The CMS MIP Timing Detector

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On behalf of the CMS Collaboration

EPS-HEP

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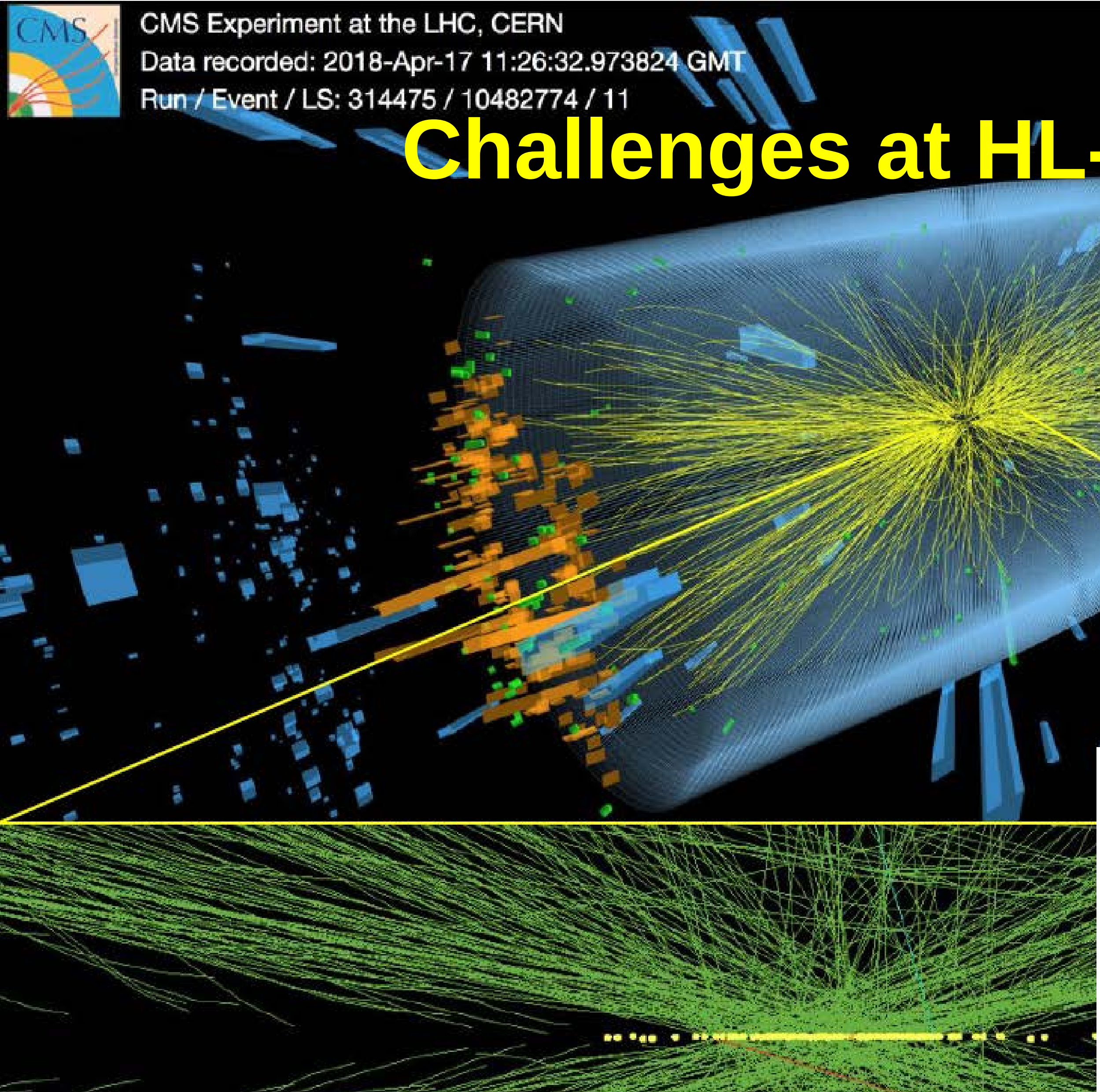
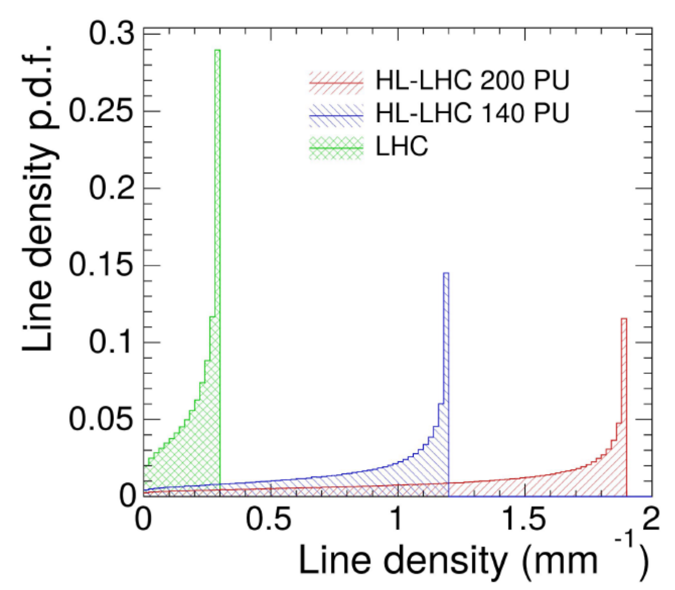
Challenges at HL-LHC



