Developments in Precision Timing Calorimetry

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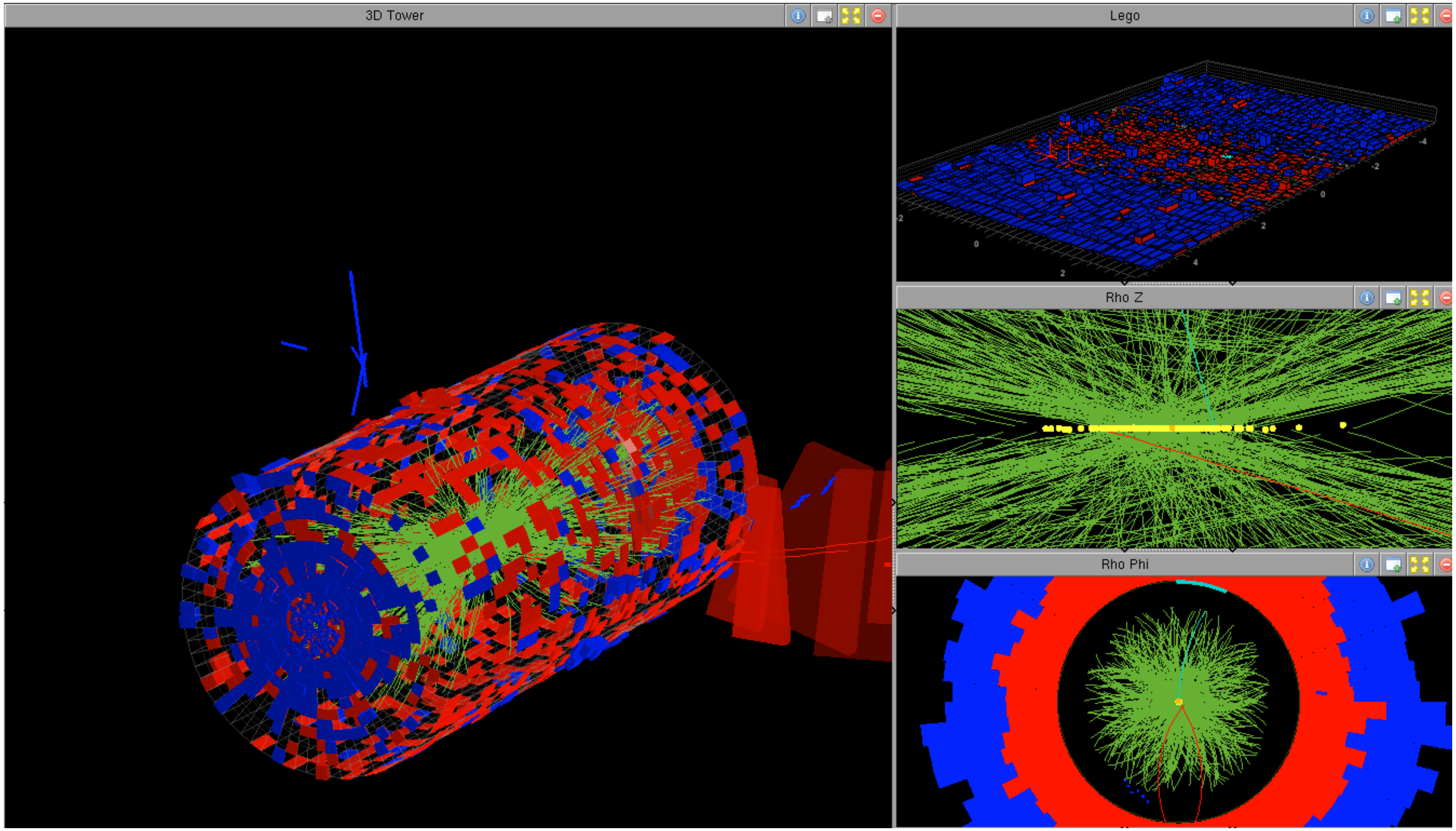
Overview

- Motivations : Why precision timing?
- Latest Developments:
  - Silicon-based calorimeters
  - MCP-based calorimeters
  - Crystal-based calorimeters

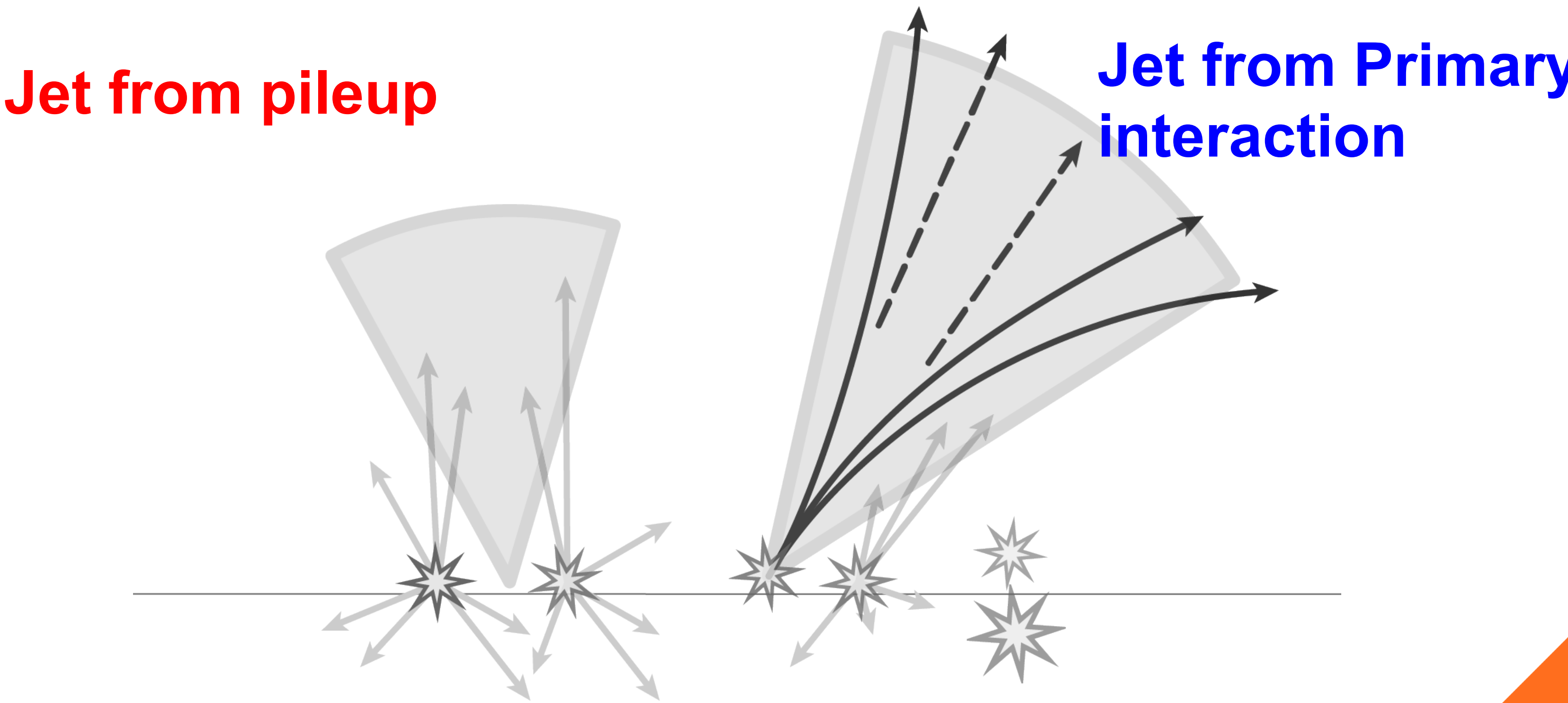
High Luminosity → High Pileup!

Future Hadron Colliders must face high pileup



Calorimeters face unique pileup challenges

- Pileup jets can be misidentified



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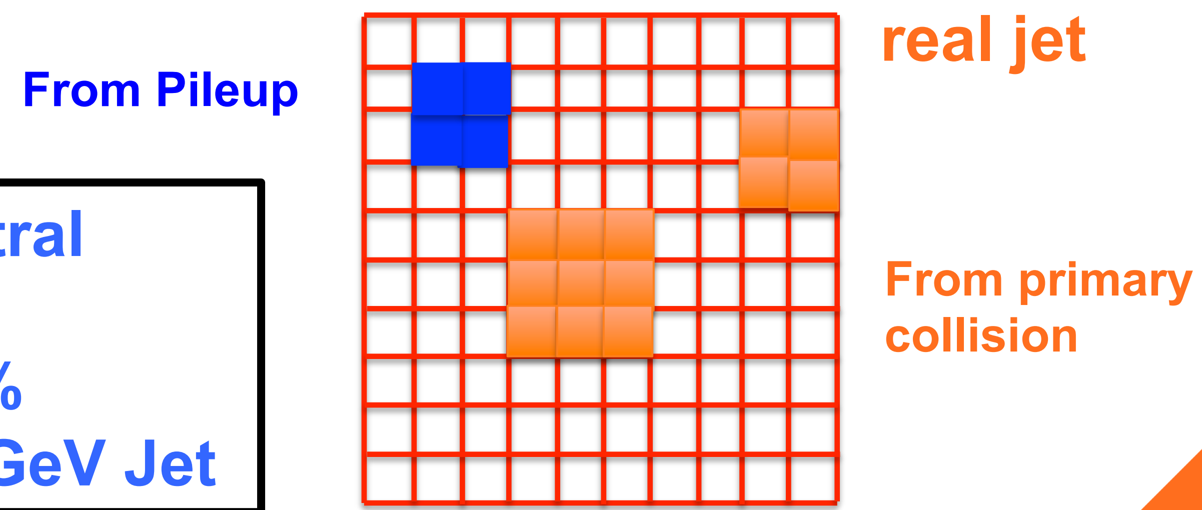
Calorimeters face unique pileup challenges

