Timing sensor studies and application to Higgs factories in Japan

Taikan Suehara (ICEPP, U. Tokyo)

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  - Scintillator/Cherenkov detectors
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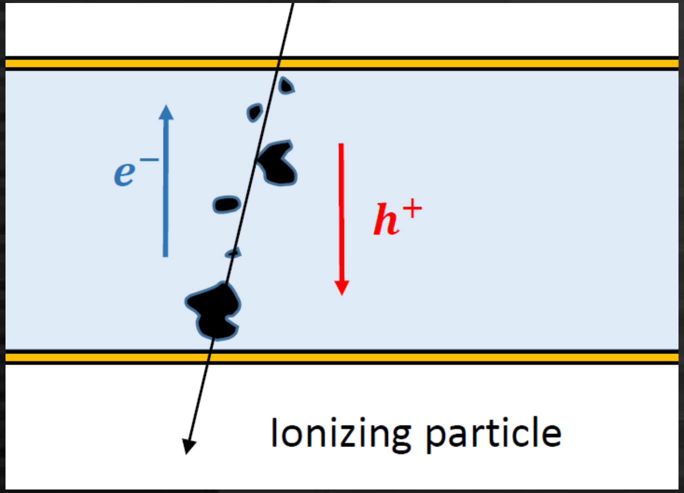
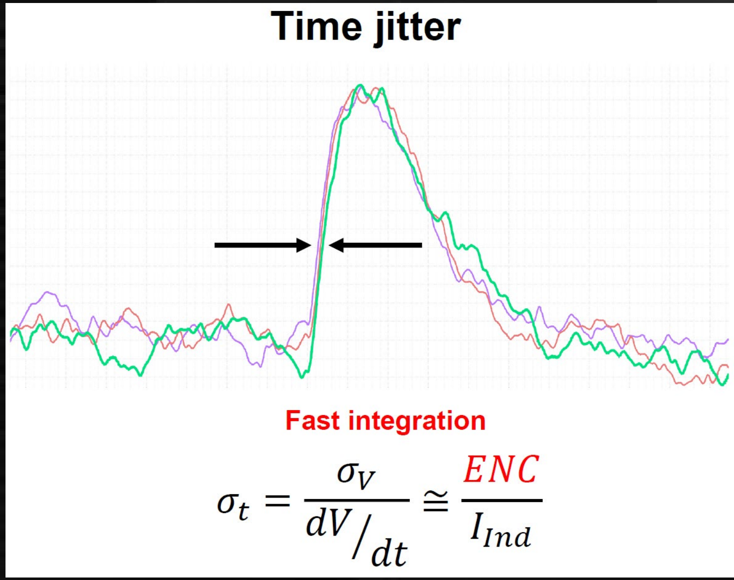
  - Particle ID
  - Improving particle flow performance
  - Secondary photon ID
- Possible design of timing detector (and consideration)

Silicon sensors: factors contributing timing meas.

Timing resolution factors: ${\sigma_t}^2 = {\sigma_s}^2 + {\sigma_n}^2$

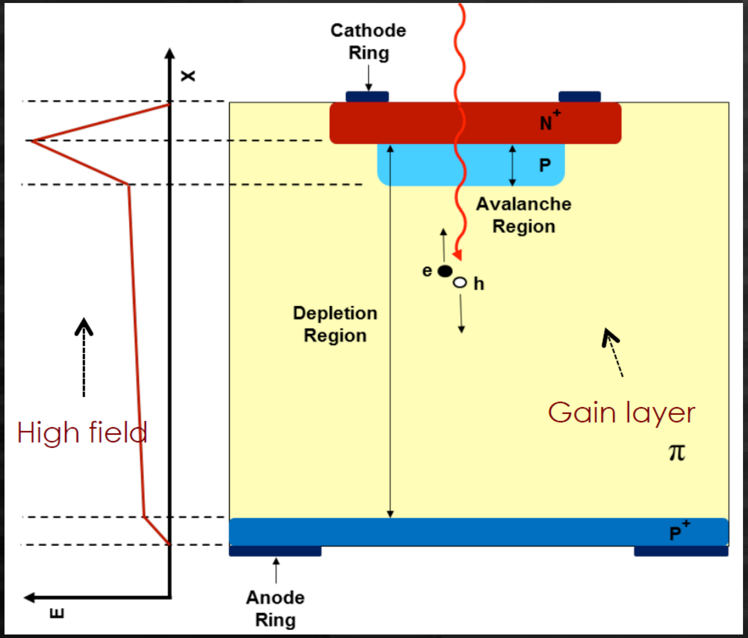
- ${\sigma_s}^2$: Timing resolution of sensor itself
  - Landau Fluctuation: uncertainty caused by fluctuation of energy deposit along the sensor
    → ~10% of charge collection time
    Thin sensors and fast drifting time desired
- ${\sigma_n}^2$: Uncertainty caused by electric noise
  - Signal rise time divided by S/N ratio
    → thicker sensor desired (trade-off)
  - S/N ratio improved by avalanche gain → LGAD (or SPAD)
  - $\sigma_n \sim C^2$ Capacitance affects both rise time and S/N ratio
- Other aspects: clock distribution, time walk, etc.

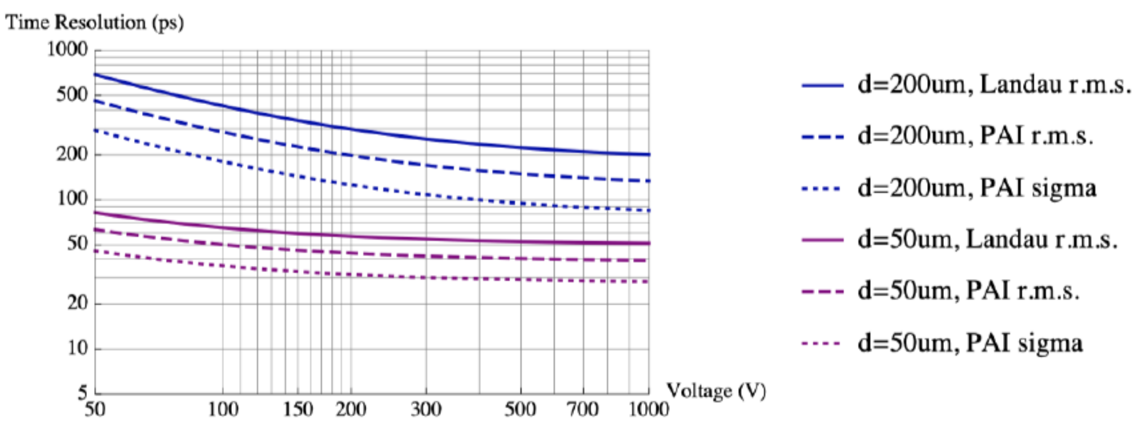


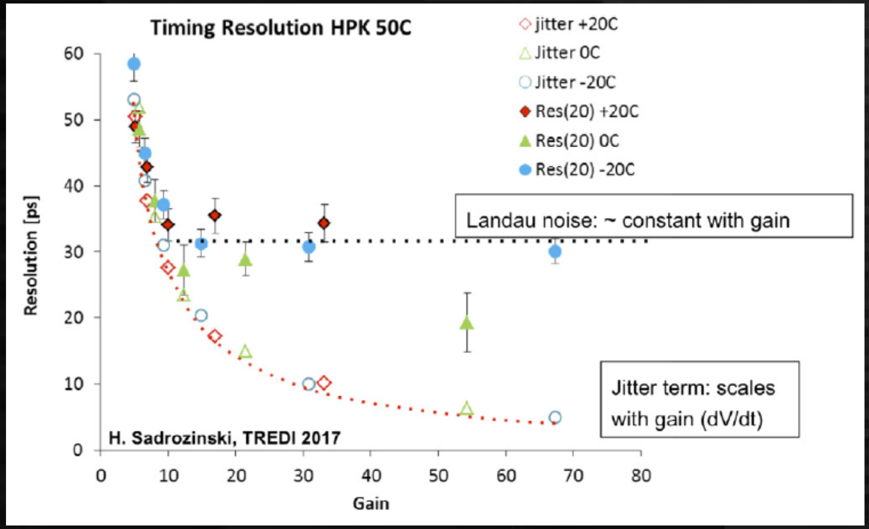


Avalanche Detectors (LGAD)

