5D Calorimetry

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Introduction

- **Precision timing at the level of 10-30ps 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
  - Suppress out-of-time beam Induced backgrounds at muon colliders
  - Identify long-lived particles (LLPs) and expand the reach for new phenomena
  - Enable particle ID capabilities at low momentum
  - Provide depth segmentation in fiber calorimeters and improved jet energy resolution with 5D Particle Flow
- **R&D to investigate the full potential of fast timing detectors in future Higgs Factories is one of the highest priority directions in HEP**
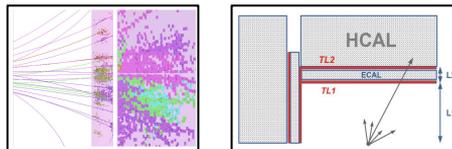
FCC-hh and muon Collider
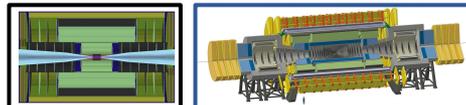
Full 4D Tracking
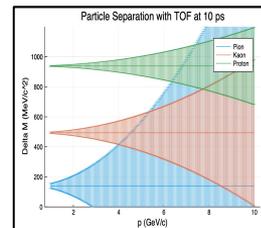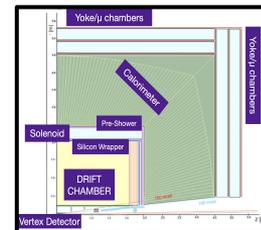BIB rejection (muC) and pileup suppression (FCC-hh) at extremely high radiation environments

Higgs Factory

5D Calorimetry
Exploit the time structure of hadronic showers to enhance PFA and improve jet energy resolution

