Test beam characterization of sensor prototypes for the CMS MTD barrel timing layer

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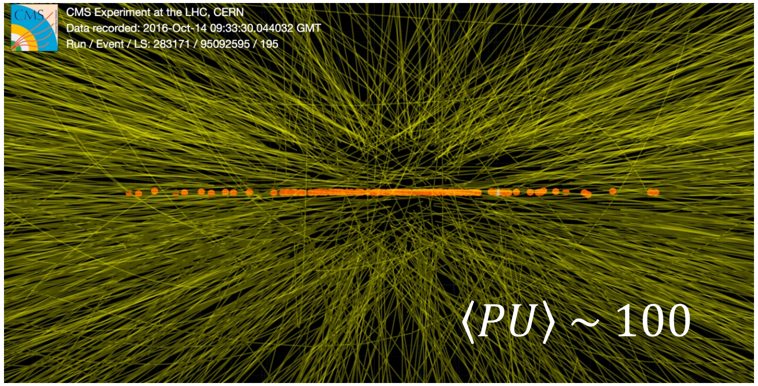
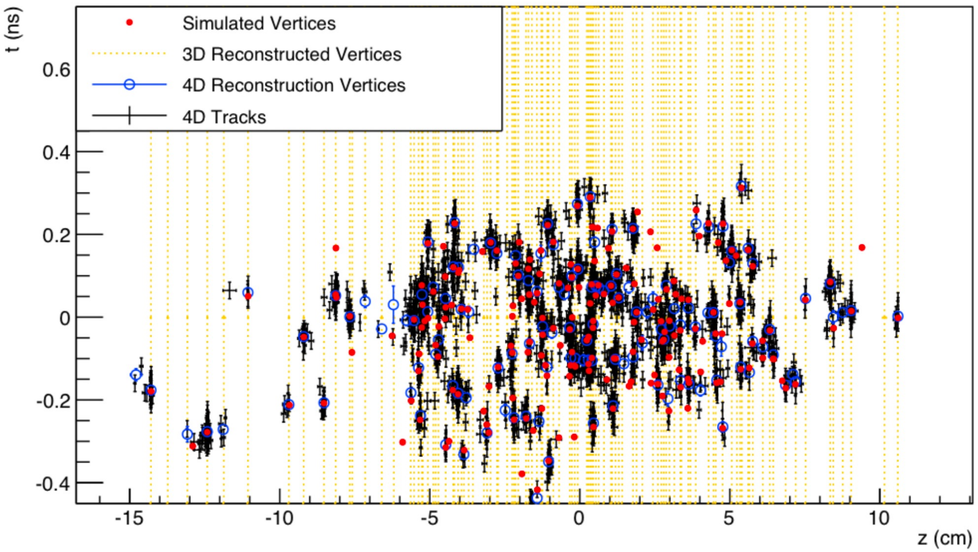
Background & Overview

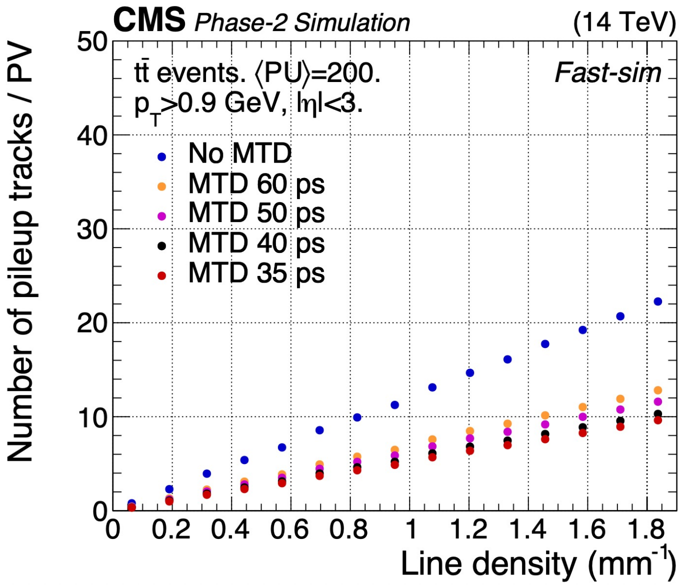
Challenges of High-Luminosity LHC (HL-LHC)

