Adding precise timing to detectors

Short Summary of
Mini-workshop on fast timing detector technology

Katja Krüger,

Workshop: A detector for a Higgs factory and beyond: ILD

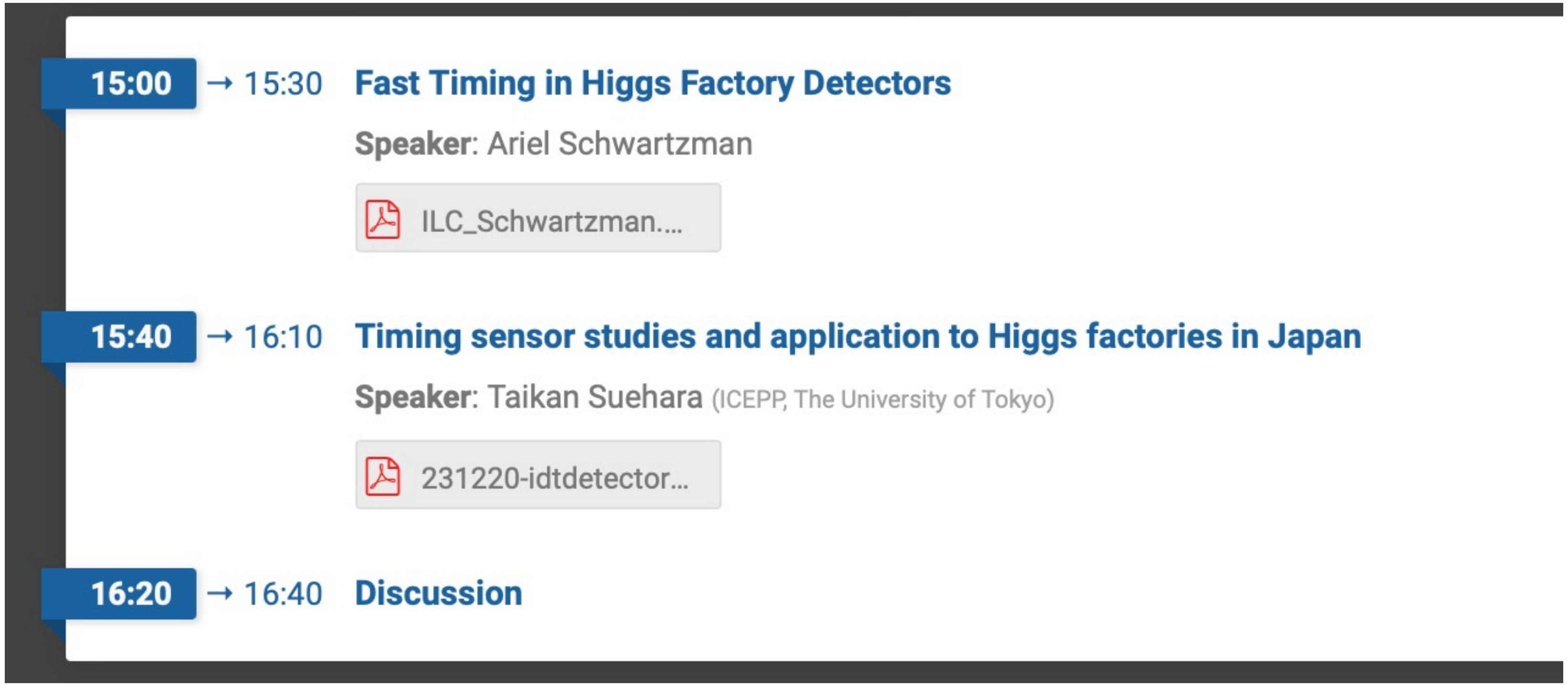
CERN, 15 January 2024

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

ILC IDT WG3 Mini-Workshop on Fast Timing

- Virtual Workshop on 20 December 2023



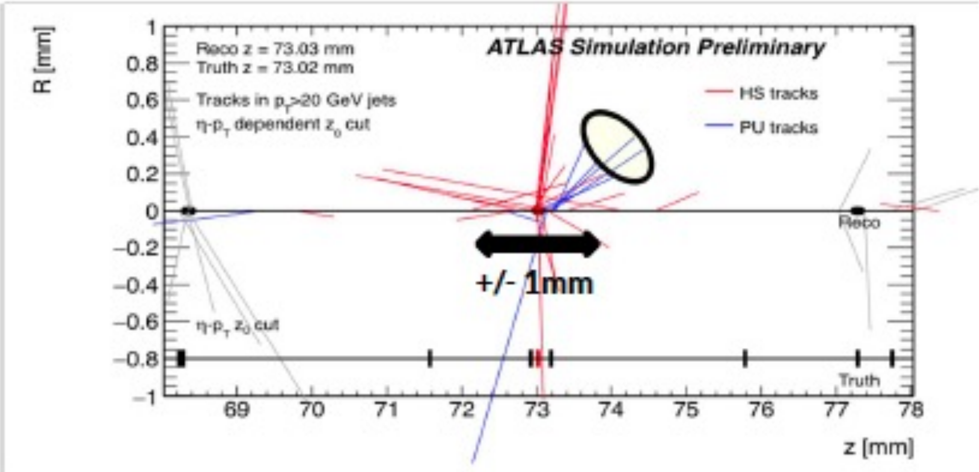
- About 30 participants
- Very lively and interesting discussions