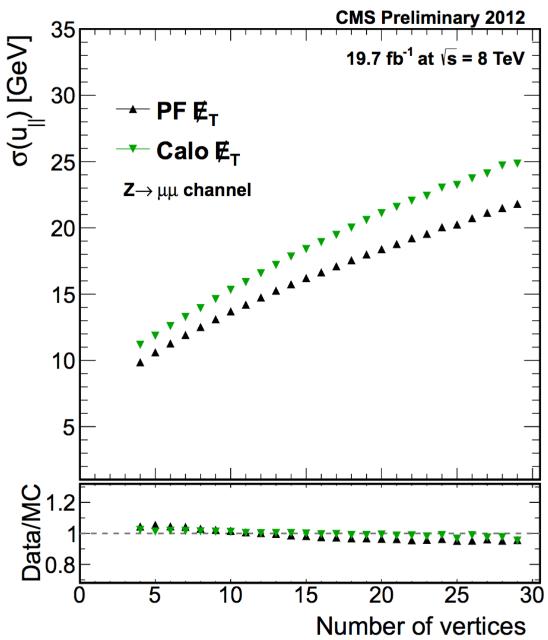
- Pileup jets can be misidentified
- Particles and energy from pileup contaminate the calorimeter signal



At 140 PU, Neutral pileup particles contribute 100% energy to a 50 GeV Jet

Calorimeters face unique pileup challenges

- Pileup jets can be misidentified
- Particles and energy from pileup contaminate the calorimeter signal
- Missing transverse energy resolution severely degraded



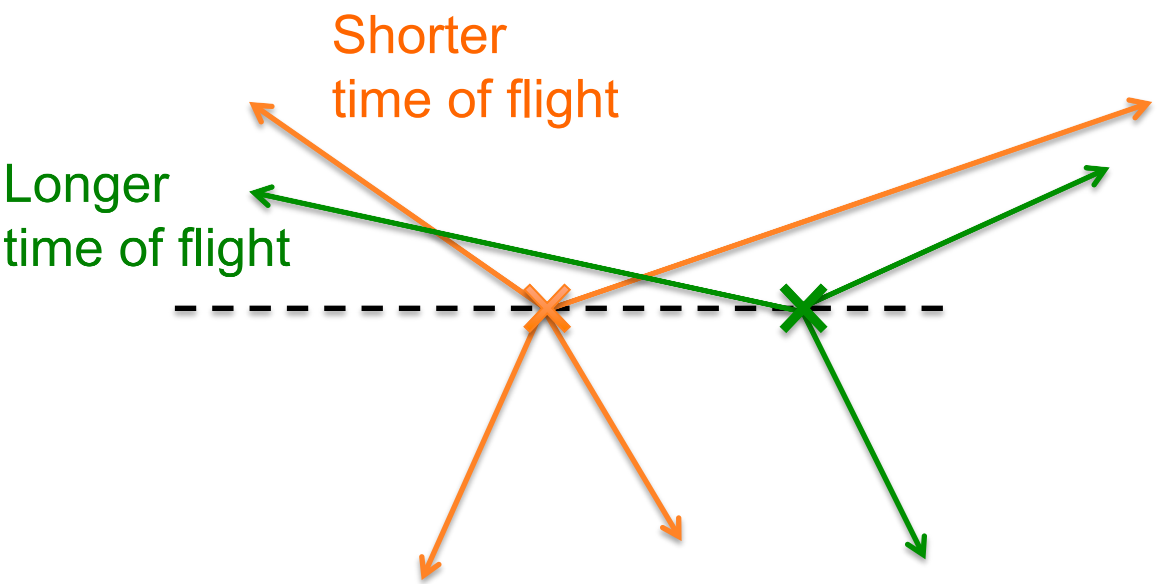
Every pileup interaction contributes ~3 GeV in quadrature to the MET resolution

At 200 PU → ~40 GeV

Precision Timing As a Solution

An obvious solution…

Measure the time stamp of a particle at the interaction point → Identify which vertex it came from



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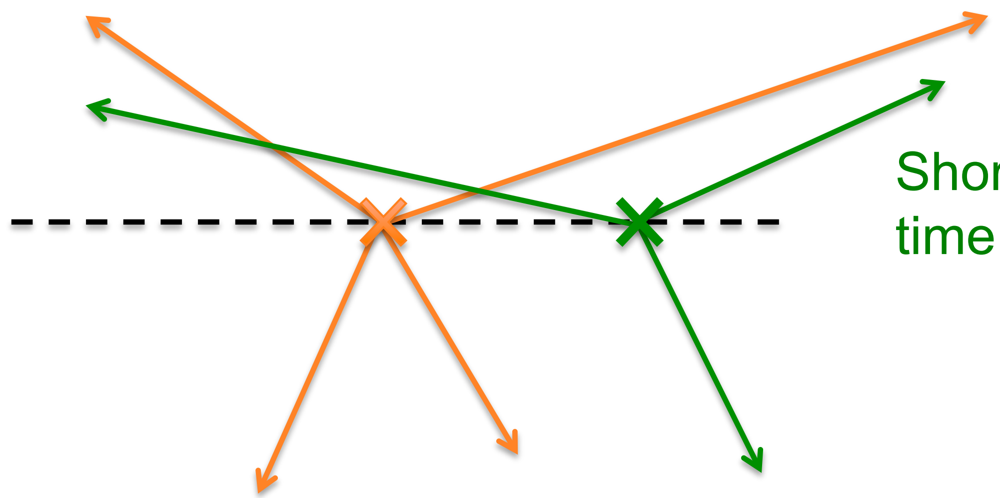
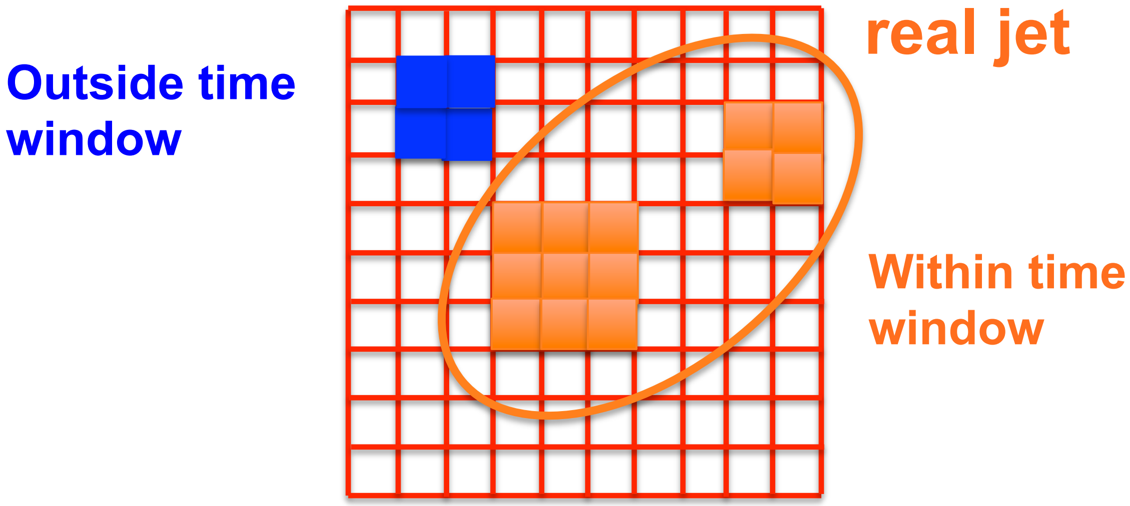


How to use Time Information?

Allows to identify the calorimeter clusters that correspond to pileup and to remove them



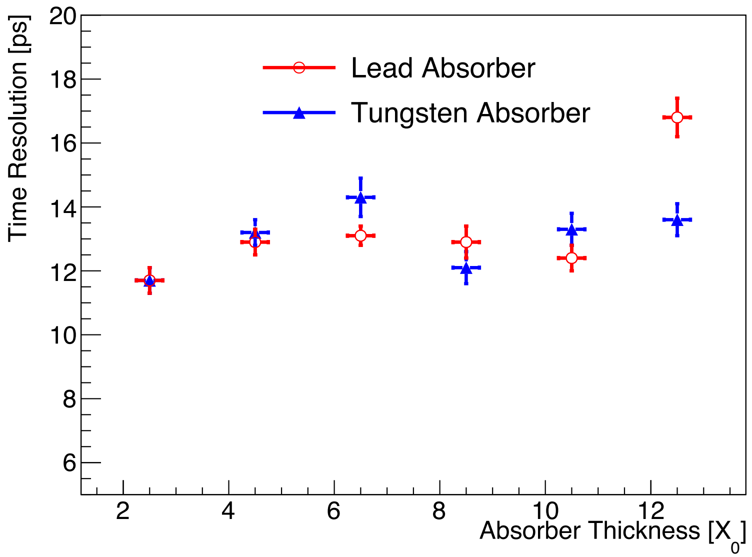
Intrinsic limitations?

