Precision Timing with the CMS MIP Timing Detector for High-Luminosity LHC

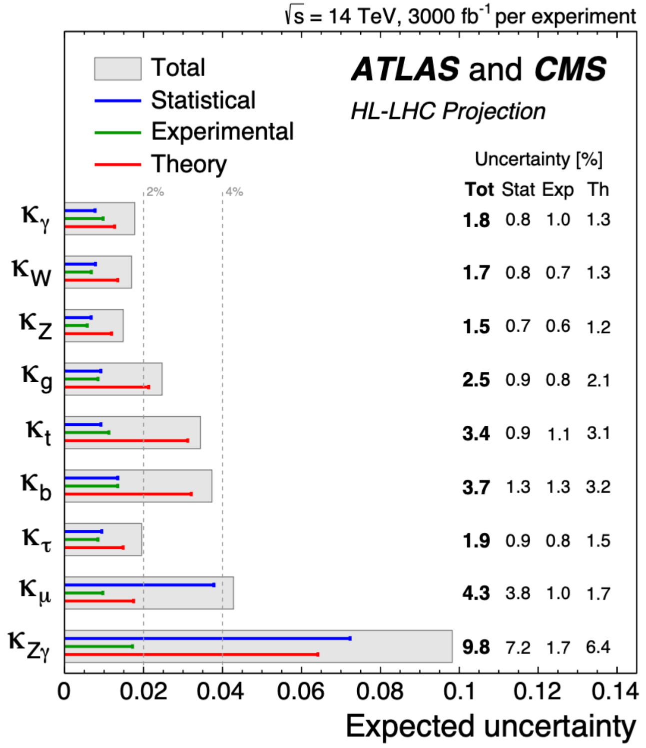
Frank Golf (Boston University)

On behalf of the CMS Collaboration

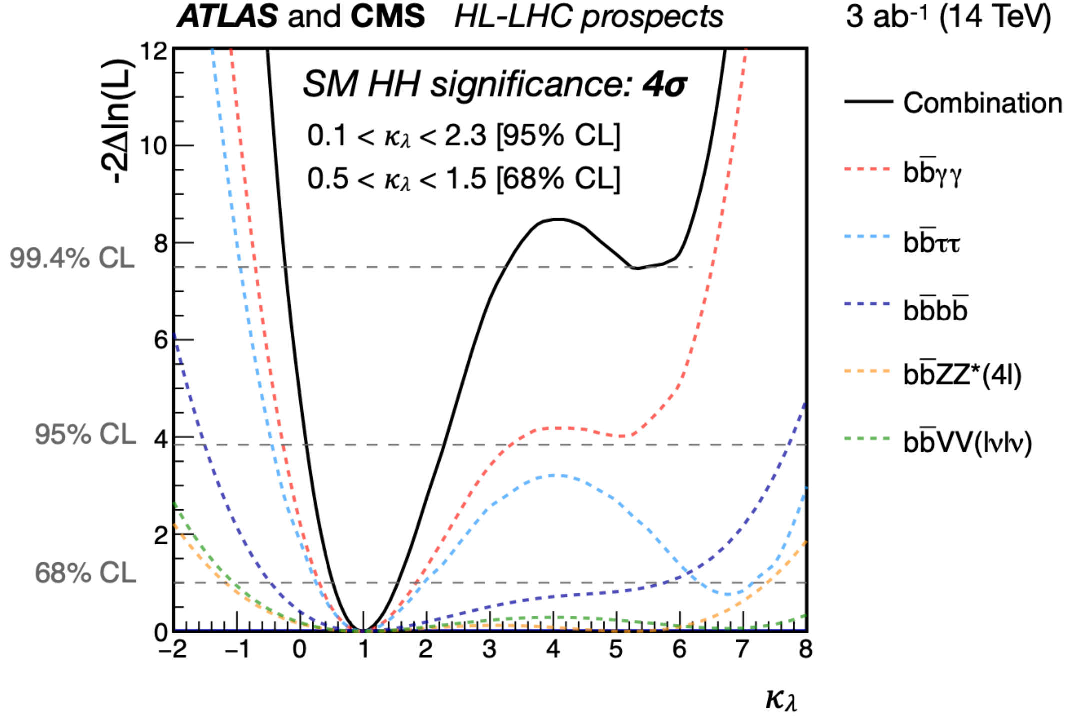
Motivation for High-Luminosity LHC (HL-LHC)

Precision tests of the standard model and searches for rare beyond-the-SM phenomena.

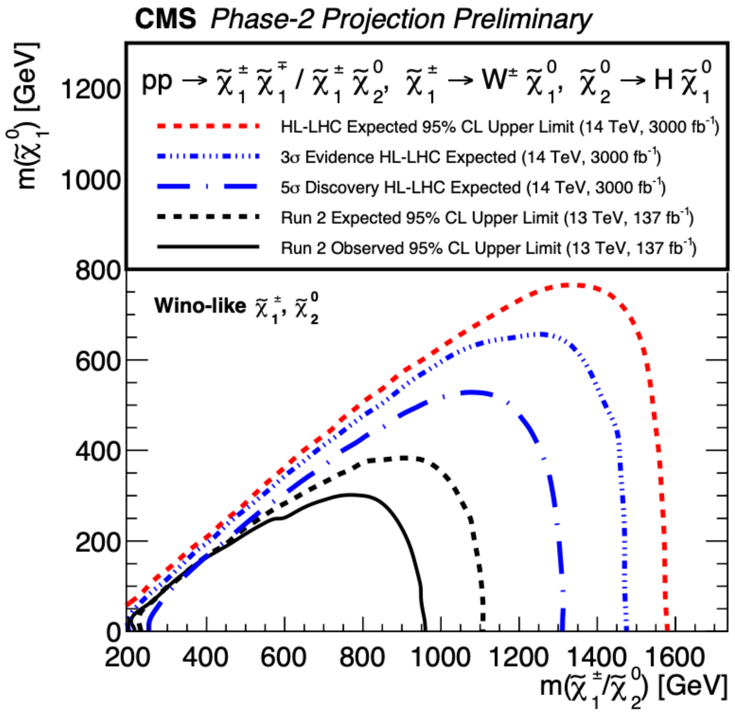
Precision measurements of the Higgs boson couplings



Measurement of the Higgs boson self-coupling via direction observation of di-Higgs boson production



Searches for dark matter candidates, long-lived particles, new gauge bosons, new interactions, etc.

