HL-LHC performance of CMS

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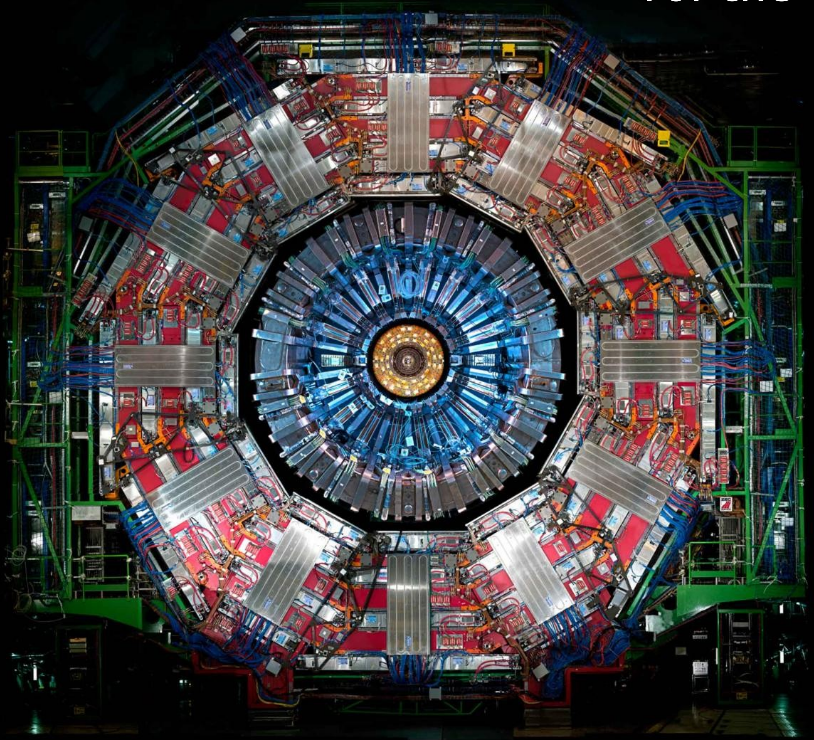
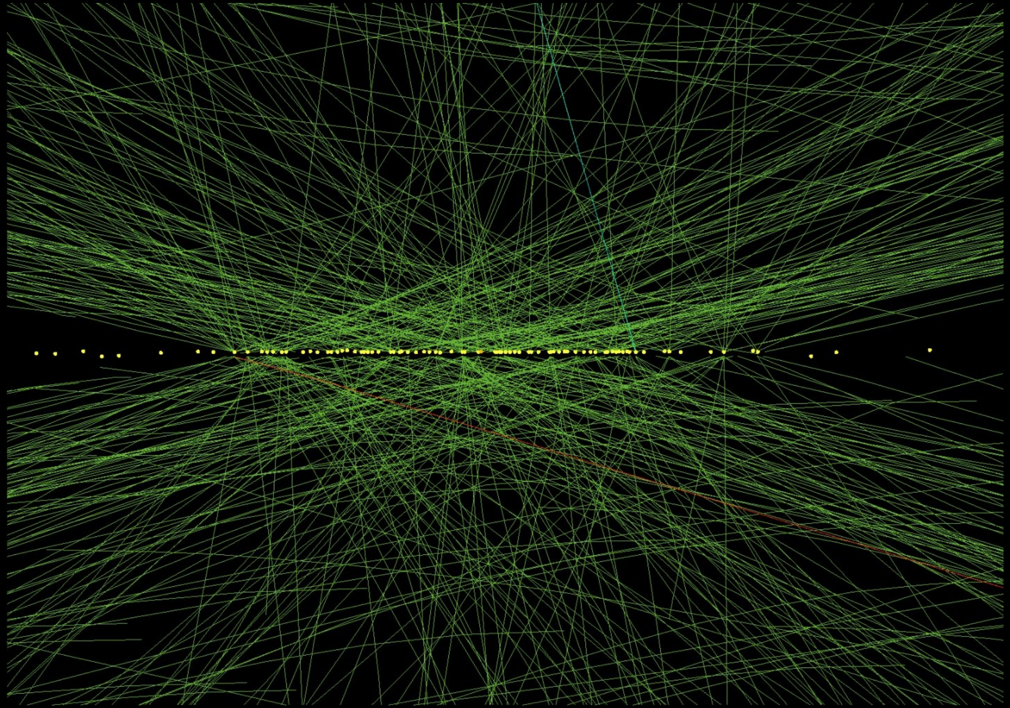
for the CMS Collaboration