- Increased **pileup**
  - Nominal : $L_{inst} = 5.0 \times 10^{34}$ cm^{-2}s^{-1} (140 pileup)
  - Ultimate : $L_{inst} = 7.5 \times 10^{34}$ cm^{-2}s^{-1} (200 pileup)
- Pileup + radiation damage → **degrade particle ID/reconstruction efficiency**
- Approach: exploit **timing information** to recover Phase 1 PU conditions via **4D vertex reconstruction**



^A high-pileup event from 2016

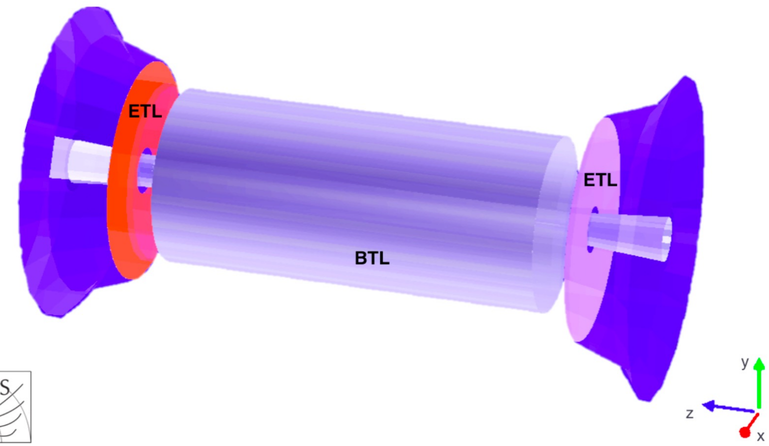




CMS MIP Timing Detector (MTD)

- Two subdetectors, the **barrel (BTL)** and **endcap (ETL) timing layers**, will provide hermetic coverage up to |η| < 3.0

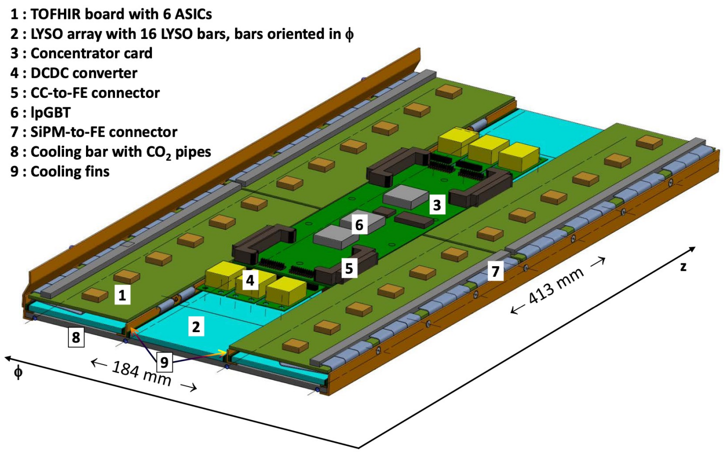
- Designs fit requirements: different cumulative radiation dosages and development constraints
  - ETL: higher radiation dosage, more time for R&D, accessible during shutdown
  - BTL: constrained by installation timeframe, no access during shutdown

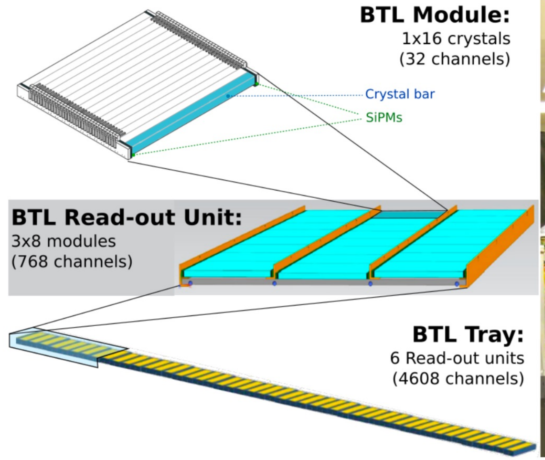


- Expected physics impact:
  - Improved particle isolation, vertex ID, p_T^{miss} reco
  - Time-of-flight detector for charged particle ID → improvements for heavy ion and flavor physics
  - Projected di-Higgs improvements summarized below

	Signal increase (%)		Expected significance	
Di-Higgs decay	BTL	BTL+ETL	No MTD	MTD
bbbb	13	17	0.88	0.95
bb$\tau\tau$	21	29	1.3	1.6
bb$\gamma\gamma$	13	17	1.7	1.9
bbWW			0.53	0.58
bbZZ			0.38	0.42
Combined			2.4	2.7