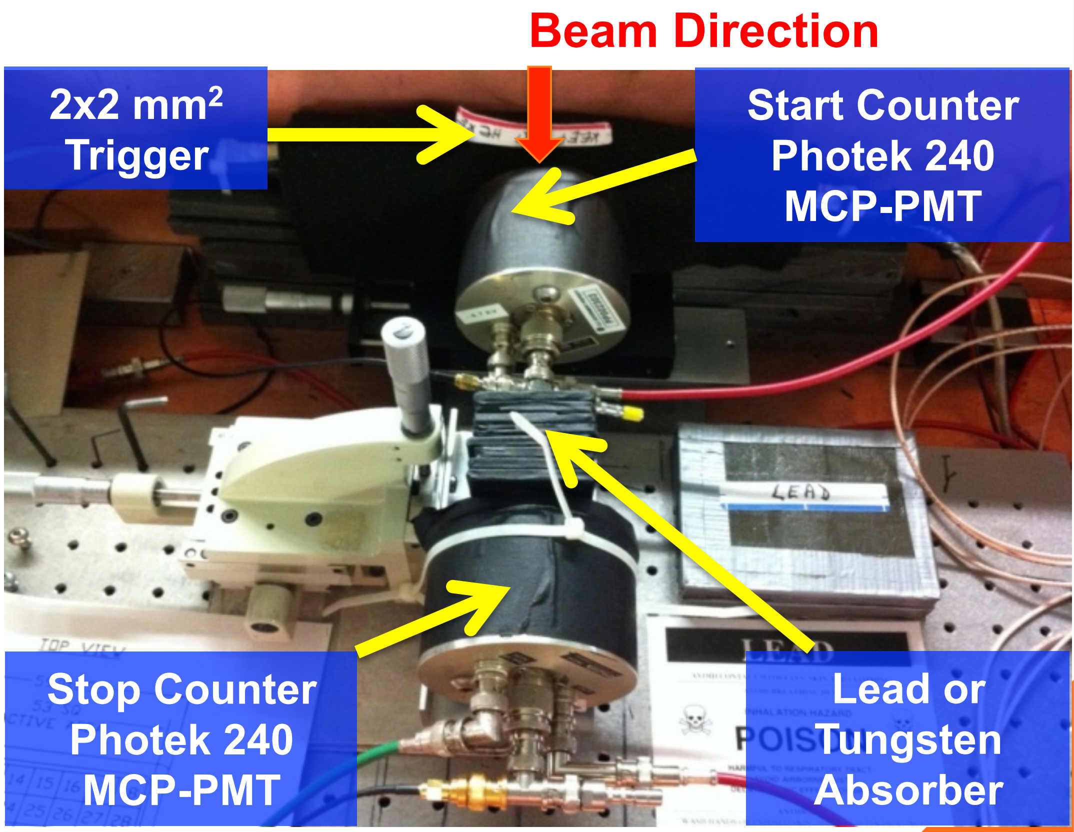
- Limitations from Physics:
    - Electromagnetic Shower Fluctuations?
- Limitations from Hardware:
    - Detector Sensor Limitation
    - Digitization Limitation
    - Clock Synchronization

Past 2 years have seen tremendous progress on understanding many of these items

EM Shower Fluctuations

- Using the most precise timing device (Photek-240 MCP-PMT), it was shown that the impact of EM shower fluctuations are **below the 10ps level**





Si Xie, et al: "Study of the timing performance of micro channel plate photomultiplier for use as an active layer in shower maximum detector.", NIM A, 795 (2015) p. 288-292

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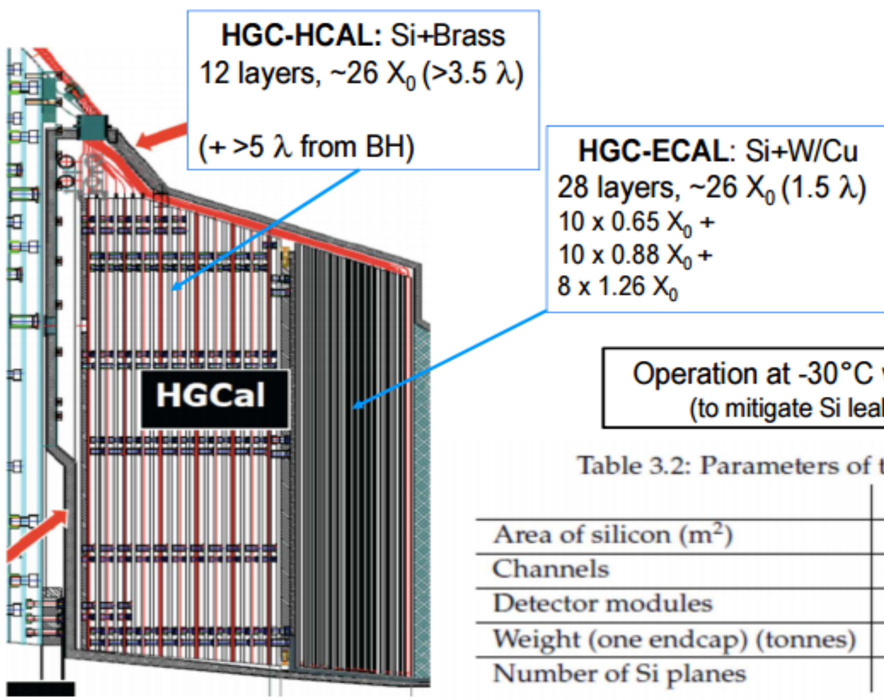
Silicon-Based Calorimeters

- Well studied calorimeters with possibility of high granularity digital readout
- CMS Phase II Upgrade proposed to use a silicon-based design and significantly increased interest in HEP community



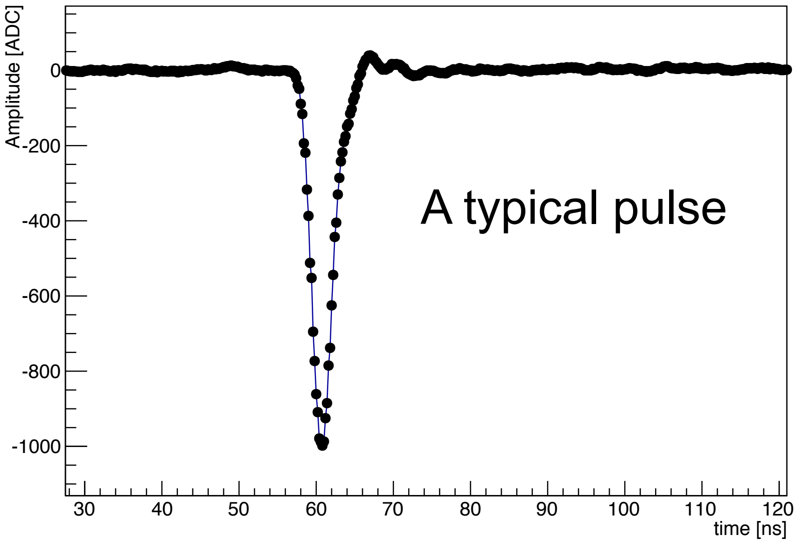
Operation at -30°C via CO_2 Cooling
(to mitigate Si leakage current)

Table 3.2: Parameters of the EE and FH.

	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

Silicon-Based Calorimeters

- Silicon-based calorimeters have a number of intrinsic advantages:
  - Fast primary signal formation (few ns)
  - No secondary time-scales from scintillation or photon transport

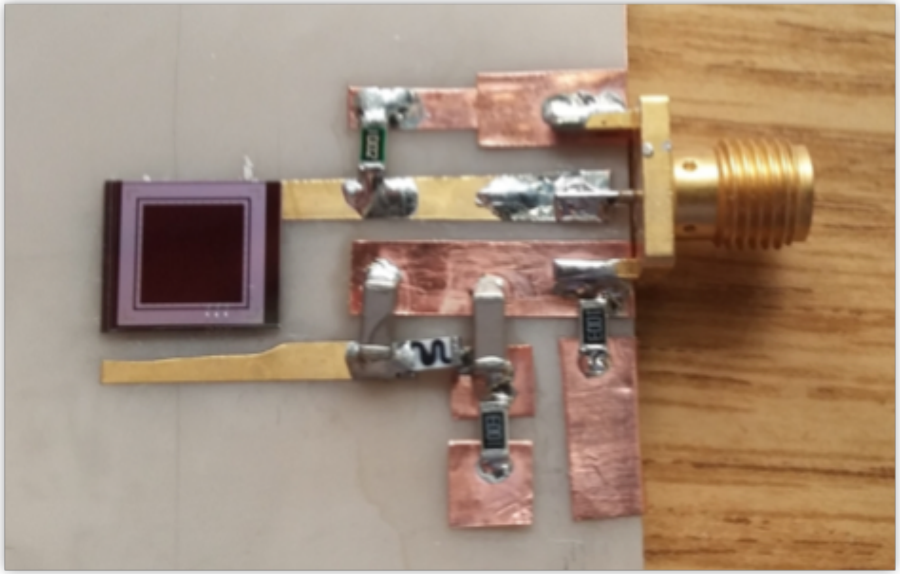


32 GeV electrons, $6X_0$ Tungsten

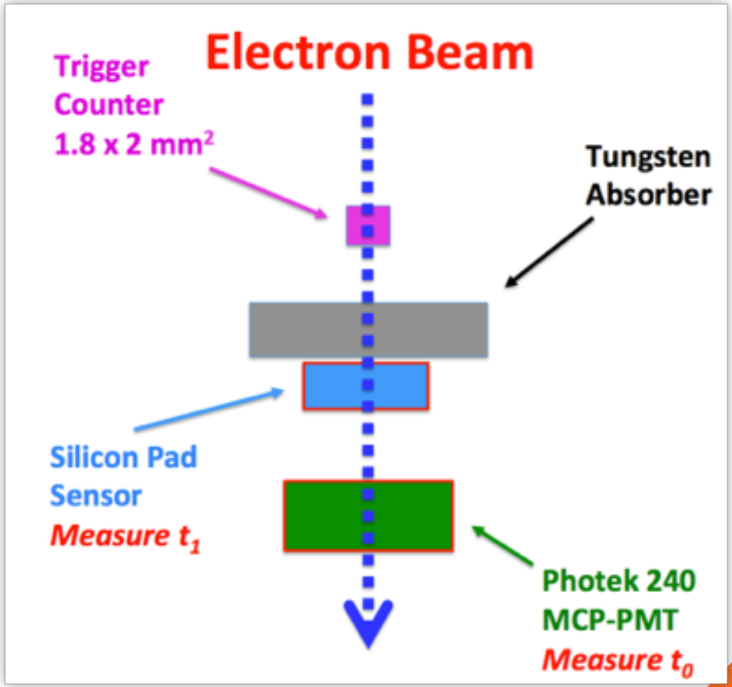
Precision Timing with Silicon

- Many testbeam studies in the past year on timing properties of silicon sensors, with many positive results