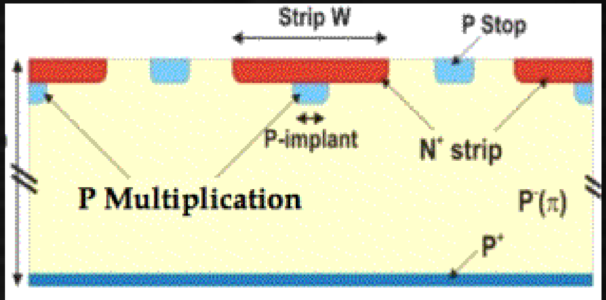
- Difficult to get high S/N with thin sensors
  → Avalanche gain
  - Already widely used in optical detectors (APD/SiPM)
  - Low Gain Avalanche Detector (LGAD)
    - Developed for HL-LHC pileup separation (ATLAS HGTD / CMS MTD)
    - G = 10-100, radiation tolerance OK (with increasing HV)
    - Finally dominated by Landau fluctuation (~30 psec with current structure) → Thinner active layer





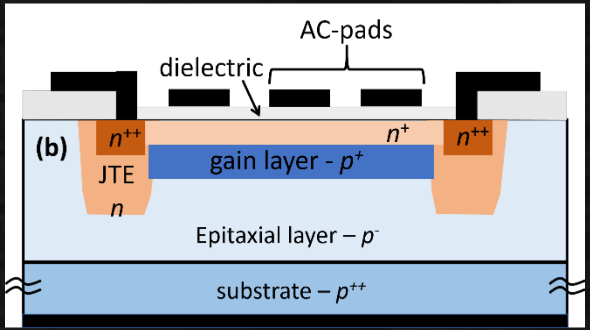


Various structures of LGADs



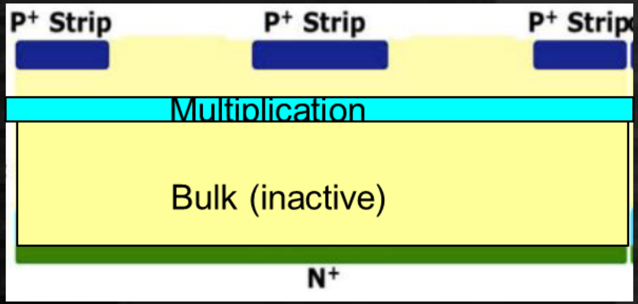
Reach-through LGAD

- Standard structure well investigated
- Resolution limited to 30 psec
- Issue: inactive region between channels → AC-LGAD / inverse



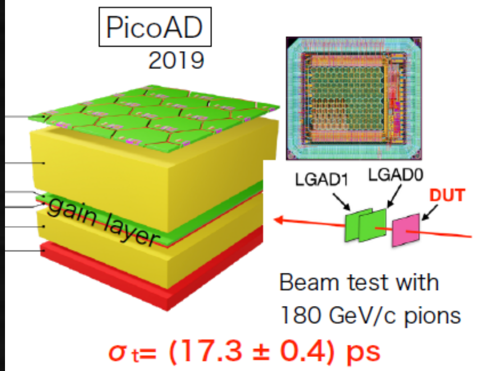
AC LGAD: AC-coupled electrodes with planar gain layer: good for strips

K. Nakamura et al. working in Japan in FCC/EIC context



Inverse LGAD (single sided)

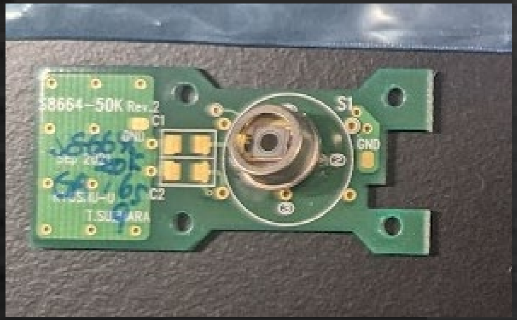
- The same structure as reverse APD
- Current structure has 5-10 μm active thickness (confirmed with ion injection) → too thin (limited by the production process)
- Intrinsically low Landau Fluctuation
- Relatively flat multiplication expected (tbc)
- Lower cross talk than AC-LGAD expected (tbc)



Monolithic LGAD with SiGe process

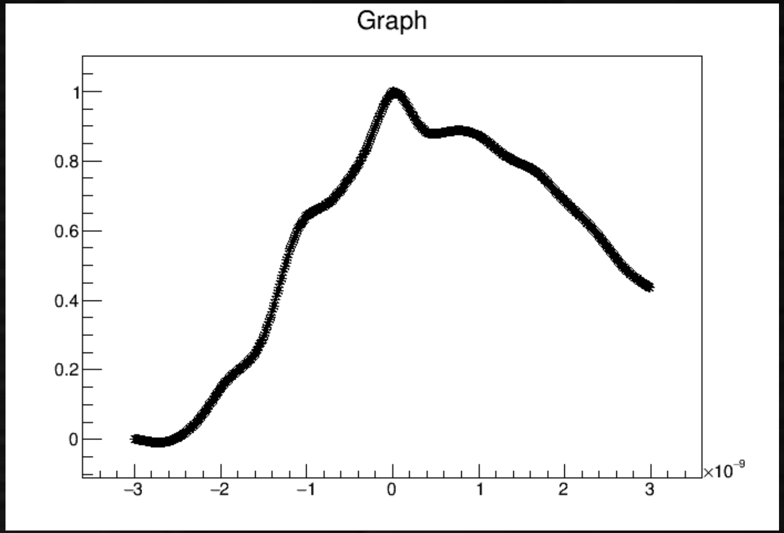
Our study for inverse LGAD

- Commercial sensors (Hamamatsu APD)
  - Reach-through type: S3884 (1.5 mm ϕ, 10 pF) @ 183V
  - Inverse type: S8664-20K (2 mm ϕ, 11 pF) @ 420V
- Readout
  - 3 GHz discrete amp (mini-circuit GALI-S66+)
  - R&S RTO64 Oscilloscope
    - 2GHz analog bandwidth, 10 GSPS
- Irradiation
  - Beta from ^{90}Sr
  - Test beam



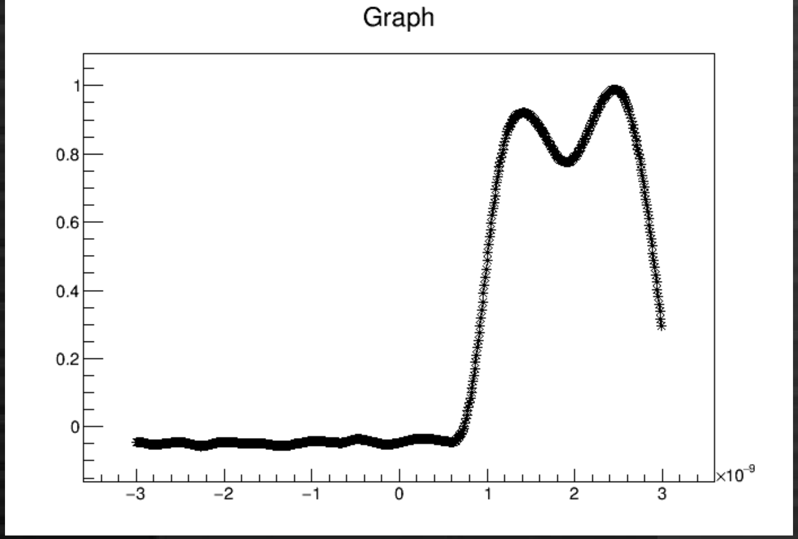
2 GHz oscilloscope

Waveforms with ^{90}Sr

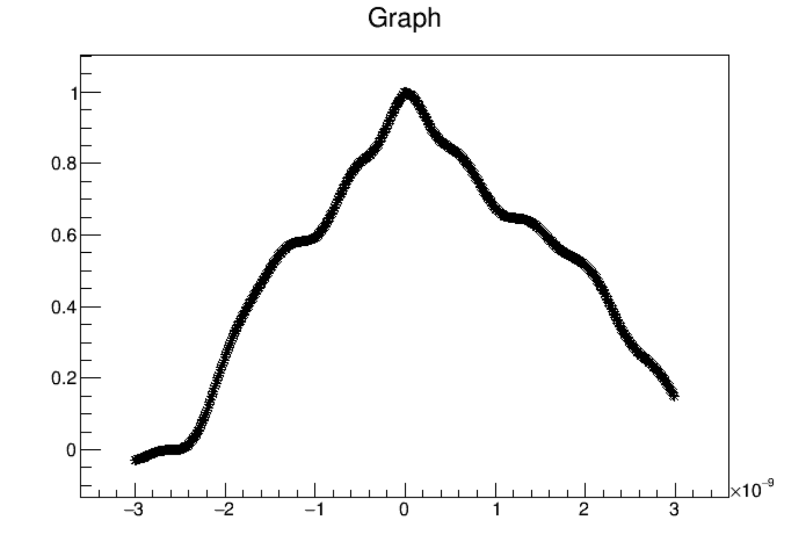


S2385 (95 pF)