- 40-mm cylindrical layer housed inside CMS tracker support tube (TST)
- Installation inside TST imposes important limitations:
  - Much shorter R&D and installation timeline to align with tracker installation
  - BTL inaccessible during shutdown: sensor components must withstand radiation dosage through end of HL-LHC lifetime

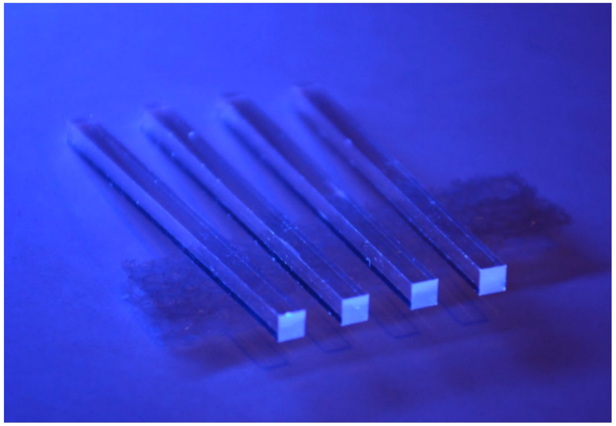


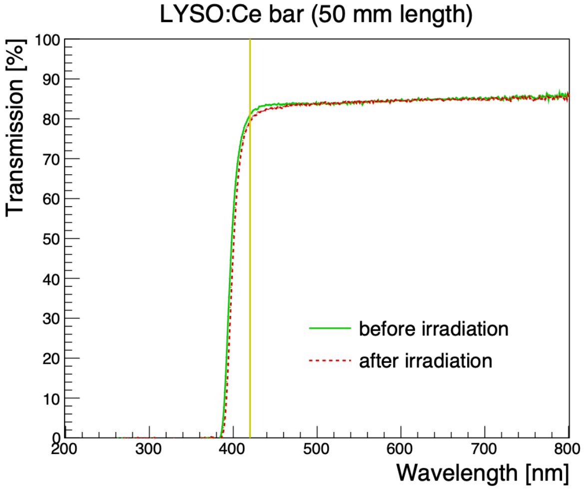


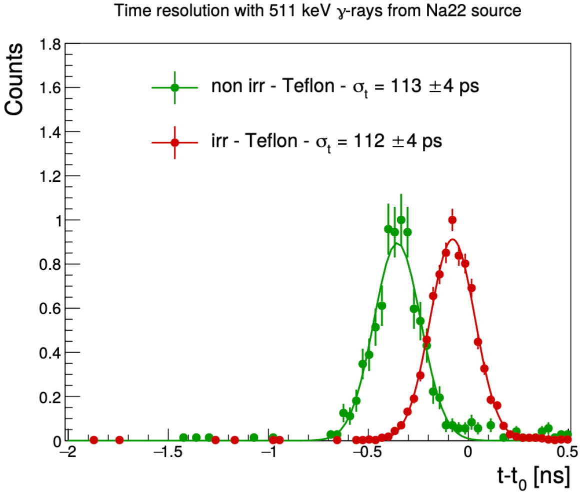
- Sensors:
  - Cerium-doped lutetium yttrium orthosilicate (**LYSO:Ce**) crystal scintillators
  - Silicon photomultipliers (**SiPMs**) at each end
- Nominal operating temperature of –35°C (up to –45°C) to limit noise-induced timing jitter

LYSO:Ce Crystals

- Cerium-doped lutetium yttrium orthosilicate (LYSO:Ce) crystal scintillation medium
- Well-studied in PET applications; potential vendors widely available
- **Benefits**:
  - High light yield (~4×10^4 photons/MeV)
  - Fast scintillation rise time (<100 ps)
  - Short decay time (~40 ns)
  - High density (7.1 g/cm^3): MPV of MIP deposited energy ~0.86 MeV/mm
  - Exceptionally radiation-hard

