HEP_15: Testbeams with the highly granular SiW ECAL and implementation of timing information

*Co-PI

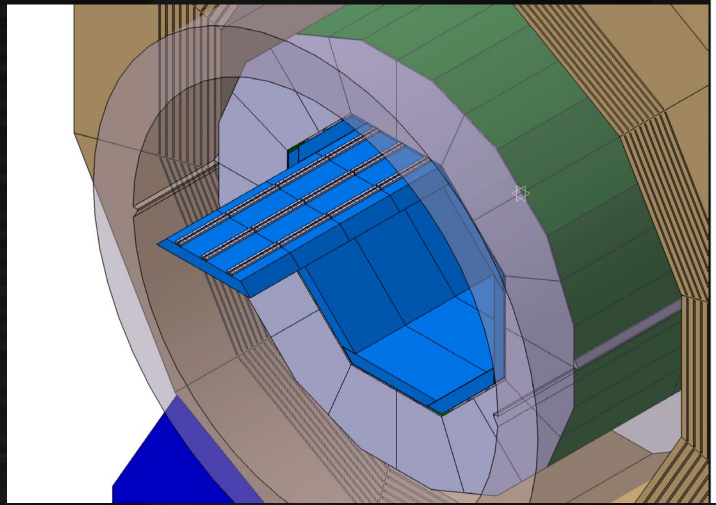
2023 team:

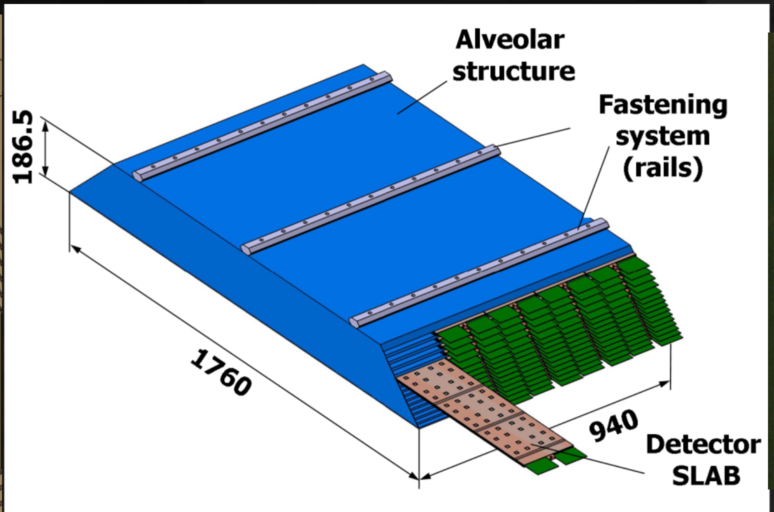
T. Suehara*, K. Kawagoe, T. Yoshioka (Kyushu U.), D. Jeans (KEK), R. Poeschl*, D. Breton, J. Maalmi, J. Jeglot (IJClab), V. Boudry (LLR), S. Callier (OMEGA), Y. Okugawa (IJClab/Tohoku U.)

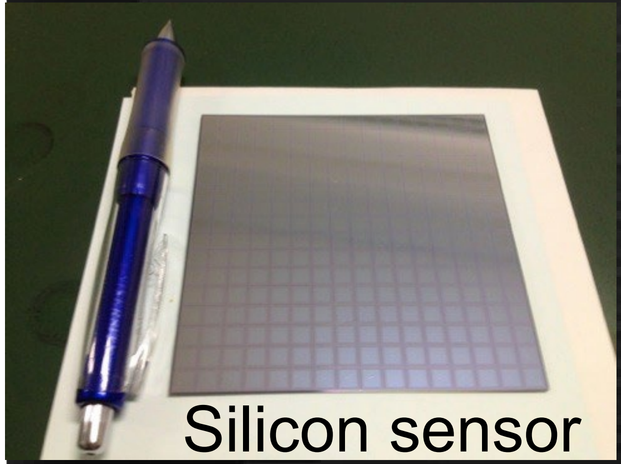
2024 team:

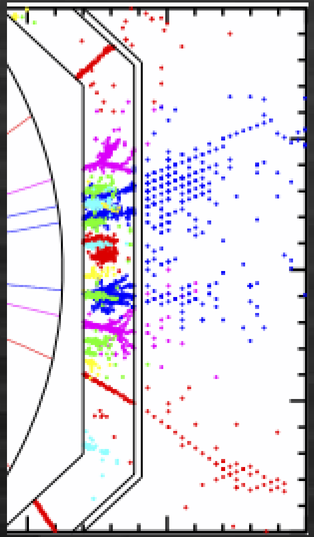
Japanese side: T. Suehara*, T. Murata (U. Tokyo), D. Jeans (KEK), T. Fusayasu (Saga U.)
French side: R. Poeschl*, D. Breton, J. Maalmi (IJClab), V. Boudry, X. Xia (LLR)

ILD SiW-ECAL: Overview



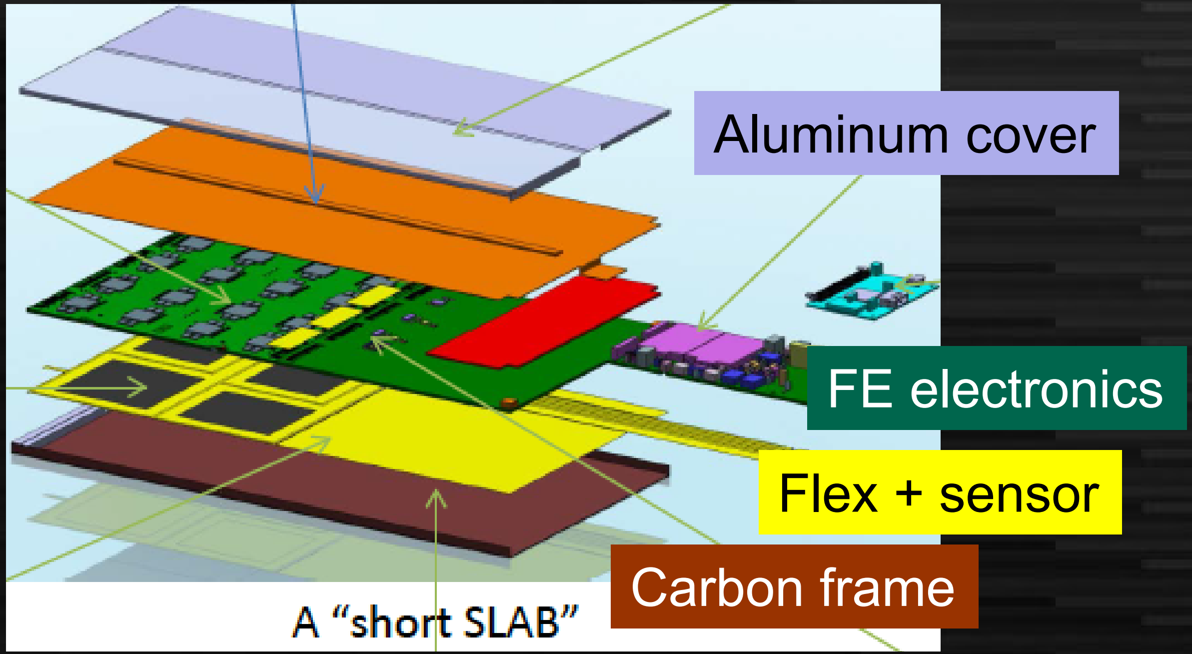






Particle flow

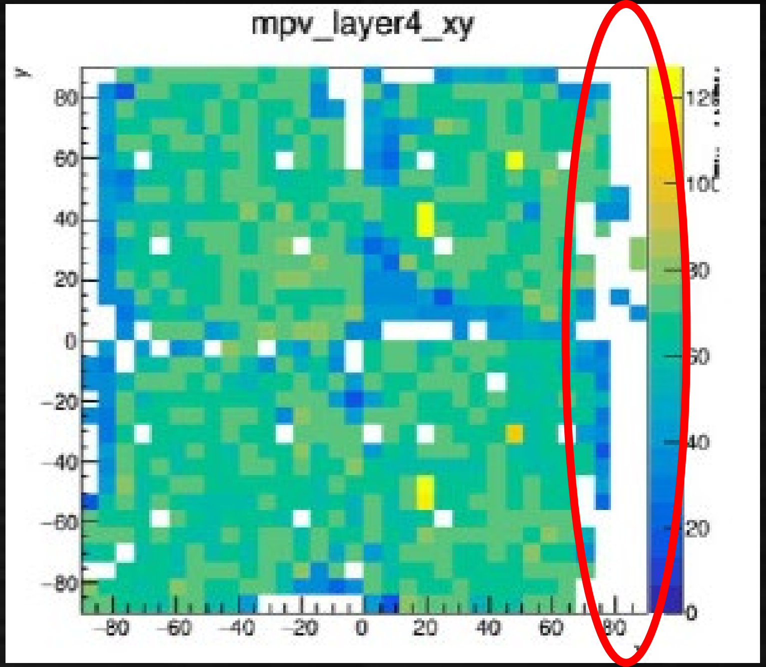
ILD: one of two ILC detector concepts
(also adapting to circular colliders)
ILD ECAL: 20-30 layers of sandwich calorimeter with tungsten absorber and 5x5 mm - segmented silicon diodes
(~ 10^8 channels in total)
PCB with ASICs (SKIROC2) embedded

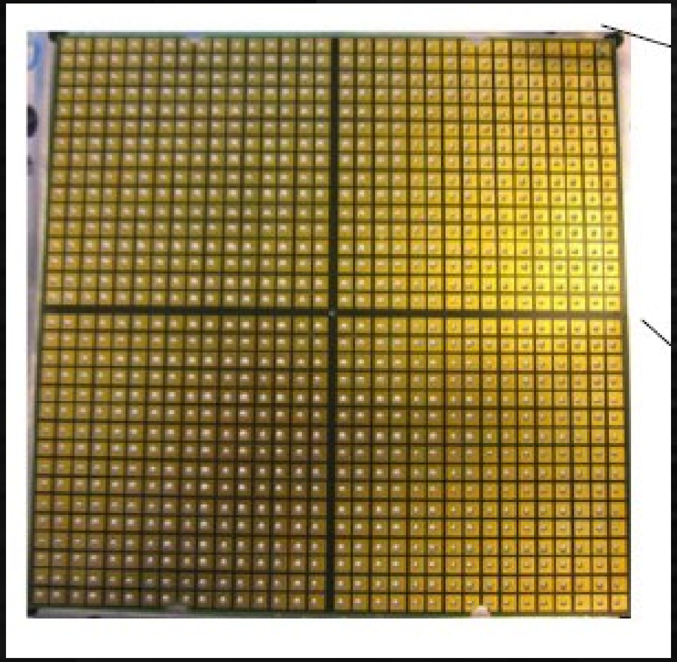


Achievements in FY2023

1. Finalizing design of the SiW-ECAL with performance evaluation
   - Investigating sensor-delamination issue
   - Prototype with FEV2.1
2. Exploring picosec timing capabilities of the ECAL
   - Investigation with test beam
3. Development of DNN-based PFA and application of timing
   - Implementation of track-cluster matching
     based on GravNet / object condensation
4. Application to non-collider projects
   - KEK Linac beam dump experiment (EBES) → background investigation

