CMS detector performance for HL-LHC

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for the CMS collaboration

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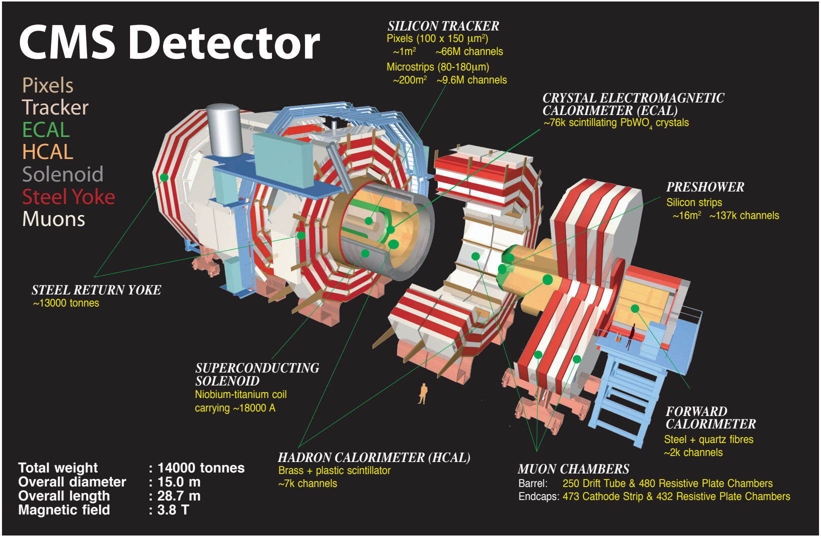
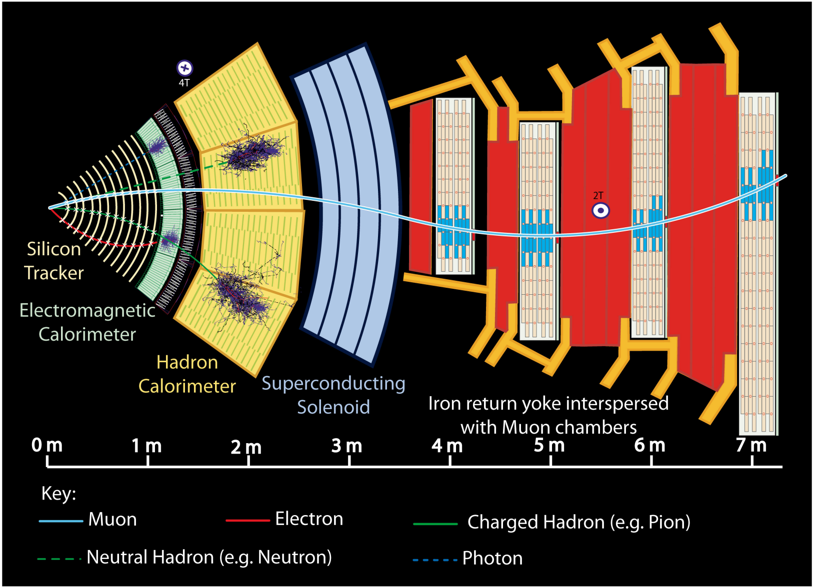
Workshop on the physics of HL-LHC,
and perspectives at HE-LHC
CERN

