The CMS ECAL Upgrade for Precision Crystal Calorimetry at the HL-LHC

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On behalf of the CMS collaboration

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Outline

The CMS ECAL

- **at LHC**:
  - ➔ Results and performance during RunI and RunII.
- **at HL-LHC:**
  - ➔ Detector challenges.
    - ➔ Trigger.
    - ➔ Pile-up and noise mitigation.
  - ➔ Upgrade design and goals.
  - ➔ Prospects for the upgraded detector.

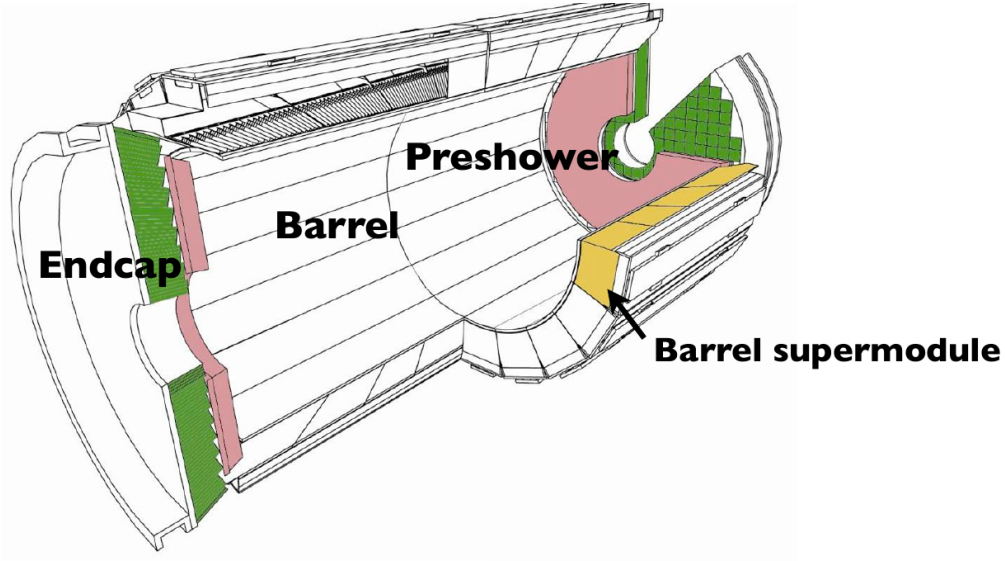
The CMS ECAL

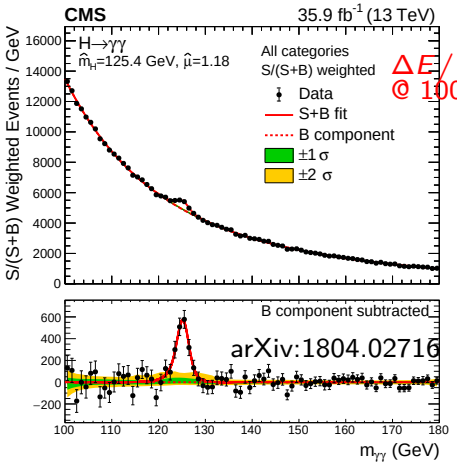
- **CMS main features are the compact design and the high (3.8 T) magnetic field.**

- The CMS ECAL is an homogeneous crystal scintillator ($PbWO_4$), the design was driven by volume constrains and energy performance requirements.

- **ECAL has been a key component for the observation of the Higgs boson**.

  ➔ **Excellent resolution** and **electron/photon ID** crucial for Higgs analysis.





$\Delta E/E = 0.5\%$ @ 100GeV

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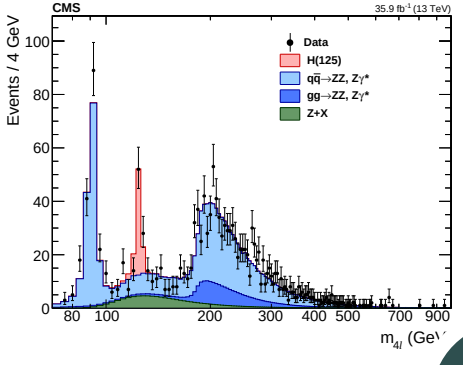


HL-LHC and CMS upgrades

- **HL-LHC goal**: $\times 10$ **integrated luminosity** delivered to the experiments (ATLAS, CMS):