Sensor delamination





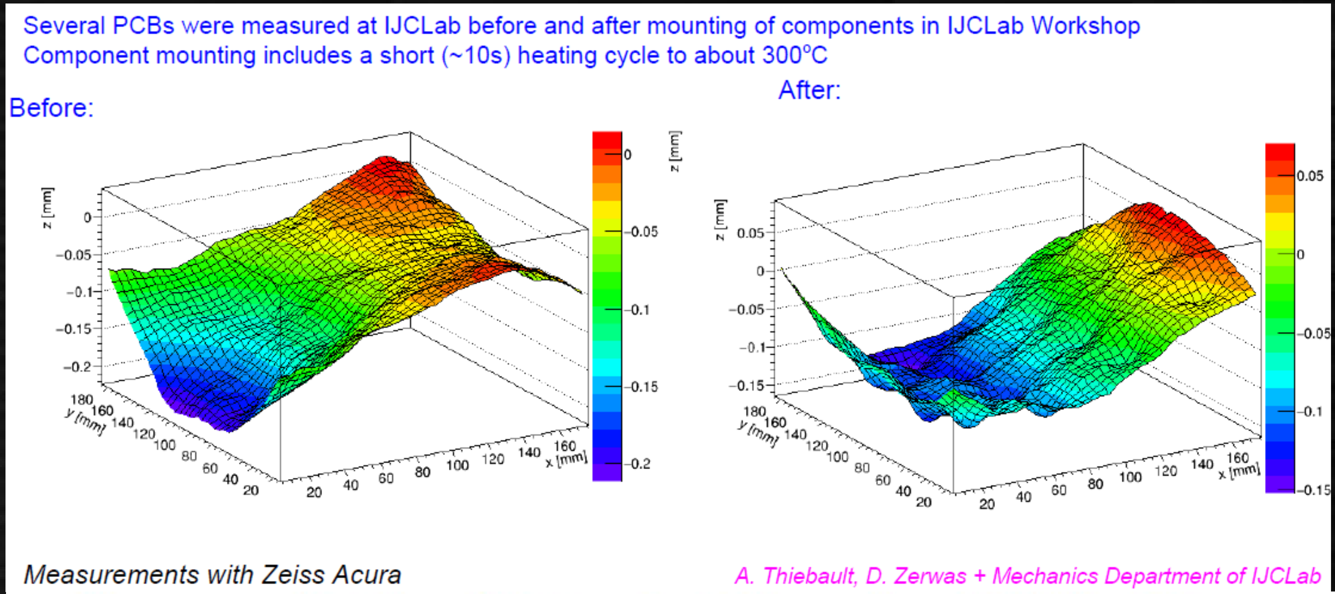
Conductive glue may be detached due to (possible causes)

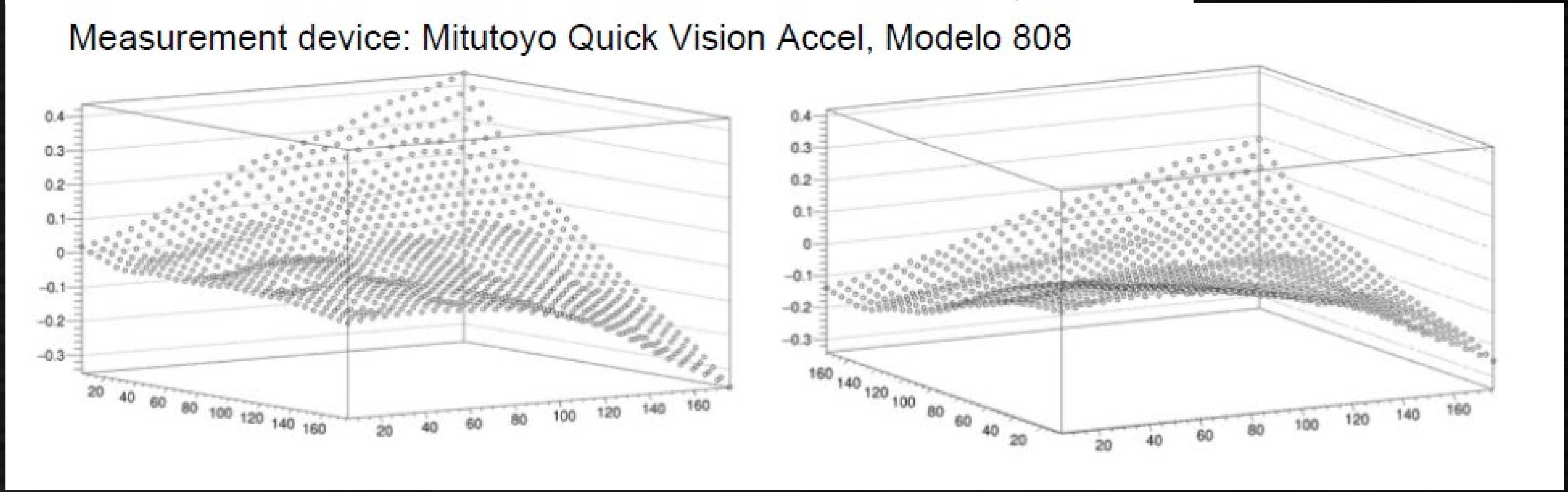
- Force due to board/sensor deformation
  - From initial assembly
  - Long-term deformation by
    - Temperature, humidity…
- Aging of glue

Investigation topics

- Measuring deformation and force
- More strong connection by
  - (non-conductive) underfill to fill the gap between sensor and PCB
  - Double-sided tape
  - Another glue (if aging matters)
- Or complete redesign (flex PCB, ACF, wire-bonding etc.)

Measuring deformation of PCBs





A few 100 μm non-flatness seen
Some disagreement between multiple testing sites
– under investigation

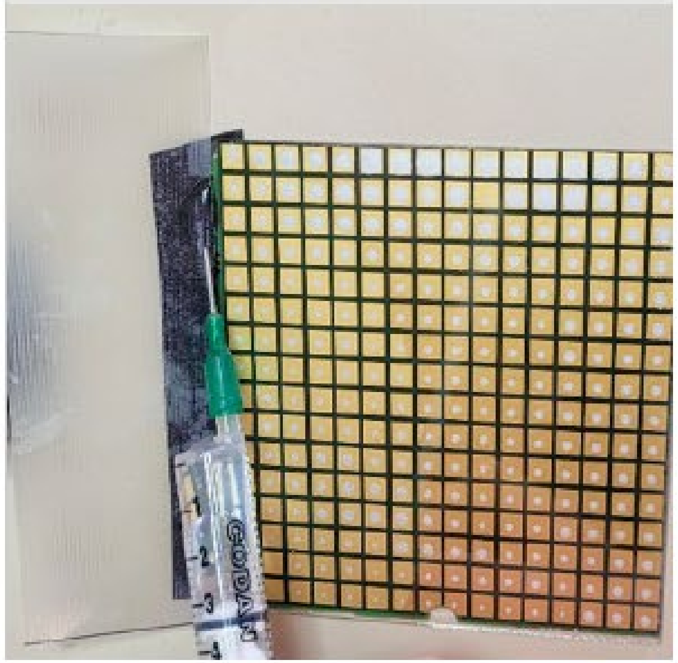
Hybridisation - Underfill

Support conductive glue dots with supplementary potting resine

EPO-TEK® 301-2

- From data sheet
  - Two component optical and semiconductor grade epoxy resin
  - Low viscosity, long potlife and good handling characteristics

Injection of underfill



- Resin propagates via capillary effect
- Takes ~20 min. to fill 9x9 cm^2 surface

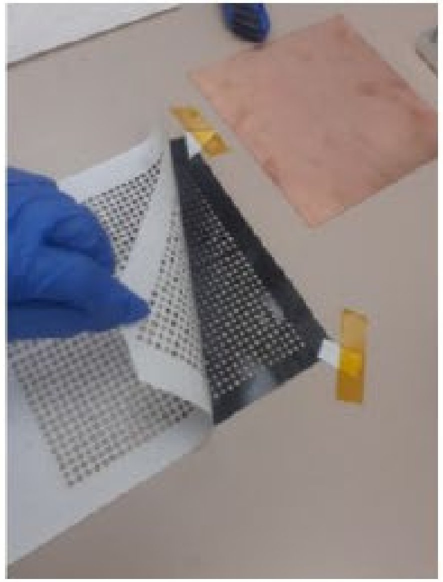
Requires curing at 80°C ...

... but remains flexible after curing

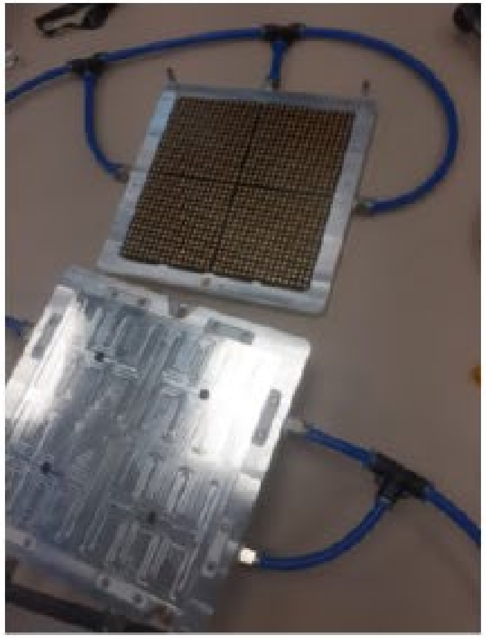
A. Thiebault, A. Gallas+ Mechanics Department of IJCLab

Hybridisation – Double sided tape

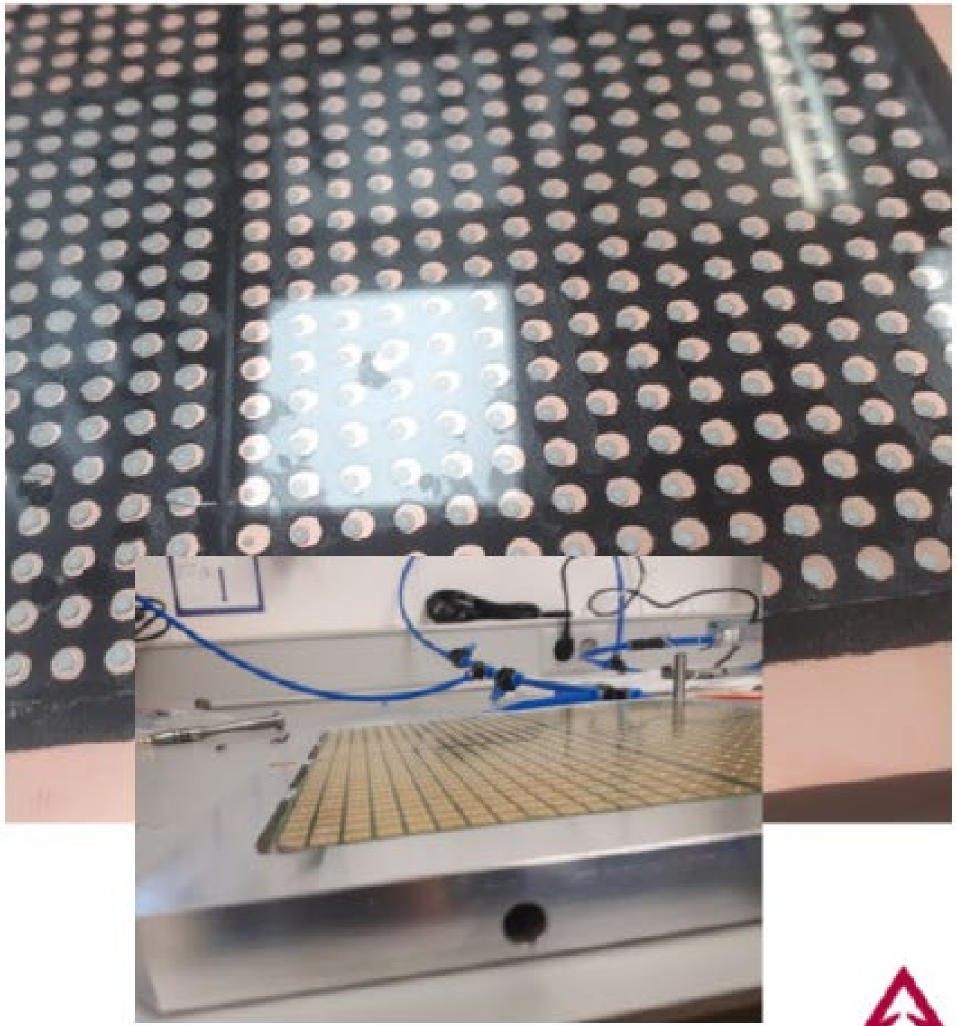
- Perforated stencil of thin 250um double tape 3M VHB 5907F
- Idea inspired by CMS HGCAL