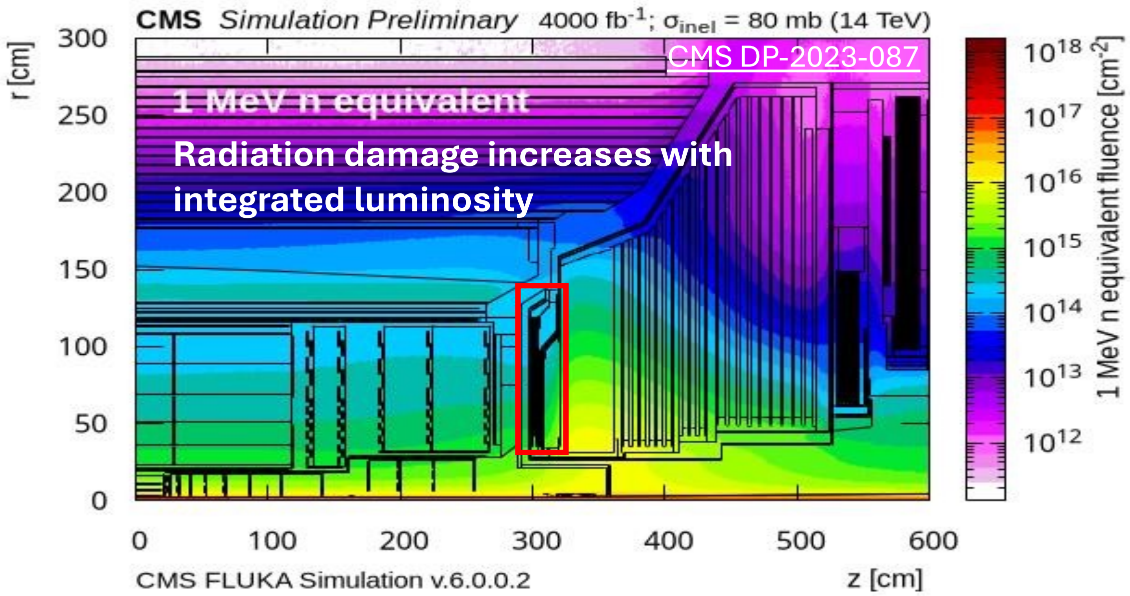


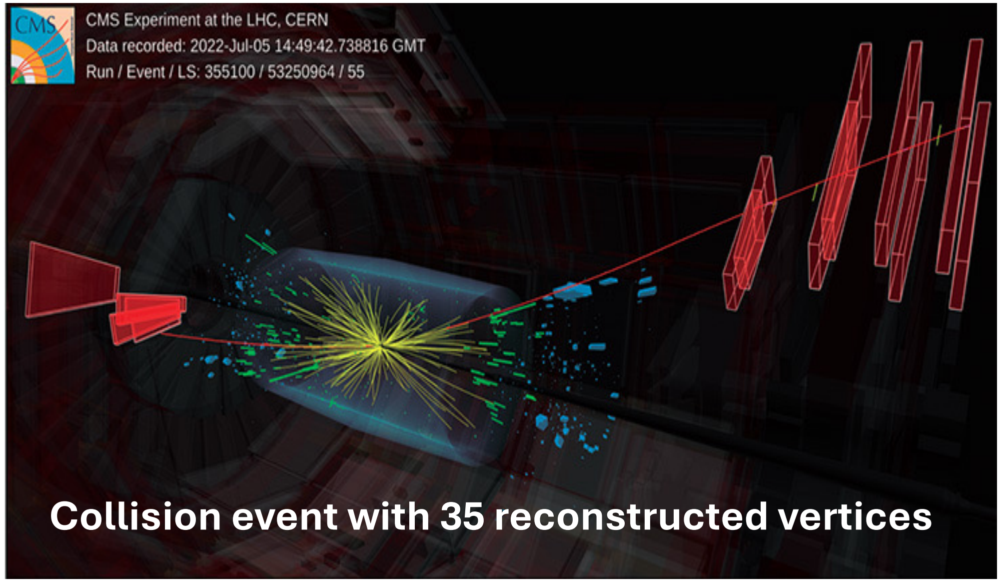
CMS PAS FTR-22-001

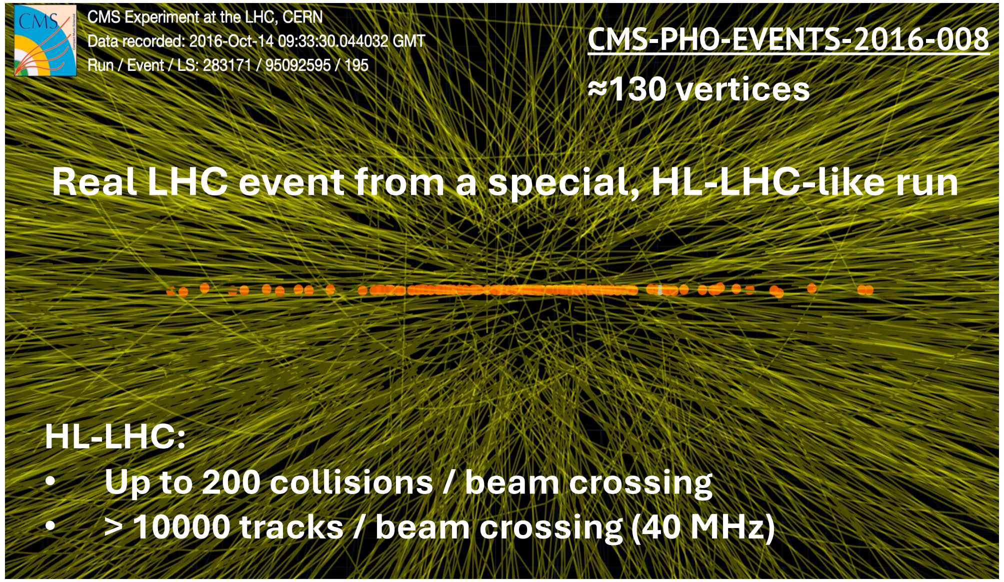
How to achieve HL-LHC goals

Upgrade of the accelerator complex optics and injectors to increase the beam intensity.

- Luminosity delivery by LHC (2009-2025):
  - ~ 400 fb^{-1} / experiment , ~280 fb^{-1} delivered so far
- Target luminosity for HL-LHC (2029-2042):
  - > 3000 fb^{-1} / experiment
  - 1 year of HL-LHC equivalent to ~10 years of LHC!

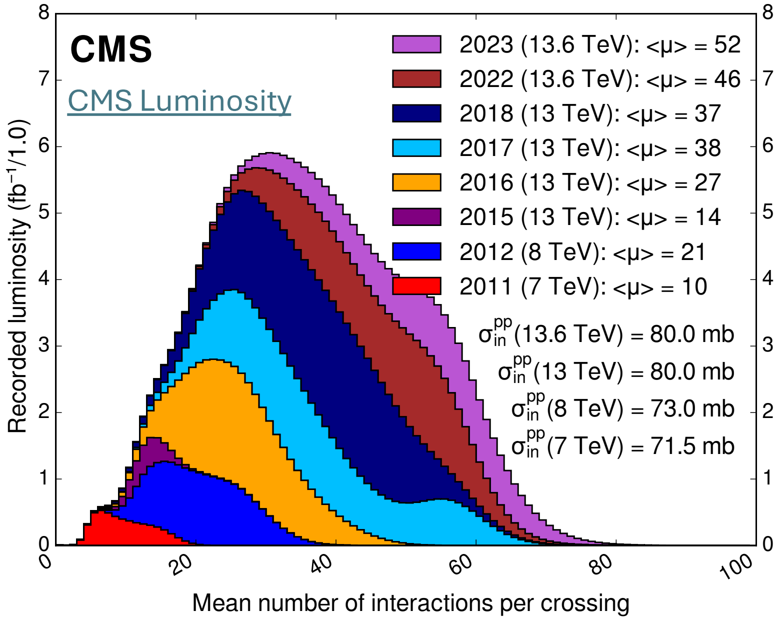




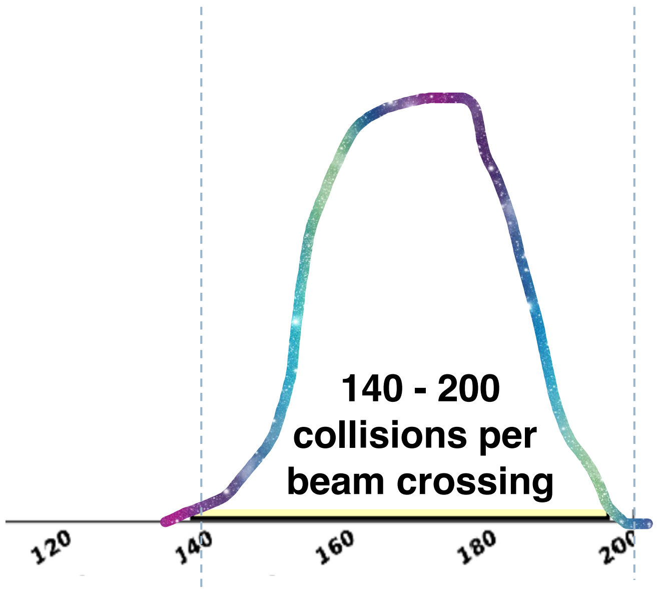


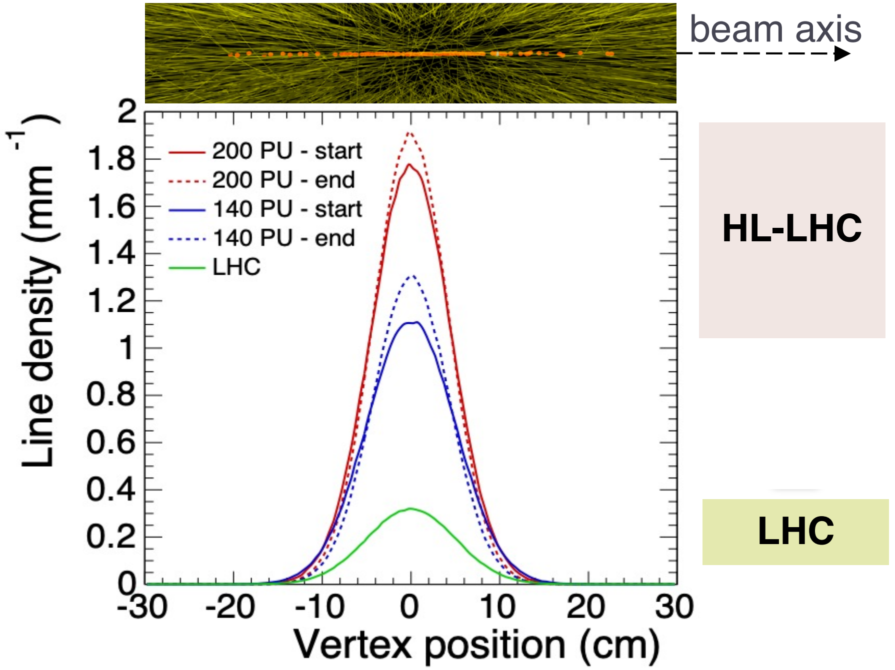
Experimental challenges at HL-LHC

CMS average pileup at LHC



at HL- LHC





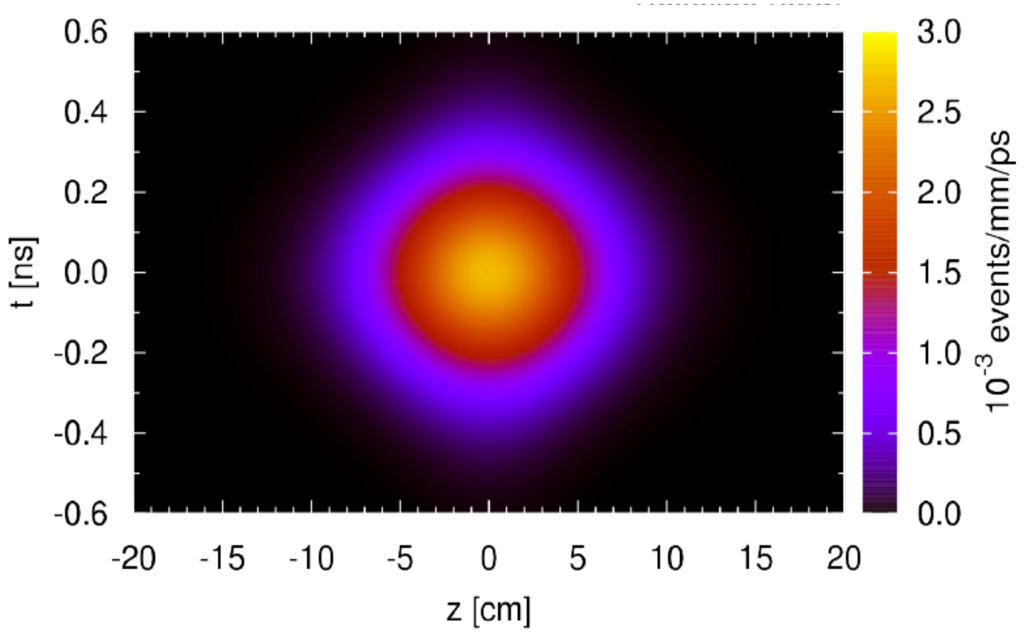
Reconstruction depends on track-vertex assignments that become ambiguous when track resolution is comparable to vertex separation.