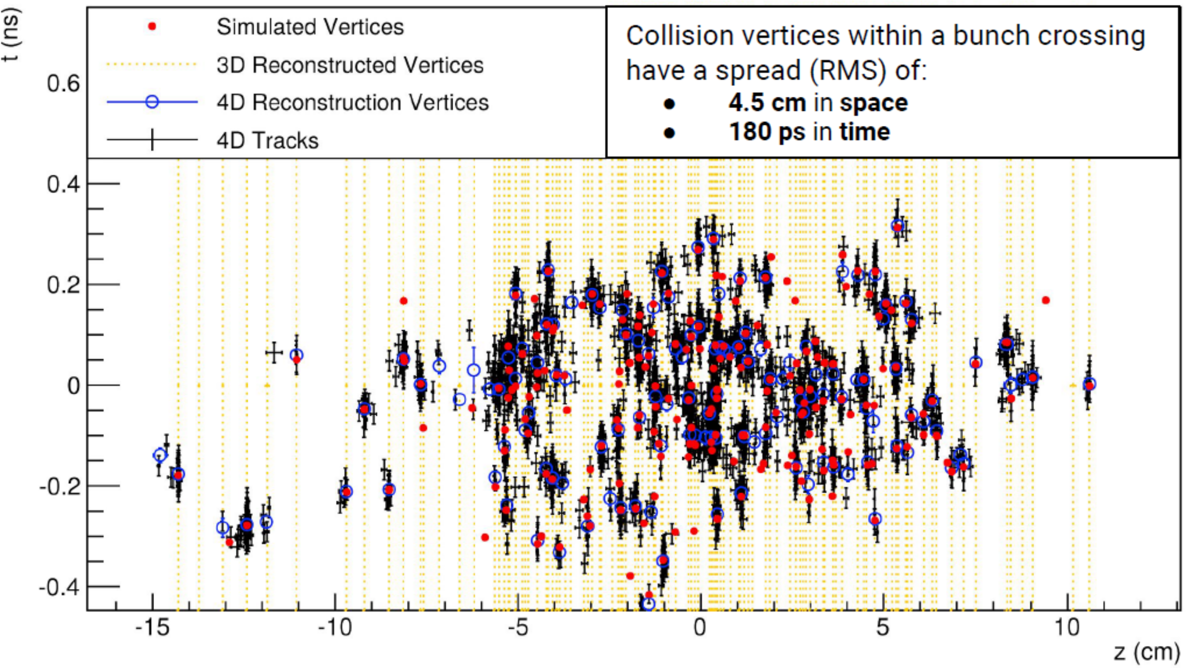


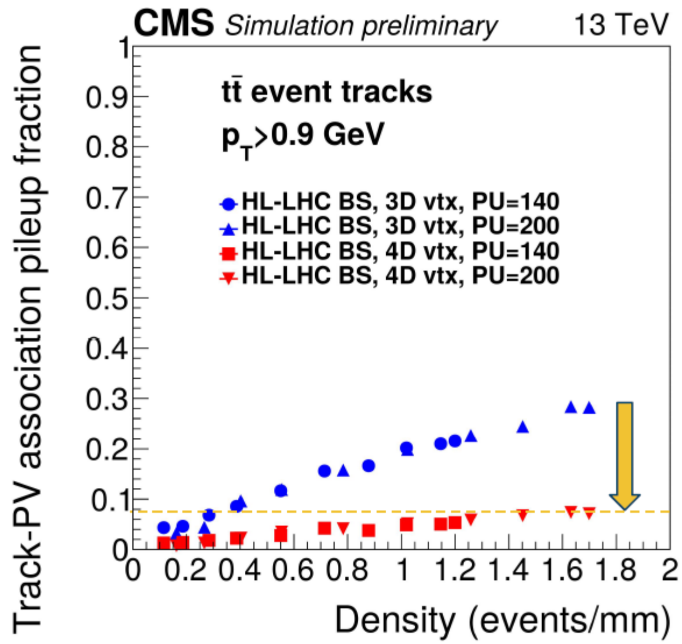
Number of collisions per bunch crossing (**pile-up**):

- Phase I LHC: ~40 collisions
- High Luminosity LHC: 140-200 collisions

PU Mitigation with MIP Timing

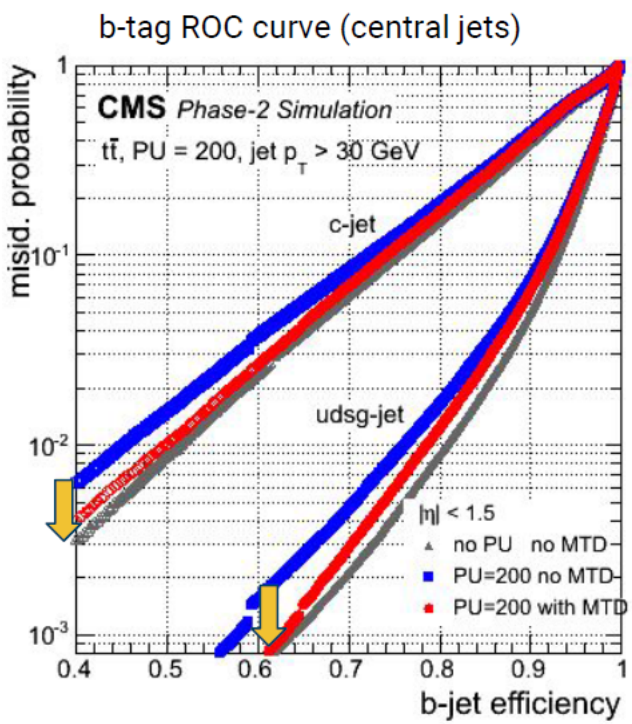
- Time tagging tracks with a resolution of 30-50 ps
  - 4D vertex reconstruction
  - Requirement of time compatibility for track-vertex association
  - CMS calorimeters will have precision timing capabilities too
- Reduce effective pile-up to the level of current CMS detector
  - Slicing beam spot (time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

