The CMS MIP Barrel Timing Detector

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On behalf of the CMS MTD Collaboration

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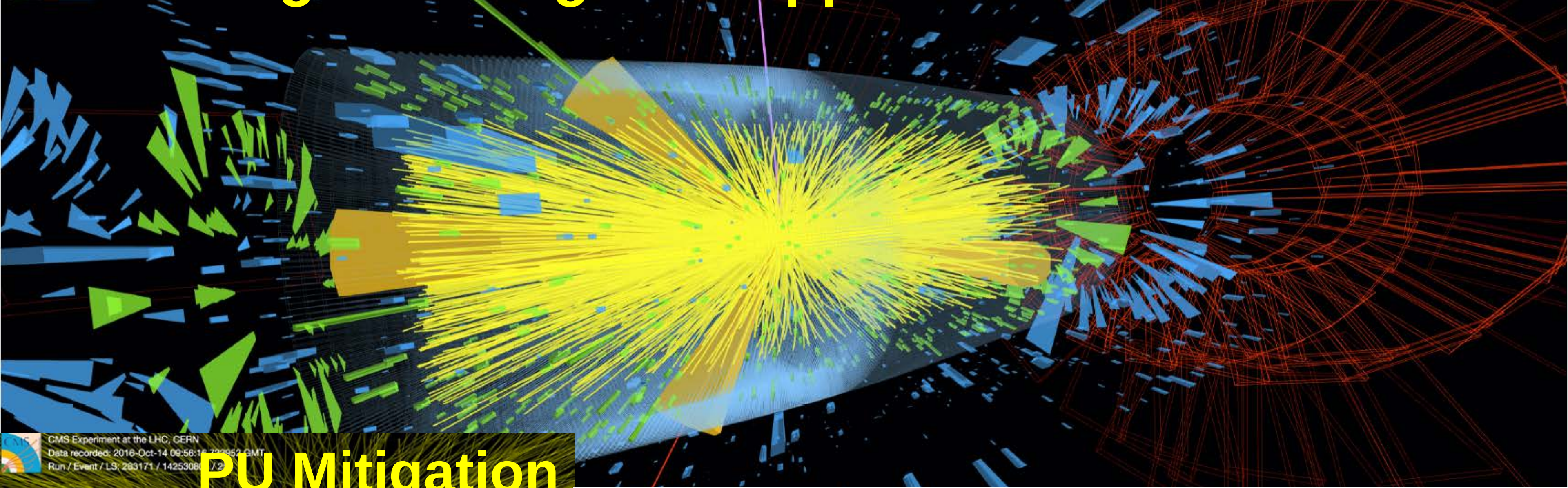
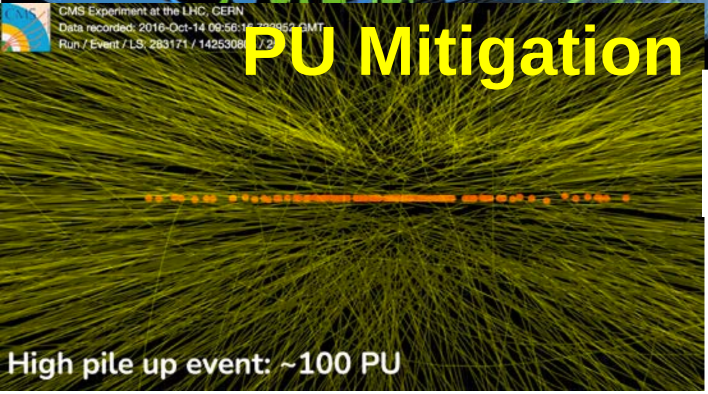
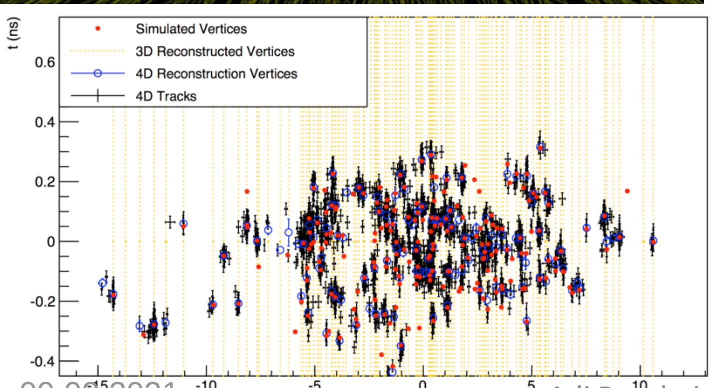
Timing Challenges & Opportunities at HL-LHC

