



CMS Upgrade Plans and Potential

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on behalf of the CMS Collaboration

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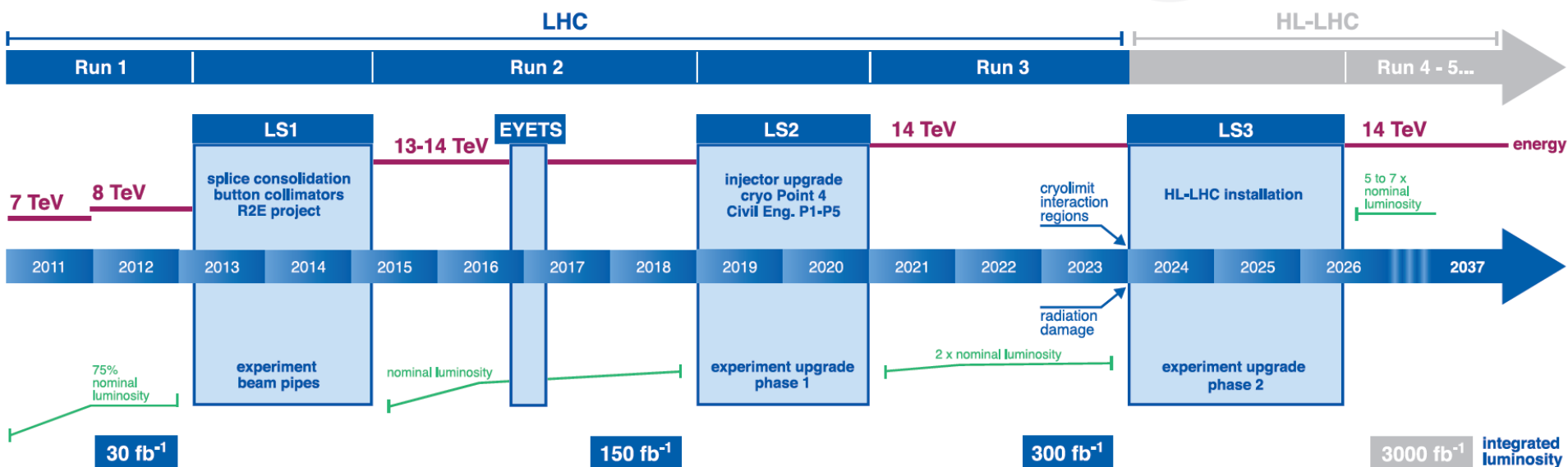
Roadmap



LHC / HL-LHC Plan



High
Luminosity
LHC

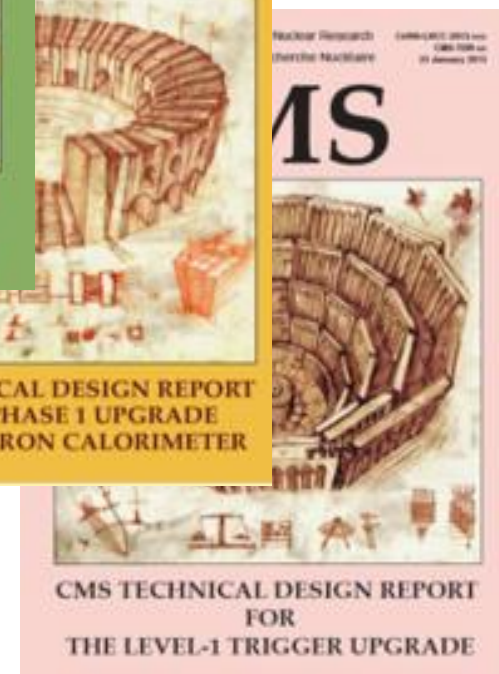
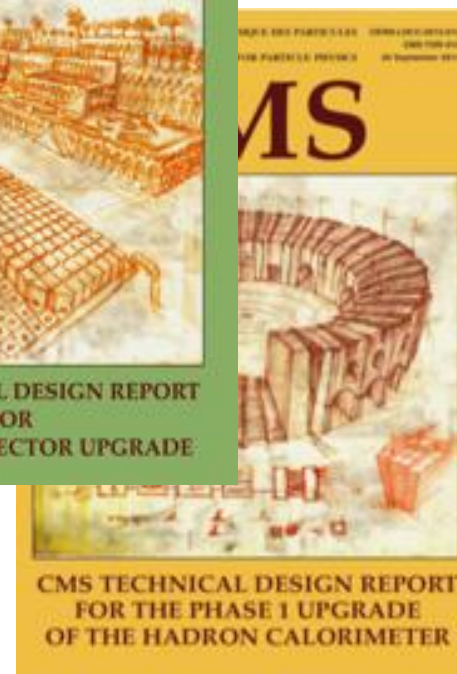
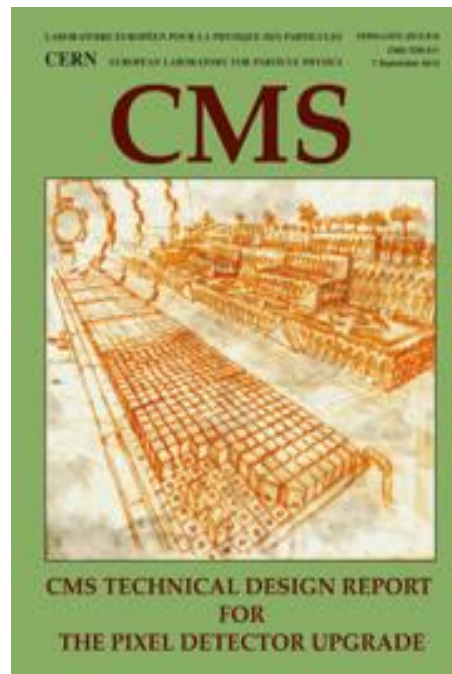


- Phase-1: on-going, leading collaboration to HL-LHC
- Phase-2: concluding R&D, finalizing project details, sail through HL-LHC

Phase-1 Overview



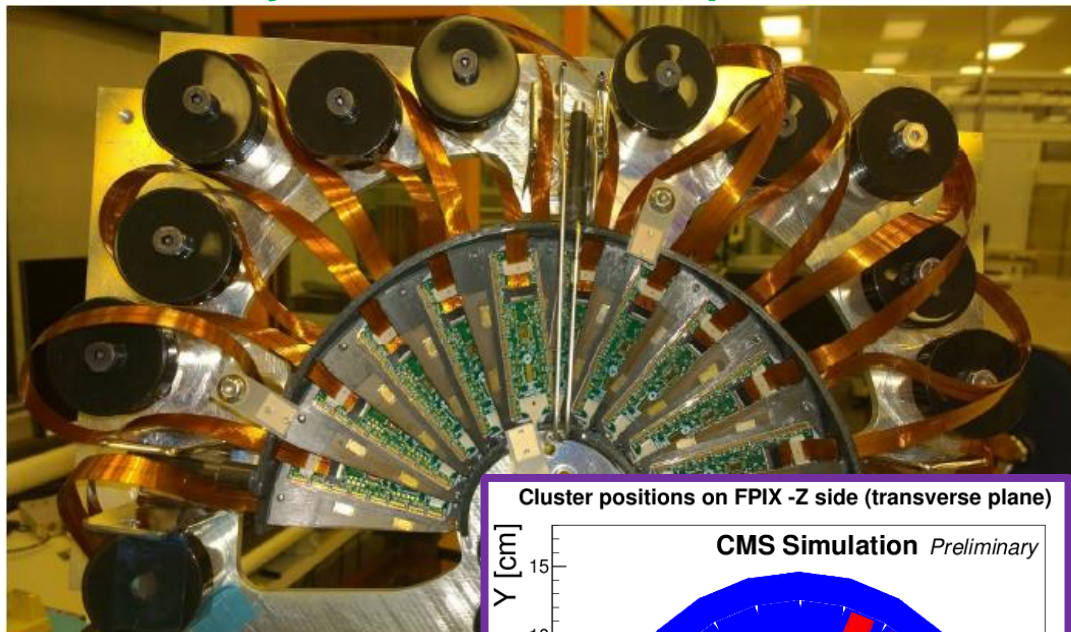
- Pixel Tracker
 - 4-layer barrel and 3-disk forward tracker
 - High-rate readout chip
- Hadronic Calorimeter
 - Improved photodetectors
 - Faster and more robust front-end and back-end electronics
- Trigger System
 - Upgrade of muon and calorimeter L1 trigger
 - Move to high-performance FPGA-based electronics



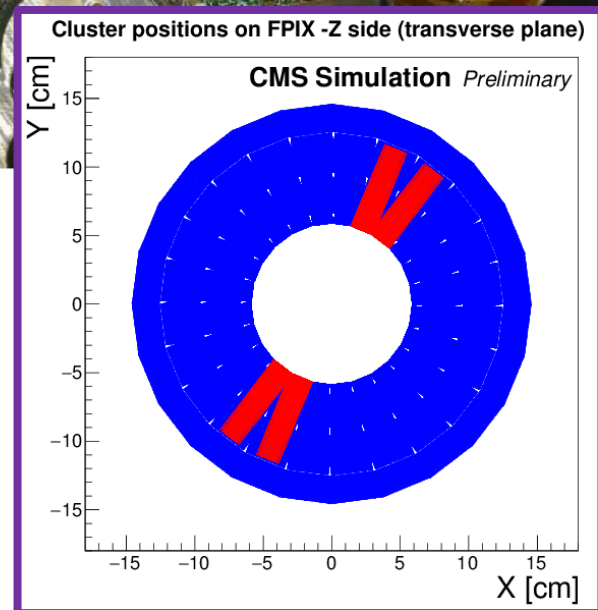
Pixel Tracker

Fully assembled endcap half-disk

- One additional layer in barrel and one in endcap regions
 - Reduce fake rate, improve track resolution and efficiency
 - Maximize 4-hit coverage in $|\eta| < 2.5$ range
- New front-end electronics
 - Allow efficient operations at high rate, multiplexing of data to increase bandwidth



Simulation of hits
in pilot blades
Currently taking
2016 collision data



Hadronic Calorimeter



- **Photodetectors**

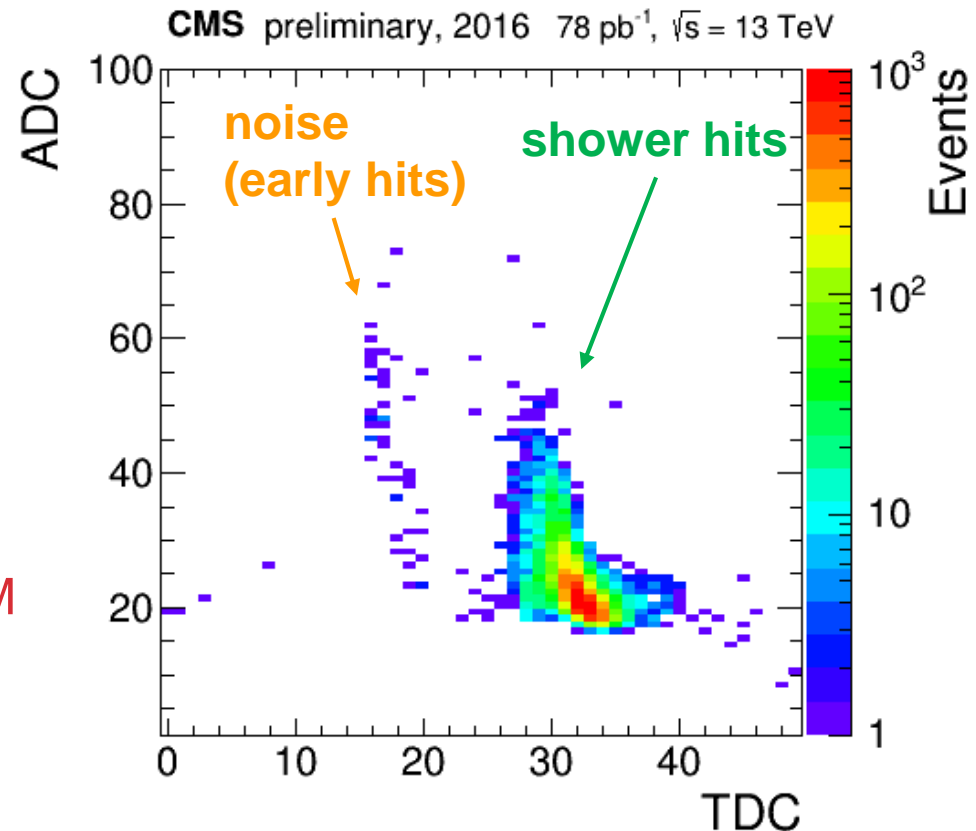
- Barrel, Endcap and Outer calorimeters: SiPM replace HPD; higher S/N separation, insensitive to magnetic field
- Forward calorimeter: multi-anode PMT replace single-readout PMT; allow for removal of anomalous signals