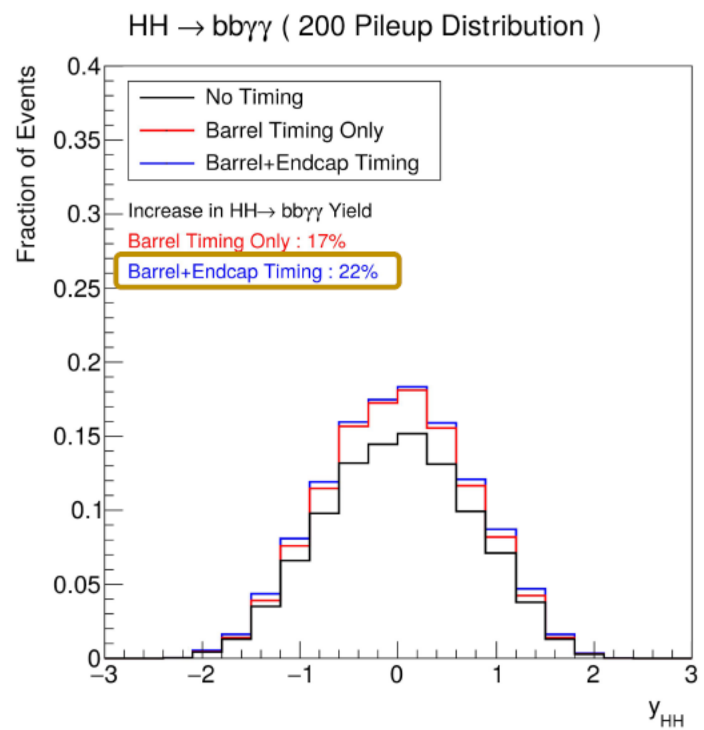




Enhancing Particle Reconstruction

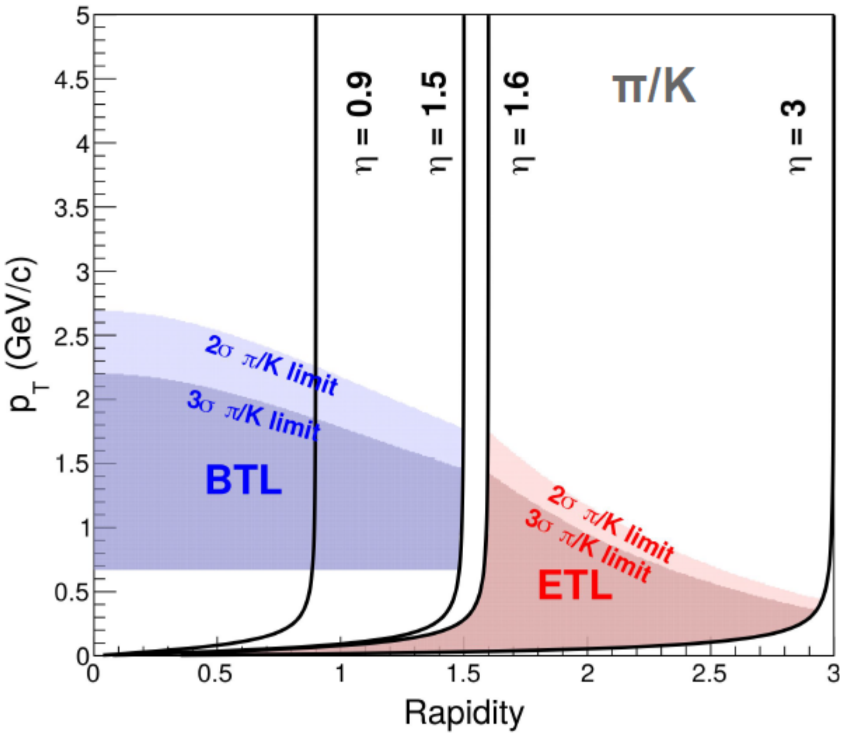
- **Reduction of pile-up enhances quality of CMS particle reconstruction at HL-LHC.**
  - **Increased b-tagging efficiency**
  - **Increase of photon and lepton identification, efficiency and isolation**
  - **Improved missing transverse momentum resolution**
  - **Reduction of fake jet reconstruction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

