Precision Timing with the CMS MIP Timing Detector

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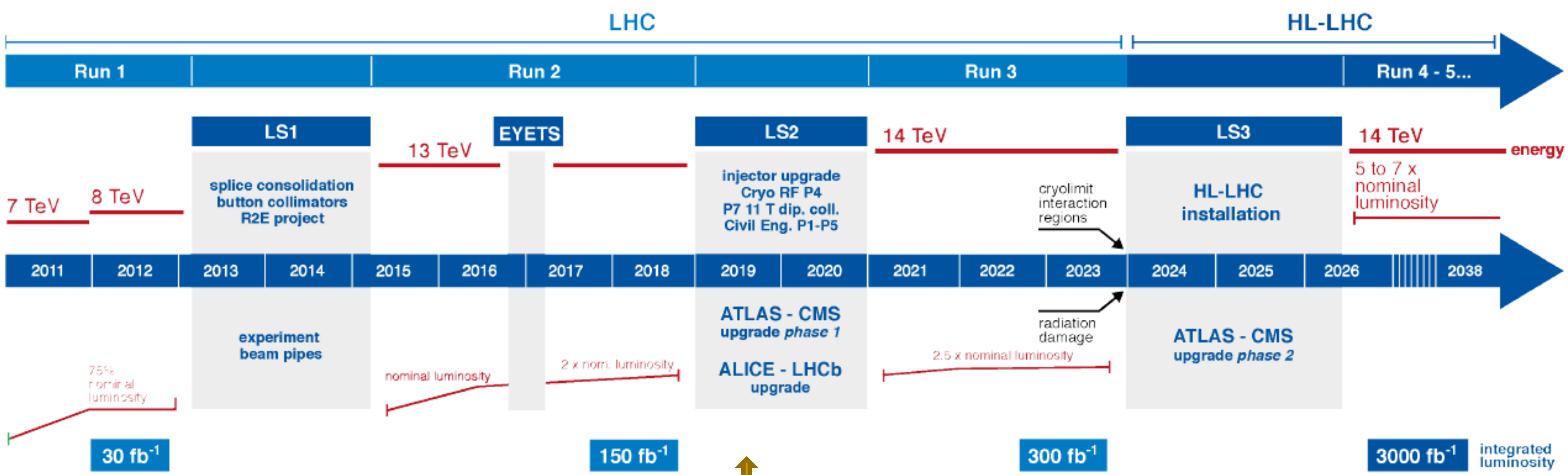
on behalf of the CMS Collaboration