The Current CMS Detector



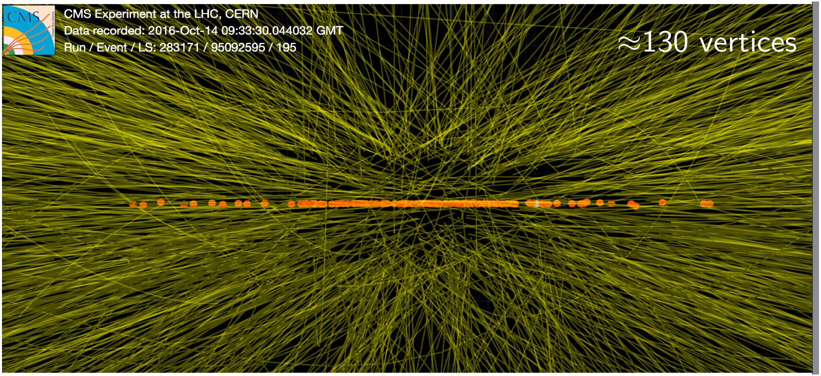
The Current CMS Detector



HL-LHC and Phase II Upgrades

- **HL-LHC:** Significant upgrade of LHC and injectors to increase beam intensity
  - $L_{\text{inst}} > 5 \times 10^{34}$ cm^{-1} s^{-1}, up to **140-200 pileup**
  - Ultimate integrated luminosity target of **3000 fb**$^{-1}$ (baseline)
- **Phase II Detector Upgrades:** Significant upgrades of ATLAS and CMS for HL-LHC conditions
  - Radiation hardness
  - Mitigate physics impact of high pileup
- Physics Goals/Opportunities:
  - Precision Higgs Measurements
  - Higgs Self Coupling
  - Precision Electroweak Measurements
  - Extend BSM searches to smaller production cross sections
  - Precision measurements of rare B decays
  - Heavy Ion Physics

Proof of Concept, Proof of Challenge



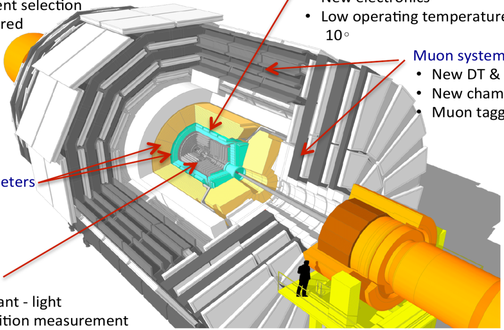
- Real-life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches

CMS Phase II Upgrades

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature ≈ 10◦

Muon systems
- New DT & CSC electronics
- New chambers $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

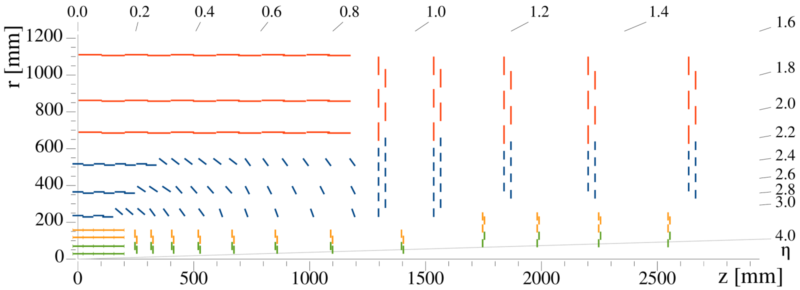


New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta \simeq 3.8$

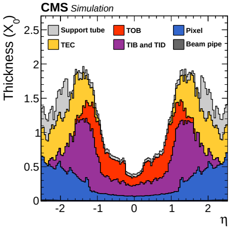
Beam radiation and luminosity
Common systems and infrastructure

Tracker Upgrades

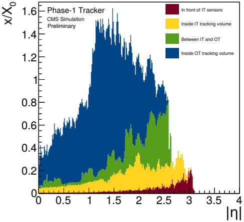


- Upgraded tracking detectors to cope with increased radiation hardness and occupancy demands
- Rapidity coverage of inner tracker (pixel detector) extended to $|\eta| = 4$
- Addition of hardware track trigger capabilities

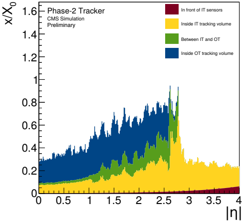
Evolution of the Material Budget



(a) Phase-0



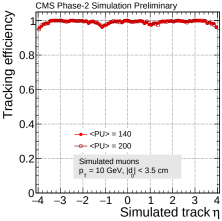
(b) Phase-1 (Now)



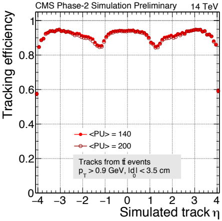
(c) Phase-2

- Substantial reduction of the material budget with respect to present detector

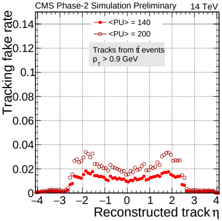
Tracking Performance: Efficiency/Fake Rate