Stencil made at IFIC (laser drill)

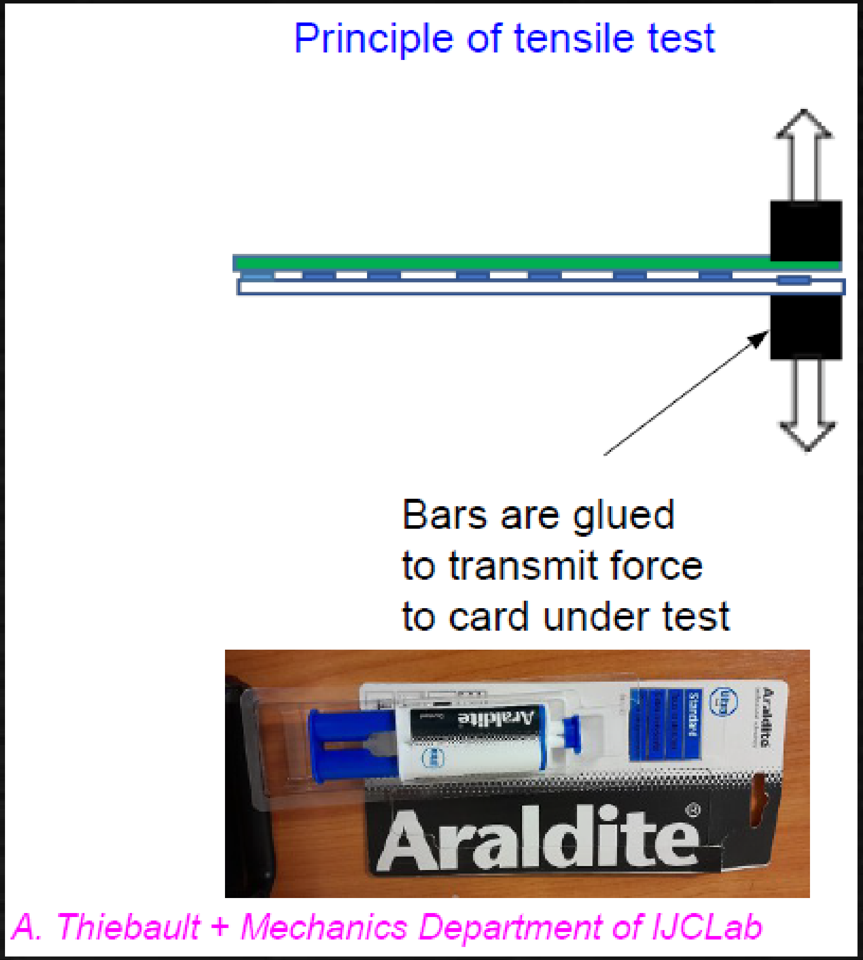


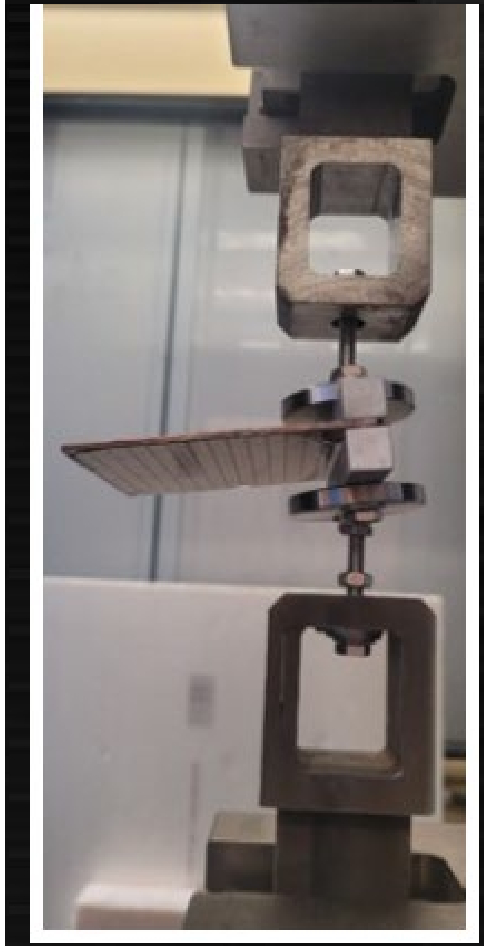
One 18x18cm^2 model completed at IFIC

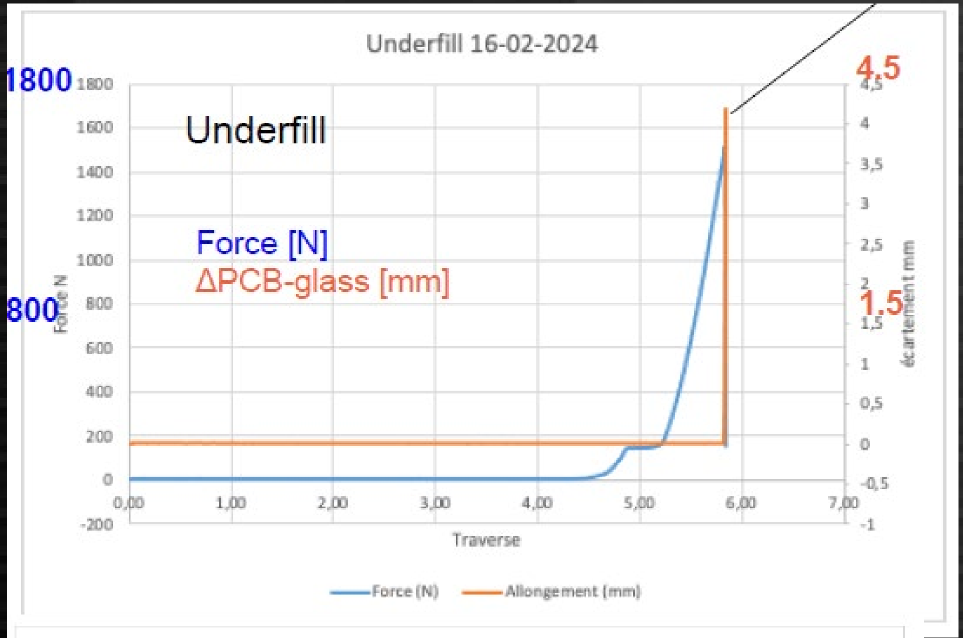


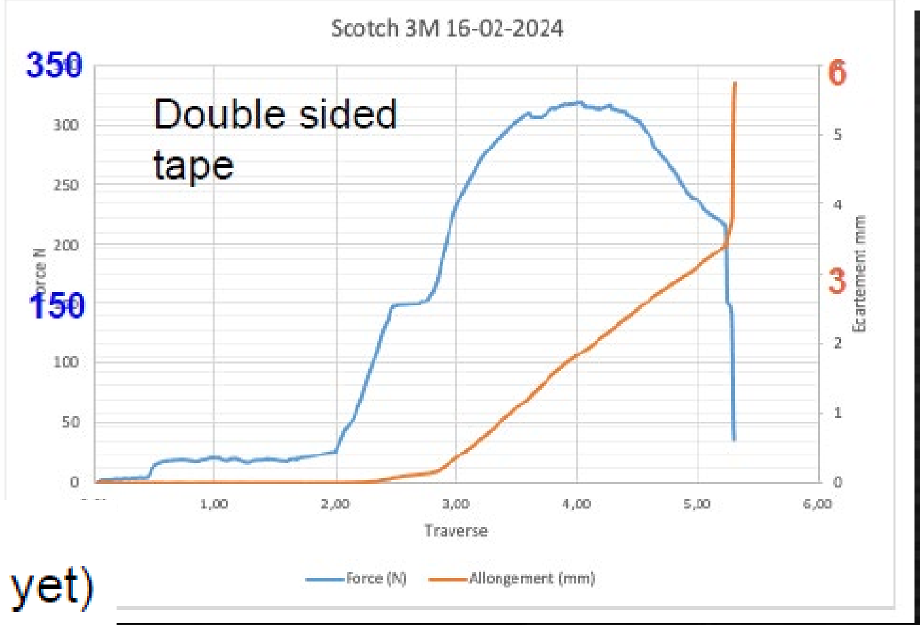
A. Irles, D. Zerwas + Mechanics Department of IJCLab

Tensile test









- First test reveals that underfill resists to even strong external forces
- Set up to measure actual force on glue dots in place (but no results yet)

