Precision Timing with the CMS MIP Timing Detector

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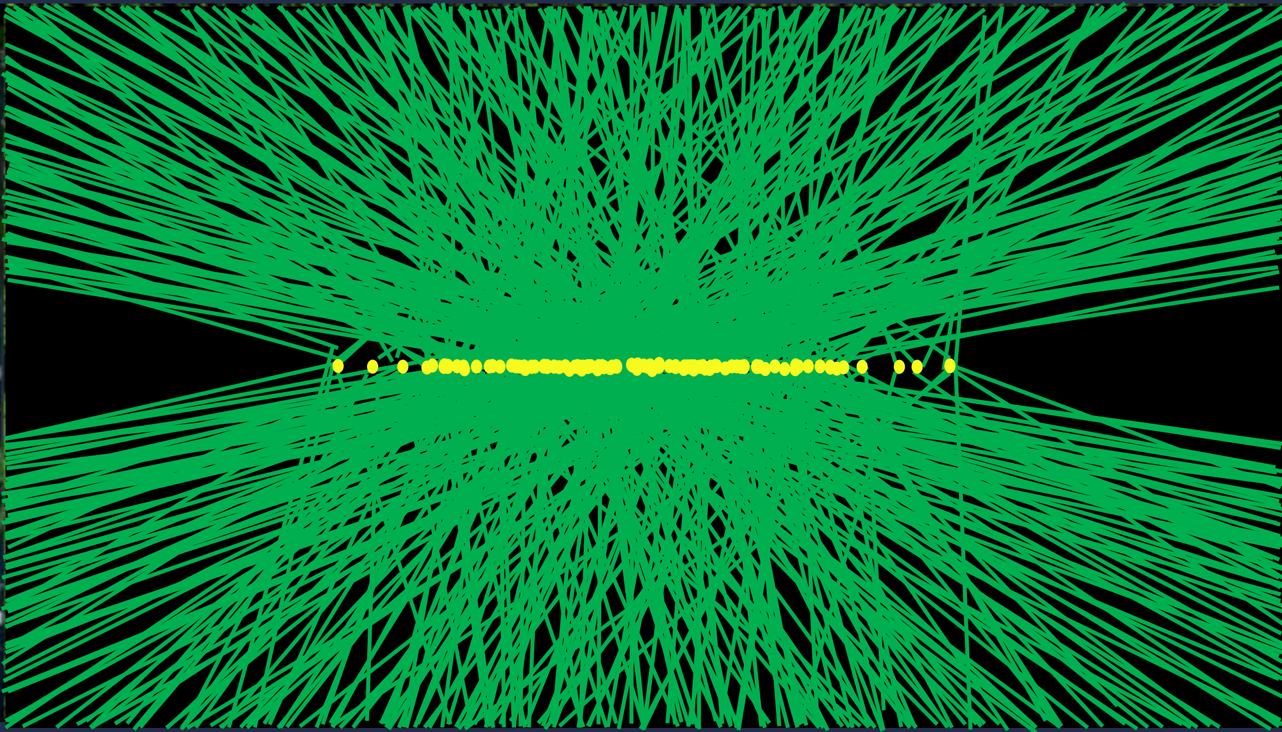
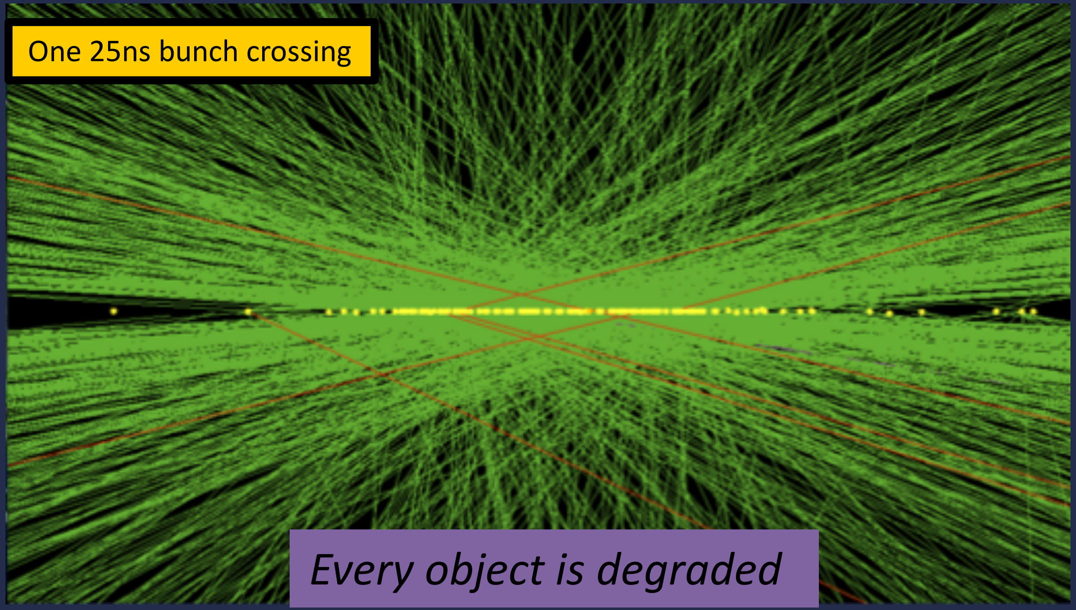


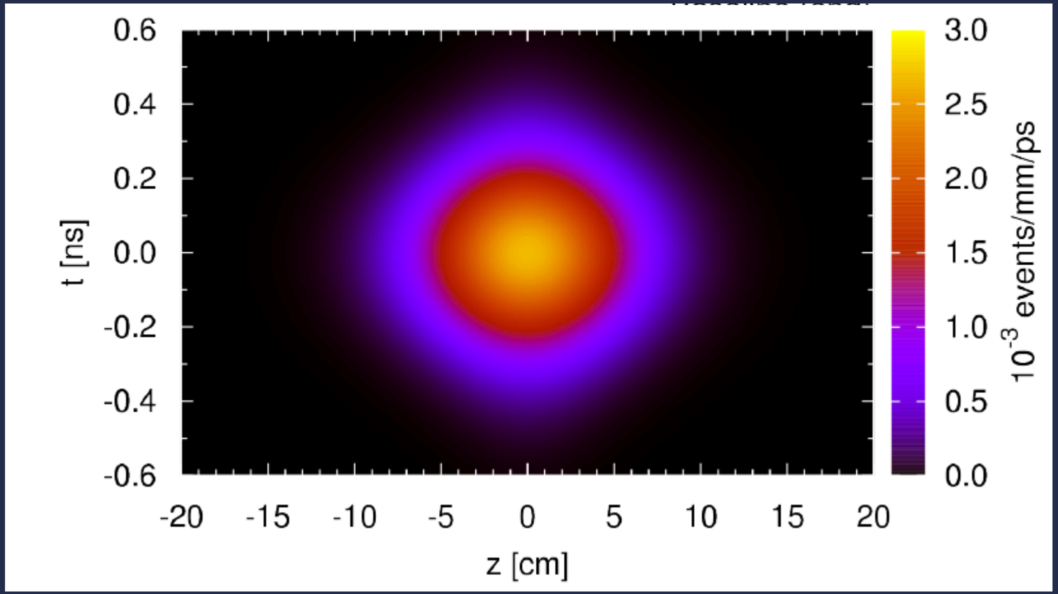
The High-Luminosity Era of the LHC

- Increasingly clear that, if the LHC can access evidence for new dynamics, then:
  …it likely has a very low cross section
  …it could be hidden in regions we have overlooked
  …it very well could be subtle – "hidden in the tails"

