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

*Co-PI

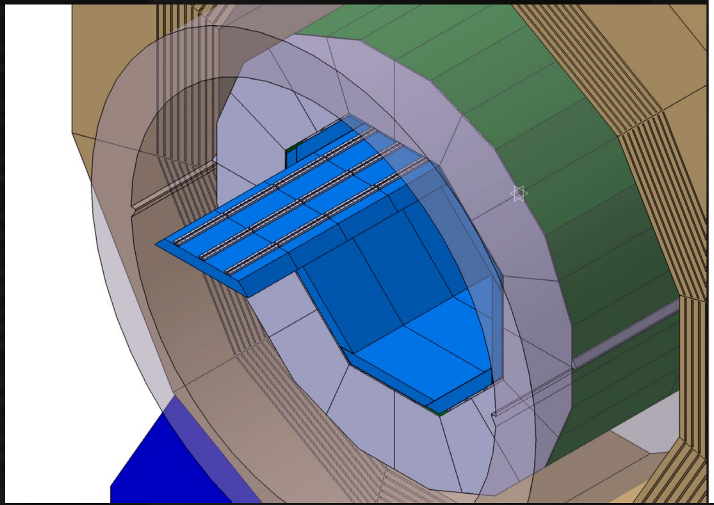
2024 team:

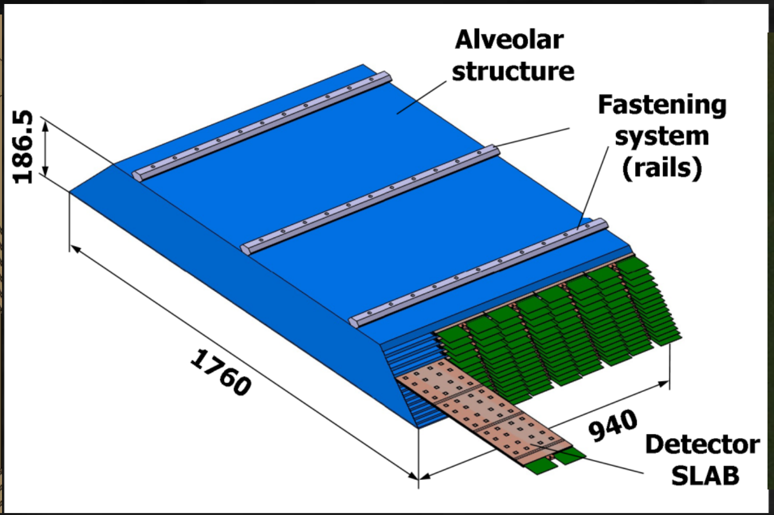
Japanese side: T. Suehara*, T. Murata (U. Tokyo), D. Jeans (KEK), T. Fusayasu (Saga U.)
French side: R. Poeschl*, D. Breton, J. Maalmi (IJClab), V. Boudry, X. Xia (LLR)

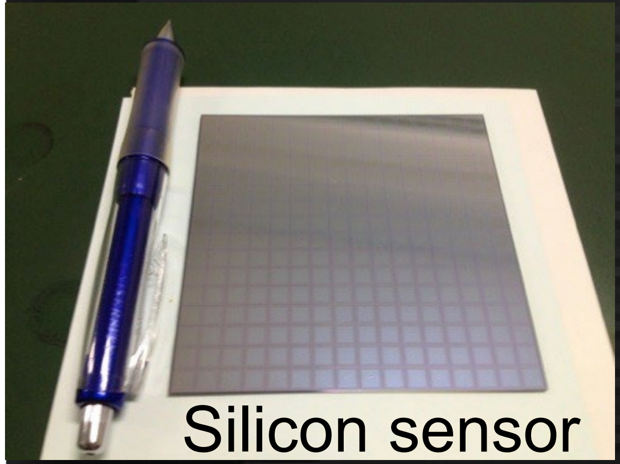
2025 team:

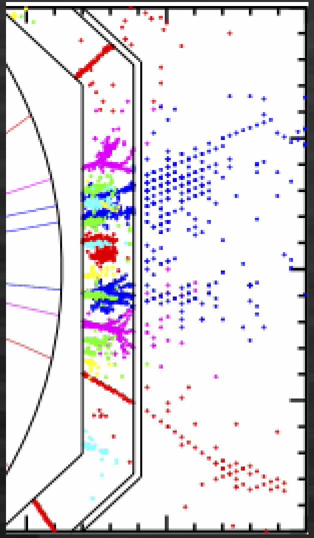
Japanese side: T. Suehara*, T. Murata, T. Takatsu (U. Tokyo), D. Jeans (KEK), T. Fusayasu (Saga U.)
French side: R. Poeschl*, D. Breton, J. Maalmi, X. Xia, J. Hernandez (IJClab), V. Boudry, Y. Shi (LLR)

ILD SiW-ECAL: Overview

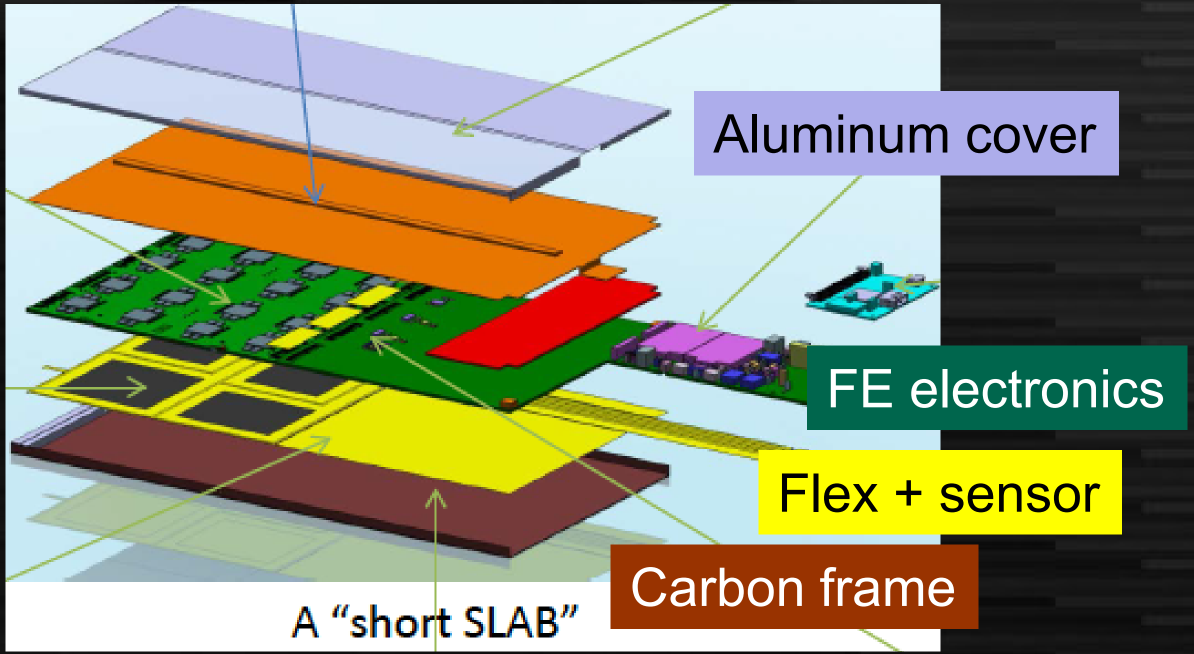








ILD: one of two ILC detector concepts
(also adapting to circular colliders)
ILD ECAL: 20-30 layers of sandwich calorimeter with tungsten absorber and 5x5 mm - segmented silicon diodes
(~ 10^8 channels in total)
PCB with ASICs (SKIROC2) embedded



Achievements in FY2024

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   – New gluing method and assembly
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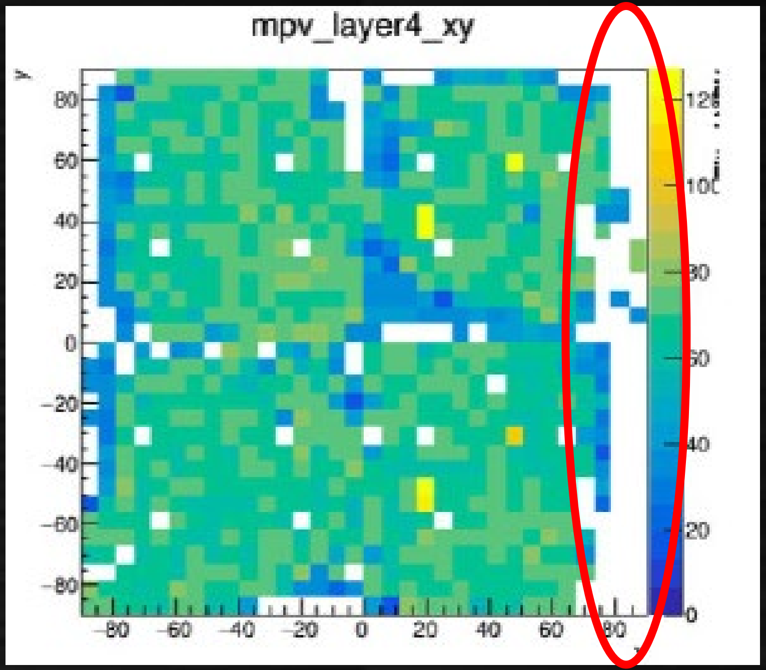
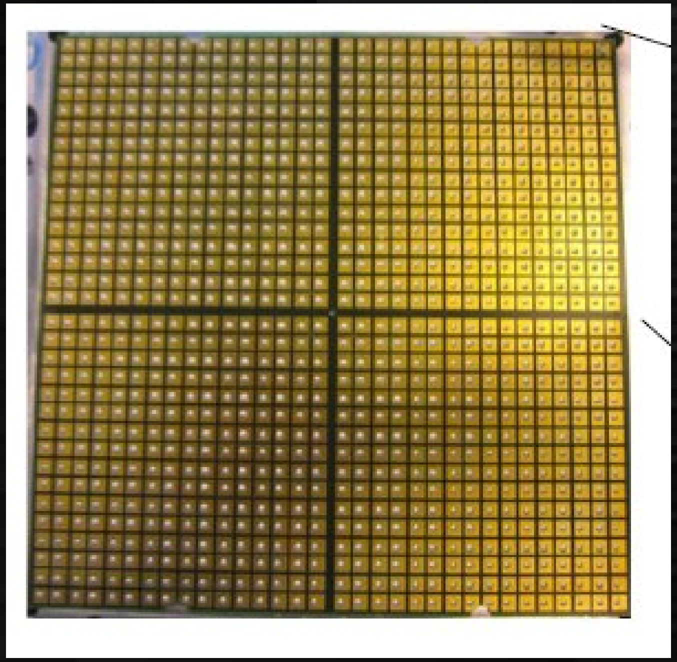
Sensor delamination





Conductive glue may be detached due to (possible causes)

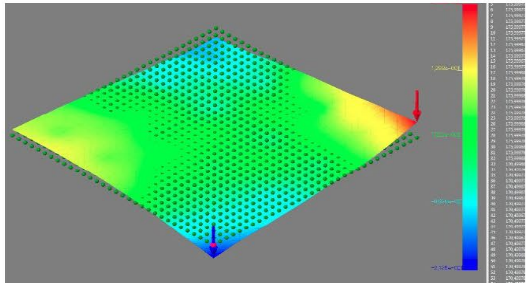
- Force due to board/sensor deformation
  - From initial assembly
  - Long-term deformation by
    - Temperature, humidity…
- Aging of glue

Hybridization studies (2024):
How to assemble silicon sensors & PCB ?