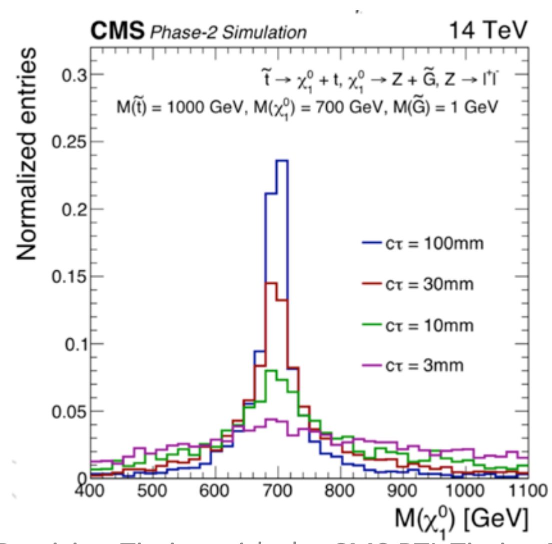


PU Mitigation

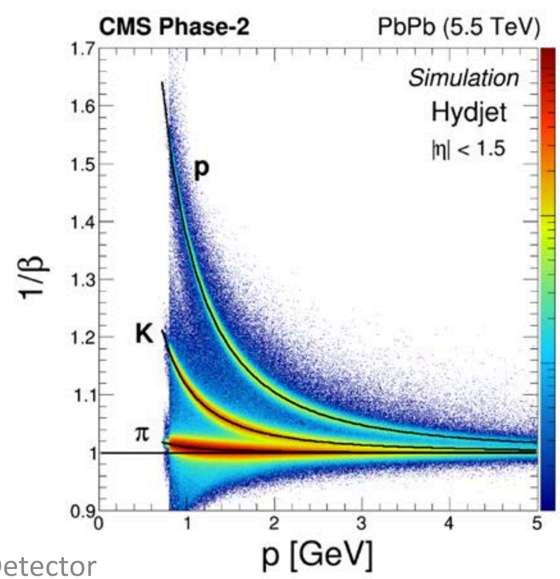




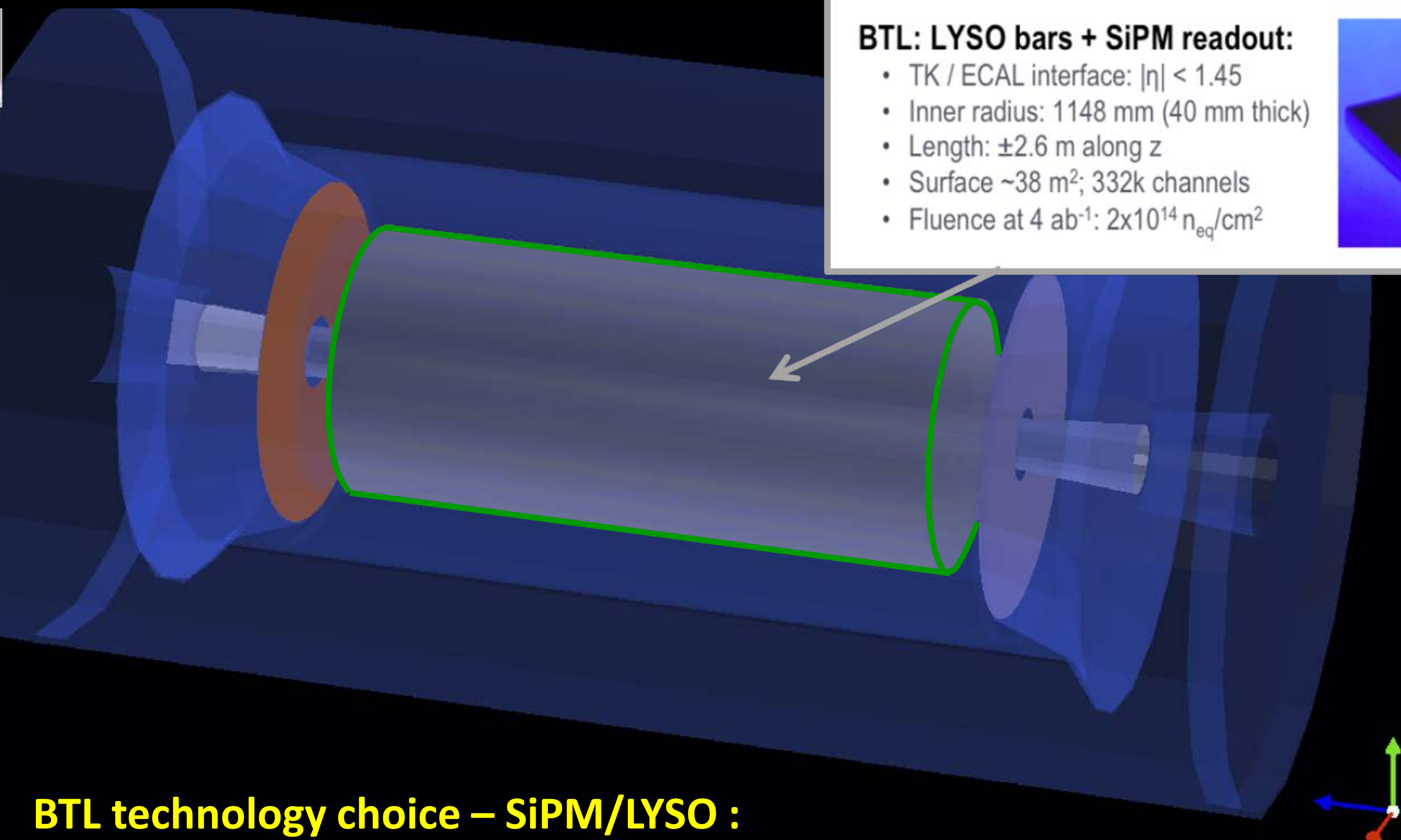
New physics reach



Improved reconstruction

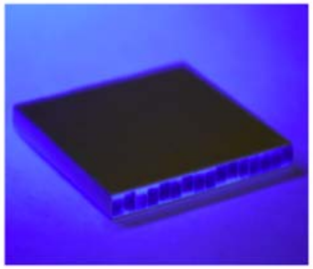


The CMS Barrel Timing Layer



BTL: LYSO bars + SiPM readout:

- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2\times10^{14}\ n_{eq}/cm^2$