- **Front-end Electronics**

- New readout chips matching SiPM
- More robust, redundant clock and control system

- **Back-end Electronics**

- Modern μ TCA system
- Satisfy latency and rate requirements for HL-LHC

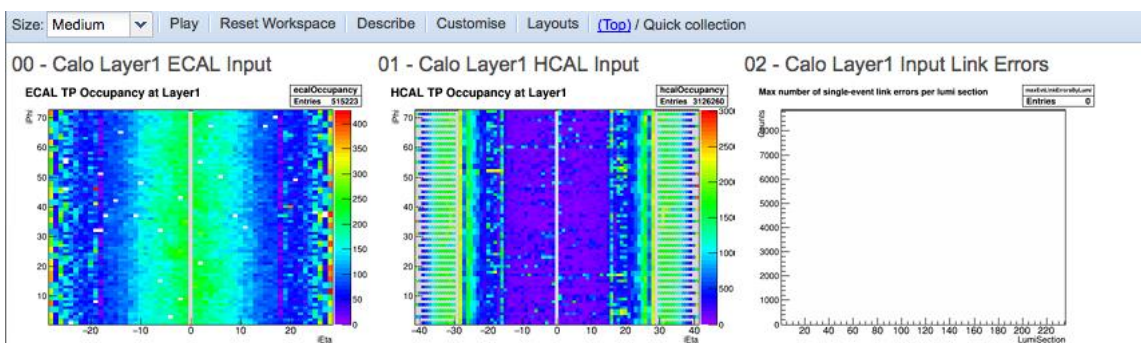
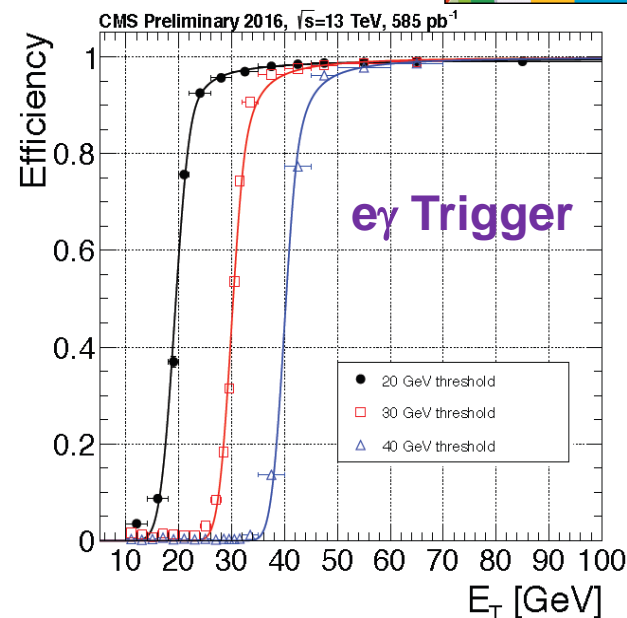


**Hadronic Forward (HF)
2016 data w/ Phase-1
FE and BE DAQ**

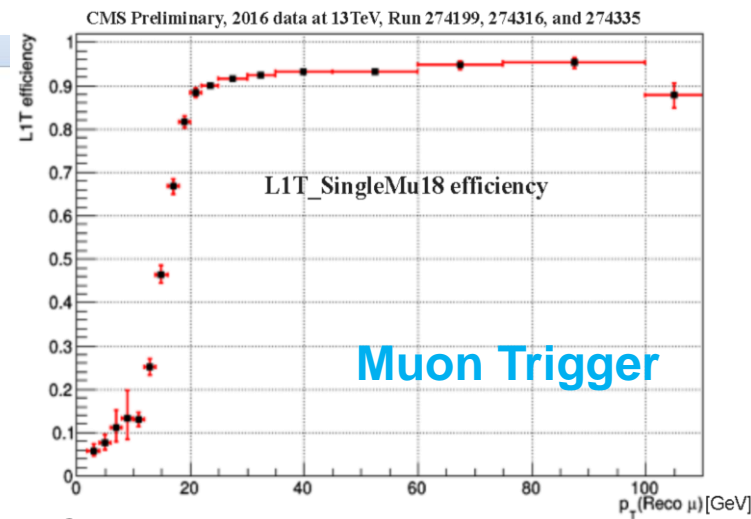
L1 Trigger



- Motivated by need to maintain Run-1 performance during Run-2 and Run-3
 - Move to FPGA-based architecture, and μ TCA back-end
- Completed upgrade
 - Deployed system in stages
- Entered commissioning phase with 2016 collision data