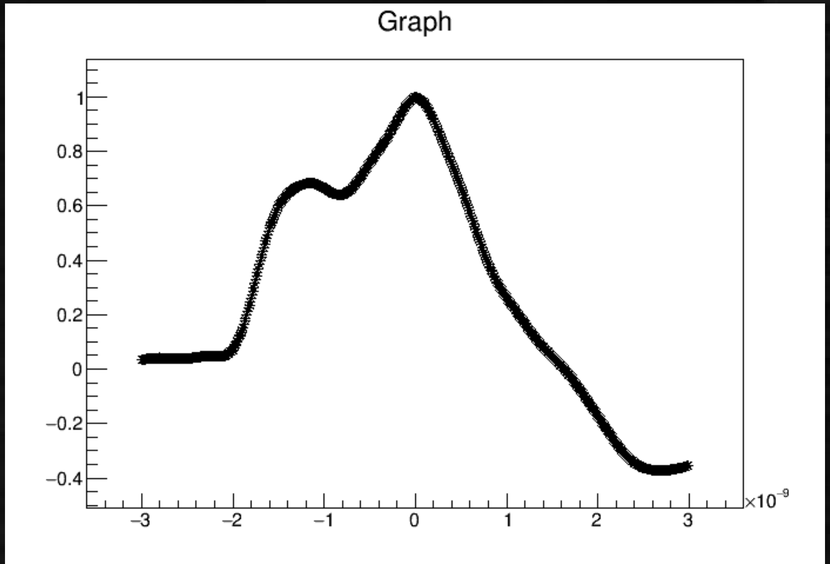
Average of ~30 waveforms
Smaller capacitance
→ faster rise time
Subtle differences by
RT and inverse APDs



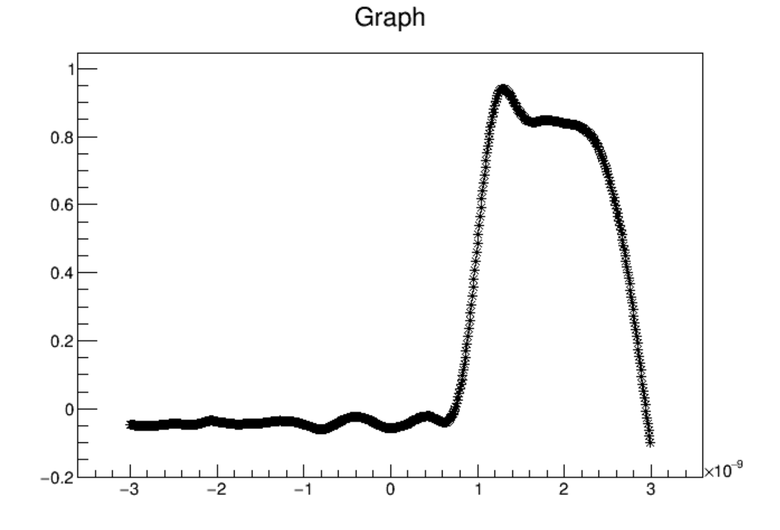
S3884 (10 pF)



S8664-55 (80 pF)

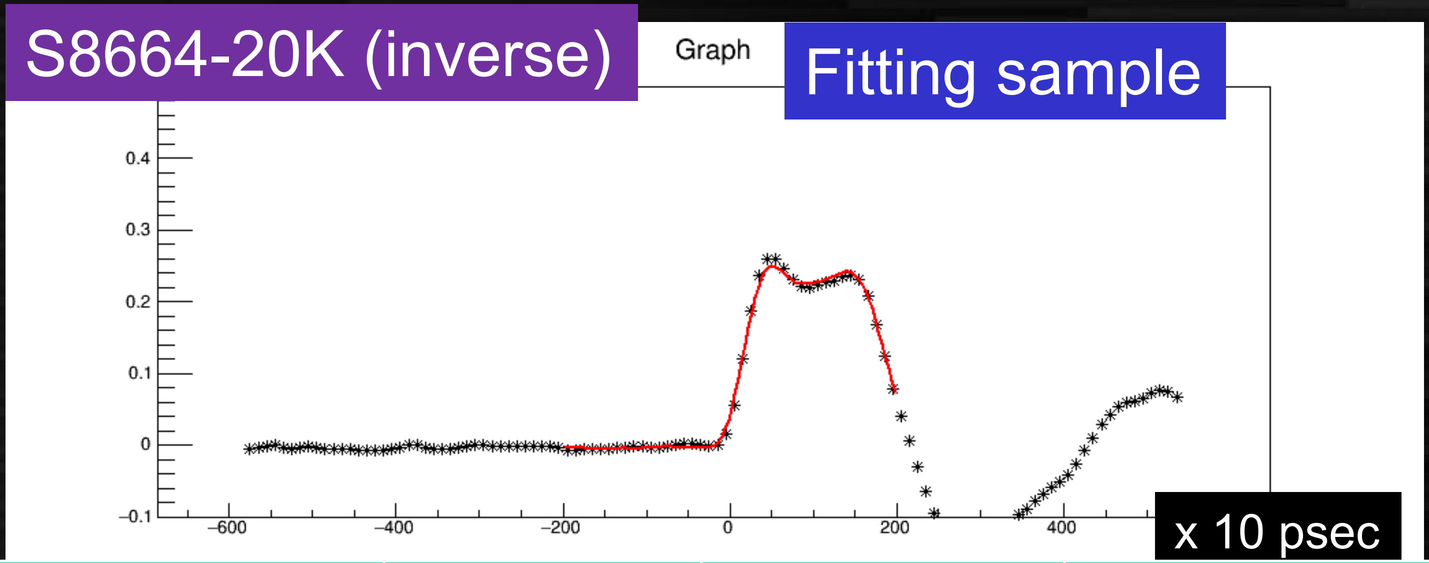


S8664-30K (22 pF)



S8664-20K (11 pF)

Fitting of waveforms



	Signal reso [ps]	Pedestal reso [ps]	Quad difference [ps]
S3884 (Reach-through)			
20% height	30.4	6.9	29.6
50% height	19.6	5.2	18.9
80% height	14.5	8.9	11.4
S8664-20K (inverse)			
20% height	11.5	6.2	9.7
50% height	7.5	4.9	5.7
80% height	18.4	8.6	16.3

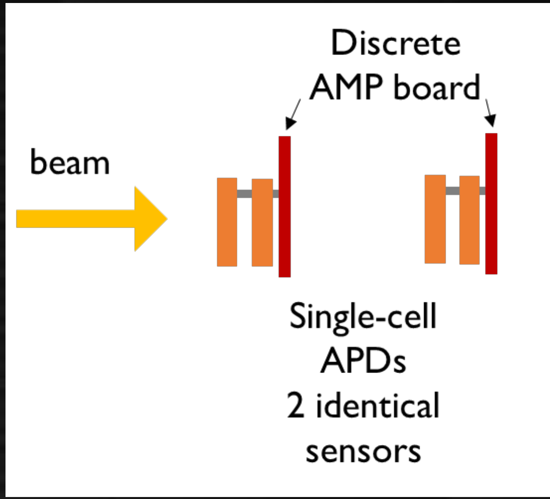
1. Average waveform obtained with a few 100 waveforms (Synchronizing timing of 50% height of signal)
2. Fitting individual waveforms for amplitudes and timing by the average waveform
3. Evaluating deviation of timing between fitted spectra and waveforms
   - 20/50/80% height
4. Noise contribution estimated by adding pre-signal waveform to signal time window

To be confirmed with test beam

Test beams: latest results to be analyzed

Previous TB (2021)

