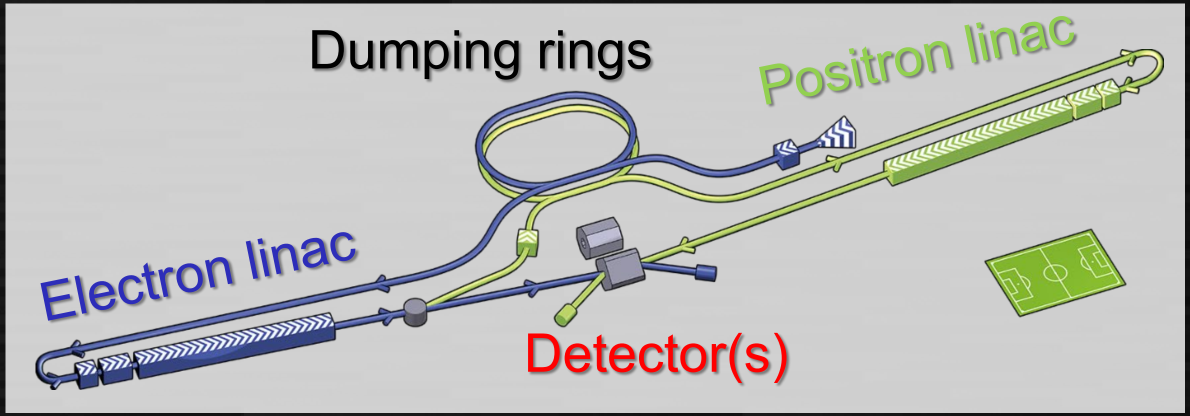


Rey.Hori

Linear accelerator of 20 km
w/ superconducting cavities
e^+e^- collision at $\sqrt{s}$ = 250 GeV
(upgrade: -50 km to >1 TeV)

Site candidate: Tohoku region of Japan





- 250 GeV with 20 km, 32 MV/m
- Upgrade path:
  - ~45 MV/m with improved surface treatment
  - ~70 MV/m with travelling-wave cavity
  - ~100 MV/m with thin-film cavity?

ILC: a history

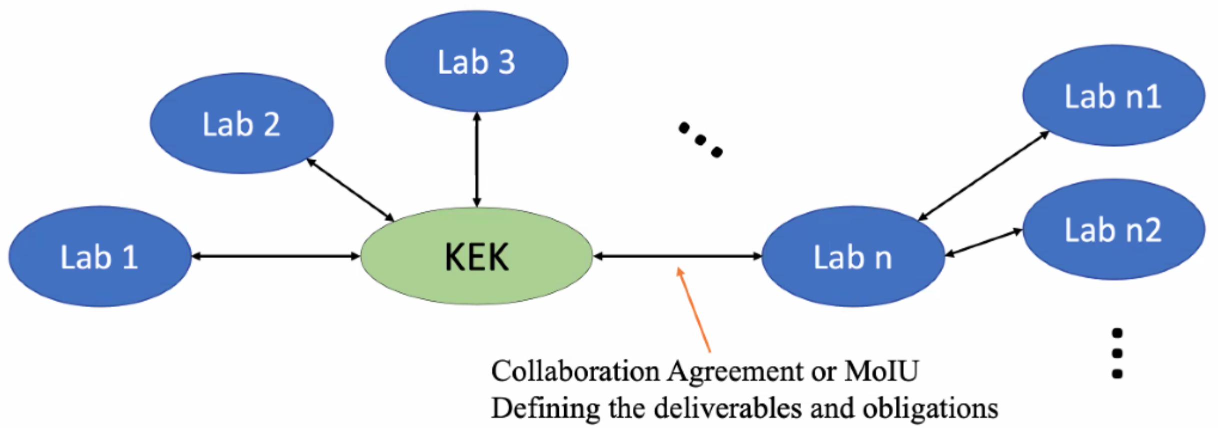
- 2004 Superconducting technology chosen
  → ILC project started by combining several projects (GLC, NLC, Tesla)
- 2013 ILC TDR and detector DBD report
  - 500 GeV baseline with 30 km tunnel
- ~2017 ILC Re-baseline to 250 GeV (after the Higgs discovery)
  - 250 GeV CM energy is a "sweet spot"
- 2020 ILC International Development Team (from LCC/LCB)
  - Chair: Tatsuya Nakada (EPFL)
- 2021 ILC Pre-lab proposal
- 2021 ILC-Japan (chair: S. Asai, renewing steering structure in Japan)
- 2021-22 MEXT expert panel
- 2023 ILC Technology Network

IDT and ILC Technology Network

ILC Technology Network

- Jointly organised by IDT and KEK
- Based on the institutional commitment, unlike for IDT-WG2
  Bilateral agreements between KEK and a partner laboratory (Collaboration Agreement/MoU)

From FY2023 (JP)



Topic: major accelerator components (SRF, source, …)

IDT is an international promotion body for ILC project realization

Current strategy:

- ILC technology network
- International Expert Panel

A few years to real Pre-lab

International Expert Panel (IEP):

- Scheme for (funding) International Projects
- ILC-specific discussion

→ Connection to more official inter-governmental discussion

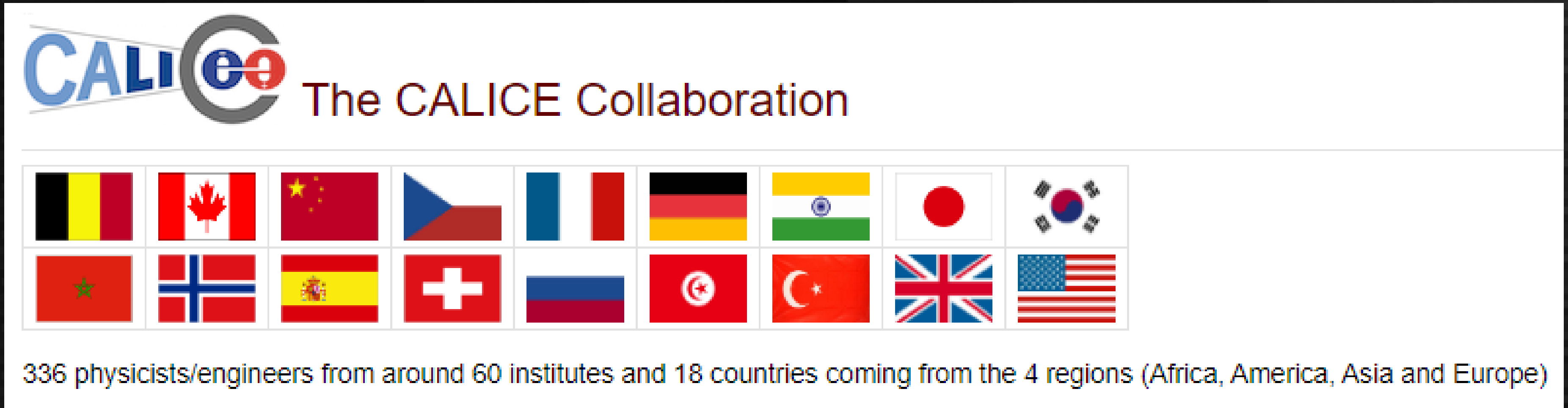
Discussions in Committee for Future Planning

- CFP: Committee of "young" researchers under JAHEP
  - Term: Sep. 2021 – Sep. 2023
  - Members: 26 (from experiments and accelerators, + a few theorists)
  - Mandate: Clarify ILC facility/tech/value and also discussing alternatives
- Current topics: considering scenarios of 3 possible futures
  - Realizing an energy-frontier e+e- collider in Japan (ILC++)
  - Pushing flavor physics in case of no EF collider in Japan
  - Pursuing possibility to realize muon collider (in Japan or elsewhere)
- Town-hall meeting in 28th March, at KEK/Kyoto/Zoom

Revisiting ILC-like scenario compared with possible alternatives

CALICE Collaboration

https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome



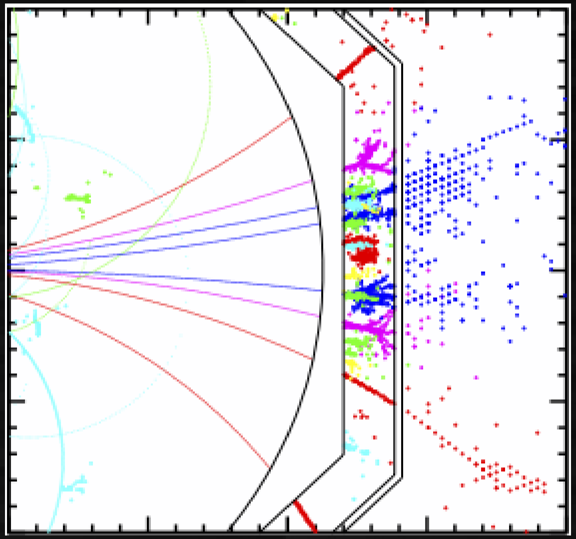
Projects: Particle Flow (PFA) Calorimeter

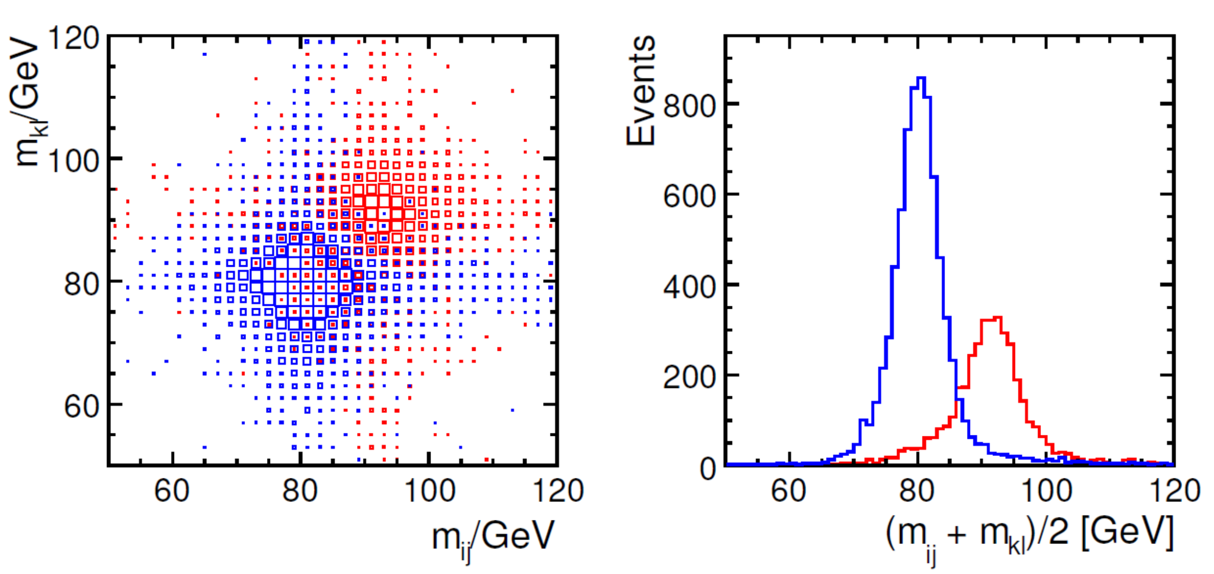
- Silicon-Tungsten ECAL
- Scintillator-Tungsten ECAL
- MAPS ECAL
- Analog HCAL (Scintillator)
- Semi-Digital HCAL (Glass RPC)
- Digital HCAL (mostly terminated)