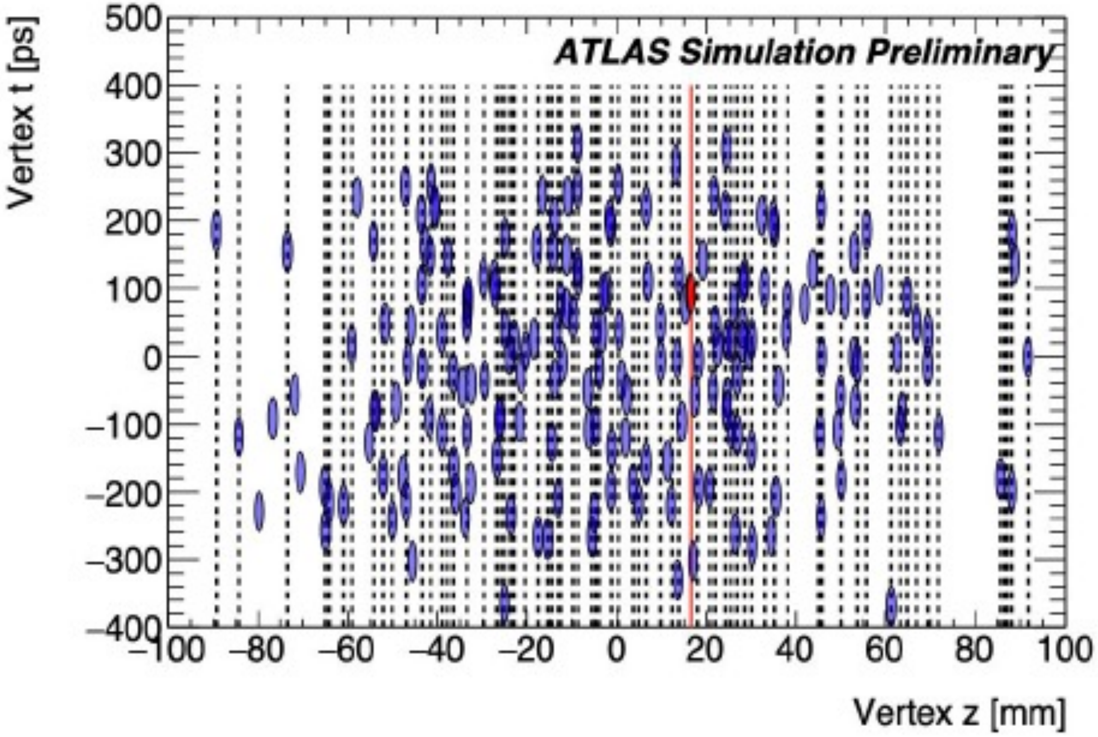
Introduction

- **While the use of timing in collider detectors has a long history, <u>precision timing at the level of 10-30ps</u> is a new capability for the next generation of particle physics detectors at all future colliders**
  - Address the increasing complexity of events at hadron colliders
    - 4D trackers to resolve vertices at very high pileup densities
  - Identify long-lived particles (LLPs) and expand the reach for new phenomena
  - Enable particle ID capabilities at low momentum
  - Improve calorimetry measurements (PFA and jet energy resolution)
  - Suppress out-of-time beam Induced backgrounds (muon collider)
- **R&D to investigate the full potential of fast timing detectors in future Higgs Factories is an exciting opportunity for the particle physics community**

2

Fast Timing at the HL-LHC





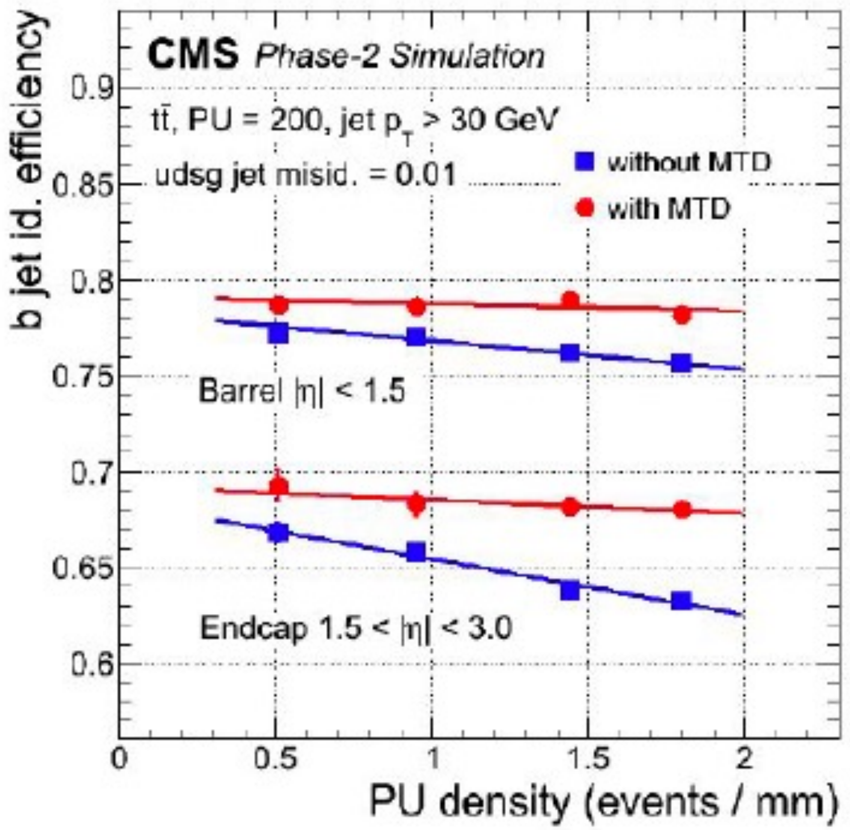
At the HL-LHC, the typical separation between vertices can be comparable to the track longitudinal impact parameter resolution: **the association o tracks to vertices becomes ambiguous**!