PIC 2019 - Taipei

Large Hadron Collider

LHC / HL-LHC Plan



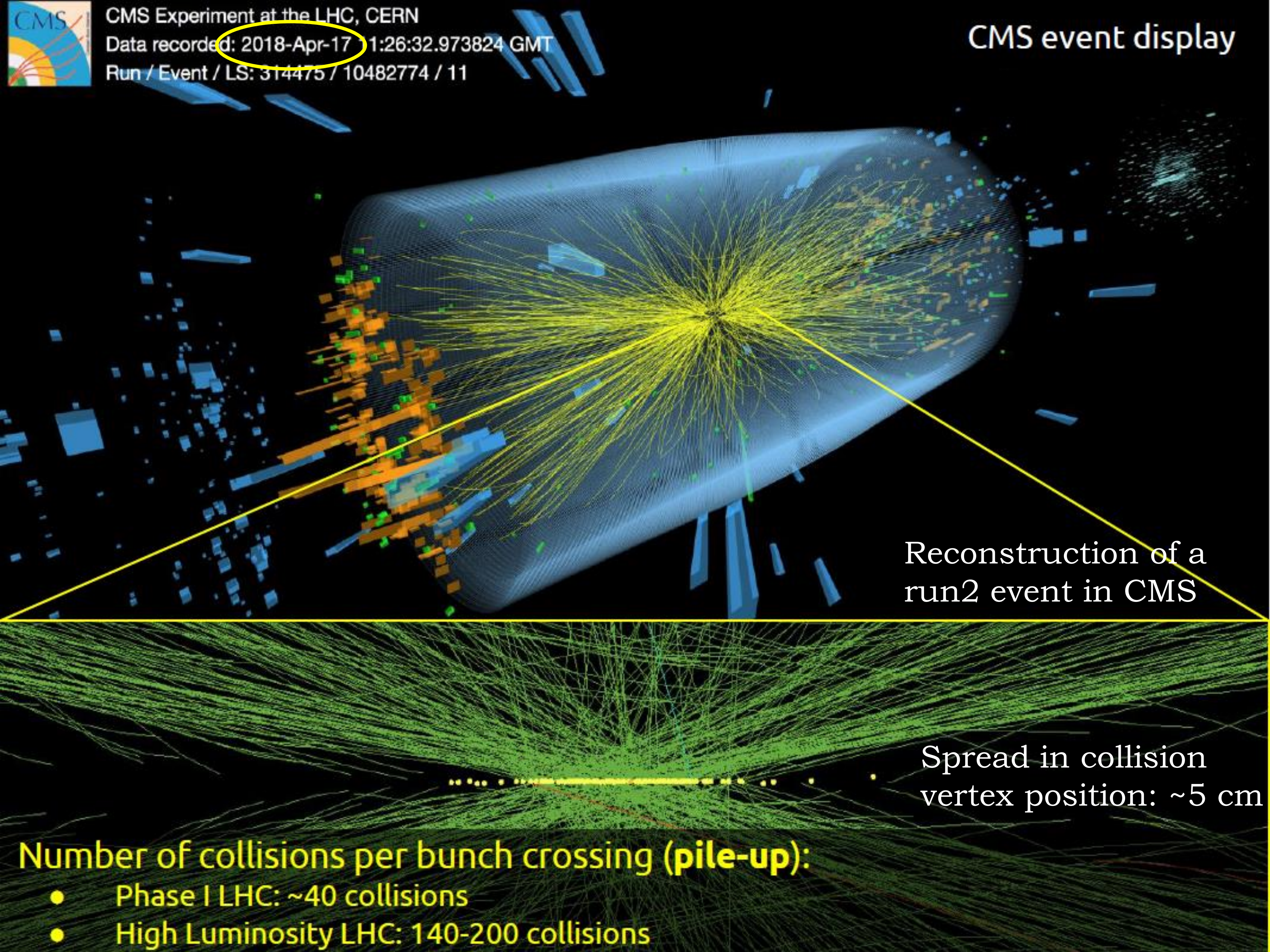
Higgs boson discovery

We are here.

	LHC	HL-LHC	
E =	7–14	14	TeV
$\mathcal{L}_{peak}$ =	2	5–7.5	$\cdot 10^{34} cm^{-2} s^{-1}$
PU_{peak} =	40–60	**150–200**	
$\int \mathcal{L}$ =	≥50	**250–320**	fb^{-1} /year
$\int \mathcal{L}$ =	300–500	3000–4000	fb^{-1} total

Very challenging for event reconstruction.

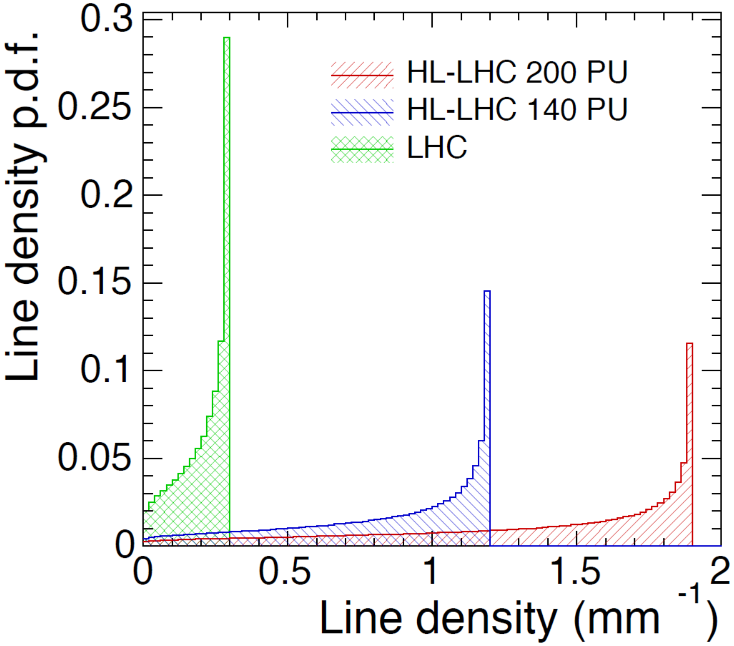
A ten times large dataset for physics and a real challenge for the detector radiation resistance.