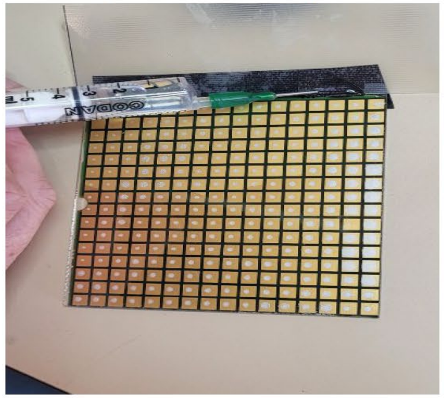
Revisiting gluing (IFIC, IJClab, DMLAB)

- PCB metrology
  - Bef. & After curing & soldering
- Glue formula & preparation
- Gluing methods
  - Robot
  - Stencil
- Reenforcement
  - Filling glue
  - Adhesive films

IJClab (méca)

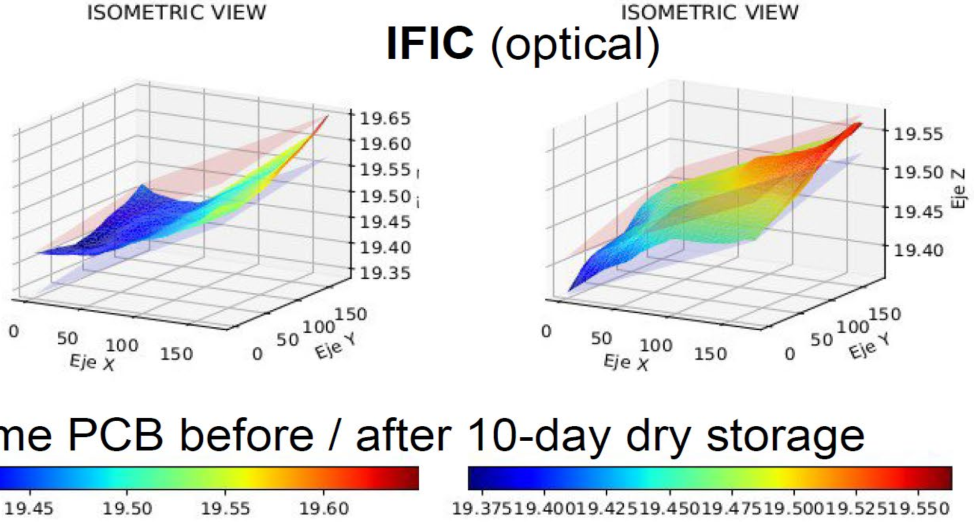


Conductive glue + filling (~invisible) on a glass plate



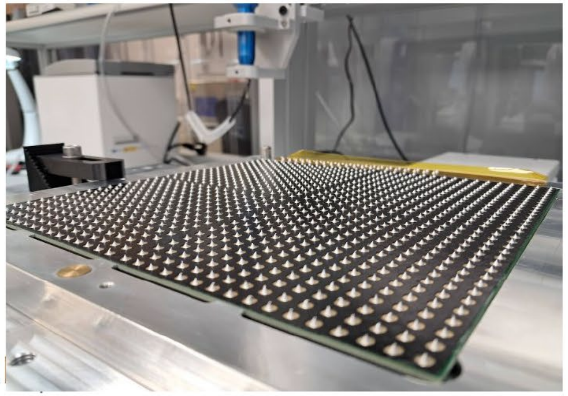
Flatness of PCB

IFIC (optical)



Same PCB before / after 10-day dry storage

Measurements by C. Orero, IFIC



Puncturated adhesive film (**DMLab**)
+
conductive glue dots

ASU2025_001 + 002 (2025)

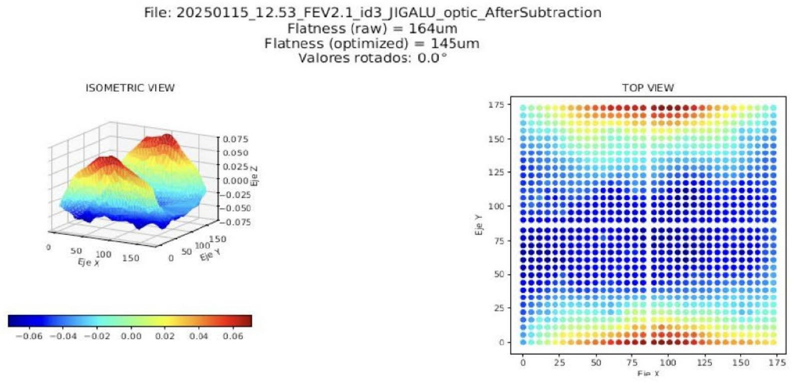
Metrology of PCBs

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

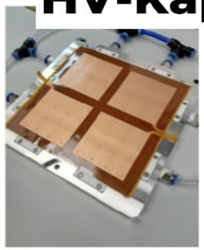
▷ **We could not do conclusive metrologies of the PCBs upon reception**

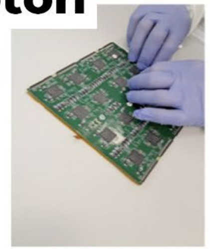
- Small differences between FEV2.0 and 2.1 and w/ w/o components which make the tools available not suitable... we aim for precision mechanics, we require detailed mechanics models and designs
- At arrival + after drying, requires at least 1 month of time for the full process. → so we decided to dry them before having the definitive tooling (which took some time to be produced)

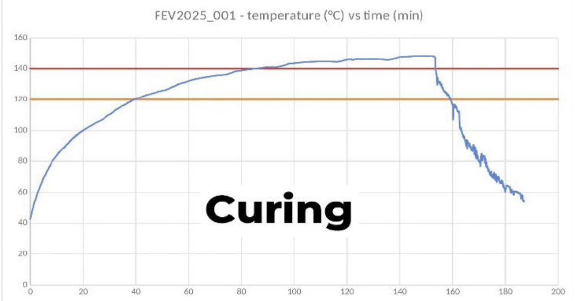
▷ **Metrologies after drying them – FEV2.1 id3 – "flatness" of 145um**

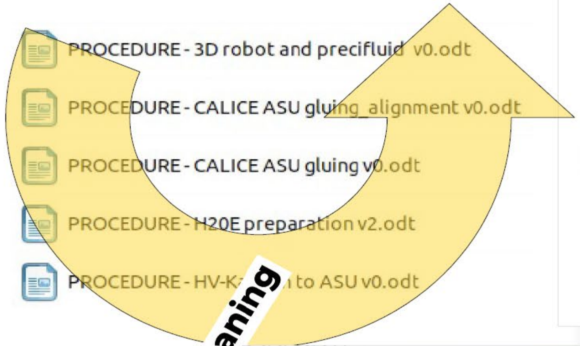


HV-Kapton

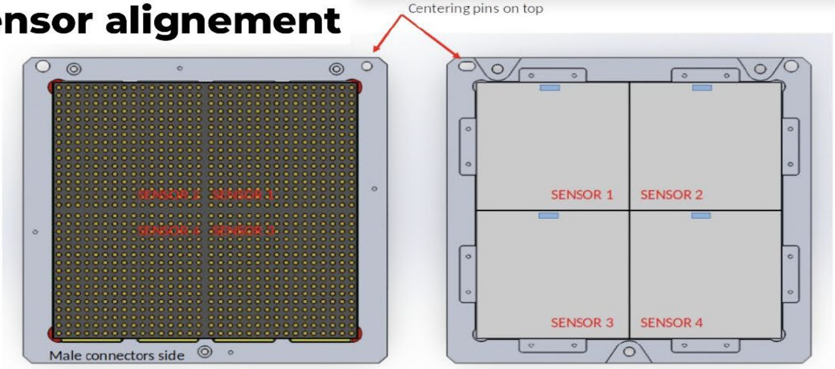






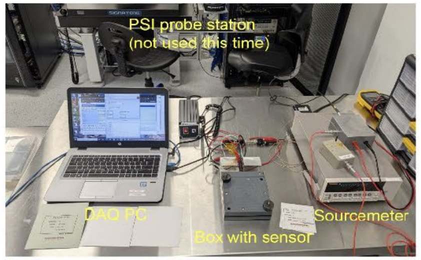


Sensor alignement

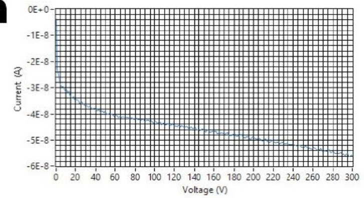


Sensor characterization

(Simplified) Setup at IJCLab



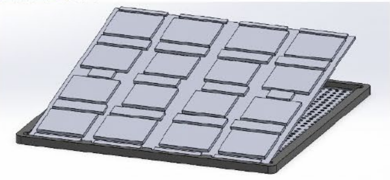
Typical I-V Curve

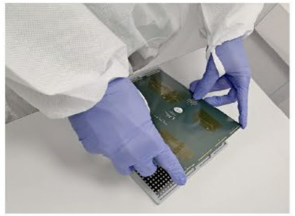


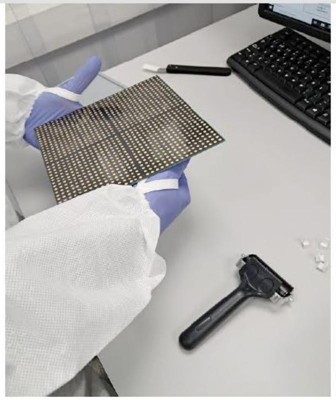
- Reasonable I-V curve though leakage current ~ factor two lower than in HPK data sheet
- Tests allow to validate that there is no major problem with sensors

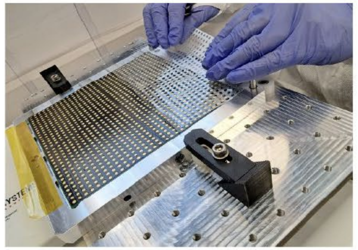
J. Jeglot, A. Torento, R.P., (R. Cornat)

Sensor and electronics cleaning









3M tape

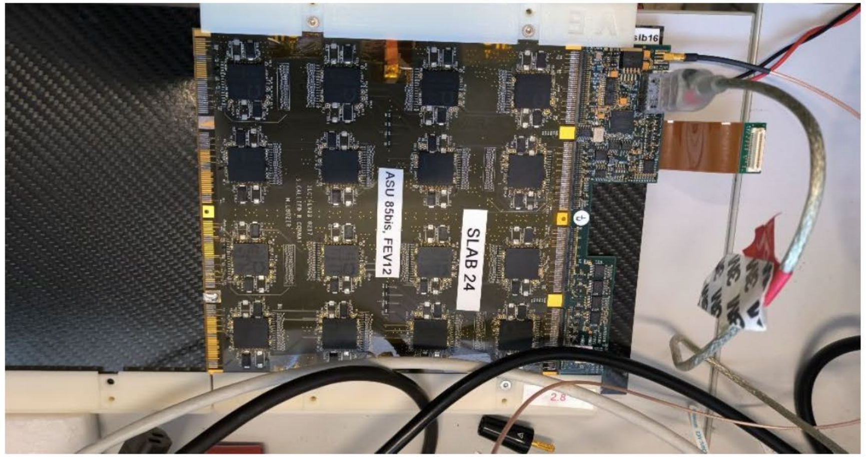
Test setup

ECAL geometry

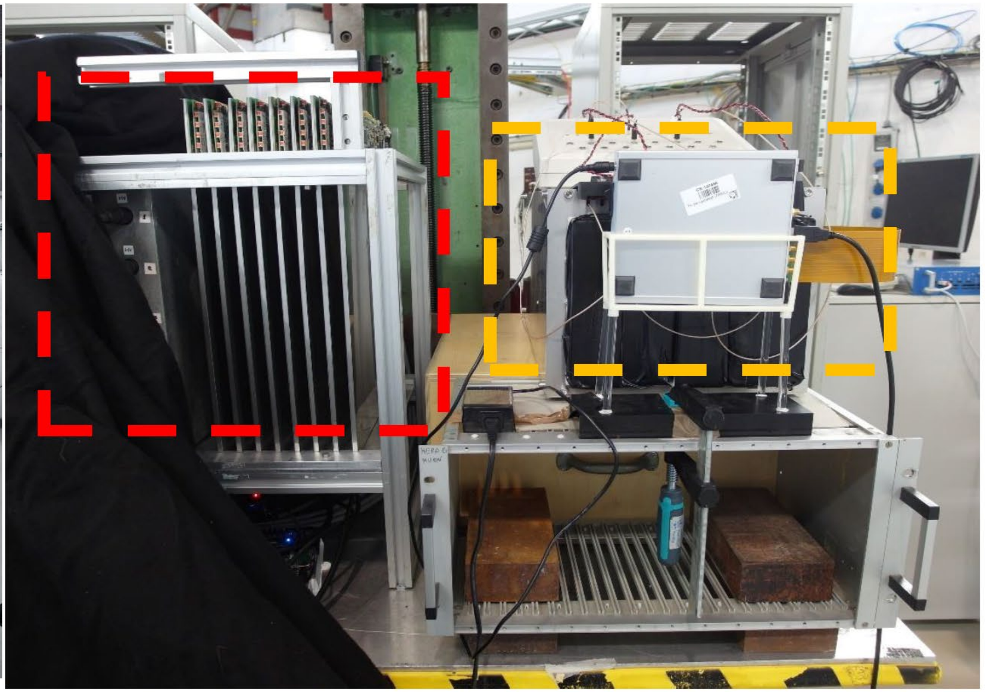
- 3 layers
  - 1 chip on board,2 produced recently
  - 16 SKIROC ships
  - 32×32 cells: $5.5 \times 5.5\ mm^2$
  - No absorbers

Data Taking

- ECAL:Mar 4th - Mar 6th
  - Configuration and calibration
  - Position scan
  - a blown fuse identified and replaced
- ECAL+HCAL: Mar 7th – Mar 8th
  - Configuration and calibration
  - Position scan
  - TDC test