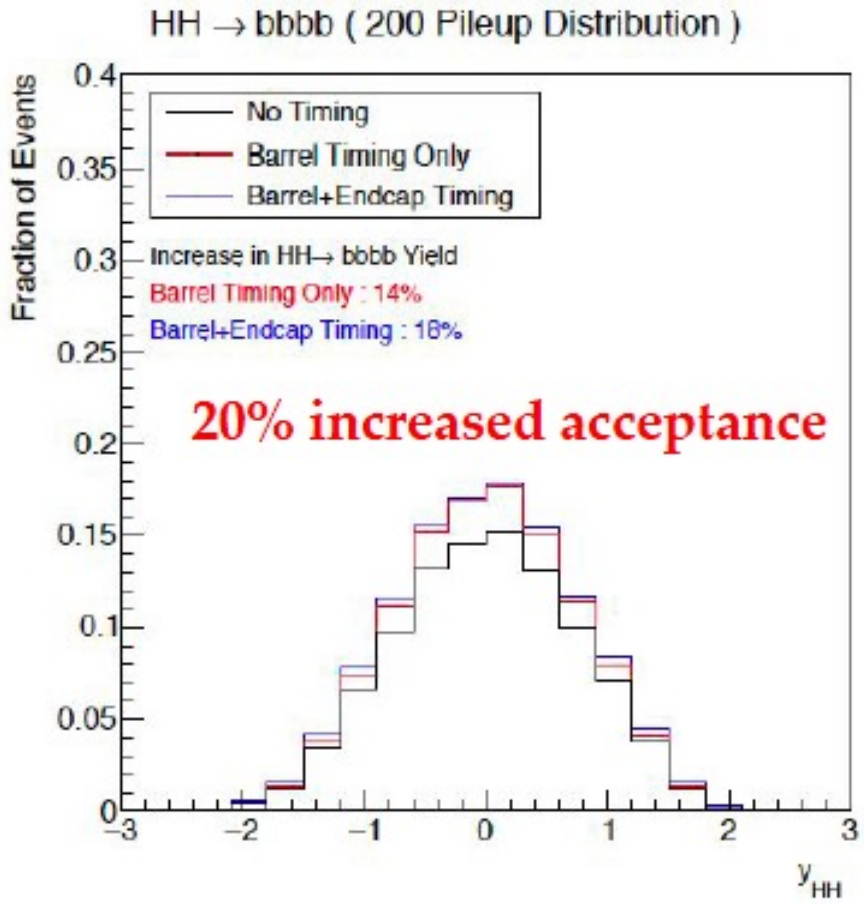
Exploit the time spread of collisions to reduce pileup contamination

Nominal HL-LHC Luminous region σ_t = 180ps
(30ps detector) → 30/180 = **6x pile-up rejection**

3

Physics impact: Di-Higgs





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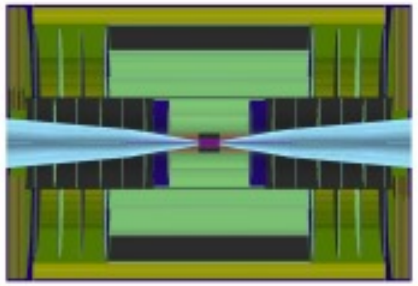
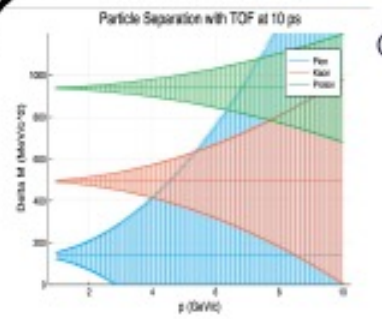
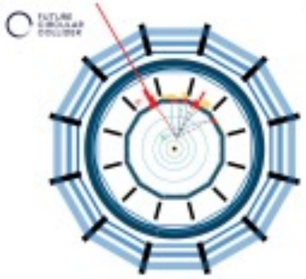
Fast timing in Higgs Factories



Suppression of beam induced backgrounds at muon colliders

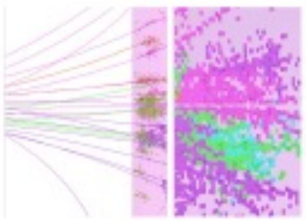
Full 4D tracking

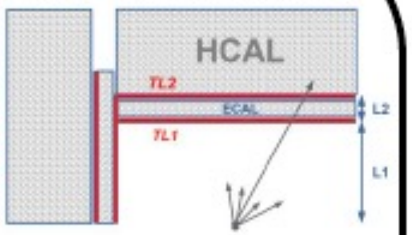




Time of Flight for Particle ID at low momentum and Long Lived particles

Timing layers





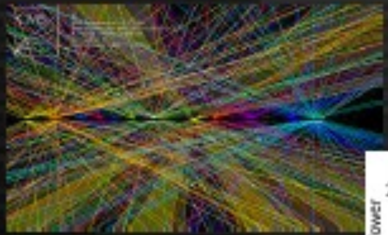
Exploit the time structure of hadronic showers to enhance PFA and improve jet energy resolution

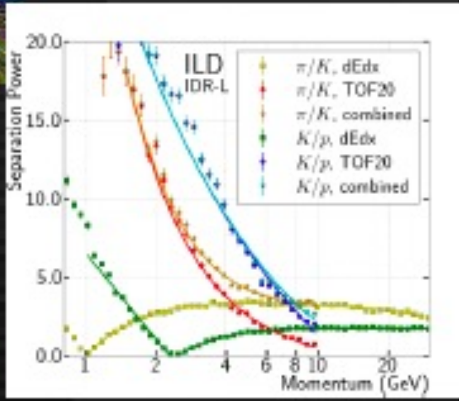
5D Calorimetry

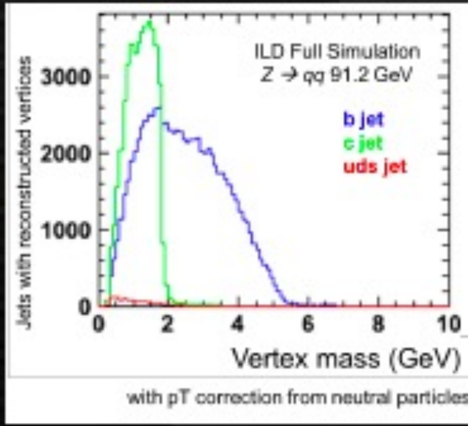
Timing layers or volumetric timing

Target timing resolutions for Higgs factories

- 30 psec ($c\delta t$ = 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 ($c\delta t$ = 3 mm)
  - Separation of neutral and charged particles in calorimeter → 5D particle flow
- 1 psec ($c\delta t$ = 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