CMS Experiment at the LHC, CERN
Data recorded: 2018-Apr-17 11:26:32.973824 GMT
Run / Event / LS: 314475 / 10482774 / 11
CMS event display
Reconstruction of a run2 event in CMS
Spread in collision vertex position: ~5 cm
Number of collisions per bunch crossing (pile-up):
Phase I LHC: ~40 collisions
High Luminosity LHC: 140-200 collisions

The HL-LHC challenge

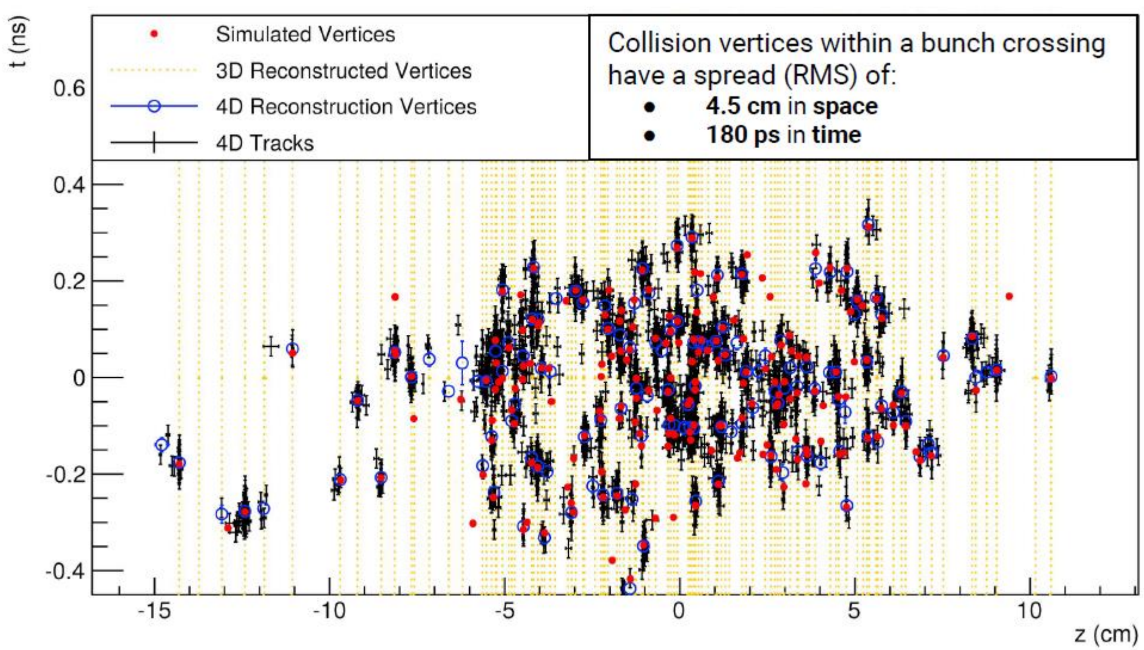
- Up to 5x higher vertex density
- Optimal cut at 1 mm for track-vertex compatibility
- Vertex density > 1 mm^{-1} means pile-up contamination and event reconstruction degradation

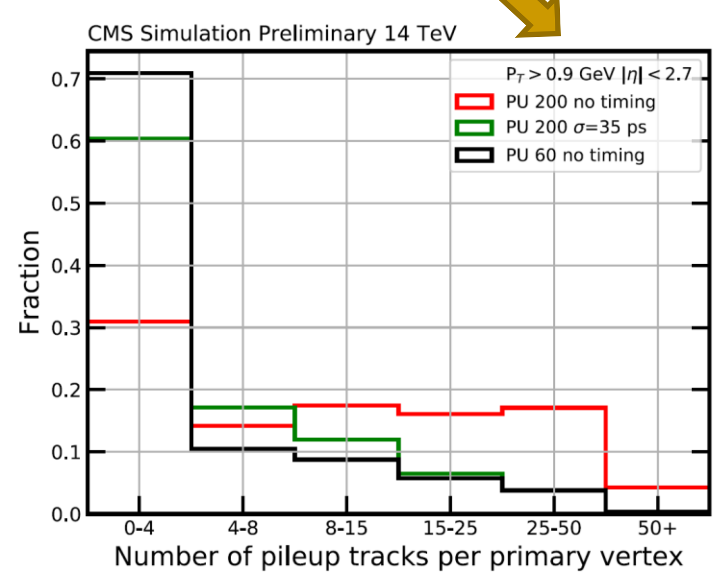
Probability density functions of the line density along the beam axis.



A Detector for MIP Timing

- Approach: <u>time tagging tracks with 30-50 ps resolution</u>
  - 3D → 4D vertex reconstruction
  - time compatibility for track-vertex association
- Goal: reduce the actual Phase2 pile-up to the current Phase1 size by slicing the beam spot in time slices.

