The CMS MIP Timing Detector

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Challenges at HL-LHC

Number of collisions per bunch crossing (pile-up):
- Phase I LHC: ~40 collisions
- High Luminosity LHC: 140-200 collisions
PU Mitigation with MIP Timing

- Time tagging tracks with a resolution of 30-50 ps
  - 4D vertex reconstruction
  - Requirement of time compatibility for track-vertex association
  - CMS calorimeters will have precision timing capabilities too
- Reduce effective pile-up to the level of current CMS detector
  - Slicing beam spot (time spread ~180 ps) in consecutive time slides (exposures)
Enhancing Particle Reconstruction

- Reduction of pile-up enhances quality of CMS particle reconstruction at HL-LHC.
  - Increased b-tagging efficiency
  - Increase of photon and lepton identification, efficiency and isolation
  - Improved missing transverse momentum resolution
  - Reduction of fake jet reconstruction from pile-up.
- 10%-20% gain in s/sqrt(B) for many Higgs decay channels.
Enabling new Physics Studies

- Enabling measurements of velocity for low $p_T$ hadrons:
  - Particle ID: $\pi/K$ up to 2 GeV, $p/K$ up to 5 GeV
  - New reach for Heavy ion physics at CMS
- 4D vertex reconstruction of primary and secondary vertices:
  - Provides a closed kinematic for Long Lived Particles
Design of the CMS MIP Timing Layer

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage for $|\eta|<2.9$

**Barrel**
- Surface: $\sim 36\ m^2$
- Number of channels: $\sim 331k$
- Radiation level: $\sim 2\times10^{14}\ n_{eq}/cm^2$
- Sensors: LYSO crystals / SiPM

**ENDCAPS**
- Surface: $\sim 15\ m^2$
- Number of channels: $\sim 4000k$
- Radiation level: $\sim 2\times10^{15}\ n_{eq}/cm^2$
- Sensors: Low gain avalanche diodes
MTB Barrel Sensor

- Use industry standard technology
  - Cost effective coverage of BTL area

- LYSO crystals as scintillator
  - Excellent radiation tolerance
  - Dense (7.1 g/cm³), bright (40k ph/MeV)
  - Fast rise time O(100ps), decay time ~40 ns

- Silicon Photomultipliers as photo-sensors
  - Compact, insensitive to magnetic fields, fast
  - Optimal SiPM cell size : 15 µm
  - High dynamic range, rad tolerant
  - Photo Detection efficiency : 20-40%

- High aspect ratio geometry :
  - Enhance light collection efficiency
  - Minimize SiPM area / Crystal area
  - Reduce power consumption
  - Better timing performance
MTD Barrel Sensor performance

- 30 ps and below achieved in test beam measurements.
- Uniform time response and resolution across sensor area
- Combination of two SiPMs per LYSO crystal improves resolution
MTD Barrel Performance

- Detector timing performance evolution during operation
  - Photo statistics and noise term dominate
  - Clock distribution, electronics and digitization negligible

- Radiation damage will increase SiPM dark count rate (DCR) up to 60 GHz.

- DCR noise mitigation by:
  - CO$_2$-cooling to -30 °C
  - Annealing of SiPMs at 15 °C during shutdowns
  - Optimizing SiPM operating point
  - Dedicated noise cancelation circuit in the Front End ASIC
MTD Barrel Detector Layout

- Detector mounted on the inner surface of the Tracker Support Tube.
- Common cold volume & services
- Single layer, 40 mm thick, segmented into 72 trays
- Each tray consists of 6 Readout Units with 24 modules each

Sensor module: 16 LYSO bars, 2 SiPM arrays, ~52x57 mm

Current CMS Tracker Support Tube
MTD Endcap Sensor

- Low Gain Avalanche Diodes:
  - Optimized for precision timing
  - Highly doped $p^+$ region just below the n-type implants
  - Moderate internal gain of 10 to 30
  - Radiation tolerance sufficient for endcap fluence

- Sensor optimization
  - Thin detectors to maximize slew rate $(dV/dt) : \sim 50 \ \mu m$
  - Small pixel size to minimize capacitance: $1.3 \times 1.3 \ mm^2$
  - Small sensors $(21x42 \ mm^2)$ filled with pixels for optimal wafer usage
  - Maximize efficiency $(85 \rightarrow 92\%)$ by reducing space between pixels
MTD Endcap Test Beam Results

- Sensor performance close to final specs:
  - Pixel efficiency close to 100%
  - Array fill factor 90%
  - Sensor uniformity 2%

- Target time resolution of 30 ps per pixel
  - Noise jitter term <25 ps for gain > 15
  - Intrinsic limit from Landau fluctuation
  - Spatial non-uniformity of energy deposition
  - Constant term: ~25 ps
  - Robust double layer design
MTD Endcap Performance

- Sensors irradiated up to fluence expected in CMS
- Time resolution maintained at < 40 ps after $1.5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
  - Increase of bias voltage to compensate gain loss
  - Cooling to -30 °C to minimize leakage current
- R&D targeting further improved radiation tolerance
MTD Endcap Detector Layout

- Double mounted on the endcap calorimeter.
- Sensor modules on two sides of support disk.
- Detector thickness ~40 mm
- Services run across modules in service channels to periphery.
- Separate cold volume.
CMS MTD for HL-LHC

- Mitigate harsh pile-up conditions at HL-LHC with precision timing
  - Enhance CMS particle reconstruction by reducing effective pile-up

- High impact on the HL-LHC physics program
  - Enable TOF for particle ID
  - Enable 4D reconstruction
  - Enables LLP signatures
  - Enhance statistical significance of Higgs analysis

- CMS HL-LHC upgrade includes a MIP Timing detector:
  - Hermetic device to time tag tracks with 30-50 ps resolution
  - LYSO crystals with SiPM readout in the barrel
  - LGAD in the endcaps