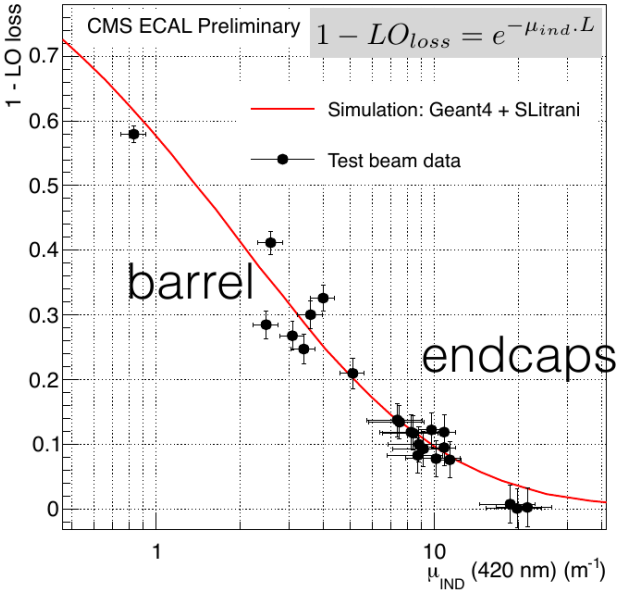
	LHC	HL-LHC baseline	HL-LHC ultimate*
$\mathcal{L}_{inst}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	2×10^{34}	5×10^{34}	7.5×10^{34}
PU (n_{vtxs})	40-60	140	200

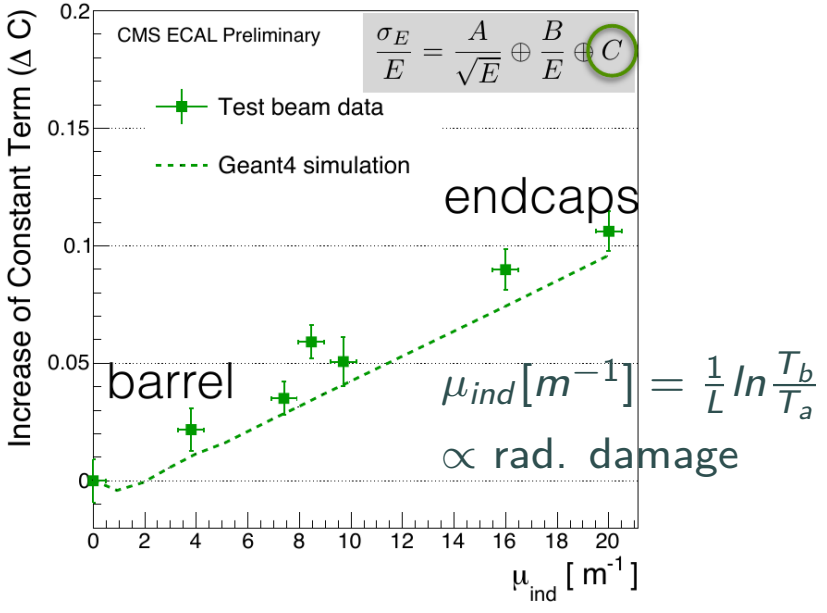
*unexpected at the time of original ECAL TDR.

- **CMS upgrade**
  - ➔ Larger tracker ($|\eta| = 4$) and muon spectrometer ($|\eta| = 2.8$) acceptances.
  - ➔ Larger first level trigger (L1) rate: 100kHz ➔750kHz.
  - ➔ Tracking information at L1.
  - ➔ Detector upgrades to cope with larger radiation levels and higher pile-up.

CMS calorimeters at HL-LHC

- **Endcaps**: complete replacement of current calorimeters to cope with expected radiation flux.
  - ➔ Radiation tolerant high granularity, silicon based, sampling calorimeter (HGCAL).
- **Barrel**: same technology ➔upgraded readout electronics.
  - ➔ **ECAL**: $PbWO_4$ + APD.
  - ➔ **HCAL**: Brass/plastic scintillator + SiPM.