Purpose

- Interface to test beam
- Collaboration on readout
  - ROC series by OMEGA
  - Detector Interface
  - Clock/spill distribution
- Collaboration meetings
  - Next: Gottingen, 29-31 March

Particle Flow Algorithm





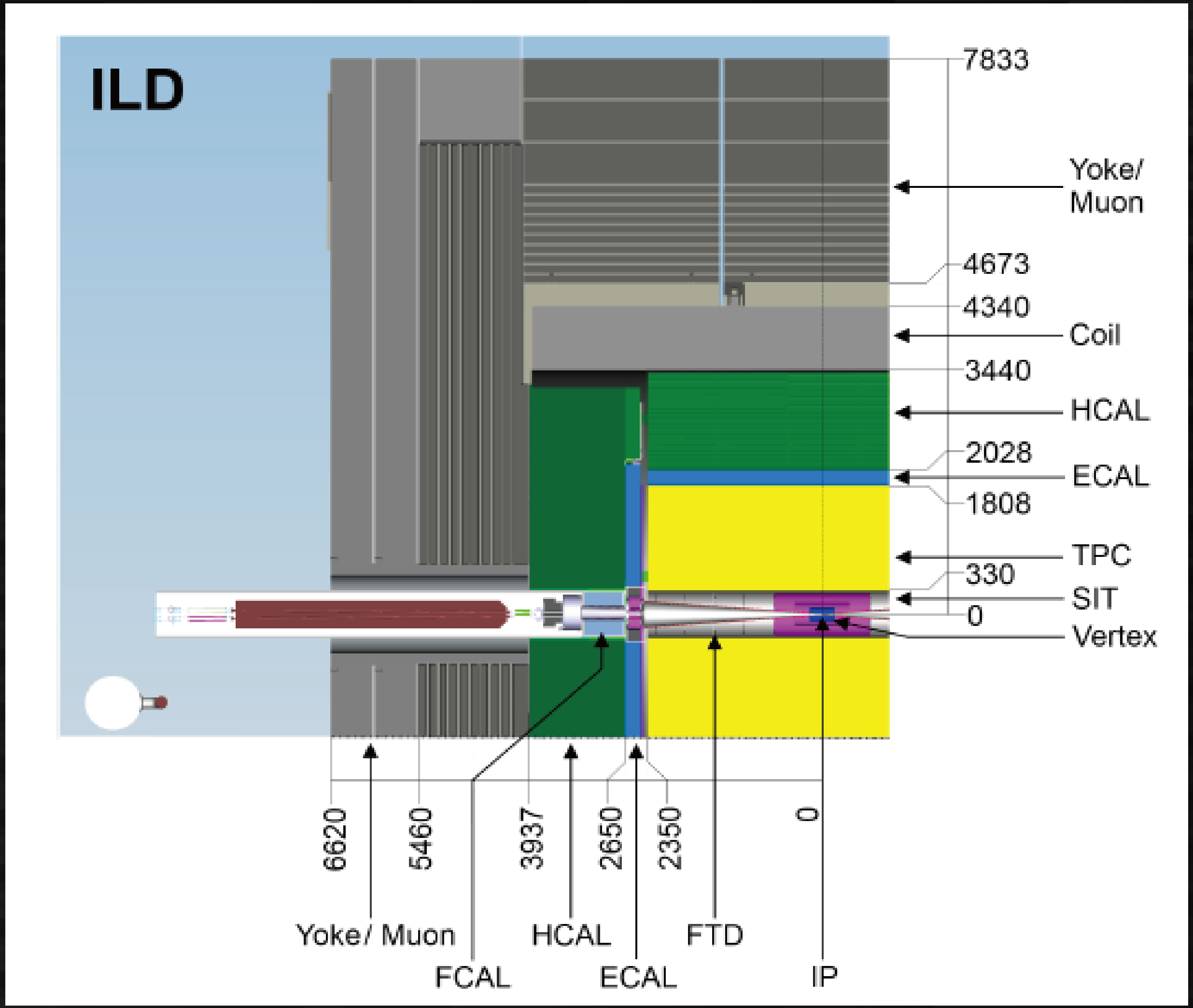
Particle flow:
separate each particle inside a jet to eliminate clusters of charged particles

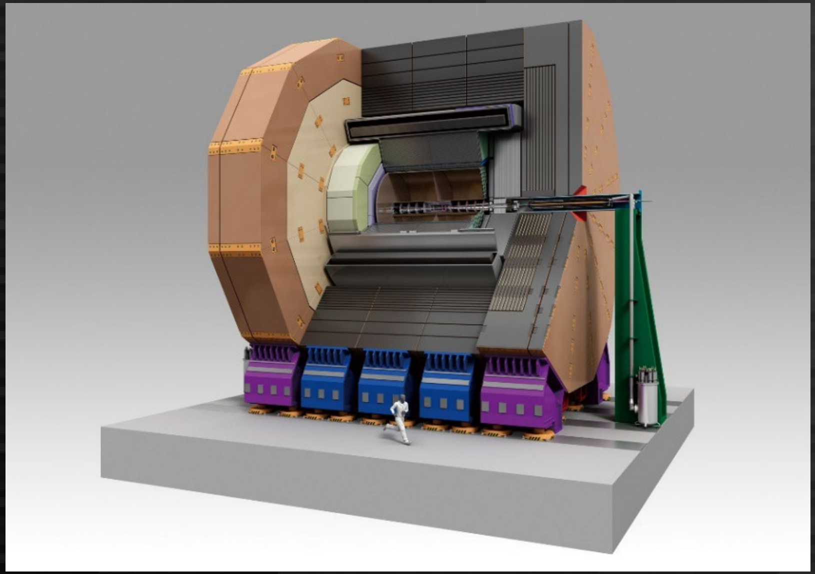
Hadronic WW/ZZ separation

Finely-granular calorimeter is critical for PFA

$E_{jet}(\mathrm{PFA}) = E_{tr}\ (60\%) + E_{\gamma}\ (30\%) + E_{nh}\ (10\%)$
$E_{jet}(\mathrm{non\text{-}PFA}) = E_{\gamma}\ (30\%) + E_{h}\ (70\%)$

ILD detector

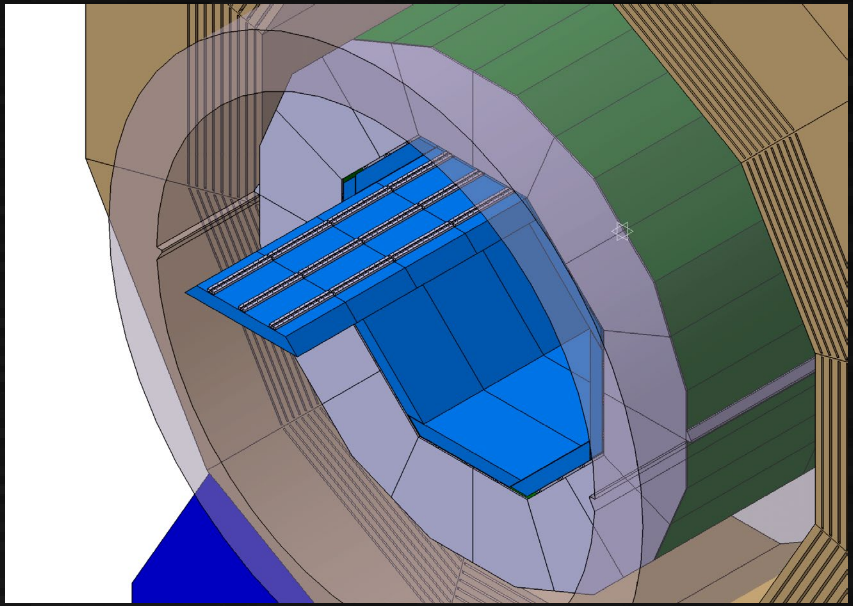


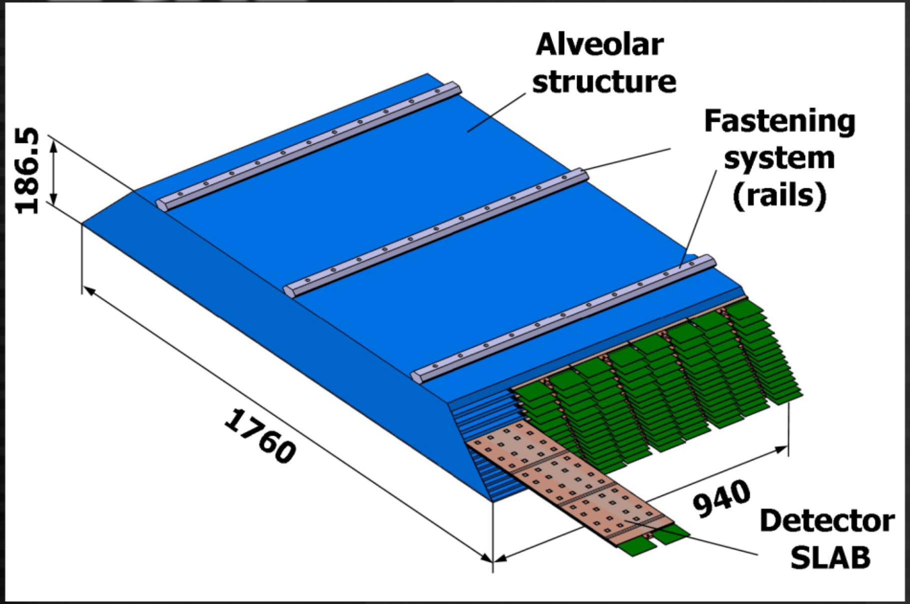


One of two ILC detectors

- Pixel vertex detector
- Silicon tracking (SIT/SET/ETD/FTD)
- Gas TPC
- ECAL/HCAL/FCAL
- SC Coil (3.5 Tesla)
- Muon detector inside iron yoke