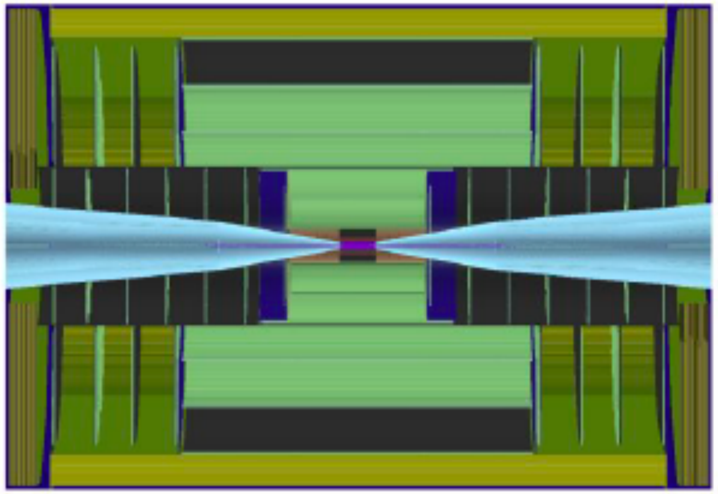


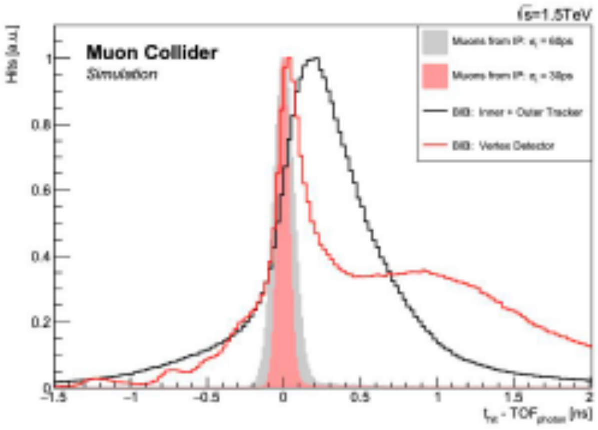


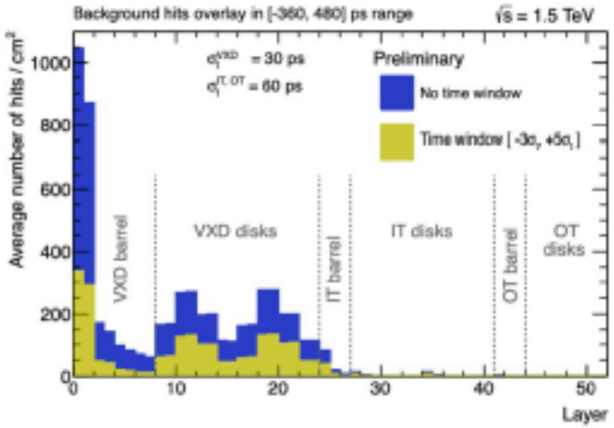


Taikan Suehara, Timing detector meeting of IDT-WG3 detector WG, 20 Dec. 2023 page 17

Muon Collider: 4D Tracking







Full 4D tracking design to address the challenge of Beam Induced Backgrounds

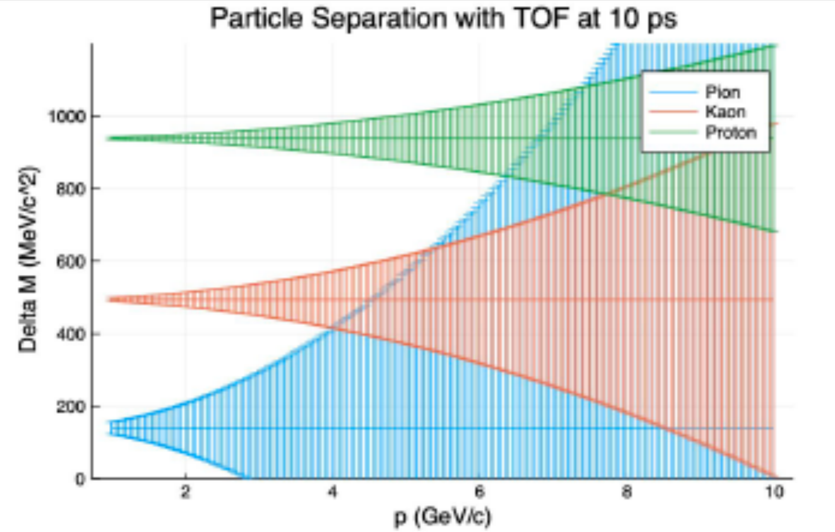
- **Picosecond timing plays a key role reducing the hit densities from BIB** (10 x HL-LHC!)
- Large number of hit combinations create a challenge for tracking pattern recognition
- **Timing information reduces hit densities by a factor of 2**

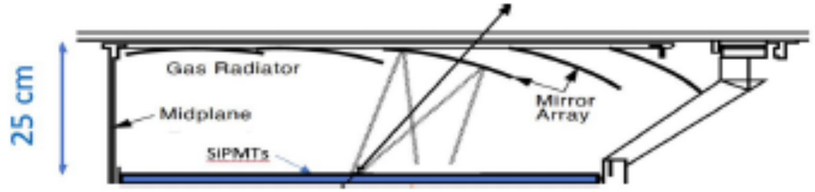
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
Sensor Thickness	$50\mu m$	$100\mu m$	$100\mu m$
Time Resolution	30ps	60ps	60ps
Spatial Resolution	$5\mu m \times 5\mu m$	$7\mu m\times 90\mu m$	$7\mu m \times 90\mu m$

ToF: Particle ID

Updating the SiD Detector concept [Breidenbach, et. al.]

- Large-radius timing layers in the in front of the calorimeter can provide **Time-of-Flight (ToF) for PID**
  - Flavour physics
- Need 10ps resolution for K/pi separation at low momentum (up to ~3-4 GeV)
- **Complements other PID sub-detectors in the low momentum region**
  - RICH detector for high (10-50 GeV) momentum
    - Strange tagging for H→ss
    - Fast-timing (~100ps) for background suppression





Strange quark as a probe for new physics in the Higgs sector, J. Va'vra, et.al.