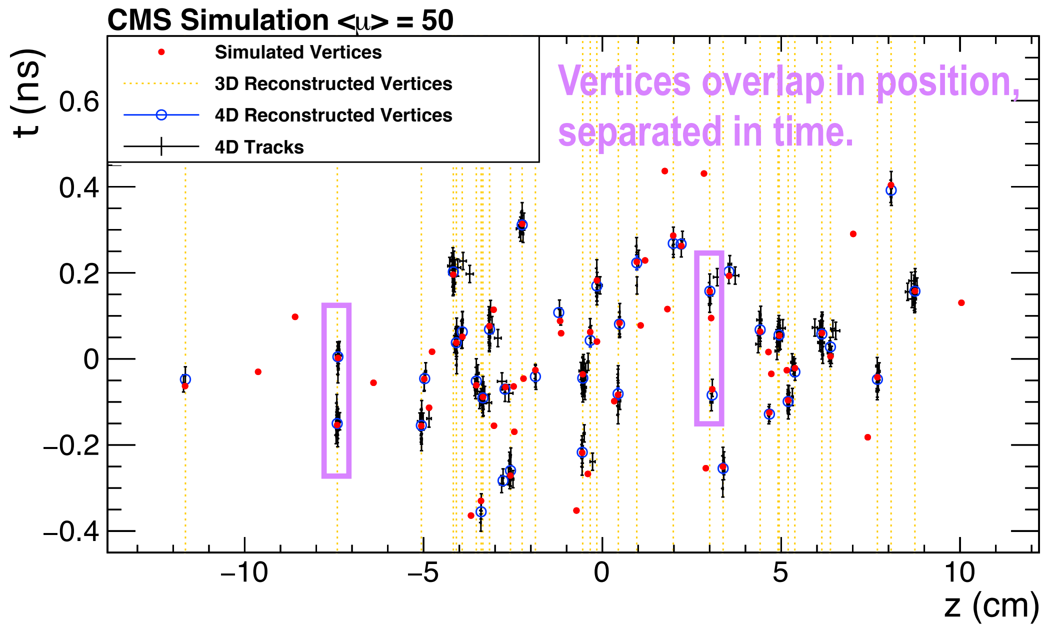
- Vertex merging and the incorrect association of tracks with vertices distorts the final state kinematics.
- The efficiencies to correctly identify jets, leptons, and photons are affected; <u>every object is degraded</u>!
- Degraded reconstruction results in loss of sensitivity, undermining physics objectives motivating HL-LHC.

Mitigating pileup with precision timing at CMS for HL-LHC

Upgrade CMS detector to mitigate pileup and radiation damage.

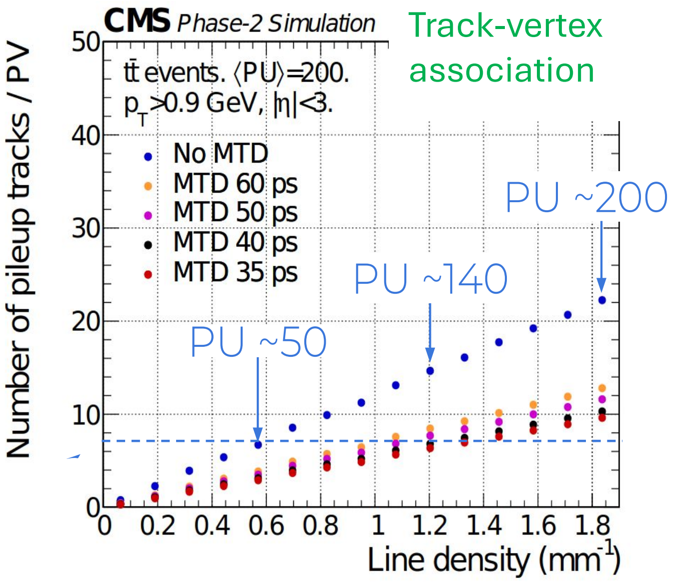
- New tracker and calorimeters with enhanced granularity and radiation tolerance. Nonetheless, the event density will challenge the enhanced spatial resolution of these new detectors.
- **A new MIP Timing Detector (MTD) for precision timing of minimum ionizing particles (MIPs)**
  - Exploit beam spot spread to reduce PU: “slice” in successive O(50) ps time frames.
  - Spatially overlapping vertices resolved in time → enhance track-vertex association comparable to LHC.



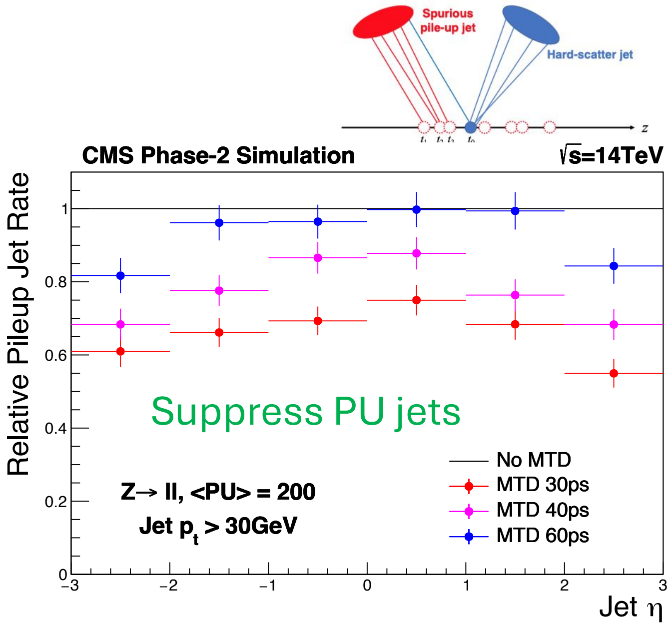


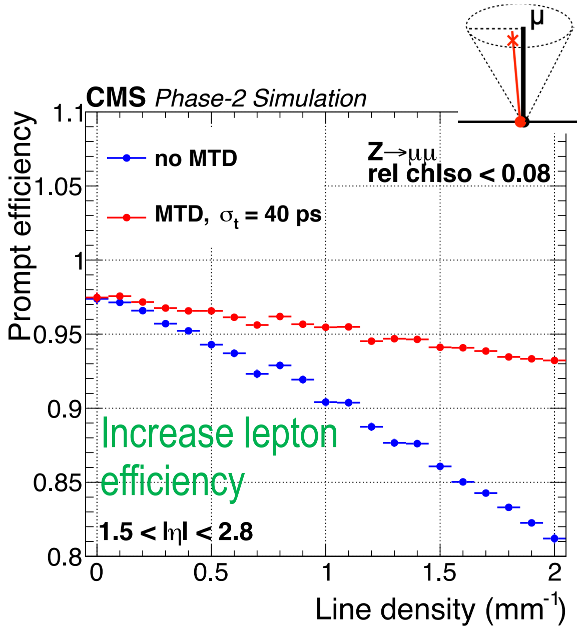
4-D vertexing leads to significant sensitivity gains across the HL-LHC physics program

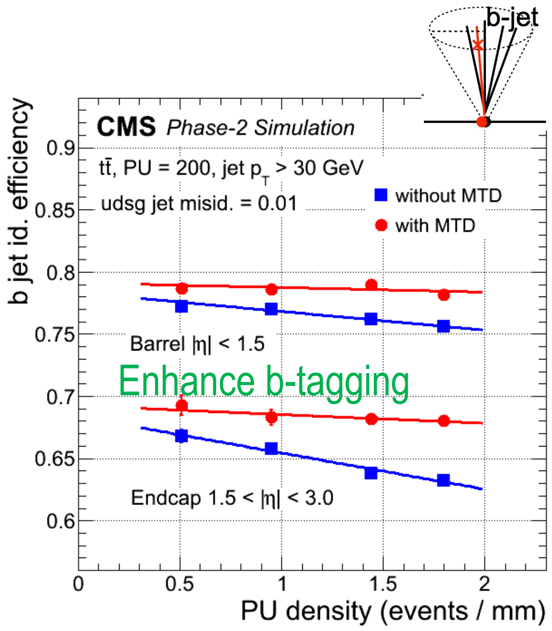
Improving Event Reconstruction



[CMS MTD Technical Design Report]



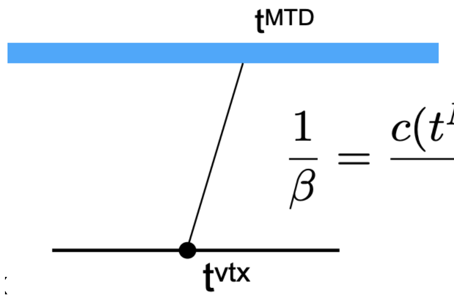




CMS DP-2022-025

Improvements in object identification compound in multi-object final states, including measurements of the Higgs boson. Timing will enhance the sensitivity of Higgs boson measurements equivalent to a **~20-30% increase in integrated luminosity, or ~3 additional years of HL-LHC data taking!** CMS DP-2022-025

New Capability: Time-of-flight

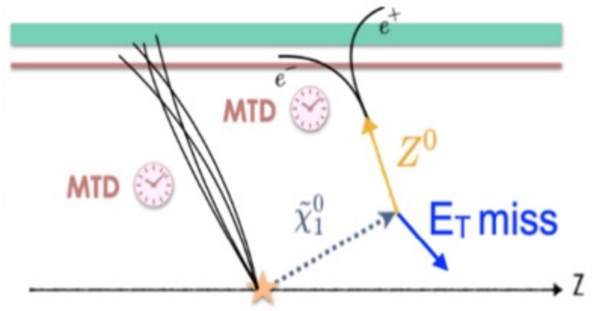


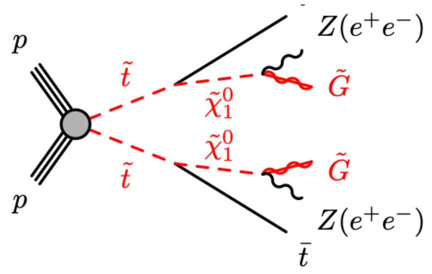
$$\frac{1}{\beta} = \frac{c(t^{MTD} - t^{vtx})}{L}$$