Higgs Factory

Tracking Timing Layers

Particle ID
LLP searches

2

Calorimetry at Future Colliders

- **The Calorimeter is one of the critical components of a Higgs Factory detector**
  - essential for the precision measurement of jets, and it represents the dominant component of the overall cost
- The Calorimeter is also the sub-detector that exhibits the greatest variation among proposed designs with two opposing approaches: **Particle Flow** (PFA) (tracking plus high granularity calorimetry) and **Dual Readout** (DRO) (Scintillating and Cherenkov light for *e/h* compensation)
- **Higgs boson precision measurements require unprecedented jet energy resolution to separate hadronic W's, Z's, and H's**
- 3-4% ΔE/E at 100 GeV
  - Very difficult to achieve with traditional calorimetry
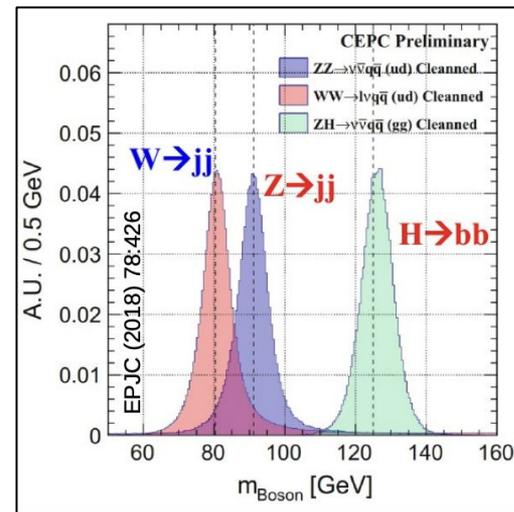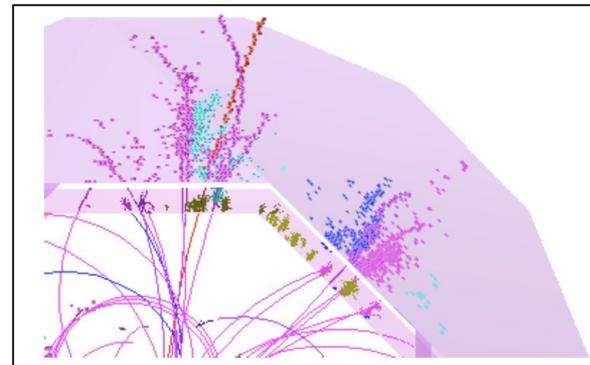
5D Calorimetry and PFA
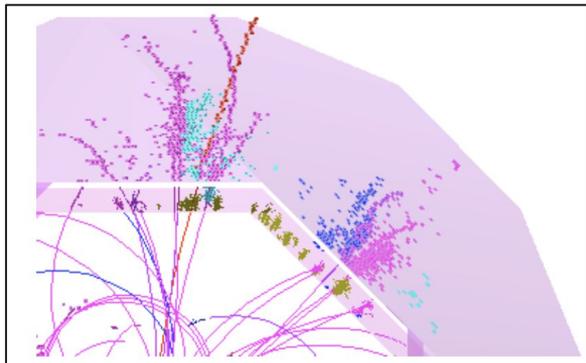
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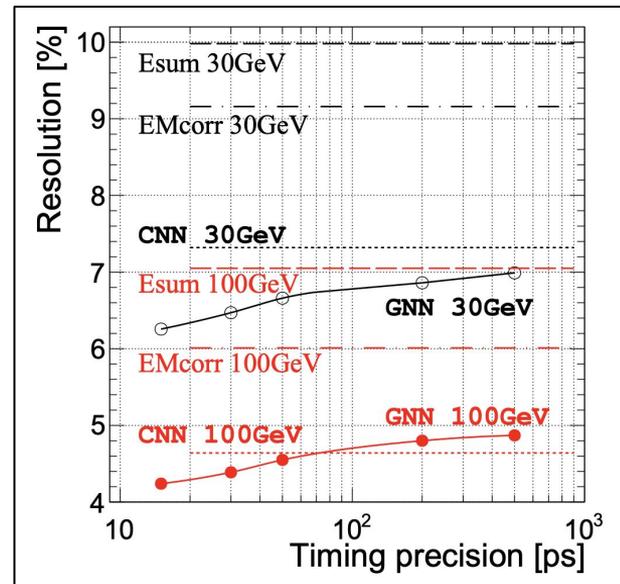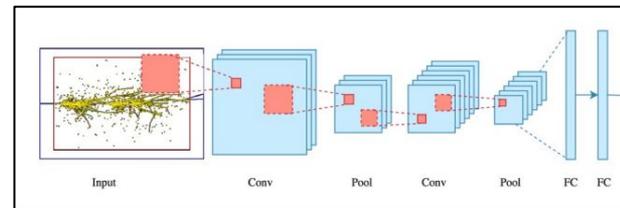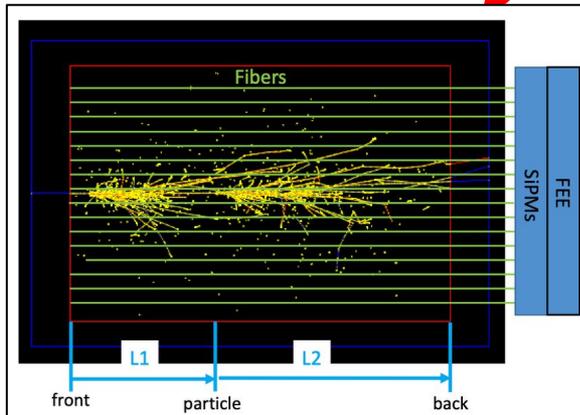
- **Performance of particle flow limited by the ability to accurately associate *tracks to calorimeter* clusters**
  - Challenging when showers overlap in space
- **Exploit the full space-time structure of showers to improve the jet energy resolution (5D PFA)**
- **Example: IDEA fiber dual-readout hadronic calorimeter**
  - 50ps time resolution for ~2cm depth segmentation
  - $t = L_1/c + L_2/(c/n)$, with $n=1.46$
- **Fast timing can also provide ToF for LLP and PID, and BIB suppression at muon colliders**

HG-DREAM

- Larger scintillation and Cherenkov towers are 12x16 mm^2 and the smaller tower size in the core is 12x4 mm^2. They are readout by SiPMs
- **Timing performance of this or similar fiber calorimeter (scintillation and Cherenkov) is critical, and the LESA facility offers a unique opportunity for this purpose**