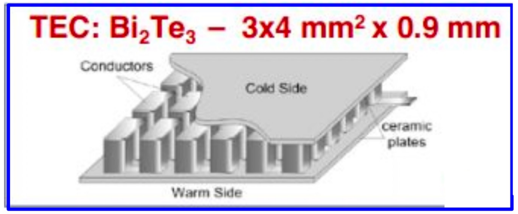


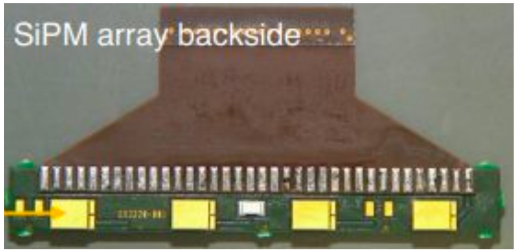


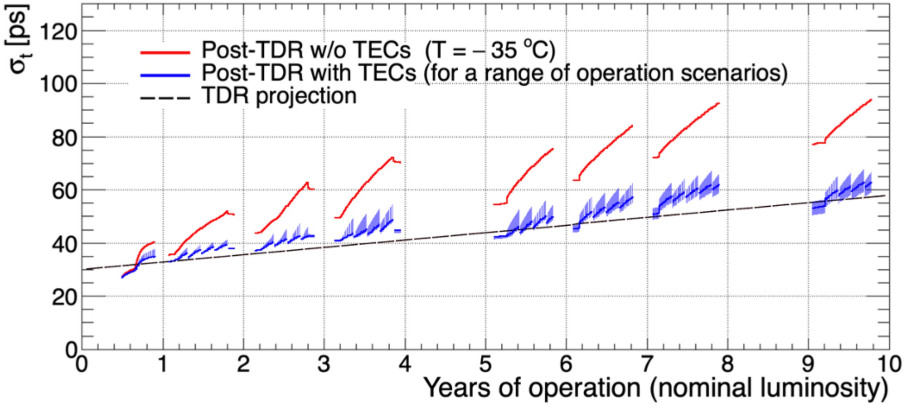


Silicon Photomultipliers (SiPMs)

- **Benefits**:
  - Compact, robust, and insensitive to magnetic fields
  - Photon detection efficiency (PDE) of 20–40%
  - Optimal cell size of 15 µm chosen
  - Good radiation tolerance
- **Challenges**:
  - Thermal noise (dark count rate, or DCR) increases with irradiation and temperature
  - Linear drift in breakdown voltage with radiation exposure
- **Solutions**:
  - Periodic SiPM annealing (40°C) during shutdown to mitigate radiation damage
  - Reduce SiPM operating temperature using thermoelectric cooling (TEC)
  - Dedicated noise cancellation circuit in ASIC
  - Optimize operating point