Flavor physics with heavy ions

π/K separation up to 2-3 GeV

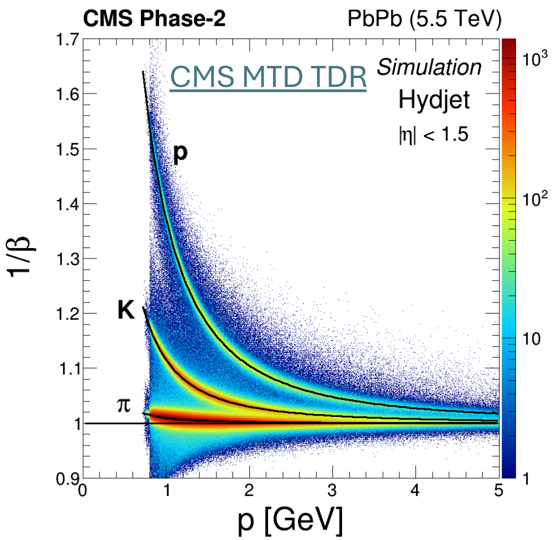
and K/p separation up to 5 GeV

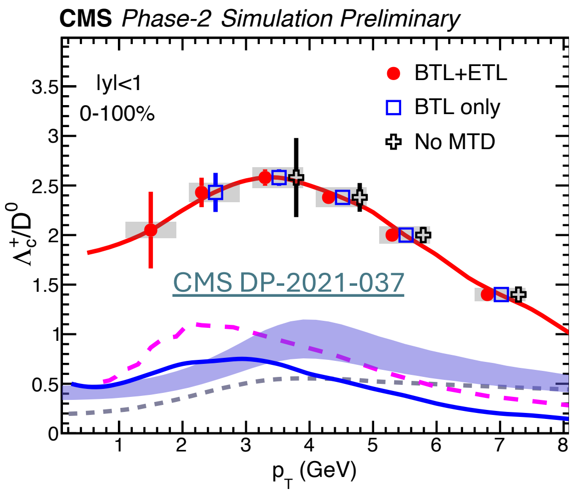


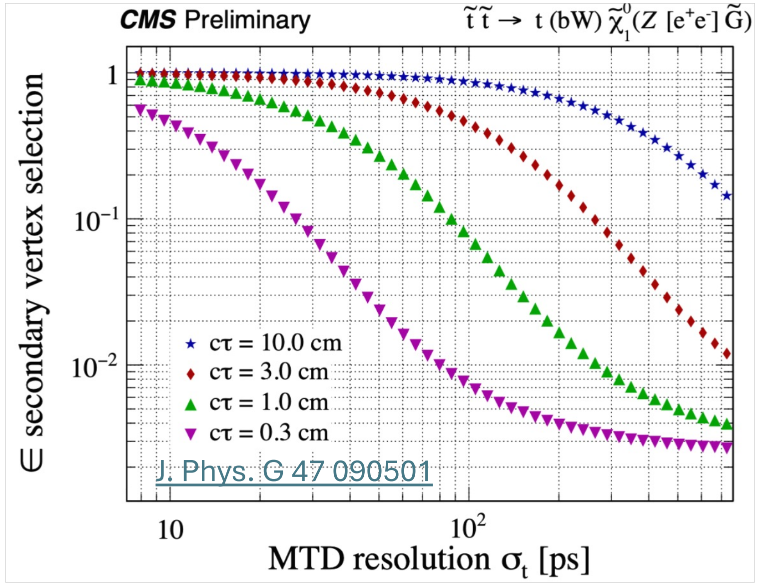


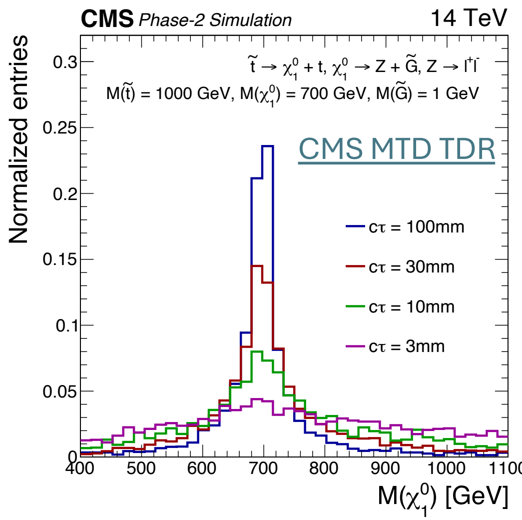
BSM: LLP, heavy stable charged particles, …

Vast acceptance extension from vertex-object timing fundamentally changes how we execute these searches



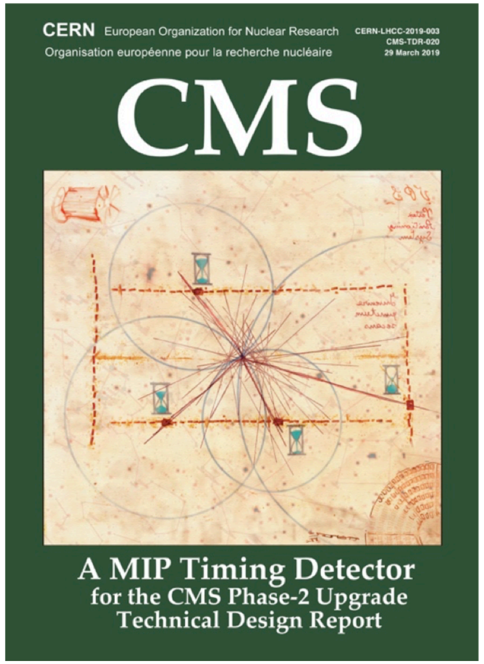


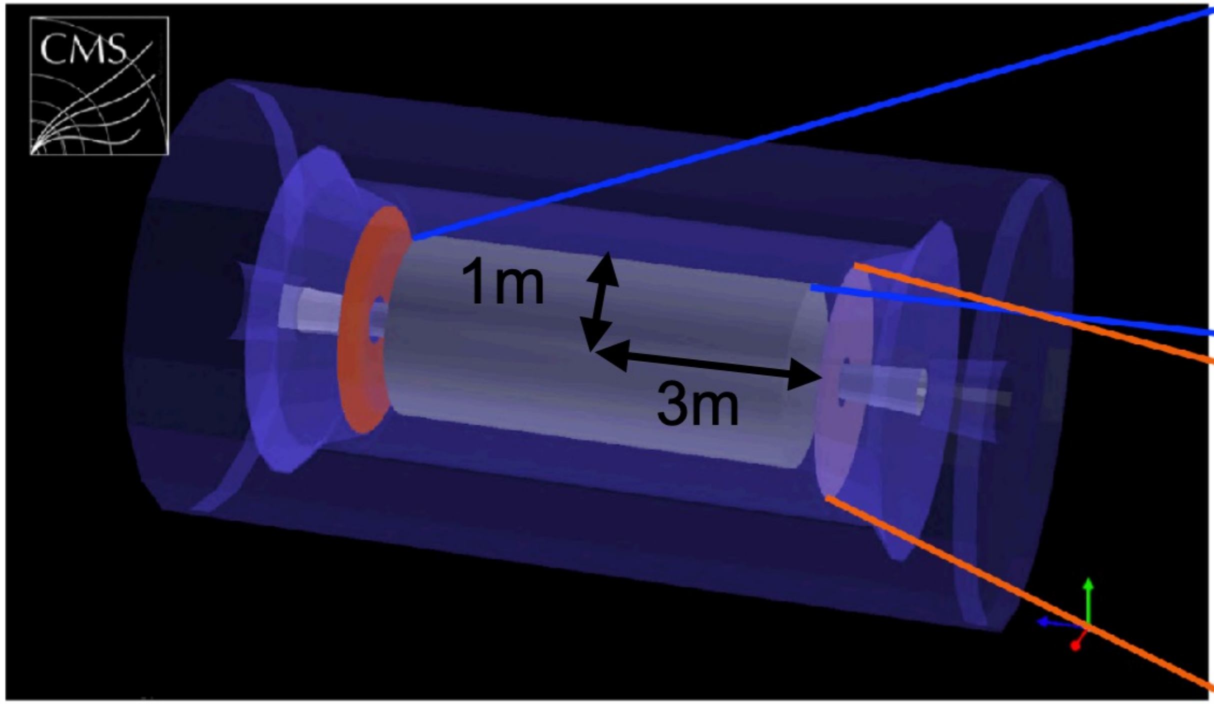




CMS MIP Timing Detector (MTD)

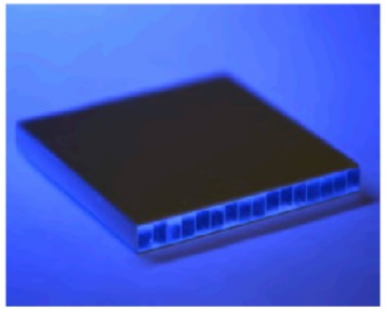
- CMS MTD is comprised of 2 thin timing layers installed between the tracker and the calorimeters, providing almost hermetic coverage for $|\eta|<3$.
- Choice of sensor technologies for barrel and endcap timing layers driven by technology maturity, radiation hardness, power consumption, and cost and schedule considerations.





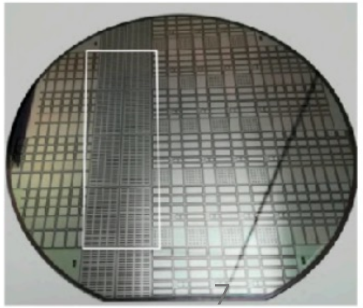
BTL: LYSO bars + SiPM read-out

- TK/ECAL interface ~ 45 mm thick
- $|\eta| < 1.45$ and $p_T > 0.7$ GeV
- Active area ~ 38 m^2 ; 332k channels
- Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2

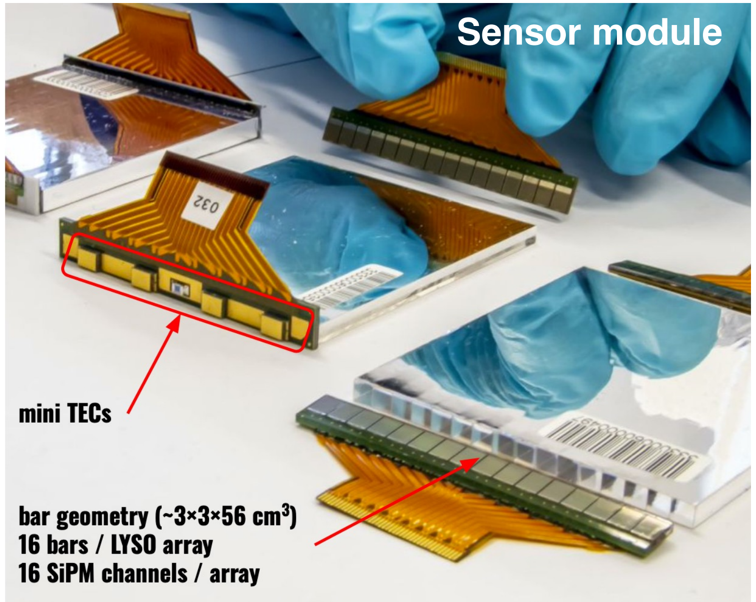


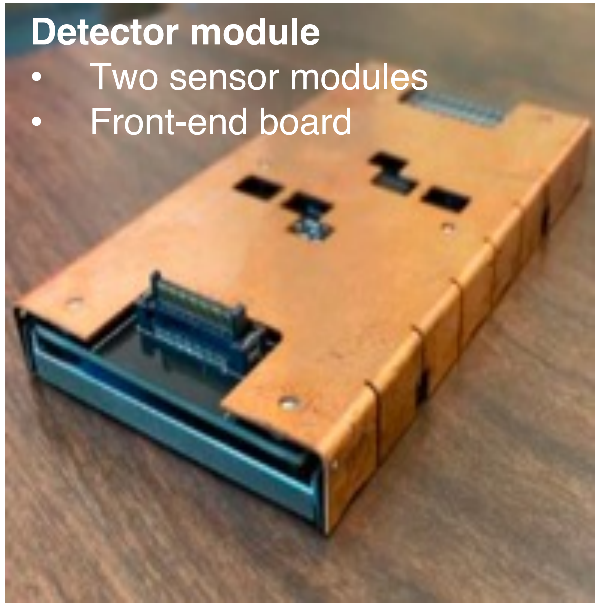
ETL: Si with internal gain (LGAD)