New FE boards

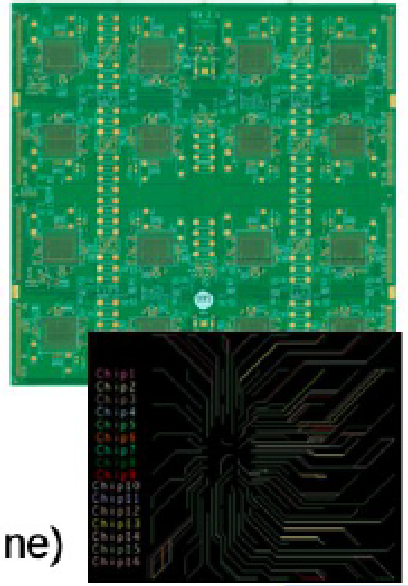
LLR, IJCLab, LPNHE, OMEGA

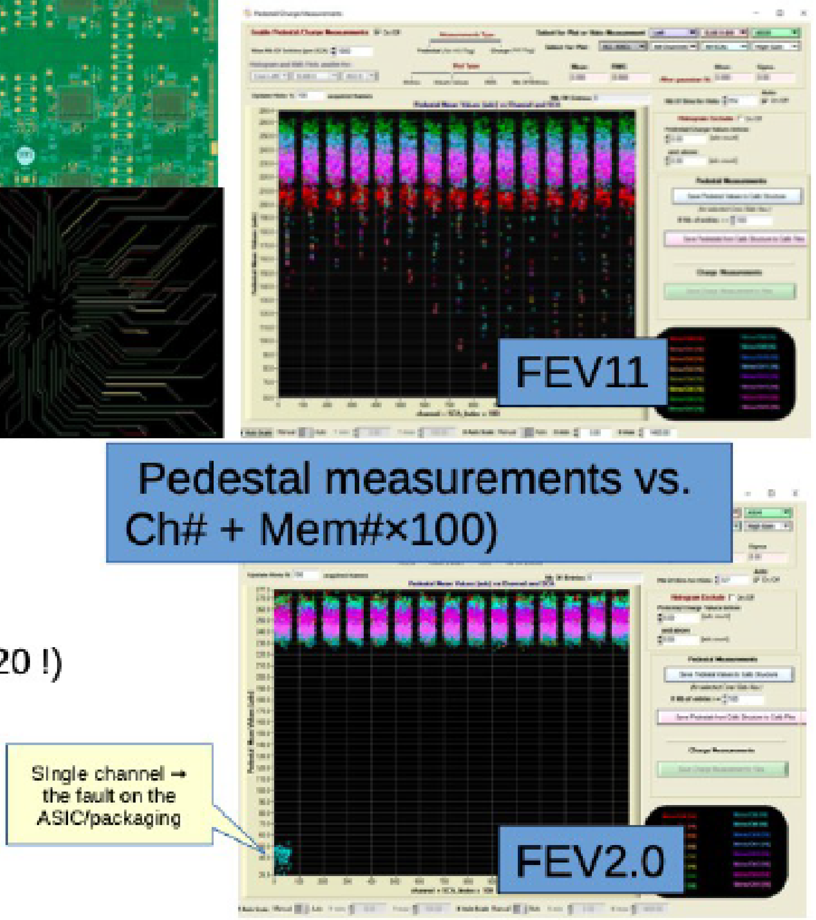
Improvements:

- Power distributions
  - Local power regulation
  - Local High Voltage filtering & Supply
- Signal distribution (buffering), data paths
- Monitoring (single ID, temp, probe analogue line)
- ASIC shielding/routing

Status:

- pre-version 2.0 tested, minor corrections needed
  - Noise uniformity dramatically improved (ex: outliers in thr. / 20 !)
- version 2.1 produced, … in metrology
  - before cabling, 2nd metrology, gluing, …
  - All material available : ASICs being tested

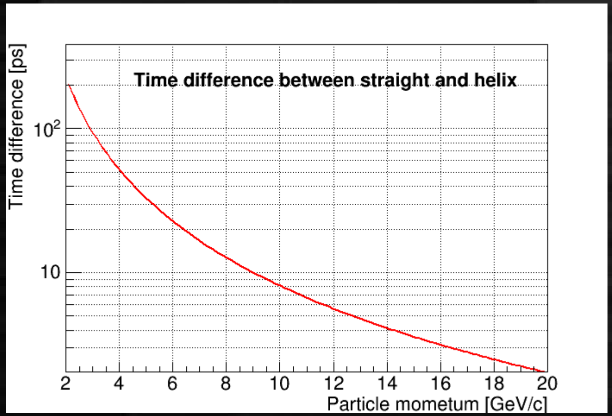




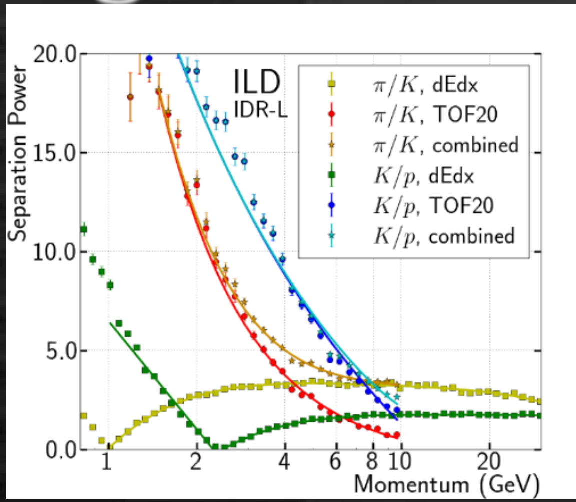
Goal: build 15 layer stack based on these Boards

Timing for calorimetry: possible targets

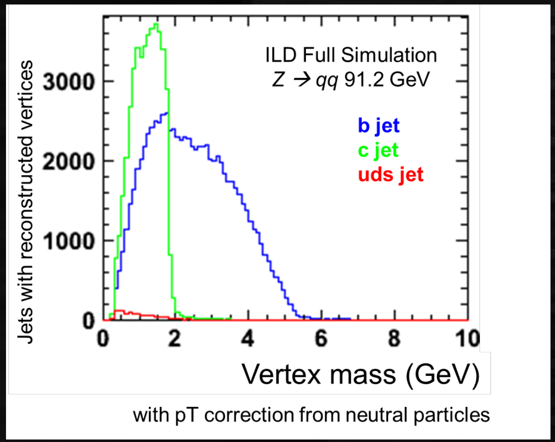
- π/K/p separation with Time-Of-Flight method
  - 30 psec (for cluster)
    Moderate performance to fill gap of dE/dx
  - A few psec (for cluster)
    up to 5-10 GeV (80-90% of jet particles)
- Track separation at PFA
  - By distance of helices and straight lines
  - ~10 psec/cluster necessary for 10 GeV track
  - Software dependent → DNN
- Secondary photon ID from b/c
  - Including photons to vertex mass → flavor ID
  - A few psec/cluster required!
  - Photons can be averaged over many hits



Timing resolution for separation of helices



PID at ILD. 10 hits with 20 psec resolution are averaged, effective timing resolution: ~7 psec

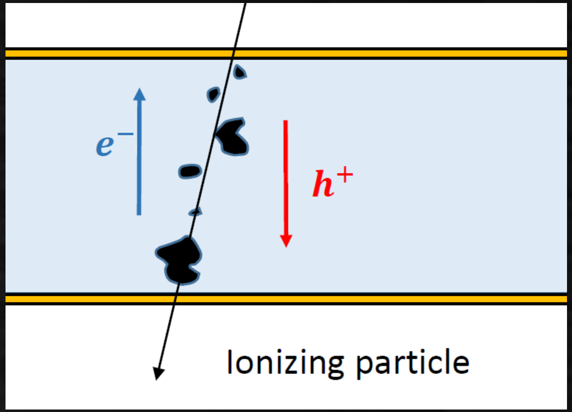


Vertex mass of secondary tracks (only) from b/c jets

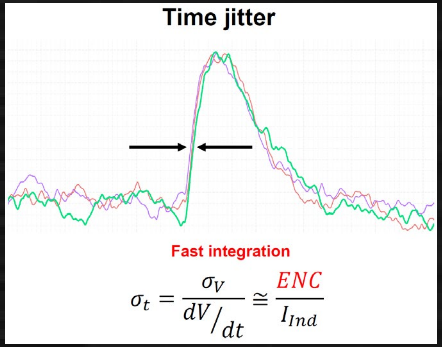
Study of LGAD/APD

APD: photon sensor with essentially the same structure as LGAD

Timing resolution for silicon

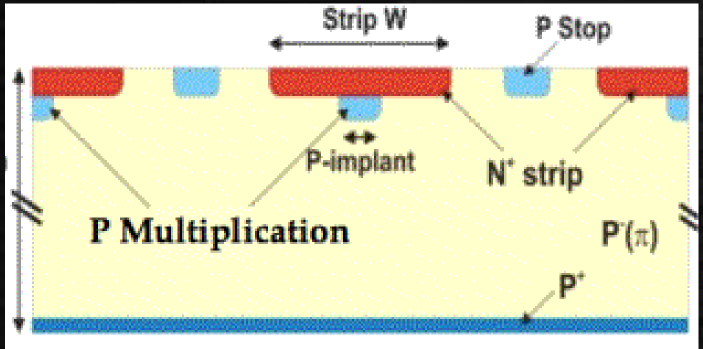


Landau fluctuation: caused by distribution of energy deposit along the track: fast collection time (thin active thickness) → better reso



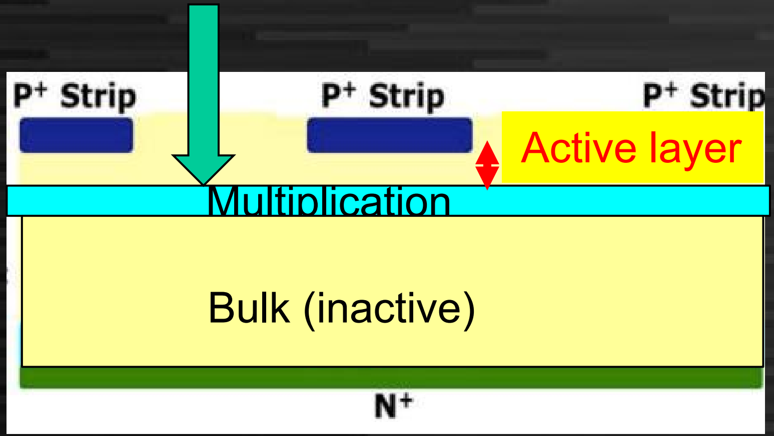
Jitter by noise:
~Rising time / S/N ratio
Big signal preferred
→ internal gain

LGAD/APD types



Reach-through type:
intensively studied
for ATLAS HGTD etc.
~30 psec Landau fluctuation

Doping from surface

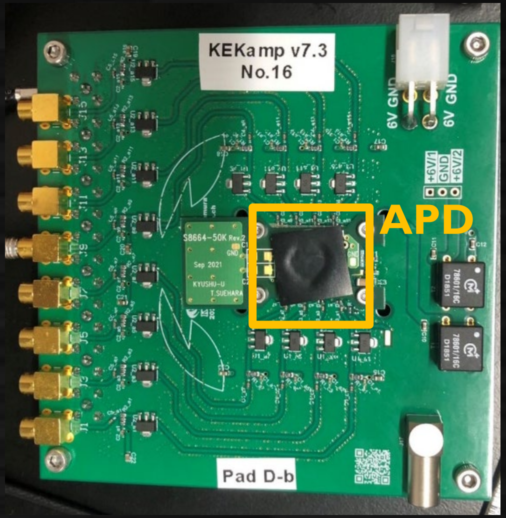


Inverse type (single sided process)
Multiplication by deep injection
Thinner active layer (5-10 μm)
→ Smaller Landau fluctuation?