A gaseous RICH detector for SiD or ILD 8

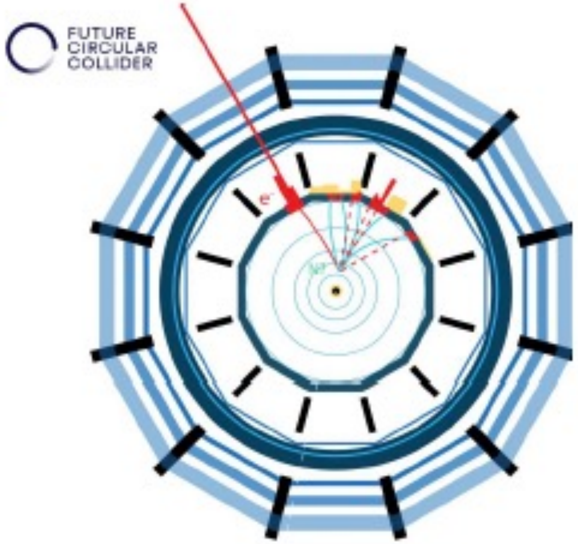
ToF: Long Lived Particles

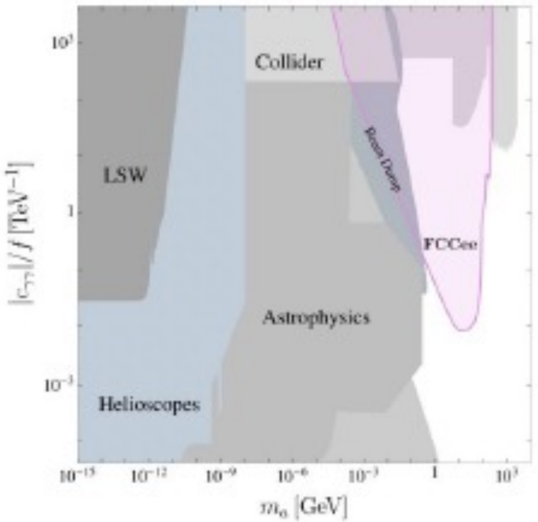
Exploit high luminosity Z run of FCC-ee to search for LLP:

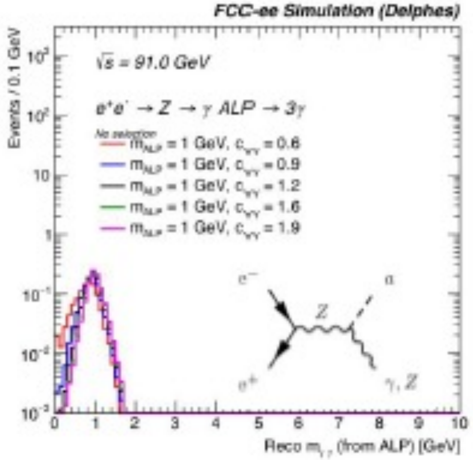
- Heavy Neutral Leptons
- Axion-like particles
- Exotic Higgs decays

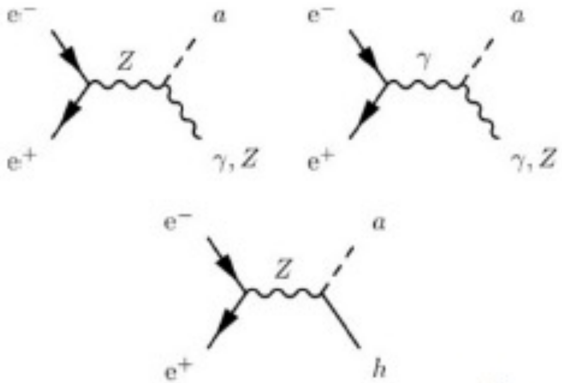
Timing information:

- Simultaneous determination of mass and proper decay time combining decay path and ToF
- Combine with displaced vertex reconstruction for enhanced performance









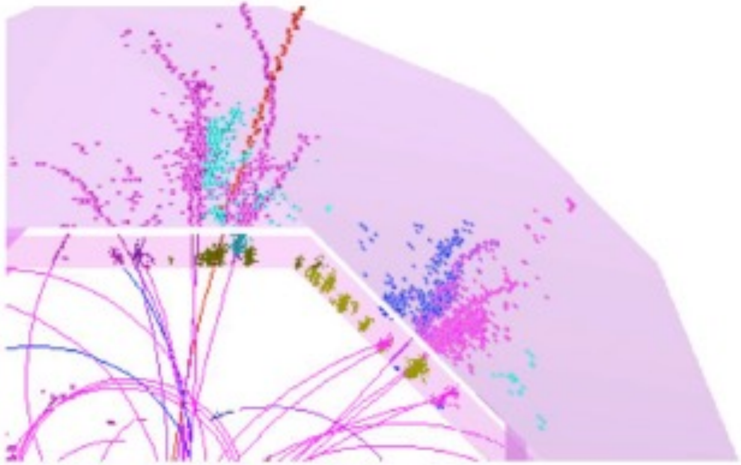
[Searches for Long-Lived Particles at the Future FCC-ee]

9

5D Calorimetry

Precision timing for collider-experiment-based calorimetry [Chekanov, et. al.]