(a) ϵ (High p_T muons)



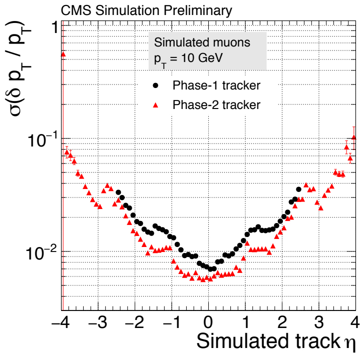
(b) Efficiency



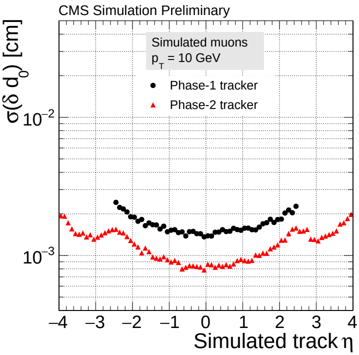
(c) Fake Rate

- High efficiency maintained across coverage
- Significant, but manageable increase of the fake rate with pileup

Tracking Transverse Momentum/Impact Parameter Resolution



(a) p_t

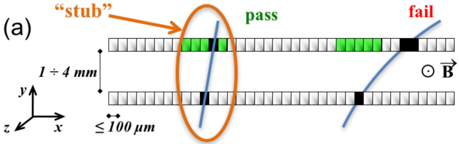


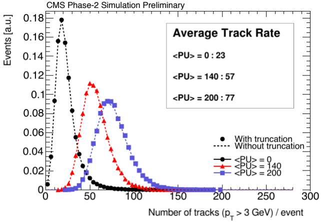
(b) d_0

- Significant improvements in resolution with respect to current detector

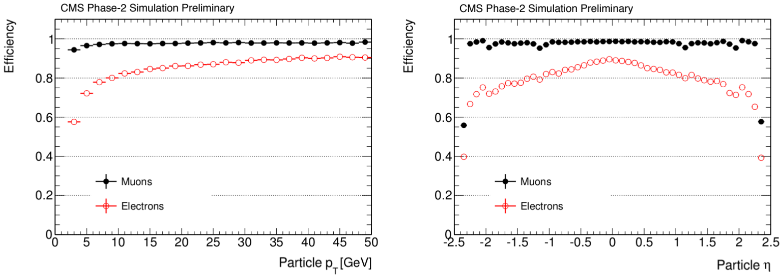
L1 Track Trigger

- Outer tracker provides hardware trigger capabilities
- Readout of full detector at 40 MHz is not feasible $\rightarrow$ p_T modules with two closely spaced sensors provide a **local** p_T measurement, and allow on-detector application of p_T thresholds for hardware trigger
- Hardware trigger receives track stubs with $p_T > 2$ GeV $\rightarrow$ 10-100x reduction in data-volume
- Coverage up to $|\eta| = 2.4$



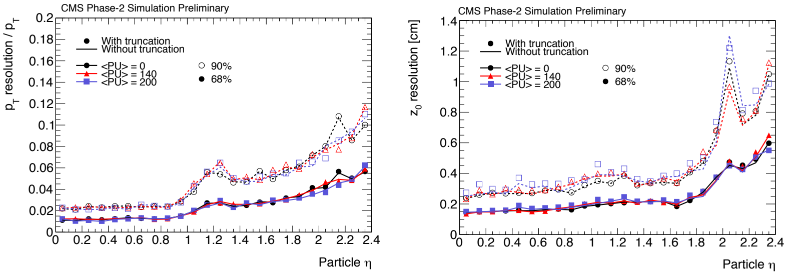


L1 Track Trigger Performance



- Performance shown for $p_T > 3$ GeV
- Excellent efficiency possible for muons
- Electrons are more challenging due to material interactions (further algorithmic improvements possible)

