D_RD_42: Development of highly-granular silicon-tungsten calorimeter for circular and linear Higgs factories (with summary of HEP_15)

Members

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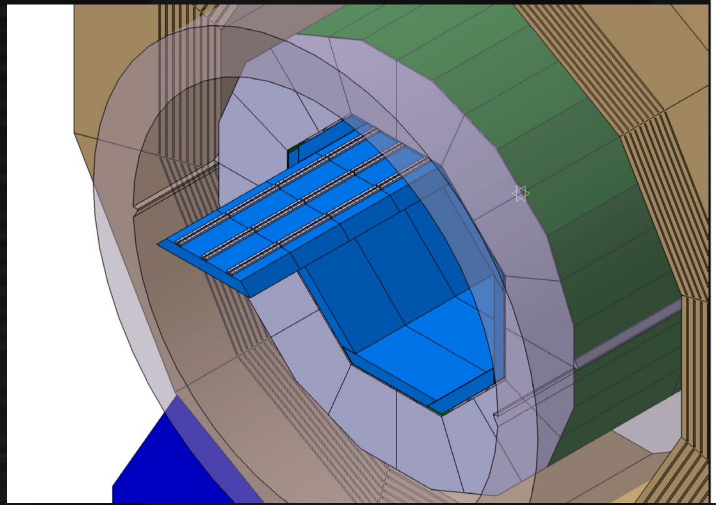
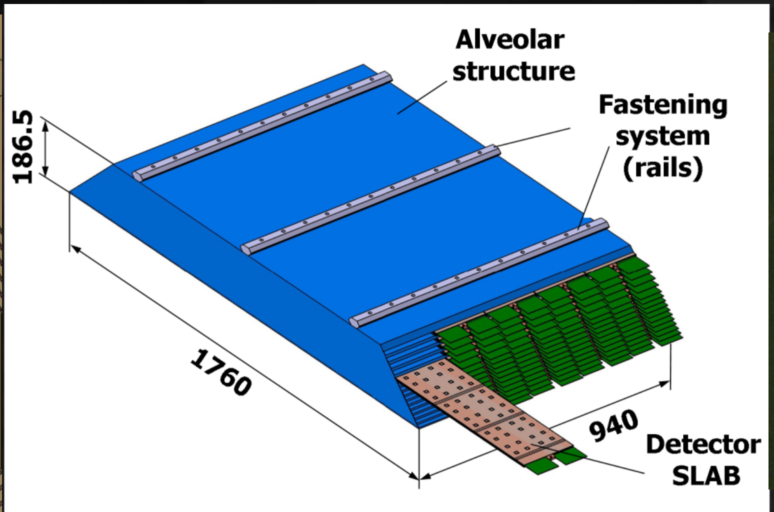
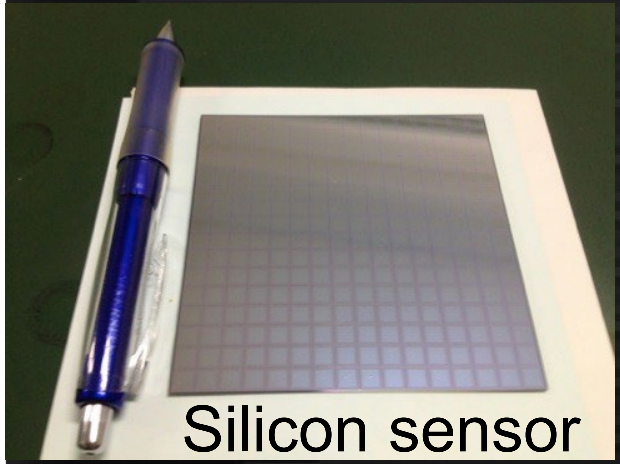
French side: V. Boudry*, H. Liang, Y. Shi (LLR), R. Poeschl, X. Xia, J. Marquez-Hernandez (IJClab)

*Co-PI

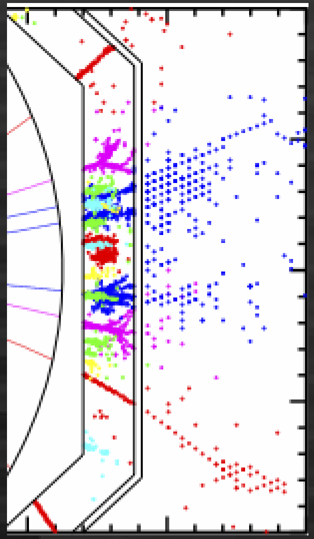
ILD SiW-ECAL: Overview





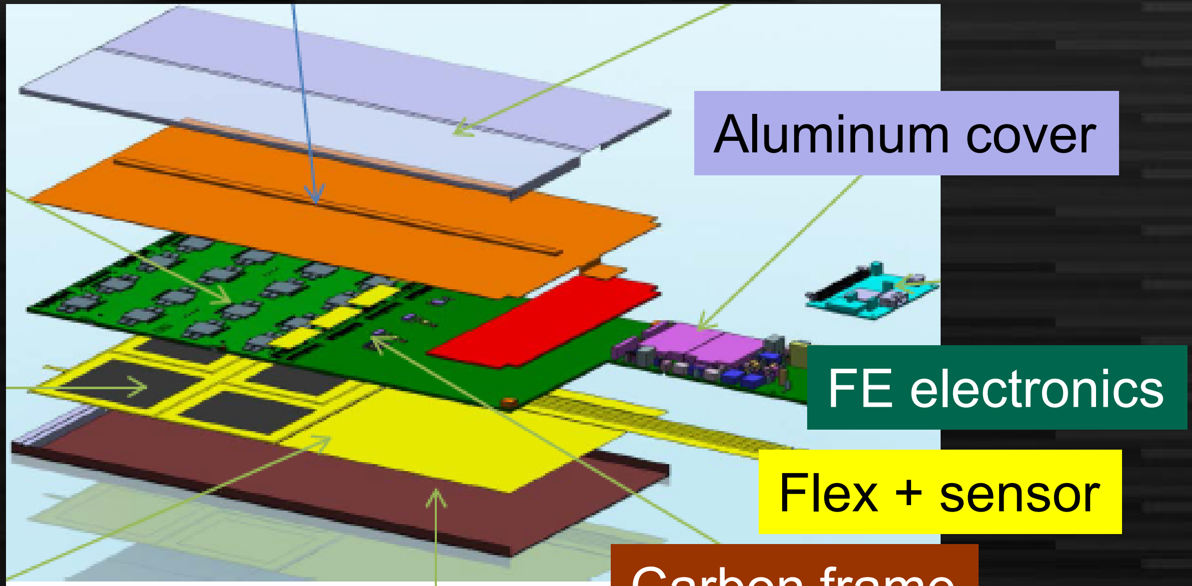


Silicon sensor



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^2 - segmented silicon diodes
(~ 10^8 channels in total)
PCB with ASICs (SKIROC2) embedded



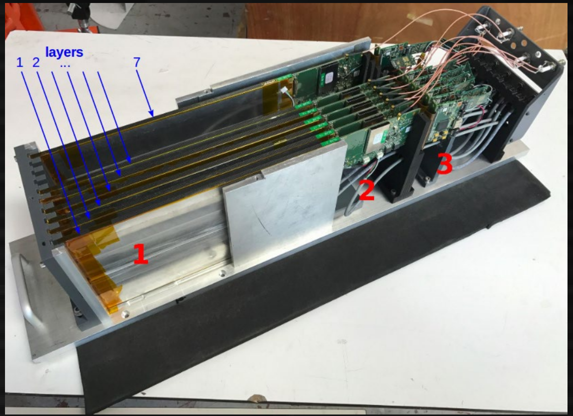
A "short SLAB"

History: HEP_07 and HEP_15

- HEP_07 started as development of SiW-ECAL tech. prototype
  - First layers of technological prototype at ~2013
  - Test beams every 1-2 years since then (DESY and CERN)
    - Including common data taking with analog and semi-digital HCAL
    - Improvements on sensors (GR/thickness), ASIC/electronics, assembly etc.
- HEP_15 was the successor project (2022-25)
  - Issues of long stability on gluing: new method in 2025
    - (non-conductive) adhesive tape to support conductive glue
  - Study on timing sensors (5D ECAL)
  - Particle flow with machine learning
  - Applications (LUXE, EBES)

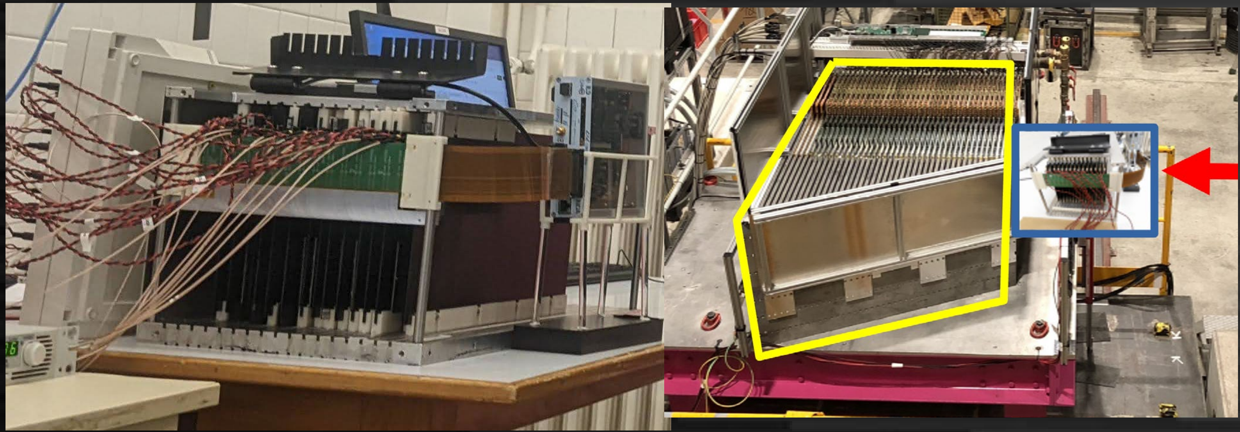
This TYL helped us a lot
esp. on exchange of young students
(8 students accepted for secondment)
leading a few PhDs and many masters

Test Beams – demonstration of technical feasibility

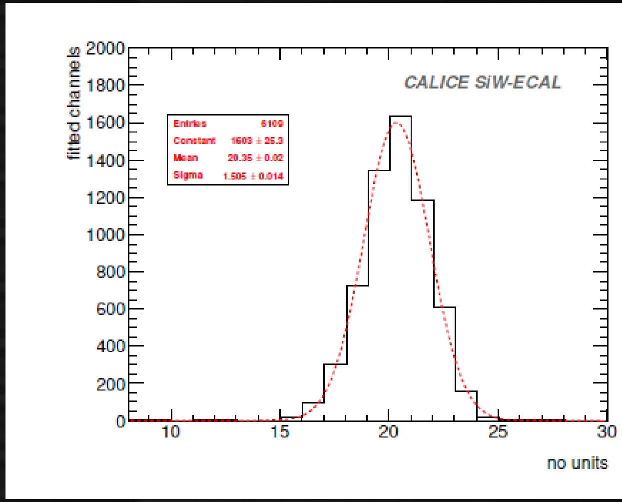


2017 DESY

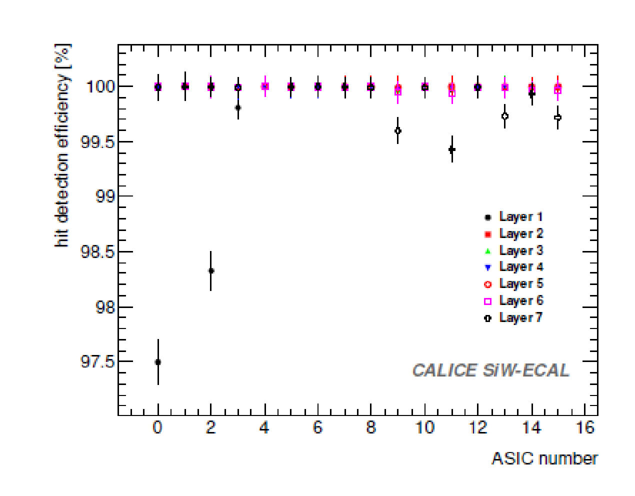
2018 CERN SPS



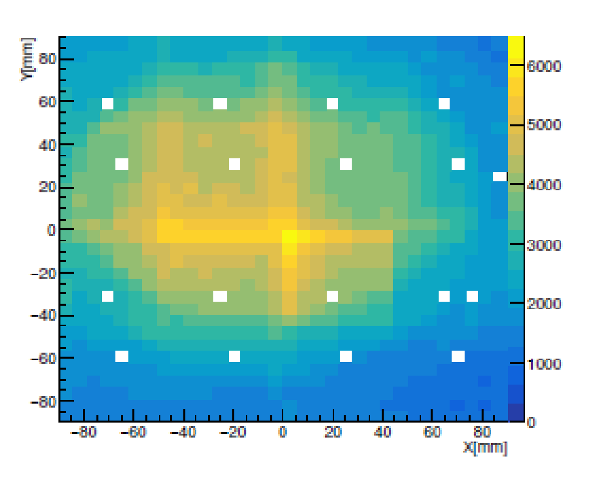
2021-22 DESY and CERN SPS



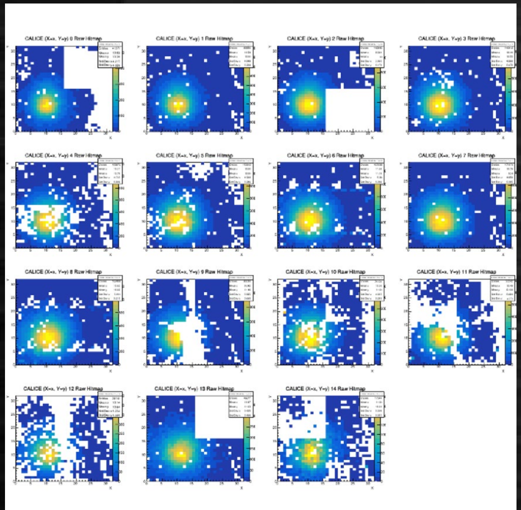
S/N ratio (2017)



Hit efficiency (2017)
arXiv: 1902.00110



Hit map (SPS 2018)

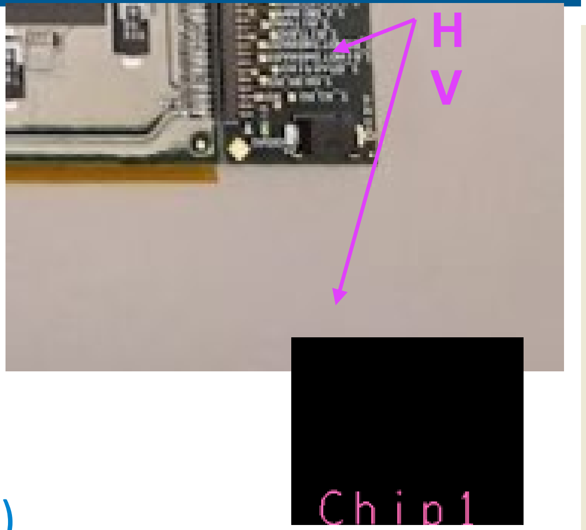


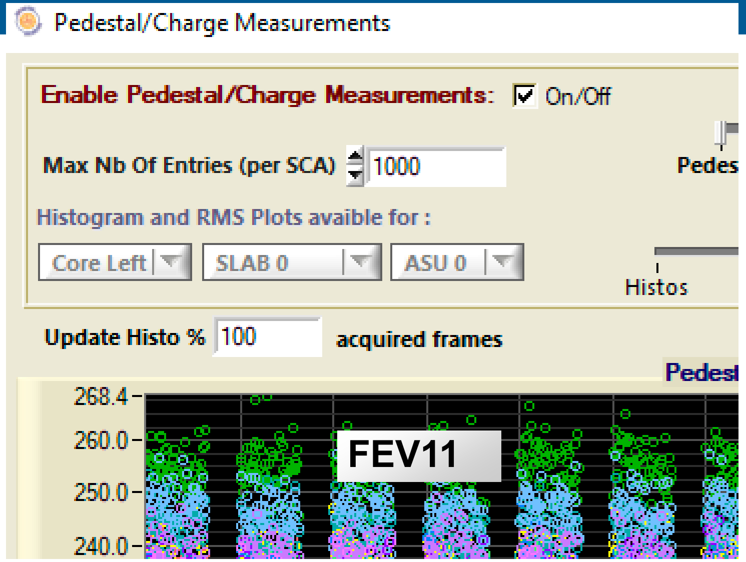
Hit map (SPS 2022)
Delamination issue

FEv2.1 : the (ultimate?) FE boards for the SKIROCs

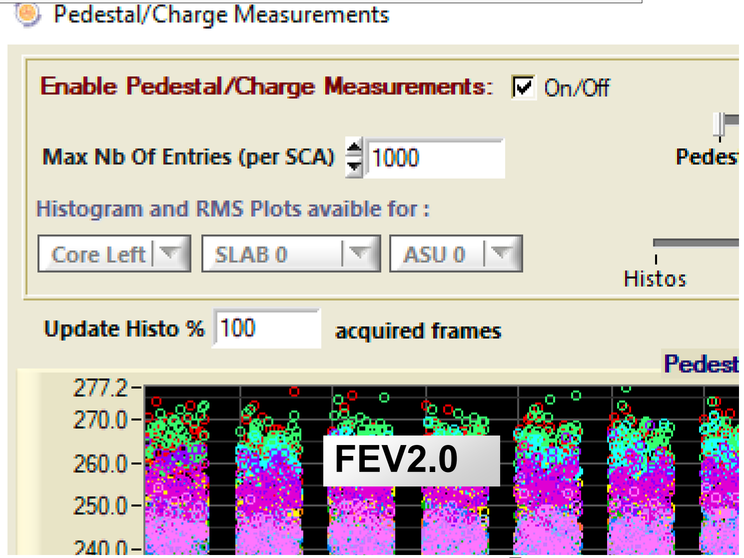
Many Improvements:

- Power & Bias distributions :
  - Local LV power regulation with LDO’s
  - Local HV distribution & filtering
- Signal distribution (buffering), data paths
- Monitoring (single ID, temp, probe analogue line)
- ASIC shielding/routing





Pedestal measurements vs. Ch# + Mem# ✕ 100)



Status:

- Noise uniformity dramatically improved (ex: outliers in thr. / 20)
- version 2.1 produced (minor correction w.r.t. v2.0)

SIngle channel → the fault on the ASIC/packaging

Assembly chain:

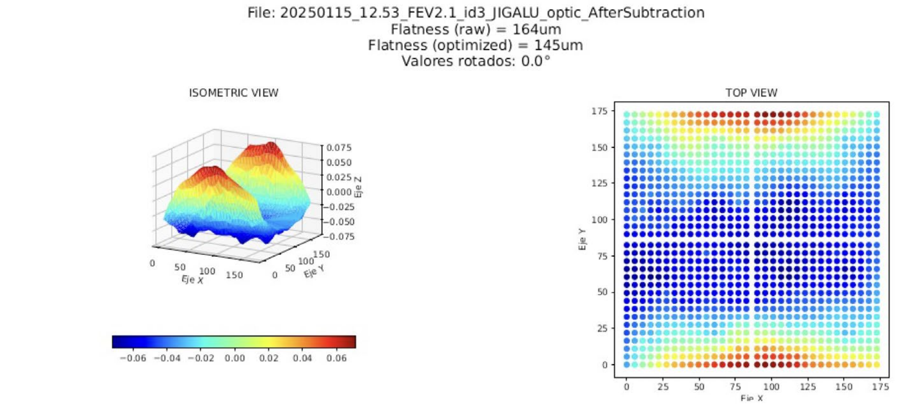
Metrology of PCBs

IFIC INSTITUT DE FÍSICA CORPUSCULAR

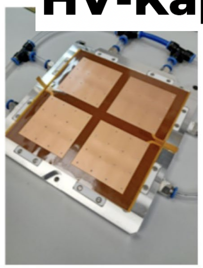
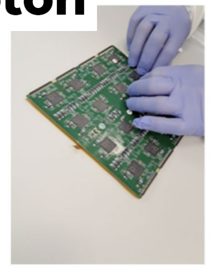
▷ **We could not do conclusive metrologies of the PCBs upon reception**

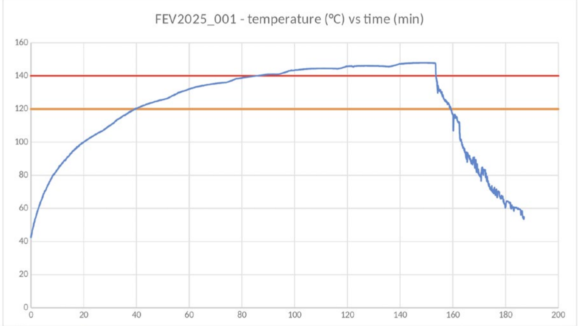
- Small differences between FEV2.0 and 2.1 and w/ w/o components which make the tools available not suitable… we aim for precision mechanics, we require detailed mechanics models and designs
- At arrival + after drying, requires at least 1 month of time for the full process. → so we decided to dry them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