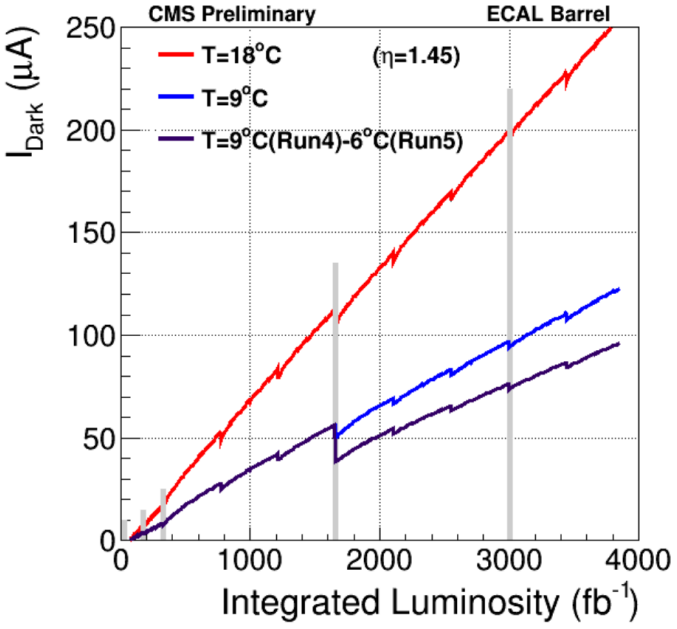


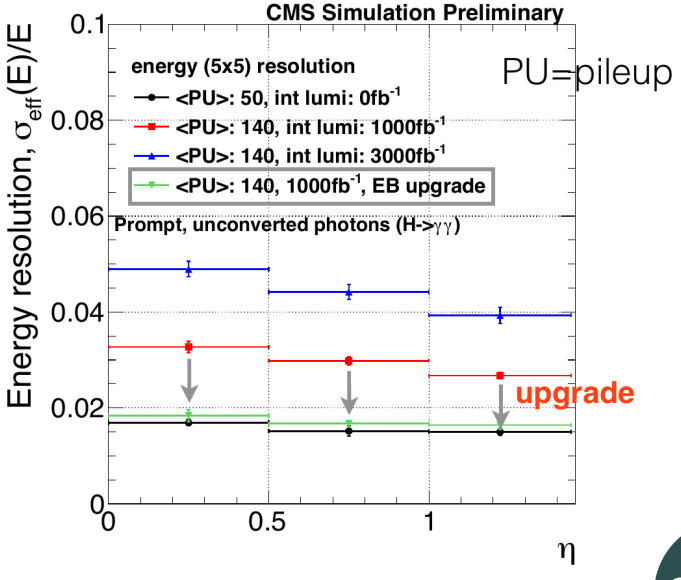
Barrel crystals will retain 50% of the light output after 3000 fb^{-1}.

Limited degradation of energy resolution.

ECAL APD performance

- ECAL barrel photo-sensors will continue to operate during HL-LHC:
  - ➔ Increase in APD leakage current due to radiation damage ➔**APD noise will dominate HL-LHC energy resolution**.
  - ➔ **Mitigation**:
    - ➔ **Lower ECAL operation temperature** $6 - 9°C$ (now $18°C$).
    - ➔ **Shorter pre-amplifier shaping time (reduce PU impact, better S/N)**.