ECAL

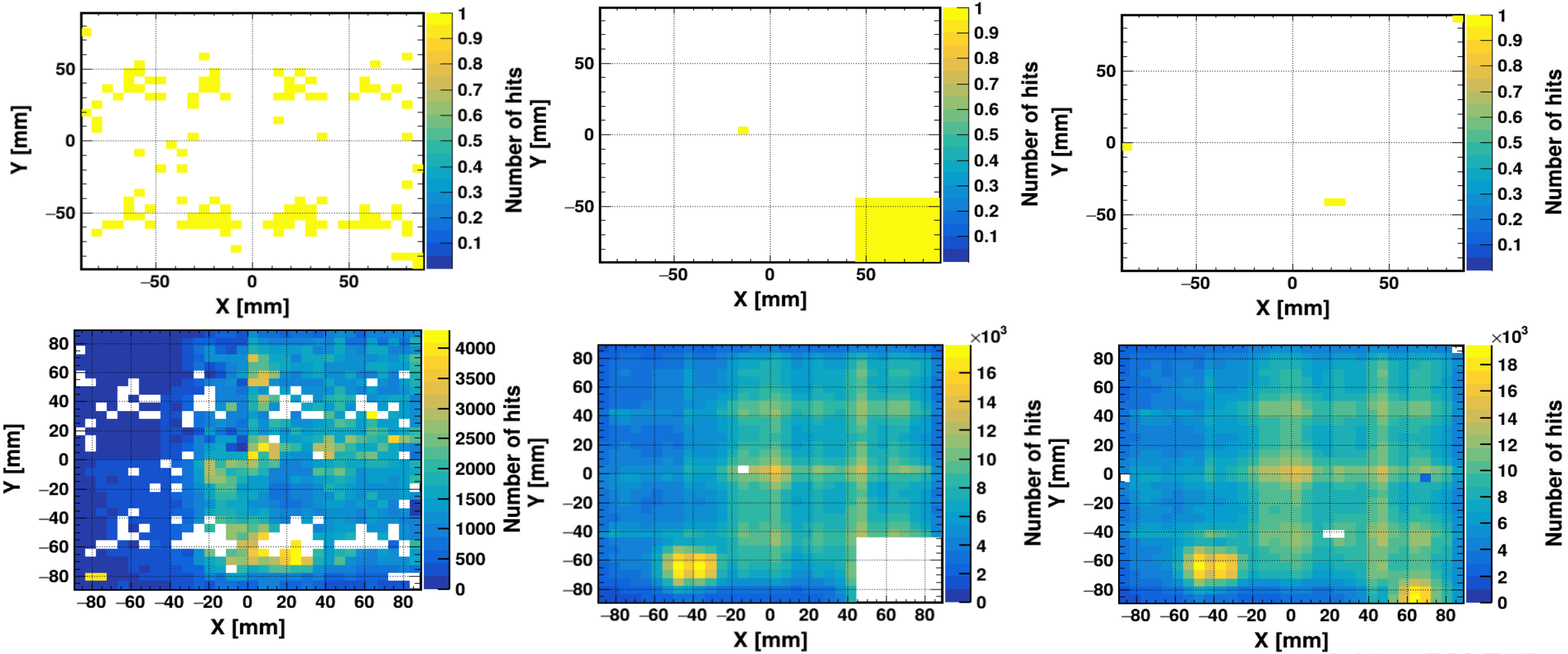


ECAL+AHCAL

Beam

Hit Map

The hit maps are in consistency with the masking channels

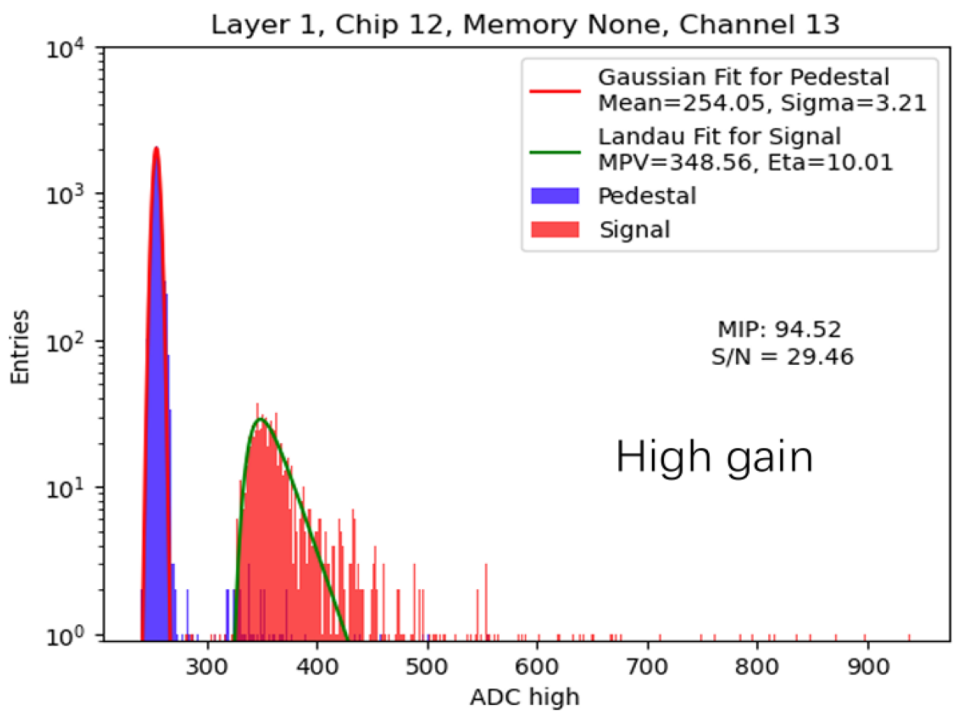


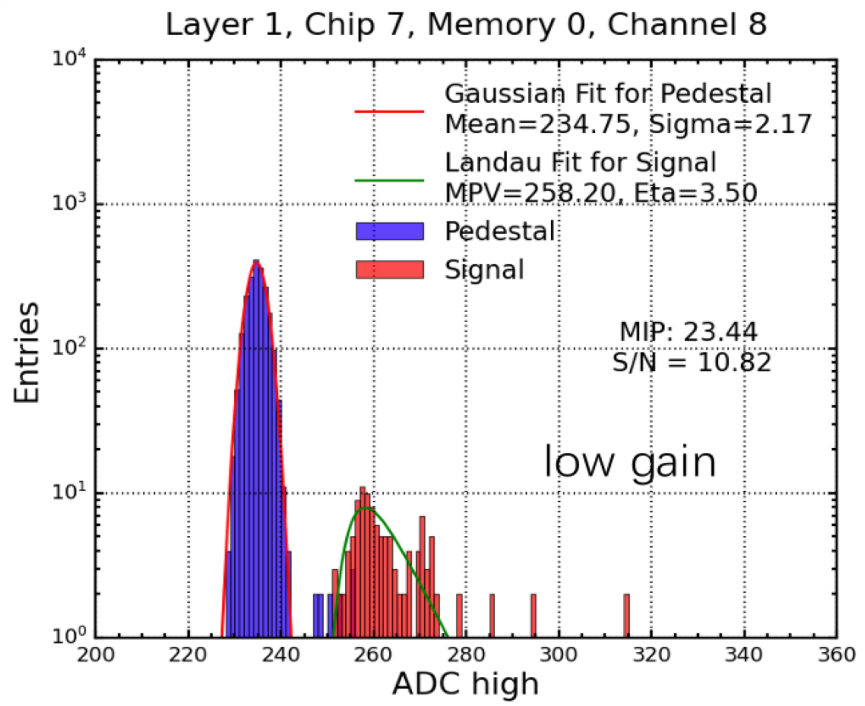
Mask map(up) andHit maps(down): layer 8, layer11 and layer12

2025/4/2

Signal Noise Ratio(S/N)

- Pedestal is obtained by the beam data with hitbit=0
- High gain: MPV ~90 ADC(after pedestal extraction), S/N ~ 30
- Low gain: MPV~ 23 ADC, S/N~ 11





Single channel's S/N for high gain and low gain

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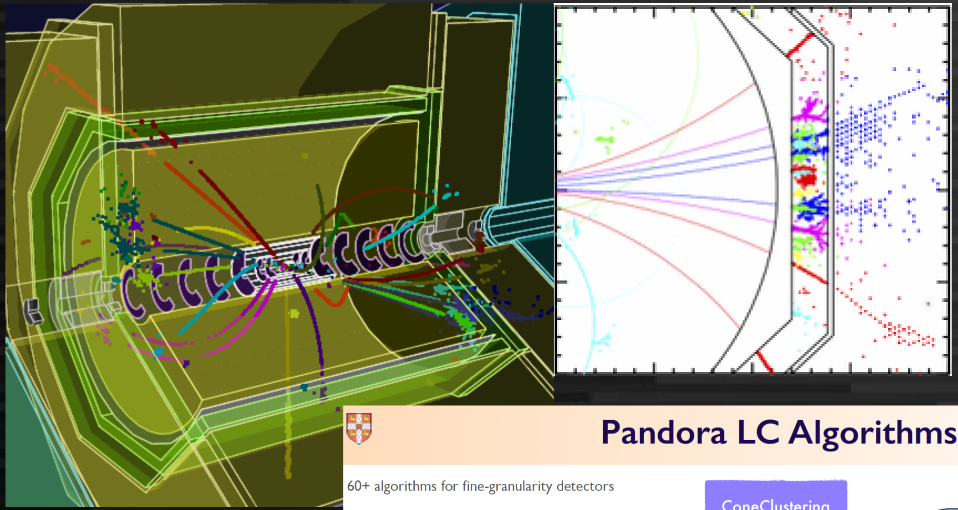
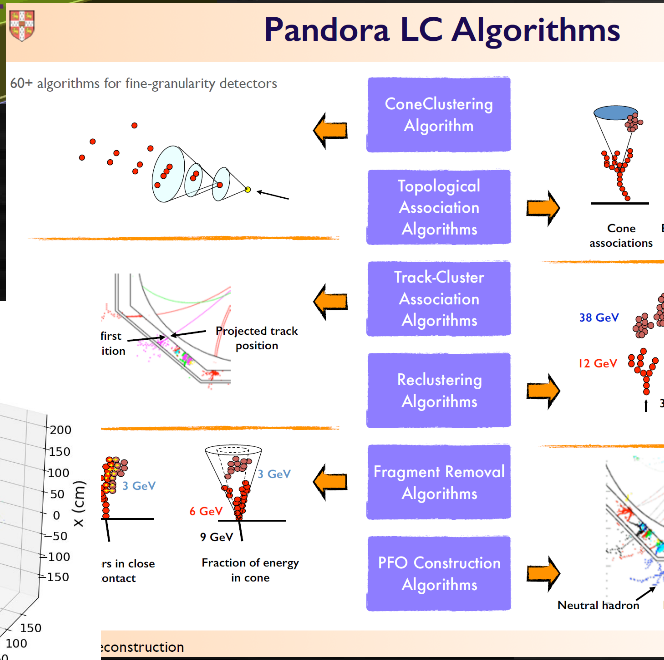
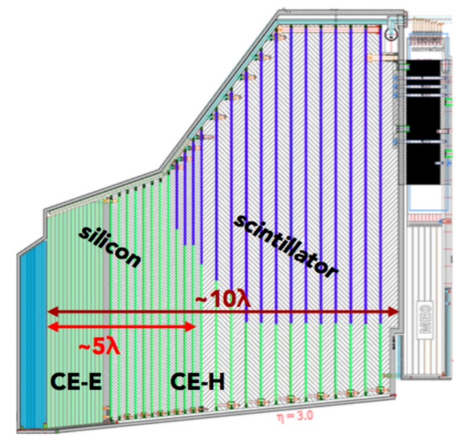
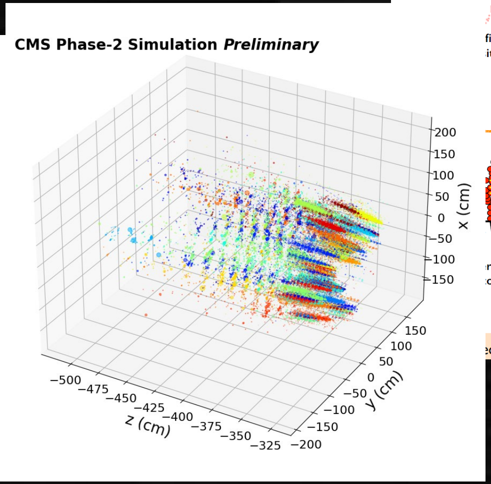
Particle flow with DNN: introduction