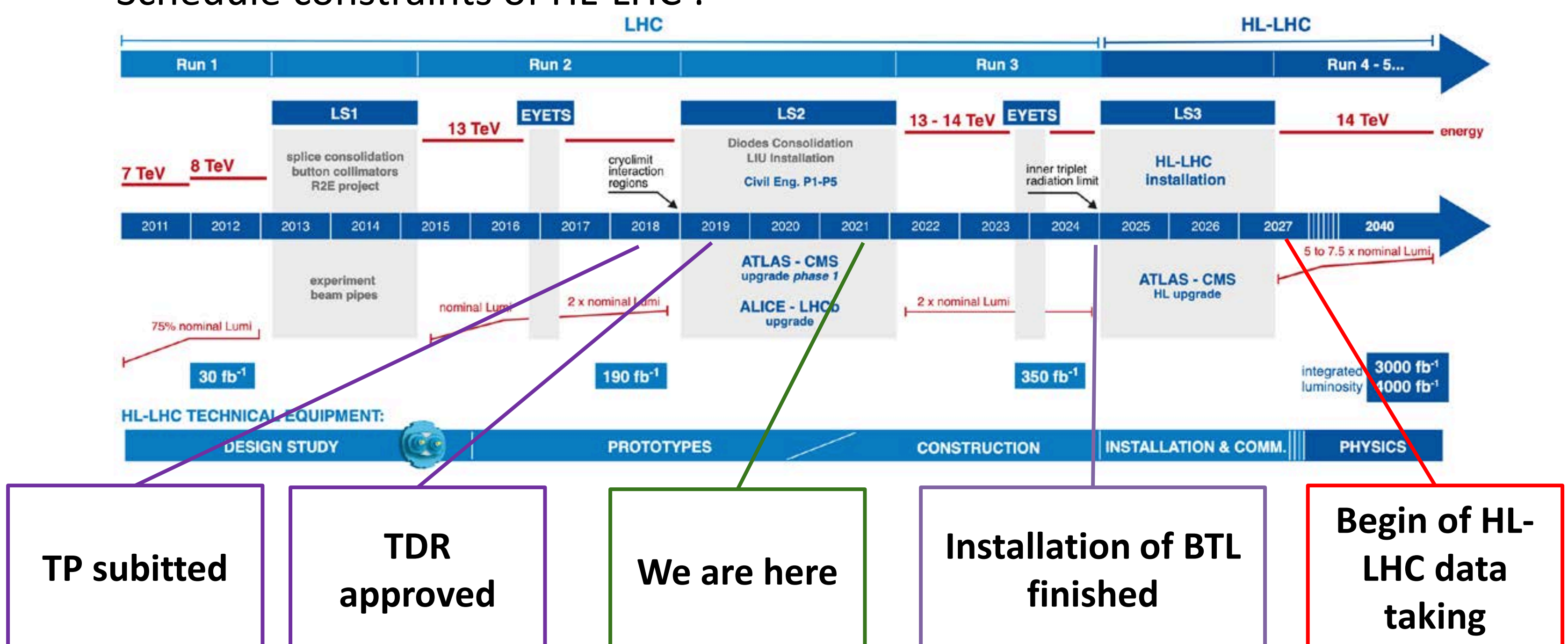


BTL technology choice – SiPM/LYSO :

- **Timing performance <30 ps with MIPs in LYSO/SiPM demonstrated.**
- **Radiation hardness established at the required level.**
- **Extensive experience with SiPM in CMS & LYSO in HEP & PET**
- **Cost effective mass market components**

Design constraints

- Time resolution 30-40 ps at the start of HL-LHC, <60 ps up to 3000 fb^{-1}.
  - Requires additional measures to maintain EOL performance.
- Radiation levels for BTL after 3000 fb^{-1} :
  - Fluence $1.65 – 1.9 \times 10^{14}$ n_{eq}/cm^2 , **Dose : 18-32 kGy**
- Maintenance free operation inside the tracker cold volume.
  - Requirement to run SiPMs **below -30 C** to limit dark count rate (DCR).
- Cover ~38 m^2 of area at the outer circumference of the CMS tracker.
- Schedule constraints of HL-LHC :



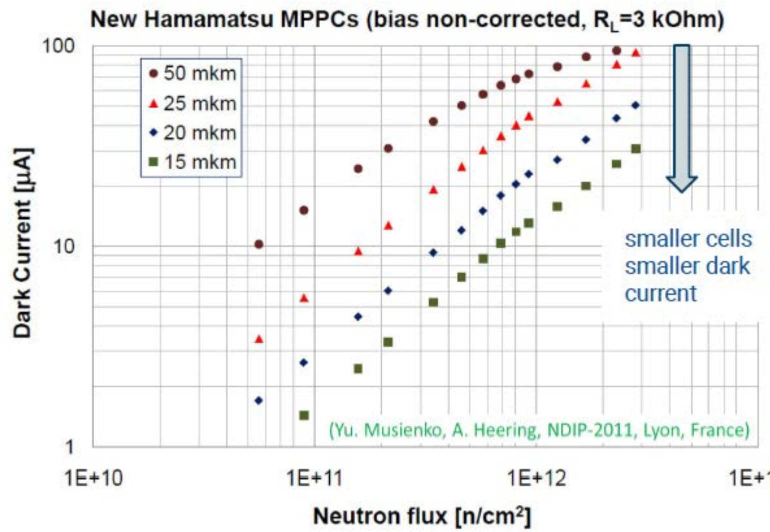
MTD Barrel Sensor

- Maximize raw signal yield and rise time to optimize timing performance.

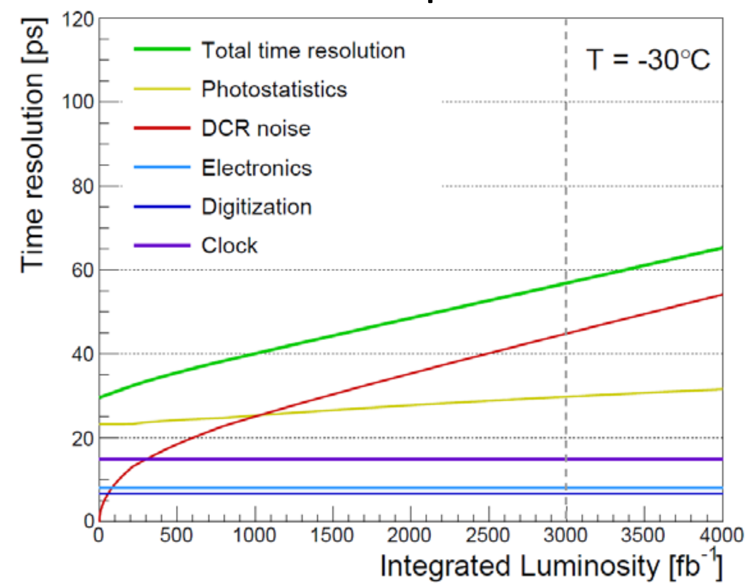
- LYSO crystals as scintillator
  - Excellent radiation tolerance
  - Bright (40k ph/MeV)
  - Fast rise time O(100ps), decay time ~40 ns

- 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 (~5 %)
  - Minimize SiPM area / Crystal area
  - Reduce power consumption
  - Better timing performance