Inverse LGAD can achieve both uniform response and high resolution up to 10 psec
→ try with commercial APDs (from Hamamatsu)

Test beam at KEK AR test beam line (Dec. 2023)

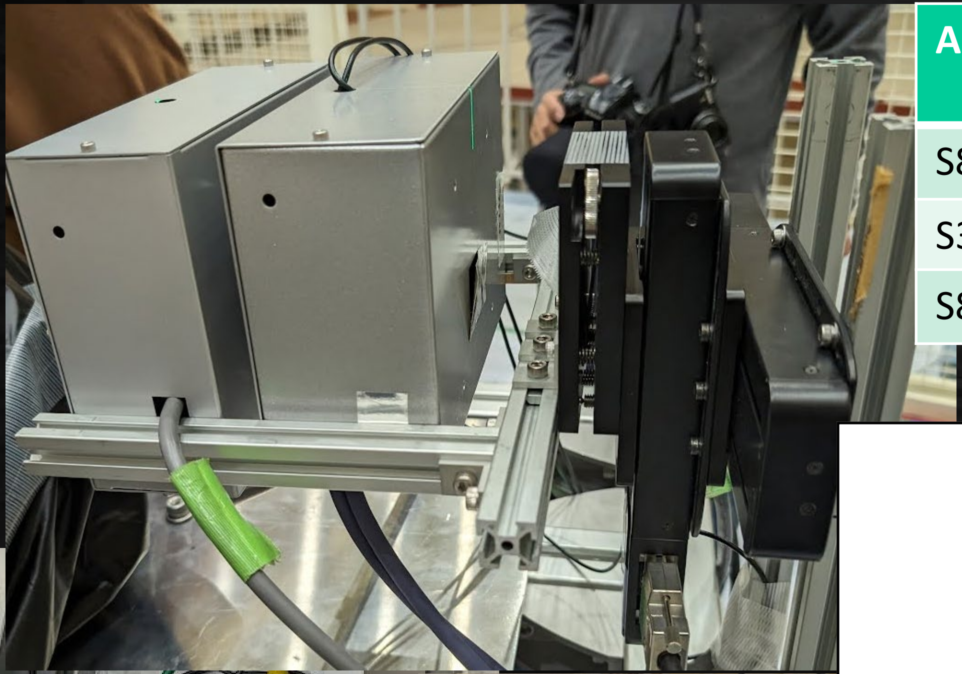
3 GHz amplifier board
(designed by K. Nakamura (KEK))



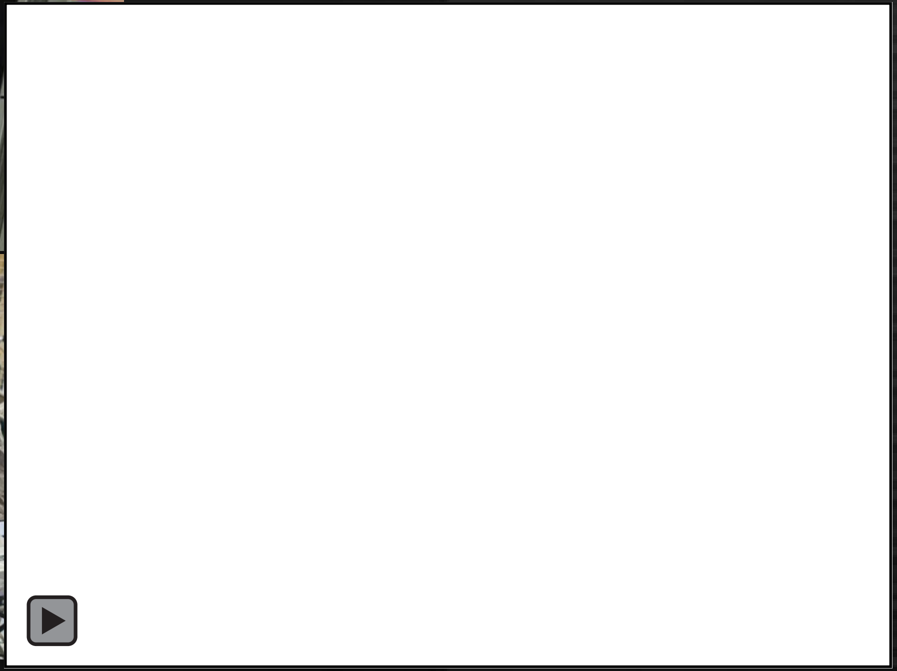
R&S RTO64
Oscilloscope
(2 GHz,
10 GSPS)

APDs	Type	Size [mm]	Cap. [pF]
S8664-20K	Inverse	2ϕ	11
S3884	Reach-through	1.5ϕ	10
S8664-50K	Inverse	5ϕ	40

Tested sensors

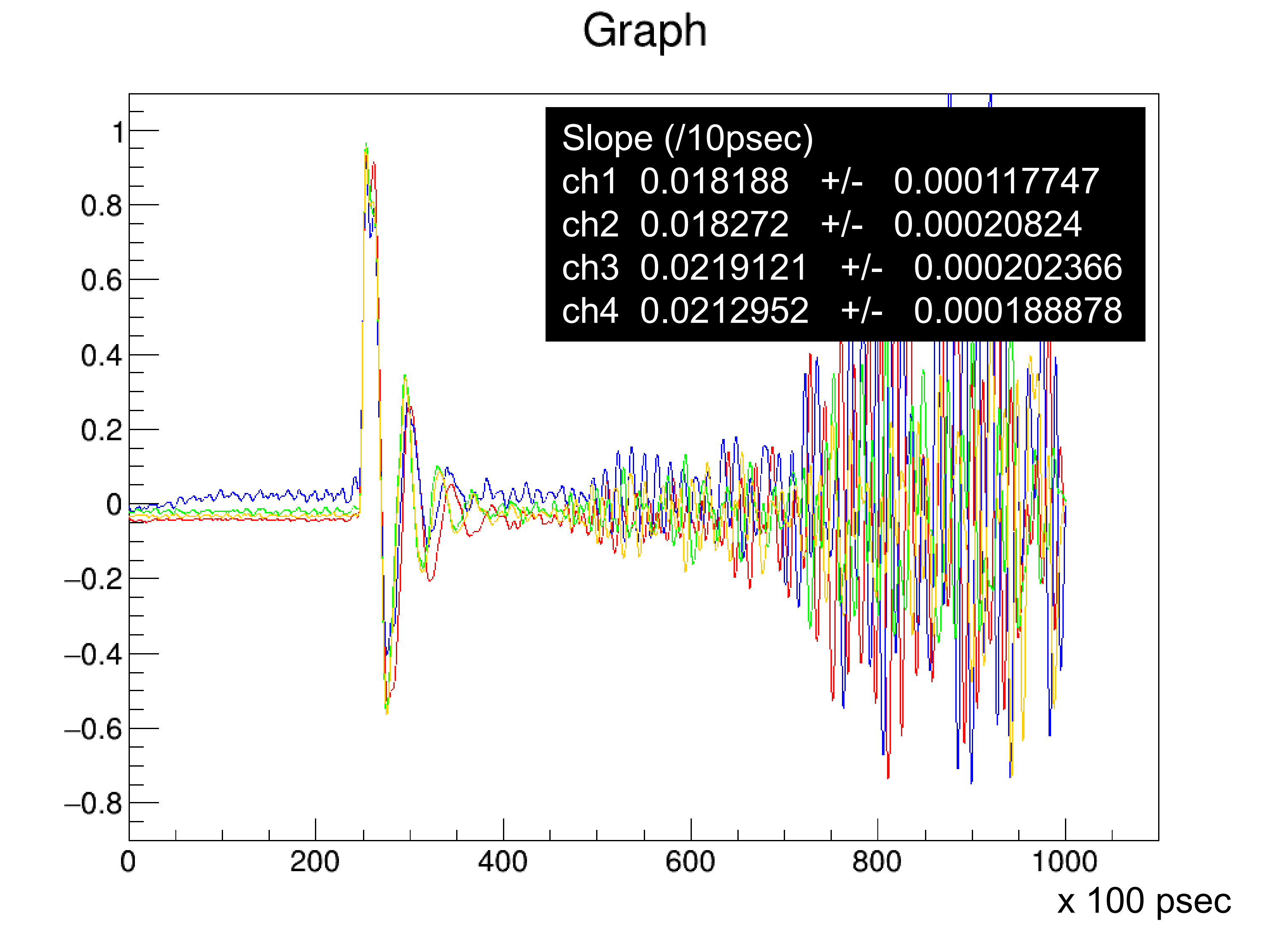


Setup @ beam line



Waveform

Average waveform

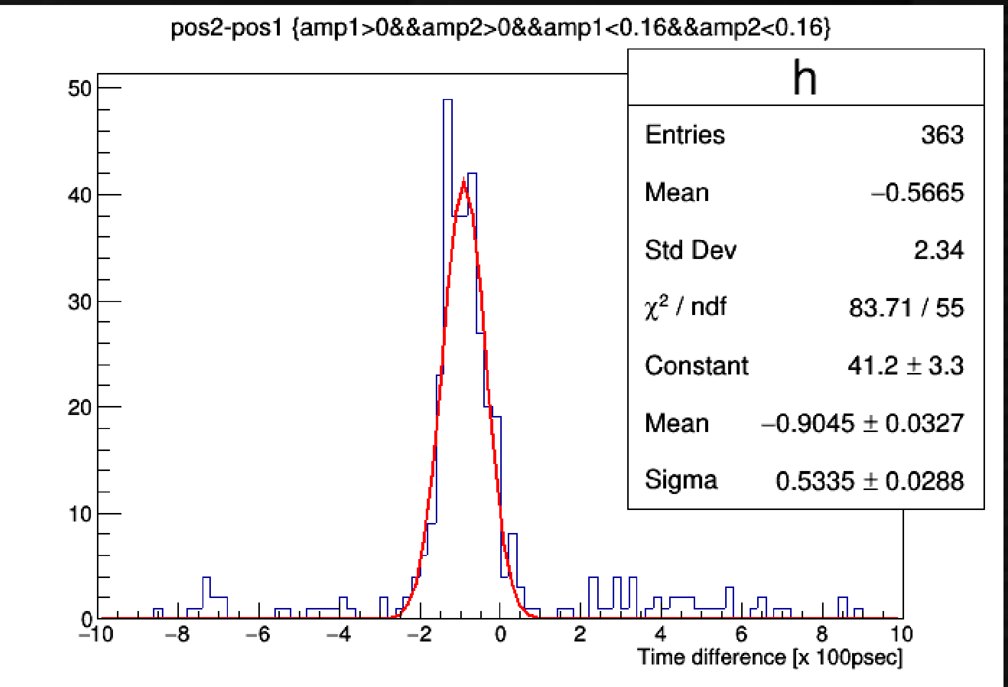


Averaging 500-4000 waveforms

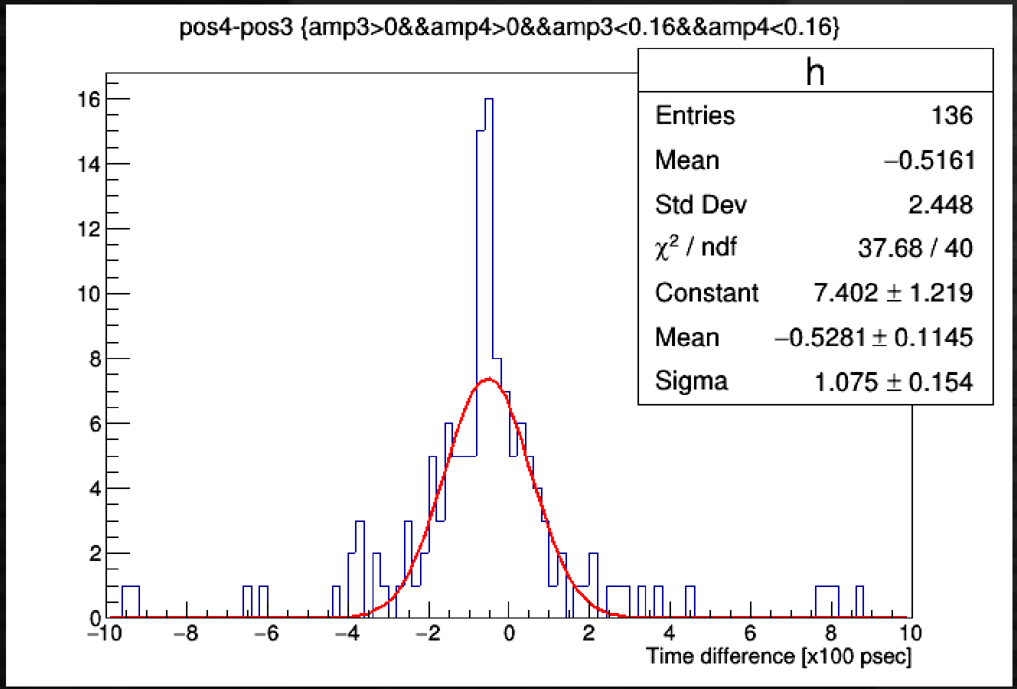
- Horizontal axis aligned at 50% amplitude (at 250)
- Anti-coincidence applied
  - To keep independent from analysis sample
- Average spectrum after normalizing maximum to 1
  - Then noise is also amplified
- Having problem on ch2 pedestal