- Focus now is the <u>*luminosity*</u> – high luminosity running
  - A redesign of the collider aimed towards the following goals:
    - Achieve a peak instantaneous luminosity of 5.0E34 $cm^{-2}s^{-1}$ ← x5 increase over design parameter!
    - Accumulate an integrated luminosity of 250/fb per year ← x3.5 increase over single best year (2018, 68/fb)!
  - This would allow for a total integrated luminosity of 3000/fb to be accumulated over 12 years of running
    - Recall, CMS has accumulated 178/fb of integrated luminosity so far
    - This would be ***x17 larger*** than the sample we have already recorded in the first decade of running
  - Further, the re-design allows the machine to ultimately go to 7.5E34 and 4000/fb, which can be invoked depending on conditions and what we observe

The Challenge of the HL-LHC era

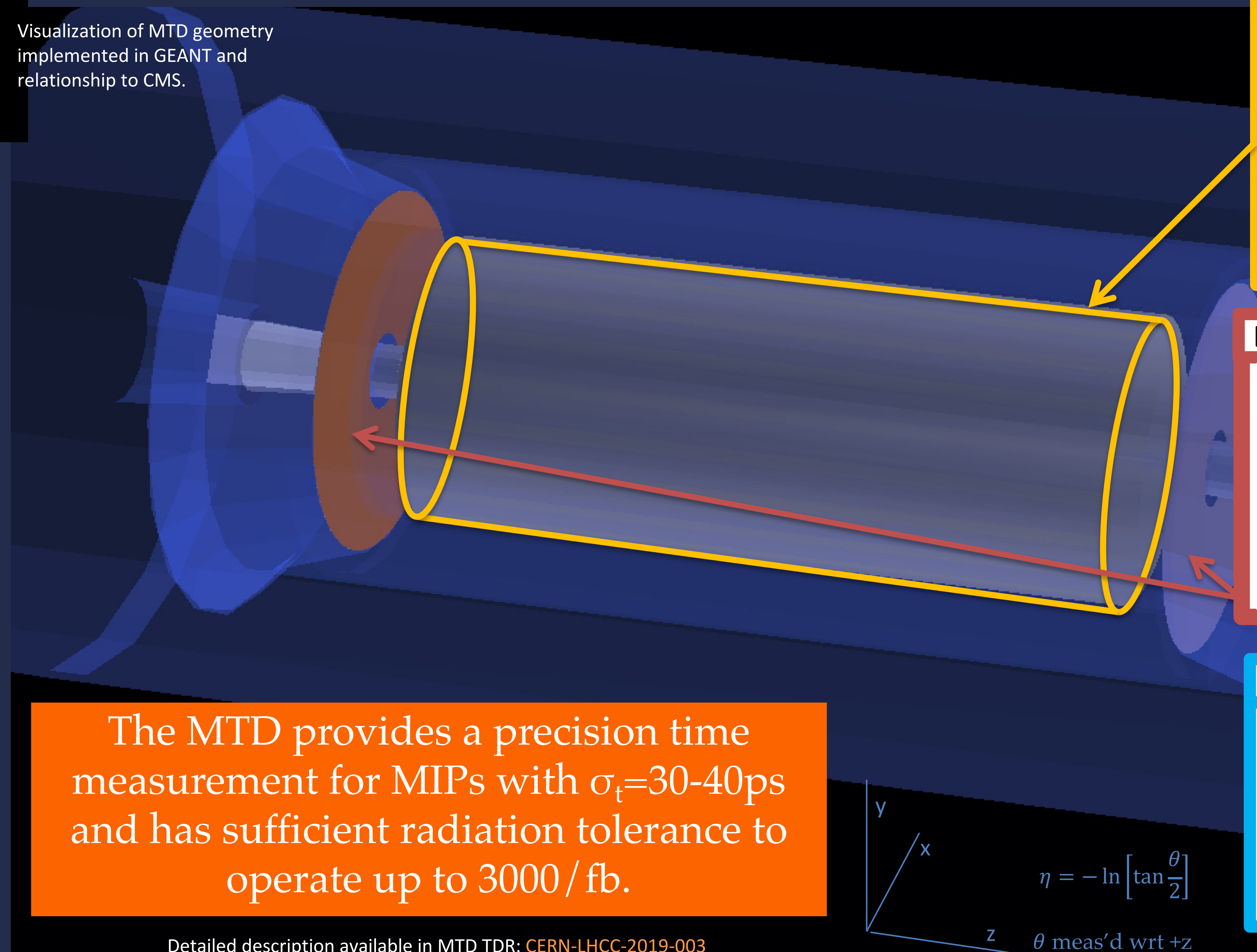




- Dealing with the effects of pileup interactions will be a major challenge of the HL-LHC era
- Although PU interactions significantly overlap in space, they are **more separable in space + time.**
- Imagine separating the 25ns beam crossing into consecutive time slices
  - **Each exposure has far fewer vertices** than when integrating over an event's complete time profile.
- Per-particle timing provided by the **MIP Timing Detector (MTD)** allows 4D track and vertex reconstruction
  - PU reduced in each time slice
  - Every object is improved
  - **Significant benefit to CMS physics program**

MTD Conceptual Design

Visualization of MTD geometry implemented in GEANT and relationship to CMS.



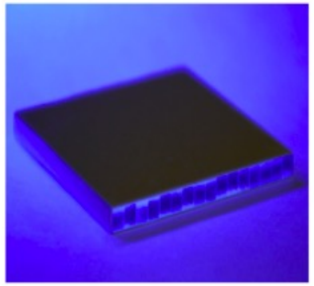
$$\eta = -\ln\left[\tan\frac{\theta}{2}\right]$$

θ meas'd wrt +z

Barrel Timing Layer (BTL)

LYSO bars + SiPM readout

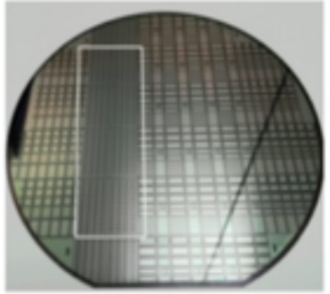
- TK/ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm
- Thickness: 40 mm
- Length: ±2.6 m along z
- Area: 38 m^2
- 332k channels



Endcap Timing Layer (ETL)

Si with internal gain (LGAD):

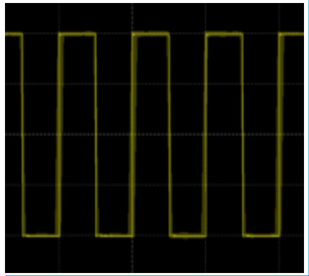
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position: z = ±3.0 m (45mm thick)
- Surface ~14 m^2; 8.5M channels
- Fluence: up to 2E15 n_{eq}/cm^2
- 1.3x1.3 mm^2 pixels: 9M channels



Reference clock

Backbone of the MTD system:

- Sampling clock frequency of 160 MHz sync'd to LHC bunch crossings
- RMS jitter of <15 ps
- Distributed to **9.3M channels separated by up to 6 meters**



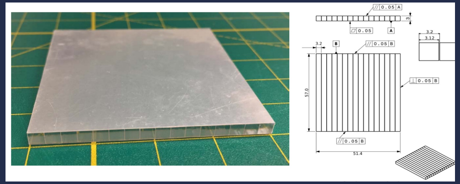
The MTD provides a precision time measurement for MIPs with σ_t=30-40ps and has sufficient radiation tolerance to operate up to 3000/fb.