- 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



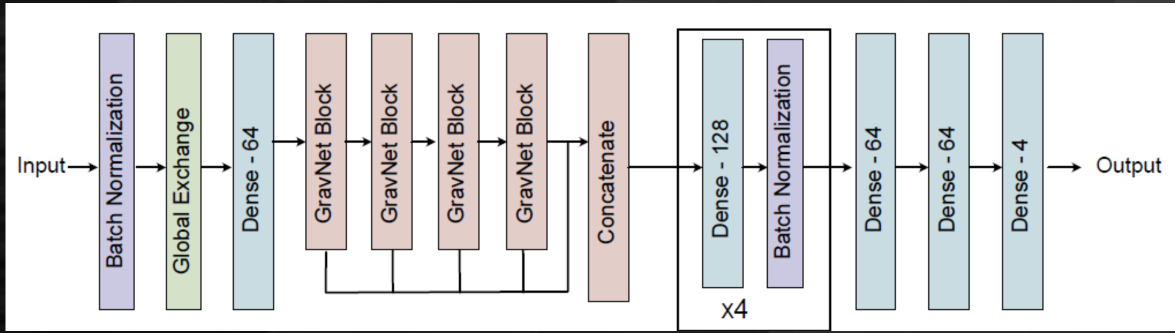






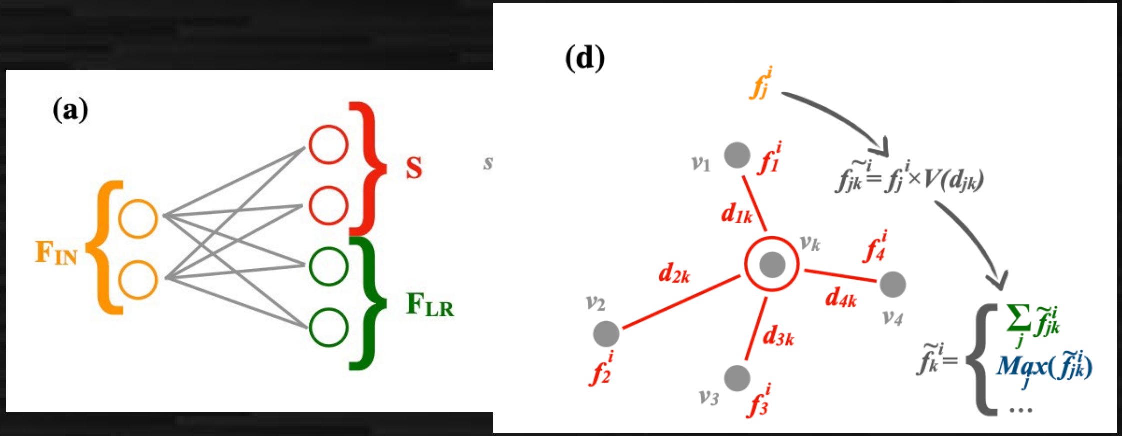
PFA: clustering algorithm

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



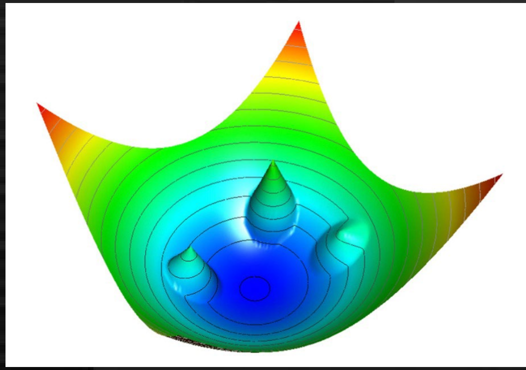
GravNet arXiv:1902.07987

- 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

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

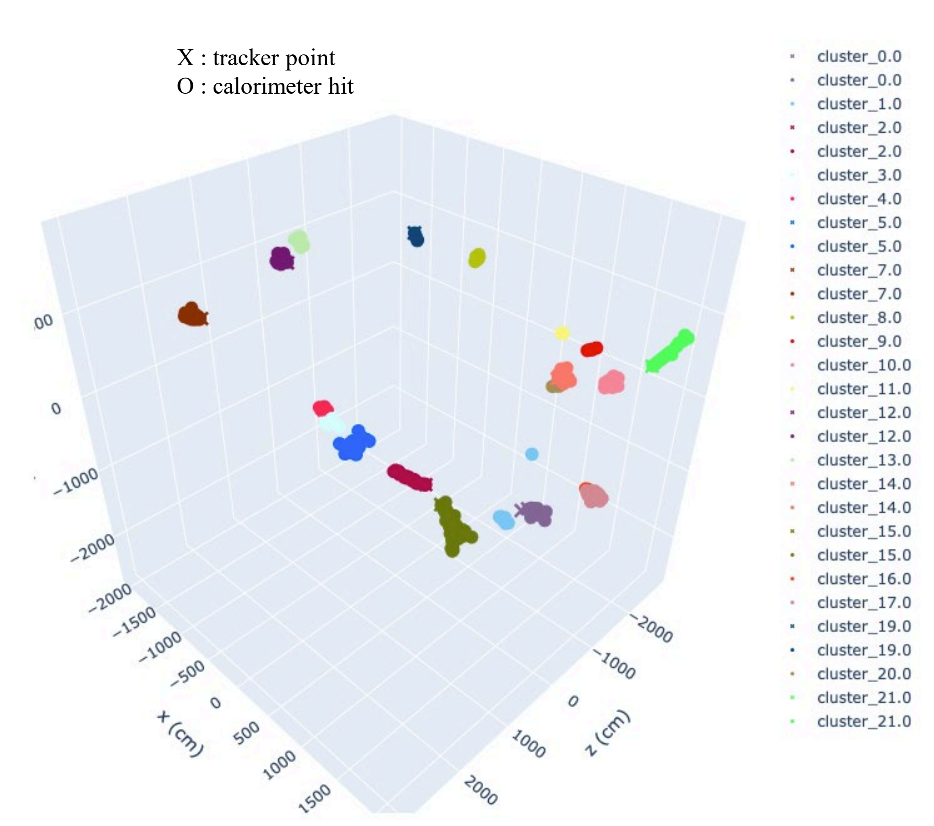
L_V: attractive/repulsive potential to condensation points / tracks

L_β: Pulling up β of the condensation points / tracks

Tracks are prioritized over other condensation points

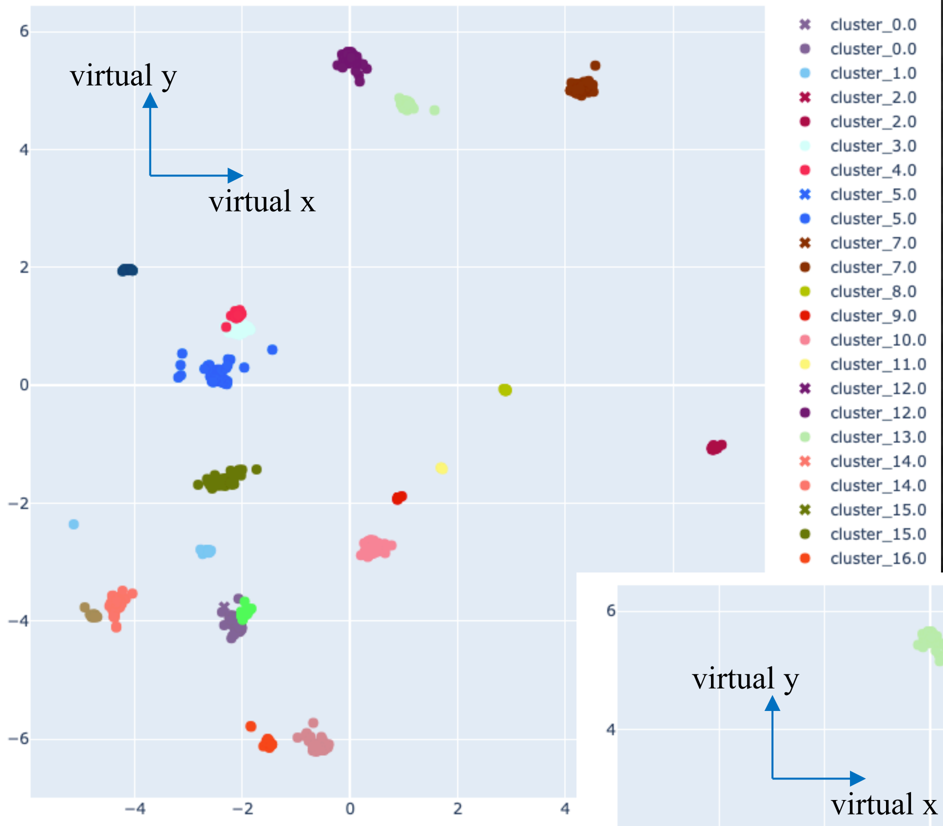
Current number of parameters: ~420K

Event display



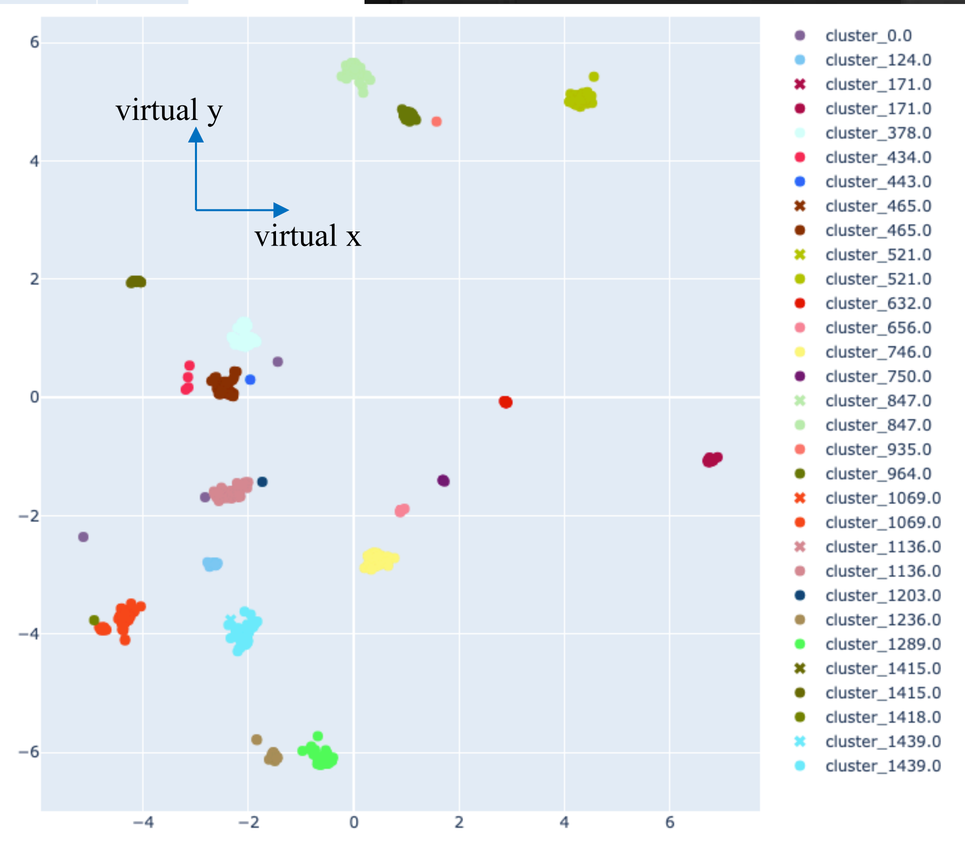
Input features
Real coordinate in detector