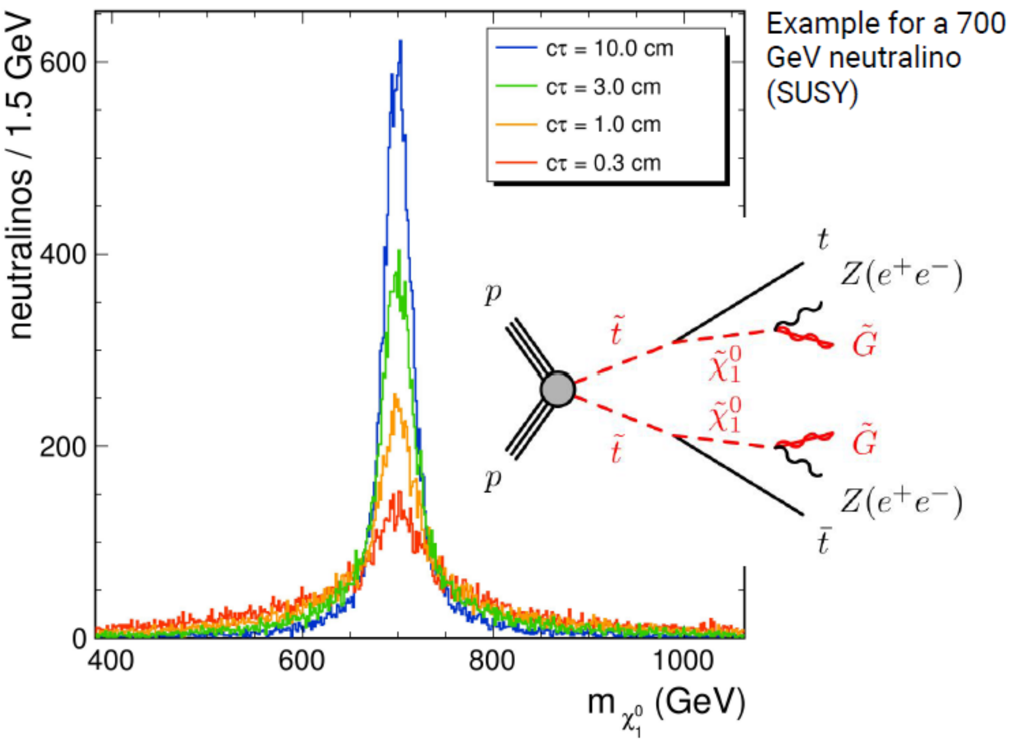




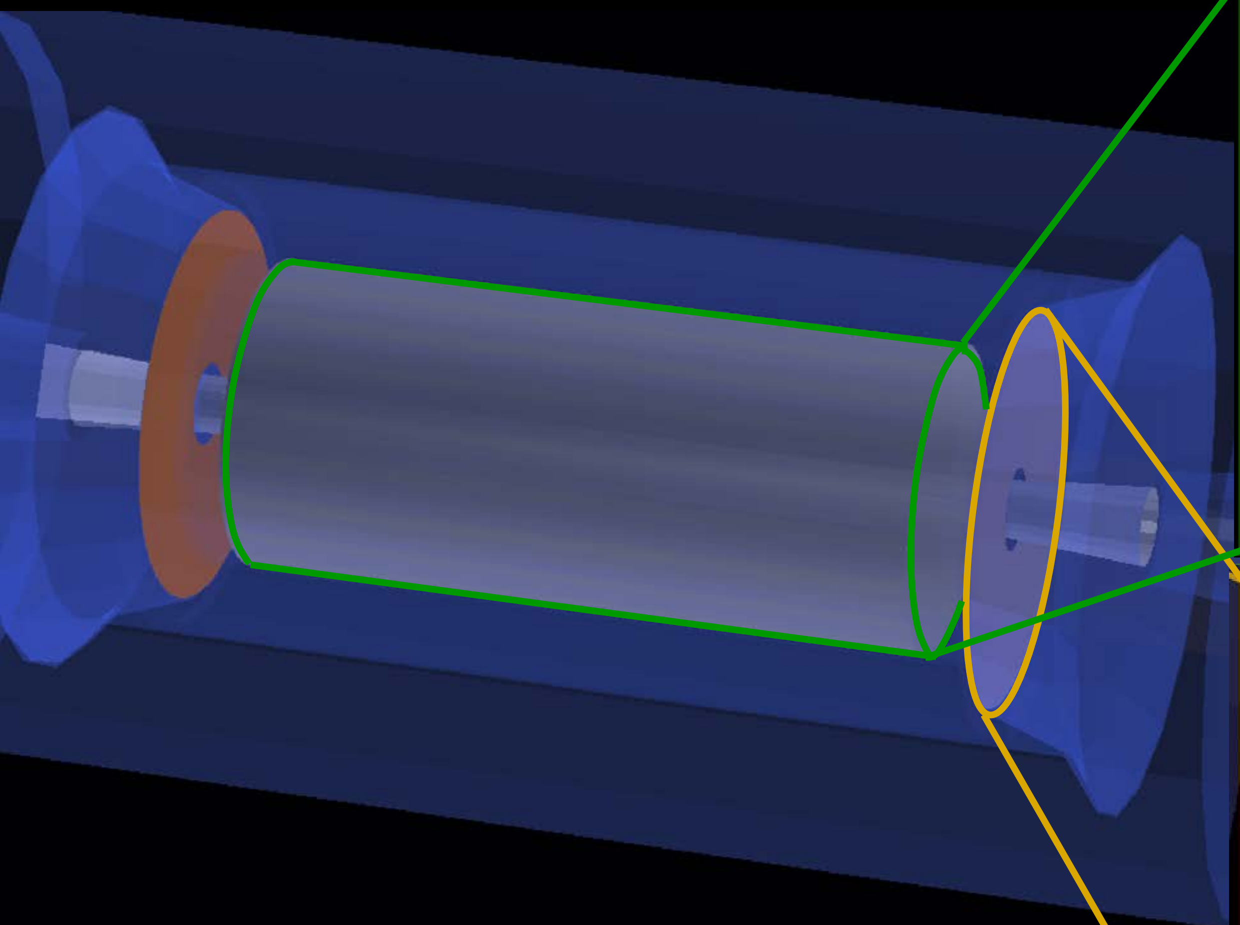
Enabling new Physics Studies

- Enabling measurements of velocity for low p_T hadrons :
  - Particle ID : π/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



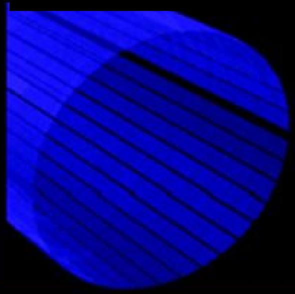


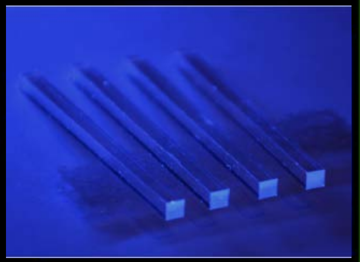
Design of the CMS MIP Timing Layer



Barrel

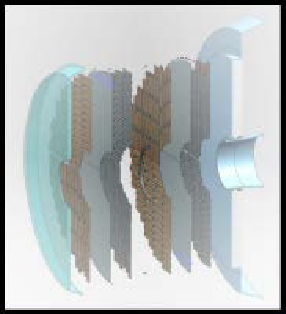
Surface ~36 m^2
Number of channels ~331k
Radiation level ~2×10^{14} n_{eq}/cm^2
Sensors : LYSO crystals / SiPM

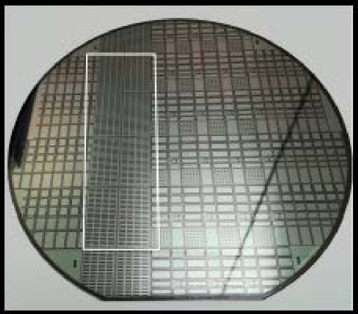




ENDCAPS

Surface ~ 15 m^2
Number of channels ~ 4000k
Radiation level ~ 2×10^{15} n_{eq}/cm^2
Sensors: Low gain avalanche diodes

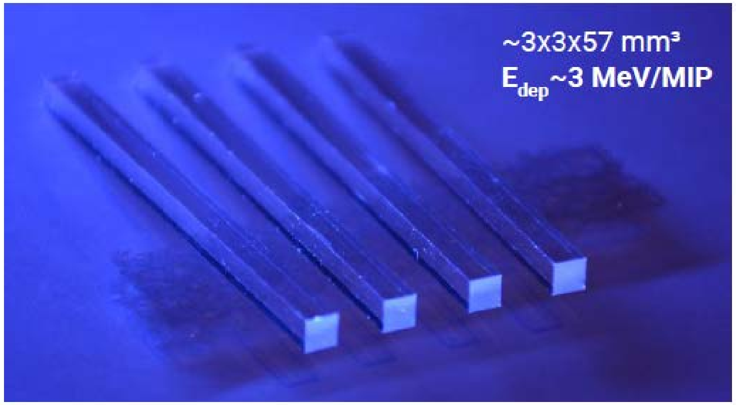


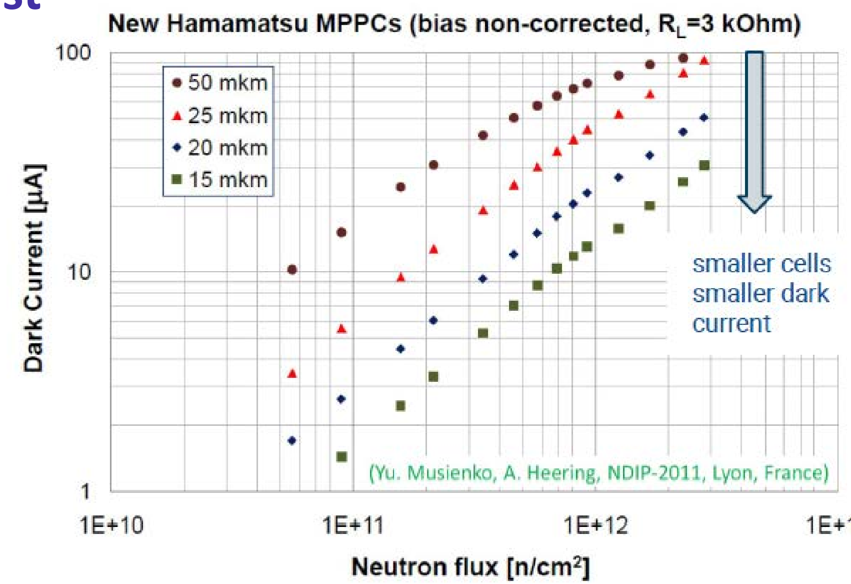


- **Thin layer between tracker and calorimeters**
- **MIP sensitivity with time resolution of 30-50 ps**
- **Hermetic coverage for $|\eta|<2.9$**