At Fermilab Testbeam Facility



6mm x 6mm Si sensor, thickness 325 μm



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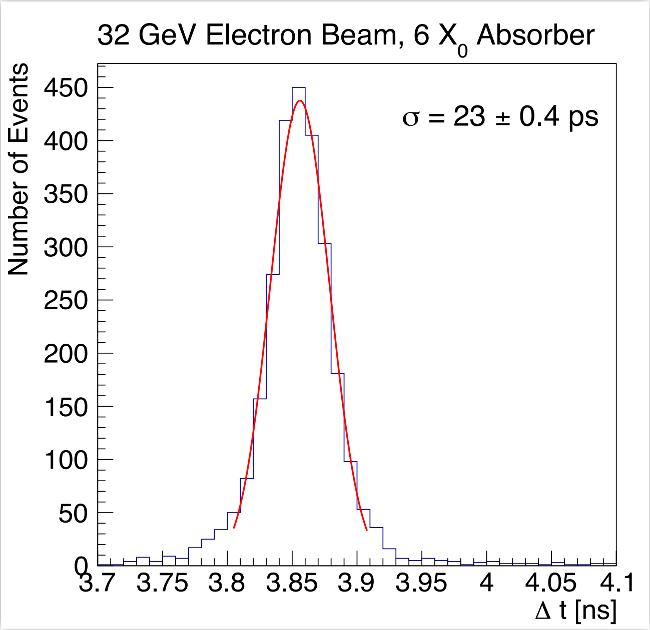

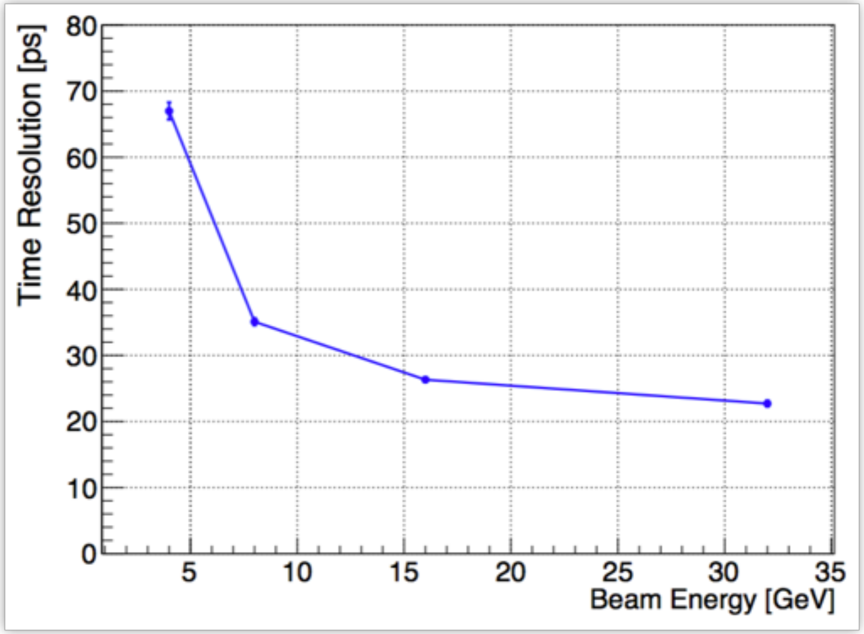

Achieved 23ps time resolution for 32 GeV electron showers

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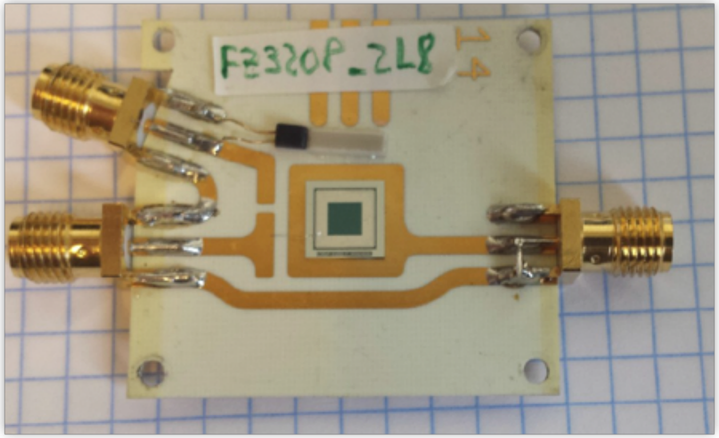
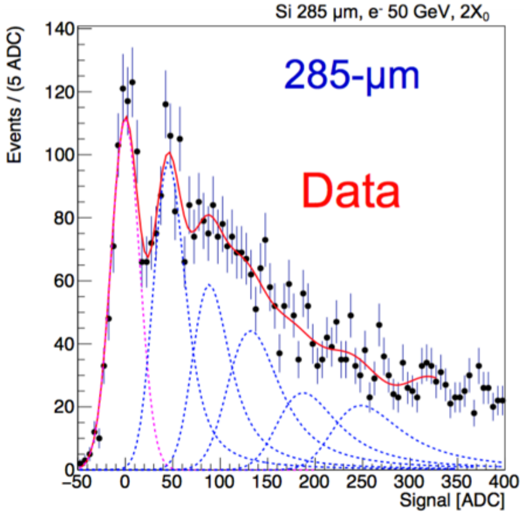
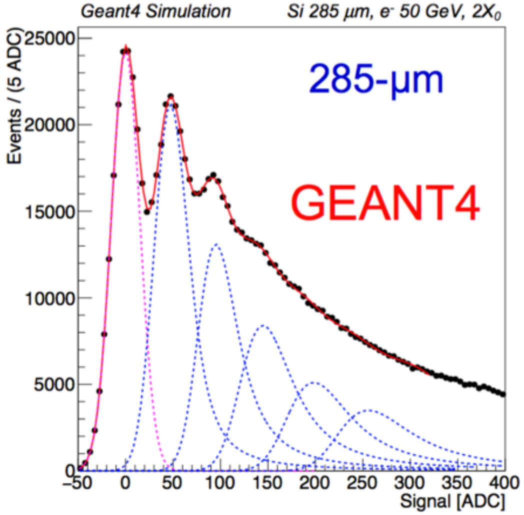
At CERN







Nice agreement with simulation

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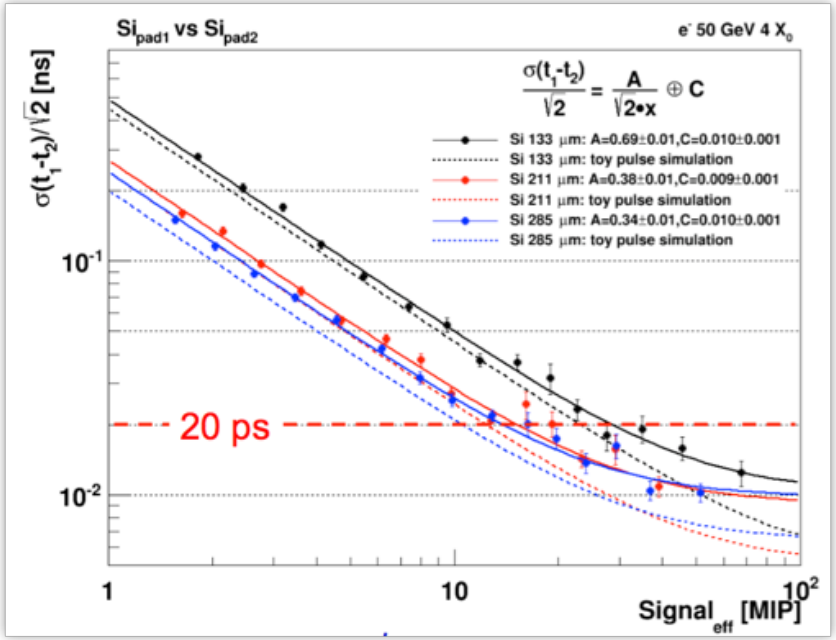

Time resolution measurements consistent with results from Fermilab testbeam studies