Colored by true clusters



Output features
Virtual coordinate

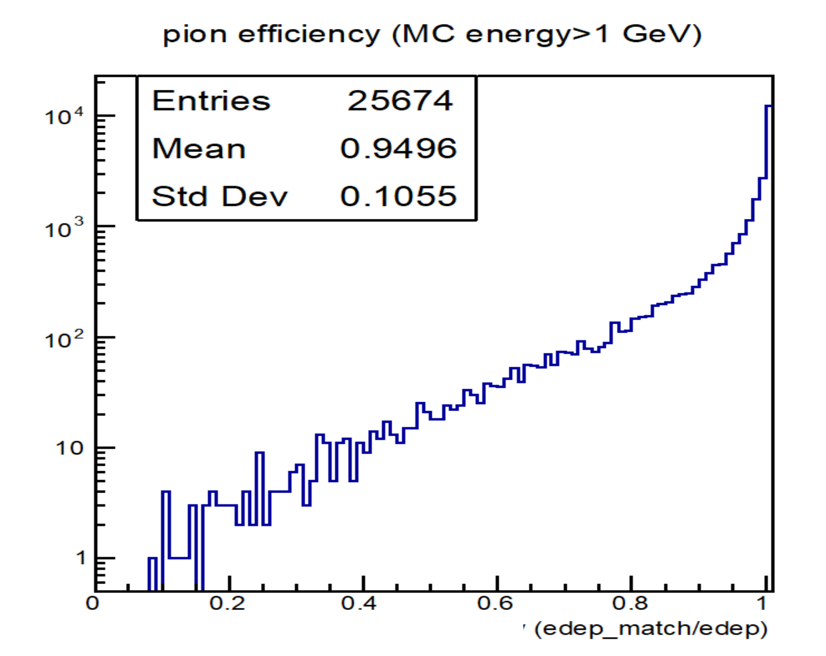
Colored by
true clusters

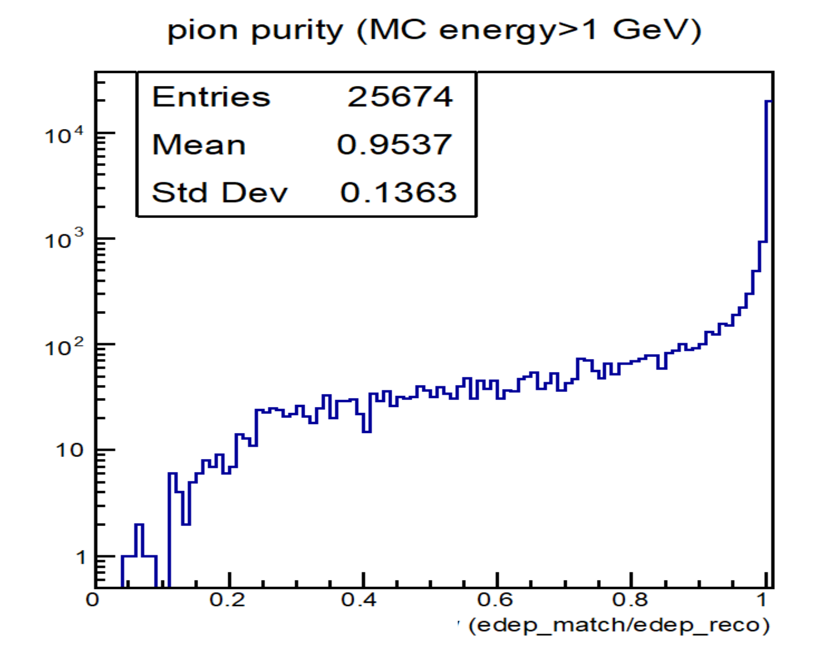


Colored by
reconstructed clusters

Quantitative evaluation

- Make 1-by-1 connection of MC and reconstructed cluster
  - Reconstructed cluster with highest fraction of hits from the MC is taken
  - Reconstructed cluster having largest fraction of MC hits is only allowed to connect to the MC cluster (and other clusters are discarded)
- Quantitative comparison with PandoraPFA
  - Compared “efficiency” and “purity” of particle flow
    - Efficiency : (reconstructed cluster energy that matches the MC cluster) / (MC cluster energy)
    - Purity : (reconstructed cluster energy that matches the MC cluster) / (reconstructed cluster energy)





Results on efficiency and purity (preliminary)

Algorithm train/test	Electron eff.	Pion eff.	Photon eff.	Electron pur.	Pion pur.	Photon pur.
GravNet 10 taus/10 taus	92.8%	94.4%	94.5%	91.6%	98.7%	97.1%
PandoraPFA 10 taus	98.7%	88.5%	99.0%	94.6%	99.1%	98.4%
GravNet jets/jets	91.2%	87.6%	89.9%	66.7%	86.8%	80.3%
PandoraPFA jets	97.7%	87.8%	98.1%	71.5%	83.8%	84.0%

Pion reconstruction is slightly better by GravNet, but electrons/photons are not
Need more intelligent clustering method → under study

Energy regression: ongoing work

Add E_{tr} and E_{hit} to the output of the network (for each hit)
Add terms (1, 2) to object condensation loss

Cluster energy (MC vs reco) at 10 taus event

truth clustering

real clustering

Two additional loss term

1. E_{tr} at condensation points to be regressed to MC cluster energy

$$L_{E,charged} = \frac{1}{2}\sum_{i}\left(E_{truth,i} - E_{pred,cond,i}\right)^2$$

2. Sum of E_{hit} of all energies to be regressed to MC cluster energy

$$L_{E,nerutral} = \frac{1}{2}\sum_{i}\left(E_{truth,i} - \sum_{j} E_{pred,calo,i,j}\right)^2$$

3. Use E_{tr} for charged clusters and use sum of E_{hit} for neutral clusters

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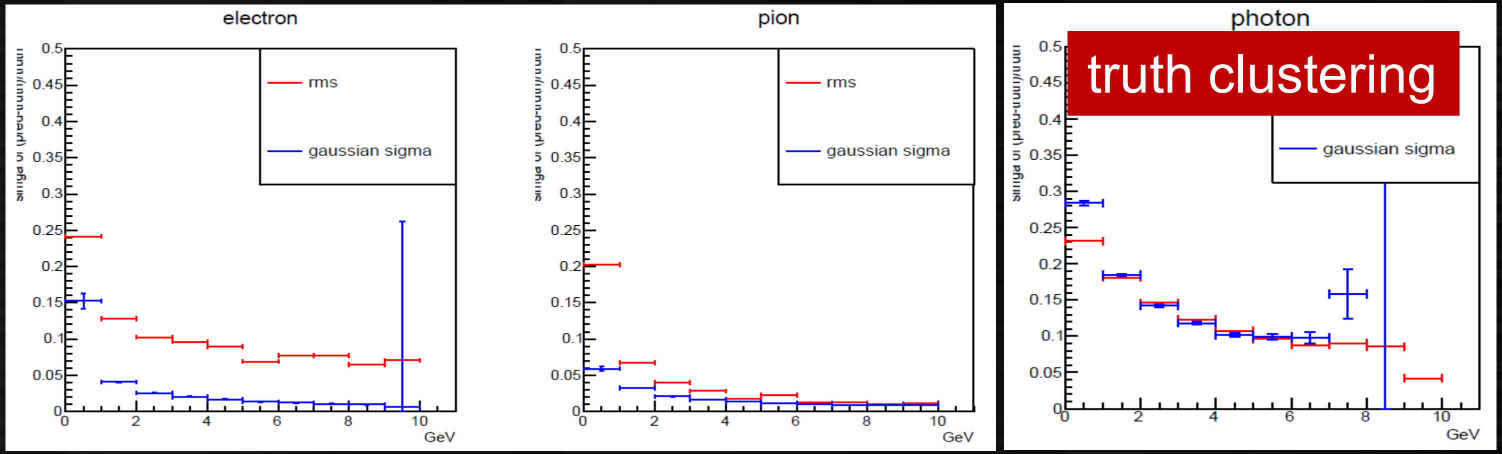

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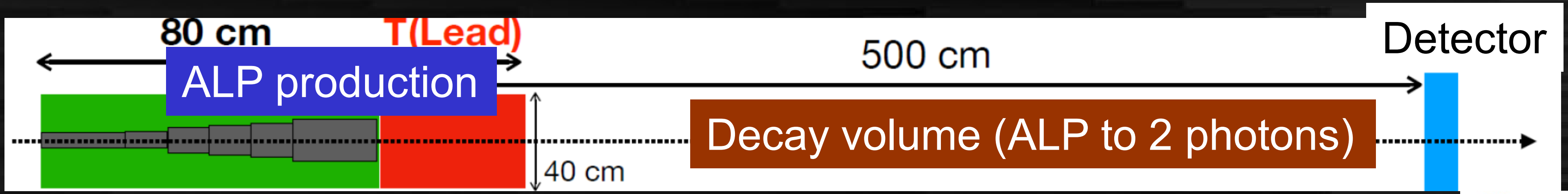
EBES (Eletron Beam-dump Experiment at SY3)

- 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



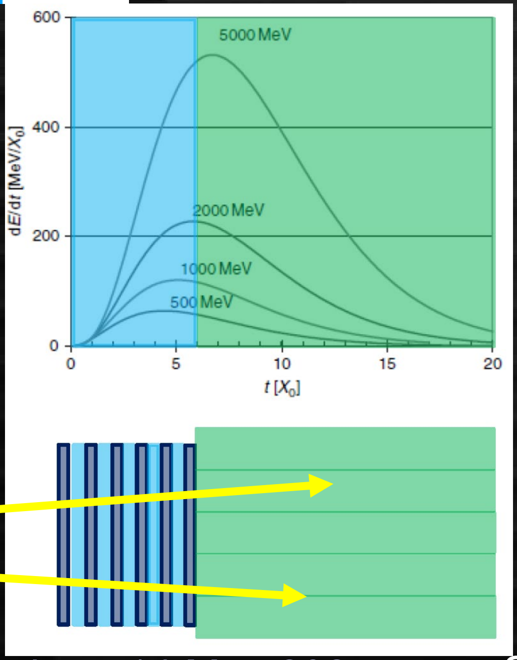
2 photon clusters should be seen as ALP signal

Tungsten + Iron

Lead

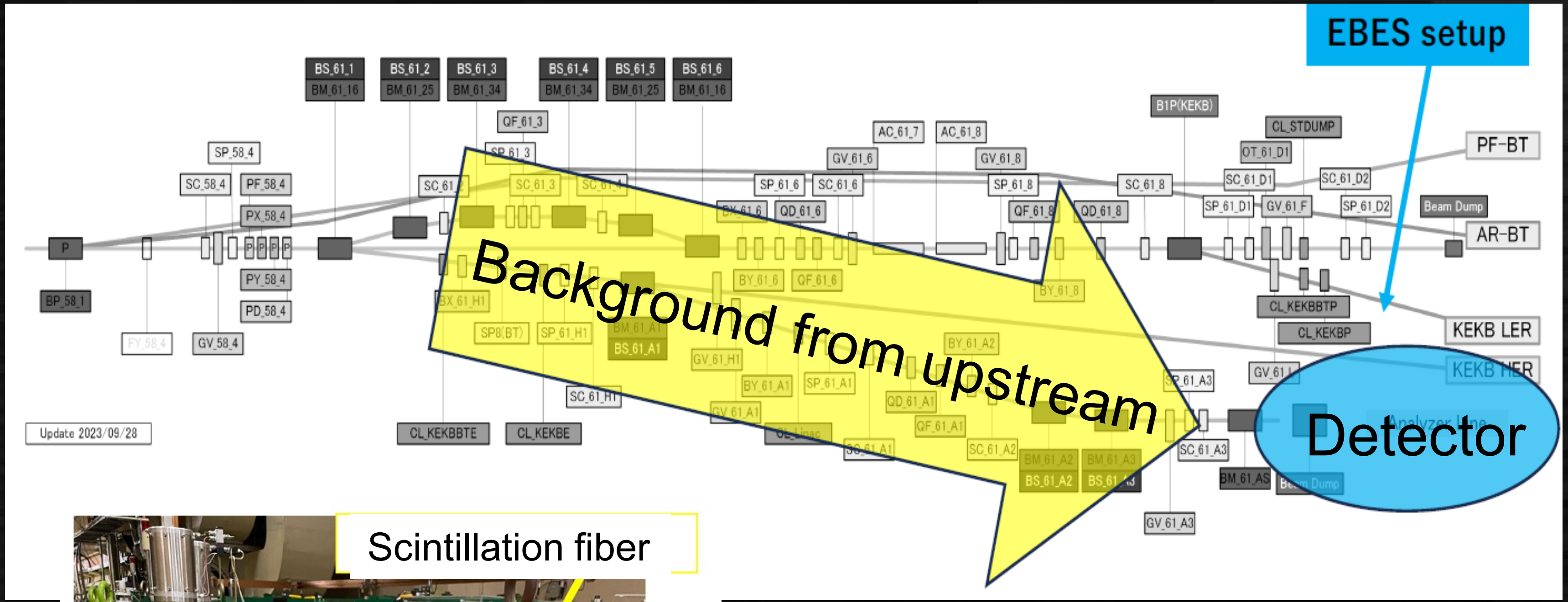
Pilot run at SY3 in July 2022

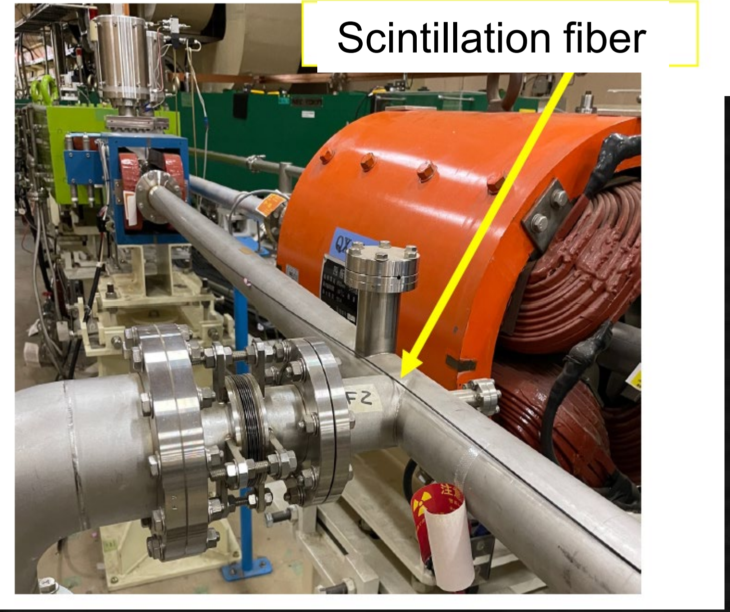
Huge background from upstream seen in pilot run in 2022



Understanding beam background (2023)