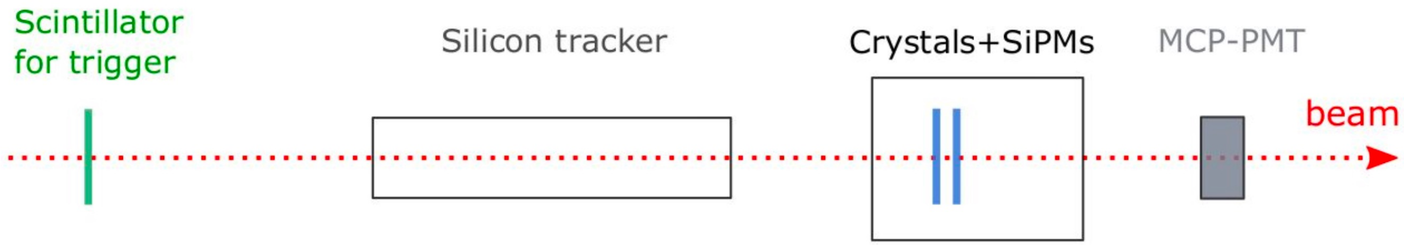




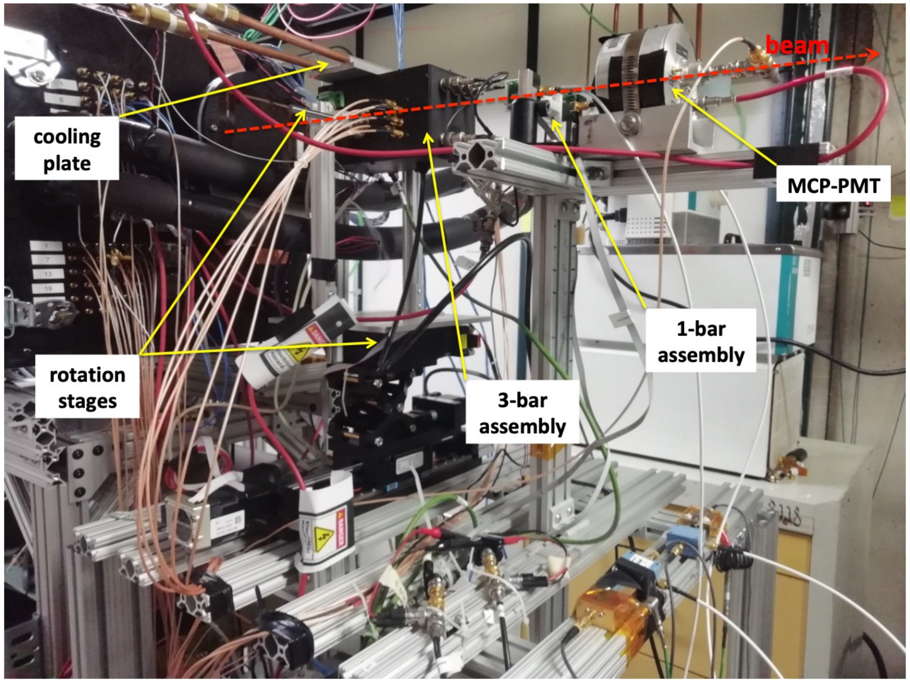
Fermilab 2019 Test Beam

Test Beam Studies

- Performed at FNAL Test Beam Facility (FTBF) using 20k–50k spills of 120-GeV protons



- Setup:
  - Scintillation counter (10 cm^2)
  - Silicon tracker telescope
  - Microchannel plate detector (MCP-PMT)
  - LYSO:Ce crystals + SiPMs



Full discussion: [arXiv:2104.07786v2]

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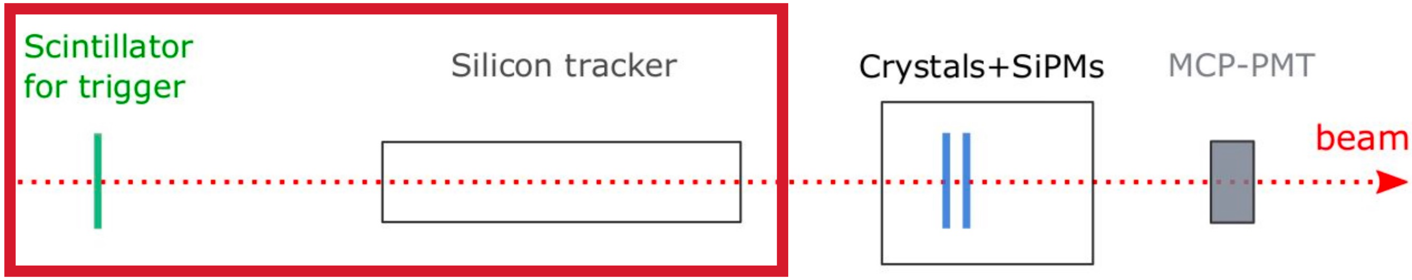
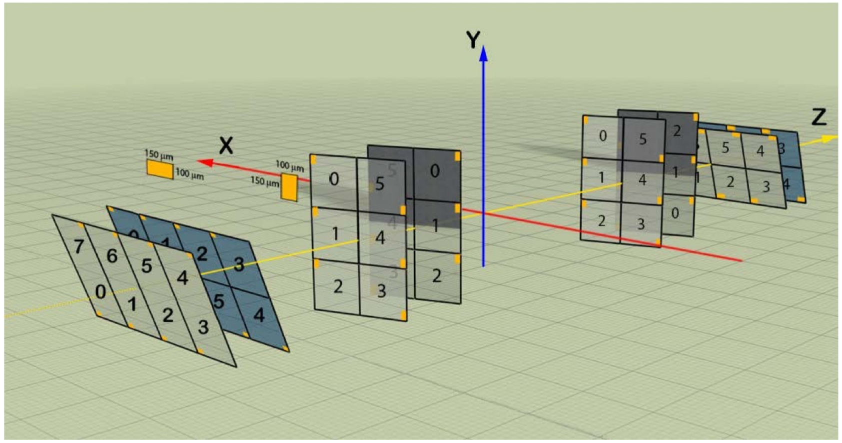
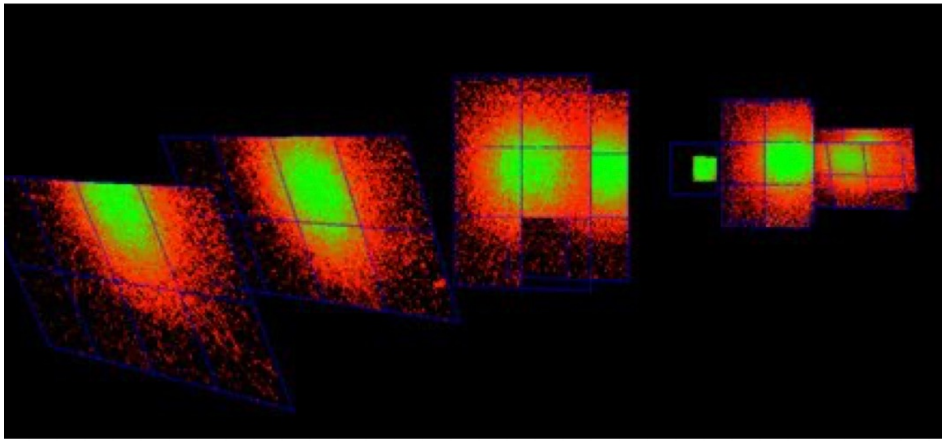