- Structure seen in pedestal
  - Synchronized noise?
- The big noise at >500 is induced by beam injection

Overall timing resolution



Inverse (S8664-20K)
Probably affected by ch2
having bigger noise
(37 psec overall timing resolution)
Consistent to be explained with noise (42ps)
→ small Landau fluctuation expected

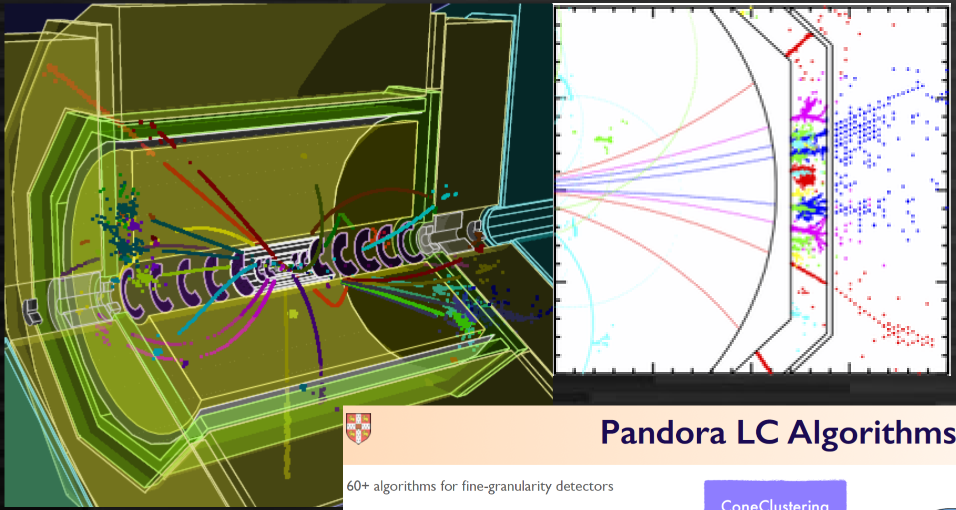


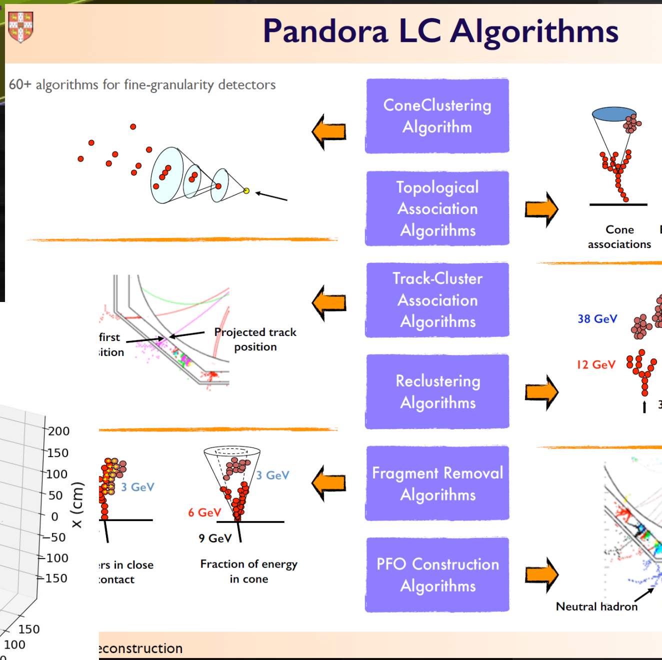
Reach-through (S3884)
Peak is sharp but having a tail
(need to investigate) low statistics
Expected noise contribution is 28 psec

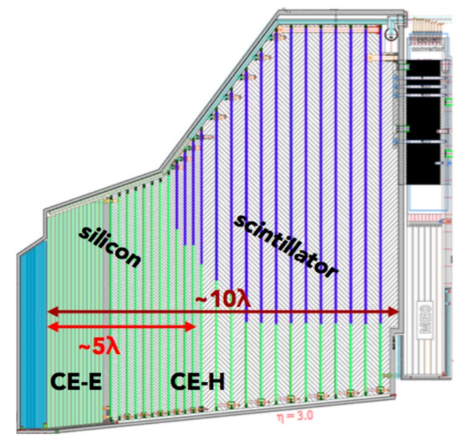
More investigation necessary
(depending on personpower and budget)

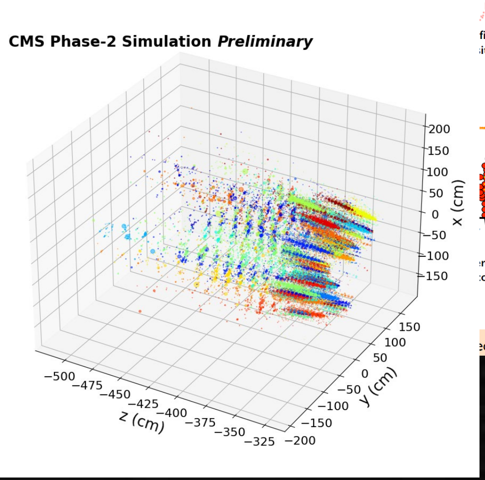
Particle flow with DNN: introduction

- Separation of cluster at calorimeter
  - Charged or neutral cluster
- Essential for jet energy resolution
- Current algorithm: PandoraPFA
  - Combination of various process
  - Not easy to optimize or adding more info
- CMS HGCal clustering
  - Similar to ILD calo
  - Good for starting point



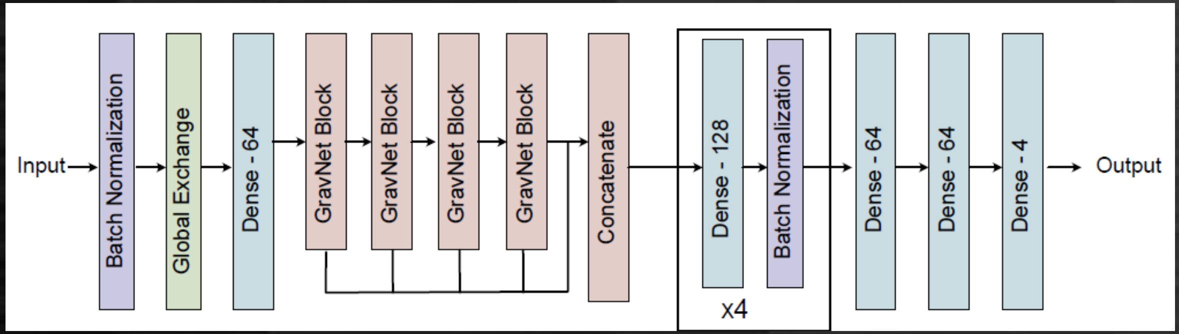






PFA: clustering algorithm

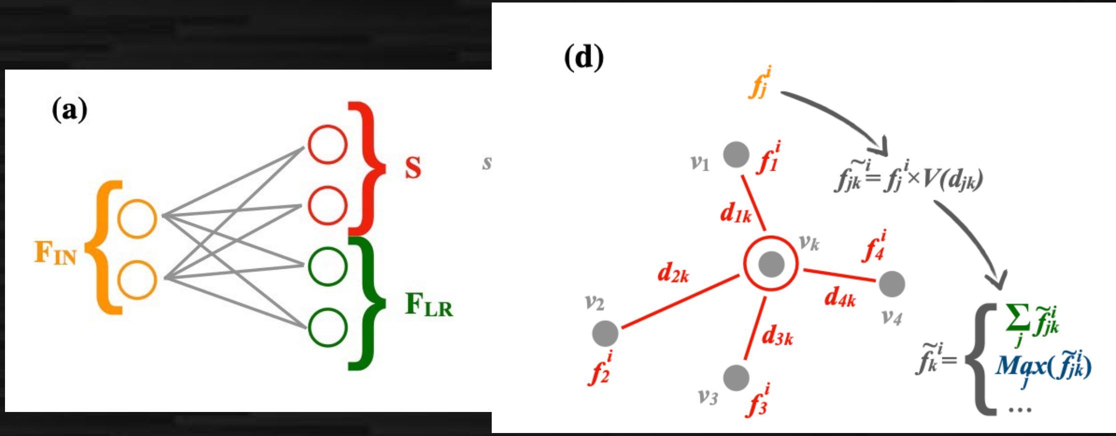
- Input: position/energy/timing of each hit
- Output: virtual coordinate and β for each hit



GravNet

arXiv:1902.07987

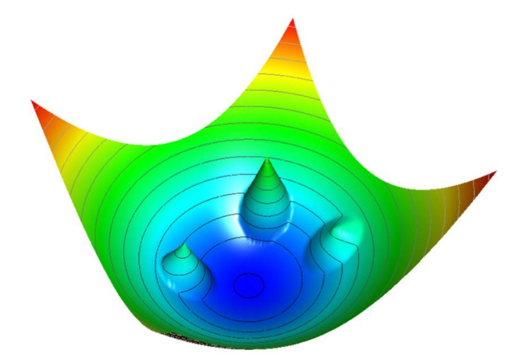
- The virtual coordinate (S) is derived from input variables with simple MLP
- Convolution using "distance" at S (bigger convolution with nearer hits)
- Concatenate the output with MLP



Object Condensation (loss function)

arXiv:2002.03605

$$L = L_p + s_C(L_\beta + L_V)$$



- Condensation point: The hit with largest β at each (MC) cluster
- L_V: Attractive potential to the condensation point of the same cluster and repulsive potential to the condensation point of different clusters
- L_β: Pulling up β of the condensation point
- L_p: Regression to output features