660 MeV e- beam @ ELPH (Tohoku)



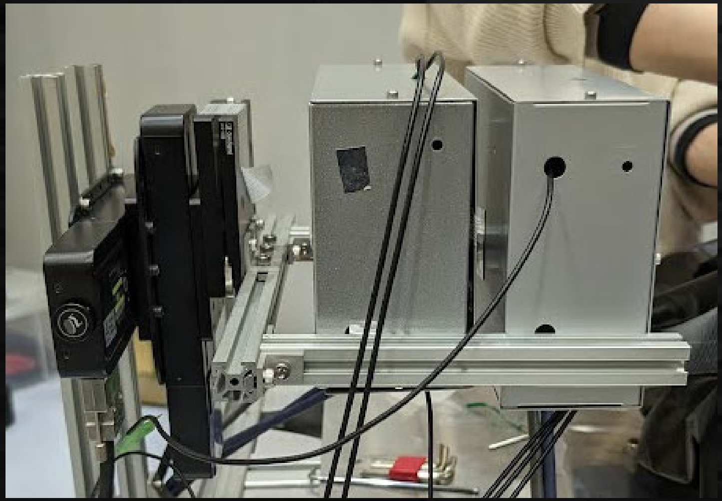
Big sensors
(5 mm ϕ)
big capacitance
Slower digitizer

Dominated by
jitter with noise

APD sensor	Cut of charge	Timing resolution
S8664-50K (Inverse type)	> 18 fC	123 ps
	> 36 fC	63 ps
S2385 (reach through type)	> 18 fC	178 ps
	> 36 fC	89 ps

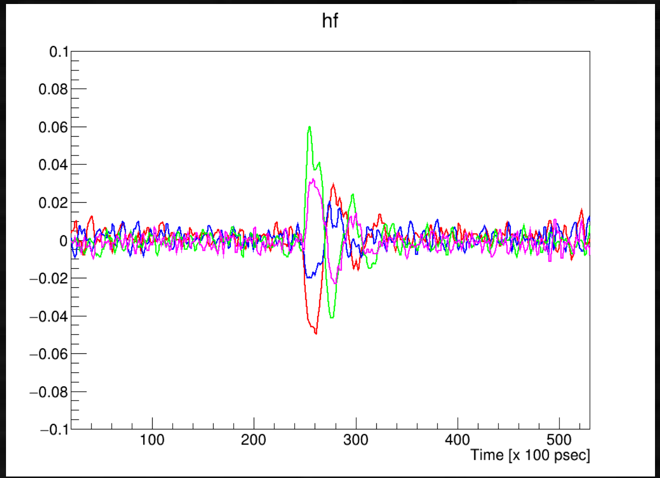
Latest TB (This month)

~3 GeV e- beam @ PF-AR (KEK)



Smaller sensors
(1.5/2 mm ϕ)
Latest setup

5 boards
(1 for trigger)
inside



Details to be analyzed soon!

Development of New Calorimeter

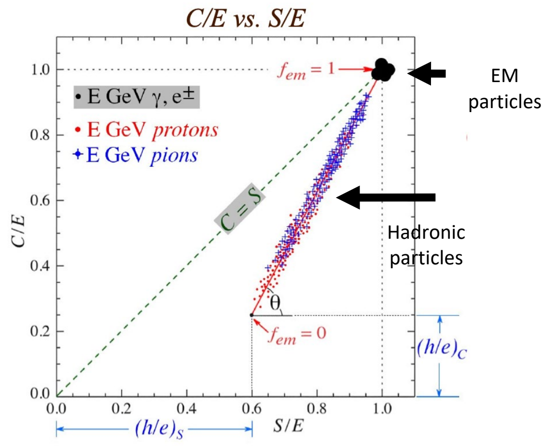
New R&D program in “U.S.-Japan Science and Technology Cooperation Program in High Energy Physics”

US J. Freeman (Fermilab, PI), C. Gatto (NIU)

Japan W. Ootani (Tokyo, PI), T. Takeshita (Shinshu), T. Suehara (Tokyo), D. Jeans (KEK), K. Matsuoka (KEK)

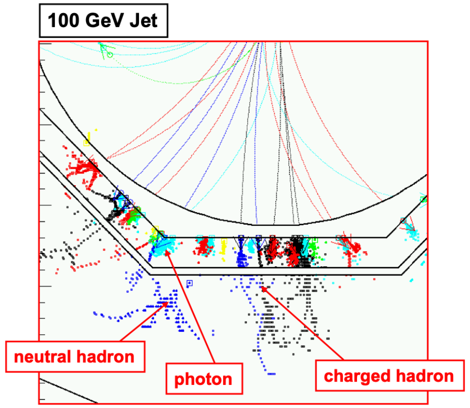
Dual-Readout calorimetry
Better performance at high energy, PID

High-Granularity calorimetry
Better performance at low energy



Y. Kim, EIC Calorimeter Workshop 2021

New calorimetry for future colliders



psec timing
PID, BG reduction, improve PFA

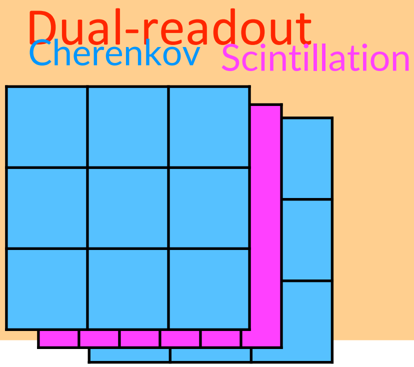
Overview of Research Plan

How to Combine High-granularity and Dual-readout with Excellent Timing

Cherenkov detector

Cherenkov radiator + UV-GasPM

- High-granularity readout
- psec timing
- Low-cost



Scintillation detector

SiPM-on-strip technology

- High-granularity
- low-cost

Fast timing front-end electronics

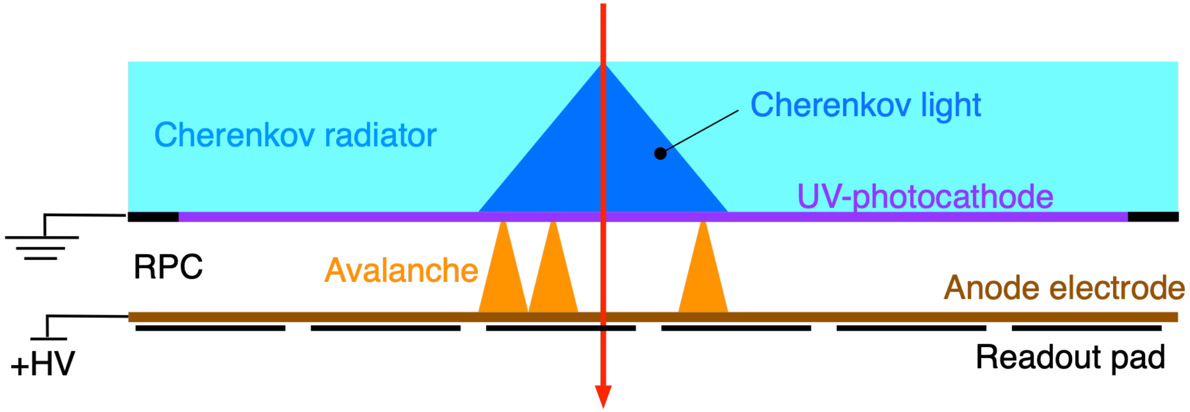
Simulation and analysis tools

Prototyping and beam test at FTBF

Demonstrate performance of proposed calorimeter technology

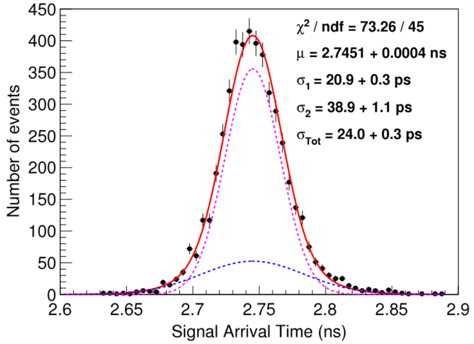
Cherenkov Detector with psec-timing

- **Proposed concept**
  - Cherenkov radiator + UV-GasPM
  - UV-GasPM
    - Photocathode: CsI
    - Electron multiplier: DLC-RPC
- **Expected Advantages**
  - Uniform and efficient Cherenkov readout
  - Excellent timing (thin gap without no drift region)
  - High-rate capable
  - Low- and uniform- mass distribution
  - Large area at low-cost
  - High-granularity with segmented readout pad for RPC
- **Target timing resolution**
  - $\mathcal{O}(\mathbf{10ps})$ with multiple photoelectrons from Cherenkov light