MTB Barrel Sensor

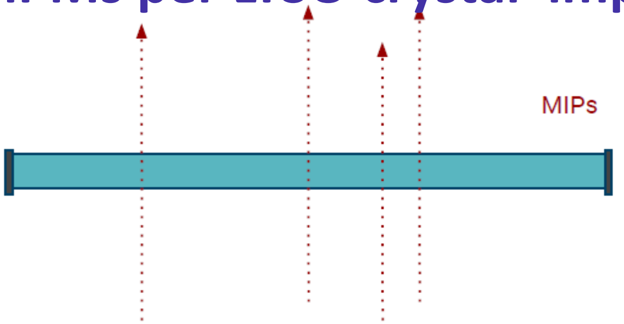
- Use industry standard technology
  - Cost effective coverage of BTL area
- LYSO crystals as scintillator
  - Excellent radiation tolerance
  - Dense (7.1 g/cm^3), bright (40k ph/MeV)
  - Fast rise time O(100ps), decay time ~40 ns
- Silicon Photomultipliers as photo-sensors
  - Compact, insensitive to magnetic fields, fast
  - Optimal SiPM cell size : 15 mµ
  - 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

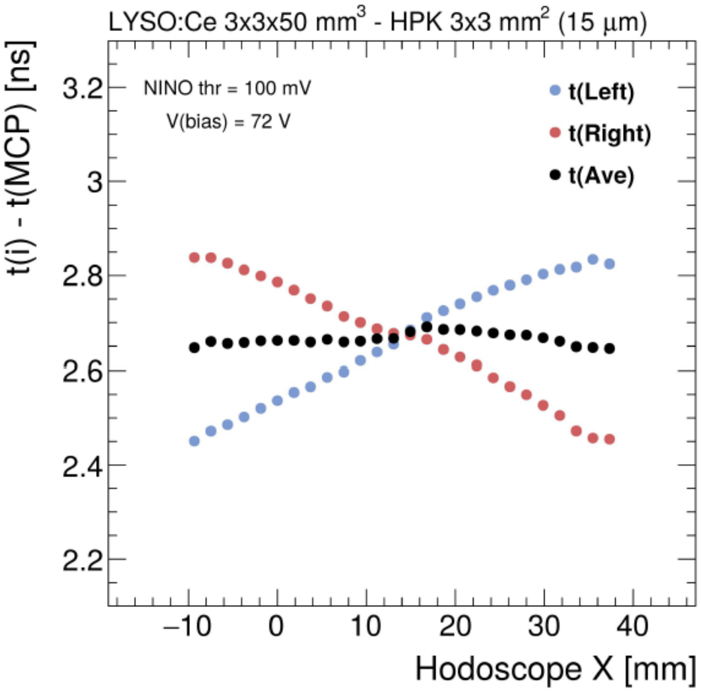


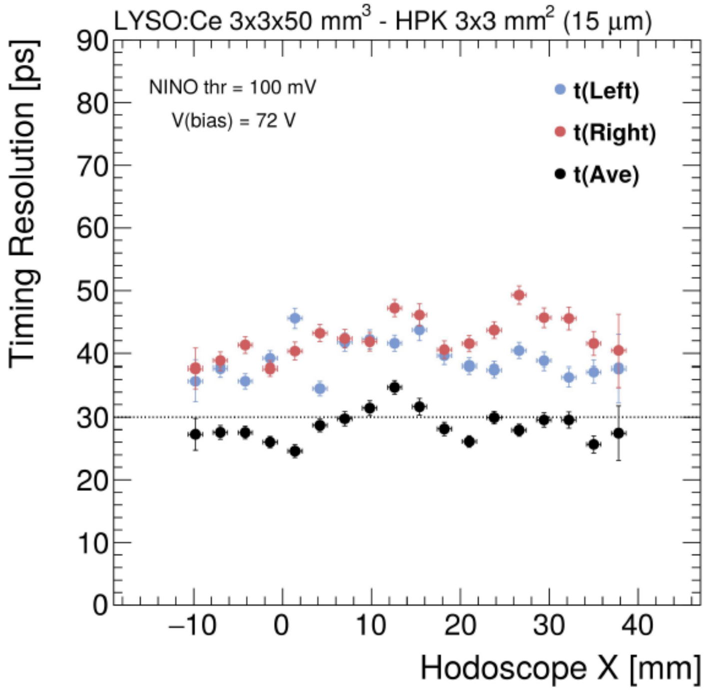


MTD Barrel Sensor performance