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

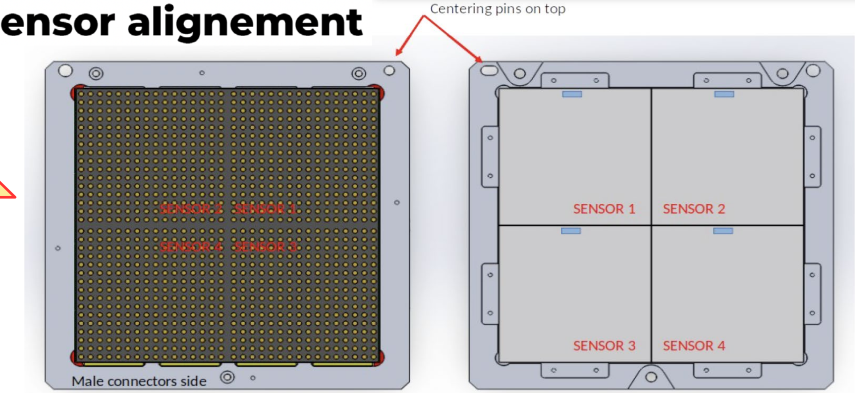


HV-Kapton



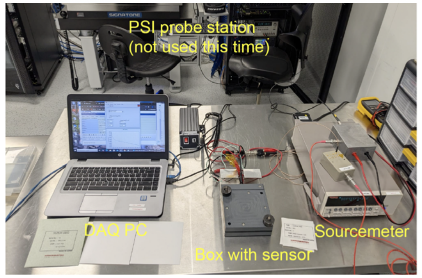
Sensor alignement



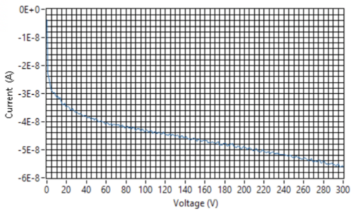
- PROCEDURE - 3D robot and precifluid v0.odt
- PROCEDURE - CALICE ASU gluing_alignment v0.odt
- PROCEDURE - CALICE ASU gluing v0.odt
- PROCEDURE - H20E preparation v2.odt
- PROCEDURE - HV-Kapton to ASU v0.odt

Sensor characterization

(Simplified) Setup at IJCLab



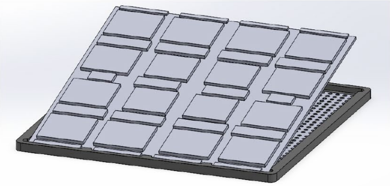
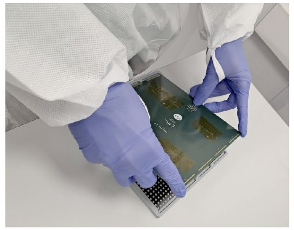
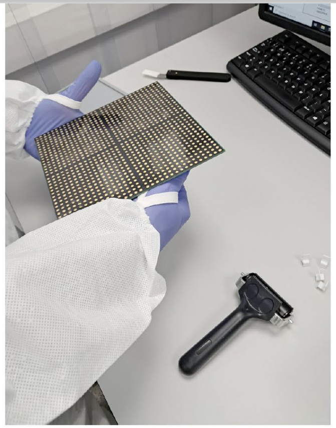
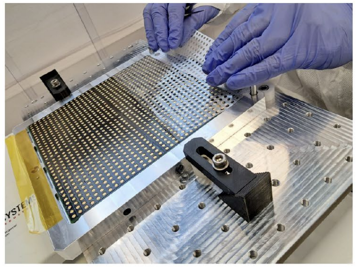
Typical I-V Curve



- 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

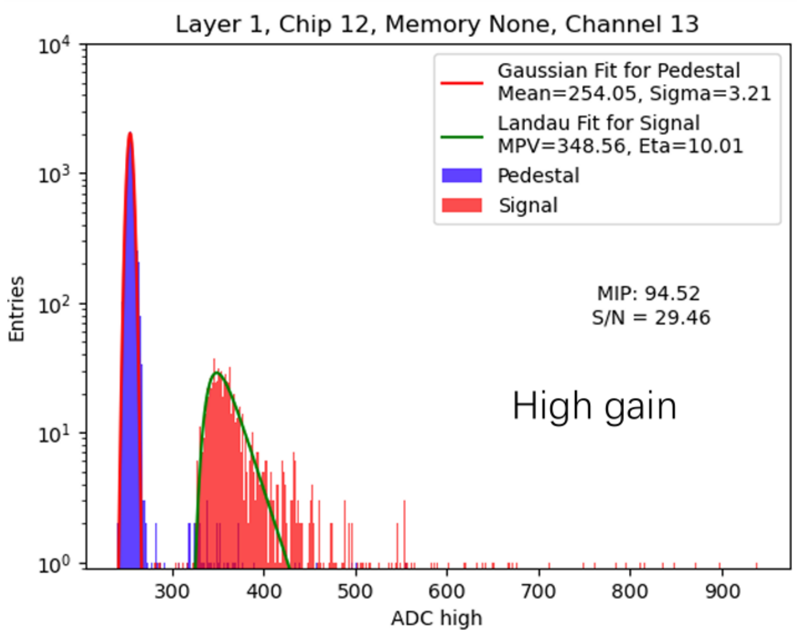





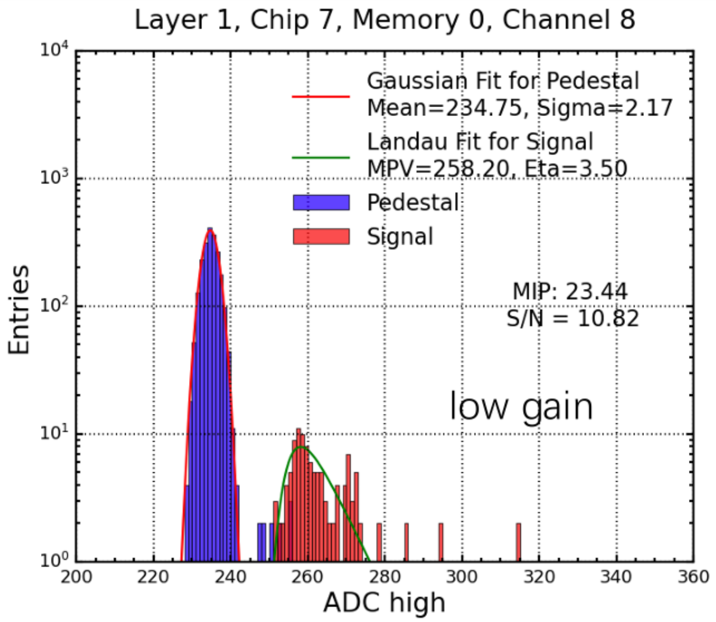
3M tape

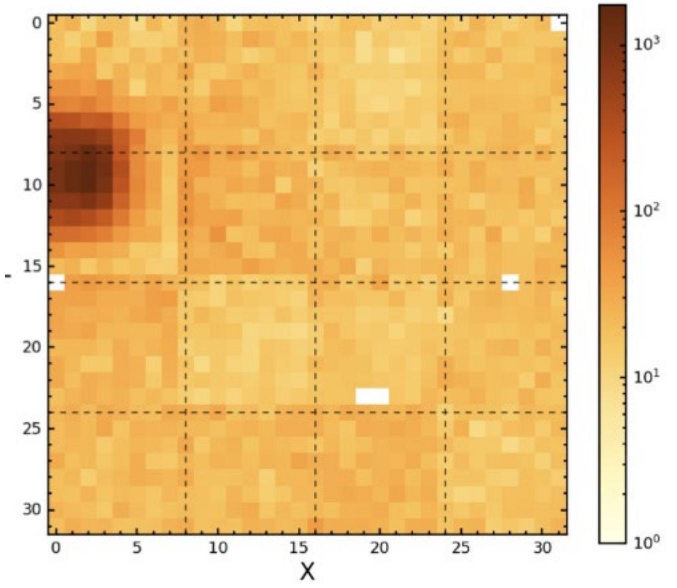
HW readiness

Two FEV2.1 boards have been tested at DESY in March 2025 (low-E e⁻ without W absorbers)

– Worked perfectly: “out of the box”, 2‰ masked channels (without fine tuning), in low gain mode







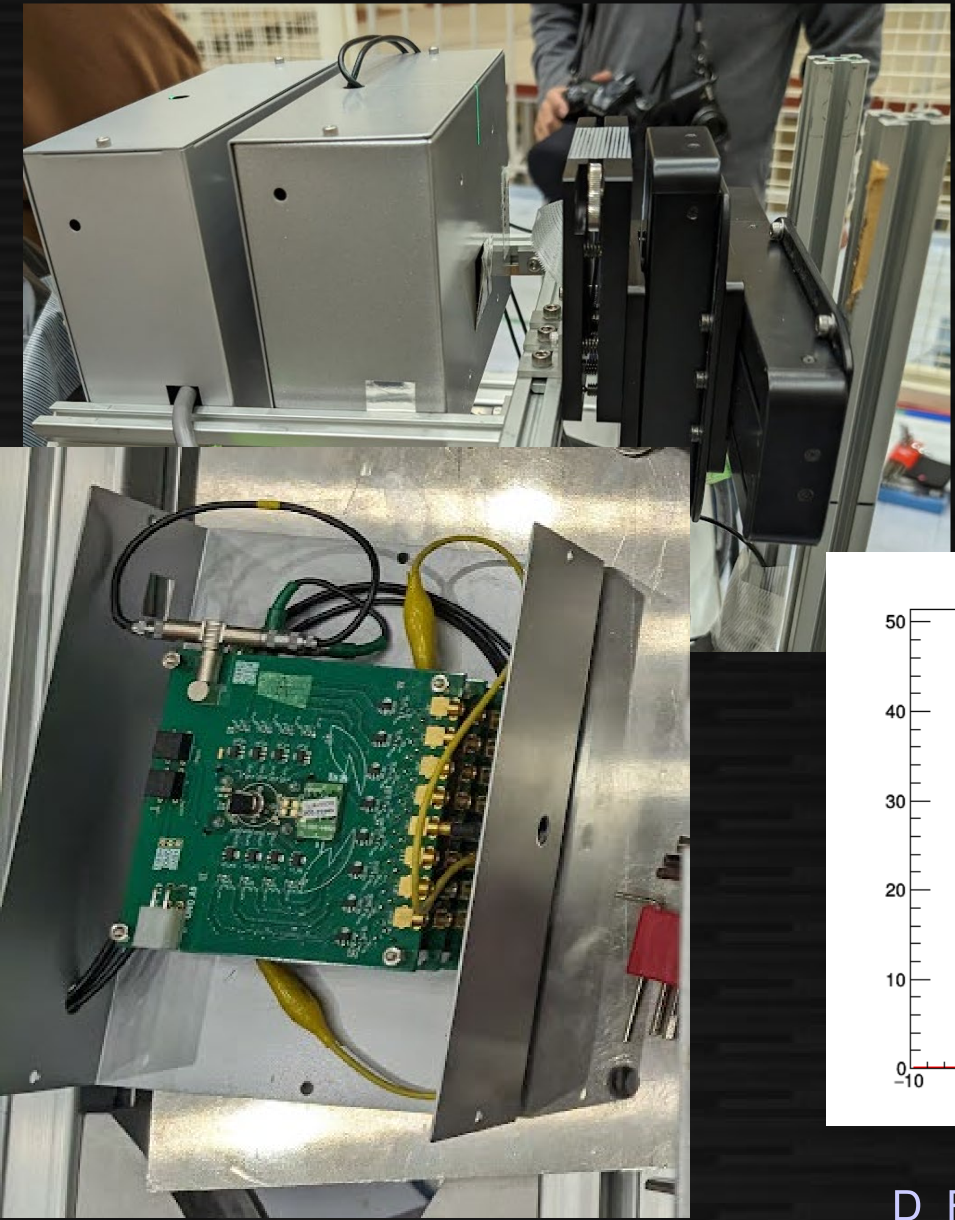
– Run in lower gain mode possible (~ standard for high dynamic range)

– Tentativeof TDC enabling : not conclusive (but was a maybe bit hastly)

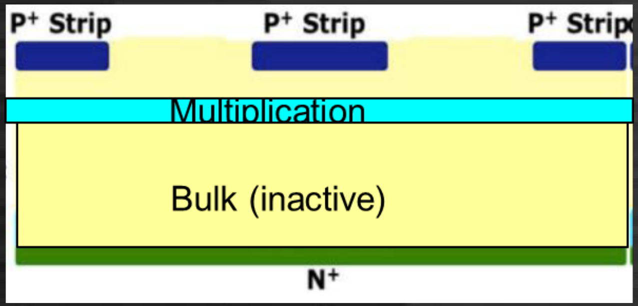
Xin Xia (IJClab)

Readly to go to full prototype!

Timing sensors: test at PF-AR

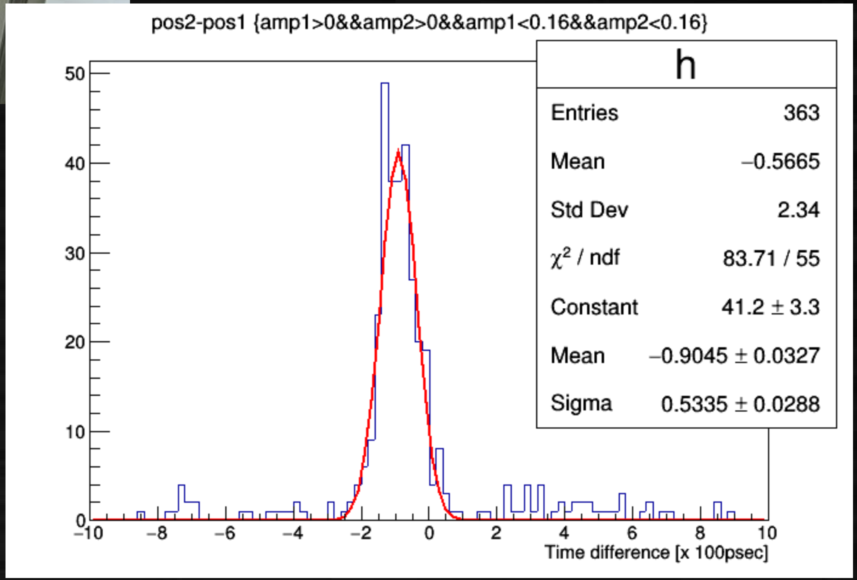


2 x 2 APDs
(S8664-20K, S3884)
1 trigger APD (S8664-50K)



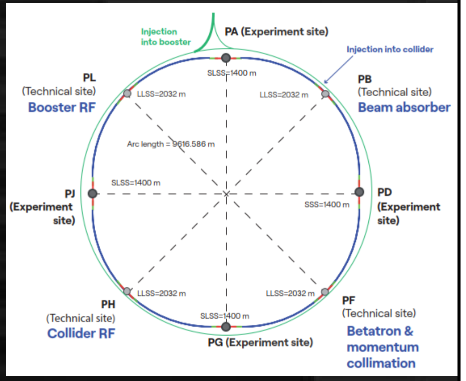
Inverse LGAD (single sided)

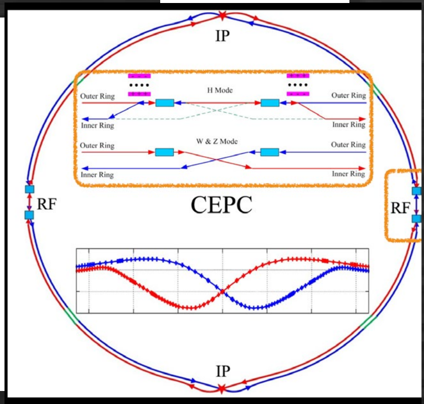
APDs	Type	Size [mm]	Capacitance [pF]
S8664-20K	Inverse	2ϕ	11
S3884	Reach-through	1.5ϕ	10
S8664-50K	Inverse	5ϕ	40



Inverse APDs have excellent timing resolutions (<30 psec Landau noise) but seem to have issues in lower signal strength
Dedicated ASIC may be needed for further studies

D_RD_42: SiW-ECAL for circular and linear colliders

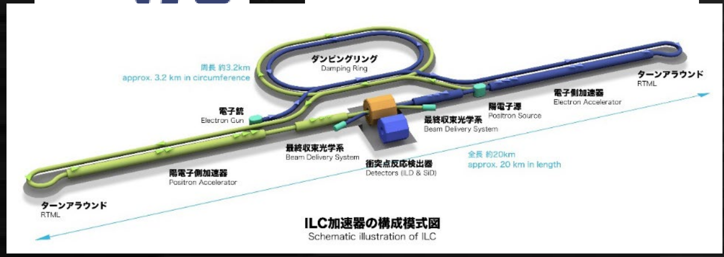




1. Motivations for new SiW-ECAL development

- Strong candidates of e+e- Higgs factory: FCC-ee and CEPC
- Common effort with LC possible for detector development
  - Most of the requirements are similar
- Some difference exists: necessary modifications
  - Continuous readout: redesign on readout and heat dissipation
  - Tolerance on higher collision rate – not serious on calorimeters

2. Research topics



- Finalizing current prototype: full SiW-ECAL for pulsed readout
  - Would be used for applications of non-colliders
- Redesigning of SiW-ECAL prototype compatible for circular/linear
  - CALOROC for continuous readout
- Rapidly developing AI: PFA becomes one of the major targets

(Almost) Uniform Prototype:

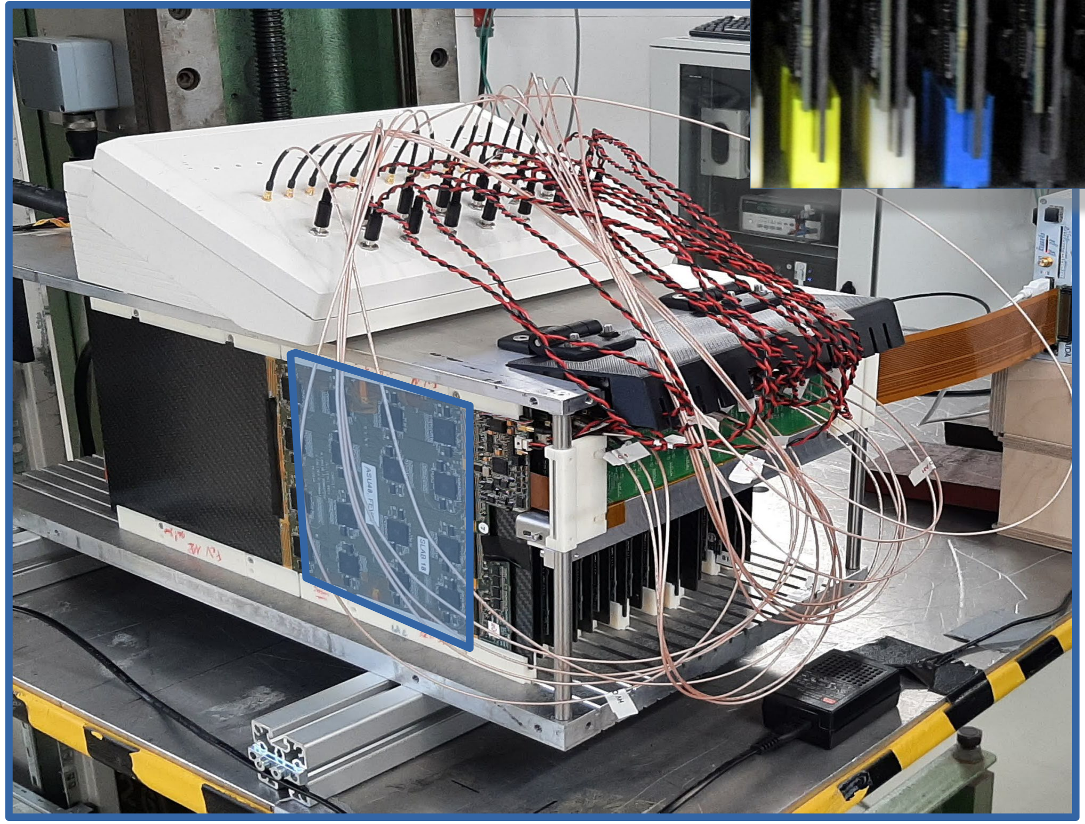
A Stack of 15 uniform sensor layers, separated by W absorbers (non-uniform)

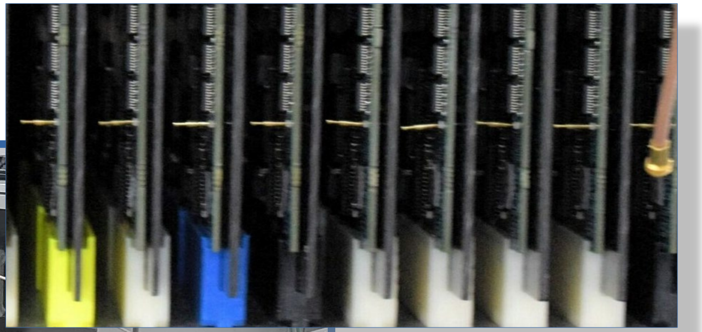
- 15 Sensor layer made of :
  - 4 wafers [500 µm × (16×5.5mm)² Si PIN Diodes]⇒18×18 cm²
  - 1 PCB (FEv2.1)
  - 16 ASICs (SKIROC2a)
- Tungsten absorbers:
  - 8 × **4.2 mm** [1.2 X_0] + 7 × **5.6 mm** [1.6 X_0]

    Total= 20.8 X0

Stack is being prepared in EU:

- Test of wafers & glueing in IFIC Valencia
- Commissioning in IJCLab/LLR

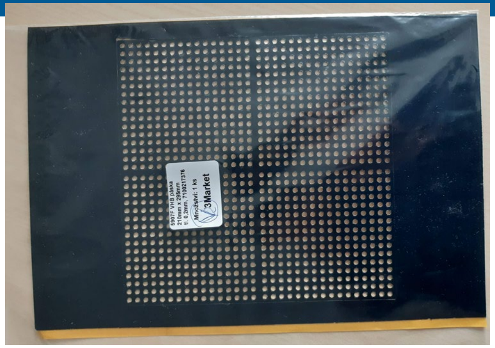


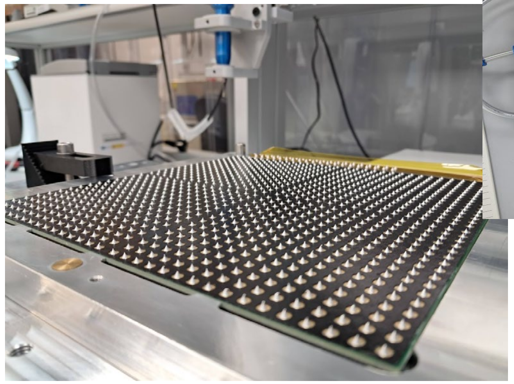


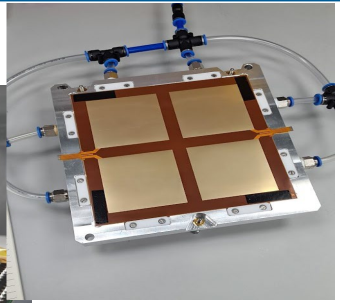
HW Readiness

13 additional boards in production

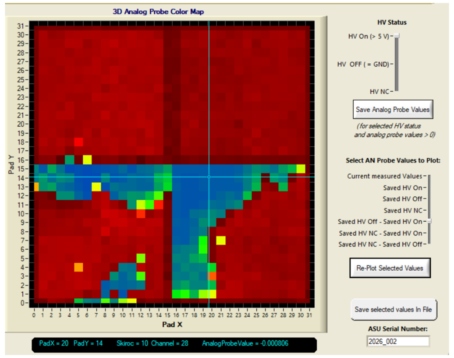
- Supplies: ✓
  - 13 HV Kaptons ✓
  - 13 3M gluing tapes (DMLab) ✓
  - 13 new FEV2.1 produced (soldered) in December, tested in January (IJCLab) ✓
  - 52 wafers available, 26 fully tested (rest in ≤ 3 weeks, IFIC) ✓
- 9 new boards assembled, with lower curing temperature
  - Tests in IFIC and IJClab with analogue probe (connectivity map) and 90Sr sources
  - Still some flatness issues, one board incompletely glued
    Rest seems OK (tests just started).
- 4 boards to be glued & tested in 2 weeks



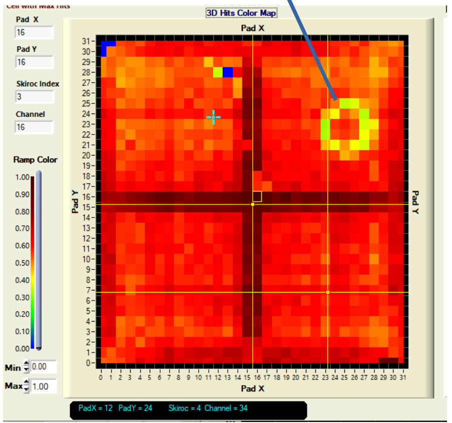




Roman's wedding ring



"HV-on – HV-off" map



^{90}Sr quick response (Hit map, 5 mins)

Aim of the test

Goal 1: establish the **proper response to e⁻** over the full range of Energy

- First check the response at low and high E (~20 GeV, ~100 GeV)
  - Previous unexpected features: missing cells, delamination, collective effects at HE (~recovery time of HV)

Goal2 : measure the **performances for e⁻** (as proxy for γ's)

- Calibration of every cell using a large muon beam ➞ MIP energy scale and noise, timing
- Quantify the e⁻ response in the range from 10 (5?) to 160 GeV, in equals steps of $\sqrt{E}$
- Check the uniformity of response in a (x,y) scan

Goal 3: record the response to **low energy π's** 10–30 GeV

Goal 4: prepare a **reference sample for GEANT4 :** standardized sample, ⊃ digitizer (with timing)

Test beam period: 17-25 June 2026 at CERN SPS

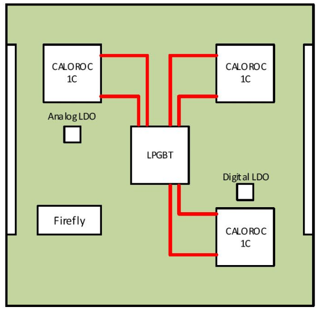
Fast Forward

New Electronics: CALOROC1C (for Si and ℓAr, based on HKROC and HGCROC)

- 1st prototypes being packaged
- New technology (TSMC130ns)
  - < 10 mW/ch
- Adapted for continuous readout, low occupancy
  - ➞ New FE boards :
    - I2C, data concentrator (lpGBT), cont. data flux, improved timing performances
    - 1st prototype based on HKROC (~ pin-2-pin compatible CALOROCs)

New front end boards for FCC

- Study new chips CALOROC
  - Adapt HKROC test board for Si sensors
- Study clock distribution system
- Study LPGBT to aggregate data
- Propose design with 3 CALOROC (108 chn)
  - I2c (slow control)
  - Clock distribution
  - LPGBT or similar
  - Power distribution
  - Measure power, noise, temperature, performances
  - Solution to chain boards
- Propose design for 512 channels
  - Equivalent to 5x miniFEB
  - Power estimation: 37mW/chn



Power estimation: 46mW/chn

J. Nanni @ French FCC-DRD WS, nov2025

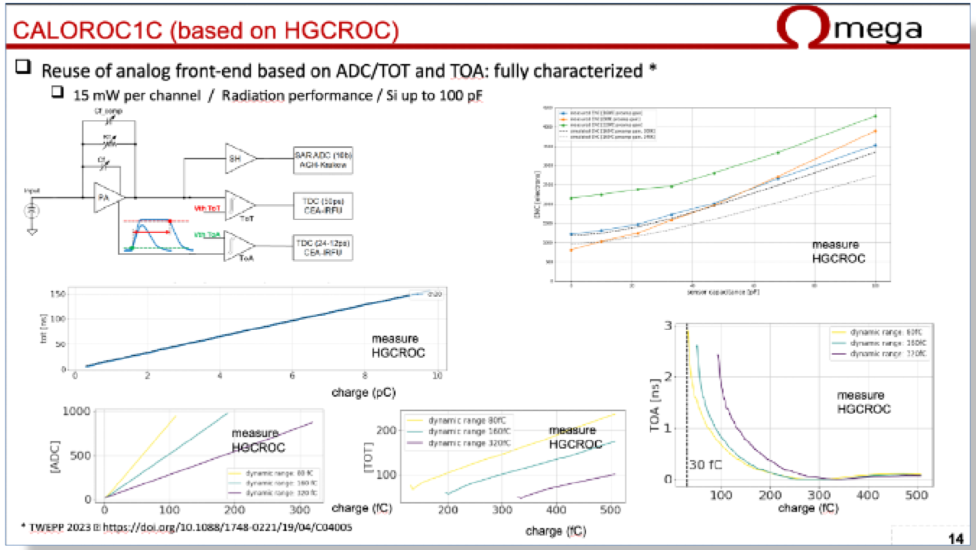
Recent Progress: CALOROC1C design (Si and ℓAr) – Ωmega

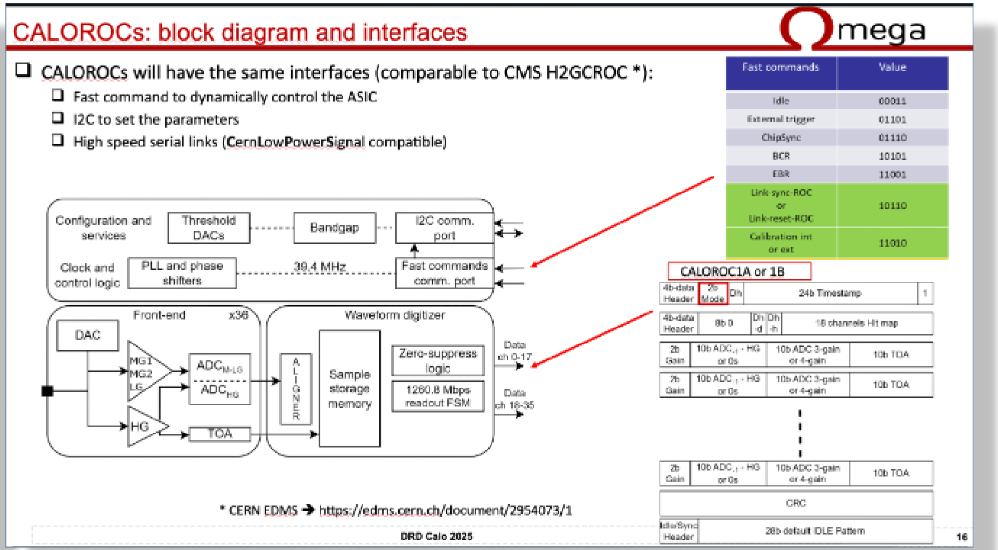
New ASICs

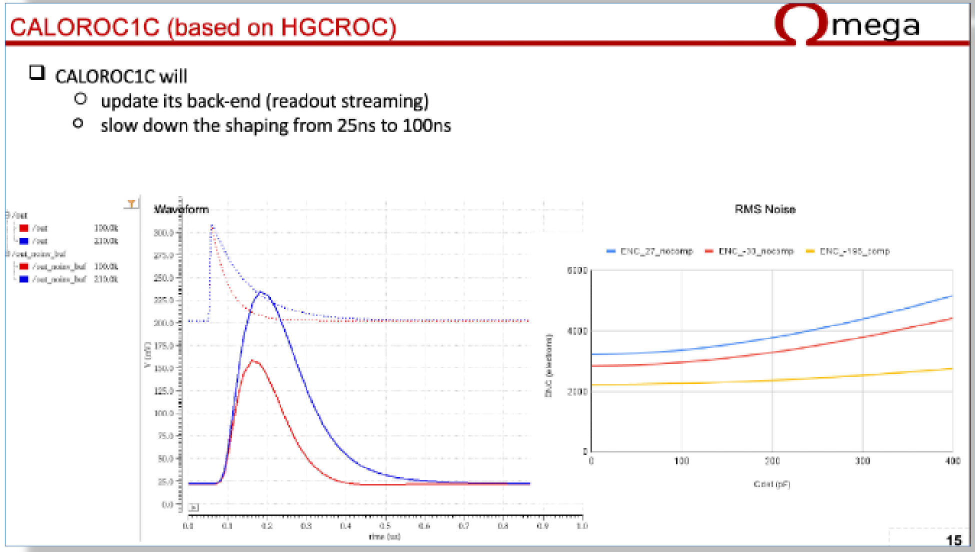
- Based on HGCROC, HKROC

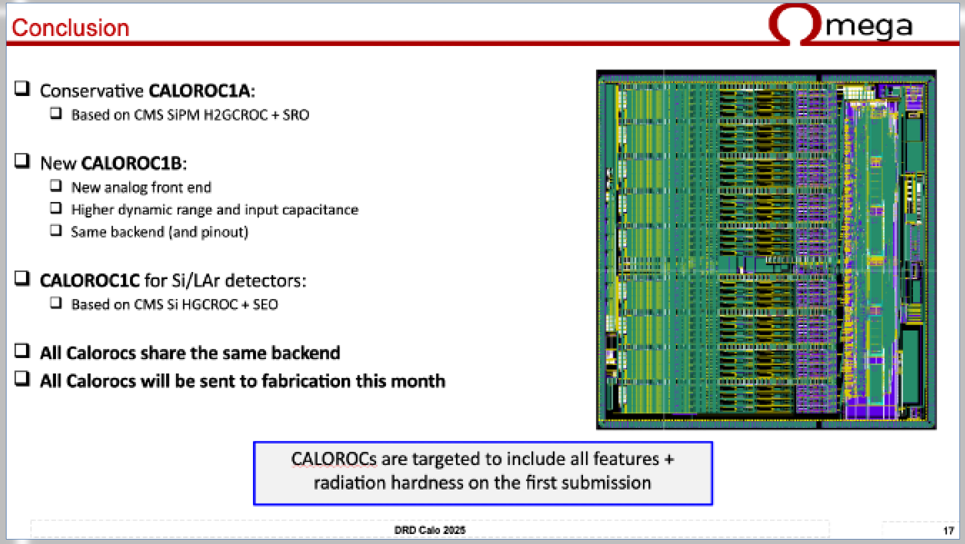
‘Almost’ Compatible:

- PCB & DAQ work can start with HKROC









Towards a Compact cooling system

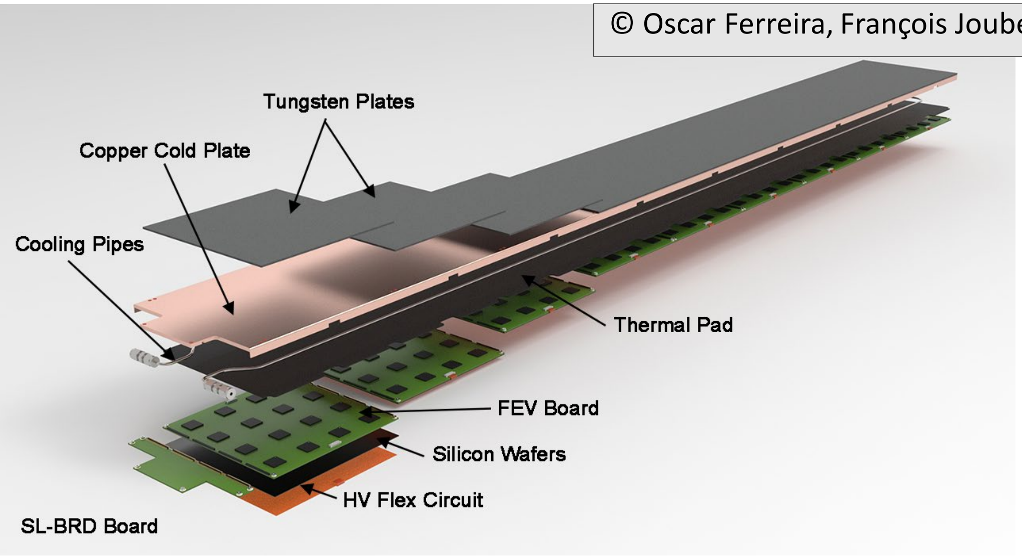
“Boosted Standard Slab”

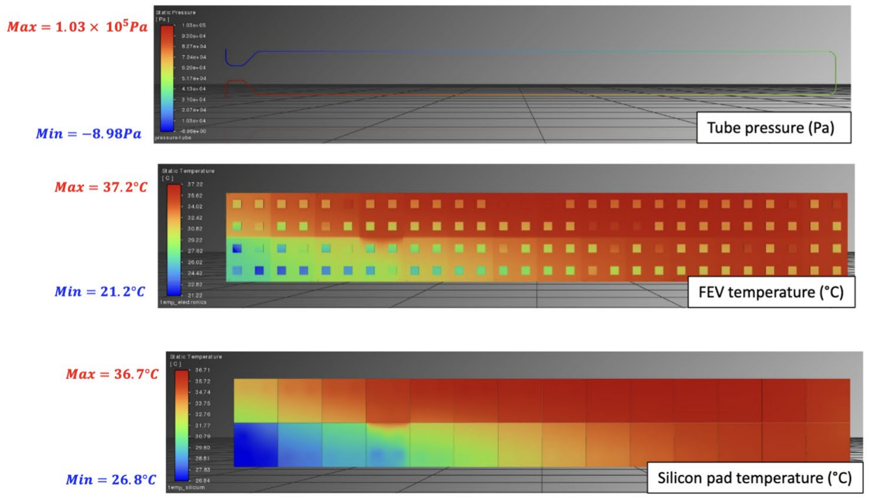
- ➞ 210W (30W/ASU) : ASICs + Concentrators + PS…
  - (ILC like in CC ~ 130W)

Active cooling:

- 4 mm Cu plate with 1/8’’ Stainless Steel Tubing
- 0.2 ℓ/min of water @ 15°C

Simulations
Adiabatic, but for heat bridge at the end, $t = \infty$





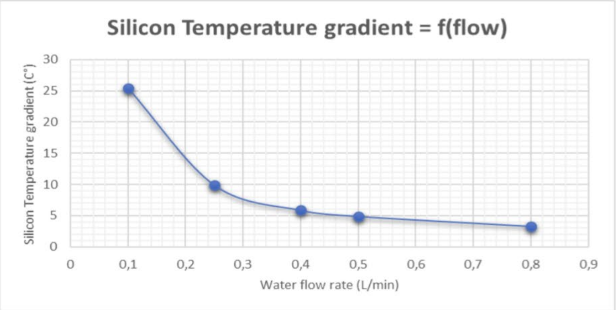
Inlet flow rate : 0.25L/min

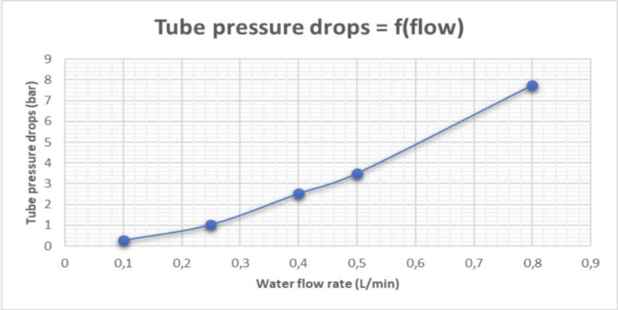
Results :

- Pressure drop : 1.03 bar
- **Silicon temperature gradient : 9.87°C**

- Preliminary results resumed in the following graphs.
- Operating point between **0.25 L/min** and **0.45 L/min** for allowable pressure drops.