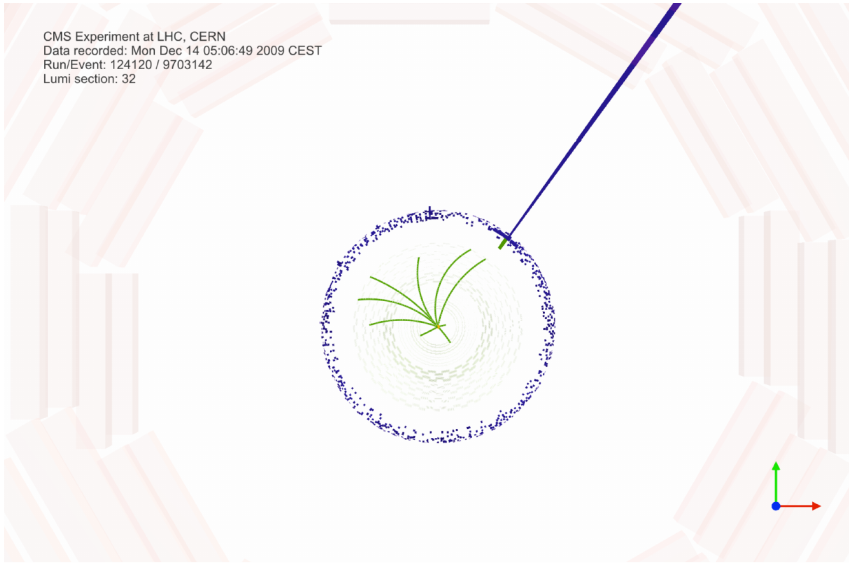




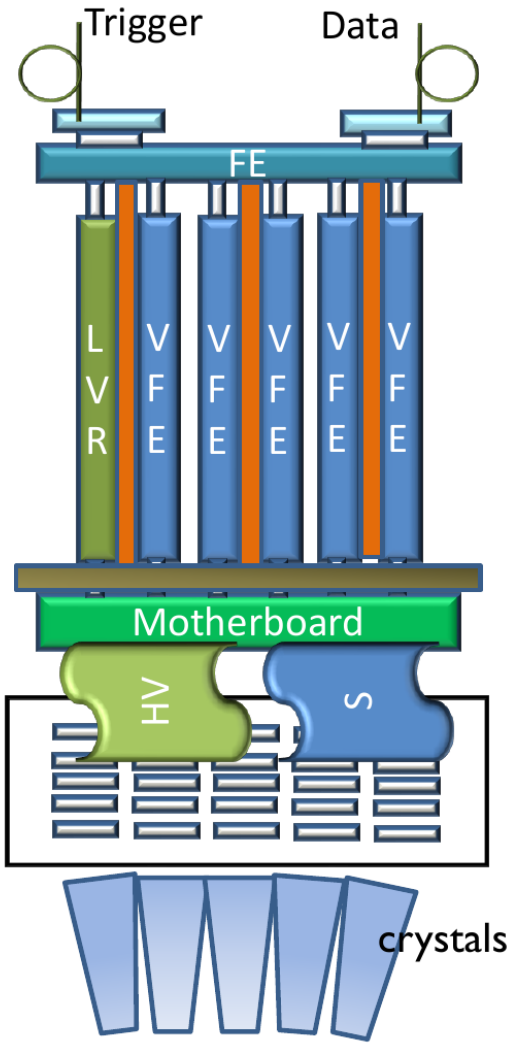
ECAL trigger

- **Improved Level-1 trigger capabilities needed at HL-LHC**:
  - ➔ **larger trigger rates** and **trigger latencies** mandatory to exploit increased luminosity and implement Level-1 track-trigger.

- **Improved rejection of ECAL APD anomalous signals required**.
  - ➔ "Spike" from direct hadron ionization in APD volume.
    - ➔ Large isolated signals.
    - ➔ Faster signal than scintillation.
  - ➔ **Will dominate L1 trigger at HL-LHC if unsuppressed.**



ECAL upgrade key aspects

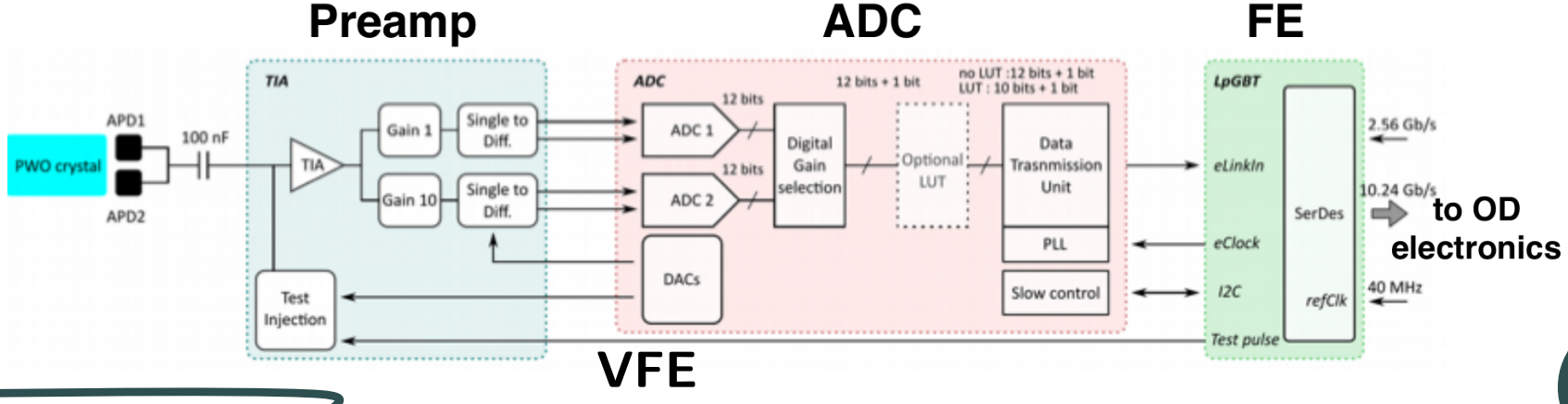


- **Replace off-detector electronics:**
  - ➔ To cope with higher output bandwidth from FE and upgraded CMS L1 trigger.
- **Replace on-detector electronics** (VFE and FE):
  - ➔ New pre-amplifier + ADC running at 160MHz.
    - ➔ Spike rejection, pileup and noise mitigation.
    - ➔ Precise time measurement.
- **Run Colder:**
  - ➔ mitigate increase in radiation induced APD noise.

The upgrade is needed to retain the excellent CMS ECAL performance.