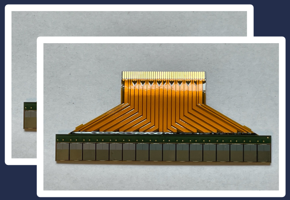
Detailed description available in MTD TDR: CERN-LHCC-2019-003

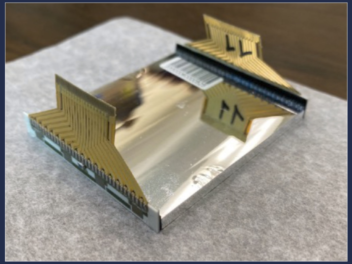
Sensitive Elements

BTL: Cerium-doped LYSO readout by a silicon photo-multipliers (SiPMs)

- Fast and bright crystal
- Radiation tolerant
- Well-understood commodities

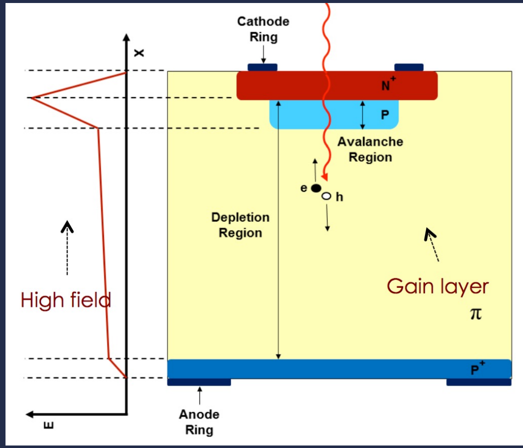


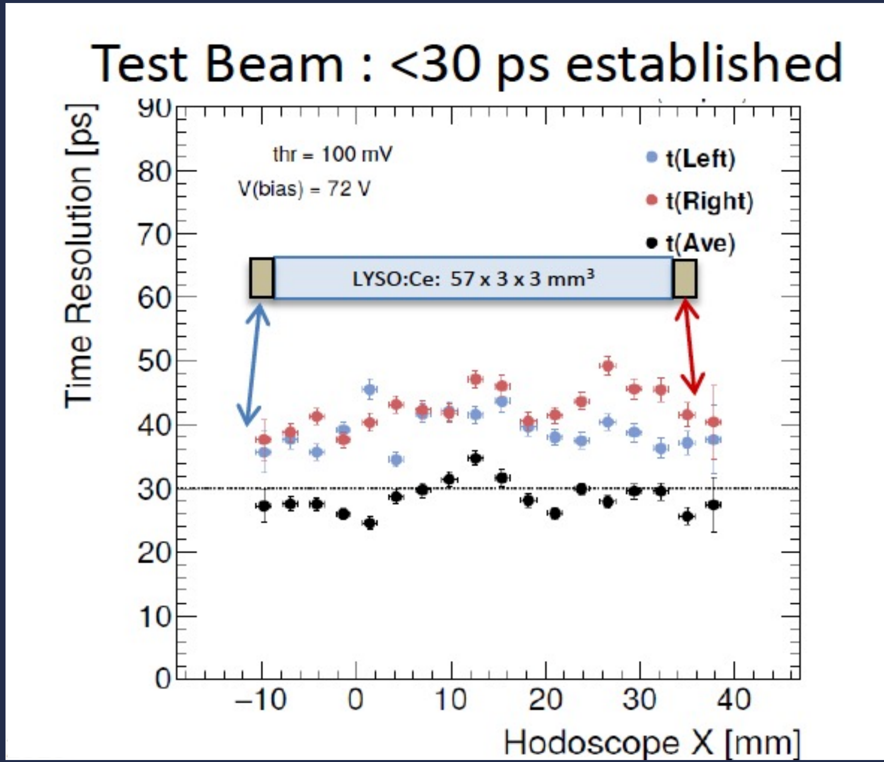


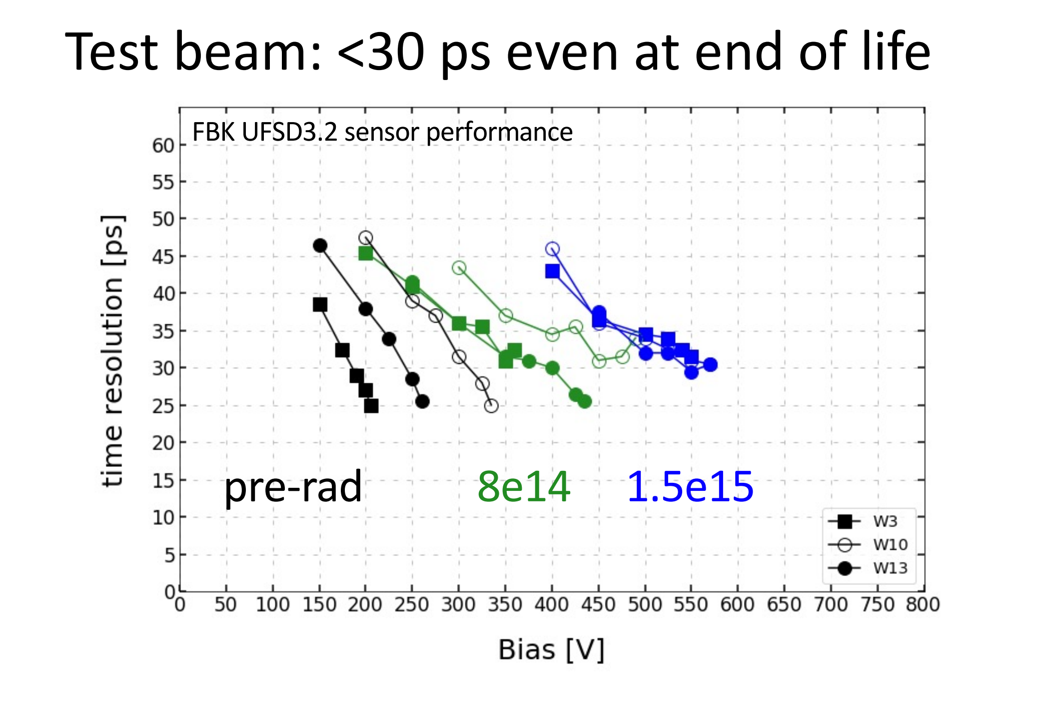


ETL: "Low-Gain Avalanche Diode" (LGAD)

- Large signal, large slew-rate ⇒rapid electrical response
- More signal in less material ⇒ short drift time, better timing resolution
- Low gain ⇒ low shot noise, below electronics pedestal