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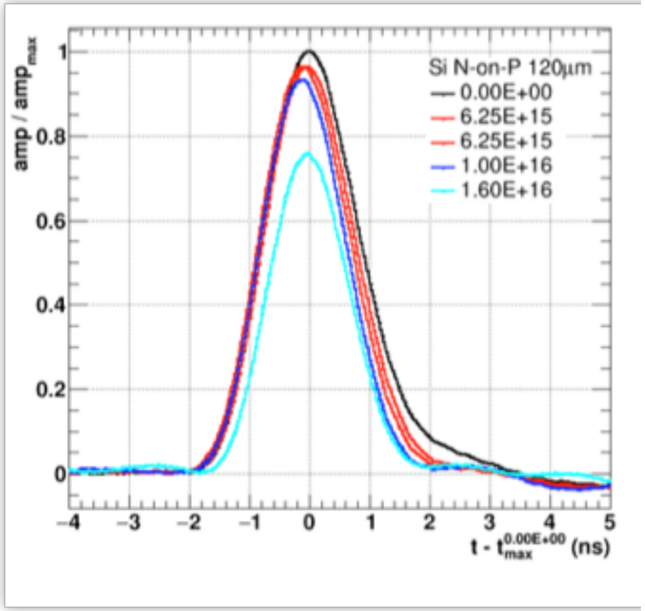
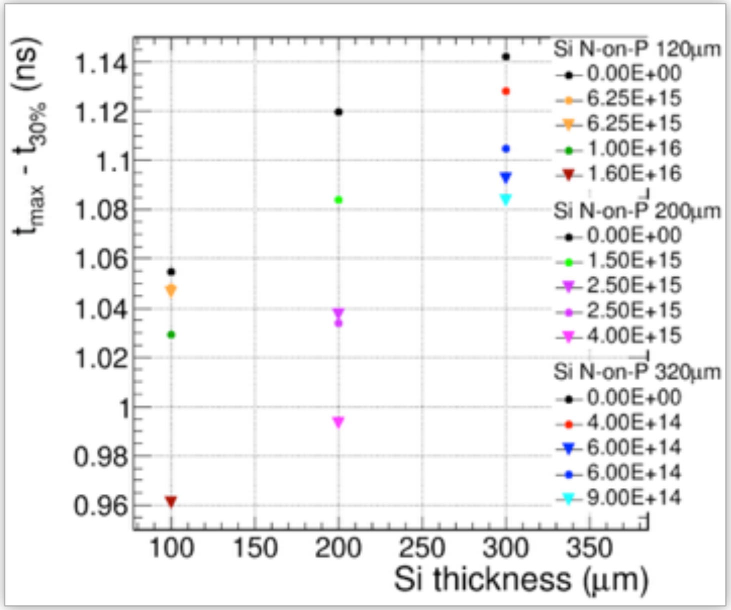
At CERN





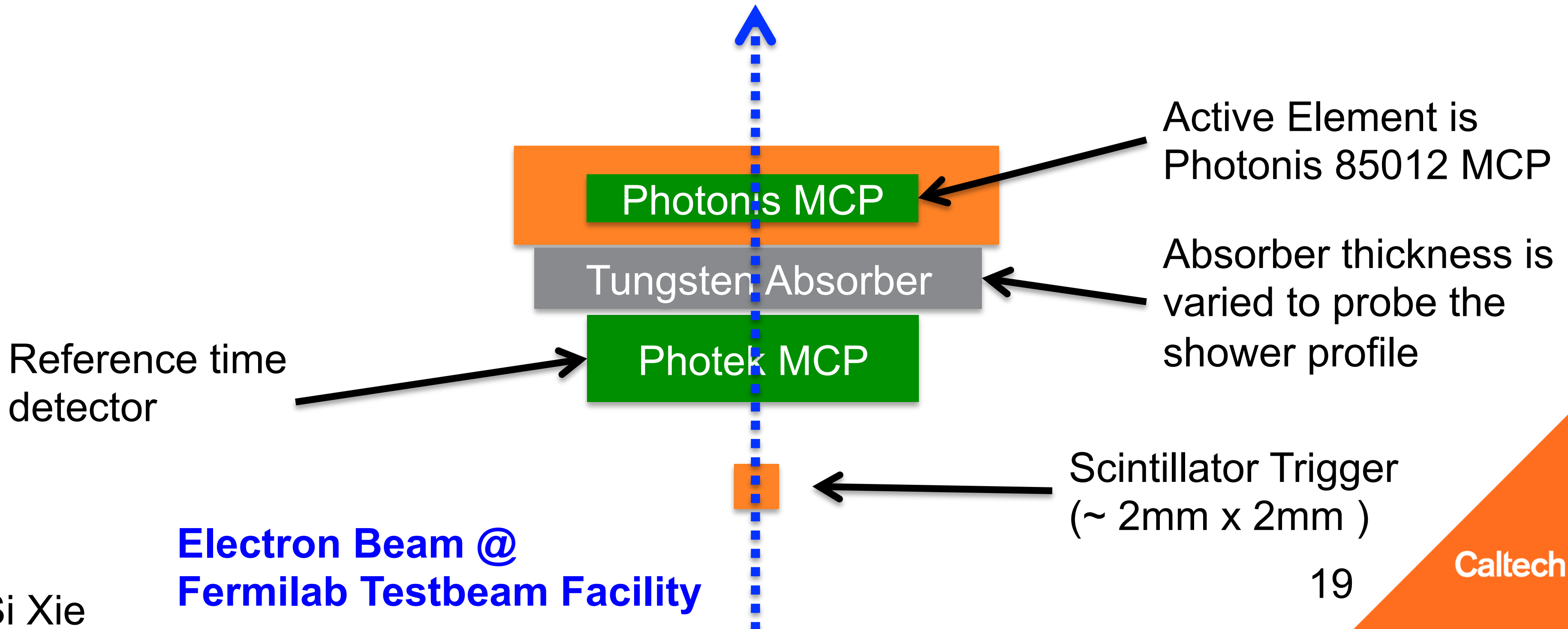
Radiation Damage studies:

- Reduction in pulse amplitude and rise-time

Micro-Channel Plate (MCP) Based Calorimeters

- Similar advantages as silicon-based calorimeters
  - Directly sensitive to secondary shower particles
- Potentially higher gain than silicon sensors : > 10^5

- Studies performed at Fermilab Testbeam Facility



Photonis Micro-Channel Plate (MCP)

- Pixelated 8x8 , 6.5mm pitch per pixel
- 25 μm pores
- Active area 5.3cm x 5.3cm
- Standard Operating Gain: 10^5

Photonis 85012
MCP

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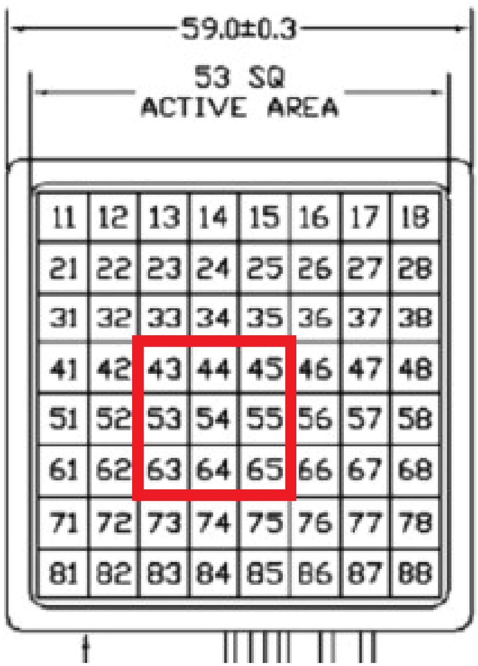
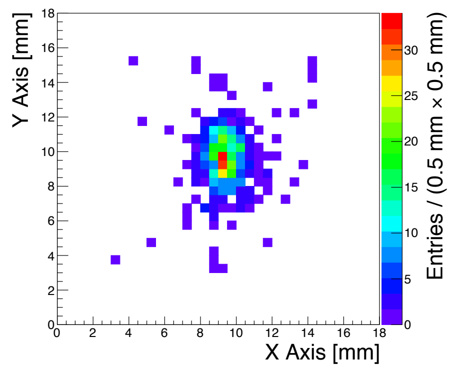
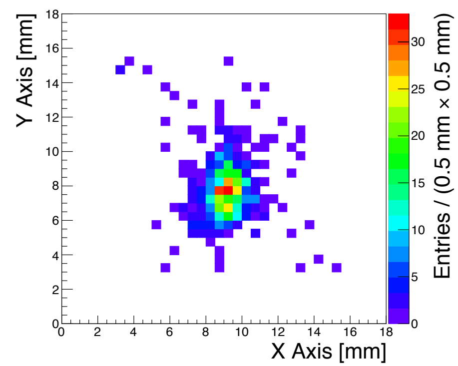
Pixelated Readout

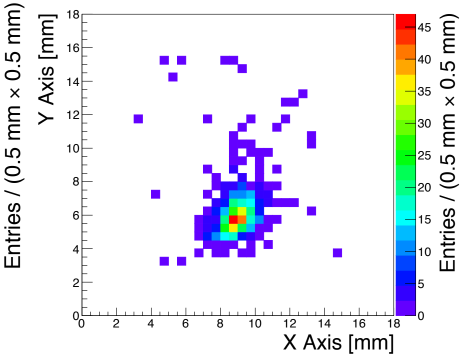
- Pixelated readout allowed for studies of position and time resolution