Prototype is being built (LLR)





Yearly plans

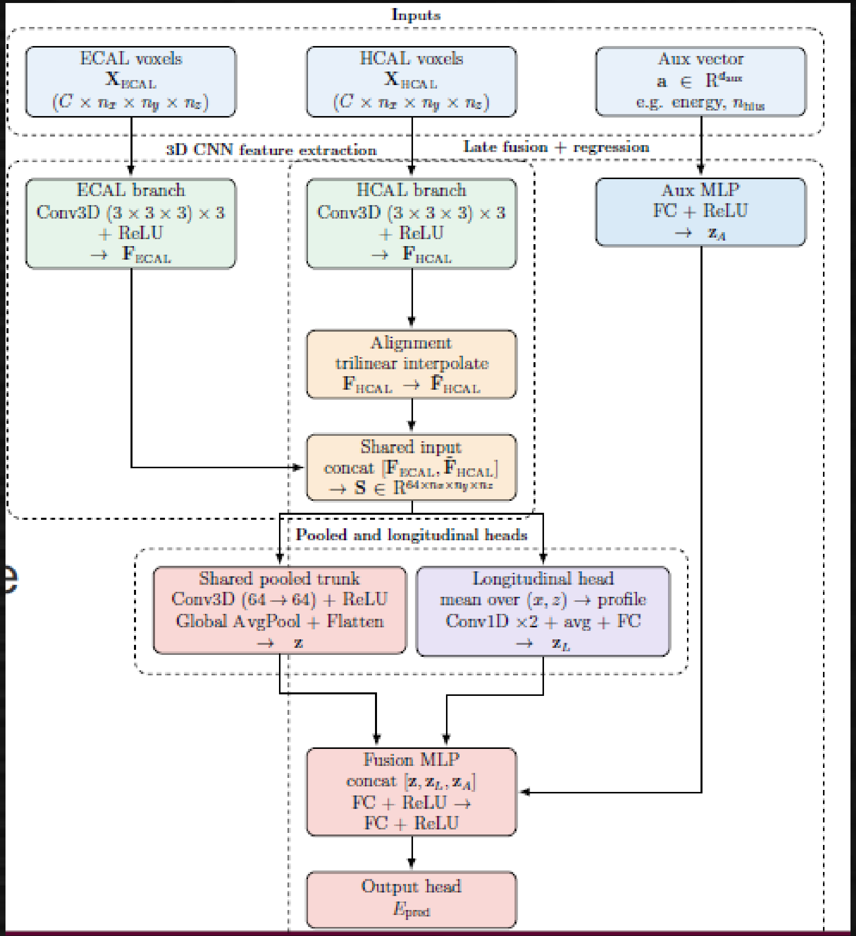
- 2026: Complete test beam with 15 layers and SKIROC2A
  - Paper aims to be published in 2026 or early 2027 if layers work appropriately
- 2026: CALOROC test, Design of compatible frontend
- 2027: production/test of first layers (with small sensors?)
- 2028-29: test of full prototype
  → full demonstration of SiW-ECAL with continuous readout
  - Also long slab to be tested
- 2027-28: realistic design for FCC-ee
  - To meet detector call

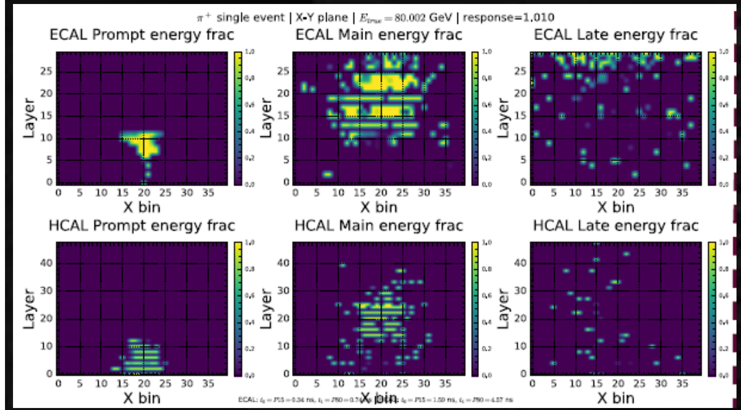
ML activities on calorimeter reconstruction

- Rapidly increasing activities in both FR and JP sides!
  - JP: AI for science is promoted from MEXT with multiple funding
- Energy regression of single particle
  - 3D-CNN model for improving hadron resolution (FR)
  - Calibration/regression of test beam geometry (JP)
  - Study on detector configuration (FR)
- Particle flow and detector optimization
  - GNN particle flow (+ improvements with cross attention) (JP)
    - With and without timing info
- JP-FR collaboration: a few meetings/year, to be more activated

Energy regression of single particles

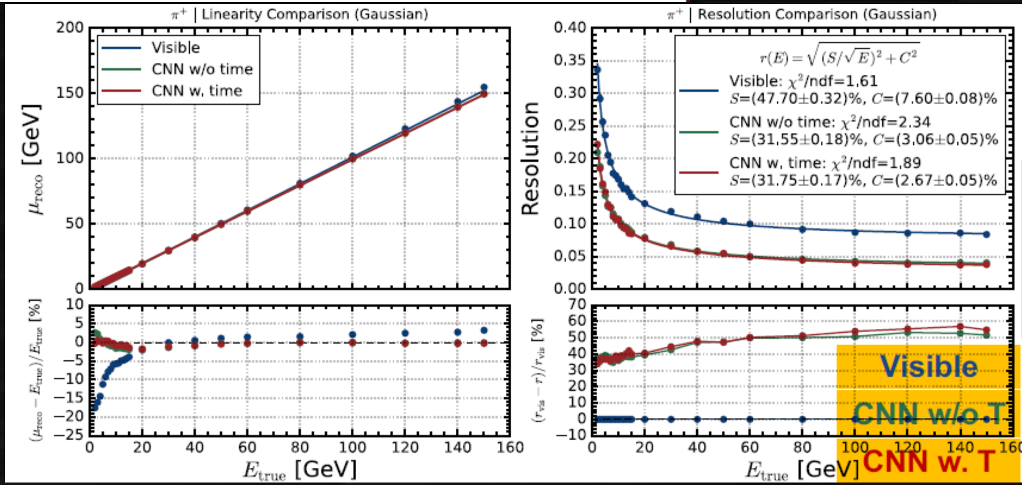
- ILD detector model (SiW-ECAL + AHCAL)
- 3D-CNN based model with optional timing (prompt, main, late)





Big improvements on pion:
stochastic term 48 → 32%

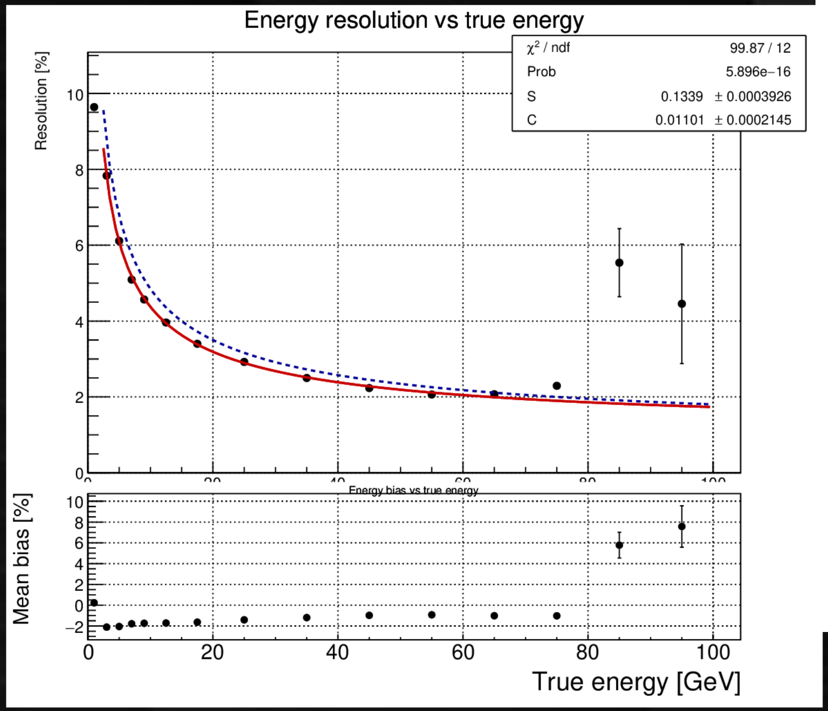
X. Xia (IJClab)



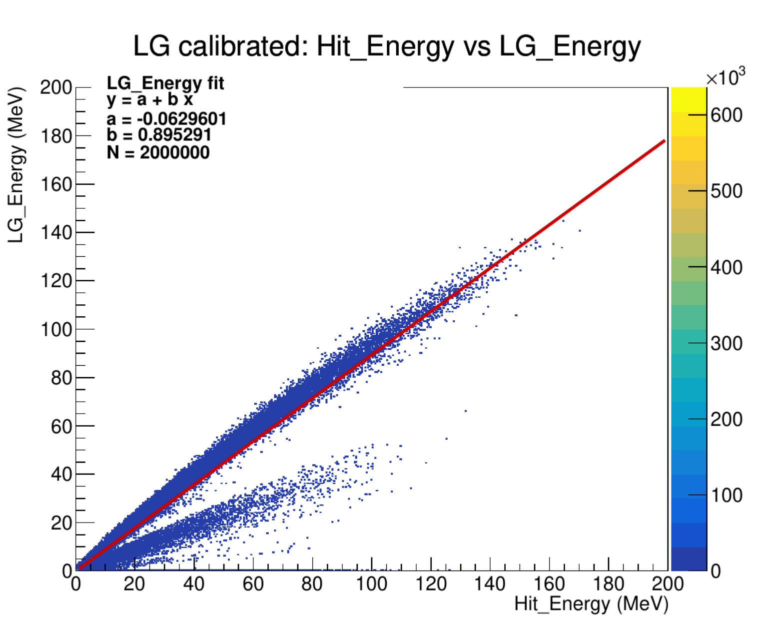
	Linearity	Resolution $r(E) = \sqrt{\left(\frac{S}{\sqrt{E}}\right)^2 + C^2}$ S	C
Visible	18%	47.7%	7.6%
CNN w/o T	3%	31.6%	3.1%
CNN w. T	2%	31.8%	2.7%

Energy regression with GNN for test beam

- GravNet + MLP + regression loss on ScECAL test beam geometry
  - GravNet structure similar to GNN-PFA algorithm
  - RMS loss normalized by expected E reso on 15%/sqrt (E) + 1%
- FiLM technique for calibration
  - Additional filter to input of GNN to implement TB to sim conversion
  - (ongoing work)



13.4 % / sqrt(E[GeV]) + 1.1%



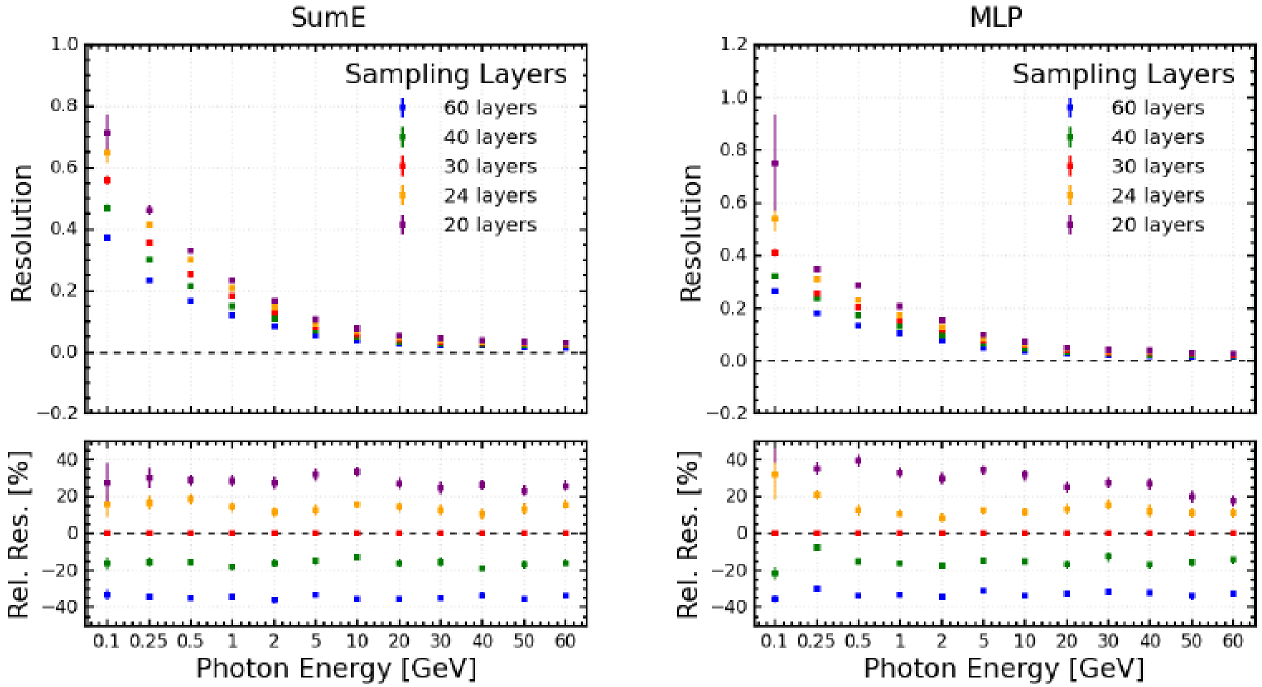
Calibration factor applied to realistic TB sim. (ongoing)

Photon reconstruction by various detector config.

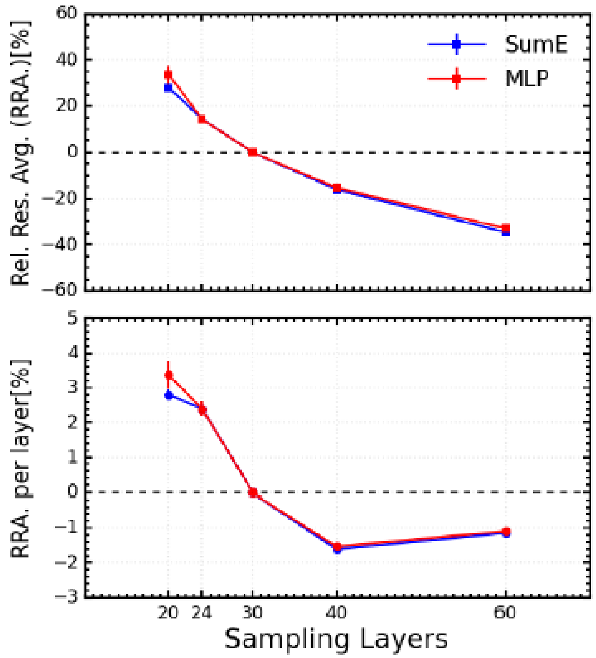
Number of Sampling Layers

Y. Shi (LLR)

- The MLP benefits more from finer longitudinal segmentation
- At least 24 layers needed for MLP, but increasing the sampling layers leads to diminishing returns above 40, 30 layers were recommended



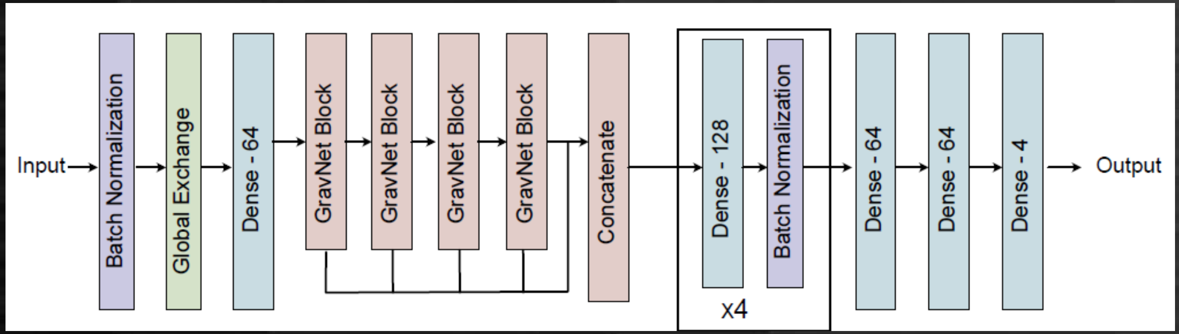
Resolution of ECAL with different sampling layers



Resolution improvement per layer

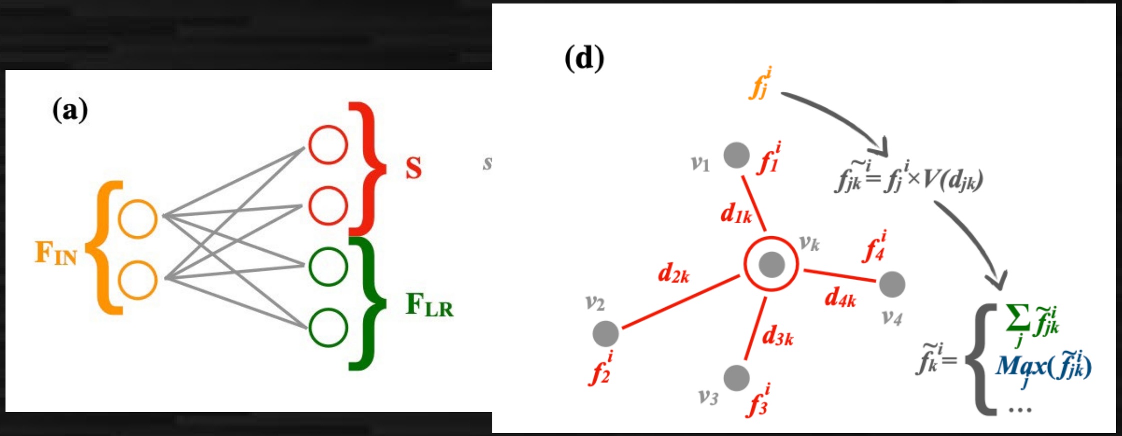
GNN-based PFA

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



GravNet arXiv:1902.07987

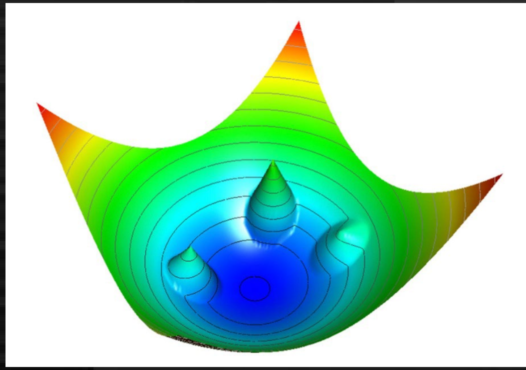
- The virtual coordinate (S) is derived from input variables with simple MLP
- Convolution using "distance" at S (bigger convolution with nearer hits)
- Concatenate the output with MLP



Object Condensation (loss function)

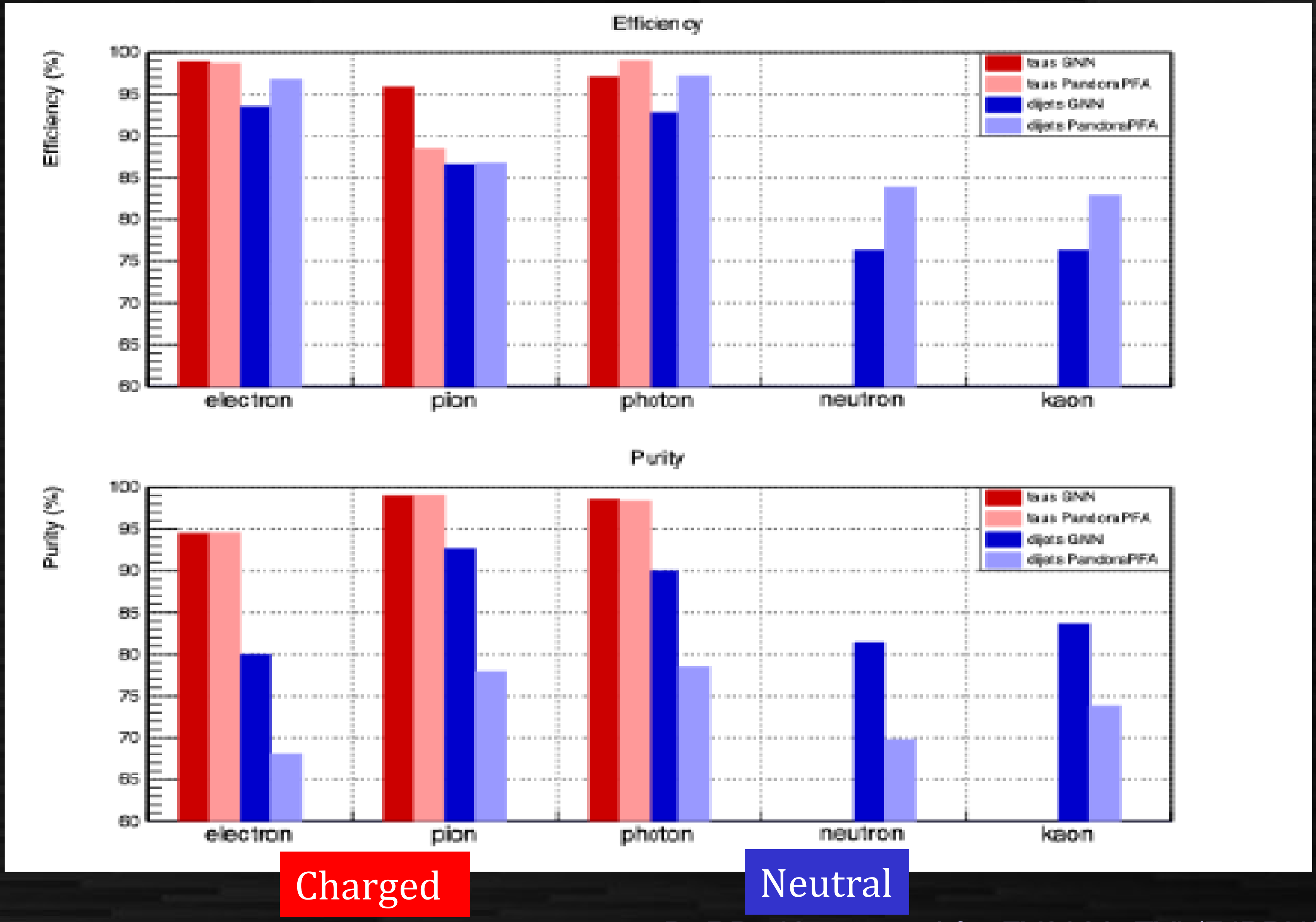
arXiv:2002.03605

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



- 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

Clustering performance: GNN vs Pandora



T. Murata (UTokyo)

Red: 10 taus
Blue: di-jets
Thick color: GNN-based PFA
Thin color: PandoraPFA

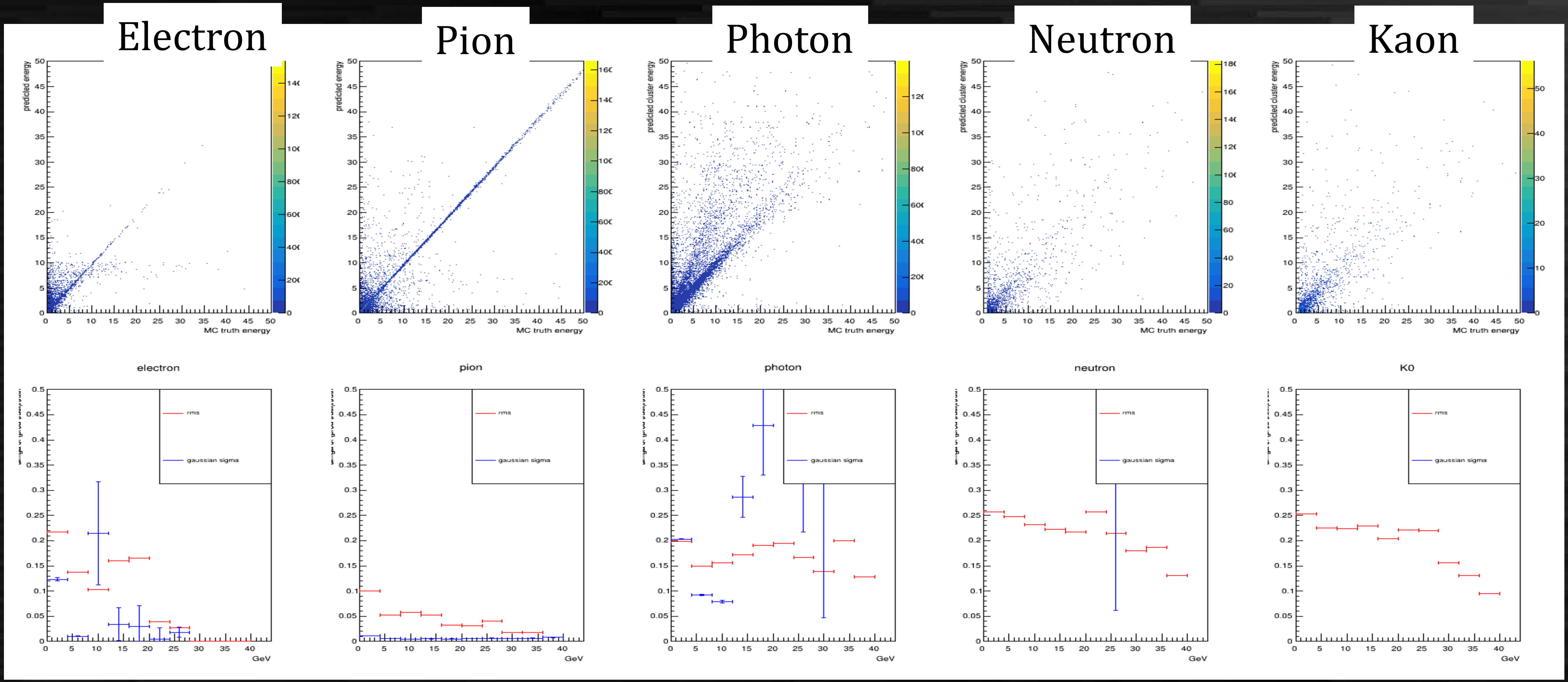
Pion: GNN > Pandora

Electron, photon, neutron, kaon:
Efficiency: GNN < Pandora
Purity: GNN > Pandora

Overall:
competitive performance achieved
Pion reconstruction is especially important in jet reconstruction
→ good expectation