CALICE/ILD SiW-ECAL



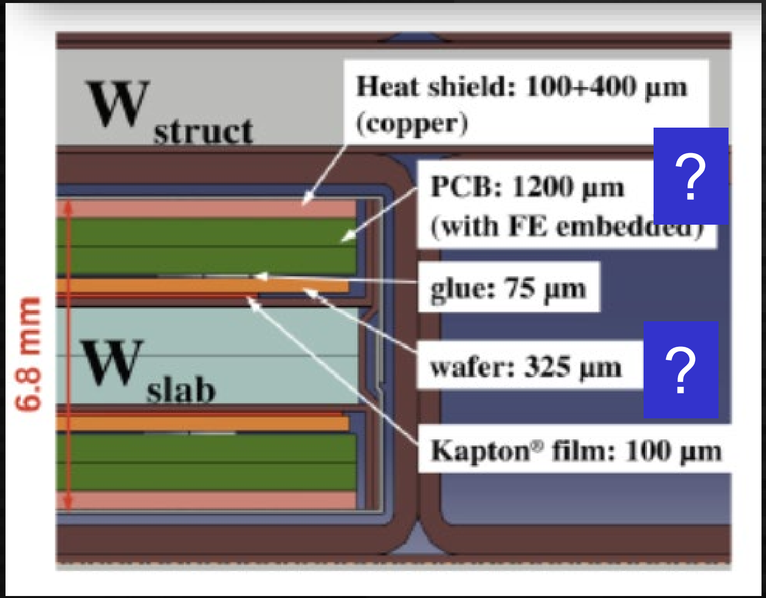


20-30 layers of sandwich calorimeter with tungsten absorber and 5x5 mm - segmented silicon diodes ($\sim 10^8$ channels in total)

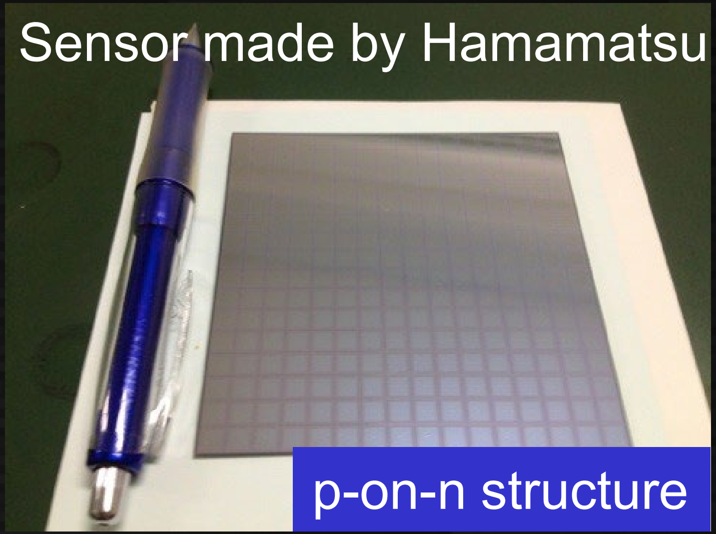
PCB with ASICs embedded

Other options:

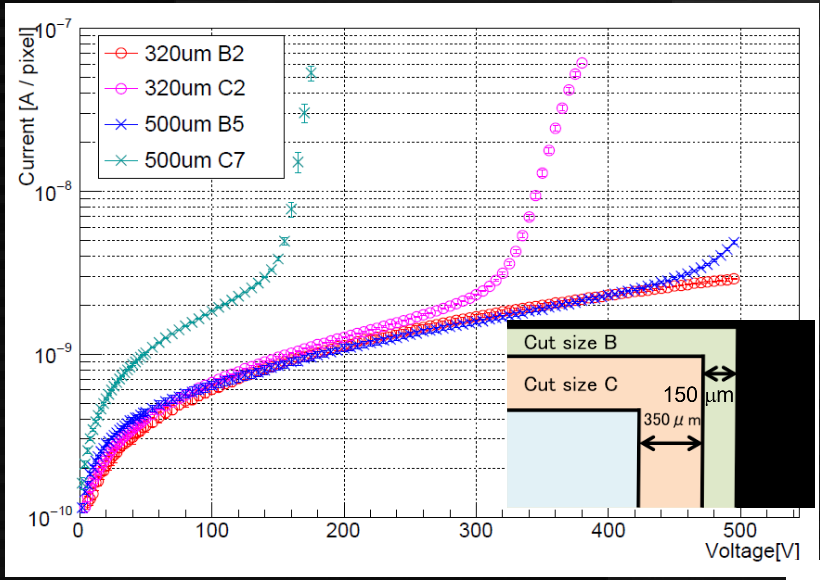
- Scintillator strip (5 x 45 mm, alternating)
- MAPS (50 μm pixel, digital readout)



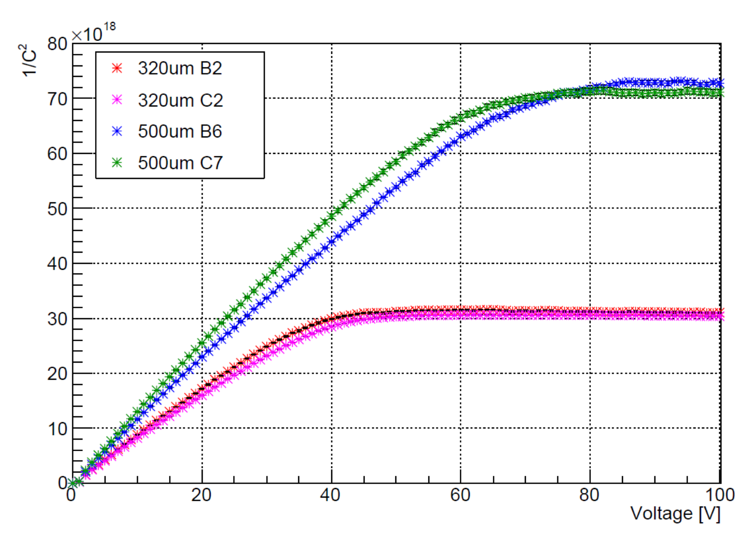
SiW-ECAL: the sensors



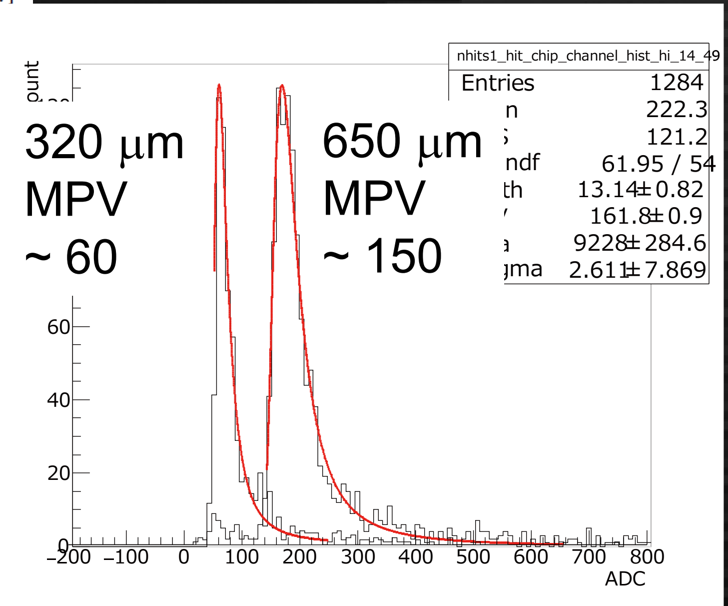
5.5 mm x 256 pixels, 9 x 9 cm / sensor
320/500/650 μm thickness



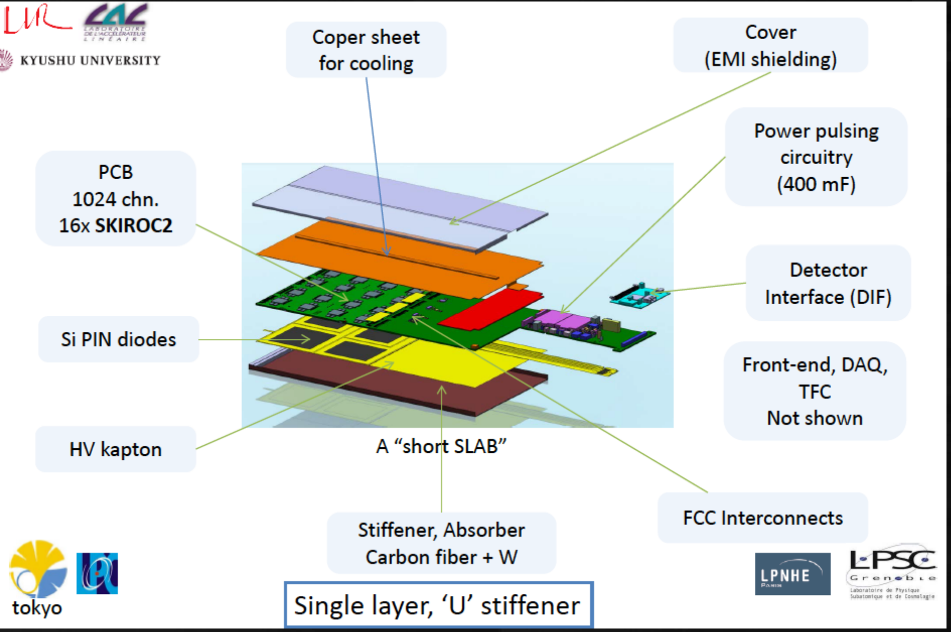
Sensor without guard-ring structure for easier assembly and more active area on the edge
Moderate breakdown voltage (depending on edge structure)



V_{FD} ~ 40 V (320 μm), 70 V (500 μm), 110 V (650 μm)