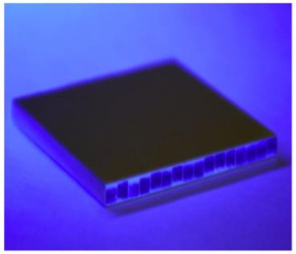




Design of the CMS MTD (Mip Timing Detector)

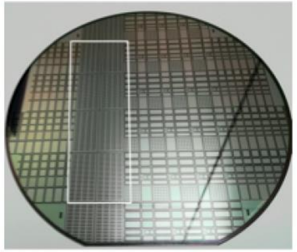
BTL: LYSO bars + SiPM readout:

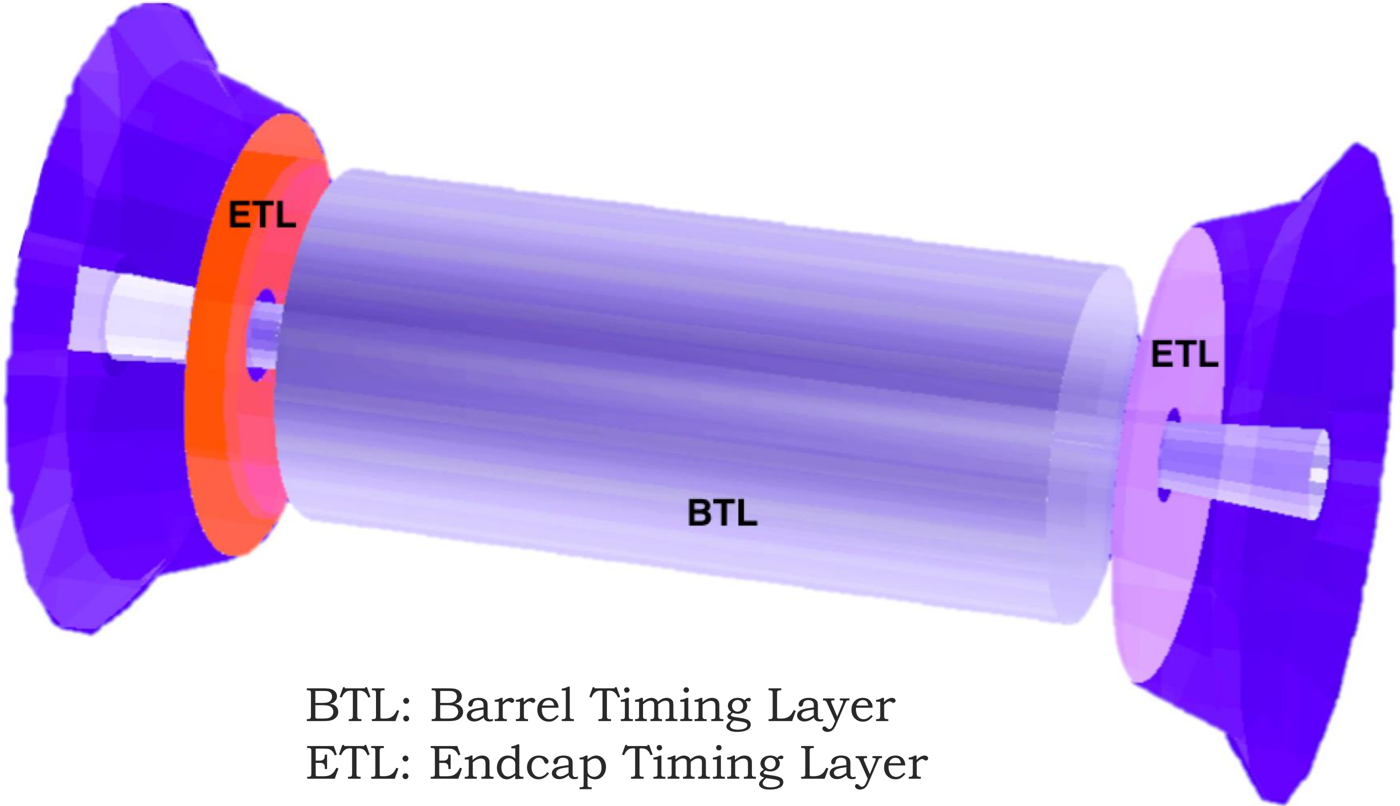
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2×10^{14} n_{eq}/cm^2



ETL: Si with internal gain (LGAD):

- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2





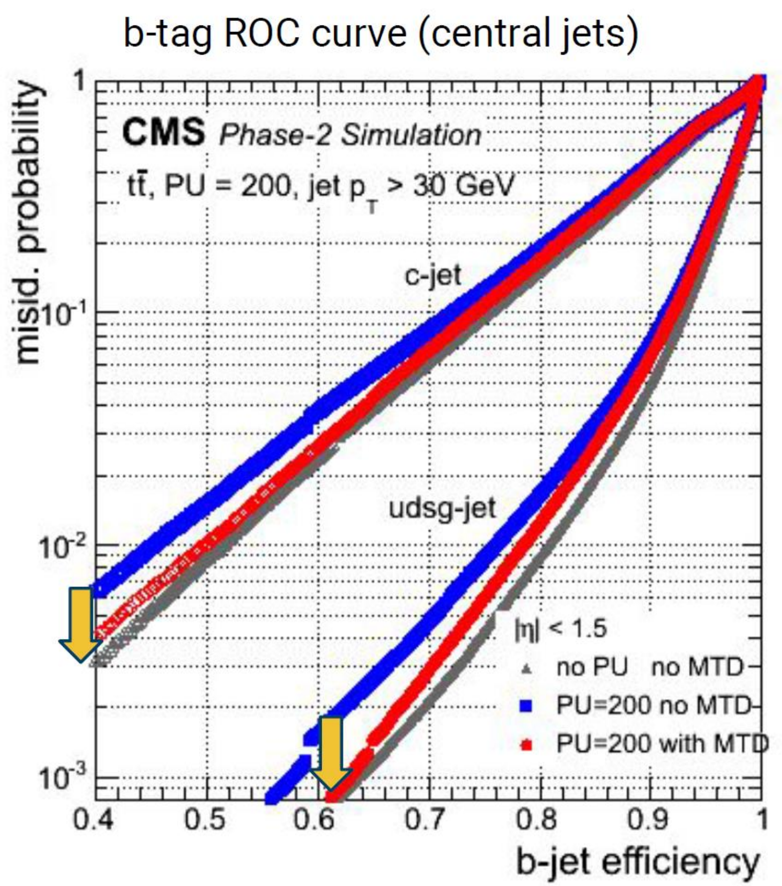
BTL: Barrel Timing Layer
ETL: Endcap Timing Layer

Improvement in the physics performance with the MTD

- Reconstruction performance
  - Higher b-tagging efficiency.
  - Improvement in identification and isolation of photons and leptons.
  - Better rejection of fake jets due to pile-up
  - Better missing transverse momentum resolution

- Signal yield gain in many Higgs decay channels.

- Velocity measurement from TOF: π/K and K/p discrimination for low p_T hadrons.