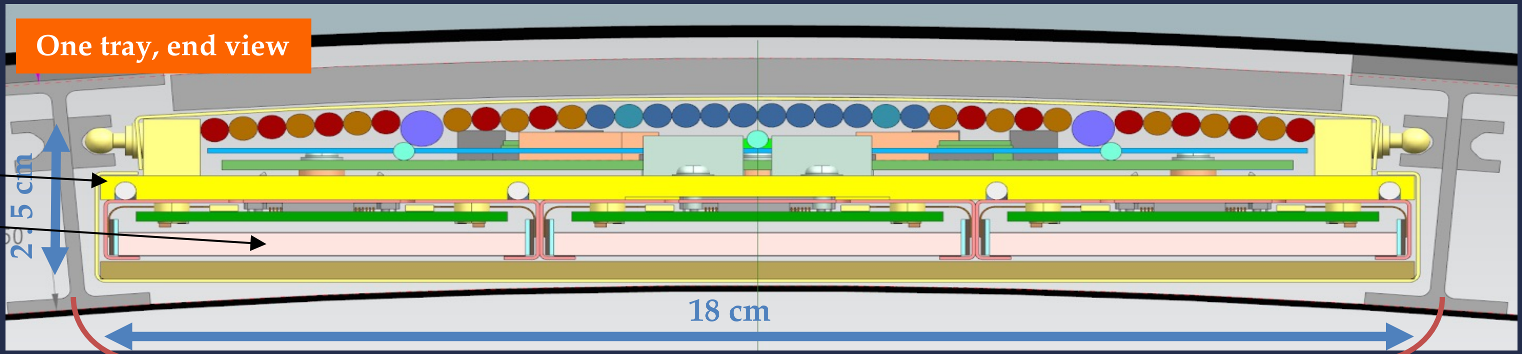




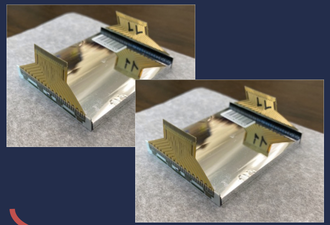


BTL Design Overview

- 331k total channels from 165k LYSO bars
- Main components: Trays
  - Mechanical support & CO_2 via **cooling plate**:
  - LYSO, SiPMs, FE boards comprise **Detector Modules**
  - DMs grouped in **Readout Units**
- Tray details:
  - 72 trays (36 in $\phi \times 2$ in η)
  - Each tray has dimensions : 250 x 18 x 2.5 cm^3
  - 6 RUs per tray.



LYSO+SiPM Sensor Modules



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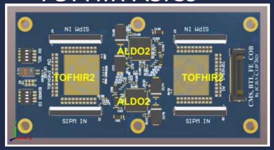
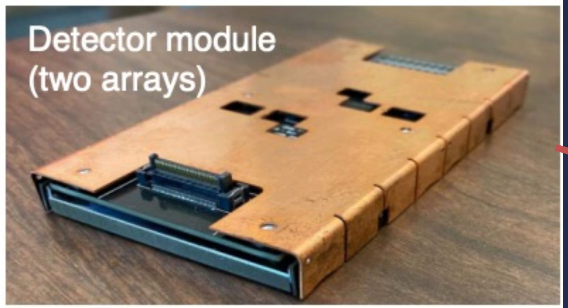
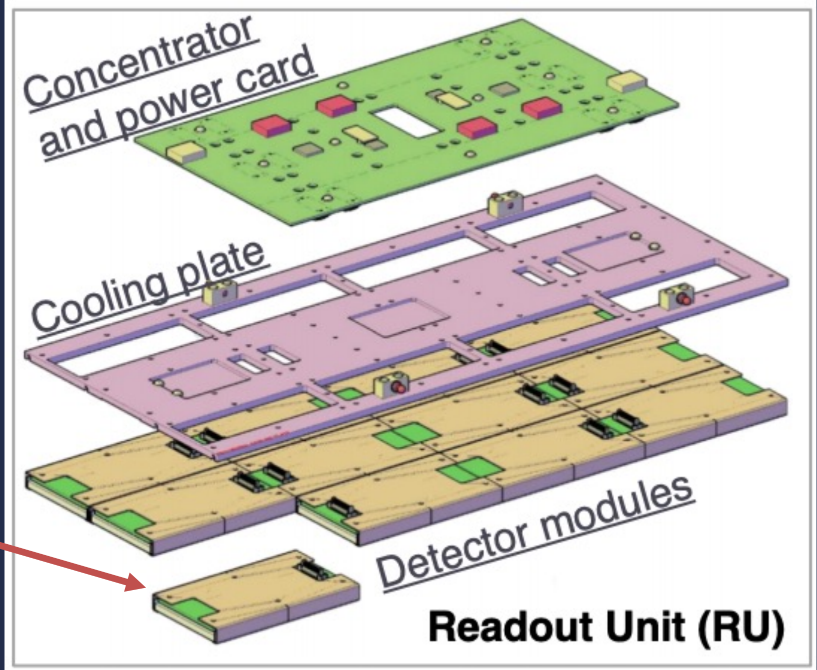
FE Boards housing TOFHIR ASICs