PICOSEC detector

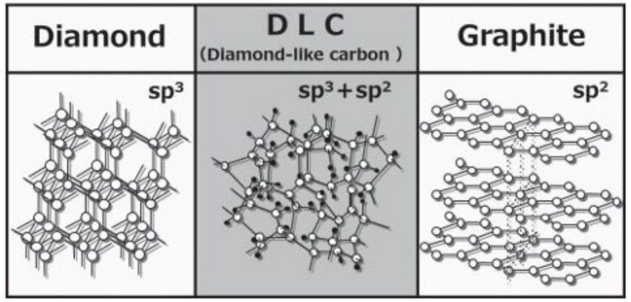
- Similar concept
- Based on Micromegas
- <20ps timing resolution for MIP



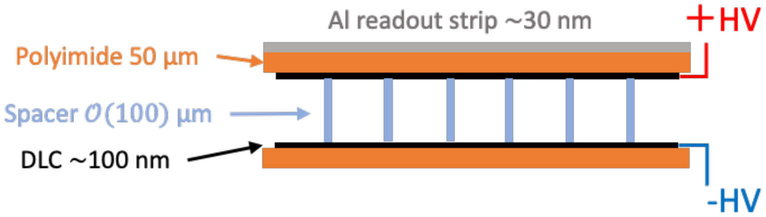
https://doi.org/10.1016/j.nima.2018.04.033

Technologies for Cherenkov Detector

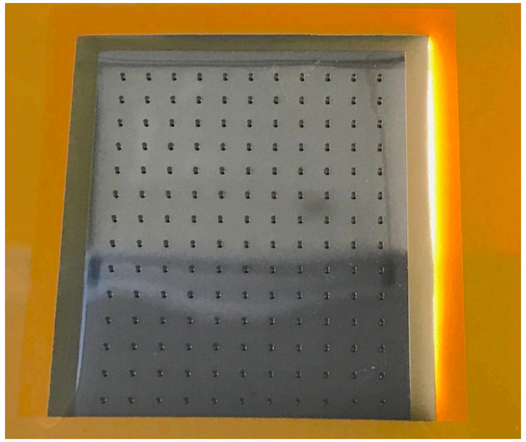
- **Ultra-low-mass high-rate-capable RPC for MEG II experiment**
  - Diamond-Like-Carbon (DLC) -based electrode
  - Ultra-low mass: $0.1\% X_0$ with 4 layers
  - High efficiency: $> 90\%$ with 4 layers
  - Good time resolution: $160-170\text{ps}$ with single layer (no optimisation for timing)
  - High rate capability: $> 1\text{MHz/cm}^2$
- **Fast timing photo-detector based on RPC-GasPM**
  - Single photon resolution of 25ps with prototype



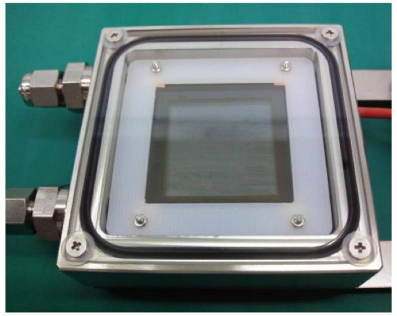
Ref) https://pcs-instruments.com/articles/the-science-behind-diamond-like-coatings-dlcs/

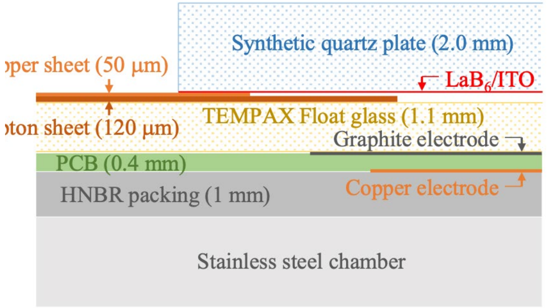


DLC on Kapton



Prototype of Gas PM with RPC (KEK, K. Matsuoka)

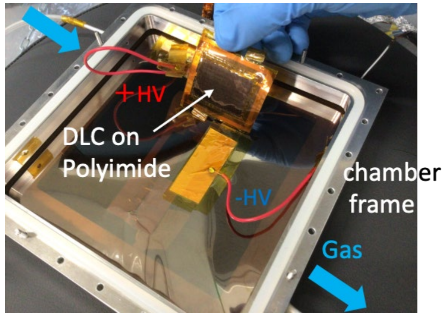


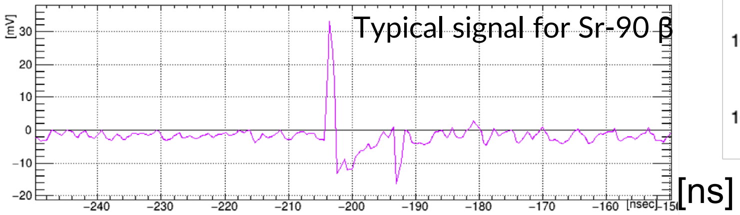


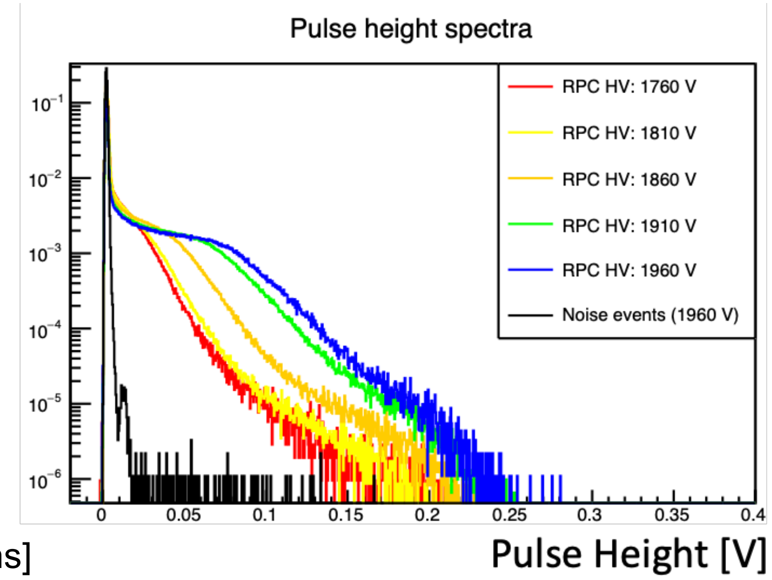
https://arxiv.org/abs/2302.12694

Performance Test of RPC

- **First test of DLC-RPC with thinner gap**
  - Gap: $192\mu\mathrm{m}$
  - Anode: $4\mathrm{M}\Omega/\mathrm{sq}$, Cathode: $40\text{-}55\mathrm{M}\Omega/\mathrm{sq}$
  - Gas: R134a/SF6/isobutane (94/1/5)
  - NOT optimised for timing yet

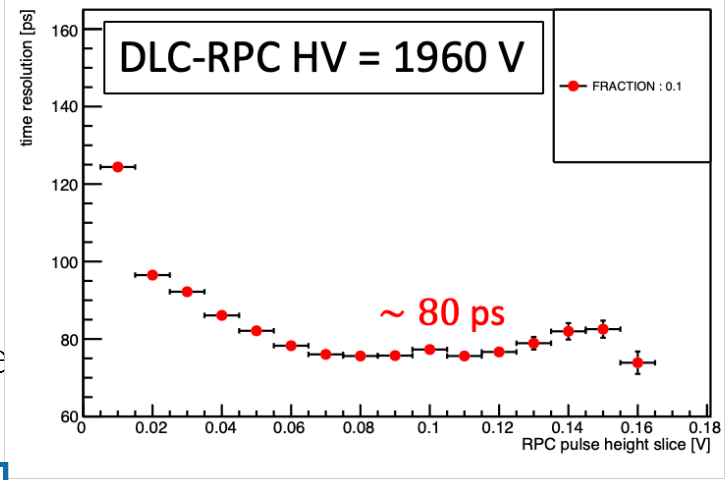






- **Timing resolution of RPC**
  - Best resolution of 80ps obtained for large signal
    - Large signal = avalanche over full gap length in GasPM
    - Average # primary electrons ~2

⇒Single photoelectron time resolution: $80\mathrm{ps}\times\sqrt{2}\sim 110\mathrm{ps}$



- **Timing resolution expected for Cherenkov detector**
  - Expected # photoelectrons with (3mm-thick MgF2 and CsI photocathode ≳10