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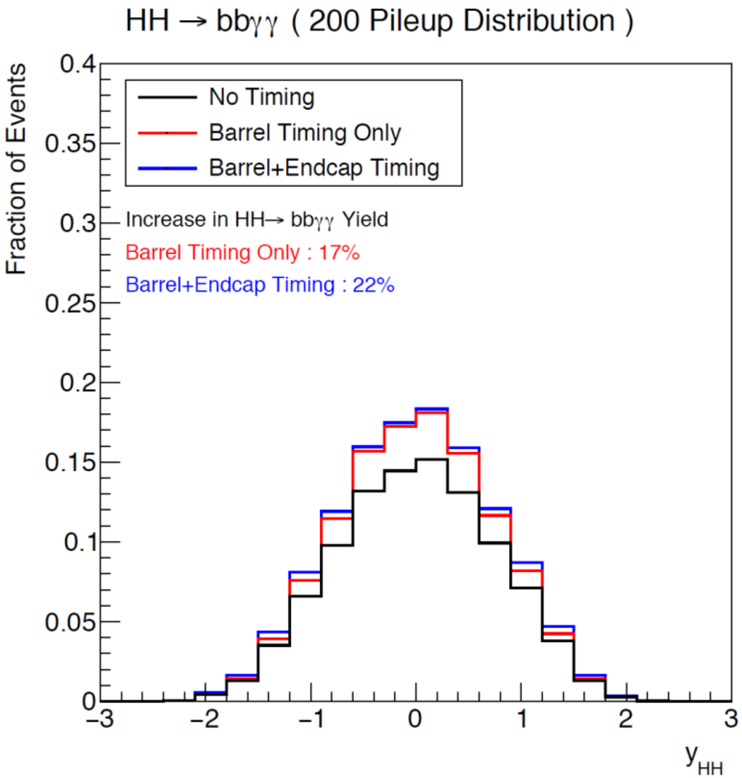
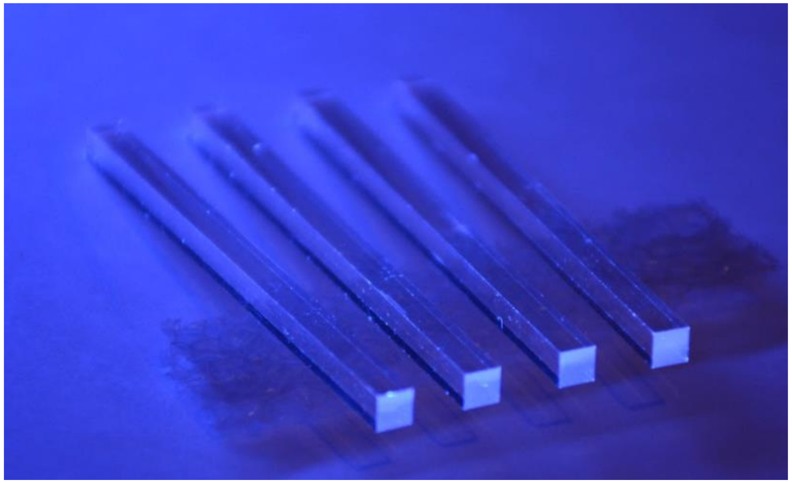
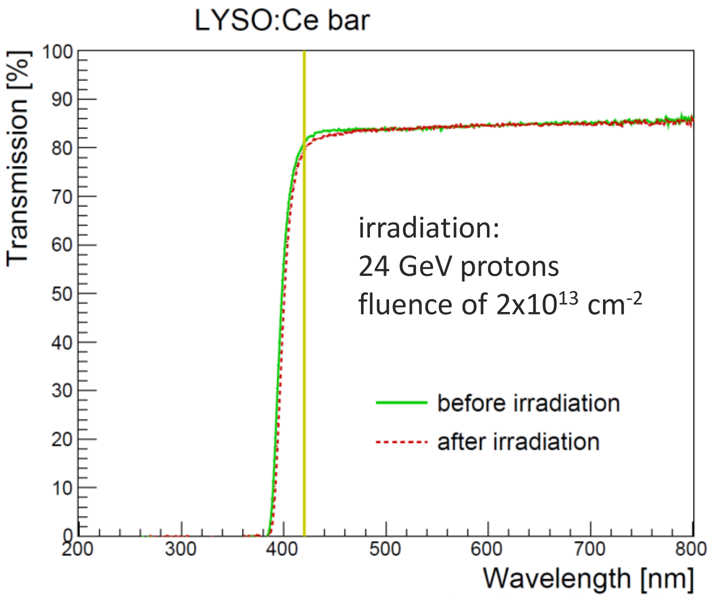


- Velocity measurement from TOF: π/K and K/p discrimination for low p_T hadrons.

MTD barrel: sensor choice

- LYSO:Ce crystal as scintillator
  - Dense (>7.1 g/cm^3)
  - High light yield (40000 ph/MeV)
  - Fast rise time O(100)ps and decay time ~40 ns
  - **Excellent radiation tolerance**