- 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





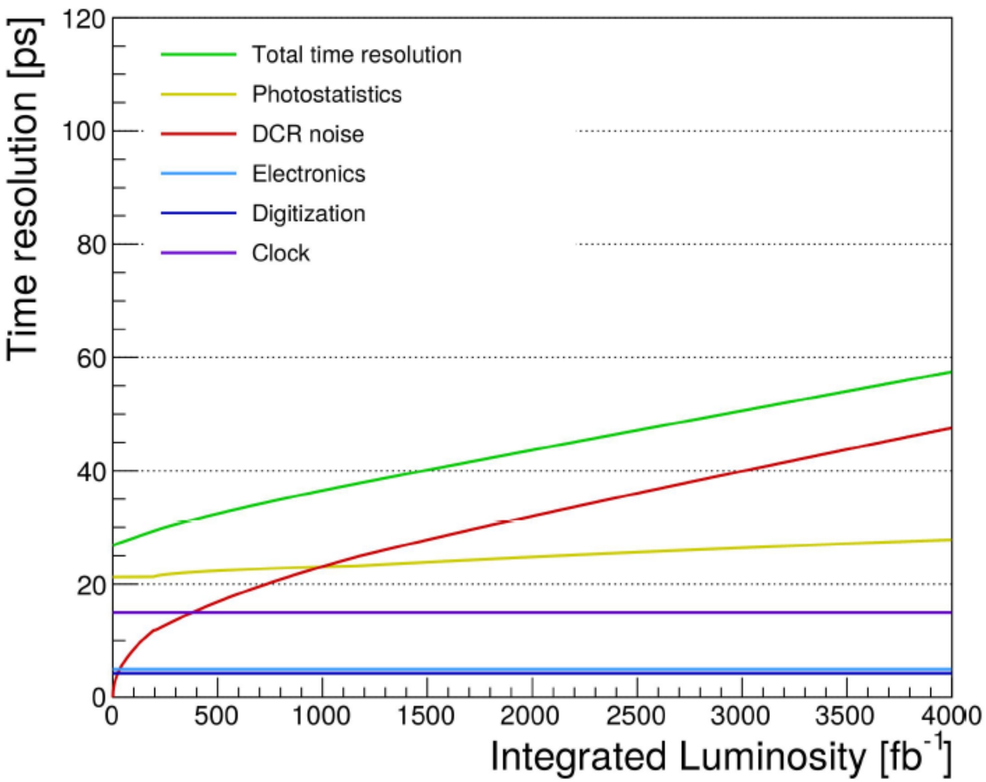


MTD Barrel Performance

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

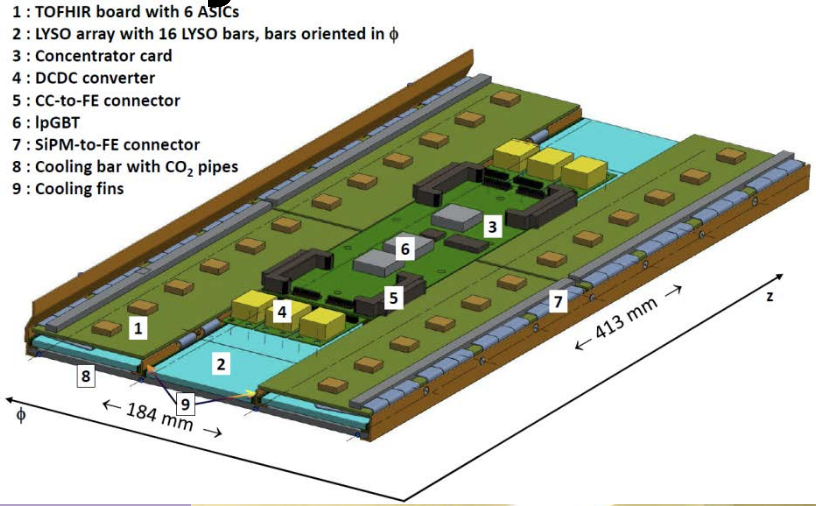
- Radiation damage will increase SiPM dark count rate (DCR) up to 60 GHz.

- 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

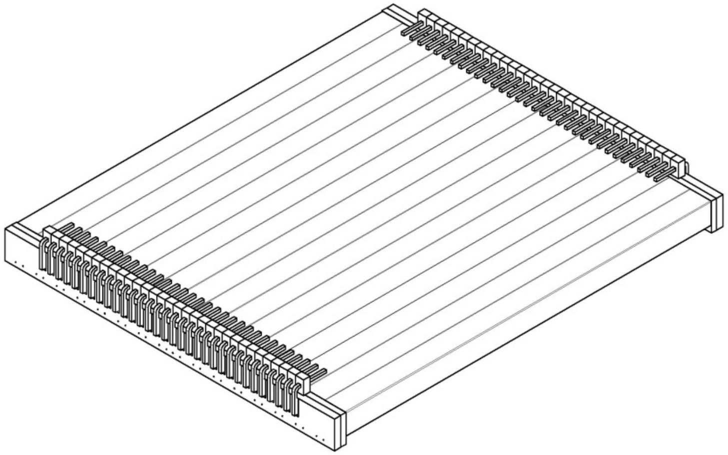


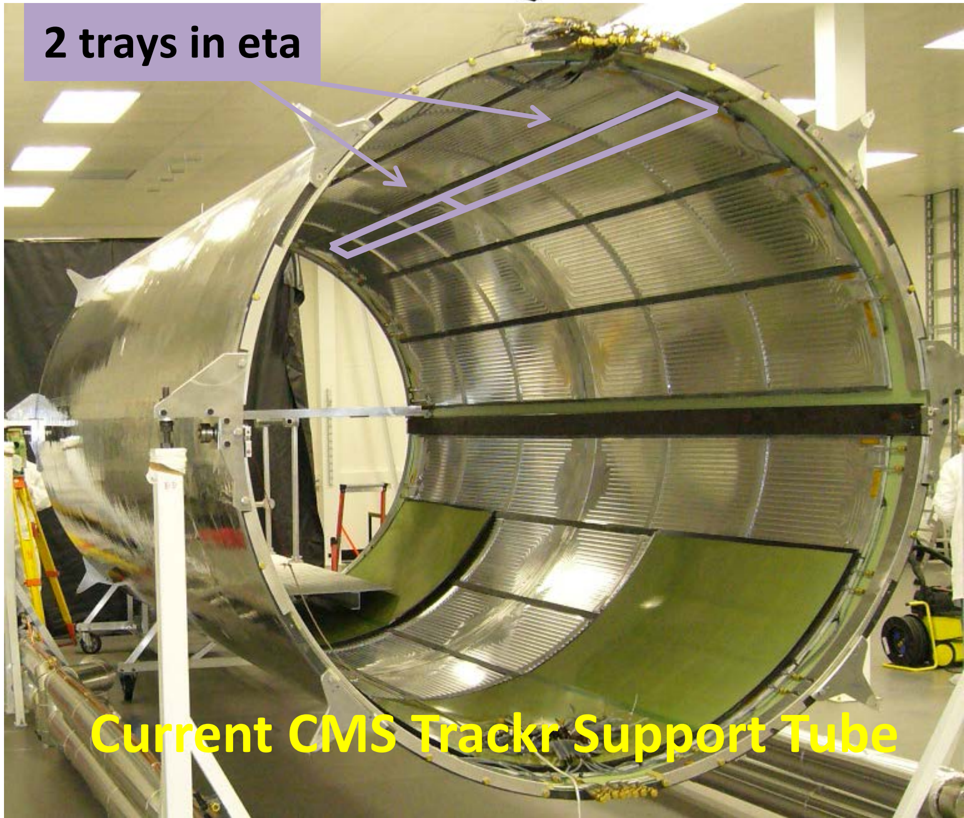
MTD Barrel Detector Layout

- 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



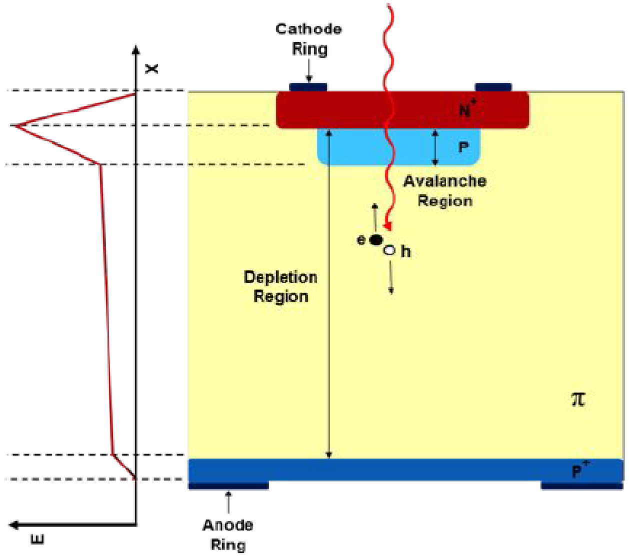
Sensor module : 16 LYSO bars, 2 SiPM arrays, ~52x57 mm