More optimization ongoing by FR internship in Tokyo

Energy regression: di-jet sample



Performance not satisfactory: another implementation with cross attention ongoing

Plans on ML reconstruction

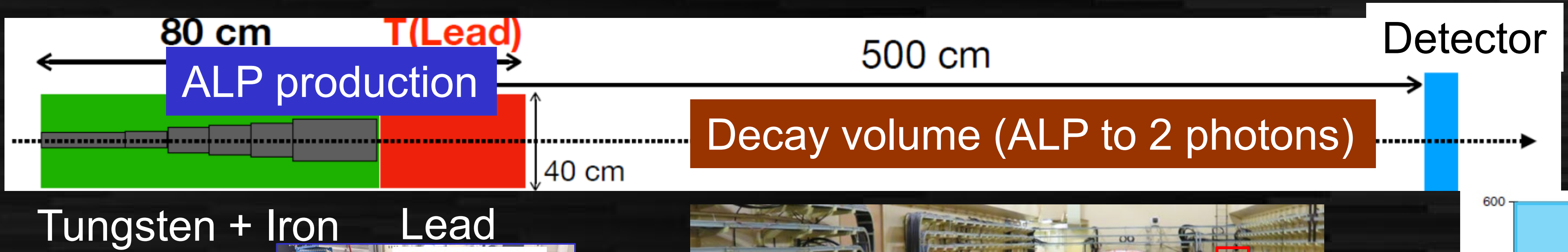
- Regression of single particles
  - Quantitative comparison between CNN, GNN and others
  - Comparison of detector parameters with state-of-the-art network
  - Adaptation to test beam (of past and planned one this year)
    - Optimization of calibration method necessary
- Full particle flow reconstruction
  - GNN + cross attention method
    - Basic implementation done, now being optimized
    - Performance of clustering OK (but not best now): to be improved
    - Energy/position regression (and PID) to be done
    - PID network with transformer with exceeding performance exists, to be combined

Applications

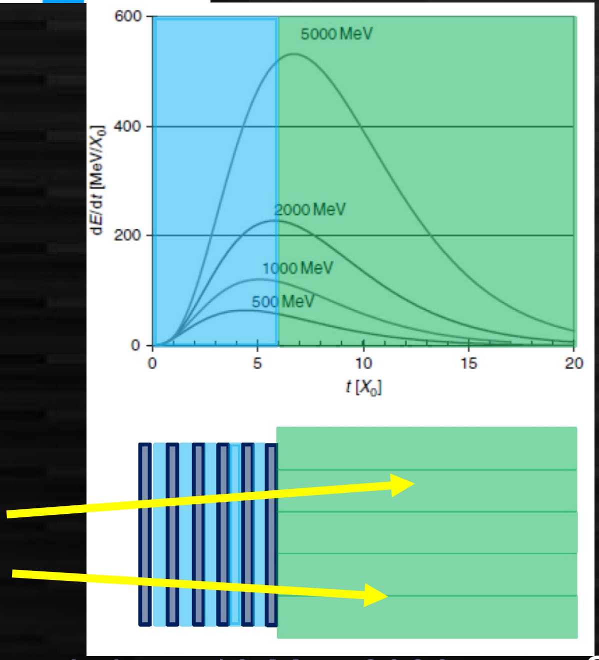
- EBES at KEK
- (LUXE at DESY/XFEL)
- (Lohengrin on Bonn)
- SHiP at CERN

Applications: EBES (beam dump exp. at KEK)

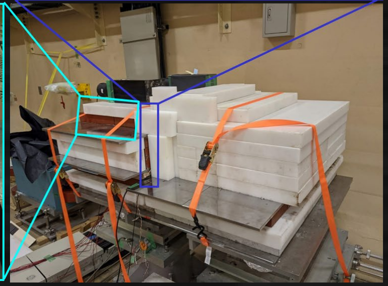
- Sub-GeV ALP (Axion-Like Particle) produced at beam dump of KEK Linac switching-yard (SY) 3 (7 GeV e^- / 4 GeV e^+/e^-) decaying to 2 photons
- Combination of 5 SiW-ECAL layers and PbO Cherenkov calorimeters



2 photon clusters should be seen as ALP signal

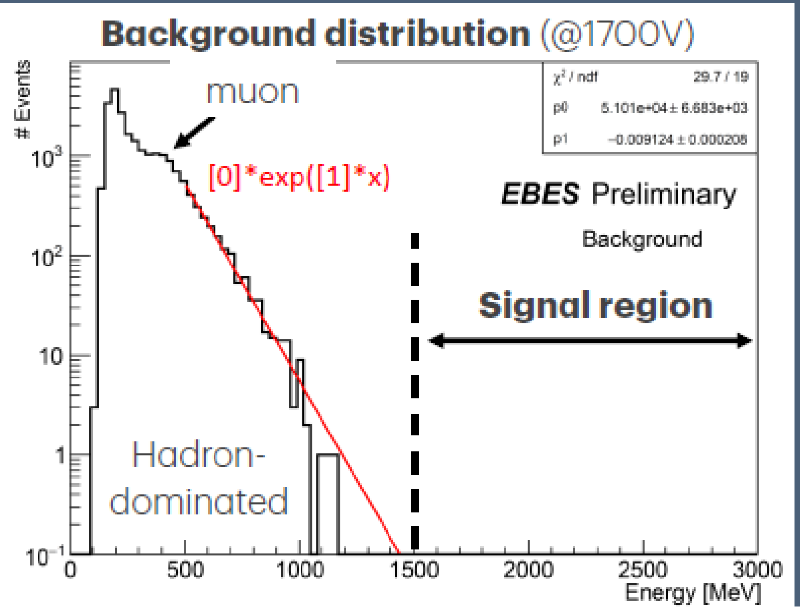


Pilot run at SY3 in July 2022

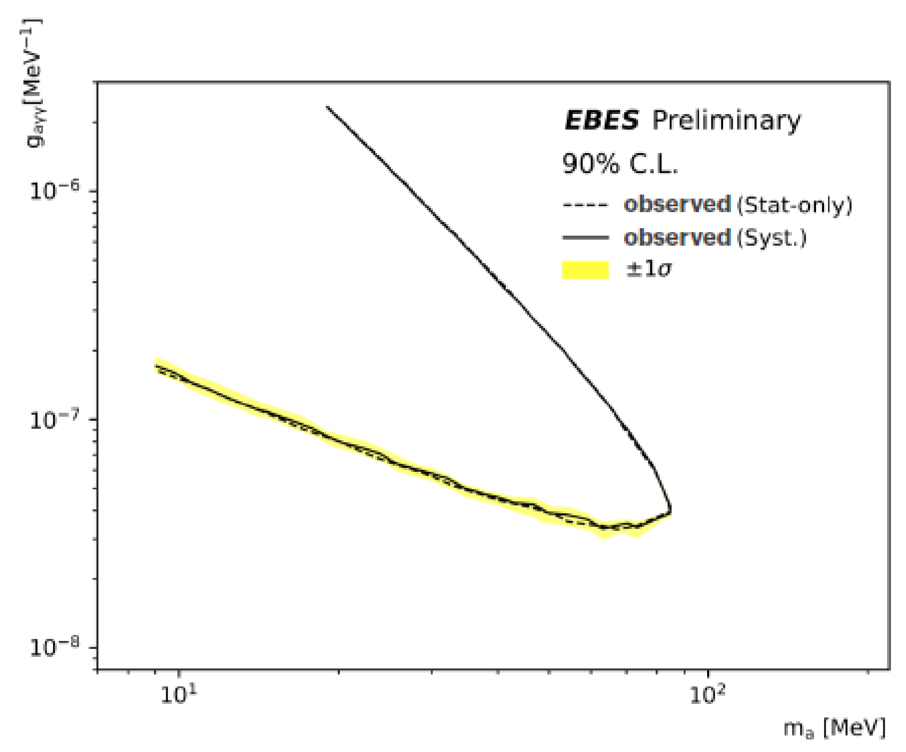


Huge background from upstream seen in pilot run in 2022

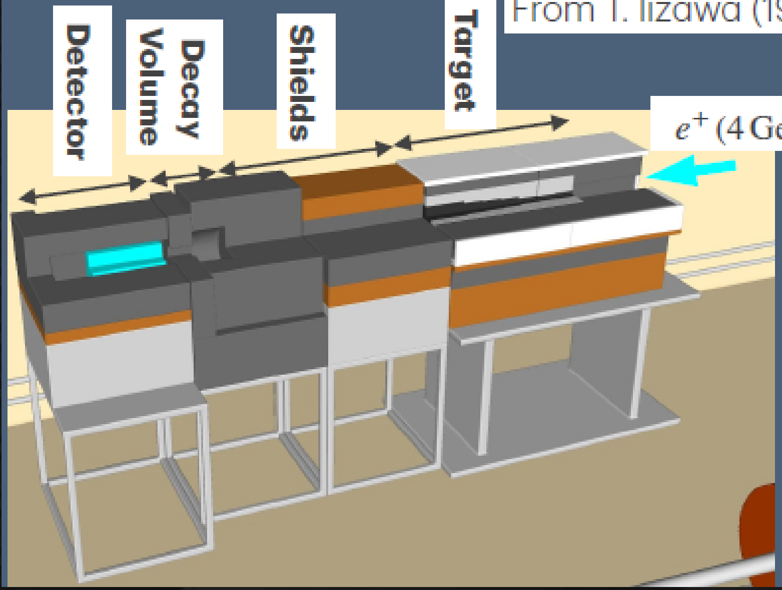
Pilot Run in 2023



From T. Iizawa (19pT1-7)



From T. Iizawa (19pT1-7)

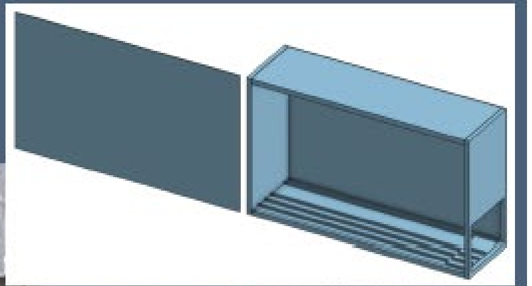


- Results from just 3 hours of DAQ
  - Bunch charge ~ 0.1 nC
  - **Collected 1.3×10^{14} positrons on target**
- **One PbO cherenkov detector used**
- Set the ADC threshold high
  and searched in the background-free region

3

Result open on arXiv:2605.07108 (submitted to PTEP)

Phase-1 Setup ②



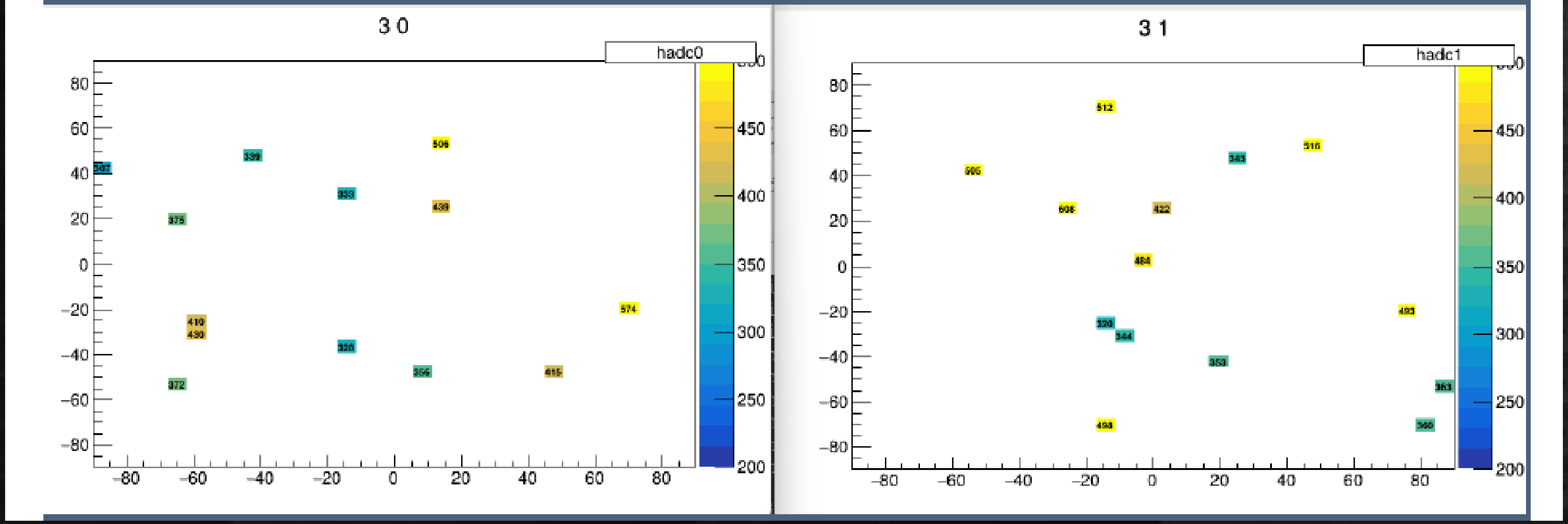
PbO Cherenkov calorimeter

Sensitive area ~ 18x18㎠
Pixel size ~ 5x5㎟
1024 pixels in total

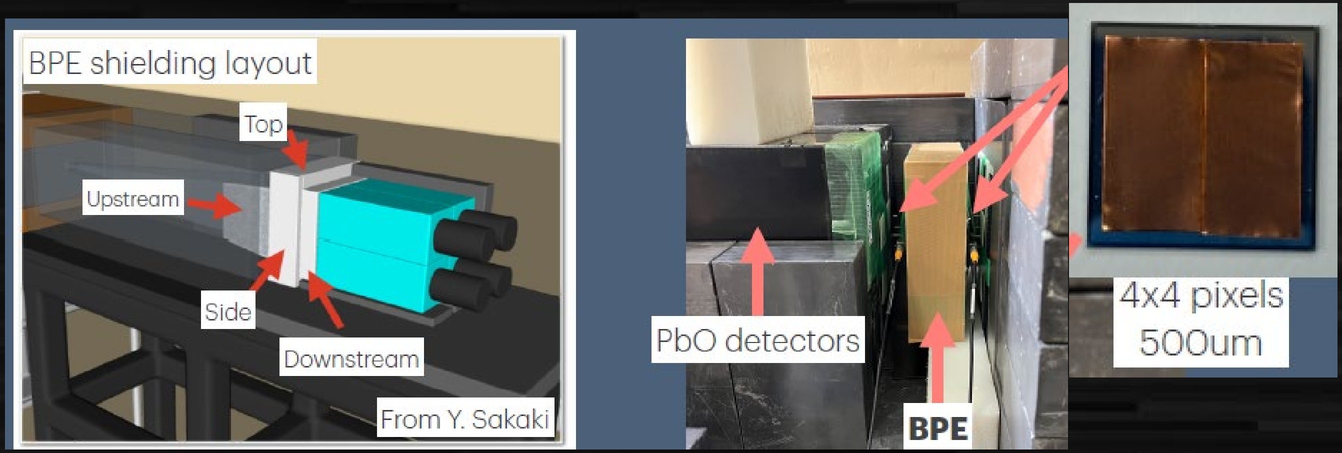
Silicon detector
※ 2-3 layers used
※ Without absorber layers

- Main calorimeter is **PbO Cherenkov calorimeter**
  - Developed for the barrel electromagnetic calorimeter for VENUS at the KEK TRISTAN
  - **DF6 lead-grass block of 12x11.6㎠ x30㎝ read by a PMT**
  - Calibrated at PF-AR TBL (Test Beam Line) using electron beam in 2023
- Data were recorded using a 12-bit CAMAC-ADC and a 12-bit/3.2 GSPS waveform digitizer (WaveCatcher by IJCLab)

Hit Map of Silicon Detector (7 GeV)



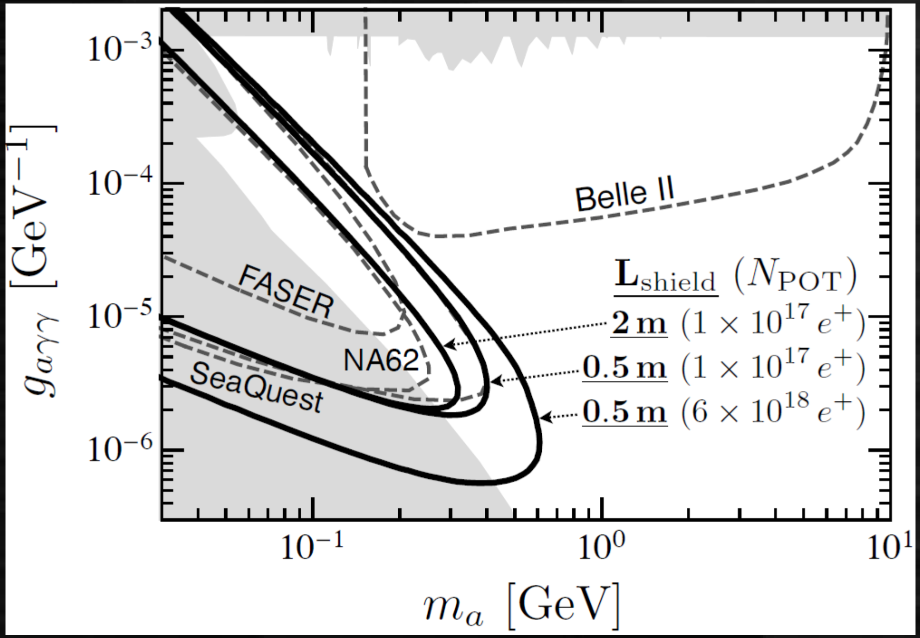
- Should be combination of MeV neutrons and penetrating muons
- Muons should be identified as straight line (and low signal): investigation ongoing (a bit difficult with 2 layers)
- Radiation issues identified…
  (dark current increase, hit pixels)
  Now checking with small sensors
- May have additional run on June/July 2026 (before summer shutdown)



Plans on EBES

- 2025-2026
  - Analysis of 2025 run (without silicon)
  - Investigating of signal at silicon sensors
    - Main target: separate muons and neutrons
  - Optimizing neutron shielding (by boron-doped plastic)
- 2026-2027
  - First combined run with silicon + PbO
  - More layers (layers used at CERN TB?)
- 2027-2028
  - Muon-sweep magnet?
  - First full-scale run expected