- Setup:
  - **Scintillation counter (10 cm^2)**: trigger
  - **Silicon tracker telescope**: spatial (x-y) information on the beam
  - Microchannel plate detector (MCP-PMT)
  - LYSO:Ce crystals + SiPMs





Source: FTBF Tracking Telescope [link]

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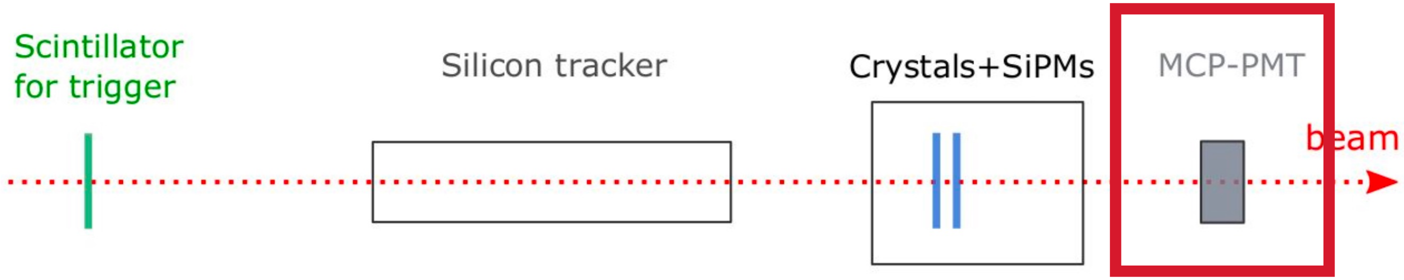
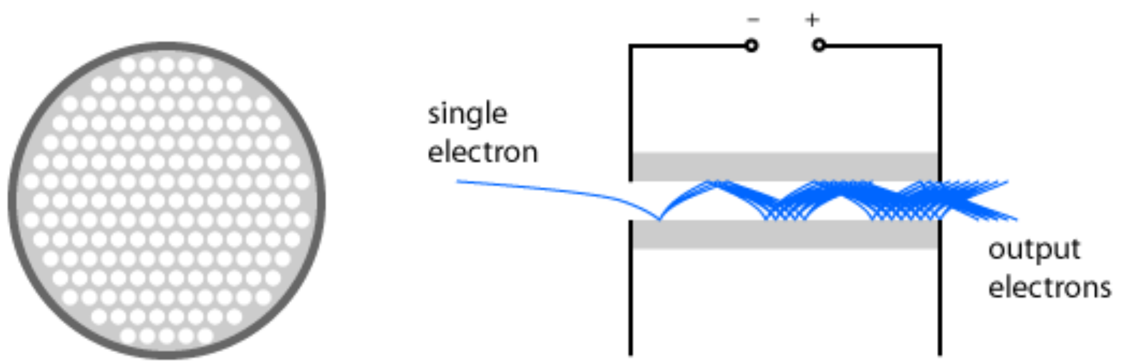