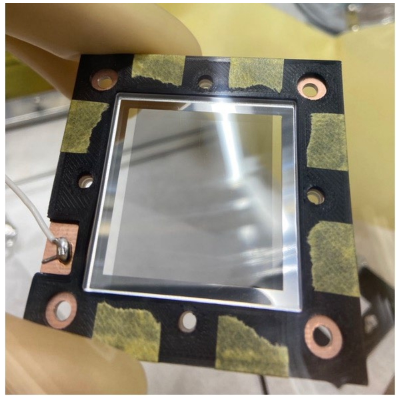
⇒Expected timing resolution 35ps

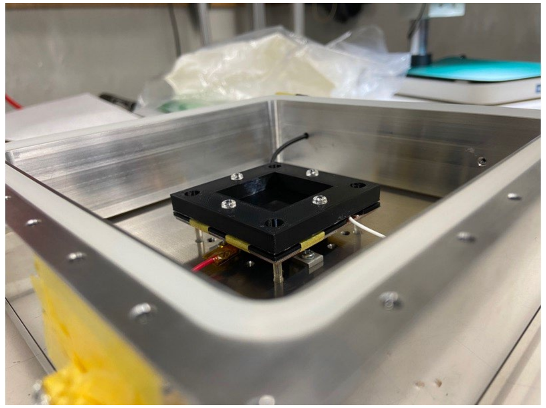
Promising. (N.B. still not optimised for timing)

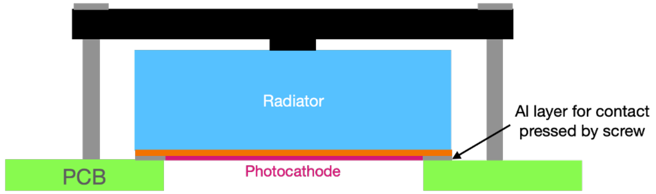
First Prototypes of Cherenkov Detector

- **Two types of radiators with photocathode**
  - **Hamamatsu**: MgF_2(2.4mm) + Cr(3nm) + CsI (10nm)
  - **Fermilab**: MgF_2(3mm) + Cr(18nm) + CsI (18nm)
- **Test of first prototypes in progress**

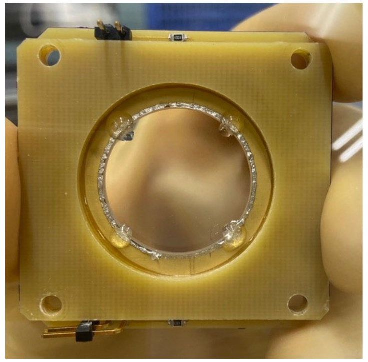
Hamamatsu

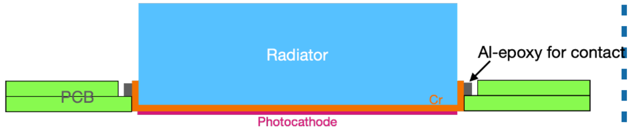






Fermilab





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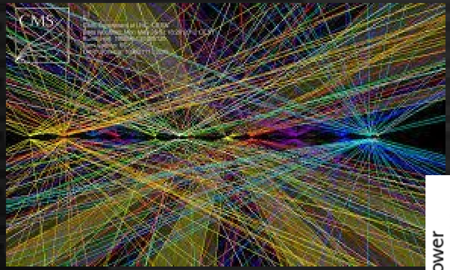
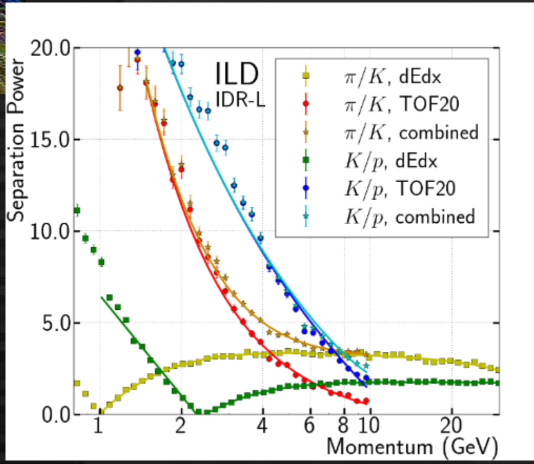
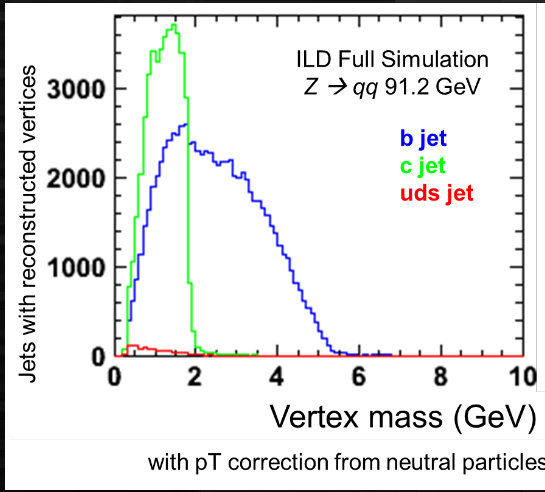
  - Silicon sensor (LGAD)
  - Scintillator/Cherenkov detectors (slides from W. Ootani)
- Application of timing measurements to Higgs factories
  - Pileup rejection?
  - Particle ID
  - Improving particle flow performance
  - Secondary photon ID
- Possible design of timing detector (and consideration)

Target timing resolutions for Higgs factories

- 30 psec (cδt = 1 cm) realistic goal
  - ToF π/K/p separation
    (up to 5-10 GeV/c @ O(m) from IP)
  - Pileup separation in FCCee?
- 10 psec (cδt = 3 mm)
  - Separation of neutral and charged particles in calorimeter
    → 5D particle flow
- 1 psec (cδt = 0.3 mm) for EM component
  - Identifying secondary photons from b/c for flavor tagging
- Timing resolution = single hit resolution x √(N hits)
  - Averaging effective in calorimeters

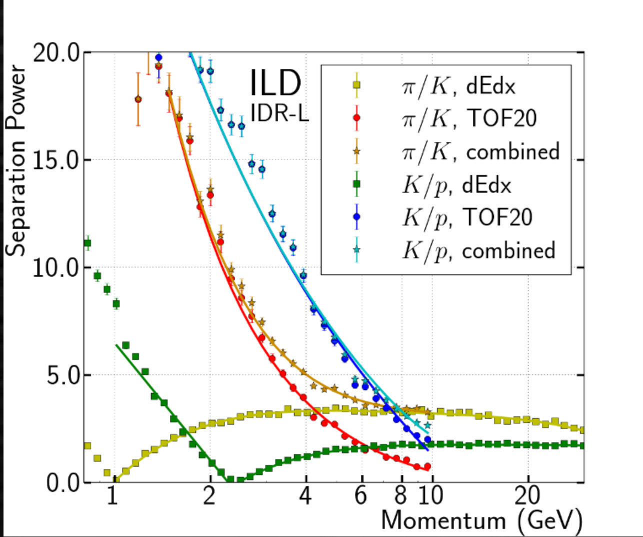


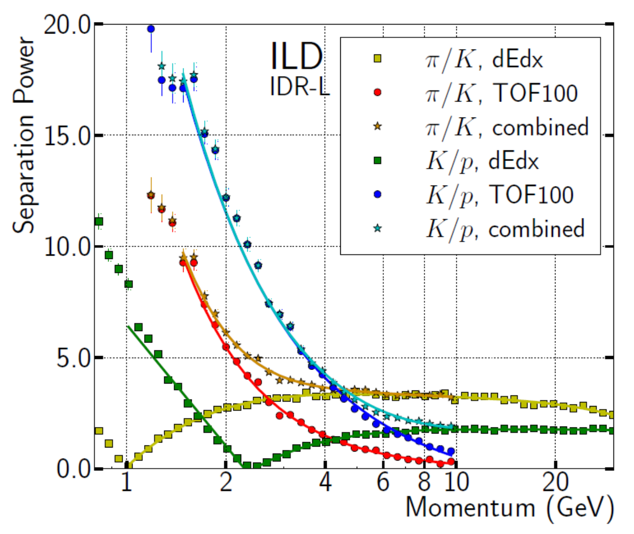




Particle ID (π, K, p) at ILD

- dE/dx in TPC
  - ~3 sigma for π/K, ~2 sigma for K/p
  - Can be improved by pixel readout
  - Impossible momentum at 1-2 GeV
- ToF at calorimeters
  - PID with simple reconstruction (averaging over O(10) hits)
    - 100 psec hit reso → separation up to 2-3 GeV
    - 20 psec hit reso → separation up to 3-5 GeV
  - Precise flight length estimation needed
    - Available in ILD software
  - More intelligent reconstruction using O(100) hits desired
    - Machine learning target: to be done