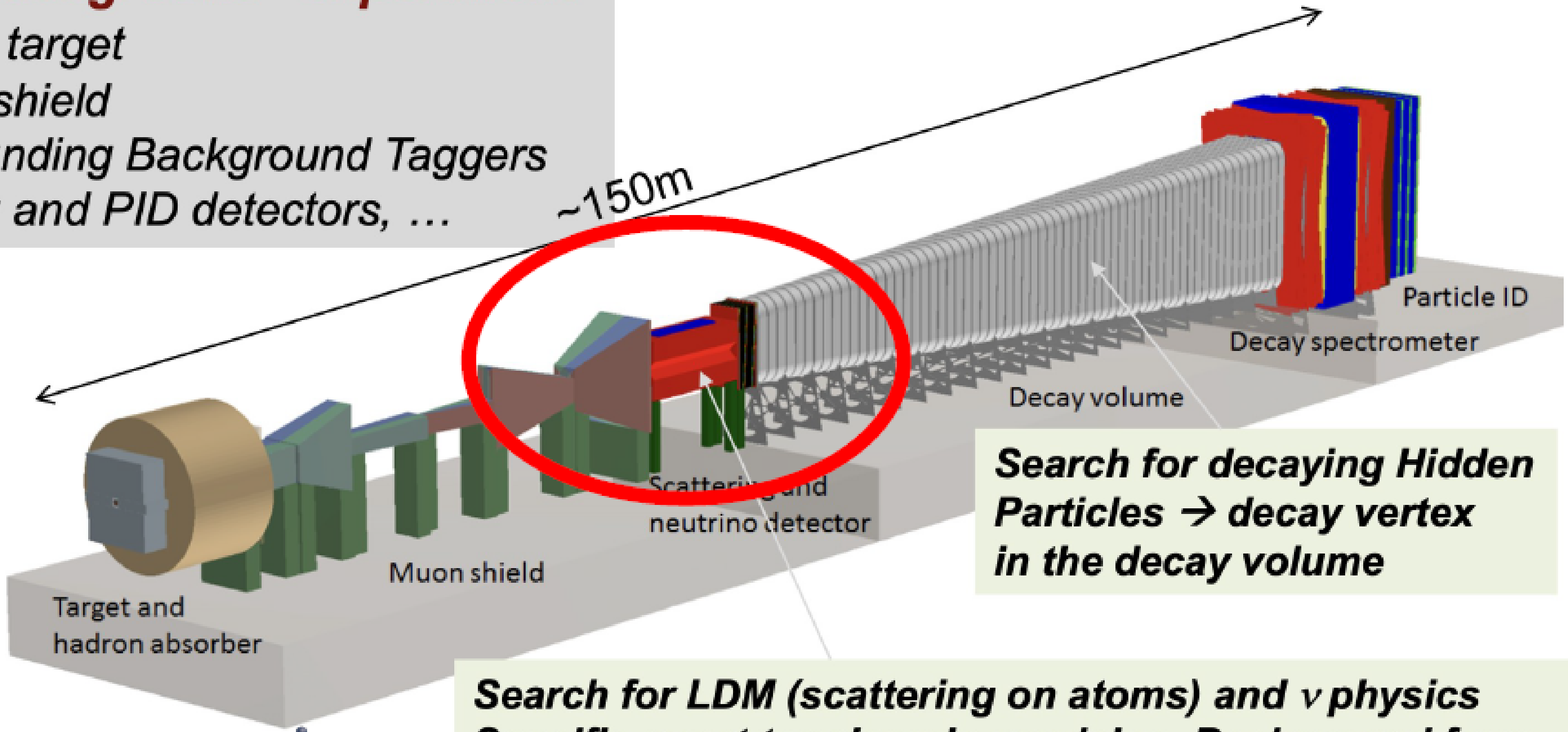
Sensitivity to ALPs



SHiP - Scattering and Neutrino Detector

"Zero background" experiment

- *Heavy target*
- *Muon shield*
- *Surrounding Background Taggers*
- *Timing and PID detectors, …*



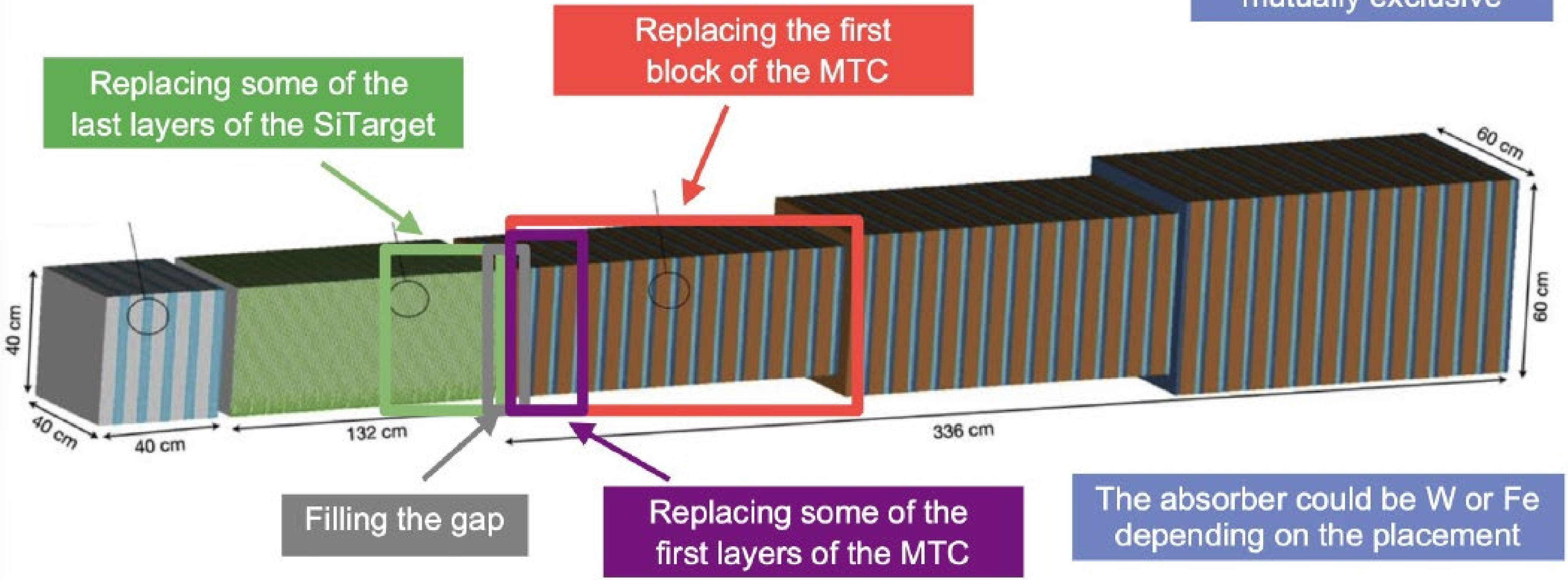
Search for decaying Hidden Particles → decay vertex in the decay volume

Search for LDM (scattering on atoms) and ν physics Specific event topology in emulsion. Background from neutrino interaction for LDM searches can be reduced to a manageable level

A SiPad Detector for SND?

Where would it fit?

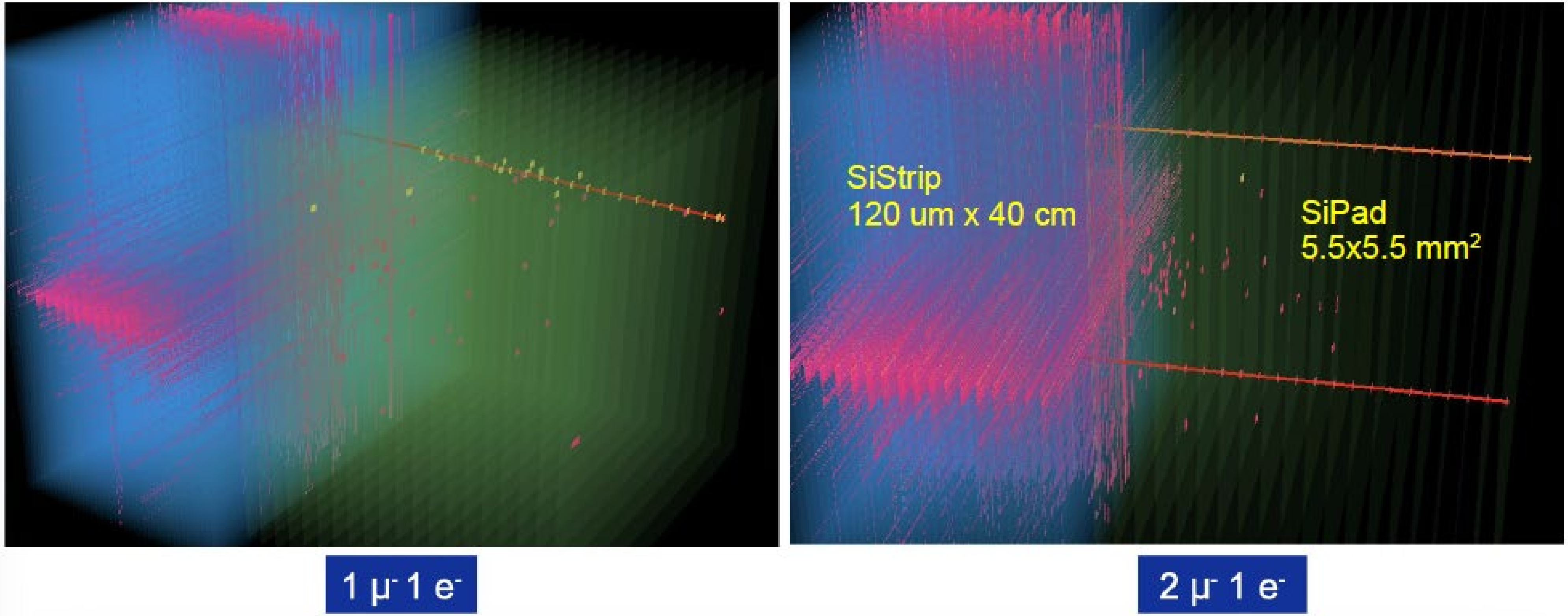
These options are not mutually exclusive



The absorber could be W or Fe depending on the placement

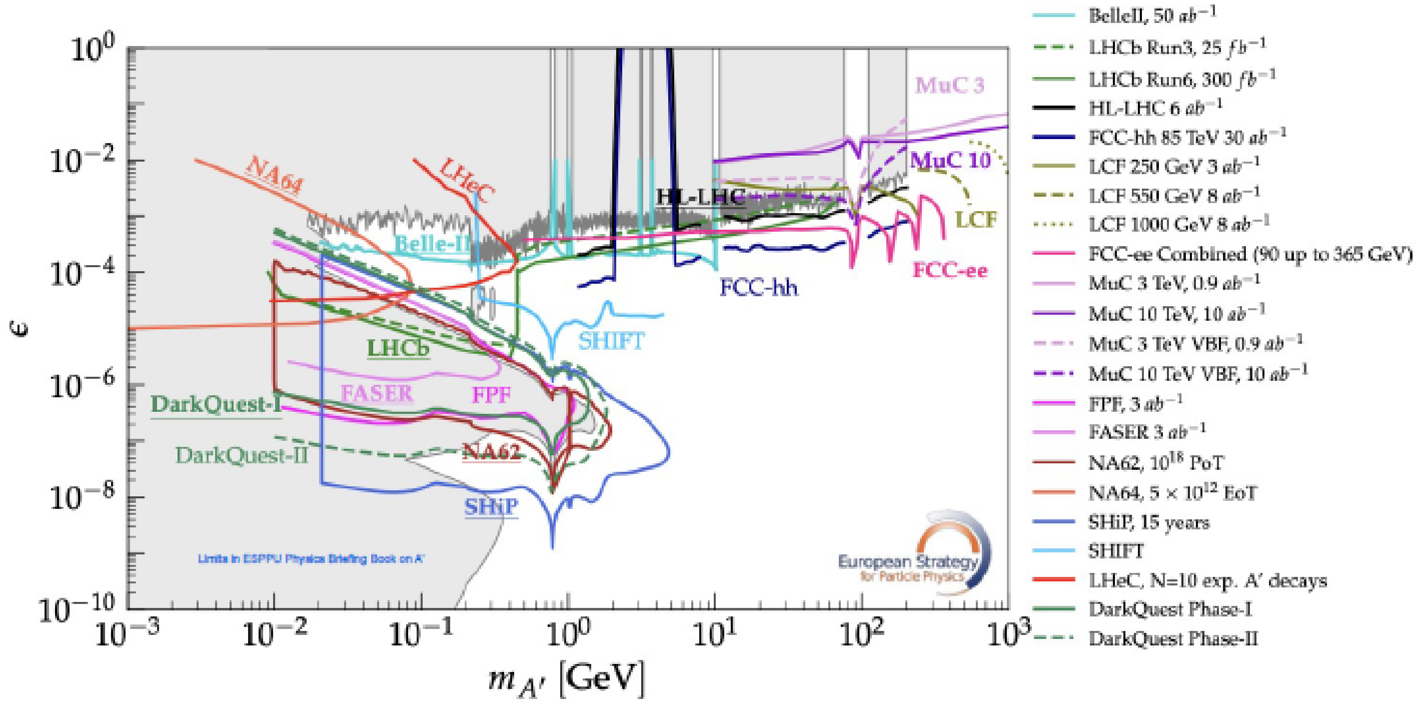
Optimisation about to start

Implementation of SiPad into SHiP

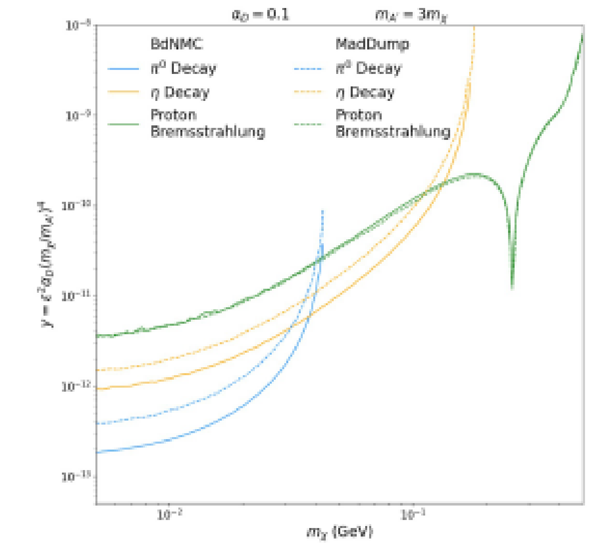


- (Outstanding) Work in progress by Postdoc Jesus Marquez
  - Implementation of SiPad and SiStrip Detectors
  - Next step scintillating tiles and SciFi of MTC

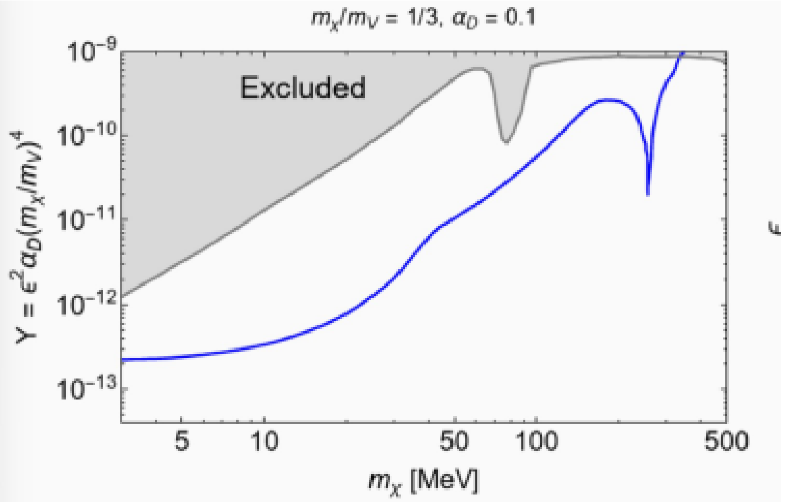
Sensitivity to Dark Photons and Dark Matter Particles



Contributions to Dark Photon Limits (E.Svensson)



Limits on χ by SHiP (M. Climescu at Queen Mary)



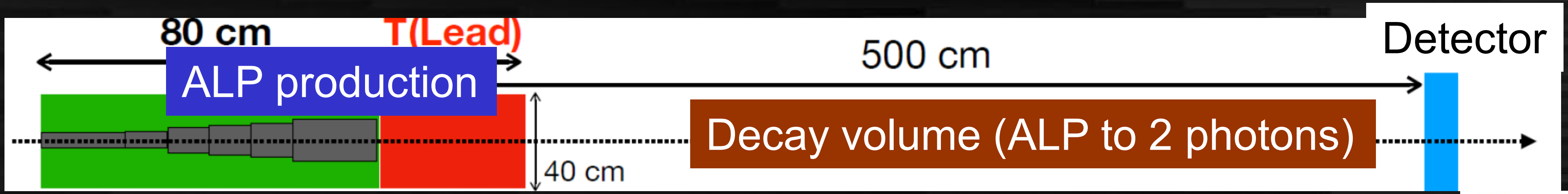
- SHiP sensitive to Dark Photons and Dark Matter Fermions in regime up to 5 GeV
- SHiP will dominate the phase space of (kinematically allowed) dark photon masses

Summary

- HEP_07 and HEP_15 finished successfully
  - Many achievements on JP-FR collaboration on SiW-ECAL
  - 8+ students exchange in 10 years (including test beam)
- In D_RD_42 focus on continuous readout, ML and applications
  - Final test beam of current prototype planned → publish full paper
  - New layers based on CALOROC to be designed/fabricated
    - Design and production 2026, lab test -2027 and test beam 2027-29
  - ML applications being studied, more active collaboration expected
    - For state-of-the-art PFA performance, detector design and test beam application
  - Application to multiple non-collider experiments ongoing
    - First physics results will come very soon!

EBES (Eletron Beam-dump Experiment at SY3)

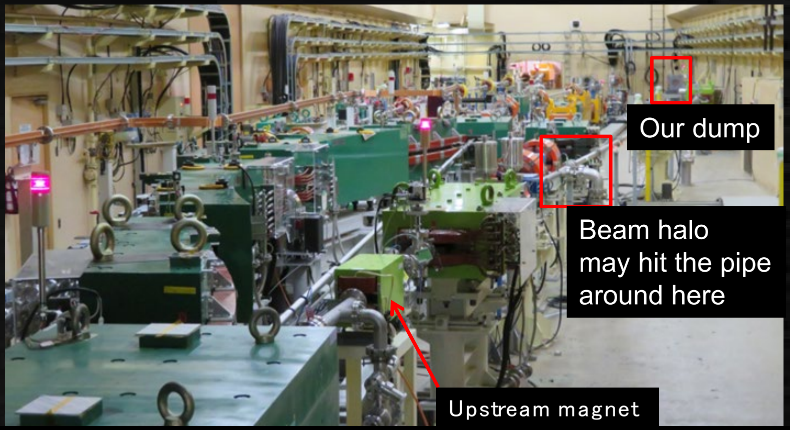
- Sub-GeV ALP (Axion-Like Particle) produced at beam dump of KEK Linac switching-yard (SY) 3 (7 GeV e^- / 4 GeV e^+/e^-) decaying to 2 photons
- Combination of 5 SiW-ECAL layers and PbO Cherenkov calorimeters



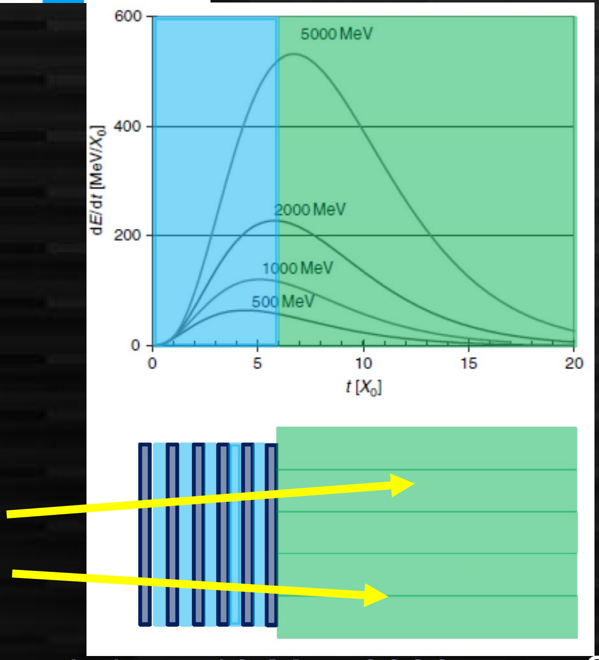
Tungsten + Iron Lead

2 photon clusters should be seen as ALP signal

Pilot run at SY3 in July 2022

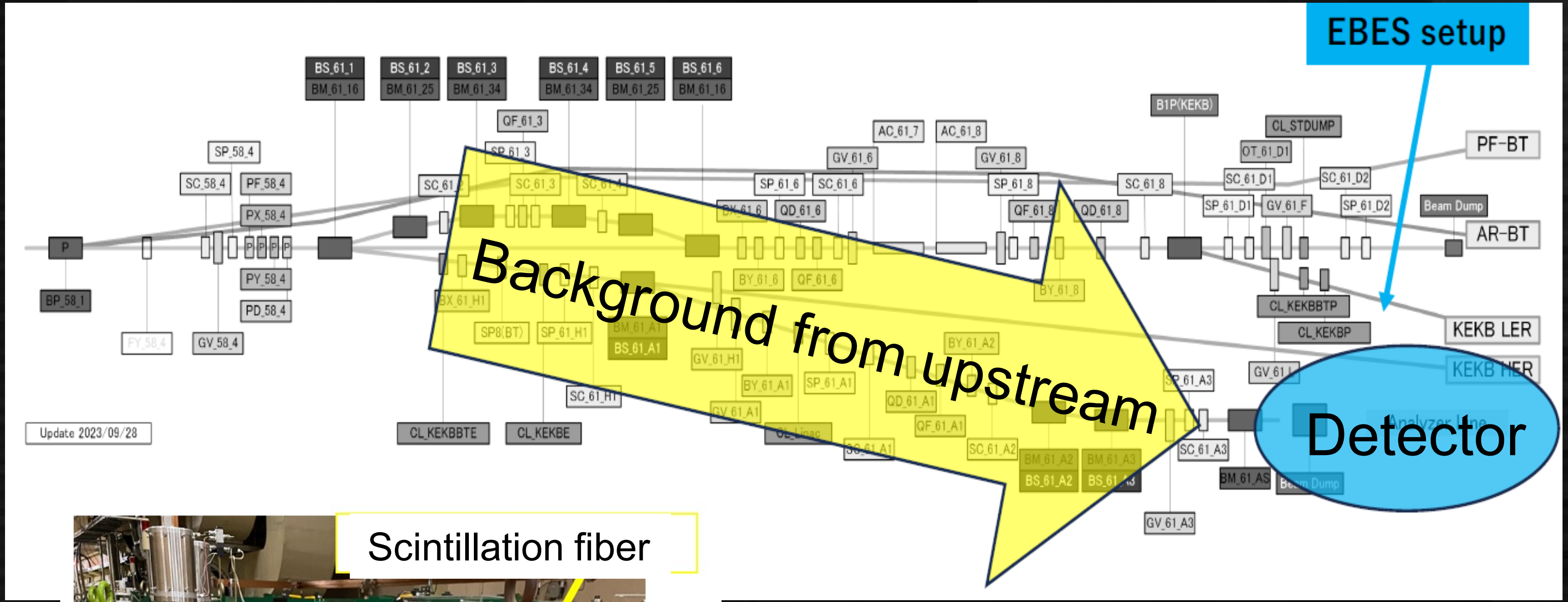


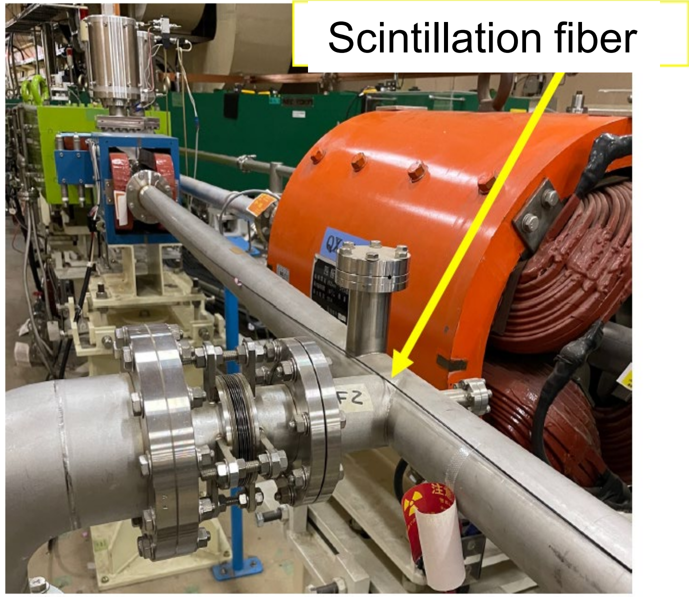
Huge background from upstream seen in pilot run in 2022