Resolution <60 ps @ 3 ab^{-1}

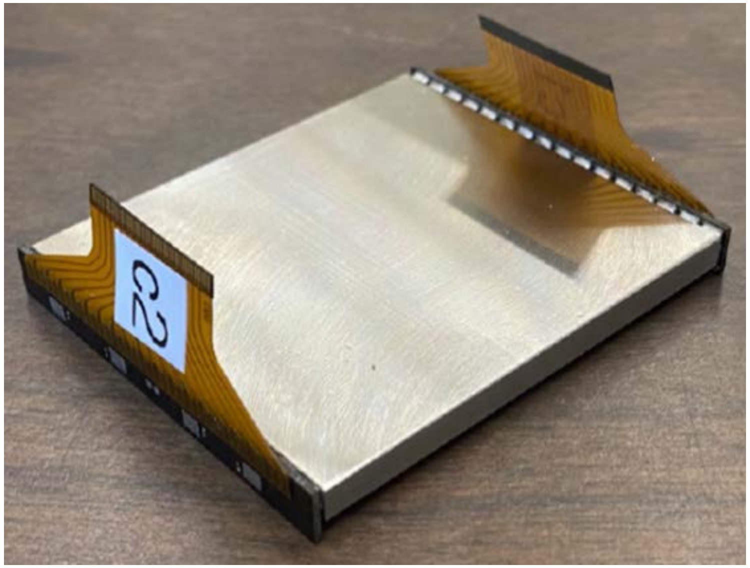


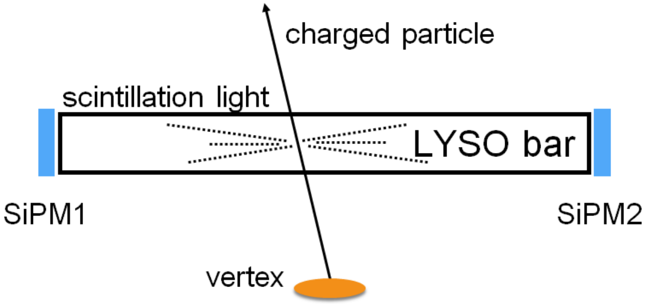
Sensor geometry choice

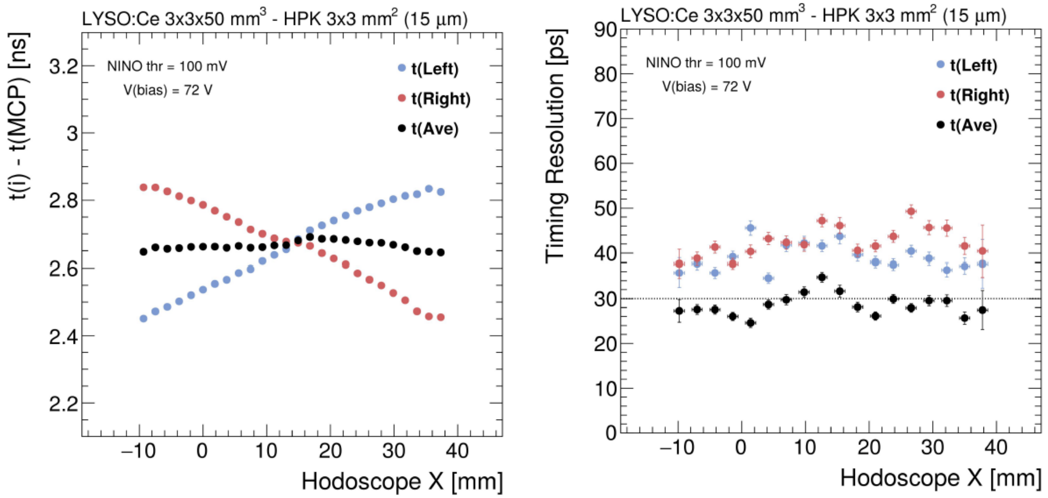
- Scintillation light measured with a pair of Silicon Photomultipliers (SiPMs), one at each end of the crystal bar
  - Minimize impact point position dependency
  - Minimization of active area and power budget
  - Maximization of resolution ($\sqrt{2}$ improvement)
  - Determination of track position with O(mm) resolution

BTL module :

- 16 LYSO bars, read out by 32 SiPMs,
- Size 51 x 57 mm, thickness 2.4, 3.0, 3.75 mm