- **Setup**:
  - Scintillation counter (10 cm^2): trigger
  - Silicon tracker telescope: spatial (x-y) information on the beam
  - **Microchannel plate detector (MCP-PMT)**: Photek 240, $\sigma_t \sim 12$ ps; provides reference time
  - LYSO:Ce crystals + SiPMs



a) front view of microchannel plate b) electron avalanche in a single channel

Source: RP Photonics

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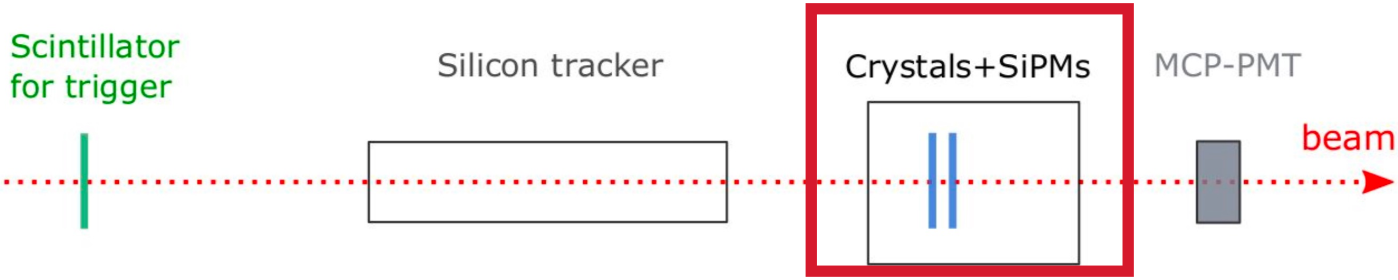
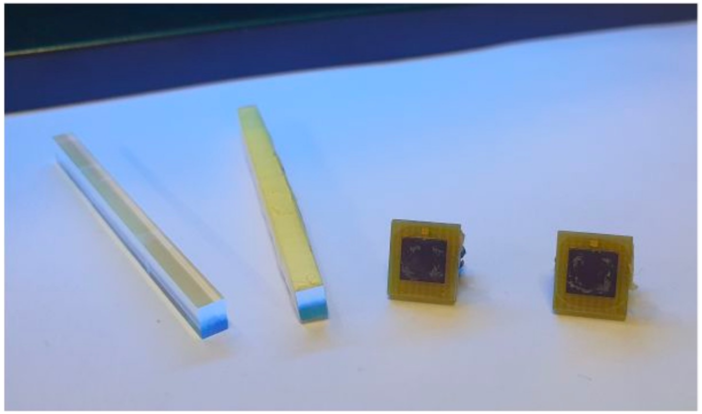
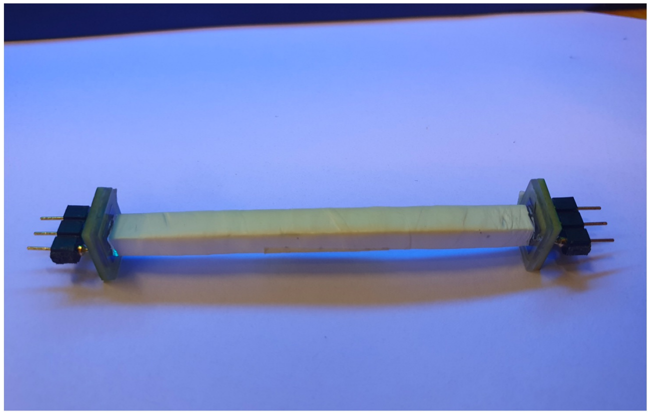


- Setup:
  - Scintillation counter (10 cm^2): trigger
  - Silicon tracker telescope: spatial (x-y) information on the beam
  - Microchannel plate detector (MCP-PMT): Photek 240, σ_t~12 ps; provides reference time
  - LYSO:Ce crystals + SiPMs: different SiPM manufacturers + LYSO dimensions





Test Beam Studies

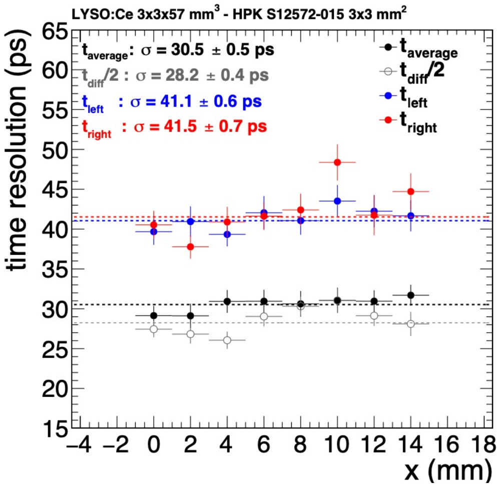
- LYSO bars:
  - Tested dimensions 3 × t × 57 mm^3 (varied thickness t between 2, 3, ad 4 mm)
  - Variable radial thickness to maintain constant slant depth traversed by outgoing MIPs in CMS
  - Units coated in Teflon layers to avoid light leakage + prevent damage
- SiPMs (unirradiated): two manufacturers
  - S12572-015 SiPMs from Hamamatsu (HPK); active area of 3x3 mm^2
  - SiPMs from Fondazione Bruno Kessler (FBK); active area of 5x5 mm^2
- Custom electronic boards to apply SiPM bias and perform readout (*not* BTL ASICs)