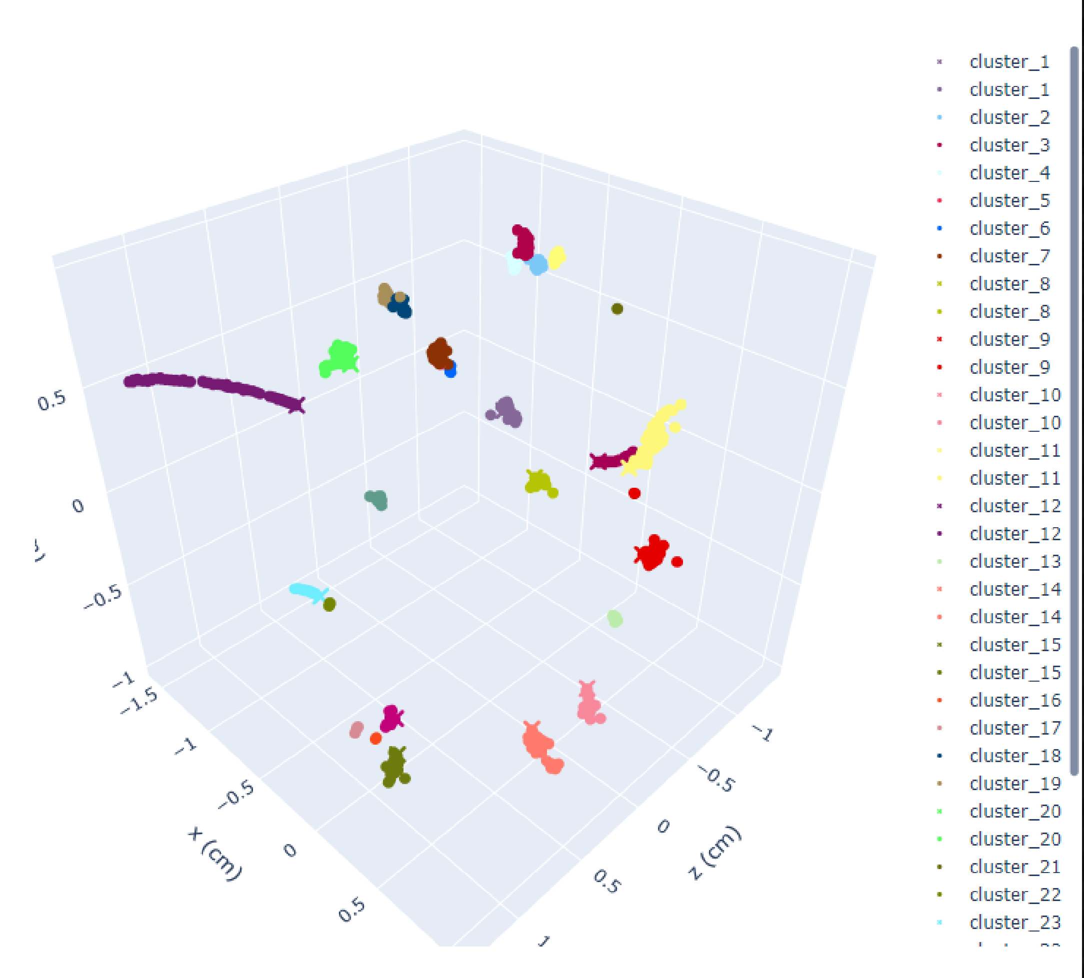
What we implemented: track-cluster matching

- PFA is essentially a problem "to subtract hits from tracks"
- HGCAL algorithm does not utilize track information
  - Only calorimeter clustering exists
- Putting tracks as "virtual hits"
  - Located at entry point of calorimeter
  - Having "track" flag (1=track, 0=hit)
  - Energy deposit = 0
- Modification on object condensation to forcibly treat tracks as condensation points (details next page)
  - Also modifying clustering algorithm to avoid double-track clusters

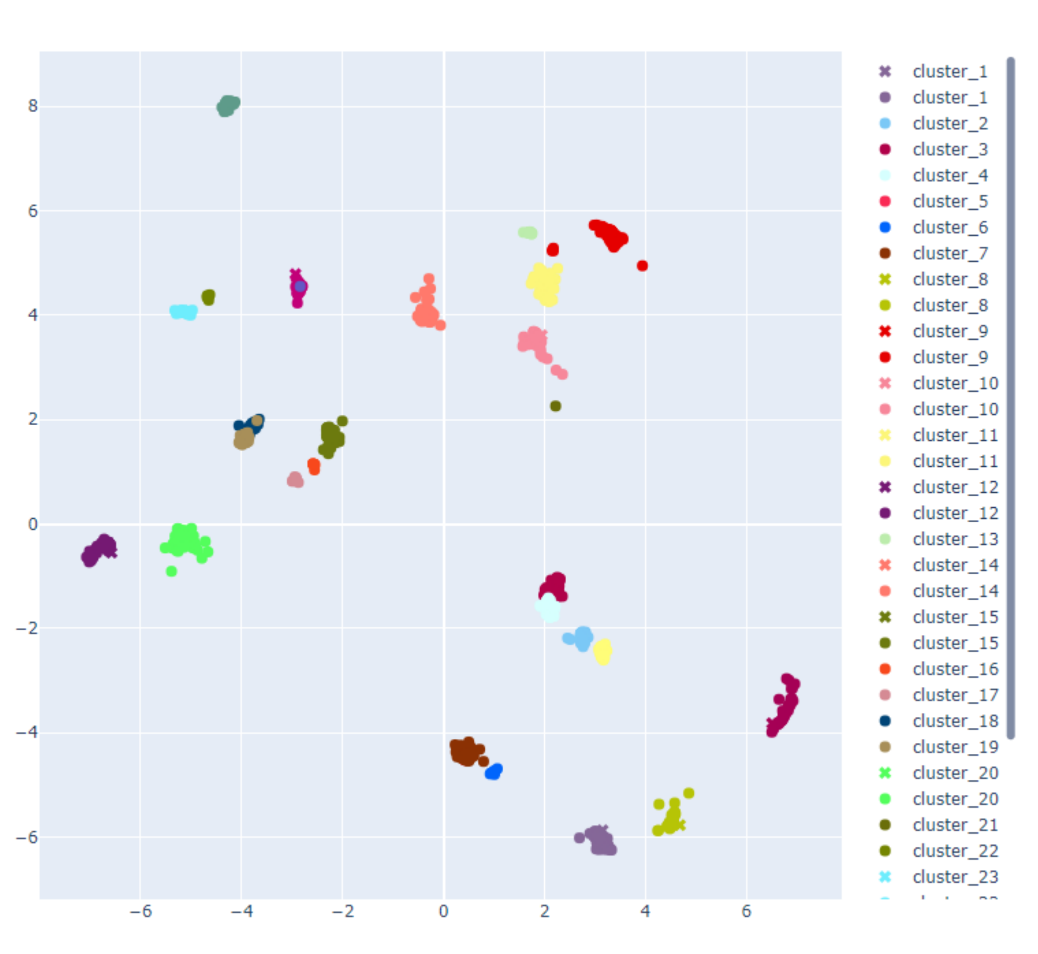
Current number of parameters: ~420K

Event display – looks working

10 Taus @ 10 GeV each

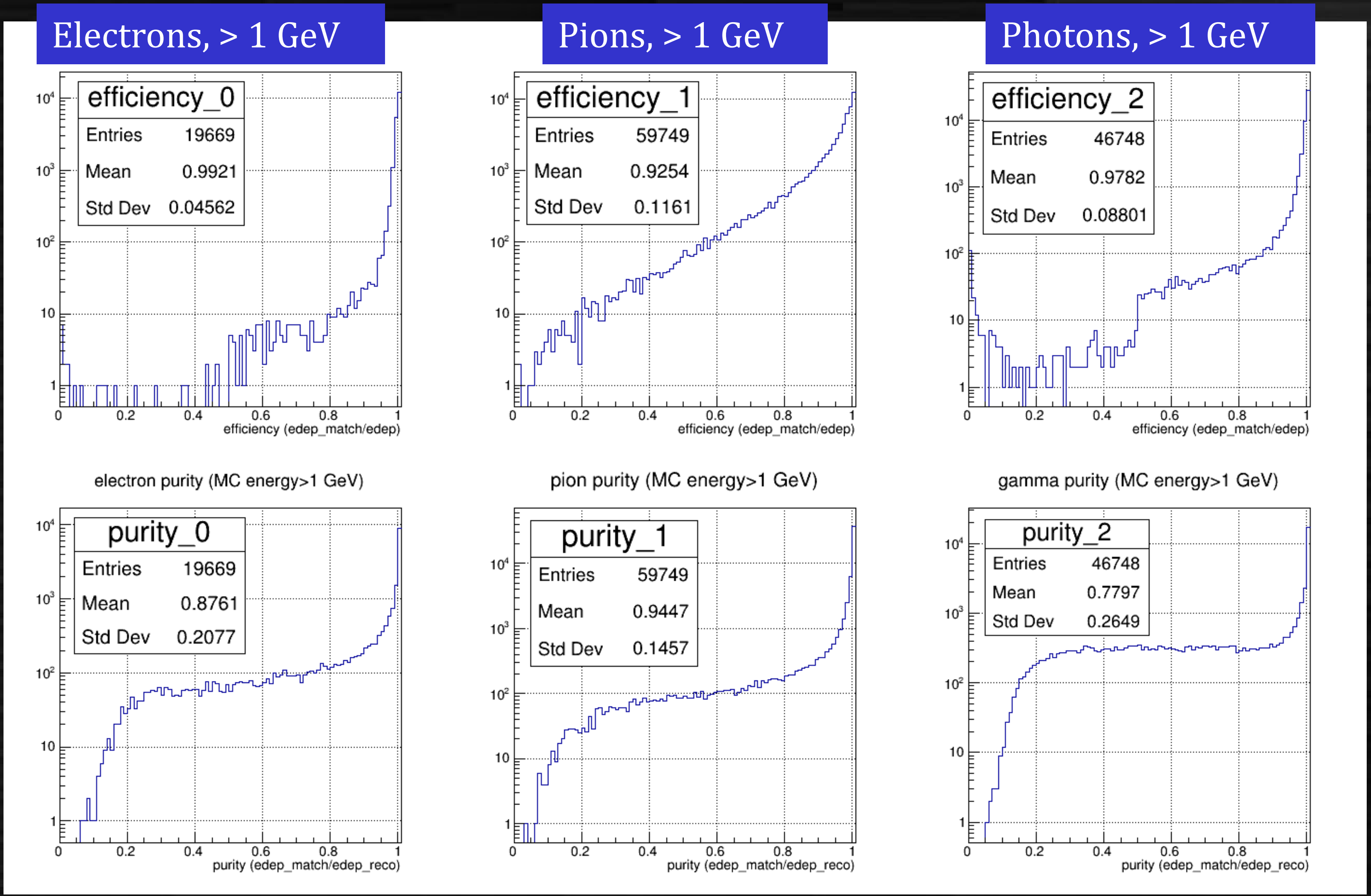


Real 3D coordinate



Output from GNN

Efficiency & purity for GNN, tau train/tau pred



Efficiency:
>90% for all particles
slightly low in pions

Purity:
>85% for all tracks
78% for photons
→ merged photons?

Reasonably well reconstructed!