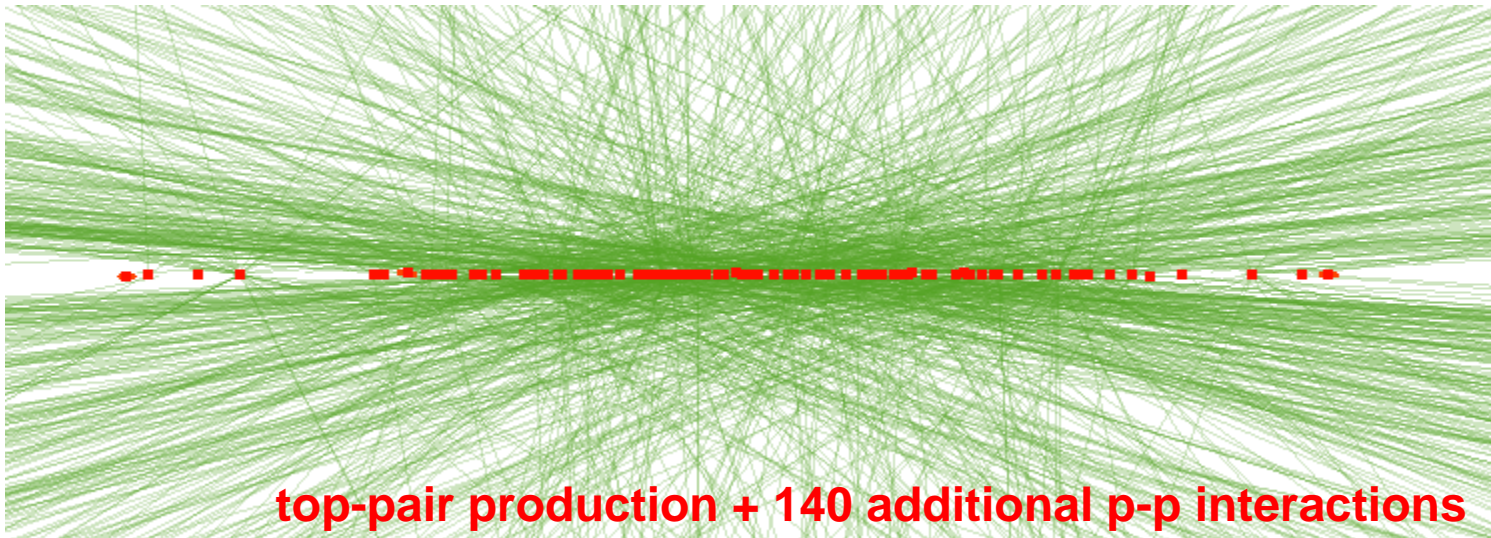


Data Quality Monitoring: L1 Calo trigger inputs

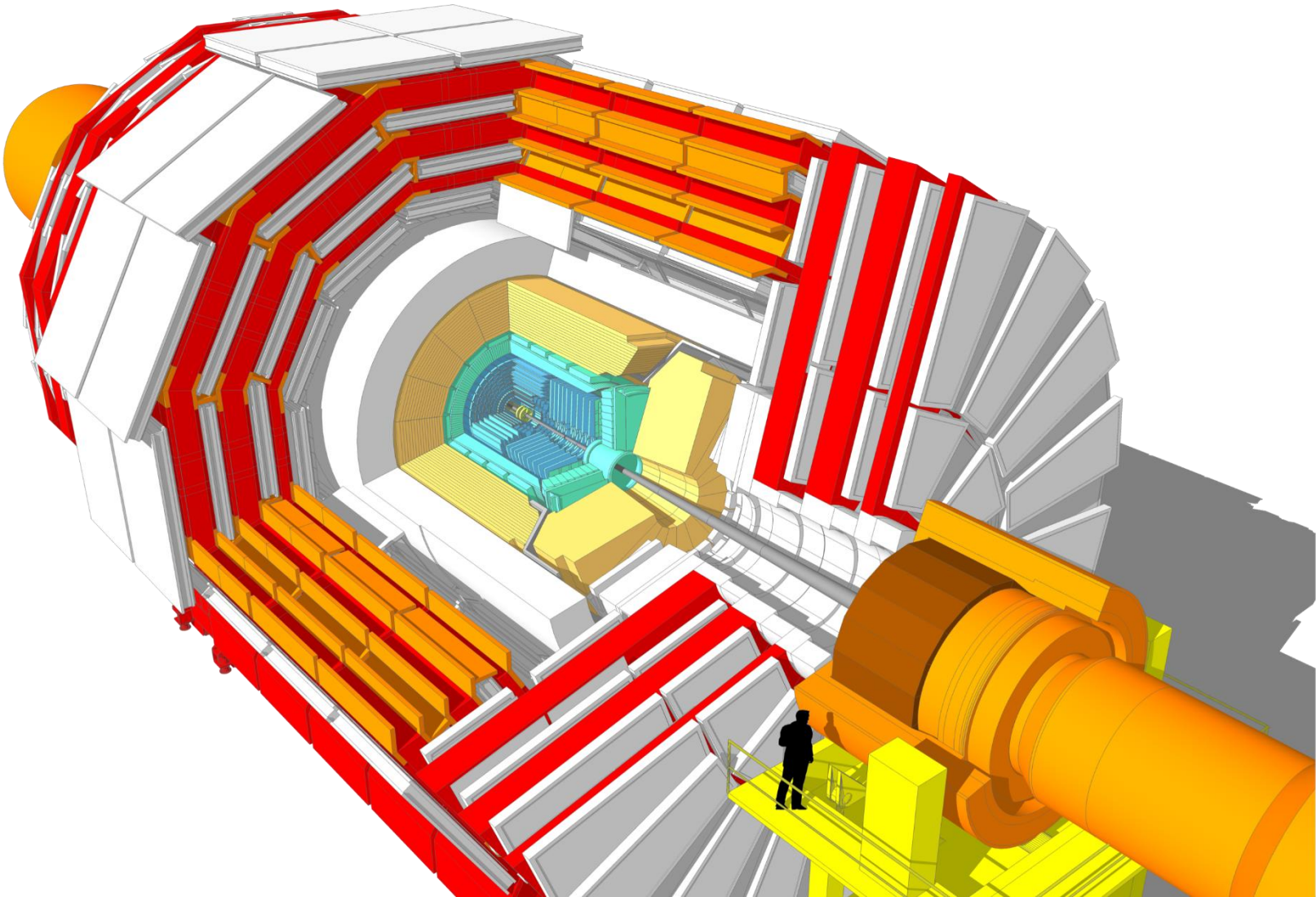


Phase-2 Motivations

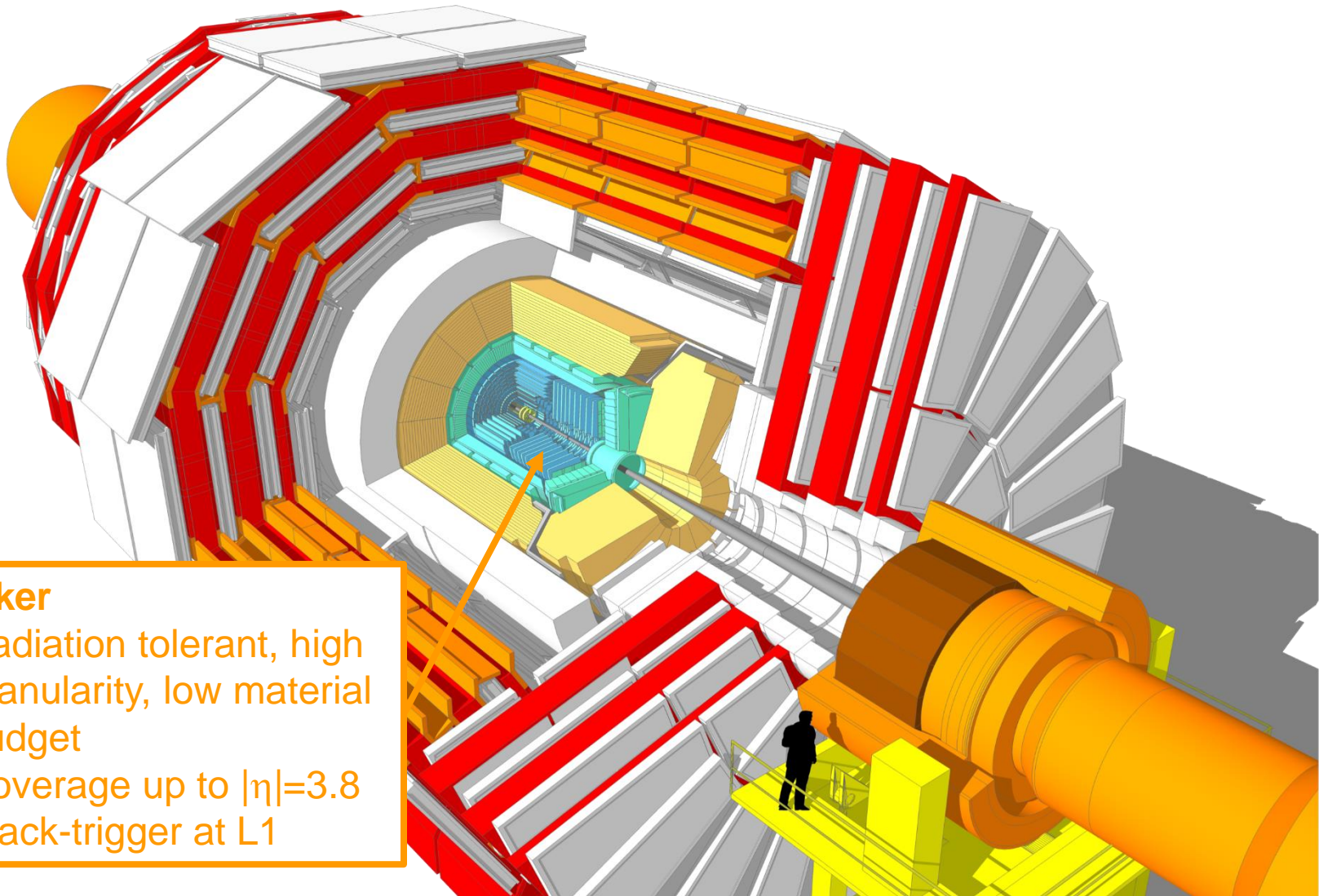
- Radiation-induced ageing
 - Replacement of tracker and part of calorimeters
- High pile-up in Run-4
 - Upgrade of front-end and back-end electronics, trigger and DAQ
- Physics
 - Access opportunities at 3/ab: Higgs; SUSY; SMP rare decays



Phase-2 Overview



Phase-2 Overview



Tracker

- Radiation tolerant, high granularity, low material budget
- Coverage up to $|\eta|=3.8$
- Track-trigger at L1

Phase-2 Overview

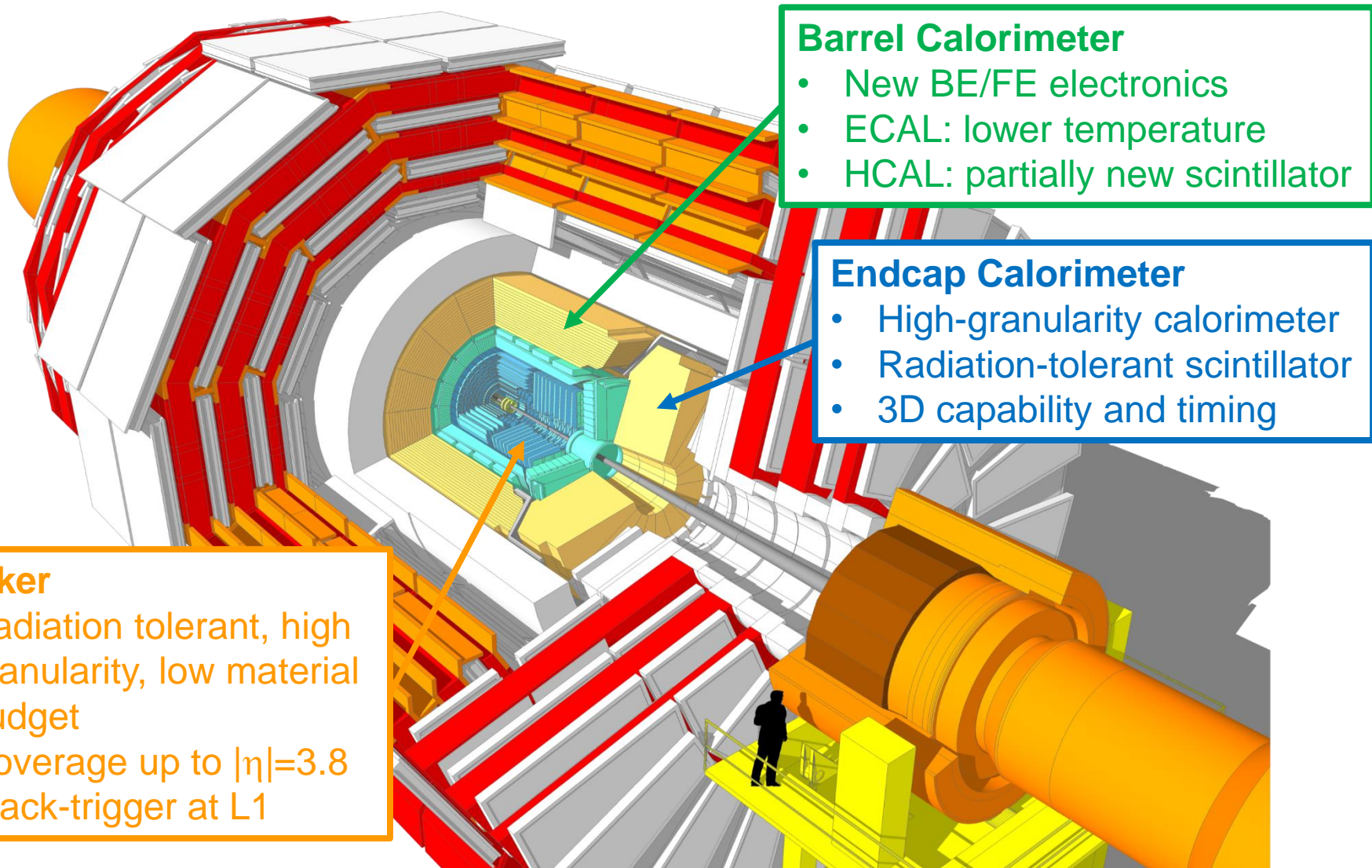
Barrel Calorimeter

- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator

Tracker

- Radiation tolerant, high granularity, low material budget
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Phase-2 Overview



Phase-2 Overview

Muon System

- New DT/CSC BE/FE electronics
- GEM/RPC coverage in $1.5 < |\eta| < 2.4$
- Muon-tagging in $2.4 < |\eta| < 3.0$

Barrel Calorimeter

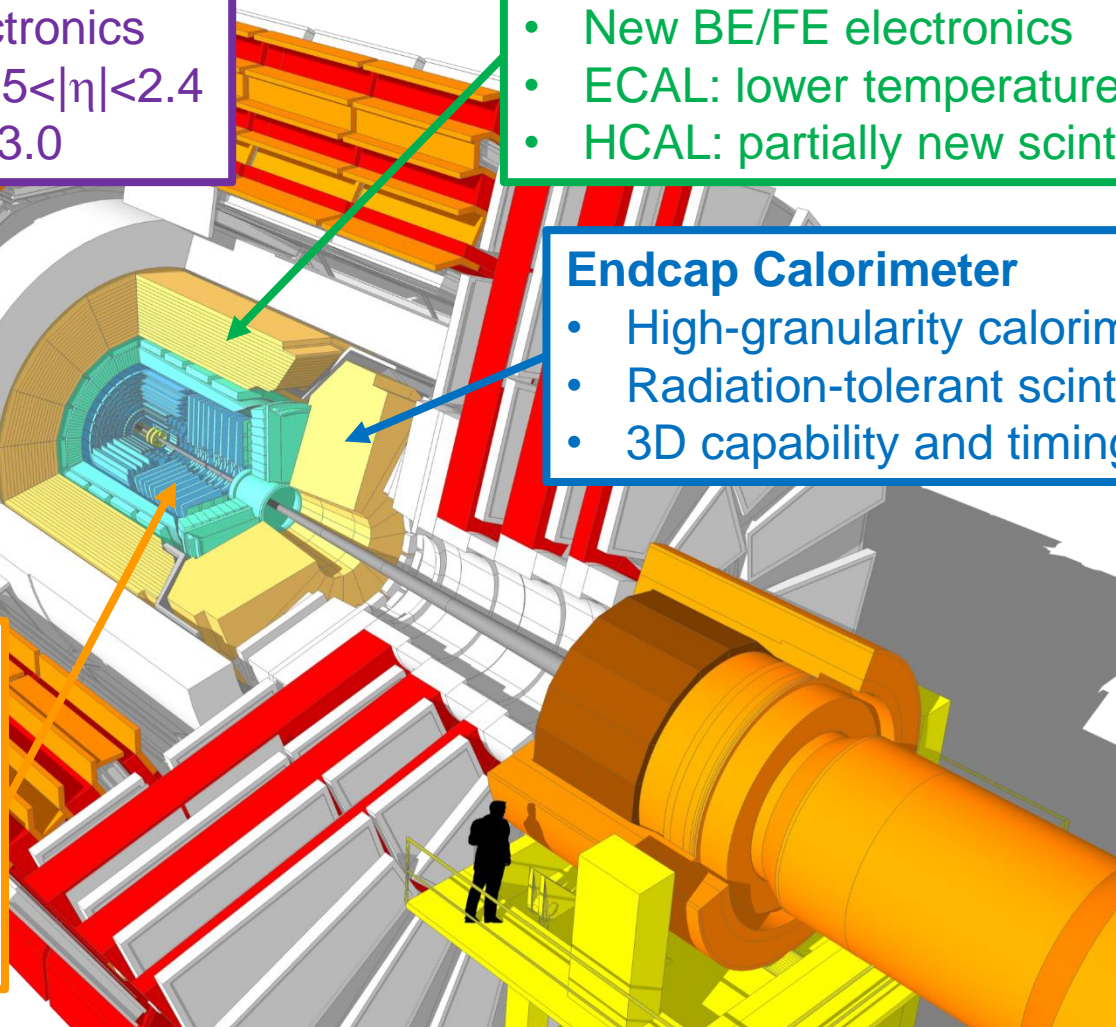
- New BE/FE electronics
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Endcap Calorimeter

- High-granularity calorimeter
- Radiation-tolerant scintillator
- 3D capability and timing

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Trigger and DAQ

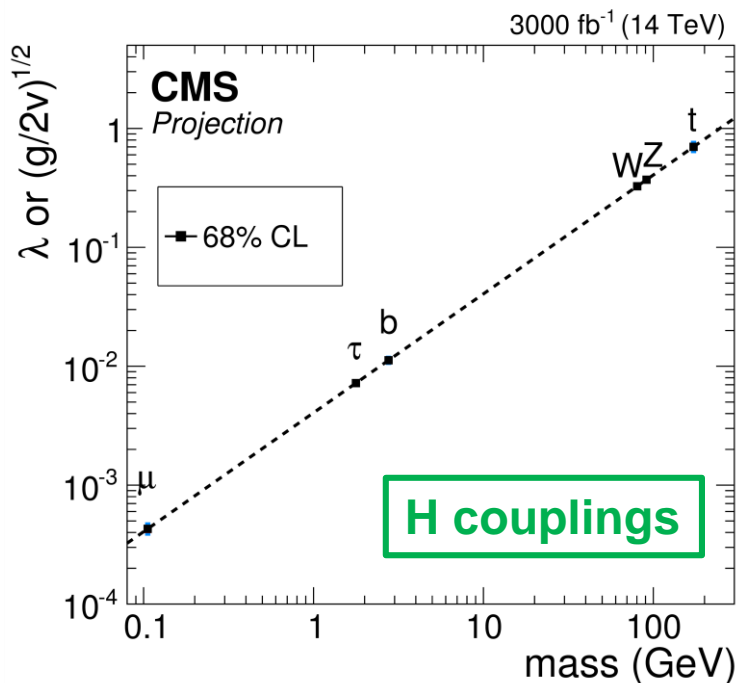
- Track-trigger at L1
- L1 rate $\sim 750\text{kHz}$
- HLT output $\sim 7.5\text{kHz}$