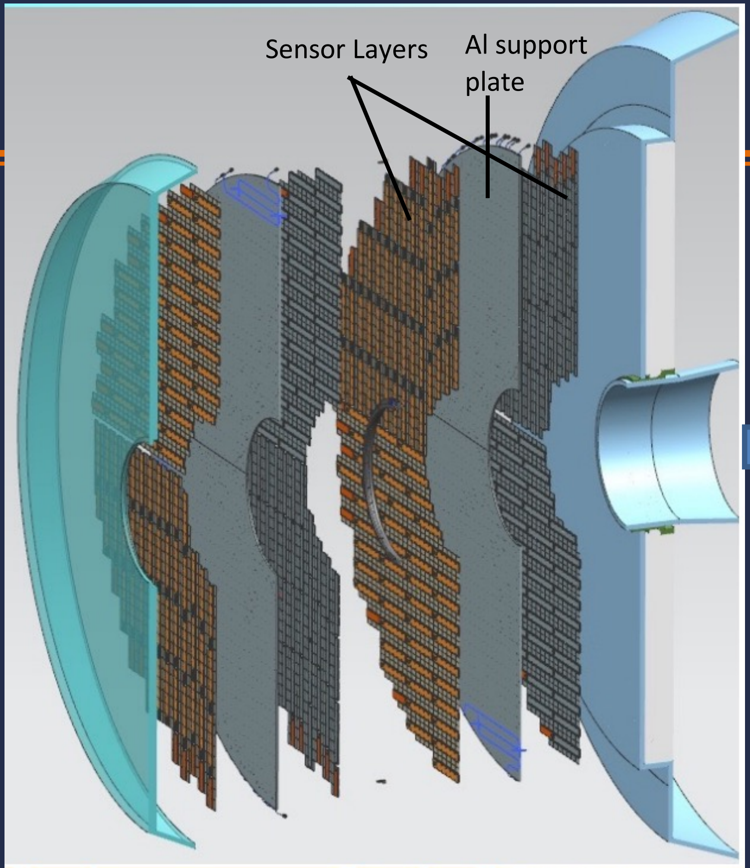


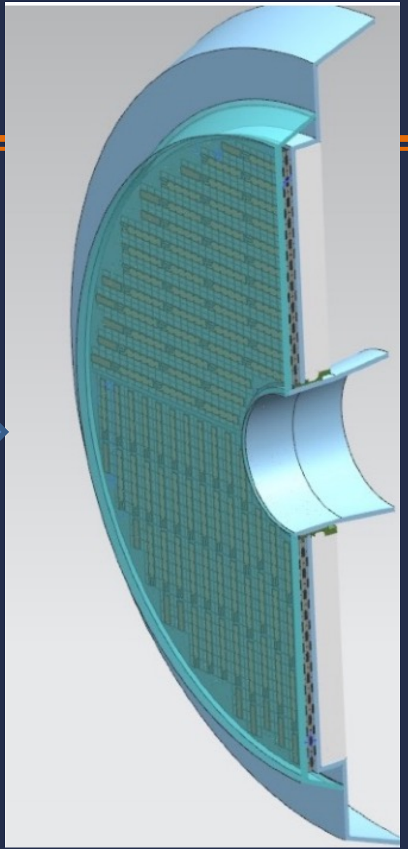


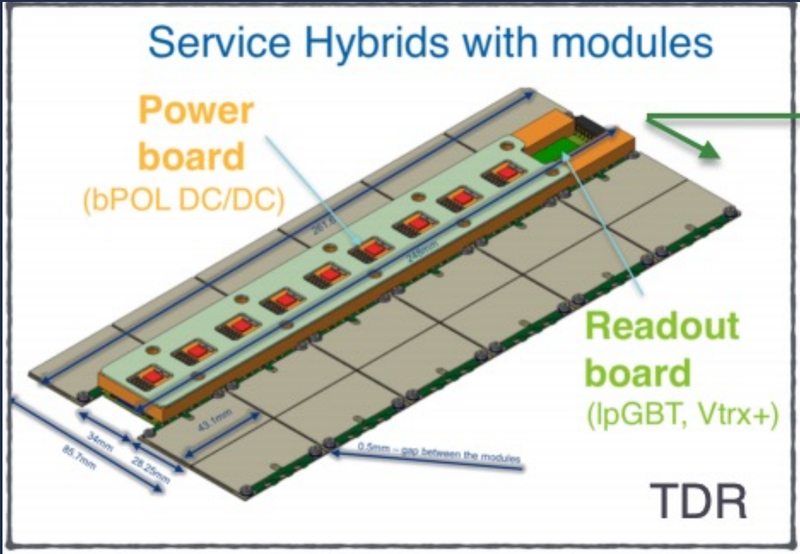


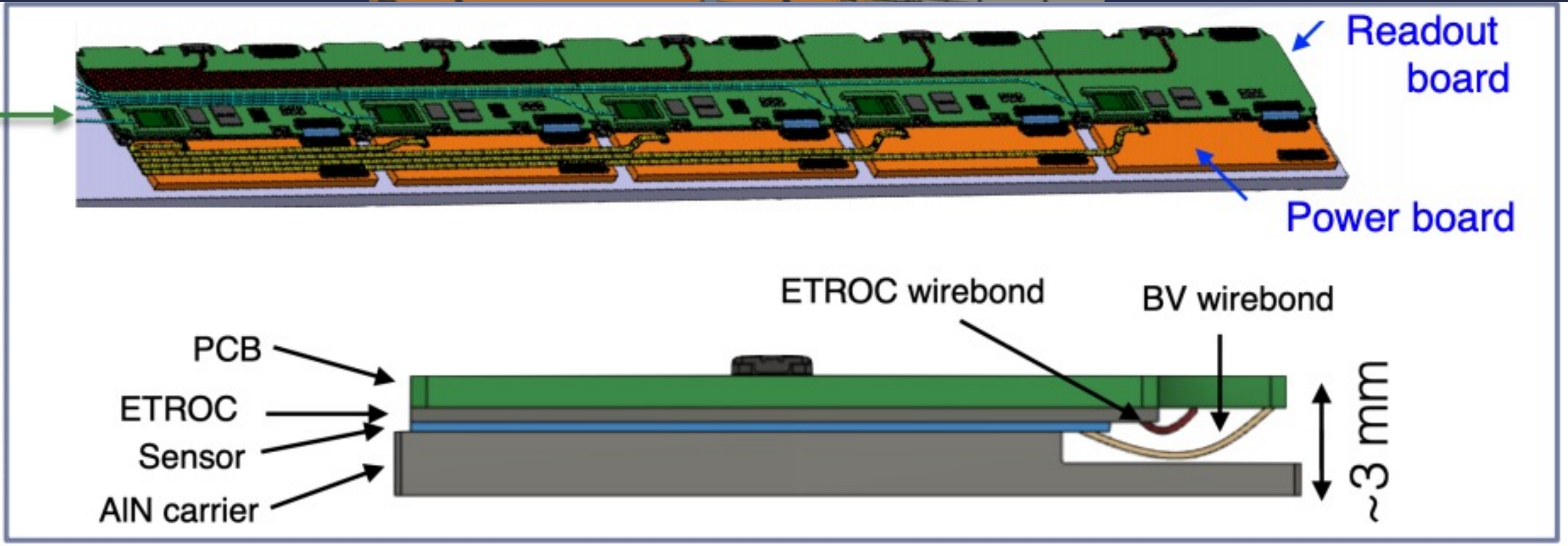
ETL Design Overview

- Main component: Modules
  - LGAD sensors bump-bonded to ASICs
  - Interspersed with readout boards
- Implementation in CMS
  - Two layers of silicon sensors covering $1.6 < |\eta| < 3.0$
  - Sensors mounted in rows on each face of Al cooling disks
  - Readout boards placed between sensor rows, staggered wrt opposite face for full sensor coverage.
  - Two such disks/endcap to provide average of 1.8 hits/track.
  - Mounted on neutron moderator upstream of the CE, in an independently cooled and accessible volume.