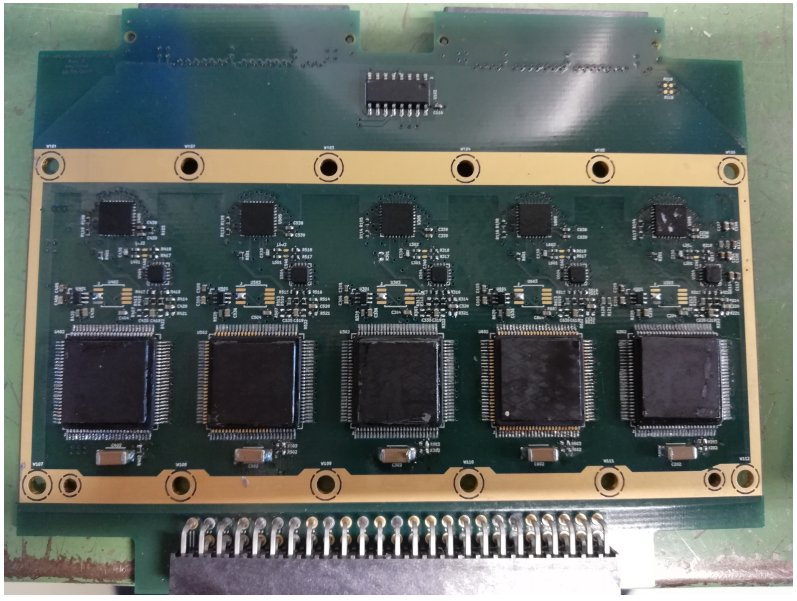
TDR design choices

- **Pre-amplifier:** Trans Impedance Amplifier (TIA) architecture:
  - ➔ matches the requirements for noise, pileup mitigation and CMS-wide effort for hermetic precision timing.
  - ➔ 2 TeV dynamic range (two gain ranges, G1 and G10) with 10 MeV LSB.
- **ADC designed chosen**: 12 bit, 160MHz sampling frequency.
  - ➔ Custom chip designed by external company + data compression system.
- **FE card design**:
  - ➔ Fast optical links to stream crystal data off-detector through CERN lpGBT/VL+ chip.
- **Off-detector electronics (OD)**:
  - ➔ FPGA based. Will provide single crystal information to L1 trigger (750 kHz, 12.5 μs latency).

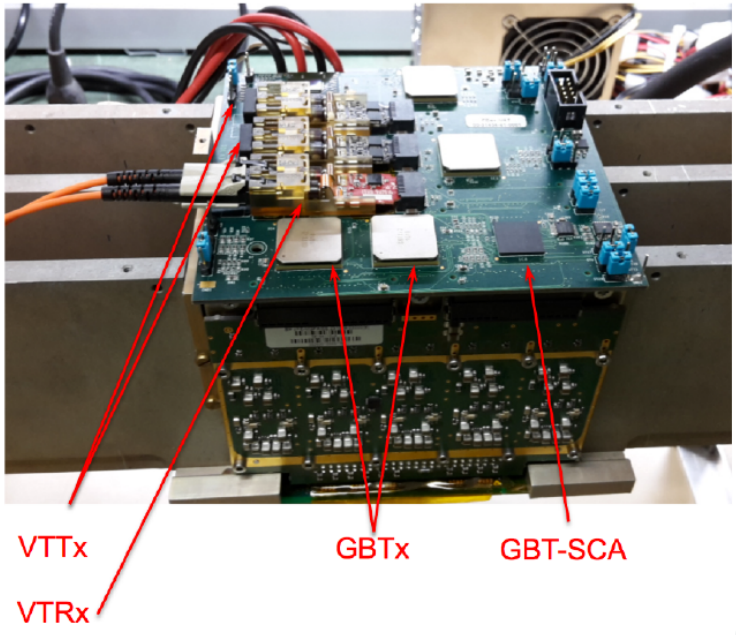


VFE and FE R&D progress

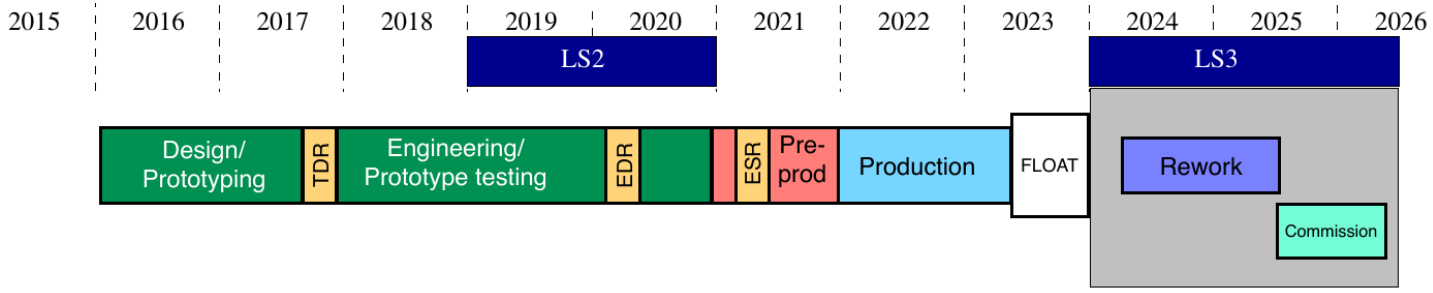
- **VFE prototype (TIA)** tested in recent test beams:
  - Noise performance matches expectation for HL-LHC.