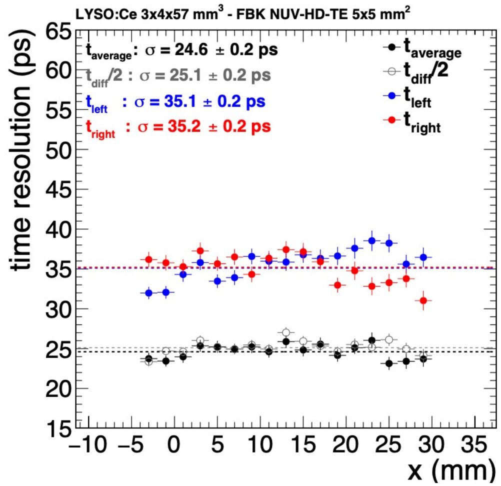
Sensor ID	Crystal dimensions [mm^3]	SiPM type	SiPM active area [mm^2]
HPK1	$3 \times 3 \times 57$	HPK S12572-015	3×3
HPK2	$3 \times 3 \times 57$	HPK S12572-015	3×3
HPK3	$3 \times 3 \times 57$	HPK S12572-015	3×3
FBK1	$3 \times 2 \times 57$	FBK NUV-HD-TE	5×5
FBK2	$3 \times 3 \times 57$	FBK NUV-HD-TE	5×5
FBK3	$3 \times 4 \times 57$	FBK NUV-HD-TE	5×5

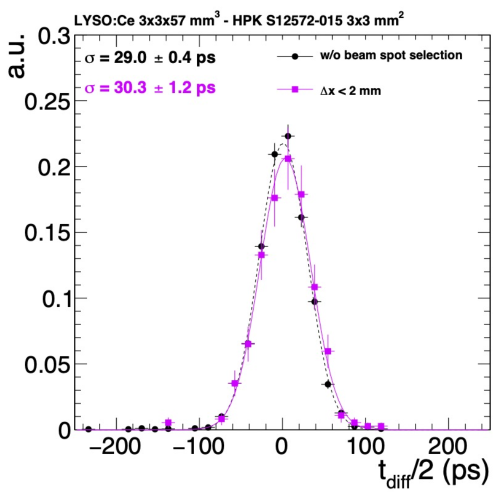
Time Resolution

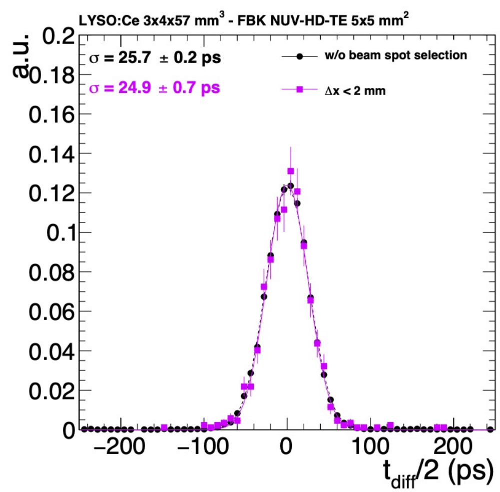
- Figures of merit:

- $\Delta t_{bar} = \frac{1}{2}(t_L + t_R) - t_{MCP}$
- $t_{diff} = t_L - t_R$
- $t_L - t_{MCP}$
- $t_R - t_{MCP}$









Target time resolution achieved:

- 30ps for 3×3×57 LYSO attached to HPK
- 25ps for 3×4×57 LYSO attached to FBK

See paper for additional discussion on impact of slant thickness and impact point

Summary + Next Steps

- Improvements from MIP precision timing:
  - Pileup mitigation—recover CMS Phase 1 conditions in optimal scenario
  - Particle isolation, vertex identification, missing PT reconstruction, time-of-flight measurement

- Test beam campaign of BTL sensor units achieved target time resolution (30 ps)

- Additional beam campaigns to test prototypes:
  - Study end-of-life sensor performance (irradiation scenarios) with TECs
  - Test TOFHIR ASIC and readout electronics performance

Thank you!