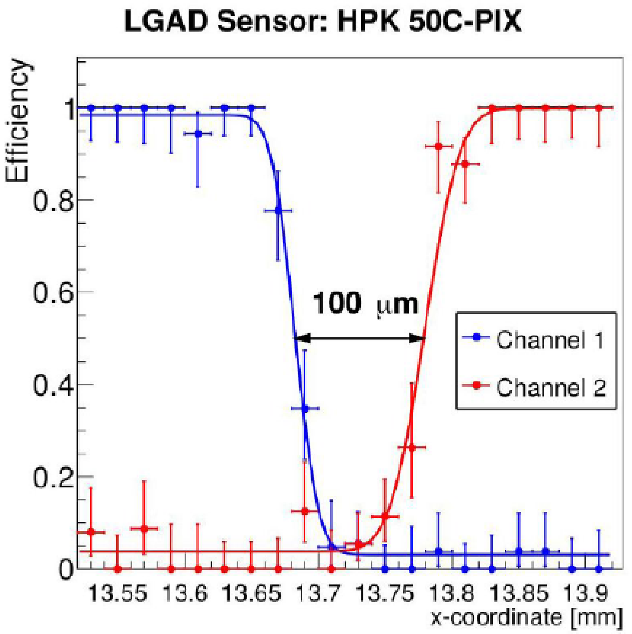


MTD Endcap Sensor

- 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

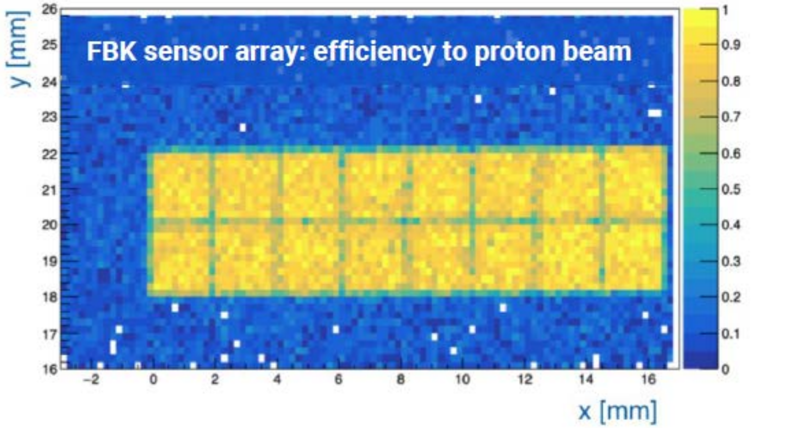


- Sensor optimization
  - Thin detectors to maximize slew rate (dV/dt) : ~50 μm
  - Small pixel size to minimize capacitance : 1.3 x 1.3 mm^2
  - Small sensors (21x42 mm^2) filled with pixels for optimal wafer usage
  - Maximize efficiency (85→92%) by reducing space between pixels