- **Performance of particle flow reconstruction depends on the ability to associate showers to particles**
  - Challenging when showers overlap in space
- **Precision timing information can help resolve close-by particles, exploiting the full space-time structure of showers**, improving the jet energy resolution
  - separate delayed shower components from neutron induced processes
  - resolve track-cluster associations following shower development cell-to-cell (PFA pattern recognition)



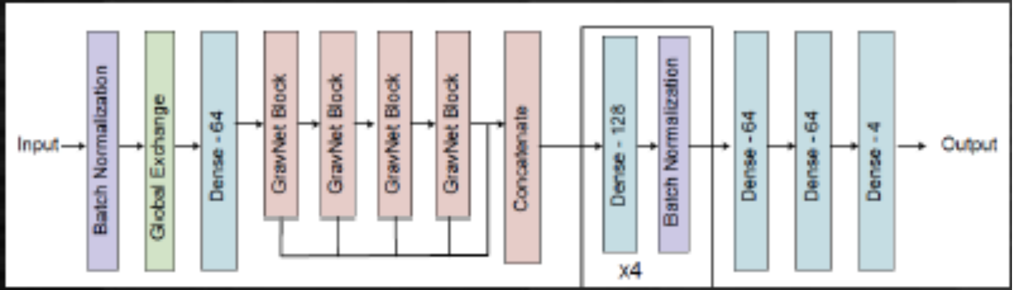
Different approaches:

- Volume (cell-level) timing
- Dedicated timing cells
- Timing layers within the calorimeter

10

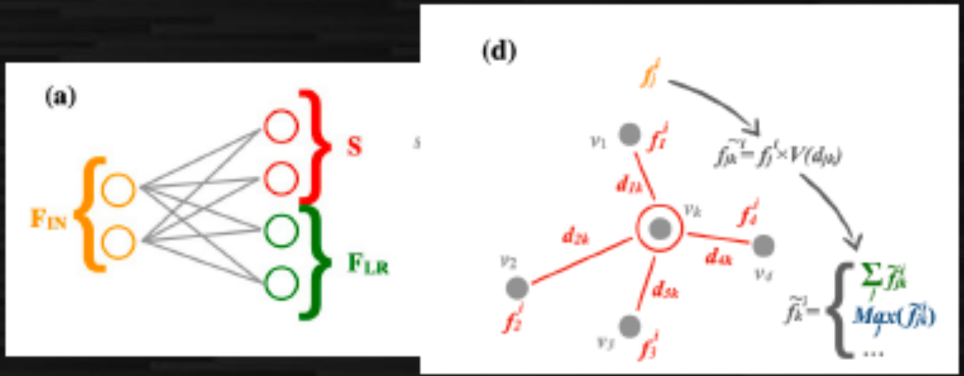
PFA with GNN: algorithm

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



GravNet arXiv:1902.07987

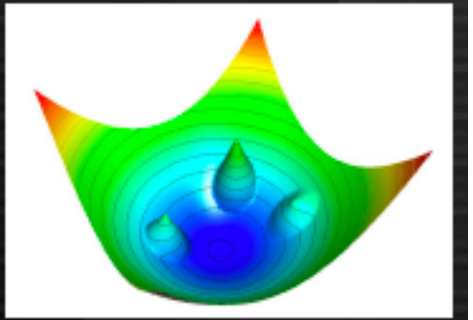
- The virtual coordinate (S) is derived from input variables with simple MLP
- Convolution using "distance" at S (bigger convolution with nearer hits)
- Concatenate the output with MLP



Object Condensation (loss function)

arXiv:2002.03605

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



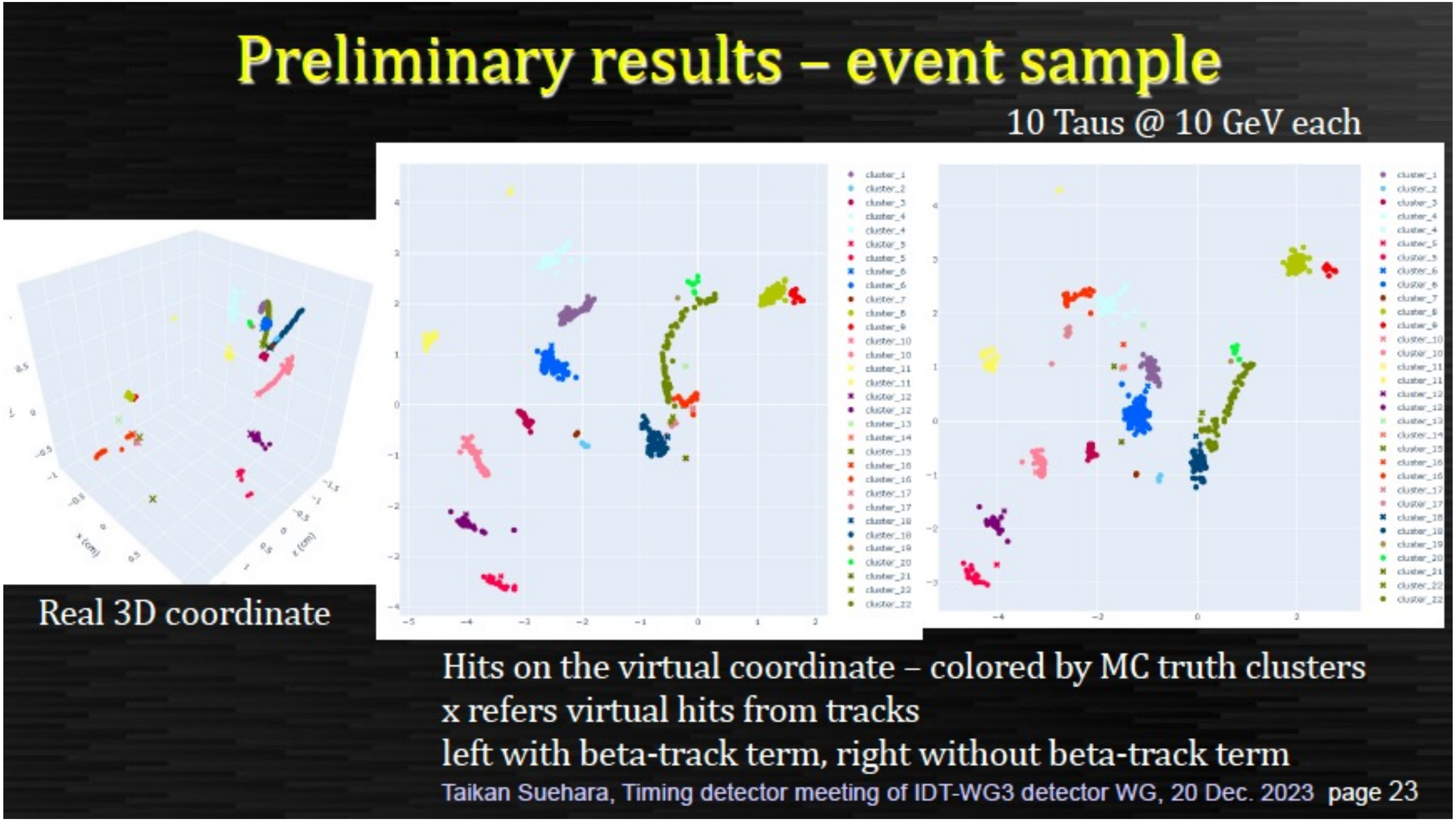
- Condensation point: The hit with largest β at each (MC) cluster
- L_V: Attractive potential to the condensation point of the same cluster and repulsive potential to the condensation point of different clusters
- L_β: Pulling up β of the condensation point
- L_p: Regression to output features