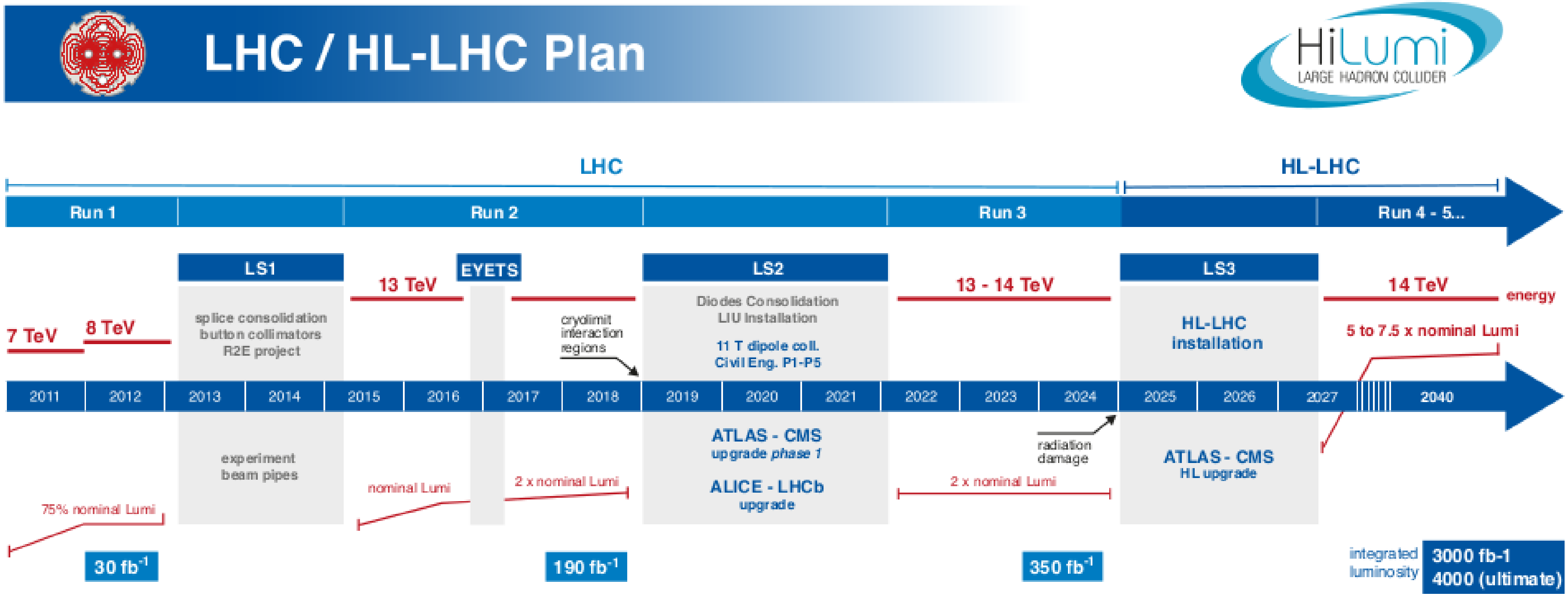


VBS at Snowmass 26th Jan 2021

Outline

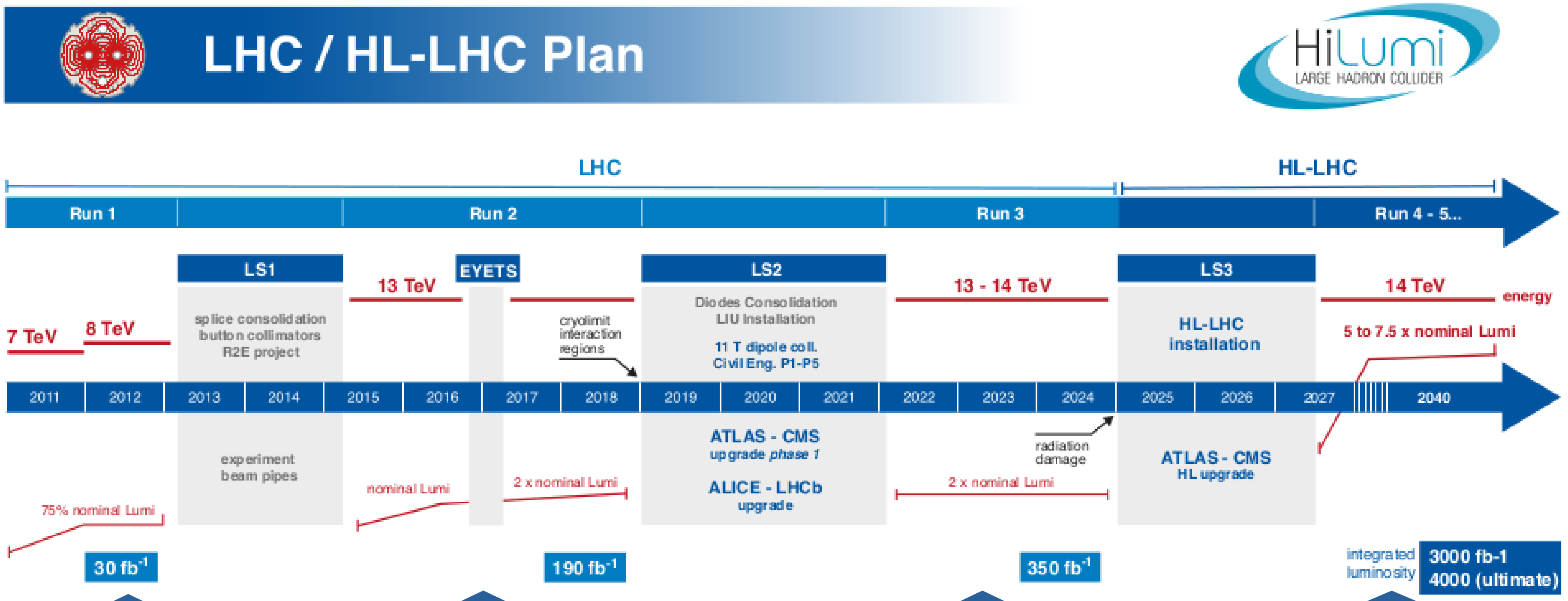
- Introduction
- The CMS detector
- Challenges in the HL-LHC era
  - High radiation environment
    → need to use radiation-hard materials in both the detectors and front-end electronics
  - High pileup environment
    → deal with higher multiplicity, increased trigger rate and tricky event reconstruction
- The HL-LHC CMS upgrade
- Conclusions

LHC: the plan



- HL-LHC goal: collect 3000 fb^{-1} (4000 fb^{-1} in best case scenario)
- Increasing the luminosity is experimentally challenging, for both accelerator and detectors
- While the c.m. energy stays the same, luminosity increases by a factor 3 at HL-LHC wrt Run 3

LHC: the plan



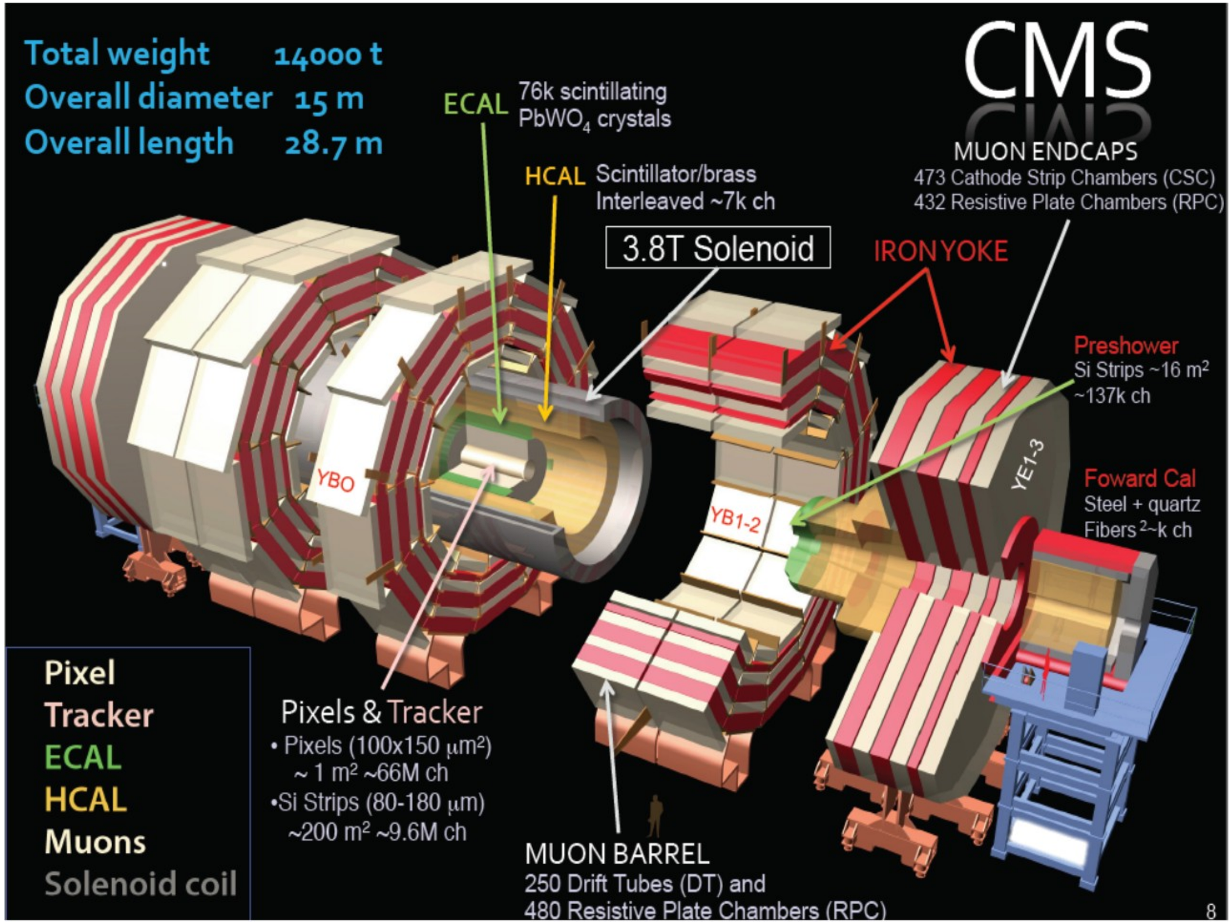
$0.75 \cdot 10^{34}$ cm^{-2}s^{-1}
50 ns / bunch
<pile up> ~ 40