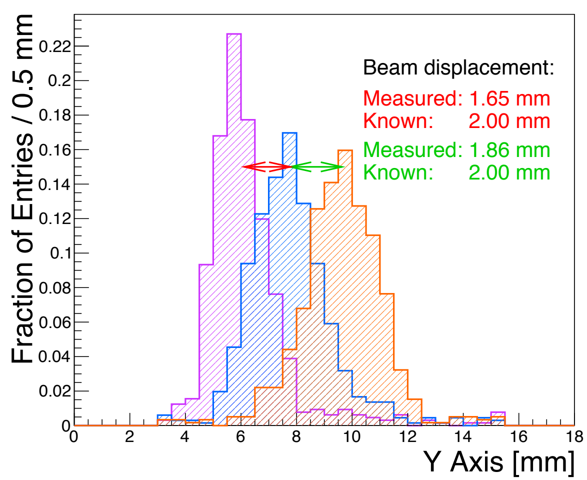
$$\vec{\mathbf{p}} = \frac{\sum_{i \in \text{pixels}} Q_i \vec{p_i}}{\sum_{i \in \text{pixels}} Q_i}$$











Beamspot location clearly identifiable

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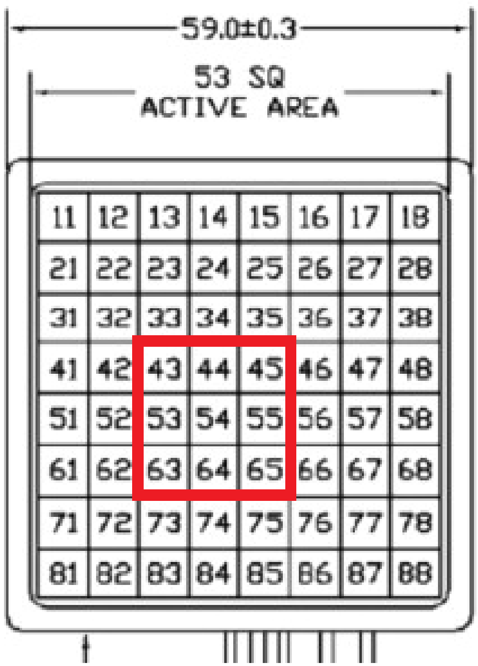

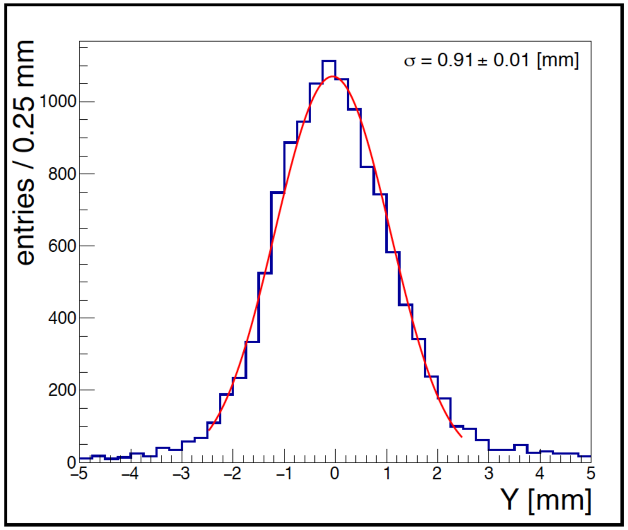

Obtained position resolution of 1mm (with 6mm pixels)

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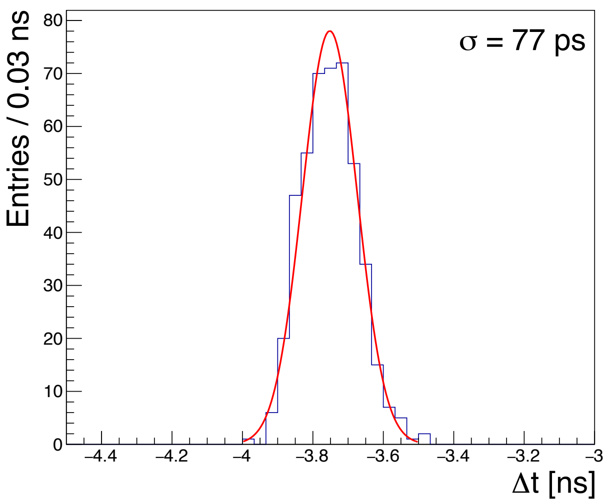
Pixelated Readout

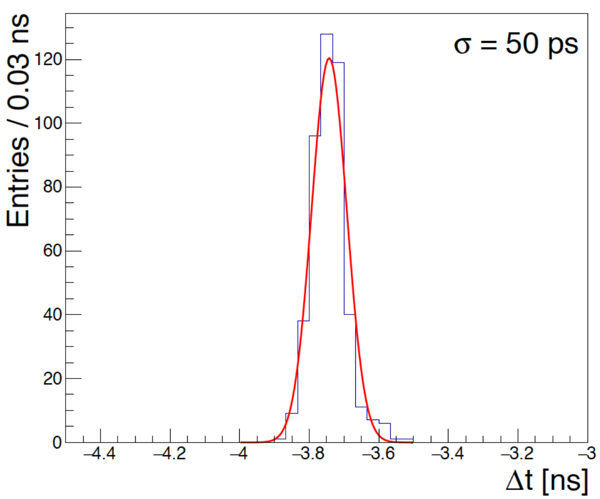
- Pixelated readout allowed for studies of position and time resolution

$$t = \frac{\sum_{i \in \text{pixels}} Q_i t_i}{\sum_{i \in \text{pixels}} Q_i}$$

Single Pixel



Combined All Pixels

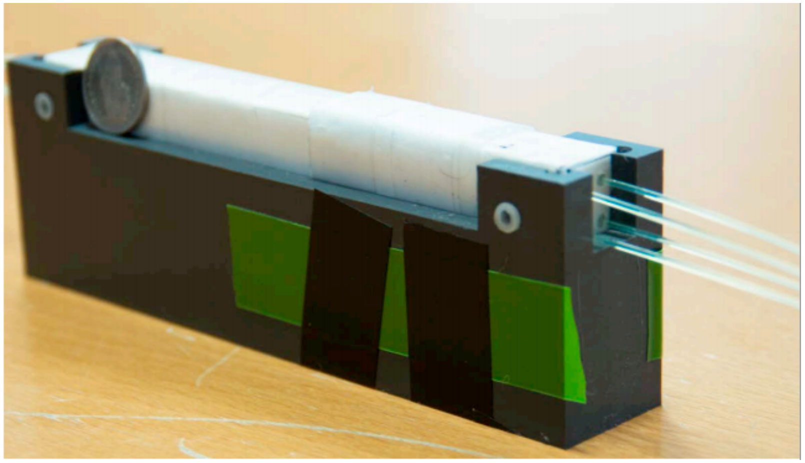


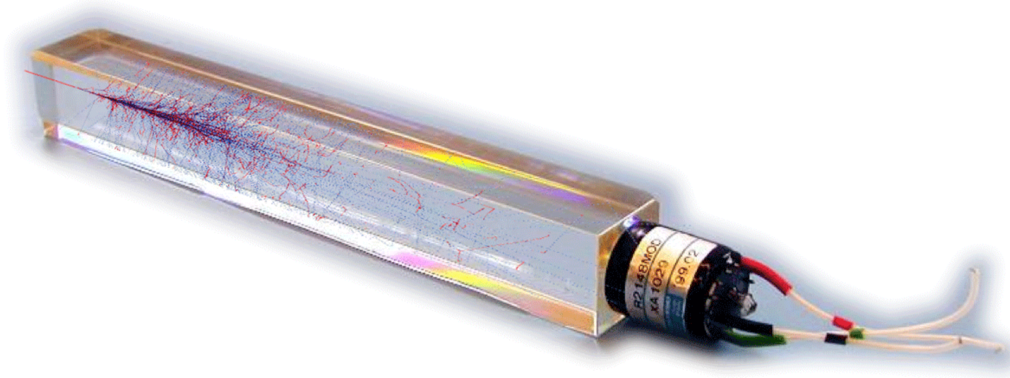
Combining Multiple Calorimeter Layers

- Very recent (June 2016) testbeam studies used multiple sensitive layers that sampled the shower twice
- Demonstrated improved time resolution using information from multiple layers

Crystal Calorimeters

- Calorimeter type with a long history in HEP
- Certain crystals give large light yield (eg. LYSO) and is ideal for precision timing





Tungsten-LYSO Shashlik Prototype

Lead Tungstate (CMS ECAL)