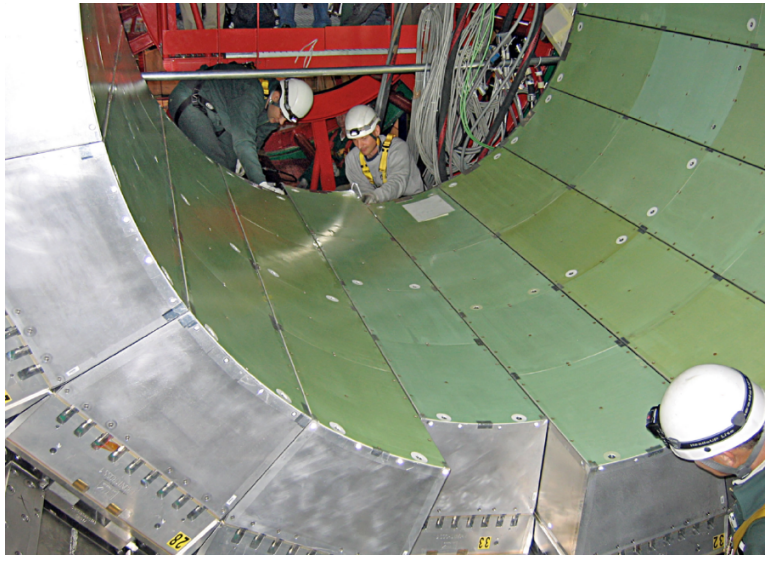
- **FE demonstrator equipped with GBT chips:**
  - Data streaming tested with legacy VFE and trigger boards.



Detector refurbishment

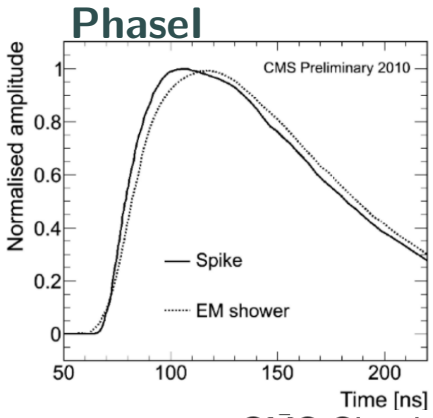


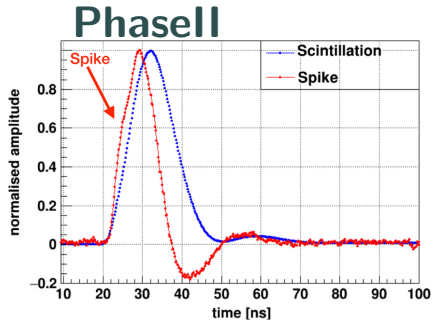
- **Replacement of all detector services** during CERN LS3:
  - ➔ LV/HV lines, cooling pipes, readout and control links.
  - ➔ Improve insulation of water cooling pipes coupled to new cooling system.
    - ➔ **Will allow to cool the detector to** $9^{\circ}C$. Lower temperatures will require further upgrades of the cooling system.