$1.5 \div 2 \cdot 10^{34}$ cm^{-2}s^{-1}
25 ns / bunch
<pile up> ~ 40÷60

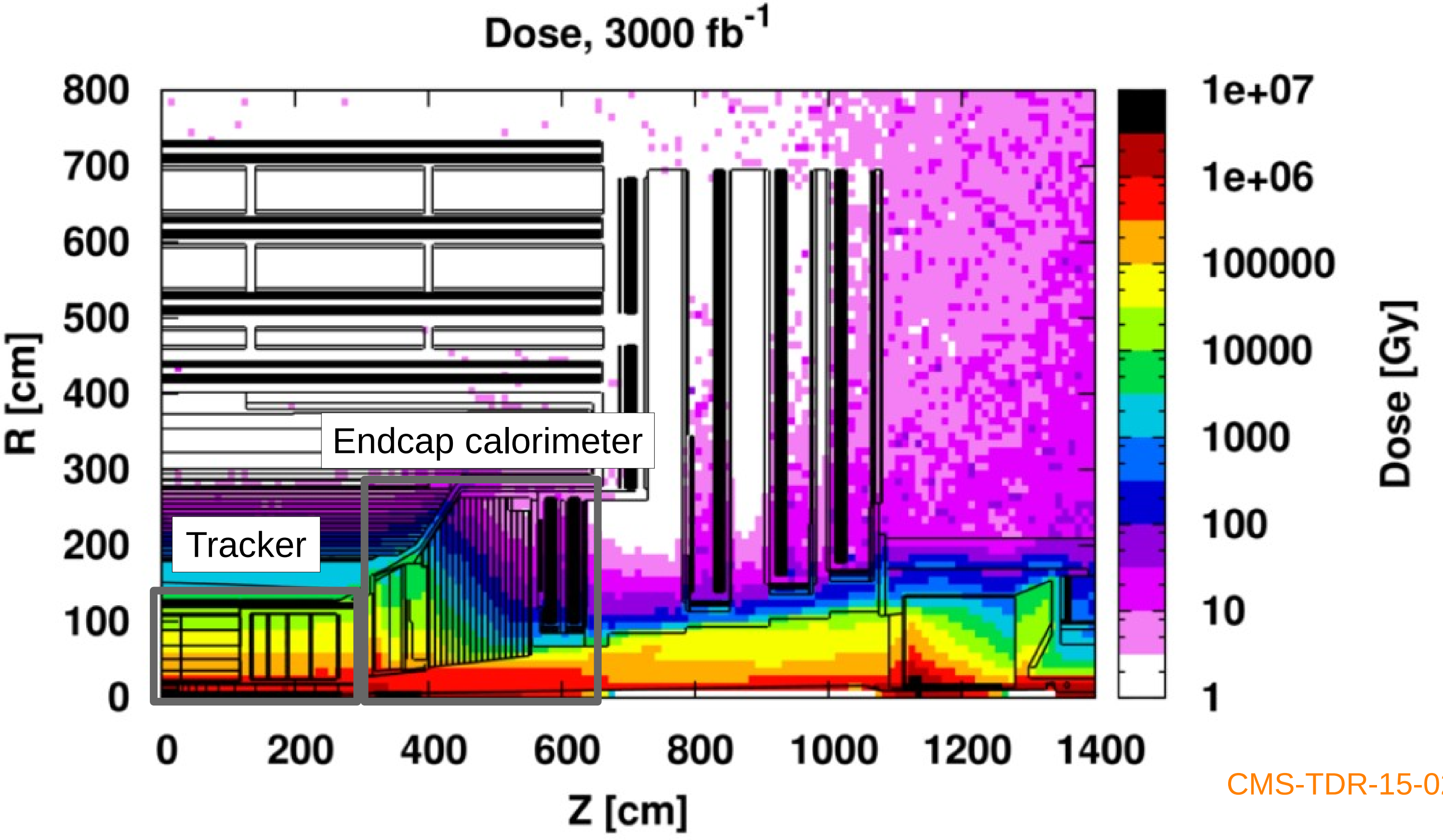
$2 \div 3 \cdot 10^{34}$ cm^{-2}s^{-1}
25 ns / bunch
<pile up> ~ 60

$5 \div 7.5 \cdot 10^{34}$ cm^{-2}s^{-1}
25 ns / bunch
<pile up> ~ 140÷200

The CMS detector



Radiation environment



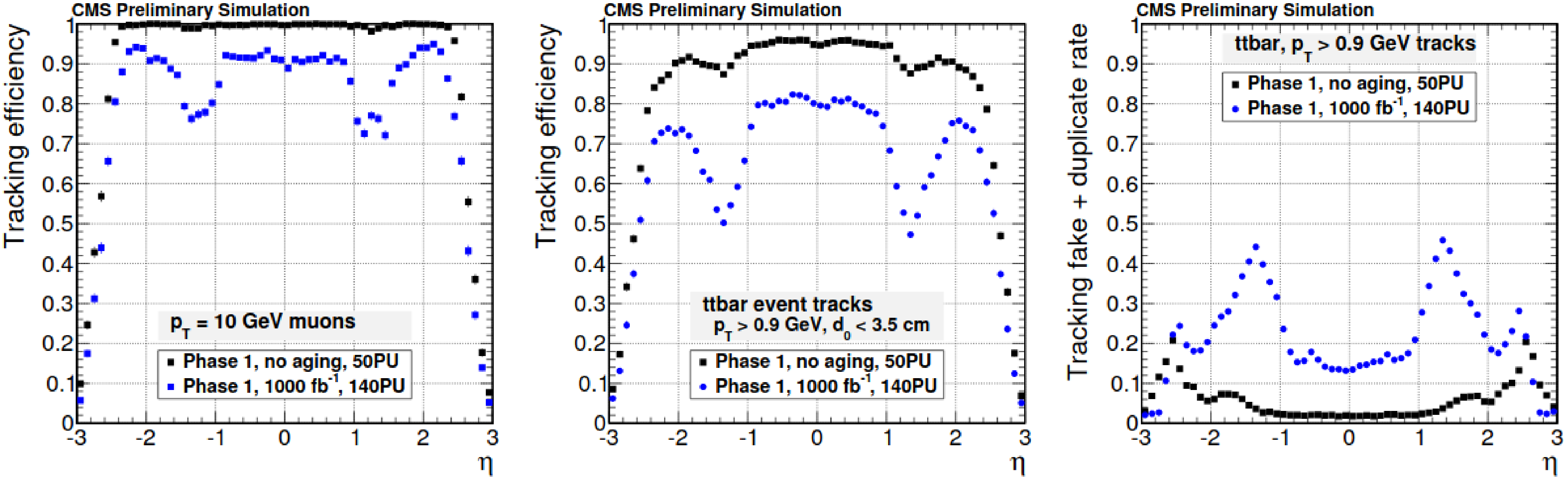
CMS-TDR-15-02

Predicted total radiation dose in CMS at 3000 fb^{-1}

HL-LHC upgrades strategy

- Maintain current performance at extreme PU
- Sustain rates and radiation doses

Current CMS tracker in HL-LHC environment

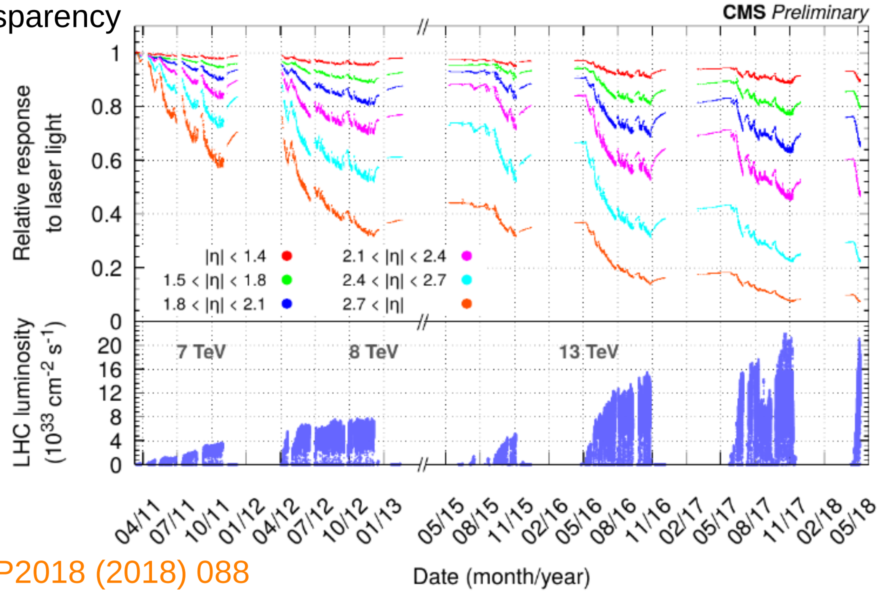


CMS-TDR-15-02

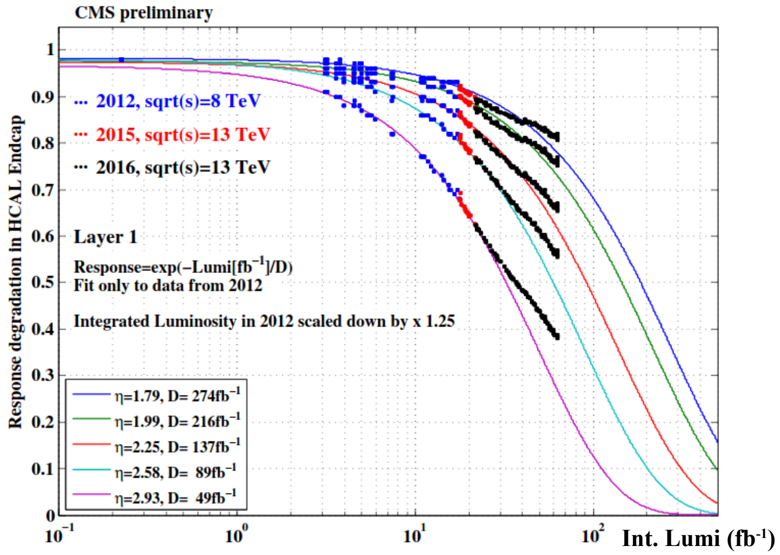
- Current tracker designed to sustain a luminosity of $1 \cdot 10^{34} cm^{-2} s^{-1}$
- Expected to start degrading at 500 fb^{-1}
- Spatial resolution decreased due to decreased charge sharing between neighboring pixels
- Leakage current increases dramatically, compromising many modules