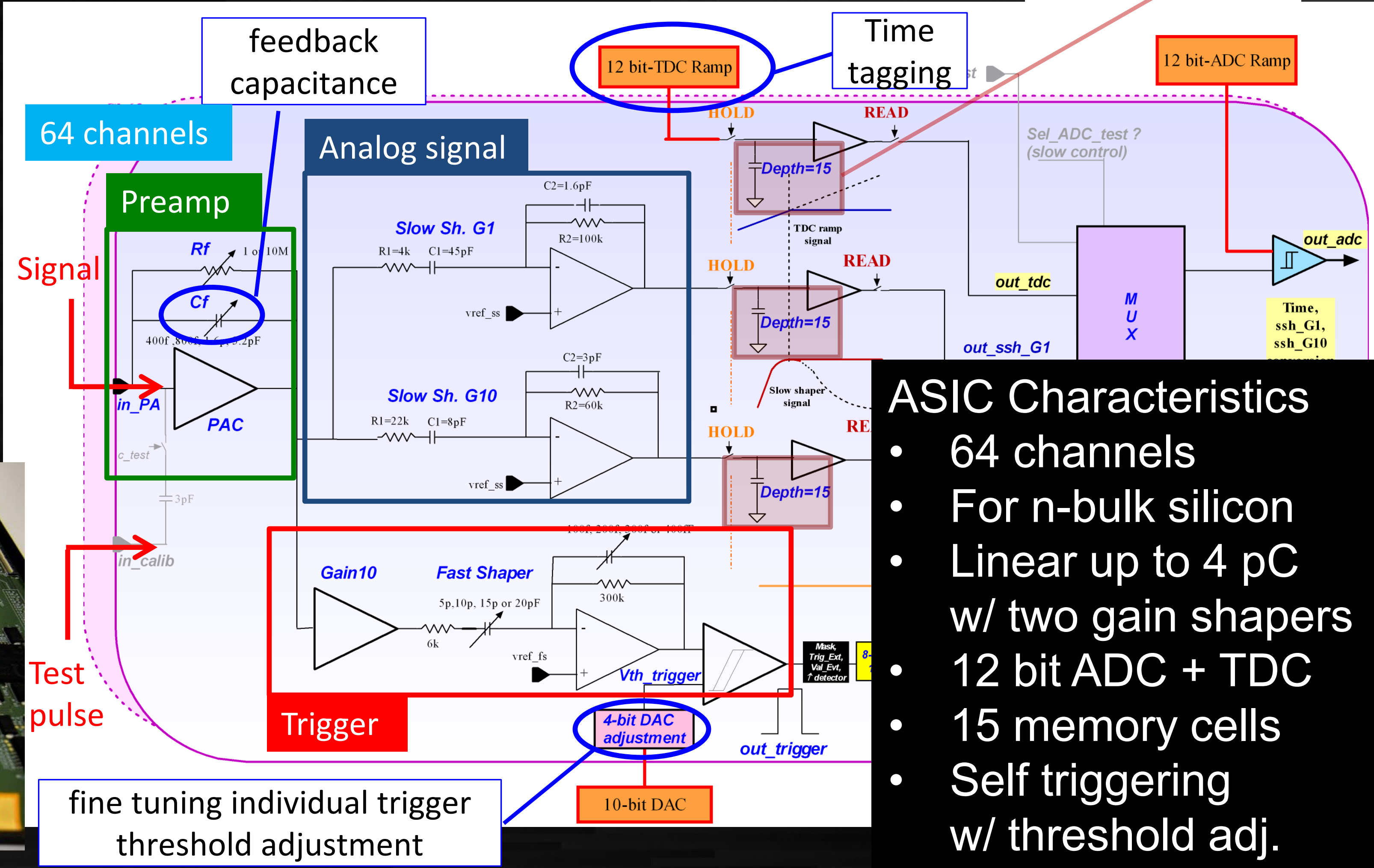


Prototype and readout electronics



Recent prototype

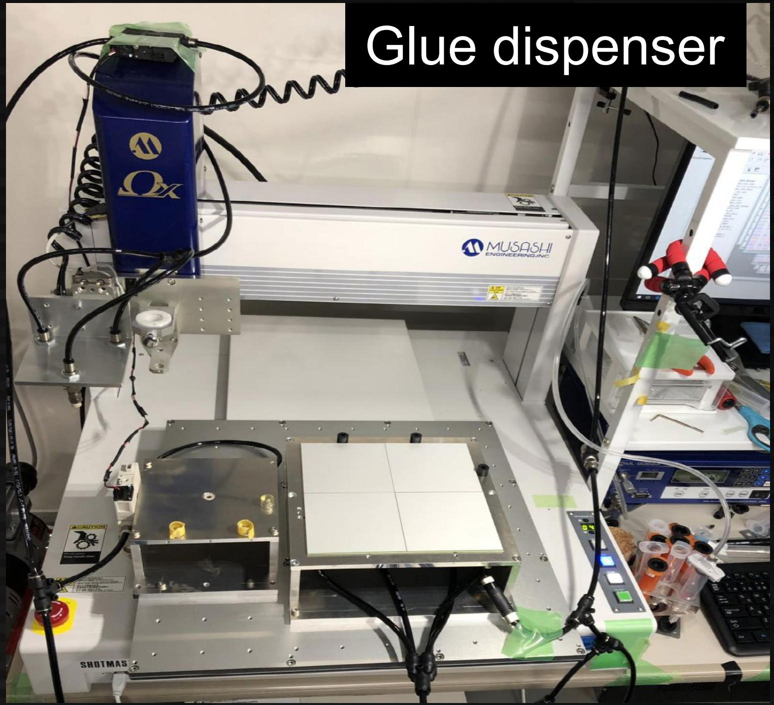
SKIROC2/2A schematic



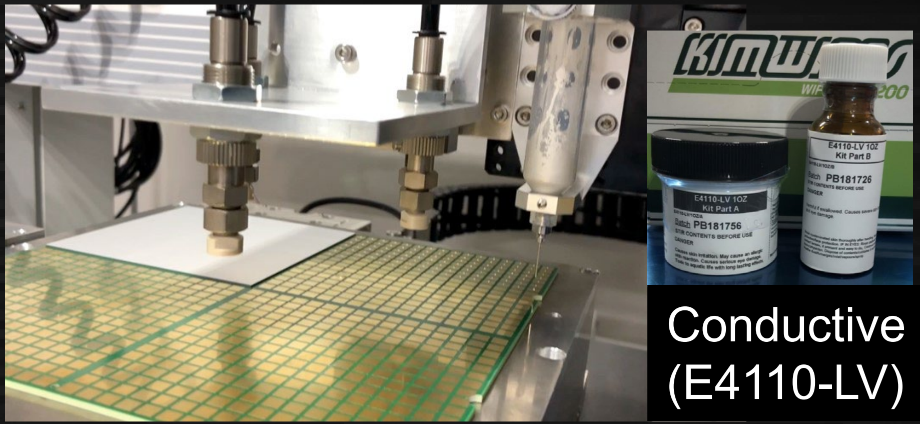
ASIC Characteristics

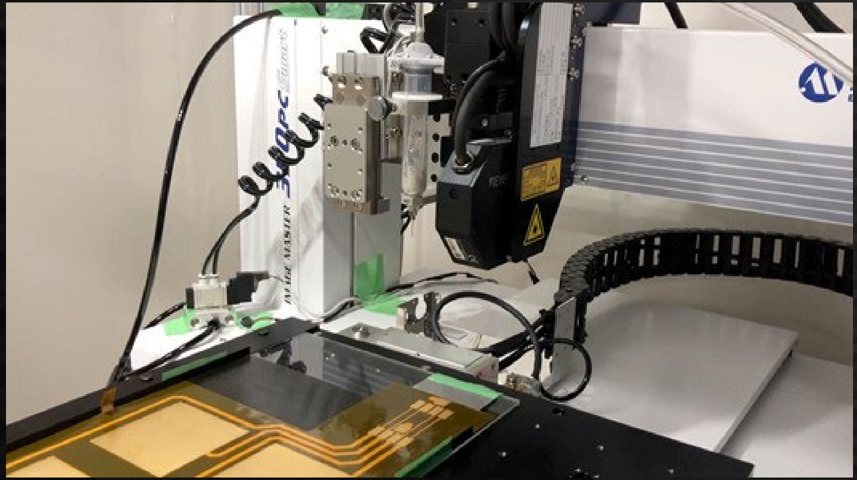
- 64 channels
- For n-bulk silicon
- Linear up to 4 pC w/ two gain shapers
- 12 bit ADC + TDC
- 15 memory cells
- Self triggering w/ threshold adj.
- Power pulsing

Detector Assembly (in Kyushu)

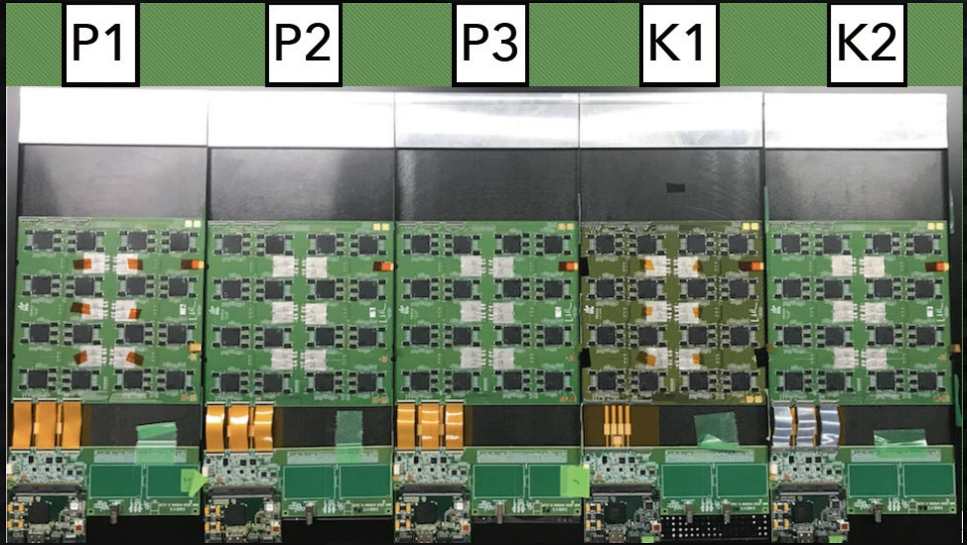


Glue dispenser



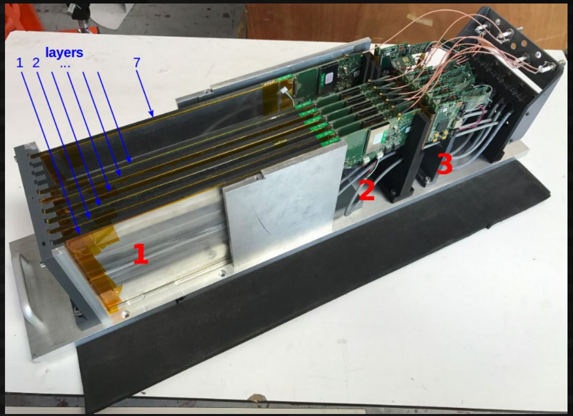


Gluing flex to PCB/sensor assembly
with automatic alignment



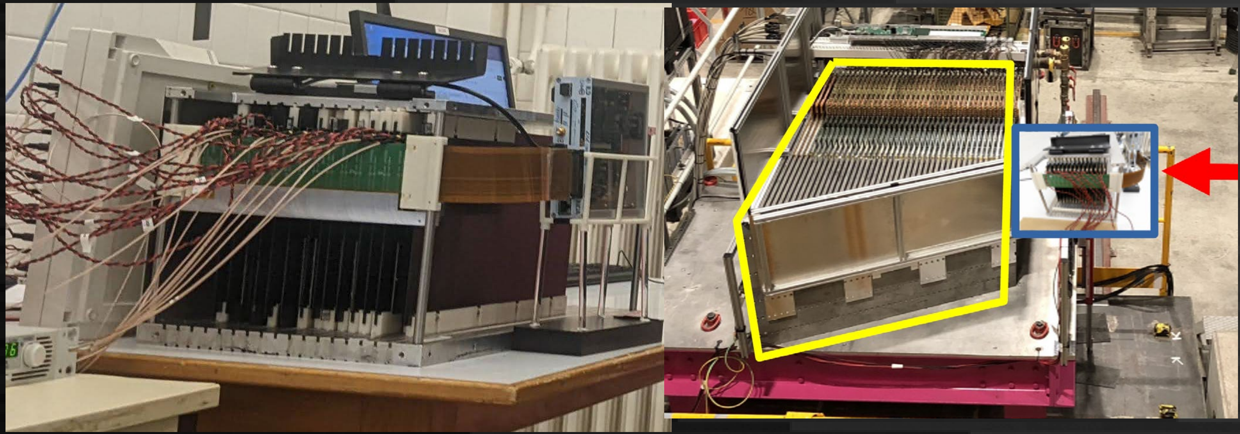
Conductive glue
(E4110-LV)