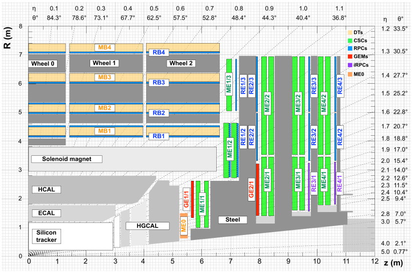
L1 Track Trigger Performance



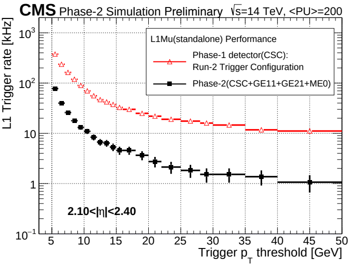
- Performance shown for $p_T > 3$ GeV
- z_0 resolution sufficient for some level of pileup mitigation

Muon System Upgrades

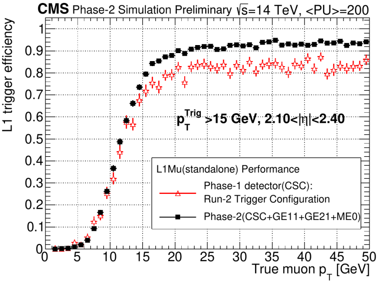
- Upgrade electronics for radiation hardness and upgraded trigger/readout requirements
- Additional GEM chambers in front of existing forward muon (CSC) system, and additional RPC's to improve trigger and reconstruction performance in region $1.6 < |\eta| < 2.4$
- ME0: New GEM chambers to extend muon system coverage to $|\eta| = 2.8$ and further improve trigger and reconstruction performance in $2.0 < |\eta| < 2.4$ region



- Improved measurement of forward muons drastically reduces trigger rate at a given threshold, with increased efficiency



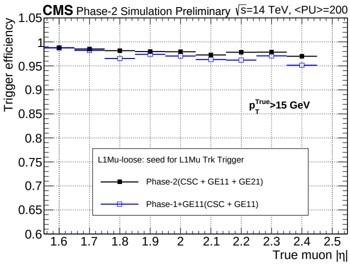
(a) Trigger Rate



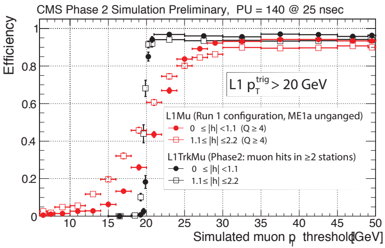
(b) Trigger Eff.

Level 1 Muon Trigger

- High efficiency maintained over full trigger coverage up to $|\eta| < 2.4$ (further improvement possible with addition of ME0)
- Combination with track trigger dramatically improves momentum resolution



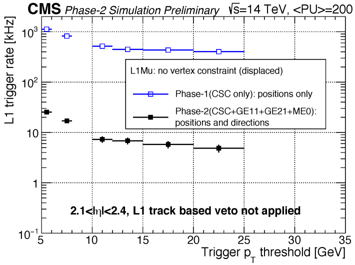
(a) Efficiency



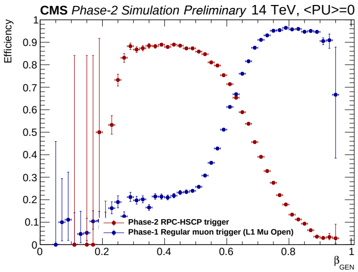
(b) Turn-on

Level 1 Displaced Muon Trigger

- Improved measurement of forward muons allows efficient triggering on displaced muons with greatly reduced rates (further reduction possible with track trigger veto)
- Improved timing resolution of RPC's (O(ns)) allows efficient triggering on (slow-moving) Heavy Stable Charged Particles



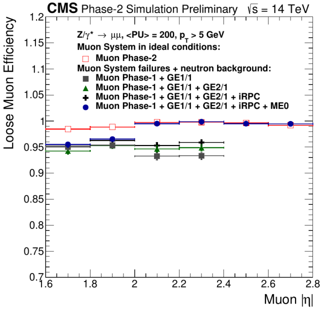
(a) Displaced Rate



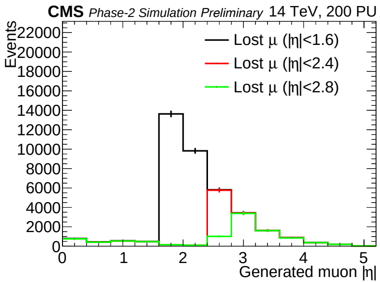
(b) HSCP Eff.