Current CMS calorimeters response

ECAL transparency
(Run 1/2)



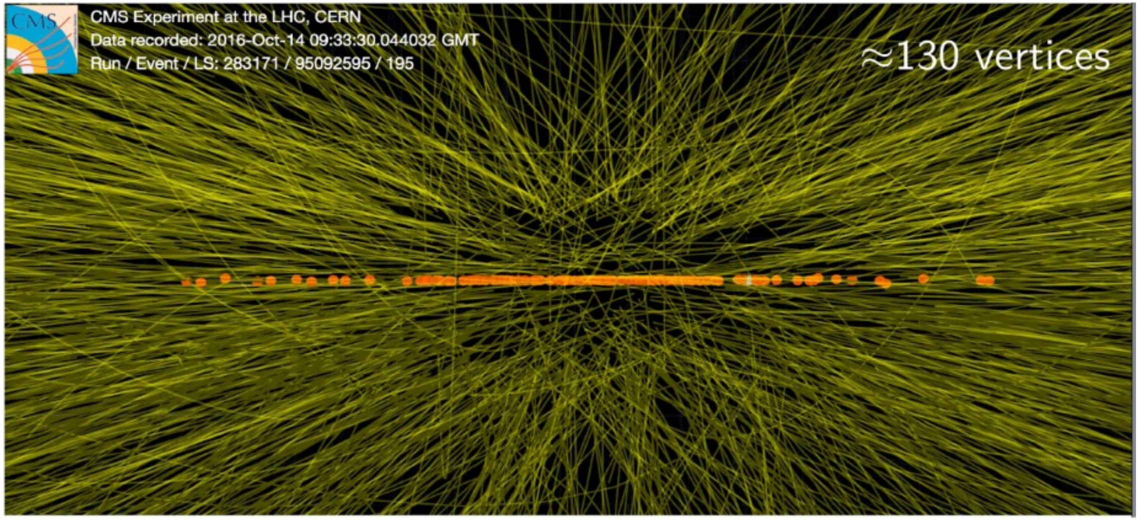
PoS LHCP2018 (2018) 088



CMS-CR-2017-293

- Extensive studies of radiation damage
  - With test electron beams and using CMS data from Run 1 / Run 2
  - Compared with full CMS simulations
- Results of studies
  - Barrel ECAL/HCAL can survive 3000 fb^{-1}, if upgraded
  - Must replace ECAL and HCAL endcaps before HL-LHC

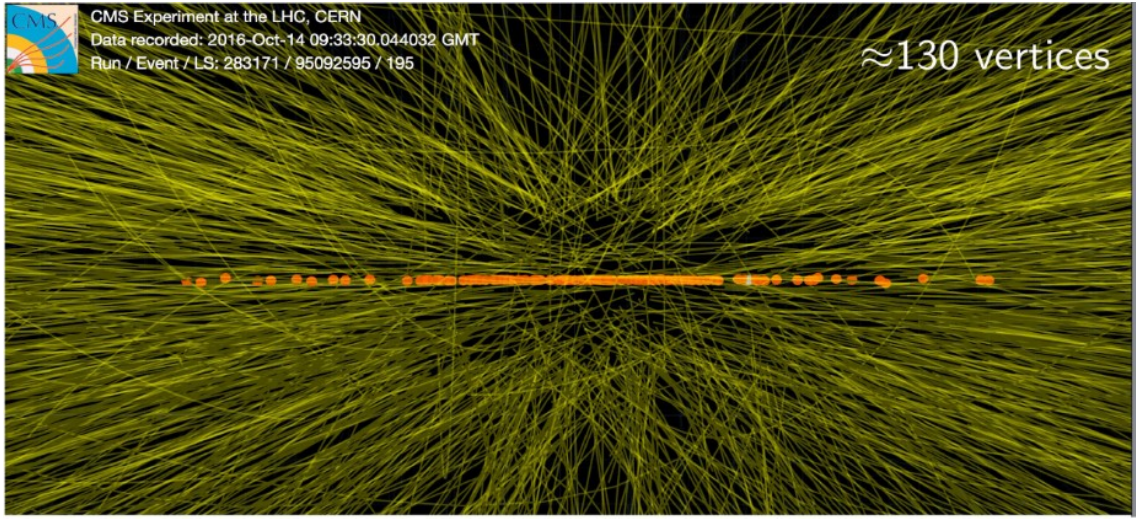
Pileup environment



A CMS event from a special run in 2016 with HL-LHC like pileup interactions

- Extremely harsh operating condition
  - Expected average pileup of 140÷200
  - Increased particle density
  - Extra energy in calorimeters
- L1 trigger rate at 40 MHz can't rely on calorimeter + muon info only
  - Track info at L1 crucial to retain full physics potential

Pileup environment



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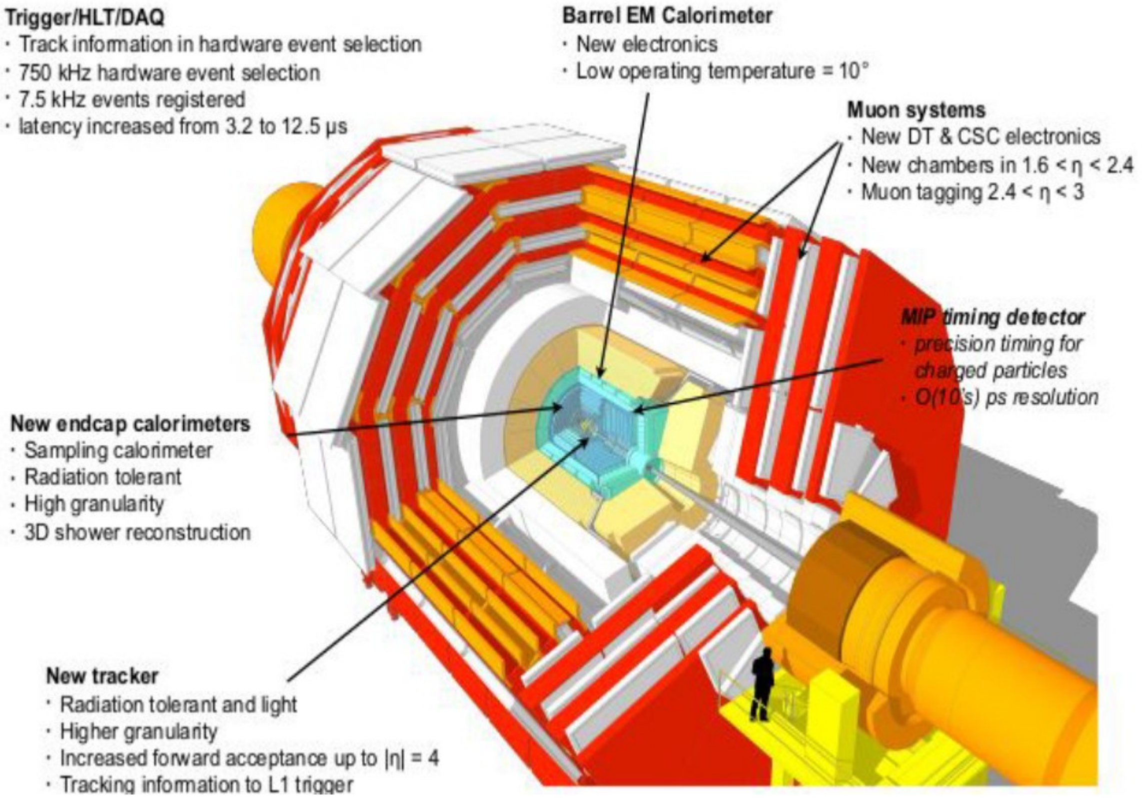
- Pileup mitigation
  → High granularity detectors needed to identify particles associated with the primary vertex with high efficiency
  → Precise timing measurement in tracker and calorimeters to associate tracks and energy clusters to each vertex