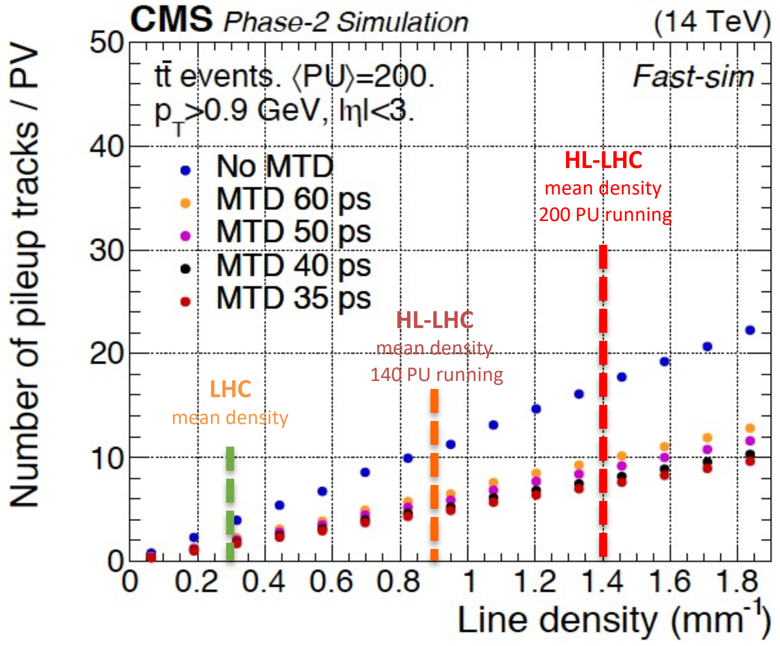


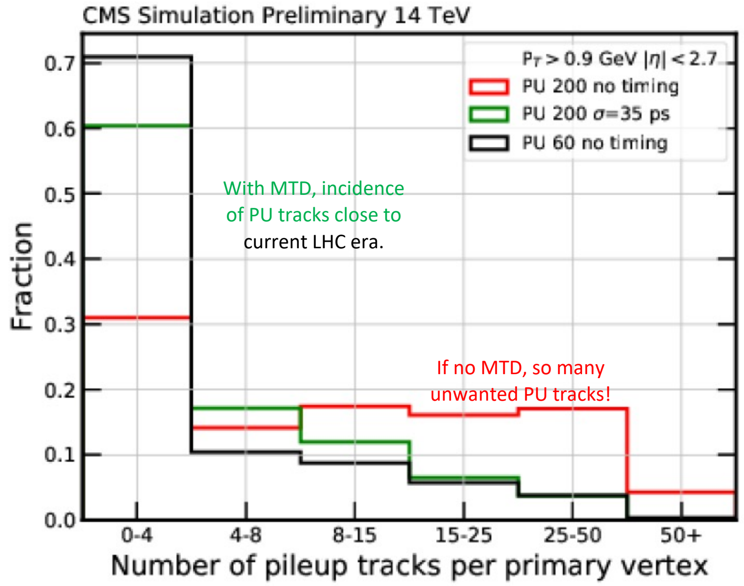




Timing Impact: Primary Vertex Finding

- Primary mission of the MTD: **pileup mitigation**
- One domain in which this is crucial: the identification of the *primary vertex*
  - The p-p collision location in a 25 ns bunch crossing from which the interesting physics process originates
  - Constructed from *charged particle tracks* that are consistent with a common location
  - Tracks from spatially-nearby pileup interactions can be inadvertently added to the primary vertex
- **Time-aware primary vertex reconstruction** reduces incorrect association of tracks from nearby pileup interactions by a factor of 2:
  - Fully offsets the impact of the transition from 140 → 200 PU running
  - Brings per-vertex track purity close to typical current LHC running conditions



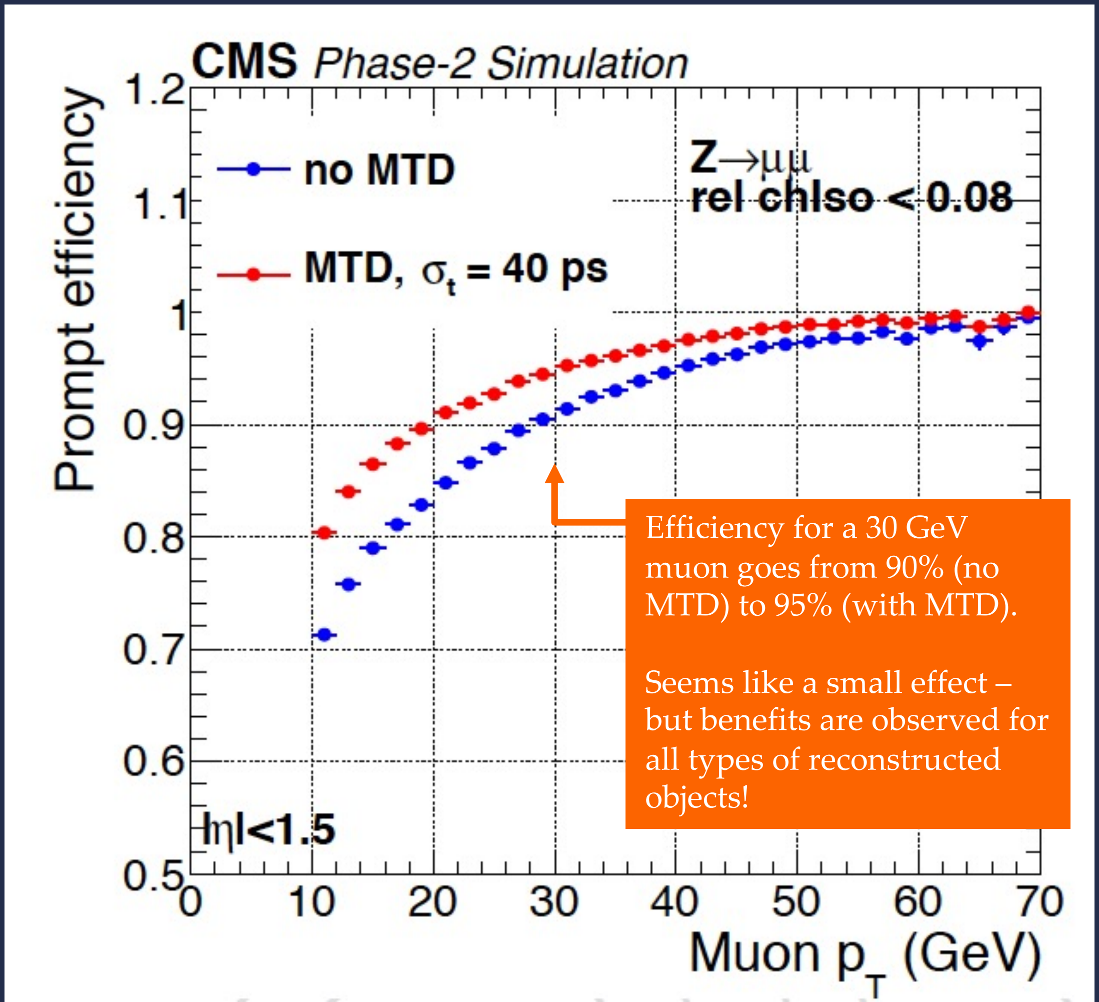


Timing Impact: Isolated Charged Lepton Identification

- Charged leptons are crucial for identification of Z and W boson decays
  - Example: $H \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$

- Charged leptons from W and Z decays are typically *isolated* from other activity in the event
  - Charged leptons also come from decays of hadrons, which can be interesting in their own right but are not what we seek when looking for W/Z signatures
  - Usually such leptons are close by to other activity in the detector
  - So we veto such non-isolated candidates

- Tracks from PU interactions can overlap with an authentic, isolated charged lepton



Timing information from MTD helps by flagging tracks that should not be used to determine whether a candidate is isolated.