Extended Muon η Coverage

- ME0 extends offline muon reconstruction and identification to $|\eta| < 2.8$, relevant for many searches and measurements
- 17% increase in acceptance for $H \to ZZ \to 4\mu$
- Substantial reduction in "lost lepton" background for searches with same-sign dileptons



(a) Reco+ID Efficiency

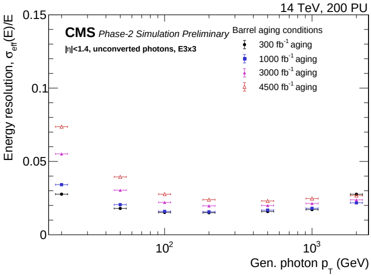


(b) "Lost lepton" $|\eta|$ from WZ

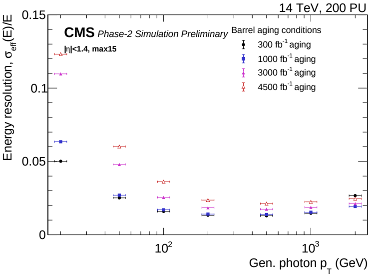
Barrel Electromagnetic Calorimeter Upgrade

- Lower operating temperature to mitigate additional noise in APD's due to radiation damage
- Upgrade electronics to accommodate trigger rate and latency requirements
- New electronics will provide full detector granularity to hardware trigger
- Significantly reduced shaping time and increase of sampling rate to 160 MHz for precision timing, improved suppression of anomalous signals and out-of-time pileup

Barrel Photon Energy Resolution



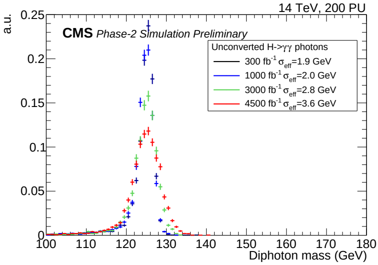
(a) Unconverted (3x3)



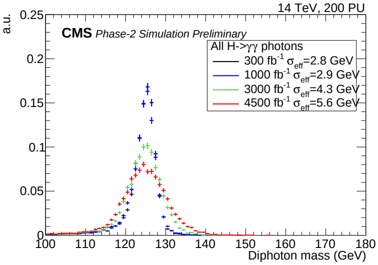
(b) Inclusive

- Several contributions to the energy resolution
  - Additional noise in APD's induced by radiation damage
  - Constant term degraded by hadron-damage induced longitudinal non-uniformities
  - In-time pileup contributes additional energy to clusters
  - No containment/multivariate energy corrections tuned for these conditions

Barrel Photon Energy Resolution



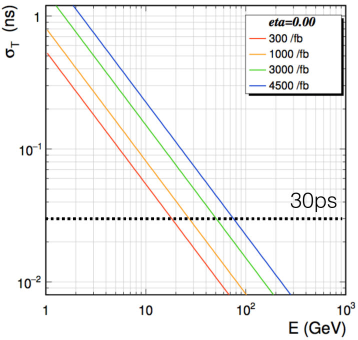
(a) Unconverted (3x3)



(b) Inclusive

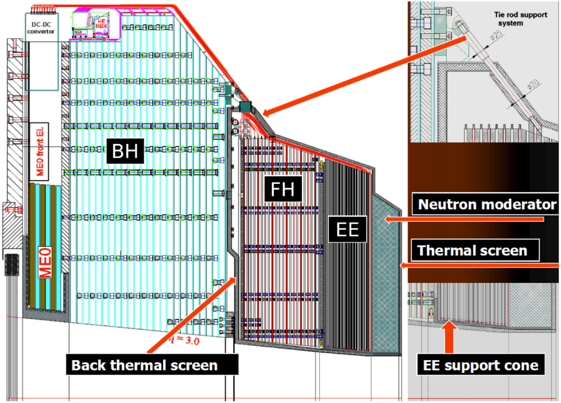
- Containment/Multivariate energy corrections not present here, but have large demonstrated gains in Run 1/2
- Expectation that with optimization of clustering, pileup suppression, multivariate energy corrections, performance will be much closer to current detector/conditions