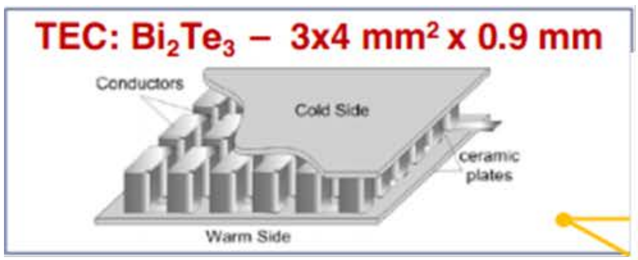


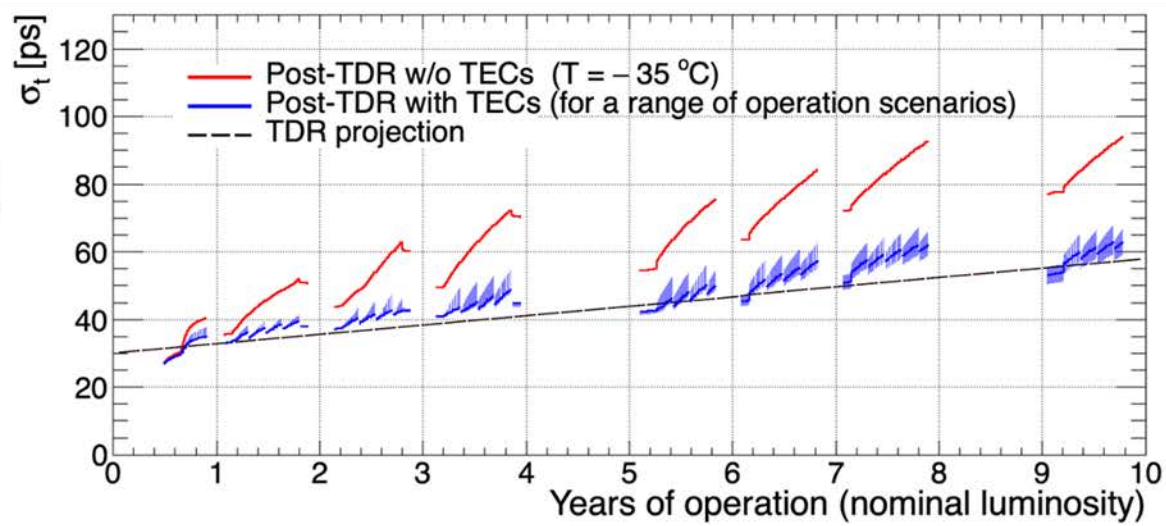




Further Improvement in Design: TEC

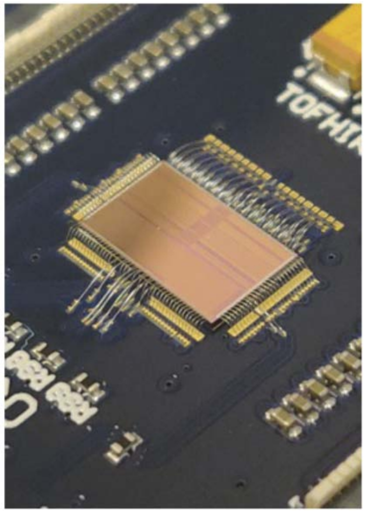
- **Two handles to mitigate impact of SiPMs dark count rate (DCR) due to large radiation budgets :**
  - **Reduce temperature**
  - **Annealing of SIPMs**
- **Added Thermoelectric Coolers (TEC) coupled to SiPMs :**
  - **Reduce operational temperature from -35 °C (CO_2) to -45 °C (CO2 + TEC).**
  - **Allow annealing in situ during detector maintenance at +40 °C**



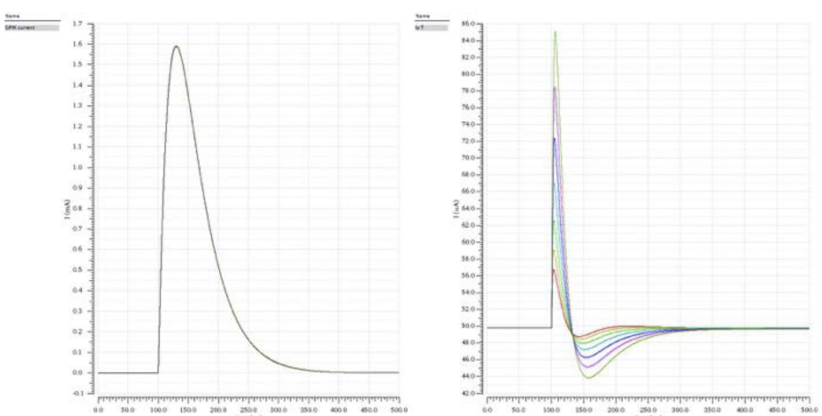


DCR Mitigation with the BTL ASIC

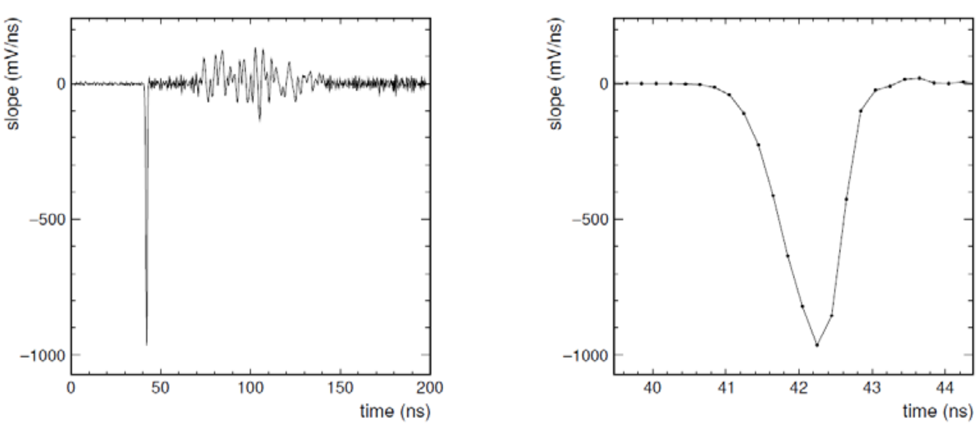
- Dedicated readout ASIC (TOFHIR) is being developed for BTL.
  - Derived from TOFPET ASIC developed for PET applications.
- Key feature is a noise suppression filter :
  - Inverted and delayed pulse subtract from the input pulse
  - Restores baseline at the rising edge of the pulse.
- Improves time resolution by about a factor 2 at EOL.



Simulation of TOFHIR DCR cancelation
Left : Input pulse
Right : Pulse after subtraction of delayed input pulse



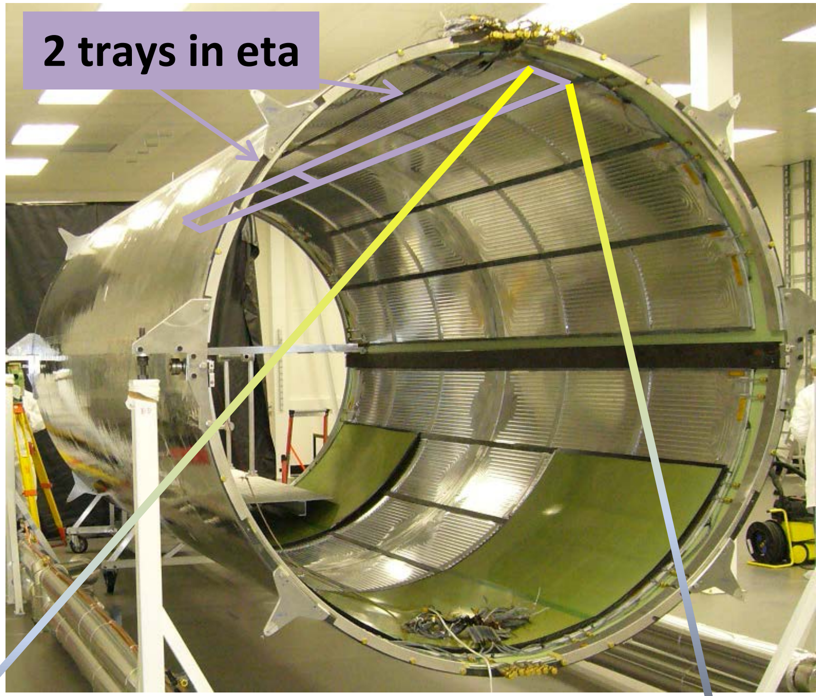
Experimental data of DCR cancelation :
Left : Sum of input and inverted and delayed input pulse.
Right : Zoom on rising edge of same pulse