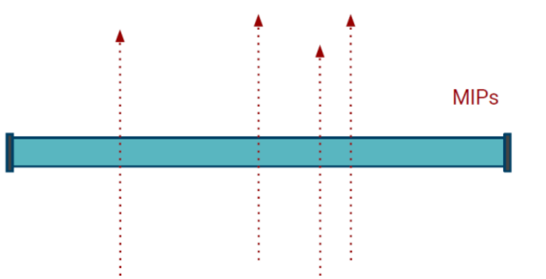


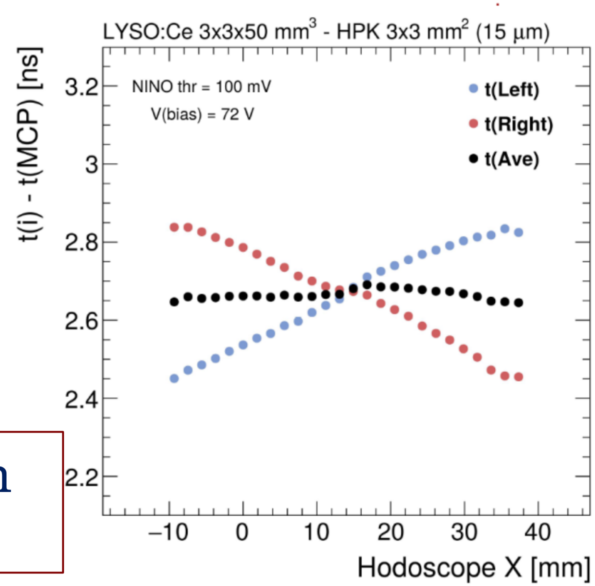


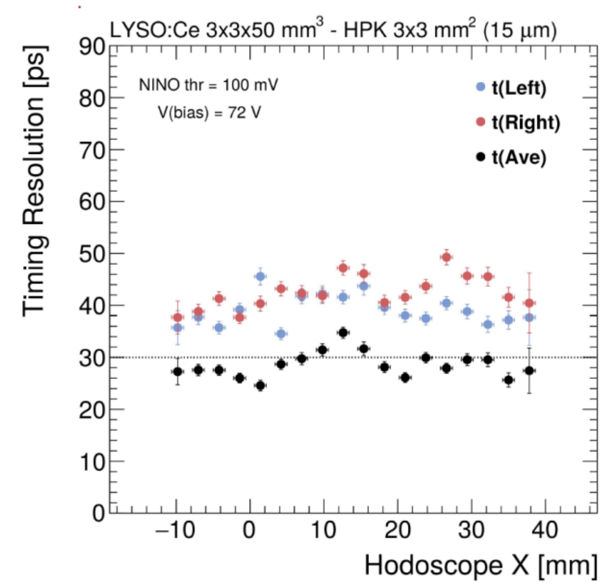
- Silicon Photomultipliers as photo-detectors
  - Compact, insensitive to magnetic fields, fast
  - High dynamic range
  - Good radiation tolerance
  - Good Photon Detection Efficiency at 420 nm: 20-40%

BTL sensor performance (test beam results)

- LYSO (3x3x57 mm) bars read-out by SiPMs at both ends → two different times (left and right) from each channel.
- Time is sensitive to the light propagation along bar.
- **Average time**: uniform response vs impact point, resolution improved and around 30 ps (matching requirements)
- **Time difference**: impact point along the bar with O(5 mm) resolution





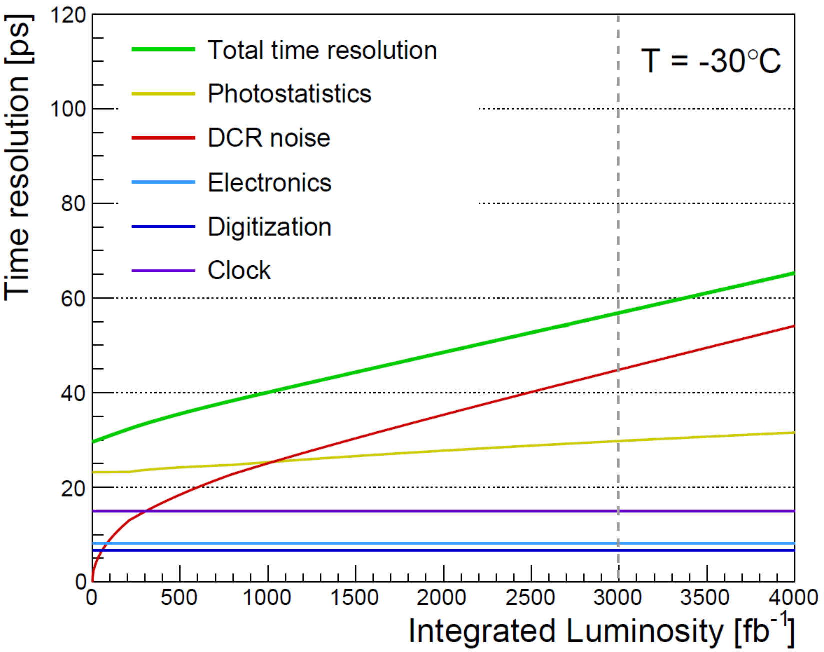


Average MIP deposition in LYSO bars ~ 4 MeV.