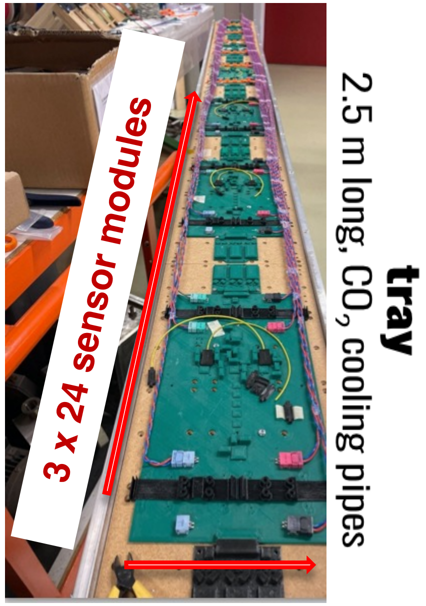
- On the HGC nose ~ 99 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~ 14 m^2; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2

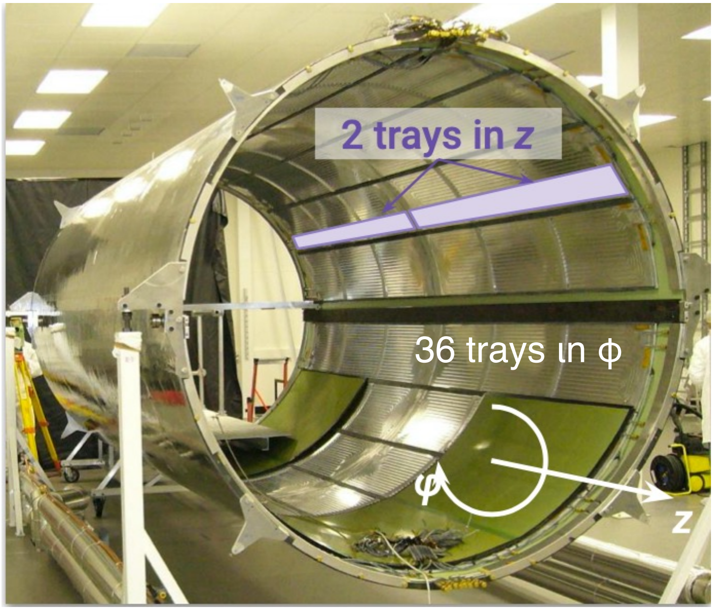


Design of the Barrel Timing Layer (BTL)









Single layer of sensor modules with 16 LYSO:Ce crystal bars.

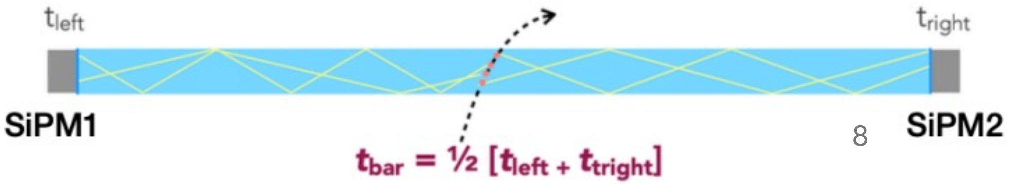
- Established technology. Fast with large light yield and excellent radiation hardness.

2 arrays of 16 SiPMs w/ thermoelectric coolers (TECs).

- Compact and fast with high photon detection efficiency. Robust operation in B-field.

Dual-end readout: 2 measurements / track.

- Improve resolution by √2, mean time independent of impact point. Time resolution ≲60 ps at end-of-life.
- Measure track position with O(mm) resolution.



Understanding the BTL Performance

Expected BTL time resolution:

$$\sigma_t^{BTL} \sim \sigma_t^{stat} \oplus \sigma_t^{elec} \oplus \sigma_t^{DCR}$$

- **Photon statistics**:

$$\sigma_t^{stat} \propto \frac{1}{\sqrt{N_{PE}}} \sim \sqrt{\frac{\tau_R \tau_D}{E_{dep} \cdot LY \cdot LCE \cdot PDE}}$$

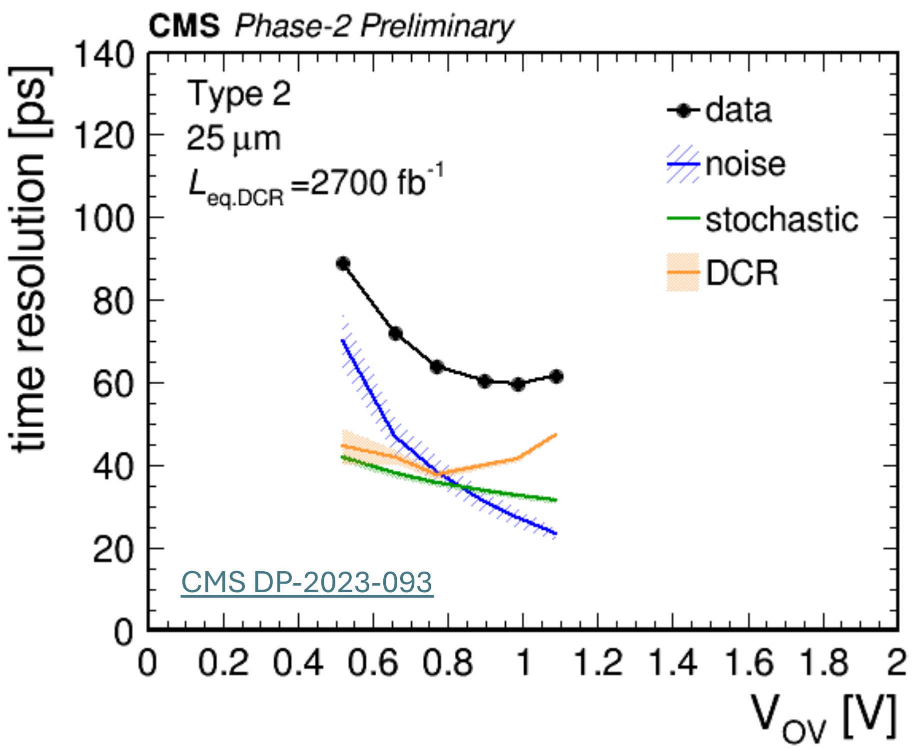
- **Electronics contribution**:

$$\sigma_t^{elec} \sim \frac{\sigma_{noise}}{N_{PE}}$$

- **Dark count rate (DCR) contribution**:

$$\sigma_t^{DCR} \propto \sqrt{DCR}/N_{PE}.$$

Benefit from bright scintillator and fast SiPM response.



DCR is the dominant contribution to the BTL time resolution at end-of-life. The single-photon DCR increases up to O(10) GHz after 3000 fb^{-1} (2E14 n_{eq}/cm^2).

Mitigating DCR contribution in BTL

Smart thermal management with TECs

- Local cooling and heating provides x10 reduction of the dark count rate with SiPMs at –45 °C during operations and in-situ annealing at +60 °C during technical stops.

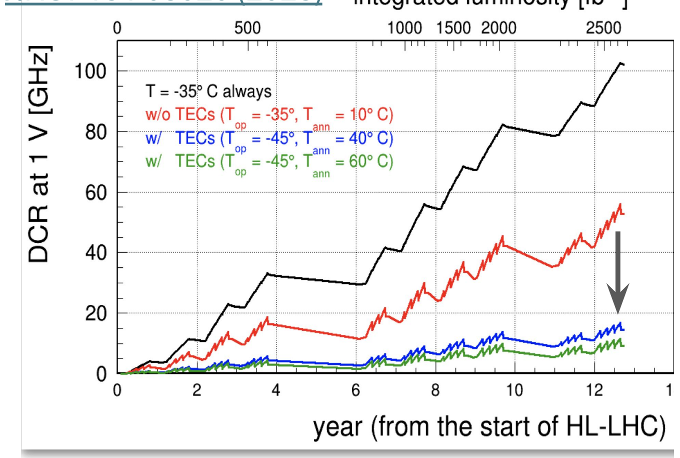
Optimize SiPM cell size.

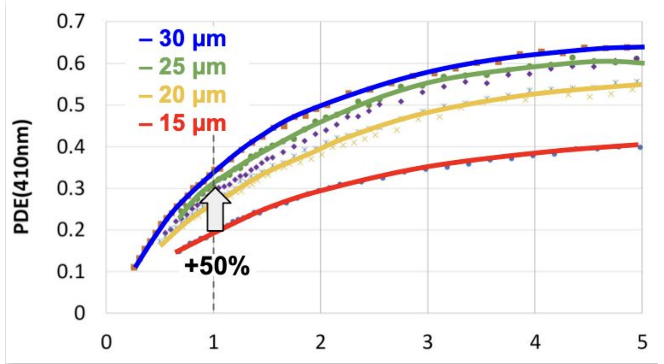
- Trade-off between photodetection efficiency and gain (better for larger cell area) and DCR/power dissipation. Cell size of 25 μm optimal for BTL.

DCR noise cancellation in the readout chip (TOFHIR2) with differential leading-edge discrimination

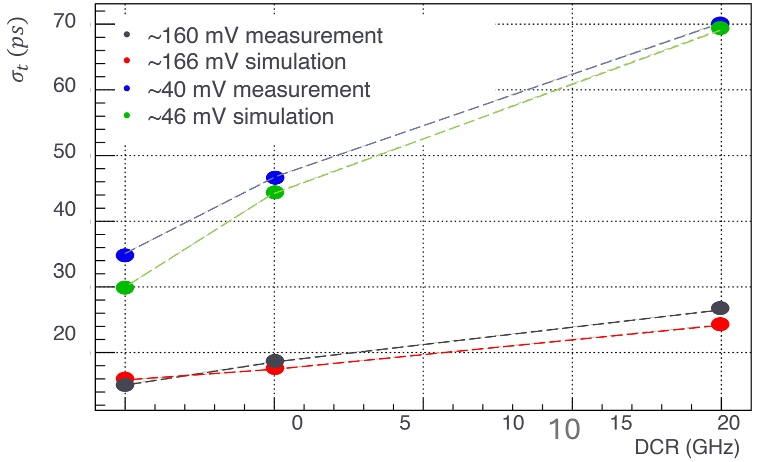
- Inverted and delayed pulse added to the original pulse (DLED).
- Preserve fast signal rising edge while cancelling correlated noise.