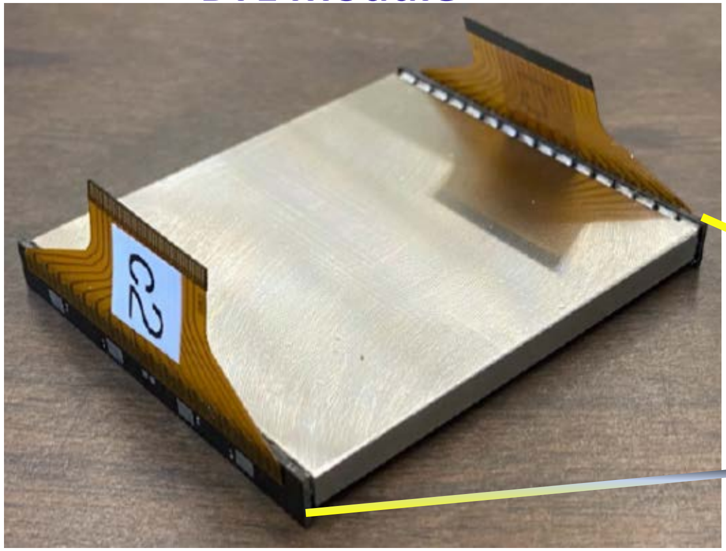
BTL Layout & Design

- BTL attached to inner wall of Tracker Support Tube
- Cold volume shared with Tracker
- BTL Segmentation :
  - 72 trays (36 in $\varphi \times 2$ in η)
  - 331k readout channels, 165k LYSO bars, organized in 10368 modules, 6 Readout Units per tray.
  - Tray dimensions : 250 x 18 x 2.5 cm
  - Module dimensions : 51x57 mm^2

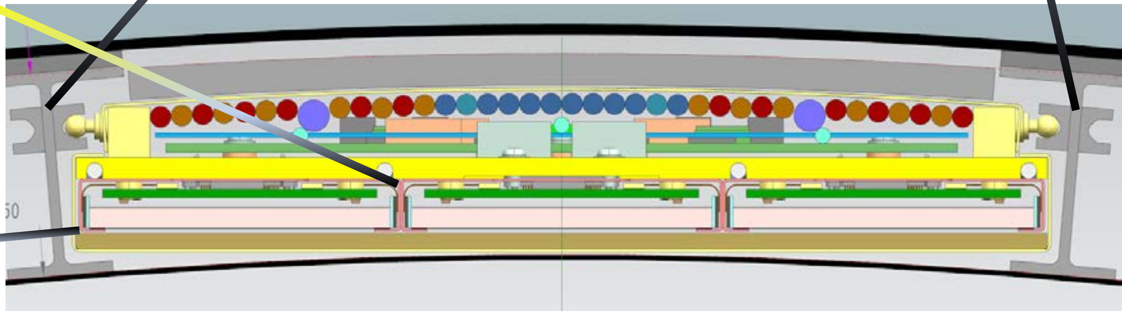
Current TST – HL-LHC upgrade very similar