BTL timing performance

- Time resolution will degrade with the LHC integrated luminosity.
- Main contribution from Dark Count Rate due to the SiPM defects induced by irradiation.
  - Mitigation cooling at -30 °C
  - Possible mitigation with SiPM annealing during downtime.
- Degradation from photostatistics partially mitigated by tuning bias voltage (and therefore PDE).
- Other contributions are stable in time, not affected by irradiation.

$$\sigma_t^{\mathrm{BTL}} = \sigma_t^{\mathrm{clock}} \oplus \sigma_t^{\mathrm{digi}} \oplus \sigma_t^{\mathrm{ele}} \oplus \sigma_t^{\mathrm{phot}} \oplus \sigma_t^{\mathrm{DCR}}$$



MTD Endcap: the radiation challenge

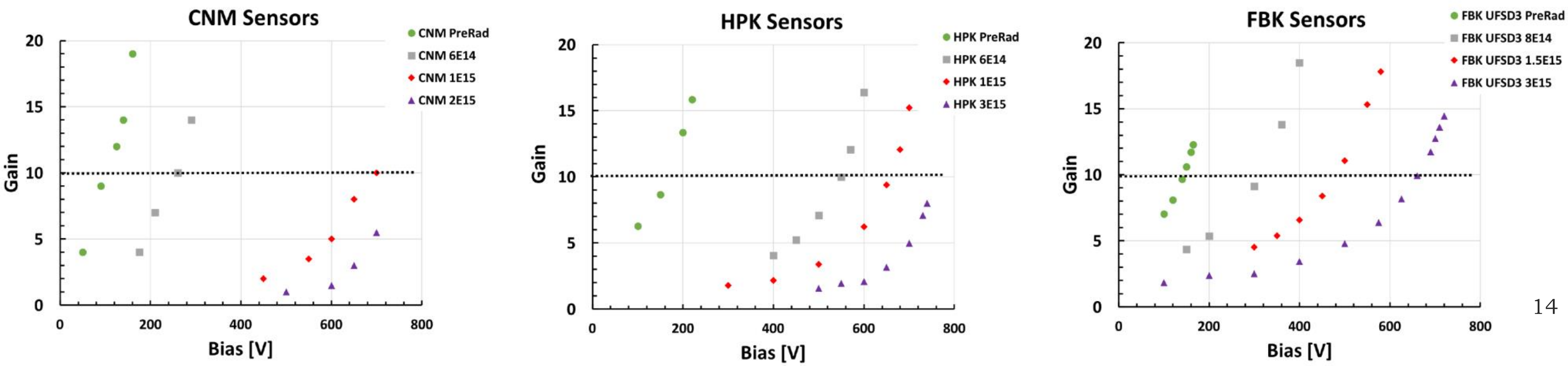
- Higher and non-uniform radiation dose in the Endcap region.
  - A factor 10 in the neutron flux comparing central barrel and outer Endcap
  - A factor 30 in integrated radiation dose.
- SiPM radiation hardness is not adequate for such high doses.
- **Low Gain Avalanche Detectors (LGADs)** will be use in Endcap.
  - Internal gain: 10-30

Region	$\|\eta\|$	r (cm)	z (cm)	3000 fb^{-1} n_{eq}/cm^2	3000 fb^{-1} Dose (kGy)
Barrel	0.0	117	0	1.65×10^{14}	18
Barrel	1.15	117	170	1.80×10^{14}	25
Barrel	1.45	117	240	1.90×10^{14}	29
Endcap	1.6	127	304	1.5×10^{14}	19
Endcap	2.0	84	304	3.0×10^{14}	50
Endcap	2.5	50	304	7.5×10^{14}	170
Endcap	3.0	30	304	1.7×10^{15}	490

ETL sensor performance: radiation resistance

- The low gain is needed to allow segmentation and to keep the leakage current low. However the goal is to maintain a gain > 10 (resolution < 40 ps) until the end of HL-LHC.
- The gain decreases due to the irradiation: tuning of bias voltage to compensate gain loss.

Gain as a function of bias voltage <u>for different neutron fluences</u> for sensors manufactured by Centro Nacional de Microelectronica (CNM), Hamamatsu Photonics (HPK) and Fondazione Bruno Kessler (FBK).



Conclusions

- CMS will upgrade the detector for the HL-LHC (2026-2036) → MTD: a new timing detector to mitigate harsh pile-up conditions.
- This detector will bring a completely new capability to CMS: the ability to measure precisely the production time of MIPs.
- **Barrel Timing Layer**: LYSO:Ce crystals with SiPM readout.
- **Endcap Timing Layer**: LGADs optimized for precision timing.
- Full CMS physics program will benefit: PU reduction, lepton and photon reconstruction, increase of effective luminosity, etc.
- Successful test beam campaign in progress: results show good agreement with expectation.
- A time resolution of 30 ps is achievable both in BTL and ETL; will degrade to only 40-60 ps at the end of HL-LHC.
- **MTD Technical Design Report** will be public in the next few weeks.