Preliminary

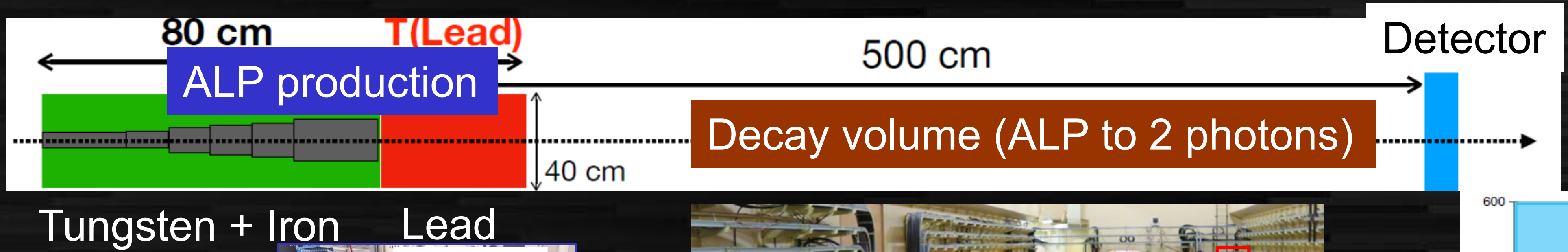
Comparison of results with Pandora Preliminary

Algorithm train/test	Electron eff.	Pion eff.	Photon eff.	Electron pur.	Pion pur.	Photon pur.
GravNet 10 taus/10 taus	99.2%	92.5%	97.8%	87.6%	94.5%	78.0%
GravNet 10 taus/jets	91.3%	88.1%	89.8%	62.2%	81.3%	64.4%
GravNet jets/jets	90.5%	89.7%	87.1%	65.6%	83.3%	70.9%
PandoraPFA 10 taus	99.3%	94.0%	99.1%	91.8%	94.6%	97.2%
PandoraPFA jets	80.2%	90.4%	79.0%	75.0%	90.6%	77.7%
PandoraPFA jets (ILCSoft)	96.7%	95.5%	96.4%	97.1%	90.4%	97.7%

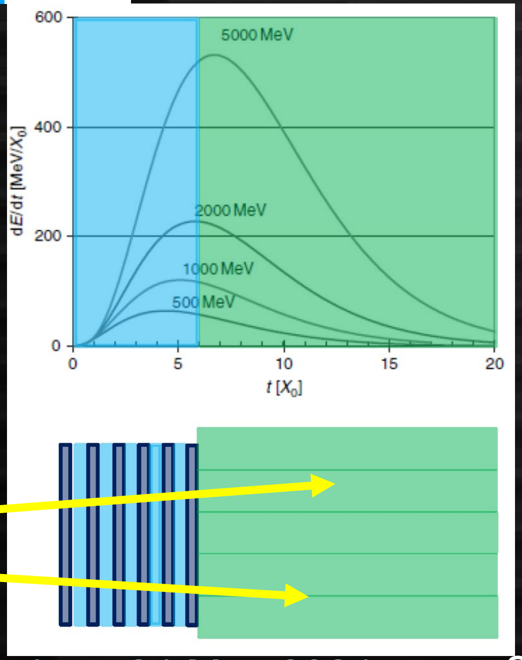
Still too early to conclude, but performance of GNN comparable to PandoraPFA at least on pions, which have less uncertainty related to MC truth definitions

EBES (Eletron Beam-dump Experiment at SY3)

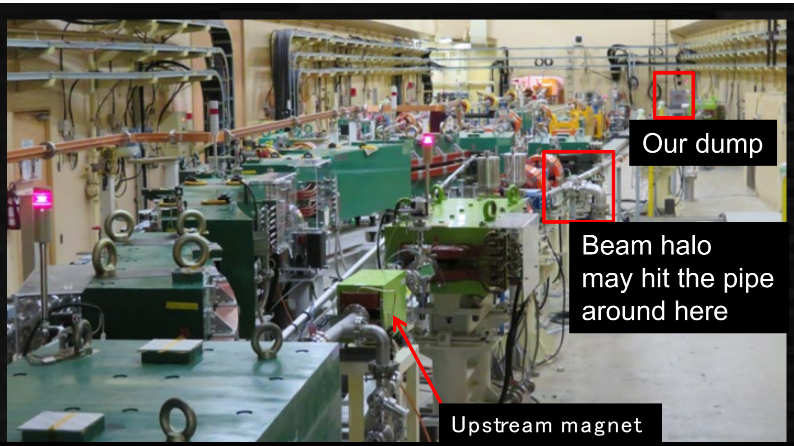
- Sub-GeV ALP (Axion-Like Particle) produced at beam dump of KEK Linac switching-yard (SY) 3 (7 GeV e^- / 4 GeV e^+) decaying to 2 photons
- Combination of 5 SiW-ECAL layers and PbO Cherenkov calorimeters



2 photon clusters should be seen as ALP signal

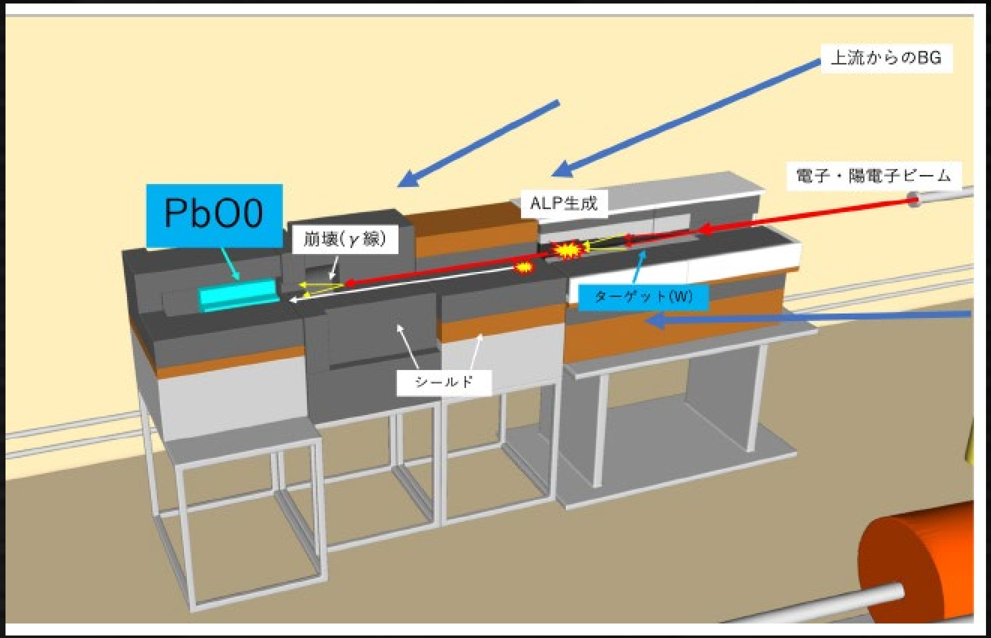


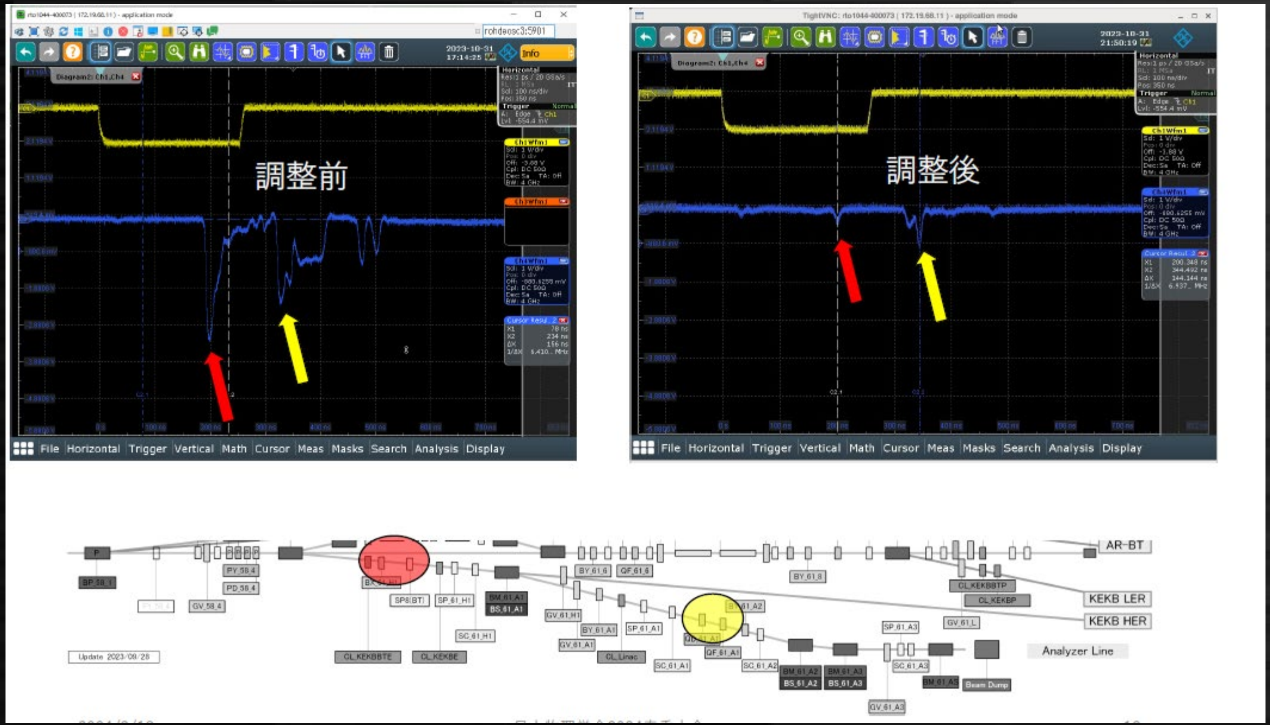
Pilot run at SY3 in July 2022



Huge background from upstream seen in pilot run in 2022

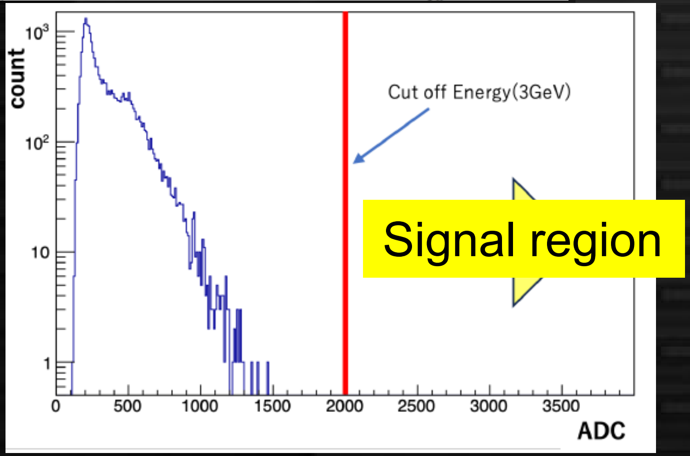
Noise reduction and 2nd run in 2023





Short distance measurement between PbO (gamma detector) and beam dump
→ proof of possibility of background reduction

Beam tuning with radiation monitor to reduce background from upstream



0 background at 2023 run

Summary of Plans in FY2024

1. Finalizing design of the SiW-ECAL with performance evaluation
   - Investigating sensor-delamination issue
     - Confirming stability of underfill
     - Establishing procedure with minimal effect of deformation
   - Prototype with FEV2.1 → proceed after fixing issue above, assembly of 15 layers
2. Exploring picosec timing capabilities of the ECAL
   - Investigation with higher statistics, by multi-cell APD or RI test
3. Development of DNN-based PFA and application of timing
   - First implementation done → aim for better performance and timing inclusion
     French side is also starting DNN study: more collaboration foreseen this FY
4. Application to non-collider projects
   - KEK Linac beam dump experiment (EBES) → 3rd run with 5 Si layers to get first result
   - High-field QED with laser-beam collision at DESY (LUXE) → Long slab test