Impact on Physics – Highlights

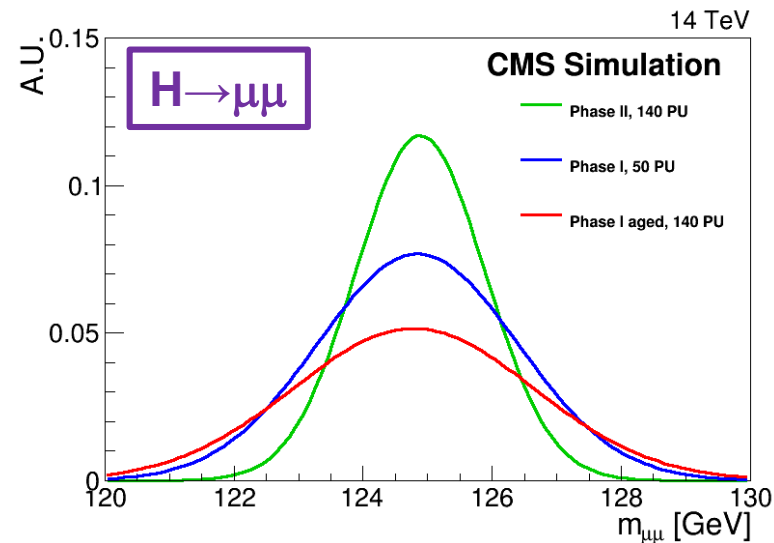
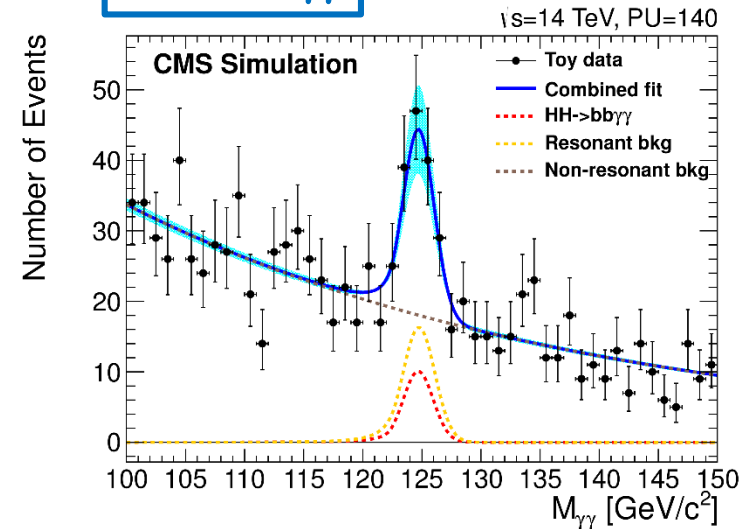


• Higgs Physics

- O(%) precision on couplings
- VBF and associated production
- Rare $H \rightarrow \mu\mu$ and HH decays



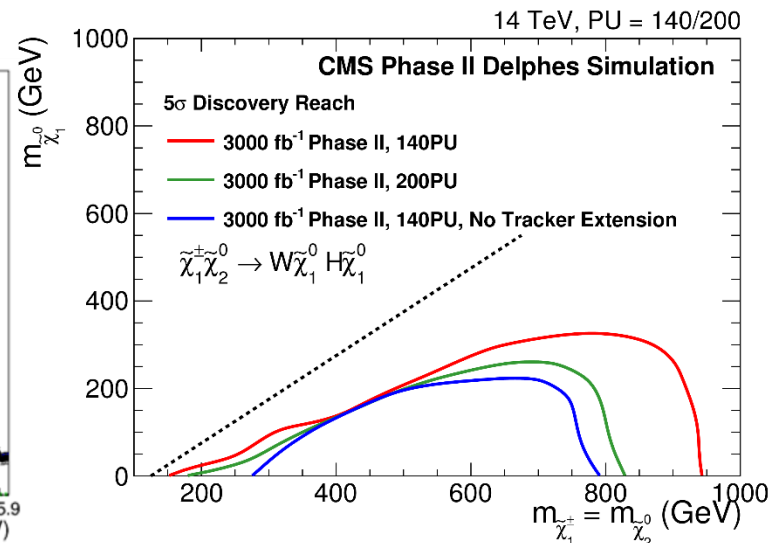
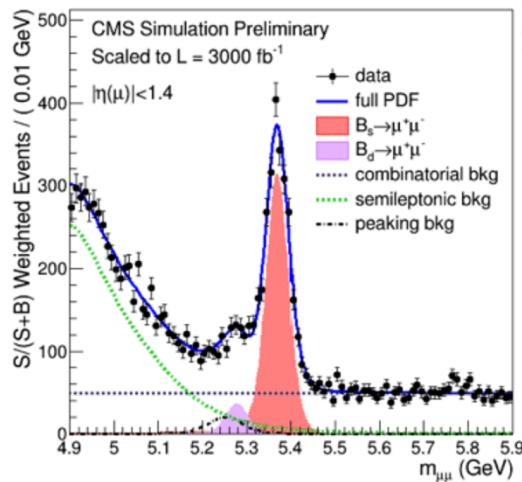
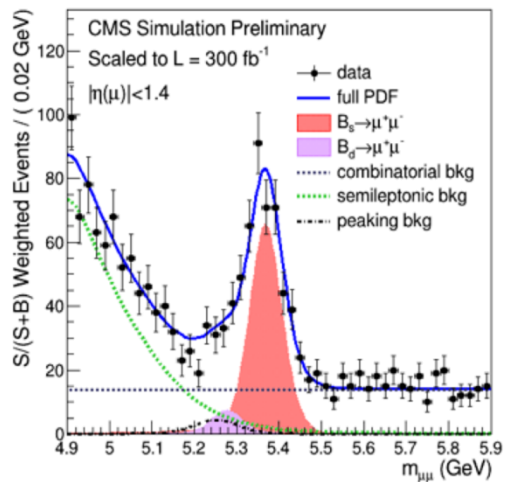
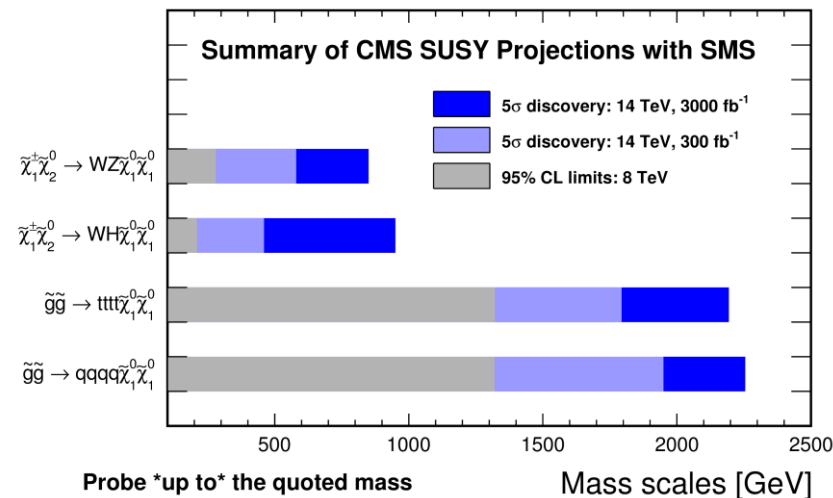
$HH \rightarrow b\bar{b}\gamma\gamma$



More Physics



- SUSY and beyond
 - Look into stealth and compressed SUSY scenarios
 - Dark-matter searches in mono-X channels, including mono-Higgs
- Standard Model physics
 - Rare decays: $B_{s,d} \rightarrow \mu\mu$
 - Vector-boson scattering



Tracker



- **Outer Tracker**

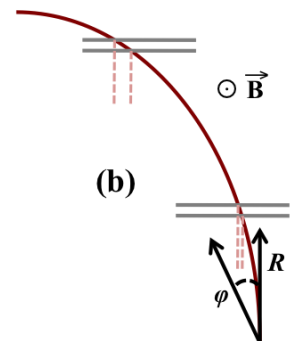
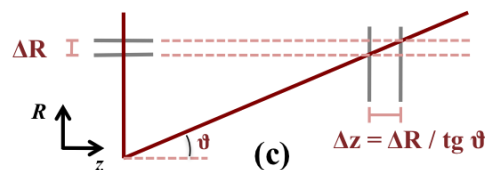
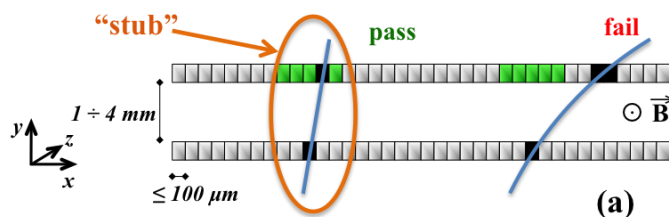
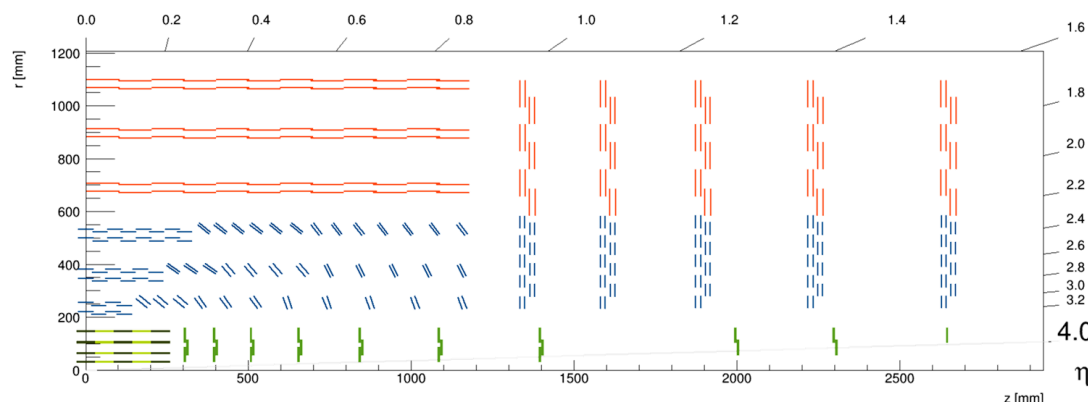
- Double-layer modules for trigger purpose
 - 6 barrel layers; 5 forward disks
- Higher granularity
 - 4 times current detector

- **Pixel Tracker**

- 10 forward disks, coverage up to $|\eta| \sim 3.8$
- Inner layer at 3cm from beamline

- **Mechanics and Electronics**

- Low material budget
- Operations at -30C
- Readout at 750kHz



Barrel Calorimeters



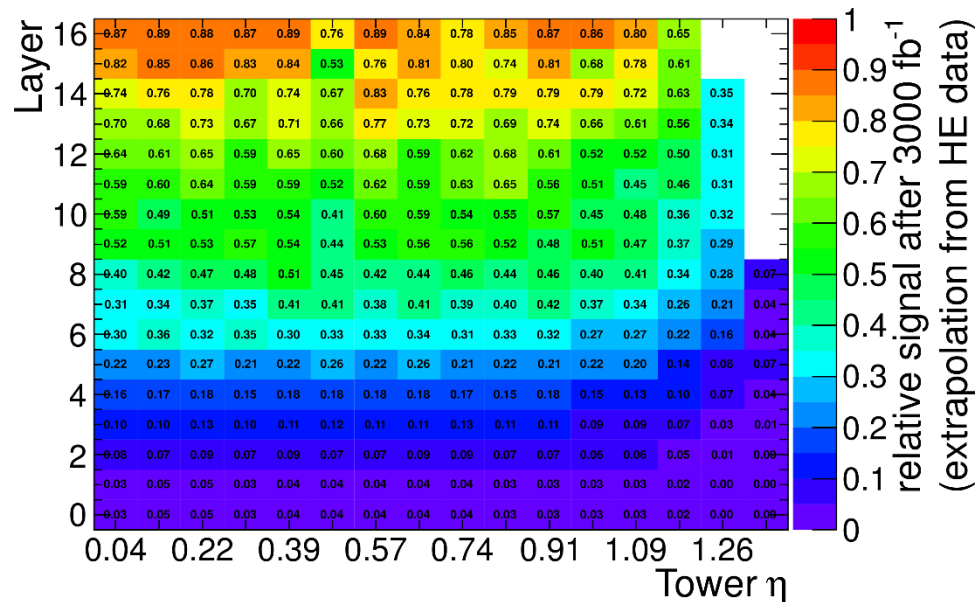
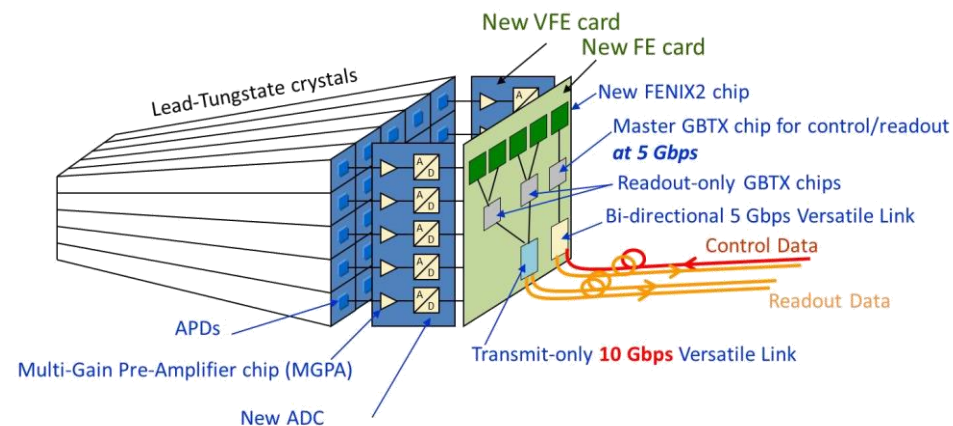
- Electromagnetic Calorimeter