Switching yard 3



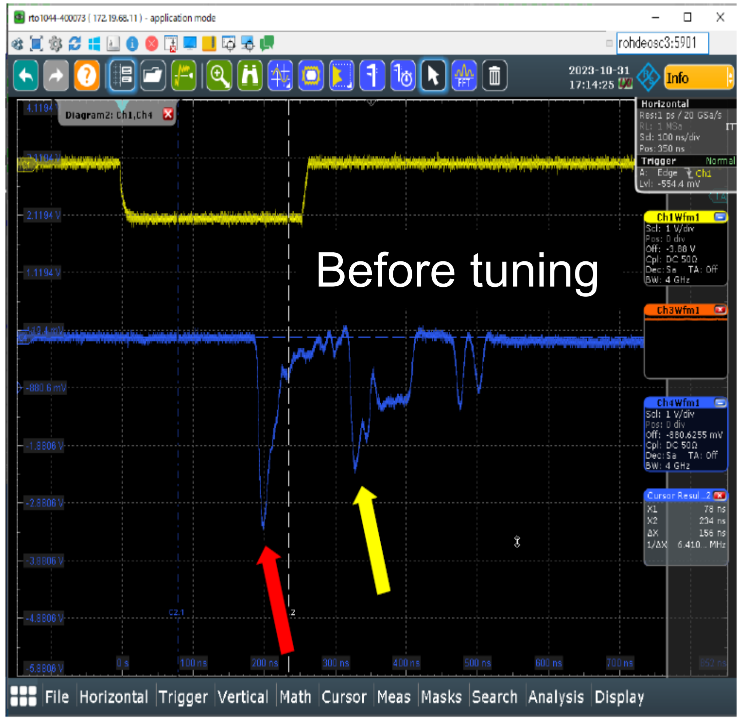


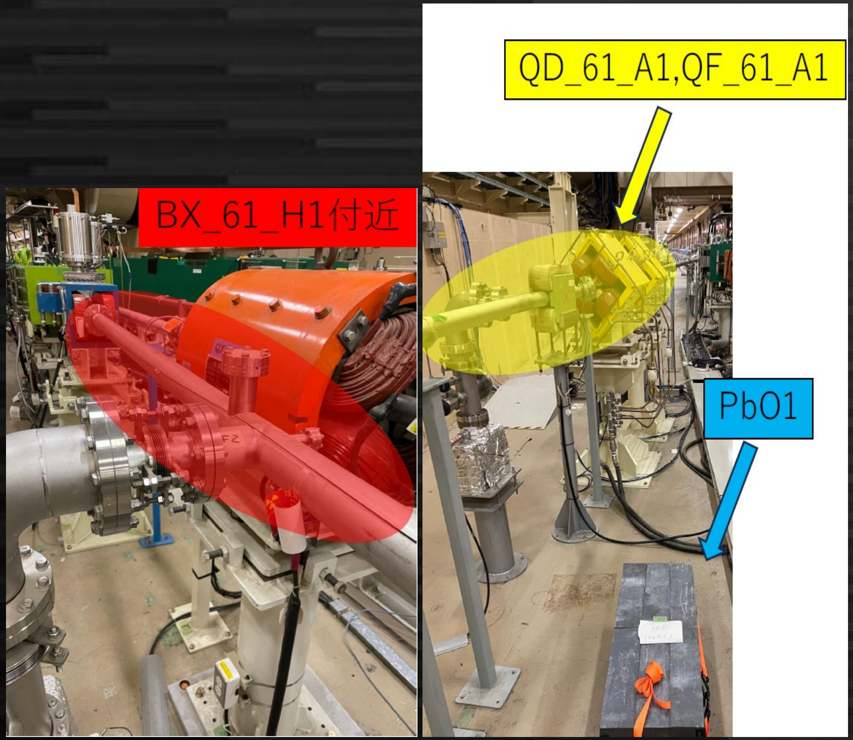
Scintillation fiber produces signal around the beam pipe on which particles hit and produce background

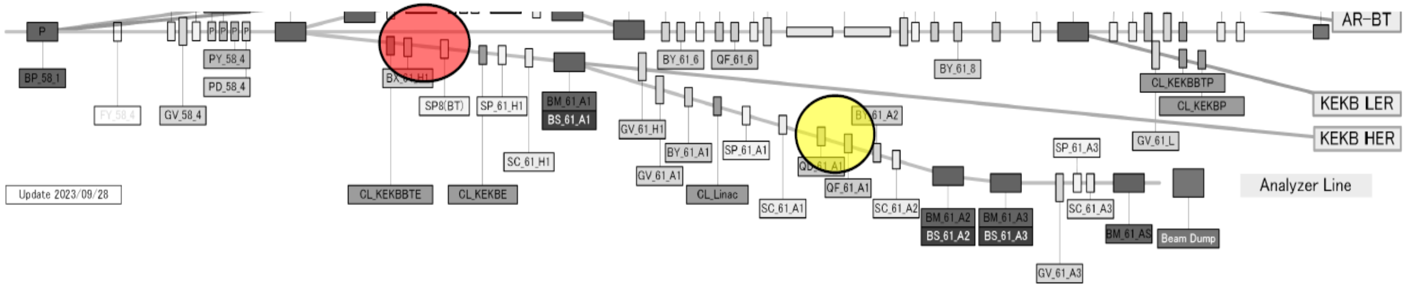
Position can be obtained from timing spectrum

Shielding of beam dump is also updating

Reduction of background by beam tuning





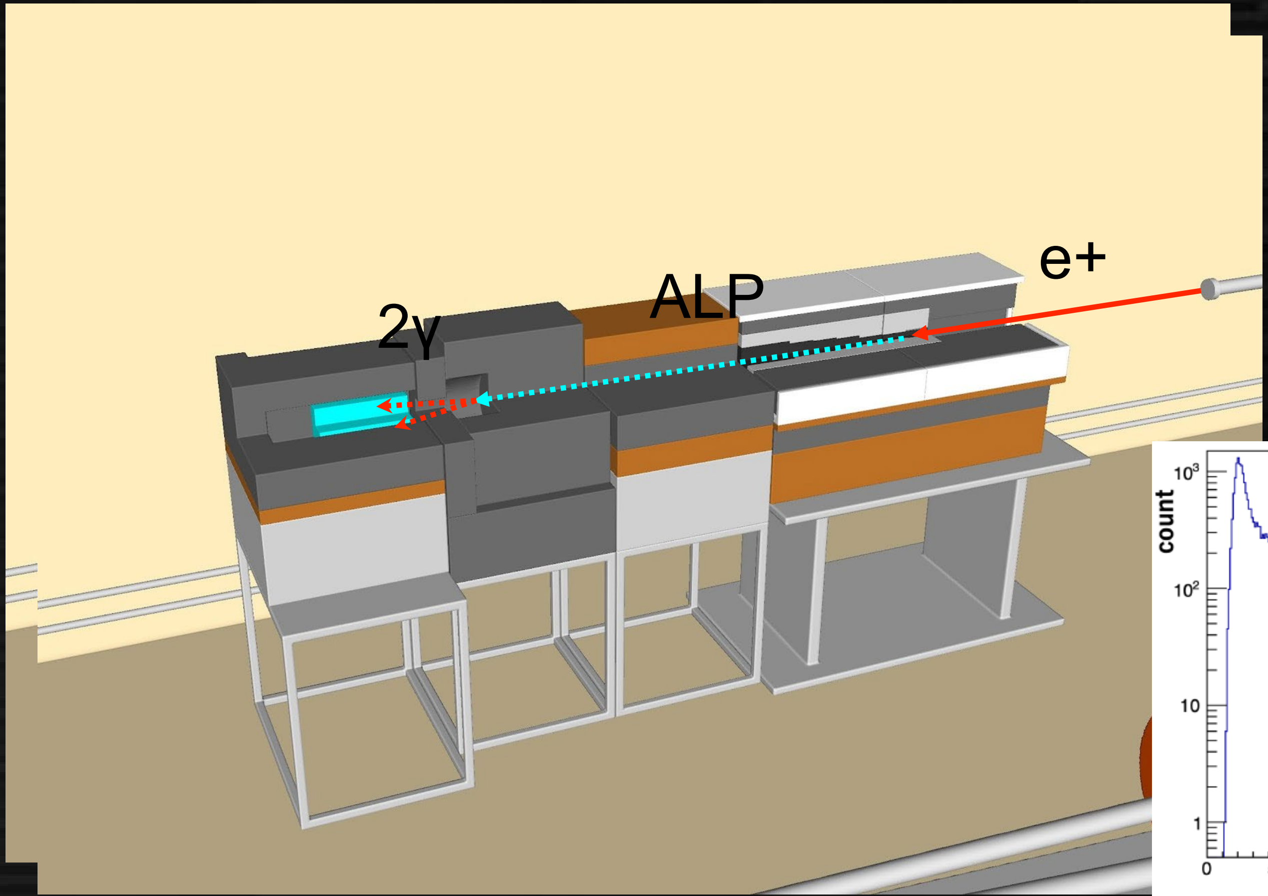


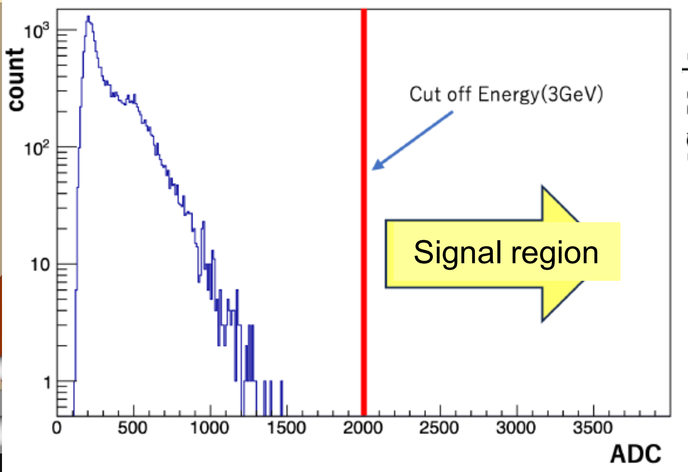
Hitting places found
With beam tuning reduction of ~2 order of magnitude obtained (but still not enough)

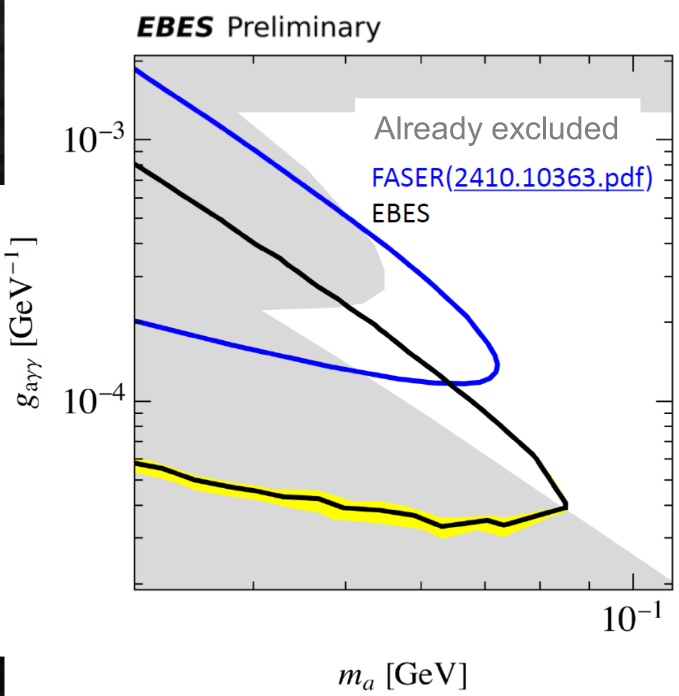
Pilot run with very short re-conversion length

4 GeV positron run with minimal charge (0.1 nC) conversion length of 28 cm

in Dec. 2023





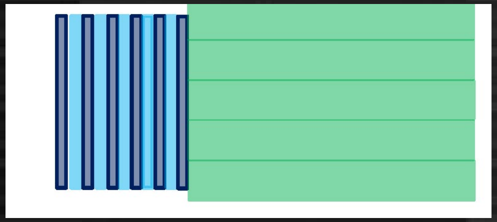


Almost no distance to reconvert ALP → 2γ but background is shielded by beam dump itself! (background source not seen from detector)

Already gives exclusion region (statistics only)