Test Beams – demonstration of technical feasibility

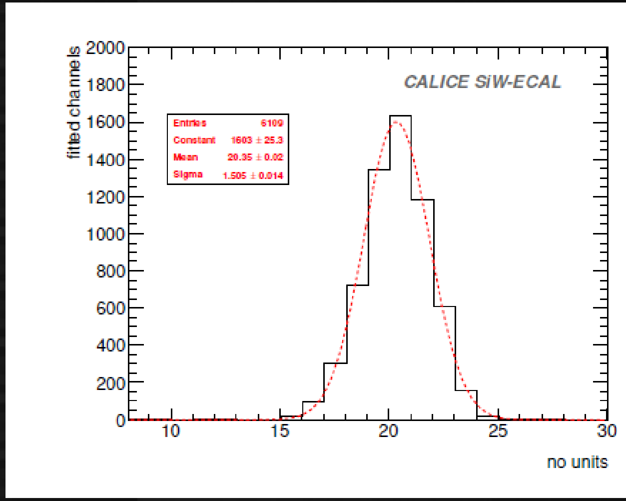


2017 DESY

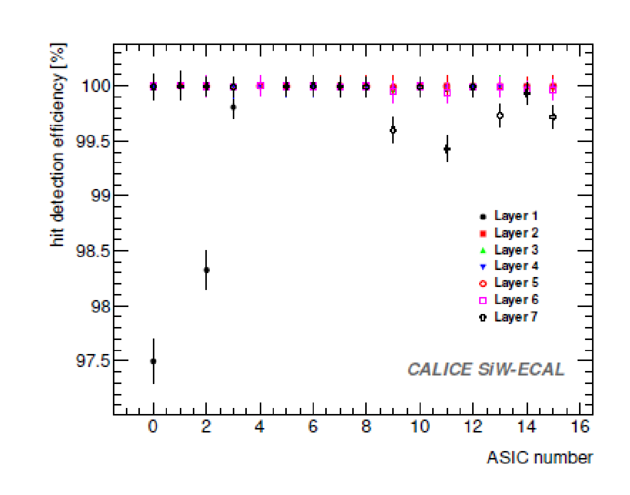
2018 CERN SPS



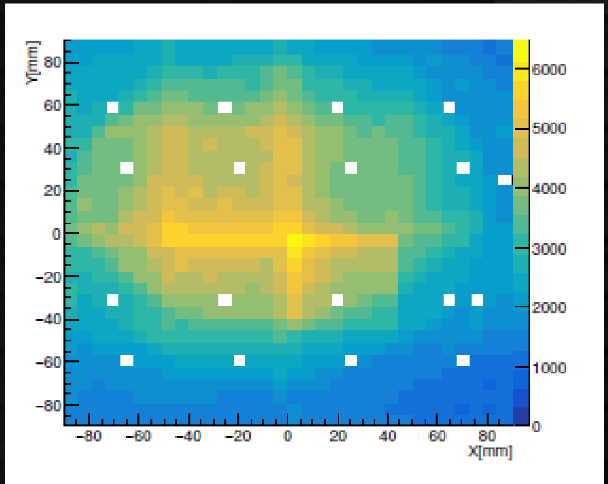
2021-22 DESY and CERN SPS



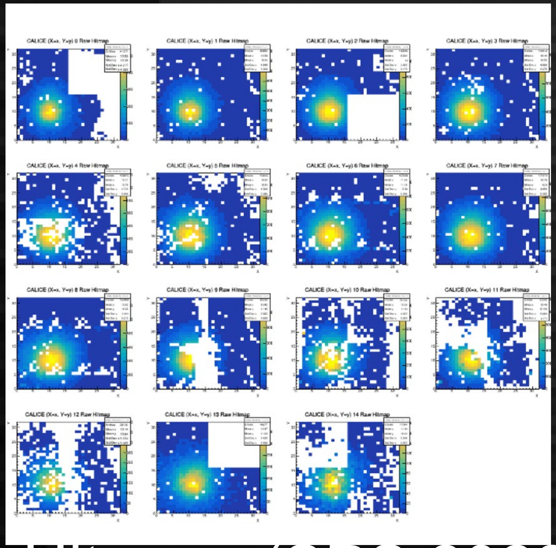
S/N ratio (2017)



Hit efficiency (2017)
arXiv: 1902.00110



Hit map (SPS 2018)

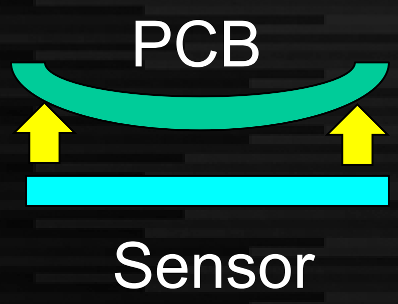


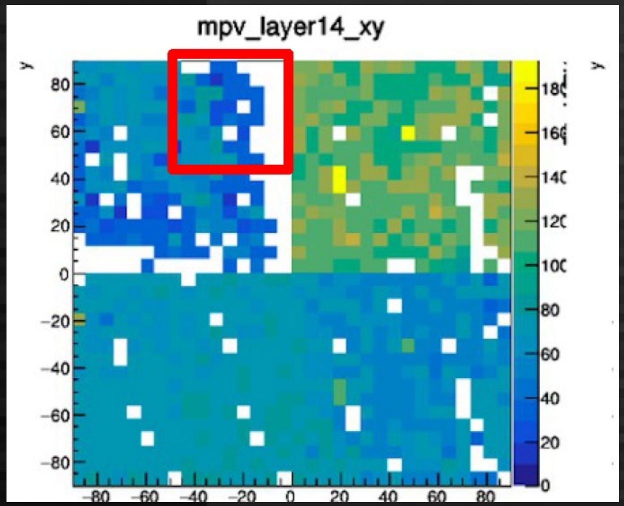
Hit map (SPS 2022)

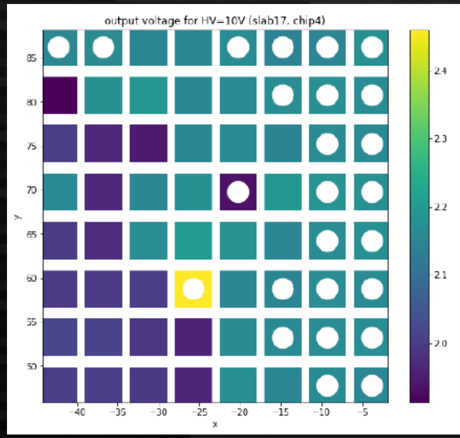
Issues of sensor delamination

- Sensor delamination: appeared in recent years (aging issue)
  - Some sensors are mechanically detached
  - Some sensors are partly inactive
    → Conductive glue detached
- Possible causes
  - Long-time force by bending PCB
    - Gluing sensors with pressure→ should be lifted?
    - By temperature or humidity
  - Degradation of glue

→ Now under investigation

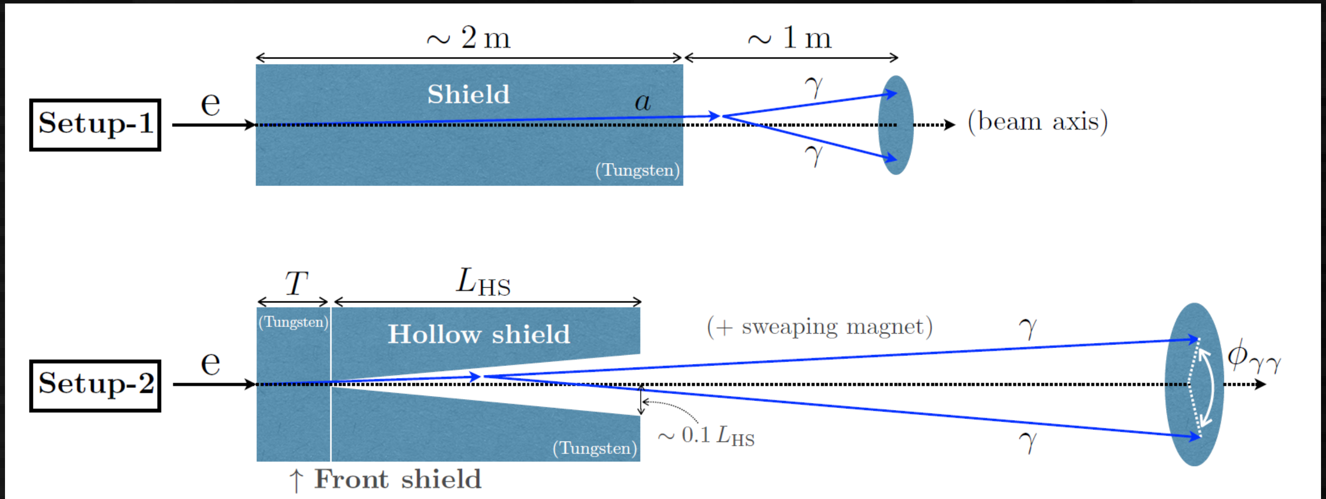


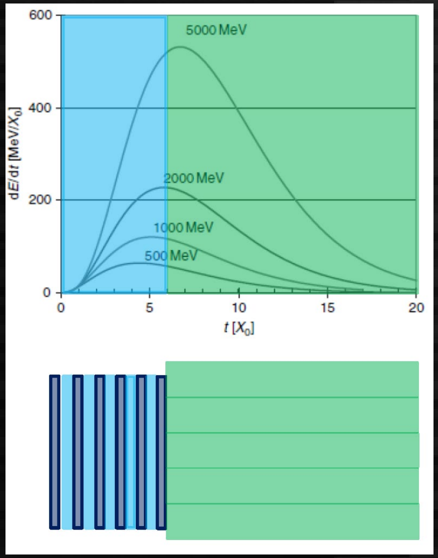




Application to smaller experiments

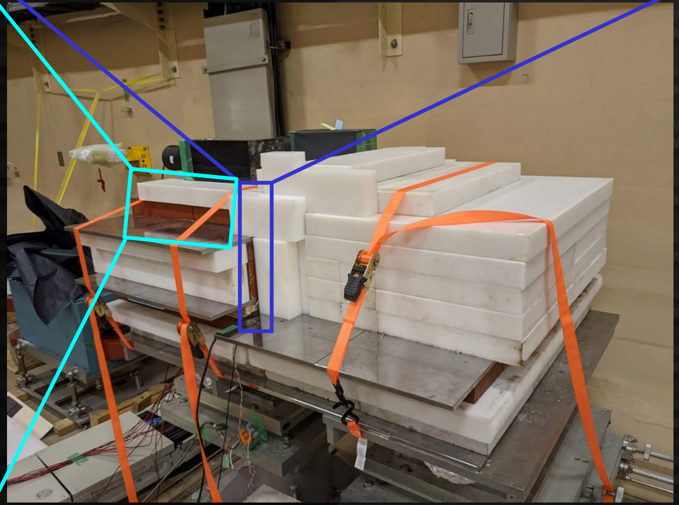
EBES experiment: ALP (Axion-Like Particle) search at KEK Linac beam dump