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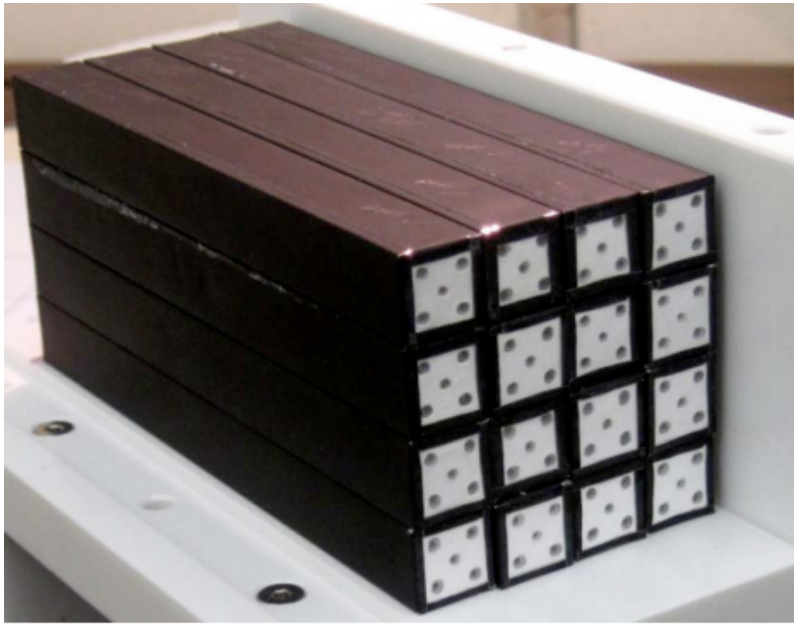
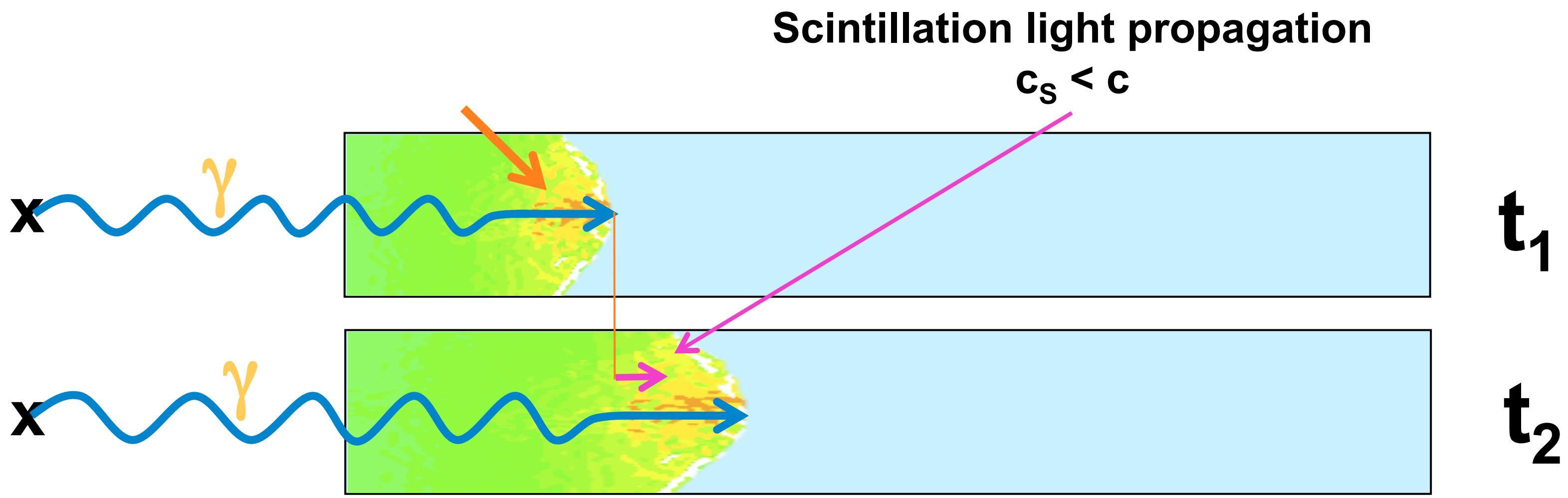
- Certain crystals give large light yield (eg. LYSO) and is ideal for precision timing



Tungsten-LYSO
Shashlik Prototype

Crystal Calorimeters

- Timing in crystal calorimeters are further complicated by:
  - Optical Transit
  - Scintillation



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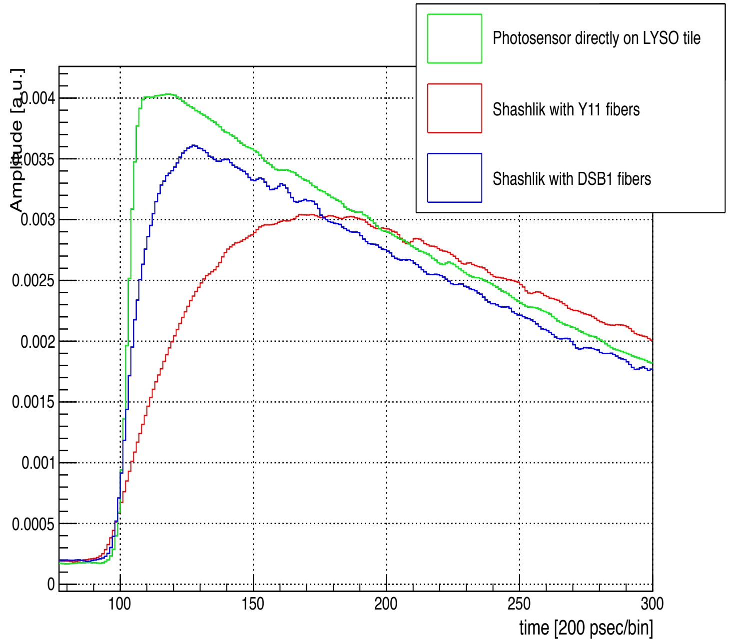
Crystal Calorimeters

- Timing in crystal calorimeters are further complicated by:
  - Optical Transit
  - Scintillation
  - Wave-length shifting fibers

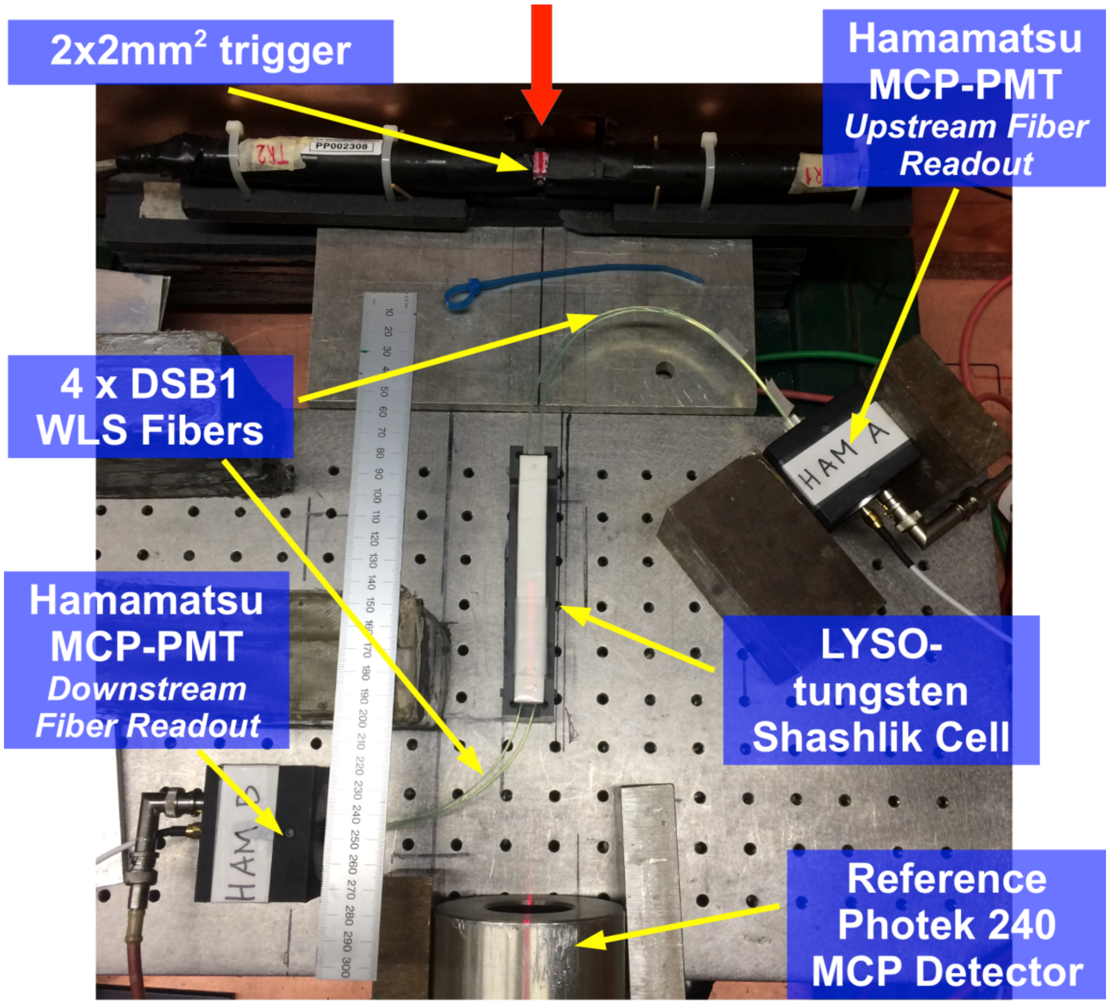
Recent testbeam studies have tried to understand these effects