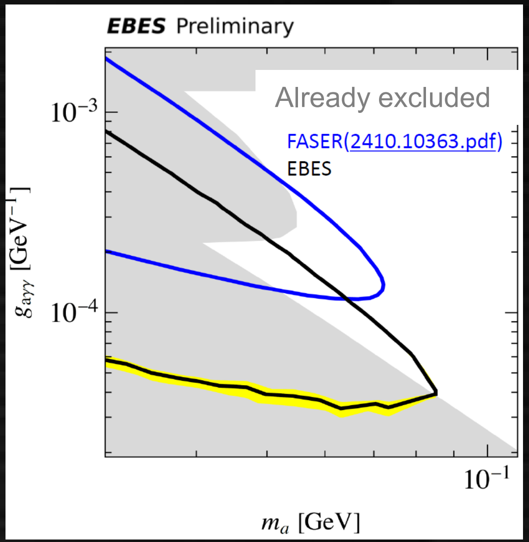
Recent Progress/plans

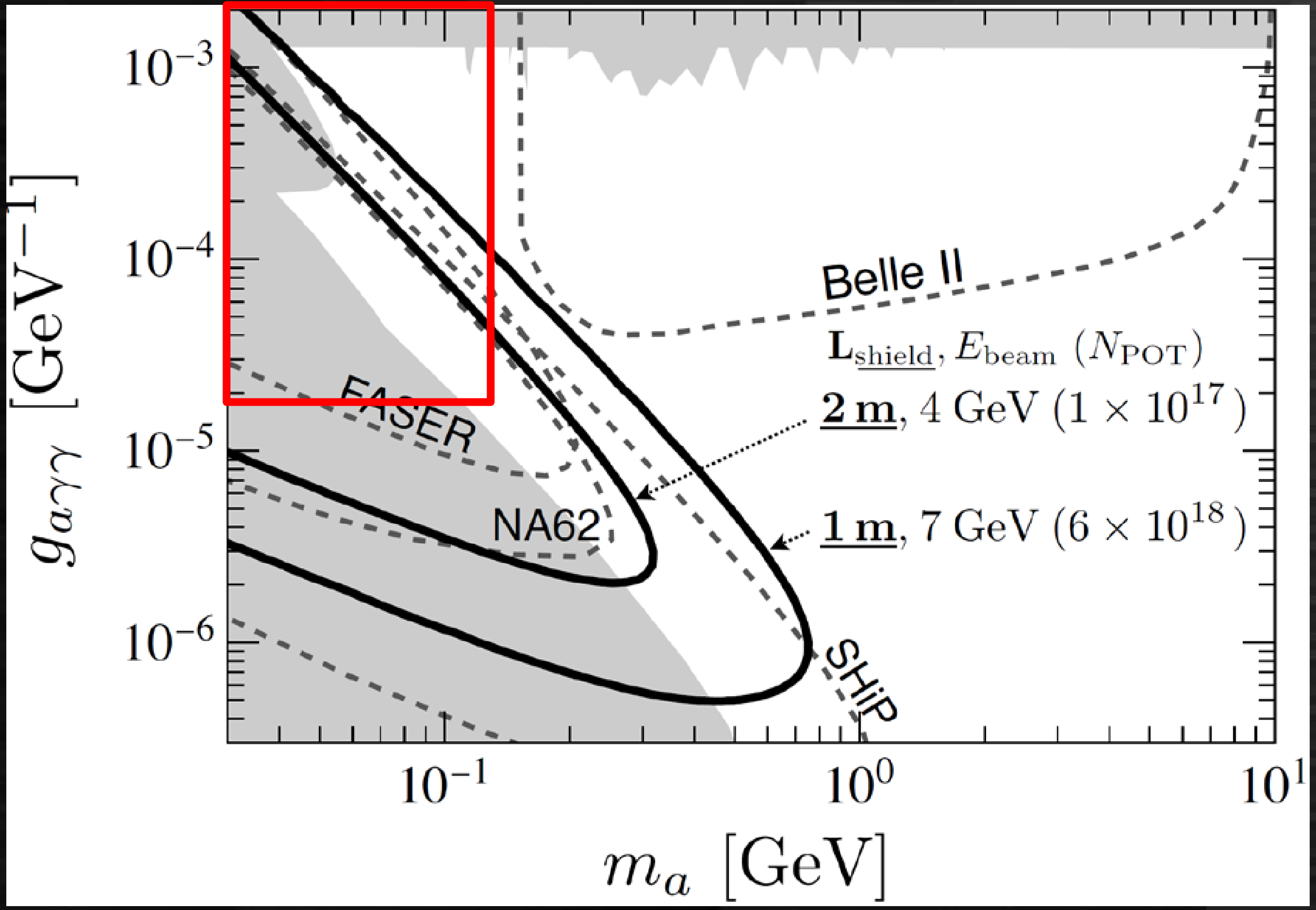
- Additional budget to put silicon sensors approved (Feb. 2025)
  - FY2025-27, ~80kEUR in total
  - ~5 silicon layers + sweeping magnet for 7 GeV run
  - (optionally) reuse old silicon layers to make fully-silicon (~15 layers) setup
  - AI-based accelerator tuning
- Next physics run later 2025 with ~100 cm conversion



  - 3-5 silicon layers with a few X0 of tungsten in front of PbO calorimeter
    - To be placed to beam line at summer 2025
    - Identifying background of charged particles (incl. reconstructing direction)
    - Identifying photons from beam dump
  - Preparing magnet (cables, power, shielding) to setup in 2026

Planned sensitivity





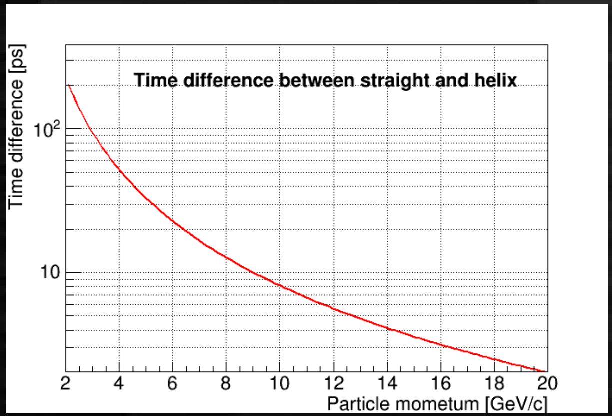
Shielding: 2 m → 1 m (2027)
Re-conversion: 28 cm → 1 m (2025)
Beam energy: 4 GeV → 7 GeV
(need sweep magnet, 2026)

Summary of Plans in FY2025

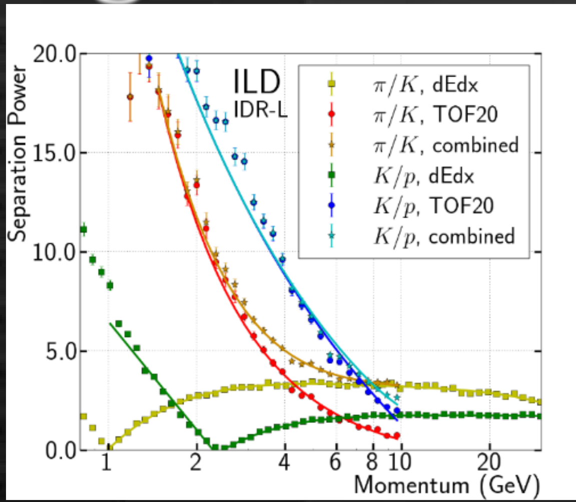
1. Assemble SiW-ECAL layers with new electronics (FEV2.1) and test performance
   - 2 layers have been tested in Mar. 2025
     - No critical issues → moving to the prototype production (up to 15 layers) A few layers from Japan?
     - To be tested at DESY/CERN, investigating performance as calorimeter (e.g. energy resolution)
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
   - Energy regression is done with reasonable performance → to be finished in this FY
   - Replacement with transformer being tried (by a French intern in Tokyo (iLANCE))
4. Application to non-collider projects
   - KEK Linac beam dump experiment (EBES) → KAKENHI approved, silicon layers to be installed this FY, collaboration with IJClab for electronics
   - Other applications (LUXE, Lohengrin, SHiP (new))

Timing for calorimetry: possible targets

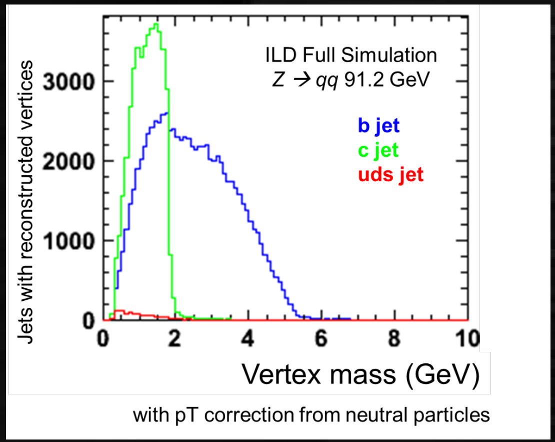
- π/K/p separation with Time-Of-Flight method
  - 30 psec (for cluster)
    Moderate performance to fill gap of dE/dx
  - A few psec (for cluster)
    up to 5-10 GeV (80-90% of jet particles)
- Track separation at PFA
  - By distance of helices and straight lines
  - ~10 psec/cluster necessary for 10 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

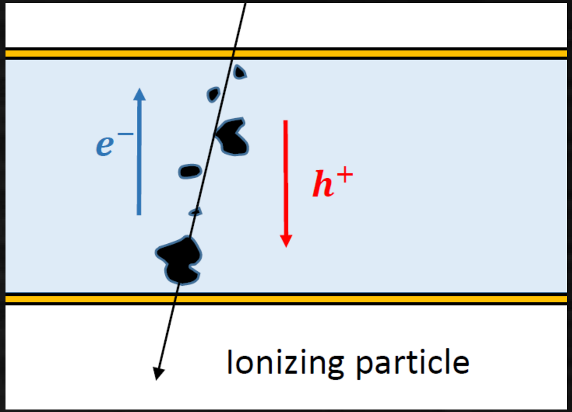


Vertex mass of secondary tracks (only) from b/c jets

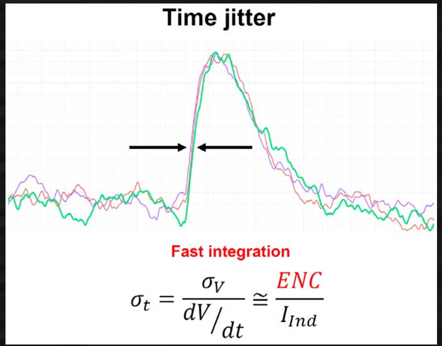
Study of LGAD/APD

APD: photon sensor with essentially the same structure as LGAD

Timing resolution for silicon

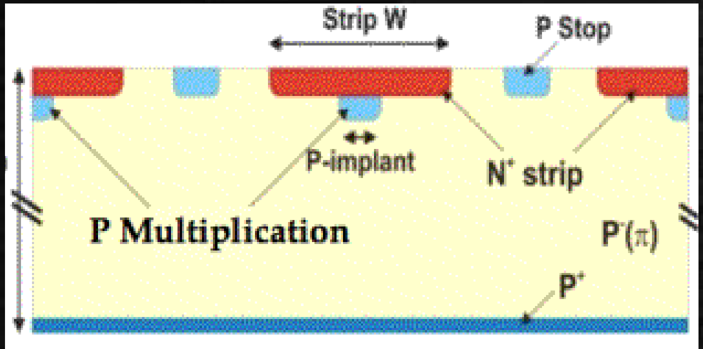


Landau fluctuation: caused by distribution of energy deposit along the track: fast collection time (thin active thickness) → better reso



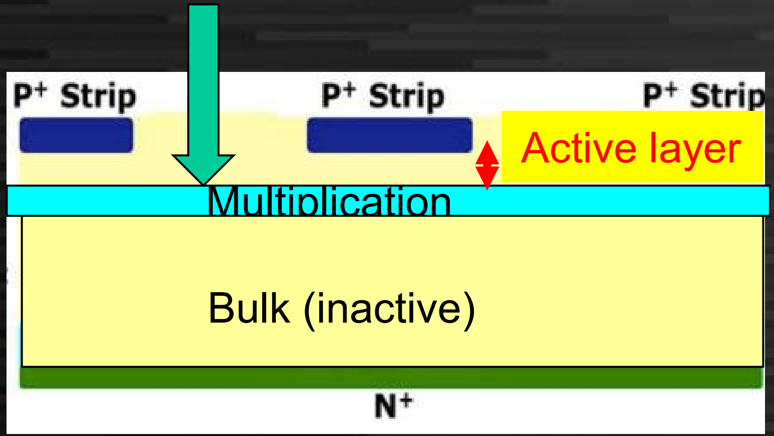
Jitter by noise:
~Rising time / S/N ratio
Big signal preferred
→ internal gain

LGAD/APD types



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

Doping from surface

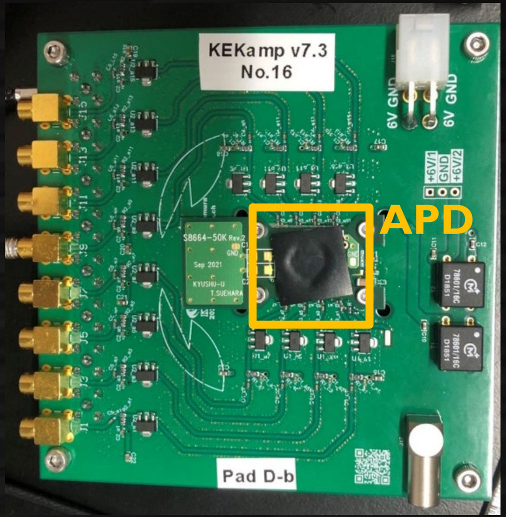


Inverse type (single sided process)
Multiplication by deep injection
Thinner active layer (5-10 μm)
→ Smaller Landau fluctuation?