BTL module

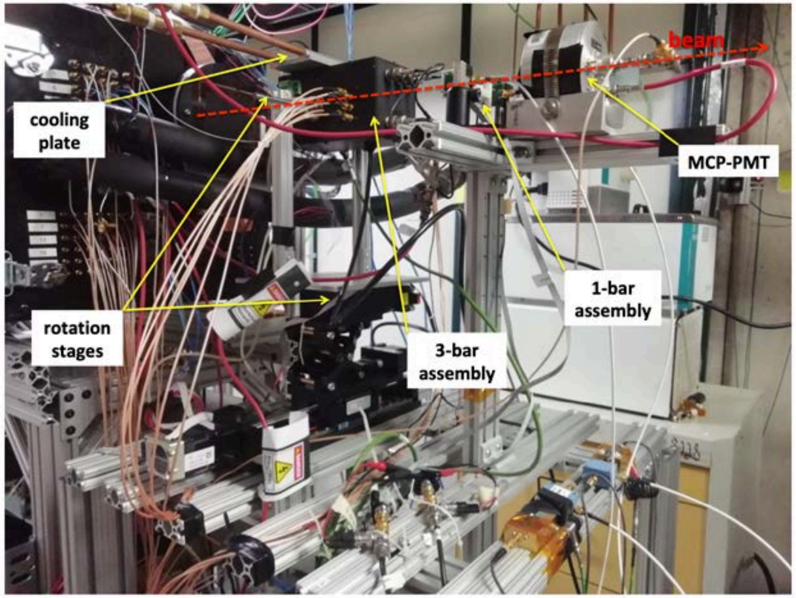


BTL tray, transvers (phi) cross section

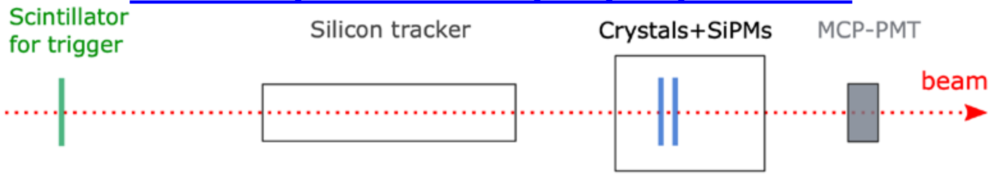


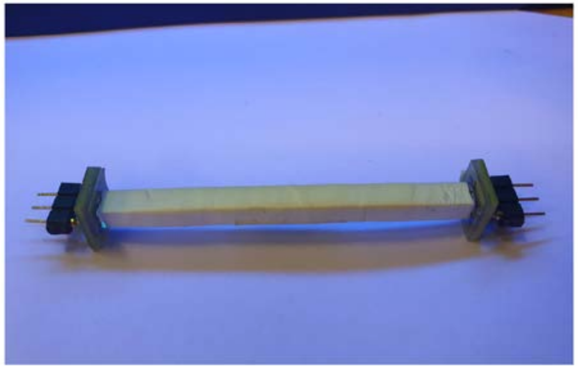
BTL Performance in Test Beam

- Testbeam to test resolution and uniformity of LYSO crystals
- 120 GeV protons beam.
- Silicon tracker telescope to measure proton position and Micro Channel Plate-PMT (MCP-PMT) used as reference time
- Two different SIPMs tested (HBK and FBK). Box at 25^0C
- Layout allowing rotation of crystals vs direction of beam
- Recent test beams at PSI and CERN with TOFHIR readout, analysis ongoing.



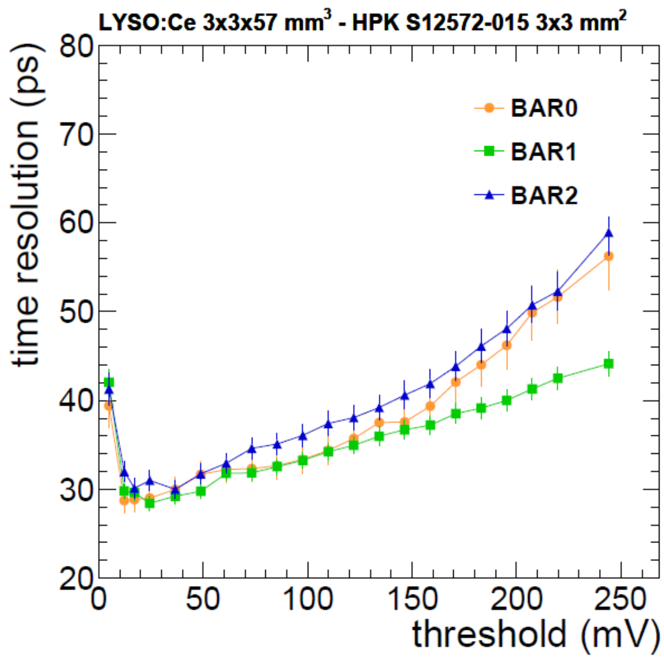
JINST: [10.1088/1748-0221/16/07/P07023](10.1088/1748-0221/16/07/P07023)





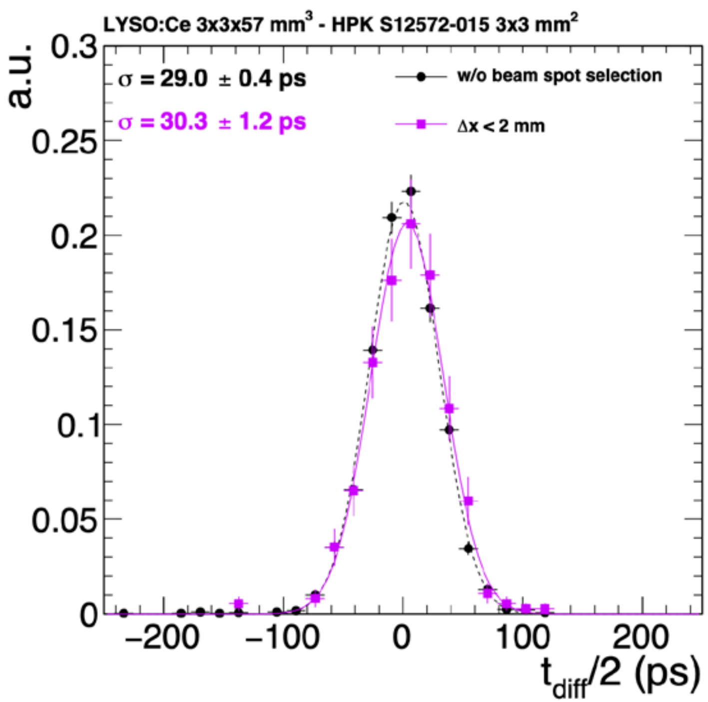
BTL Timing Measurement

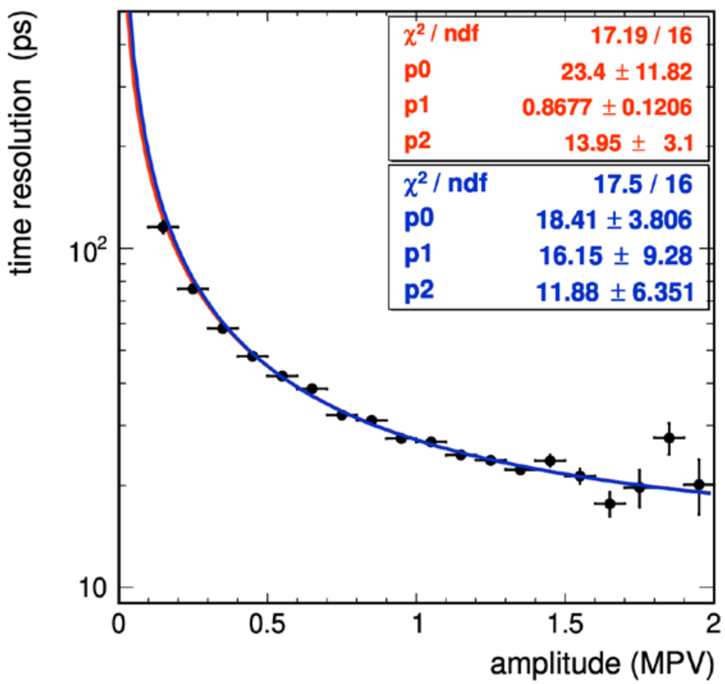
- In FNAL test beam shown , timing extracted from the leading edge of SiPM pulse.
- At low thresholds, timing resolution improves with increasing threshold due to larger S/N.
- At larger thresholds, timing resolution deteriorates as fluctuations on the arrival time of the Nth photon add more jitter.
- In case of BTL, minimum varies as DCR add noise. Optimal threshold in the range of 50 photo electrons.