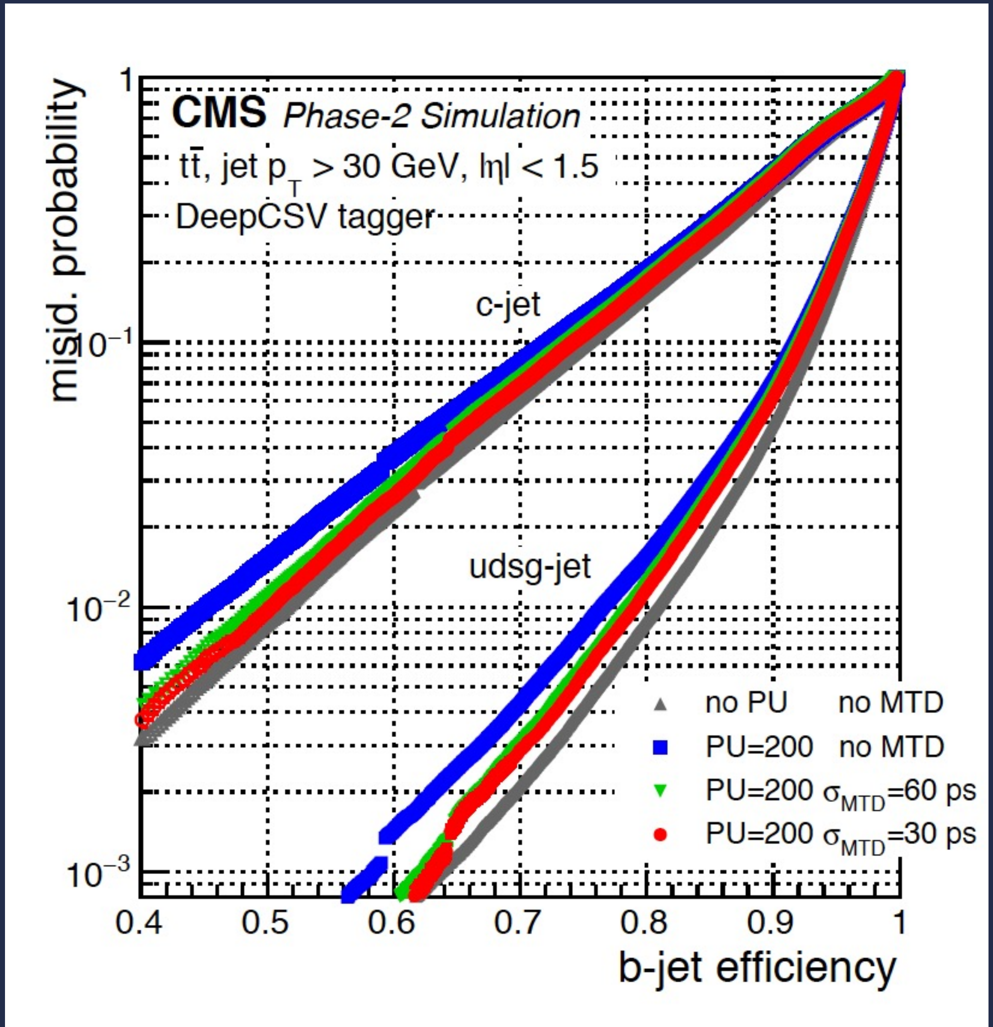
Timing Impact: b-jet Identification

- Decays of bound states of quarks manifest themselves in CMS as a spray of particles we refer to as a *jet*
  - Mostly protons, pions, kaons
  - It is valuable to know the *origin story* of a specific jet:
    - *Did this jet come originally from a quark or a gluon?*
    - *If from a quark, was it from a b or c quark?*

- b-quark jets are important:
  - Primary decay mode of the Higgs, via $H \to b\bar{b}$
  - Exclusive decay mode of the top quark, via $t \to W^+ b$

- Special property of b-quark jets:
  - b-quark lifetime is relatively long: τ = ~1.5ps
  - This means a b-quark jet starts from a decay significantly displaced from where it was produced: $c\tau = {\sim}0.5\ mm$

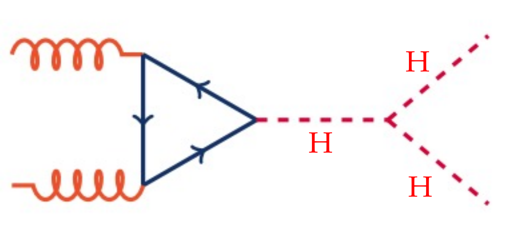
- PU interactions hurt our ability to identify the displaced vertex associated with a b-jet:
  - Reduced efficiency for authentic b-jets
  - Increased the incidence of false positives from non-b-jets

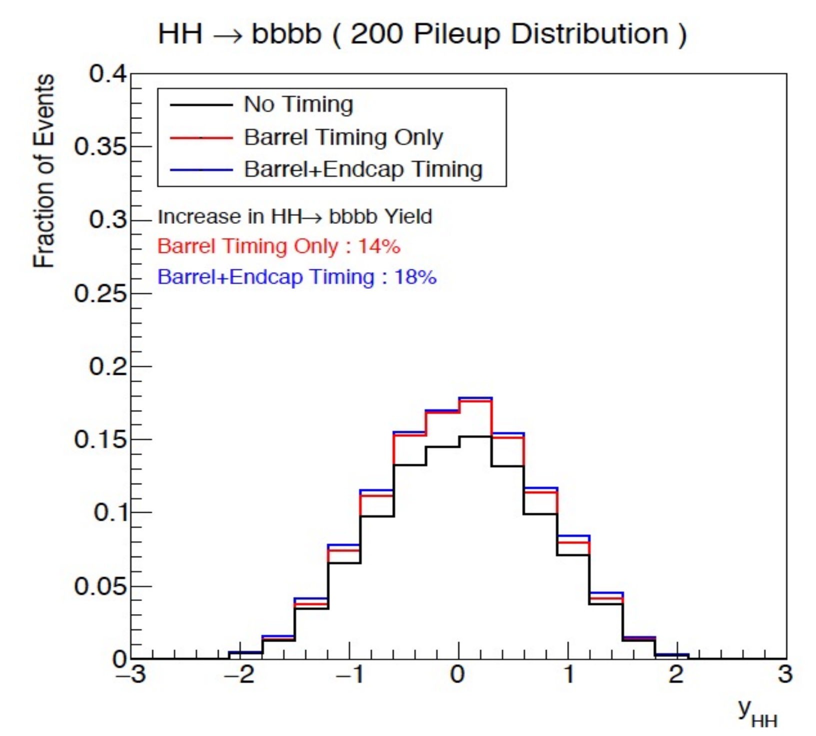


Timing information from MTD helps by restricting displaced vertex ID to tracks consistent in the time domain.