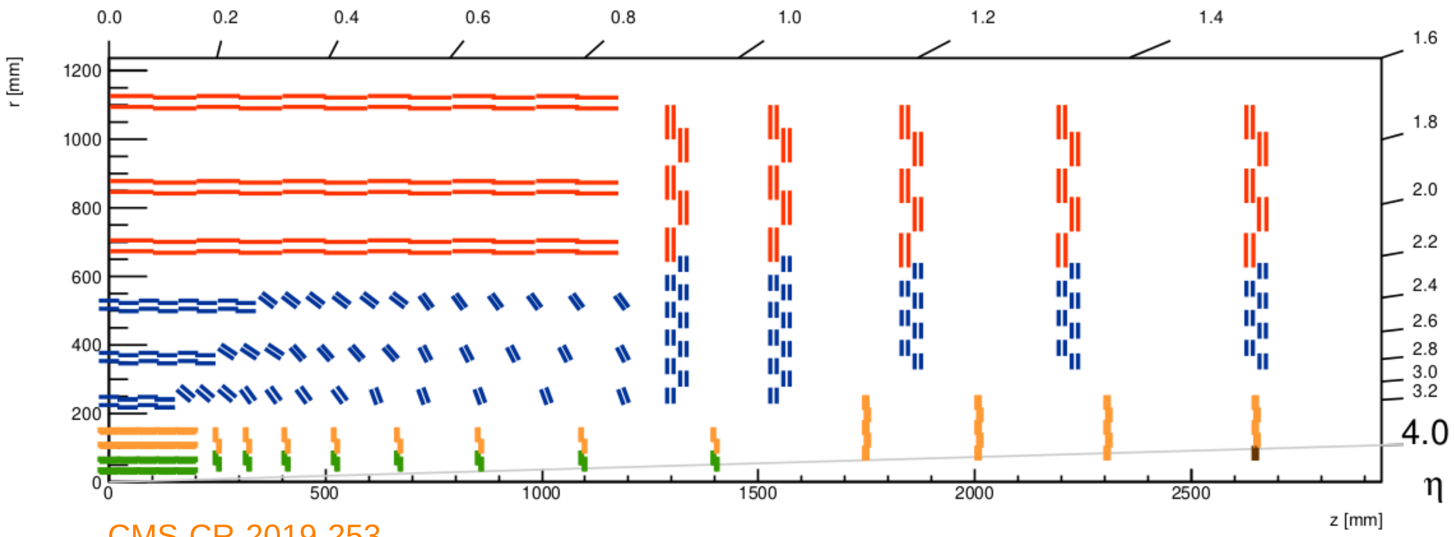
CMS Phase-2 upgrade overview



- CMS upgrades include
  - a new tracker with improved radiation hardness and p_T resolution
  - increased muon coverage
  - a new forward calorimeter with high granularity and resolution (HGCAL)
  - replacing electronics
  - increased trigger bandwidth and latencies
  - track info used at L1 trigger
- The Phase-2 upgrade of the CMS detector is expected to perform even better than current detector
  - longer lifetime of detectors
  - increased readout bandwidth
  - pileup mitigation

Phase-2 tracker upgrade

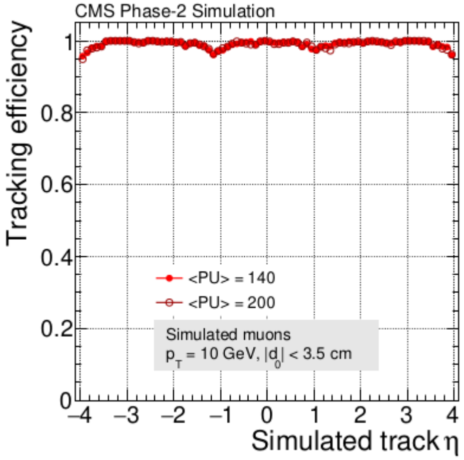
- The tracker is designed to
  - withstand > 3000 fb^{-1} and increased radiation levels
  - cope with the occupancy demands
- Addition of hardware track to trigger capabilities
  - detector modules will have built-in capability to select high-pT (≥2 GeV) tracks
  - tracker information at L1 trigger to reduce event rate still keeping physical potential

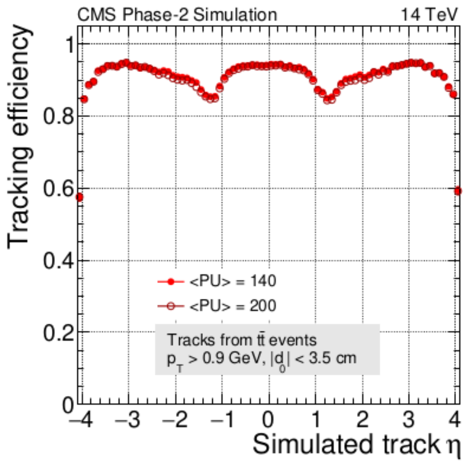


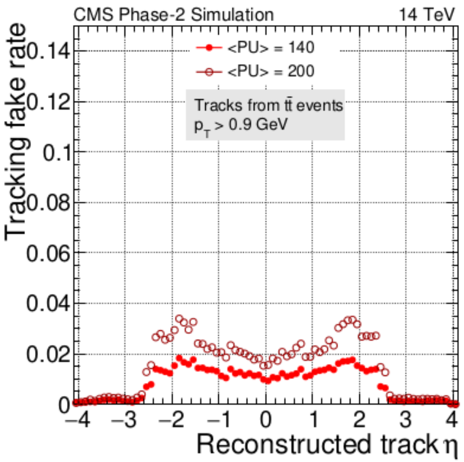
CMS-CR-2019-253

- Inner tracker (IT)
  - pixel sensors
  - narrower pitch than current pixel detector
  - increased granularity
  - coverage up to |η|=4.0
  - 1x2 and 2x2 ROCs
- Outer tracker (OT)
  - design driven by addition of trigger hardware
  - pixel-strip & 2-strip sensors
  - progressively tilted modules