Taikan Suehara, Timing detector meeting of IDT-WG3 detector WG, 20 Dec. 2023 page 21

Work in Progress: track-cluster matching

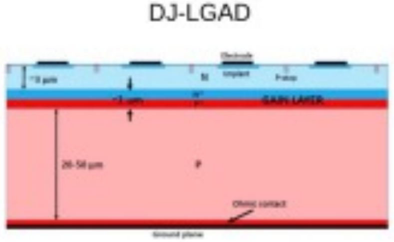
- PFA is essentially a problem "to subtract hits from tracks"
- HGCAL algorithm does not utilize track information
  - Only calorimeter clustering exists
- Simple extension to include track information
  - Adding "virtual hits" derived from track information
    - Hits at position where the track enters 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)

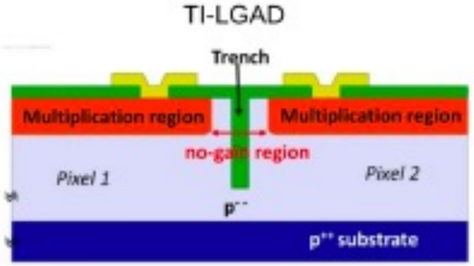
Taikan Suehara, Timing detector meeting of IDT-WG3 detector WG, 20 Dec. 2023 page 22

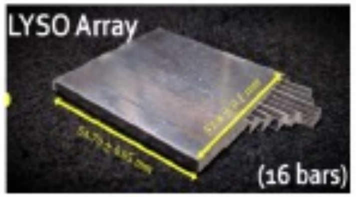

Preliminary results – event sample
10 Taus @ 10 GeV each
Real 3D coordinate
Hits on the virtual coordinate – colored by MC truth clusters
x refers virtual hits from tracks
left with beta-track term, right without beta-track term
Taikan Suehara, Timing detector meeting of IDT-WG3 detector WG, 20 Dec. 2023 page 23

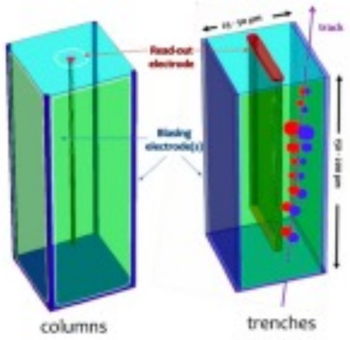
Detector Technologies

- **Timing layers / 4D tracking:**
  - (LYSO) Crystals + SiMPS (timing layers)
  - Silicon sensors (timing layers / 4D tracking)
    - **Advanced LGADs** with O(10ps) and O(10um) resolution
      - AC-LGAD, TI-LGAD, DJ-LGAD, Buried LGAD, DS-LGAD
    - **Monolithic CMOS**
      - LGAD MAPS, miniCACTUS, PicoAD, Monolith, HV-CMOS, DMAPS
    - Silicon Carbide LGADs
    - 3D silicon sensors
- **Volume calorimeter timing:**
  - LGAD or Silicon pads in Si+W calorimeter (CMS HGCAL)
  - Highly granular crystals
  - Plastic scintillator tiles or strips + SiPMs
  - RPC can cover large active areas for digital hadronic calorimeters (SDHCAL CALICE)





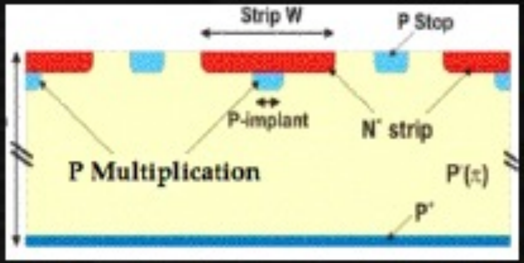




4-Dimensional Trackers [Berry, et. al]

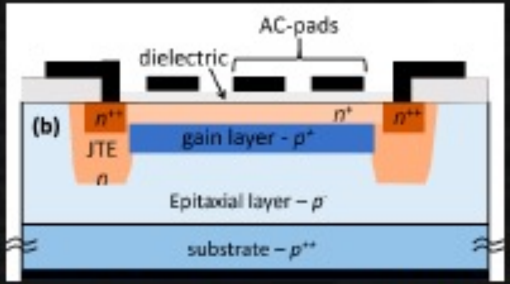
15

Various structures of LGADs



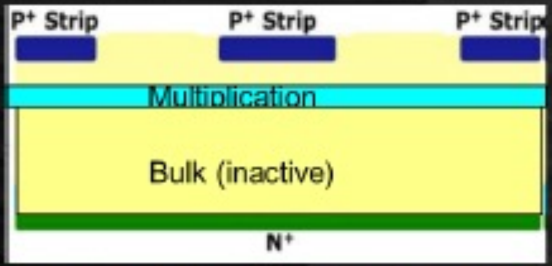
Reach-through LGAD

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



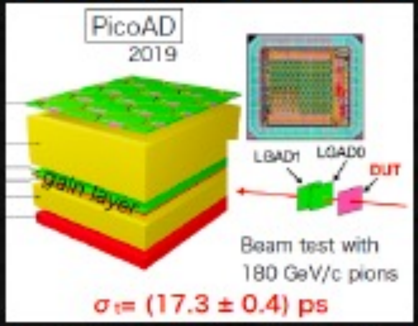
AC LGAD: AC-coupled electrodes with planar gain layer: good for strips