Barrel Electromagnetic Calorimeter Precision Timing



- Timing resolution limited by the APD dark current rather than the crystals themselves
- Target resolution of 30 ps achievable for moderate energy photons
- Precision timing can help matching of photons to primary vertices for photon id, di-photon invariant mass

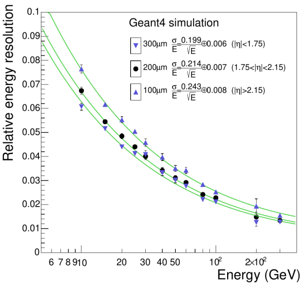
Endcap Calorimeter Upgrade



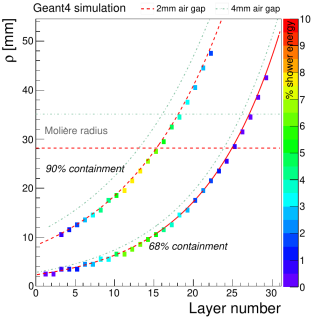
- Entirely new endcap calorimeter: High granularity silicon detector with tungsten/brass absorber in EE/FH
- Plastic scintillator and brass absorber for back hadronic section

Endcap Calorimeter Performance

- Full set of performance studies to come with TDR in the near future



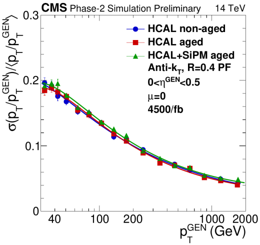
(a) Energy Resolution



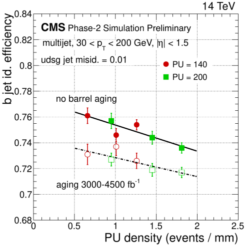
(b) Shower Profile

- Silicon sensors have excellent time resolution for sufficiently large charge deposition → precision timing for ∼ all electromagnetic showers and hadronic showers of sufficiently high energy

(Central) Jet/b-tagging Performance

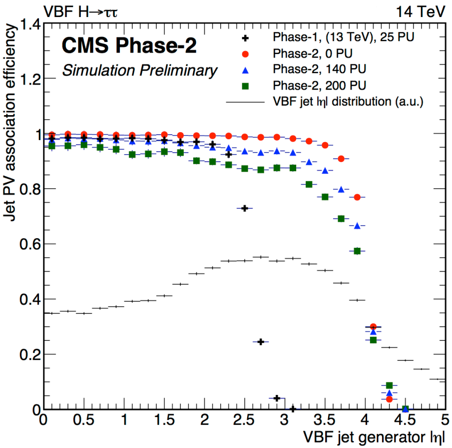


(a) Jet Energy Res.



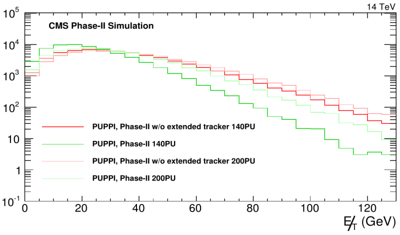
(b) b-tag Efficiency

Pileup Jet Discrimination

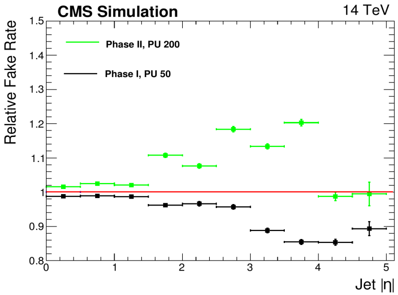


- Extension of tracking acceptance leads to greatly improved pileup jet suppression over wider range of phase space for VBF-like processes

But there are still challenges: Physics Impact of Pileup (from CMS Phase-2 Scoping Document)