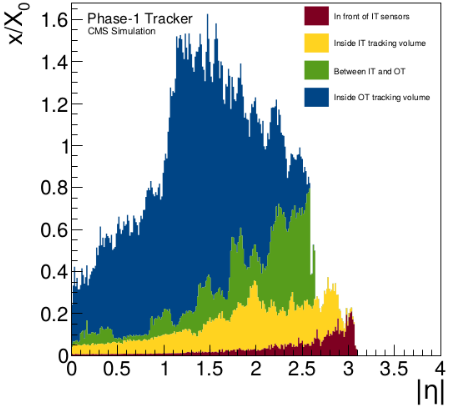
Phase-2 tracker performances

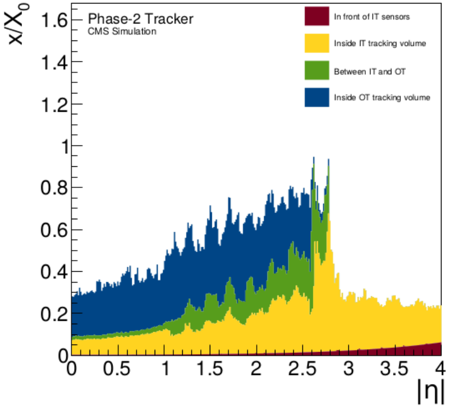






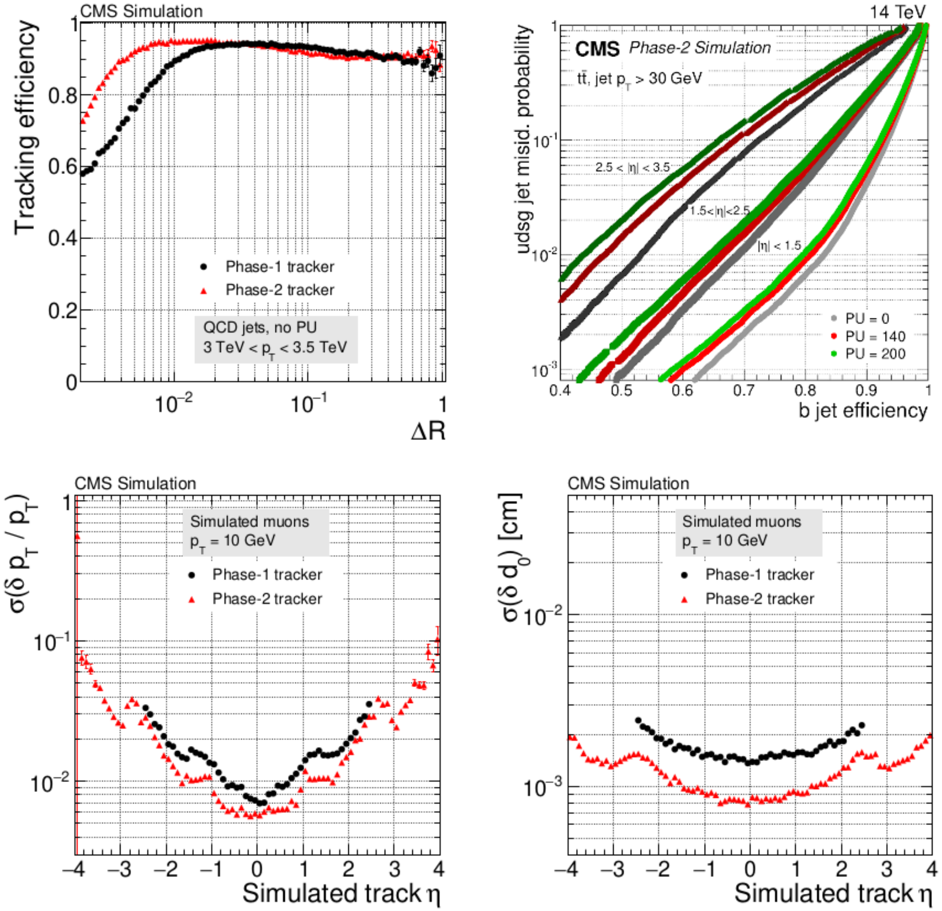
CMS-TDR-014





- High efficiency maintained over the full η coverage both for muons (p_T=10 GeV) and tt events (p_T>0.9 GeV)
- Level of fake tracks increases with pileup, but still under control (always <4% even at 200 PU)
- Substantial reduction of material budget with respect to Phase-1 tracker

Tracking performance Phase-1 vs 2

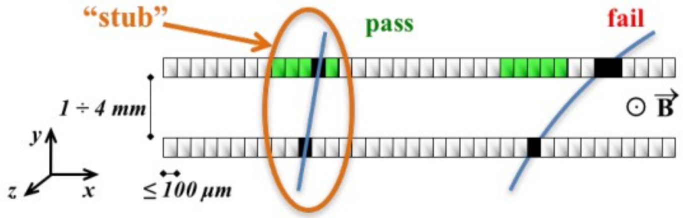


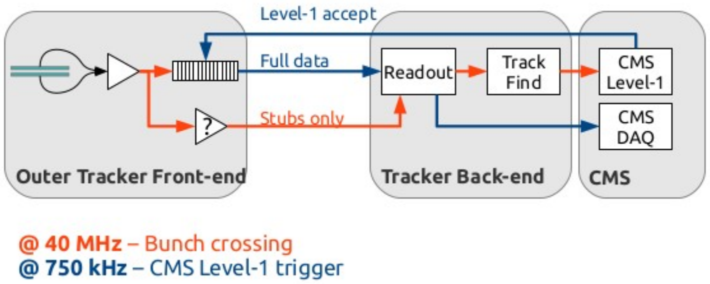
- Extended η coverage
- Increased tracking efficiency
- Improved p_T resolution in Phase-2 tracker
- Improved resolution on impact parameter d_0
- b-tagging extended to high η region

CMS-TDR-014

L1 tracking

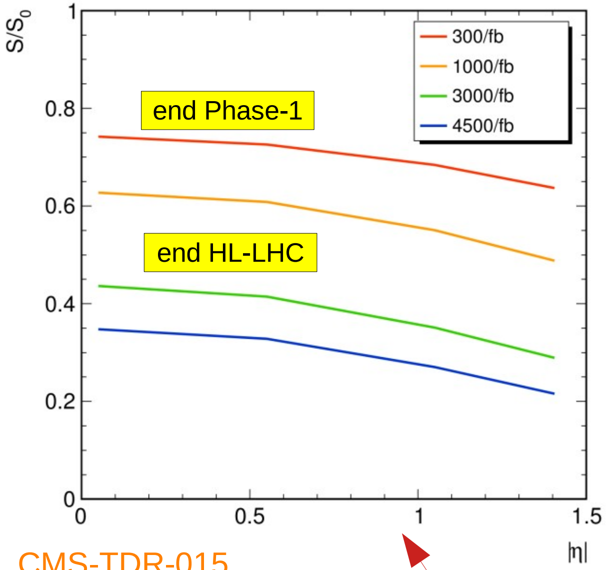
- Availability of tracking information at L1 enables CMS to
  - improve p_T resolution of various objects (e.g. muons)
  - mitigate impact of pileup interactions
  - exploit track isolation
  - perform particle-flow reconstruction of physics objects at the trigger level
- The detector front-end of OT modules is designed to select high-p_T tracks at
  - two closely-spaced single-sided sensors
  - a local p_T measurement is possible by correlating hits on the two sensors
  - limited in angular acceptance up to |η|=2.4



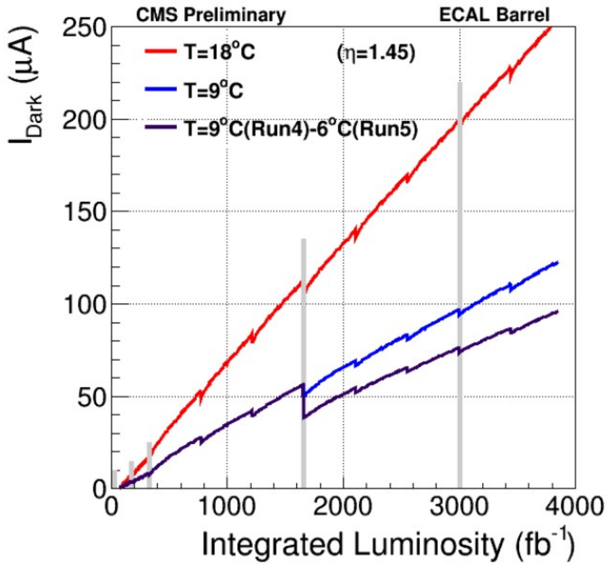


CMS-CR-2019-253

Phase-2 ECAL upgrade



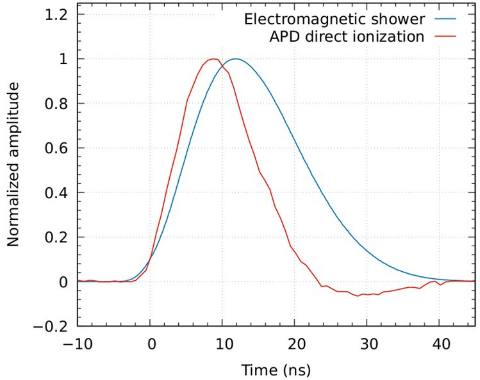
CMS-TDR-015



The upgrades include:

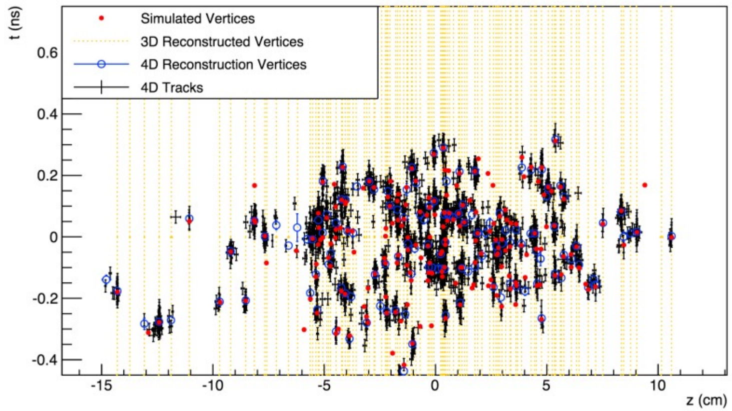
- Crystal geometry untouched
- Single crystal info at L1 trigger instead of 5x5 crystal tower
- Front-end + readout electronics upgraded to cope with trigger requirements
- Shorter signal length allows to distinguish between EM shower and anomalous spikes in APDs