JINST 18 P08020 (2023)





[J. Varela, IEEE—NSSMIC-2020]

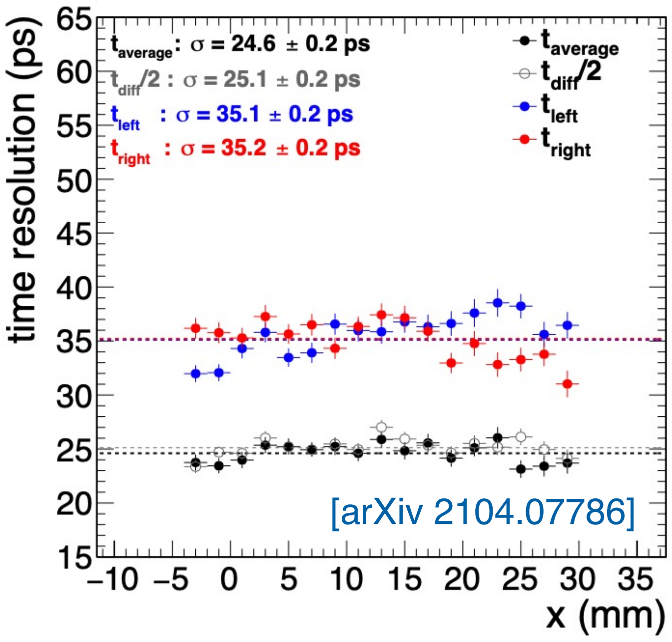


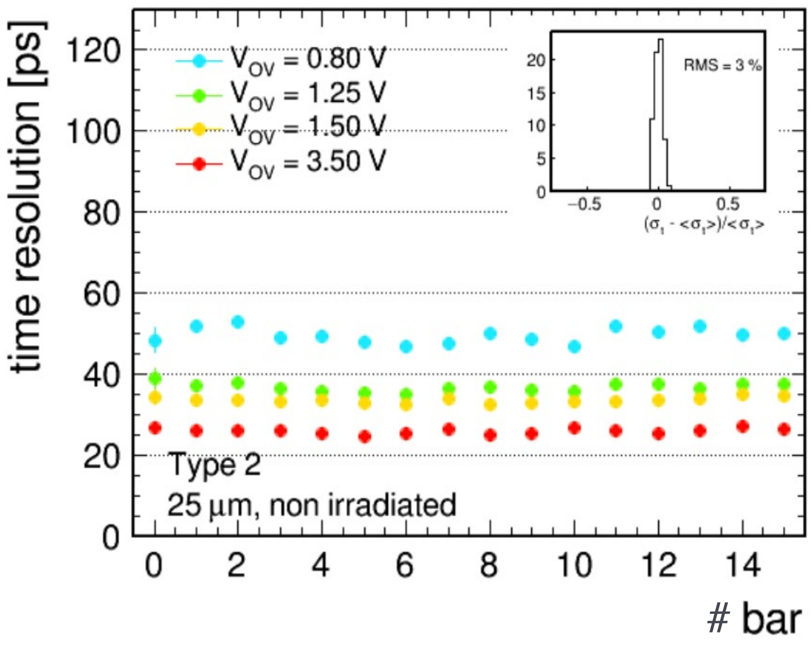
Performance of prototype BTL detector

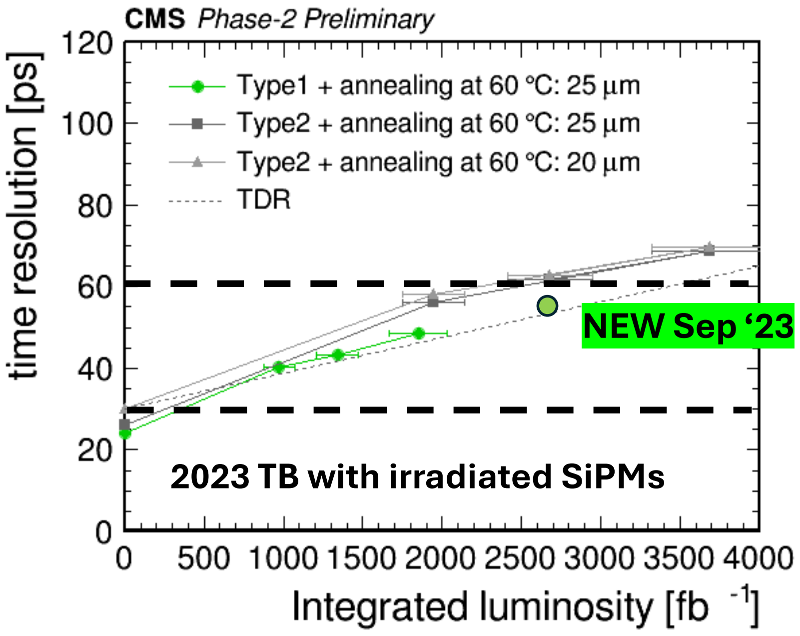
Module optimization and prototyping effort complete:

- Thermal operation with CO_2 and TECs and response stability under thermal cycles validated.
- Readout ASIC (TOFHIR2) performance and functionality fully validated in laboratory and beams.
- Prototypes with LYSO arrays (Type 1) and SiPM cells (25 μm) maximizing S/N validated with beam data.

Uniformity along the bar (old) and across the bars (new 2023) [before irradiation]

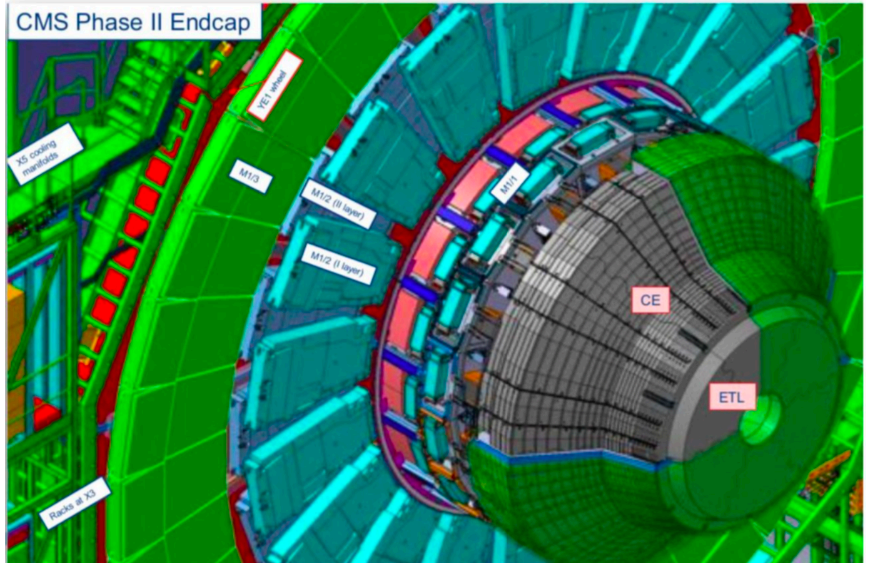


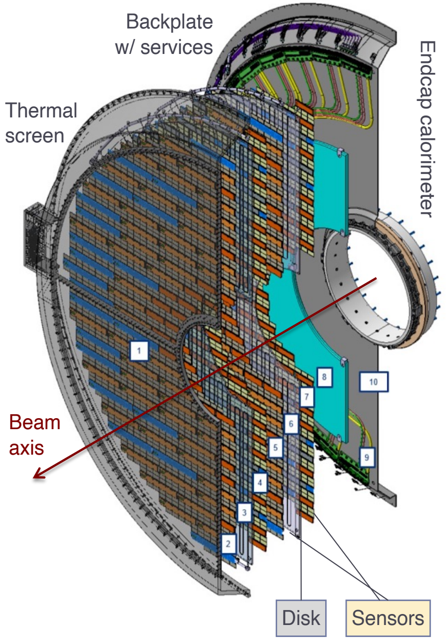




Performance demonstrated. Next: production, assembly, and integration (2024-2025).

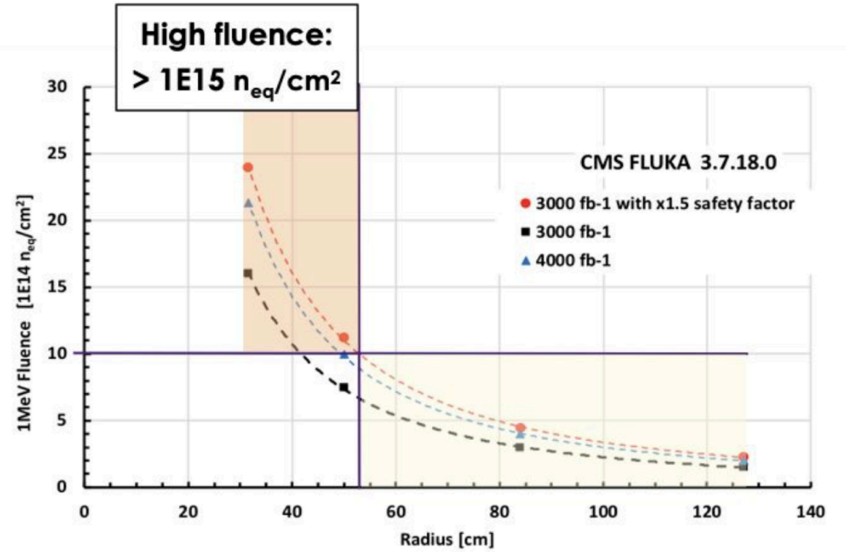
Design of the Endcap Timing Layer (ETL)

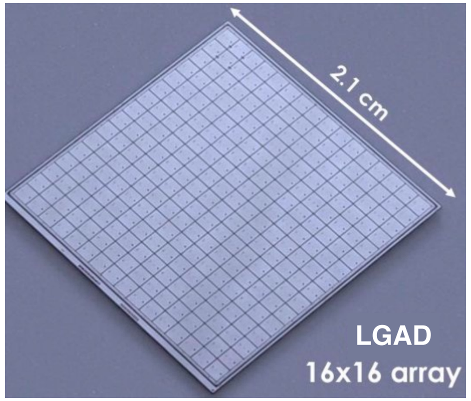


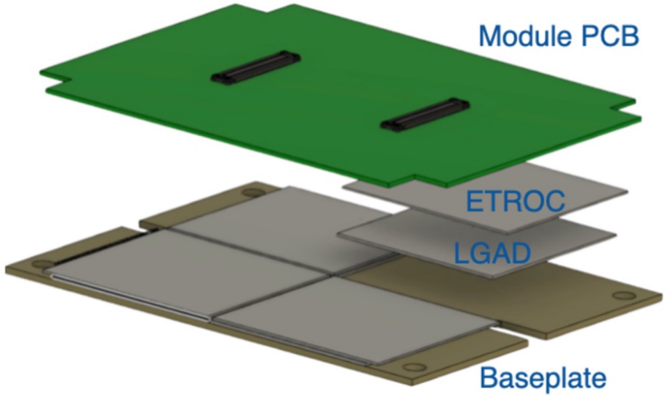


Each endcap is comprised of 2 cooling disks.