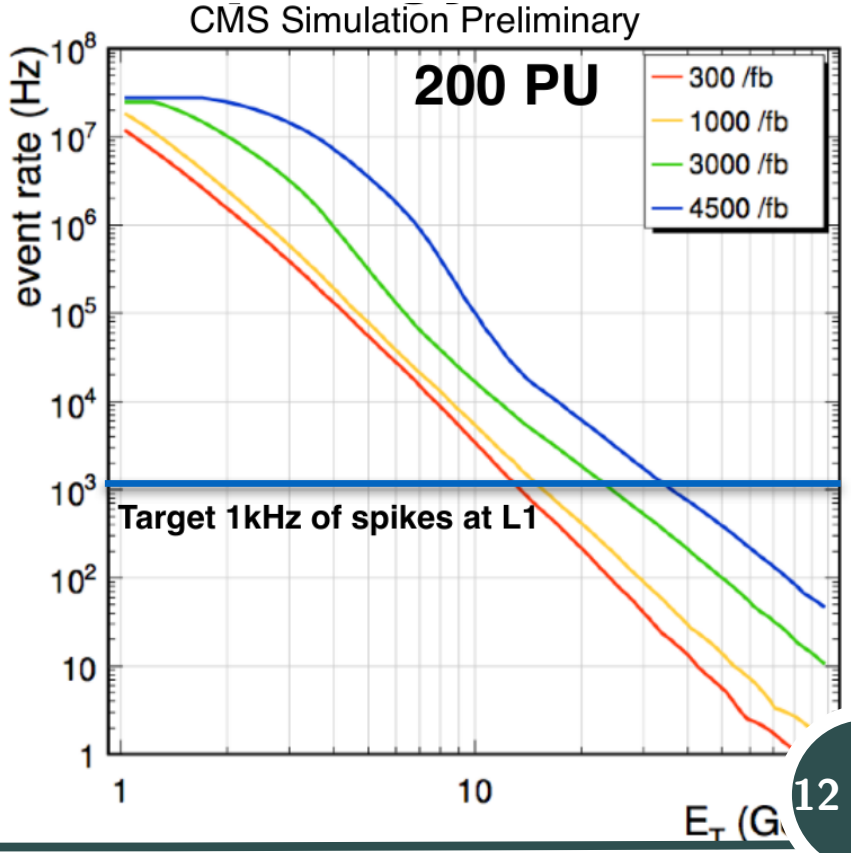
ECAL upgrade impact on trigger

- **Spike suppression target: 1kHz @ L1 trigger** ($E_T > 5$ GeV).





- **Shower shape discrimination**: sensitive to noise and PU.
- Even with single crystal granularity the method used during Phase-I does not provide enough spike suppression.



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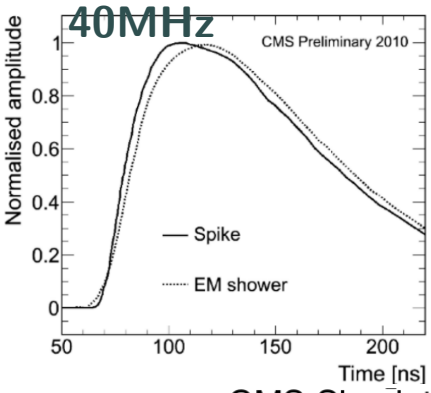
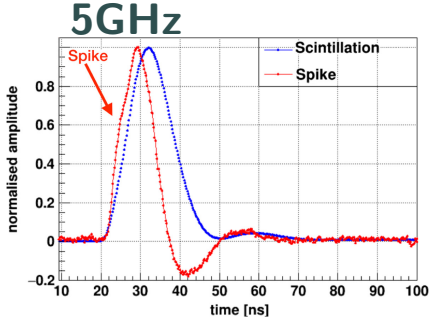
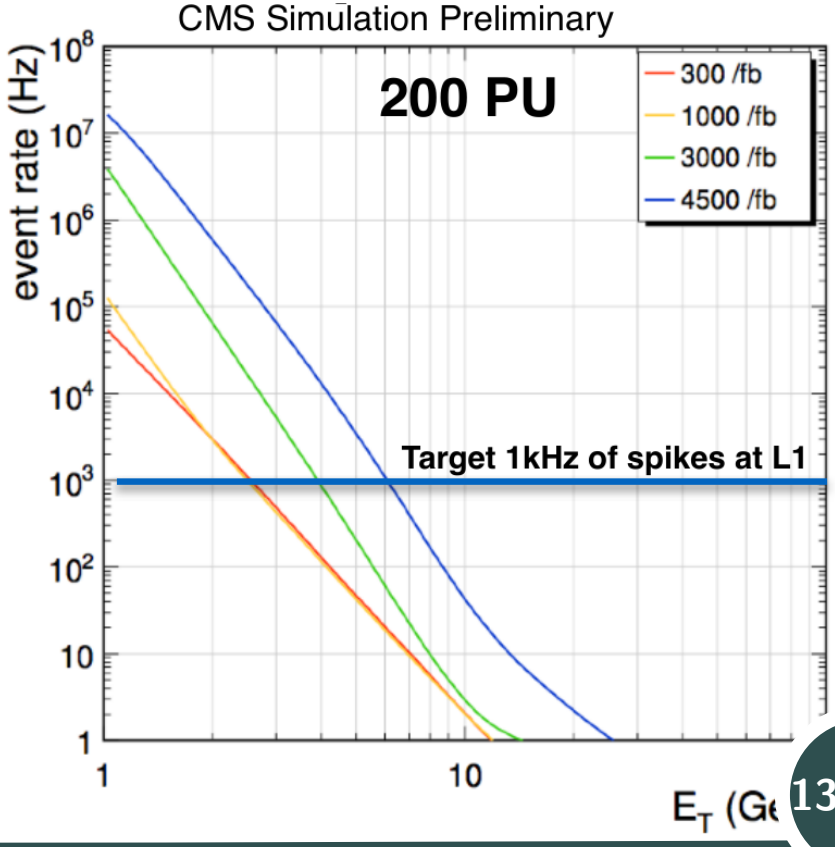