Energy	β (π)	β (K)	β (p)	Δt (π/K)	Δt (K/p)
5 GeV	0.9996	0.9951	0.9822	30 ps	88 ps
10 GeV	0.9999	0.9988	0.9956	7 ps	21 ps

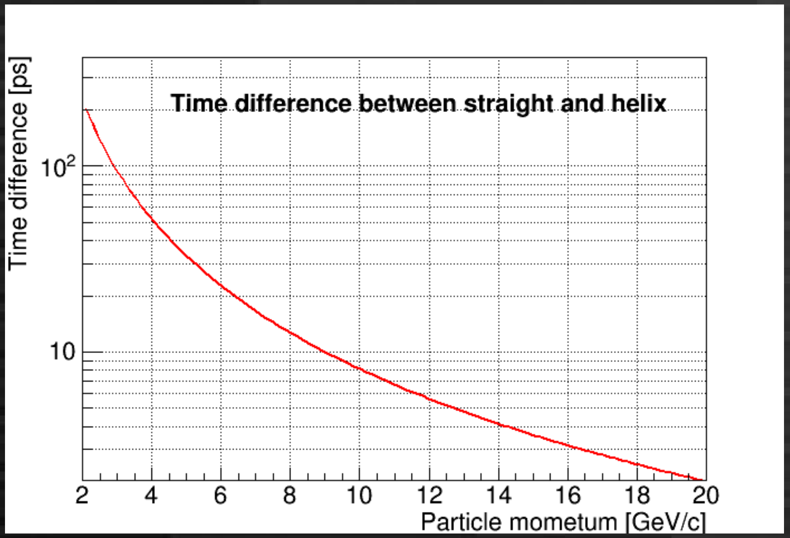
@2m flight length

Physics usage of particle (kaon) ID
- Flavor tagging (esp. strange tagging)
- Quark charge ID

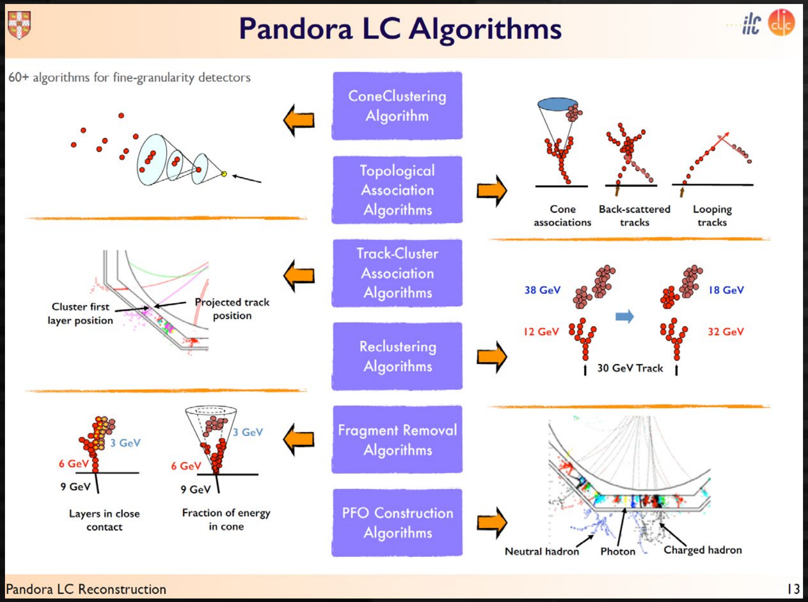
5D particle flow

- Cluster separation is essential in PFA
- Timing information should help separation of photons and charged particles
  - Flight length is longer in charged particle due to the magnetic field
- < 10 psec resolution is necessary

- Need software development for investigating actual performance
- Aim to fully replace PFA with modern ML method (ongoing work)

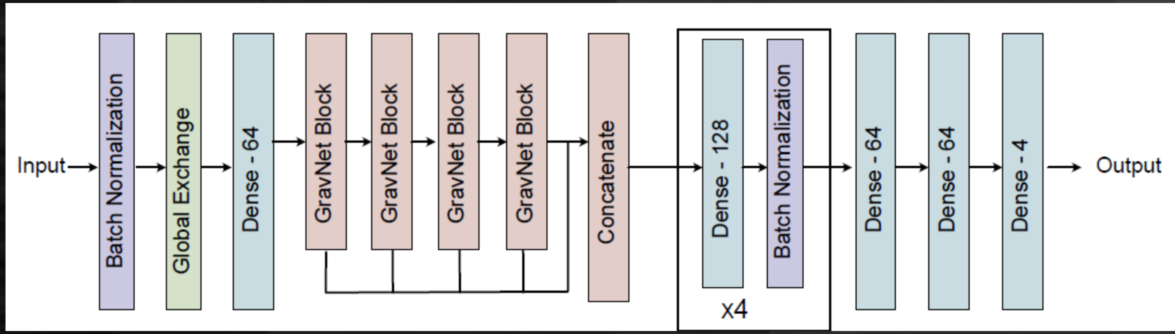


10 psec can separate < 9 GeV tracks from photons (1.8 m distance)



PFA with GNN: algorithm

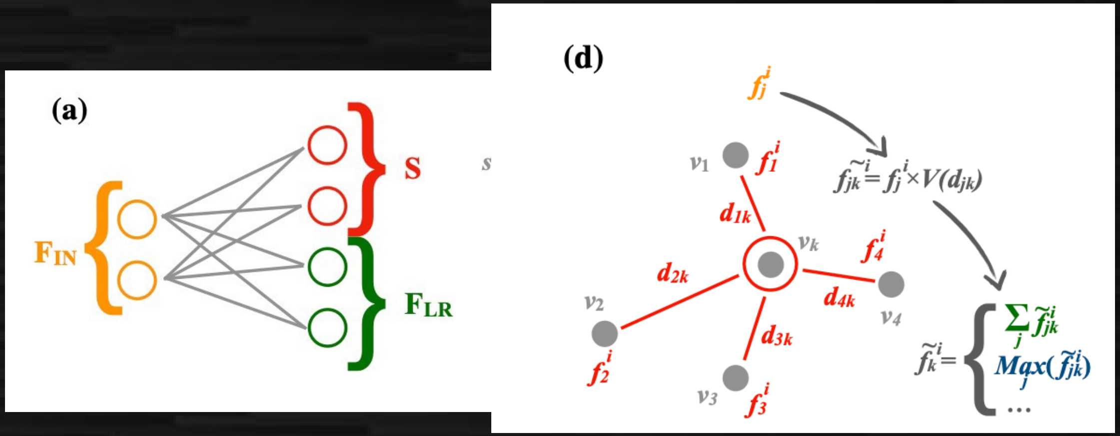
- Input: position/energy/timing of each hit
- Output: virtual coordinate and β for each hit



GravNet

arXiv:1902.07987

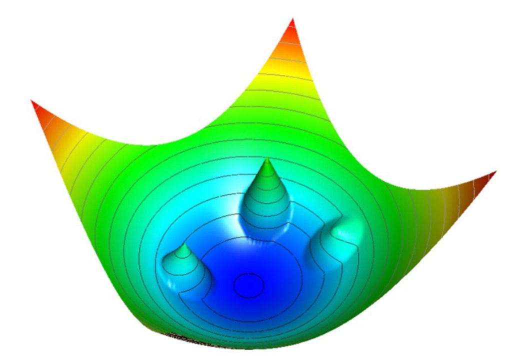
- The virtual coordinate (S) is derived from input variables with simple MLP
- Convolution using "distance" at S (bigger convolution with nearer hits)
- Concatenate the output with MLP