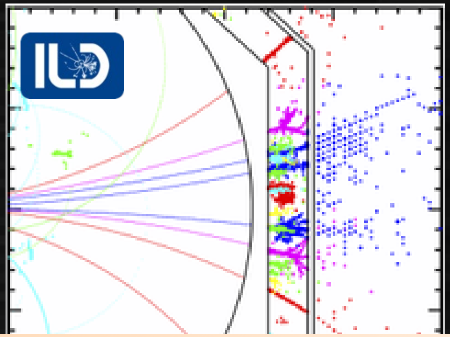


Measuring two photons behind the dump
Pilot run in 2022: huge background seen (1000-10000 particles per bunch) from upstream: need shielding

Application to intense QED experiment (LUXE at DESY) also ongoing

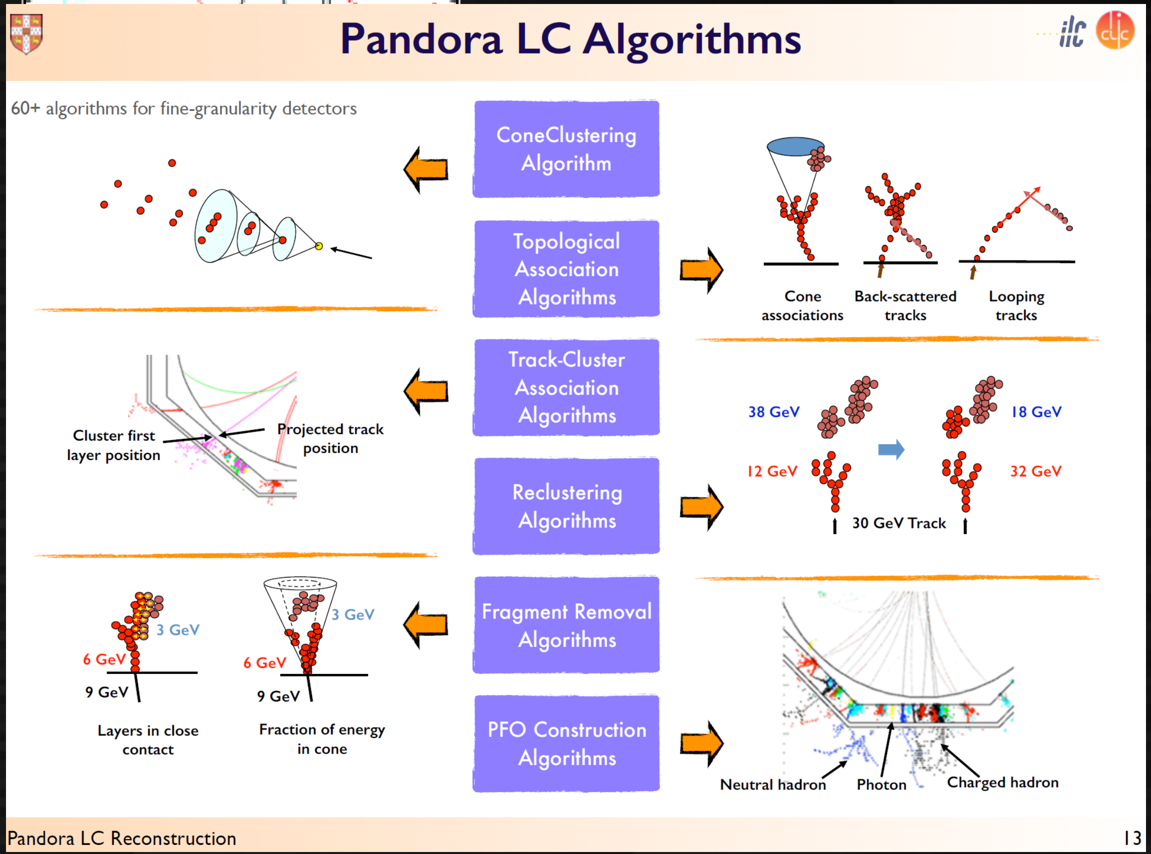


New development: Particle flow with deep learning



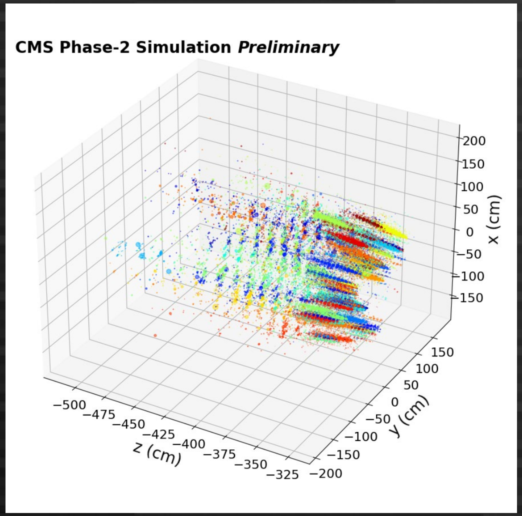
Particle flow: the key algorithm of reconstruction for calorimeters

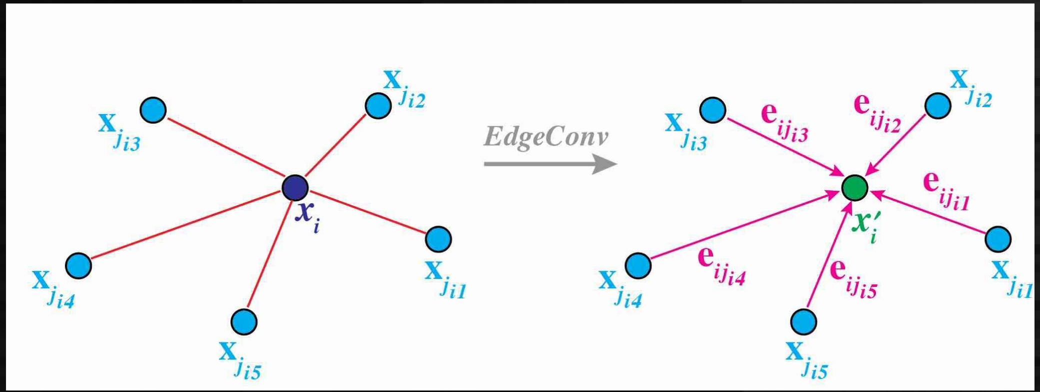
Current algorithm (2008)



DNN-based algorithm being developed for CMS HGCAL

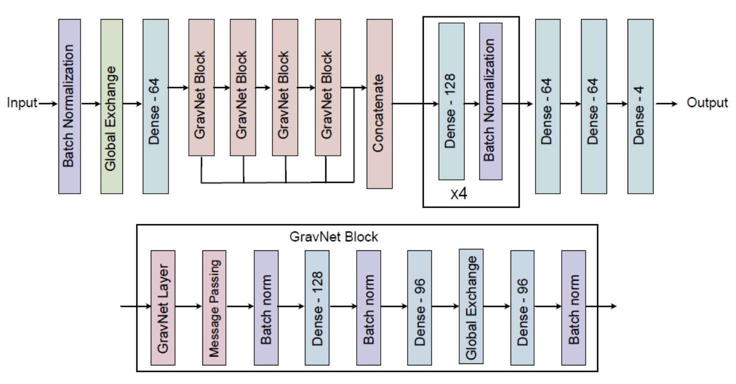
Ability to cope with ~200 PU still to be proved in either DNN or non-ML methods





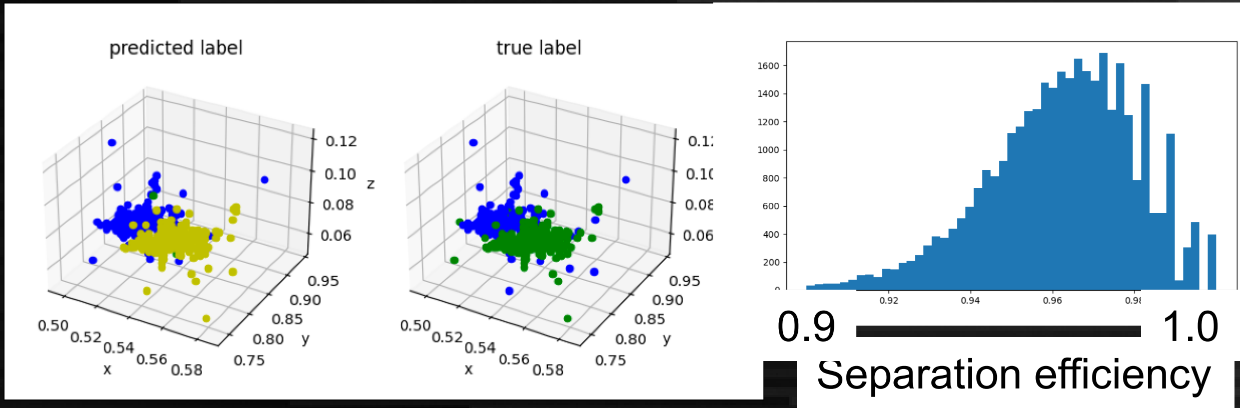
Graph neutral network (GNN): convoluting neighbor nodes using “adjacency”

Particle flow with GNN

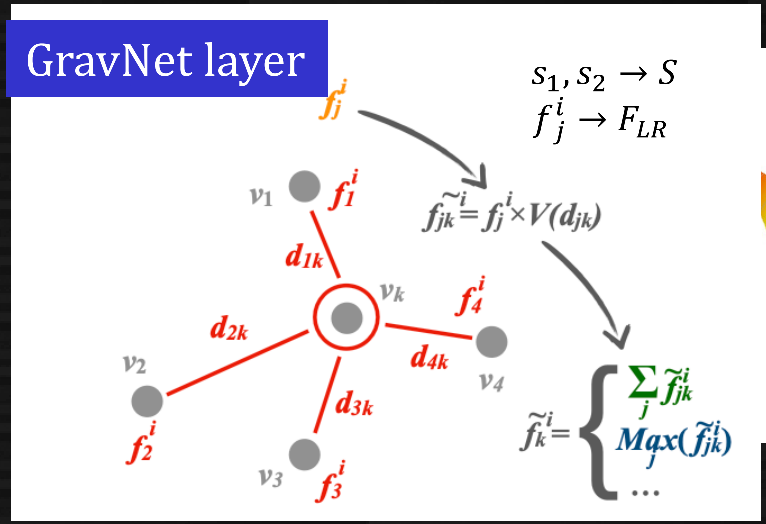


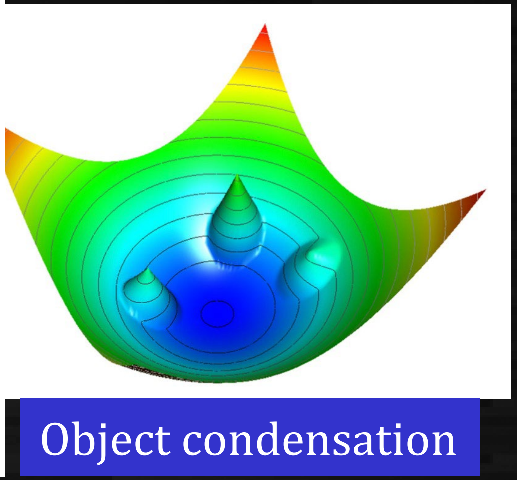
- Algorithm for calorimeter clustering
  - GravNet layer x 4 (concatenated)
    - Contrastive learning on virtual coordinate
  - Object condensation loss function
    - Make one "condensation point" per cluster
    - Attract hits to condensation points with the same true cluster in (another) virtual coordinate