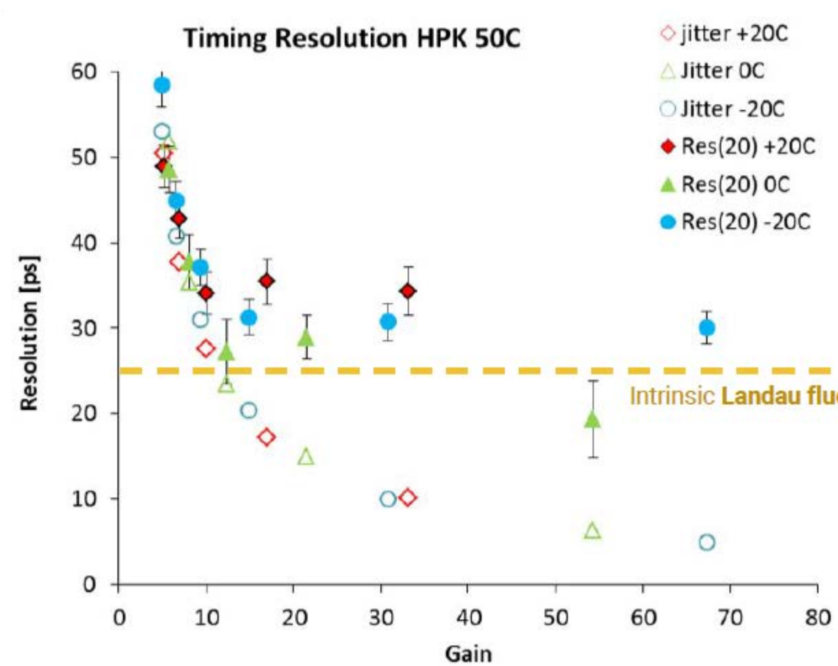


MTD Endcap Test Beam Results

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

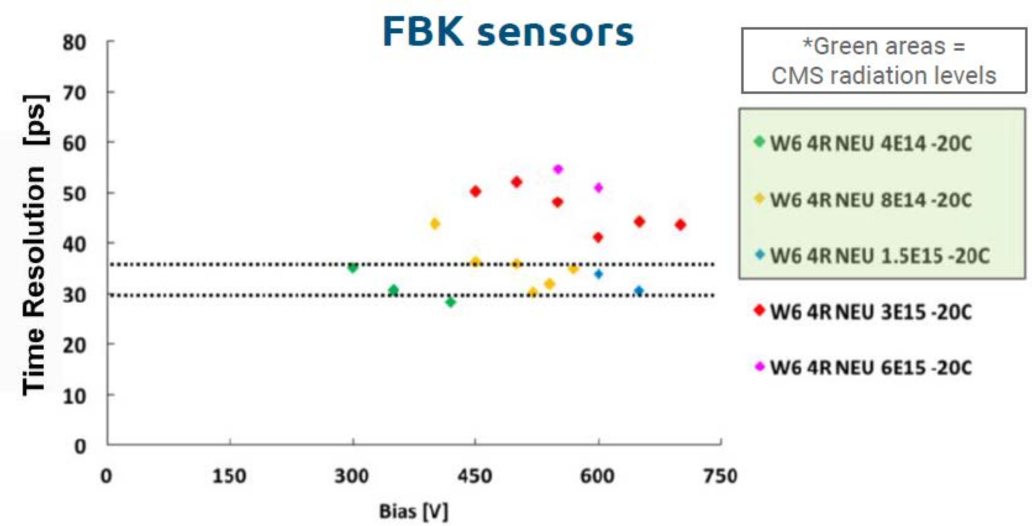


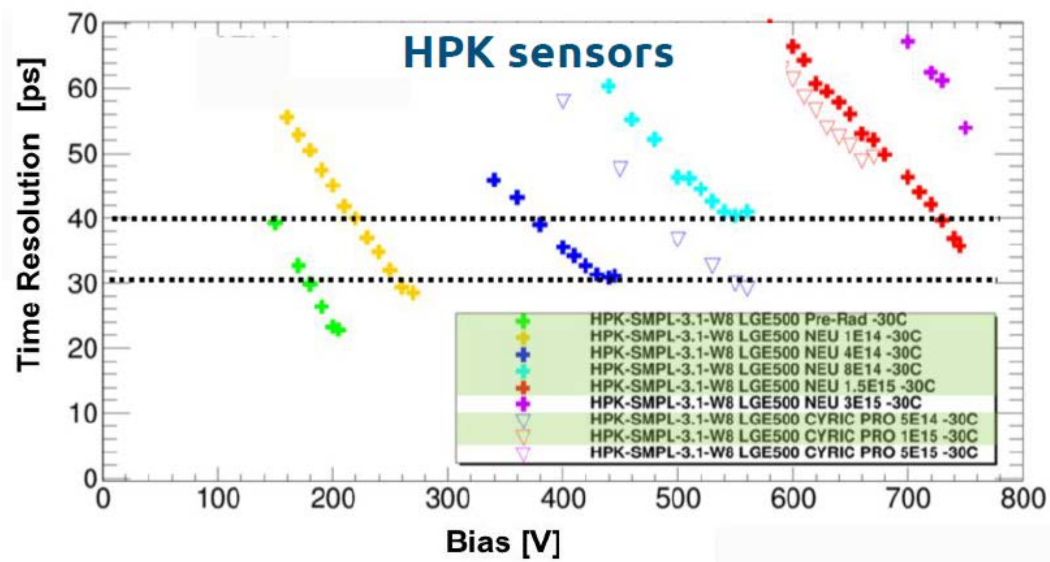
- Target time resolution of 30 ps per pixel
  - Noise jitter term <25 ps for gain > 15
  - Intrinsic limit from Landau fluctuation
  - Spatial non-uniformity of energy deposition
  - Constant term : ~25 ps
  - Robust double layer design



MTD Endcap Performance

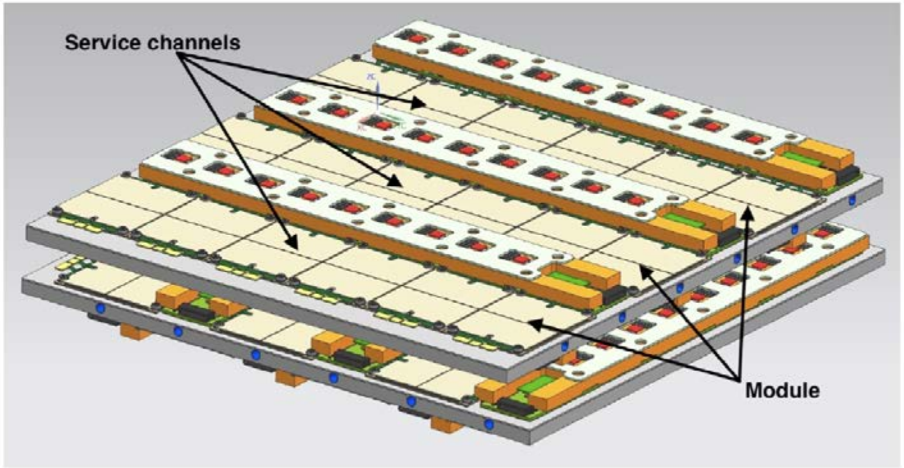
- Sensors irradiated up to fluence expected in CMS
- Time resolution maintained at < 40 ps after $1.5\times10^{15}\ n_{eq}/cm^2$
  - Increase of bias voltage to compensate gain loss
  - Cooling to -30 °C to minimize leakage current
- R&D targeting further improved radiation tolerance

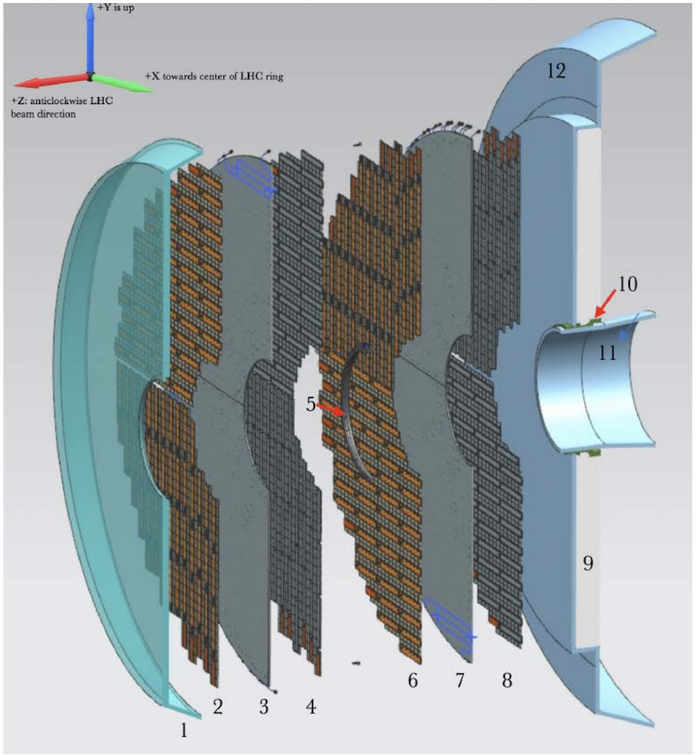




MTD Endcap Detector Layout

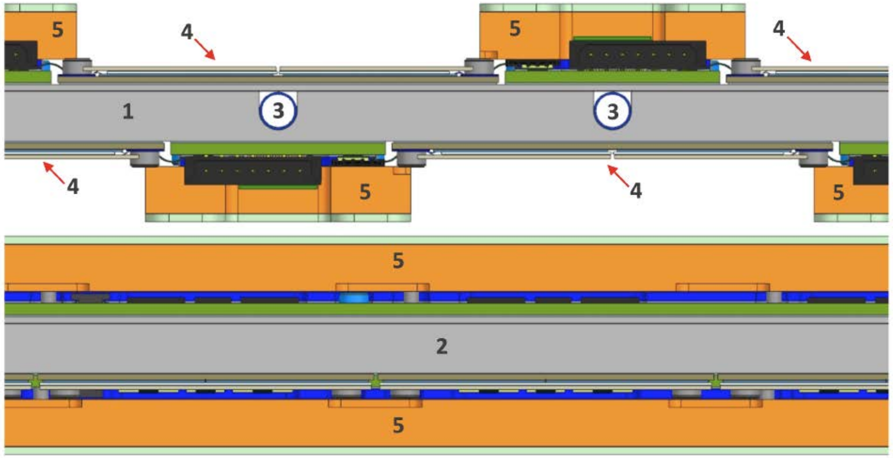
- Double mounted on the endcap calorimeter.
- Sensor modules on two sides of support disk.
- Detector thickness ~40 mm
- Services run across modules in service channels to periphery.
- Separate cold volume.





1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

1: ETL disk 1;
2: ETL disk 2;
3: Cooling tube
4: module
5: power + readout boards



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