Detector modules, comprised of Low Gain Avalanche Diode (LGAD) sensors bump-bonded to a custom readout ASIC (ETROC) are mounted on both sides of each disk, providing up to two measurements (50 ps/hit) per track (35 ps).







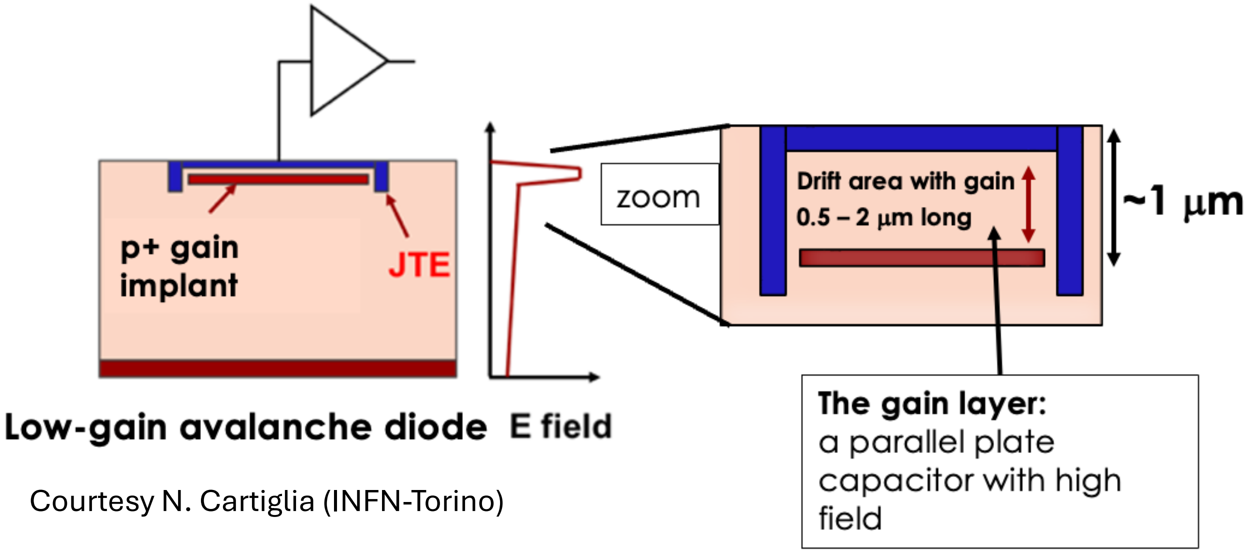
Design and operation targets and challenge:

- ETROC targets handling small signals, down to ~5 fC.
- Sensor targets >8 fC at end-of-life; fluence >1 x 10^{15} n_{eq}/cm^2 in the 15% innermost region

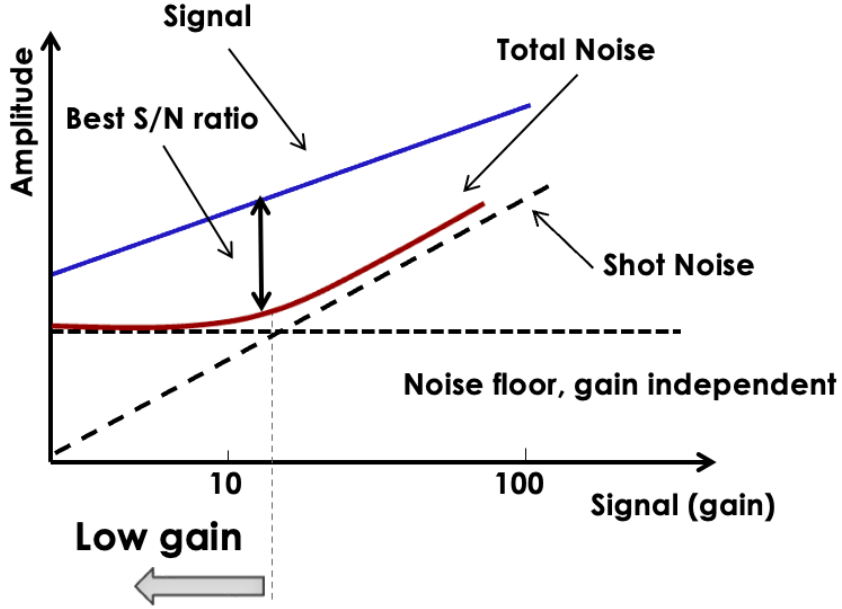
Precision timing in high radiation environment: LGAD sensors

Silicon structure optimized for time measurements (~30 ps from sensor).

- A moderately p-doped implant creates a volume of high field, where charge multiplication happens.
- The wider or deeper the gain layer, the lower the doping level.
- Different designs lead to different properties; e.g. more or less radiation resistance, easier fabrication, more uniformity, etc.
- Thickness (50 µm) a trade-off between signal size and time jitter of primary ionization.
- The success of LGADs rests on the fact that the sensor noise is hidden by the electronic noise.



Courtesy N. Cartiglia (INFN-Torino)



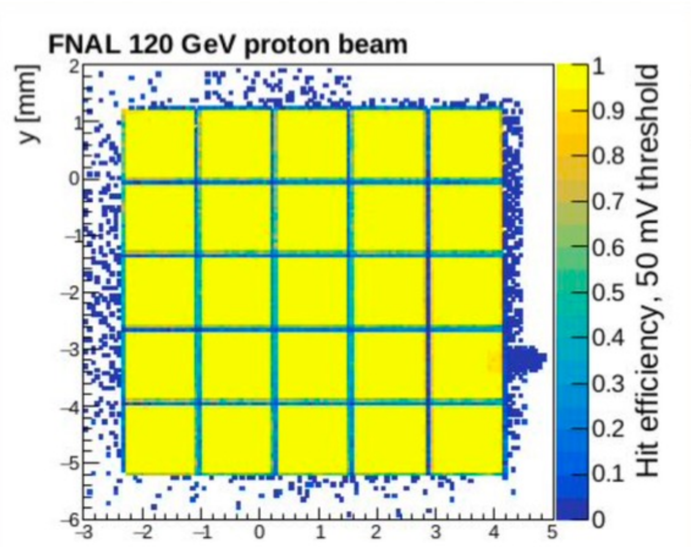
Precision timing in high radiation environment: LGAD sensors

Worked with multiple vendors to optimize LGAD arrays.

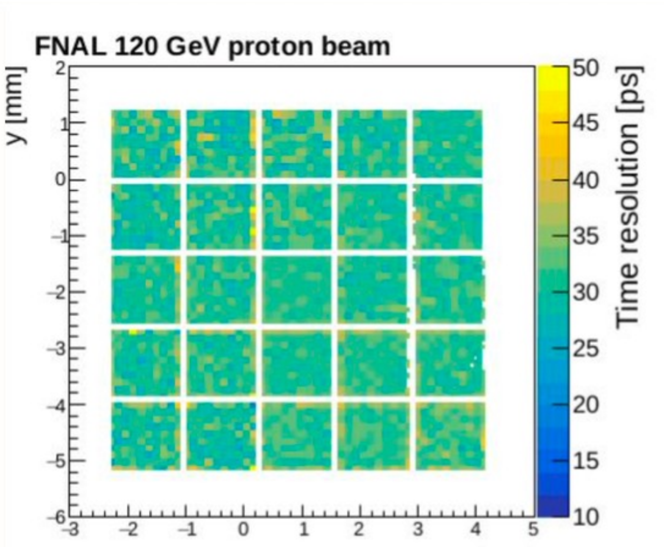
- Excellent uniformity, fill-factor, and production yield (>70%) per wafer.

Increase bias voltage to maintain gain after irradiation.

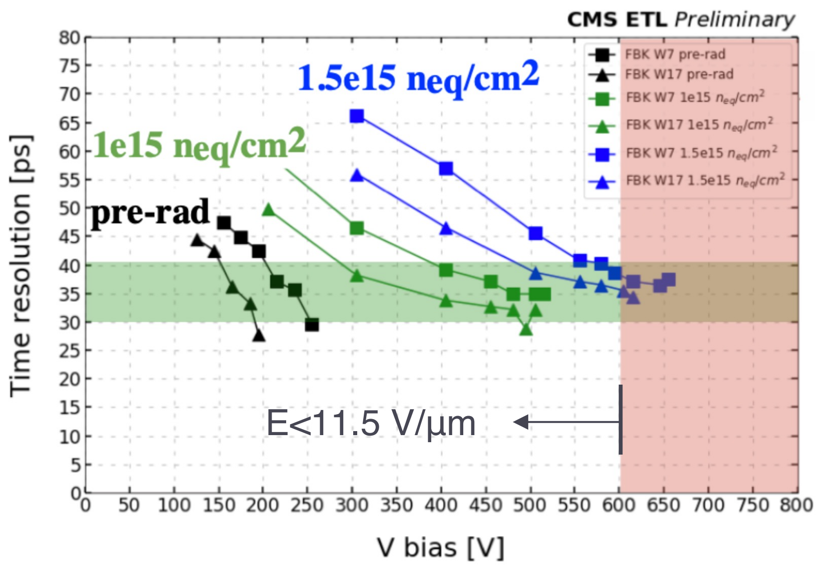
- Test beam studies show sparking damage to sensors for E-field above 11.5 V/μm.
- Prototype LGAD sensors characterized before and after irradiation proven to meet ETL requirements (>8 fC) for E-fields below 11.5V/μm.