- Homogeneous, PbWO_4
- New front-end and back-end electronics to satisfy HL-LHC trigger requirements
- Cooling to 8C and optimization of VFE (very-front-end) electronics to reduce noise

- Interesting side-effect: cooling PbWO_4 increases its light output

- Hadronic Calorimeter

- Plastic/brass sampling calorimeter
- Replacement of inner layers with radiation-tolerant scintillator
- New back-end electronics

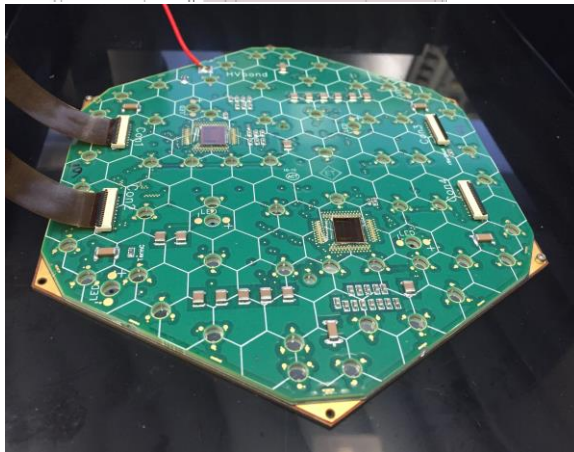


- Challenging conditions push toward new paradigm

- High-granularity silicon-readout, based on ILC/CALICE detector
- Si/W EE, $26X_0$, 1.5λ ; Si/brass FH, 3.5λ
- Plastic scintillator/brass BH, 5λ

- Vibrant R&D activity

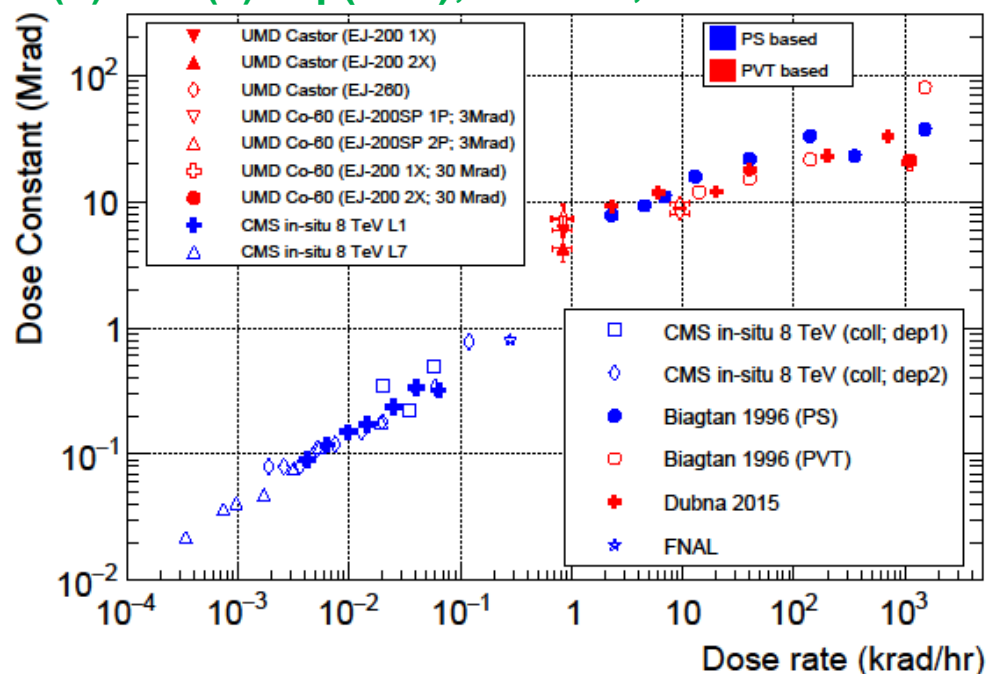
- Radiation-tolerant on-detector electronics
- Cold plastic scintillator



A Taste of On-Going R&D

- At the end of Run-1, observed faster-than-predicted radiation damage on plastic scintillator
 - Tests usually performed at high dose rate: counter-intuitively, damage is larger if dose rate is smaller
- Multiple venues of investigation opened, for both barrel and endcap hadronic calorimeter upgrade
 - Radiation damage vs. dose rate, temperature, oxygen concentration
 - Improvement on radiation tolerance by switching to longer-wavelength scintillators (green vs. blue) and increasing concentration of scintillator dopants

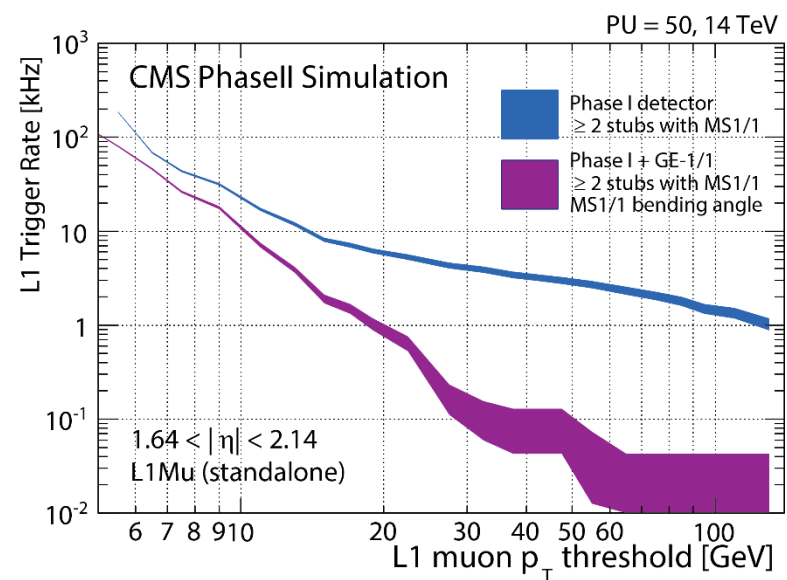
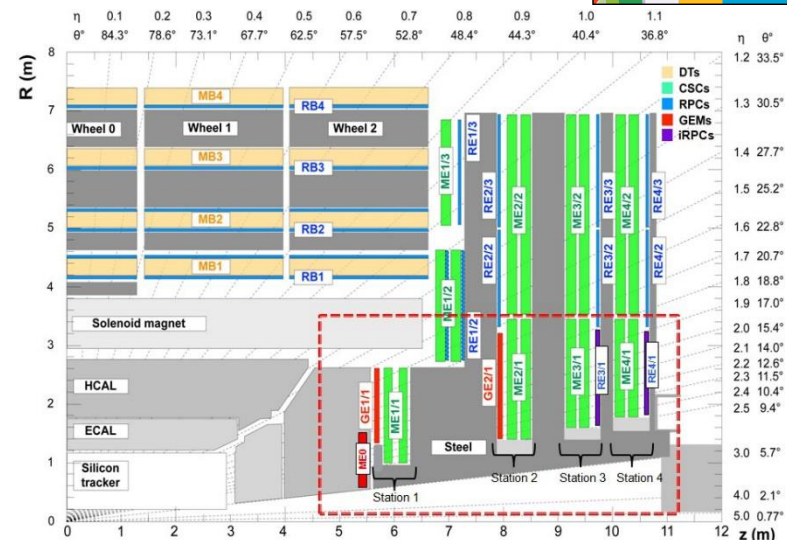
$$LY(d) = LY(0) \cdot \exp(-d/D); \text{ d: dose, D: dose constant}$$



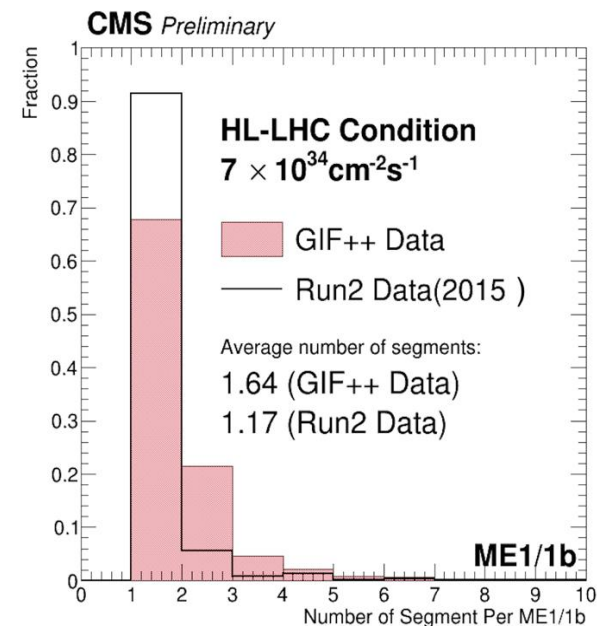
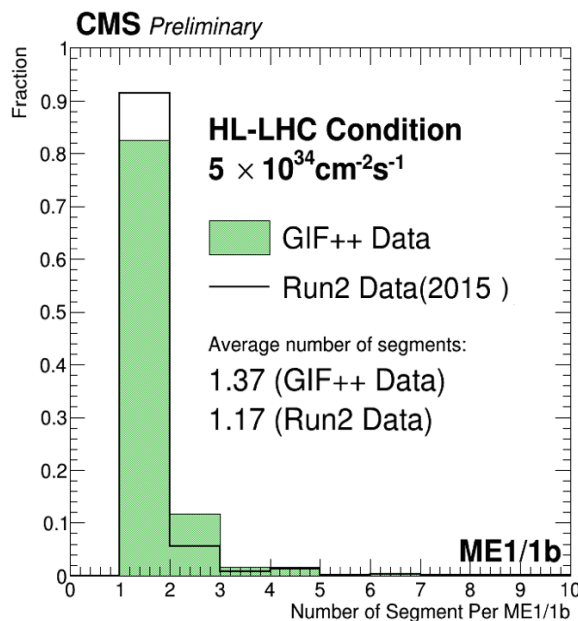
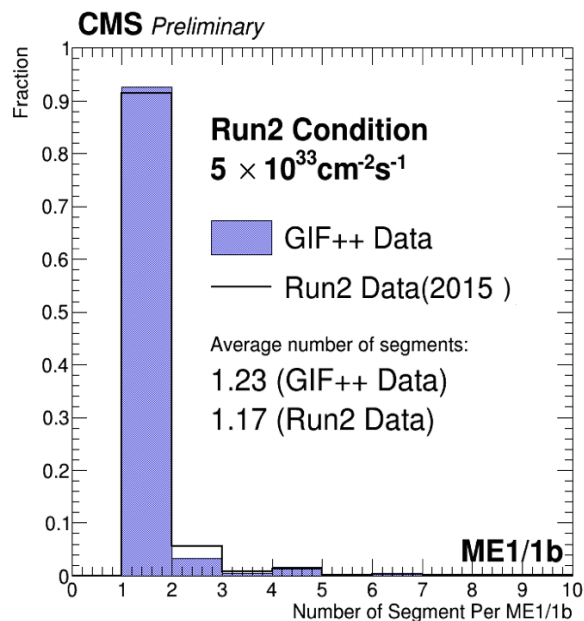
Muon System