Object Condensation (loss function)

arXiv:2002.03605

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



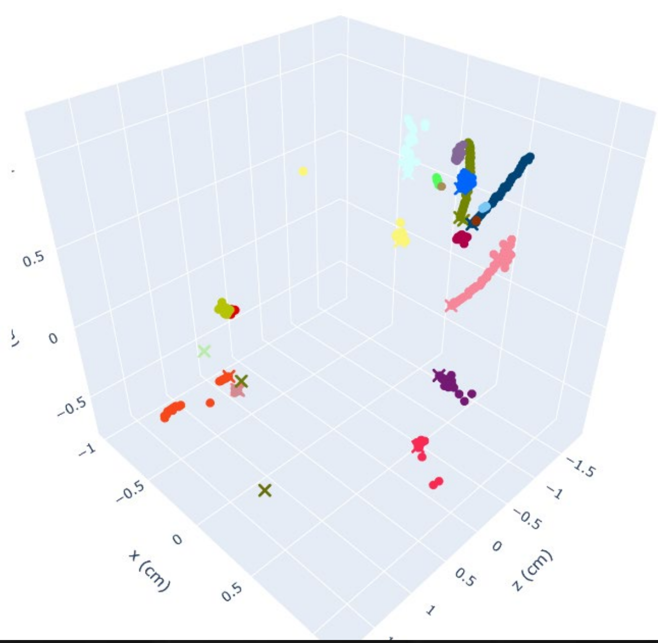
- Condensation point: The hit with largest β at each (MC) cluster
- L_V: Attractive potential to the condensation point of the same cluster and repulsive potential to the condensation point of different clusters
- L_β: Pulling up β of the condensation point
- L_p: Regression to output features

Work in Progress: track-cluster matching

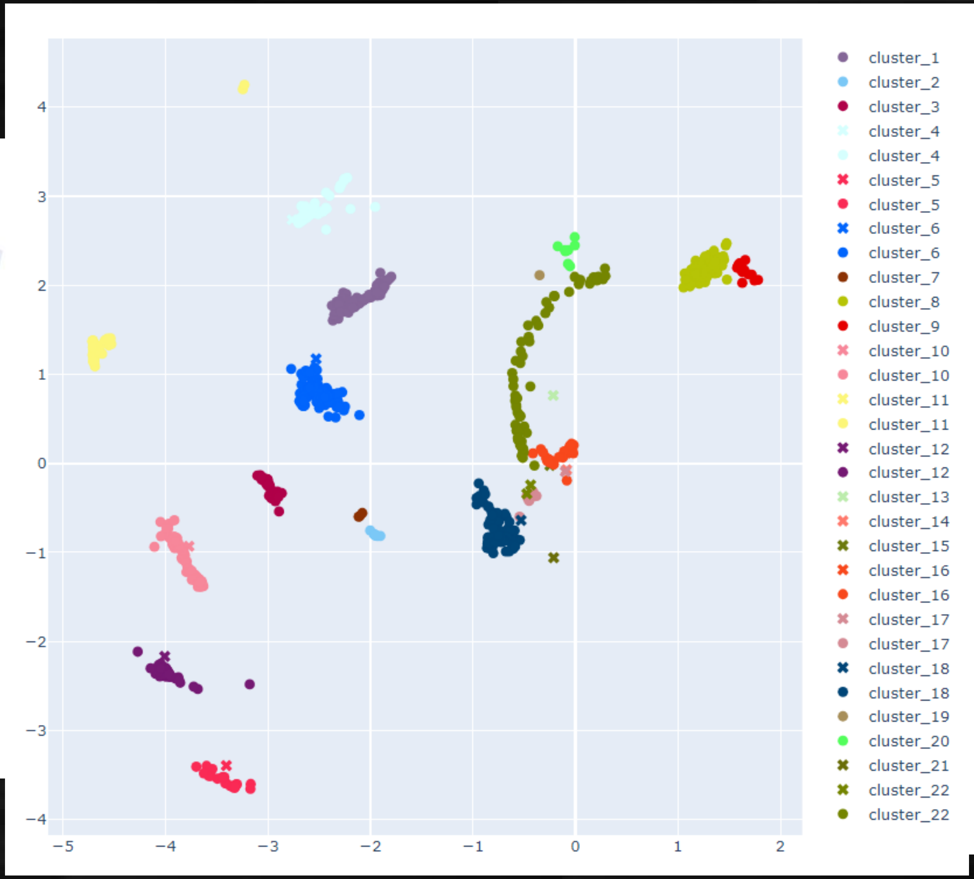
- PFA is essentially a problem "to subtract hits from tracks"
- HGCAL algorithm does not utilize track information
  - Only calorimeter clustering exists
- Simple extension to include track information
  - Adding "virtual hits" derived from track information
    - Hits at position where the track enters the calorimeter (from LCIO StackState)
  - Add a term to the object condensation loss function
    - Pulling up β of tracks (virtual hits) to promote them to condensation points (in addition to the usual beta-term, called beta-track term)
  - Evaluate fraction of (MC) charged clusters to be correctly assigned to clusters with tracks (virtual hits)

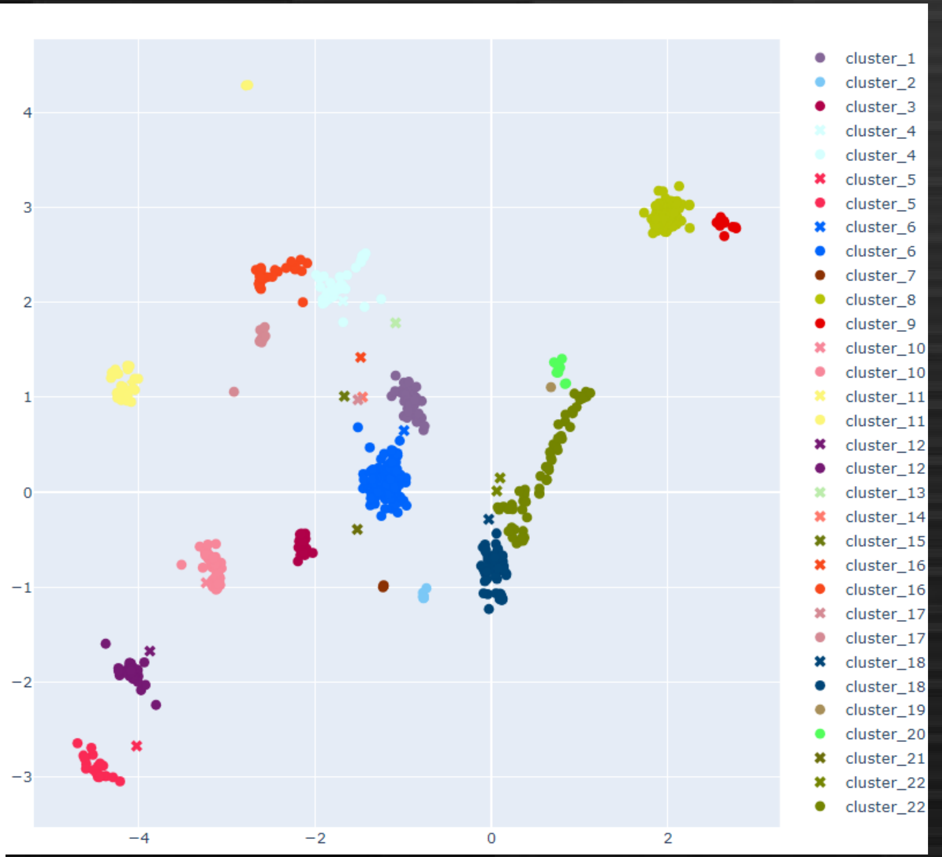
Preliminary results – event sample

10 Taus @ 10 GeV each



Real 3D coordinate





Hits on the virtual coordinate – colored by MC truth clusters
x refers virtual hits from tracks
left with beta-track term, right without beta-track term

Consideration for detector design

- Time-of-flight: where to implement?
  - External tracker: just a few hits; need ultimate resolution
    Covering area is big: maybe strip sensors?
  - Calorimeter (either ECAL or HCAL) also usable for PFA improvement
    Averaging over many hits powerful but reconstruction more difficult
    Problem on electronics (power consumption)
    - Which layers to be replaced (or fully replaced?) to be investigated
- PID: only applicable to low energy tracks…physics impact?
  - Quark charge ID usually rely on high-energy tracks
  - RICH is more powerful? (then need to reduce radius of trackers
    → thinner sensor with LGAD for < μm resolution?)
- Need to establish detector design with psec timing

Summary

- Some efforts in Japan for psec timing ongoing
  - LGAD sensors (inverse, AC-LGAD, pixel?)
  - Cherenkov with GasPM
- Application of psec timing
  - Particle ID
  - Improving PFA
  - Secondary photons?
- Concrete design as well as establishing physics case is necessary in parallel to hardware development