Differently doped fibers can lead to faster rise-time and better time resolution

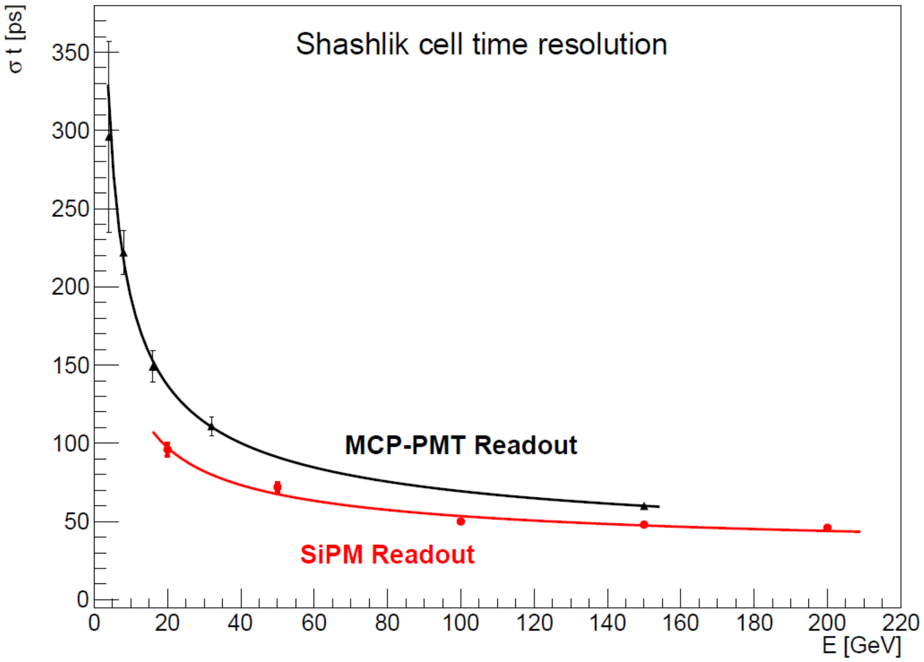
Shashlik Fiber Prototype

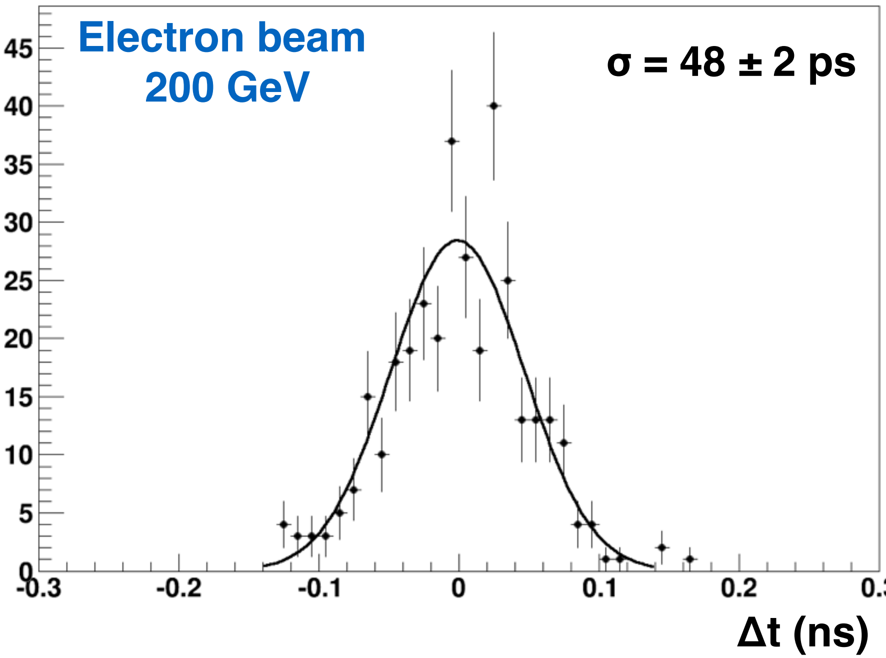
- Proof of concept demo with shashlik fiber prototype



Shashlik Fiber Prototype

- Proof of concept demo with shashlik fiber prototype
- Observe scaling with 1/√E – driven by S/N
- Can reach ~50ps at highest energies





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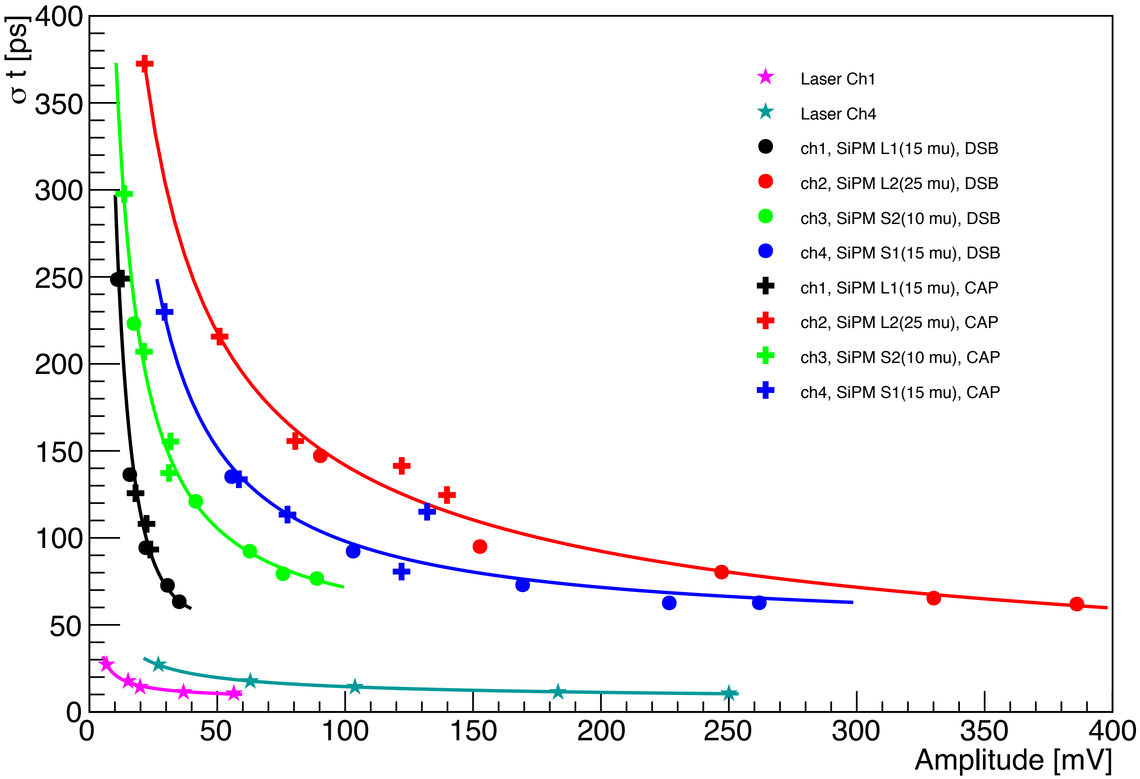
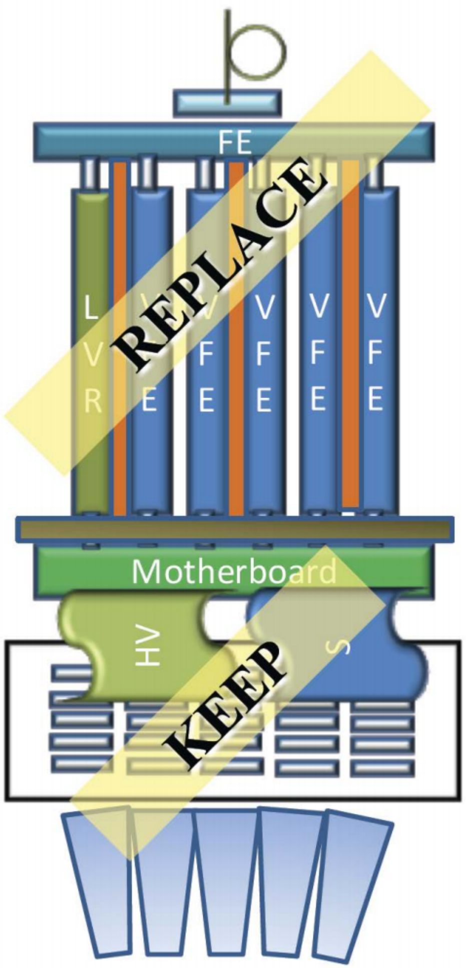
Shashlik Fiber Prototype

- Further studies have been performed on radiation-hard capillary fibers and achieve similar time resolution for the same S/B



CMS Barrel ECAL Upgrade

- Front-end readout electronics planned to be replaced
- Trans-impedance amplifier, oversampling & reduced CR-RC shaping time all improve timing performance
  - Primarily motivated by need to cope with higher L1 bandwidth



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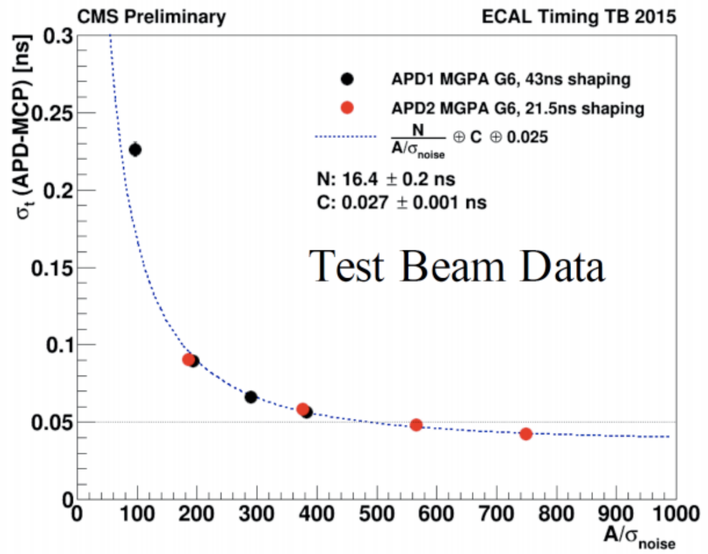
- Front-end readout electronics planned to be replaced
- Trans-impedance amplifier, oversampling & reduced CR-RC shaping time all improve timing performance
  - Primarily motivated by need to cope with higher L1 bandwidth
- Testbeam measurements indicate time resolution of 30-35ps can be achieved



Summary

- Lots of excellent progress in precision timing calorimeters over the past couple of years
- Progress on multiple fronts:
  - Silicon and MCP based calorimeters
  - Shashlik-fiber calorimeters
  - Homogeneous crystal calorimeters

- No fundamental show-stoppers for ~20ps level precision
- Many test beam studies already achieve sub-20ps precision

- Major next step : demonstrate 20ps precision in a large synchronized system

Backups