- Extension of current muon system
 - Current chambers predicted to survive until end of HL-LHC
 - Complete coverage of RPC up to $|\eta| \sim 2.4$ with fine-pitch chambers
- New GEM chambers
 - Improve trigger and reconstruction
 - Extend muon tagging to $|\eta| \sim 3$
- Installation schedule
 - First GEM detector scheduled for installation during LS2 (2019-2020)
 - Fine-pitch RPC, Muon-Tagger chambers and second GEM station will be installed during LS3 (2024-2025)



A Glance at HL-LHC Conditions

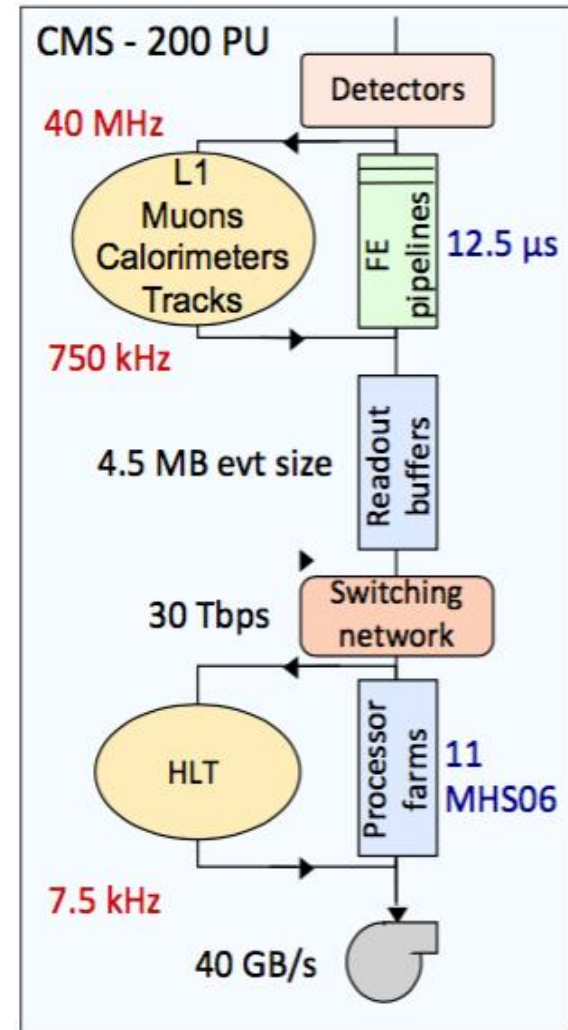


- CERN GIF++: Cs-137 source and muon beam
 - Can mimic running conditions at HL-LHC luminosities
- Comparing number of segments in CSC to Run-2 data
 - Good match between Run-2 and GIF++ data in Run-2 conditions
 - Can measure expected number of segments in HL-LHC conditions

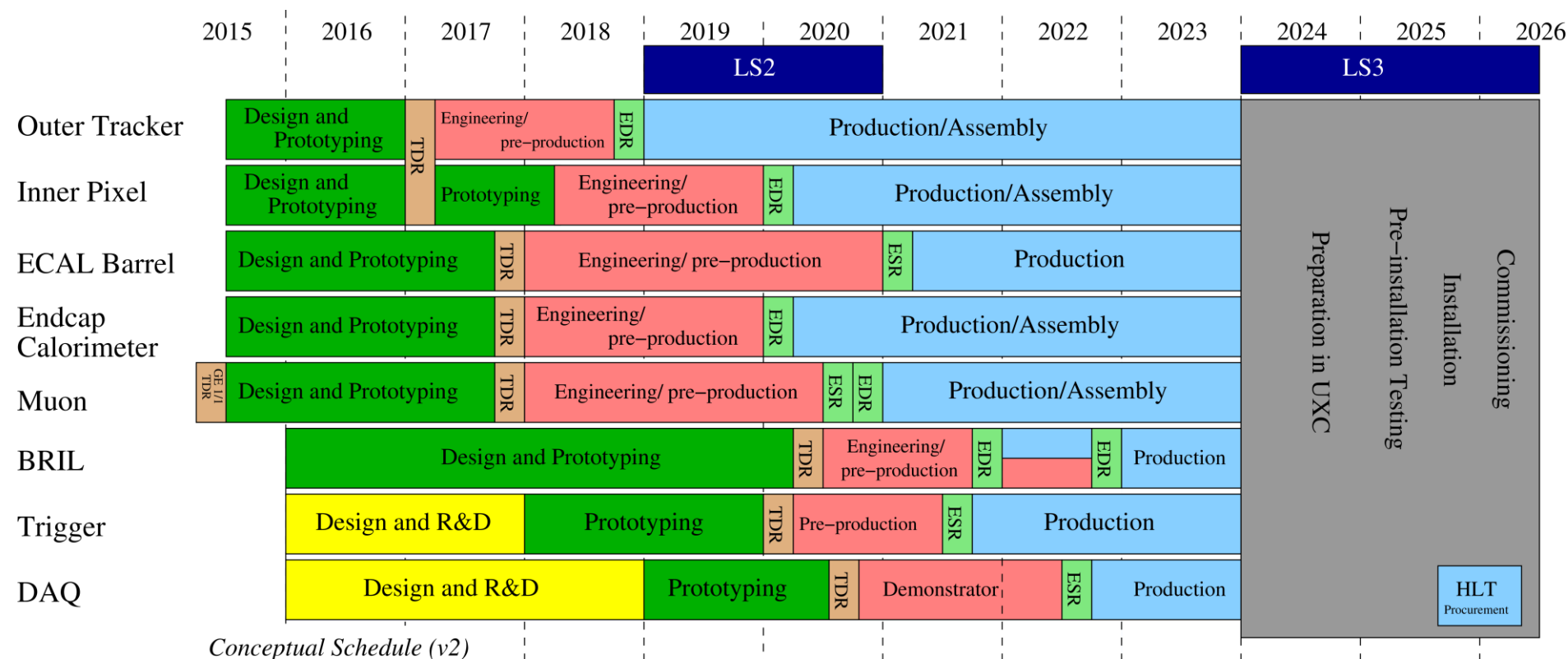
Trigger and DAQ



- L1 Trigger
 - Increase output to 750kHz, latency to 12.5 μ s, from 100kHz with 3.4 μ s latency
 - New track-trigger
- High-Level Trigger
 - Processing power scales with pile-up and L1 rate: expect factor ~ 50 w.r.t. Run-1
 - Output rate increase by ~ 10 to 7.5kHz
- DAQ
 - Increase bandwidth (800 links @ 100Gbps) to reach 30Tbps throughput



Upgrade Detailed Schedule



- Technical Design Reports expected in the course of 2017
- Current focus is design and prototyping toward TDRs

Concluding Remarks

- Upgrade projects are a continuous effort, overlapping with operations
 - Unique opportunity for training new physicists; important to establish strong community to share knowledge of key personnel and ensure growth of next generation of physicists
- Phase-1 upgrade is very well underway
 - Many parts are already installed and in commissioning phase, others are in production, scheduled for installation
- Phase-2 upgrade is in its initial stage: a larger effort for which the experience gained with Phase-1 upgrade is invaluable
 - Very exciting R&D programs on-going to define the future detectors
- The HL-LHC will open an astonishing set of physics opportunities
 - A successful upgrade program is crucial to exploit them



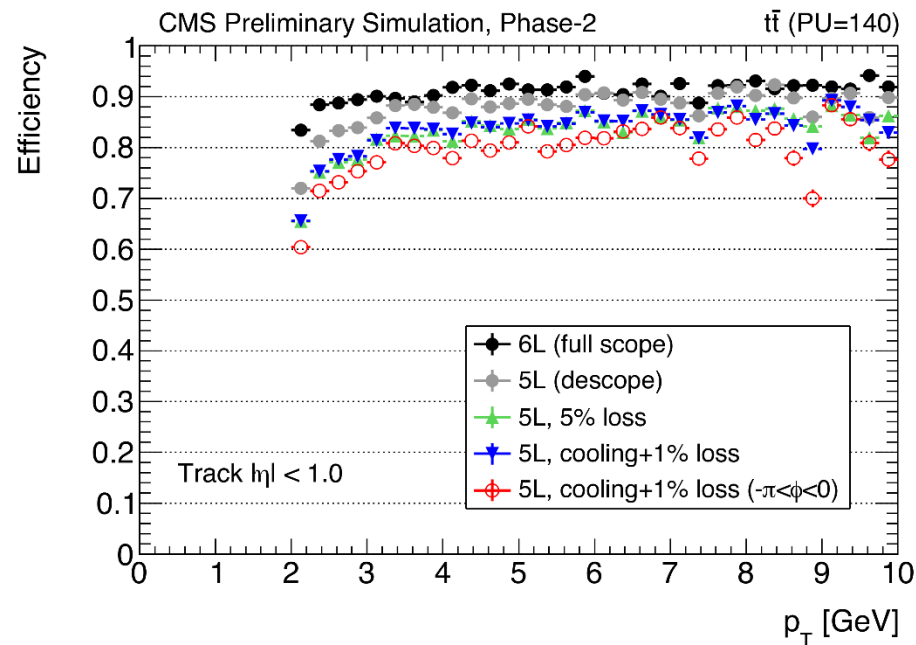
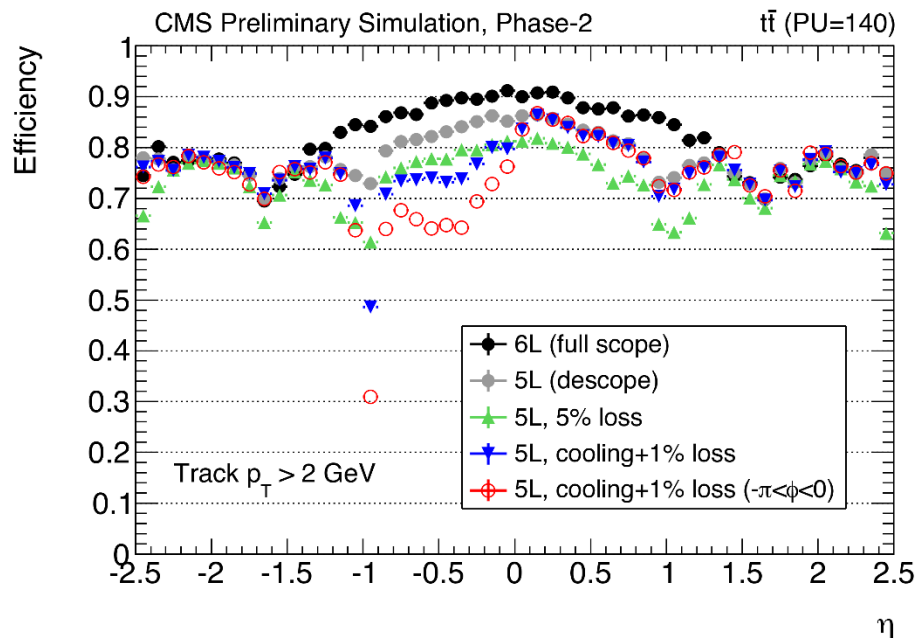
Backup

Short Bibliography

- Phase-1 Pixel Detector Upgrade TDR
 - <http://cds.cern.ch/record/1481838/files/CMS-TDR-011.pdf>
- Phase-1 Hadron Calorimeter Upgrade TDR
 - <http://cds.cern.ch/record/1481837/files/CMS-TDR-010.pdf>
- Phase-1 Level-1 Trigger Upgrade TDR
 - <http://cds.cern.ch/record/1556311/files/CMS-TDR-012.pdf>
- Phase-2 CMS Upgrade Technical Proposal
 - <http://cds.cern.ch/record/2020886/files/LHCC-P-008.pdf>
- Phase-2 CMS Upgrade Scope Document
 - <http://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf>