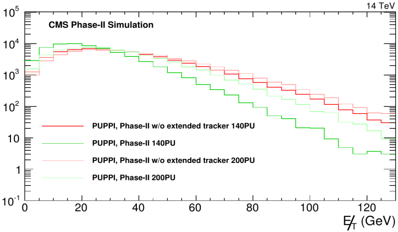
(a) $\not\!\!E_T$ Tails



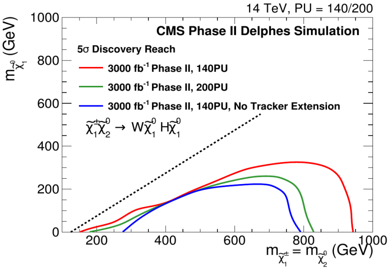
(b) Jets from PU

- Contamination of **neutrals** scales with overall PU to first order

Physics Impact of Pileup (from CMS Phase-2 Scoping Document)



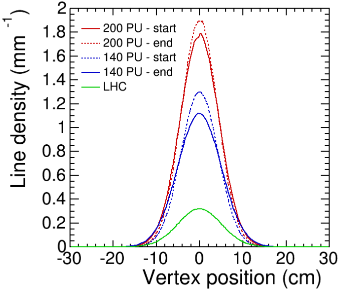
(a) $\not{E}_T$ Tails

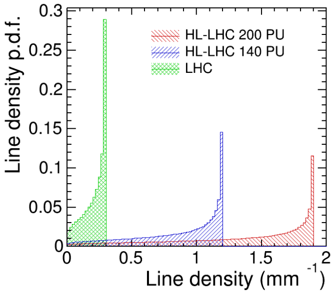


(b) EWK SUSY Search

- Significant impact on physics reach

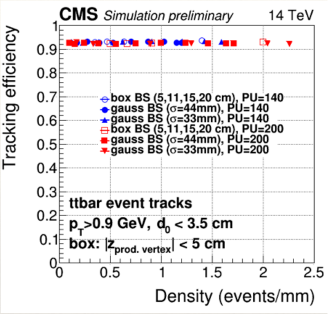
HL-LHC Luminous Region



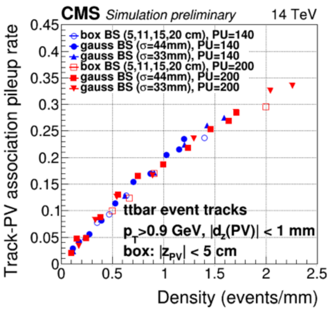


- Total amount of pileup and width of luminous region evolve over the course of a fill
- Linear **pileup density** further varies over the luminous region

Pileup Density Impact: Track-PV Association



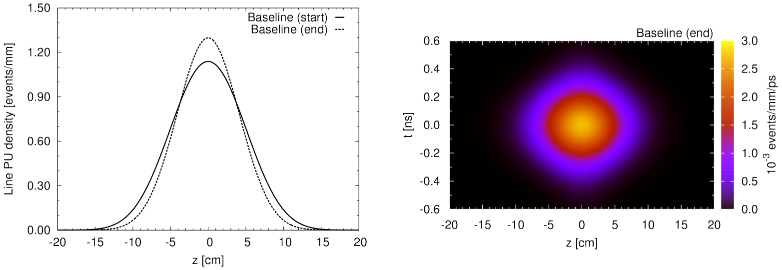
(a) Tracking Efficiency



(b) Pileup Tracks in Hard PV

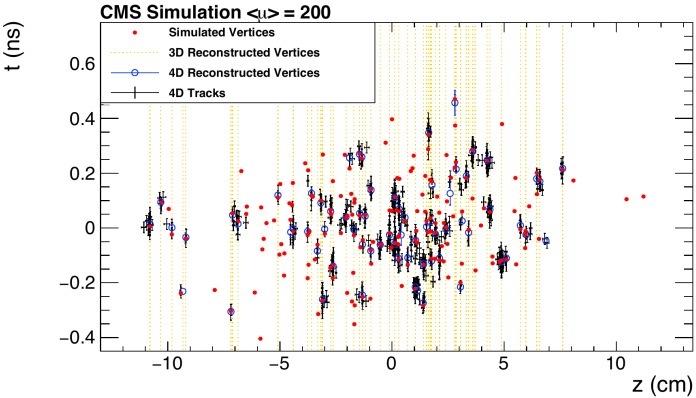
- Primary vertex and tracks from hard interaction can still be reconstructed efficiently, but pileup contamination increases rapidly as a function of pileup density (pure geometric effect, independent of total pileup)
- **Quantities based on charged particles are currently nearly free of pileup, will not be so at HL-LHC**