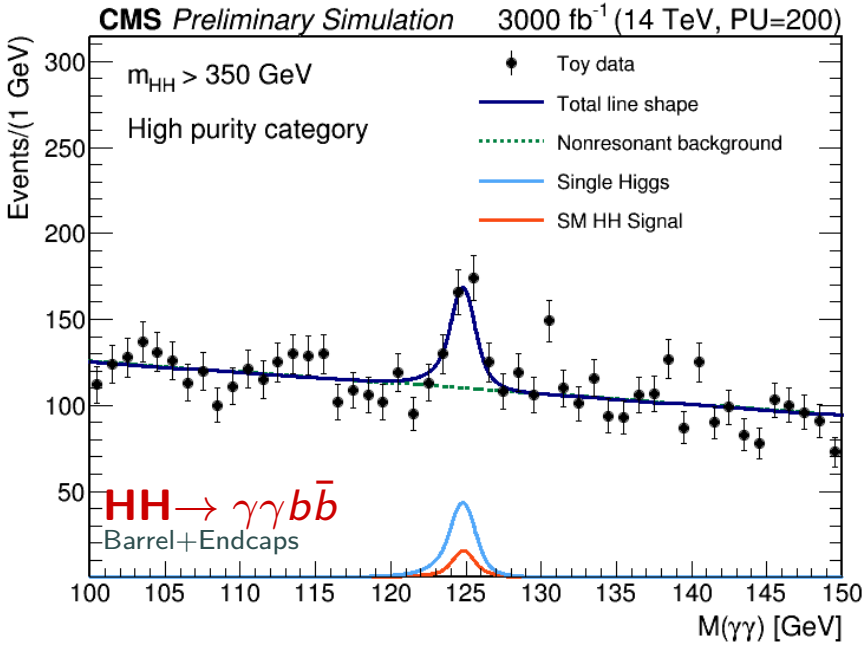
- **Shape discrimination essential to achieve desired suppression level**.
  - ➔ Requires faster pre-amp and higher sampling frequency.



ECAL upgrade impact on physics analysis

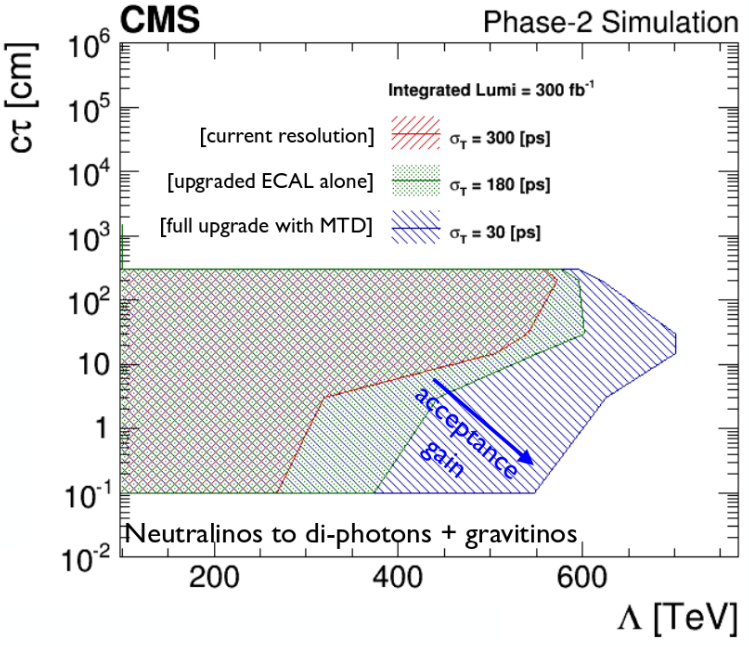
- **CMS physics program** at HL-LHC includes:
  - ➔ Precise measurement of the Higgs properties (e.g. self-coupling).
  - ➔ Search for BSM in exotic channels.

ECAL energy resolution.



ECAL time resolution.

+ hermetic precision timing.



Summary

- **CMS ECAL performance has been key to the Higgs discovery/characterization during LHC RunI/II.**

- **Upgrade needed to maintain great performance throughout HL-LHC**:
  - ➔ Mitigate noise/pileup increase.
  - ➔ Improve trigger capabilities.
  - ➔ Add precise time information to the event reconstruction.
  - ➔ TDR published last year, **prototypes being tested.**

- **Upgraded detector will again impact key aspect of the CMS physics program.**

Additional material

Scintillation signal vs temperature.

- No significant shape changes with crystal temperature observed in TB (TIA prototype + 5GHz ADC).