HL-LHC – L1 Track-Trigger

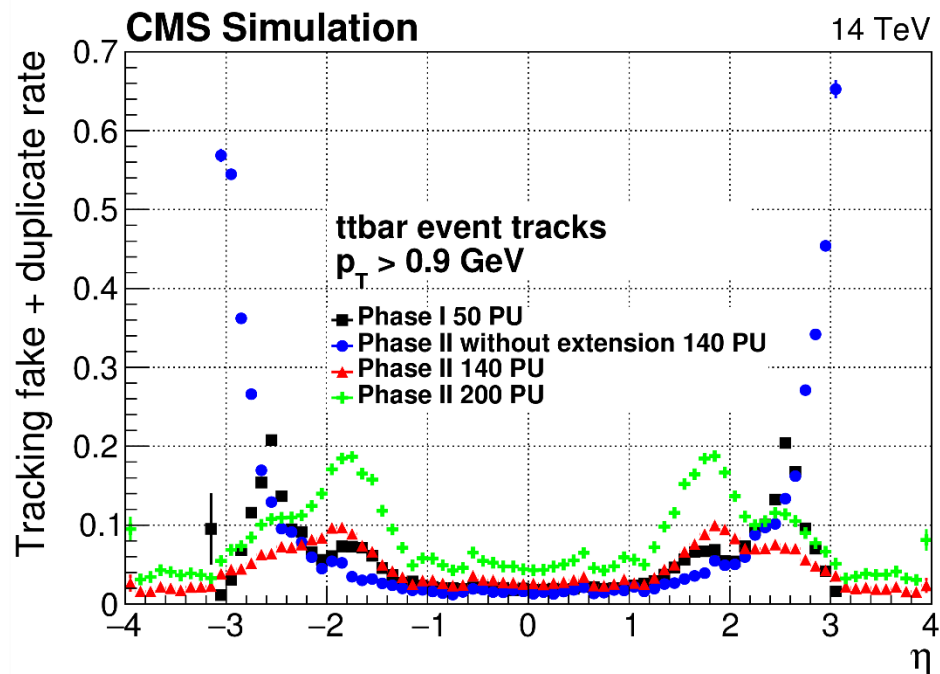
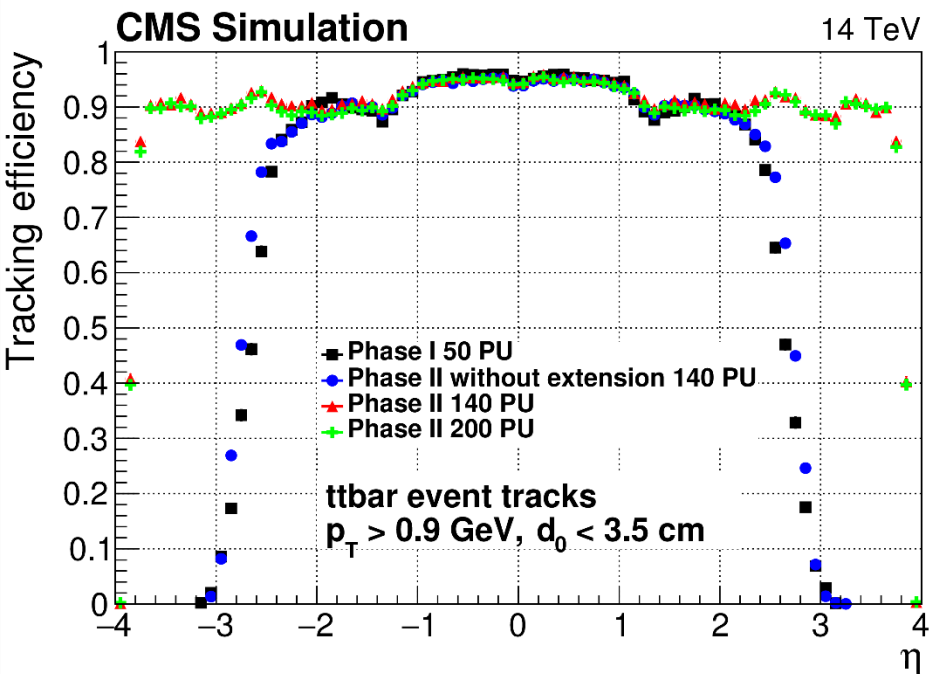
Results from Phase-2 CMS Upgrade Scope Document



Track trigger efficiency as function of pseudo-rapidity and transverse momentum for different detector configurations, with top-pair charged particles. The red dots show the efficiency in the limited angular region of the missing cooling loop

HL-LHC – Tracker Performance

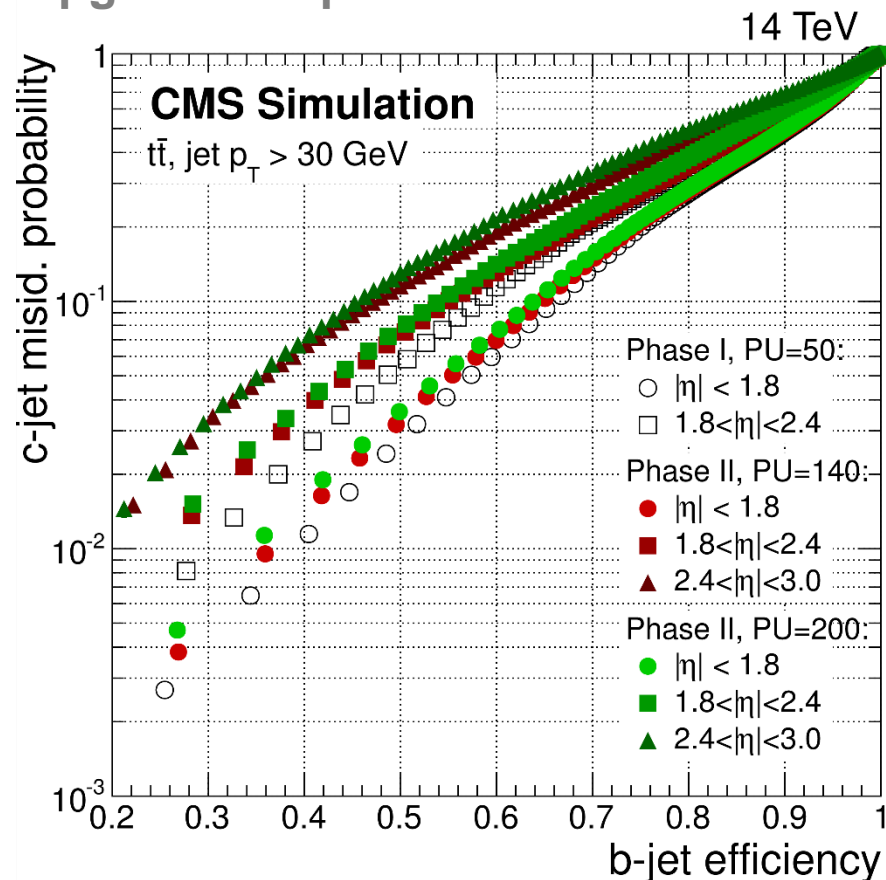
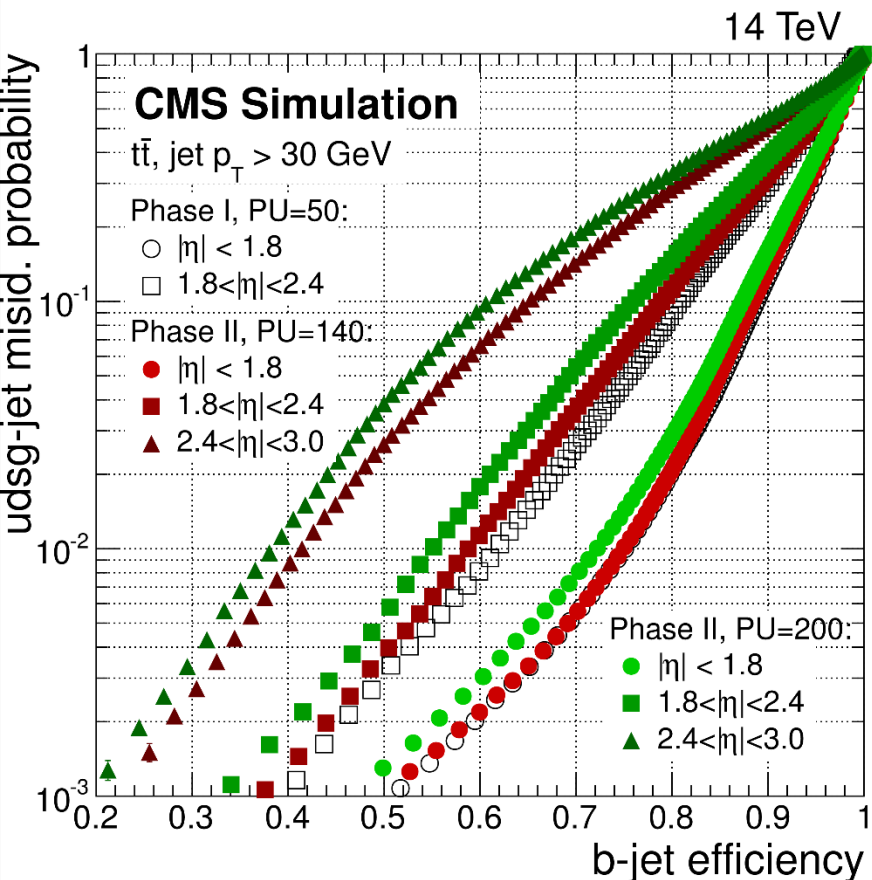
Results from Phase-2 CMS Upgrade Scope Document



Track reconstruction efficiency (left) and track mis-reconstruction rate (right) for $p_T > 0.9 \text{ GeV}$, as a function of η for top-pair events. The results are shown for three configurations, the full scope detector with 140 (red) and 200 (green) pileup events and without the forward extension of the tracker (blue) with 140 pileup events. Results based on Phase I detector with 50 (black) pileup events are also included

HL-LHC – B-tagging Performance

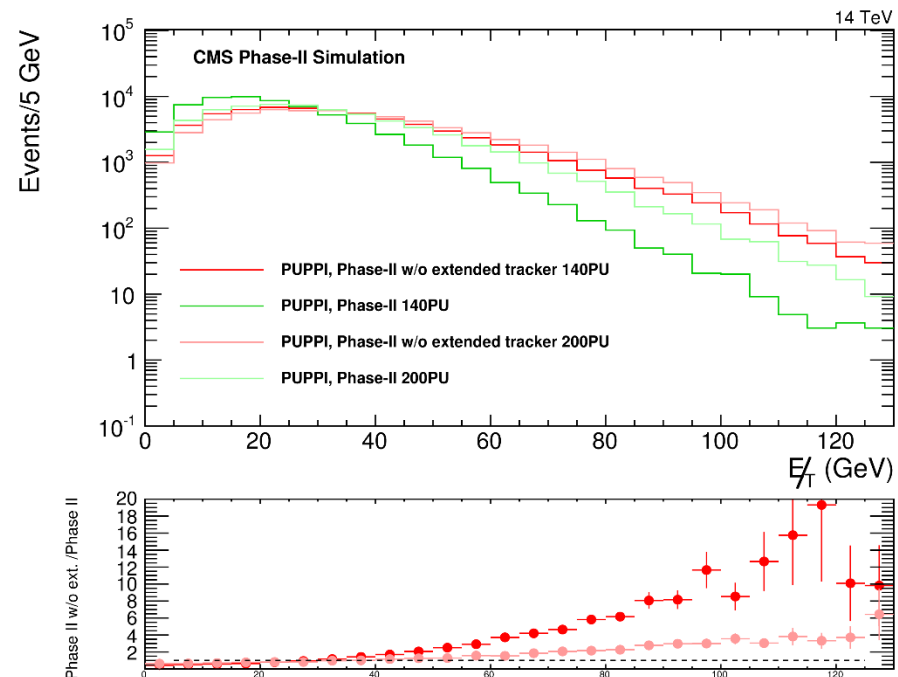
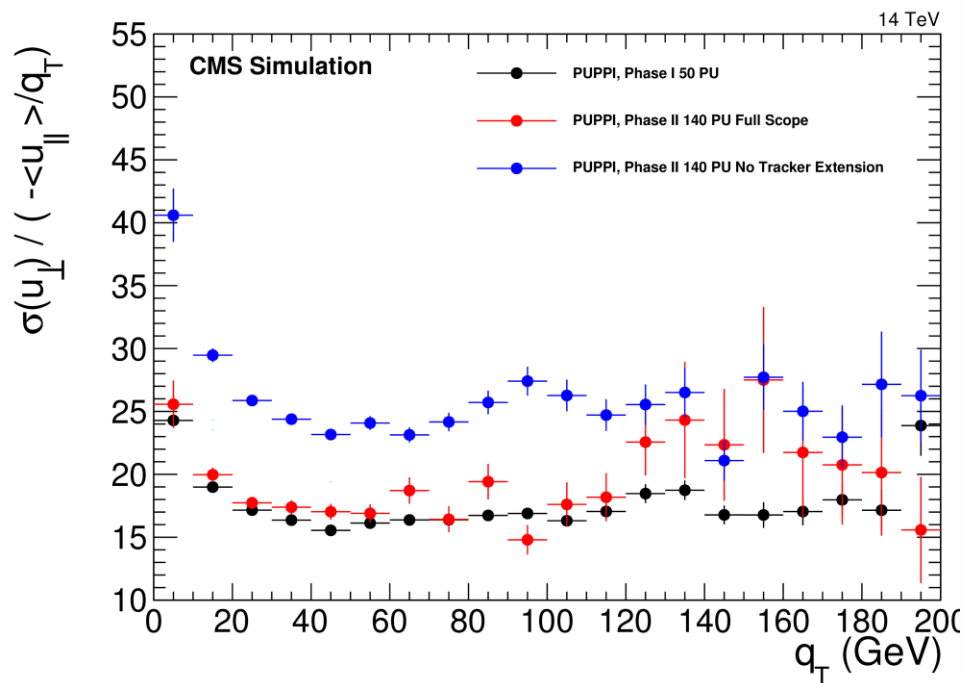
Results from Phase-2 CMS Upgrade Scope Document



b-jet tagging performance studied with top-pair events at $\langle \text{PU} \rangle = 140$ (red) and $\langle \text{PU} \rangle = 200$ (green) for different pseudorapidity ranges. Results based on Phase I detector at $\langle \text{PU} \rangle = 50$ (open black) are also shown. Performance is expressed as misidentification probability for udsg-jets (left) and c-jets (right) as a function of b-jet tagging efficiency. Events are selected only if the correct primary interaction vertex is reconstructed. Good b-jet tagging capability extends to high pseudorapidity