Mitigation with Precision Timing



- Interactions are also distributed in time with a spread of 150-200 ps
- A detector with 10's of ps timing resolution could meaningfully distinguish between interactions on the basis of timing

Mitigation with Precision Timing

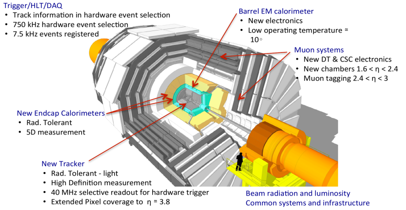


- With sufficient time resolution and coverage for charged particles, traditional three-dimensional vertex fit can be upgraded to a four-dimensional fit

Additional Timing Capabilities

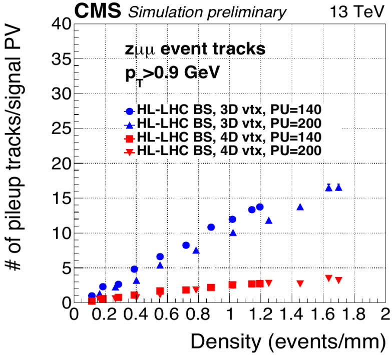
- Calorimeter upgrades can already provide precision timing for high energy photons in the central region, moderate energy photons, and higher energy hadrons in the forward region
- **Additional capabilities: MIP timing to cover large fraction of charged particles in the event**
- **Targeting $\sigma_t = 30$ ps**
- **Extension to Phase-II Upgrade: MIP timing layer**
- Concept for central region: Thin **LYSO + SiPM** layer built into tracker barrel support tube (in between tracker and ECal Barrel)

  $\rightarrow$ precision timing for charged particles and converted photons

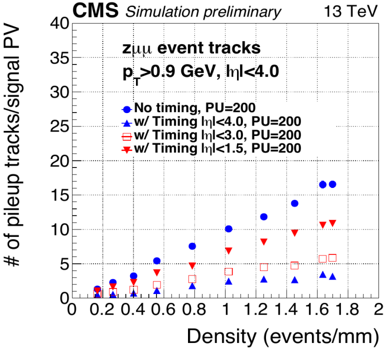


- Concept for forward region (more stringent radiation hardness requirements): **LGAD** (Silicon with Gain), with baseline location as additional final layer of strip tracker
- TP in preparation

Effect of Precision Timing on Track-PV Association



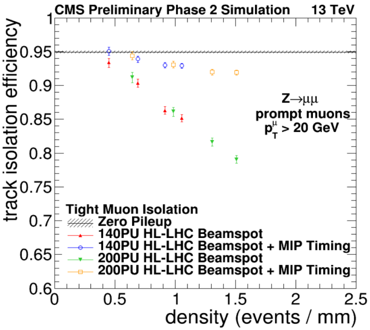
(a) Total # of tracks/hard PV



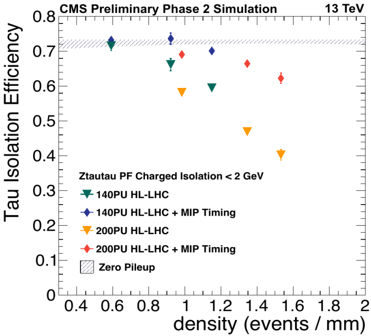
(b) η Coverage Variation

- $\sim$ **5x reduction in effective pileup in terms of charge multiplicity**

Lepton Charged Isolation with Precision Timing



(a) Prompt μ Efficiency



(b) Prompt τ Efficiency

- Significant effect on lepton charged isolation efficiency at fixed working point ($\sim$ constant background rejection)

Conclusions

- Comprehensive set of upgrades in progress for CMS at HL-LHC in order to cope with increased radiation dose and maintain physics performance at high pileup
- Still to come at this workshop: All of the exciting physics which is enabled by this upgraded detector with multiple ab^{-1} of data from HL-LHC