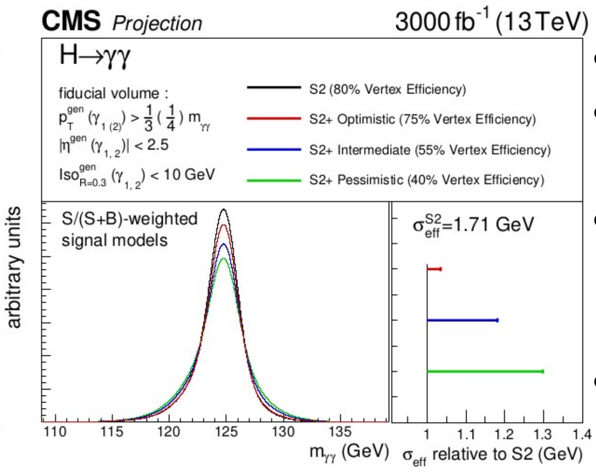
- Phase-1 crystals are kept since the transparency loss will be only 50% of the phase-1 value
- Increased radiation corresponds to increased dark current in APDs
  → can be kept under control by further cooling the detector to 9°C



PoS LeptonPhoton2019 (2019) 097

Phase-2 ECAL resolution



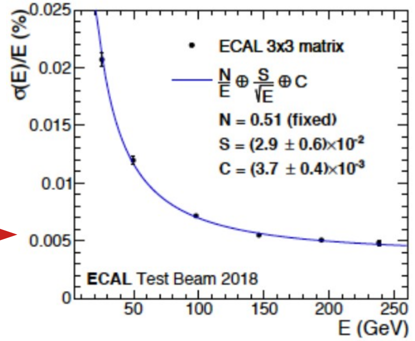


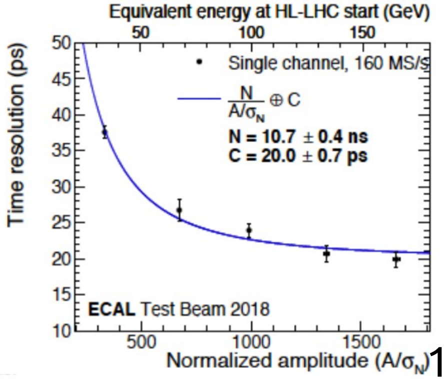
PoS LeptonPhoton2019 (2019) 097

The upgrades include:

- Crystal geometry untouched
- Single crystal info at L1 trigger instead of 5x5 crystal tower
- Front-end + readout electronics upgraded to cope with trigger requirements
- Shorter signal length allows to distinguish between EM shower and anomalous spikes in APDs

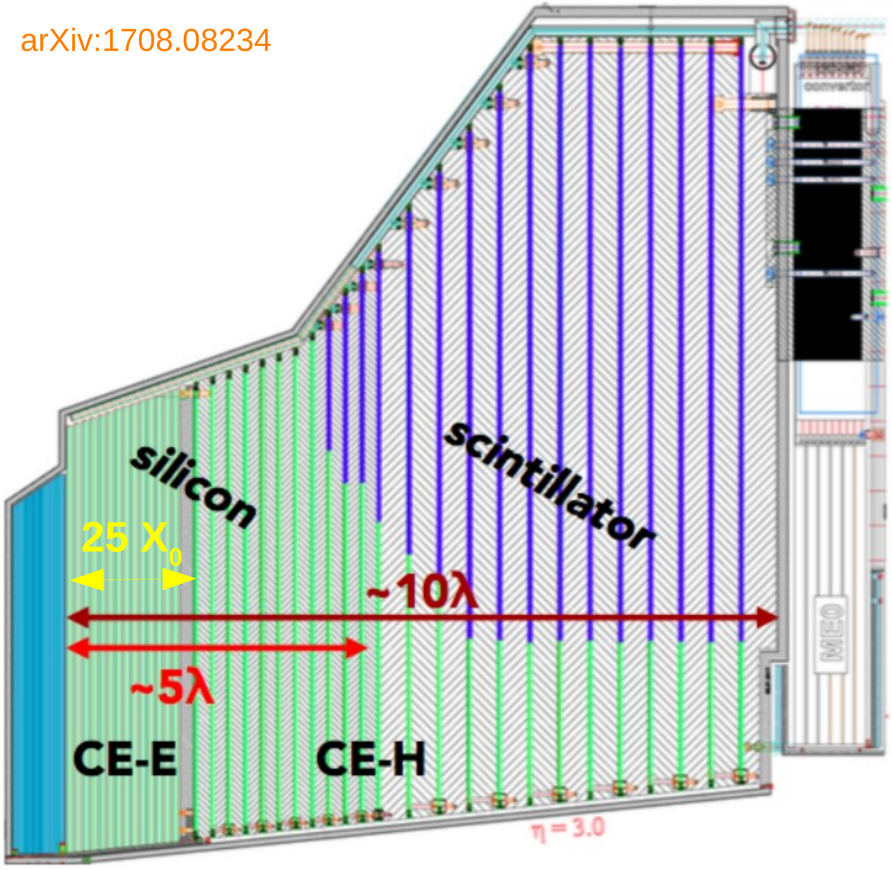
- Precision time resolution (≤ 30ps) fundamental to distinguish many interaction vertices piling up
- Timing info is crucial to recover the Higgs boson mass resolution
- Electron beam tests show that 1% resolution is achievable



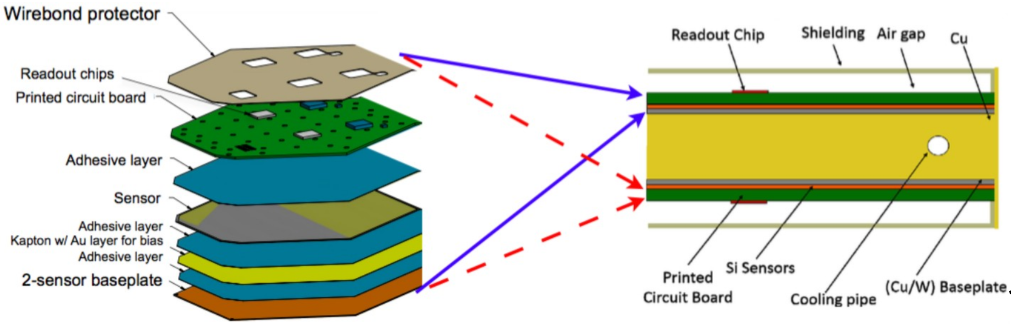


Endcap calorimeter: HGCAL

arXiv:1708.08234



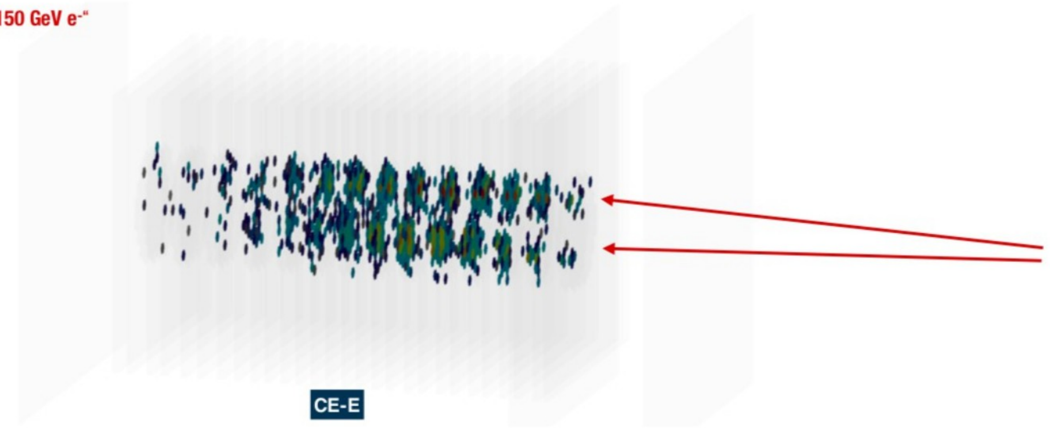
- Sampling calorimeter for CMS Phase-2
- Active elements: 320μm-thick silicon sensors, plastic scintillator
- Combination of electromagnetic (EE) and hadronic (FH+BH) sections
- Acceptance of 1.5 < |η| < 3.0
- Unprecedented transverse and longitudinal segmentation into hexagon cells of ~1 cm^2
- Full system maintained at -30°C
- In EE, 28 sampling layers in 30 cm thanks to double sided sensors