Applying to ILC detector
collaboration with L. Gray, T. Klijnsma (FNAL)



Study on two photon separation with ILC detector





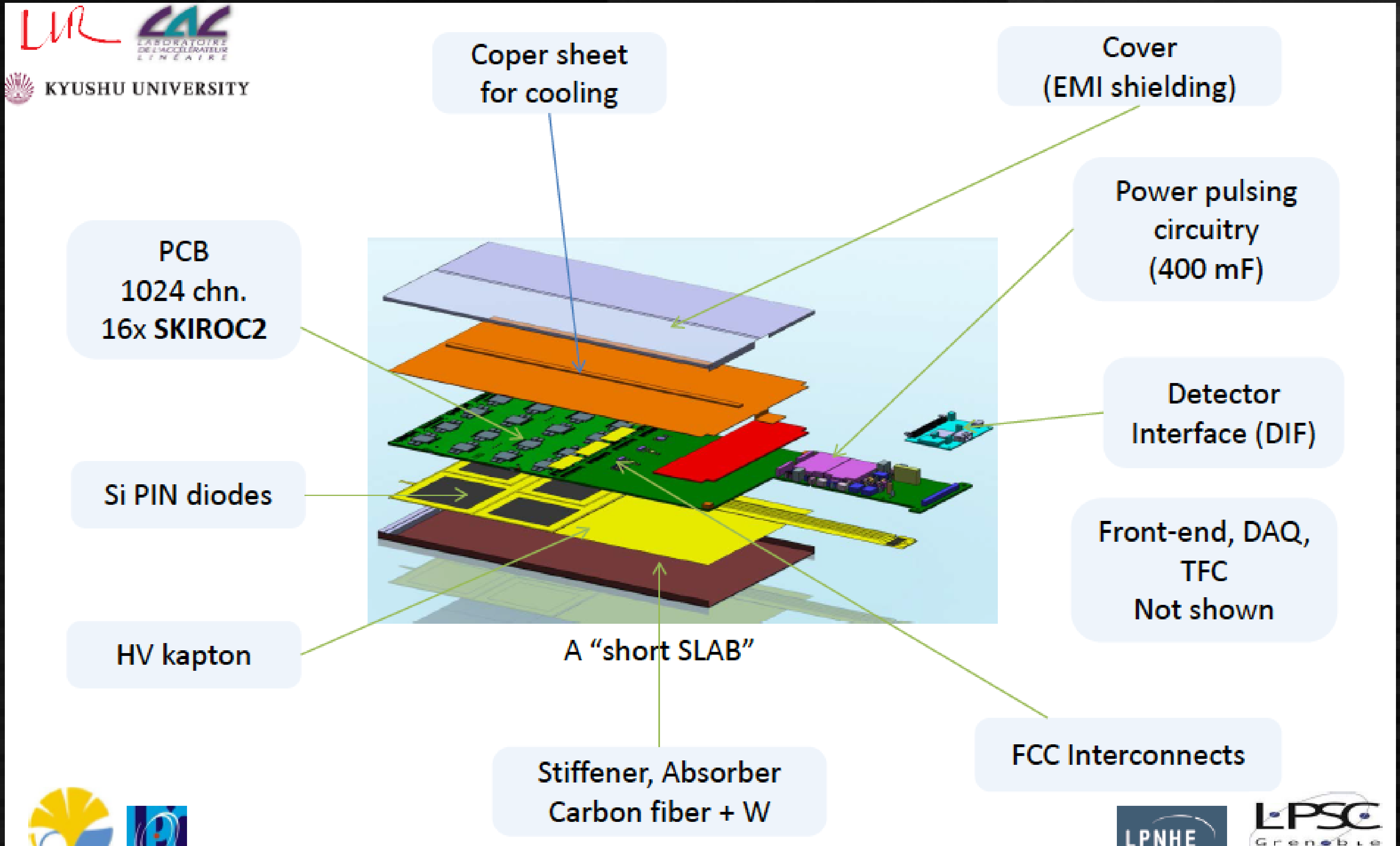
Plans on the developments for ILC

- Track-cluster matching (for full PFA)
- Including picosec timing (as HGCAL)
- Detector optimization (eg. pixel size)

Summary

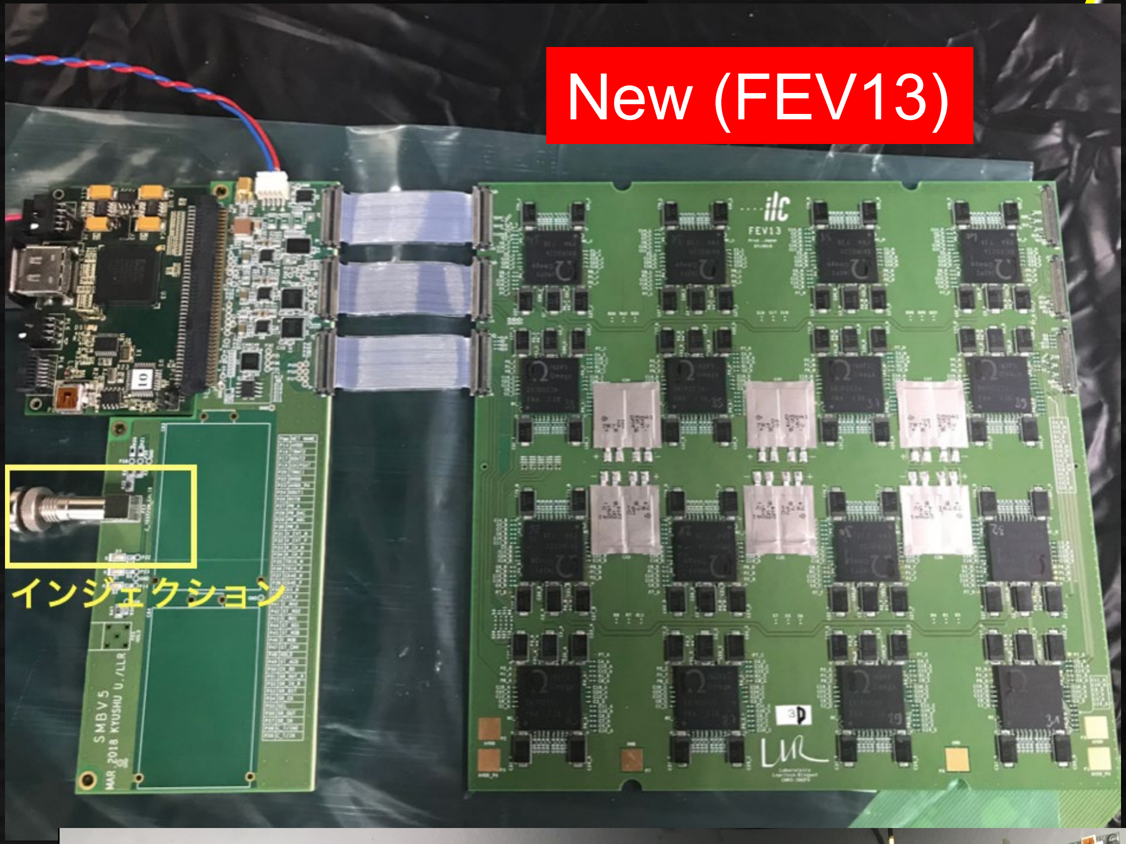
- Higgs factory (HF) is the key project for HEP after HL-LHC
- ILC (as well as other HFs) is evolving but decision yet to come
- High-granular calorimetry is a key detector components for HF
- Silicon pads are important baseline technology for ECAL
- We are realizing quasi ILC-compatible technology
- Several issues (eg. delamination) need to be addressed
- Application to smaller experiment starts to be forseen
- Interesting application of modern DNN for Particle Flow
- Hope to inform you good news soon.
  Any support and help important and super-welcome!