HL-LHC – E_T^{miss} Performance

Results from Phase-2 CMS Upgrade Scope Document

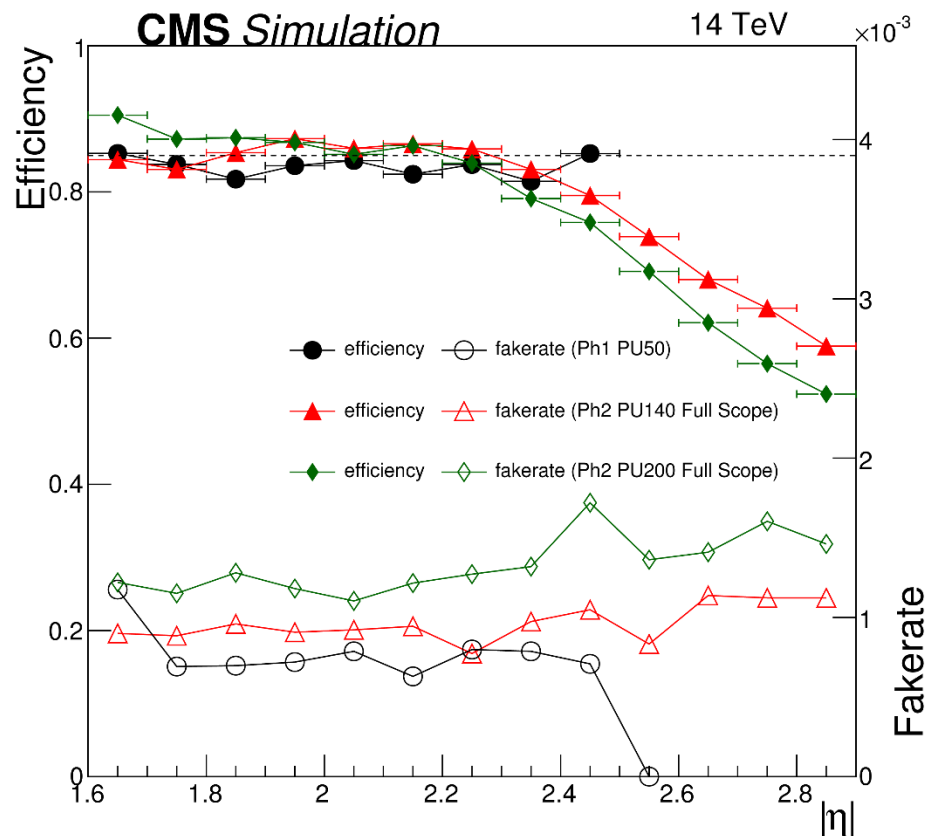
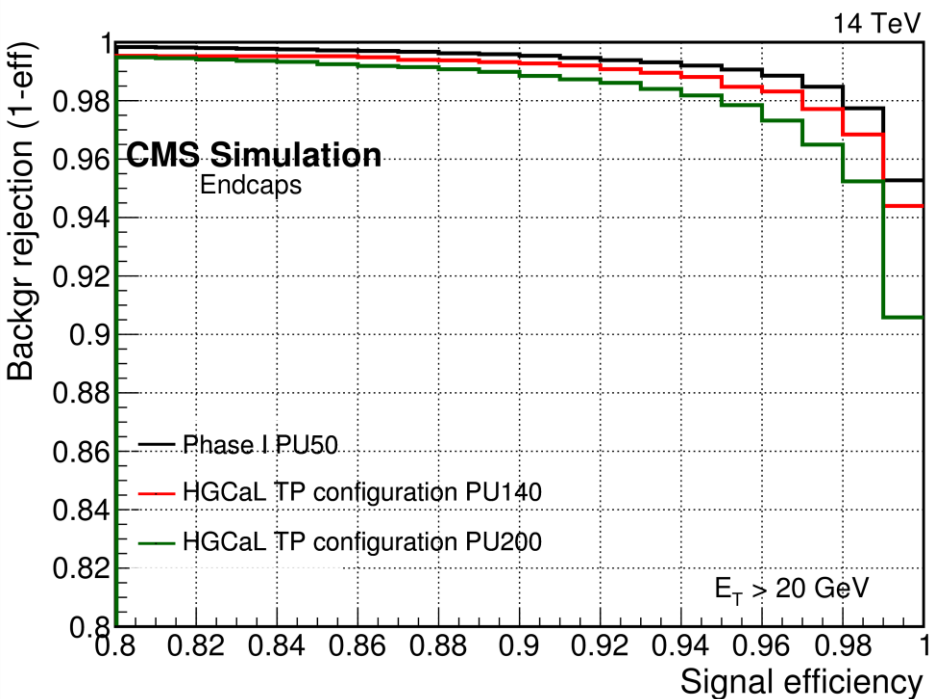


E_T^{miss} distribution for the perpendicular component of hadronic recoil to Z boson, measured in $Z \rightarrow \mu\mu$ at $\langle \text{PU} \rangle = 140$ with the high- η tracking extension (red) and without (blue). Results for Phase I at $\langle \text{PU} \rangle = 50$ (black) are also included

The E_T^{miss} distribution for the reference detector with (green) and without (red) the high- η tracking extension and the ratio of the number of events observed without and with the tracking extension vs E_T^{miss} for events at $\langle \text{PU} \rangle = 140$ and $\langle \text{PU} \rangle = 200$

HL-LHC – ECAL Performance

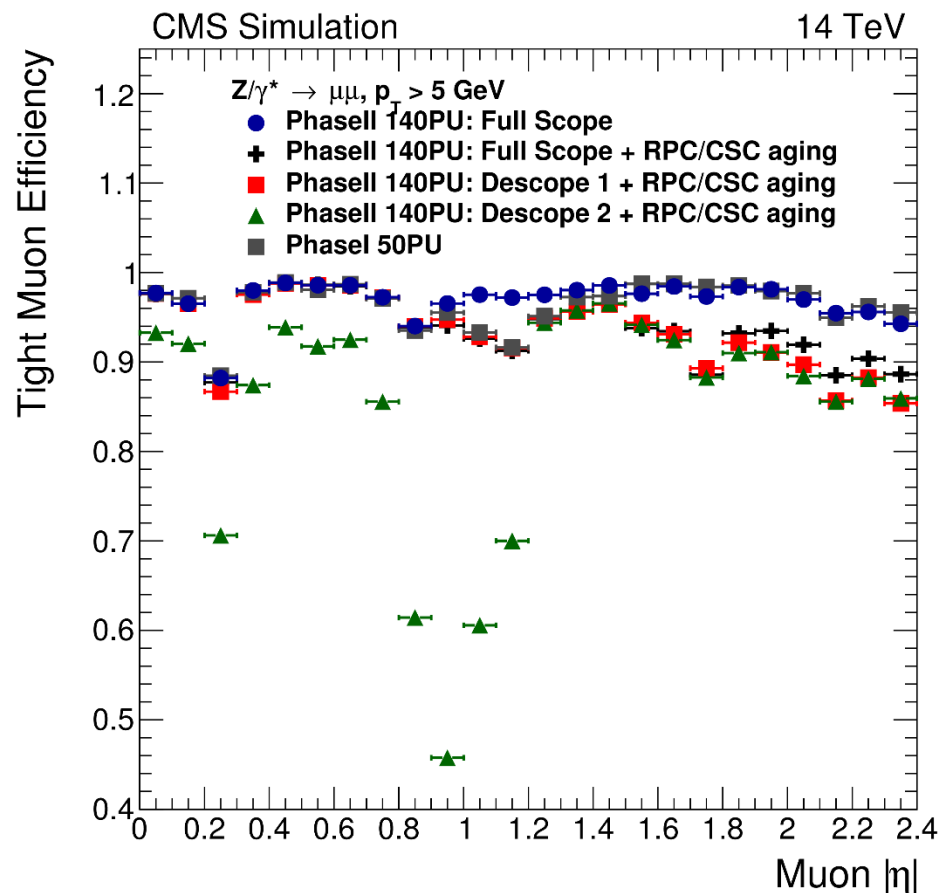
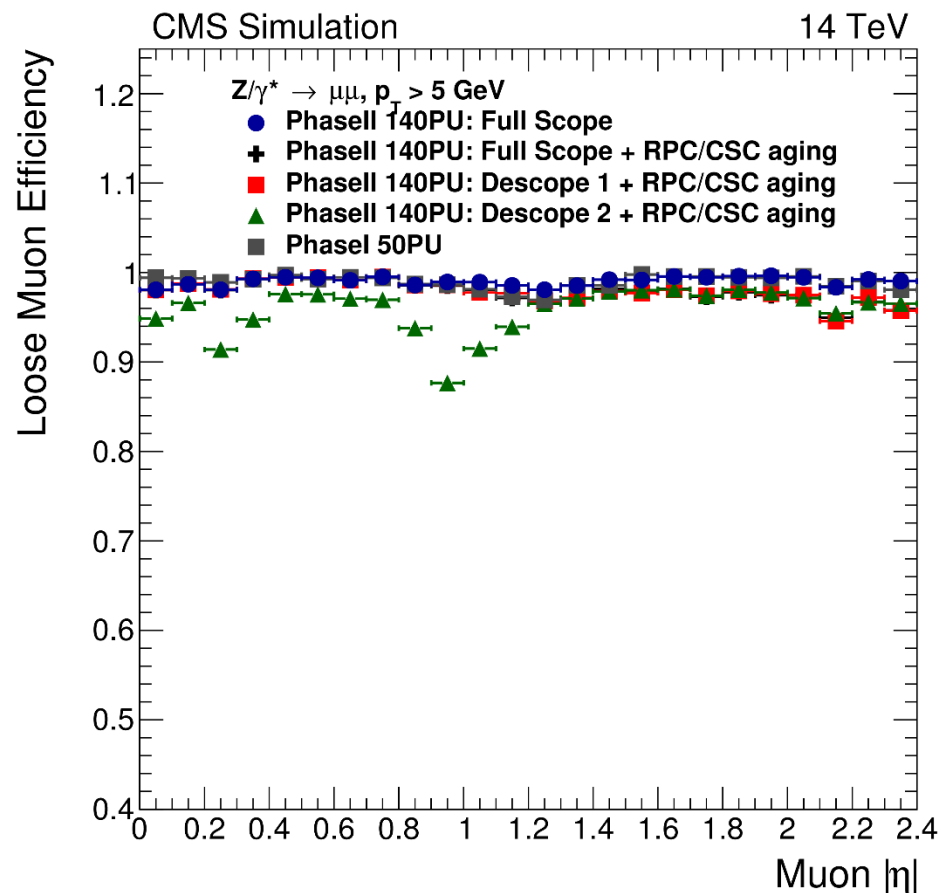
Results from Phase-2 CMS Upgrade Scope Document



Electron identification in the endcap calorimeter for Drell-Yan events (left) and photon selection efficiency and fake rate in bins of $|\eta|$ for samples of simulated events with a photon and a jet (right). Results are shown for reference configuration at $\langle \text{PU} \rangle = 140$ (red) and $\langle \text{PU} \rangle = 200$ (green) and Phase I configuration at $\langle \text{PU} \rangle = 50$ (black)

HL-LHC – Muon Performance

Results from Phase-2 CMS Upgrade Scope Document



Loose Muon identification efficiency (left) and Tight Muon Identification efficiency (right) in Drell-Yan events as a function of the $|\eta|$ of the simulated muon for different detector scenarios