Timing Impact: Measurement of Di-Higgs Production

- Ultimate characterization of the Higgs through measurement of its self-coupling
  - Accessible through di-Higgs production:





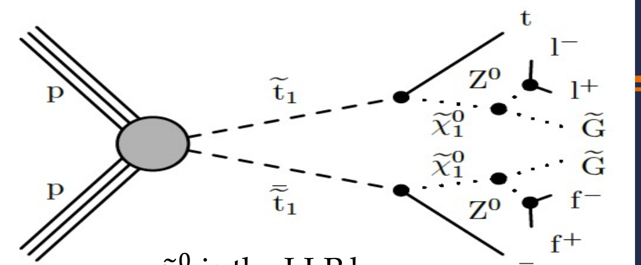
- Search for HH production exploits many final state signatures
  - Cumulative benefits from MTD from each of the object-level gains
  - Examples:
    - $HH \rightarrow bbbb$: MTD provides 18% increase in signal yield
    - $HH \rightarrow bb\gamma\gamma$: 22% increase in signal yield
  - Considering all di-Higgs final states, the MTD provides statistical power equivalent to ***25% more HL-LHC data***

	Expected significance	
Di-Higgs decay	No MTD	MTD
bbbb	0.88	0.94
bb$\tau\tau$	1.3	1.48
bb$\gamma\gamma$	1.7	1.83
bbWW	0.53	0.58
bbZZ	0.38	0.42
Combined	2.4	2.63

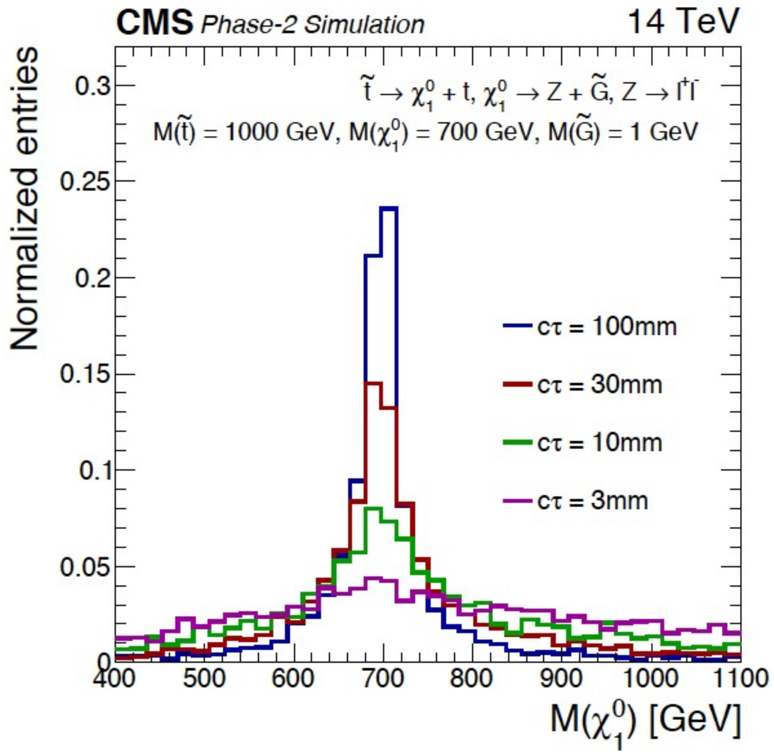
Timing Impact: Long Lived Particles

- Long-lived particles (LLPs) are hallmarks of several BSM theories
  - Feeble interaction with matter → low decay prob → long lifetime
  - Attractive hypothesis for particle dark matter
  - LHC experiments have been looking for LLPs in Runs 1,2:
    - Focus on identifying significantly displaced decay vertices – *spatial analysis only*
- MTD offers a completely new capability in LLP searches
  - Kinematic constraint from LLPs visible decay daughters
  - Space+time information → LLP's *velocity*
  - Coupled with the reconstructed energy deposited from the decay produces → LLP's *mass*

One example:

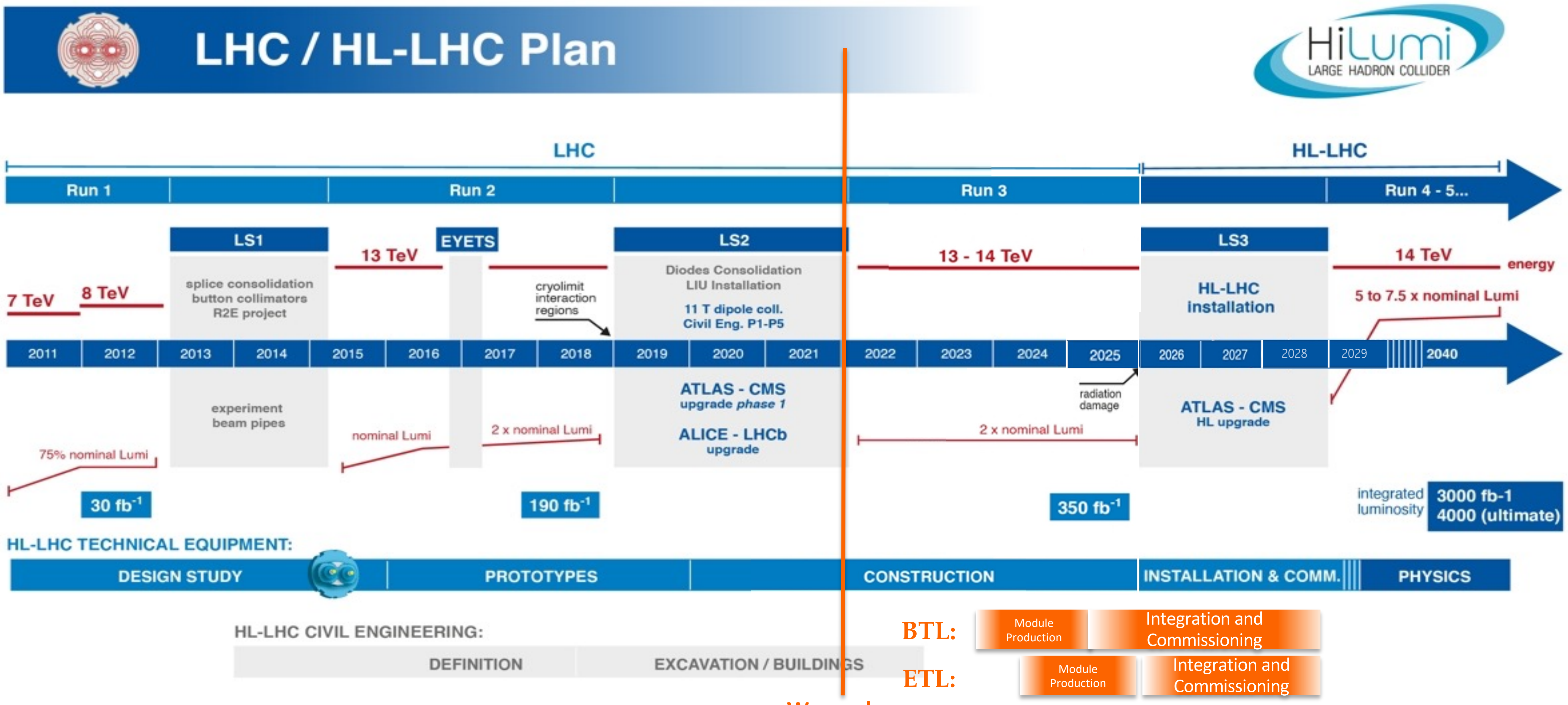


$\tilde{\chi}_1^0$ is the LLP here.



*Without the MTD, **there would be no mass information** for an observed LLP beyond the trivial constraint provided by the 25ns LHC clock.*

Timeline: The High Luminosity LHC Era



Adapted from https://project-hl-lhc-industry.web.cern.ch/content/project-schedule

Summary and Outlook

- The High Luminosity era of the LHC is on the horizon. The large new accumulated data sample comes at a penalty in terms of pileup interactions flooding the detector.
- The MTD will rely on precision timing of particles produced inside CMS to provide significant pileup mitigation, furthering the experiment's mission in the HL-LHC era.
- The MTD also brings new capabilities to CMS that could help uncover the elusive signs of new dynamics.