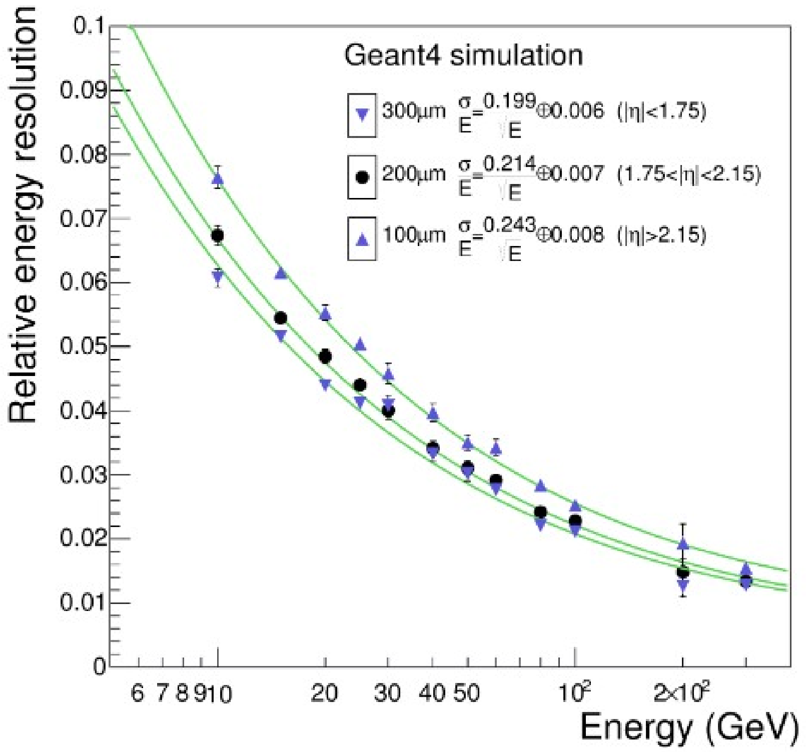


HGCAL energy resolution

- Simulation predicts an energy resolution below 5% for 300μm-thick sensors
- Timing performance and high granularity allow to use HGCAL as an imaging calorimeter
  → PF reconstruction improved at high η
- Target time resolution: 30 ps for clusters with p_T > 5 GeV

June 2018 run 407 - event 1:
"150 GeV e-"

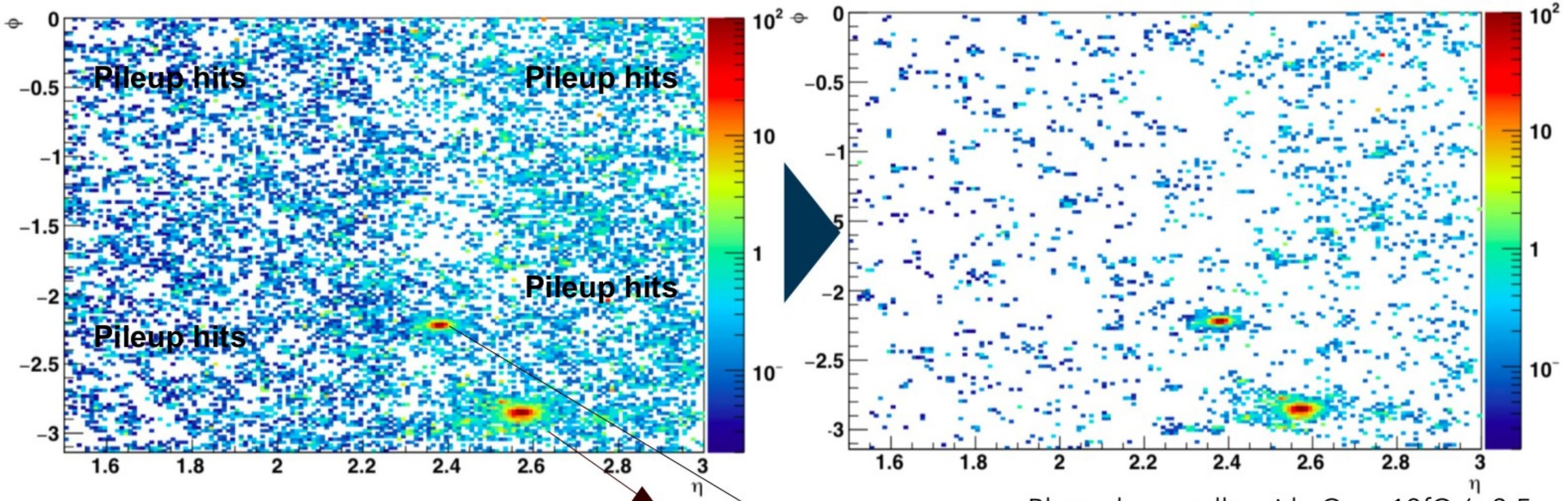


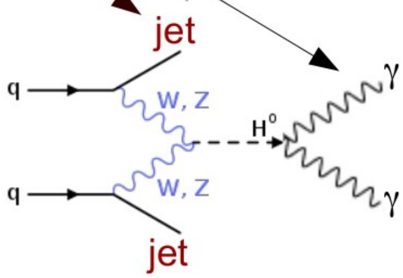


J. Phys. : Conf. Ser. 928 (2017) 012025

HGCAL timing

Simulation of VBF H→γγ event in HGCAL with and without timing selection (timing cut |Δt| < 90 ps)

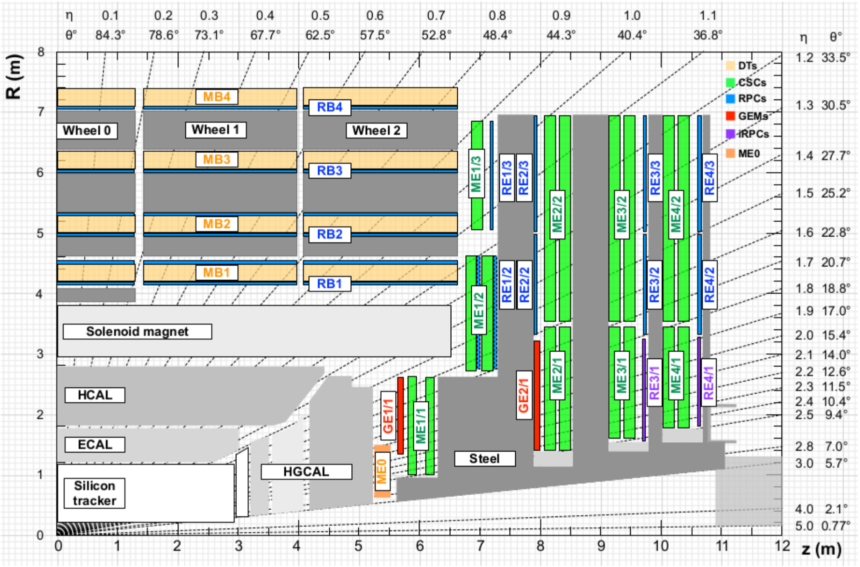




- Plots show cells with Q > 12fC (~3.5 MIPs @300µm - threshold for timing measurement) projected to the front face of the endcap calorimeter.
- Concept: identify high-energy clusters, then make timing cut to retain hits of interest

Muon detector upgrade

- Enhance muon performance in the forward region
  - addition of RPC (iRPC) and GEM (GE1/1, GE2/1) chambers in the forward region to improve efficiency, fake rejection and resolution in the region 1.6 < |η| < 2.4
  - extend coverage up to |η| = 2.8 with new chambers (ME0)
- Upgrade electronics to cope with increased radiation, meet trigger/readout latency requirements



- Higher efficiency
  - more hits along the muon's trajectory in the forward muon system due to the new chambers
  - better interplay detectors ⟺ faster electronics
- Lower rate
  - improved identification and momentum measurement
- Extended coverage in η for multi-muon triggers

CMS-TDR-016

Conclusions

- HL-LHC aims at collecting 3000 fb^{-1} of collision data by 2040
- Overall CMS acceptance increased, up to $|\eta| = 4.0$
- New tracking detector, track info included in L1 trigger
- New endcap electromagnetic + hadronic calorimeter, HGCAL
- ECAL FE electronic replaced, allowing for timing of signals
- Extended muon detector
- Simulations and tests suggest that CMS will maintain the current performance or even improve