Understanding beam background (2023)

Switching yard 3



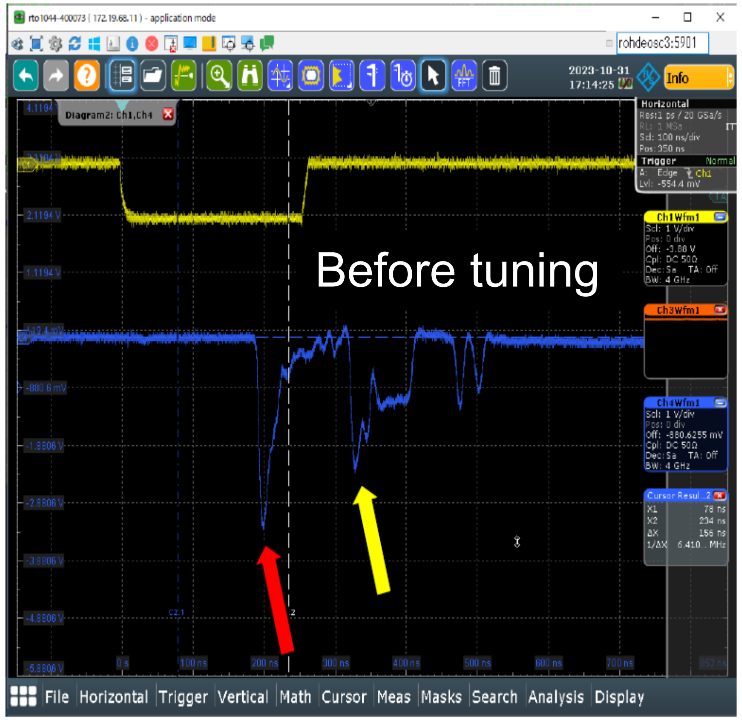


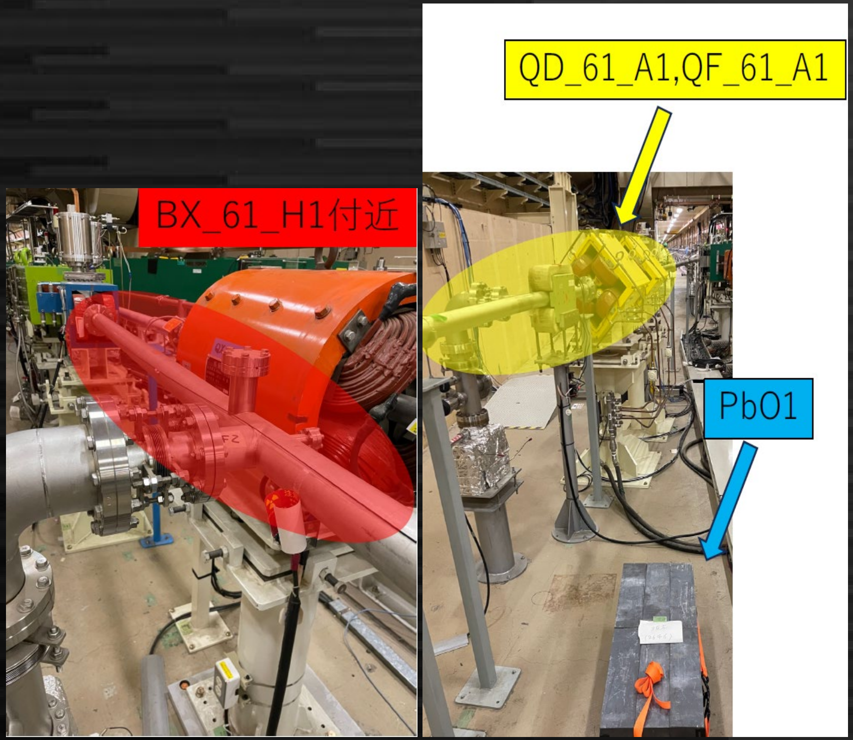
Scintillation fiber produces signal around the beam pipe on which particles hit and produce background

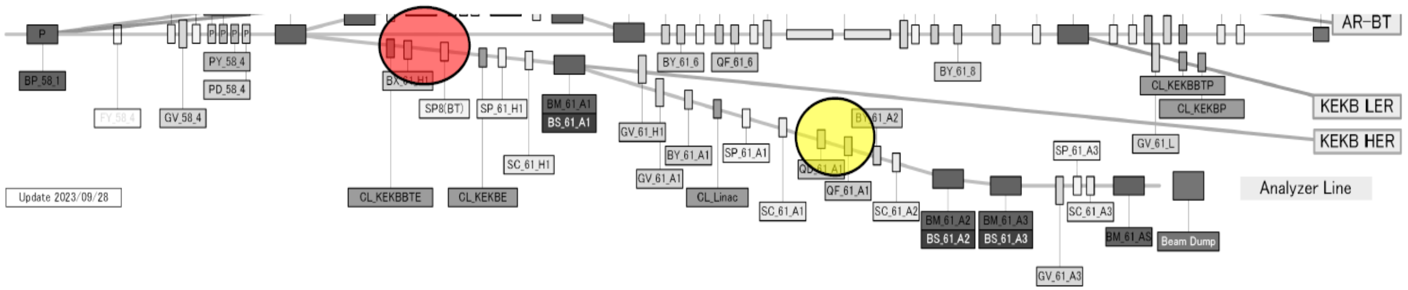
Position can be obtained from timing spectrum

Shielding of beam dump is also updating

Reduction of background by beam tuning



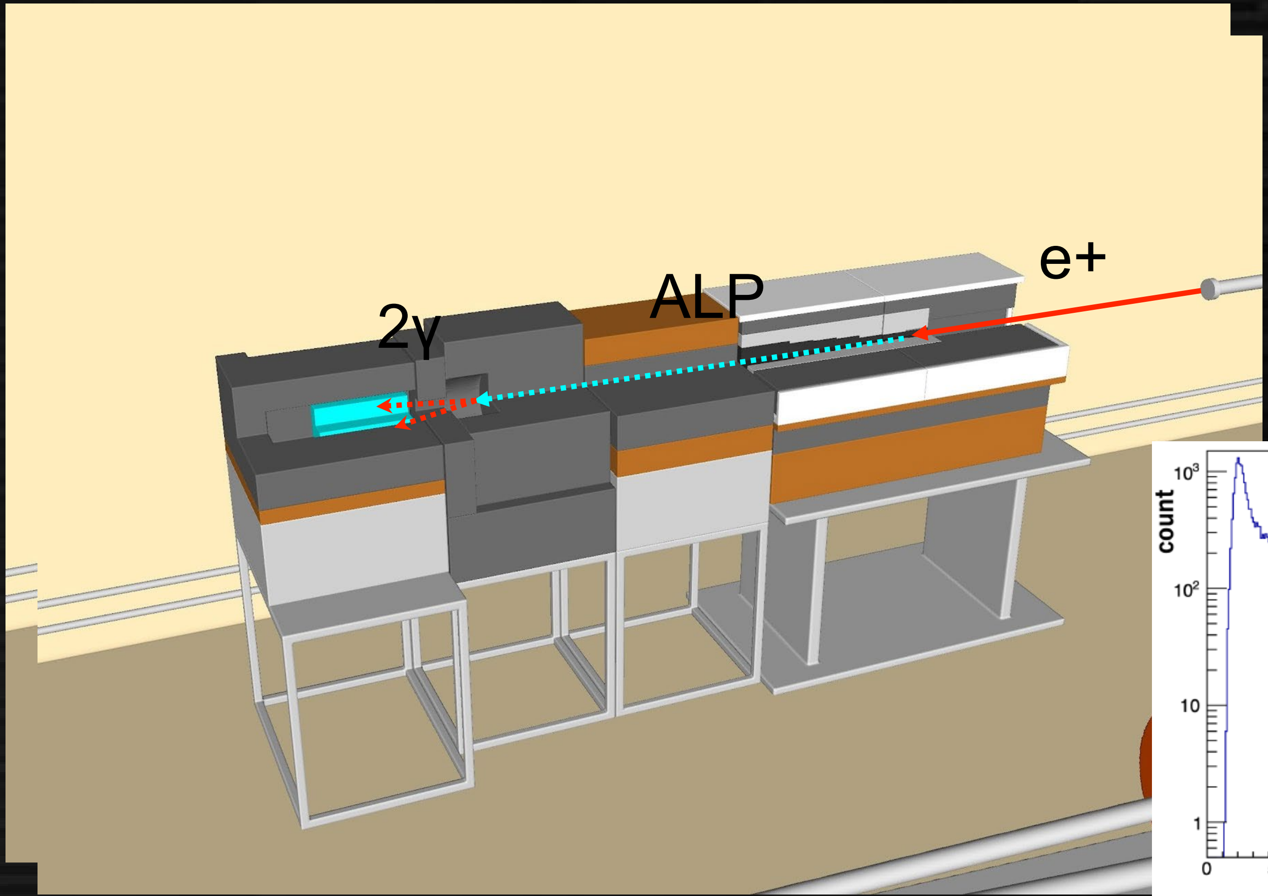


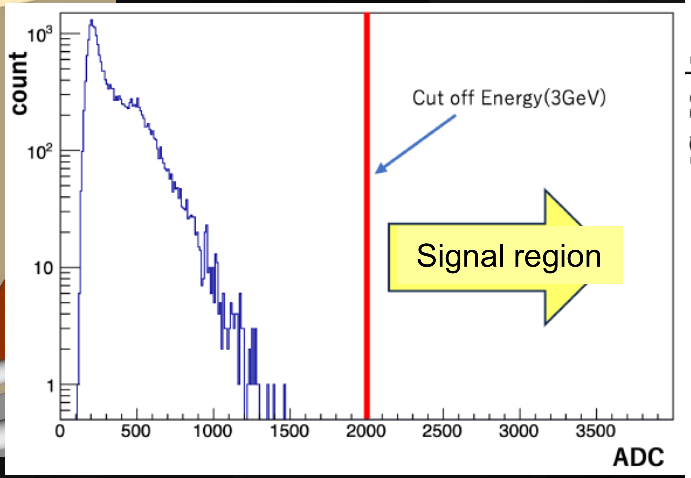


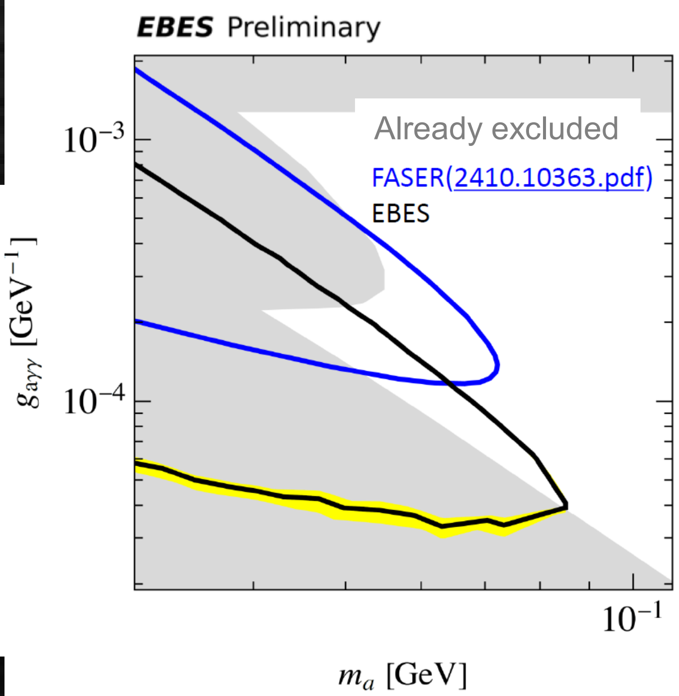
Hitting places found
With beam tuning reduction of ~2 order of magnitude obtained (but still not enough)

Pilot run with very short re-conversion length

4 GeV positron run in Dec. 2023
with minimal charge
(0.1 nC) conversion length of 28 cm





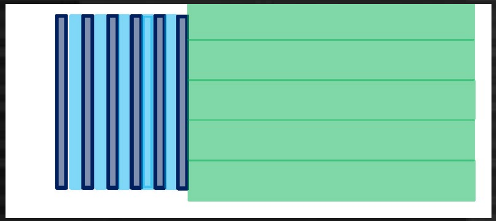


Almost no distance to reconvert ALP → 2γ but background is shielded by beam dump itself! (background source not seen from detector)

Already gives exclusion region (statistics only)

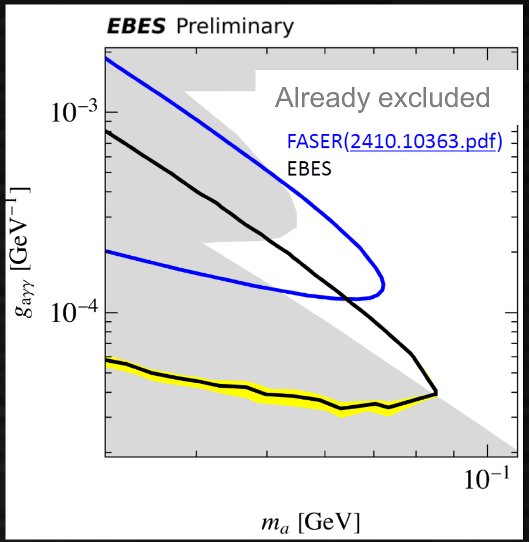
Recent Progress/plans

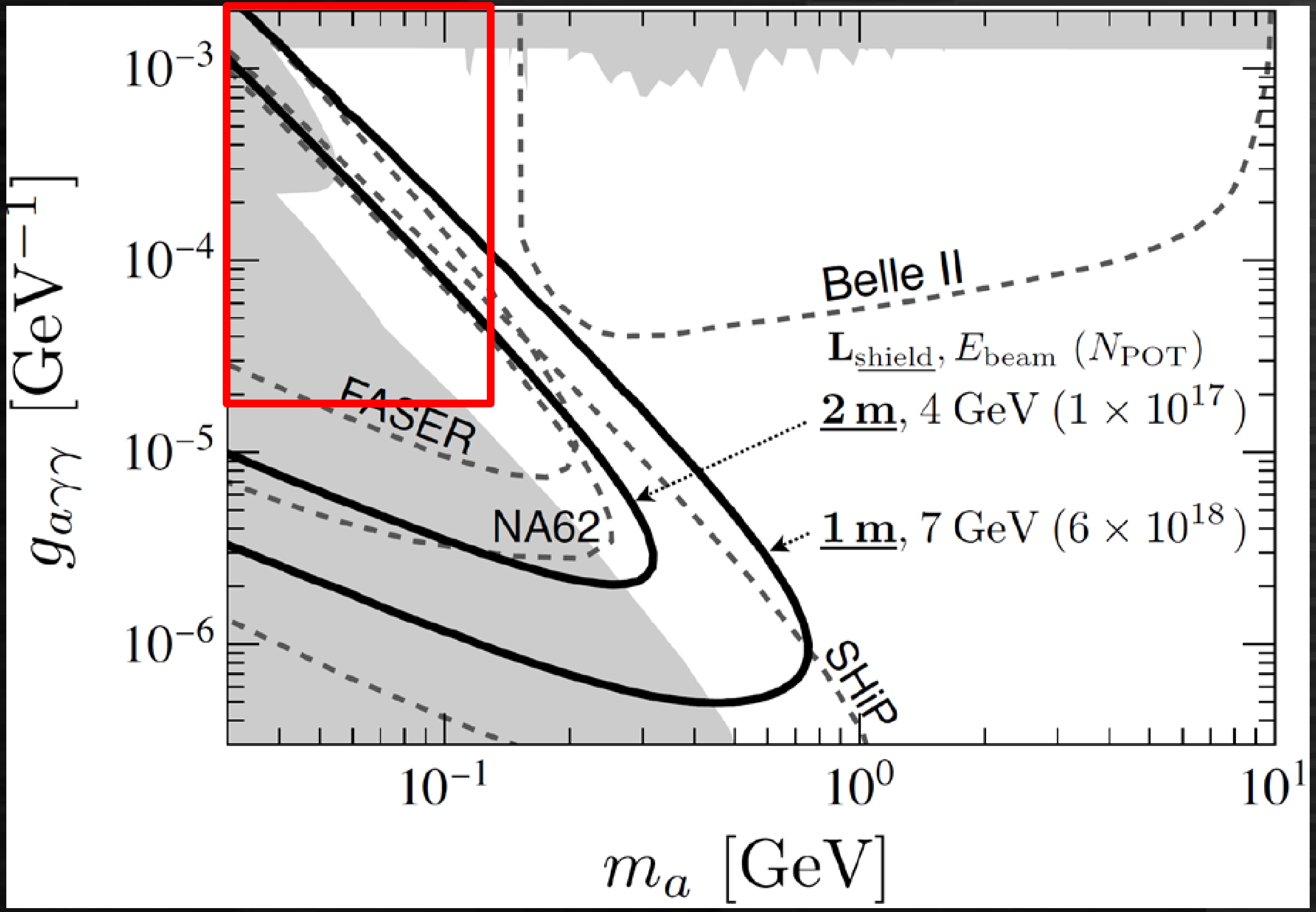
- Additional budget to put silicon sensors approved (Feb. 2025)
  - FY2025-27, ~80kEUR in total
  - ~5 silicon layers + sweeping magnet for 7 GeV run
  - (optionally) reuse old silicon layers to make fully-silicon (~15 layers) setup
  - AI-based accelerator tuning
- Next physics run later 2025 with ~100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





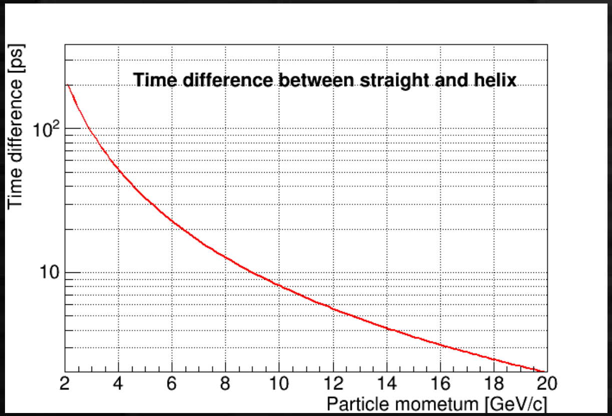
Shielding: 2 m → 1 m (2027)
Re-conversion: 28 cm → 1 m (2025)
Beam energy: 4 GeV → 7 GeV
(need sweep magnet, 2026)