Pulse Train Studies
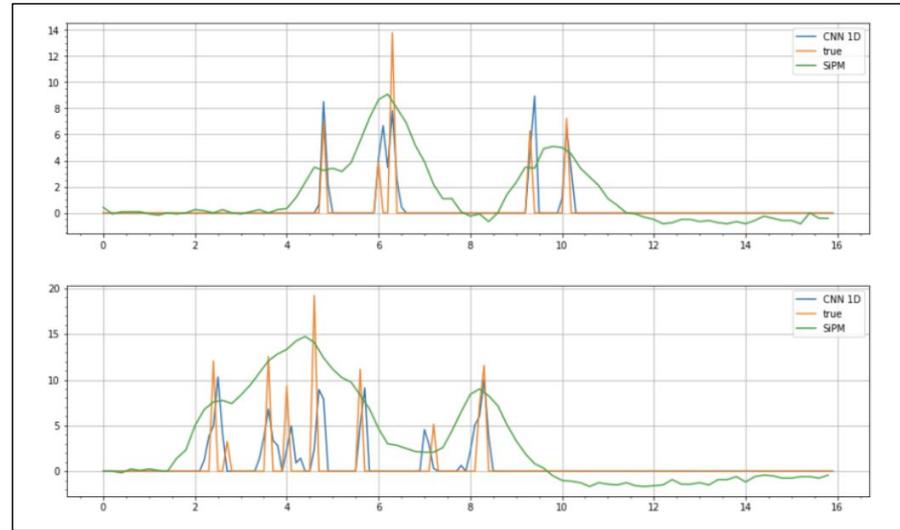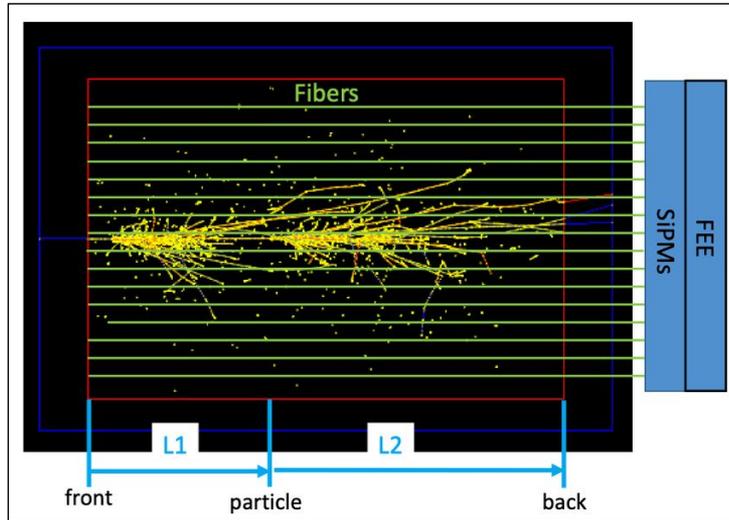
SiPM pulse shape is extract from TB23 data. Pseudo-data are produced by overlapping pulses and added Gaussian noise. Time separation between pulses ranged 0-2.6 ns. Overall arrival time is varied by ±0.8 ns

It seems possible to deconvolve overlapping SiPM (Cherenkov) pulses to reveal the true distribution of shower components using CNN:

Green: Convoluted SiPM pulse train **Blue**: Deconvoluted SiPM pulse train **Orange**: True pulse train

Use Case at SLAC's LESA Facility

- **Out of time pileup studies**
- **Multi-particle reconstruction**
  - Image reconstruction techniques with high granularity
- **Timing measurements**
  - Multi-photon pulse shape studies
  - Timing of shower structure
    - Testbed for AI/ML techniques
  - Studying timing of light detectors (e.g. fast SiPMs, dSiPMs)
  - Timing resolution
- **Sub-ps time structure of LESA facility critical to achieve these possibilities**
  - No external timing reference needed (e.g. MCP-PMT)
  - Could not use for hadronic calorimetry studies
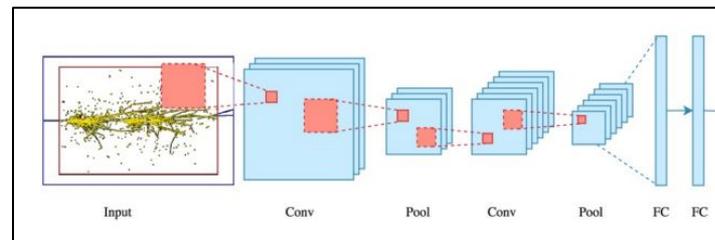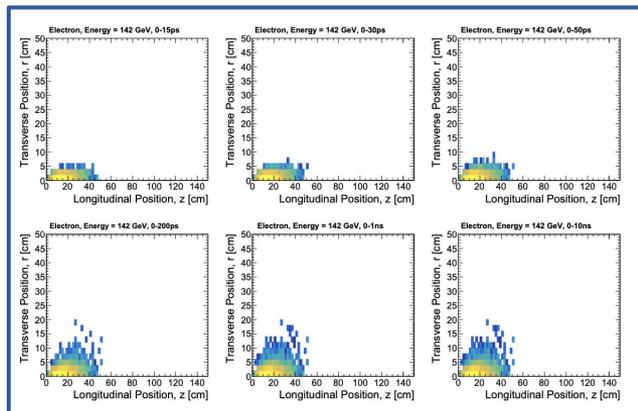- Ideal for test fiber and different absorber structure

Summary

- **Fast timing detectors at the level of O(10ps) is a transformative new capability for the next generation of detectors at future colliders**

- **5D Calorimetry is an emerging new concept that promises impressive gains in physics performance**

- Major R&D efforts within the US and abroad to develop and test 5D calorimeter prototypes

- **LESA Facility would provide unique opportunities to characterize the time performance of 5D calorimeter demonstrators and their underlying technologies (SiPMs, dSiPMs, fibers, …)**

Backup

5D Dual Readout PFA with Fast Timing

electron

charged pion