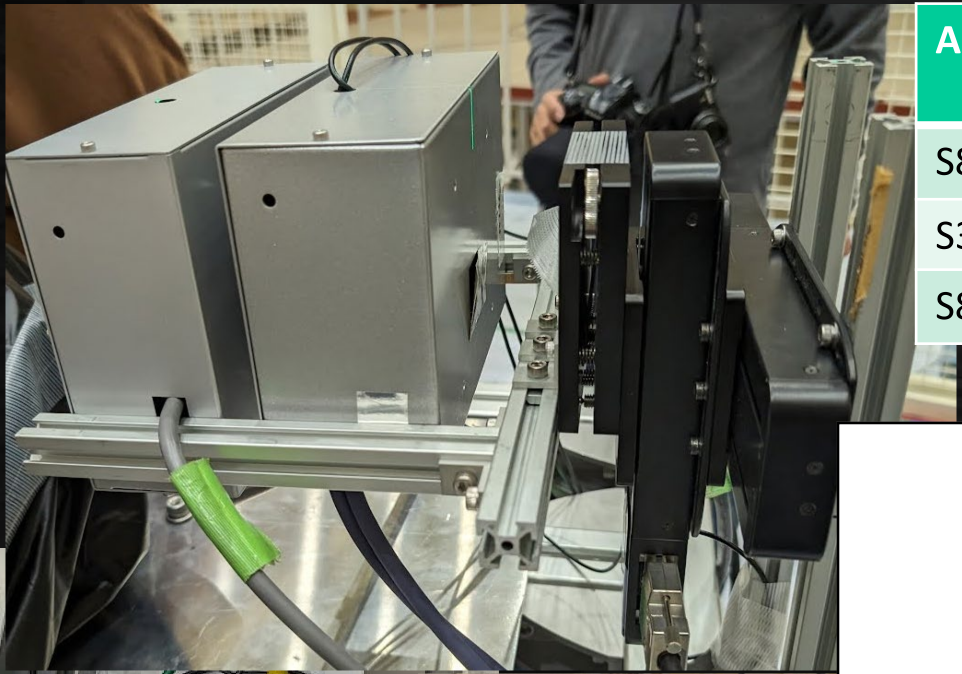
Inverse LGAD can achieve both uniform response and high resolution up to 10 psec
→ try with commercial APDs (from Hamamatsu)

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

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



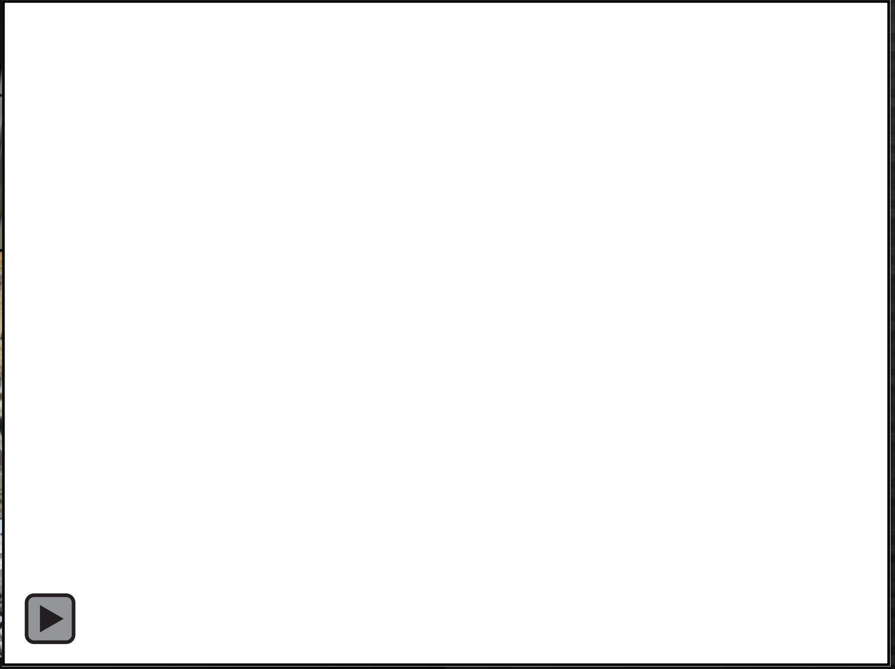
R&S RTO64
Oscilloscope
(2 GHz,
10 GSPS)



Setup @ beam line

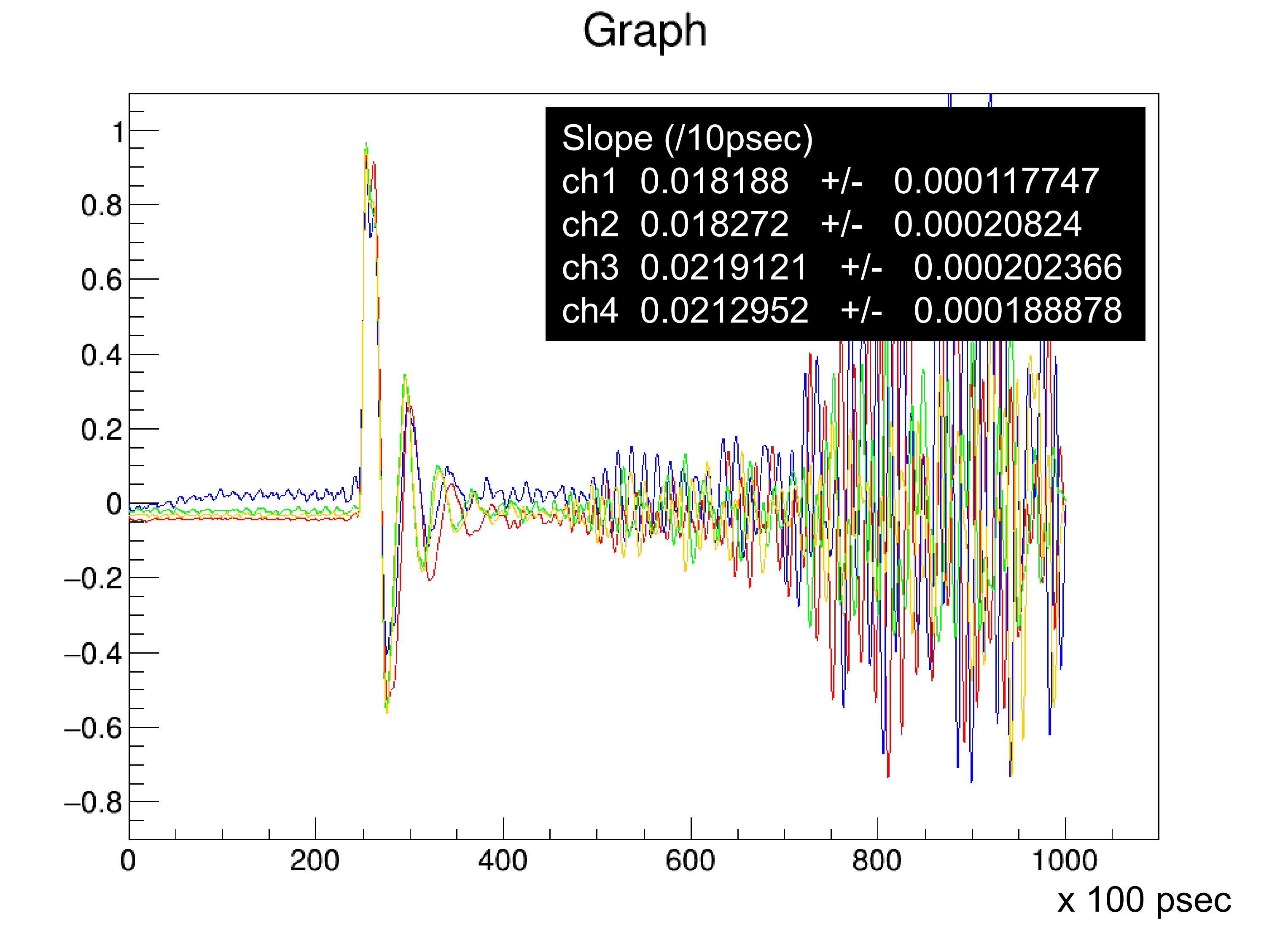
APDs	Type	Size [mm]	Cap. [pF]
S8664-20K	Inverse	2ϕ	11
S3884	Reach-through	1.5ϕ	10
S8664-50K	Inverse	5ϕ	40

Tested sensors



Waveform

Average waveform

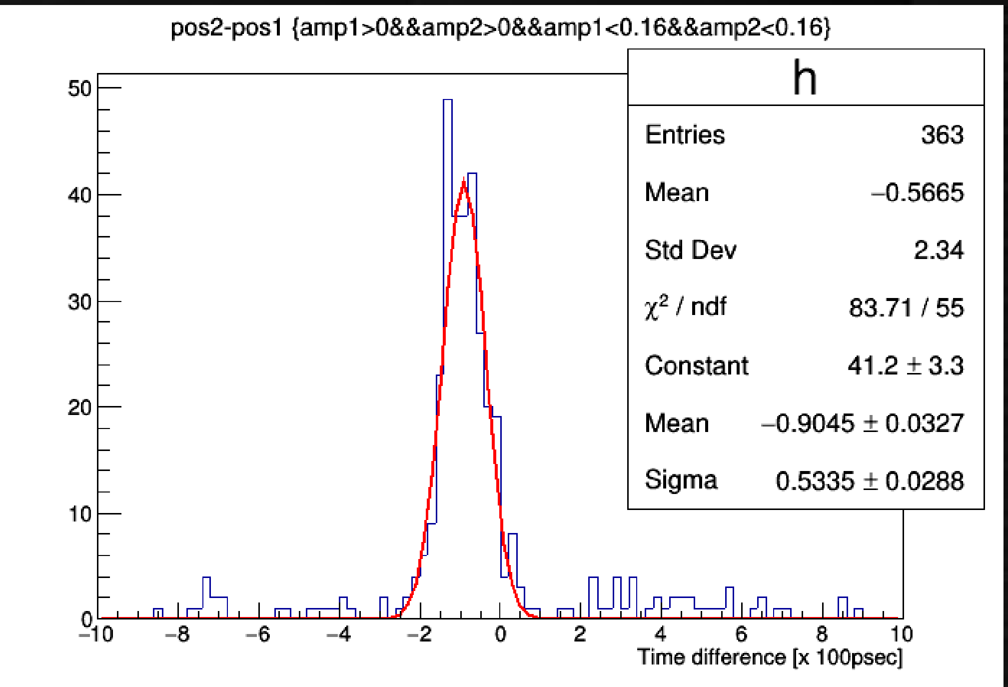


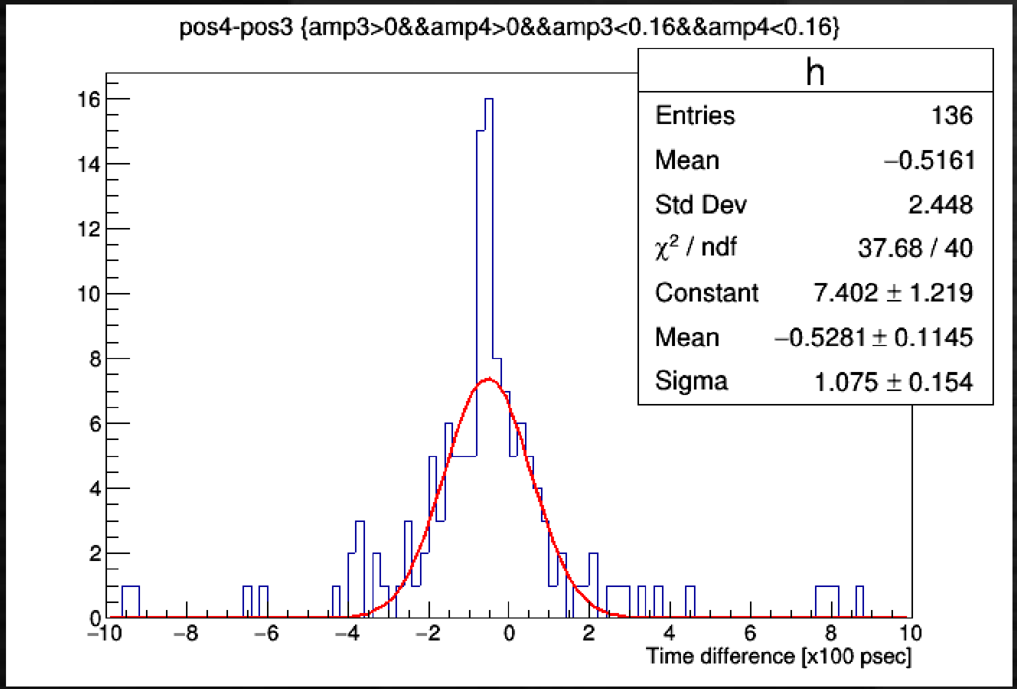
Averaging 500-4000 waveforms

- 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)