Summary of Plans in FY2025

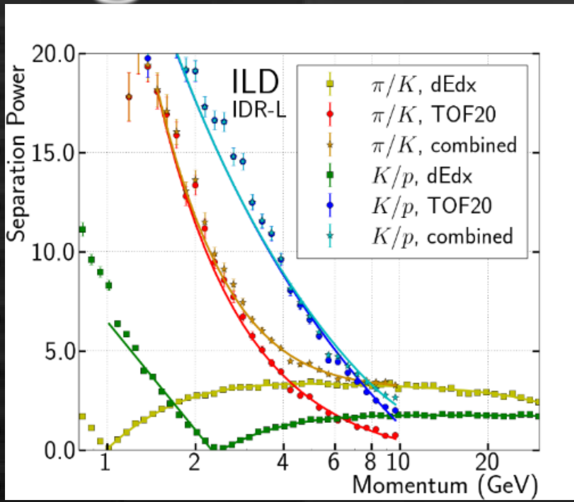
1. Assemble SiW-ECAL layers with new electronics (FEV2.1) and test performance
   - 2 layers have been tested in Mar. 2025
     - No critical issues → moving to the prototype production (up to 15 layers) A few layers from Japan?
     - To be tested at DESY/CERN, investigating performance as calorimeter (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

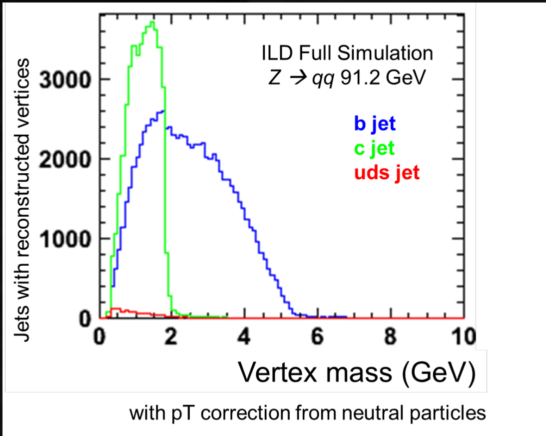
- π/K/p separation with Time-Of-Flight method
  - 30 psec (for cluster)
    Moderate performance to fill gap of dE/dx
  - A few psec (for cluster)
    up to 5-10 GeV (80-90% of jet particles)
- Track separation at PFA
  - By distance of helices and straight lines
  - ~10 psec/cluster necessary for 10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

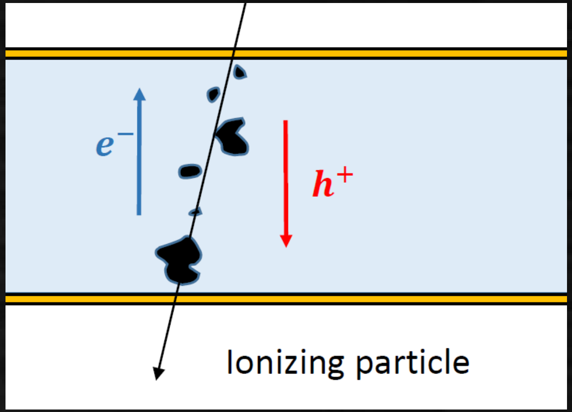


Vertex mass of secondary tracks (only) from b/c jets

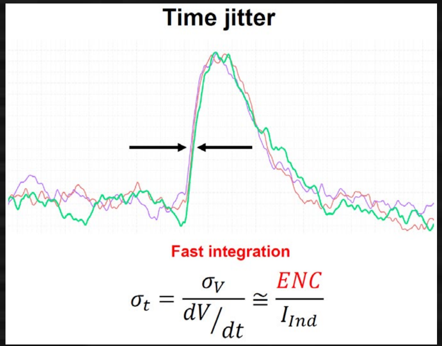
Study of LGAD/APD

APD: photon sensor with essentially the same structure as LGAD

Timing resolution for silicon

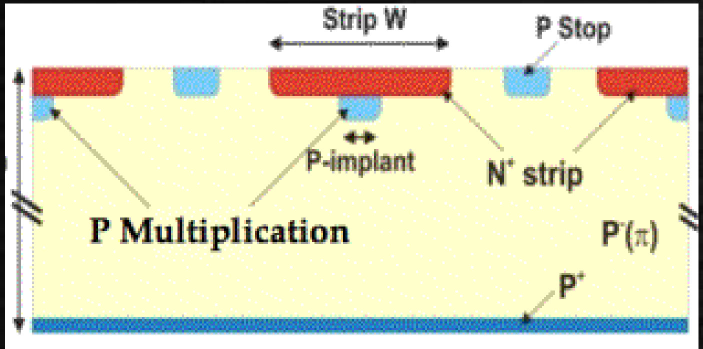


Landau fluctuation: caused by distribution of energy deposit along the track: fast collection time (thin active thickness) → better reso



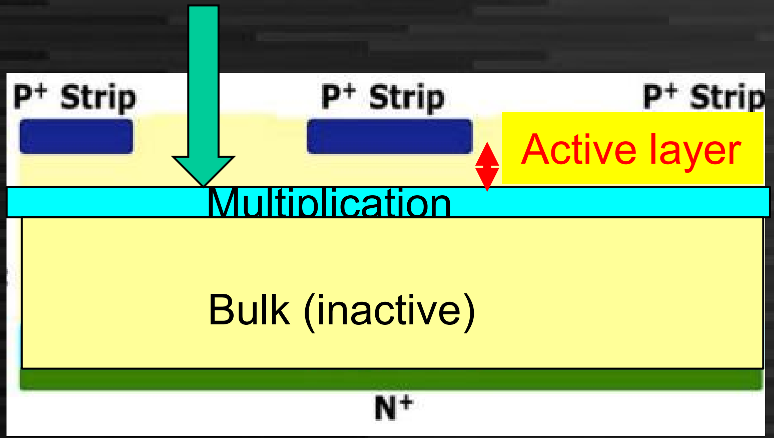
Jitter by noise:
~Rising time / S/N ratio
Big signal preferred
→ internal gain

LGAD/APD types



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

Doping from surface

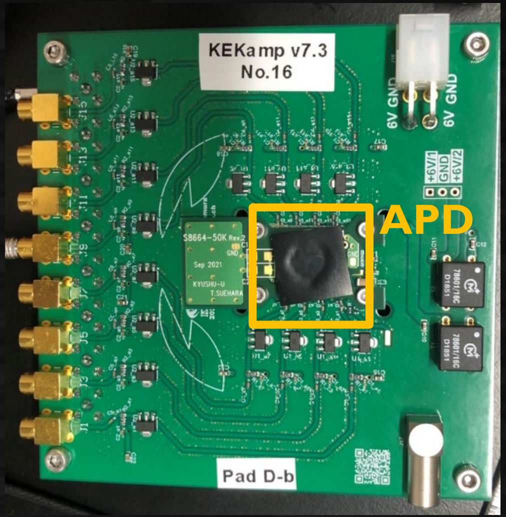


Inverse type (single sided process)
Multiplication by deep injection
Thinner active layer (5-10 μm)
→ Smaller Landau fluctuation?

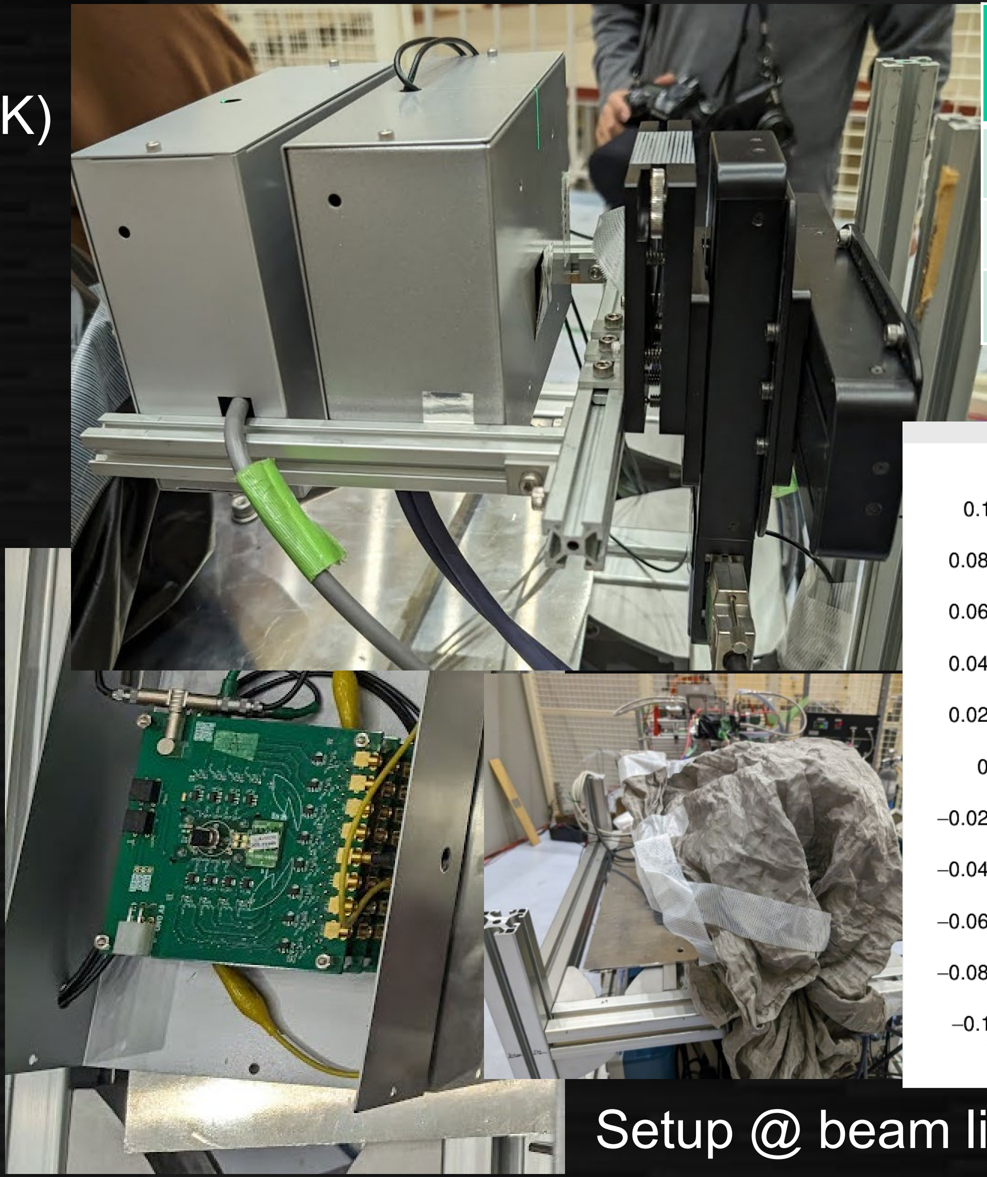
Inverse LGAD can achieve both uniform response and high resolution up to 10 psec
→ try with commercial APDs (from Hamamatsu)

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

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



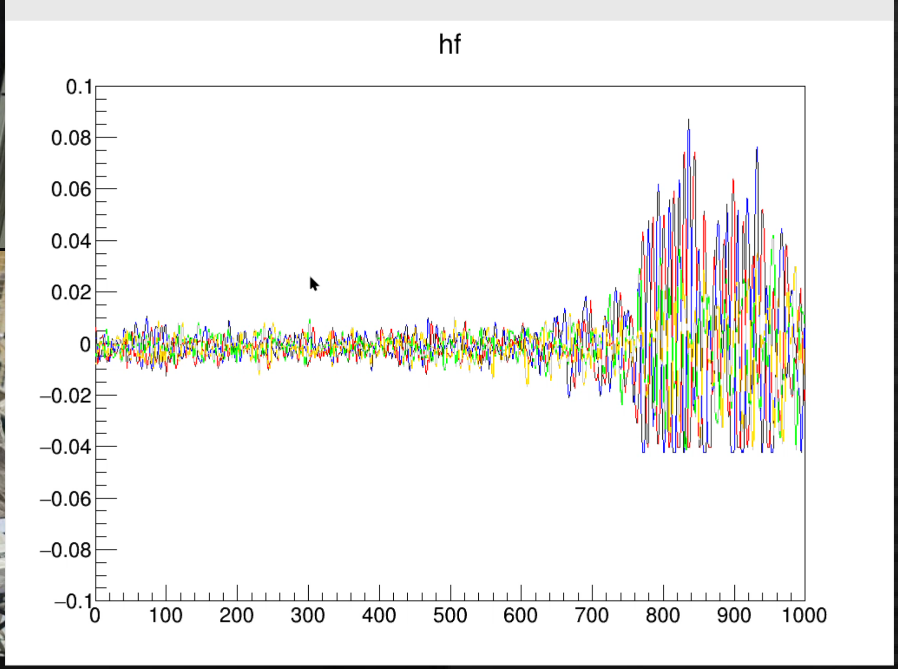
R&S RTO64 Oscilloscope
(2 GHz,
10 GSPS)



Setup @ beam line

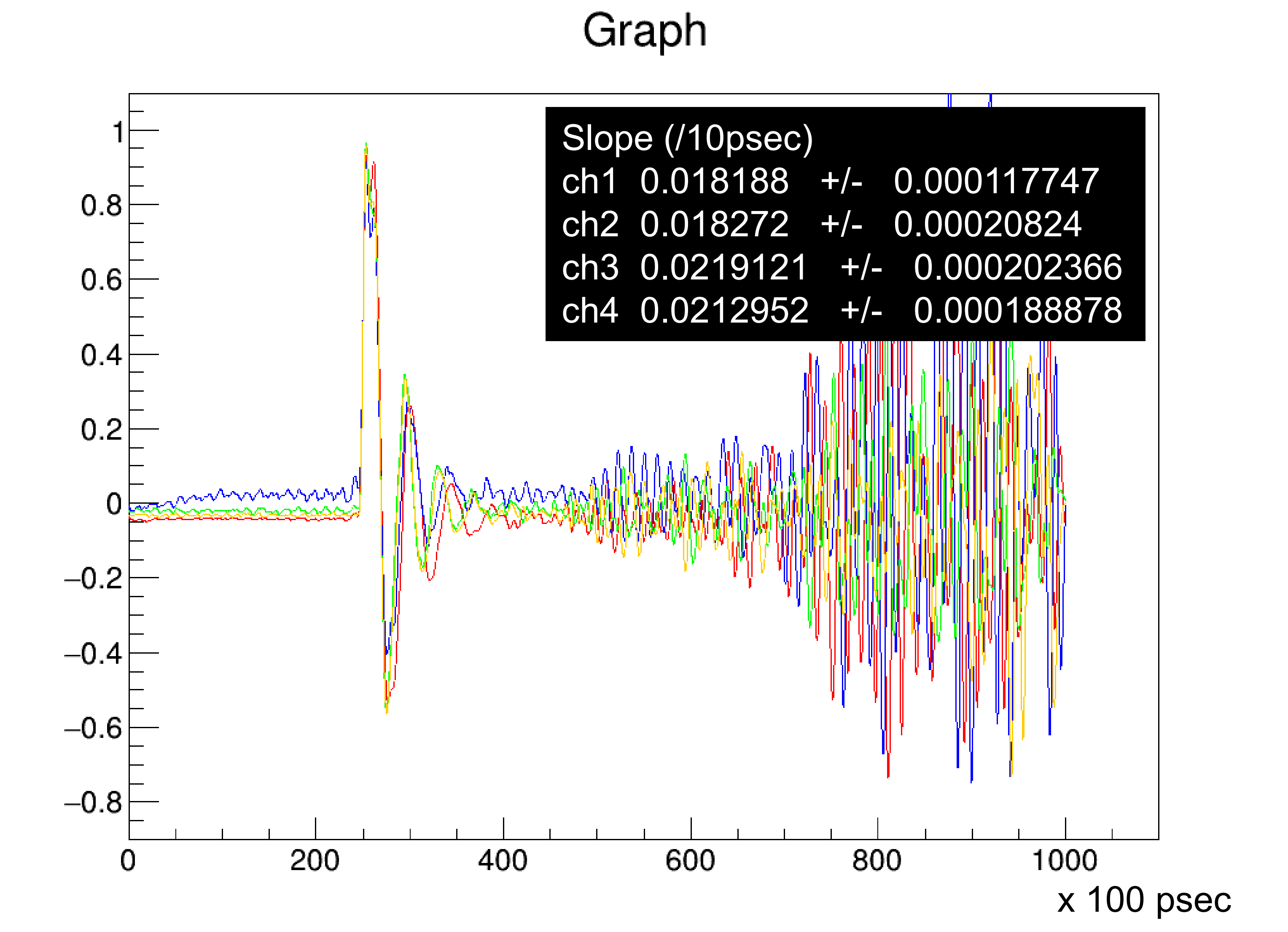
APDs	Type	Size [mm]	Cap. [pF]
S8664-20K	Inverse	2ϕ	11
S3884	Reach-through	1.5ϕ	10
S8664-50K	Inverse	5ϕ	40

Tested sensors



Waveform

Average waveform

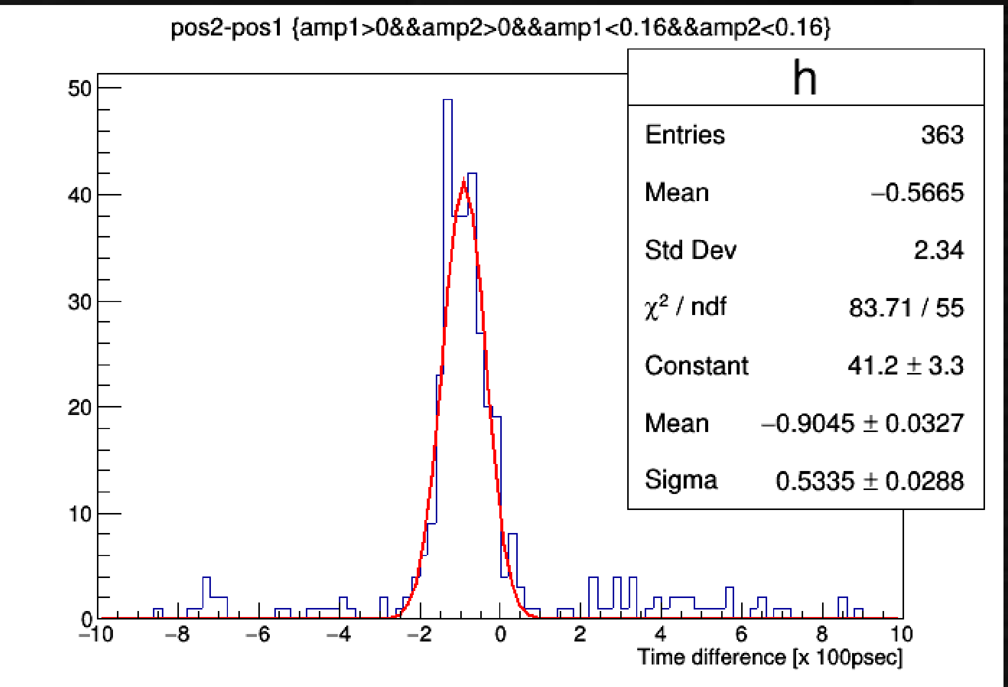


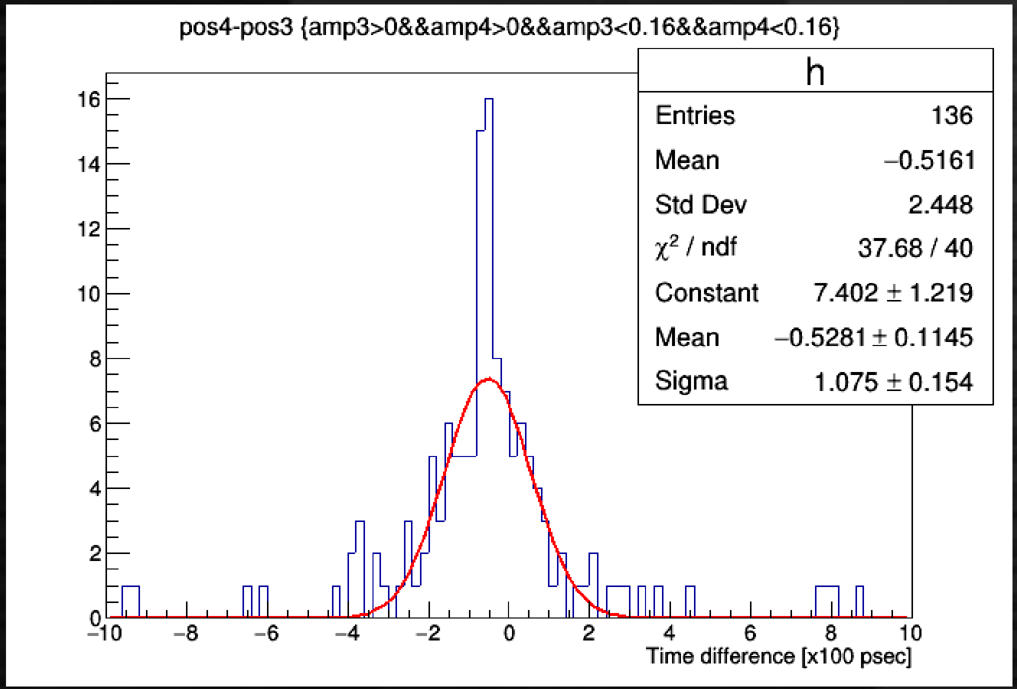
Averaging 500-4000 waveforms

- 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)