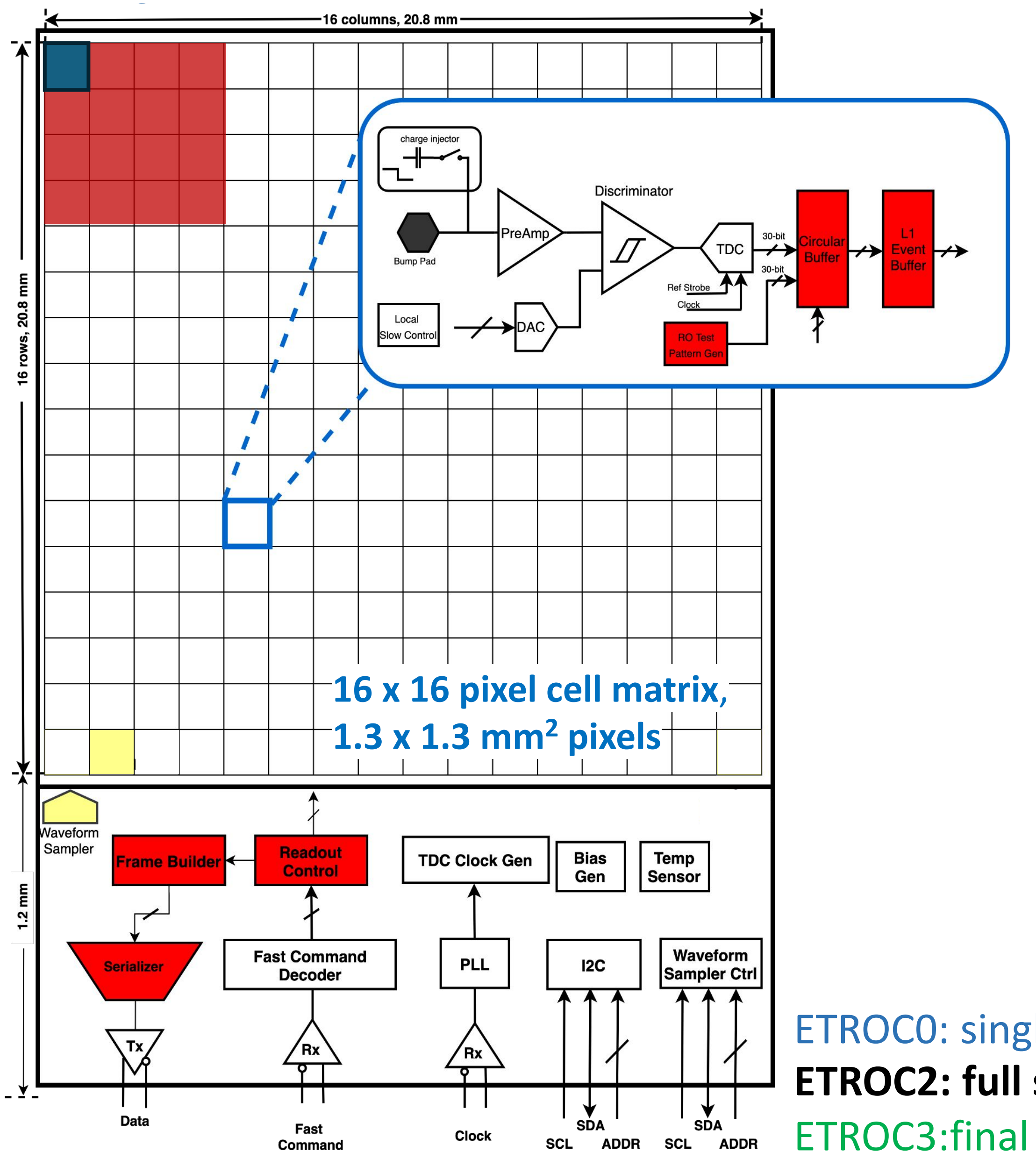
FBK 5x5 array



FBK 5x5 array



Precision timing at low power: ETROC ASIC



Design features:

- Preamplifier + discriminator, auto threshold calibration
- Single TDC measures Time-Of-Arrival (TOA) and Time-Over-Threshold (TOT), and delay cell time (CAL)
- 16x16 clock tree distribution
- Radiation hard waveform sampler
- Charge injection for testing & calibration

Performance specifications:

- TSMC 65nm technology, 100 MRad (TID spec)
- Low noise and fast rise time
- Low power: $\lesssim$ 4 mW / channel at end-of-life
- ASIC contribution to time resolution $\lesssim$ 40 ps at end-of-life

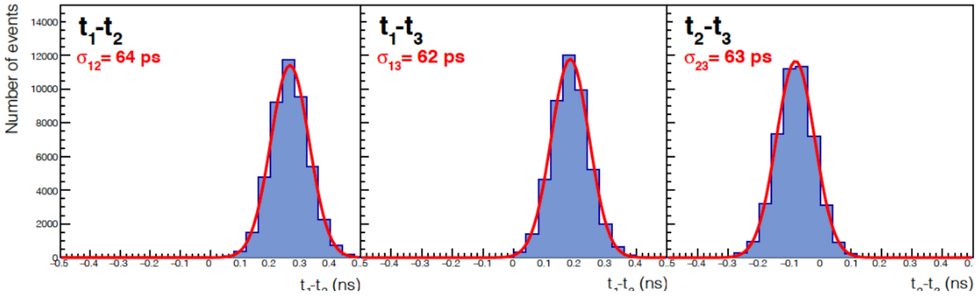
ETROC0: single analog channel

ETROC1: with TDC, 4x4 channel-clock tree

ETROC2: full size, full functionality, testing now!

ETROC3:final chip, submit next year

Performance of prototype ETL detector

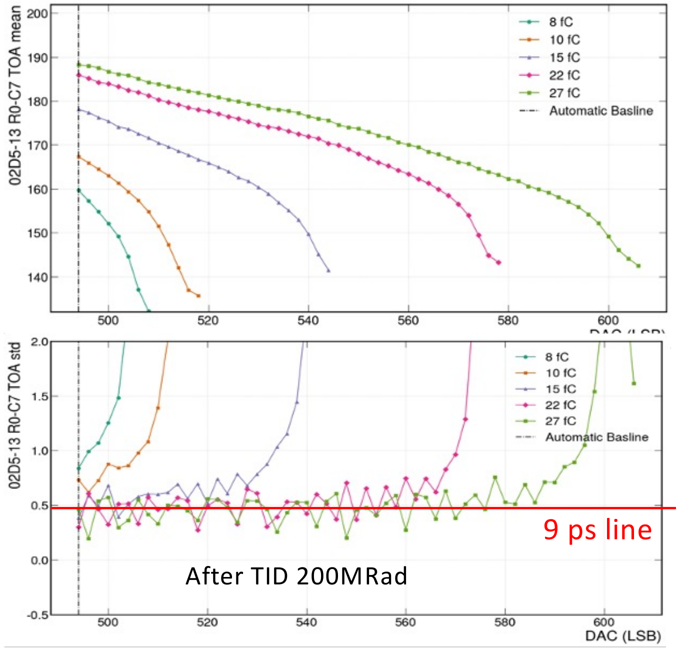


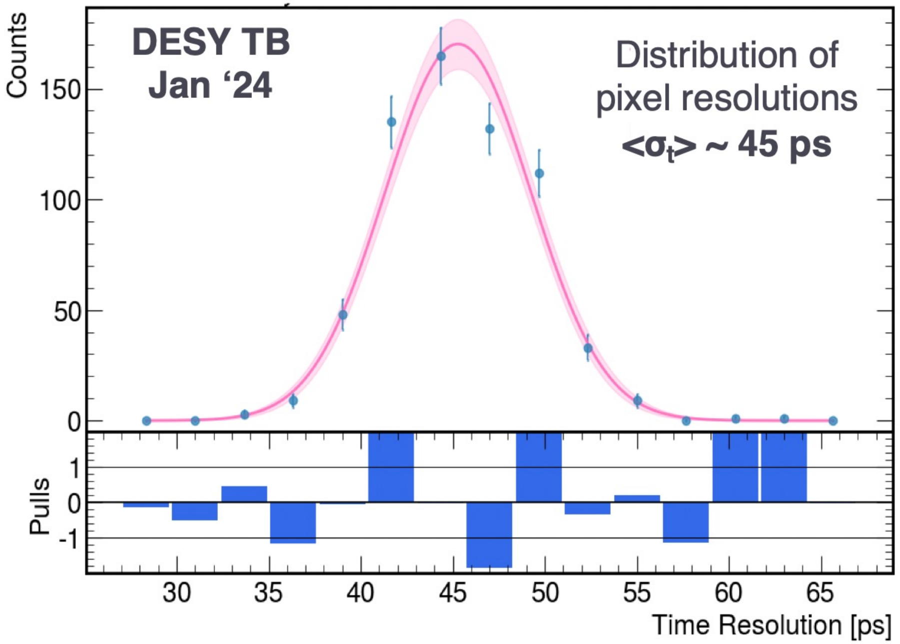
LGAD+ETROC1 resolution is 42-46 ps from TDC digital outputs

$$\sigma_i = \sqrt{0.5 \cdot (\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)}$$

Test results with ETROC1 wire-bonded to LGAD sensor demonstrate expected performance.

ETROC2 TID testing at CERN





Extensive testing of ETROC2 prototypes with bump-bonded sensors underway. Initial results confirm measurements with ETROC1.

Summary

MTD is one of the most challenging and rewarding detectors of the CMS upgrade.

- It will be essential at HL-LHC with broad impacts across the CMS physics program by providing a handle to mitigate pile-up contributions, thereby improving object reconstruction, and enabling new physics opportunities by providing time-of-flight capabilities.
- MTD is a pioneering effort demonstrating a new capability that will enable a fully time-aware event reconstruction that is foreseen to be essential to future collider-based particle physics experiments, in the near term (e.g. EIC) and beyond (e.g. a future hadron collider).

Mature design for MTD has been established through extensive prototyping and testing, verifying that the sensor technologies meet the design targets for HL-LHC.

- BTL design is fully validated, and the detector is beginning the production era.
- ETL is in a decisive phase of final prototyping before moving to construction.