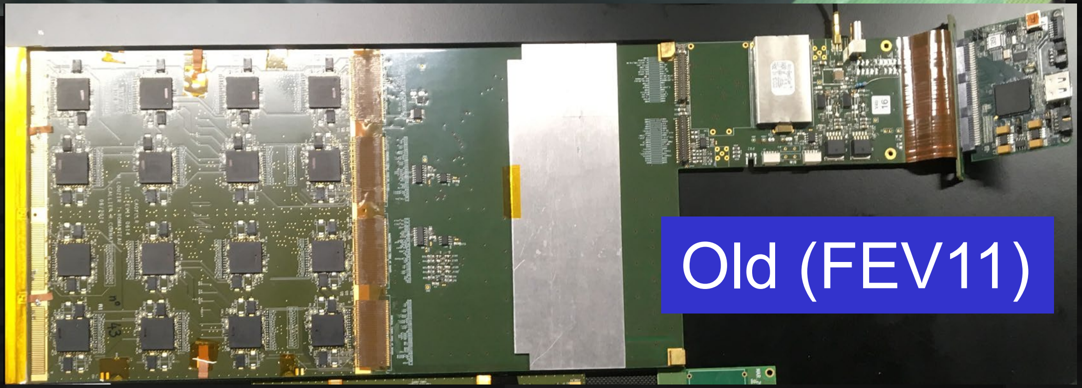
Technological Prototype



Single layer, 'U' stiffener

Electronics: FEV/SMB/DIF

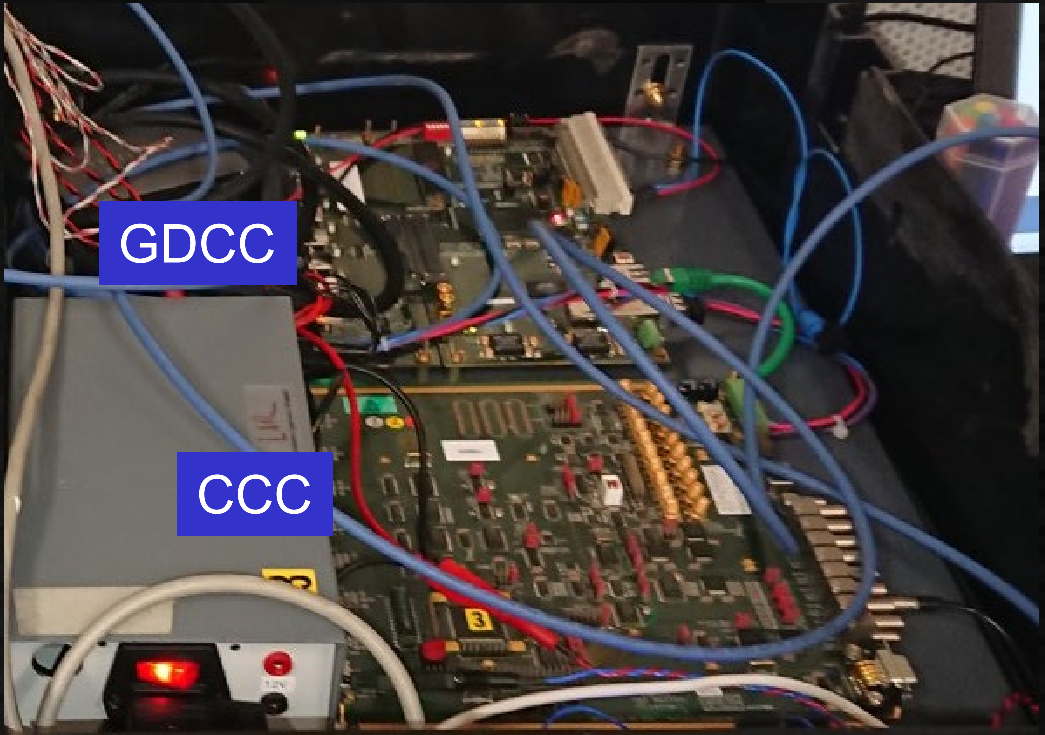


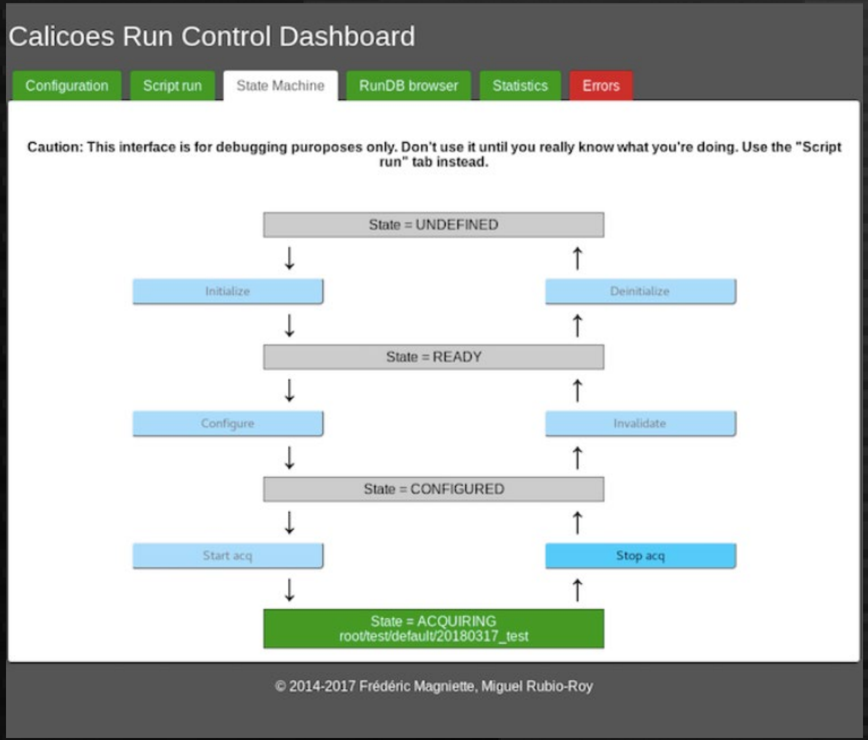


Slab assembly

- FEV
  - 16 ASICs (256 ch)
  - 4 sensors embedded
  - Thin super-capacitors for power-switching at 5 Hz
  - 12 layers
    3 power planes of 3.3V (PA, Analog, Digital)
  - Thin flat connector/cable
- SMB
  - Regulators/repeaters
  - HV filter (CR)
- DIF
  - FPGA (Spartan3) (will be redesigned)
  - HDMI I/O

Interface cards and DAQ





- GDCC (Giga Data Concentration Card)
  - Interface to DIFs via 8 HDMI ports
  - RJ45 to PC (GbE) for data transfer (raw Ethernet protocol)
- CCC (Clock Control Card)
  - 10 HDMI IOs
  - Distribute clock (40 or 50 MHz)
  - Distribute spill via HDMI (fast command)
  - Busy treatment
- CALICOES (DAQ)
- Configuration by XML
- Control by GUI
- Python script

Test beams: what we have learned

- The prototypes work reasonably good
  - Some missing channels due to the noise
  - Some issues on triggering (retriggering)
  - Acquisition rate limited by data transfer
    Need more efficient communication
  - Improvements needed for mechanical support
- Common run with HCAL partially done
  - Sometimes suffered from noise from other detectors
  - Common clock/spill/DAQ non-trivial
  - Several options, complicated (human) relations

Discussions on sensor production

- 8-inch sensors (initiated by CMS production)
  - Production in HPK possible from 2020
    - They are preparing the production line
  - Standard thickness should be 700 μm
    - Thinning possible (with additional cost)
  - Cost/area similar to 6-inch sensors
    - 2-3 EUR/cm^2 in mass production (> 100 k sensors)
  - Resistivity may be lower (means higher V_{FD})
- Alternative producers: still missing (with large qty)
- Guard rings: effective for higher V_{BD} but must be grounded (by wire etc.) 0 GR promising with low V_{FD}

OMEGA ASICs for silicon pads

- SKIROC2/2A
  - Only for n-bulk, optimized on ILC bunch structure
- SKIROC2CMS
  - Rolling buffer (no trigger selection)
  - Focused on timing resolution
  - Dual polarity
- SKIROC3
  - Final version for ILD SiW-ECAL?
  - Zero suppression
- HGCROC
  - Under development for HGCAL in CMS

Integration to bigger detectors

“Long slab” prototype

The realistic “module 0” should be prepared before the construction

- 20-30 layers of long slab (-1k sensors)
- Tungsten absorber and mechanical support, cooling
- Space-compatible adapters
- Firmware and software efficient enough to read -20 long slabs
- Cooperation with HCAL and trackers with common DAQ
- Reasonable maturity on quality control in production and test

Summary

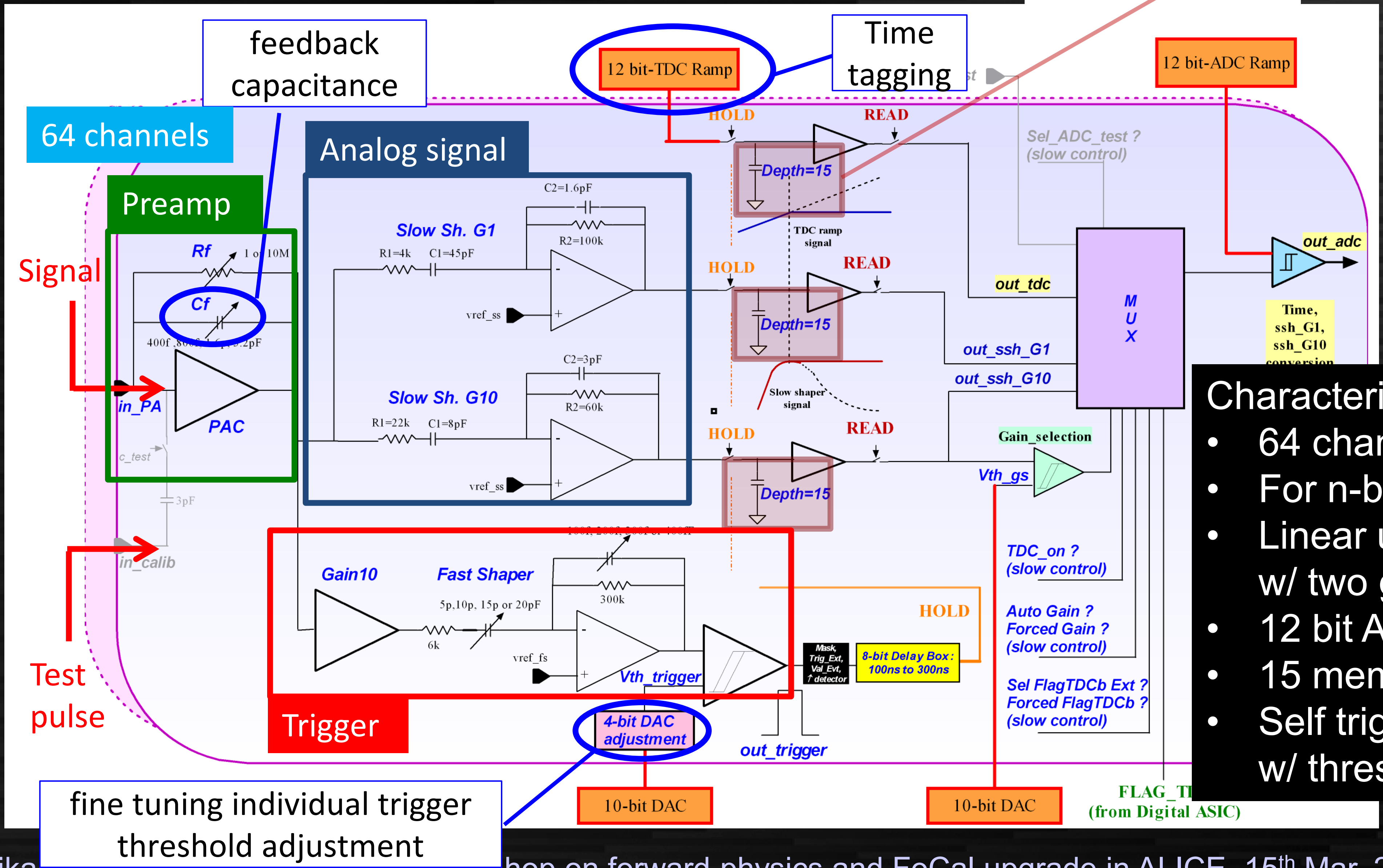
- ILC has just been pushed forward with the statement of March 7th from MEXT.
- SiW-ECAL is a key element of ILD detector.
- Technological prototypes were fabricated and the basic functions confirmed.
- Bigger prototype towards “module 0” is now being prepared.
- Collaboration with FoCAL people is already at some level; more desired.
- ILC welcomes young people with future hope.

ILC Project: The Situation

- 2004 Superconducting technology chosen
  → ILC project started by combining several projects
- 2007 Reference Design Report
- 2013 ILC TDR and detector DBD report
- 2013 Japanese site selection → Tohoku
- 2008- Big supports from politics, economics, locals etc.
  - Federation of diet members for ILC from 2008 (> 100 members)
  - Advanced Accelerator Association (executives of big companies)
  - A lot more

- 2019 (A kind of) Expression of Interest from government
  - To be considered in European Strategy 2020-
- ~2022 International agreement on construction foreseen?

SKIROC2/2A (Analog part)



Characteristics

- 64 channels
- For n-bulk silicon
- Linear up to 4 pC w/ two gain shapers
- 12 bit ADC + TDC
- 15 memory cells
- Self triggering w/ threshold adj.