Time resolution

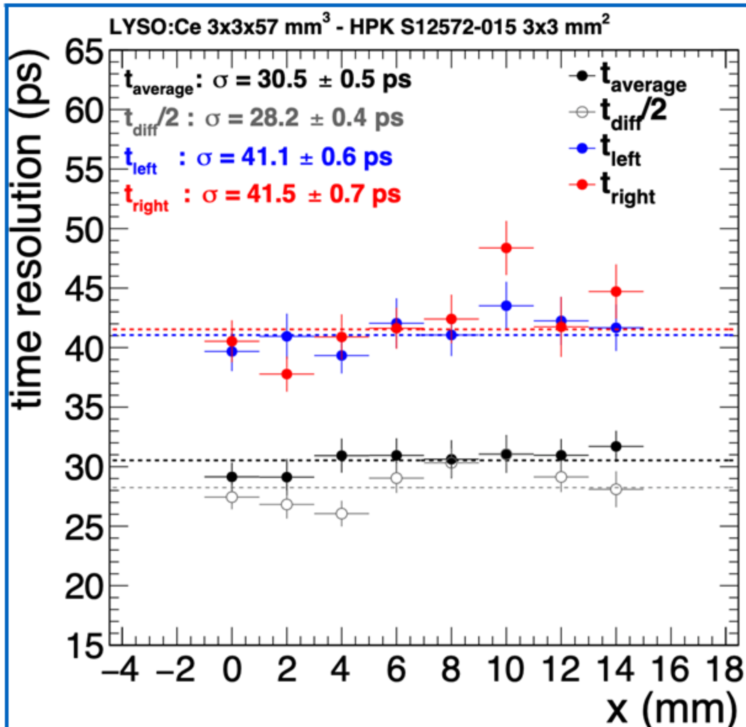
- **Estimated as $\sigma_{t_{average}}$ and $\sigma_{t_{diff}}/2$ where**
  - $\Delta t_{bar} = t_{average} - t_{MCP} = (t_{left} + t_{right})/2 - t_{MCP}$ and $\sigma_{t_{average}} = \sqrt{\sigma^2_{\Delta t_{bar}} - \sigma^2_{t_{MCP}}}$
  - $t_{diff} = t_{left} - t_{right}$
- **Resolution for MIP below 30 ps**
- **Improves with increased light output and, for sufficiently high thresholds, scales with the inverse of the square root of amplitude**

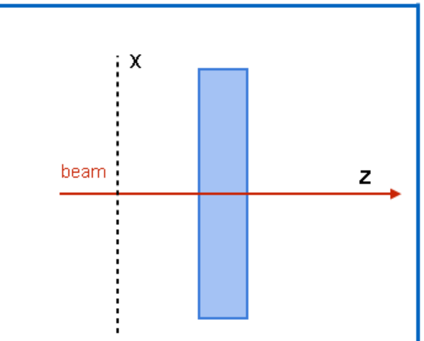


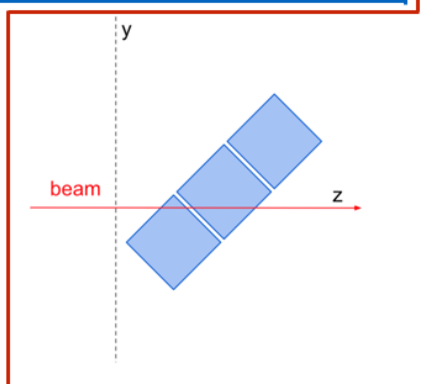


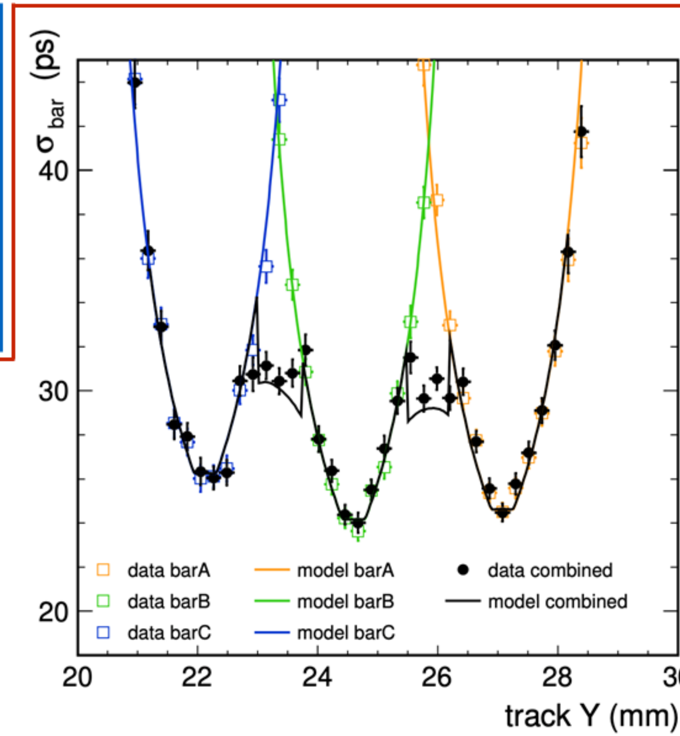
Sensor Uniformity

- In the detector, particles will cross LYSO bars at broad range of impact angles depending on their pT.
  - LYSO bar thickness varies along eta in three groups (2.4, 3.0, 3.75 mm) to equalize effective path lenght.
- Uniform response and resolution along the bar :
  - Effect of gaps negligible if < 200 μm, expect gap ~ 80 μm for final bar arrays









CMS MTD for HL-LHC

- **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**
  - **Enhance CMS particle reconstruction by reducing effective pile-up**

- **CMS MIP Timing Detector well advanced :**
  - **BTL transitioning from last prototype rounds to pre-series stage.**
  - **Design choices and concepts confirmed in lab and beam tests.**
  - **Detector production scheduled to start in 2022.**