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

Taikan Suehara, Timing detector meeting of IDT-WG3 detector WG, 20 Dec. 2023 page 5

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

Taikan Suehara, Timing detector meeting of IDT-WG3 detector WG, 20

	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

Taikan Suehara, Timing detector meeting

To be confirmed with testbeam results

10

Development of New Calorimeter

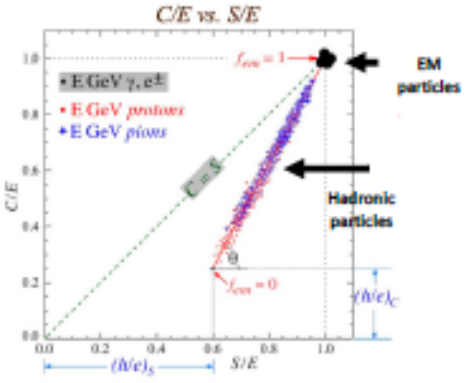
New R&D program in "U.S.-Japan Science and Technology Cooperation Program in High Energy Physics"

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)

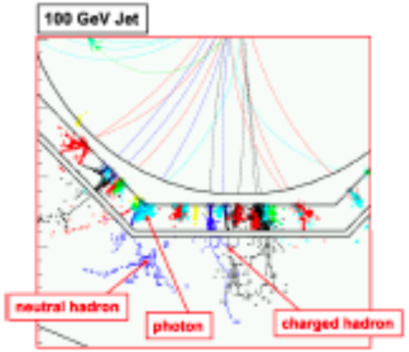
Dual-Readout calorimetry
Better performance at high energy, PID

High-Granularity calorimetry
Better performance at low energy



Y. Kim, EIC Calorimeter Workshop 2021

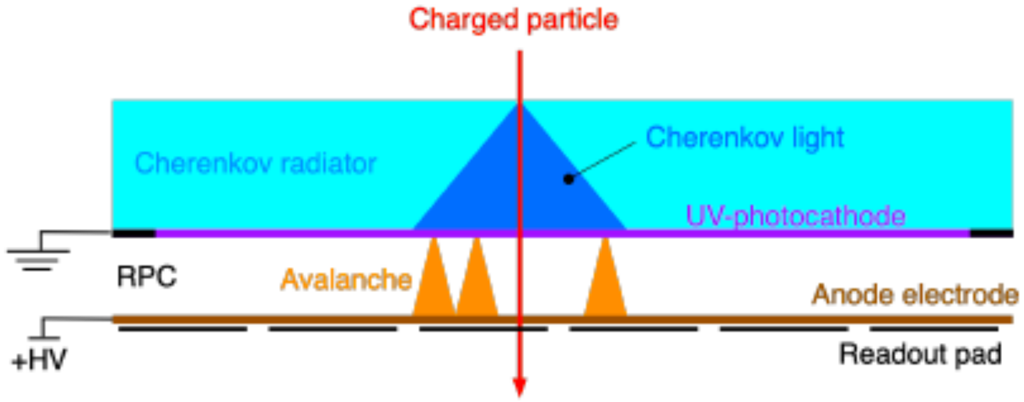
New calorimetry for future colliders



psec timing
PID, BG reduction, improve PFA

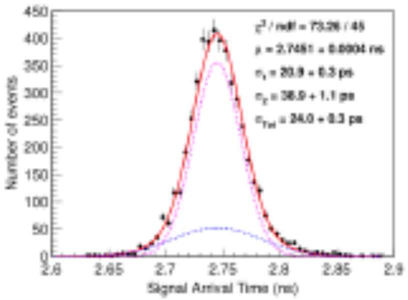
Cherenkov Detector with psec-timing

- **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**
  - $\sigma(10ps)$ 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

Electronics and System Design

- **The development of fast electronics is a critical element for realizing large-scale detectors**
  - impacts cooling and mechanics which can deteriorate performance in space/time
- HL-LHC timing ASICs are a revolutionary step forward to bring ps timing to collider experiments, applying similar techniques at Higgs Factories present **many challenges**:
  - High granularity → **ASICs with smaller pixel sizes**, maintaining power consumption
  - Including the required electronics for timing extraction (TDCs and memories) in pixel pitches of O(10um) → **adoption of deeper low power and fast nodes beyond 65nm**
  - The entire pixel electronics will need to be designed with **low power techniques and novel timing extraction architectures**
  - **Clock distribution**

Electronics for Fast Timing [Braga, et. al.]

- **System design:**
  - The fine spatial resolution demands towards low material budget and low power may require a mix of layers with different balance of spatial and time resolutions or a combination of 3D + 1D timing layers
  - Full-scale calorimeters with 10ps resolution in each cell can be very challenging. Alternatives include dedicated time-cells, or timing layers within the calorimeter

Name	Sensor	Node [nm]	Pixel size [μm^2]	Temporal precision [ps]	Power [W/cm^2]
ETROC	LGAD	65	1300x1300	~ 40	0.3
ALTIROC	LGAD	130	1300x1300	~ 40	0.4
TDCpix	PIN	130	300x300	~ 120	0.32 matrix + 4.8 periphery
TIMEPIX4	PIN, 3D	65	55x55	~ 200	0.4 analog + 0.3 digital
TimeSpot1	3D	28	55x55	~ 30 ps	3-5
FASTPIX	MAPS	180	20x20	~ 130	5-10
miniCACTUS	MAPS	150	500x1000	~ 90	0.15 – 0.3
MonPicoAD	MAPS	130 SiGe	100x100	~ 36	1.8
Monolith	Multi Junct. MAPS	130 SiGe	100x100	~ 25	0.9

4D Tracking: Present Status and Perspective, N. Cartiglia, et. al.

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

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